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The $\cos 2\phi$ asymmetry of Drell–Yan and J/ψ production in unpolarized $p\bar{p}$ scattering

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Abstract. We investigate the $\cos 2\phi$ azimuthal asymmetry in Drell–Yan and J/ψ production from unpolarized $p\bar{p}$ scattering at GSI-HESR energies. The contribution to this asymmetry arising from 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 in an unpolarized hadron, is explicitly evaluated, and predictions for the GSI-HESR kinematic regime are presented. We show that the $\cos 2\phi$ asymmetry is quite sizable both on the J/ψ peak and in the Drell–Yan continuum region. Therefore these processes may offer experimentally viable access to the Boer–Mulders function in the early unpolarized stage of GSI experiments.

1 Introduction

The spin structure of hadrons is under intense investigation, both theoretically and experimentally. In hadron–hadron scattering one would naively speculate that the polarization of at least one of the incoming hadrons, the beam or the target, or of both, is needed in order to investigate the spin properties of hadrons. However this is not the case if one takes into account the intrinsic momentum of partons. It is known in fact that there is a new kind of leading-twist transverse-momentum-dependent distribution function, the so called Boer–Mulders function $h_1^\perp(x, \mathbf{k}_T^2)$ [1, 2], which describes the transversity of quarks inside an unpolarized hadron. This new function, which is chirally odd, manifests itself through the coupling to another chiral-odd quantity, such as the transversity distribution h_1, the Collins function $H_1^\perp$, or another Boer–Mulders function[1]. Therefore the spin structure of hadrons can also be studied in physical processes without beam and/or target polarization. It has been argued by Boer [2] that $h_1^\perp(x, \mathbf{k}_T^2)$ can account for the large $\cos 2\phi$ azimuthal asymmetry observed in the unpolarized pion–nucleon Drell–Yan process [4–6]. The origin of $h_1^\perp(x, \mathbf{k}_T^2)$ has been addressed in [7–9]. The first calculation of $h_1^\perp(x, \mathbf{k}_T^2)$, in a quark–scalar diquark model, was reported by Goldstein and Gamberg [10]. Soon after this work, Boer, Brodsky, and Hwang [11], using a similar model, showed that the analyzing power ν of the $\cos 2\phi$ asymmetry could be as high as 30% in the unpolarized $p\bar{p}$ Drell–Yan process, and smaller in pp scattering. The Boer–Mulders function of the pion was calculated [12, 13] in a quark–spectator–antiquark model and shown to reproduce, in combination with the corresponding distribution of the proton [14], the $\cos 2\phi$ asymmetry in the $\pi^- N$ Drell–Yan process measured by the NA10 Collaboration [4, 5]. The Boer–Mulders function, combined with the Collins function, can also produce the $\cos 2\phi$ asymmetries of semi-inclusive pion leptoproduction from unpolarized nucleons [15–17].

Recently, the $\cos 2\phi$ azimuthal asymmetry of the $p\bar{p}$ Drell–Yan process has received much attention, as there have been proposals to study spin phenomena in polarized and unpolarized $p\bar{p}$ scattering at the high-energy storage ring (HESR) of GSI [18, 19]. There have been numerical simulations [20, 21] as well as model calculations [11, 22] of the $\cos 2\phi$ asymmetry in the unpolarized $p\bar{p}$ Drell–Yan process. The purpose of this paper is to investigate the $\cos 2\phi$ asymmetry of Drell–Yan and J/ψ production in unpolarized $p\bar{p}$ scattering, using a model of $h_1^\perp(x, \mathbf{k}_T^2)$ [13, 14, 17] that has been adjusted to fit the NA10 $\pi^- N$ Drell–Yan data [4, 5] and shown to be in agreement with the ZEUS [23] and EMC [24] semi-inclusive DIS data. As we will see, in the GSI kinematic domain the $\cos 2\phi$ asymmetry turns out to be rather large. In particular, the advantage of studying the J/ψ production is that, while its $\cos 2\phi$ asymmetry is similar in size to the corresponding asymmetry of the Drell–Yan continuum production, the counting rate on the J/ψ peak is two orders of magnitude higher compared to the region above this peak.

