5° convegno nazionale sulla Fisica di ALICE

Trieste, 14 settembre 2009

Gluon saturation effects on J/ψ production in A-A collisions at RHIC (and LHC)

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Marzia Nardi
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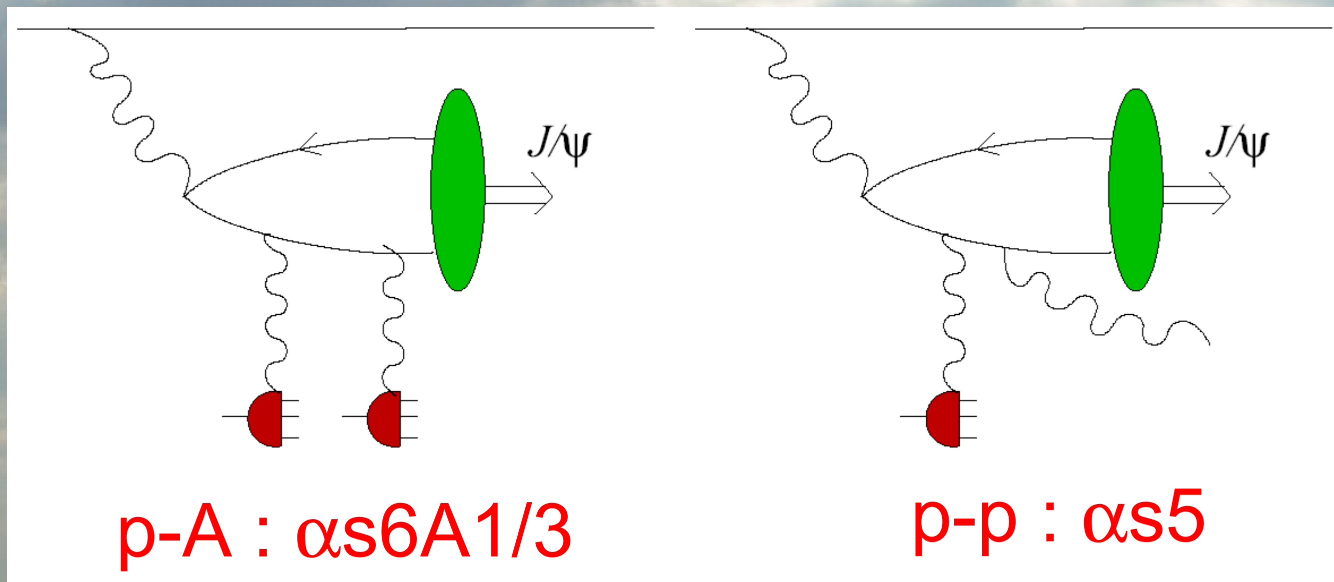
p(d)-A : D. Kharzeev, K. Tuchin,
Nucl.Phys. A 770(2006) 40 [hep-ph/0510358]

A-A : D. Kharzeev, E. Levin, M.N., K. Tuchin
Nucl.Phys.A826:230-255,2009 [arXiv:0808.2954]

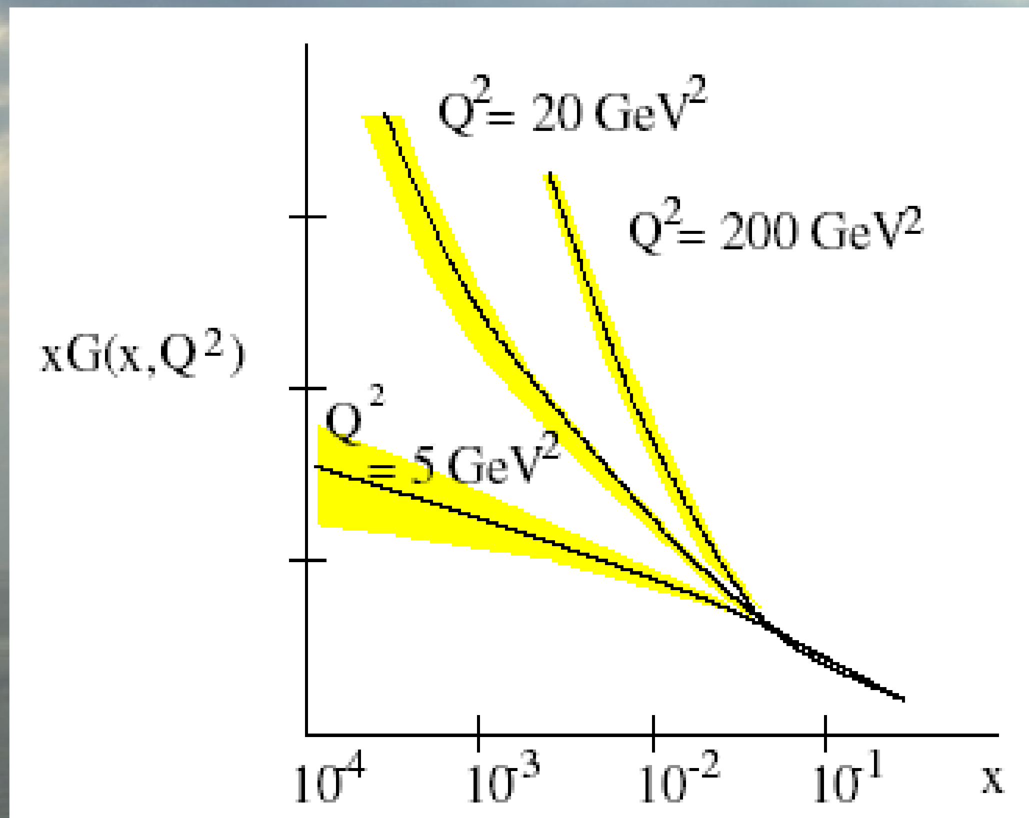
p-p vs p-A



In the saturation regime : αs2A1/3~1 ◎ for heavy nuclei the first process is dominant.

Hadron scattering at high energy

From HERA:



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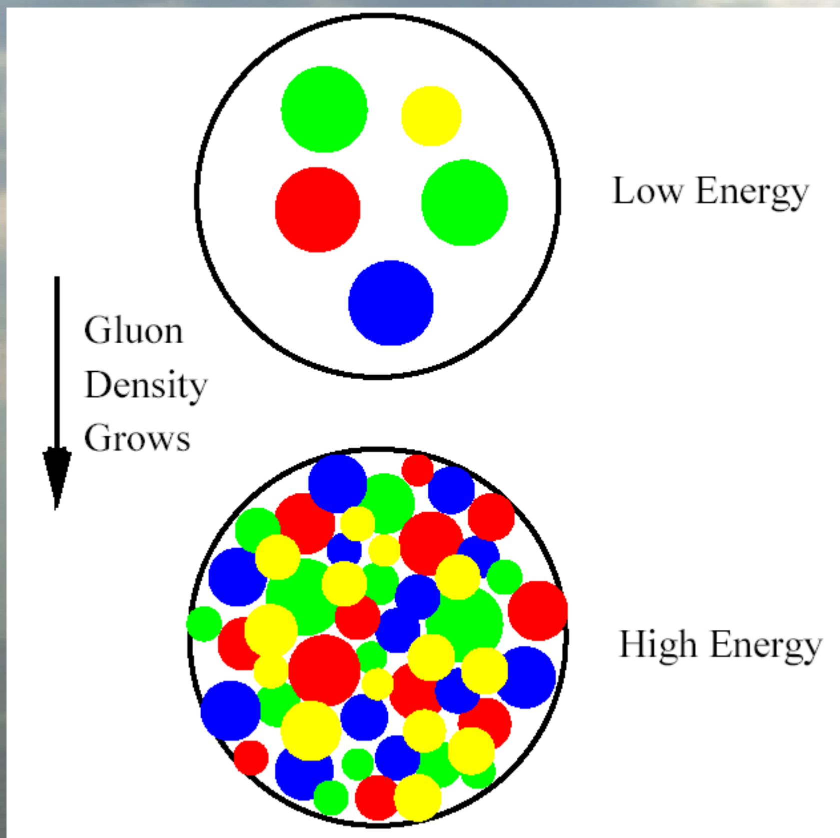
Gluon density in handrons



At high energies hadrons appear dense.

