Sivers gluon distribution in $p^\uparrow p \to D X$ at RHIC

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The Sivers Mechanism

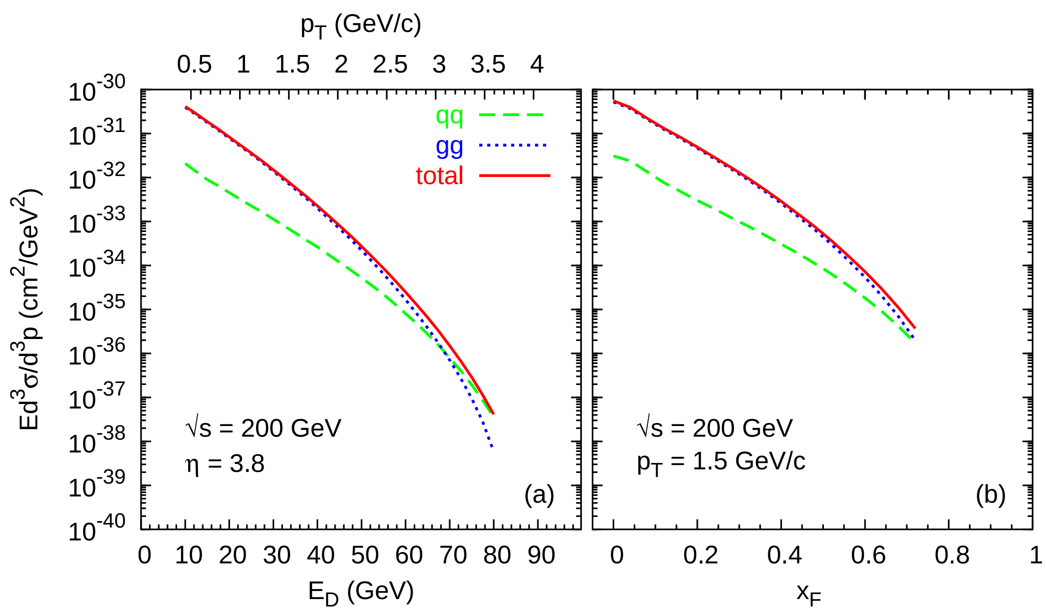
The pdf's and the ff's are phenomenological quantities which have to be obtained from experimental observation and cannot be theoretically predicted. The pdf's of unpolarized nucleons are now remarkably well known; their $k_{\perp}$ dependence is usually assumed to be of a gaussian form, and the average $k_{\perp}$ value can be fixed so that it agrees with experimental data.

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, but nothing is experimentally known on the transverse spin distribution. When parton intrinsic transverse momenta are taken into account, many more distribution and fragmentation functions arise, like the Sivers function $\Delta^N f(x, \boldsymbol{k}_{\perp}) \propto f_{1T}^{\perp}(x, k_{\perp})$, which describes the probability density of finding unpolarized partons inside a transversely polarized proton.

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 disentangle them.

$p^{\uparrow}p \to DX$ allows a clear measurement of the Sivers gluon distribution function

D mesons originate from c or $\bar{c}$ quarks, which at LO can be created either via $q\bar{q} \to c\bar{c}$, or via $gg \to c\bar{c}$. The elementary cross section for the gluon fusion process includes contributions from s, t and u-channels, and turns out to be much larger than the $q\bar{q}$ annihilation cross section, which receives contribution from the s-channel alone. Therefore, $gg \to c\bar{c}$ 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.



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, 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 cannot be polarized, and there cannot be any Collins fragmentation effect.

Therefore, transverse single spin asymmetries in $p^\uparrow p \to DX$ can only be generated 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.

Sivers gluon distribution in $p^\uparrow p \to D X$ at RHIC

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

$$d\sigma^\uparrow - d\sigma^\downarrow = \frac{E_D \, d\sigma^{p^\uparrow p \to D X}}{d^3\boldsymbol{p}_D} - \frac{E_D \, d\sigma^{p^\downarrow p \to D X}}{d^3\boldsymbol{p}_D}$$

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

$$\times \left\{ \sum_q \left[\Delta^N f_{q/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a}) \, \hat{f}_{\bar{q}/p}(x_b, \boldsymbol{k}_{\perp b}) \, \frac{d\hat{\sigma}^{q\bar{q} \to Q\bar{Q}}}{d\hat{t}}(x_a, x_b, \boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}, \boldsymbol{k}_D) \, \hat{D}_{D/Q}(z, \boldsymbol{k}_D) \right] \right.$$

$$\left. + \left[\Delta^N f_{g/p^\uparrow}(x_a, \boldsymbol{k}_{\perp a}) \, \hat{f}_{g/p}(x_b, \boldsymbol{k}_{\perp b}) \, \frac{d\hat{\sigma}^{gg \to Q\bar{Q}}}{d\hat{t}}(x_a, x_b, \boldsymbol{k}_{\perp a}, \boldsymbol{k}_{\perp b}, \boldsymbol{k}_D) \, \hat{D}_{D/Q}(z, \boldsymbol{k}_D) \right] \right\}$$

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.

