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

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The production of $D$ mesons in the scattering of transversely polarized protons off unpolarized protons at 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 $gq \to c\bar{c}$ 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 sizeable spin asymmetry measured in $p^\uparrow p \to DX$ at mid-rapidity values will be a direct indication of a non zero 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 $\Delta^N f_{g/p^\uparrow}$.

PACS numbers: 13.88.+e, 12.38.Bx, 13.85.Ni

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 non-perturbative 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 $k_\perp$ have to be taken into account to improve agreement with data on unpolarized cross sections at intermediate energies [1,2]. Moreover, without intrinsic $k_\perp$ one would never be able to explain single spin asymmetries within 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 [3,5], the usual factorized structure of the collinear scheme has been generalized with inclusion of intrinsic $k_\perp$, so that the cross section for a generic process $AB \to CX$ reads:

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

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, $q(x) \equiv f_{q/p}(x) \equiv f_{q^T}(x)$, are now remarkably well known; one measures them in exclusive 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 $k_\perp$, and $k_\perp = |k_\perp|$.

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 $\Delta q(x) \equiv g_1^T(x)$ – but nothing is experimentally known on the transverse spin distribution – the transversity function $\Delta_T q(x) \equiv \delta q(x) \equiv h_1^T(x)$. 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 $\Delta^N f(x, k_\perp) \propto f_{1T}^N(x, k_\perp)$ [6,7], which describes the probability density of finding unpolarized partons inside a transversely polarized proton; similarly, the Collins fragmentation function [8].
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 \[14\].

One of the difficulties in gathering experimental information on these new spin and $k_\perp$ 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 $\Delta^N f(x,k_\perp)$ 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 $p^+p$ 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 $\Delta^N f_{g/p^+}(x,k_\perp)$.

Let us consider the usual single spin asymmetry

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

for $p^+p \to DX$ processes at RHIC energy, $\sqrt{s} = 200$ GeV. These $D$ mesons originate from $c$ or $\bar{c}$ quarks, which at LO can be created either via a $qq$ annihilation, $qq \to cc$, or via a gluon fusion process, $gg \to cc$. 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 $qq \to cc$ cross section, which receives contribution from the $s$-channel alone. Therefore, the gluon fusion dominates the whole $p^+p \to DX$ process up to $x_F \approx 0.6$. Beyond this the $qq \to cc$ contribution to the total cross section becomes slightly larger than the $gg \to cc$ contribution, due to the much smaller values, at large $x$, of the gluon pdf, as compared to the quark ones (see Fig. 1).

As the gluons cannot carry any transverse spin the elementary process $gg \to cc$ results in unpolarized final quarks. In the $qq \to cc$ 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 charged quarks fragmenting into the observed $D$ mesons cannot be polarized, and there cannot be any Collins fragmentation effect [see further comments after Eq. \[14\]].

Therefore, transverse single spin asymmetries in $p^+p \to DX$ can only be generated by the Sivers mechanism, namely a spin-$k_\perp$ asymmetry in the distribution of the unpolarized quarks and gluons inside the polarized proton, coupled respectively to the unpolarized interaction process $q\bar{q} \to cc$ and $gg \to cc$, and the unpolarized fragmentation function of either the $c$ or the $\bar{c}$ quark into the final observed $D$ meson. That is \[14\]:

$$d\sigma^\uparrow - d\sigma^\downarrow = \frac{E_D d\sigma^\uparrow_{p^+p \to DX}}{d^3p_D} - \frac{E_D d\sigma^\downarrow_{p^+p \to DX}}{d^3p_D}$$

$$= \int dx_a dx_b dz d^2k_{\perp a} d^2k_{\perp b} d^3k_D \delta(k_D \cdot \hat{p}_c) \delta(\hat{s} + \hat{t} + \hat{u} - 2m_Q^2) C(x_a, x_b, z, k_D)$$

$$\times \left\{ \sum_q \left[ \Delta^N f_{q/p^+}(x_a, k_{\perp a}) \tilde{f}_{\bar{q}/p^+}(x_b, k_{\perp b}) \frac{d\sigma^{qq\to QQ}}{dt}(x_a, x_b, k_{\perp a}, k_{\perp b}, k_D) \tilde{D}_{D/Q}(z, k_D) \right] + \left[ \Delta^N f_{g/p^+}(x_a, k_{\perp a}) \tilde{f}_{\bar{q}/p^+}(x_b, k_{\perp b}) \frac{d\sigma^{gg\to QQ}}{dt}(x_a, x_b, k_{\perp a}, k_{\perp b}, k_D) \tilde{D}_{D/Q}(z, k_D) \right] \right\},$$

