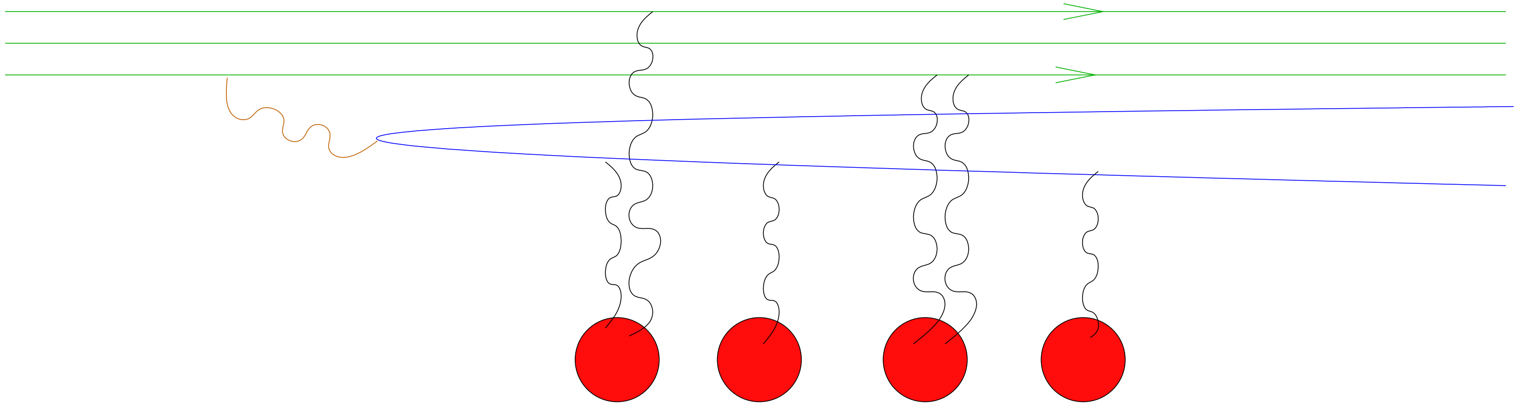
Open and hidden charm production in d-A and A-A collisions

Kirill Tuchin

November, 8 2004

$q\bar{q}$ pair production in a nucleus rest frame



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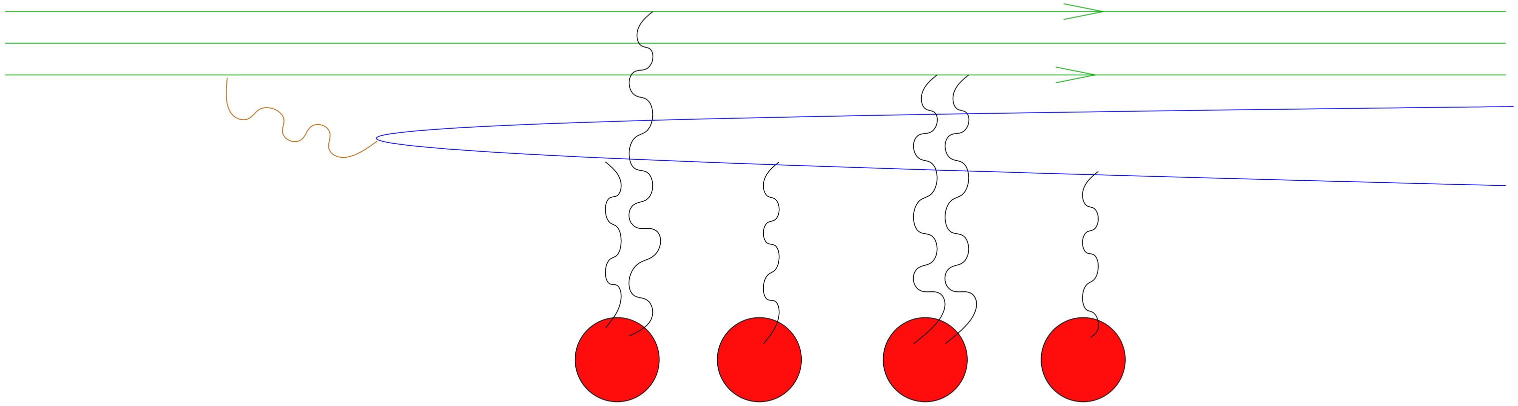

