Accessing Sivers gluon distribution via transverse single spin asymmetries in $p^{\uparrow}p \to DX$ processes at BNL RHIC

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The production of D mesons in the scattering of transversely polarized protons off unpolarized protons at BNL RHIC offers a clear opportunity to gain information on the Sivers gluon distribution function. D production at intermediate rapidity values is dominated by the elementary $gg \to c\bar{c}$ channel; contributions from $q\bar{q} \to c\bar{c}$ s-channel become important only at very large values of x_F. In both processes there is no single spin transfer, so that the final c or $\bar{c}$ quarks are not polarized. Therefore, any transverse single spin asymmetry observed for D's produced in $p^{\uparrow}p$ interactions cannot originate from the Collins fragmentation mechanism, but only from the Sivers effect in the distribution functions. In particular, any sizable spin asymmetry measured in $p^{\uparrow}p \to DX$ at midrapidity values will be a direct indication of a nonzero Sivers gluon distribution function. We study the $p^{\uparrow}p \to DX$ process including intrinsic transverse motion in the parton distribution and fragmentation functions and in the elementary dynamics and show how results from RHIC could allow a measurement of $\Delta^N f_{g/p^{\uparrow}}$.

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I. INTRODUCTION AND FORMALISM

Within the QCD factorization scheme, the cross section for an inclusive large p_T scattering process between hadrons, like $pp \to h + X$, is calculated by convoluting the elementary partonic cross sections with the parton distribution functions (pdf's) and fragmentation functions (ff's). These objects account for the soft nonperturbative part of the scattering process, by giving the probability density of finding partons inside the hadrons (or hadrons inside fragmenting partons) carrying a specific fraction x (or z) of the parent light-cone momentum. The parton intrinsic motion—demanded by uncertainty principle and gluon emission—is usually integrated out in the high energy factorization scheme, and only partonic collinear configurations are considered. However, it is well known that the quark and gluon intrinsic transverse momenta $\boldsymbol{k}_\perp$ have to be taken into account to improve agreement with data on unpolarized cross sections at intermediate energies [1,2]. Moreover, without intrinsic $\boldsymbol{k}_\perp$ one would never be able to explain single spin asymmetries (SSA) within the QCD factorization scheme; several large single spin asymmetries have been observed [3–5], which in a collinear configuration are predicted to be either zero or negligibly small. Although not rigorously proven in general [6,7], the usual factorized structure of the collinear scheme has been generalized with inclusion of intrinsic $\boldsymbol{k}_\perp$, so that the cross section for a generic process $AB \to CX$ reads

$$d\sigma = \sum_{a,b,c} \hat{f}_{a/A}(x_a, \boldsymbol{k}_{\perp a}) \otimes \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b}) \otimes d\hat{\sigma}^{ab\to c\cdots}(x_a, x_b, \boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}) \otimes \hat{D}_{C/c}(z, \boldsymbol{k}_{\perp C}). \quad (1)$$

The pdf's and the ff's are phenomenological quantities which have to be obtained—at least at some scale—from experimental observation and cannot be theoretically predicted. The pdf's of unpolarized nucleons, $q(x) \equiv f_{q/p}(x) \equiv f_1^q(x)$, are now remarkably well known; one measures them in inclusive deep inelastic scattering processes at some scale, and, thanks to their universality and known QCD evolution, can use them in different processes and at different energies. The $k_\perp$ dependence of $\hat{q}(x, k_\perp)$ is usually assumed to be of a Gaussian form, and the average $k_\perp$ value can be fixed so that it agrees with experimental data. Notice that, in our notations, a hat over a pdf or a ff signals its dependence on $\boldsymbol{k}_\perp$ and $k_\perp = |\boldsymbol{k}_\perp|$.

When considering polarized nucleons the number of pdf's involved grows and dedicated polarized experiments have to be performed in order to isolate and measure these functions. We have by now good data on the pdf's of longitudinally polarized protons, the helicity distribution $\Delta q(x) \equiv g_1^q(x)$, but nothing is experimentally known on the transverse spin distribution, the transversity function $\Delta_T q(x) \equiv \delta q(x) \equiv h_1^q(x)$. The situation gets much more intricate when parton intrinsic transverse momenta are taken into account. Many more distribution and fragmentation functions arise, like the Sivers function $\Delta^N f(x, \boldsymbol{k}_\perp) \propto f_{1T}^{\perp}(x, k_\perp)$ [8,9], which describes the probability density of finding unpolarized partons inside a transversely polarized proton; similarly, the Collins fragmentation function [6] gives the number density of unpolarized hadrons emerging in the fragmentation of a transversely polarized quark. These are the functions which could explain single spin asymmetries in terms of parton dynamics [10,11].

