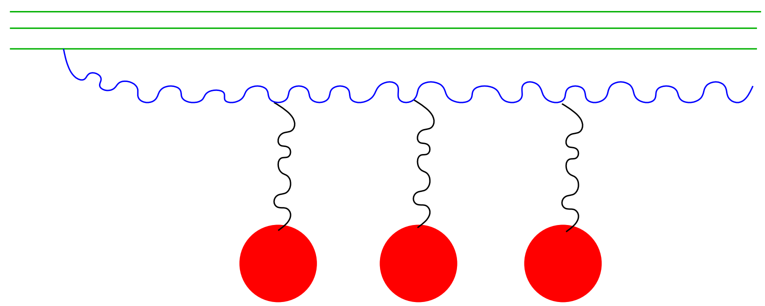
Forward Physics at RHIC: Onset of Saturation in CGC

Kirill Tuchin

October 22, 2004

Gluon production in pA scattering at small x

In a nucleus rest frame



At small Bjorken x hard processes develop over large "coherence length" l_c (Ioffe, 69)

$$l_c = \frac{1}{E_{qg} - E_q} \simeq \frac{1}{M\, x} \gg R_A$$

Two separated in time stages of a gluon production at low x:

1. Emission of a low x gluon $q \to qg$ over time l_c/c at a given impact parameter b_t.

2. *Instantaneous* interaction of a gluon with a nucleus with amplitude $N_G(r_t, b_t, x)$.

Saturation at low x

Glauber formula = approximation of independent scatterings:

$$N_G(r_t, b_t, y) = 1 - e^{-r_t^2 Q_s^2/4}$$

with rapidity $y = \ln(1/x)$

One-nucleon scattering amplitude at given b_t:

$$N_G^{(1)} = r_t^2 \, \pi^2 \, \alpha_s \, \rho \, T(b_t) \, xG(r_t, x)/(2\, C_F)$$

♣ Saturation: at $r_t > 1/Q_s \Rightarrow N_G = 1$ (independent of r_t, x, b_t).

The saturation scale: $Q_s^2 \propto A^{1/3}$. For a big nucleus $Q_s \gg \Lambda_{\rm QCD} \Rightarrow \alpha_s(Q_s^2) \ll 1$

This is a *quasi-classical* picture since N_G is given by the tree-level graphs.

Classical limit of QCD

$$S_{\rm QCD} = \int d^4x \sum_q \bar{q}(x)(i\gamma^\mu D_\mu - m_q)q(x) - \frac{1}{4g^2}{\rm tr}\,\tilde{G}_{\mu\nu}(x)\,\tilde{G}^{\mu\nu}(x)$$

with $A_\mu = \frac{1}{g}\tilde{A}_\mu$.

The classical limit = high occupation numbers. At small x it implies that $S_{\rm YM} \gg 1$.

It corresponds to small coupling constant $\alpha_s \ll 1$ and strong fields $\tilde{A} \sim 1 \Rightarrow$

$$g \ll 1\,, \quad A_\mu \sim \frac{1}{g} Q_s \gg 1$$

Color Glass Condensate = strong color field + small coupling

(Gribov, Levin, Ryskin, 82; Mueller, Qiu, 86, McLerran, Venugopalan, 94)

Gluon distribution

Unintegrated gluon distribution

$$\phi(x,\underline{k}) = \frac{dxG(x,\underline{k})}{d^2k} = \frac{C_F}{\alpha_s (2\pi)^3}\int d^2b\, d^2r\, e^{-i\underline{k}\cdot\underline{r}}\,\nabla_r^2\, N_G(\underline{r},\underline{b},x)$$

Gluon production cross section in a quasi-classical approximation (Yu. Kovchegov, A. Mueller, 98)

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

♣ In general $\phi(x,\underline{k})$ is not a universal function :(

Gluon distribution

Unintegrated gluon distribution

$$\phi(x,\underline{k}) = \frac{dxG(x,\underline{k})}{d^2k} = \frac{C_F}{\alpha_s(2\pi)^3}\int d^2b\, d^2r\, e^{-i\underline{k}\cdot\underline{r}}\,\nabla_r^2\, N_G(\underline{r},\underline{b},x)$$

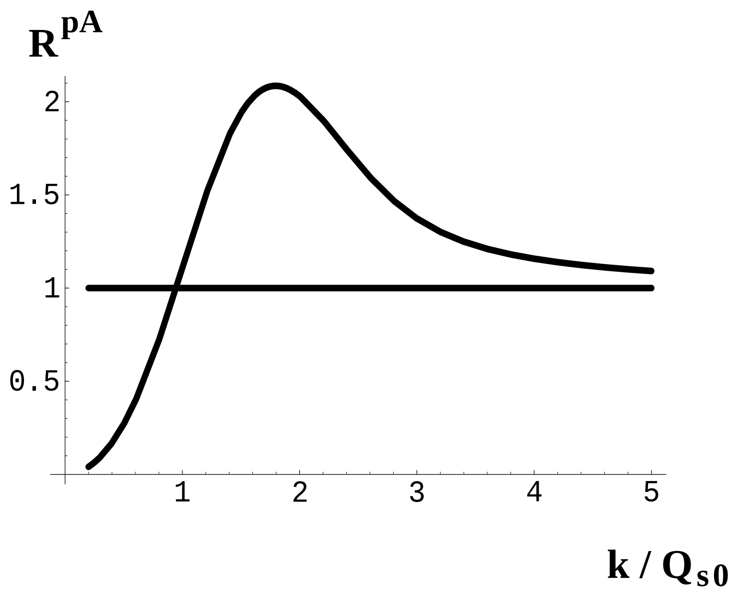
Gluon production cross section in a quasi-classical approximation (Yu. Kovchegov, A. Mueller, 98)

