Cronin Effect and High-p_T Suppression in pA Collisions

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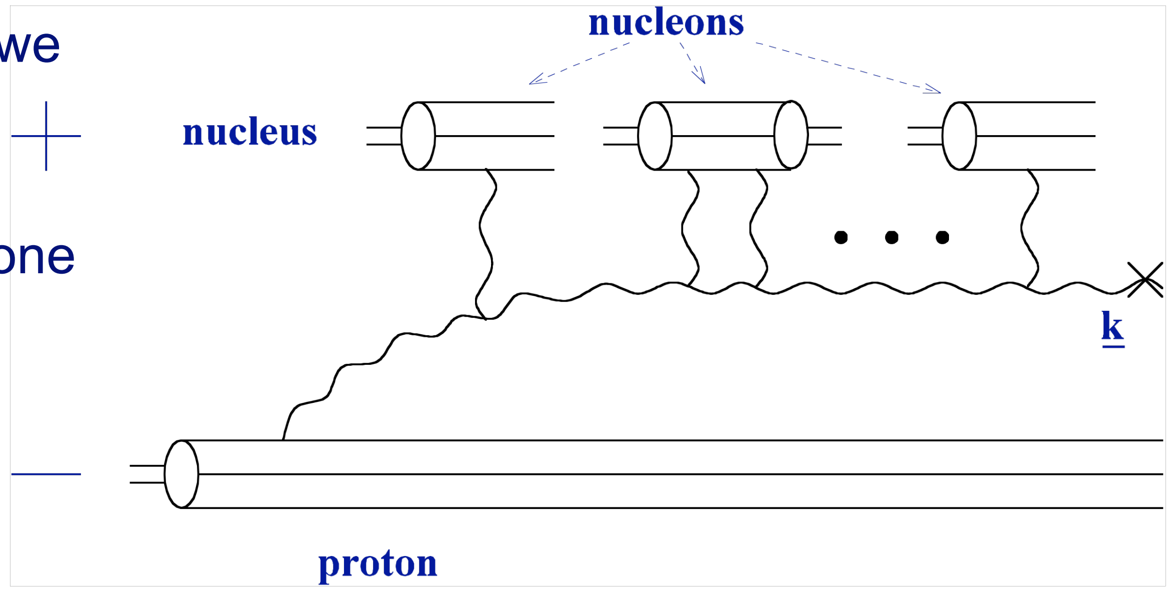
Based on work done in collaboration with
Dmitri Kharzeev and Kirill Tuchin, hep-ph/0307037

Gluon Production in pA: McLerran-Venugopalan model

Classical gluon production: we need to resum only the multiple rescatterings of the gluon on nucleons. Here's one of the graphs considered.

Yu. K., A.H. Mueller, hep-ph/9802440



Resulting inclusive gluon production cross section is given by

$$\frac{d\sigma}{d^2k\,dy} = \frac{1}{(2\pi)^2}\int d^2b\,d^2x\,d^2y\,e^{i\underline{k}\cdot(\underline{x}-\underline{y})}\underbrace{\frac{\alpha C_F}{\pi^2}\frac{\underline{x}\cdot\underline{y}}{x^2\,y^2}}_{\substack{\text{proton's}\\ \text{wave function}}}\left[N_G(\underline{x})+N_G(\underline{y})-N_G(\underline{x}-\underline{y})\right]$$

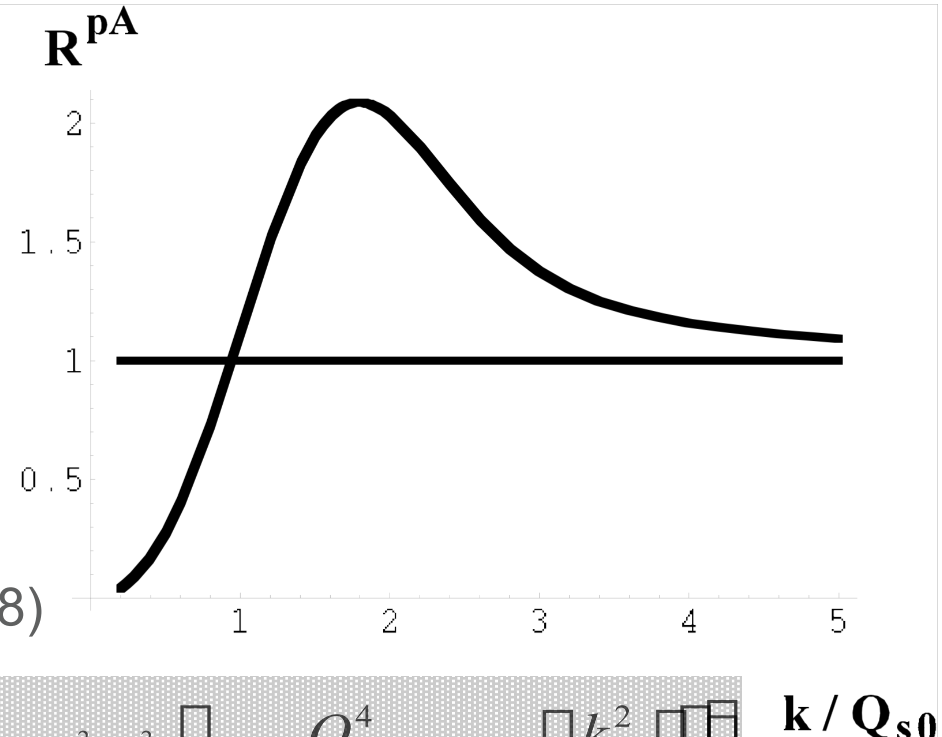
With the gluon-gluon dipole-nucleus forward scattering amplitude

$$N_G(x, Y=0) = 1 - e^{-x^2 Q_s^2/4}$$

McLerran-Venugopalan model: Cronin Effect

Defining

$$R^{pA} = \frac{\dfrac{d\sigma^{pA}}{d^2k\,dy}}{A\,\dfrac{d\sigma^{pp}}{d^2k\,dy}}$$



we can plot it for the quasi-classical cross section calculated before. One can actually do the integration analytically obtaining (Y.K., A. M. '98)

$$R^{pA}(k_T) = \frac{k^4}{Q_S^4}\left[-\frac{1}{k^2} + \frac{2}{k^2}e^{-k^2/Q_S^2} + \frac{1}{Q_S^2}e^{-k^2/Q_S^2}\left(\ln\frac{Q_S^4}{4\Lambda^2 k^2} + Ei\left(\frac{k^2}{Q_S^2}\right)\right)\right]$$