A new phenomenon is expected : ***parton saturation***

McLerran, hep-ph/0311028

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Saturation scale in nuclei

- Consider a nucleus or hadron interacting with an external probe, exchanging Q
- Transverse area of a parton ~ 1/Q2
- Cross section parton-probe : $\sigma \sim \alpha$s/Q2
- If many partons interact : S~Npartonσ
- In a nucleus : NA=NpartonA   [Nparton = xG(x,Q2)]
- The parton density saturates when S~πRA2
- Saturation scale : Qs2 ~ αs(Qs2)NA/πRA2 ~A1/3
- At saturation NA is proportional to 1/αs
- Qs2 is proportional to the (transverse) density of participating nucleons nA=NA/πRA2; larger for heavy nuclei.
- NA~ Qs2 /αs(Qs2)

Color Glass Condensate

Classical effective theory : high density limit of QCD

- color : partons are colored
- glass : they evolve slowly compared to their natural time-scale
- condensate : their density is proportional to the inverse of the coupling constant, typical of a Bose condensate.

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Hadron production from the CGC

Hadron multiplicities can be described in a parton saturation model (KLN), based on the **Color Glass Condensate** theory. In particular :

- Au-Au and d-Au collisions at RHIC, √sNN=20÷200 GeV
- Pb-Pb and p-Pb collisions at LHC, √sNN= 5500 GeV
  - total multiplicity
  - centrality dependence
  - rapidity dependence

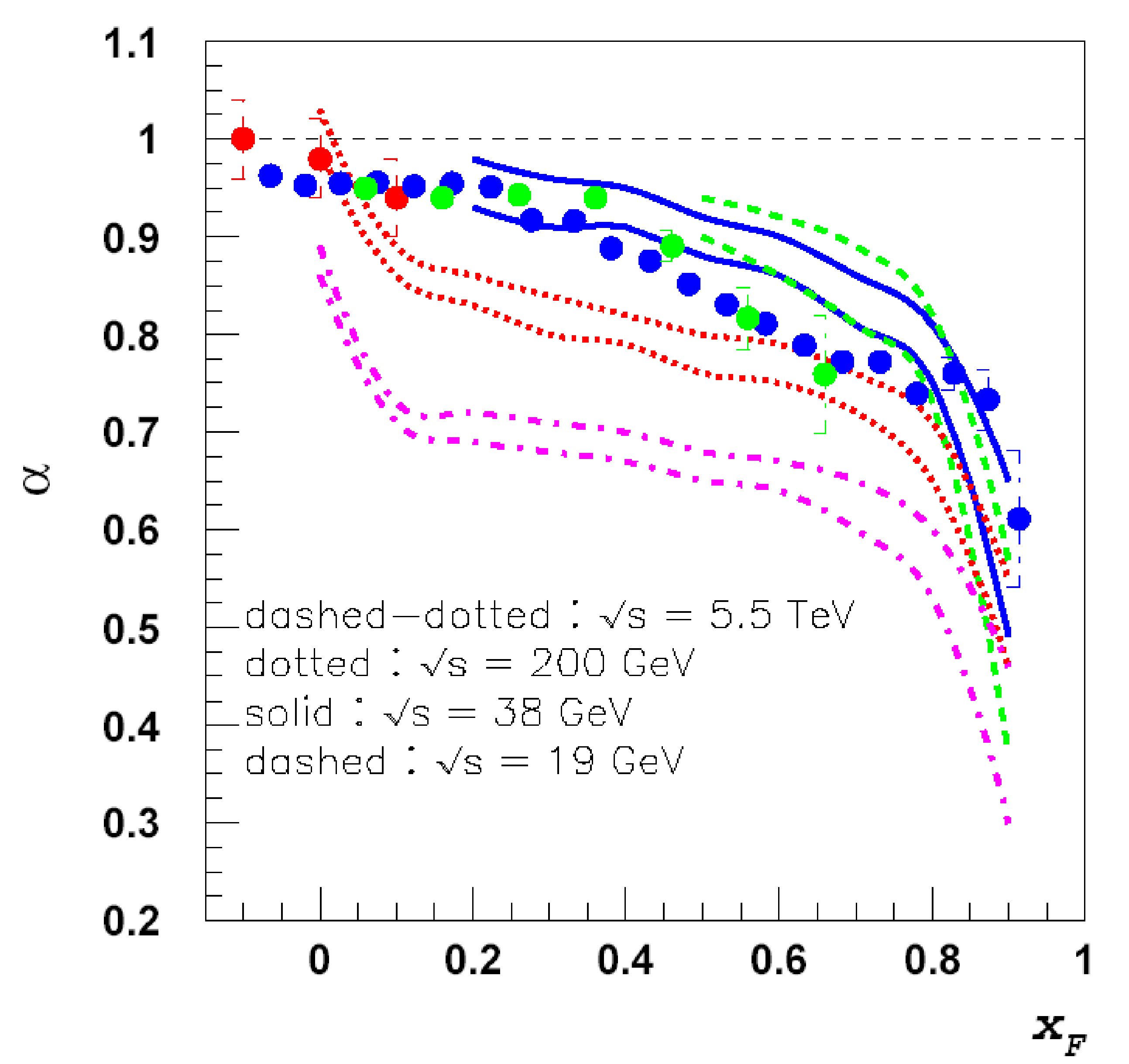
J/ψ production

The production mechanism of J/ψ in nuclear collisions at RHIC energies is different from that in pp collisions, because of gluon saturation in the nucleus.

In p-A:

- at forward y more suppression
- at backward y weak enhancement

p-A : results

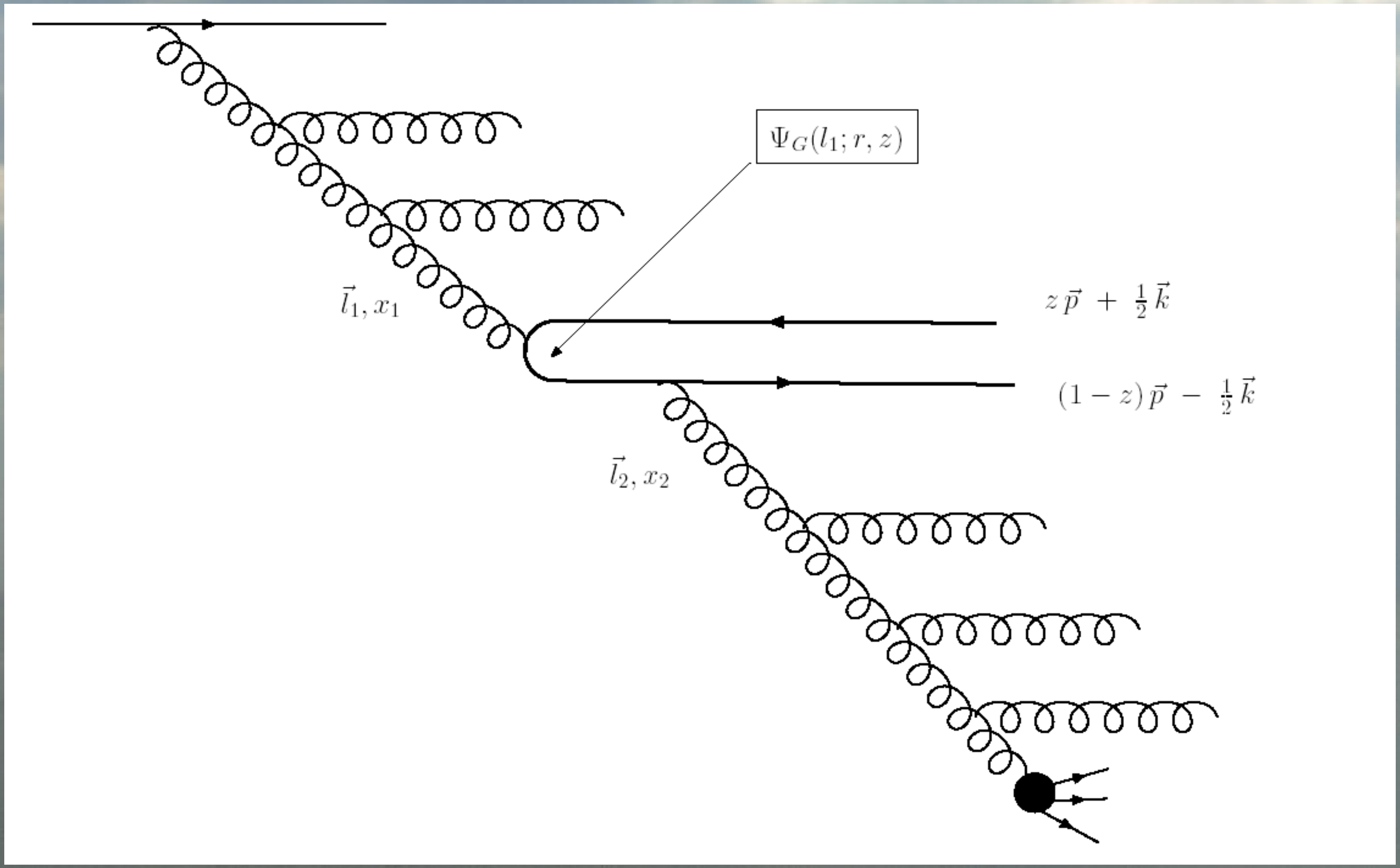


D.Kharzeev and K.Tuchin

Nucl.Phys. A 770 (2006) 40

[arXiv:hep-ph/0510358]

Inclusive c-cbar production in hadron-hadron collisions



Inclusive c-cbar production in hadron-hadron collisions

$$\frac{d\sigma(pp)}{dY\, d^2k} = \int \frac{d^2 l_1}{2\pi} \phi_G(x_1, \underline{l}_1^2) \int \frac{d^2 l_2}{2\pi\, l_2^2} \phi_G(x_2, \underline{l}_2^2)$$
$$2 \int d^2 r\, dz\; \Psi_G(l_1, r, z) \left(1 - e^{i\,\underline{l}_2 \cdot \underline{r}}\right) e^{-i\,\frac{1}{2}\underline{k}\cdot\underline{r}}$$
$$\int d^2 r'\; \Psi_G^*(l_1, r', z) \left(1 - e^{-i\,\underline{l}_2 \cdot \underline{r}'}\right) e^{i\,\frac{1}{2}\underline{k}\cdot\underline{r}'}$$

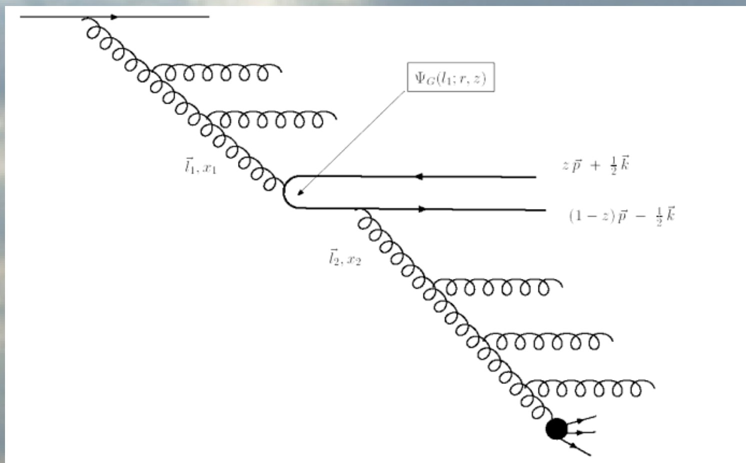
$$xG(x, Q^2) = \int^{Q^2} dl^2\, \phi(x, \underline{l}^2)$$

$$x_{1,2} = (m_{c,t} + m_{\bar{c},t}) e^{\pm Y} / \sqrt{s}$$

$$\sigma(x, r^2) \equiv 2\,\frac{N_c \alpha_s}{\pi} \int \frac{d^2 l}{2\pi\, l^2} \left(1 - e^{i\,\underline{r}\cdot\underline{l}}\right) \phi(x, l^2) \longrightarrow \frac{\pi^2 \alpha_s}{3} r^2\, xG^{DGLAP}(x, 4/r^2)$$

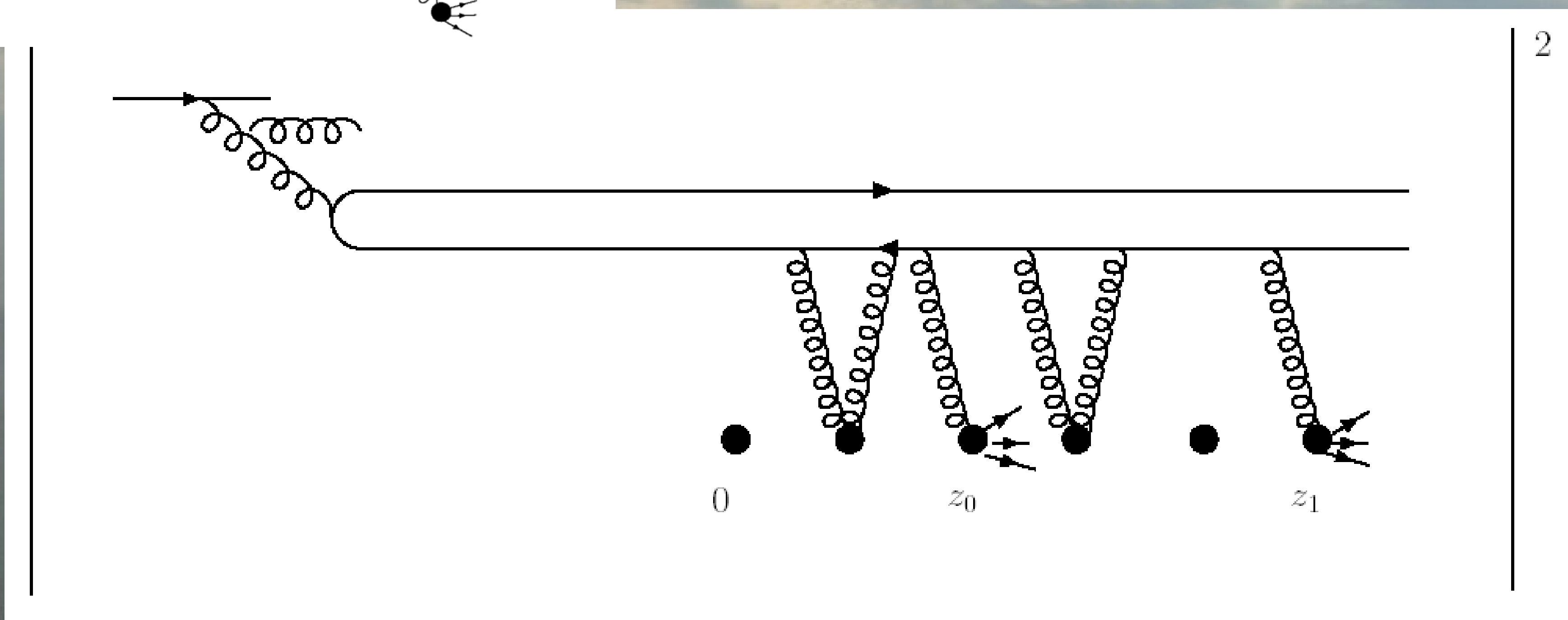
Dipole-hadron interaction:

Hadron-(heavy)nucleus collisions



p-p

p-A



Hadron-(heavy)nucleus collisions

$$\frac{d\sigma_{in}(pA)}{dY\, d^2k\, d^2b} =$$

$$\int \frac{d^2 l_1}{2\pi}\, \phi_G(x_1, l_1) \int d^2 r\, dz\, \left(1 - e^{i\,\underline{l_2}\cdot\underline{r}}\right)\, e^{-i\,\frac{1}{2}\underline{k}\cdot\underline{r}}$$

$$\int d^2 r'\, \left(1 - e^{i\underline{l_2}\cdot\vec{r}'}\right)\, e^{i\,\frac{1}{2}\underline{k}\cdot\underline{r}'}\, \Phi_G(l_1, r, r', z)$$

$$\int_0^{2R_A} \rho\, \hat{\sigma}_{in}(x_2, r, r')\, dz_0\, e^{-(\sigma(x_2, r^2) + \sigma(x_2, r'^2))\, \rho\, 2\, R_A}$$

$$\sum_{n=0}^{\infty} \int_{z_0}^{2R_A} d\, z_1\, \ldots \int_{z_{n-2}}^{2R_A} dz_{n-1} \int_{z_{n-1}}^{2R_A} dz_n\, \rho^n\, \hat{\sigma}^n_{in}(x_2, r, r')$$

Hadron-(heavy)nucleus collisions

In the saturation regime:

$$\sigma(x, r^2)\, \rho\, 2R_A = \frac{1}{4} r^2\, Q_s^2(A, x)$$

$$\underline{\zeta} = m_c \underline{r}$$

$$\frac{d\sigma_{tot}(pA)}{dY\, d^2k\, d^2b} \propto x_1 G(x_1, m_c^2) \int d^2\zeta\, d^2\zeta'\, e^{i\underline{k}\cdot(\underline{\zeta}-\underline{\zeta}')/(2m_c)} \left(\frac{\underline{\zeta}\cdot\underline{\zeta}'}{2\,\zeta\,\zeta'} K_1(\zeta) K_1(\zeta') + K_0(\zeta)\, K_0(\zeta') \right)$$
$$\times \left(1 - \exp\left(-\zeta^2\, Q_s^2/4m_c^2\right) - \exp\left(-\zeta'^2\, Q_s^2/4m_c^2\right) + \exp\left(-(\zeta-\zeta')^2\right) Q_s^2/4m_c^2\right)\right) .$$

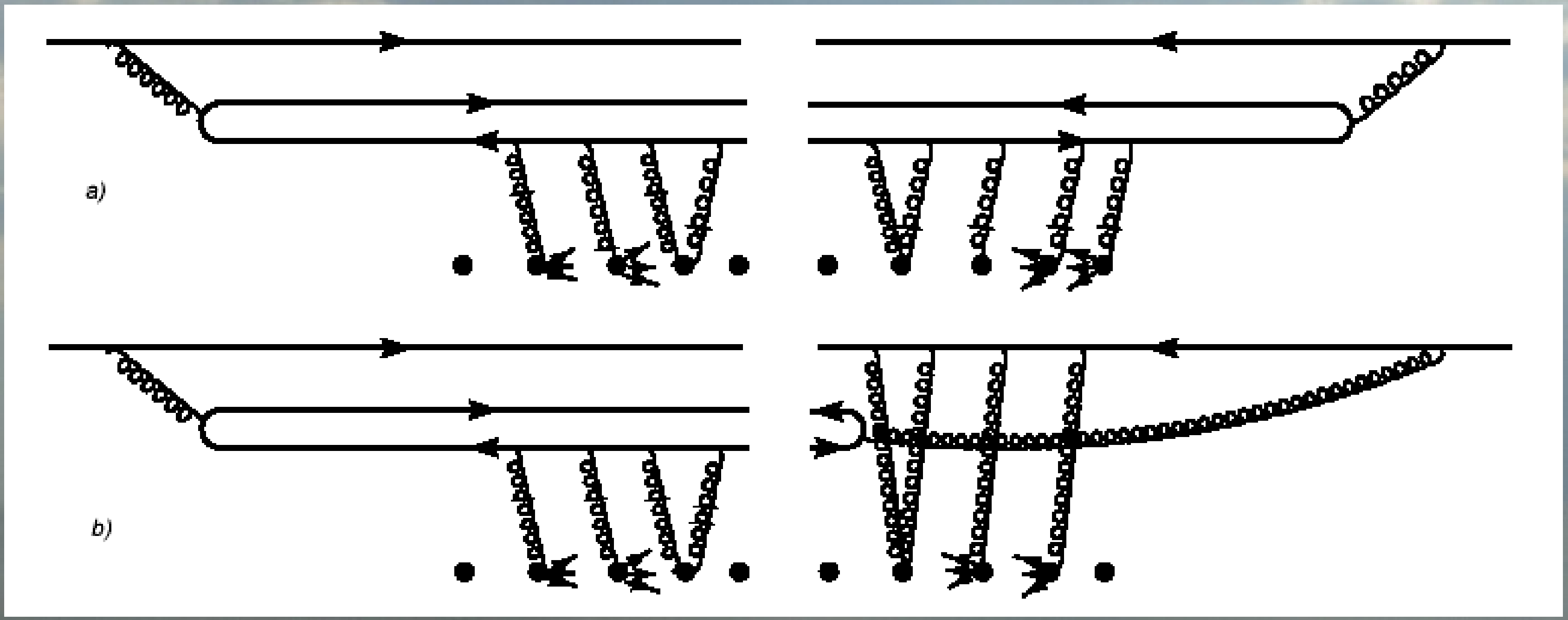
$$\frac{d\sigma_{tot}(pA)}{dY\, d^2k\, d^2b} \propto x_1 G(x_1, m_c^2) \sim \exp(-\lambda Y)$$

If ***Qs>>mc*** :

In hadron-hadron:

$$\frac{d\sigma(pp)}{dY\, d^2k\, d^2b} \propto x_1 G(x_1, m_c^2)\, x_2 G(x_2, m_c^2)$$

A-A collisions at RHIC



A-A collisions at RHIC

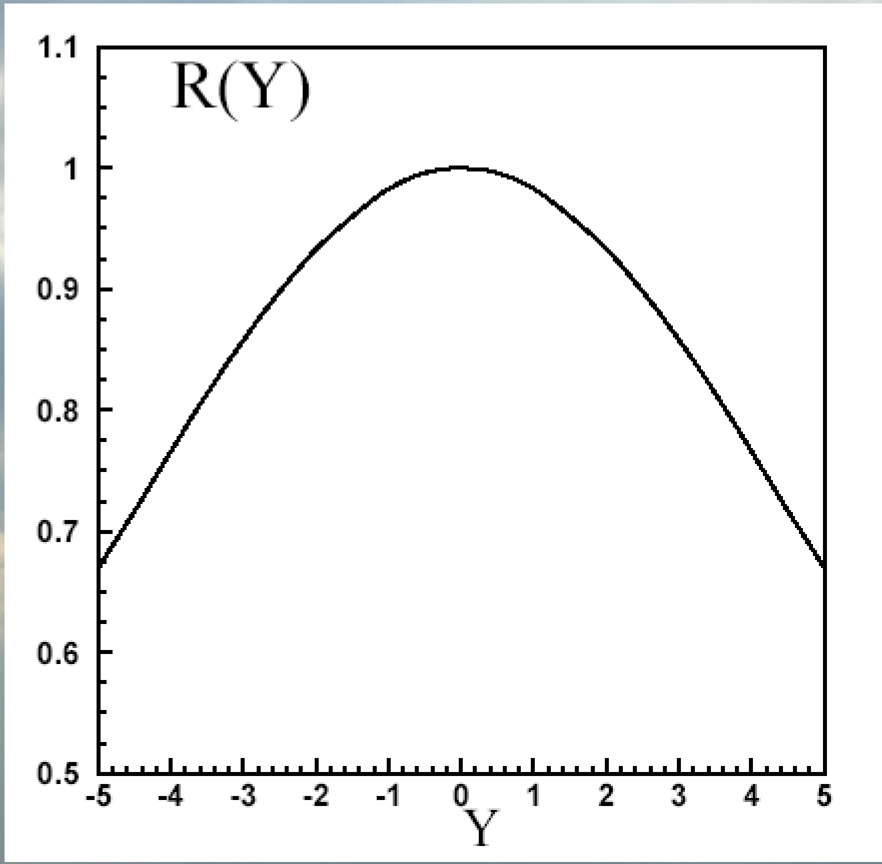
$$\frac{d\sigma_{tot}(AA)}{dY\, d^2k\, dy} \;\propto\; \int d^2\zeta\, d^2\zeta'\, e^{i\vec{k}\cdot(\vec{\zeta}-\vec{\zeta}')/2m_c} \left(\frac{\underline{\zeta}\cdot\underline{\zeta}'}{2\,\zeta\,\zeta'} K_1(\zeta) K_1(\zeta') \;+\; K_0(\zeta)\, K_0(\zeta') \right)$$

