Charmonium and open charm production and saturation

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Nuclei as heavy as bulls through collision generate new states of matter

BNL, May 12, 2010

Factorization ?

Hard pQCD:

Factorization $\longrightarrow$ Universal pdf's $\longrightarrow$ Phenomenology

- Factorization is broken if the hard amplitude involves *simultaneous* interactions with more than two partons at a time.

- Coherent scattering: $l_c >> R_A$ (coherence effects start at $l_c \sim R_p$)

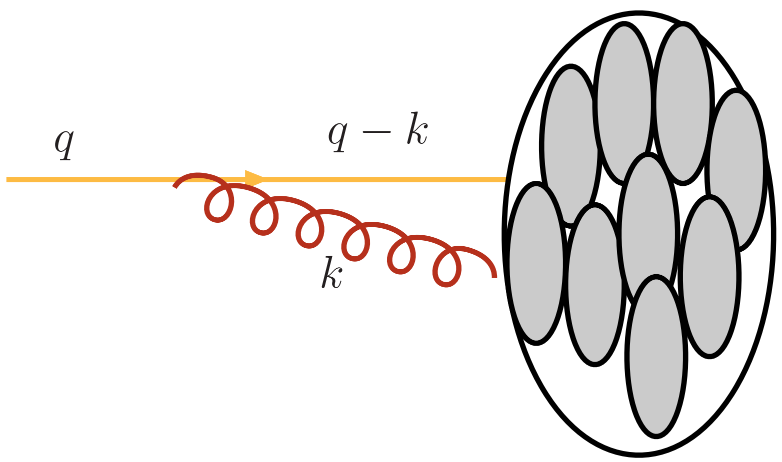
Coherence

Landau-Lifshitz, II §80: “Scattering of waves with large frequencies”

$$d\sigma = \left(\frac{e^2}{mc^2}\right)^2 \overline{\left|\sum e^{-i\mathbf{q}\mathbf{r}}\right|^2} \sin^2\theta \, do. \qquad q\sim 1/\lambda \qquad l_c = \lambda$$

Coherent scattering: $\lambda \gg R \;\Rightarrow qr \ll 1 \;\Rightarrow e^{iqr} = 1$

Incoherent scattering: $\lambda \ll R \;\Rightarrow qr \gg 1 \;\Rightarrow e^{iq(r_a - r_b)} = \delta_{ab}$ Raman (combinational) light scattering



$$l_c = \frac{1}{k_- + (q-k)_- - q_-} \approx \frac{1}{Mx}$$

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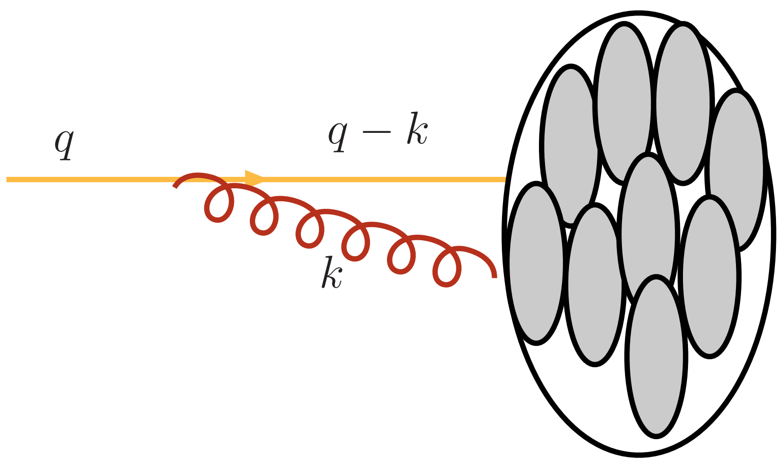

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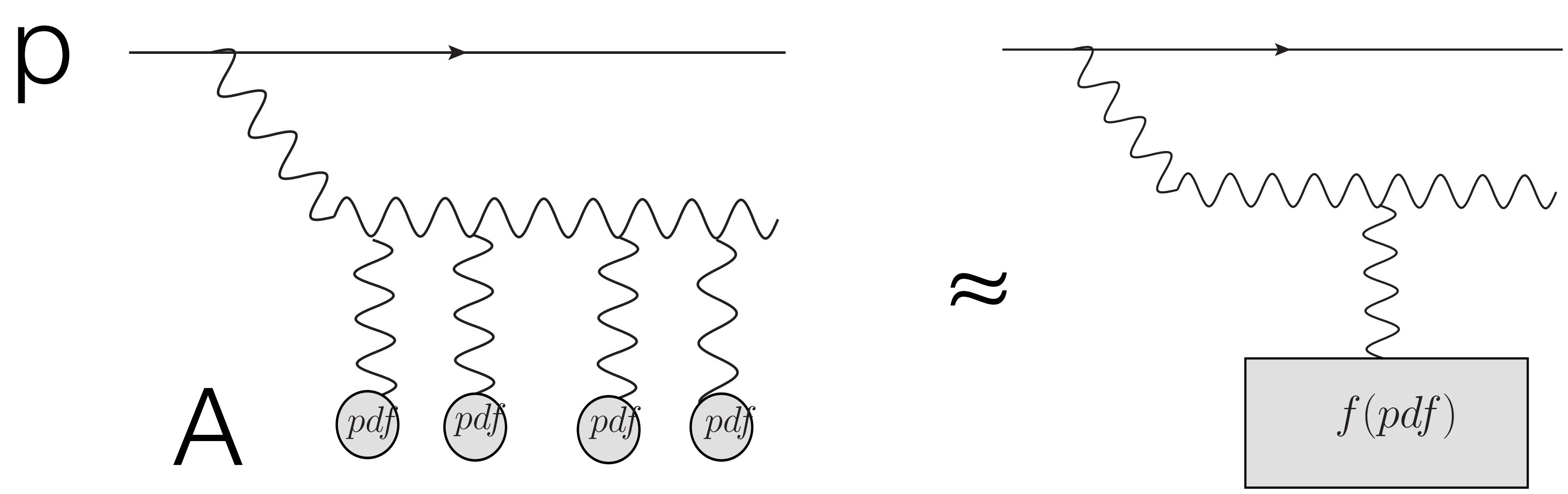
CGC/saturation = implementing the coherence.

Inclusive gluons

Kovchegov, KT, 2001

There is an approximate k_T - factorization (LO). Though no pdf's...

$$\frac{d\sigma^{pA}}{d^2k\ dy} = \frac{C_F}{\alpha_s\,\pi\,(2\pi)^3}\,\frac{1}{\underline{k}^2}\int d^2B\,d^2b\,d^2z\,\nabla_z^2\,n_G(\underline{z},\underline{b}-\underline{B},0)\,e^{-i\underline{k}\cdot\underline{z}}\,\nabla_z^2\,N_G(\underline{z},\underline{b},0).$$



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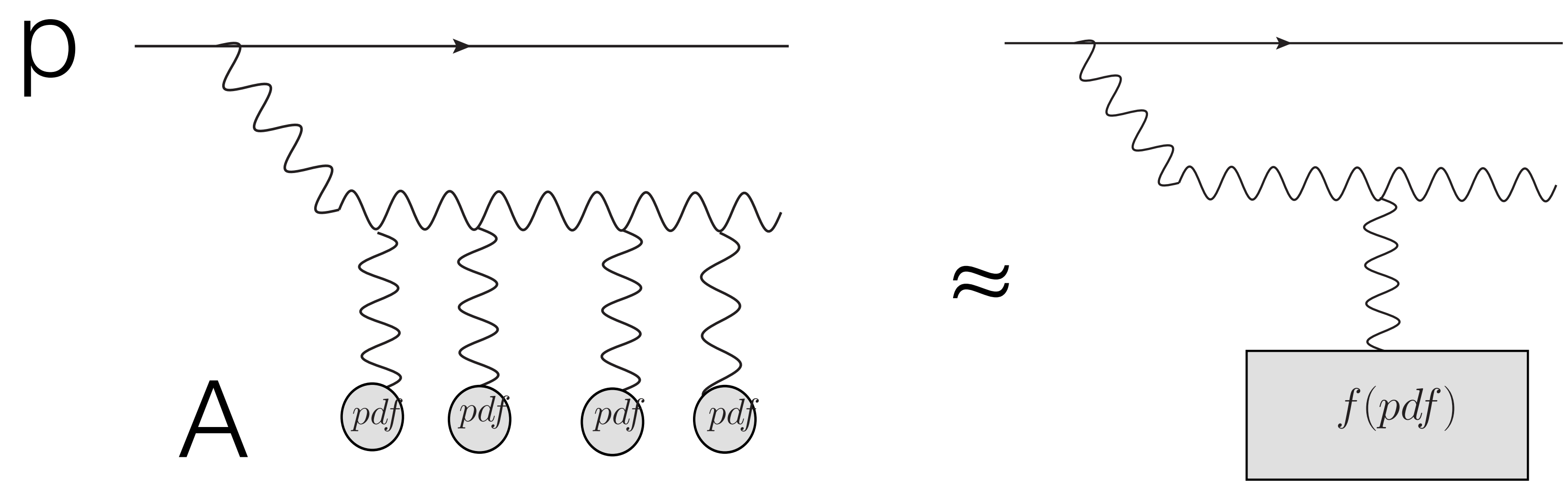
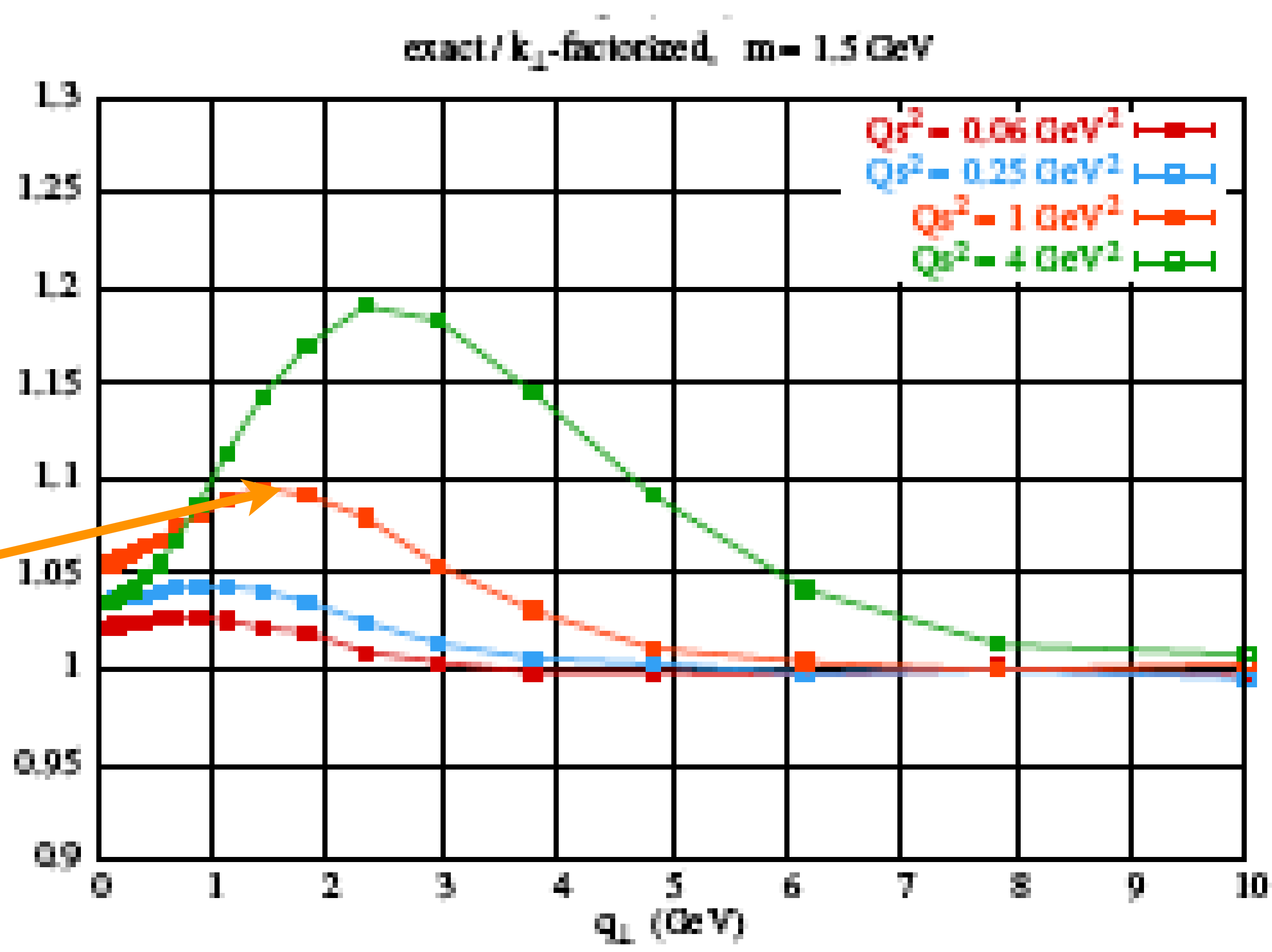