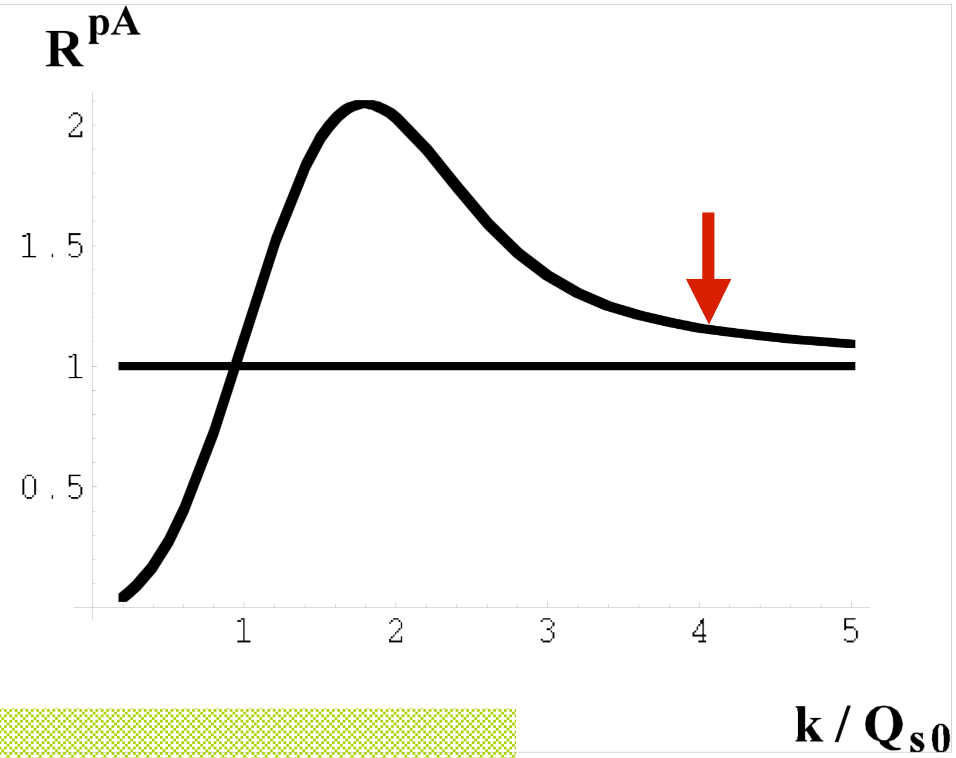
Classical gluon production leads to Cronin effect!

(see also B. Kopeliovich et al, '02, R. Baier et al, '03)

Proof of Cronin Effect

➢ Plotting a curve is not a proof of Cronin effect: one has to trust the plotting routine.

➢ To prove that Cronin actually does take place one has to study the behavior of R^{pA} at large k_T
(cf. Dumitru, Gelis, Jalilian-Marian, quark production, '02-'03):



Note the sign!

$$R^{pA}(k_T) = 1 + \frac{3}{2}\frac{Q_S^2}{k^2}\ln\frac{k^2}{\square^2} + \ldots, \qquad k_T \; \square$$

R^{pA} approaches 1 from above at high p_T ⇨ there is an enhancement!

Cronin Effect

$$R^{pA}(k_T) = 1 + \frac{3}{2}\frac{Q_S^2}{k^2}\ln\frac{k^2}{\square^2} + \ldots, \qquad k_T \ \square$$

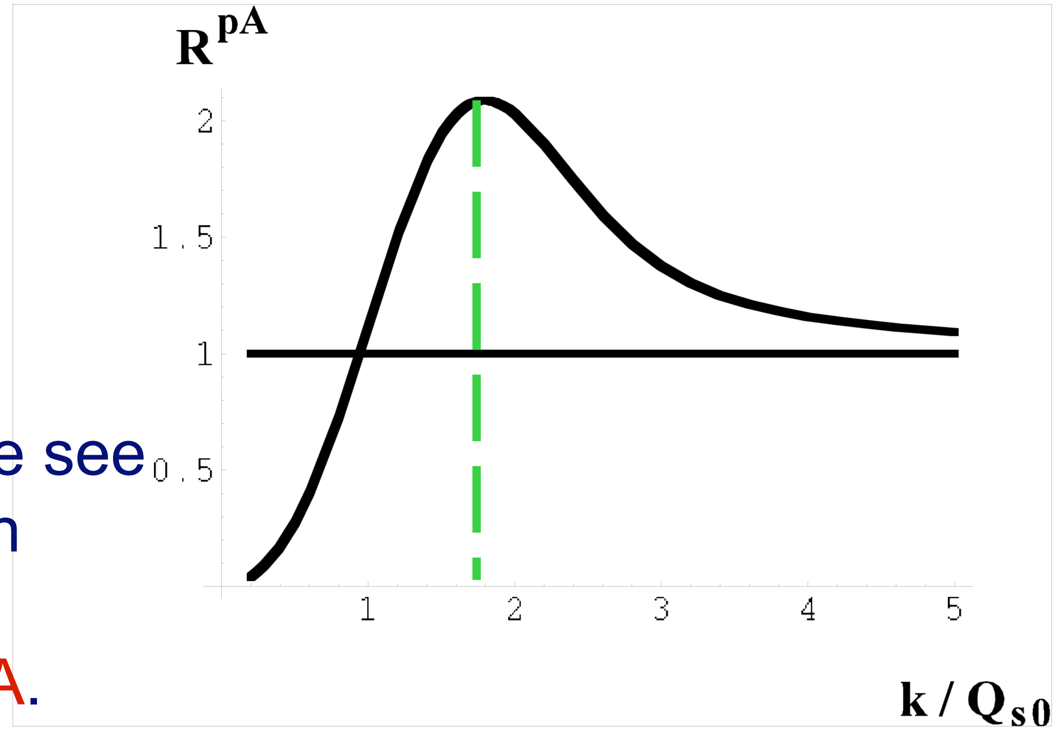
The position of the Cronin maximum is given by