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

♣ In general $\phi(x,\underline{k})$ is not a universal function :(However it is the same for gluon production in pA and for DIS :)

Cronin effect

Using a simple Glauber model $N_G(\underline{r}, \underline{b}, x) = 1 - \exp \frac{Q_s^2 r^2}{4}$ we get



Quasi-classical parton production leads to Cronin effect!

(D. Kharzeev, Yu. Kovchegov, K.T., 03; R. Baier, A. Kovner, U. Wiedemann, 03; B. Kopeliovich, J. Nemchik, A. Schafer, A. Tarasov, 02; A. Accardi, M.Gyulassy, 03; I. Vitev, 03)

Cronin peak

♣ The position of the Cronin maximum is given by

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

since $Q_s^2 \sim A^{1/3}$.

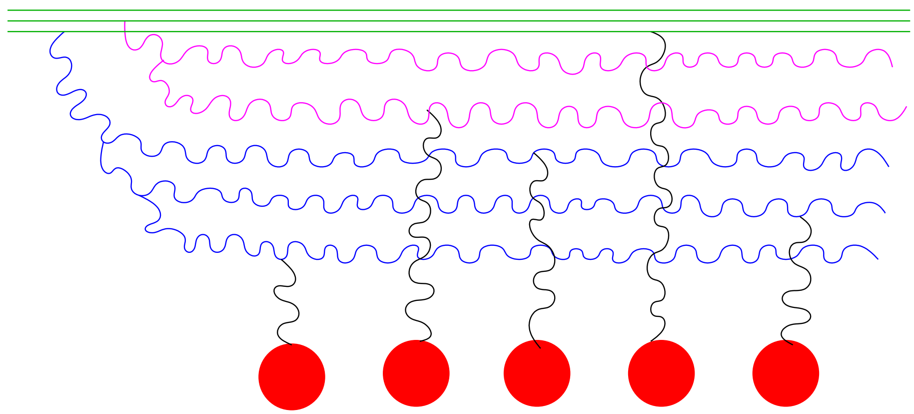
$$R^{pA} = 1 + \frac{3}{2}\frac{Q_s^2}{k^2}\ln\frac{k^2}{\Lambda^2} + \ldots\,, \quad k \to \infty$$

♡ 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!

Quantum evolution



Each emitted gluon contributes

$$\alpha_s \, \ln \frac{1}{x} \sim 1$$

All gluons give

$$\sum_n \frac{1}{n!} (\alpha_s \, \ln \frac{1}{x})^n \sim x^{-\lambda}$$

Therefore, the saturation scale increases with $1/x$ as:

$$Q_s^2 \propto A^{1/3} \, x^{-\lambda}$$

Geometric scaling of gluon distribution

$Q_s(x)$ is the only scale at low $x \Rightarrow \phi(x, \underline{k})$ is a function of only one variable $k/Q_s(x)$.

The geometric scaling holds as long as the BFKL evolution dominates over DGLAP one:

$$\alpha_s \log Q_s^2/\Lambda^2 \sim \alpha_s y > \alpha_s \log k_t^2/Q_s^2$$

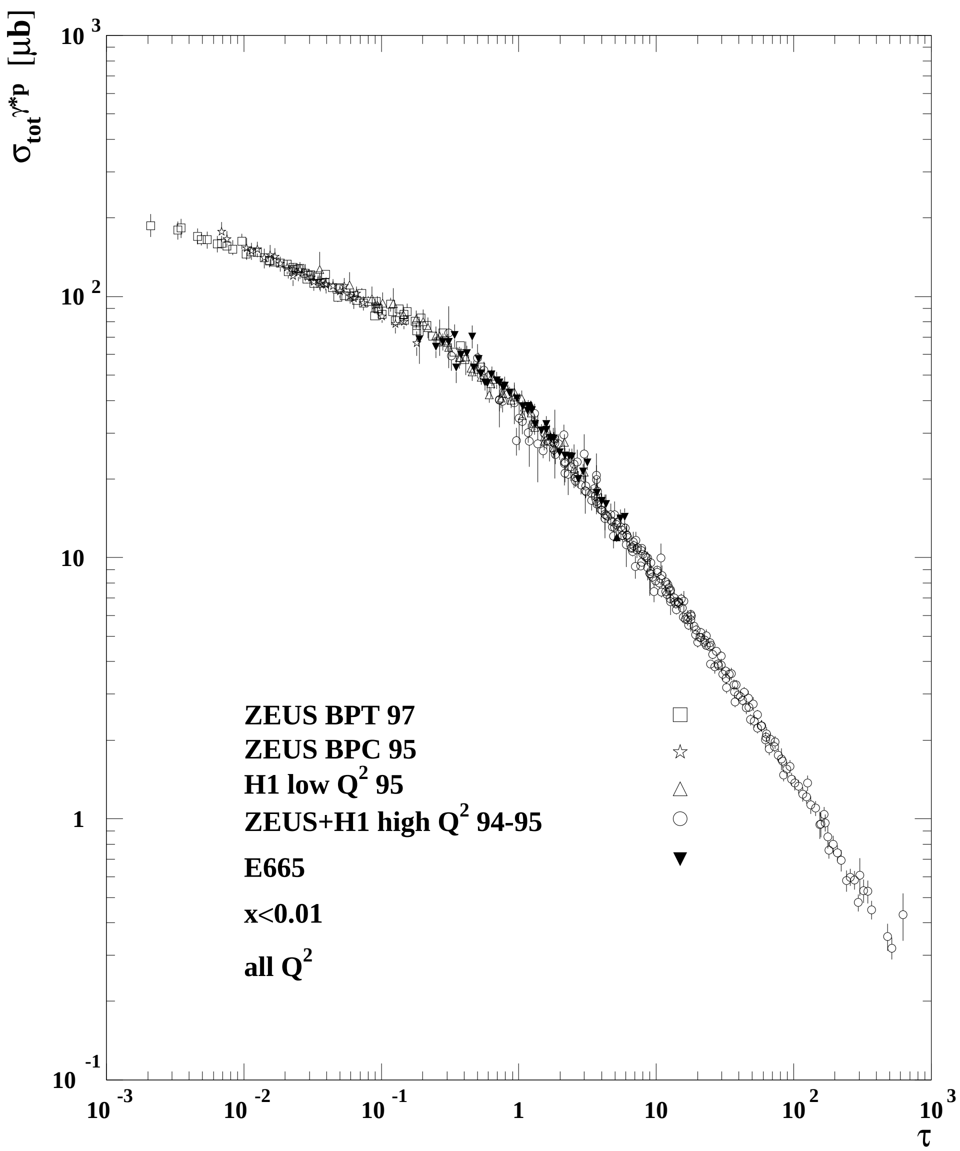
$$k_t < k_{\rm geom} = Q_s^2(x)/\Lambda$$

(Levin, K.T., 01; Iancu, McLerran, Itakura, 02).

Experimental signatures of the Geometric Scaling

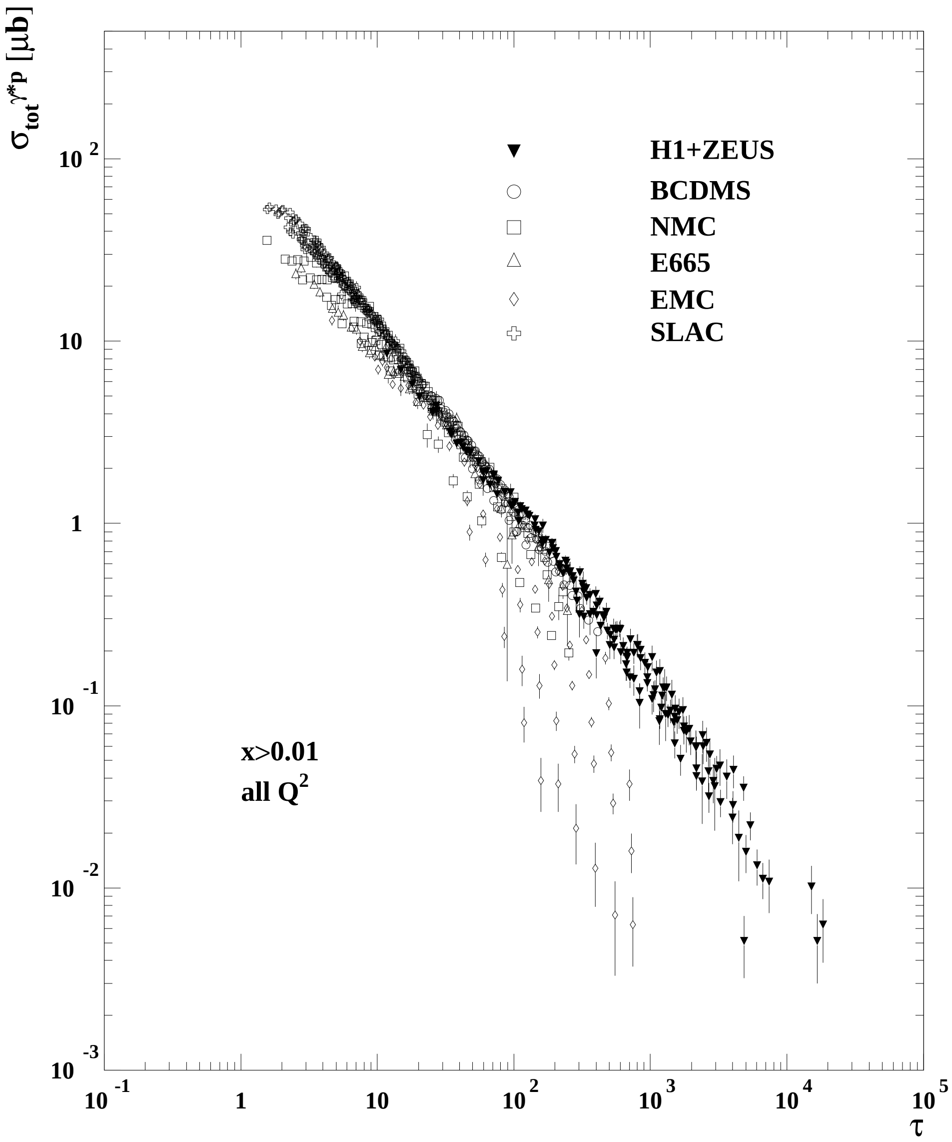
- $\sigma_{\text{tot}}^{DIS}(x, Q^2) = f(Q^2/Q_s^2(x))$

