Gluon saturation effects on single spin asymmetries

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SSA in $p\,p^{\uparrow} \to h\,X$ at moderately large p_T are naturally described with $\boldsymbol{k}_T$-odd TMDs

(Sivers; Collins; Anselmino *et al.*; Mulders *et al.*; ...)

$\boldsymbol{k}_T$-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

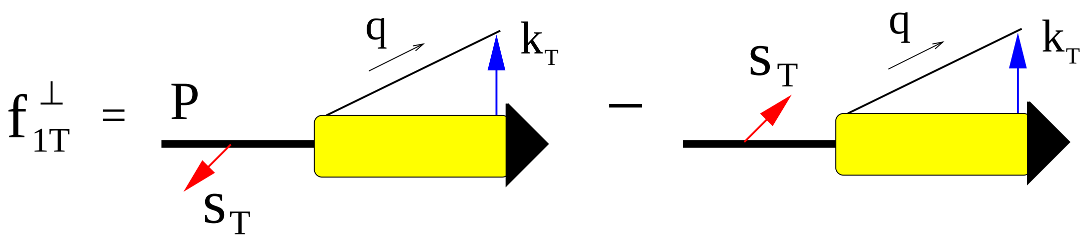
Single transverse-spin asymmetries

$$A_N = \frac{\sigma(p\,p^\uparrow \to \pi\,X) - \sigma(p\,p^\downarrow \to \pi\,X)}{\sigma(p\,p^\uparrow \to \pi\,X) + \sigma(p\,p^\downarrow \to \pi\,X)}$$

SSA have been observed in $p\,p^\uparrow \to \pi\,X$ *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 $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the cross section

Probing the derivative

$$
\begin{aligned}
A_N &\propto d\sigma(p^\uparrow p \to hX) - d\sigma(p^\downarrow p \to hX) \\
&\propto \int d^2k_t \, \Delta^N f_{q/p^\uparrow}(x, \vec{k}_t) \, d\sigma^{qp \to q'X}(\vec{q}_t - \vec{k}_t) \\
&= \int_{\text{h.p.}} d^2k_t \, \Delta^N f_{q/p^\uparrow}(x, \vec{k}_t) \, \left[d\sigma^{qp \to q'X}(\vec{q}_t - \vec{k}_t) - d\sigma^{qp \to q'X}(\vec{q}_t + \vec{k}_t) \right] \\
&\approx \Delta^N f_{q/p^\uparrow}(x) \, \left[d\sigma^{qp \to q'X}(q_t - \langle k_t \rangle) - d\sigma^{qp \to q'X}(q_t + \langle k_t \rangle) \right] \\
&\approx \Delta^N f_{q/p^\uparrow}(x) \, (-2\langle k_t \rangle) \, \frac{d\sigma^{qp \to q'X}(q_t)}{dq_t}
\end{aligned}
$$

Here $q_t \gg \langle k_t \rangle \approx 200$ 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 $p\,p \to h\,X$ 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)

Golec-Biernat & Wüsthoff, PRD 59 (1999) 014017 & PRD 60 (1999) 114023

Despite the relatively low Q_s, small-x effects for $p_t \gtrsim Q_s$ 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

