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On the cos 2ϕ asymmetry in unpolarized leptoproduction

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Abstract

We investigate the origin of the cos 2ϕ azimuthal asymmetry in unpolarized semi-inclusive DIS. The contributions to this asymmetry arising from the intrinsic transverse motion of quarks are explicitly evaluated, and predictions for the HERMES and COMPASS kinematic regimes are presented. We show that the effect of the leading-twist Boer–Mulders function $h_1^\perp(x, \mathbf{k}_T^2)$, which describes a correlation between the transverse momentum and the transverse spin of quarks, is quite significant and may also account for a part of the cos 2ϕ asymmetry measured by ZEUS in the perturbative domain.

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1. Introduction

The importance of the transverse-momentum distributions of quarks for a full understanding of the structure of hadrons has been widely recognized in the last decade [1–4]. In semi-inclusive deep inelastic scattering (SIDIS), the $\mathbf{k}_T$-dependent distributions give rise to various azimuthal and/or single-spin asymmetries, which are currently under direct experimental scrutiny [5,6]. Two leading-twist distributions of great relevance for their phenomenological implications are the Sivers function $f_{1T}^\perp(x, \mathbf{k}_T^2)$ [7] and its chirally-odd partner $h_1^\perp(x, \mathbf{k}_T^2)$, the so-called Boer–Mulders function [4]. These two distributions describe time-reversal odd correlations between the intrinsic momenta of quarks and transverse spin vectors [8]. In particular, $f_{1T}^\perp$ represents an azimuthal asymmetry of unpolarized quarks inside a transversely polarized hadron, whereas $h_1^\perp$ represents a transverse-polarization asymmetry of quarks inside an unpolarized hadron. Recently, it has been proven by a direct calculation [9] that $f_{1T}^\perp$ and $h_1^\perp$ are non-vanishing: interference diagrams with a gluon exchanged between the struck quark and the target remnant generate non-zero asymmetries. The presence of a quark transverse momentum smaller than Q ensures that these asymmetries are proportional to M/k_T, rather than to M/Q, and therefore are leading-twist quantities. Moreover, a careful consideration of the Wilson-line structure of $\mathbf{k}_T$-dependent parton densities shows that $f_{1T}^\perp$ and $h_1^\perp$ are not forbidden by time-reversal invariance [10,11] (for a possible chiral origin of these distributions, see [12]).

The Sivers function $f_{1T}^\perp$ is known to be responsible for a $\sin(\phi - \phi_S)$ single-spin asymmetry in transversely polarized SIDIS [5,6,13]. The Boer–Mulders function $h_1^\perp$ produces azimuthal asymmetries in *unpolarized* reactions. Boer [14] argued that it can account for the observed cos 2ϕ asymmetries in unpolarized πN Drell–Yan processes [15,16]. This was quantitatively confirmed in [17,18], where $h_1^\perp$ was calculated in a simple quark-spectator model and shown to explain the Drell–Yan data fairly well.

A similar cos 2ϕ asymmetry occurs in unpolarized leptoproduction. As we shall see, there are three possible mechanisms generating this asymmetry: (1) non-collinear kinematics at order k_T^2/Q^2 [19]; (2) the leading-twist Boer–Mulders

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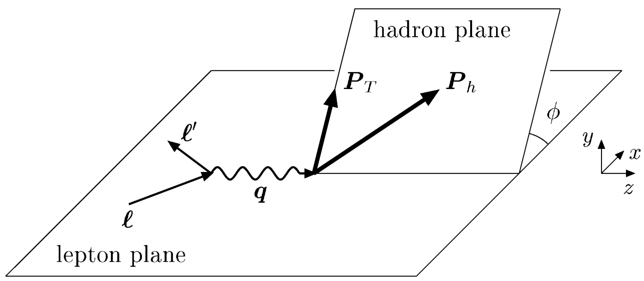

Fig. 1. Lepton and hadron planes in semi-inclusive deep inelastic scattering.

function [4] coupling to a specular fragmentation function, the so-called Collins function [20], which describes the fragmentation of transversely polarized quarks into unpolarized hadrons; (3) perturbative gluon radiation [21–24]. The purpose of this Letter is to study the first two sources of the $\cos 2\phi$ asymmetry, both related to the intrinsic transverse motion of quarks. They are especially relevant in the HERMES kinematic regime ($\langle Q^2\rangle \sim 2\ \mathrm{GeV}^2$), but the Boer–Mulders contribution, being leading twist, can also survive at higher Q^2 and partly account for the asymmetry measured by ZEUS in this domain [25].