$$k_T \sim Q_S \sim A^{1/6}$$

as $Q_S^2 \sim A^{1/3}$.

Using the formula above we see that the height of the Cronin peak is

$$R^{pA}(k_T = Q_S) \sim \ln Q_S \sim \ln A.$$



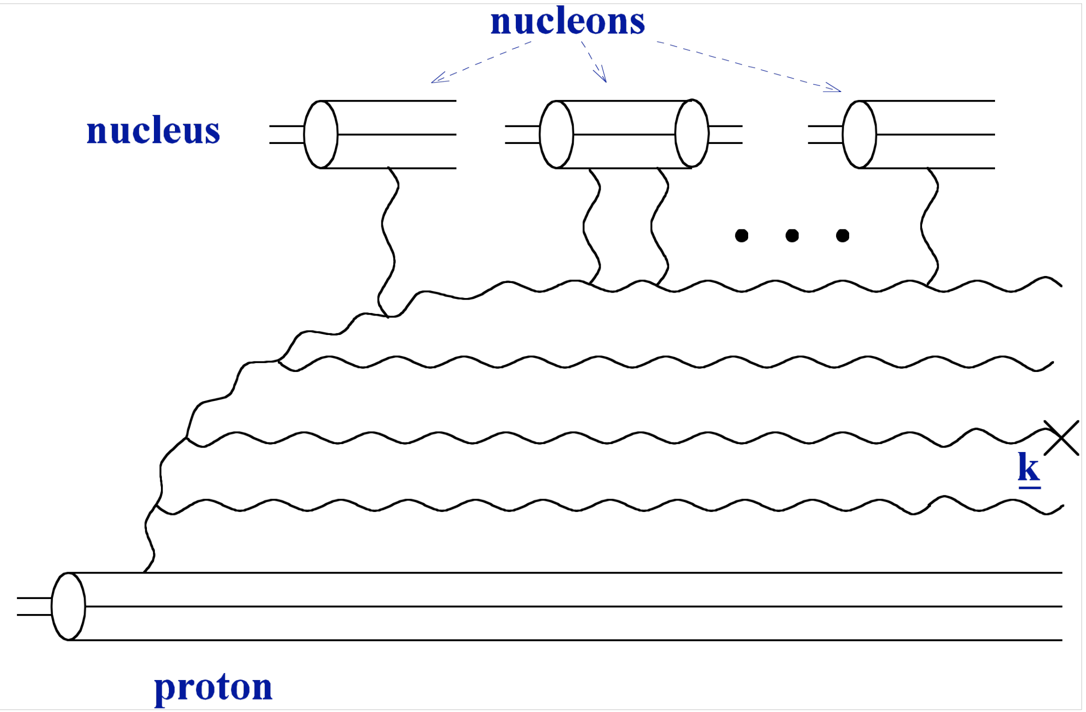
⇨ The height and position of the Cronin maximum are increasing functions of centrality!

Including Quantum Evolution

To understand the energy dependence of particle production in pA one needs to include quantum evolution resumming graphs like this one. This resums powers of

□ ln 1/x = □ Y.

This has been done in Yu. K., K. Tuchin, hep-ph/0111362.



The rules accomplishing the inclusion of quantum corrections are

Proton's LO wave function ⇨ Proton's BFKL wave function and $N(x, Y=0) \square \; N(x, Y)$