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One of the difficulties in gathering experimental information on these new spin and $\boldsymbol{k}_\perp$ dependent pdf's and ff's is that most often two or more of them contribute to the same physical observable, making it impossible to estimate each single one separately.

In Ref. [12] it was shown how properly defined single spin asymmetries in Drell-Yan processes depend only on the Sivers distribution function $\Delta^N f(x, \boldsymbol{k}_\perp)$ of quarks (apart from the usual known unpolarized quark distributions). In Ref. [13] it has been suggested to look at back-to-back correlations in azimuthal angles of jets produced in $p^\uparrow p$ RHIC interactions in order to access the gluon Sivers function. We consider here another case which, again, would isolate the gluon Sivers effect, making it possible to reach direct independent information on $\Delta^N f_{g/p^\uparrow}(x, \boldsymbol{k}_\perp)$.

Let us consider the usual single spin asymmetry

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \tag{2}$$

for $p^\uparrow p \to DX$ processes at RHIC energy, $\sqrt{s} = 200$ GeV. These D mesons originate from c or $\bar{c}$ quarks, which at leading order can be created either via a $q\bar{q}$ annihilation, $q\bar{q} \to c\bar{c}$, or via a gluon fusion process, $gg \to c\bar{c}$. The elementary cross section for the fusion process includes contributions from s, t, and u channels, and turns out to be much larger than the $q\bar{q} \to c\bar{c}$ cross section, which receives contribution from the s channel alone. Therefore, the gluon fusion dominates the whole $p^\uparrow p \to DX$ process up to $x_F \simeq 0.6$. Beyond this the $q\bar{q} \to c\bar{c}$ contribution to the total cross section becomes slightly larger than the $gg \to c\bar{c}$ contribution, due to the much smaller values, at large x, of the gluon pdf, as compared to the quark ones (Fig. 1).

As the gluons cannot carry any transverse spin the elementary process $gg \to c\bar{c}$ results in unpolarized final quarks. In the $q\bar{q} \to c\bar{c}$ process one of the initial partons (that inside the transversely polarized proton) can be polarized; however, there is no single spin transfer in this s-channel interaction so that the final c and $\bar{c}$ are again not polarized. One might invoke the possibility that also the quark inside the unpolarized proton is polarized [14], so that both initial q and $\bar{q}$ are polarized: even in this case the s-channel annihilation does not create a polarized final c or $\bar{c}$. Consequently, the charmed quarks fragmenting into the observed D mesons *cannot be polarized*, and there cannot be any Collins fragmentation effect [see further comments after Eq. (9)].