Geometric scaling in $\gamma^* p$ at $x < 0.01$ (HERA)



(Stasto, Golec-Biernat, Kwiecinski, 2000)

No geometric scaling in $\gamma^* p$ at $x > 0.01$ (HERA)



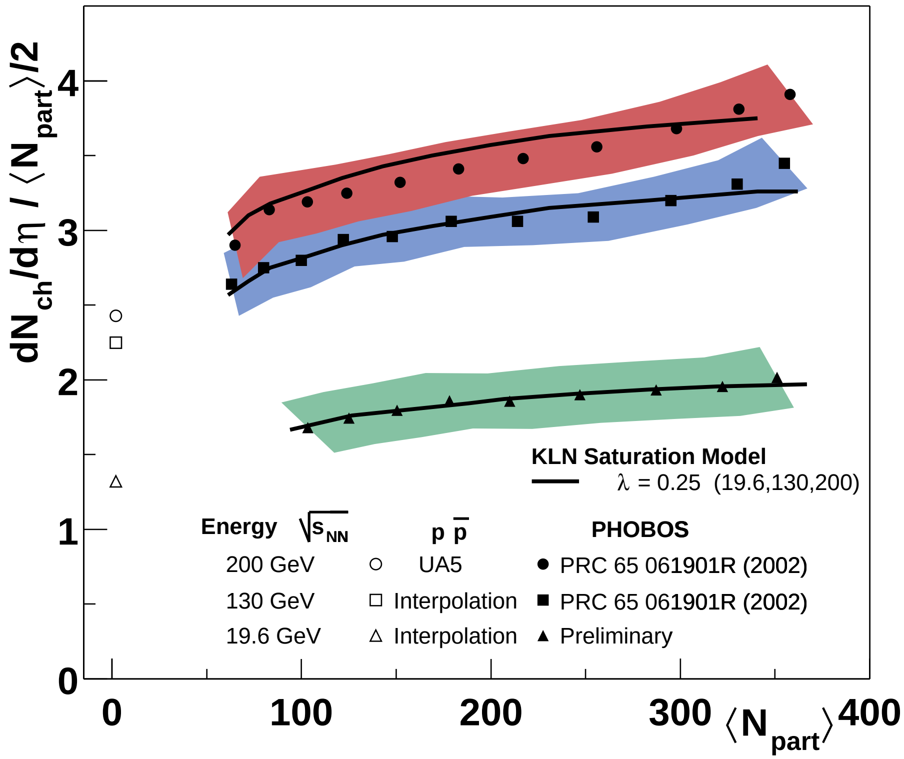
(Stasto, Golec-Biernat, Kwiecinski, 2000)

Experimental signatures of Geometric Scaling

- $\sigma_{\rm tot}^{DIS}(x,Q^2) \,=\, f(Q^2/Q_s^2(x))$
- $\frac{dN^{AA}}{dy} \propto \frac{S_A\, Q_s^2(x)}{\alpha_s(Q_s^2(x))} \propto A\,\log A \Rightarrow \frac{dN^{AA}}{A\, dy} \propto \log A$ (Kharzeev, Levin, 01)

  in pQCD: $\propto A^{1/3}$

Geometric scaling in AA (RHIC)



(Kharzeev, Levin, 2000)

Anomalous dimension γ of gluon distribution

$$\phi_A(x, q_t) \propto S_A \left(\frac{Q_s^2}{q_t^2}\right)^\gamma$$

- pQCD regime $q_t \gg k_{\rm geom}$:

$$\gamma \to 1 \Rightarrow \phi_A(x, q_t) \propto S_A \frac{Q_s^2}{q_t^2} \sim A$$

