Azimuthal asymmetries in unpolarized Drell-Yan processes and the Boer-Mulders distributions of antiquarks

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Using a previous extraction of the quark Boer-Mulders distributions from semiinclusive deep inelastic scattering data, we fit the unpolarized Drell-Yan data on the cos 2φ asymmetry, determining the antiquark Boer-Mulders distributions. A good agreement with the data is found in the region of low q_T, where the transverse-momentum factorization approach applies.

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I. INTRODUCTION

One of the most relevant results of high-energy spin physics in the last decade has been the discovery of many interesting correlations between the transverse momentum and the transverse spin of quarks (for reviews, see Ref. [1, 2]). A surprising consequence of these correlations is that there may exist non-trivial spin effects in unpolarized hard processes, generated by a leading-twist, chiral-odd, transverse-momentum dependent distribution function, the so-called Boer–Mulders function h_1T(x, k_T^2) [3], which represents a transverse–polarization asymmetry of quarks inside an unpolarized hadron. The origin of h_1T was clarified in Refs. [4–7] and the first calculation in a realistic quark–diquark model was reported by Goldstein and Gamberg [8]. In 1999 Boer [9] suggested that h_1T could explain the large cos 2φ asymmetries observed in unpolarized πN Drell-Yan production [10, 12], which were not understood in terms of purely perturbative QCD effects [10, 13, 14]. This finding was confirmed by more refined model calculations [15]. A comparable or even larger asymmetry is predicted for pp Drell-Yan production [16, 21], a process to be studied in the next years at the GSI High-Energy Storage Ring [22, 23]. While πN and pp probe valence distributions, pp and pD Drell-Yan reactions are sensitive to the sea distributions and therefore the corresponding cos 2φ asymmetries are expected to be smaller. This is indeed what the E866/NuSea experiment found: the cos 2φ dependence observed in pD dimuon production is of the order of few percent [24, 25].

A cos 2φ asymmetry also occurs in unpolarized semiinclusive deep inelastic scattering (SIDIS), where it has been measured in the low transverse-momentum region by HERMES [26], COMPASS [27] and CLAS [28]. In SIDIS the Boer–Mulders distribution couples to a chiral-odd fragmentation function, the Collins function h_1T(x, k_T^2), which represents the fragmentation of transversely polarized quarks into polarized hadrons. Recently, we presented a systematic phenomenological analysis of the various contributions to the cos 2φ asymmetries in unpolarized SIDIS [30], and of the preliminary HERMES and COMPASS results [31]. In the kinematics of these experiments the perturbative term is found to be negligible, whereas the order-k_T^2/Q^2 contribution from non-collinear kinematics (the so-called Cahn effect [32, 33]) is quite large. The Boer–Mulders effect is also sizable and generates a negative (positive) asymmetry for π^− (π^+), due to the expected negative sign of the u distribution. Combining the Cahn contribution (which is positive and roughly the same for π^+ and π^−) with the Boer-Mulders contribution, we predicted a π^− asymmetry larger than the π^+ asymmetry [30]. Our results turned out to be in fair agreement with the first SIDIS measurements of the cos 2φ asymmetry, as shown in our most recent study [31], where we attempted an extraction of the Boer-Mulders distributions from the HERMES and COMPASS preliminary data. Since the present statistics is not sufficient to allow a complete determination of h_1T, the strategy of Ref. [31] was to use the same functional form as the Sivers function obtained from SIDIS data in Ref. [34] and parametrize the normalization coefficient. Results compatible with impact-parameter expectations [33] combined with lattice findings [30], and with model calculations [37] were found. However, the SIDIS data leave the Boer-Mulders sea totally unconstrained. Thus, in order to get the antiquark distributions h_1T one needs an extra source of information.