One can trace the origin of the (approximate) factorization in that there is no restriction on the quantum numbers of the product (Spin, Color etc.)

Inclusive c-quark: approx. factorization

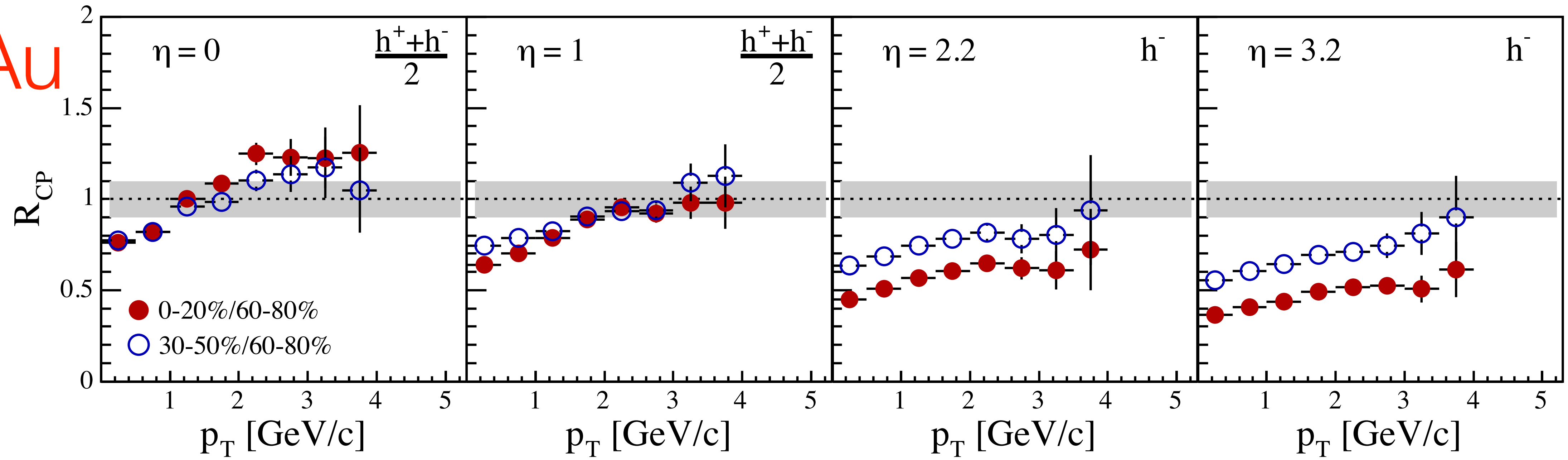


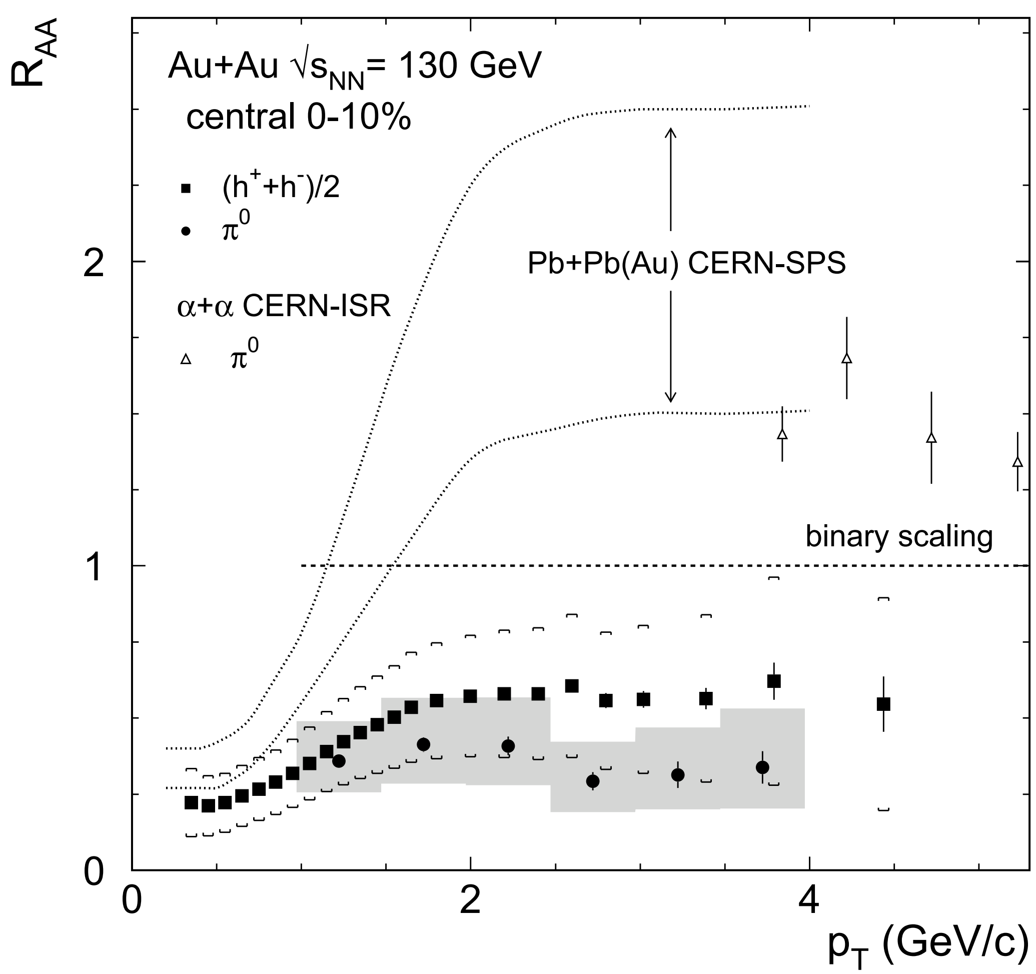
RHIC

Fujii, Gelis, Venugopalan

Phenomenology: light hadrons

dAu





Due to factorization we can infer the size of the cold nuclear matter effect in AA from that in DA