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[1] For a review of transverse polarization phenomena, see [3]

2 The $\cos 2\phi$ asymmetry in Drell–Yan and J/ψ production

The Drell–Yan process represents an ideal window on the hadron structure, since it probes only parton densities. We are interested in the transverse-momentum distribution of the lepton pairs; hence we have to consider the intrinsic transverse momenta of partons inside the hadrons. The non-collinear factorization theorem for a Drell–Yan process has been recently proven by Ji, Ma and Yuan [25] for $Q_T \ll Q$.

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

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

where θ and ϕ are, respectively, the polar angle and the azimuthal angle of dileptons in the Collins–Soper frame [26]. At leading order, the ϕ-independent term of the unpolarized Drell–Yan cross section for proton–antiproton collisions is

$$\frac{\mathrm{d}\sigma^{\mathrm{DY}}_{p\bar{p}}}{\mathrm{d}\Omega\mathrm{d}x_1\mathrm{d}x_2\mathrm{d}^2\mathbf{q}_T} = \frac{\alpha^2_{\mathrm{em}}}{12M^2}(1+\cos^2\theta) \times\sum_a e_a^2\int \mathrm{d}^2\mathbf{k}_T\mathrm{d}^2\mathbf{p}_T\delta^2(\mathbf{k}_T+\mathbf{p}_T-\mathbf{q}_T) \times f_1^a\left(x_1,\mathbf{k}_T^2\right) f_1^a\left(x_2,\mathbf{p}_T^2\right)\,, \quad (2)$$

where M^2 is the invariant mass squared of the lepton pair and $\mathbf{q}_T$ is the transverse momentum of the virtual photon in the frame where the two colliding hadrons are collinear. In (2) we denoted by $f_1(x,\mathbf{k}_T^2)$ the unintegrated quark number density in the proton, and we used the fact that the antiquark distributions in the antiproton are equal to the quark distributions in the proton.

We will consider the ν term in (1). It is known that gluon radiation processes give rise to a non-zero $\cos 2\phi$ asymmetry, which in case of $q\bar{q}$ annihilation dominance is given by $\nu = Q_T^2/(M^2+3Q_T^2/2)$ [27]. Various quantitative analyses [4, 5, 28, 29] show that perturbative corrections are unable to reproduce both the magnitude and the Q_T-dependence of ν as observed by NA10 in the region $M \sim 4$–8 GeV, but for lower M values the perturbative asymmetry might be relevant. In the present paper we will focus on the Boer–Mulders contribution to the $\cos 2\phi$ asymmetry, which has been shown to explain the NA10 results [2] and represents a large effect in the moderate-Q_T region we are interested in.[2]

[2] Concerning the perturbative contributions to azimuthal asymmetries, a forthcoming analysis of $\cos 2\phi$ distributions in semi-inclusive DIS shows that at moderate Q^2 and low P_T the Boer–Mulders effect largely dominates over the perturbative contribution (at large Q^2 the situation is reversed) [30].

The expression for the contribution of the Boer–Mulders distribution to the unpolarized cross section is [2]

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{DY}}_{p\bar{p}}}{\mathrm{d}\Omega\mathrm{d}x_1\mathrm{d}x_2\mathrm{d}^2\mathbf{q}_T}\right|_{\cos 2\phi} = \frac{\alpha^2_{\mathrm{em}}}{12\,M^2}\sin^2\theta \times\sum_a e_a^2\int \mathrm{d}^2\mathbf{k}_T\mathrm{d}^2\mathbf{p}_T\delta^2(\mathbf{k}_T+\mathbf{p}_T-\mathbf{q}_T) \times\frac{\left(2\hat{\mathbf{h}}\cdot\mathbf{k}_T\hat{\mathbf{h}}\cdot\mathbf{p}_T-\mathbf{k}_T\cdot\mathbf{p}_T\right)}{m_N^2} \times h_1^{\perp a}\left(x_1,\mathbf{k}_T^2\right) h_1^{\perp a}\left(x_2,\mathbf{p}_T^2\right)\cos 2\phi\,, \quad (3)$$

where $\hat{\mathbf{h}} \equiv \mathbf{q}_T/Q_T$, with $Q_T \equiv |\mathbf{q}_T|$. This term, with its peculiar angular dependence, gives a parton model explanation for the $\cos 2\phi$ asymmetry observed in the unpolarized πN Drell–Yan process [4, 5].