In recent years, the $\cos 2\phi$ asymmetry in leptoproduction was phenomenologically studied by some authors [26,27]. In [26] only the $\mathcal{O}(k_T^2/Q^2)$ term and the perturbative contribution were included, whereas the Boer–Mulders effect was not considered. Our calculation is more similar to that presented in [27], the main differences being that we use a model for $h_1^\perp$ adjusted on the Drell–Yan data [18], and compute the asymmetry according to its experimental definition (which incorporates a cutoff on the transverse momentum of the final hadron).

2. The $\cos 2\phi$ asymmetry in unpolarized SIDIS

The process we are interested in is unpolarized SIDIS:

$$l(\ell) + p(P) \to l'(\ell') + h(P_h) + X(P_X). \tag{1}$$

The SIDIS cross section is expressed in terms of the invariants

$$x = \frac{Q^2}{2P\cdot q}, \qquad y = \frac{P\cdot q}{P\cdot \ell}, \qquad z = \frac{P\cdot P_h}{P\cdot q}, \tag{2}$$

where $q = \ell - \ell'$ and $Q^2 \equiv -q^2$. We adopt a reference frame such that the virtual photon and the target proton are collinear and directed along the z axis, with the photon moving in the positive z direction (Fig. 1). We denote by $\mathbf{k}_T$ the transverse momentum of the quark inside the proton, and by $\mathbf{P}_T$ the transverse momentum of the hadron h. The transverse momentum of h with respect to the direction of the fragmenting quark will be called $\mathbf{p}_T$. All azimuthal angles are referred to the lepton scattering plane (we call ϕ the azimuthal angle of the hadron h, see Fig. 1).

Taking the intrinsic motion of quarks into account, the SIDIS cross section reads at leading order

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}^2\mathbf{P}_T} &= \frac{2\pi\alpha_{\mathrm{em}}^2 s}{Q^4}\sum_a e_a^2 x\big[1+(1-y)^2\big] \\ &\quad\times \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{p}_T\,\delta^2(\mathbf{P}_T - z\mathbf{k}_T - \mathbf{p}_T) \\ &\quad\times f_1^a\big(x,\mathbf{k}_T^2\big) D_1^a\big(z,\mathbf{p}_T^2\big),\end{aligned} \tag{3}$$

where $f_1^a(x,\mathbf{k}_T^2)$ is the unintegrated number density of quarks of flavor a and $D_1^a(z,\mathbf{p}_T^2)$ is the transverse-momentum dependent fragmentation function of quark a into the final hadron. We recall that the non-collinear factorization theorem for SIDIS has been recently proven by Ji, Ma and Yuan [28] for $P_T \ll Q$.

As shown long time ago by Cahn [19], the transverse-momentum kinematics generates a $\cos 2\phi$ contribution to the unpolarized SIDIS cross section, which has the form

$$\begin{aligned}\left.\frac{\mathrm{d}\sigma^{(\mathrm{HT})}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}^2\mathbf{P}_T}\right|_{\cos 2\phi} &= \frac{8\pi\alpha_{\mathrm{em}}^2 s}{Q^4}\sum_a e_a^2 x(1-y) \\ &\quad\times \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{p}_T\,\delta^2(\mathbf{P}_T - z\mathbf{k}_T - \mathbf{p}_T) \\ &\quad\times \frac{2(\mathbf{k}_T\cdot\mathbf{h})^2 - \mathbf{k}_T^2}{Q^2} f_1^a\big(x,\mathbf{k}_T^2\big) D_1^a\big(z,\mathbf{p}_T^2\big)\cos 2\phi,\end{aligned} \tag{4}$$

where $\mathbf{h} \equiv \mathbf{P}_T/P_T$. Notice that this contribution is of order k_T^2/Q^2, hence it is a (kinematic) higher twist effect.

