GLUON SATURATION AND QUARKONIUM PRODUCTION IN HEAVY-ION COLLISIONS

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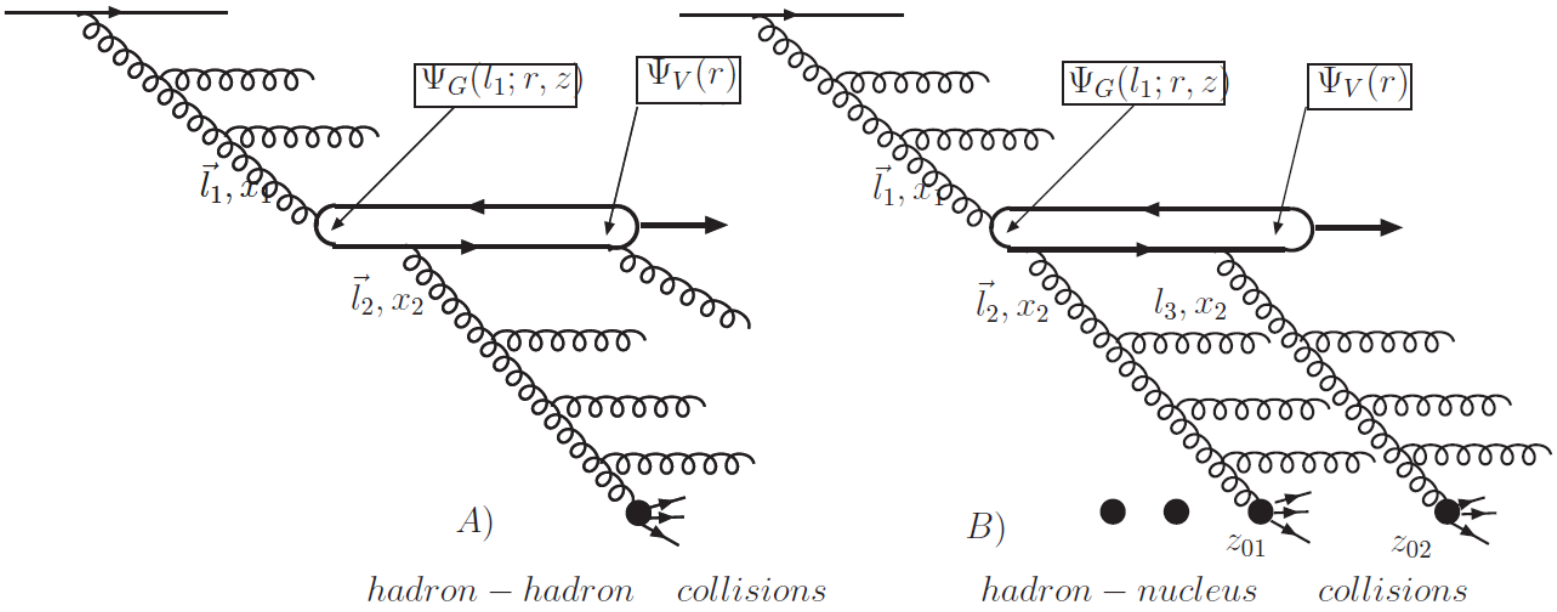
J/Ψ production from pA to AA at RHIC and LHC

J/ψ production in pp and in pA (AB) are different processes:



α_s^5 $\alpha_s^6 A^{1/3}$

In the saturation regime $\alpha_s^2 A^{1/3} \sim 1$

D.Kharzeev, E.Levin, M.N., K. Tuchin, NPA 826(2009) 230 [arXiv:0809.2933]; PRL 102 (2009) 152301 [arXiv:0808.2954]

p-A Collisions

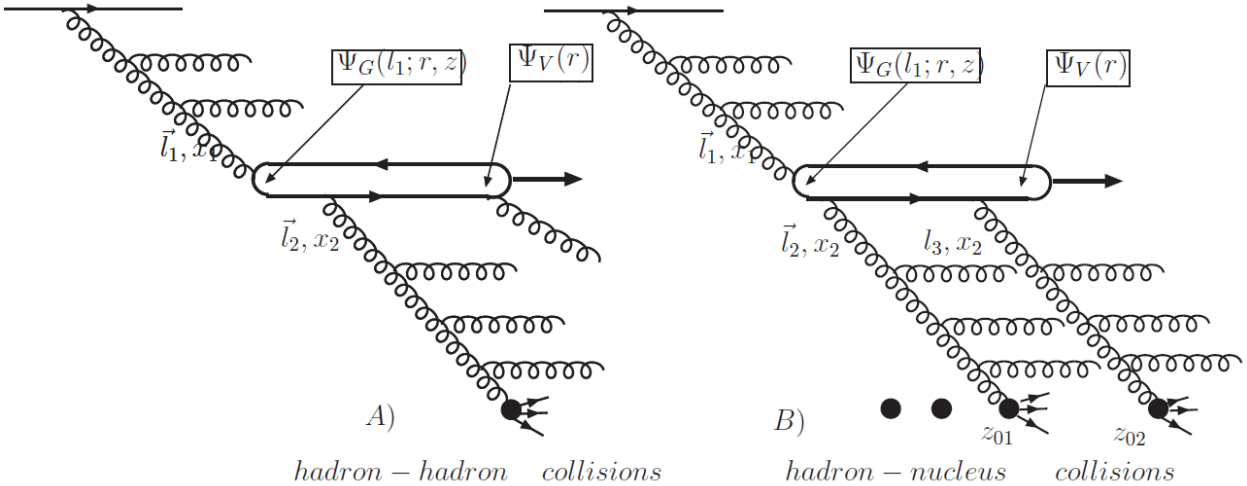
Due to large coherence length at high energies the $c\overline{c}$ pair can simultaneously interact with many nucleons.