From (2) and (3) we get the following expression of the coefficient ν in (1) (with $\lambda = 1$, $\mu = 0$):

$$\nu = \frac{2\sum_a e_a^2\mathcal{H}[h_1^{\perp a},h_1^{\perp a}]}{\sum_a e_a^2\mathcal{F}[f_1^a,f_1^a]}\,, \quad (4)$$

where we used the notation

$$\mathcal{F}[f_1^a,f_1^a] = \frac{1}{M^2}\int \mathrm{d}^2\mathbf{k}_T\mathrm{d}^2\mathbf{p}_T\delta^2(\mathbf{k}_T+\mathbf{p}_T-\mathbf{q}_T) \times f_1^a\left(x_1,\mathbf{k}_T^2\right) f_1^a\left(x_2,\mathbf{p}_T^2\right) = \frac{1}{M^2}\int \mathrm{d}k_T k_T\int_0^{2\pi}\mathrm{d}\chi \times f_1^a\left(x_1,\mathbf{k}_T^2\right) f_1^a\left(x_2,|\mathbf{q}_T-\mathbf{k}_T|^2\right)\,, \quad (5)$$

$$\mathcal{H}[h_1^{\perp a},h_1^{\perp a}] = \frac{1}{M^2}\int \mathrm{d}^2\mathbf{k}_T\mathrm{d}^2\mathbf{p}_T\delta^2(\mathbf{k}_T+\mathbf{p}_T-\mathbf{q}_T) \times\frac{\left(2\hat{\mathbf{h}}\cdot\mathbf{k}_T\hat{\mathbf{h}}\cdot\mathbf{p}_T-\mathbf{k}_T\cdot\mathbf{p}_T\right)}{M^2} \times h_1^{\perp a}\left(x_1,\mathbf{k}_T^2\right) h_1^{\perp a}\left(x_2,\mathbf{p}_T^2\right) = \frac{1}{M^2}\int \mathrm{d}k_T k_T\int_0^{2\pi}\mathrm{d}\chi \times\frac{\mathbf{k}_T^2+Q_T k_T\cos\chi-2\mathbf{k}_T^2\cos^2\chi}{m_N^2} \times h_1^{\perp a}\left(x_1,\mathbf{k}_T^2\right) h_1^{\perp a}\left(x_2,|\mathbf{q}_T-\mathbf{k}_T|^2\right)\,, \quad (6)$$

and χ is the angle between $\mathbf{q}_T$ and $\mathbf{k}_T$. The asymmetry coefficient ν given in (4) depends on the kinematic variables x_1, x_2, M and Q_T. The GSI-HESR kinematics probes the large x region, where the valence quarks and in particular the u sector dominate, so that (4) can be simplified to

$$\nu = \frac{2\mathcal{H}[h_1^{\perp u},h_1^{\perp u}]}{\mathcal{F}[f_1^u,f_1^u]}\,. \quad (7)$$

Another promising process to study transverse spin physics at GSI-HESR is J/ψ production, which has been proposed [31, 32] as a method to access transversity by measuring the double spin asymmetry. The J/ψ production events are identified by a peak in the dilepton invariant mass spectrum at $M = m_{J/\psi} = 3.097\,\mathrm{GeV}$, so one can choose $M^2 \simeq 9\,\mathrm{GeV}^2$. At the GSI-HESR energy scale ($s =$ 30–45 GeV^2 in the fixed-target mode, or $s =$ 100–200 GeV^2 in the collider mode), J/ψ production is dominated by $q\bar{q}$ annihilation [33]. Since the J/ψ is a vector particle and the $q\bar{q}J/\psi$ coupling has the same helicity structure as the $q\bar{q}\gamma^*$ coupling, one can get the J/ψ production cross section by replacing the quark electric charges by the J/ψ vector couplings to $q\bar{q}$ and to $\ell^+\ell^-$,

$$16\pi^2\alpha_{\mathrm{em}}^2 e_a^2 \to \left(g_a^{\mathrm{V}}\right)^2 \left(g_\ell^{\mathrm{V}}\right)^2 , \tag{8}$$

and the virtual photon propagator by a Breit–Wigner function,

$$\frac{1}{M^4} \to \frac{1}{\left(M^2 - m_{J/\psi}^2\right)^2 + m_{J/\psi}^2 \Gamma_{J/\psi}^2} , \tag{9}$$

where $\Gamma_{J/\psi}$ is the J/ψ width. This model successfully accounts for the SPS J/ψ production data at moderate s [34–36].