$$\times \left[\frac{1}{\zeta^2} \;\left(1 \;-\; \exp\left(-\zeta^2\, Q_s^2(A_1)/8m_c^2\right)\right)\; \left(1 \;-\; \exp\left(-\zeta^2\, Q_{s,A_2}^2/8m_c^2\right)\right) \right.$$

$$+ \frac{1}{\zeta'^2} \;\left(1 \;-\; \exp\left(-\zeta'^2\, Q_{s,A_1}^2/8m_c^2\right)\right)\; \left(1 \;-\; \exp\left(-\zeta'^2\, Q_{s,A_2}^2/8m_c^2\right)\right)$$

$$\left. - \;\frac{1}{(\underline{\zeta}-\underline{\zeta}')^2} \;\left(1 \;-\; \exp\left(-(\underline{\zeta}-\underline{\zeta}')^2\, Q_{s,A_1}^2/8m_c^2\right)\right)\; \left(1 \;-\; \exp\left(-(\underline{\zeta}-\underline{\zeta}')^2\, Q_{s,A_2}^2/8m_c^2\right)\right) \right]$$

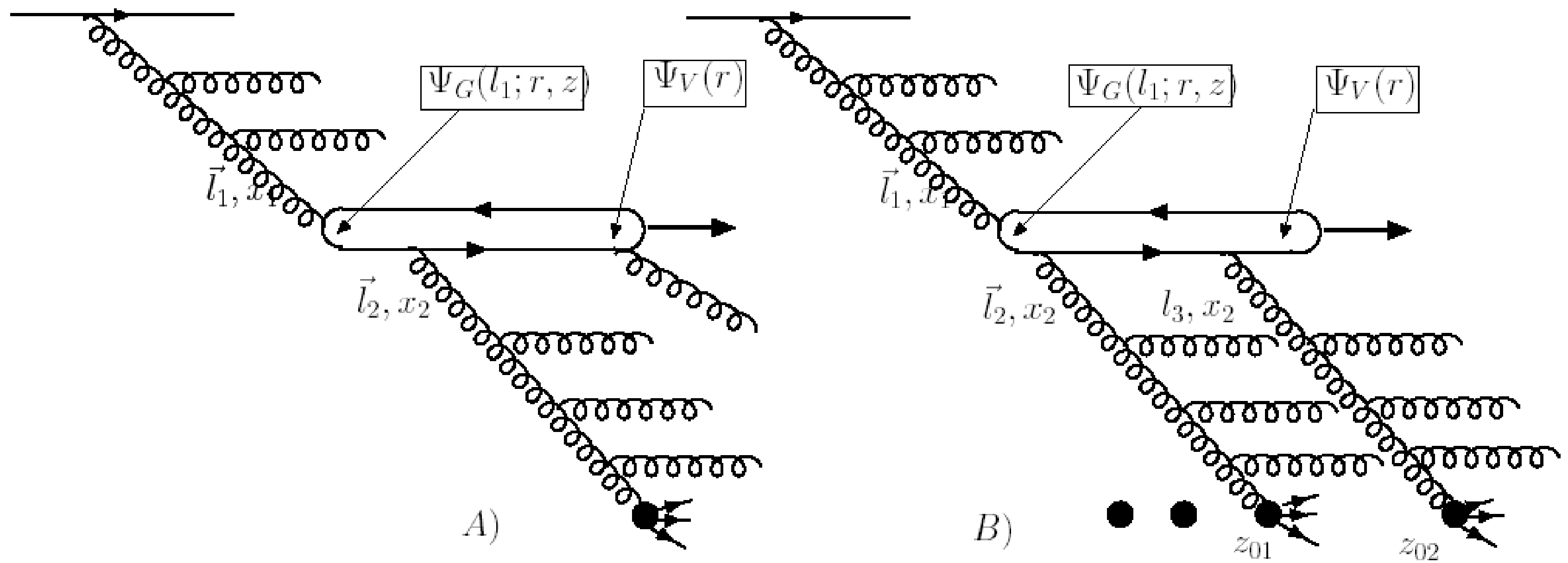
$$R(Y) \;=\; \frac{\left.\frac{d\sigma_{tot}(AA)}{dY\, d^2k\, d^2b}\right|_{\underline{k}=0}}{\left.\frac{d\sigma_{tot}(AA)}{dY\, d^2k\, d^2b}\right|_{\underline{k}=0,\, Y=0}}$$



In p-p collisions this ratio is more flat

(away from fragmentation regions)

J/ψ production: pp & pA



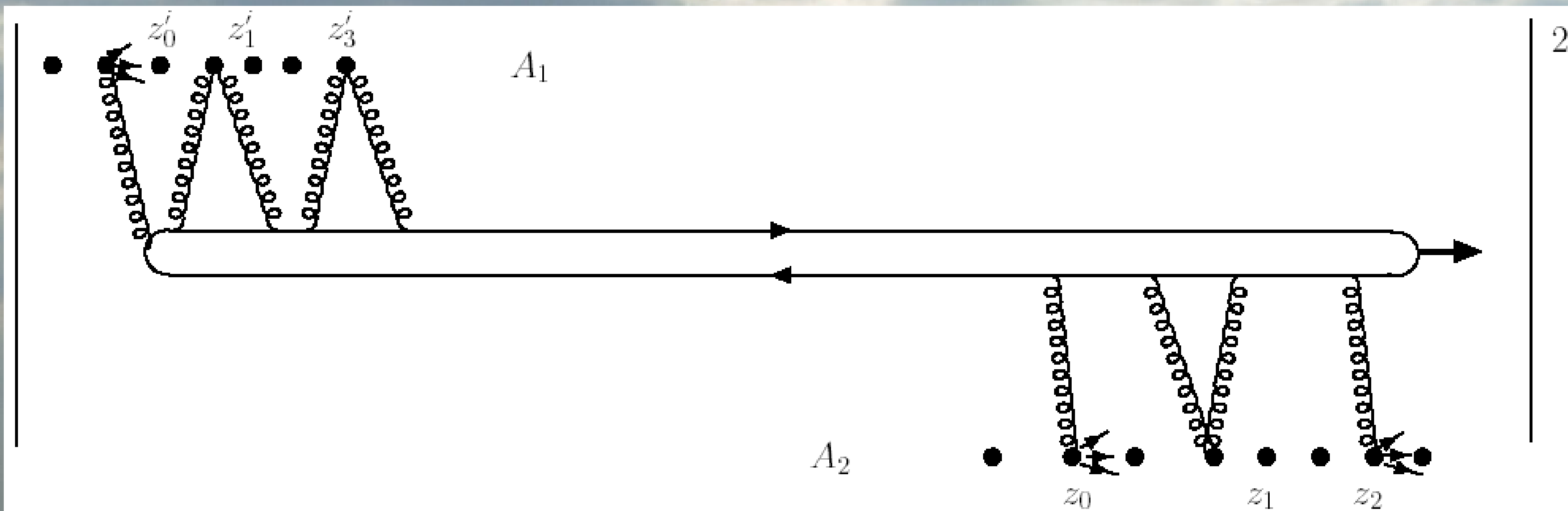
hadron − hadron collisions *hadron − nucleus collisions*