The low-x quantum evolution of the dipole scattering amplitude become increasingly important at smaller x and leads eventually to gluon saturation: weaker dependence of the scattering amplitude on the nuclear atomic weight A.

Collision scaling does not work!

At LHC: p-Pb data are necessary, pp and Pb-Pb are not enough !

p-A Collisions



$$\frac{\mathrm{d}\sigma_{pA\to JX}}{\mathrm{d}y\mathrm{d}^2\mathbf{b}} = 8\pi\, xG(x,a^2)\int_0^1 \mathrm{d}z\int_0^1 \mathrm{d}z'\int\frac{\mathrm{d}^2\mathbf{k}}{16\pi^3}\int\frac{\mathrm{d}^2\mathbf{k}'}{16\pi^3}\int\frac{\mathrm{d}^2\mathbf{p}}{4\pi^2}$$
$$\times\Psi^g_{\lambda_1\lambda_2}(\mathbf{k},\mathbf{p},z)\psi^{J*}_{\lambda_1\lambda_2}(\mathbf{k},z)\Psi^{g*}_{\lambda_1'\lambda_2'}(\mathbf{k}',\mathbf{p},z')\psi^{J}_{\lambda_1'\lambda_2'}(\mathbf{k}',z')\mathcal{T}_{gA\to JX}(\mathbf{p})$$

$a^2 = Q^2/4 + m^2$

$\Psi^g_{\lambda\lambda'}$ is the amplitude for a gluon to split into a $q\bar{q}$ pair.

$\psi^J_{\lambda\lambda'}$ is the amplitude for a J/ψ to split into a $q\bar{q}$ pair.

$\mathcal{T}_{gA\to JX}$ is the forward elastic scattering amplitude

Forward scattering amplitude for $c\bar{c}$ production in pA in the coordinate space:

$$\mathcal{T}_{gA\to c\bar{c}X}(\mathbf{r},\mathbf{r}') = \mathcal{T}^{el}_{gA\to c\bar{c}A}(\mathbf{r},\mathbf{r}') + \mathcal{T}^{inel}_{gA\to c\bar{c}X'}(\mathbf{r},\mathbf{r}')$$

$$\mathcal{T}^{el}_{gA\to c\bar{c}A}(\mathbf{r},\mathbf{r}') = \left(1-\mathrm{e}^{-r^2Q_s^2/8}\right)\left(1-\mathrm{e}^{-r'^2Q_s^2/8}\right)$$

$$\mathcal{T}^{inel}_{gA\to c\bar{c}X'}(\mathbf{r},\mathbf{r}') = \mathrm{e}^{-(\mathbf{r}-\mathbf{r}')^2Q_s^2/8} - \mathrm{e}^{-r^2Q_s^2/8}\mathrm{e}^{-r'^2Q_s^2/8}$$

$$\mathcal{T}_{gA\to c\bar{c}X}(\mathbf{r},\mathbf{r}') = 1-\mathrm{e}^{-r^2Q_s^2/8} - \mathrm{e}^{-r'^2Q_s^2/8} + \mathrm{e}^{-(\mathbf{r}-\mathbf{r}')^2Q_s^2/8}$$

The color state of $c\bar{c}$ is not fixed: all possible quantum states of $c\bar{c}$ are included before projecting it onto the J/Ψ wave function.
The used approximation is valid if the c mass is much larger than any transverse momentum scale of the proton.

J/Ψ production in p-A

We need to sum over the even number of *inelastic* scattering of $c\bar{c}$ in the nucleus.
One inelastic scattering is proportional to $\mathbf{r} \cdot \mathbf{r}' Q_s^2$

$$\mathcal{T}^{inel}_{gA \to c\bar{c}X'}(\mathbf{r}, \mathbf{r}') = \mathrm{e}^{-(\mathbf{r}-\mathbf{r}')^2 Q_s^2/8} - \mathrm{e}^{-r^2 Q_s^2/8} \mathrm{e}^{-r'^2 Q_s^2/8}$$
$$\mathcal{T}^{inel}_{gA \to JX'}(\mathbf{r}, \mathbf{r}') = \mathrm{e}^{-r^2 Q_s^2/8} \mathrm{e}^{-r'^2 Q_s^2/8} \left(\cosh(2\mathbf{r} \cdot \mathbf{r}' Q_s^2/8) - 1 \right)$$

