

A scenic view of a bay with many sailboats and a city in the background. The text is overlaid on the image.

Charmonium
in pA and AA collisions
(SPS-RHIC-LHC)

Boris Kopeliovich
Valparaiso, Chile

Brookhaven
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Outline



J/ψ suppression in pA
 Leading/higher twist shadowing,
 absorption, color transparency, etc.



Nontrivial transition.
 Double color filtering, “Cold nuclear matter” is not cold, etc.



Charmonium survival in a dense medium
 Probing the transport coefficient

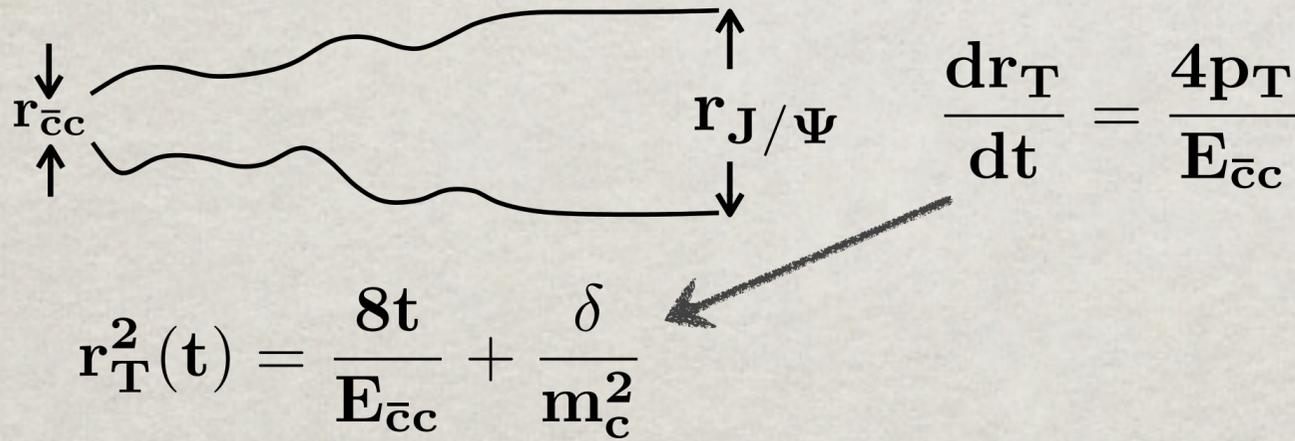
pA: J/Ψ formation and color transparency

A $\bar{c}c$ dipole is produced with a small separation $r_{\bar{c}c} \sim \frac{1}{m_c} \sim 0.1 \text{ fm}$

and then evolves into a J/Ψ mean size $r_{J/\Psi} \sim 0.5 \text{ fm}$

during formation time $t_f = \frac{2E_{J/\Psi}}{m_{\Psi'}^2 - m_{J/\Psi}^2} = 0.1 \text{ fm} \left(\frac{E_{J/\Psi}}{1 \text{ GeV}} \right)$

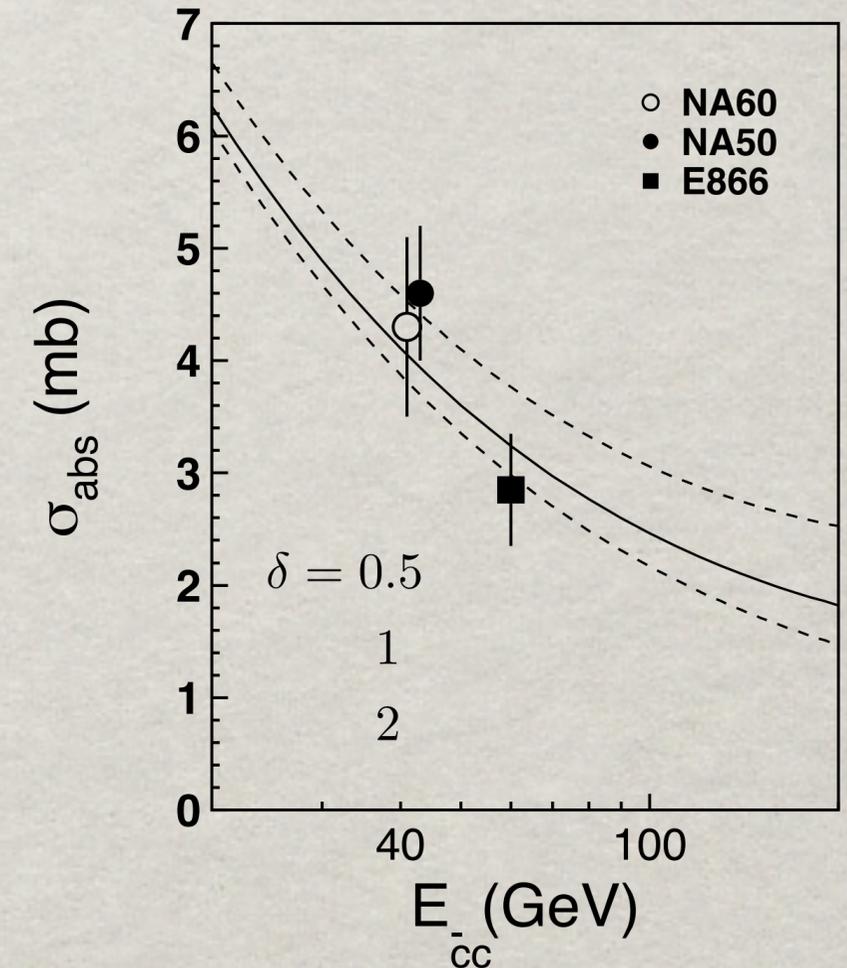
Perturbative expansion



The mean cross section is L-dependent

$$\bar{\sigma}_{\text{abs}}(L, E_{\bar{c}c}) = \frac{1}{L} \int_0^L dl \sigma_{\text{abs}}(l) = C(E_{\bar{c}c}) \left(\frac{4L}{E_{\bar{c}c}} + \frac{\delta}{m_c^2} \right)$$

$$R_{pA} = \frac{1}{A\sigma_{\text{abs}}} \int d^2b \left[1 - e^{-\sigma_{\text{abs}} T_A(b)} \right]$$