The second k_T-dependent source of the $\cos 2\phi$ asymmetry involves the Boer–Mulders distribution $h_1^\perp$ coupled to the Collins fragmentation function $H_1^\perp$ of the produced hadron. The explicit expression of this contribution to the cross section is [4]

$$\begin{aligned}\left.\frac{\mathrm{d}\sigma^{(\mathrm{LT})}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}^2\mathbf{P}_T}\right|_{\cos 2\phi} &= \frac{4\pi\alpha_{\mathrm{em}}^2 s}{Q^4}\sum_a e_a^2 x(1-y) \\ &\quad\times \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{p}_T\,\delta^2(\mathbf{P}_T - z\mathbf{k}_T - \mathbf{p}_T) \\ &\quad\times \frac{2\mathbf{h}\cdot\mathbf{k}_T\,\mathbf{h}\cdot\mathbf{p}_T - \mathbf{k}_T\cdot\mathbf{p}_T}{zMM_h} h_1^{\perp a}\big(x,\mathbf{k}_T^2\big) H_1^{\perp a}\big(z,\mathbf{p}_T^2\big)\cos 2\phi.\end{aligned} \tag{5}$$

It should be noticed that this is a leading-twist contribution, not suppressed by inverse powers of Q.

The asymmetry measured in experiments is defined as

$$\langle\cos 2\phi\rangle = \frac{\int \mathrm{d}\sigma\,\cos 2\phi}{\int \mathrm{d}\sigma}, \tag{6}$$

where the integrations are performed over the measured ranges of x, y, z and with a lower cutoff P_c on P_T, which is the minimum value of P_T of the detected charged particles. Using Eqs. (3) and (5), $\langle\cos 2\phi_h\rangle$ is given by

$$\langle\cos 2\phi\rangle = \frac{\iiiint \sum_a e_a^2 2x(1-y)\{\mathcal{A}[f_1^a, D_1^a] + \frac{1}{2}\mathcal{B}[h_1^{\perp a}, H_1^{\perp a}]\}}{\iiiint \sum_a e_a^2 x[1+(1-y)^2]\mathcal{C}[f_1^a, D_1^a]}, \tag{7}$$

where

$$\iiiint \equiv \int_{P_c}^{P_{T,\max}} \mathrm{d}P_T\, P_T \int_{x_1}^{x_2} \mathrm{d}x \int_{y_1}^{y_2} \mathrm{d}y \int_{z_1}^{z_2} \mathrm{d}z \tag{8}$$

and (χ is the angle between $\mathbf{P}_T$ and $\mathbf{k}_T$)

$$\begin{aligned}\mathcal{A}\big[f_1^a, D_1^a\big] &\equiv \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{p}_T\, \delta^2(\mathbf{P}_T - z\mathbf{k}_T - \mathbf{p}_T) \\ &\quad \times \frac{2(\mathbf{k}_T\cdot\mathbf{h})^2 - \mathbf{k}_T^2}{Q^2} f_1^a\big(x, \mathbf{k}_T^2\big) D_1^a\big(z, \mathbf{p}_T^2\big)\cos 2\phi \\ &= \int_0^\infty \mathrm{d}k_T\, k_T \int_0^{2\pi} \mathrm{d}\chi \frac{2\mathbf{k}_T^2\cos^2\chi - \mathbf{k}_T^2}{Q^2} \\ &\quad \times f_1^a\big(x, \mathbf{k}_T^2\big) D_1^a\big(z, |\mathbf{P}_T - z\mathbf{k}_T|^2\big),\end{aligned} \tag{9}$$