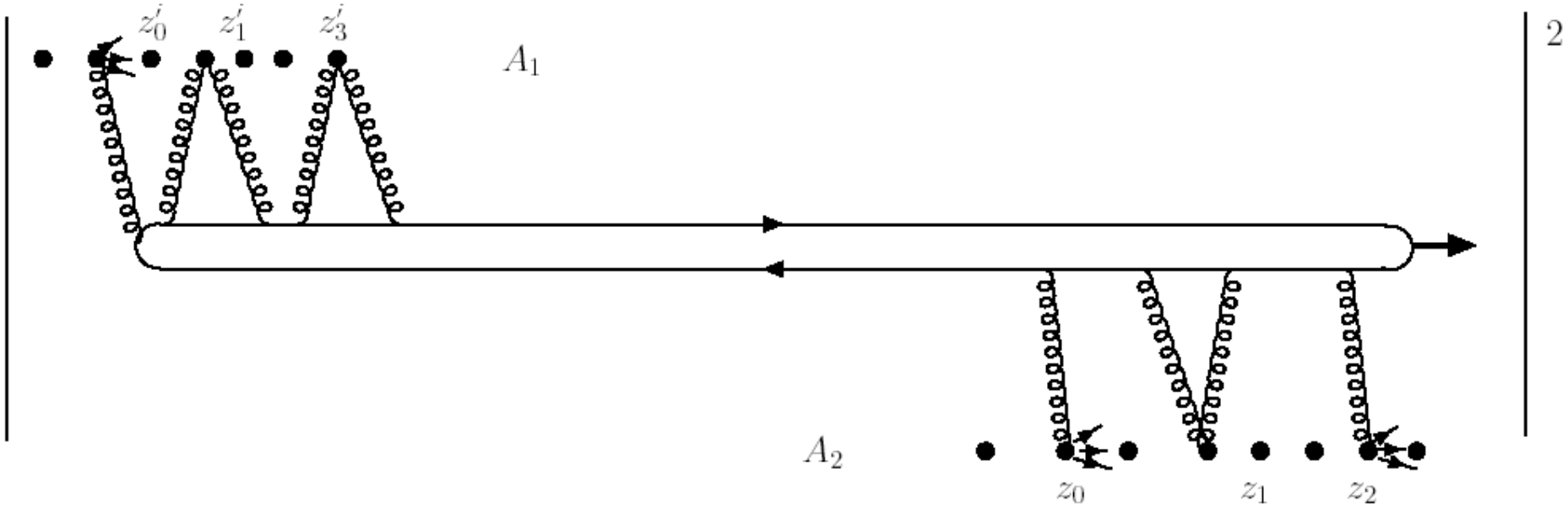
For the elastic part:

$$\mathcal{T}^{el}_{gA \to JA}(\mathbf{r}, \mathbf{r}') = \mathcal{T}^{el}_{gA \to c\bar{c}A}(\mathbf{r}, \mathbf{r}')$$

Total amplitude:

$$\mathcal{T}_{gA \to JX}(\mathbf{r}, \mathbf{r}') = \mathcal{T}^{el}_{gA \to JA}(\mathbf{r}, \mathbf{r}') + \mathcal{T}^{inel}_{gA \to JX'}(\mathbf{r}, \mathbf{r}')$$

A-A Collisions



"Traditional" approximation for J/ψ production cross section in nucleus-nucleus: approximate wave function for J/ψ

$$\frac{1}{S_A}\frac{\mathrm{d}\sigma^{trad}_{AA\to JX}}{\mathrm{d}y\mathrm{d}^2b} = \frac{4N_c}{\alpha_s\pi^2}\frac{\alpha_s G_2}{\pi}\mathcal{P}\int \mathrm{d}^2r\int \mathrm{d}^2r'$$
$$\times\left[\frac{a^2}{2}\frac{\mathbf{r}\cdot\mathbf{r}'}{rr'}K_1(ar)K_1(ar') + m^2K_0(ar)K_0(ar')\right]\mathcal{T}_{AA\to c\bar{c}A}(\mathbf{r},\mathbf{r}')$$
$$\simeq \frac{4N_c}{\alpha_s\pi^2}\frac{\alpha_s G_2}{\pi}\mathcal{P}\int \mathrm{d}^2r\int \mathrm{d}^2r'$$
$$\frac{m^2r^2}{4}K_2(m_c,r)\,\frac{m^2r'^2}{4}K_2(m_c,r')\,\mathcal{T}_{AA\to c\bar{c}A}(\mathbf{r},\mathbf{r}')$$

$\mathcal{P}=$ prob. of soft gluon radiation, assumed to be constant

$$G_2 = \frac{g^2\alpha_s}{\pi^2 M}|\psi^{J*}(0)|^2$$

Leading contribution to J/ψ production cross section:

$$
\begin{aligned}
\frac{1}{S_A}\frac{\mathrm{d}\sigma_{AA\to JX}}{\mathrm{d}y\mathrm{d}^2b} = \frac{4N_c}{\alpha_s\pi^2}\frac{\alpha_s G_2}{\pi}\int \mathrm{d}^2r \int \mathrm{d}^2r' \\
\times\left[\frac{a^2}{2}\frac{\mathbf{r}\cdot\mathbf{r}'}{rr'}K_1(ar)K_1(ar') + m^2K_0(ar)K_0(ar')\right] \\
\times\left\{\frac{1}{r^2}\left(1-\mathrm{e}^{-r^2Q_{s1}^2/8}\right)\left(1-\mathrm{e}^{-r^2Q_{s2}^2/8}\right)\right. \\
+\frac{1}{r'^2}\left(1-\mathrm{e}^{-r'^2Q_{s1}^2/8}\right)\left(1-\mathrm{e}^{-r'^2Q_{s2}^2/8}\right) \\
-\frac{1}{2}\left[\frac{1}{(\mathbf{r}-\mathbf{r}')^2}\left(1-\mathrm{e}^{-(\mathbf{r}-\mathbf{r}')^2Q_{s1}^2/8}\right)\left(1-\mathrm{e}^{-(\mathbf{r}-\mathbf{r}')^2Q_{s2}^2/8}\right)\right. \\
\left.\left.+\frac{1}{(\mathbf{r}+\mathbf{r}')^2}\left(1-\mathrm{e}^{-(\mathbf{r}+\mathbf{r}')^2Q_{s1}^2/8}\right)\left(1-\mathrm{e}^{-(\mathbf{r}+\mathbf{r}')^2Q_{s2}^2/8}\right)\right]\right\}
\end{aligned}
$$