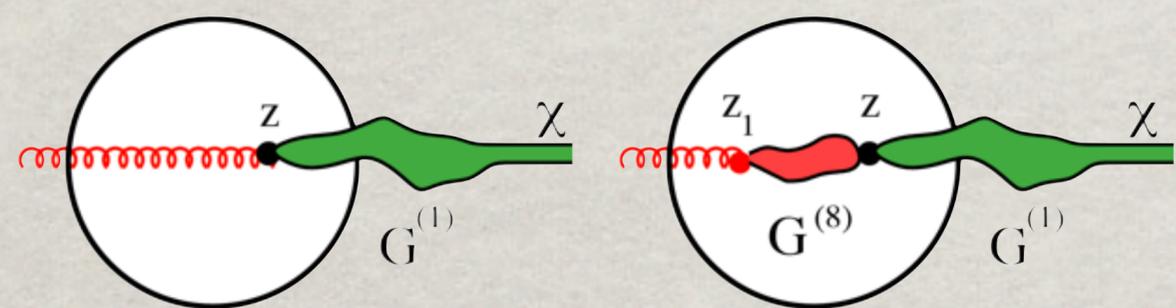


pA: Higher twist c-quark shadowing

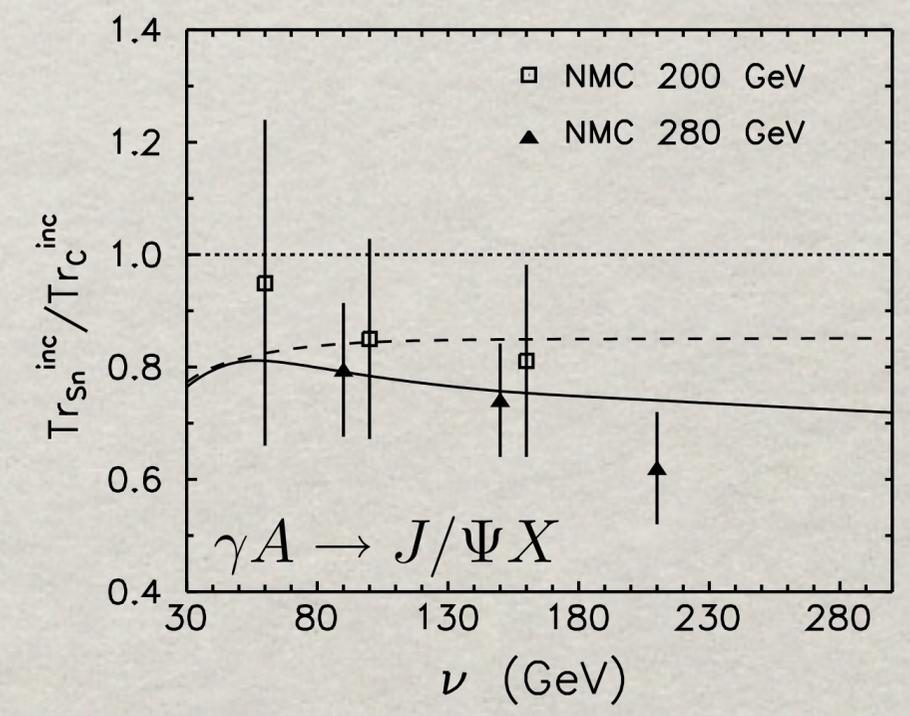
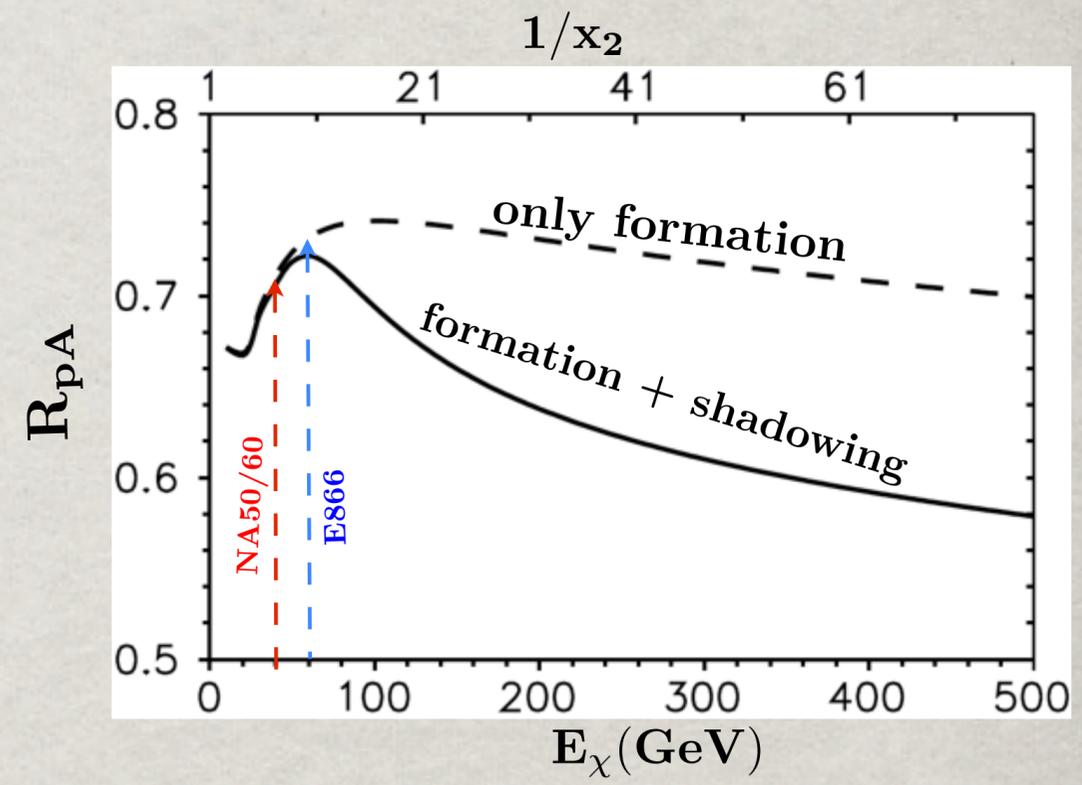
At higher energies $\bar{\sigma}_{abs}$ is affected by another time scale, the lifetime of a $c\bar{c}$ fluctuation

$$t_p = \frac{2E_{J/\Psi}}{m_{J/\Psi}^2} = \frac{1}{x_2 m_N} \quad (5 \text{ times shorter than } t_f)$$

If $t_p \gtrsim R_A$ the initial state fluctuation $g \rightarrow \bar{q}q$ leads to shadowing corrections related to a non-zero $\bar{c}c$ separation.



Path integral technique: all possible paths of the quarks are summed up; $\sigma_{abs}(r_T, E_{\bar{c}c})$ gives the imaginary part of the light-cone potential.



pA : Leading twist gluon shadowing

The coherence length for gluon shadowing is much shorter than for quarks

$$l_c^g = \frac{P^g s}{m_{J/\psi}^2 m_N} x_1 (1 - x_1)$$

$P^g \approx 0.1$ is independent of the scale.