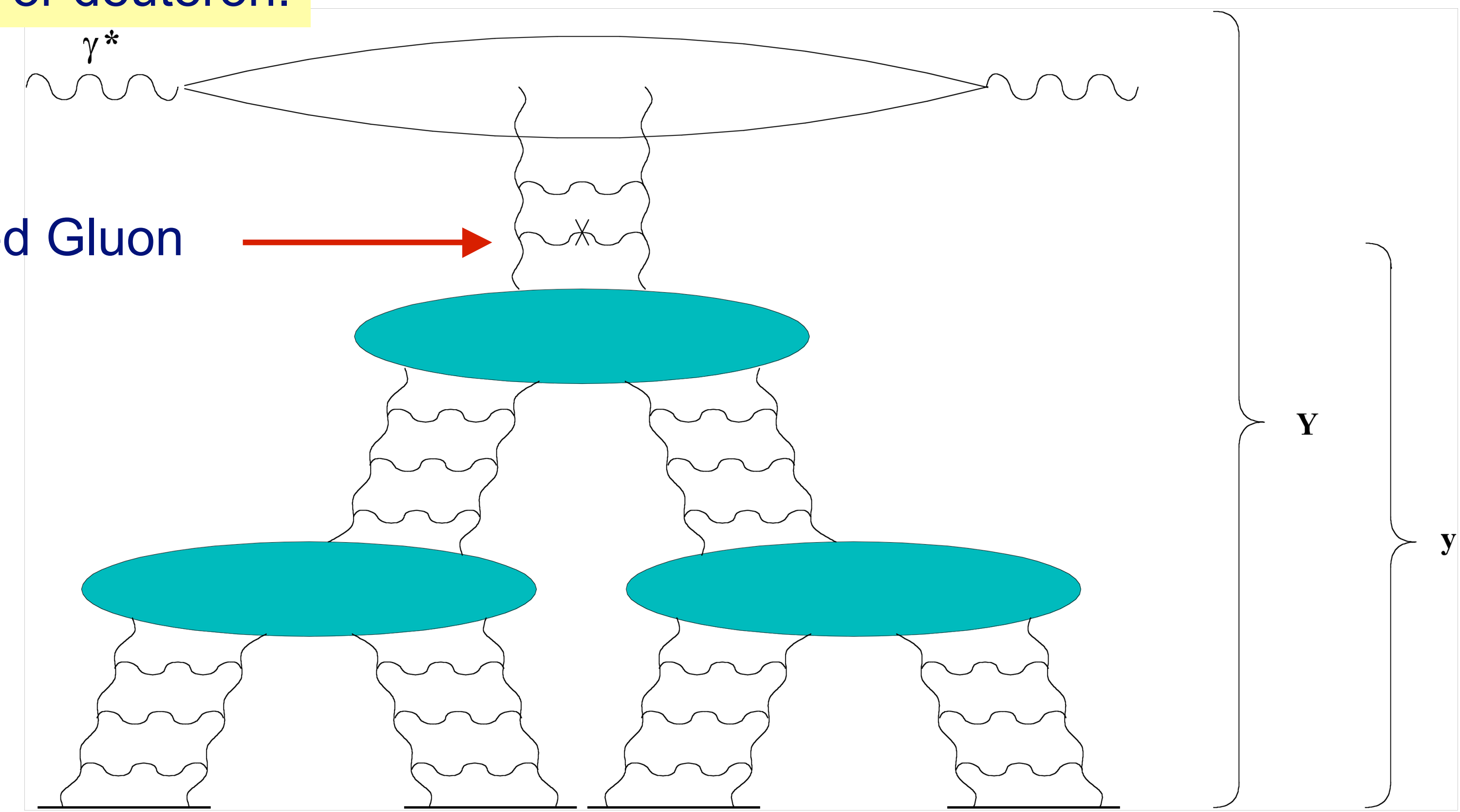
where the dipole-nucleus amplitude N is to be found from (Yu. K., Balitsky)

$$\frac{\partial N(Y,k^2)}{\partial Y} = \square_s K_{BFKL} \quad N(Y,k^2) \square \square_s [N(Y,k^2)]^2$$

Including Quantum Evolution

Can be proton or deuteron.

Produced Gluon



In the traditional fan diagram language the calculated gluon production cross section is pictured above for DIS.

Including Quantum Evolution

Amazingly enough, gluon production cross section reduces to k_T –factorization expression:

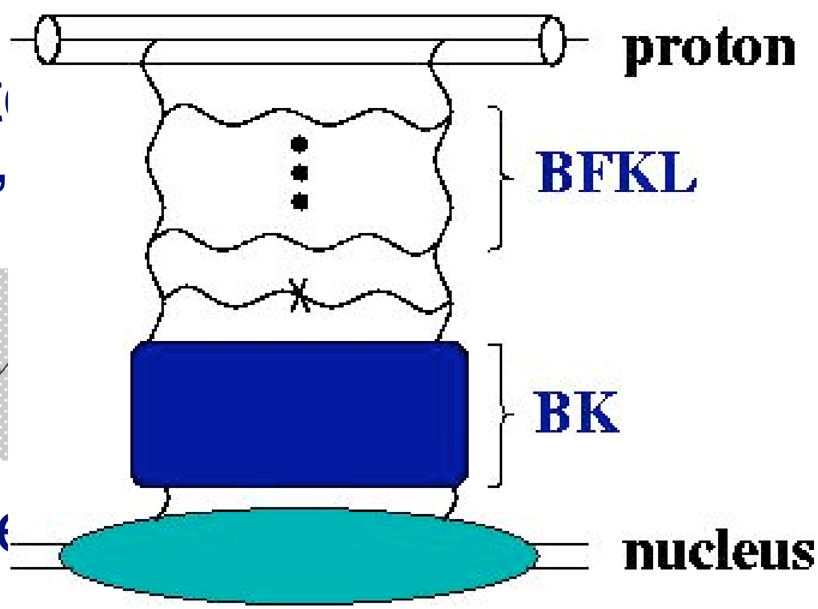
$$\frac{d\sigma^{pA}}{d^2k\,dy} = \frac{2\alpha_S}{C_F}\frac{1}{k^2}\int d^2q\,\phi_p(\underline{q}, Y-y)\,\phi_A(\underline{k}-\underline{q}, y)$$