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 $D = D^-$, $\bar{D}^0$. Notice that $z$ is the light-cone momentum fraction along the fragmenting parton direction, identified by $\hat{p}_c$, $z = p_D^+/p_c^\perp$. 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 $k_{\perp a}$ and $k_{\perp b}$ have only $X$ and $Y$ components, while $k_D$ has all three components; the function $\delta(k_D \cdot \hat{p}_c)$ ensures that the integral over $k_D$ is only performed along the appropriate transverse direction, $k_{\perp D}$, 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 \[15\]:

$$C = \frac{s}{\pi z^2 x_a x_b} \left( \frac{E_D + \sqrt{p_D^2 - k_{\perp D}^2}}{4(p_D^2 - k_{\perp D}^2)} \right)^2 \left[ 1 - \frac{z^2 m_Q^2}{(E_D + \sqrt{p_D^2 - k_{\perp D}^2})^2} \right]^2.$$
Notice that for collinear and massless particles this factor reduces to the familiar $\hat{s}/\pi z^2$. The Sivers distribution functions $\hat{s}$ for quarks and gluons are defined by

$$\Delta^N f_{a/p^*}(x_a, k_{\perp a}) = \hat{f}_{a/p^*}(x_a, k_{\perp a}) - \hat{f}_{a/p^*}(x_a, -k_{\perp a}),$$

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

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:

$$\frac{d\hat{\sigma}^\Rightarrow QQ}{dt} = \frac{\pi a_s^2}{s^2} \frac{2}{9} \left( 2\tau_1^2 + 2\tau_2^2 + \rho \right),$$

$$\frac{d\hat{\sigma}^\Rightarrow gg}{dt} = \frac{\pi a_s^2}{s^2} \frac{1}{8} \left( \frac{4}{3\tau_1\tau_2} - 3 \right) \left( \tau_1^2 + \tau_2^2 + \rho - \frac{\rho^2}{4\tau_1\tau_2} \right),$$

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

$$\tau_1 = \frac{m_Q^2 - \hat{t}}{\hat{s}},$$

$$\tau_2 = \frac{m_Q^2 - \hat{u}}{\hat{s}},$$

$$\rho = \frac{4m_Q^2}{\hat{s}}.$$

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

$$d\sigma^+ + d\sigma^- = E_D d\sigma^p p^- \rightarrow DX d^3p_D + E_D d\sigma^p p^- \rightarrow DX d^3p_D = 2E_D d\sigma^p p^- \rightarrow DX d^3p_D$$

$$= 2 \int dx_a dx_b dz d^2k_{\perp a} d^2k_{\perp b} d^3k_D \delta(k_D \cdot \hat{p}_\perp) \delta(\hat{s} + \hat{t} + \hat{u} - 2m_Q^2) C(x_a, x_b, z, k_D)$$

$$\times \left\{ \sum_q \left[ \hat{f}_{q/p}(x_a, k_{\perp a}) \hat{f}_{\bar{q}/p}(x_b, k_{\perp b}) \frac{d\hat{\sigma}^\Rightarrow QQ}{dt}(x_a, x_b, k_{\perp a}, k_{\perp b}, k_D) \hat{D}_{D/Q}(z, k_D) \right] + \left[ \hat{f}_{\bar{g}/p}(x_a, k_{\perp a}) \hat{f}_{g/p}(x_b, k_{\perp b}) \frac{d\hat{\sigma}^\Rightarrow gg}{dt}(x_a, x_b, k_{\perp a}, k_{\perp b}, k_D) \hat{D}_{D/Q}(z, k_D) \right] \right\}.$$
fact, as the \( gg \rightarrow c\bar{c} \) elementary scattering largely dominates the process up to \( x_F \simeq 0.6 \) (see Fig. 1), any sizeable single spin asymmetry measured in \( p^+p \rightarrow DX \) at moderate \( x_F \)'s would be the direct consequence of a non zero contribution of \( \Delta^N f_{g/p^+} \). For \( x_F \gtrsim 0.6 \) the competing \( q\bar{q} \rightarrow c\bar{c} \) term becomes approximately the same size as \( gg \rightarrow c\bar{c} \) (see 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, \( \Delta^N f_{g/p^+}(x_a, k_{\perp a}) = 0 \), and the quark Sivers function \( \Delta^N f_{q/p^+}(x_a, k_{\perp a}) \) is taken to be at its maximum allowed value at any \( x_a \); the second given by the opposite situation, where \( \Delta^N f_{q/p^+} = 0 \) and \( \Delta^N f_{g/p^+} \) is maximized in \( x_a \).

Concerning the \( k_{\perp} \) dependence of the unpolarized pdf's and the Sivers functions, we adopt, both for quarks and gluons, a most natural and simple factorized Gaussian parameterization

\[
\hat{f}(x, k_{\perp}) = f(x) \frac{1}{\pi \langle k_{\perp}^2 \rangle} e^{-k_{\perp}^2/\langle k_{\perp}^2 \rangle},
\]

\[
\Delta^N f(x, k_{\perp}) = \Delta^N f(x) \frac{1}{\pi \langle k_{\perp}^2 \rangle} e^{-k_{\perp}^2/\langle k_{\perp}^2 \rangle} \frac{2k_{\perp} M}{k_{\perp}^2 + M^2} \cos(\phi_{k_{\perp}}),
\]

where \( M = \sqrt{\langle k_{\perp}^2 \rangle} \) and \( \phi_{k_{\perp}} \) is the \( k_{\perp} \) 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 \( k_{\perp} \) behaviour, 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 \( P \cdot (p \times k_{\perp}) \) where, with our frame choice, \( P = (0, 1, 0) \) is the proton polarization vector, \( p = (0, 0, 1) \) is the unit vector along the polarized proton motion and \( k_{\perp} = (\cos(\phi_{k_{\perp}}), \sin(\phi_{k_{\perp}}), 0) \).