$$\begin{aligned}&\mathcal{B}\big[h_1^{\perp a}, H_1^{\perp a}\big] \\ &\quad \equiv \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{p}_T\, \delta^2(\mathbf{P}_T - z\mathbf{k}_T - \mathbf{p}_T) \\ &\qquad \times \frac{2\mathbf{h}\cdot\mathbf{k}_T\mathbf{h}\cdot\mathbf{p}_T - \mathbf{k}_T\cdot\mathbf{p}_T}{zMM_h} h_1^{\perp a}\big(x, \mathbf{k}_T^2\big) H_1^{\perp a}\big(z, \mathbf{p}_T^2\big) \\ &\quad = \int_0^\infty \mathrm{d}k_T\, k_T \int_0^{2\pi} \mathrm{d}\chi \frac{\mathbf{k}_T^2 + (P_T/z)k_T\cos\chi - 2\mathbf{k}_T^2\cos^2\chi}{MM_h} \\ &\qquad \times h_1^{\perp a}\big(x, \mathbf{k}_T^2\big) H_1^{\perp a}\big(z, |\mathbf{P}_T - z\mathbf{k}_T|^2\big),\end{aligned} \tag{10}$$

$$\begin{aligned}&\mathcal{C}\big[f_1^a, D_1^a\big] \\ &\quad \equiv \int \mathrm{d}^2\mathbf{k}_T \int \mathrm{d}^2\mathbf{p}_T\, \delta^2(\mathbf{P}_T - z\mathbf{k}_T - \mathbf{p}_T) f_1^a\big(x, \mathbf{k}_T^2\big) D_1^a\big(z, \mathbf{p}_T^2\big) \\ &\quad = \int_0^\infty \mathrm{d}k_T\, k_T \int_0^{2\pi} \mathrm{d}\chi\, f_1^a\big(x, \mathbf{k}_T^2\big) D_1^a\big(z, |\mathbf{P}_T - z\mathbf{k}_T|^2\big).\end{aligned} \tag{11}$$

3. Calculation and results

In order to calculate $\langle\cos 2\phi\rangle$ one needs to know the k_T- and p_T-dependent distribution and fragmentation functions appearing in Eqs. (9)–(11). Independent information on the Boer–Mulders function $h_1^\perp(x, \mathbf{k}_T^2)$ can be obtained from the study of the $\cos 2\phi$ azimuthal asymmetry in unpolarized Drell–Yan processes, which has been measured in πN collisions [15,16]. In [17,18] this asymmetry was estimated by computing the $h_1^\perp$ distribution of the pion and of the nucleon in a quark spectator model [29,30]. To compute the $\cos 2\phi$ azimuthal asymmetry in SIDIS we adopt the same distributions $h_1^\perp(x, \mathbf{k}_T^2)$ and $f_1(x, \mathbf{k}_T^2)$ used in [18]. We assume that the observables are dominated by u quarks (i.e., we consider π^+ production). The set of the transverse-momentum dependent distribution functions is (for simplicity, we consider a spectator scalar diquark [18,30])

$$f_1^u\big(x, \mathbf{k}_T^2\big) = N(1-x)^3 \frac{(xM+m)^2 + \mathbf{k}_T^2}{(L^2 + \mathbf{k}_T^2)^4}, \tag{12}$$

$$h_1^{\perp u}\big(x, \mathbf{k}_T^2\big) = \frac{4}{3}\alpha_s N(1-x)^3 \frac{M(xM+m)}{[L^2(L^2 + \mathbf{k}_T^2)^3]}, \tag{13}$$

where N is a normalization constant, m is the constituent quark mass, and

$$L^2 = (1-x)\Lambda^2 + xM_d^2 - x(1-x)M^2. \tag{14}$$

Here Λ is a cutoff appearing in the nucleon–quark–diquark vertex and M_d is the mass of the scalar diquark. As it is typical of all model calculations of quark distribution functions, we expect that Eqs. (12) and (13) should be valid at low Q^2 values, of order of 1 GeV^2. The average transverse momentum of quarks inside the target, as computed from (12), turns out to be $\langle k_T^2\rangle^{1/2} \simeq 0.54$ GeV.