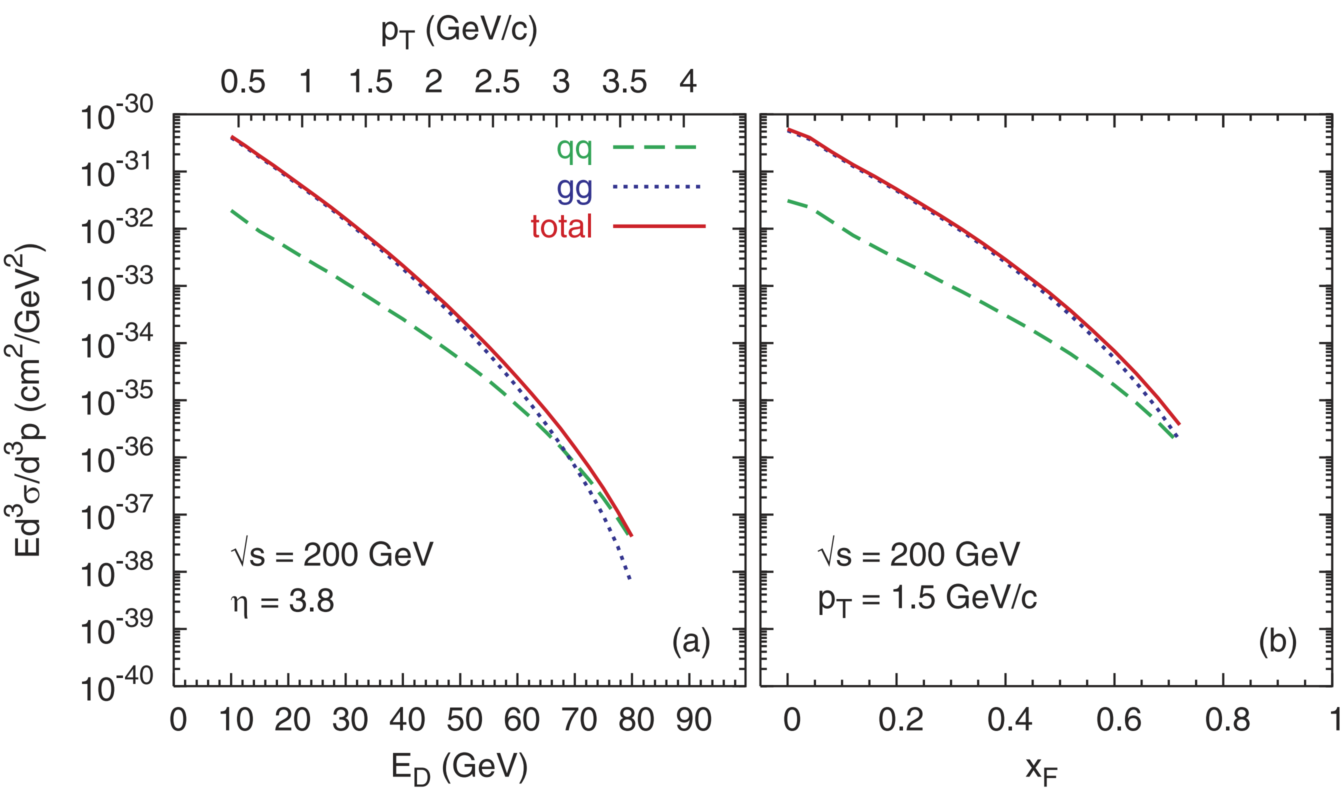

FIG. 1 (color online). The unpolarized cross section for the process $pp \to DX$ at $\sqrt{s} = 200$ GeV, as a function of E_D and p_T at fixed pseudorapidity $\eta = 3.8$ (a), and as a function of x_F at fixed transverse momentum $p_T = 1.5$ GeV/c (b), calculated according to Eqs. (9) and (10). The solid lines are the full cross section, whereas the dashed and dotted lines show the $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$ contributions separately.

Therefore, transverse single spin asymmetries in $p^\uparrow p \to DX$ can be generated only by the Sivers mechanism, namely, a spin-$\boldsymbol{k}_\perp$ asymmetry in the distribution of the unpolarized quarks and gluons inside the polarized proton, coupled, respectively, to the unpolarized interaction process $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$, and the unpolarized fragmentation function of either the c or the $\bar{c}$ quark into the final observed D meson. That is [6,15],

$$\begin{aligned} d\sigma^\uparrow - d\sigma^\downarrow &= \frac{E_D d\sigma^{p^\uparrow p\to DX}}{d^3\boldsymbol{p}_D} - \frac{E_D d\sigma^{p^\downarrow p\to DX}}{d^3\boldsymbol{p}_D} \\ &= \int dx_a dx_b dz d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b} d^3\boldsymbol{k}_D \delta(\boldsymbol{k}_D\cdot\hat{\boldsymbol{p}}_c)\delta(\hat{s}+\hat{t}+\hat{u}-2m_Q^2)C(x_a,x_b,z,\boldsymbol{k}_D) \\ &\times\Bigg\{\sum_q\Bigg[\Delta^N f_{q/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a})\hat{f}_{\bar{q}/p}(x_b,\boldsymbol{k}_{\perp b})\frac{d\hat{\sigma}^{q\bar{q}\to Q\bar{Q}}}{d\hat{t}}(x_a,x_b,\boldsymbol{k}_{\perp a},\boldsymbol{k}_{\perp b},\boldsymbol{k}_D)\hat{D}_{D/Q}(z,\boldsymbol{k}_D)\Bigg] \\ &+\Bigg[\Delta^N f_{g/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a})\hat{f}_{g/p}(x_b,\boldsymbol{k}_{\perp b})\frac{d\hat{\sigma}^{gg\to Q\bar{Q}}}{d\hat{t}}(x_a,x_b,\boldsymbol{k}_{\perp a},\boldsymbol{k}_{\perp b},\boldsymbol{k}_D)\hat{D}_{D/Q}(z,\boldsymbol{k}_D)\Bigg]\Bigg\}, \end{aligned} \tag{3}$$