The Sivers functions \( \Delta^N f_{a/p^+}(x_a, k_{\perp a}) \) for both quarks and gluons must respect the positivity bound

\[
\frac{|\Delta^N f_{a/p^+}(x_a, k_{\perp a})|}{2 \hat{f}_{a/p}(x_a, k_{\perp a})} \leq 1 \quad \forall x_a, k_{\perp a},
\]

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

\[
\Delta^N f_{a/p^+}(x_a) \leq 2 \hat{f}_{a/p}(x_a).
\]
For the fragmentation function $\hat{D}_{D/Q}(z, k_{\perp}D)$ we adopt a similar model, in which we assume factorization of $z$ and $k_{\perp}D$ dependences

$$\hat{D}_{D/Q}(z, k_{\perp}D) = D_{D/Q}(z) g(k_{\perp}D).$$  \hfill (14)$$

where $D_{D/Q}(z)$ is the usual parton distribution available in the literature (see for instance Ref. 19) and $g(k_{\perp}D)$ is a gaussian function of $|k_{\perp}D|^2$ analogous to that in Eq. (10), normalized so that, for a fragmenting quark of momentum $p_c$,

$$\int d^3k_D \delta(k_D \cdot \hat{p}_c) \hat{D}_{D/Q}(z, k_D) = D_{D/Q}(z).$$  \hfill (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 pseudo-rapidity $\eta = 3.8$ (notice that $x_F \approx E_D/(100 \text{ GeV})$). In Fig. 1(b) the same cross section is presented as a function of $x_F$ at fixed $p_T = 1.5$ GeV/c. The $x$ and $Q^2$-dependent parton distribution functions $f_{g/p}(x, Q^2)$ are taken from MRST01 20, while the $k_{\perp}$ dependence is fixed by Eq. (10) with $\sqrt{\langle k_{\perp}^2 \rangle} = 0.8$ GeV/c 19; similarly, the fragmentation functions $D_{D/Q}(z, Q^2)$ are from Ref. 19, with the $k_{\perp}$ dependance fixed by $\sqrt{\langle k_{\perp}^2 \rangle} = 0.8$ 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 $Q^2 = m^2_q$. 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.

Fig. 2 shows our estimates for the maximum value of the single spin asymmetry in $p^+ p \to DX$. The dashed line shows $|A_N|$ when the quark Sivers function is set to its maximum, i.e. $\Delta_N f_{g/p}(x) = 2 f_{g/p}(x)$, 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 pseudo-rapidity 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 $\Delta_N f_{g/p}(x) = 2 f_{g/p}(x)$ and $\Delta_N f_{g/p} = 0$: in this case the asymmetry presents a sizeable maximum in the central $E_D$ and positive $x_F$ energy 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, $p_T \leq 1$ GeV/c) and the partonic cross sections $d\sigma/dt$ 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

![Figure 2](image_url)
more sensitively dependent on $\phi_{k_\perp}$: then $A_N$ grows and a peak develops in correspondence of $\phi_{k_\perp} \approx 0$. Similarly, one can understand the behaviour of $|A_N|_{\text{max}}$ in the negative and positive $x_F$ regions, Fig. 2(b). Only at very large $E_D$ and $x_F$ the $qg \to c\bar{c}$ contribution becomes important, and a rigorous analysis in that region will only be possible when data from independent sources will provide enough information to be able to separate the two contributions.

By looking at Fig. 2(b) it is natural to conclude that any sizeable single transverse spin asymmetry measured by STAR or PHENIX experiments at RHIC in the region $E_D \leq 60$ 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 $p^+p$ 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 $\Delta^N f_g/p^\perp$.

Once more, intrinsic parton motions play a crucial role and have to be properly taken into account. Adopting a simple model to parameterize 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 $\Delta^N f_g/p^\perp$ is maximal and $\Delta^N f_q/p^\perp = 0$ or $\Delta^N f_g/p^\perp = 0$ and $\Delta^N f_q/p^\perp$ is maximal. Our results hold for $D = D^+, D^-, D^0, \overline{D}^0$. Both the cross section and $A_N$ could soon be measured at RHIC.

It clearly turns out that any sizeable contributions to the $p^+p \to DX$ single spin asymmetry at low to intermediate $E_D$’s or $x_F$’s would be a most direct indication of a non zero gluon Sivers function.

Acknowledgments

We thank C. Aidala and L. Bland for interesting and inspiring discussions. The authors are grateful to INFN for continuous support to their collaboration. M. Boglione is grateful to Œrél Italia for awarding her a grant from the scheme “For Women in Science”. E. Leader is grateful to the Royal Society of Edinburgh Auber Bequest for support. U.D. and F.M. acknowledge partial support from “Cofinanziamento MURST-PRIN03”.

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