Generalizing to include quantum evolution effects...
Initial condition for the BK evolution equation is the Glauber-Mueller formula for the forward dipole-nucleus elastic scattering amplitude:

$$N(\mathbf{r}, \mathbf{b}, y_0) = 1 - \mathrm{e}^{-r^2 Q_s^2(y_0)/8}$$

In the KKT model[1]:

$$N(\mathbf{r}, 0, y_0) = 1 - \mathrm{e}^{-\frac{1}{4}(r^2 Q_s^2)^{\gamma(r,y)}}$$

where the anomalous dimension is parameterized,
$Q_s^2(y) = \Lambda^2 A^{1/3} \mathrm{e}^{\lambda y} = 0.13\,\mathrm{GeV}^2\,\mathrm{e}^{\lambda y}\,N_{coll}$ ($\Lambda = 0.6$ GeV and $\lambda = 0.3$ are fixed by DIS data)

[1] K.Tuchin, NPA 798, 61(2008); D.Kharzeev, Y.Kovchegov, K.Tuchin, PLB 599, 23 (2004)

Results

We compute the nuclear modification factor

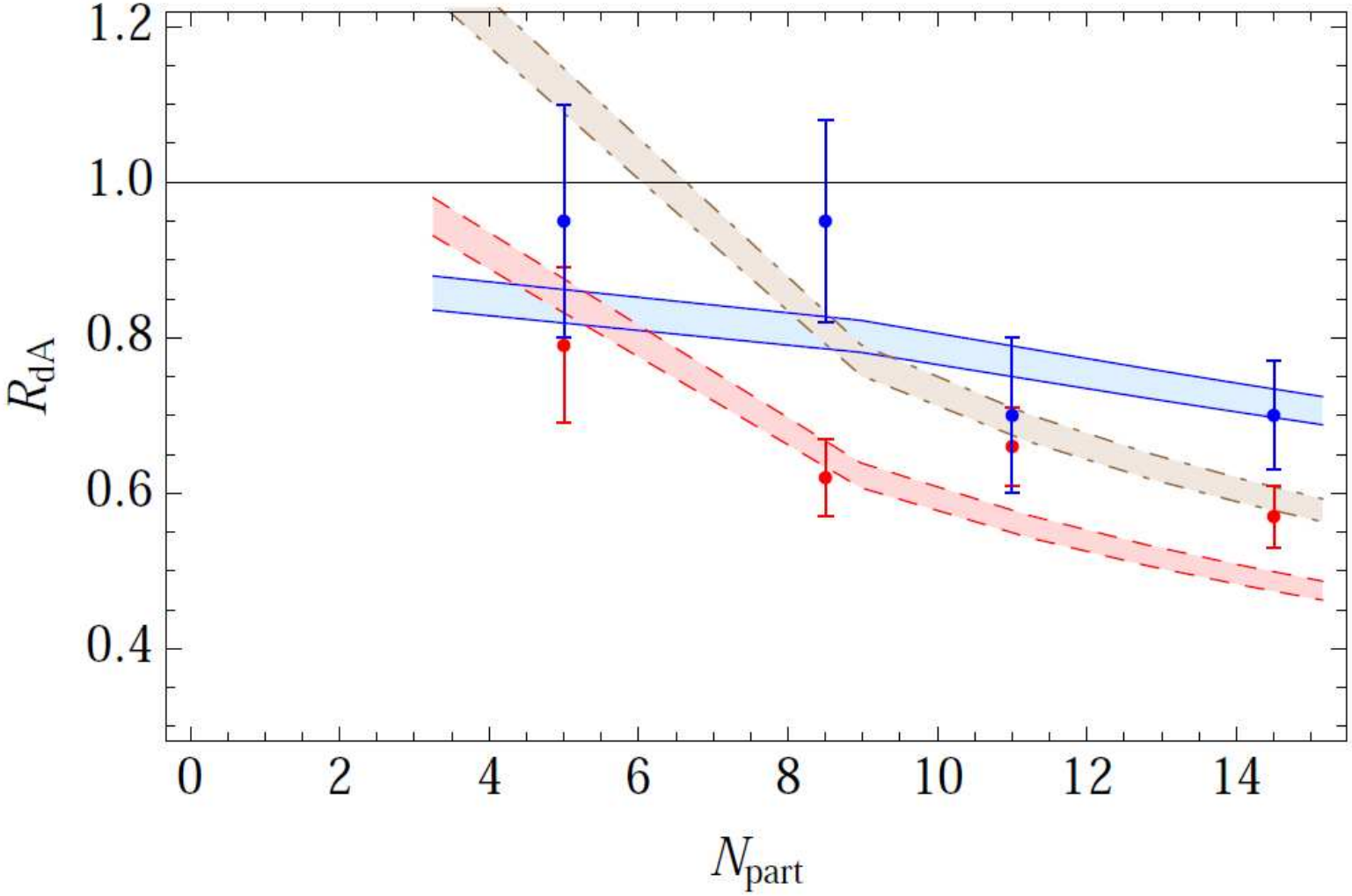
$$R_{AB} = \frac{\int_{\mathcal{S}} \mathrm{d}^2 b \, \frac{\mathrm{d}\sigma_{AB\to JX}}{\mathrm{d}y \mathrm{d}^2 b}}{AB \frac{\mathrm{d}\sigma_{pp\to JX}}{\mathrm{d}y}}$$