This is why there is no shadowing above $\tilde{x}_2 \gtrsim 0.01$ where $\tilde{x}_2 = x_2 / (1 - x_1)$

in particular, gluon shadowing should not affect

any of the fixed-target experiments $l_c^g < 1$ fm

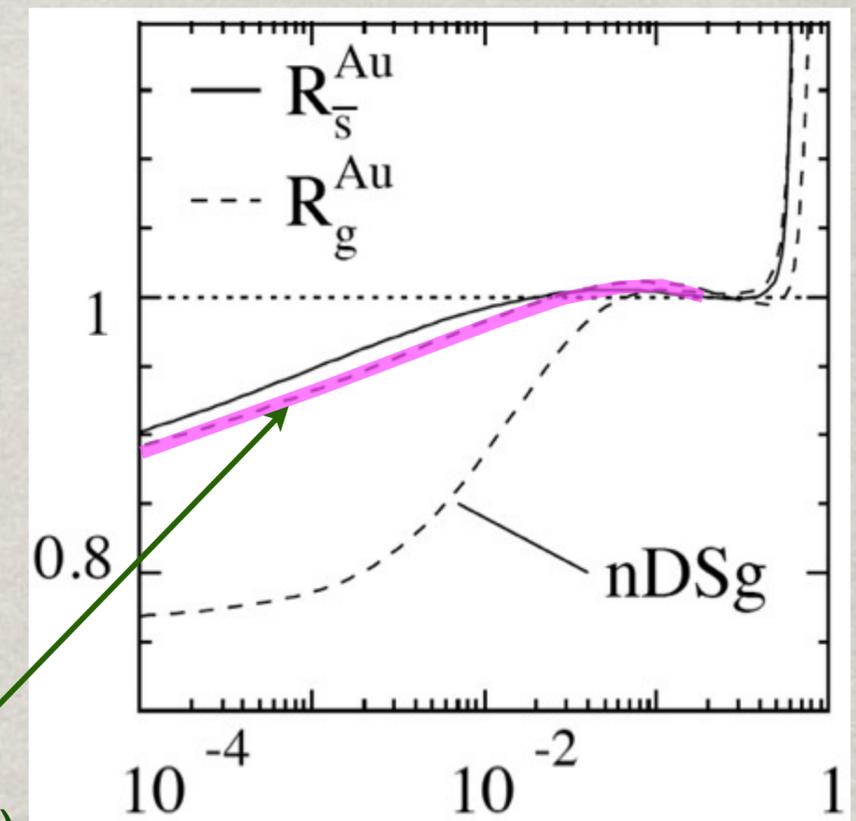
No gluon shadowing at RHIC at $x_F = 0$,
since $x_2 \geq 0.018$ is too large.

At forward rapidities x_2 is falling as

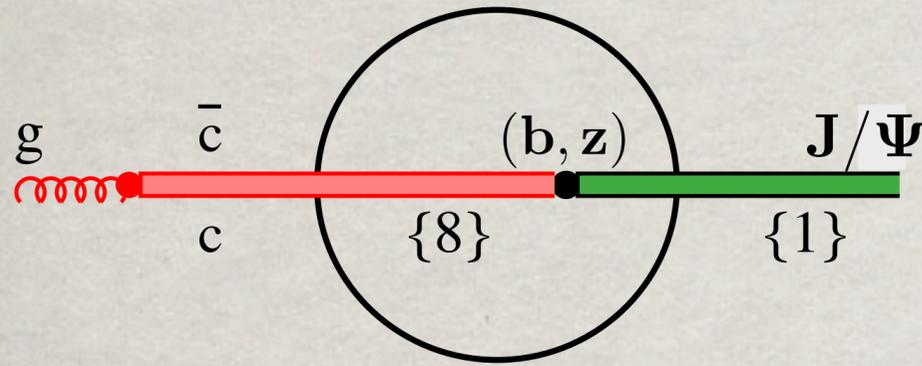
$$x_2 \geq e^{-\eta} \sqrt{(m_{J/\psi}^2 + \langle p_T^2 \rangle) / s}$$

Still gluon shadowing is very weak

NLO: D. de Florian & R. Sassot (2004)



pA: Charmonium suppression at RHIC/LHC



The $\bar{c}c$ pair attenuates not only in final state (breakup), but also in initial state (shadowing)

$$S_{pA}(b, z) = \int d^2 r_T K_0(m_c r_T) r_T^2 \Psi_{J/\psi}(r_T) e^{-\frac{1}{2} \sigma_{\bar{c}cg}(r_T) T_-(b, z) - \frac{1}{2} \sigma_{\bar{c}c}(r_T) T_+(b, z)}$$

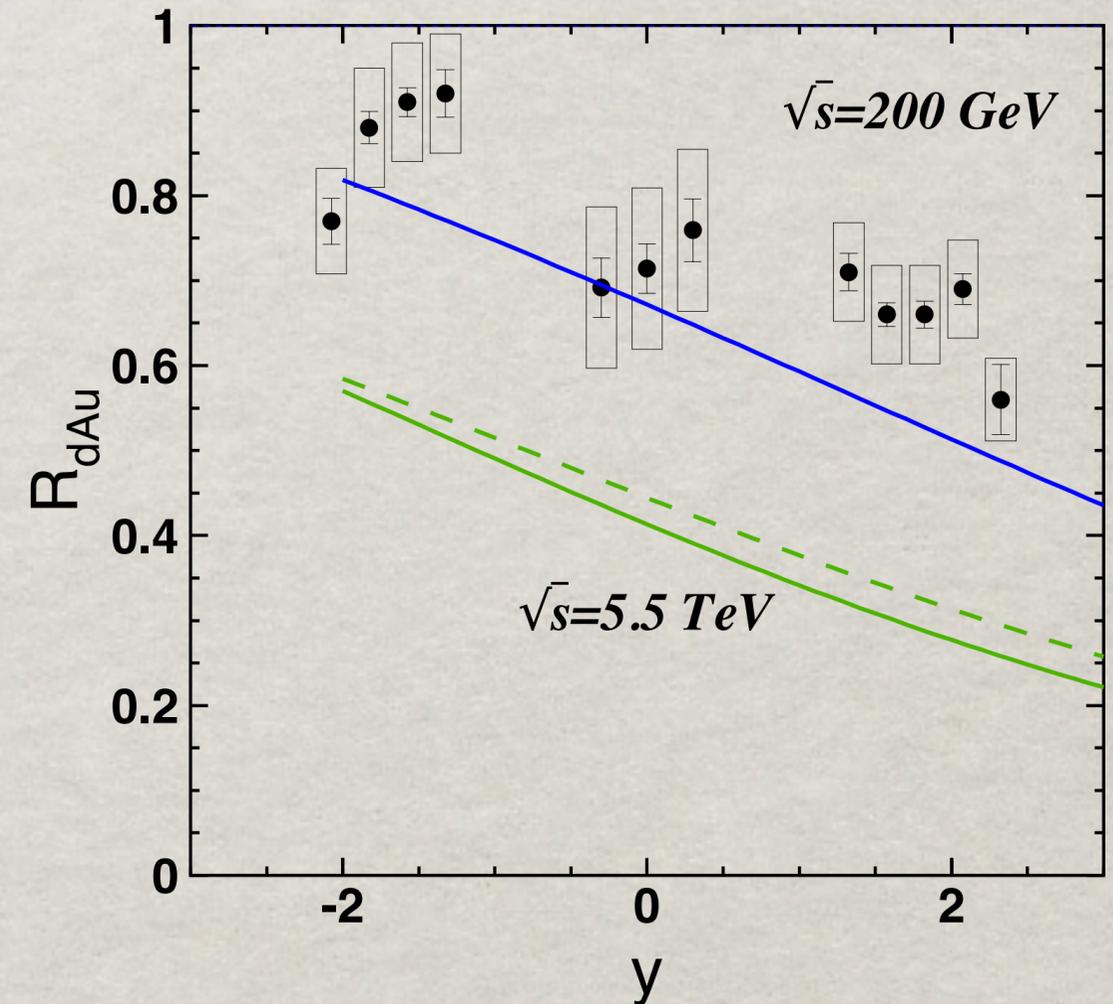
$$T_-(b, z) = \int_{-\infty}^z dz' \rho_A(b, z')$$

$$T_+(b, z) = T_A(b) - T_-(b, z)$$

$$T_A(b) = T_-(b, \infty)$$

$$\sigma_{\bar{c}cg}(r_T) = \frac{9}{4} \sigma_{\bar{c}c}(r_T/2) - \frac{1}{8} \sigma_{\bar{c}c}(r_T)$$