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

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

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

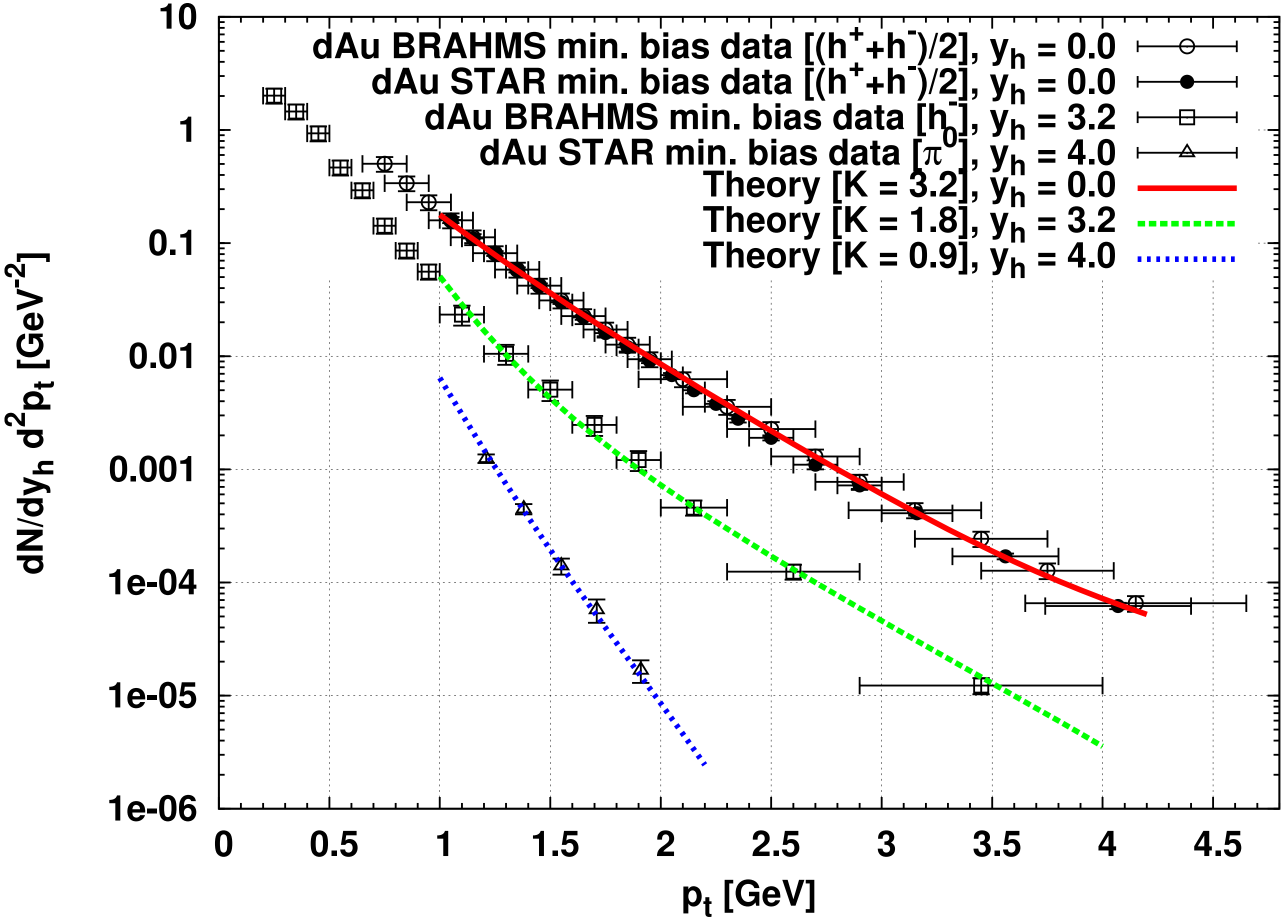
The anomalous dimension γ follows partly from theory and partly from phenomenology

