CGC effects on J/ψ production

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based on work with D. Kharzeev, G. Levin and M. Nardi

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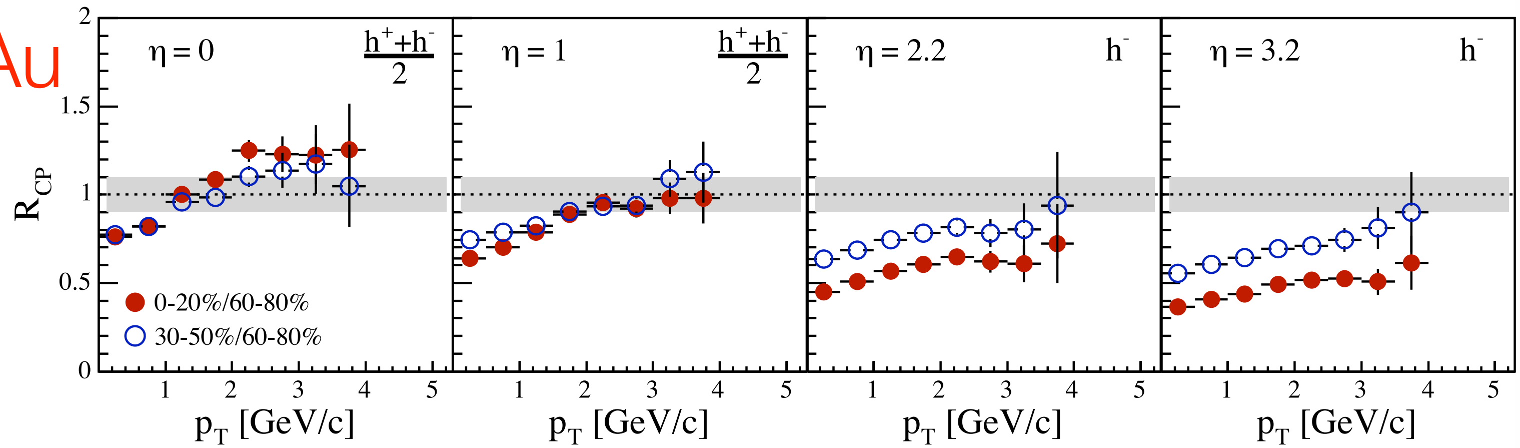
Nuclei as heavy as bulls through collision generate new states of matter

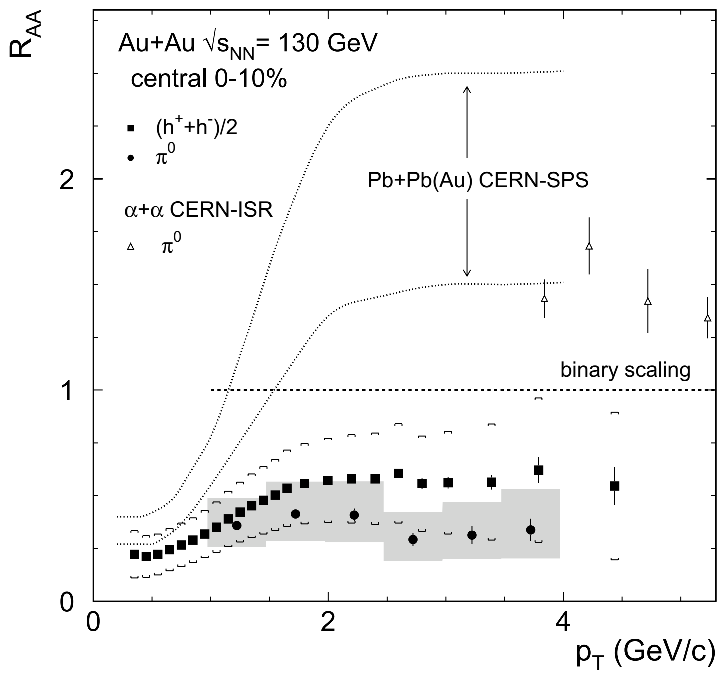
26th Winter Workshop on Nuclear Dynamics
Jan.2-9 2010 Ocho Rios, Jamaica

Introduction I

Inclusive light hadron and open charm production at √s=200 GeV

dAu





Conclusion: at y=0 there are no *"cold nuclear matter"* effects that produce suppression in inclusive q and G production.

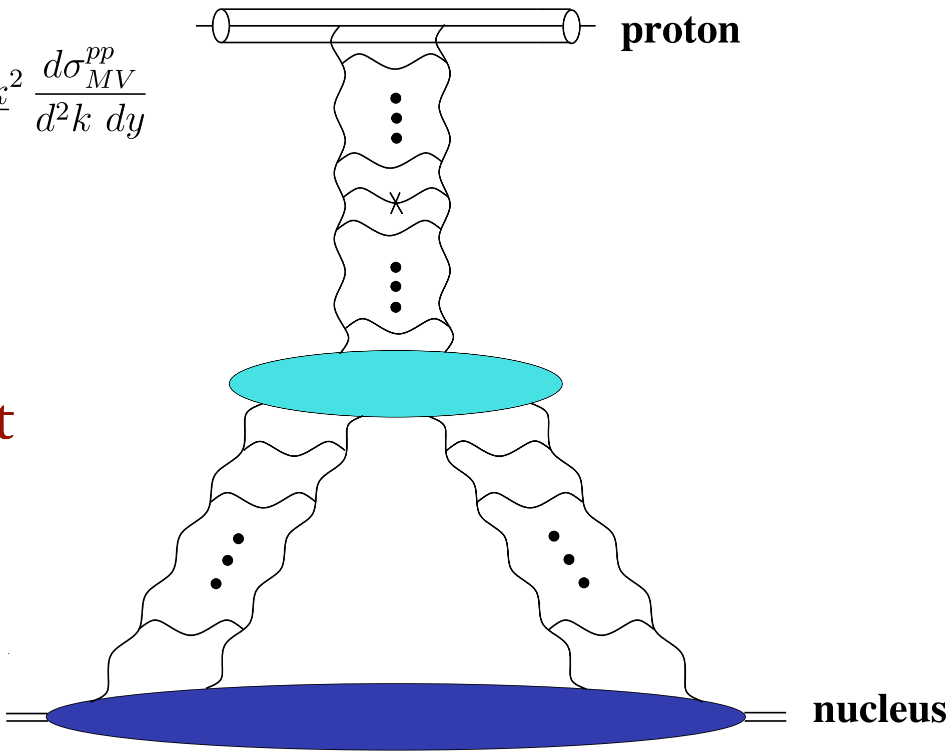
BUT: This is true only if there is a factorization between the nuclei!