with the prot… …ated

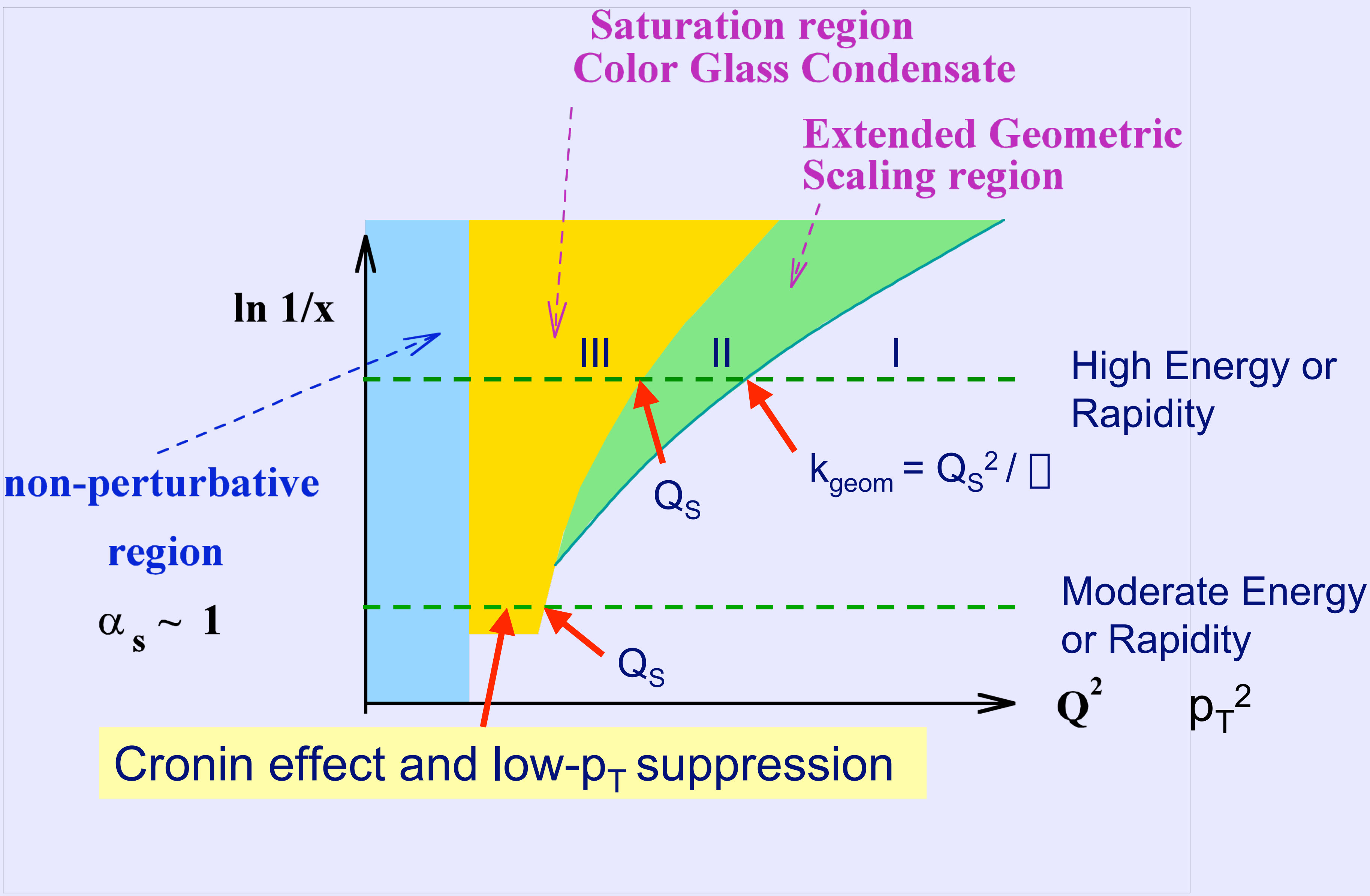
distributions’

$$\phi^{p,A}(k, y \;\ldots\; N_G^{p,A}(x, b, y)$$

with $N_G^{p,A}$ the… …le on a p or A.



Phase Diagram of High Energy QCD



Region I: Double Logarithmic Approximation

At very high momenta, $p_T >> k_{geom}$, the gluon production is given by the double logarithmic approximation, resumming powers of $\alpha_S \ln \frac{1}{x} \ln \frac{p_T^2}{\Lambda^2}$

Resulting produced particle multiplicity scales as

$$\frac{dN^{pA}}{d^2k\,dy} \propto \frac{Q_{S0}^2 \Lambda^2}{k^4} \exp\left[2\sqrt{2\bar{\alpha}\, y \ln \frac{k}{Q_{S0}}}\right] \qquad \text{with} \qquad \bar{\alpha} = \frac{\alpha N_C}{\pi}$$

where y=ln(1/x) is rapidity and $Q_{S0} \sim A^{1/6}$ is the saturation scale of McLerran-Venugopalan model. For pp collisions Q_{S0} is replaced by Λ leading to

$$R^{pA} \propto \exp\left[2\sqrt{2\bar{\alpha}\, y}\left(\sqrt{\ln \frac{k}{Q_{S0}}} - \sqrt{\ln \frac{k}{\Lambda}}\right)\right] < 1$$

as $Q_{S0} >> \Lambda$.

$R^{pA} < 1$ in Region I ⇨ There is suppression in DLA region!

Region II: Anomalous Dimension

At somewhat lower but still large momenta, $Q_S < k_T < k_{geom}$, the BFKL evolution introduces anomalous dimension for gluon distributions:

$$\varphi(k,y) \sim \left(\frac{Q_S^2}{k^2}\right)^{\gamma}$$ with BFKL γ=1/2 (DLA γ=1) $$\varphi(k,y) \sim \frac{Q_S}{k}$$

The resulting gluon production cross section scales as

$$\frac{dN^{pA}}{d^2k\,dy} \sim \frac{Q_{S0}\,\Lambda^2}{k^3}\,e^{(\alpha_P - 1)y}$$

such that

$$R^{pA} \sim \frac{k_T}{Q_{S0}} \sim A^{-1/6}\,\frac{k_T}{\Lambda}$$

Kharzeev, Levin, McLerran, hep-ph/0210332

For large enough nucleus $R^{pA} << 1$ – high p_T suppression!