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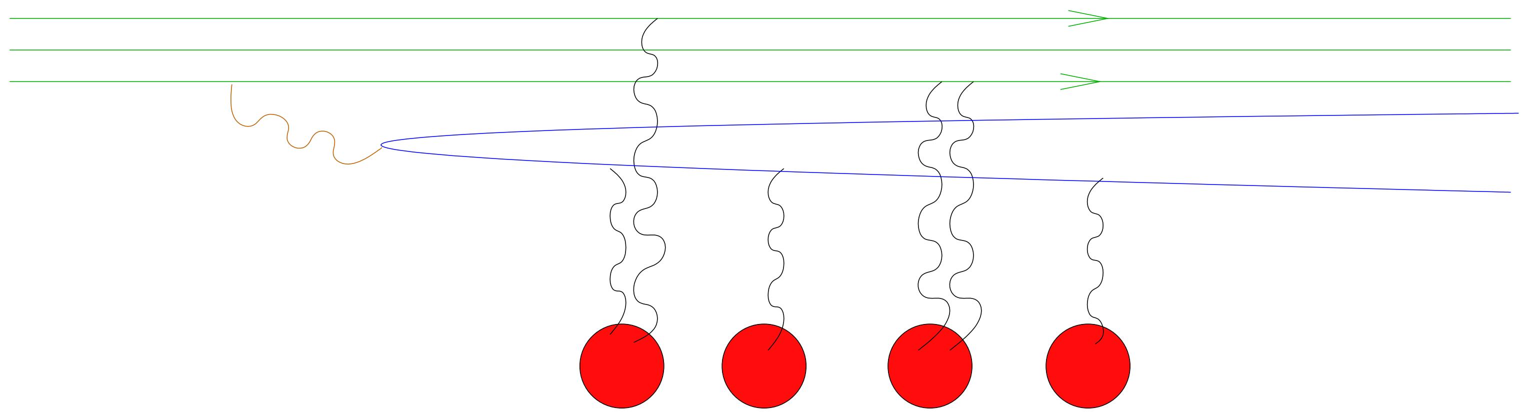

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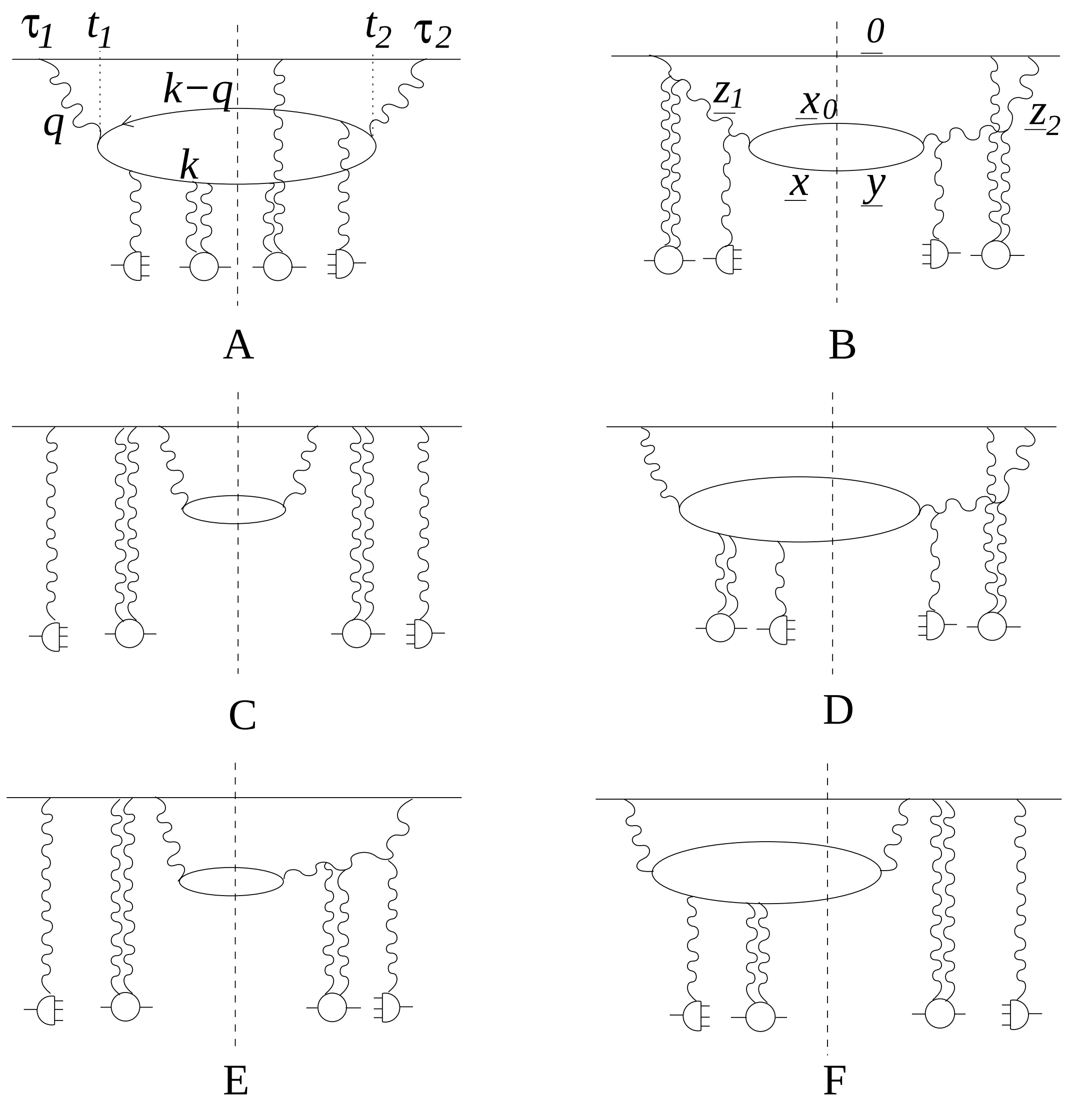
- Interaction time is $\tau_{\rm int} \simeq R_A/c \simeq 7$ fm.
- We can use *the dipole model* at $y > 0$: the $q\bar{q}$ and the gluon are produced over time much longer than $\tau_{\rm int}$.