where $q = u, \bar{u}, d, \bar{d}, s, \bar{s}$ and $Q = c$ or $\bar{c}$, according to whether $D = D^+, D^0$ or $D = D^-, \overline{D}^0$. Notice that z is the light-cone momentum fraction along the fragmenting parton direction, identified by $\hat{\boldsymbol{p}}_c$, $z = p_D^+/p_c^+$. Throughout the paper we choose XZ as the D production plane, with the polarized proton moving along the positive Z axis and the proton polarization $\uparrow$ along the positive Y axis. In such a frame $\boldsymbol{k}_{\perp a}$ and $\boldsymbol{k}_{\perp b}$ have only X and Y components, while $\boldsymbol{k}_D$ has all three components; the function $\delta(\boldsymbol{k}_D\cdot\hat{\boldsymbol{p}}_c)$ ensures that the integral over $\boldsymbol{k}_D$ is performed only along the appropriate transverse direction, $\boldsymbol{k}_{\perp D}$, that is the transverse momentum of the produced D with respect to the fragmenting quark direction. The factor C contains the flux and relevant Jacobian factors for the usual transformation from partonic to observed meson phase space, which, accounting for the transverse motion, reads [15,16]

$$\begin{aligned} C &= \frac{\hat{s}}{\pi z^2}\frac{\hat{s}}{x_a x_b s}\frac{\left(E_D+\sqrt{\boldsymbol{p}_D^2-\boldsymbol{k}_{\perp D}^2}\right)^2}{4(\boldsymbol{p}_D^2-\boldsymbol{k}_{\perp D}^2)} \\ &\times\left[1-\frac{z^2m_Q^2}{\left(E_D+\sqrt{\boldsymbol{p}_D^2-\boldsymbol{k}_{\perp D}^2}\right)^2}\right]^2. \end{aligned} \tag{4}$$

Notice that for collinear and massless particles this factor reduces to the familiar $\hat{s}/\pi z^2$. The Sivers distribution functions [8] for quarks and gluons are defined by

$$\begin{aligned} \Delta^N f_{a/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a}) &= \hat{f}_{a/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a}) - \hat{f}_{a/p^\downarrow}(x_a,\boldsymbol{k}_{\perp a}) \\ &= \hat{f}_{a/p^\uparrow}(x_a,\boldsymbol{k}_{\perp a}) - \hat{f}_{a/p^\uparrow}(x_a,-\boldsymbol{k}_{\perp a}), \end{aligned} \tag{5}$$

where a can either be a light quark or a gluon. Similarly, $\hat{D}_{D/Q}(z,\boldsymbol{k}_{\perp D})$ is the probability density for a quark Q to fragment into a D meson with light-cone momentum fraction z and intrinsic transverse momentum $\boldsymbol{k}_{\perp D}$.

The heavy quark mass m_Q is taken into account in the amplitudes of both the partonic processes and the resulting elementary cross sections are

$$\frac{d\hat{\sigma}^{q\bar{q}\to Q\bar{Q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{2}{9}(2\tau_1^2+2\tau_2^2+\rho), \tag{6}$$

$$\frac{d\hat{\sigma}^{gg\to Q\bar{Q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{1}{8}\left(\frac{4}{3\tau_1\tau_2}-3\right)\left(\tau_1^2+\tau_2^2+\rho-\frac{\rho^2}{4\tau_1\tau_2}\right), \tag{7}$$

where $\tau_{1,2}$ and ρ are dimensionless quantities defined in terms of the partonic Mandelstam variables $\hat{s}$, $\hat{t}$, and $\hat{u}$ as

$$\tau_1 = \frac{m_Q^2-\hat{t}}{\hat{s}}, \qquad \tau_2 = \frac{m_Q^2-\hat{u}}{\hat{s}}, \qquad \rho = \frac{4m_Q^2}{\hat{s}}\cdot \tag{8}$$