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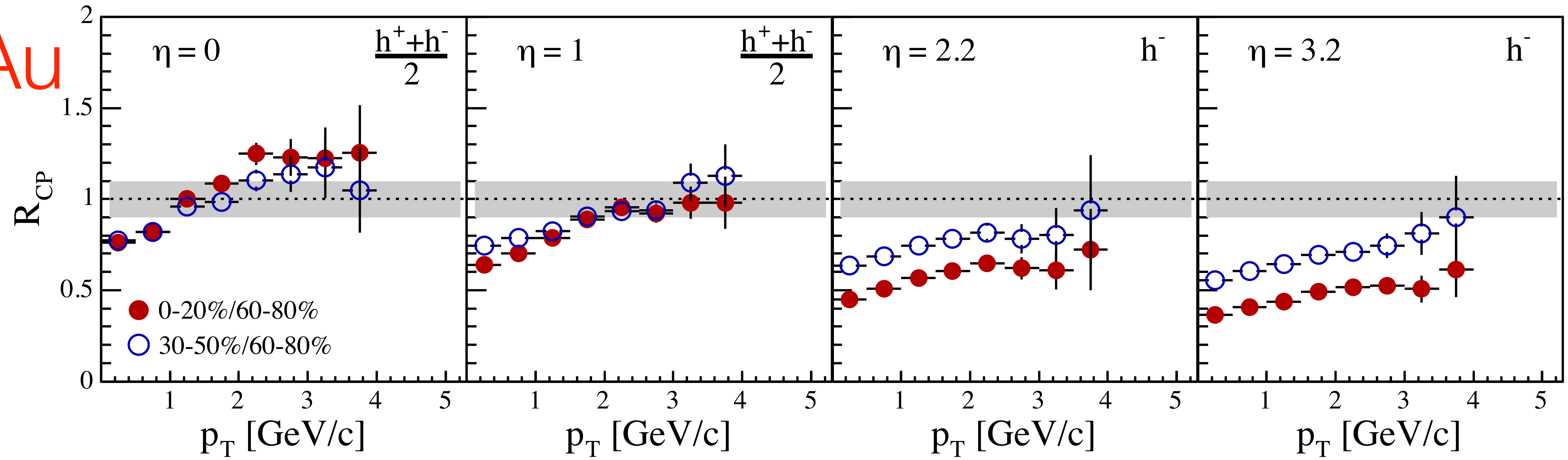
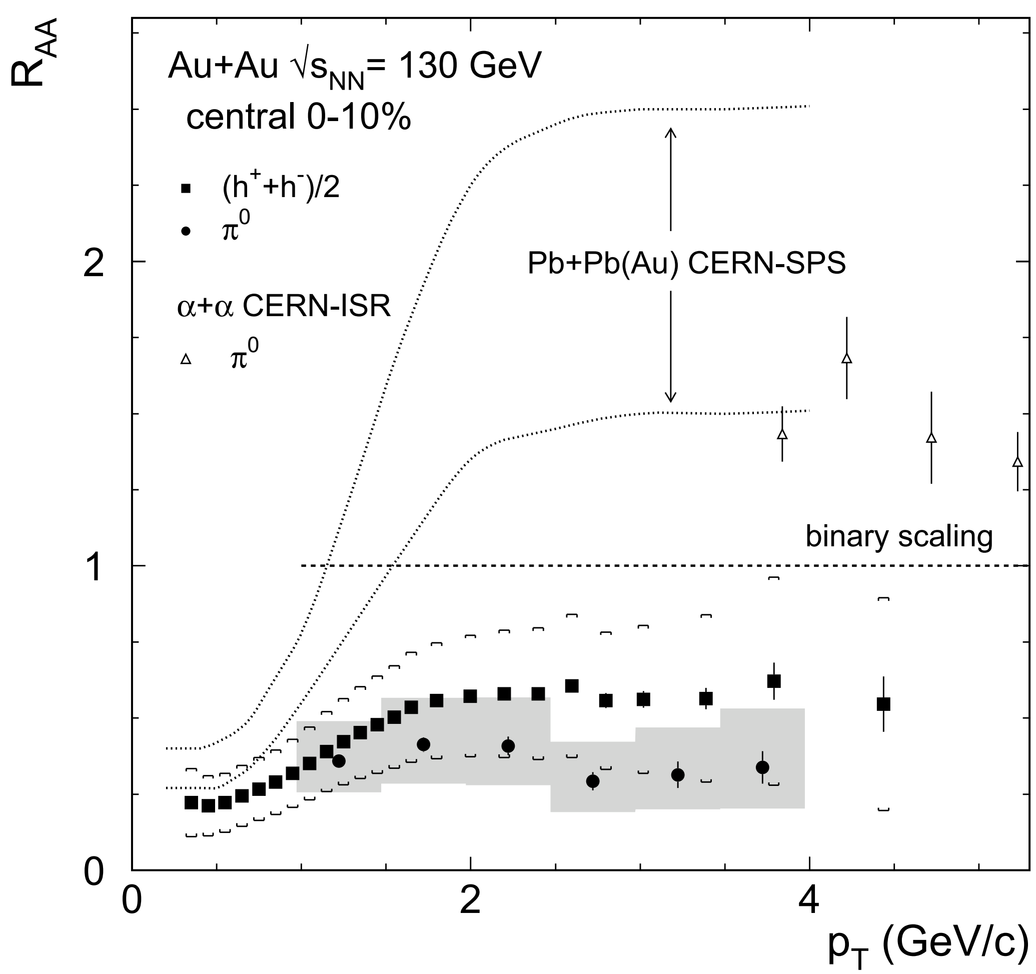


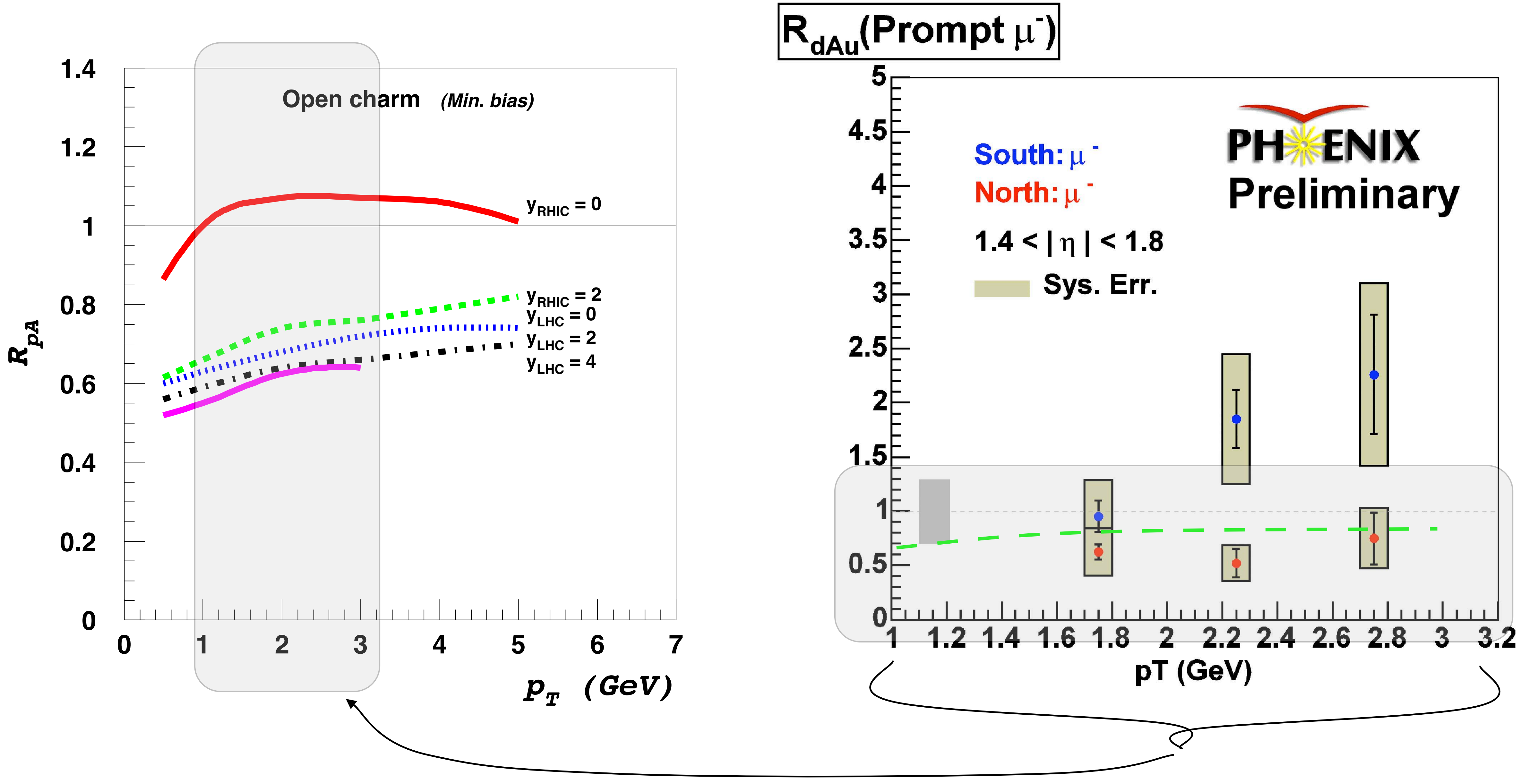


Due to factorization we can infer the size of the cold nuclear matter effect in AA from that in DA