Kovchegov, KT, 2001

Theoretical support: an <u>approximate</u> k_T - factorization holds in G and light q production.

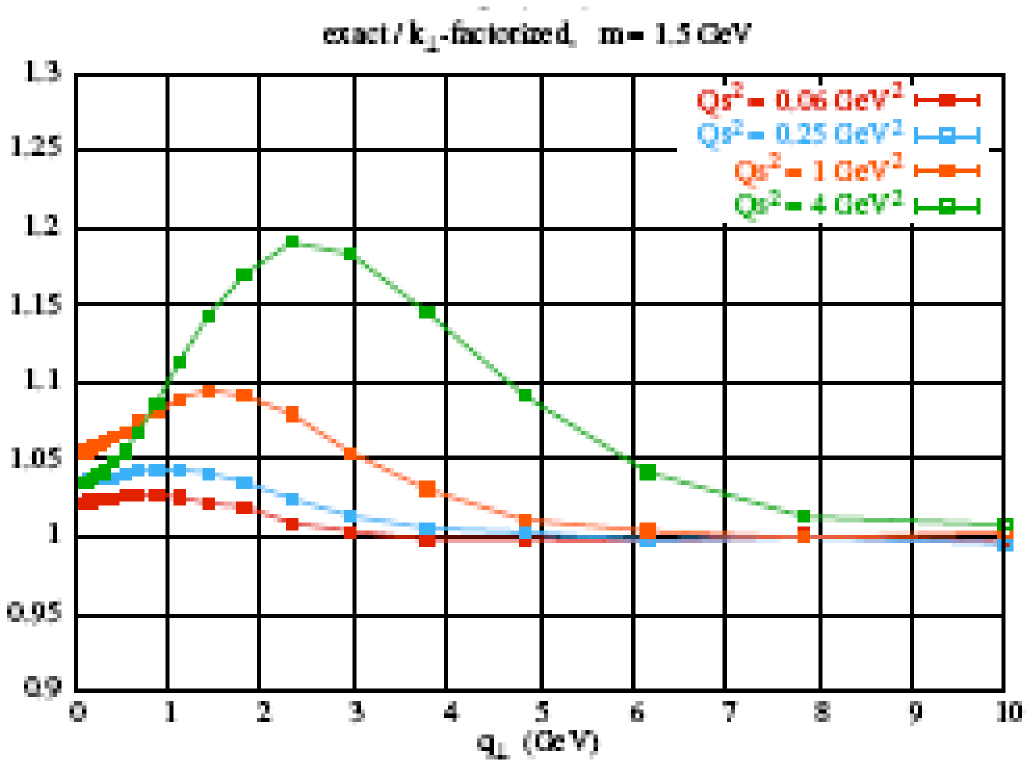
$$\frac{d\sigma^{pA}}{d^2k\ dy} = \frac{C_F}{\alpha_s\,\pi\,(2\pi)^3}\,\frac{1}{\underline{k}^2}\int d^2B\,d^2b\,d^2z\,\nabla_z^2\,n_G(\underline{z},\underline{b}-\underline{B},0)\,e^{-i\underline{k}\cdot\underline{z}}\,\nabla_z^2\,N_G(\underline{z},\underline{b},0).$$

$$\int d^2k\,\underline{k}^2\,\frac{d\sigma^{pA}_{MV}}{d^2k\ dy} = A\int d^2k\,\underline{k}^2\,\frac{d\sigma^{pp}_{MV}}{d^2k\ dy}$$



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.)

