Gluon saturation effects on single spin asymmetries

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Abstract. We consider forward pion production in $pp$ collisions at RHIC energies, which probes the so-called Extended Geometric Scaling region. Upon inclusion of small-$x$ effects via an anomalous dimension within the Color Glass Condensate formalism at leading order in $\alpha_s$, a good description of the cross section as a function of the transverse momentum of the produced pion is obtained. The latter is essential for extractions of the Sivers effect from polarized $pp$ collisions, since it is a sensitive probe of the slope of the cross section. Hence, the presented approach is well suited to extract the Sivers effect from single spin asymmetries in forward pion production at high energies.

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INTRODUCTION

Single transverse-spin asymmetries (SSAs) have been observed in $p^+p \rightarrow hX$ in fixed target experiments [1] at $\sqrt{s} \approx 20$ GeV and in collider experiments at RHIC [2] at $\sqrt{s} = 200$ GeV for hadron rapidities $y_h$ up to 4. At moderately large $p_t$ of the produced hadron, such SSAs find a natural explanation in terms of $k_T$-odd transverse momentum dependent parton distribution functions (TMDs), which essentially probe the derivative of the cross section. Therefore, if there are changes in the cross section, for instance due to small-$x$ effects, then this may result in changes in the SSAs which have nothing to do with changes in the spin effect itself. Here the small-$x$ effects on SSAs in forward hadron production at RHIC will be discussed as an illustration of this point. It is based on Ref. [3]. For the spin effect we will restrict to the Sivers effect [4] (usually denoted by $\Delta^N f_{q/p^\uparrow}$ or $f_{1T}^\perp$), which is a $k_T$-odd TMD. As said, it probes the derivative of the cross section which can be seen (approximately) as follows:

$$A_N \approx d\sigma(p^\uparrow p \rightarrow hX) - d\sigma(p^\downarrow p \rightarrow hX) \propto \int d^2k_t \Delta^N f_{q/p^\uparrow}(x, \vec{k}_t) d\hat{\sigma}(\vec{q}_t - \vec{k}_t)$$

$$\approx \Delta^N f_{q/p^\uparrow}(x) \left[d\hat{\sigma}(\vec{q}_t - \langle k_t \rangle \hat{x}) - d\hat{\sigma}(\vec{q}_t + \langle k_t \rangle \hat{x})\right] \approx -2\langle k_t \rangle \Delta^N f_{q/p^\uparrow}(x) \hat{x} \cdot \vec{q}_t \frac{d\hat{\sigma}(q_t)}{dq_t},$$

where $\hat{\sigma} = \sigma^{qp \rightarrow q'X}$. The first approximation follows from the assumption [5] that the Sivers function $\Delta^N f_{q/p^\uparrow}(x, \vec{k}_t)$ is sharply peaked around an average transverse momentum ($\langle k_t \rangle \approx 200$ MeV) that points predominantly in a direction $\hat{x}$ orthogonal to the spin direction, with a magnitude $\Delta^N f_{q/p^\uparrow}(x)$. The approximations can also be viewed as resulting from a collinear expansion ($\langle k_t \rangle \ll q_t$).

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The above shows that $A_N$ can increase if the Sivers effect gets stronger, but also if the average transverse momentum increases or if the slope of the cross section gets steeper. If one does not have a good description of the cross section, then the extracted Sivers functions from $A_N$ data may not have the correct magnitude. Therefore, we will first discuss the cross section description of forward hadron production in $p p$ collisions.

**EXTENDED GEOMETRIC SCALING REGION**

If $y_h$ is sufficiently large, then one can probe small $x$ values in the unpolarized proton and resummation of logarithms in $1/x$ may be necessary. In $p p \rightarrow hX$ at RHIC ($\sqrt{s} = 200$ GeV), $y_h \sim 4$ allows to probe $x \sim 10^{-4}$. At small $x$ one probes mainly gluons and the gluon distribution is thought to display saturation (characterized by a scale $Q_s$). For $Q_s \gtrsim 1$ GeV, the Color Glass Condensate (CGC) formalism can be employed. HERA data indicate that for $x \sim 10^{-4}$: $Q_s \sim 1$ GeV [6]. For $p_t \sim Q_s$ saturation effects modify the cross section, but even for $p_t$ values significantly above $Q_s$ small-$x$ effects alter the slope of the cross section w.r.t. the standard pQCD treatment. For $Q_s \lesssim p_t \lesssim Q_{gs} \equiv Q_s^2/\Lambda$ –the ‘extended geometric scaling’ region– quark-CGC scattering is well-described by the following replacement in the factorized cross section description:

$$d\sigma^{qp \rightarrow q'X} \otimes g(x,q_t) \rightarrow N_F(x,q_t) \propto Q_s^2(x) \text{F.T.}(r_t^2)\gamma(x,r_t),$$