Leading order diagrams



Dipole model

- Since $\tau_P \gg \tau_{\rm int}$ all dipoles $\underline{x} - \underline{x}_0$, $\underline{y} - \underline{x}_0$, $\underline{x}_1 - \underline{z}_1$ etc. are almost frozen during $\tau_{\rm int}$ (as in a glass).

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- Therefore, the scattering process proceeds in two stages:

  1. development of a dipole system long before the interaction;

  2. instantaneous dipole-nucleus interaction described by the quark (Q) and gluon (G) dipole amplitudes $N_G(r_t, b_t, y)$ and $N_Q(r_t, b_t, y)$.

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• Glauber formula $=$ approximation of independent scatterings:

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

with rapidity $y = \ln(1/x)$. Here $C_F/N_c = 1/2$ at large N_c.

Saturation at low x

- One-nucleon scattering amplitude at given b_t in the LO pQCD:

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

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

Classical limit of QCD

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

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

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

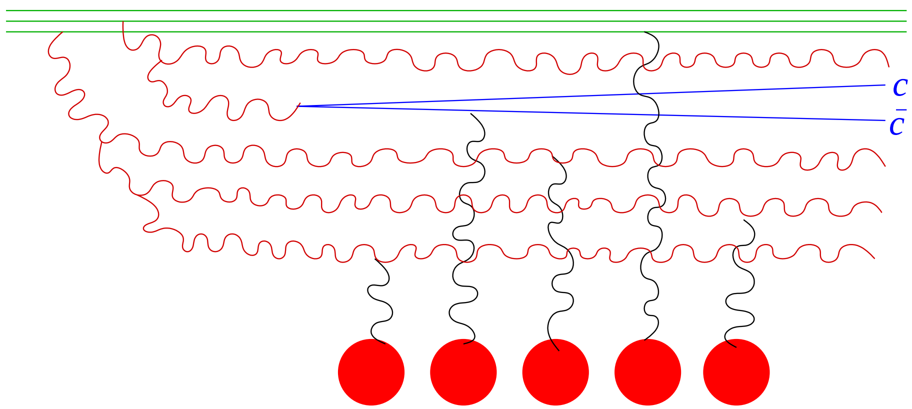
It corresponds to small coupling constant $\alpha_s \ll 1$ and strong fields $\tilde{A} \sim 1 \Rightarrow$

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

Color Glass Condensate = strong color field + small coupling

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

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:

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

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- The probability to produce $q\bar{q}$ pair from vacuum by constant chromoelectric field E:

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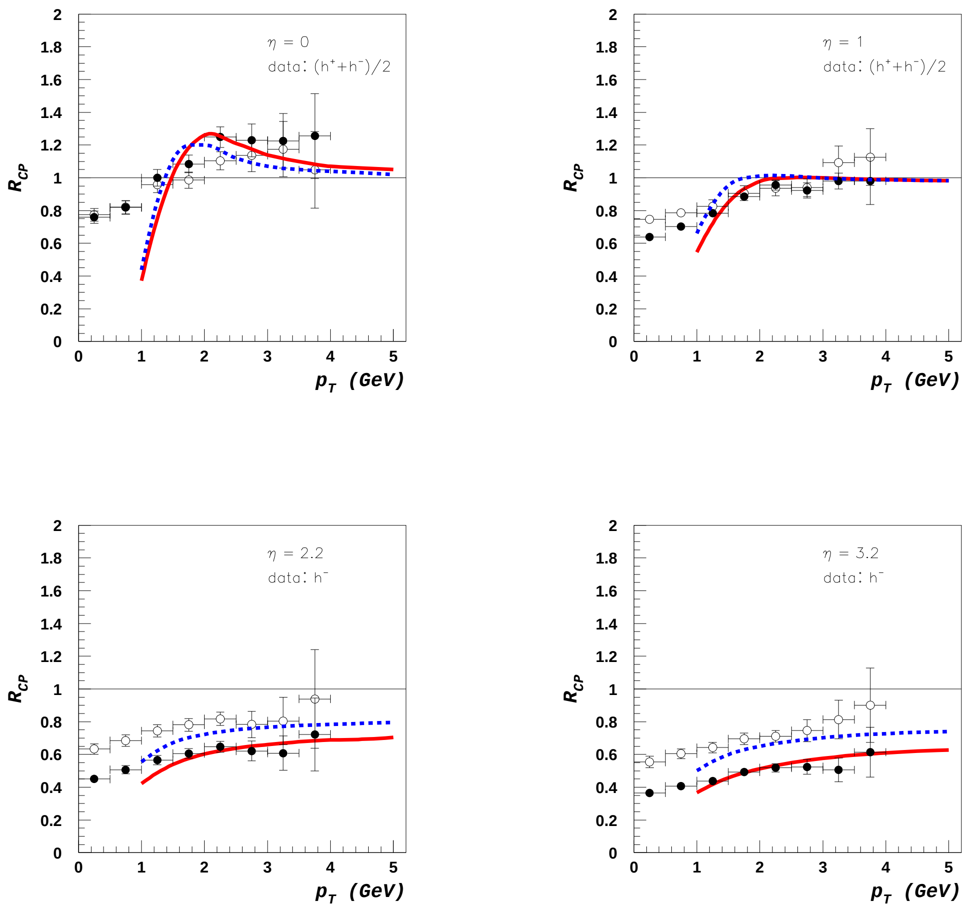
- At RHIC: $Q_s \approx 1.4\, e^{0.15\, y}$ GeV (at $b = 0$) vs $m_c \approx 1.3$ GeV.
- Therefore we expect suppression of R_{dA}(charm) at $y \gg 0$.

Charged particle production (BRAHMS)