Production of the q-anti-q pair: pA

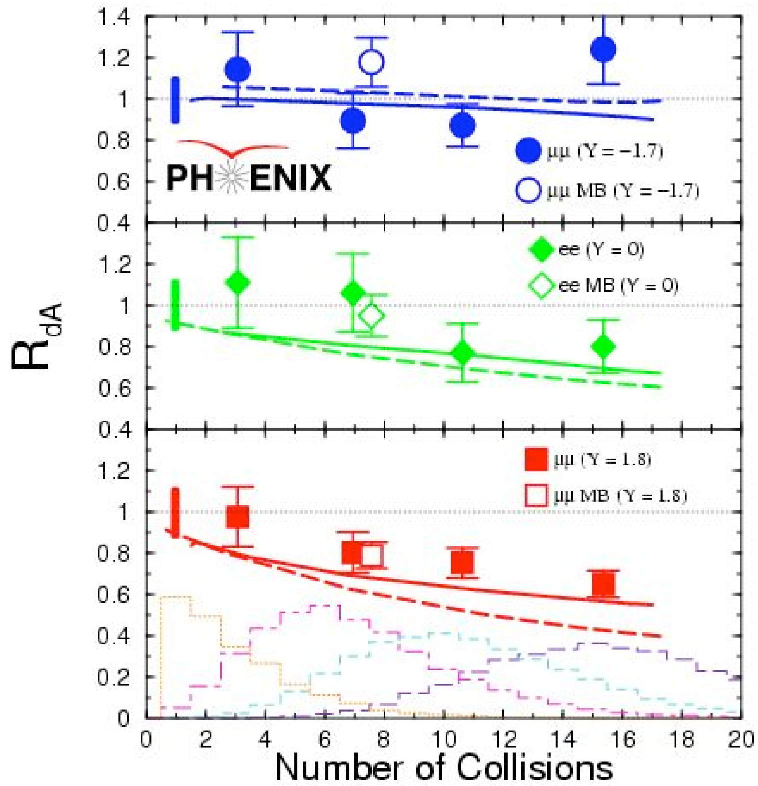


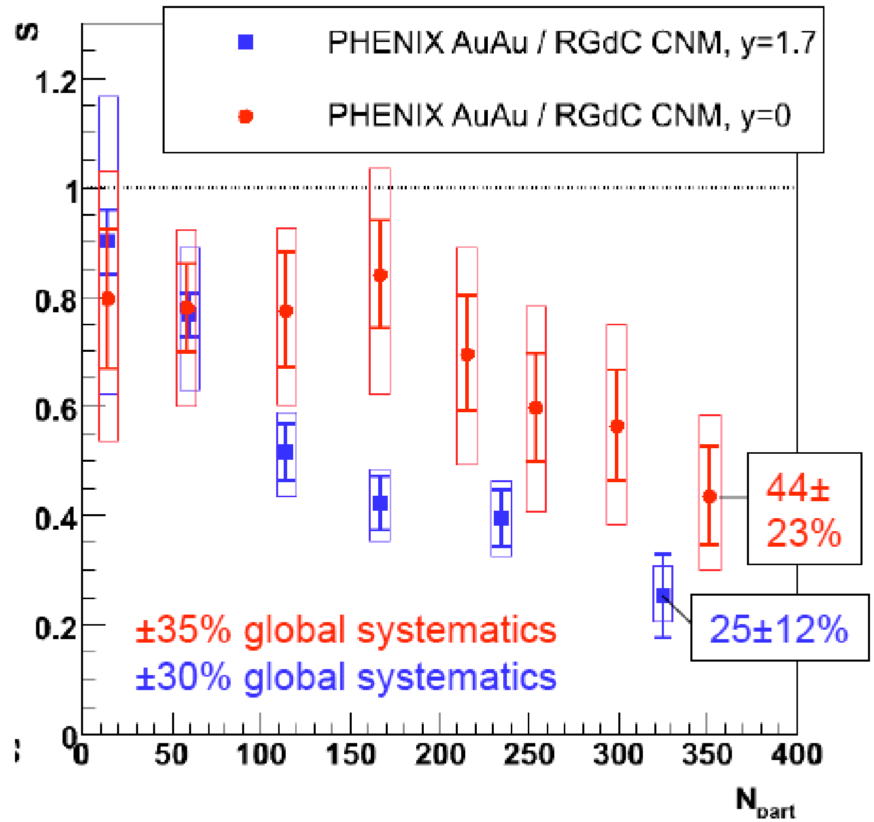
Fujii, Gelis, Venugopalan

k_T-factorization is broken down

Introduction II

Inclusive J/ψ production at √s=200 GeV





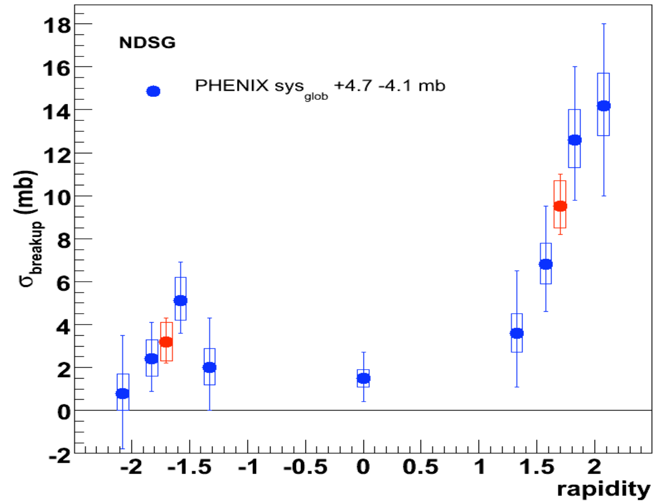
Conclusion: at y=0 the *"cold nuclear matter"* effects are insufficient to produce the observed suppression in J/ψ inclusive production **WRONG!**

Because factorization is badly broken in J/ψ production in pA and AA collisions

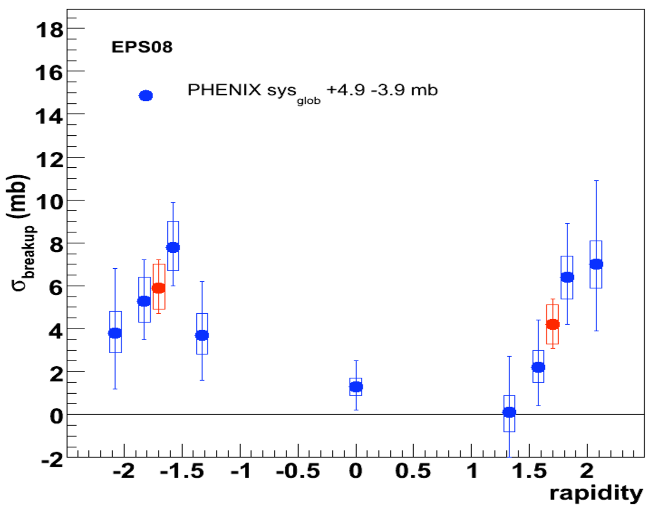
The effective absorption cross sections from fits of Ramona's calculations to PHENIX d+Au R_{CP} data are shown for each shadowing model. 3

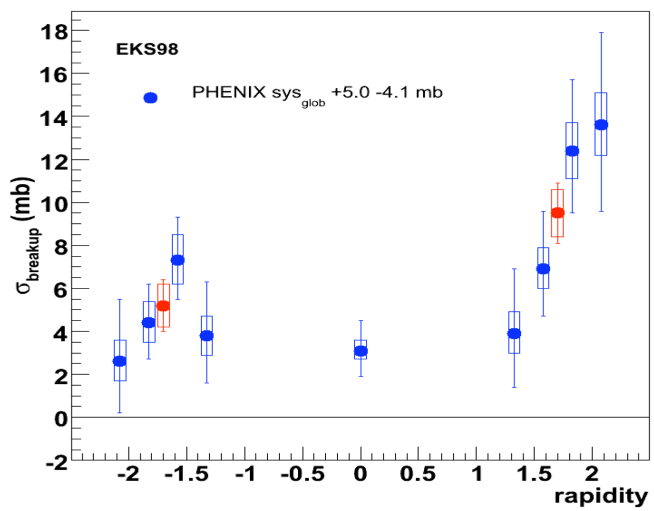
This is **not** an attempt to extract physics from the d+Au R_{CP}! This is just a parameterization of the data that is independent at each rapidity.

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

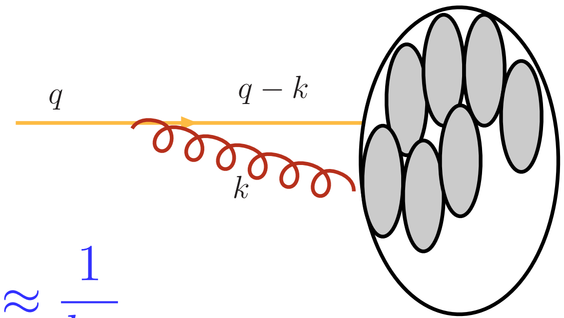


Stolen from T. Frawley





What breaks factorization? Coherence.



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

$$x = \frac{k_-}{p_-} \qquad l_c = \frac{1}{Mx}$$

1) $l_c >> R_A$ coherent scattering: all nucleons participate in scattering *simultaneously.*

2) $l_c << R_A$ incoherent scattering: every nucleon acts as independent scattering center.

Coherence in E&M

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

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

Coherent scattering:

If λ>>R ⇒ qr<<1 ⇒ Exp(i q r)=1 All scattering centers equally contribute 1.