Therefore the unpolarized $\cos 2\phi$ asymmetry in the J/ψ resonance region reads

$$\nu = \frac{2\sum_a \left(g_a^{\mathrm{V}}\right)^2 \mathcal{H}[h_1^{\perp a}, h_1^{\perp a}]}{\sum_a \left(g_a^{\mathrm{V}}\right)^2 \mathcal{F}[f_1^a, f_1^a]}, \tag{10}$$

with only e_a^2 replaced by $(g_a^{\mathrm{V}})^2$ in (4). Since the u quark dominates, this asymmetry reduces to (7), which is the same as for continuum Drell–Yan, with $M^2 \simeq 9\,\mathrm{GeV}^2$. Integrating over x_1 and x_2, we get

$$\nu(Q_{\mathrm{T}}, M) = \frac{2\int \mathrm{d}x_1 \int \mathrm{d}x_2 \mathcal{H}[h_1^{\perp u}, h_1^{\perp u}]\delta(1-\tau)}{\int \mathrm{d}x_1 \int \mathrm{d}x_2 \mathcal{F}[f_1^u, f_1^u]\delta(1-\tau)} , \tag{11}$$

where $\tau = M^2/x_1x_2s$. Notice that the relation $1-\tau = 0$ is valid for $Q_{\mathrm{T}}^2 \ll M^2$. The rapidity is defined as $y = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$ and Feynman's variable is $x_{\mathrm{F}} = x_1 - x_2$.

3 Calculation of the $\cos 2\phi$ asymmetry

To evaluate the $\cos 2\phi$ asymmetry given in (7) one needs to know the form of the k_{T}-dependent distributions appearing in the transverse-momentum convolution. Useful information on the Boer–Mulders function $h_1^\perp(x, \mathbf{k}_{\mathrm{T}}^2)$ can be obtained from the study of the $\cos 2\phi$ azimuthal asymmetry in the unpolarized πN Drell–Yan processes, which has been measured by the NA10 Collaboration [4, 5] and the E615 Collaboration [6]. In [12, 13] this asymmetry was estimated by computing the $h_1^\perp$ distribution of the pion and of the nucleon in a quark–spectator model [14, 37] and was compared with NA10 data. To compute the $\cos 2\phi$ azimuthal asymmetry in the unpolarized $p\bar{p}$ collision we adopt the same distributions $h_1^\perp(x, \mathbf{k}_{\mathrm{T}}^2)$ and $f_1(x, \mathbf{k}_{\mathrm{T}}^2)$ used in [13]. We assume that the observables are dominated by u quarks. The set of the transverse-momentum-dependent distribution functions is (for simplicity, we consider a spectator scalar diquark [13, 14])

$$f_1^u\left(x, \mathbf{k}_{\mathrm{T}}^2\right) = N(1-x)^3 \frac{\left(xm_N + m_q\right)^2 + \mathbf{k}_{\mathrm{T}}^2}{\left(L^2 + \mathbf{k}_{\mathrm{T}}^2\right)^4} , \tag{12}$$

$$h_1^{\perp u}\left(x, \mathbf{k}_{\mathrm{T}}^2\right) = \frac{4\alpha_{\mathrm{s}}}{3} N(1-x)^3 \frac{m_N(xm_N + m_q)}{\left[L^2\left(L^2 + \mathbf{k}_{\mathrm{T}}^2\right)^3\right]} , \tag{13}$$

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

$$L^2 = (1-x)\Lambda^2 + xm_{\mathrm{d}}^2 - x(1-x)m_N^2 . \tag{14}$$

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 (12) and (13) should be valid at low Q^2 values, of order of $1\,\mathrm{GeV}^2$. The average transverse momentum of quarks inside the nucleons, as computed from (12), turns out to be $\langle k_{\mathrm{T}}^2\rangle^{1/2} \simeq 0.54\,\mathrm{GeV}$. For the parameters in (12) and (13), we choose the values $m_{\mathrm{d}} = 0.8\,\mathrm{GeV}$, $m_q = 0.3\,\mathrm{GeV}$, $\Lambda = 0.6\,\mathrm{GeV}$, $\alpha_{\mathrm{s}} = 0.3$, which are the same as in [13, 17].

