Transverse Momentum Dependent Distributions
in Hadronic Collisions:

\[ p^\uparrow p \rightarrow D + X \text{ and } p^\uparrow p \rightarrow \gamma + X \]

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Abstract. Our understanding of the transverse spin structure of hadrons might definitely get improved by the information we gather on transverse momentum dependent (TMD) distributions. These new functions could also be crucial for a description of the observed transverse single spin asymmetries (SSA). In a hard scattering model for inclusive hadronic reactions, based on a generalized QCD factorization scheme, many mechanisms - namely the Sivers [1], Collins [2], Boer-Mulders [3] effects - might contribute to a SSA. We show how the \( k_\perp \) dependent phases arising from the partonic kinematics together with a suitable choice of experimental configurations could help in disentangling the above mentioned effects. We discuss their potential role in two inclusive hadronic processes: heavy meson and photon production in \( pp \) and \( p\bar{p} \) collisions.

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INTRODUCTION AND FORMALISM

The study of transverse single spin asymmetries and their interpretation in terms of parton degrees of freedom could open a new window in our understanding of the internal spin structure of hadrons. In collinear pQCD at leading twist SSA are almost vanishing, at variance with the large values observed for instance in \( p^\uparrow p \rightarrow \pi X \) processes. Among the different approaches proposed in the literature, we consider here a pQCD generalized factorization scheme with inclusion of intrinsic transverse momentum effects. At this stage this factorized description of \( AB \rightarrow CX \) processes has to be regarded as a phenomenological model based on a natural extension of the usual collinear approach for the same process. The factorized scheme with unintegrated partonic distributions has been recently proven for SIDIS and Drell-Yan processes [4]. In a series of papers [5, 6, 7] we have shown how, within the helicity formalism, a careful treatment of the noncollinear partonic configurations lead to the appearance of several spin and TMD parton distribution (pdf) and fragmentation functions (ff) together with a complex structure in terms of \( k_\perp \) dependent phases. Schematically, for the (single) polarized cross section we have (see Ref. [7] for details)

\[
d\sigma^{A,S_A+B\rightarrow C+X} = \sum_{a,b,c,d,\{\lambda\}} \rho_{\lambda_a}^{a/A,S_A} \hat{f}_{a/A,S_A}(x_a, k_{\perp a}) \otimes \rho_{\lambda_b}^{b/B} \hat{f}_{b/B}(x_b, k_{\perp b})
\]
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 process, making it very difficult to estimate each single one separately. In Refs. [6, 7] it was explicitly shown that for the transverse SSA, $A_N$, for inclusive pion production, in the kinematical region of large positive $x_F$, the only sizeable contributions come from the Sivers and, less importantly, from the Collins mechanisms.

It is then worth to consider other inclusive processes in various kinematical configurations, in order to be sensitive more directly to one particular mechanism. To this aim a careful choice of the final state could already simplify the task by reducing the partonic subprocesses and therefore the possible mixing up of different effects. We will then discuss here SSA for the inclusive production of $D$ mesons and photons in $pp$ (and $p\bar{p}$) collisions and show how such a strategy could be carried out. To this end we will employ maximized TMD distribution and fragmentation functions, keeping however their proper azimuthal phases. Namely, we adopt for each spin and TMD distribution its trivial positivity bound.

**SSA IN $pp \rightarrow D + X$**

$D$ mesons originate predominantly from $c$ or $\bar{c}$ quarks, which at LO can be created either via $q\bar{q}$ annihilation, $q\bar{q} \rightarrow c\bar{c}$, or via a gluon fusion process, $gg \rightarrow c\bar{c}$.

As the gluons cannot carry any transverse spin the elementary process $gg \rightarrow c\bar{c}$ results in unpolarized final quarks. In the $q\bar{q} \rightarrow c\bar{c}$ process one of the initial (massless) partons, that inside the transversely polarized proton, can be polarized; however, there is no single spin transfer in this $s$-channel interaction so that again the final $c$ and $\bar{c}$ cannot be polarized (no Collins effect). Analogously, for an $s$-channel process no Boer-Mulders effect can be active. We have explicitly verified that all contributions to $A_N(p^+_p \rightarrow D X)$ from $k_\perp$ dependent pdf's and ff's, aside from those involving the Sivers functions, $\Delta^N f_a/p^+$ or $f_{1T}^{z+}$ (see Ref. [8] for notation), enter with phase factors which make the integrals over the transverse momenta negligibly small.