The denominator of A_N, Eq. (2), is analogously given by

$$\begin{aligned} d\sigma^\uparrow + d\sigma^\downarrow &= \frac{E_D d\sigma^{p^\uparrow p\to DX}}{d^3\boldsymbol{p}_D} + \frac{E_D d\sigma^{p^\downarrow p\to DX}}{d^3\boldsymbol{p}_D} = 2\frac{E_D d\sigma^{pp\to DX}}{d^3\boldsymbol{p}_D} \\ &= 2\int dx_a dx_b dz d^2\boldsymbol{k}_{\perp a} d^2\boldsymbol{k}_{\perp b} d^3\boldsymbol{k}_D \delta(\boldsymbol{k}_D\cdot\hat{\boldsymbol{p}}_c)\delta(\hat{s}+\hat{t}+\hat{u}-2m_Q^2)C(x_a,x_b,z,\boldsymbol{k}_D) \\ &\times\Bigg\{\sum_q\Bigg[\hat{f}_{q/p}(x_a,\boldsymbol{k}_{\perp a})\hat{f}_{\bar{q}/p}(x_b,\boldsymbol{k}_{\perp b})\frac{d\hat{\sigma}^{q\bar{q}\to Q\bar{Q}}}{d\hat{t}}(x_a,x_b,\boldsymbol{k}_{\perp a},\boldsymbol{k}_{\perp b},\boldsymbol{k}_D)\hat{D}_{D/Q}(z,\boldsymbol{k}_D)\Bigg] \\ &+\Bigg[\hat{f}_{g/p}(x_a,\boldsymbol{k}_{\perp a})\hat{f}_{g/p}(x_b,\boldsymbol{k}_{\perp b})\frac{d\hat{\sigma}^{gg\to Q\bar{Q}}}{d\hat{t}}(x_a,x_b,\boldsymbol{k}_{\perp a},\boldsymbol{k}_{\perp b},\boldsymbol{k}_D)\hat{D}_{D/Q}(z,\boldsymbol{k}_D)\Bigg]\Bigg\}. \end{aligned} \tag{9}$$

In Eqs. (3) and (9) we consider intrinsic transverse motions in the distributions of initial light quarks, in the elementary process and in the heavy quark fragmentation function, i.e., we consider a fully nonplanar configuration for the partonic scattering. This has two main consequences: on one side, taking into account three intrinsic transverse momenta makes both the kinematics and the dynamics highly nontrivial; on the other side it generates a large number of contributions, other than the Sivers effect, which originate from all possible combinations of $\boldsymbol{k}_\perp$ dependent distribution and fragmentation functions, each weighted by a phase factor (given by some combination of sines and cosines of the azimuthal angles of the parton and final meson momenta). This topic deserves a full treatment of its own, which will soon be presented in Refs. [17,18]. At present, we only point out that we have explicitly verified that all contributions to the $p^\uparrow p \to DX$ single spin asymmetry from $\boldsymbol{k}_\perp$ dependent pdf's and ff's, aside from those of the Sivers functions, are multiplied by phase factors which make the integrals over the transverse momenta either negligibly small or identically zero. Therefore, they can be safely neglected here.

Equation (3) shows how A_N depends on the unknown Sivers distribution function; as all other functions contributing to A_N are reasonably well known (including the fragmentation function $D_{D/Q}$ [19]) a measurement of A_N should bring direct information on $\Delta^N f_{g/p^\uparrow}$ and, to some extent, $\Delta^N f_{q/p^\uparrow}$.

II. NUMERICAL ESTIMATES

So far, all analyses and fits of the single spin asymmetry data were based on the assumption that the gluon Sivers function $\Delta^N f_{g/p^\uparrow}$ is zero. RHIC data on A_N in $p^\uparrow p \to DX$ will enable us to test the validity of this assumption. In fact, as the $gg \to c\bar{c}$ elementary scattering largely dominates the process up to $x_F \simeq 0.6$ (Fig. 1), any sizable single spin asymmetry measured in $p^\uparrow p \to DX$ at moderate x_F's would be the direct consequence of a nonzero contribution of $\Delta^N f_{g/p^\uparrow}$. For $x_F \gtrsim 0.6$ the competing $q\bar{q} \to c\bar{c}$ term becomes approximately the same size as $gg \to c\bar{c}$ (Fig. 1); consequently the quark and gluon Sivers functions could contribute to A_N in approximately equal measure making the data analysis more involved, as we shall discuss below.

Since we have no information about the gluon Sivers function from other experiments, we are unable to give predictions for the size of the A_N one can expect to measure at RHIC. Instead, we show what asymmetry one can find in two opposite extreme scenarios: the first being the case in which the gluon Sivers function is set to zero, $\Delta^N f_{g/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a}) = 0$, and the quark Sivers function $\Delta^N f_{q/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a})$ is taken to be at its maximum allowed value at any x_a; the second given by the opposite situation, where $\Delta^N f_{q/p^\uparrow} = 0$ and $\Delta^N f_{g/p^\uparrow}$ is maximized in x_a.