J/ψ production: p-A

$$\frac{d\sigma_{in}^{\psi}(pA)}{dY\, d^2b} = C_F\, x_1 G(x_1, m_c^2)$$
$$\times \int_0^{2R_A} \rho\, \hat{\sigma}_{in}(x_2, r, r')\, d\, z_0 \int d^2\, r\, \Psi_G(l_1, r, z=1/2)\, \Psi_V(r) \otimes \int d^2 r' \Psi_G(l_1, r', z=1/2)\, \Psi_V(r')$$
$$\times \left(e^{-(\sigma(x_2,r^2)+\sigma(x_2,r'^2))\,\rho\, 2\, R_A} \sum_{n=0}^{\infty} \int_{z_0}^{2R_A} d\, z_1 \ldots \int_{z_1}^{2R_A} dz_2 \int_{z_{2n}}^{2R_A} dz_{2n+1}\, \rho^{2n+1}\, \hat{\sigma}_{in}^{2n+1}(x_2, r, r') \right)$$

$$\Psi_G(m_c, r, z) \otimes \Psi_V(r, z) = \sqrt{\frac{3\,\Gamma_{J/\Psi\to e^+e^-}\, M_{J/\Psi}}{48\,\pi\,\alpha_{em}}}\; \frac{m_c^3\, r^2}{4}\, K_2\,(m_c\, r)$$

J/ψ production: A-A



$$Q^2_{s,AA} = Q^2_{s,A_1}(x_1) + Q^2_{s,A_2}(x_2)$$

J/ψ production: A-A

$$\frac{1}{S_A}\frac{d\sigma(AA)}{dY\,d^2b} \propto \int d^2r\,\Psi_G(l_1,r,z=1/2)\,\Psi_V(r)\otimes\int d^2r'\,\Psi_G(l_1,r',z'=1/2)\,\Psi_V(r')$$

$$\times\, Q^2_{s,A_1}\,Q^2_{s,A_2}\,Q^2_{s,AA}\,r^2\,r'^2\,e^{-r^2 Q^2_{s,AA}/8}$$

$$\propto \frac{Q^2_{s,A_1}\,Q^2_{s,A_2}}{Q^6_{s,AA}}\,.$$

$$\frac{d\sigma(AA)}{dY} \propto \frac{d\sigma(pp)}{dY}\frac{1}{Q^6_{s,AA}} \propto \frac{d\sigma(pp)}{dY}\,e^{-3\lambda|Y|}$$

Comparing to RHIC data

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- d-Au: PHENIX Collab.

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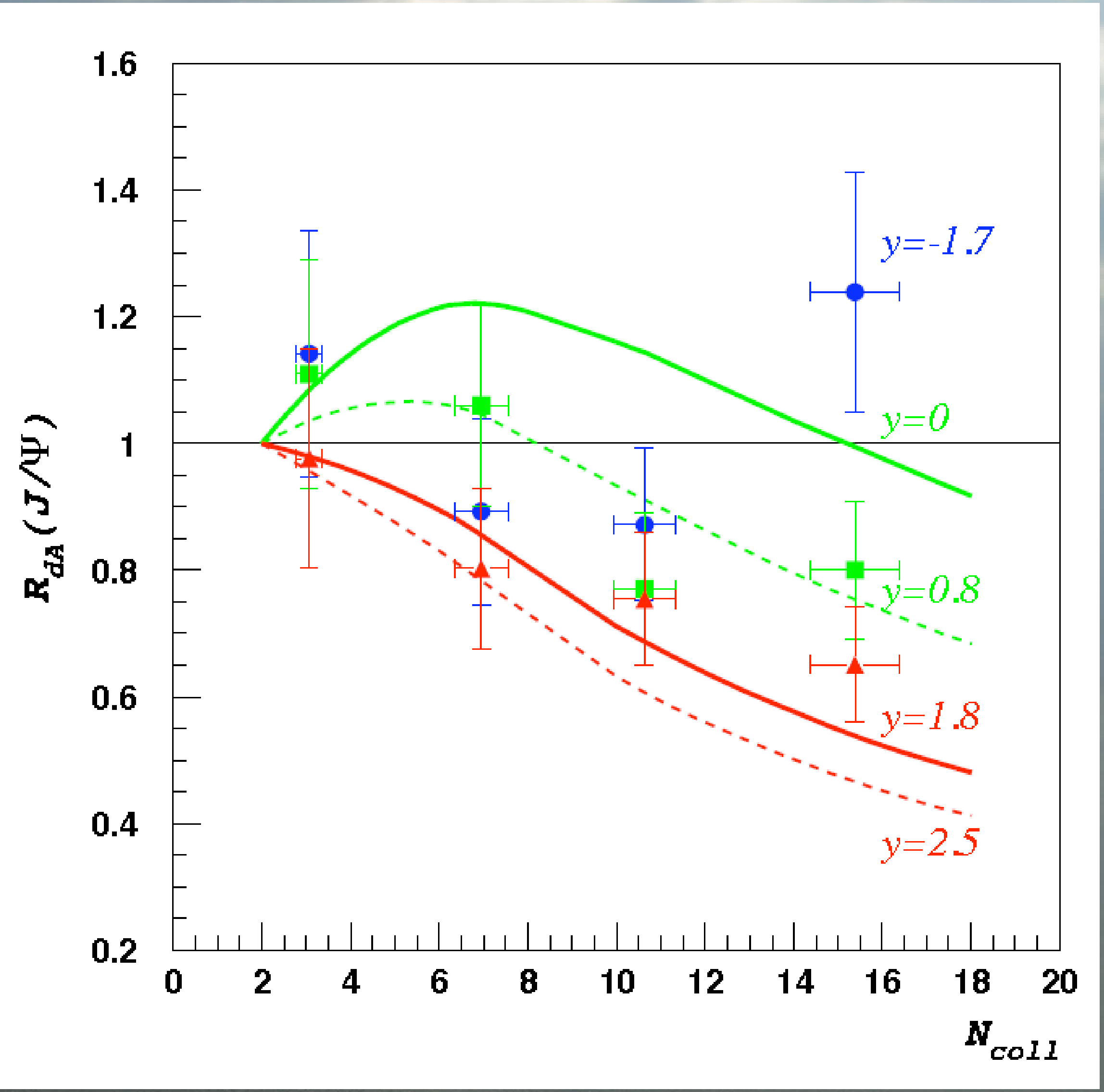
[arXiv:hep-ph/0510358]



Explicit formula for Au-Au @ RHIC

$$\frac{1}{S_A}\frac{d\sigma(AA)}{dY\,d^2b} = \frac{C_F^2}{4\pi^2\alpha_s}\int d^2r\,\Psi_G(l_1,r,z=1/2)\,\Psi_V(r)\otimes\int d^2r'\,\Psi_G(l_1,r',z=1/2)\,\Psi_V(r')$$

$$\times\frac{1}{2\underline{r}\cdot\underline{r}'}\left\{\exp\left(-\frac{1}{8}(\underline{r}-\underline{r}')^2\,\Omega_s^2\right) - \exp\left(-\frac{1}{8}(\underline{r}+\underline{r}')^2\,\Omega_s^2\right) - \exp\left(-\frac{1}{8}(\underline{r}-\underline{r}')^2\,Q_{s,A_1}^2 - \frac{1}{8}(r^2+r'^2)\,Q_{s,A_2}^2\right)\right.$$

$$+\exp\left(-\frac{1}{8}(\underline{r}+\underline{r}')^2\,Q_{s,A_1}^2 - \frac{1}{8}(r^2+r'^2)\,Q_{s,A_2}^2\right) - \exp\left(-\frac{1}{8}(\underline{r}-\underline{r}')^2\,Q_{s,A_2}^2 - \frac{1}{8}(r^2+r'^2)\,Q_{s,A_1}^2\right)$$