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

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

Dumitru, Hayashigaki, Jalilian-Marian, NPA 770 (2006) 57 & NPA 765 (2006) 464

$d\,Au$ phenomenology



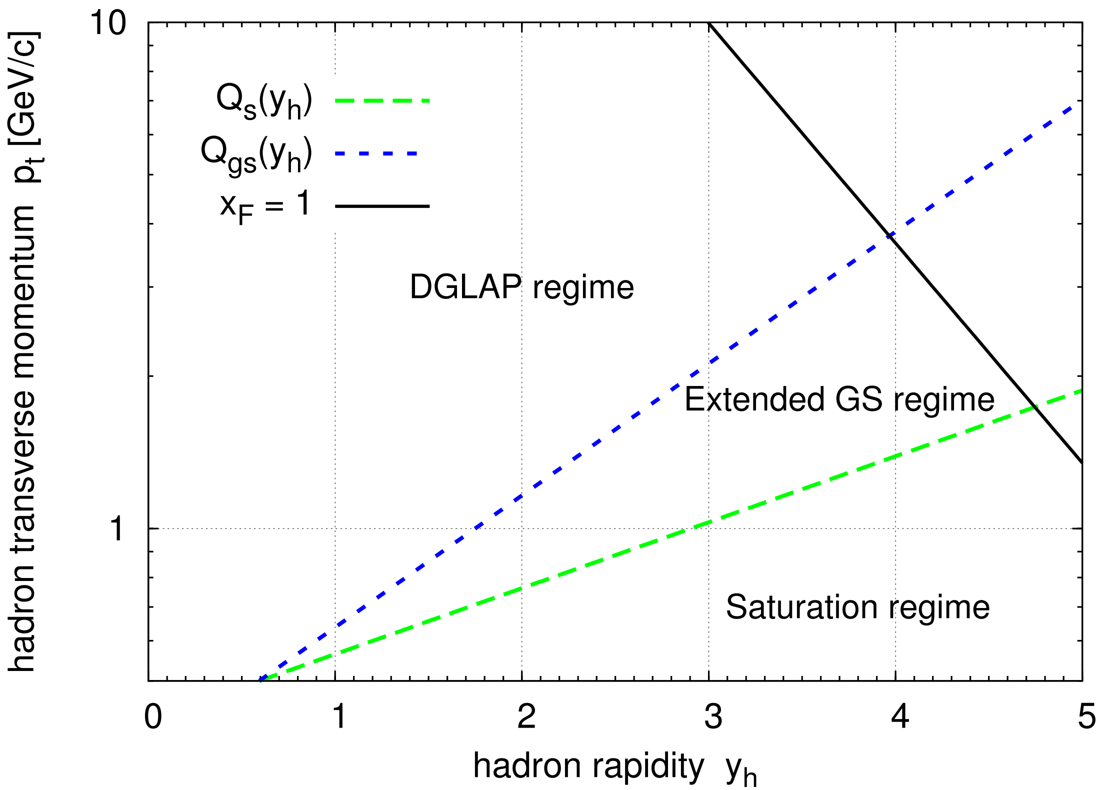
Dumitru, Hayashigaki, Jalilian-Marian, NPA 770 (2006) 57