Incoherent scattering:

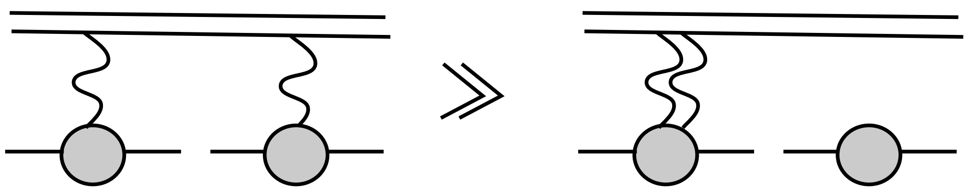
If λ<<R ⇒ qr>>1 ⇒ Exp[i q (r_a-r_b)]=1 when r_a=r_b , otherwise 0; i.e. different scattering centers are independent.

QED analogy: coherent vs Raman (combinational) light scattering

Glauber-Gribov model

Glauber: assume projectile-nucleon amplitudes are not correlated.

QCD: if $\alpha_s^2 A^{1/3} \sim 1$ QUASI-CLASSICAL APPROXIMATION

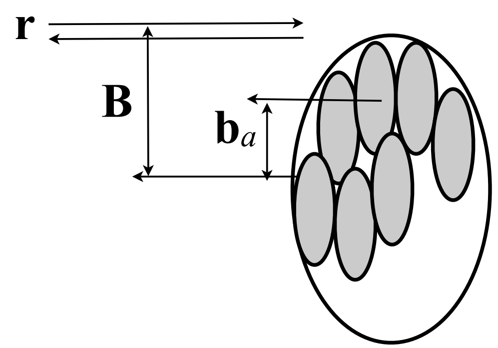


Gribov: hadrons do not diagonalize the scattering matrix => diffraction

UR particle travels along the straight lines in external field ⇒

Scattering matrix S is diagonal in the transverse coordinate space.

Beyond Factorization



Relevant variables: transverse coordinates of charges. E.g. for q and anti-q: **x** and **y** or **r**=**x-y** and **B**=(**x**+**y**)/2

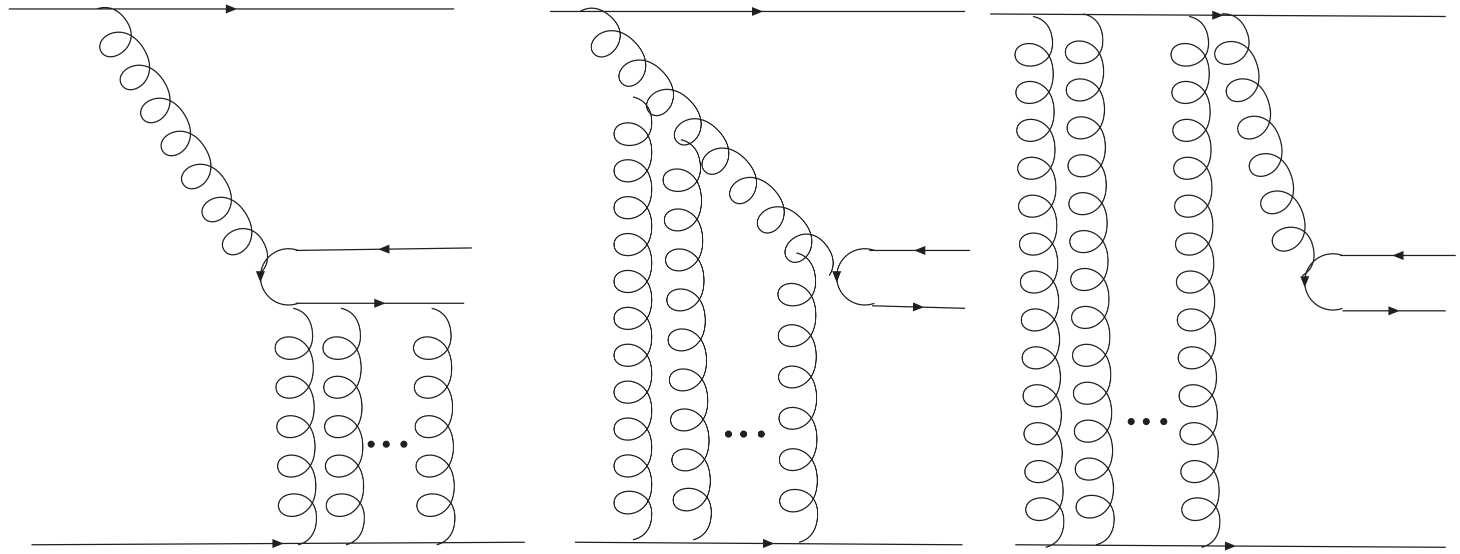
Write the scattering amplitude in terms of transverse coordinates of all excitations ⇒ `dipole model'.

$$\sigma_{\rm tot}^{q\bar{q}A}(s;\mathbf{r}) = 2\int d^2b\, N_A(\mathbf{r},\mathbf{b},Y) = 2\int d^2b\,\left(1 - e^{-\frac{1}{2}\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{r})\,\rho\, T_A(\mathbf{b})}\right)$$

Glauber-Mueller formula

In the Born approximation: $\sigma_{\rm tot}^{q\bar{q}N}(s;\mathbf{r}) = \dfrac{\alpha_s}{N_c}\pi^2\mathbf{r}^2\, xG(x,1/\mathbf{r}^2)$

Production of the q-anti-q pair: pA



Heavy quark approximation (valence quark doesn't interact):

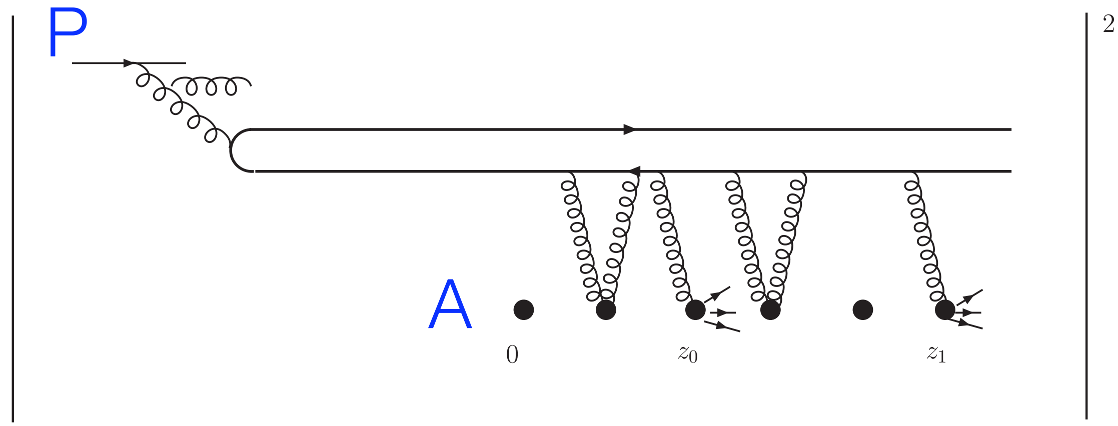
$$\frac{d\sigma_{tot}(pA)}{dY\, d^2k\, d^2b} = x_1 G(x_1, m_c^2) \int d^2 r\, e^{-i\frac{1}{2}\underline{k}\cdot\underline{r}} \int d^2 r'\, e^{i\frac{1}{2}\underline{k}\cdot\underline{r}'}\, \Phi_G(l_1, r, r', z = 1/2)$$