- black disk regime (saturation), $q_t \ll Q_s(x)$:

$$\gamma \to 0 \Rightarrow \phi_A(x, q_t) \propto S_A \sim A^{2/3}$$

Anomalous dimension γ of gluon distribution

- extended geometric scaling region $Q_s(x) \ll q_t \ll k_{\rm geom}$:

$$\gamma \simeq \frac{1}{2} \Rightarrow \phi_A(x, q_t) \propto S_A \frac{Q_s}{q_t} \sim A^{5/6}$$

♠ Nuclear gluon distribution is suppressed!

$$\frac{\phi_A(x, k_t)}{A\,\phi_p(x, k_t)} < 1$$

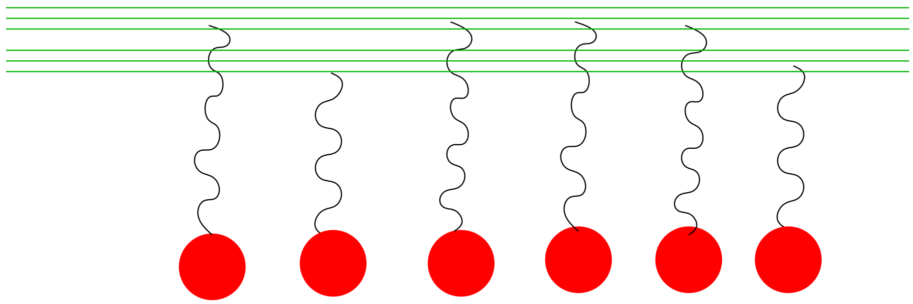
Effect of quantum evolution on particle production

$$\frac{d\sigma^{pA}}{d^2k\,dy} = \frac{2\,\alpha_s}{C_F}\frac{1}{k^2}\int d^2q\,\phi_p(q, Y-y)\quad \underbrace{\phi_A(k-q, Y)}_{suppressed\ at\ x\to 0}$$

At forward rapidities R^{pA} is *decreasing* function of rapidity and centrality.

(Kharzeev, McLerran, Levin,02; Kharzeev, Kovchegov, K.T.,03; Albacete et. al. ,03; Baier et. al. ,03)

Valence quark production in a quasi-classical approximation



Valence quark production cross section (A. Dumitru, J. Jalilian-Marian,02)

$$\frac{d\sigma_Q^{dA}}{d^2k} = \frac{S_A}{(2\pi)^2} \int d^2r\, e^{i\underline{k}\cdot\underline{r}}\, [2 - N_Q(r_t, y)],$$

with $N_Q(r_t, y)$ is the quark dipole–nucleus forward scattering amplitude

$$N_Q(r_t, y) = 1 - e^{-C_F\, r_t^2\, Q_s^2\, /4\, N_c}$$

♣ Valence quarks dominate in the fragmentation regions.

Quantitative analysis

See details in D. Kharzeev, Yu. Kovchegov, K.T., `hep-ph/0405045`

- we modeled the gluon dipole scattering amplitude as

$$N_G(r,y) = 1 - \exp\left[-\frac{1}{4}(r^2 Q_s^2)^{\gamma(y,r)}\right],$$

where the anomalous dimension γ is

$$\gamma(y,r) \;=\; \frac{1}{2}\left(1 + \frac{\xi(y,r)}{\xi(y,r) + \sqrt{2\,\xi(y,r)} + 7\zeta(3)\,c}\right)$$

with

$$\xi(y,r) \;=\; \frac{\ln\left[1/(r^2\, Q_{s0}^2)\right]}{(\lambda/2)(y - y_0)}$$

Quantitative analysis

♣ At $r \to 0$, y fixed: $\gamma \to 1$.

♠ At $y \to \infty$, r fixed: $\gamma \to 1/2$.

- The saturation scale is fixed by DIS data

$$Q_s^2 = 0.13\,\mathrm{GeV}^2\, e^{\lambda\, y}\, N_{\mathrm{coll}}$$

with $\lambda = 0.3$

- *High* x tail of quark distribution is described by the factor $(1-x)^3\, x^{0.5}$ following from the quark sum rules and the leading Regge trajectory.

- *High* x tail of gluon distribution is described by the factor $(1-x)^4$.