where the partonic cross section convoluted with the gluon distribution is replaced by a dipole forward scattering amplitude $N_F$, which depends on an anomalous dimension $\gamma$. This alters the slope of the cross section w.r.t. standard pQCD. At large $p_t$, $\gamma$ approaches $\gamma_{\text{DGLAP}} = 1 - \mathcal{O}(\alpha_s)$. The anomalous dimension $\gamma$ of Refs. [7, 8] follows partly from theory and partly from phenomenology, and is given by

$$\gamma(x,r_t) = \gamma_s + (1 - \gamma_s) \frac{\log(1/r_t^2 Q_s^2(x))}{\lambda y + d \sqrt{y} + \log(1/r_t^2 Q_s^2(x))},$$

with $\gamma_s \approx 0.627$ (which follows from BFKL evolution with saturation boundary conditions), $y = \log 1/x$, $\lambda \approx 0.3$ (as obtained from HERA data [6]). The constant $d \approx 1.2$ follows from $d$-$Au$ phenomenology, such that the cross section as function of $p_t$ is well described by the above dipole profile for both mid and forward rapidity. It describes the slope of the cross section well. Overall $p_t$-independent $K$-factors were required, but these do not alter the derivative of the cross section and hence are inconsequential for our investigation of the SSA.

The question is whether these small-$x$ effects are relevant for $p p$ scattering. It is well-known that NLO pQCD can describe the cross section as function of $p_t$ well, except for an indication of a slight deviation in slope at very forward rapidities [9, 10]. However, the latter cannot be viewed as a discrepancy given the present uncertainties in the FFs. On the other hand, using $Q_s(x) = (3 \cdot 10^{-4}/x)^{\lambda/2}$ GeV from HERA phenomenology and considering typical RHIC values for the other parameters, one finds that for $y_h \sim 4$, one is in the extended geometric scaling (EGS) region for $p_t \gtrsim 1$ GeV/c as shown in Fig. [1](left plot). Therefore, the small-$x$ effects are expected to matter.
FIGURE 1. Left: schematic indication of the extended geometric scaling regime in the $y_h$-$p_t$ plane for $p p$ collisions at RHIC. Right: transverse momentum distributions of forward inclusive $\pi^0$'s from unpolarized $p p$ collisions at $\sqrt{s} = 200$ GeV, compared to the CGC analysis of Ref. [3].

In Fig. 1 (right plot) one can see that the CGC formalism in the EGS region can describe the cross section in that region well, for standard leading order (LO) parton distribution and fragmentation functions, even without a $K$ factor. Therefore, this LO CGC formalism including the anomalous dimension forms a good starting point for fits of Sivers functions in this particular kinematic region.

SINGLE TRANSVERSE-SPIN ASYMMETRIES

From Fig. 1 (right plot) one sees that the slope gets steeper as $y_h$ increases, such that one expects that the SSA increases with $y_h$ accordingly. This is confirmed in Fig. 2, where we considered the above approach in combination with the Sivers effect. The STAR data [2, 10] can be described reasonably by adopting the Sivers function parameterization for valence quarks of Anselmino & Murgia [11] times 2. Such a quantitative adjustment is not surprising for functions fitted to SSA data from fixed target experiments, for which the cross section cannot be described with pQCD, even at NLO [12]. The good description of the cross section we have obtained indicates that these enhanced Sivers functions may be closer in magnitude to the actual Sivers effect. An improved analysis using more detailed transverse momentum dependence for the Sivers functions as investigated by Anselmino et al. [13], seems therefore worth doing.

CONCLUSIONS

At RHIC energies, forward hadron production in $p p$ scattering is in the extended geometric scaling region, for $y_h \sim 4$ and $p_t \gtrsim Q_s \sim 1$ GeV. Here small-$x$ evolution is relevant, and inclusion of the small-$x$ anomalous dimension is important (even essential in this leading order analysis). The CGC formalism can describe RHIC data (the forward hadron production cross section, in particular its derivative) very well. This is important for the extraction of Sivers functions from forward pion SSA, because changes in slope...
FIGURE 2. Single transverse-spin asymmetry $A_N$ in the rapidity interval $y_h = 3.8 \text{ - } 4.2$ for $\sqrt{s} = 200, 500 \text{ GeV}$, with two times larger Sivers functions than Ref. [11].

may otherwise be attributed to changes in the magnitude of the spin effect ($\Delta^N f_q/p^\uparrow(x)$) or the average transverse momentum. We used the STAR data for $p^\uparrow p \rightarrow \pi^0 X$ at $\sqrt{s} = 200 \text{ GeV}$ and $\langle \eta \rangle \approx y_h = 3.8$, to roughly fix the magnitude of the Sivers functions and studied the $y_h$, $p_t$ and $\sqrt{s}$ dependence of $A_N$ within the outlined approach that incorporates small-$x$ evolution. Details can be found in Ref. [3].

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