In the $D - Au$ case we use two models:

1. the leading approximation formula with a simplified treatment of nuclear density (for both D and Au) and b-dependence
2. the traditional formula with a realistic wave function for D, Woods-Saxon nuclear density for Au and an accurate b-dependence.

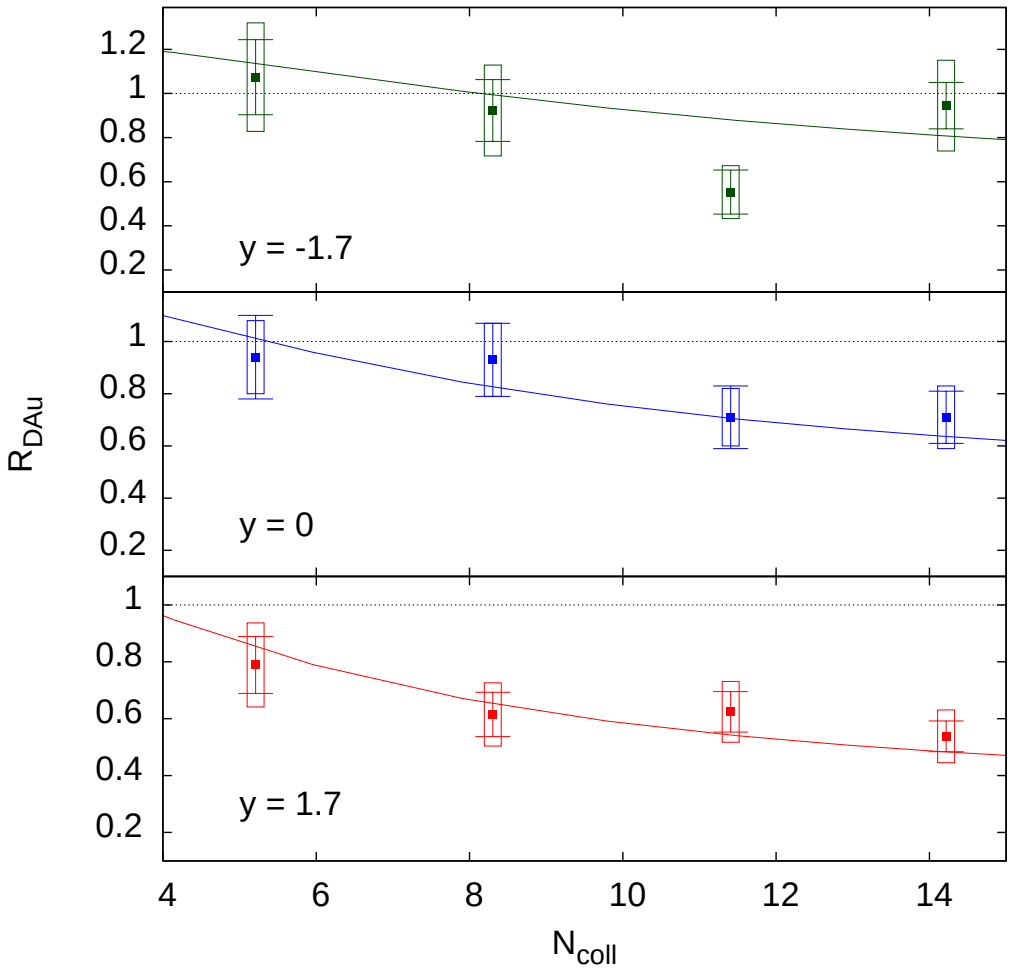
For $Au - Au$ we give results for the first case only.

Results: D-Au (1)