$$\times \left\{1 - \exp[-\sigma(x_2, r^2)\,\rho\, 2\, R_A] - \exp[-\sigma(x_2, r'^2)\,\rho\, 2\, R_A] + \exp[-\sigma(x_2, (\vec{r} - \vec{r}')^2)\,\rho\, 2R_A]\right\} .$$

KT, 2004

$$\left[\frac{1}{2}\frac{\underline{r}\cdot\underline{r}'}{r r'} K_1(r m_c)\, K_1(r' m_c) \;+\; K_0(r m_c)\, K_0(r' m_c)\right]$$

Production of the q-anti-q pair



Inelastic processes:

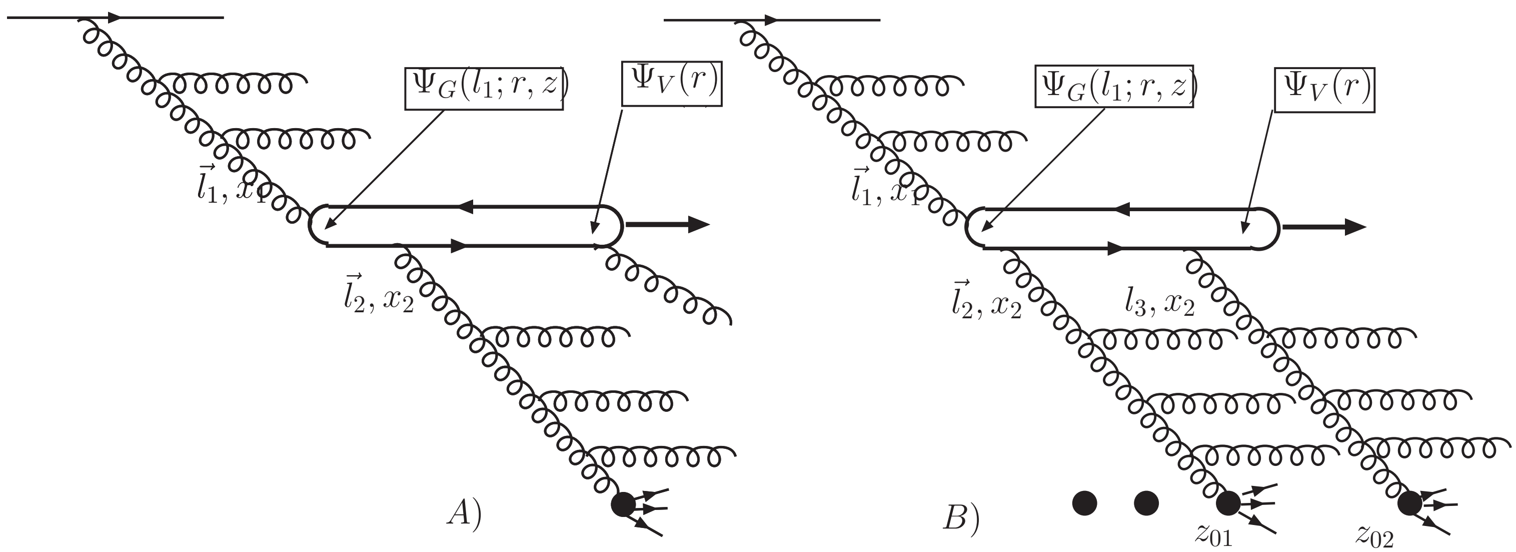
$$\frac{d\sigma_{in}(pA)}{dY\,d^2k\,d^2b} = x_1 G(x_1, m_c^2) \int d^2r \int d^2r'\,\Phi_G(m_c, r, r', z = 1/2)\, e^{i\frac{1}{2}(\underline{r}'-\underline{r})\cdot\underline{k}}$$

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

$$\times \sum_{n=0}^{\infty} \int_{z_0}^{2R_A} d\,z_1 \,\ldots \int_{z_{n-2}}^{2R_A} dz_{n-1} \int_{z_{n-1}}^{2R_A} dz_n\, \rho^n\, \hat{\sigma}_{in}^n(x_2, r, r') \qquad (\alpha_s^2 A^{1/3})^n$$

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

Production of J/ψ: pp vs pA



hadron − hadron collisions   *hadron − nucleus collisions*

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

This mechanism is dominant only for central enough collisions

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

Production of J/ψ: relevant time scales

A pre-hadron cc pair is produced over time

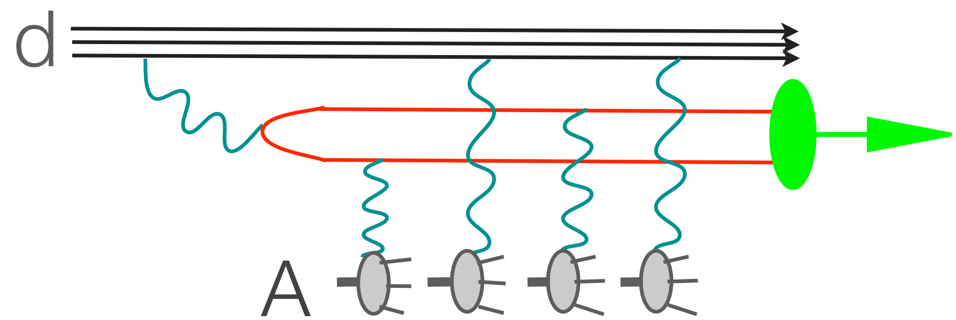
$$\tau_P = l_c/c = 7\, e^y\, \mathrm{fm}$$

J/ψ wave function is formed over time

$$\tau_F = \frac{2\, M_\psi}{M_{\psi'} - M_\psi} l_c = 42\, e^y\, \mathrm{fm}$$

- Hierarchy of scales required for the dipole model: $\tau_F \gg \tau_P \gg \tau_{INT}$

At y>≈1 cc is produced coherently over entire nucleus and J/ψ is formed outside of it.