Coming to the fragmentation functions, for $H_1^\perp$ we adopt the simple parametrization suggested by Collins [20]

$$\frac{H_1^\perp(z, \mathbf{p}_T^2)}{D_1(z, \mathbf{p}_T^2)} = \frac{M_C M_h}{M_C^2 + \mathbf{p}_T^2/z^2}, \tag{15}$$

where M_C is a free parameter. We assume a Gaussian dependence for the unintegrated unpolarized fragmentation function:

$$D_1\big(z, \mathbf{p}_T^2\big) = D_1(z)\frac{1}{\pi\langle p_T^2\rangle} \mathrm{e}^{-\mathbf{p}_T^2/\langle p_T^2\rangle}, \tag{16}$$

so that $\int \mathrm{d}^2\mathbf{p}_T\, D_1(z, \mathbf{p}_T^2) = D_1(z)$. Finally, the integrated unpolarized fragmentation function for pions $D_1(z)$ is taken from the Kretzer–Leader–Christova parametrization [31],

$$D_1(z) = 0.689\, z^{-1.039}(1-z)^{1.241} \tag{17}$$

valid at $\langle Q^2\rangle = 2.5\ \mathrm{GeV}^2$. For the parameters in Eqs. (12) and (13) we choose the values $M_d = 0.8$ GeV, $m = 0.3$ GeV, $\Lambda = 0.6$ GeV, $\alpha_s = 0.3$, which are the same as in [18]. As for the parameters in Eqs. (15) and (16), we fix M_C to 0.3 GeV and show results for two values of the average transverse momentum: $\langle p_T^2\rangle^{1/2} = 0.5$ GeV and 0.6 GeV (we checked that a variation of M_C is reproduced by a change of $\langle p_T^2\rangle^{1/2}$).

The HERMES kinematics is characterized by the following ranges: $0.02 < x < 0.4$, $0.1 < y < 0.85$, $0.2 < z < 1$, $\langle Q^2\rangle = 2\ \mathrm{GeV}^2$. Our predictions for the $\cos 2\phi$ asymmetry in this regime are displayed in Fig. 2, where we show separately the higher-twist term and the leading-twist Boer–Mulders contribution. For a typical transverse momentum cutoff $P_c = 0.5$ GeV, these two terms are comparable and the predicted asymmetry lies in the range $\langle\cos 2\phi\rangle = 0.02$–$0.04$. The x-dependence (with z integrated over the accessible interval) and the z-dependence (with x integrated over the accessible interval) are shown in Figs. 3 and 4, respectively. As one can see, the asymmetry is larger at small x and large z.

In Fig. 5 we plot our results for the x-dependent asymmetry (integrated over z) in the COMPASS kinematic domain. The correlation between x and Q^2 is such that the lowest x bin ($x = 0.005$) corresponds to $Q^2 \approx 1\ \mathrm{GeV}^2$, whereas the highest x bin in Fig. 5 ($x = 0.25$) corresponds to $Q^2 \approx 24\ \mathrm{GeV}^2$. Again, the asymmetry is of order of few percent and decreases with x.

There are available data on the $\cos 2\phi$ asymmetry in SIDIS coming from the ZEUS experiment [25]. The ZEUS kinematic ranges are: $0.01 < x < 0.1$, $0.2 < y < 0.8$, $0.2 < z < 1$, $Q^2 > 180\ \mathrm{GeV}^2$. At such large Q^2 values, the higher twist contribution is clearly irrelevant. Since only the Q^2 evolution of the

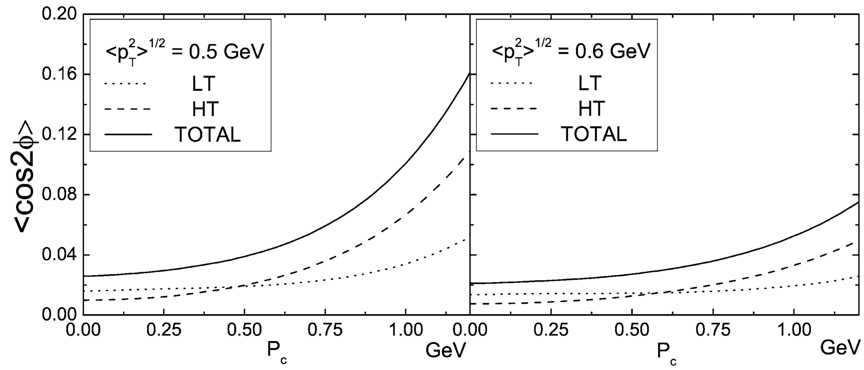

Fig. 2. The SIDIS $\cos 2\phi$ azimuthal asymmetry in the HERMES domain as a function of the cutoff P_c, for two values of $\langle p_T^2 \rangle^{1/2}$. The dotted curve is the leading-twist Boer–Mulders contribution, the dashed curve is the higher-twist term, the solid curve is the sum of the two contributions.