Compared with previous calculations of Drell–Yan asymmetries [11, 22], our model differs for the explicit form of the proton–quark–diquark effective coupling and for the values of the parameters. We adopt a dipole form factor [14] for the effective coupling, whereas in other computations this coupling is taken as a constant [11], or as a Gaussian form factor [22]. This leads to different predictions on the magnitude and the Q_{T}-dependence of the $\cos 2\phi$ asymmetry, as we will see below. Our model proved to be capable to reproduce the observed $\cos 2\phi$ asymmetry of the NA10 $\pi^- N$ Drell–Yan data with the correct Q_{T}-dependence [13].

The Drell–Yan and J/ψ production events are reconstructed from the dilepton invariant mass spectrum, where the J/ψ events correspond to the peak at the invariant mass $M = M_{J/\psi} \simeq 3\,\mathrm{GeV}$, and the genuine Drell–Yan events correspond to the continuum spectrum below and above the J/ψ peak. For the experimental programs at GSI-HESR, the center of mass energy is $s =$ 30–45 GeV^2 in the fixed-target mode and $s =$ 100–200 GeV^2 for the collider option. With $s = 45\,\mathrm{GeV}^2$ and $s = 200\,\mathrm{GeV}^2$ one has on the J/ψ peak $\tau = x_1x_2 = M^2/s \simeq 0.2$ and $\tau \simeq 0.05$, respectively. In these kinematic domains valence quarks dominate and the assumptions made above are justified.

The $\cos 2\phi$ asymmetry ν as a function of Q_{T} is shown in Fig. 1 for the fixed-target GSI kinematics. For a quantitative comparison, in the same figure we present the prediction of a model with constant quark–spectator coupling [11], obtained using the same parameters of [11] but for the kinematic domain we are considering here. We notice that both the magnitude and the Q_{T}-dependence are quite different, similarly to what happens in the πN Drell–Yan process [13]. The shape of ν in the model with a Gaussian quark–spectator coupling [22] also differs from ours and is similar to that of [11].

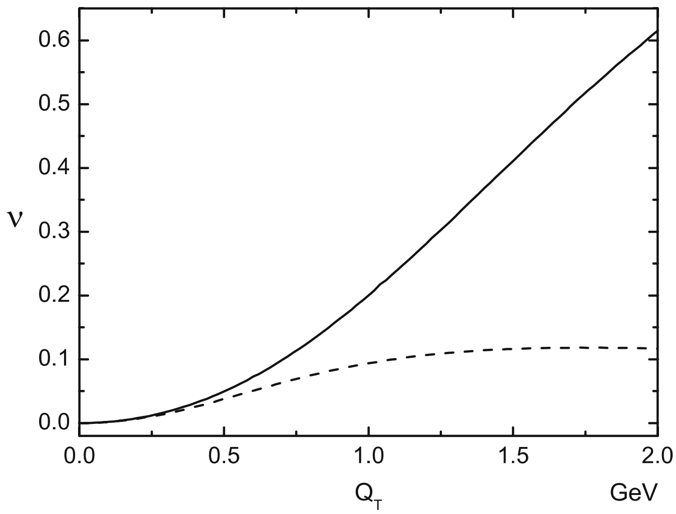

Fig. 1. The $\cos 2\phi$ azimuthal asymmetry of Drell–Yan production in $p\bar{p}$ collisions as a function of Q_{T}, for $s = 45\,\mathrm{GeV}^2$ and $M^2 = 5\,\mathrm{GeV}^2$. The *solid curve* is our prediction. The *dashed curve* is the result of [11] extended to the kinematic region of interest here