Both cross sections $\sigma_{\bar{c}cg}$ and $\sigma_{\bar{c}c}$ steeply rise with rapidity $\sigma_{\bar{c}c} \propto Q_s^2(x_2) \propto e^{0.288\eta}$ as dictated by DIS data from HERA.



pA: Cronin effect

Available pp data agree with simple p_T dependence ($p_T < 5 \text{ GeV}$)

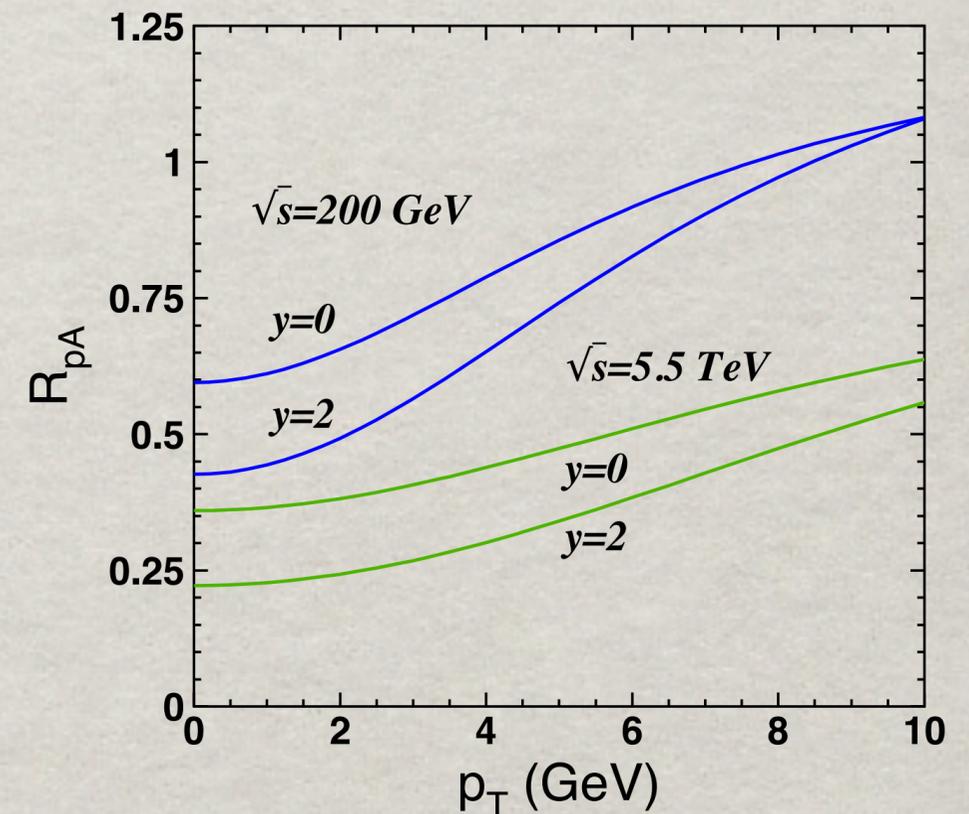
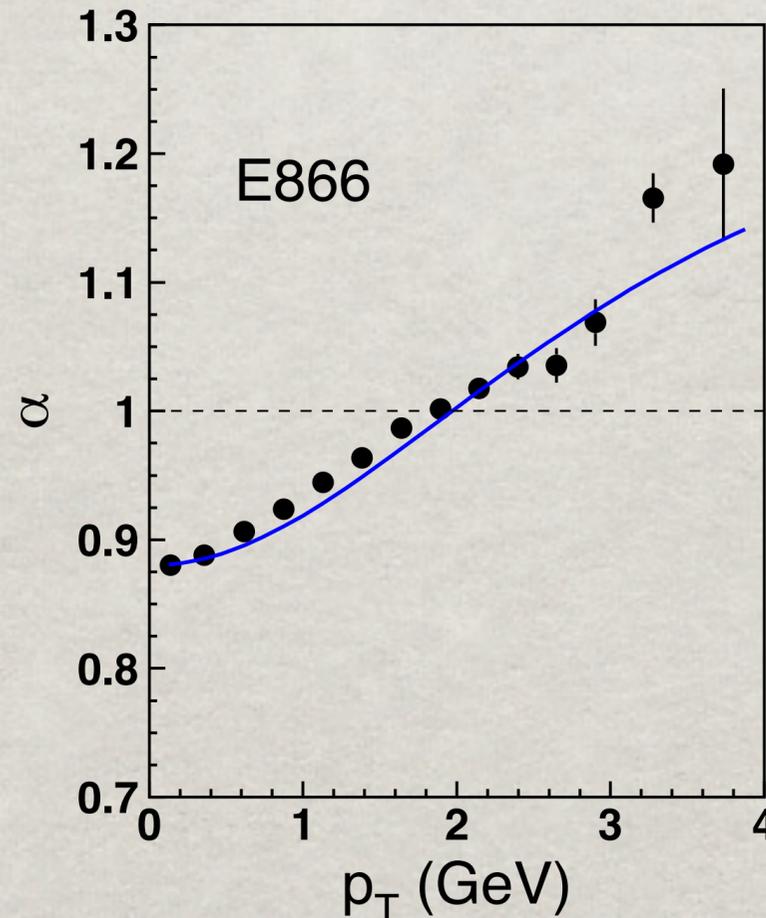
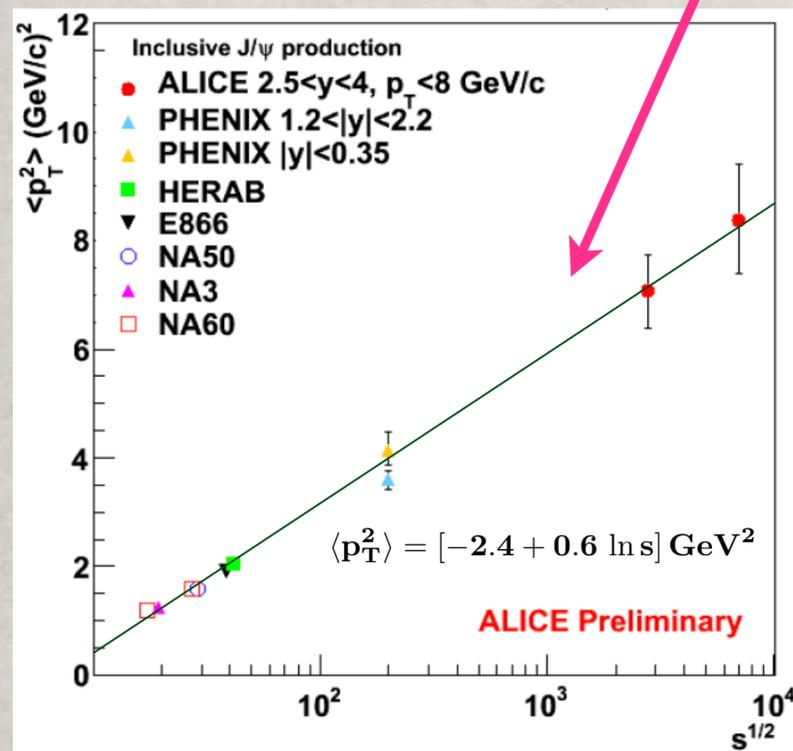
In pA collisions $\langle p_T^2 \rangle$ is increased