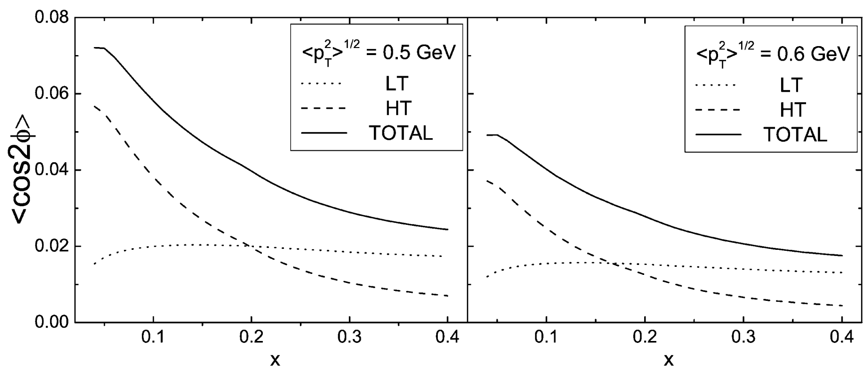

Fig. 3. The SIDIS $\cos 2\phi$ azimuthal asymmetry in the HERMES domain, as a function of x with $P_c = 0.5$ GeV. The dotted curve is the leading-twist Boer–Mulders contribution, the dashed curve is the higher-twist term, the solid curve is the sum of the two contributions.

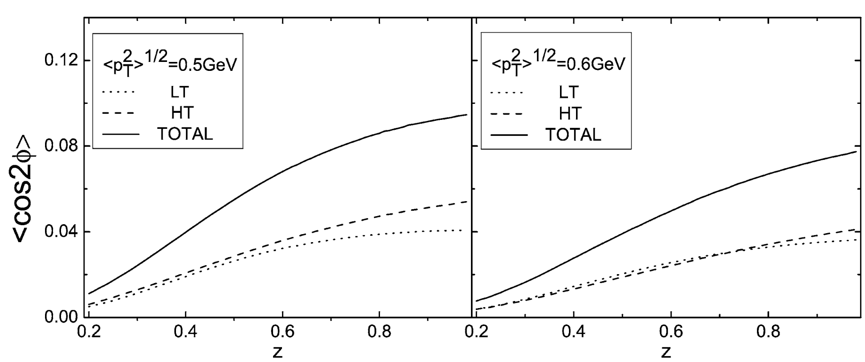

Fig. 4. The SIDIS $\cos 2\phi$ azimuthal asymmetry in the HERMES domain, as a function of z with $P_c = 0.5$ GeV. The dotted curve is the leading-twist Boer–Mulders contribution, the dashed curve is the higher-twist term, the solid curve is the sum of the two contributions.

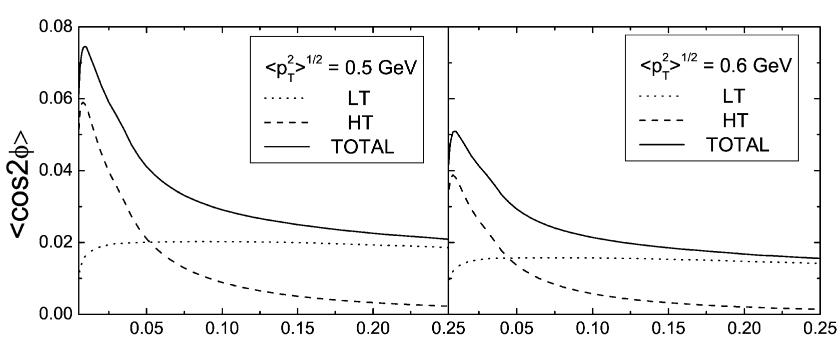

Fig. 5. The SIDIS $\cos 2\phi$ azimuthal asymmetry in the COMPASS domain, as a function of x with $P_c = 0.5$ GeV. The dotted curve is the leading-twist Boer–Mulders contribution, the dashed curve is the higher-twist term, the solid curve is the sum of the two contributions.