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



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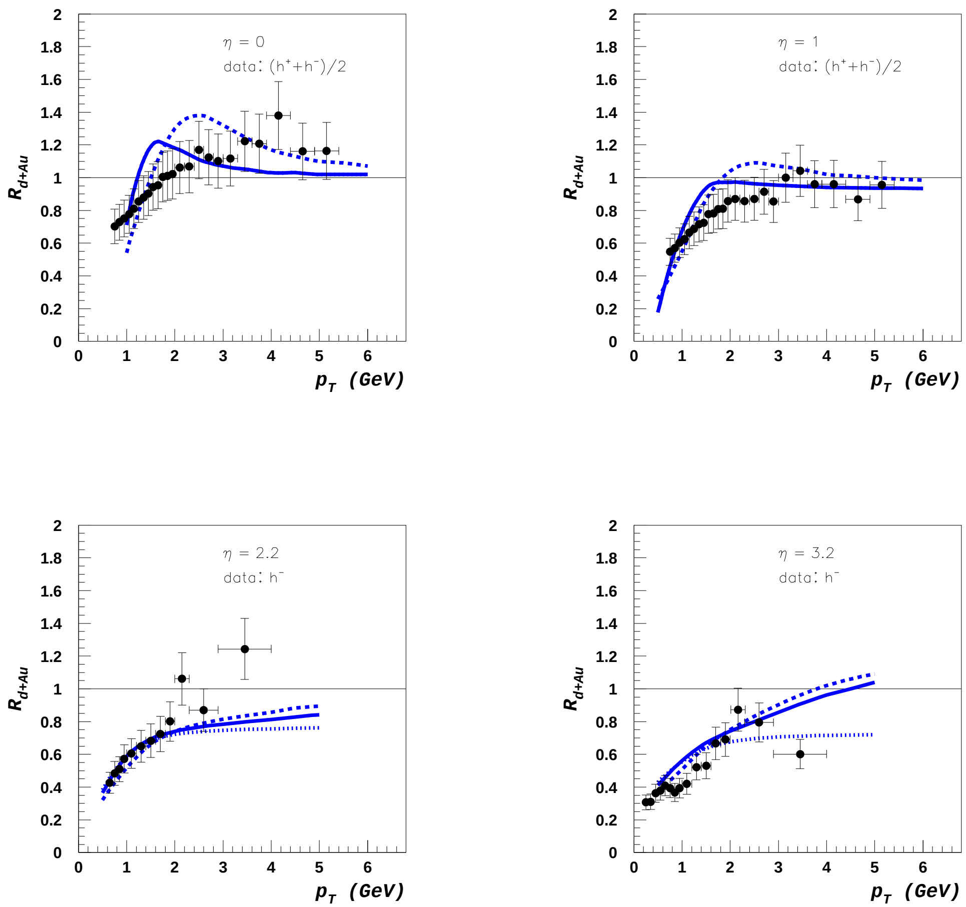
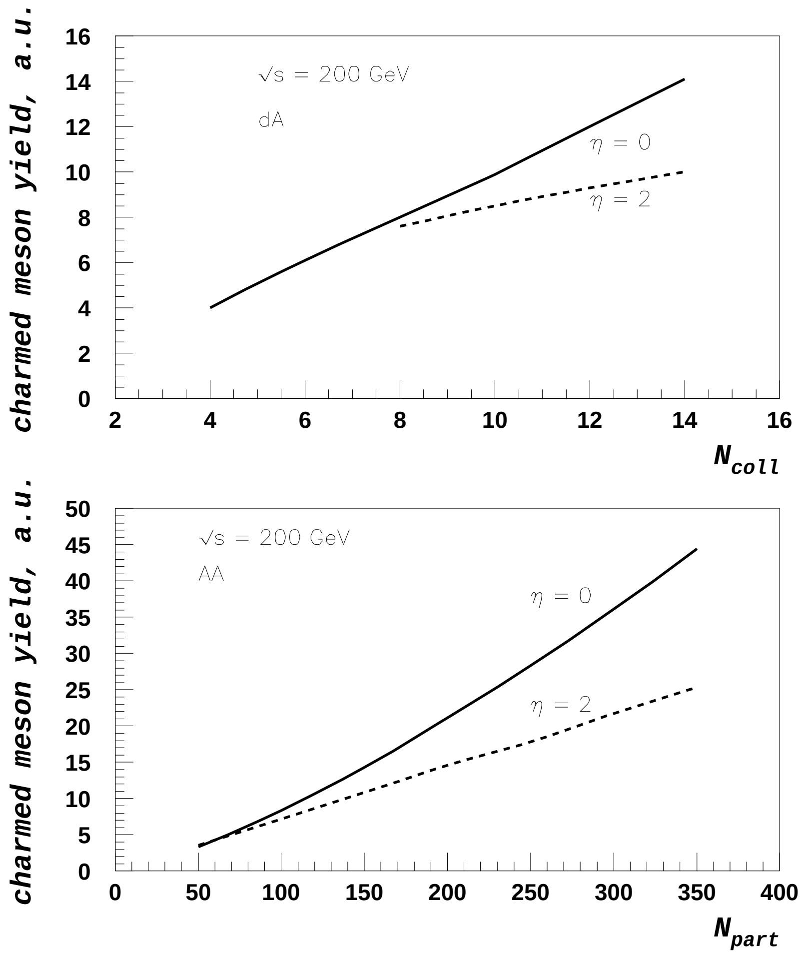
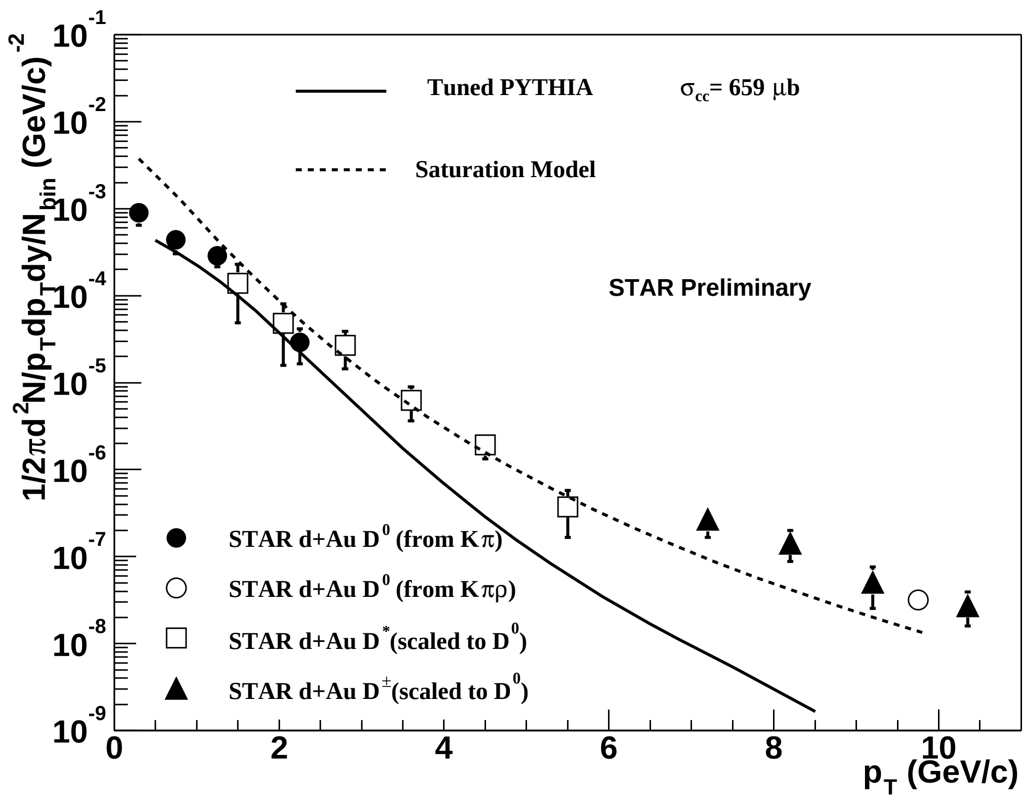


Scaling of charm spectra with atomic number A



(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 $k_{\rm intr} \simeq Q_s(x)$.
- Experimental fit: $\langle p_T \rangle = 1.32 \pm 0.08$ GeV$/c$.