Note: overall p_T-independent K-factors do not alter the derivative of the cross section

Extended geometric scaling region

$\gamma_{\rm DHJ}$ works well in $d\,Au$ 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 $p\,p$?



Using typical RHIC kinematics &

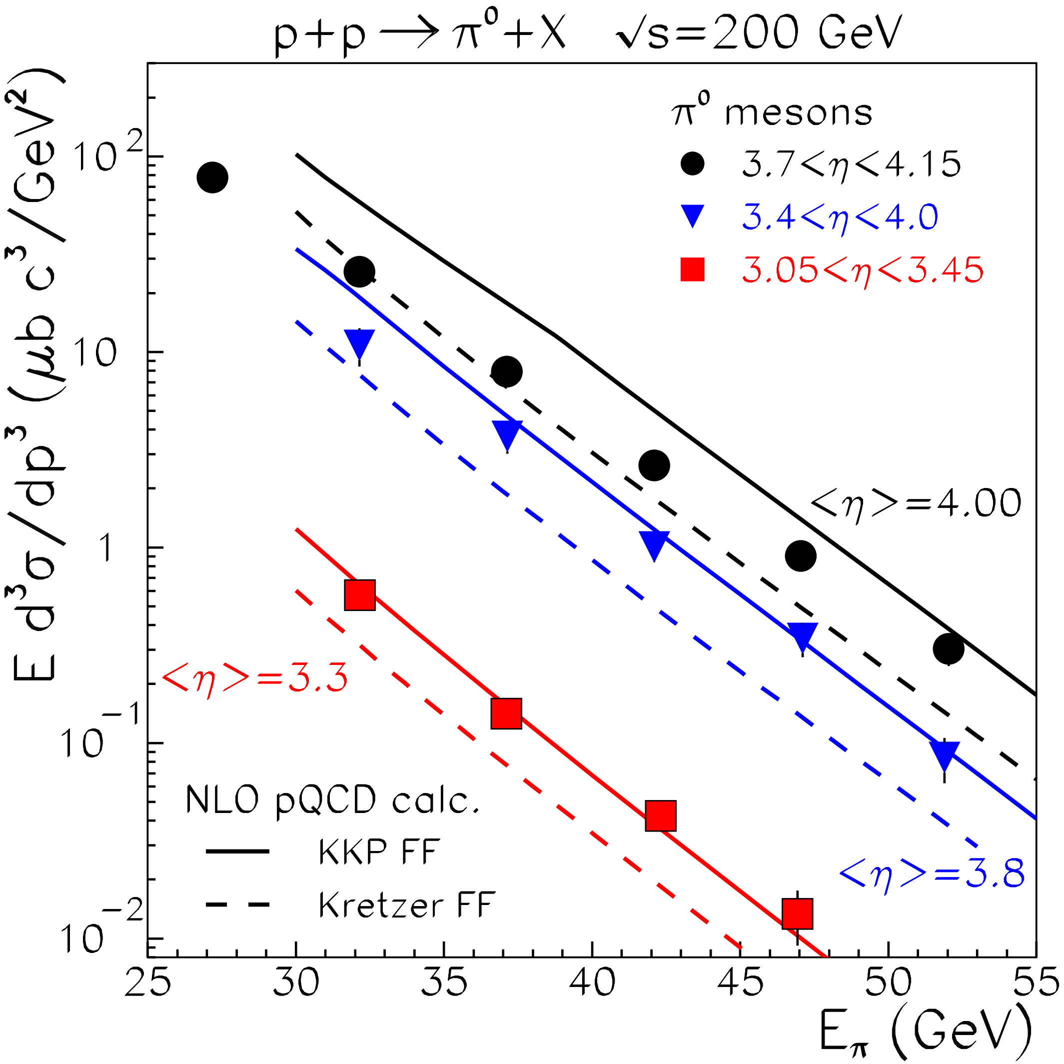
Q_s from HERA phenomenology:

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

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

D.B., Dumitru, Hayashigaki, hep-ph/0609083

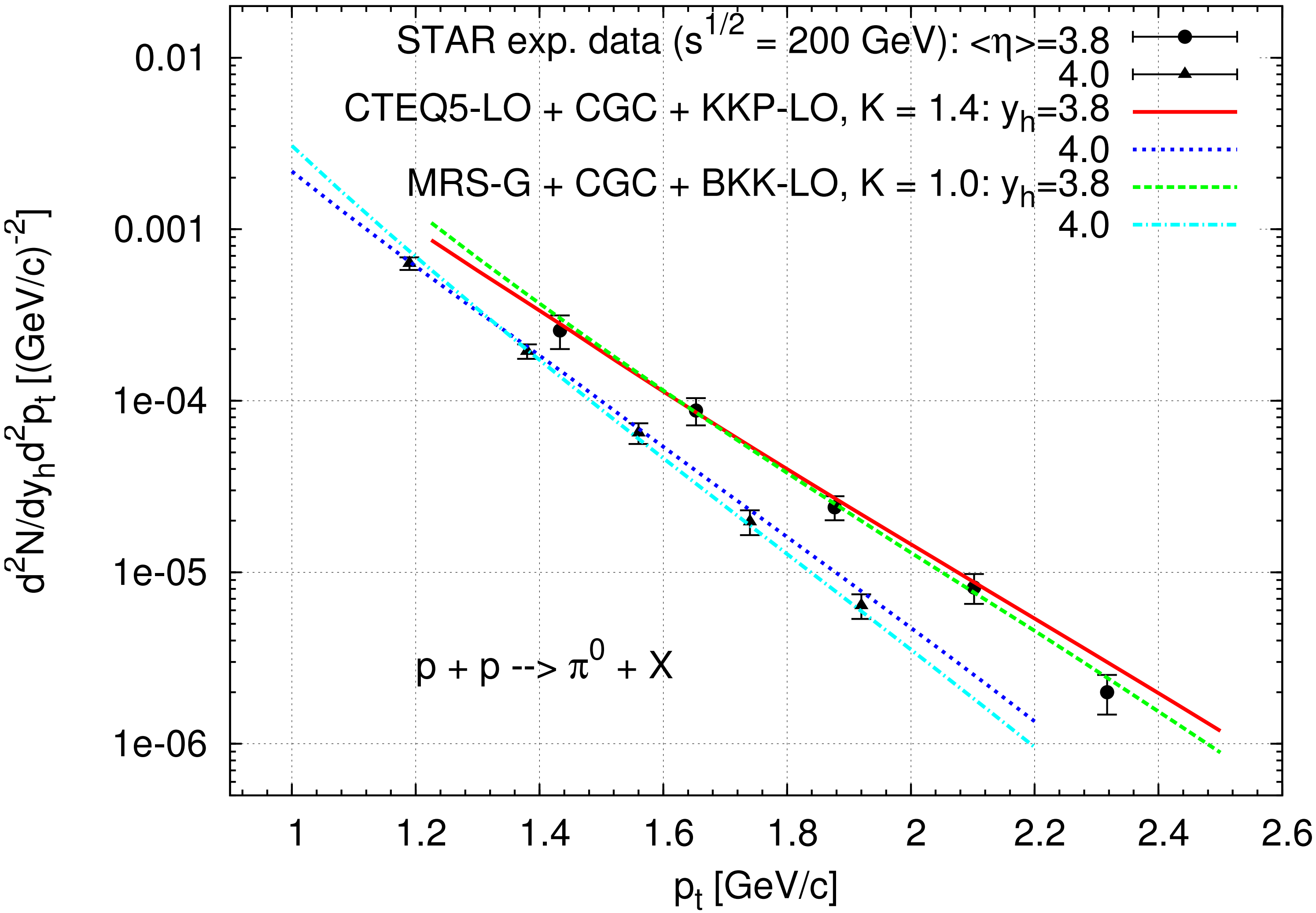