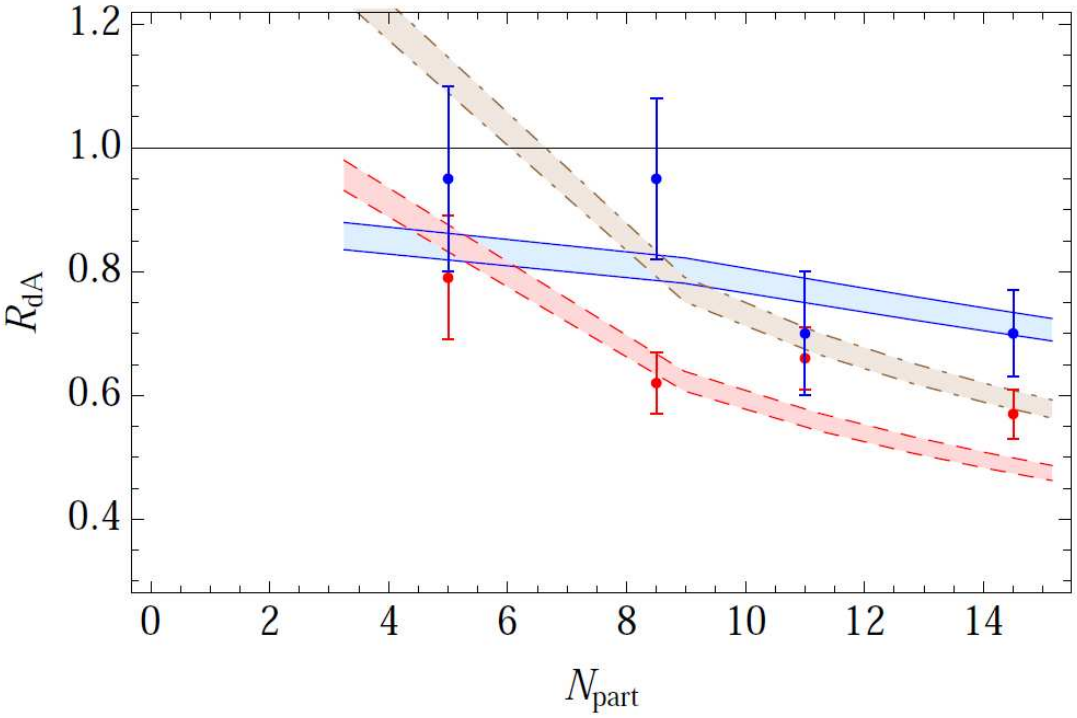
blue: $y = 0$, red: $y = 1.7$, brown: $y = 0$ at LHC

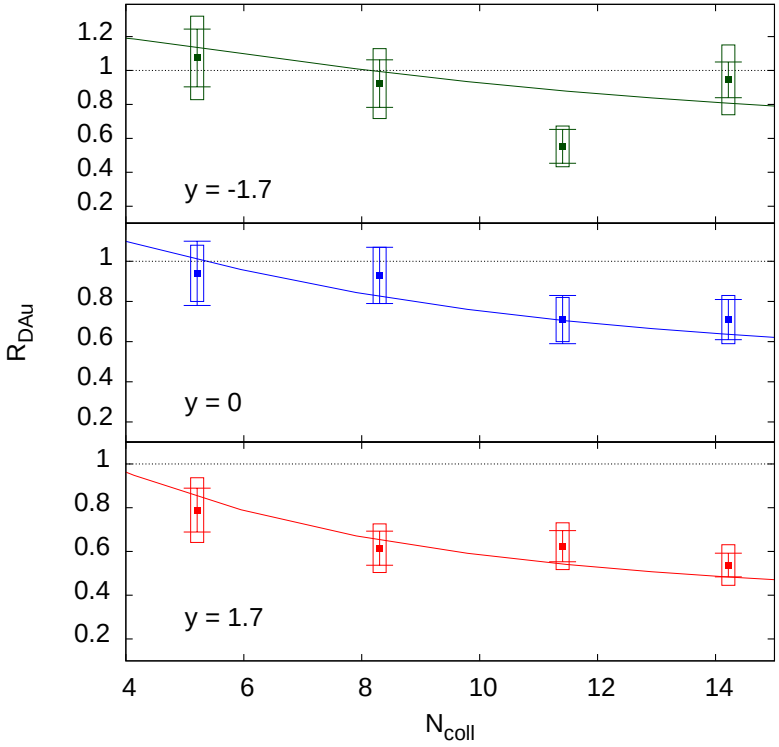
Results: D-Au (2)