In a former paper [9] it was shown how at RHIC energies, $\sqrt{s} = 200$ GeV, gluon fusion dominates the whole $p^+_p \rightarrow DX$ process, up to $x_F \simeq 0.6$, allowing a direct access to the gluon Sivers function (GSF). Here we extend that analysis at lower energies, like those reachable at J-PARC, $\sqrt{s} = 10$ GeV, (left panel in Fig. 1), and at the proposed PAX experiment at GSI, $\sqrt{s} = 14$ GeV, (Fig. 1, right panel). Clearly the $q\bar{q}$ annihilation process becomes dominant now, giving the opportunity to access directly the quark Sivers function (QSF). Notice how with $p\bar{p}$ collisions at PAX the potential QSF dominance is even more dramatic. A more detailed study will be presented elsewhere [10].

**SSA IN $pp \rightarrow \gamma + X$**

The inclusive production of direct photons in $pp$ collisions is certainly a useful tool to access TMD pdf's, due to the absence of any fragmentation process. Here again we have
FIGURE 1. Preliminary results for the maximized Sivers contributions (quark, gluon) to $A_N$, for $pp \rightarrow DX$ at J-PARC, $\sqrt{s} = 10$ GeV, (left) and for $p\bar{p} \rightarrow DX$ at PAX, $\sqrt{s} = 14$ GeV (right).

to consider only two partonic subprocesses: $q(\bar{q})g \rightarrow \gamma q(\bar{q})$ and $q\bar{q} \rightarrow \gamma g$. In principle there are three mechanisms that could contribute to the SSA: the quark Sivers effect, entering both subprocesses, the gluon Sivers effect via the Compton-like subprocess, and the Boer-Mulders effect (coupled with the transversity pdf, $h_1$) via $q\bar{q}$ annihilation. Notice that the electromagnetic coupling will enhance the $u$-flavor contributions. For $x_F > 0$, at fixed $p_T$, the dominant contribution to $A_N$ comes from the quark Sivers effect. Adopting the parameterizations of the QSF extracted from the fit to $A_N(p^\uparrow p \rightarrow \pi X)$, one gets a positive SSA, rising with $x_F$ [5]. Notice that the collinear twist-3 approach developed by Qiu and Sterman [11] and reassessed recently [12] leads to a similar description of $A_N$ for pion production, while $A_N$ for photon production comes out with an opposite sign.

Concerning the backward rapidity region, it was qualitatively argued [13] that at RHIC energies and at large $p_T$ (around 20 GeV) $A_N$ would be sensitive directly to the GSF. In our more quantitative approach, with proper treatment of the noncollinear kinematics and the relative phases, we find that the best region to hunt for the GSF at RHIC energies is, at $x_F < 0$, at $p_T$ values around 5-8 GeV. In this region $A_N$ from the GSF could be as large as 10% whereas the other mechanisms would give at most a 1% contribution.

An even more interesting case is the SSA at lower energies, like for instance at the J-PARC and PAX experiments. In the first case the QSF gives the main contribution in the forward as well as in the central rapidity region, whereas again the negative $x_F$ region is dominated by the GSF (dotted line in Fig. 2, left). At PAX, by colliding polarized protons against unpolarized antiprotons another effect becomes accessible: namely the Boer-Mulders function, $\Delta^N g_{q^+ p}$ or $h_1^\perp$, coupled to the transversity distribution. In this configuration the Compton-like subprocess is suppressed because: i) the minimum $x$ value reached is quite large, being of the order of $2p_T/\sqrt{s}$; ii) the $\bar{q}$ in $\bar{p}$ has a valence component. We have then a clear dominance of the $q\bar{q}$ subprocess. Moreover, the integration over the $k_\perp$-dependent phases does not wash out the partonic double spin asymmetry. The maximized contribution to $A_N$ from the quark Sivers effect (dashed line in Fig. 2, right) is still dominating but the one coming from the Boer-Mulders effect
FIGURE 2. Preliminary results for the maximized contributions to $A_N$, for $pp \to \gamma X$ at J-PARC, $\sqrt{s} = 10$ GeV and $x_F = -0.2$ (left), and for $p\bar{p} \to \gamma X$ at PAX, $\sqrt{s} = 14$ GeV and $x_F = 0.2$ (right).

might give $A_N$ values of the order of 20-30% (dot-dashed line, Fig. 2, right). By using the parameterizations so far extracted for the QSF one gets $A_N$ of the order 5-10% for $p_T$ around 2-4 GeV (solid line, Fig. 2, right). This means that a larger SSA observed in this region should be a clear signal of the Boer-Mulders effect and then could be another way to access the transversity distribution. A detailed study is in progress [14].

In conclusion, the combined analysis of several inclusive processes, in different kinematical situations, may provide a strategy for a better determination of the polarized TMD pdf’s and ff’s that could be responsible for several large observed azimuthal asymmetries. We have reported encouraging preliminary results for the inclusive $D$ meson and $\gamma$ production cases. These results suggest that useful information on the GSF and the Boer-Mulders pdf can be obtained. A more detailed study is in progress and will be presented elsewhere [10, 14].

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