The purpose of the present paper is indeed to extract some information on the antiquark Boer-Mulders distributions from the Drell-Yan pp and pD data on the cos 2φ asymmetry [24, 25]. We perform a fit to these data in the region of low q_T, where the transverse-momentum factorization is expected to be valid [38] and the perturbative effects are small. Since in Drell-Yan processes the Cahn contribution to the cos 2φ asymmetry is known to be negligible [39], an analysis in terms of the Boer-Mulders effect alone is possible.
II. THE COS 2Φ ASYMMETRY IN DRELL-YAN PROCESSES

The angular differential cross section for the unpolarized Drell-Yan process is usually parametrized as

$$\frac{1}{\sigma_{DY}^{\text{DY}}} \frac{d\sigma_{DY}^{\text{DY}}}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left(1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi\right).$$  \hspace{1cm} (1)

where \(\theta\) and \(\phi\) are, respectively, the polar angle and the azimuthal angle of dileptons in a dilepton center of mass frame. In particular, we adopt the Collins–Soper frame [40], where \(q\) is the angle between the dilepton axis and the bisector of \(P_1\) and \(-P_2\) (the momenta of the colliding hadrons), and \(\phi\) is the angle between the lepton and hadron planes. We denote by \(q_T \equiv |q_T|\) the transverse momentum of the lepton pair (or, equivalently, of the virtual photon). The \(\nu\) parameter in (1) is the \(\cos 2\phi\) asymmetry we are interested in.

A non-collinear factorization theorem for Drell-Yan process has been proven by Ji, Ma and Yuan [38] for \(q_T \ll Q\) (where \(Q\) is the invariant mass of the lepton pair). At order \(a_s^4\), the \(\phi\)-independent term of the unpolarized Drell-Yan cross section is

$$\frac{d\sigma_{DY}^{\text{DY}}}{d\Omega dx_1 dx_2 d^2q_T} = \frac{\alpha_{em}^2}{12 Q^2} (1 + \cos^2 \theta) \sum a e^2 a \int d^2k_{1T} d^2k_{2T} \delta^2(k_{1T} + k_{2T} - q_T) \left[ f_a^1(x_1, k_{1T}^2) f_a^1(x_2, k_{2T}^2) + (1 \leftrightarrow 2) \right].$$  \hspace{1cm} (2)

Here \(f_1(x, k_T^2)\) is the unintegrated quark number density.

The Boer-Mulders contribution to the unpolarized cross-section reads [3]

$$\frac{d\sigma_{DY}^{\text{DY}}}{d\Omega dx_1 dx_2 d^2q_T} \bigg|_{\cos 2\phi} = \frac{\alpha_{em}^2}{12 Q^2} \sin^2 \theta \sum a e^2 a \int d^2k_{1T} d^2k_{2T} \delta^2(k_{1T} + k_{2T} - q_T)$$
$$\times \frac{(2\hat{h} \cdot k_{1T} \hat{h} \cdot k_{2T} - k_{1T} \cdot k_{2T})}{m_N^2} \left[ \hat{h}_1(x_1, k_{1T}^2) \hat{h}_1(x_2, k_{2T}^2) \cos 2\phi + (1 \leftrightarrow 2) \right],$$

with \(\hat{h} \equiv q_T/q_T\).

From Eqs. (2) and (3) we get the following expression for the coefficient \(\nu\) (setting \(\lambda = 1, \mu = 0\)):

$$\nu = 2 \sum a e^2 a \hat{H}[\hat{h}_1^a, \hat{h}_1^a] \sum a e^2 a \hat{F}[f_1^a, f_1^a],$$ \hspace{1cm} (4)

with the following notations:

$$\hat{H}[\hat{h}_1^a, \hat{h}_1^a] = \int d^2k_{1T} d^2k_{2T} \delta^2(k_{1T} + k_{2T} - q_T) \times f_1^a(x_1, k_{1T}^2) f_1^a(x_2, k_{2T}^2)$$
$$= \int dk_{1T} k_{1T} \int_0^{2\pi} d\chi f_1^a(x_1, k_{1T}^2) f_1^a(x_2, |q_T - k_{1T}|^2),$$ \hspace{1cm} (5)