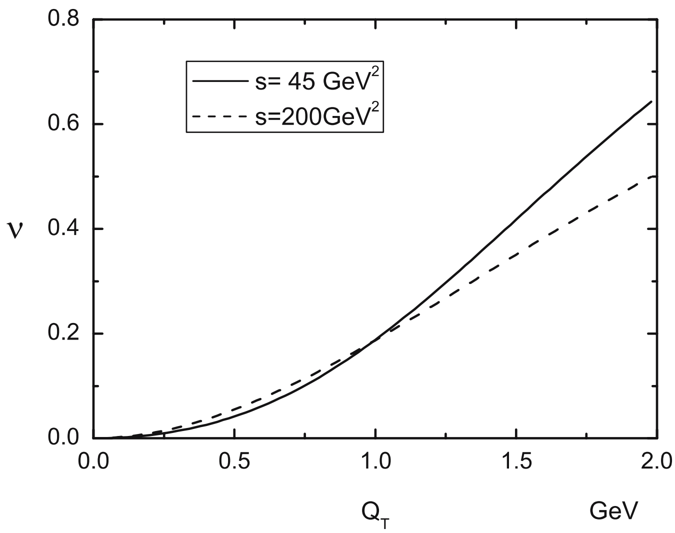

Fig. 2. The $\cos 2\phi$ azimuthal asymmetry of $p\bar{p} \to J/\psi X \to l^+ l^- X$ as a function of Q_{T}, for two values of s in the GSI-HESR kinematic domain

The Q_{T}-dependence of the $\cos 2\phi$ asymmetry ν in J/ψ production is shown in Fig. 2. As one can see, the asymmetry is sizable and increases with Q_{T}. Some difference between the two curves (corresponding to two values of s) emerges at large Q_{T}, where the asymmetry is suppressed for the larger center of mass energy. In Fig. 3 we plot ν as a function of $x_{\mathrm{F}} = x_1 - x_2$. The asymmetry lies in the range 0.2–0.3.

J/ψ production has been recently suggested by Anselmino et al. [31, 32] as a candidate reaction to probe the nucleon transversity by measuring the double transverse spin asymmetry in polarized $p^\uparrow \bar{p}^\uparrow$ process. The dilepton production rate on the J/ψ peak is two orders of magnitude larger than in the continuum region above the J/ψ mass. This makes J/ψ at GSI energies an excellent process to measure transverse polarization asymmetries. Here we applied the same idea to the unpolarized case, and in particular to the $\cos 2\phi$ asymmetry. Given the large value of ν that we found, we can say that the experimental study of J/ψ and Drell–Yan production from unpolarized proton–antiproton collisions at GSI represents a very important source of information on the Boer–Mulders distribution (of course, a complete analysis of these processes will also require a careful consideration of the perturbative effects).

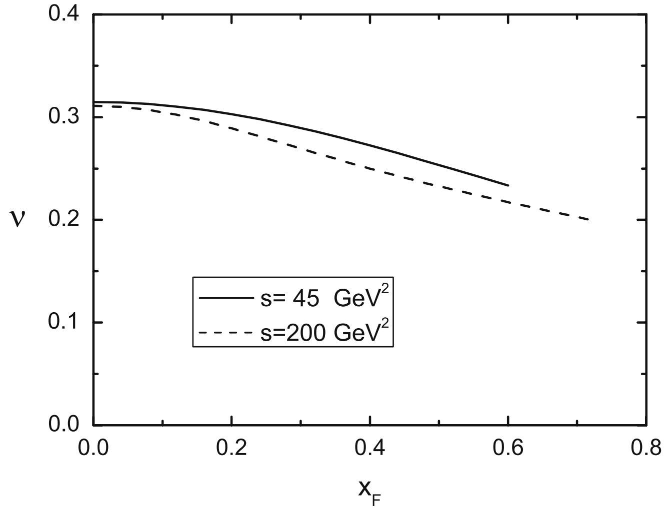

Fig. 3. The $\cos 2\phi$ azimuthal asymmetry of $p\bar{p} \to J/\psi X \to l^+ l^- X$ as a function of x_{F}, for two values of s in the GSI-HESR kinematic domain

4 Conclusion

In summary, we calculated the $\cos 2\phi$ azimuthal asymmetry of the unpolarized $p\bar{p}$ dilepton production in the continuum region and on the J/ψ peak for the GSI kinematics, relying on a model of the Boer–Mulders function previously adjusted to fit the available experimental data on πN Drell–Yan. The asymmetry turns out to be rather large, of order 0.2–0.3. The size of the asymmetry and the high counting rate in the J/ψ resonance region make the dilepton production in $p\bar{p}$ scattering at moderate energies a very promising process to detect the Boer–Mulders function in the early unpolarized stages of the future GSI experiments.

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