$$\frac{d\sigma_{pp}(J/\Psi)}{dp_T^2} \propto \left(1 + \frac{p_T^2}{6\langle p_T^2 \rangle}\right)^{-6}$$

$$\langle p_T^2 \rangle_{pA} = \langle p_T^2 \rangle_{pp} + Q_s^2$$

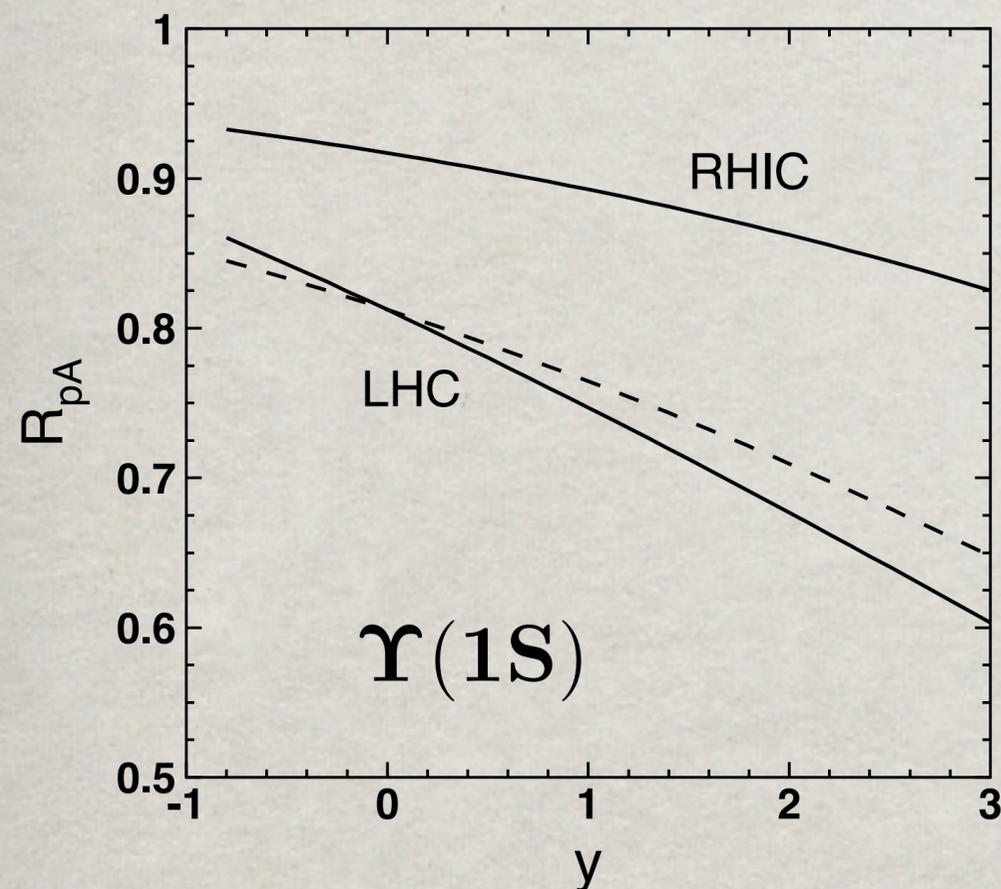
Broadening (saturation scale) is well calculated within the color dipole phenomenology

$$Q_{sA}^2(\mathbf{b}) = \bar{\nabla}_{\mathbf{r}_T}^2 \sigma_{\text{dip}}(\mathbf{r}_T) \Big|_{\mathbf{r}_T=0} \mathbf{T}_A(\mathbf{b})$$



pA: Bottomium

Similar calculations ($J/\Psi \rightarrow \Upsilon(1S)$) lead to



Suppression of the radial excitations $\Upsilon(2S)$, $\Upsilon(3S)$ is expected to be similar (compare $J/\Psi - \Psi'$), since it is mainly controlled by the size of the produced heavy dipole.

CMS @ 2.76 TeV

$\Upsilon(1S)$ R_{AA} in the most central 20%
 $- 0.60 \pm 0.12(\text{stat.}) \pm 0.10(\text{syst.})$

AA (ISI): Double color filtering

Survival probability of a dipole in a medium:

Naive: $P(\mathbf{L}) = e^{-\sigma_{\text{abs}}\rho_A \mathbf{L}}$

σ_{abs} is the break-up cross section

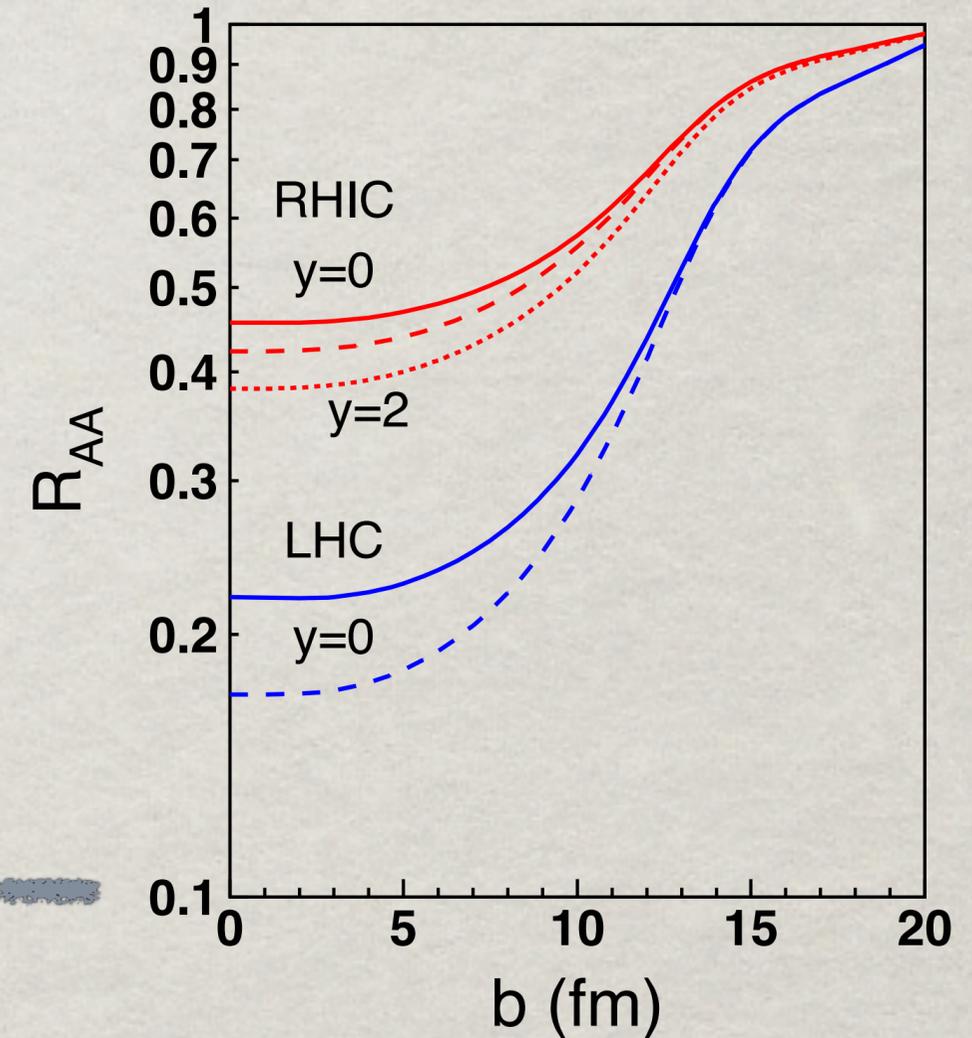
Color transparency makes the medium more transparent

$$P(\mathbf{L}) = \frac{1}{1 + \sigma_{\text{abs}}\rho_A \mathbf{L}}$$

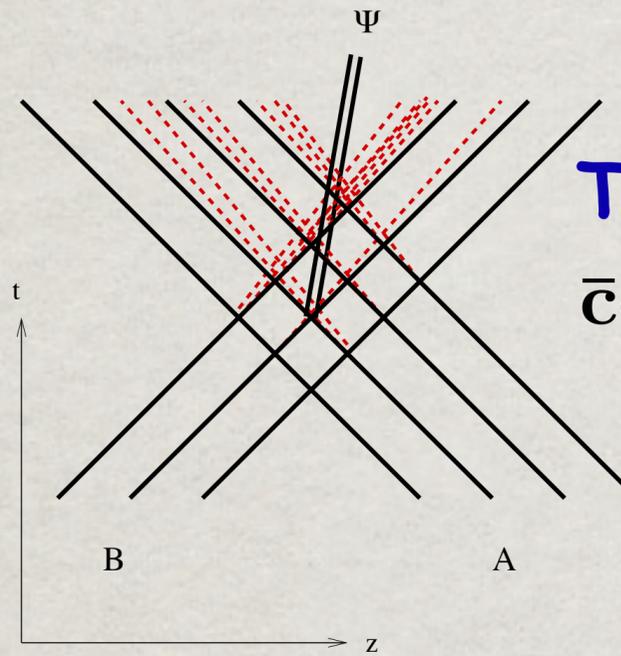
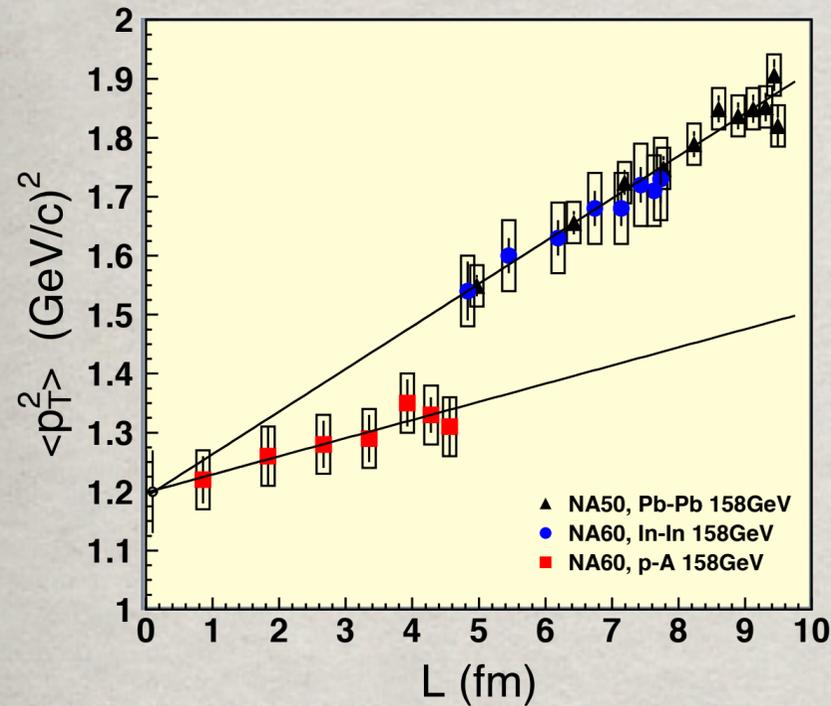
Simultaneous propagation through two nuclei

Naive: $P(\mathbf{L}_A, \mathbf{L}_B) = P(\mathbf{L}_A)P(\mathbf{L}_B) = \frac{1}{(1 + \sigma_{\text{abs}}\rho \mathbf{L}_A)(1 + \sigma_{\text{abs}}\rho \mathbf{L}_B)}$

Double color filtering: $P(\mathbf{L}_A, \mathbf{L}_B) = \frac{1}{1 + \sigma_{\text{abs}}\rho(\mathbf{L}_A + \mathbf{L}_B)}$



AA(ISI): Cold nuclear matter is not cold



J. Huefner & B.K. (1998)

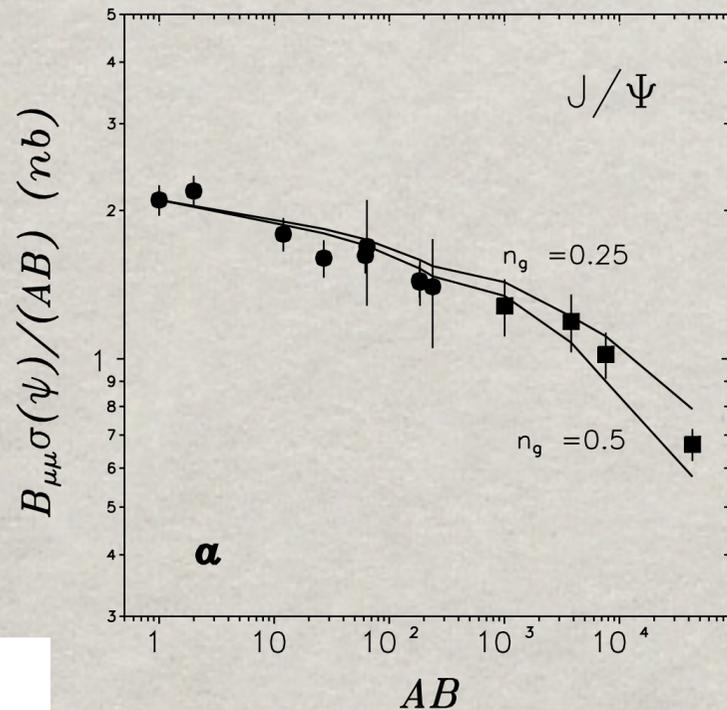
The radiated gluons participate in the $\bar{c}c$ break-up, as well as in broadening