$$\hat{F}[f_1^a, f_1^a] = \int d^2k_{1T} d^2k_{2T} \delta^2(k_{1T} + k_{2T} - q_T) \left(\frac{2\hat{h} \cdot k_{1T} \hat{h} \cdot k_{2T} - k_{1T} \cdot k_{2T}}{m_N^2}\right) h_1^a(x_1, k_{1T}^2) h_1^a(x_2, k_{2T}^2)$$
$$= \int dk_{1T} k_{1T} \int_0^{2\pi} d\chi k_{1T}^2 + q_T k_{1T} \cos \chi - 2 k_{1T}^2 \cos^2 \chi h_1^a(x_1, k_{1T}^2) h_1^a(x_2, |q_T - k_{1T}|^2),$$ \hspace{1cm} (6)

where \(\chi\) is the angle between \(q_T\) and \(k_{1T}\) and we omitted for simplicity the \((1 \leftrightarrow 2)\) terms. The asymmetry \(\nu\) in Eq. (4) depends on the kinematic variables \(x_1, x_2, Q\) and \(q_T\).

In general, there is another contribution to \(\nu\) arising from the Cahn effect, that is from purely kinematic transverse-momentum corrections to the ordinary parton model formulas. However, as shown in Ref. [39], the Cahn contribution to \(\nu\) is proportional to \((\langle k_{1T}^2 \rangle - \langle k_{2T}^2 \rangle)^2\) and hence negligible, or even strictly vanishing when the average transverse momenta of quarks (or antiquarks) in the two colliding hadrons are equal (which is what we assume here). Thus, the Boer-Mulders effect is the only non-perturbative source of a \(\cos 2\phi\) asymmetry up to order \(q_T^2/Q^2\).
\[ N_u = -18 \quad N_d = -45 \]
\[ \alpha_u = 0.73 \quad \alpha_d = 1.08 \]
\[ \beta_u = \beta_d = 3.46 \quad \mu^2 = 0.34 \text{ GeV}^2 \]

**TABLE I:** Parameters of the Boer-Mulders quark distributions \[31\].

### III. PARAMETRIZATIONS OF DISTRIBUTION AND FRAGMENTATION FUNCTIONS

Let us consider first of all the \( kT \)-dependent unpolarized distribution functions (where \( kT \) stands either for \( k_{1T} \) or for \( k_{2T} \)). We assume that these functions have a Gaussian behavior in \( kT \),

\[ f_1^q(x, kT^2) = f_1^q(x) \frac{e^{-k^2/(kT^2)^2}}{\pi(kT^2)} \]

which is supported by lattice studies \[41\] and by a recent phenomenological study of SIDIS and DY cross sections \[39\]. The integrated unpolarized distribution functions \( f_1^q \) are taken from the GRV98 fit \[42\].

Since the available SIDIS data do not allow a full extraction of the Boer-Mulders function, in Ref. \[31\] we assumed \( h_1^+ \) to be simply proportional to the Sivers function \( f_{1T}^1 \),

\[ h_1^{\perp a}(x, kT^2) = \lambda_a f_{1T}^{1a}(x, kT^2) \]

with \( f_{1T}^{1a} \) taken from a phenomenological analysis of the Sivers asymmetry \[34\] and the coefficient \( \lambda_a \) fitted to the SIDIS \( \cos 2\phi \) data. Various theoretical arguments (based on the impact-parameter picture \[35\], on large-\( N_c \) arguments \[36\], and on model calculations \[37, 38\]) suggest that the \( u \) and \( d \) components of \( h_1^+ \), at variance with \( f_{1T}^1 \), should have the same sign and in particular be both negative (which means that \( \lambda_d \) should be negative). This is indeed what we found in Ref. \[31\]. Moreover, the impact-parameter approach \[35\] combined with lattice results \[36\] predicts a \( u \) component of \( h_1^+ \) larger in magnitude than the corresponding component of \( f_{1T}^1 \), and the \( d \) components of \( h_1^+ \) and \( f_{1T}^1 \) with approximately the same magnitude (and opposite sign).