Concerning the $\boldsymbol{k}_\perp$ dependence of the unpolarized pdf's and the Sivers functions, we adopt, both for quarks and gluons, a most natural and simple factorized Gaussian parametrization

$$\hat{f}(x, \boldsymbol{k}_\perp) = f(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}, \tag{10}$$

$$\Delta^N f(x, \boldsymbol{k}_\perp) = \Delta^N f(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle} \frac{2 k_\perp M}{k_\perp^2 + M^2} \times \cos(\phi_{k_\perp}), \tag{11}$$

where $M = \sqrt{\langle k_\perp^2 \rangle}$ and $\phi_{k_\perp}$ is the $\boldsymbol{k}_\perp$ azimuthal angle. The extra factor $2k_\perp M/(k_\perp^2 + M^2)$ in the Sivers function is chosen in such a way that, while ensuring the correct small $k_\perp$ behavior, it equals 1 at $k_\perp = M$, being always smaller at other values. The azimuthal $\cos(\phi_{k_\perp})$ dependence is the only one allowed by Lorentz invariance, via the mixed vector product $\boldsymbol{P} \cdot (\hat{\boldsymbol{p}} \times \boldsymbol{k}_\perp)$ where, with our frame choice, $\boldsymbol{P} = (0, 1, 0)$ is the proton polarization vector, $\hat{\boldsymbol{p}} = (0, 0, 1)$ is the unit vector along the polarized proton motion, and $\hat{\boldsymbol{k}}_\perp = [\cos(\phi_{k_\perp}), \sin(\phi_{k_\perp}), 0]$.

The Sivers functions (11) for both quarks and gluons must respect the positivity bound

$$\frac{|\Delta^N f_{a/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a})|}{2\hat{f}_{a/p}(x_a, k_{\perp a})} \leq 1 \qquad \forall\ x_a, k_{\perp a}, \tag{12}$$

which means that Eq. (12) can be satisfied for any x_a and $\boldsymbol{k}_{\perp a}$ values by taking

$$|\Delta^N f_{a/p^\uparrow}(x_a)| \leq 2 f_{a/p}(x_a). \tag{13}$$

For the fragmentation function $\hat{D}_{D/Q}(z, \boldsymbol{k}_{\perp D})$ we adopt a similar model, in which we assume factorization of z and $\boldsymbol{k}_{\perp D}$ dependences

$$\hat{D}_{D/Q}(z, \boldsymbol{k}_{\perp D}) = D_{D/Q}(z) g(\boldsymbol{k}_{\perp D}), \tag{14}$$

where $D_{D/Q}(z)$ is the usual fragmentation function available in the literature (see for instance Ref. [19]) and $g(\boldsymbol{k}_{\perp D})$ is a Gaussian function of $|\boldsymbol{k}_{\perp D}|^2$ analogous to that in Eq. (10), normalized so that, for a fragmenting quark of momentum $\boldsymbol{p}_c$,

$$\int d^3\boldsymbol{k}_D \delta(\boldsymbol{k}_D \cdot \hat{\boldsymbol{p}}_c) \hat{D}_{D/Q}(z, \boldsymbol{k}_D) = D_{D/Q}(z). \tag{15}$$

In Fig. 1(a) we show the unpolarized cross section for the process $pp \to DX$ at $\sqrt{s} = 200$ GeV as a function of both the heavy meson energy E_D and its transverse momentum p_T, at fixed pseudorapidity $\eta = 3.8$ [notice that $x_F \simeq E_D/(100\ \text{GeV})$]. In Fig. 1(b) the same total cross section is presented as a function of x_F at fixed $p_T = 1.5\ \text{GeV}/c$. The x and Q^2-dependent parton distribution functions $f_{q/p}(x, Q^2)$ are taken from MRST01 [20], while the $k_\perp$ dependence is fixed by Eq. (10) with $\sqrt{\langle k_\perp^2 \rangle} = 0.8\ \mathrm{GeV}/c$ [15]; similarly, the fragmentation functions $D_{D/Q}(z, Q^2)$ are from Ref. [19], with the $k_\perp$ dependence fixed by $\sqrt{\langle k_\perp^2 \rangle} = 0.8\ \mathrm{GeV}/c$. We have explicitly checked that our numerical results have very little dependence on the $\langle k_\perp^2 \rangle$ value of the fragmentation functions. Finally, we have taken as QCD scale $Q^2 = m_Q^2$. The dashed and dotted lines correspond to the $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$ contributions, respectively, whereas the solid line gives the full unpolarized cross section. These plots clearly show the striking dominance of the $gg \to c\bar{c}$ channel over most of the E_D and x_F ranges covered by RHIC kinematics.