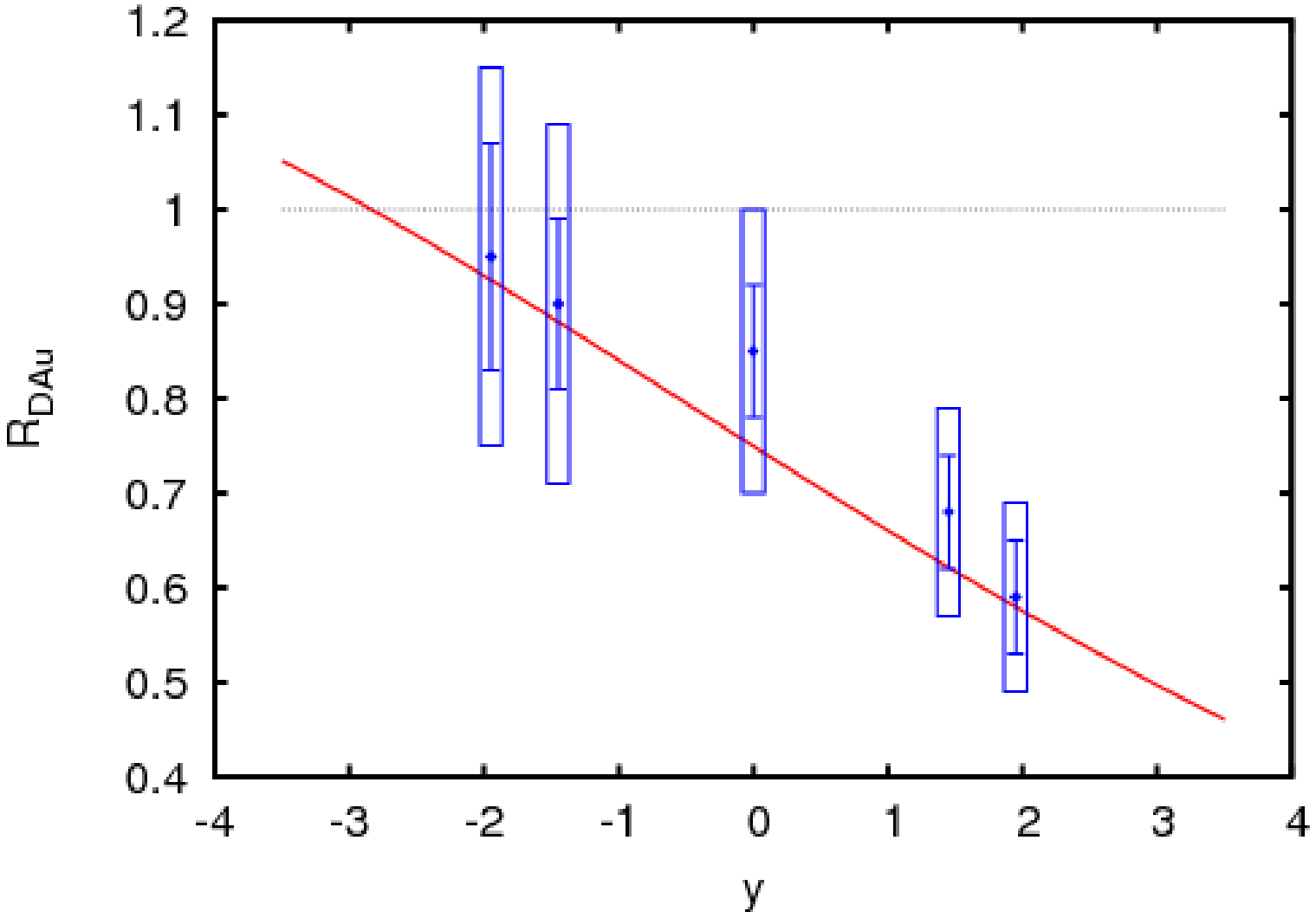
V. Mauro, Degree Thesis, Dec. 2009, Univ. of Torino

Results: D-Au (1 & 2)





Results: D-Au (2)