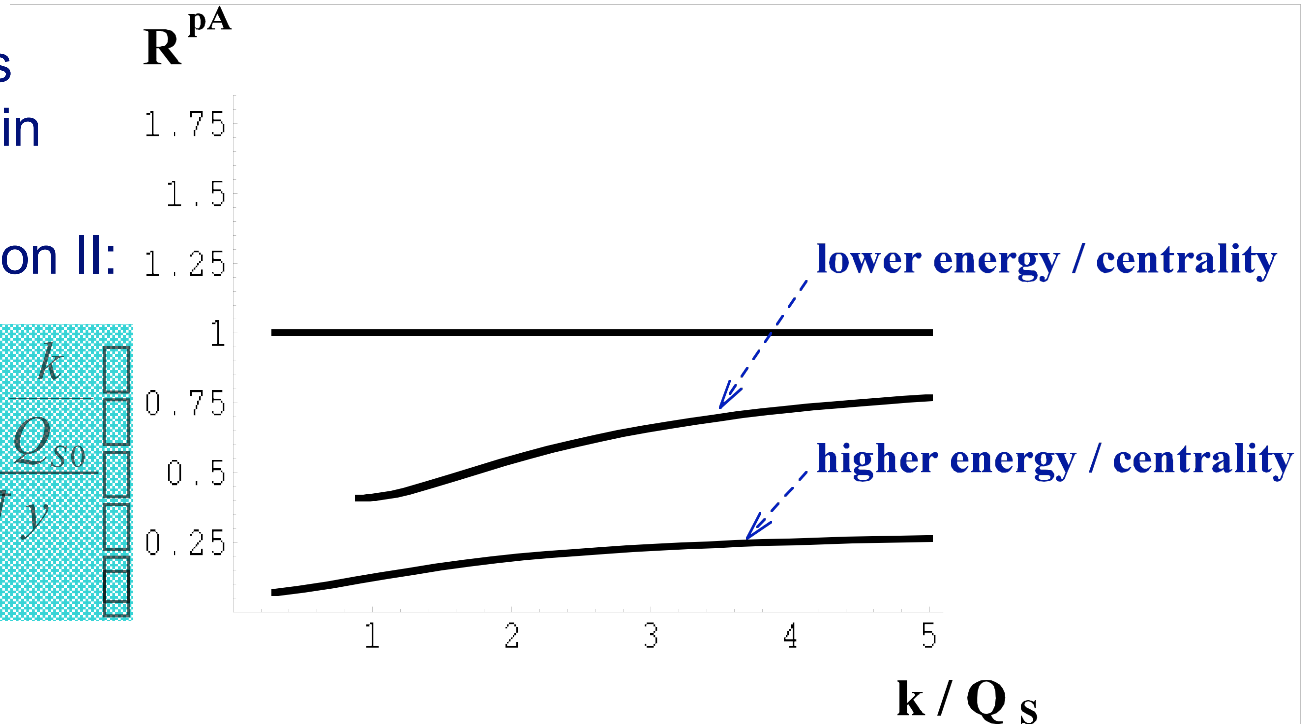
⇨ How does energy dependence come into the game?

⇨ We are in the region with $k_T >> Q_S >> Q_{S0}$. Shouldn't $R^{pA} \sim k_T / Q_{S0}$ be greater than 1 ?

Region II: Anomalous Dimension

A more detailed analysis gives the following ratio in the extended geometric scaling region – our region II:

$$R^{pA} \sim A^{-1/6} \exp\left\{ \frac{\ln^2 \frac{k}{\Lambda} - \ln^2 \frac{k}{Q_{S0}}}{14\zeta(3)\bar{\alpha}_s\, y} \right\}$$



R^{pA} is also a <u>decreasing</u> function of energy, leveling off to a constant $R^{pA} \sim A^{-1/6}$ at very high energy.

⇨ R^{pA} is a <u>decreasing</u> function of both <u>energy</u> and <u>centrality</u> at high energy / rapidity.

(D. Kharzeev, Yu. K., K. Tuchin, hep-ph/0307037)

Region III: What Happens to Cronin Peak?

✓ The position of Cronin peak is given by saturation scale Q_S , such that the height of the peak is given by R^{pA} (k_T = Q_S (y), y).

✓ It appears that to find out what happens to Cronin maximum we need to know the gluon distribution function of the nucleus at the saturation scale – $\square^A$ (k_T = Q_S, y). For that we would have to solve nonlinear BK evolution equation – a very difficult task.

✓ Instead we can use the scaling property of the solution of BK equation

$$\square^A(k,y) = \square^A\left(\frac{k}{Q_S(y)}\right), \qquad k < k_{geom}$$

Levin, Tuchin '99
Iancu, Itakura, McLerran, '02

which leads to

$$\square^A(k = Q_S, y) = \square^A\left(\frac{Q_S}{Q_S}\right) = \square^A(1) = const$$

⇨ We do not need to know $\square^A$ to determine how Cronin peak scales with energy and centrality! (The constant carries no dynamical information.)