In our SIDIS analysis the quark Boer-Mulders distributions were parametrized as

\[ h_1^{\perp a}(x, kT^2) = N_a x^{\alpha_a} (1-x)^{\beta_a} e^{-k^2_2/\mu^2} f_1^{a}(x, kT^2) \]

with the parameters \( \alpha_a, \beta_a, \mu \) borrowed from Ref. \[31\] and \( N_a \) fitted to the data. The values of these parameters are collected in Table I. Notice that, when used to calculate DY asymmetries, the Boer-Mulders distributions determined in SIDIS must be sign-reversed \[31\].

Concerning the Boer-Mulders antiquark distributions, the SIDIS data are quite insensitive to them. Therefore, in Ref. \[31\] these distributions were not fitted to the data, but just taken to be equal in magnitude to the corresponding Sivers distributions.

The Drell-Yan process, on the contrary, probes the products of quark and antiquark distributions. Thus the Drell-Yan measurements of the \( \cos 2\phi \) asymmetry \[24, 25\] can at least in principle give information about the antiquark sector of the Boer-Mulders function. An analysis of the DY \( \cos 2\phi \) asymmetry has been already performed by other authors \[45, 46\]. However, when extracting the Boer-Mulders distributions from the present DY data, one should keep in mind that the \( kT \)-factorization approach applies to the low-\( qT \) region only, whereas at large \( qT \) the observed \( \nu \) values are likely to be explainable in terms of perturbative QCD \[47, 48\]. Therefore, in our analysis we will only consider the low-\( qT \) DY data.

The antiquark Boer-Mulders distributions are parametrized as

\[ \bar{h}_1^{\perp a}(x, kT^2) = N_{\bar{a}} x^{\alpha_{\bar{a}}} (1-x)^{\beta_{\bar{a}}} e^{-k_2^2/\mu^2} f_1^{a}(x, kT^2) \]

with the same \( \alpha, \beta \) and \( \mu \) parameters as for the Sivers antiquark distributions, and the normalization coefficients \( N_{\bar{a}} \) and \( N_{\bar{d}} \) fitted to the data.

The final parameters to be considered are the average values of the quark and antiquark transverse momenta in the two hadrons, \( \langle k_{1T}^2 \rangle \) and \( \langle k_{2T}^2 \rangle \). We take these parameters to be equal to each other, \( \langle k_{1T}^2 \rangle = \langle k_{2T}^2 \rangle = \langle k_{T}^2 \rangle \), and we choose for them two different values:

Fit 1 : \( \langle k_{T}^2 \rangle = 0.25 \text{ GeV}^2 \); Fit 2 : \( \langle k_{T}^2 \rangle = 0.64 \text{ GeV}^2 \).
FIG. 1: The curves represent the results of our fit 1 to the $\nu$ asymmetry of $pD$ DY production. Data are from Ref. [24].

The smaller value, 0.25 GeV$^2$, is the one we used in our analysis of the Boer-Mulders effect in SIDIS [31], and is taken from the study of the Cahn effect of Ref. [50].

The larger value, 0.64 GeV$^2$, is the one obtained by D’Alesio and Murgia [51] in their analysis of $pp$ scattering data at $\sqrt{s} \approx 20$ GeV. A recent phenomenological study of the transverse-momentum dependence of DY cross sections has obtained a very similar value [39].