Quantitative analysis

- High x part of the anomalous dimension is described by (Ellis, Kunszt, Levin, 94)

$$\gamma(\omega) = \alpha_s \left(\frac{1}{\omega} - 1 \right)$$

- We use fragmentation functions of (Kniehl, Kramer, Potter, 01)

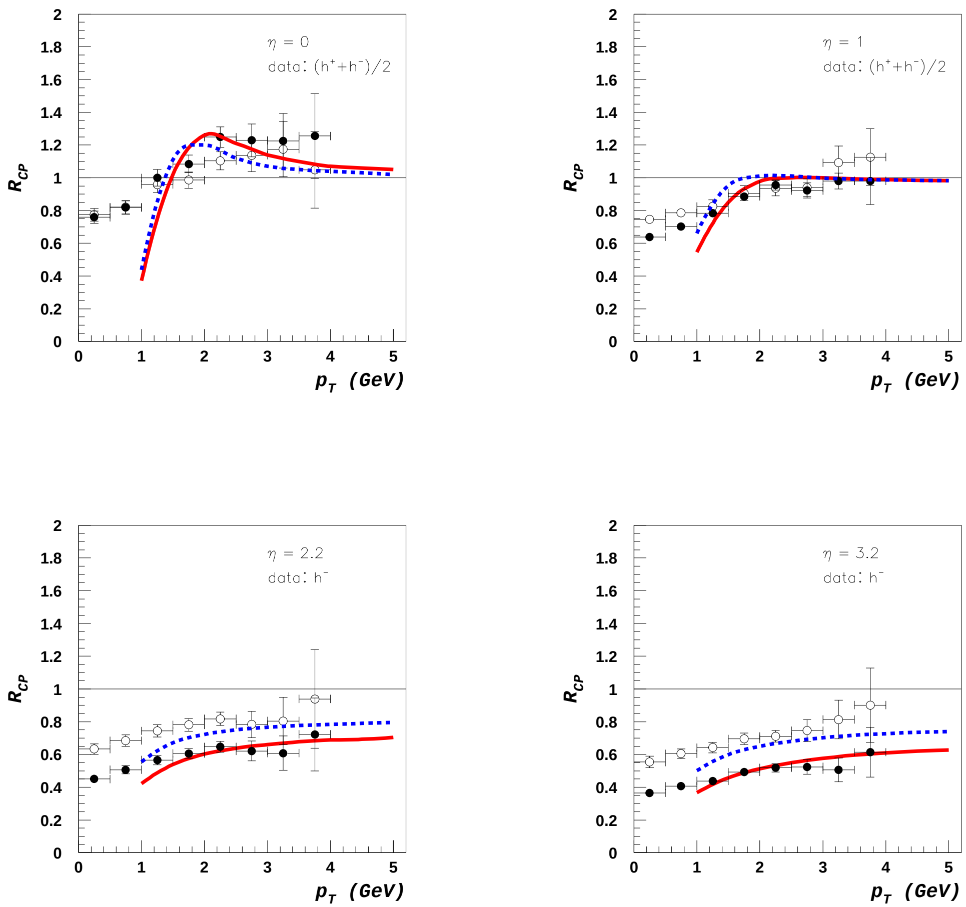
- The only fitted parameters are:

1) $y_0 = 0.6$ is the rapidity at which quantum evolution sets in;

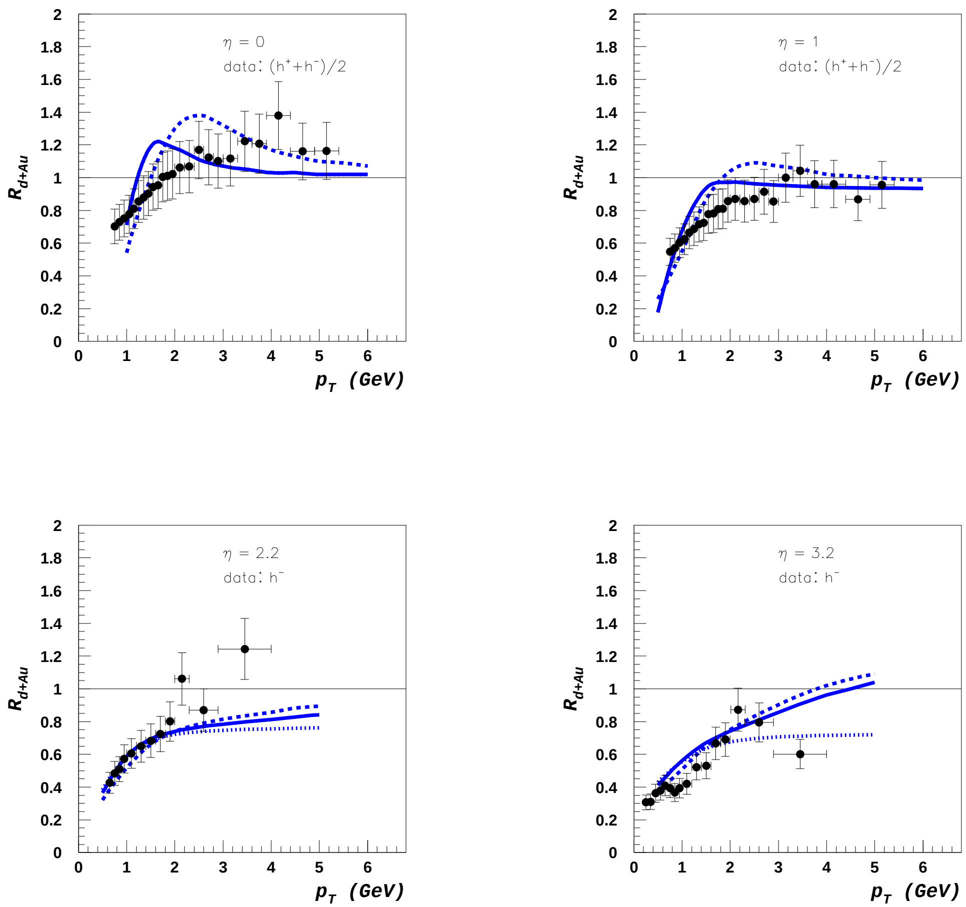
2) $c = 4$ is the coefficient in γ describing details of transition between classical regime $\gamma = 1$ and quantum regime $\gamma = 1/2$.