Typical time scales for J/Ψ production at RHIC

(Kharzeev, K.T. in preparation)

- A $c\bar{c}$ pair of J/Ψ is produced over time $\tau_P \simeq \frac{E_g}{M_\psi^2} \simeq 7\, e^y\, \mathrm{fm}$
- Charmonium wave function is formed over time $\tau_F \simeq \frac{2}{M_{\psi'} - M_\psi} \frac{E_g}{M_\psi} \simeq 42\, e^y\, \mathrm{fm}$

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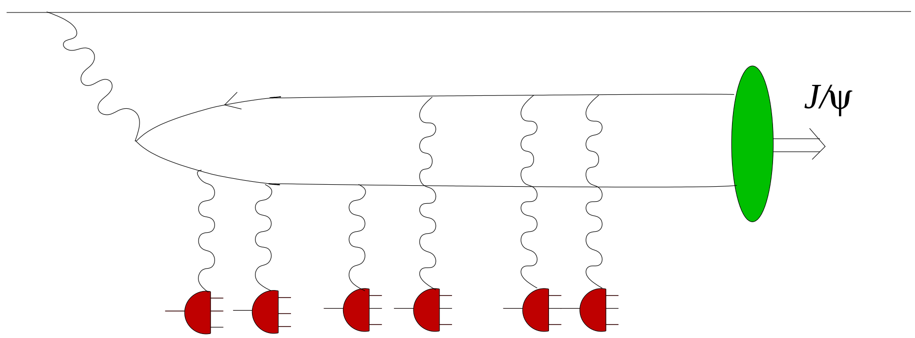
- At $y \gtrsim 0$ $c\bar{c}$ is produced coherently on a whole Au nucleus and J/Ψ is formed outside it. Therefore, $R_{dA}(J/\Psi)$ is suppressed due to gluon saturation in Au.



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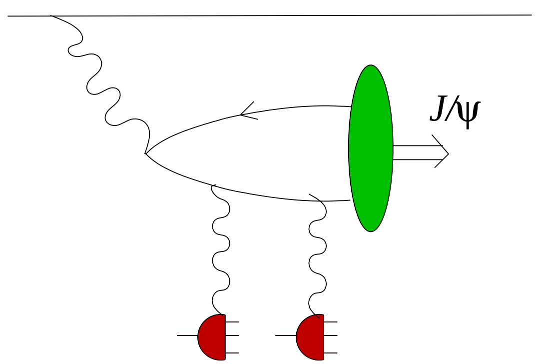

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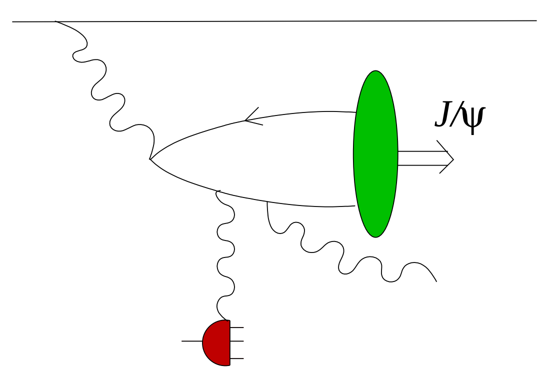
- At $-2 \lesssim y \lesssim -1$ $c\bar{c}$ is produced incoherently; J/Ψ still formed outside a nucleus. Only small nuclear effects $R_{dA}(J/\Psi) \simeq 1$ due to color transparency of a small dipole $r_t = 1/M_\psi$.



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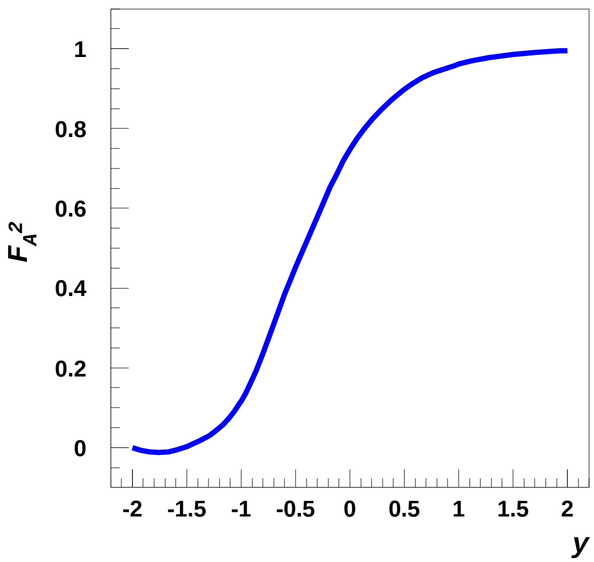
- At $y \lesssim -2$ $c\bar{c}$ is produced incoherently; J/Ψ is produced inside a nucleus and gets strongly attenuated.

