Gluon saturation effects on single spin asymmetries

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SSA in $pp \uparrow \rightarrow hX$ at moderately large $p_T$ are naturally described with $k_T$-odd TMDs (Sivers; Collins; Anselmino et al.; Mulders et al.; ...)

$k_T$-odd TMDs essentially probe the derivative of the cross section

Changes in underlying physics $\Rightarrow$ changes in cross section $\Rightarrow$ changes in SSA

This talk: small-$x$ effects on SSA in forward hadron production at RHIC

Based on: D.B., Dumitru, Hayashigaki, hep-ph/0609083
Single transverse-spin asymmetries

\[ A_N = \frac{\sigma(p p^\uparrow \rightarrow \pi X) - \sigma(p p^\downarrow \rightarrow \pi X)}{\sigma(p p^\uparrow \rightarrow \pi X) + \sigma(p p^\downarrow \rightarrow \pi X)} \]

SSA have been observed in \( p p^\uparrow \rightarrow \pi X \) \( E704 \) Collab. (’91); AGS (’99); STAR (’02); …

STAR data is for \( \sqrt{s} = 200 \) GeV and rapidities up to \( y_h \sim 4 \)

This talk is restricted to the Sivers effect \( (\Delta^N f_{q/p}^\uparrow, f_{1T}^\perp) \)

Since it is \( k_T \)-odd, it essentially probes the derivative of the cross section
Probing the derivative

\[ A_N \propto d\sigma(p^\uparrow p \to hX) - d\sigma(p^\downarrow p \to hX) \]

\[ \propto \int d^2k_t \Delta^N f_{q/p^\uparrow}(x, \vec{k}_t) \, d\sigma^{qp \to q'X}(\vec{q}_t - \vec{k}_t) \]

\[ = \int_{\text{h.p.}} d^2k_t \Delta^N f_{q/p^\uparrow}(x, \vec{k}_t) \left[ d\sigma^{qp \to q'X}(\vec{q}_t - \vec{k}_t) - d\sigma^{qp \to q'X}(\vec{q}_t + \vec{k}_t) \right] \]

\[ \approx \Delta^N f_{q/p^\uparrow}(x) \left[ d\sigma^{qp \to q'X}(q_t - \langle k_t \rangle) - d\sigma^{qp \to q'X}(q_t + \langle k_t \rangle) \right] \]

\[ \approx \Delta^N f_{q/p^\uparrow}(x) \left( -2\langle k_t \rangle \right) \frac{d\sigma^{qp \to q'X}(q_t)}{dq_t} \]

Here \( q_t \gg \langle k_t \rangle \approx 200 \text{ MeV} \)
Gluon saturation - Color Glass Condensate

If $y_h$ is sufficiently large, then one can probe small $x$ values in the unpolarized proton. One probes mainly gluons and resummation of logarithms in $1/x$ may be necessary. The gluon distribution is thought to display saturation (characterized by a scale $Q_s$). For $p_T \sim Q_s$ saturation effects modify the cross section, important for SSA.

In $p p \rightarrow h X$ at RHIC: $y_h \sim 4 \Rightarrow x \sim 10^{-4}$

HERA data: $x \sim 10^{-4} \Rightarrow Q_s \sim 1$ GeV (a perturbative scale $\Rightarrow$ CGC formalism)


Despite the relatively low $Q_s$, small-$x$ effects for $p_t \sim Q_s$ in $p p$ scattering do lead to a modification w.r.t. standard pQCD treatment.
Small-$x$ evolution

For $Q_s \lesssim p_t \lesssim Q_s^2/\Lambda$ (the 'extended geometric scaling' region) quark-CGC scattering is well-described by

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

Alters the slope of the cross section w.r.t. standard pQCD

At large $p_T$, $\gamma \rightarrow \gamma_{\text{DGLAP}} = 1 - \mathcal{O}(\alpha_s)$

The anomalous dimension $\gamma$ follows partly from theory and partly from phenomenology

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

with $\gamma_s \approx 0.627$ (BFKL+saturation b.c.), $y = \log 1/x$, $\lambda \approx 0.3$ (GBW), $d \approx 1.2$ (dAu)

Dumitru, Hayashigaki, Jalilian-Marian, NPA 770 (2006) 57

Note: overall $p_T$-independent $K$-factors do not alter the derivative of the cross section
Extended geometric scaling region

$\gamma_{\text{DHJ}}$ works well in $dAu$ at RHIC, it describes the slope of the cross section well. That is very important for SSA, but are these small-$x$ effects relevant for $pp$?

Using typical RHIC kinematics & $Q_s$ from HERA phenomenology:

\[
Q_s(x) = \left(\frac{3 \cdot 10^{-4}}{x}\right)^{0.3} \text{GeV}
\]

\[
Q_{gs}(x) \simeq Q_s^2(x)/\Lambda
\]

D.B., Dumitru, Hayashigaki, hep-ph/0609083
For very forward rapidities the slope seems to deviate from NLO pQCD
**pp phenomenology: CGC formalism**

CGC formalism forms a good starting point for fits of Sivers functions.

International Workshop on RHIC Spin Physics, September 29-30, 2006, RIKEN, Wako, Japan
Single transverse-spin asymmetry

Data can be described reasonably by the Sivers function parameterization for valence quarks of Anselmino & Murgia (PLB 442 (1998) 470) times 2

Such quantitative adjustment not surprising for fits from fixed target data
Conclusions

• The CGC formalism can describe RHIC data (cross section and derivative) very well: $d\ Au \rightarrow h\ X$ from mid to forward rapidities and $p\ p \rightarrow h\ X$ at forward rapidities.
  The slope changes are well described by the small-$x$ anomalous dimension.

• This is important for the extraction of Sivers functions from forward pion SSA.
  Changes in slope may otherwise be attributed to $\Delta^N f_{q/p^\uparrow}(x)$ or to $\langle k_t \rangle$.

• For $p^\uparrow p \rightarrow \pi^0\ X$ at $\sqrt{s} = 200$ GeV and $y_h \sim 4$ we considered CGC & Sivers effect.
  We studied the $y_h$, $p_T$ and $\sqrt{s}$ dependence using simple Sivers functions.
  Steeper slope (with increasing $y_h$) indeed leads to larger $A_N$.

  Details can be found in: D.B., Dumitru, Hayashigaki, hep-ph/0609083.

• Improved analysis (following more recent work by Anselmino, D’Alesio & Murgia) is worth doing.
Cross section - NLO pQCD

Bourrely & Soffer
Conclusion: small-$x$ evolution is relevant at RHIC energies
dAu phenomenology

\[ d + Au \rightarrow \pi^0 + X, \quad \sqrt{s_{NN}} = 200 \text{ GeV} \]

STAR Collaboration, J. Adams *et al.*
nucl-ex/0602011