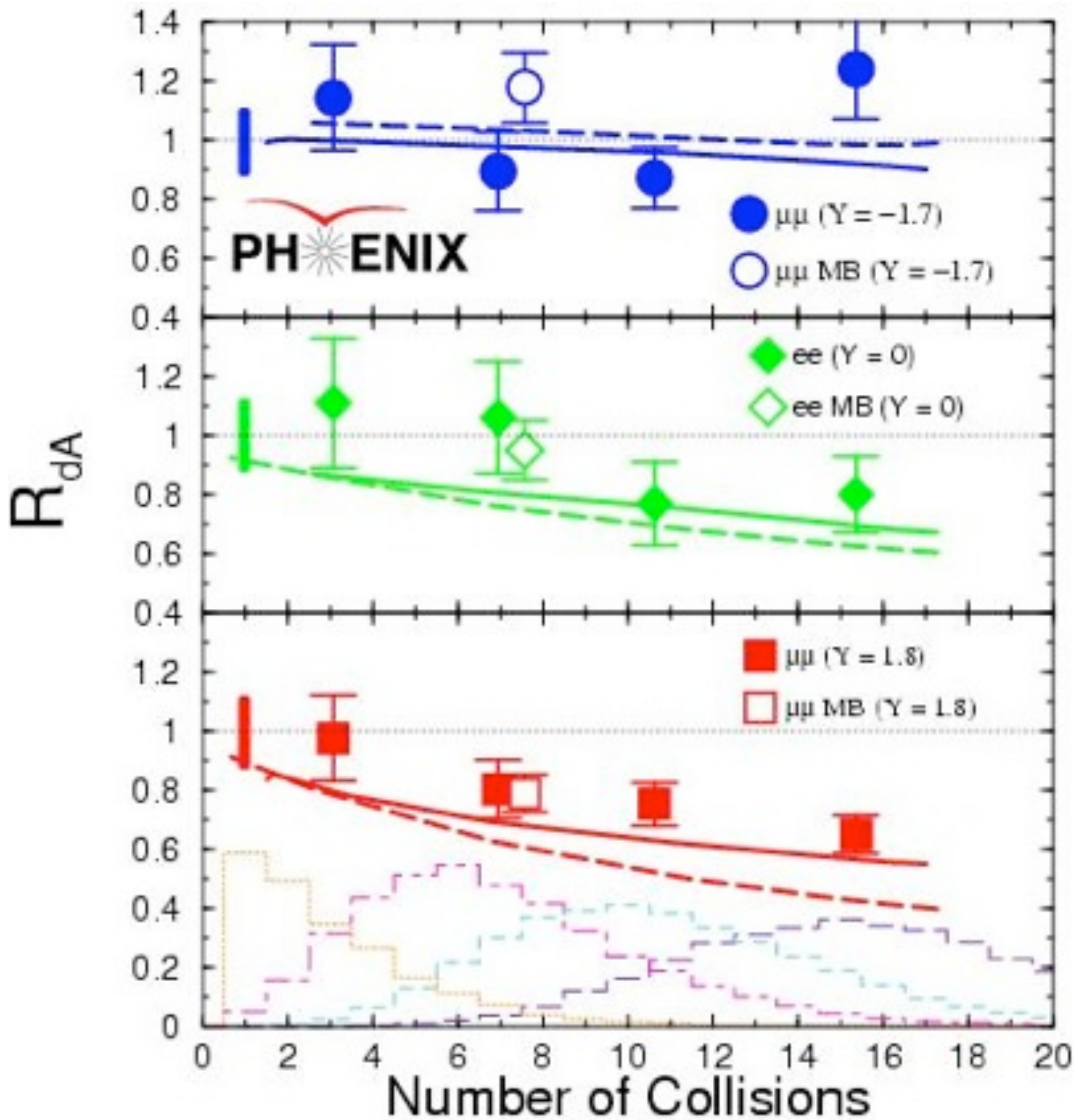
This is true only if there is a factorization between the nuclei!

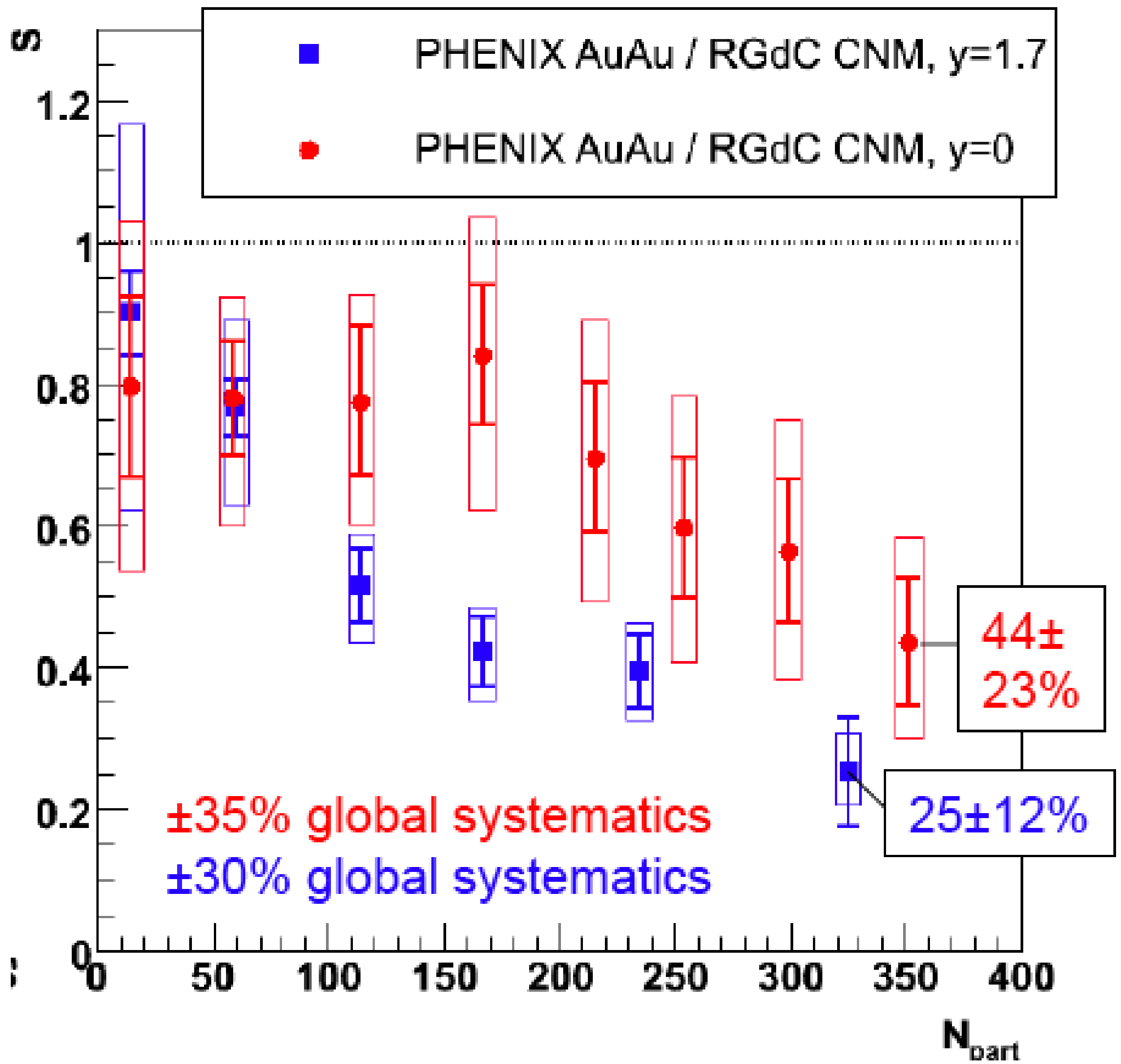
Open charm R_{pA} vs PHENIX data

KT, 2004, 2007



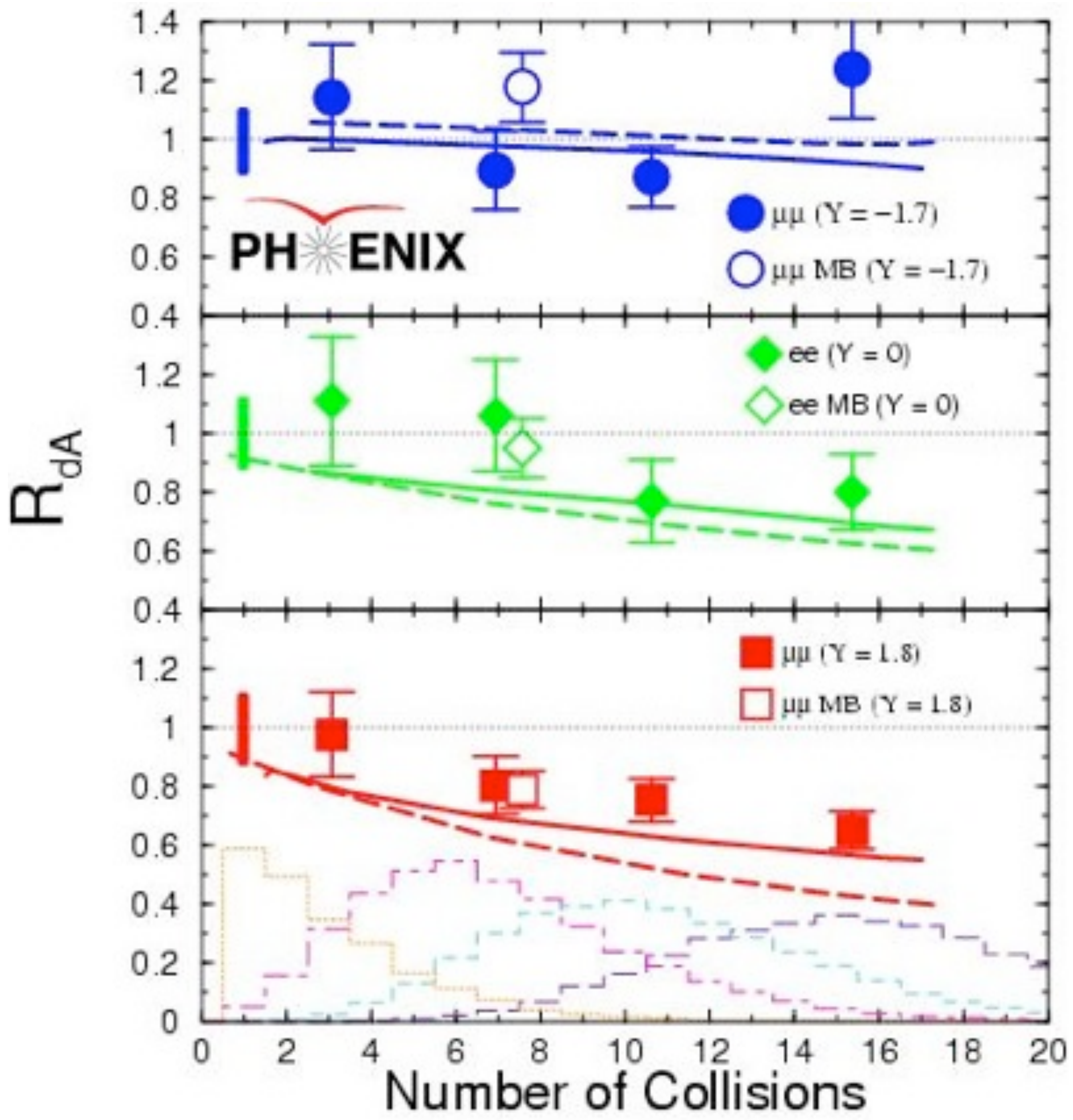
Factorization for J/ψ ?