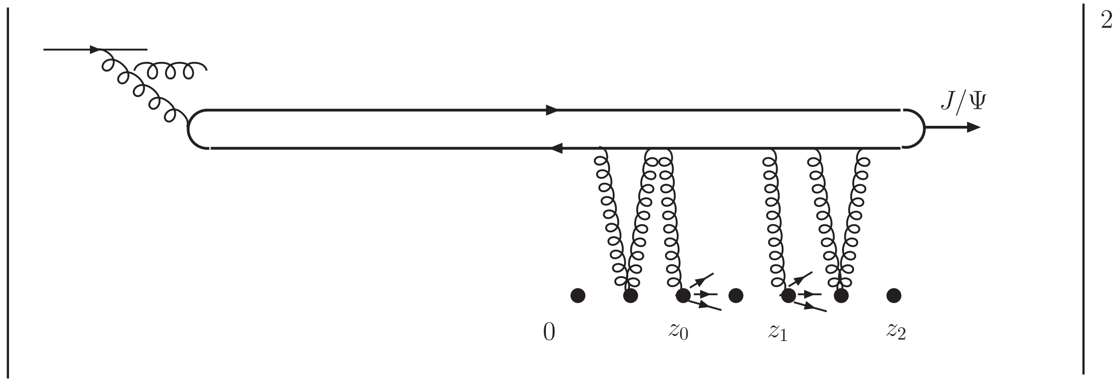


At -1<y<0 cc is produced coherently over a few nucleons. J/ψ is formed outside the nucleus. Note additional enhancement by N_{part}

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.

Propagation of c-anti-c through nucleus



Exponentiation works only at large N_c

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

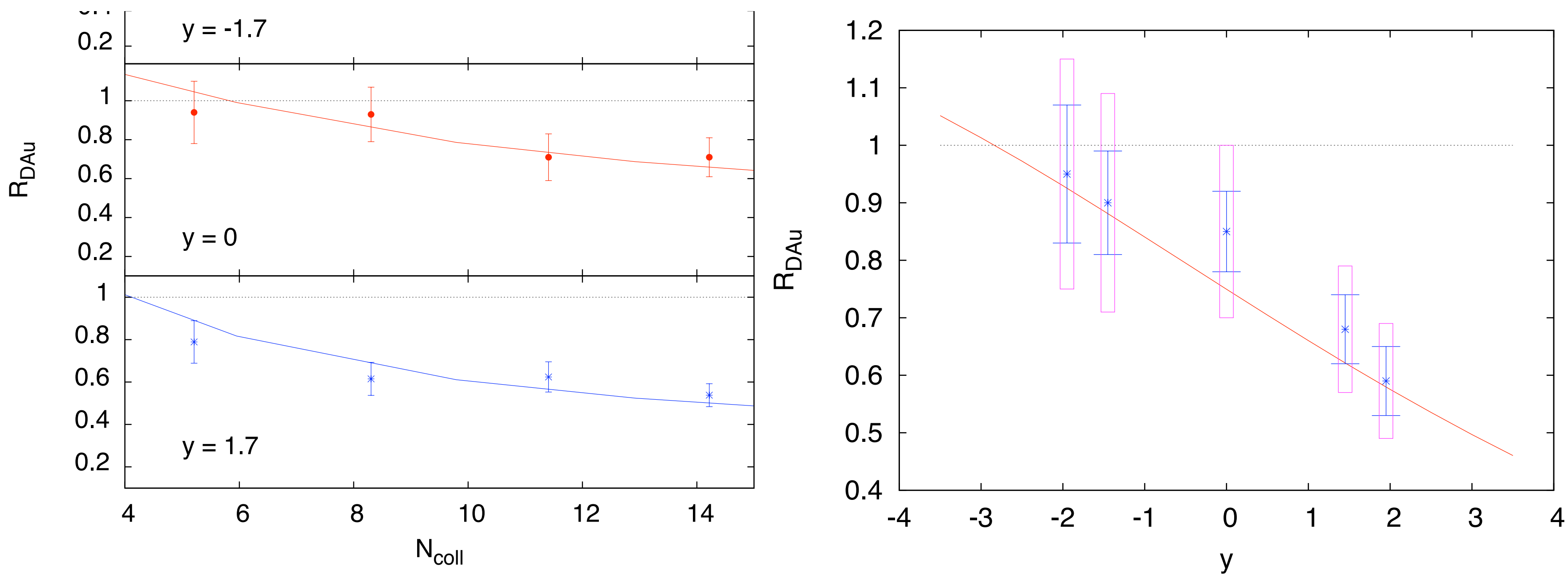
$$\frac{d\sigma_{in}(pA)}{dY\,d^2b} = C_F\,x_1 G(x_1,m_c^2)\times\int_0^{2R_A}\rho\,\hat{\sigma}_{in}(x_2,r,r')\,d\,z_0\int d^2\,r\,\Psi_G(l_1,r,z=1/2)\,\Psi_V(r)\otimes\int d^2r'\Psi_G(l_1,r',z=1/2)\,\Psi_V(r')$$

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

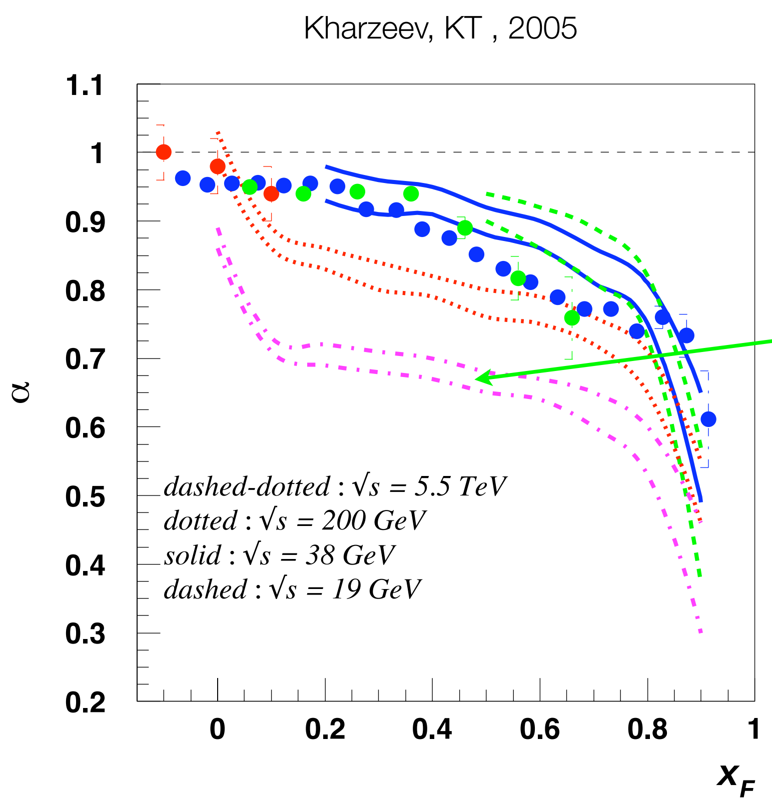
$$\frac{1}{2}\left\{\exp\left(-\sigma\left(x_2,(\underline{r}-\underline{r}')^2\right)\,\rho\,2R_A\right)+\exp\left(-(\sigma(x_2,r)+\sigma(x_2,r')+\hat{\sigma}_{in}(x_2,r,r'))\,\rho\,2R_A\right)-2\,\exp\left(-(\sigma(x_2,r)+\sigma(x_2,r'))\,\rho\,2R_A\right)\right\}$$