Figure 2 shows our estimates for the maximum value of the single spin asymmetry in $p^\uparrow p \to DX$. The dashed line shows $|A_N|$ when the quark Sivers function is set to its maximum, i.e., $\Delta^N f_{q/p^\uparrow}(x) = 2f_{q/p}(x)$, while setting the gluon Sivers function to zero. Clearly, the quark contribution to A_N is very small over most of the kinematic region, at both fixed pseudorapidity and varying E_D, Fig. 2(a), and fixed p_T and varying x_F, Fig. 2(b). The dotted line corresponds to the SSA one finds in the opposite situation, when $\Delta^N f_{g/p^\uparrow}(x) = 2f_{g/p}(x)$ and $\Delta^N f_{q/p^\uparrow} = 0$: in this case the asymmetry presents a sizable maximum in the central energy, E_D, and positive x_F region (in our configuration positive x_F means D mesons produced along the polarized proton direction, i.e., the positive Z axis). This particular shape is given by the azimuthal dependence of the numerator of A_N; see Eqs. (3) and (11). When the energy E_D is small, p_T is also very small (for instance, for $E_D \leq 23$ GeV, $p_T \leq 1\ \mathrm{GeV}/c$) and the partonic cross sections $d\hat{\sigma}/d\hat{t}$ depend only very weakly on $\phi_{k_{\perp a}}$. Therefore, when we integrate over $\phi_{k_{\perp a}}$ the partonic cross sections multiplied by the factor $\cos(\phi_{k_{\perp a}})$ from the Sivers function, we obtain negligible values. The transverse momentum p_T of the detected D meson grows with increasing E_D and the partonic cross sections become more and more sensitively dependent on $\phi_{k_{\perp a}}$: then A_N grows and a peak develops in correspondence of $\phi_{k_{\perp a}} \simeq 0$. Similarly, one can understand the behavior of $|A_N|_{\max}$ in the negative and positive x_F regions, Fig. 2(b). Only at very large E_D and x_F the $q\bar{q} \to c\bar{c}$ contribution becomes important, and a rigorous analysis in that region will only be possible when data from independent sources provide enough information to be able to separate the two contributions.

By looking at Fig. 2 it is natural to conclude that any sizable transverse single spin asymmetry measured by STAR or PHENIX experiments at RHIC in the region