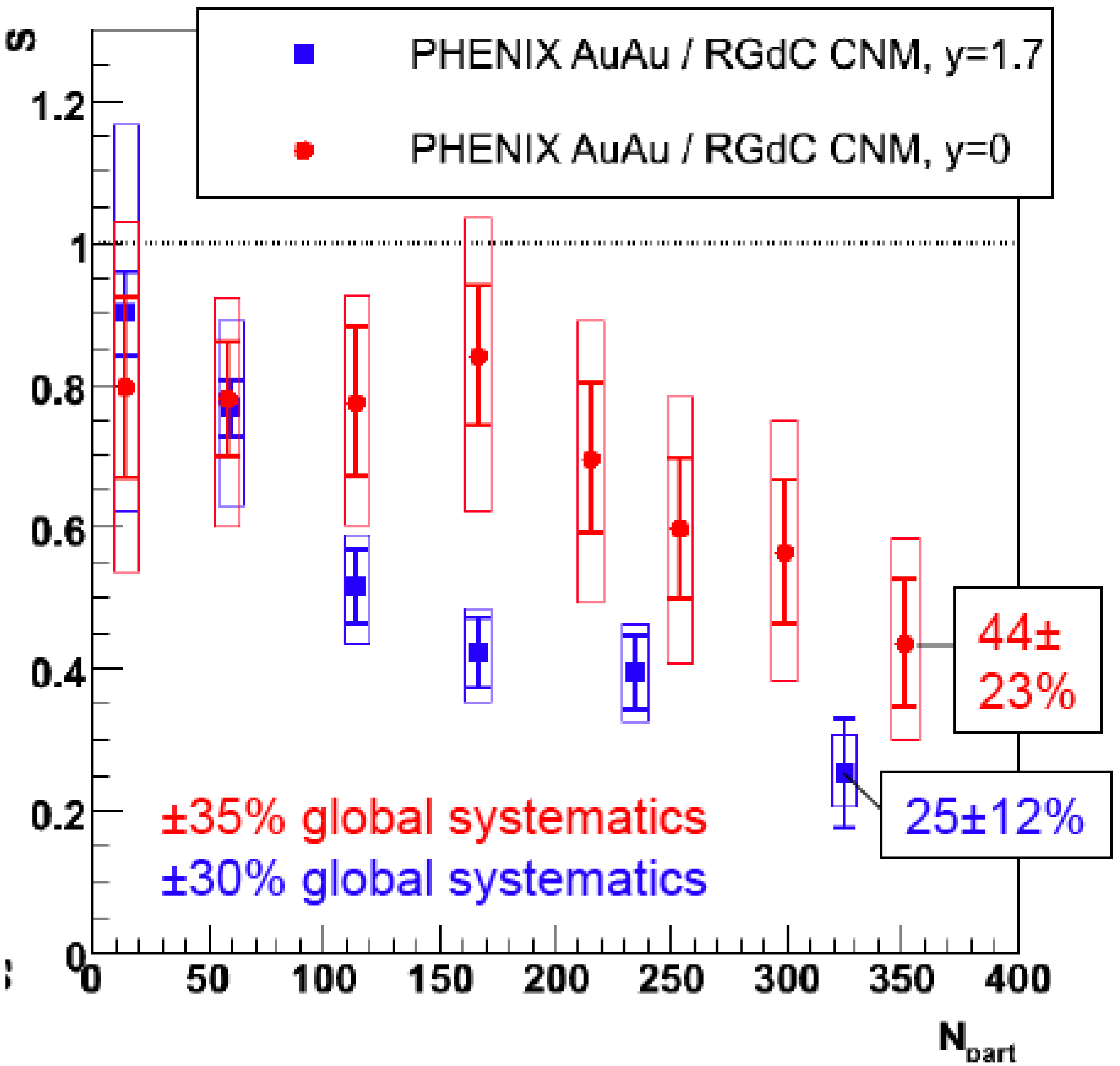




Can we infer the the cold nuclear matter effect in AA from DA?

Factorization for J/ψ ?





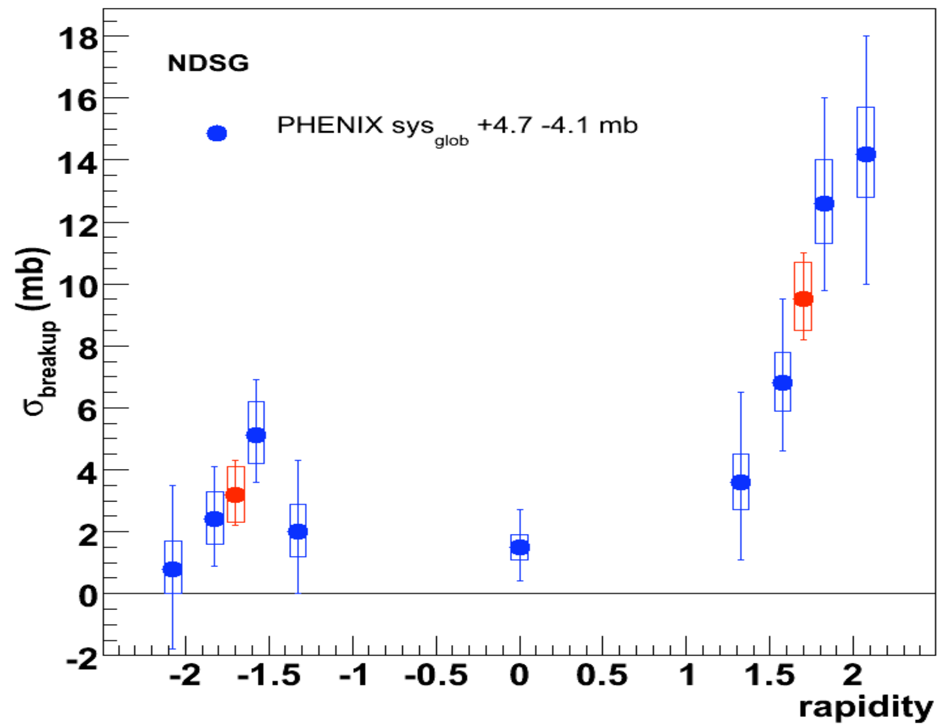
Can we infer the the cold nuclear matter effect in AA from DA?

NO! Because factorization is badly broken!

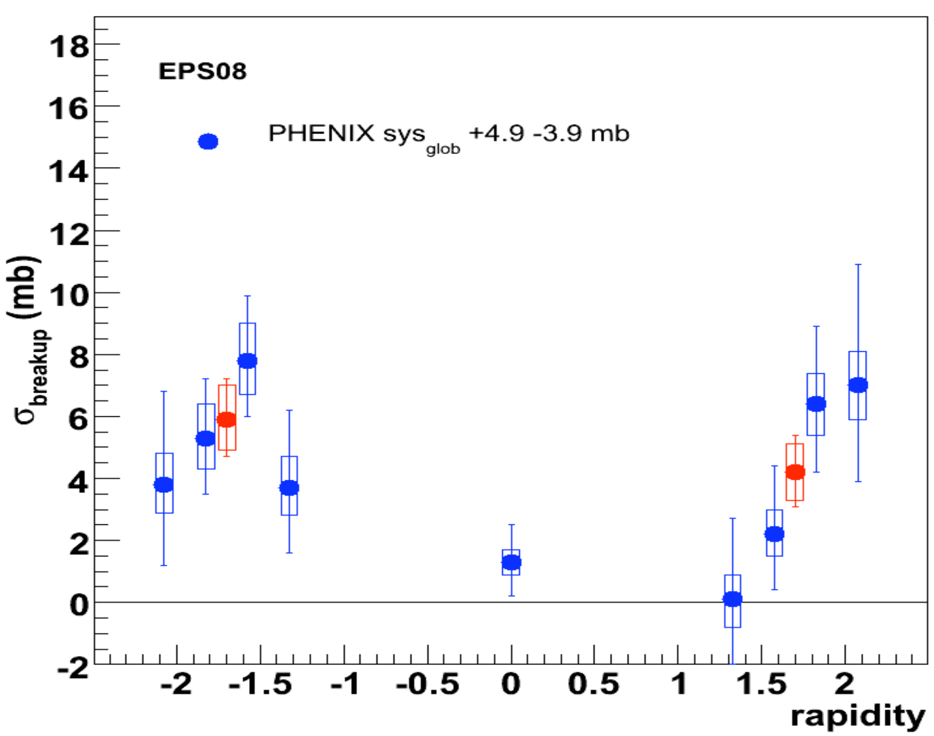
The effective absorption cross sections from fits of Ramona's calculations to PHENIX d+Au R_{CP} data are shown for each shadowing model. 3

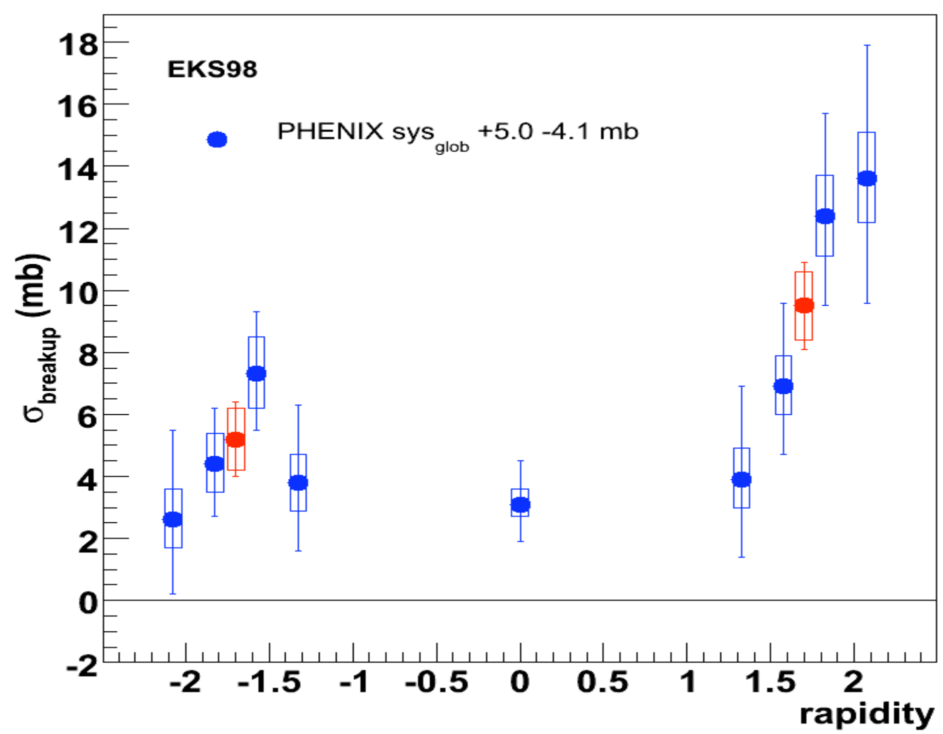
This is **not** an attempt to extract physics from the d+Au R_{CP}! This is just a parameterization of the data that is independent at each rapidity.