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.

Model for pdf's and FF's

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

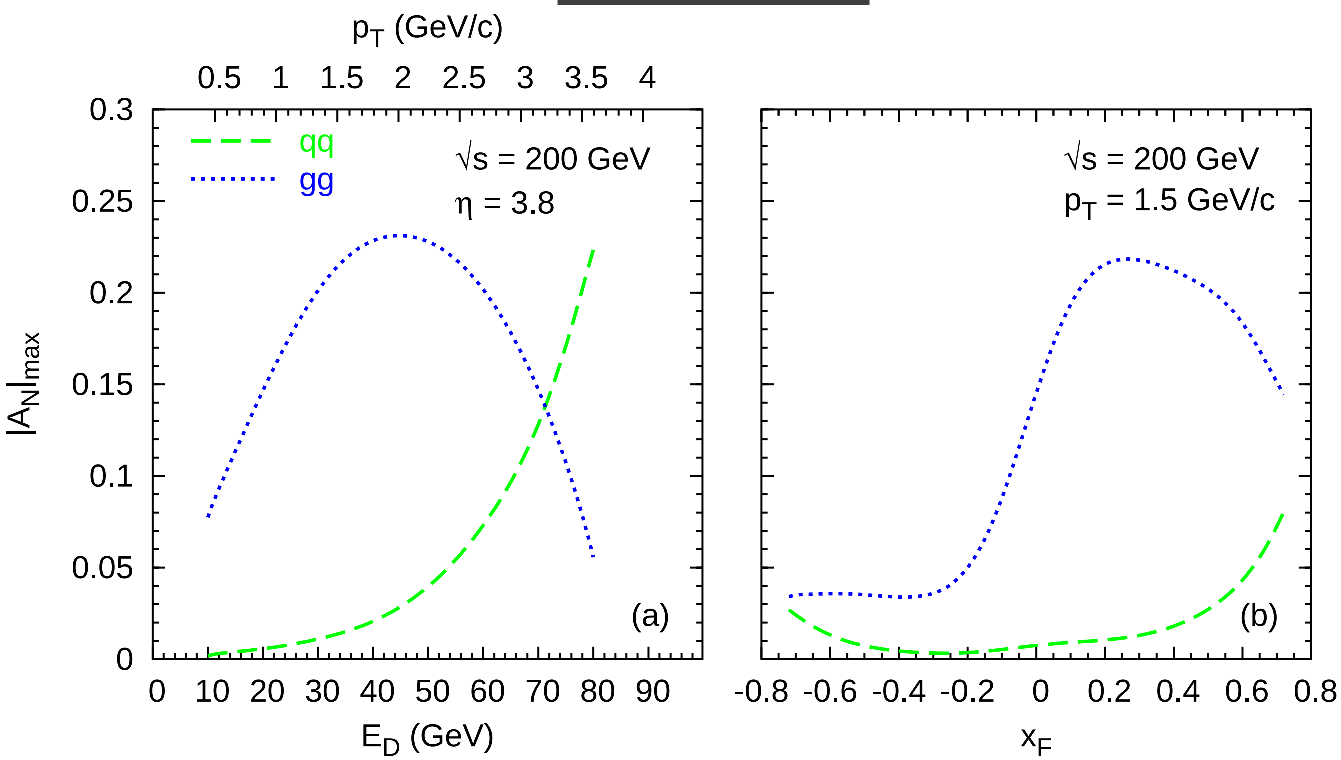
$$\Delta^N f(x, \boldsymbol{k}_\perp) = \Delta^N f(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}\,\frac{2k_\perp M}{k_\perp^2 + M^2}\,\cos(\phi_{k_\perp})\,,$$

$$\Delta^N f_{a/p^\uparrow}(x_a) \le 2\,f_{a/p}(x_a)\,.$$

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

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

Results



p_T (GeV/c)
0.5 1 1.5 2 2.5 3 3.5 4
0.3
0.25
0.2
0.15
0.1
0.05
0
$|A_N|_{max}$
qq
gg
√s = 200 GeV
η = 3.8
(a)
0 10 20 30 40 50 60 70 80 90
E_D (GeV)
√s = 200 GeV
p_T = 1.5 GeV/c
(b)
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8
x_F

Comments and Conclusions

* 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.

* 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 $\Delta^N f_{g/p^{\uparrow}}$.

* 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 $\Delta^N f_{g/p^\uparrow}$ 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 $D = D^+, D^-, D^0, \overline{D}^0$.

* Both the cross section and A_N could soon be measured at RHIC.

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