Gluon radiation time

$$l_f^g = \frac{2 E_q \alpha (1 - \alpha)}{\alpha^2 m_q^2 + k^2}$$

Broadening is not additive, it is twice stronger in AA on the same length.

$$\langle n_g \rangle = \frac{3}{\sigma_{in}(NN)} \int_{k_{min}^2}^{\infty} dk^2 \int_{\alpha_{min}}^1 d\alpha \frac{d\sigma(qN \rightarrow gX)}{d\alpha dk^2} \Theta(\Delta z - l_f^g)$$



$$\langle n_g \rangle = \begin{cases} 6.9 \times 10^{-1} & (SPS, \sqrt{s} = 20 \text{ GeV}) \\ 6.9 \times 10^{-3} & (RHIC, \sqrt{s} = 200 \text{ GeV}) \\ 1.2 \times 10^{-3} & (LHC, \sqrt{s} = 1200 \text{ GeV}) \end{cases}$$

The effect vanishes at the energies of RHIC and LHC.

AA (ISI): Excitation of higher Fock components

Like at low energies, broadening in AA collision should be enhanced compared to pA, but for another reason: **boosted saturation scale**.

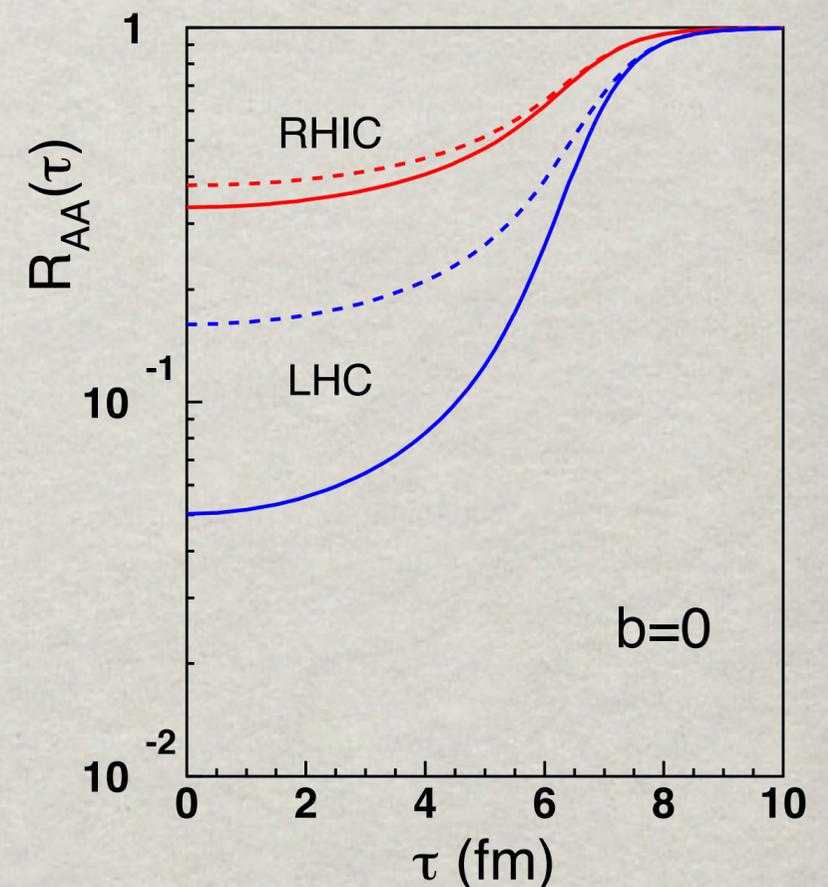
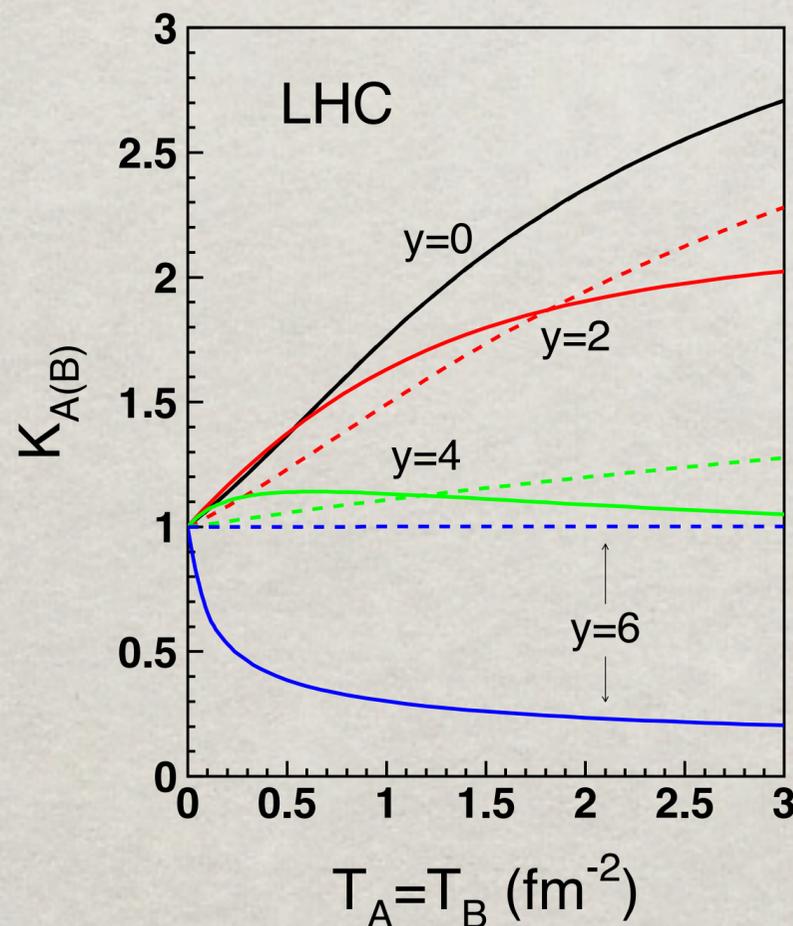
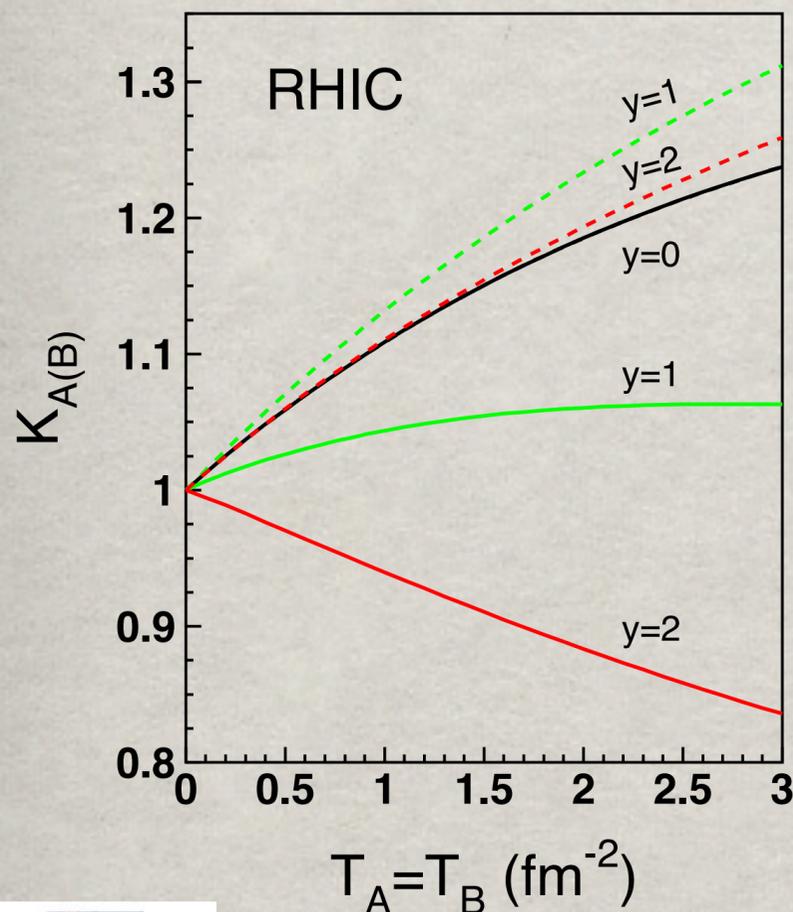
Mutual multiple interactions of the nucleons enhance the higher Fock states, containing more gluons at small x .