Our model vs PHENIX data

Kharzeev, Levin, Nardi KT , 2009 -



Breakdown of x_F-scaling

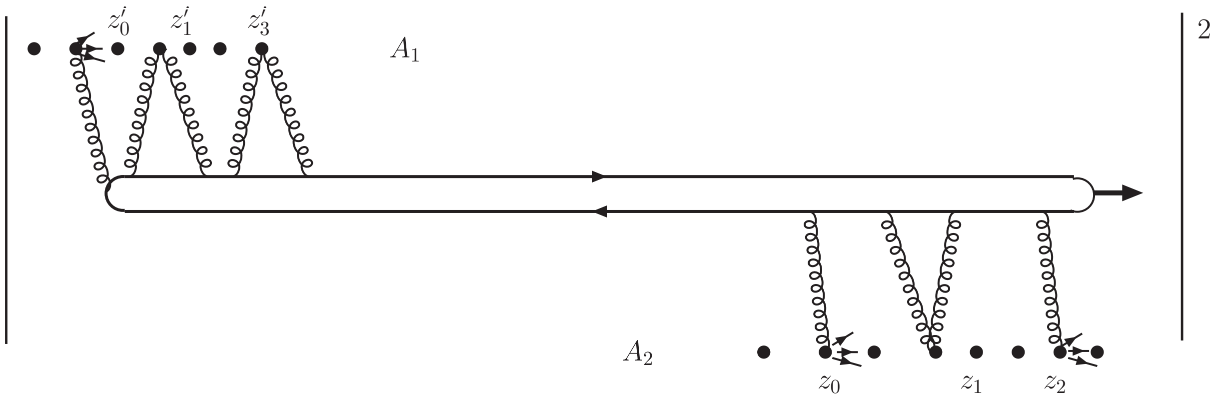


$\sigma_{pA}=A^{\alpha}\sigma_{pp}$

α=2/3 plateau: black disk regime.

Production of J/ψ: AA

Kharzeev, Levin, Nardi, KT



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

$$\{\ldots\} = \int_0^{2R_{A_2}} \int_0^{2R_{A_1}} \left(\frac{1}{8}\,Q^2_{s,A_2}\right)\left(\frac{1}{8}\,Q^2_{s,A_1}\right)(2\underline{r}\cdot\underline{r}')^2\,dz_0\,dz_0'\,\exp\left\{-\frac{1}{8}\,(r^2+r'^2)\,(Q^2_{s,A_1}+Q^2_{s,A_2})\right\}$$
$$\times\sum_{k=1}^{2n-2}\int_{z_0}^{2R_{A_2}} d\,z_1\int_{z_1}^{2R_{A_2}} dz_2\ldots\int_{z_{k-2}}^{2R_{A_2}} dz_{k-1}\,\rho^k\left(\frac{1}{8}\,Q^2_{s,A_2}\,2\,\underline{r}\cdot\underline{r}'\right)^{k-1}$$
$$\times\sum_{n=2}^{\infty}\int_{z_0'}^{2R_{A_1}} d\,z_1'\int_{z_1'}^{2R_{A_1}} dz_2'\ldots\int_{z'_{2n-k-2}}^{2R_{A_1}} dz'_{2n-k-1}\,\rho^{2n-k-1}\left(\frac{1}{8}\,Q^2_{s,A_1}\,2\,\underline{r}\cdot\underline{r}'\right)^{2n-k-2}$$

$$= \sum_{n=2}^{\infty}\left\{\frac{1}{(2n-1)!}\left(\frac{1}{8}\,(Q^2_{s,A_1}+Q^2_{s,A_2})\,2\,\underline{r}\cdot\underline{r}'\right)^{2n-1} - \frac{1}{(2n-1)!}\left(\frac{1}{8}\,Q^2_{s,A_1}\,2\,\underline{r}\cdot\underline{r}'\right)^{2n-1}\right.$$
$$\left.-\frac{1}{(2n-1)!}\left(\frac{1}{8}\,Q^2_{s,A_2}\,2\,\underline{r}\cdot\underline{r}'\right)^{2n-1}\right\}$$
$$= \sinh\left(\frac{1}{8}\,(Q^2_{s,A_1}+Q^2_{s,A_2})\,2\,\underline{r}\cdot\underline{r}'\right) - \sinh\left(\frac{1}{8}\,Q^2_{s,A_1}\,2\,\underline{r}\cdot\underline{r}'\right) - \sinh\left(\frac{1}{8}\,Q^2_{s,A_2}\,2\,\underline{r}\cdot\underline{r}'\right)$$