The red points are the averages at y = -1.7 and +1.7.

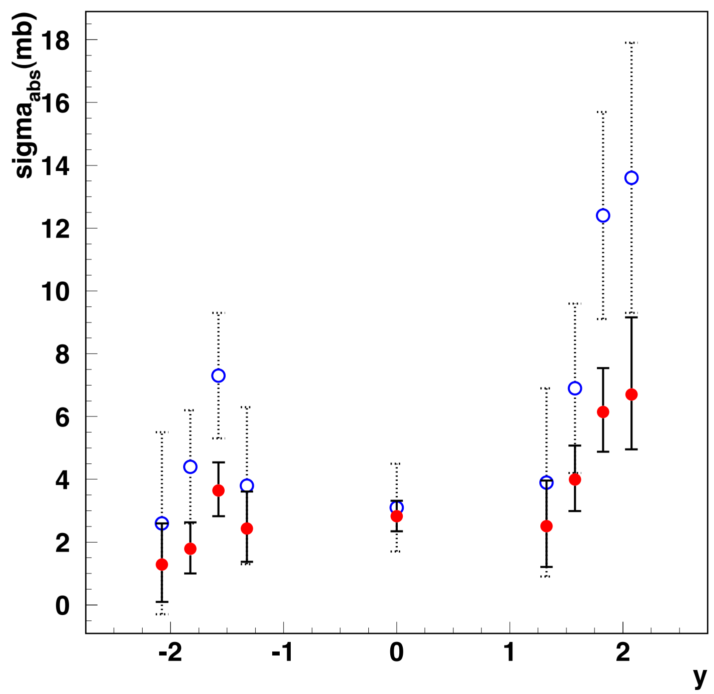


Stolen from T. Frawley

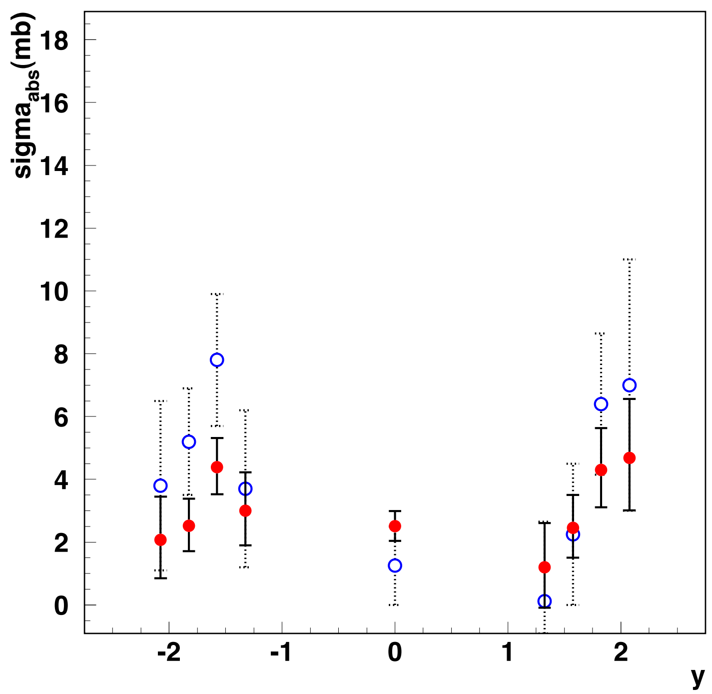




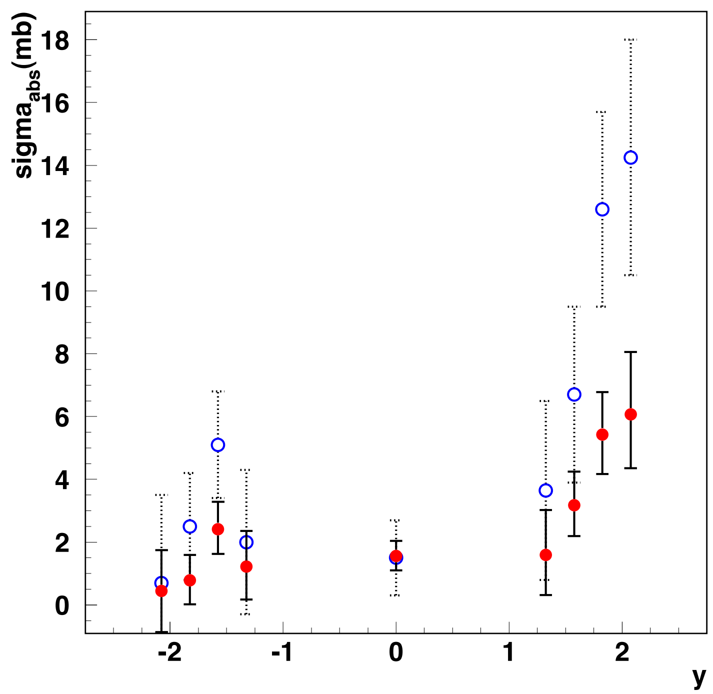
Similarly, according to Ferreiro, Fleuret, Lansberg and Rakotozafindrabe:



(a) EKS98



(b) EPS08



(c) nDSg

Production of J/ψ: relevant time scales

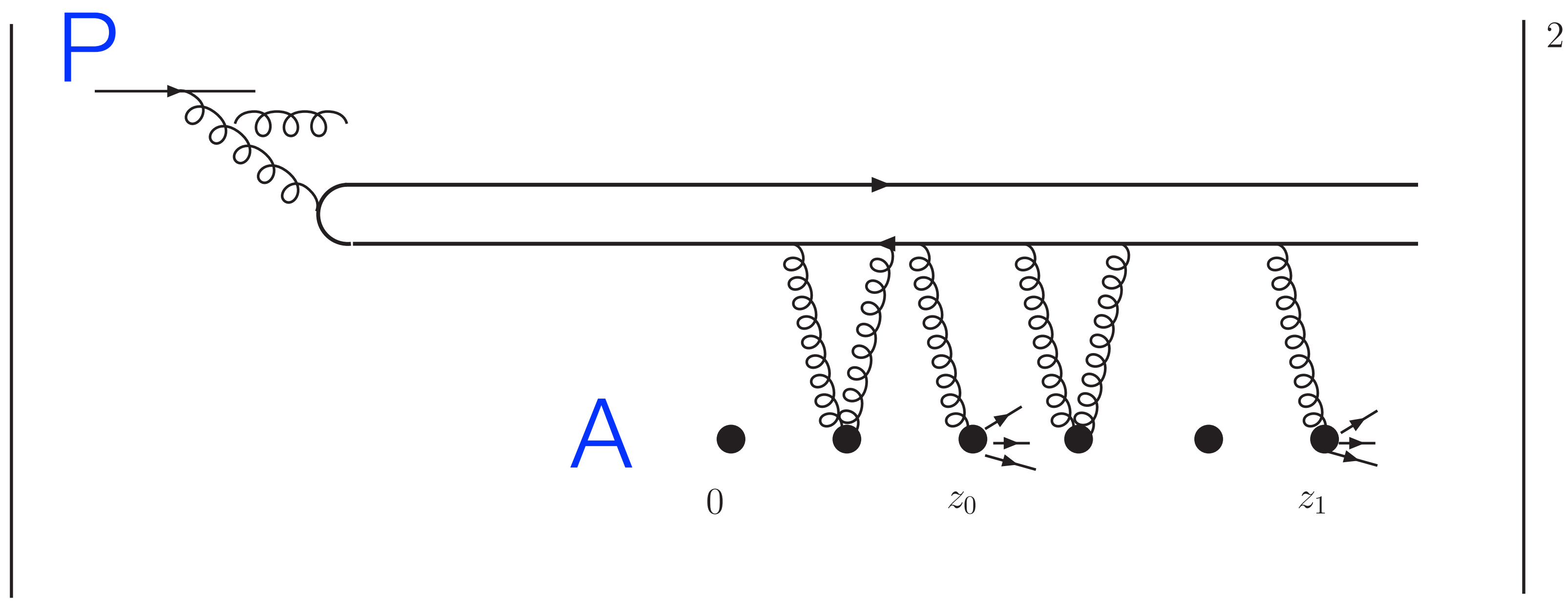
Pre-hadron cc production time $\tau_P = l_c/c = 7\, e^y \,\mathrm{fm}$

J/ψ wave function formation time $\tau_F = \dfrac{2\, M_\psi}{M_{\psi'} - M_\psi} l_c = 42\, e^y \,\mathrm{fm}$

Hierarchy of time scales: $\tau_F >> \tau_P >> \tau_{int}$

Production of the q-anti-q pair

Kopeliovich et al , 2001
KT 2004;
Blaizot, Gelis,
Venugopalan 2004;
Kovchegov, KT 2006



$$\frac{d\sigma_{in}(pA)}{dY\, d^2k\, d^2b} = x_1 G(x_1, m_c^2) \int d^2r \int d^2r'\, \Phi_G(m_c, r, r', z=1/2)\, e^{i\frac{1}{2}(\underline{r}'-\underline{r})\cdot\underline{k}}$$