IV. RESULTS

The E866/NuSea Collaboration presented data on the angular distributions of DY dimuons in $pD$ [24] and $pp$ interactions [25] over the kinematic range:

$$4.5 < Q < 15 \text{ GeV}, \quad 0 < q_T < 4 \text{ GeV}, \quad 0 < x_F < 0.8.$$ 

Concerning $q_T$, as already mentioned, we will only consider the data in the $q_T < 1.5$ GeV region, where the $k_T$ factorization applies and the perturbative contribution, roughly proportional to $q_T^2/Q^2$, is small.

Our fit 1 to the E866/NuSea data on $\nu$ is shown in Fig. 1 for $pD$ and in Fig. 2 for $pp$. The $\chi^2$ per degree of freedom is 1.24. The vertical error bars represent the statistical uncertainties. Notice that the experimental bins in all variables ($x_1$, $x_2$ and $q_T$) are quite large: for instance, the three points in the $q_T$ plot correspond (in GeV) to $(0,0.5)$, $(0.5,1.0)$, $(1.0,1.5)$. In all figures we only showed the central values of the bins.

Concerning fit 2, the corresponding curves overlap those of fit 1, with the same value of $\chi^2$/d.o.f. The difference between the Gaussian widths of the distribution is in fact compensated by the different normalizations of the antiquark distributions that we obtain from the two fits.

The values of the parameters of the antiquark distributions are listed in Table II. The first $k_T^2$ moments of the antiquark distributions, i.e.

$$\bar{h}_{1(1)}^{a}(x) = \int d^2k_T \frac{k_T^2}{2m_N^4} \bar{h}_1^a(x, k_T^2)$$

are plotted in Fig. 3. One may notice the sensible difference between the distributions extracted from the two fits. The width of the Gaussian distribution is clearly a crucial parameter, but the scarcity of present data does not allow extracting it from the fit. A combined analysis of SIDIS and DY data, and possibly of various azimuthal asymmetries, might help to improve the situation.

Finally, let us compare the present work with with the results of a recent analysis [27] of the E866/NuSea measurements. In Ref. [25] both the quark and the antiquark distributions have been extracted from $pp$ and $pD$ DY data. Since in the DY cross section $h_{1a}^{\perp}$ always couples to $\bar{h}_{1}^{\perp}$, only the magnitude of the products $h_{1}^{\perp} \bar{h}_{1}^{\perp}$ is actually determined, and the signs of the distributions are undefined. In our analysis the use of both the DY and the SIDIS data allows constraining separately the magnitudes and the signs of the Boer-Mulders quark and antiquark distributions.
FIG. 2: Our fits to the $\nu$ asymmetry of pp DY production. Data are from Ref. [25].

$\alpha_\uparrow = \alpha_\downarrow = 0.79$, $\beta_\uparrow = \beta_\downarrow = 3.46$, $\mu^2 = 0.34 \text{ GeV}^2$

| Fit   | $N_\uparrow$ | $N_\downarrow$ | $\langle k^2_T \rangle$ |
|-------|--------------|-----------------|--------------------------|
| 1     | 3.6 ± 1.0    | 1.7 ± 1.4       | 0.25 GeV$^2$             |
| 2     | 6.4 ± 1.7    | 3.0 ± 2.4       | 0.64 GeV$^2$             |

TABLE II: Parameters of the Boer-Mulders antiquark distributions.

V. CONCLUSIONS

We performed a fit to the DY data on the $\cos 2\phi$ asymmetry, showing that using the Boer-Mulders quark distributions previously extracted from SIDIS and a new set of antiquark distributions one can obtain a reasonably good description of $\nu$. However, the resulting Boer-Mulders functions depend rather strongly on the width of the Gaussian distributions, that is on the average $k^2_T$. In order to achieve a more precise determination of $h_1^\perp$ for quarks and antiquarks a combined fit of SIDIS and DY data, and of $\cos \phi$ and $\cos 2\phi$ asymmetries, must be performed. This work is now in progress.

FIG. 3: The first $k_T^2$ moments of the antiquark distributions from Fit 1 (solid curves) and Fit 2 (dashed curves).
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