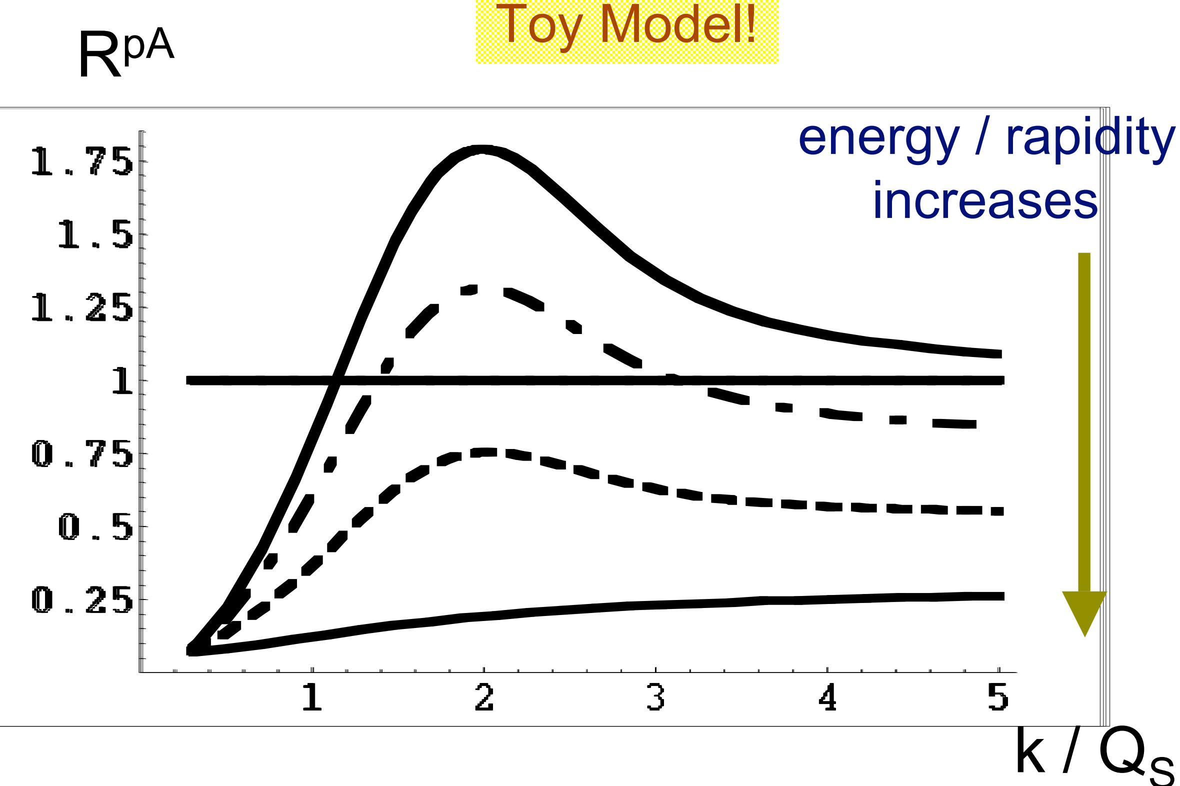
Our Prediction

Our analysis shows that as energy/rapidity increases the height of the Cronin peak decreases. Cronin maximum gets progressively lower and eventually disappears.

- Corresponding R^{pA} levels off at roughly at

$$R^{pA} \sim A^{-1/6}$$

Toy Model!



D. Kharzeev, Yu. K., K. Tuchin, hep-ph/0307037; (see also numerical simulations by Albacete, Armesto, Kovner, Salgado, Wiedemann, hep-ph/0307179 and Baier, Kovner, Wiedemann hep-ph/0305265 v2.)

⇨At high energy / rapidity R^{pA} at the Cronin peak becomes a decreasing function of both energy and centrality.

Overall Picture

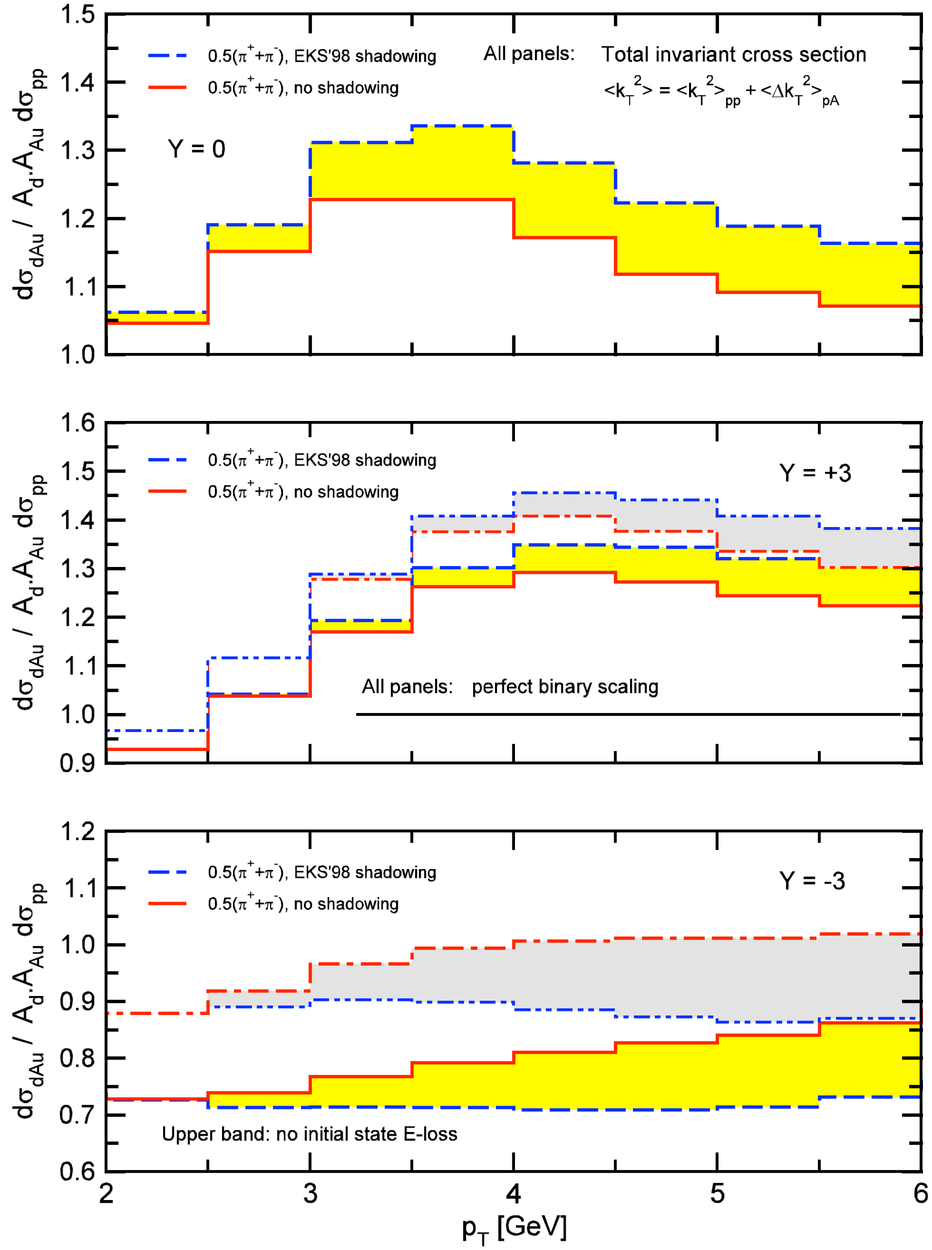
- At moderately high energy/rapidity one has to use McLerran-Venugopalan model to calculate gluon production. In McLerran-Venugopalan model one gets Cronin effect only. The height of the Cronin peak is an increasing function of centrality.
- As energy/rapidity increases quantum effects due to BK evolution become important introducing high-p_T suppression. Cronin peak gradually disappears. R^{pA} becomes a decreasing function of energy and centrality.