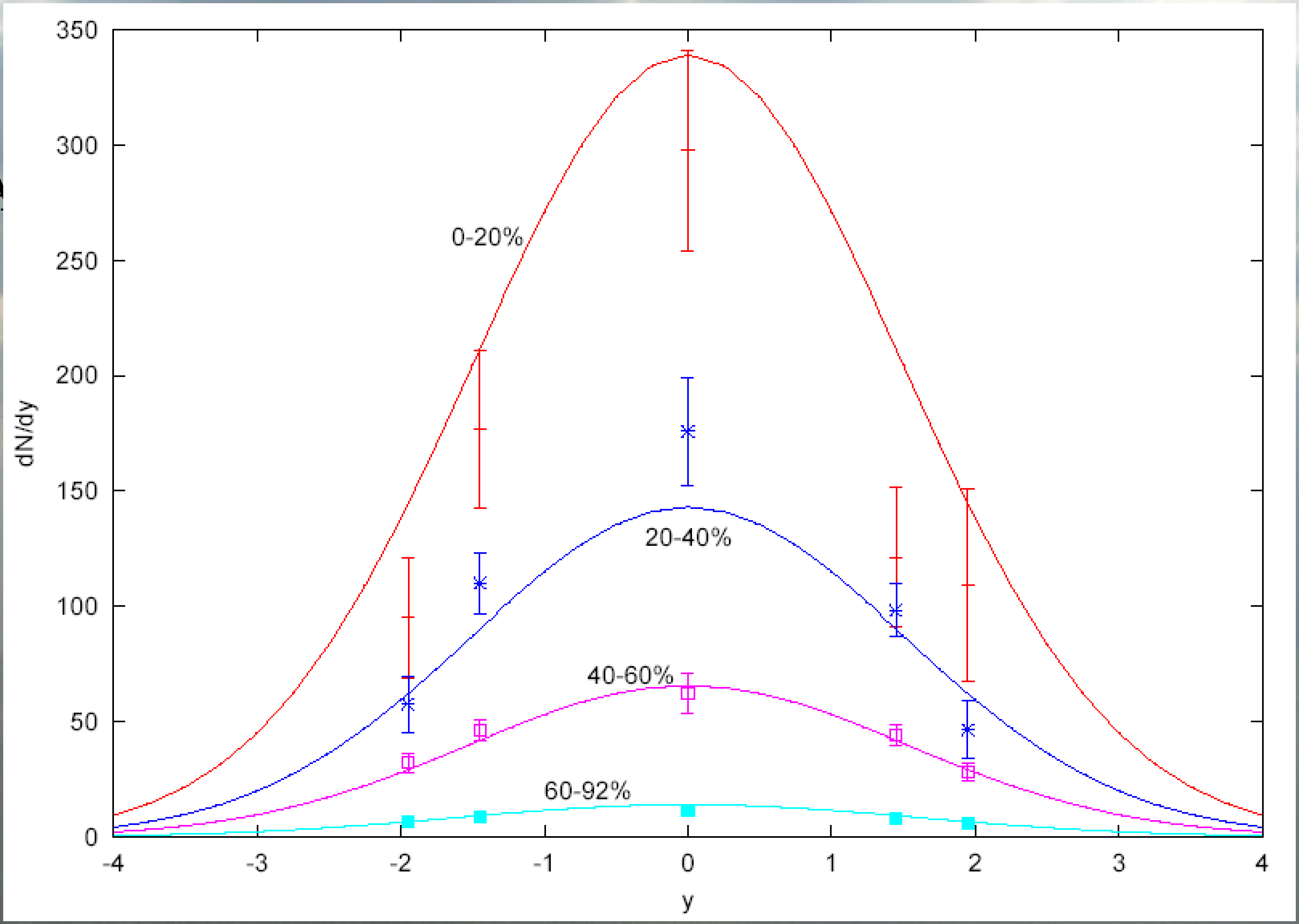
$$\left.+\exp\left(-\frac{1}{8}(\underline{r}+\underline{r}')^2\,Q_{s,A_2}^2 - \frac{1}{8}(r^2+r'^2)\,Q_{s,A_1}^2\right)\right\},$$

Approximately (for ***r>>r'***):

$$\frac{dN^{AA}(Y,b)}{dY} = C\frac{dN^{pp}(Y)}{dY}\int d^2s\,T_{A_1}(\underline{s})\,T_{A_2}(\underline{b}-\underline{s})\,\left(Q_{s,A_1}^2(x_1,\underline{s}) + Q_{s,A_2}^2(x_2,\underline{b}-\underline{s})\right)\frac{1}{m_c^2}$$

$$\times\int_0^\infty d\zeta\,\zeta^9\,K_2(\zeta)\,\exp\left(-\frac{\zeta^2}{8m_c^2}\left(Q_{s,A_1}^2(x_1,\underline{s}) + Q_{s,A_2}^2(x_2,\underline{b}-\underline{s})\right)\right).$$

A


0-20%
20-40%
40-60%
60-92%
dN/dy
y
350
300
250
200
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0
1
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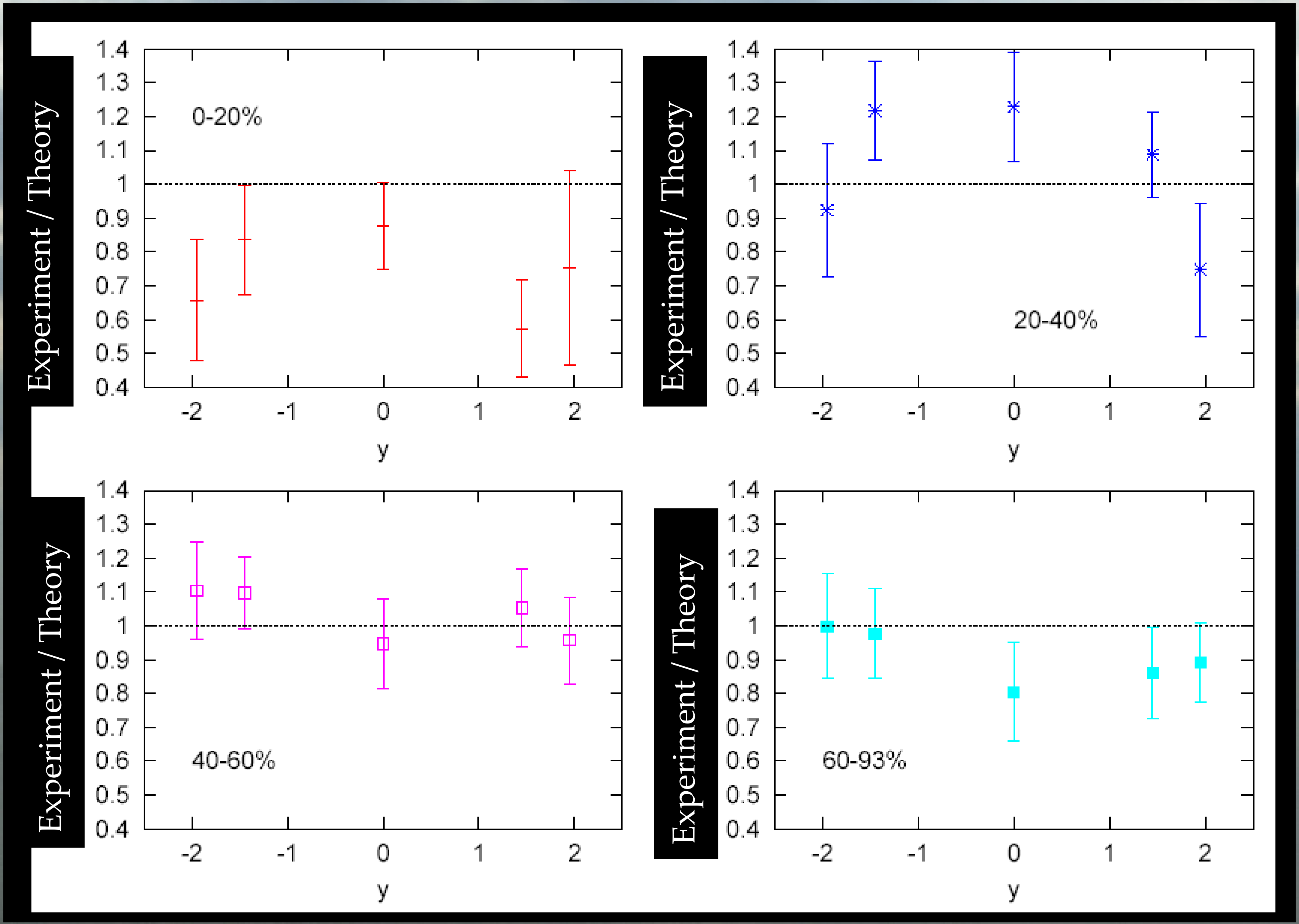
Experiment / Theory
0-20%
20-40%
40-60%
60-93%
y
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
-2
-1
0
1
2