Charged particle production (BRAHMS)

Central events: $b \approx 3$ fm. Semi-central: $b \approx 5$ fm. Perepheral: $b \approx 7$ fm.



Charged particle production (BRAHMS)



Heavy quark production by a strong field

- Strong chromoelectric field produces $q\bar{q}$ pairs from vacuum when $E > m^2/g$.

Heavy quark production by a strong field

- Strong chromoelectric field produces $q\bar{q}$ pairs from vacuum when $E > m^2/g$.
- In Color Glass Condensate: $E \sim Q_s^2/g$.

Heavy quark production by a strong field

- Strong chromoelectric field produces $q\bar{q}$ pairs from vacuum when $E > m^2/g$.
- In Color Glass Condensate: $E \sim Q_s^2/g$.

Therefore, pair production is important when

$$\boxed{Q_s > m}$$

The production pattern of heavy and light quarks is the same in the saturation region!
(Kharzeev, K.T., 03)

Heavy quark production by a strong field

- Strong chromoelectric field produces $q\bar{q}$ pairs from vacuum when $E > m^2/g$.
- In Color Glass Condensate: $E \sim Q_s^2/g$.

Therefore, pair production is important when

$$\boxed{Q_s > m}$$

The production pattern of heavy and light quarks is the same in the saturation region!
(Kharzeev, K.T., 03)

At RHIC: $m_c \approx 1.3$ GeV vs $Q_s \approx 1.4\, e^{0.15\, y}$ GeV (at $b = 0$) . Therefore we expect suppression at $y \gg 1$.

Heavy quark production by a strong field

- Strong chromoelectric field produces $q\bar{q}$ pairs from vacuum when $E > m^2/g$.
- In Color Glass Condensate: $E \sim Q_s^2/g$.

Therefore, pair production is important when

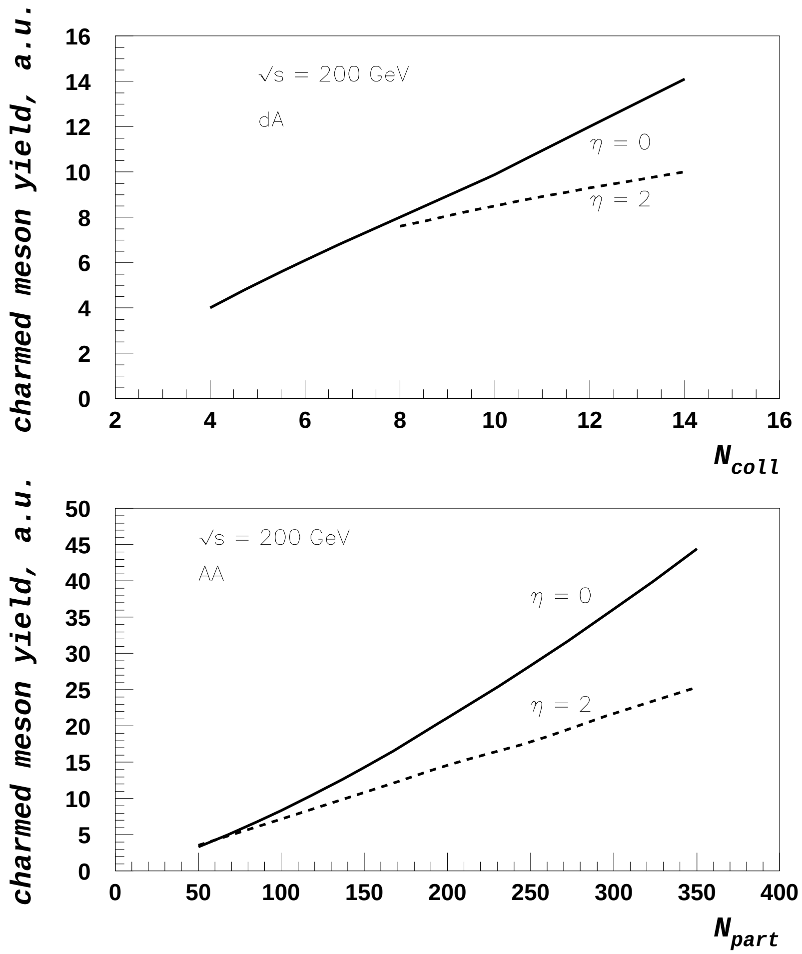
$$\boxed{Q_s > m}$$

The production pattern of heavy and light quarks is the same in the saturation region!
(Kharzeev, K.T., 03)

At RHIC: $m_c \approx 1.3$ GeV vs $Q_s \approx 1.4\, e^{0.15\, y}$ GeV (at $b = 0$) . Therefore we expect suppression of open charm at $y \gg 1$.