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

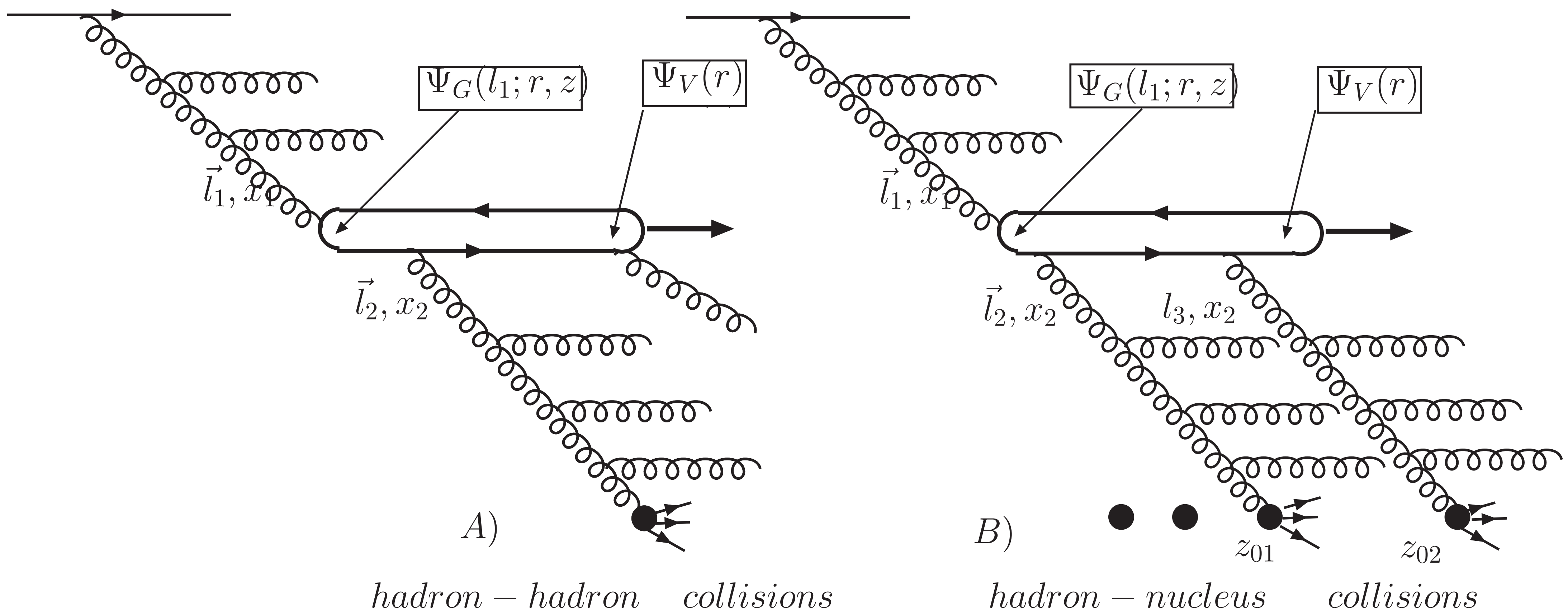
$$\times \sum_{n=0}^{\infty} \int_{z_0}^{2R_A} d\, z_1 \ldots \int_{z_{n-2}}^{2R_A} dz_{n-1} \int_{z_{n-1}}^{2R_A} dz_n\, \rho^n\, \hat{\sigma}_{in}^n(x_2, r, r')$$

$$(\alpha_s^2 A^{1/3})^n$$

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

Production of J/ψ: pp vs pA

Kharzeev, KT,2005
Kharzeev, Levin, Nardi, KT,2009

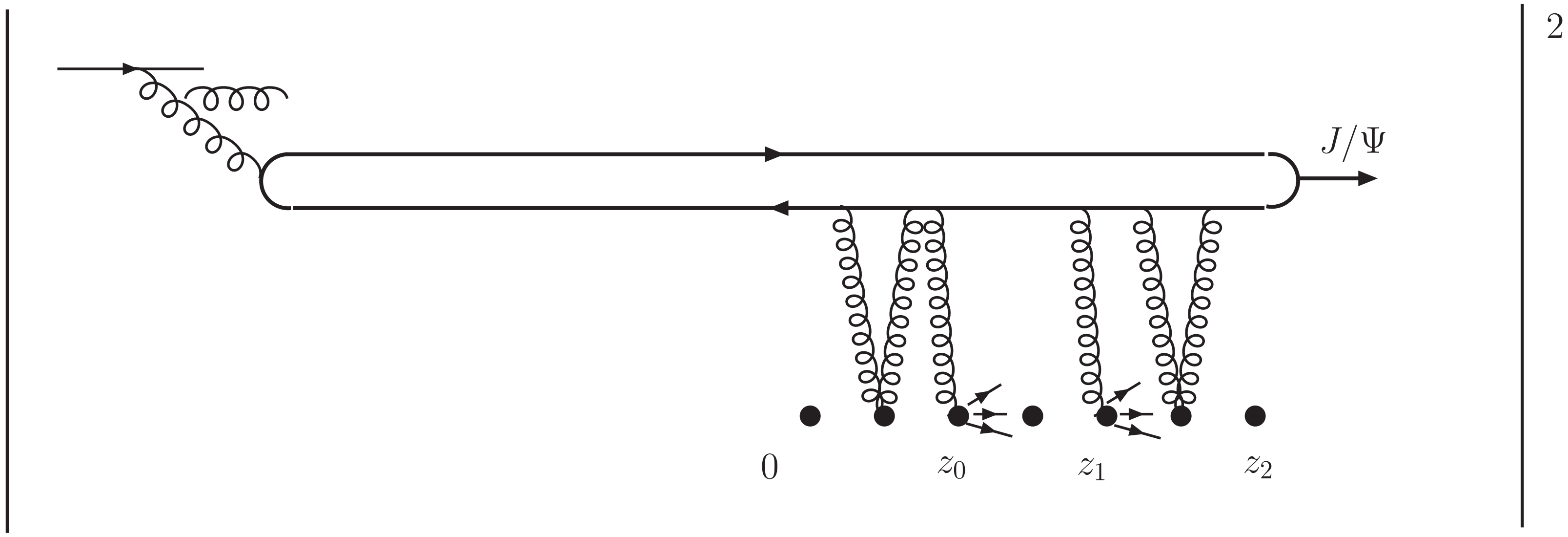


$$\alpha_s^3 A^{1/3} = \alpha_s(\alpha_s^2 A^{1/3}) \sim \alpha_s$$

$$\alpha_s^4 A^{2/3} = (\alpha_s^2 A^{1/3})^2 \sim 1$$

This mechanism is dominant for central collisions

Propagation of c-anti-c through nucleus



Only **even** number of interactions with the nucleus are allowed.

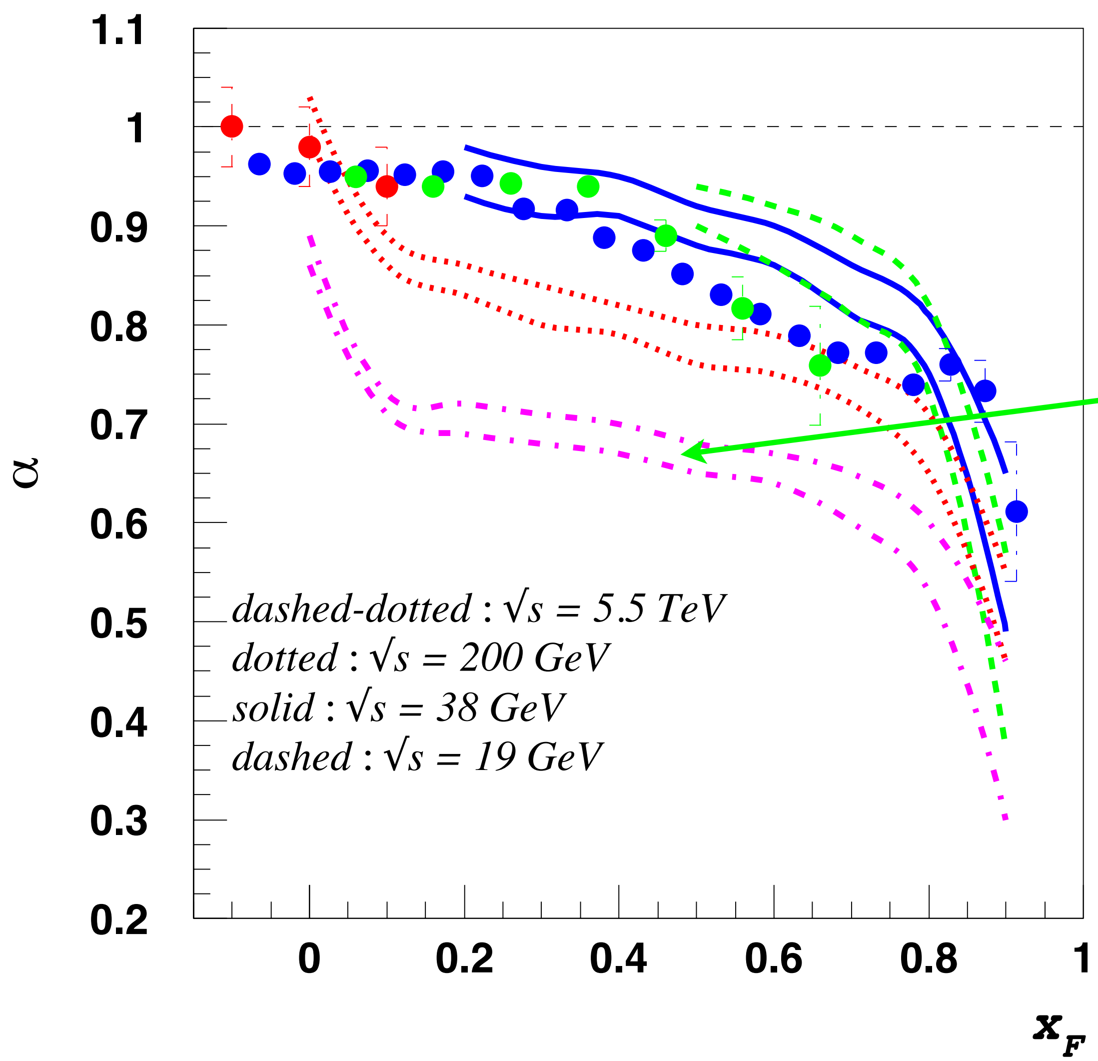
$$\frac{d\sigma_{in}(pA)}{dY\,d^2b} = C_F\,x_1 G(x_1, m_c^2)\times\int_0^{2R_A}\rho\,\hat{\sigma}_{in}(x_2,r,r')\,d\,z_0\int d^2\,r\,\Psi_G(l_1,r,z=1/2)\,\Psi_V(r)\otimes\int d^2r'\Psi_G(l_1,r',z=1/2)\,\Psi_V(r')$$

$$\times\left(e^{-(\sigma(x_2,r^2)+\sigma(x_2,r'^2))\,\rho\,2\,R_A}\sum_{n=0}^{\infty}\int_{z_0}^{2R_A}d\,z_1\int_{z_1}^{2R_A}dz_2\ldots\int_{z_{2n}}^{2R_A}dz_{2n+1}\,\rho^{2n+1}\,\hat{\sigma}_{in}^{2n+1}(x_2,r,r')\right)$$

$$\frac{1}{2}\left\{\exp\left(-\sigma\left(x_2,(\underline{r}-\underline{r}')^2\right)\,\rho\,2R_A\right)+\exp\left(-(\sigma(x_2,r)+\sigma(x_2,r')+\hat{\sigma}_{in}(x_2,r,r'))\,\rho\,2R_A\right)-2\,\exp\left(-(\sigma(x_2,r)+\sigma(x_2,r'))\,\rho\,2R_A\right)\right\}$$