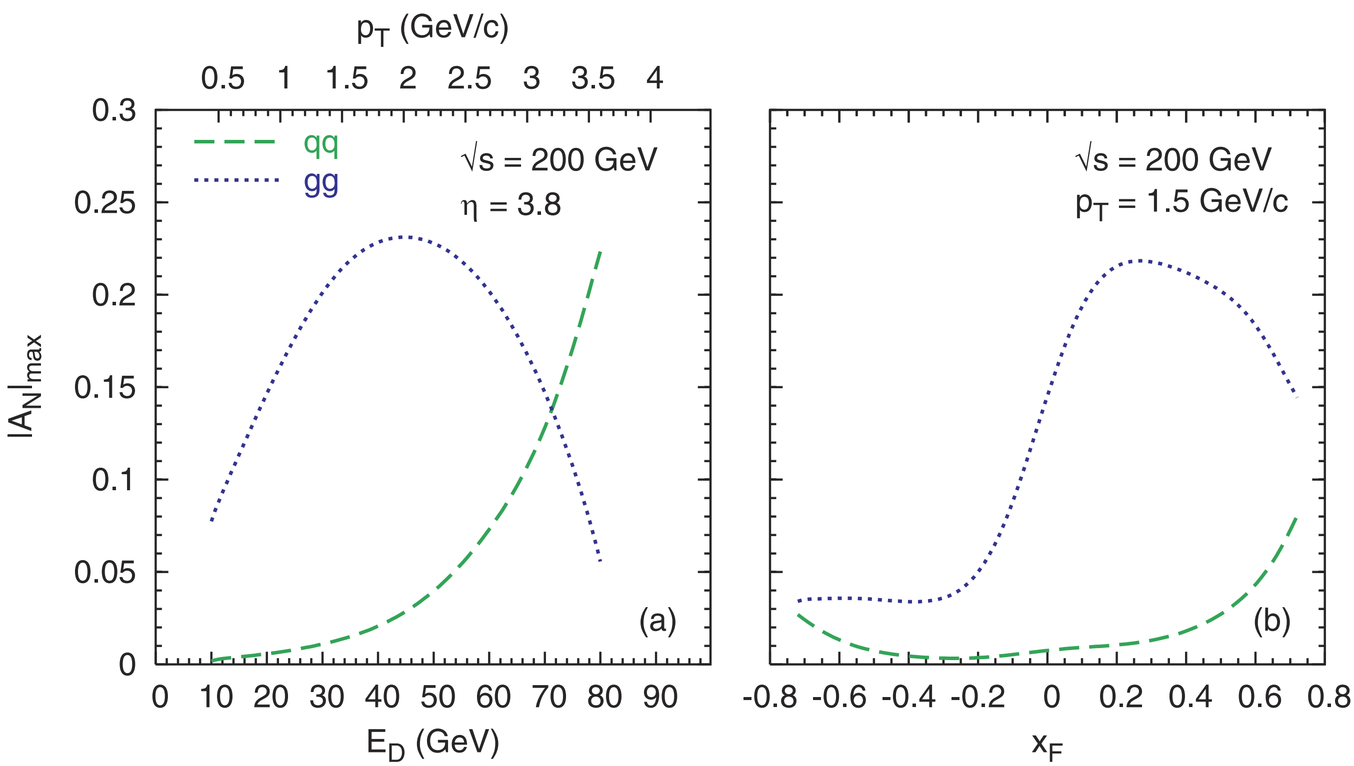

FIG. 2 (color online). Maximized values of $|A_N|$ for the process $p^\uparrow p \to DX$ as a function of E_D and p_T at fixed pseudorapidity (a), and as a function of x_F at fixed transverse momentum (b), calculated using saturated Sivers functions, according to Eq. (13) of the text. The dashed lines correspond to a maximized quark Sivers function (with the gluon Sivers function set to zero), while the dotted lines correspond to a maximized gluon Sivers function (with the quark Sivers function set to zero).

$E_D \leq 60$ GeV or $-0.2 \leq x_F \leq 0.6$ would give direct information on the size and importance of the gluon Sivers function.

III. COMMENTS AND CONCLUSIONS

We have shown that the observation of the transverse single spin asymmetry A_N for D mesons generated in $p^\uparrow p$ scattering offers a great chance to study the Sivers distribution functions. This channel allows a direct, uncontaminated access to this function since the underlying elementary processes guarantee the absence of any polarization in the final partonic state; consequently, contributions from Collins-like terms cannot be present to influence the measurement. Moreover, the large dominance of the $gg \to c\bar{c}$ process at low and intermediate x_F offers a unique opportunity to measure the gluon Sivers distribution function $\Delta^N f_{g/p^\uparrow}$.

Once more, intrinsic parton motions play a crucial role and have to be properly taken into account. Adopting a simple model to parametrize the $k_\perp$ dependence we have given some estimates of the unpolarized cross section for D meson production, together with some upper estimate of the SSA in the two opposite scenarios in which either $\Delta^N f_{g/p^\uparrow}$ is maximal and $\Delta^N f_{q/p^\uparrow} = 0$ or $\Delta^N f_{g/p^\uparrow} = 0$ and $\Delta^N f_{q/p^\uparrow}$ is maximal. Our results hold for $D = D^+$, D^-, D^0, and $\overline{D}^0$. Both the cross section and A_N could be measured at RHIC.

This might be a difficult task; the STAR Collaboration at RHIC, despite the limited running time, has already achieved significant measurements of the transverse asymmetry A_N and the unpolarized cross section, in the reaction $p^\uparrow p \to \pi X$ and in the kinematic region $x_F \gtrsim 0.2$, $E_D \lesssim 50$ GeV, at large rapidity, $\langle \eta \rangle = 3.8$ [5]. A_N is found to be large for $x_F \gtrsim 0.4$. However, the cross section for our reaction, D production, is much smaller in the same region, see Fig. 1, and a much longer data taking time would be needed to attain a reasonable statistical accuracy for the asymmetry.

All data on SSA in $p^\uparrow p \to \pi X$ processes [3–5] show large values at large x_F, which is naturally interpreted as originating from large x valence quark contributions; however, it might be that the tiny values of A_N at small x_F are due to cancellations between different mechanisms (Collins and Sivers) and different parton contributions (valence quarks, sea quarks, and, for Sivers effect, gluons). Our results for D production, due to the Sivers gluon contribution only, show that the maximized values of $|A_N|$ are large also at midrapidity, small x_F, values. This should and could be checked by the PHENIX Collaboration at RHIC, which collects data in this region.

From our results it clearly turns out that any sizable contributions to the $p^\uparrow p \to DX$ single spin asymmetry at low to intermediate E_D's or x_F's would be a most direct indication of a nonzero gluon Sivers function. Given the uniqueness of the channel, we strongly urge the RHIC experimentalists to give consideration to this possible measurement.

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