Effect of a finite production time

- At very high energies $\tau_P \sim 1/x_2 \to \infty$.

- At RHIC at $y < 0$: $\tau_P < R_A/c$. The effect of a finite production time can be taken into account by *the longitudinal nuclear form factor*

$$F_A^2(q_l) = \int d^2b_t \left| \int_{-\infty}^{\infty} dz\, \rho(b_t, z)\, e^{iq_l z} \right|^2, \quad \text{where} \quad q_l = 1/\tau_P \sim e^{-y}$$



- The dipole model cannot be applied at $y \leq 0$.

J/Ψ production in pA at forward rapidities

• In a quasiclassical approximation and $N_c \gg 1$ limit the total J/Ψ cross section per unit rapidity reads (Kharzeev, K.T.)

$$\frac{d\sigma_\psi}{dy} = S_A\, xG(x_1, M_\psi^2)\, \frac{3\,\Gamma_{ee}}{(2\pi)^2\, 48\, \alpha_{\rm em}\, M_\psi} \int_0^\infty d\zeta\, \zeta^5\, K_2(\zeta) \left(1 - e^{-\left(\frac{Q_s(x_2)\,\zeta}{2\,M_\psi}\right)^4}\right).$$

where $\zeta = M_\psi r_t$.

• The effect of *quantum evolution* can be calculated using Kharzeev–Kovchegov-K.T. model:

$$\left(\frac{Q_s(x_2)\,\zeta}{2\,M_\psi}\right) \Rightarrow \left(\frac{Q_s(x_2)\,\zeta}{2\,M_\psi}\right)^{\gamma(y,1/M_\psi)}$$

• The *anomalous dimension* $\gamma(y, r_t)$ in KKT model satisfies the DGLAP equations at $r \to 0$, y fixed and the BFKL equation at r fixed, $y \to \infty$.

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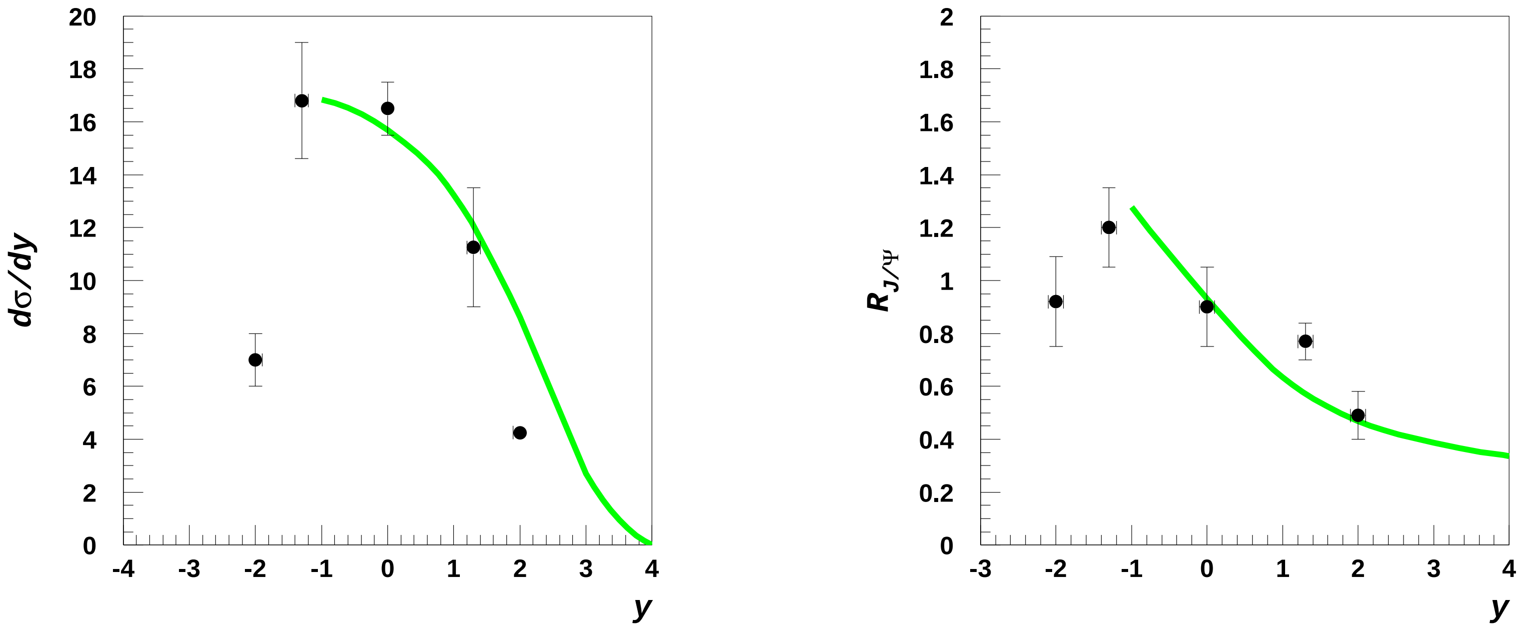