$p\,p$ phenomenology: NLO pQCD



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

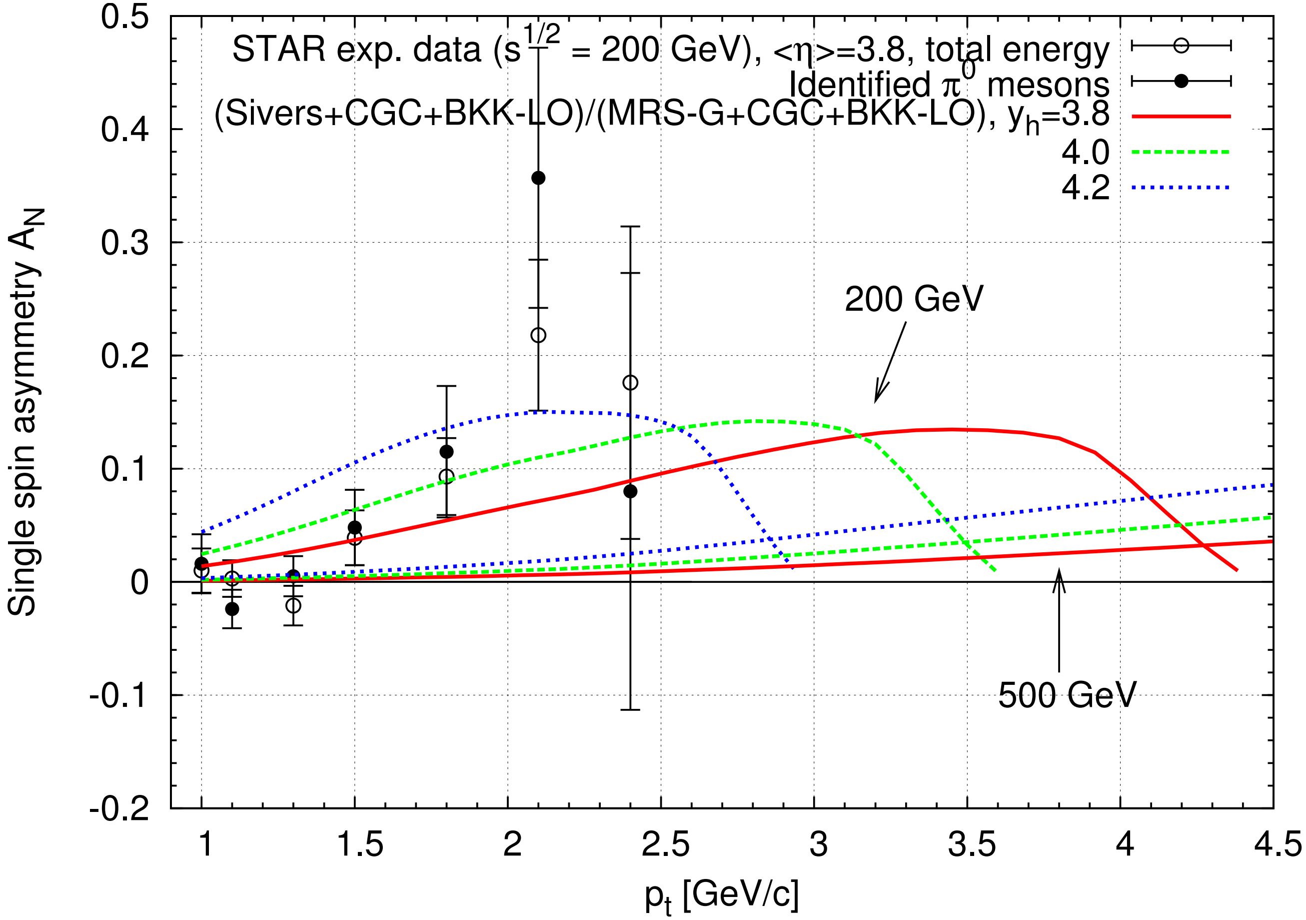
For very forward rapidities the slope seems to deviate from NLO pQCD