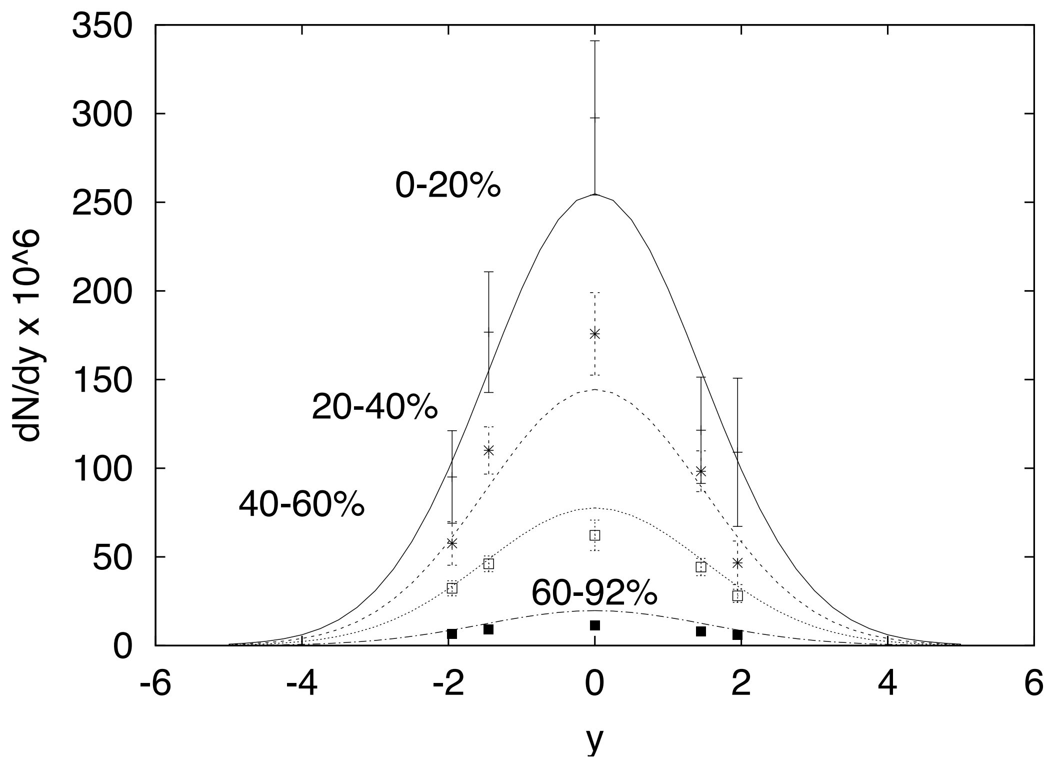
$$\frac{1}{S_A}\frac{d\sigma(AA)}{dY\,d^2b} = \frac{C_F^2}{4\pi^2\alpha_s}\int d^2r\,\Psi_G(l_1,r,z=1/2)\otimes\Psi_V(r)\int d^2r'\,\Psi_G^*(l_1,r',z=1/2)\otimes\Psi_V^*(r')$$
$$\times\frac{1}{2\underline{r}\cdot\underline{r}'}\left\{\exp\left(-\frac{1}{8}(\underline{r}-\underline{r}')^2\,(Q_{s,A_1}^2+Q_{s,A_2}^2)\right) - \exp\left(-\frac{1}{8}(\underline{r}+\underline{r}')^2\,(Q_{s,A_1}^2+Q_{s,A_2}^2)\right)\right.$$
$$-\exp\left(-\frac{1}{8}(\underline{r}-\underline{r}')^2\,Q_{s,A_1}^2-\frac{1}{8}(r^2+r'^2)\,Q_{s,A_2}^2\right)+\exp\left(-\frac{1}{8}(\underline{r}+\underline{r}')^2\,Q_{s,A_1}^2-\frac{1}{8}(r^2+r'^2)\,Q_{s,A_2}^2\right)$$
$$\left.-\exp\left(-\frac{1}{8}(\underline{r}-\underline{r}')^2\,Q_{s,A_2}^2-\frac{1}{8}(r^2+r'^2)\,Q_{s,A_1}^2\right)+\exp\left(-\frac{1}{8}(\underline{r}+\underline{r}')^2\,Q_{s,A_2}^2-\frac{1}{8}(r^2+r'^2)\,Q_{s,A_1}^2\right)\right\}$$

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

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

Fitted to Phenix DAu data

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

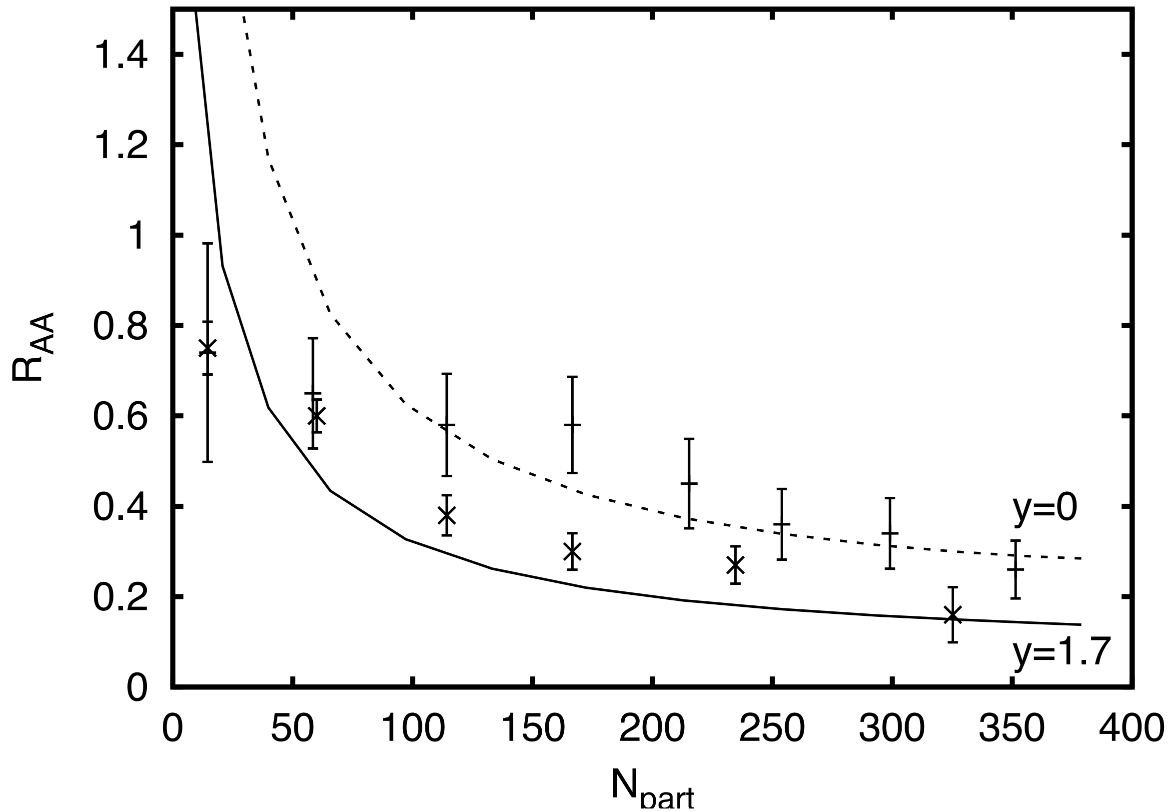


UNKNOWN CONSTANT C IS FIXED FROM DAU DATA

1. Rapidity dependence is reproduced well.

2. The width of the distribution decreases with N_{part}

Cold J/ψ suppression



Mechanism of suppression: large relative momentum between c and anti-c makes the J/ψ formation less probable.

Outlook

1. Better description of peripheral data: need to calculate a contribution of A+A→J/ψ+g mechanism

2. Prediction for higher energies and for χ's

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.**