(Kharzeev, K.T., in preparation)

- Preliminary data by PHENIX (R. Granier de Cassagnac at QM 2004).

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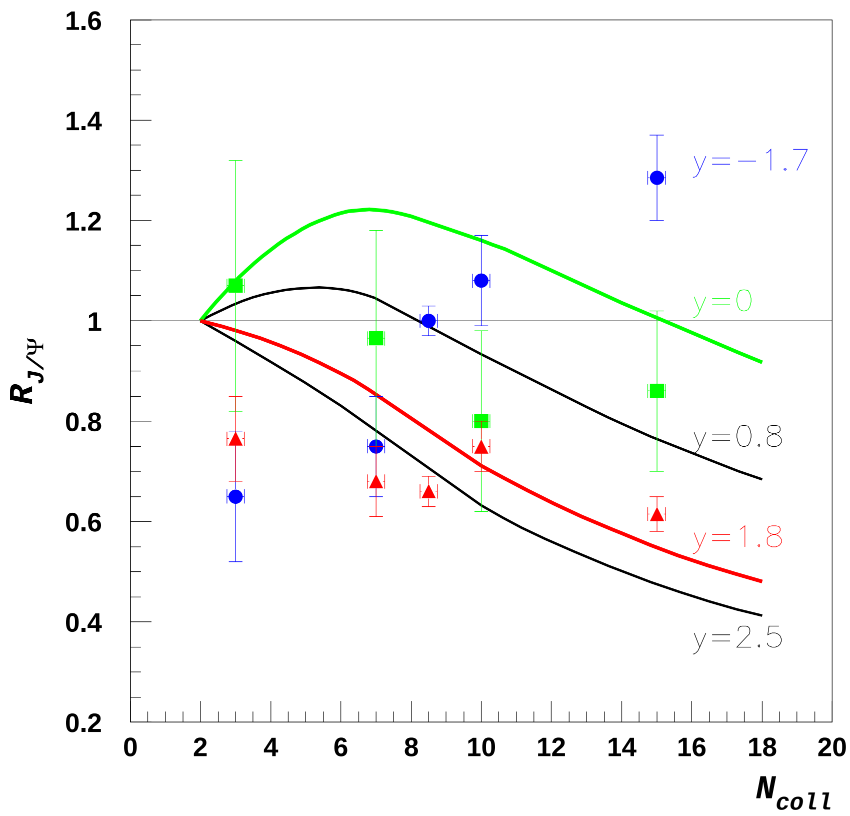

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- At LHC central rapidity interval is shifted by $\ln(5.5/0.2) = 3.3$ with respect to RHIC. Therefore, we expect that CGC will have a dramatic effect on particle production at LHC in pA and AA at $y \geq -3$.

BACK-UP SLIDES

High p_T suppression at forward rapidities at RHIC

- $\frac{d\sigma}{dk_t^2\, dy} = \frac{2\alpha_s}{C_F\, k_t^2} \int d^2 q_t\, \phi_p(q_t, Y - y)\, \phi_A(k_t - q_t, y)$

- The *unintegrated gluon distribution function* $\phi(x, q_t) = dxG(x, q_t)/dq_t^2$ encodes information about q_t-distribution of gluons in a target.

- $\phi_A(x, q_t) = \frac{C_F}{\alpha_s (2\pi)^3} \int d^2 b_t\, d^2 r_t\, e^{-i q_t \cdot r_t}\, \nabla_r^2\, N_G(r_t, b_t, x)$

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

$$\phi_A(x, q_t) \,\propto\, S_A\,(Q_s^2/q_t^2)^{1/2} \,\sim\, A^{2/3}\,A^{1/6} \sim A^{5/6} \,<\, A$$

- Nuclear gluon distribution is suppressed: $\phi_A \,<\, A\,\phi_p$

- $k_{\text{geom}} \simeq Q_s^2/\Lambda$. At RHIC at $y = 0$: $Q_s \simeq 1.3$ GeV. Hence $k_{\text{geom}} \simeq 10$ GeV.