$p\,p$ phenomenology: CGC formalism



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

Single transverse-spin asymmetry



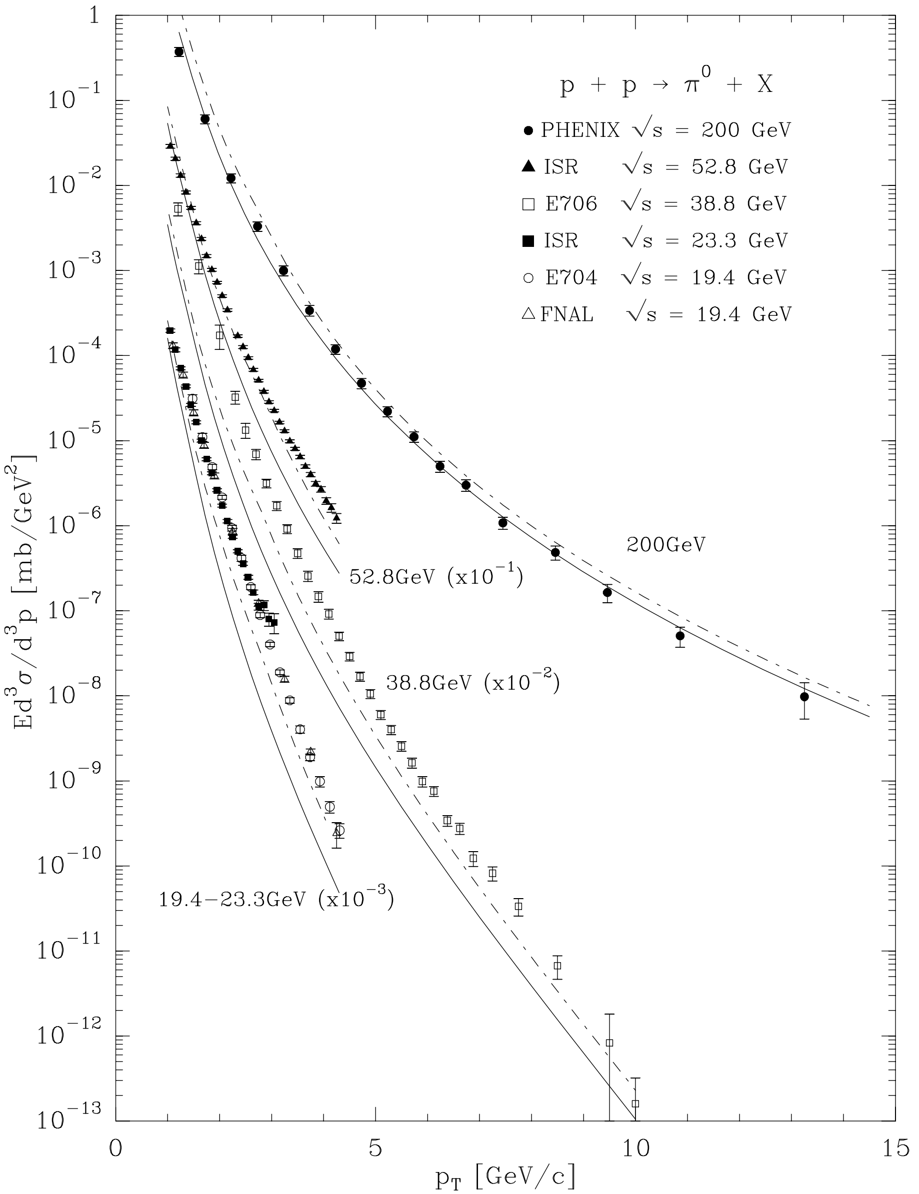
Data can be described reasonably by the Sivers function parameterization for valence quarks of Anselmino & Murgia (PLB 442 (1998) 470) *times* 2