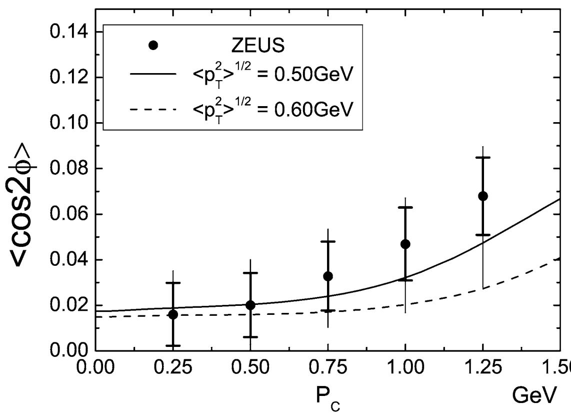

Fig. 6. The SIDIS $\cos 2\phi$ azimuthal asymmetry as a function of the cutoff P_c in the ZEUS domain. Data are from [25].

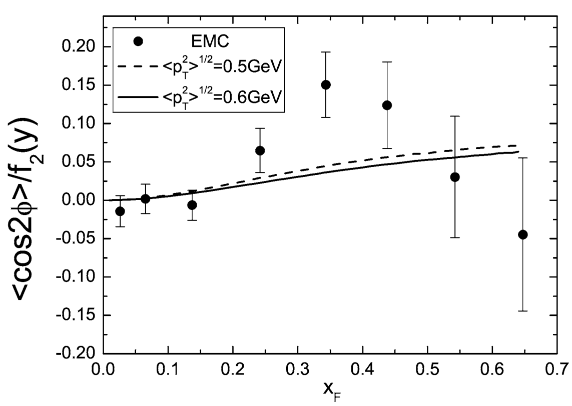

Fig. 7. The $\cos 2\phi$ azimuthal asymmetry (divided by $f_2(y) = (1 - y)/[1 + (1 - y)^2]$) as a function of $x_F \equiv 2P_L/W$ as measured by EMC [35]. The curves are our predictions.

k_T moments of $h_1^\perp$ is known [32], and not that of $h_1^\perp$ itself, we assume for simplicity that the distributions (12) and (13) scale exactly, i.e., that they are valid for any Q^2 (one should recall, however, that Sudakov form factors arising from soft gluon contributions may reduce the Boer–Mulders asymmetry at very high Q^2 [33]). The result for the $\cos 2\phi$ asymmetry in the ZEUS kinematic domain is shown in Fig. 6, where it is compared with the experimental data. The agreement is rather good for low values of the P_T cutoff (up to 0.5 GeV). For larger P_T values one expects of course a relevant perturbative contribution. Including this contribution is beyond the purpose of this Letter, which is primarily devoted to predictions for the low-Q^2 domain. A more extended analysis of the $\cos 2\phi$ asymmetries, taking into account also the perturbative term, is in progress and will be reported soon [34].

For completeness we recall that long time ago the European Muon Collaboration at CERN measured $\langle \cos 2\phi \rangle$ for $Q^2 > 4\ \text{GeV}^2$ [35]. The EMC data, however, are affected by large uncertainties and do not allow drawing definite conclusions about the magnitude and the shape of the asymmetry. The comparison of our predictions with these data is shown in Fig. 7.

In conclusion, we predicted the $\cos 2\phi$ asymmetry for semi-inclusive deep inelastic scattering in the kinematic regions of the HERMES and COMPASS experiments. We found that $\langle \cos 2\phi \rangle$ is of order of few percent and tends to be larger in the small-x and large-z region. The combined analysis of the future data on $\langle \cos 2\phi \rangle$ and of the previous ZEUS measurements in the high-Q^2 domain (where higher twist effects are irrelevant) will allow to get information on the Boer–Mulders function, shedding light on the correlations between transverse spin and transverse momenta of quarks.

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