Other Predictions

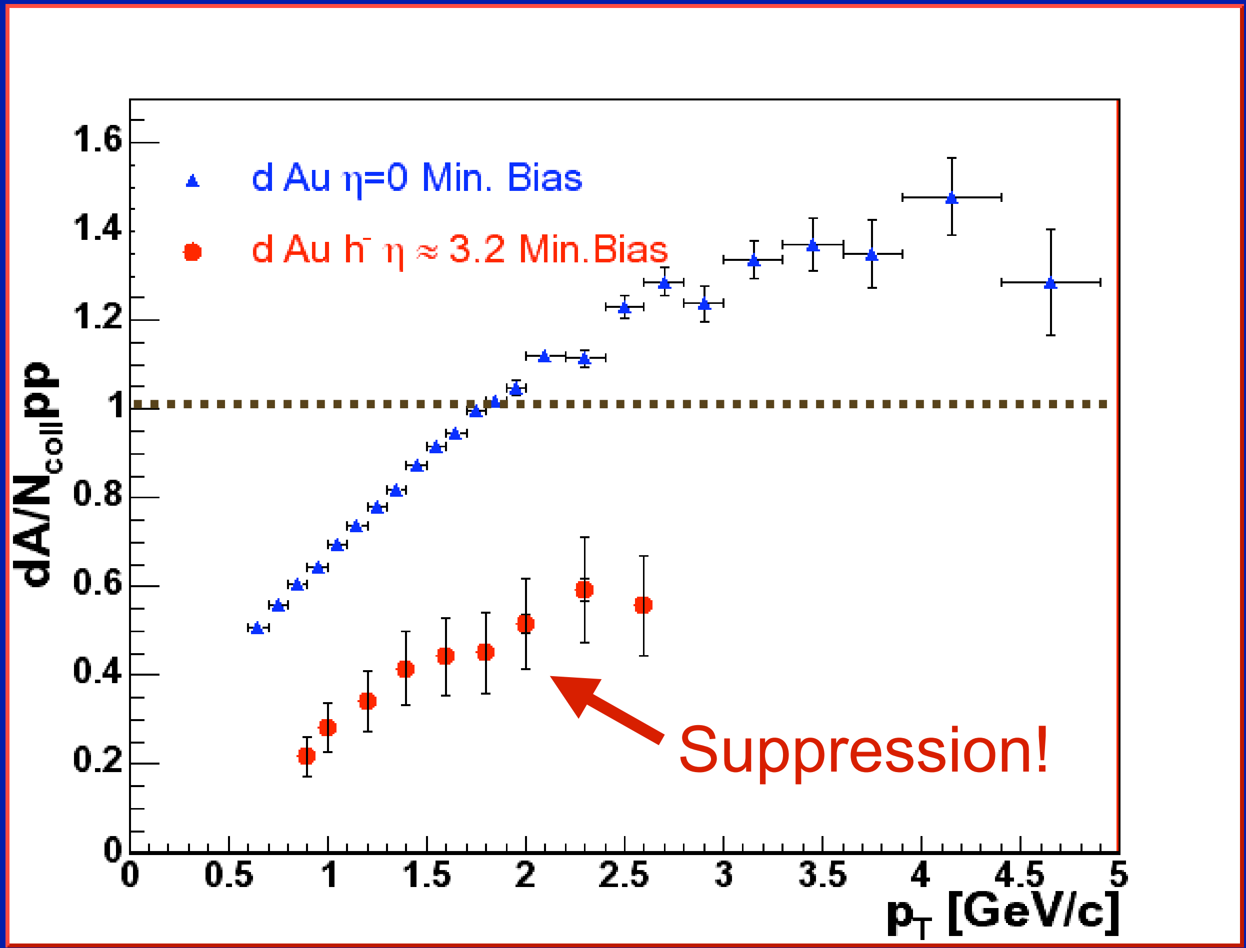
Color Glass Condensate / Saturation physics predictions are in sharp contrast with other models.

The prediction presented here uses a Glauber-like model for dipole amplitude with energy dependence in the exponent.

figure from I. Vitev, nucl-th/0302002, see also a review by M. Gyulassy, I. Vitev, X.-N. Wang, B.-W. Zhang, nucl-th/0302077



Forward Rapidity Data



BRAHMS collaboration preliminary data, presented by R. Debbe at DNP ‘03

It is very likely (pending final data) that

Color

Glass

Condensate

has just been discovered by dAu experiments at RHIC !