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:
  $d\,Au \to h\,X$ from mid to forward rapidities and $p\,p \to h\,X$ 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 $p^\uparrow\,p \to \pi^0\,X$ 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

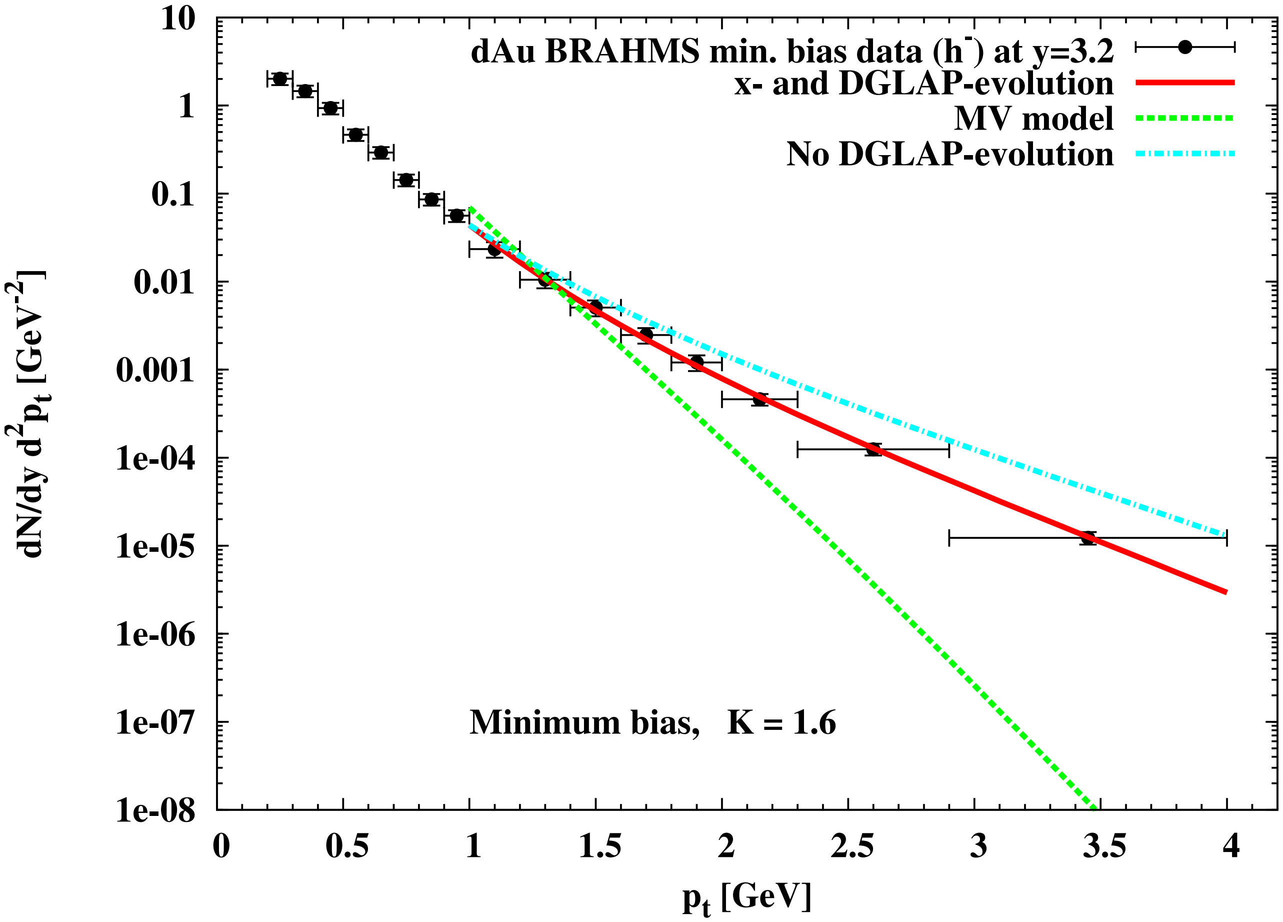
Cross section - NLO pQCD



Bourrely & Soffer

Eur.Phys.J. C36 (2004) 371

$d\,Au$ phenomenology



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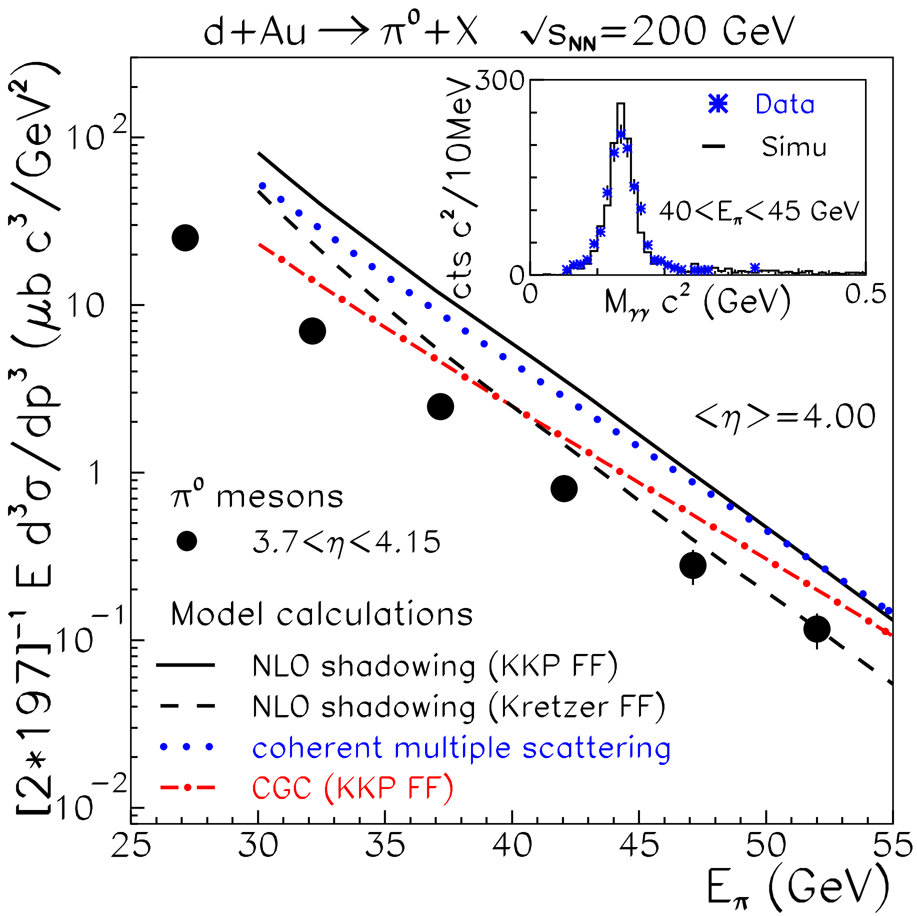
Conclusion: small-x evolution is relevant at RHIC energies

$d\,Au$ phenomenology



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