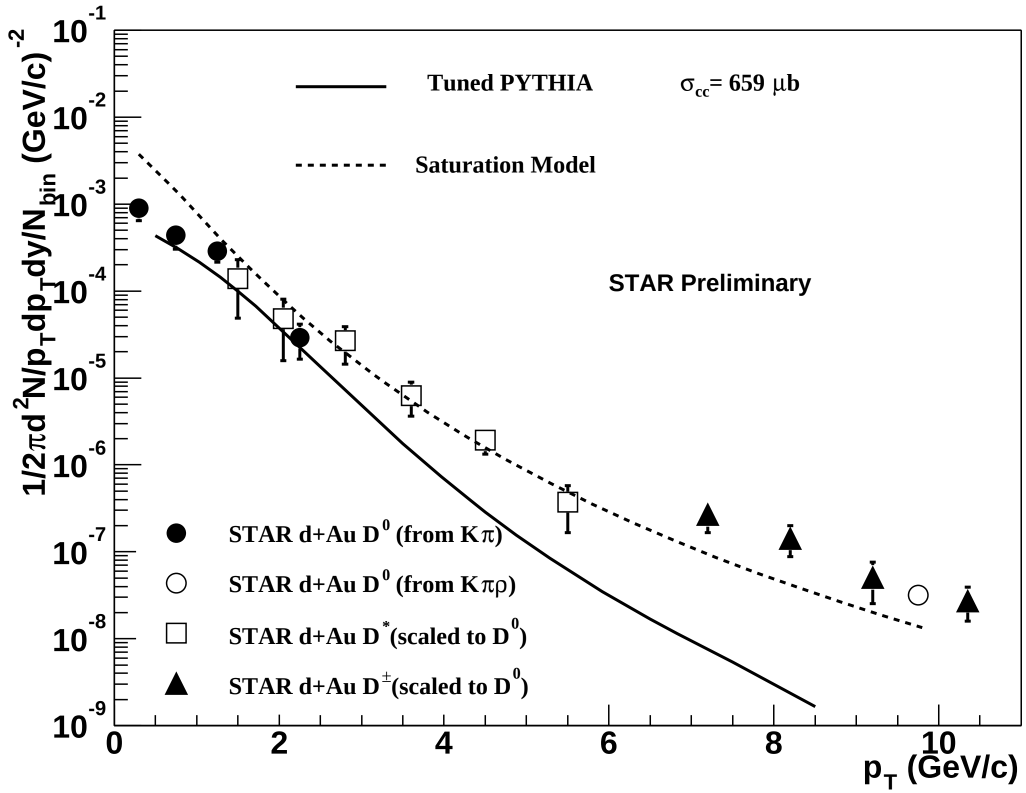
- Due to extended geometric scaling this suppression holds for large k_T.

Scaling of charm spectra with atomic number A



(Kharzeev, K.T.,03)

Open charm spectrum by STAR

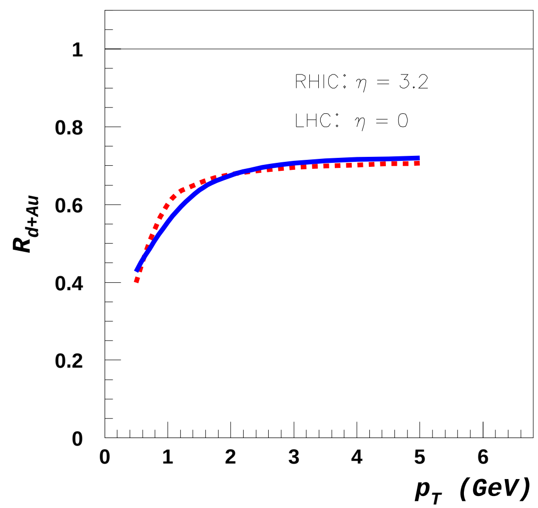


PYTHIA (pQCD) $= \sigma_{pp}^{c\bar{c}} \times A$.

Observed spectrum is much harder than in pQCD since $k_{\rm intr} \simeq Q_s(x)$.

CGC at LHC

- LHC: 3 units of rapidity more than at RHIC ⇒ saturation starts at $y_{LHC} \simeq -3$.



♣ pA and AA at LHC will be *deeply inside the saturation* regime!

♠ Look for *saturation in pp* as well.

Conclusions

At RHIC we are starting to see a novel effects due to a quasi-classical regime of QCD – the Color Glass Condensate, first signatures of which where observed at HERA.

Future tests of CGC at RHIC $y \gg 1$:

- inclusive hadrons $\surd$
- open charm ?
- hidden charm ?
- dileptons ?
- correlations and fluctuations ?