Breakdown of x_F-scaling

Kharzeev, KT , 2005



$\sigma_{pA}=A^{\alpha}\sigma_{pp}$

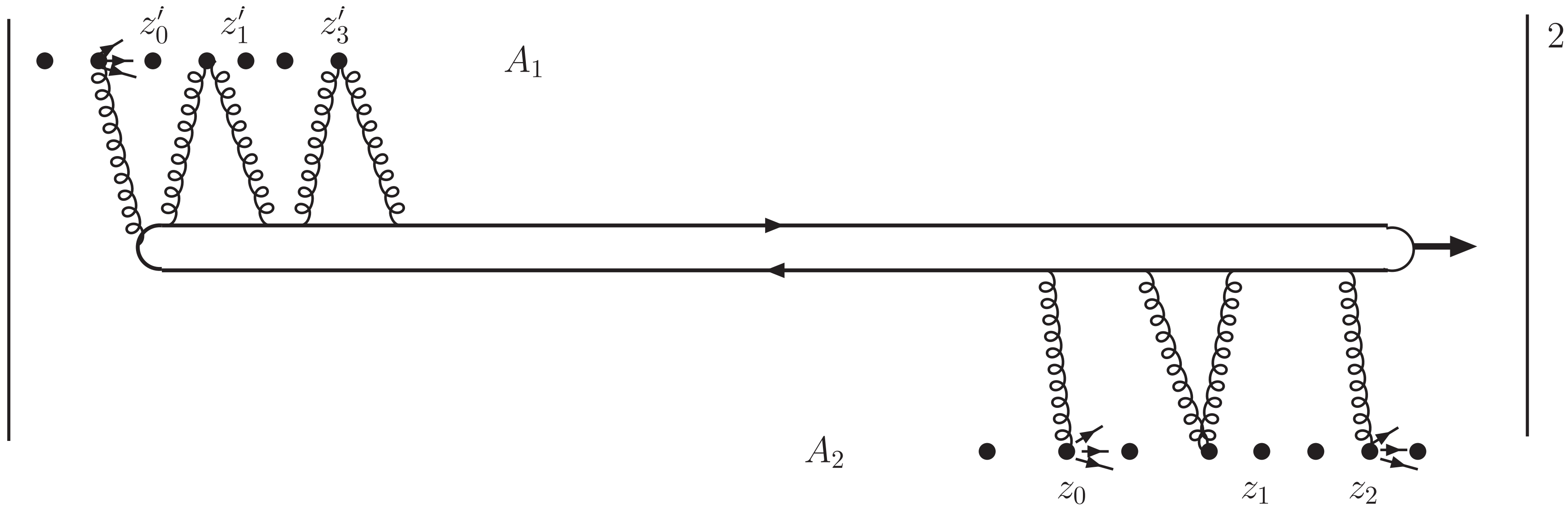
α=2/3 plateau: black disk regime.

Additional assumptions:

- J/ψ is non-relativistic. Relativistic correction depends on m but not on energy - included in prefactor.
- Parametrically small corrections due to the real part and off-diagonal matrix elements are neglected.

Production of J/ψ: AA

Kharzeev, Levin, Nardi, KT,2009



We have to sum over all **odd** number of interactions with both nuclei

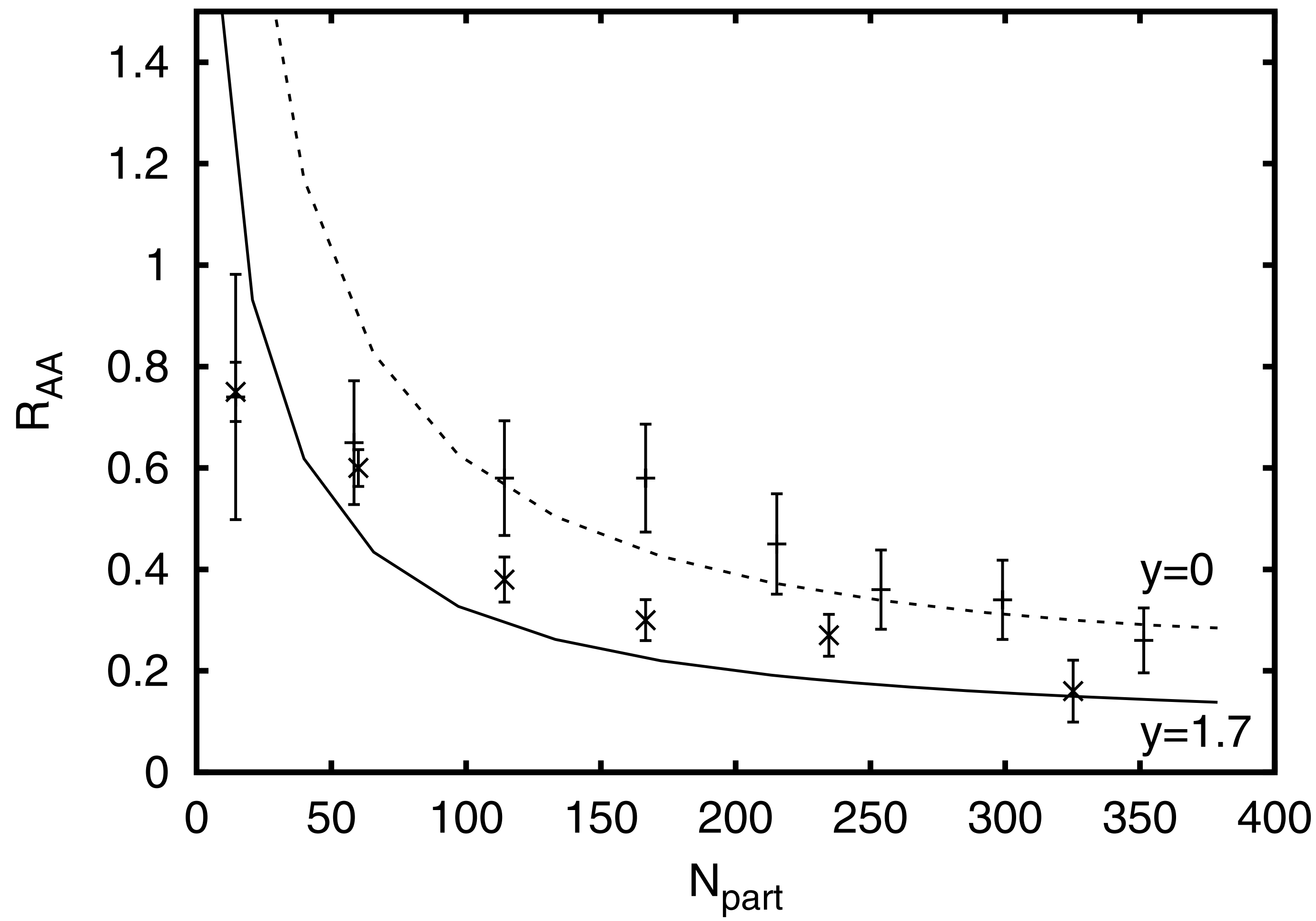
$$\frac{dN^{AA}(Y,b)}{dY} = C\frac{dN^{pp}(Y)}{dY} \int d^2 s\; T_{A_1}(\underline{s})\, T_{A_2}(\underline{b}-\underline{s})\; \left(Q^2_{s,A_1}(x_1,\underline{s}) \;+\; Q^2_{s,A_2}(x_2,\underline{b}-\underline{s})\right)\, \frac{1}{m_c^2}$$
$$\times \int_0^\infty d\zeta\; \zeta^9\; K_2(\zeta)\;\; \exp\left(-\frac{\zeta^2}{8m_c^2}\;\left(Q^2_{s,A_1}(x_1,\underl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

Fitted to Phenix DAu data

$$x_1 \;=\; \frac{m_{J/\Psi,t}}{\sqrt{s}}\, e^{-Y}\,, \quad x_2 \;=\; \frac{m_{J/\Psi,t}}{\sqrt{s}}\, e^{Y}$$

Cold J/ψ suppression

Kharzeev, Levin, Nardi, KT,2009



- Our results agree reasonably well with the data.
- Important corrections to be taken into account:
  - ✓ Finite coherence length effects $l_c \sim R_A$
  - ✓ Contribution of a conventional process: $A+A \rightarrow J/\psi+g$
- This R_{AA} does not include a suppression by plasma.

Summary

I discussed hadron production in nuclear collisions at high energies: Generally, traditional factorization schemes are broken, although sometimes they approximately hold.

I showed that J/ψ production mechanism in pp and pA/AA collisions is different due to strong coherence effects. Factorization is strongly violated.

We are convinced, that most of J/ψ suppression in AA is a cold nuclear matter effect.