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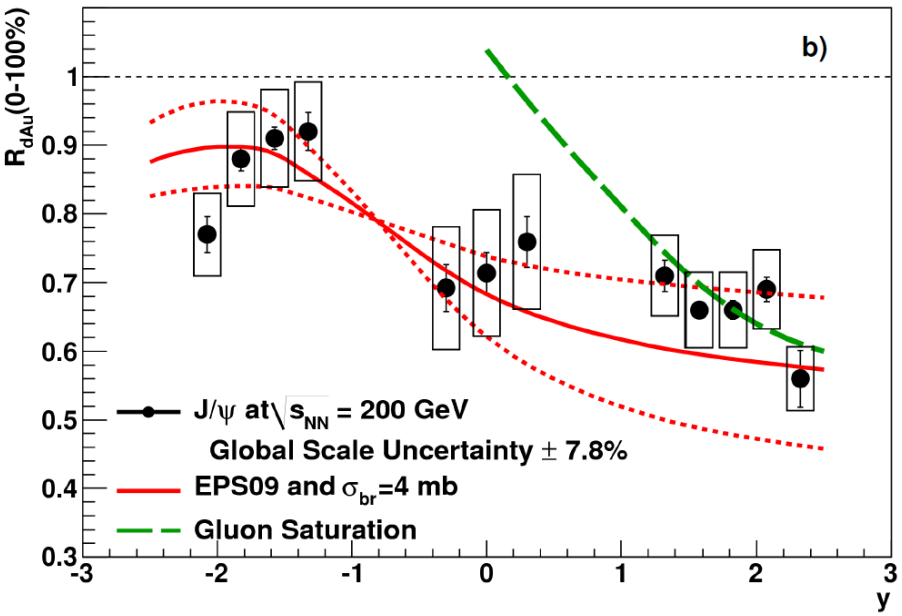
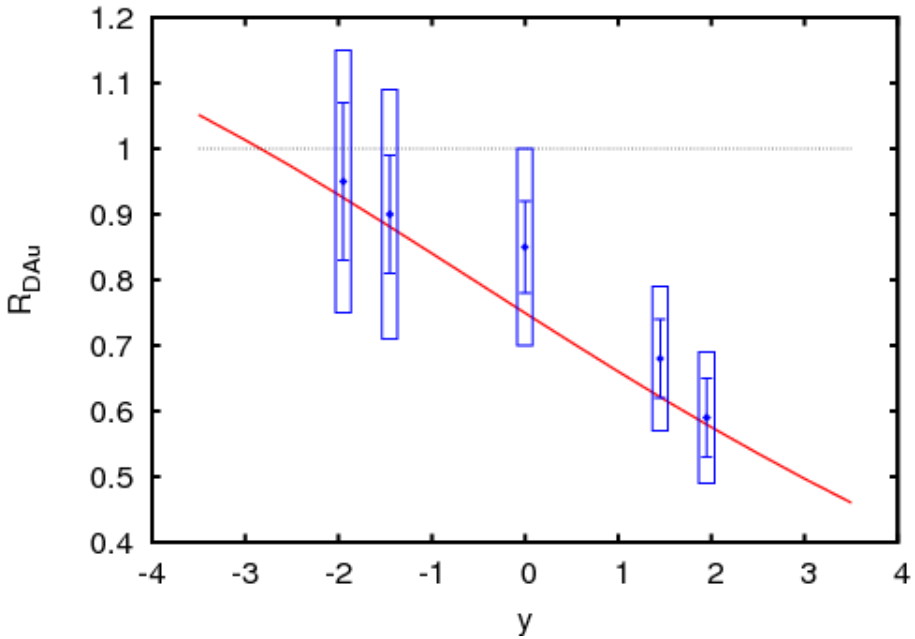
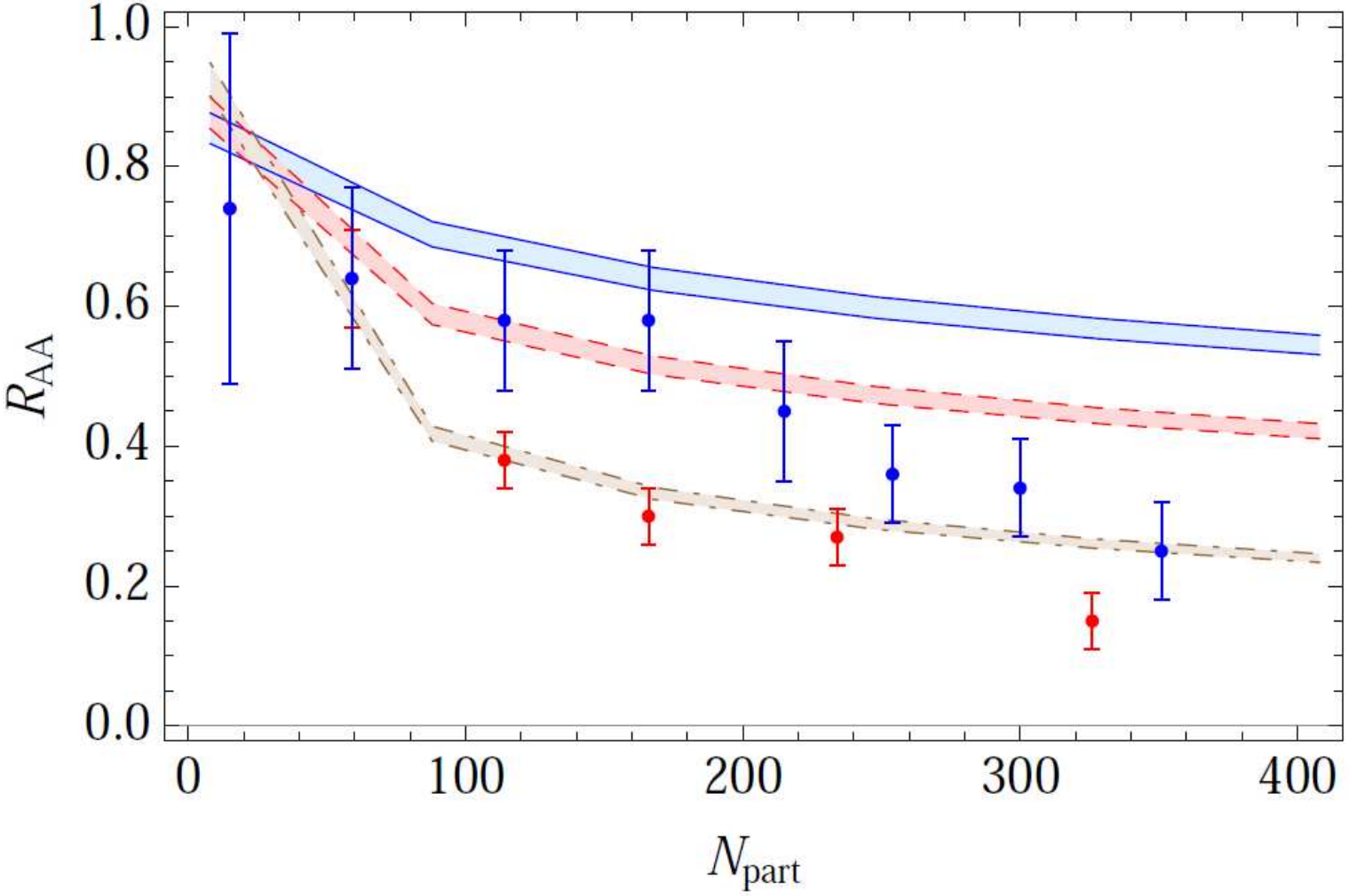
Results: D-Au (2) compared to new $D - Au$ data





PHENIX Collab.: arXiv: 1010.1246

Results: Au-Au (1)



blue: $y = 0$, red: $y = 1.7$, brown: $y = 0$ at LHC

Conclusions

The initial state effects are well described by our saturation model ($D - Au$), while data in $Au - Au$ collisions are overestimated:

Interactions with cold matter are not sufficient to explain experimental data on J/ψ suppression in AA collisions.