$$\frac{dN^{AA}(Y,b)}{dY} = C\frac{dN^{pp}(Y)}{dY} \int d^2s\, T_{A_1}(\underline{s})\, T_{A_2}(\underline{b}-\underline{s})\, \left(Q^2_{s,A_1}(x_1,\underline{s}) + Q^2_{s,A_2}(x_2,\underline{b}-\underline{s})\right) \frac{1}{m_c^2}$$
$$\times \int_0^\infty d\zeta\, \zeta^9\, K_2(\zeta)\, \exp\left(-\frac{\zeta^2}{8m_c^2}\left(Q^2_{s,A_1}(x_1,\underline{s}) + Q^2_{s,A_2}(x_2,\underline{b}-\underline{s})\right)\right).$$

- Factor C fitted to experimental data (overall fit): this is not the best thing to do... we are working d-Au analysis to get a better estimate *(V.Mauro: thesis)*

- *dNpp/dy* fitted to pp data (PHENIX)

Summary & Outlook

The production process of J/ψ in p-A and A-A is different from p-p: initial state effects are important.

Calculations based on CGC can reproduce y and b dependence of J/ψ in Au-Au at RHIC.

Some uncertainty in absolute normalization, leaving room for final state suppression (to be fixed by comparison with p(d)-Au data).

Next: study of lighter systems (Cu-Cu),

pT distribution.

back-up slides

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Time scales

- tp = c-cbar production time
  - in the pair rest frame tp0 = 1/2mc .
  - in the nucleus rest frame (γ=Eg/2mc) : tp=Eg/(2mc)2

Eg = x1 Ep

s=(x1pp+x2pt)2=2x1x2EpM=2x2EgM

s=(2mc)2

tp =1/(2x2M)

x2=mce-y/sqrt(s)

at RHIC : x2=6.5x10-3 e-y ◎ **tp =15 ey fm**

- tint = interaction time = RA/c

at high energies tp > tint

or lc=tp c > RA

tp =15 ey fm : at forward y tp is very large

- *the projectile interacts with the whole nucleus*
- *eikonal approximation for the calculation of scattering amplitude*

tf = J/ψ formation time

- in the pair rest frame $tf0 = 2/(m\psi' - m\psi)$
- in the nucleus rest frame ($\gamma = Eg/M\psi$) : $tf = 2Eg/(m\psi' - m\psi)\, M\psi$
- tf0=0.45 fm ◎ tfRHIC=41 ey fm

Inclusive c-cbar prodution in hadron-hadron collisions

$$\frac{d\sigma(pp)}{dY\, d^2k\, d^2b} = x_1 G\left(x_1, m_c^2\right) \int d^2r\, \Psi_G(m_c, r, z=1/2)\, e^{i\,\frac{1}{2}\underline{r}\cdot\underline{k}} \int d^2r'\, \Psi_G(m_c, r', z=1/2)\, e^{i\,\frac{1}{2}\underline{r}'\cdot\underline{k}}\, \hat{\sigma}_{in}(x_2, r, r')$$

$$\hat{\sigma}_{in}(x_2, r, r') \equiv \sigma(x_2, r^2) + \sigma(x_2, r'^2) - \sigma(x_2, (\underline{r} - \underline{r}')^2)$$

$$\Psi_G(m_c, r, z=1/2) = \frac{g\, t^a}{2\pi}\left(i\,\frac{\underline{r}\cdot\underline{\epsilon}^\lambda}{r}\, m\, K_1(rm_c)\,\lambda\,\delta_{s,s'} + K_0(rm_c)\, s\, m(1+s\lambda)\delta_{s,-s'}\right)$$

$$\Phi_G(m_c, r, r', z=1/2) = \frac{1}{(2\pi)^3}\,\frac{1}{2(N_c^2-1)} \sum_{\lambda,s,s'} \Psi_G(m_c, r, z=1/2)\Psi_G^*(m_c, r', z=1/2)$$

$$= \frac{1}{(2\pi)^3}\,\frac{\alpha_s m_c^2}{\pi}\left(\frac{\underline{r}\cdot\underline{r}'}{2\, r r'} K_1(rm_c)\, K_1(r'm_c) + K_0(rm_c)\, K_0(r'm_c)\right),$$

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$m_c > \Lambda_{QCD}$ ◎ perturbative QCD, but non-perturbative effects are not negligible

In A-A collisions: J/ψ suppression is a signature of QGP formation ◎ it is important to understand the production mechanism.

At RHIC : experimental data on hadron multiplicity can be explained by CGC, parton (gluon) saturation in the nuclear wave function. $Q_s^2(x_2) \gg \Lambda_{QCD}$.

For heavy quarks :

- $Q_s < m$: Q production is incoherent, pQCD
- $Q_s > m$: Q production is coherent, the projectile

Time scales in p-A collisions

- tp = c-cbar production time
  - in the pair rest frame tp0 = 1/2mc .
  - in the nucleus rest frame (γ=Eg/2mc) : tp =Eg/(2mc)2

Eg = x1 Ep

s=(x1pp+x2pt)2=2x1x2EpM=2x2EgM

s=(2mc)2

tp =1/(2x2M)

x2=mce-y/sqrt(s)

at RHIC : x2=6.5x10-3 e-y ◎ **tp =15 ey fm**

- tint = interaction time = RA/c

at high energies tp > tint

or lc=tp c > RA

tp =15 ey fm : at forward y tp is very large

- *the projectile interacts with the whole nucleus*
- *eikonal approximation for the calculation of scattering amplitude*

- tf = J/ψ formation time
  - in the pair rest frame $tf0 = 2/(m\psi' - m\psi)$
  - in the nucleus rest frame ($\gamma = Eg/M\psi$) :
    $tf = 2Eg/(m\psi' - m\psi)\ M\psi$
  - tf0=0.45 fm ◎ tfRHIC=41 ey fm

At **y>1**, at RHIC :

tf > tp > tint

J/ψ is formed outside the nucleus, no nuclear effects !

At **y<-2** the coherence is lost.

The production of J/ψ in p-A is similar to the one in pp collisions

J/ψ can be formed inside the nucleus.

c-cbar and J/ψ interact with nuclear matter.