$$\tilde{Q}_{sB}^2(x_B) = \frac{3\pi^2}{2} \alpha_s (\tilde{Q}_{sA}^2 + Q_0^2) x_B g_N(x_B, \tilde{Q}_{sA}^2 + Q_0^2) T_B$$

$$\tilde{Q}_{sA}^2(x_A) = \frac{3\pi^2}{2} \alpha_s (\tilde{Q}_{sB}^2 + Q_0^2) x_A g_N(x_A, \tilde{Q}_{sB}^2 + Q_0^2) T_A$$

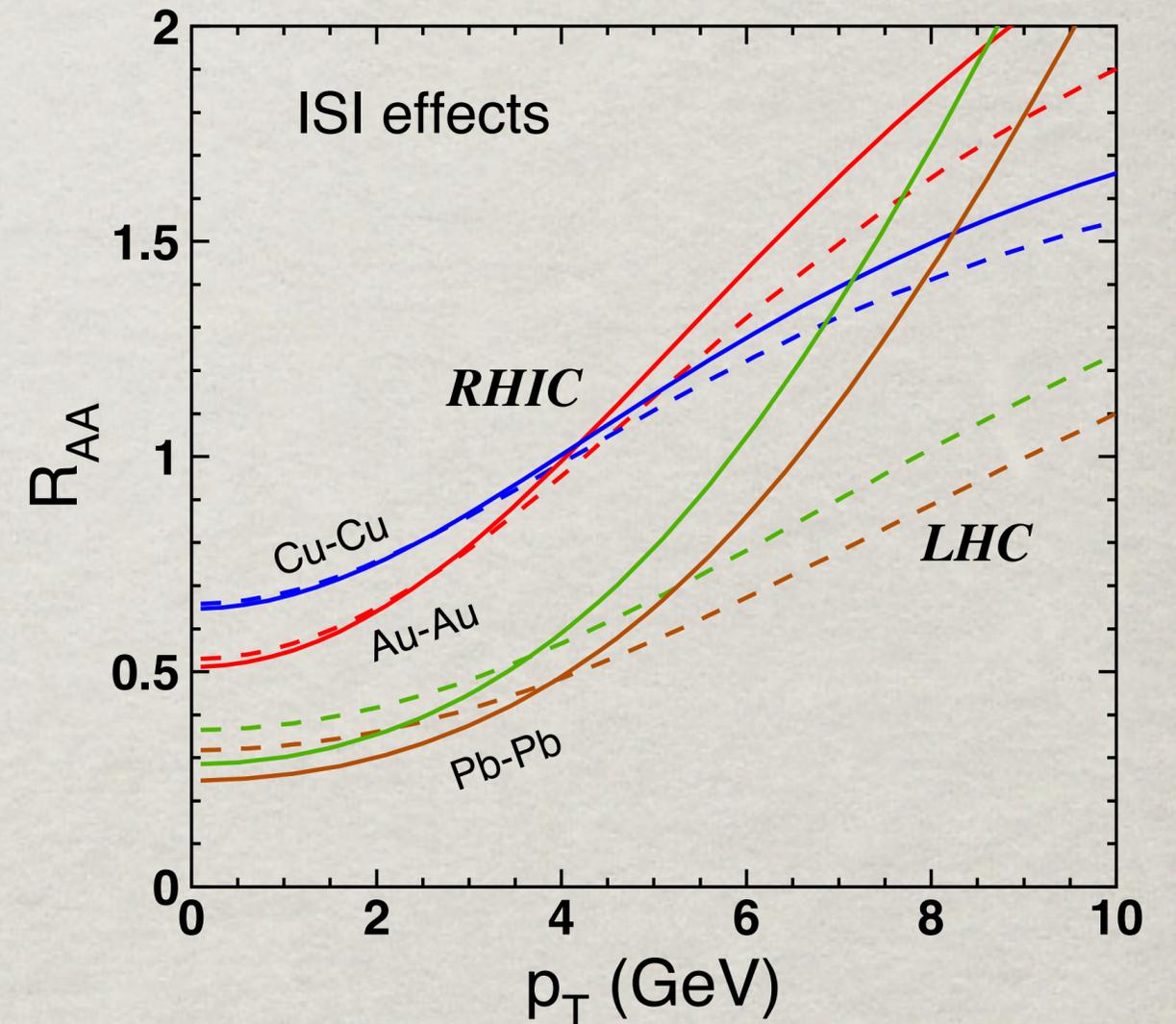
$$K_A = \tilde{Q}_{sA}^2 / Q_{sA}^2$$

Cold nuclear matter is not cold



AA: Combined ISI effects

The combined effects of nuclear shadowing for charm quarks and for gluons, color transparency, double color filtering, broadening and Cronin enhancement, and boosting of the saturation scale, the J/Ψ survival probability related to ISI in AA collisions is substantial.



The predicted p_T dependence is not reliable at $p_T > 5\text{GeV}$

★ Production time:

In the c.m. of the collision a colorless $\bar{c}c$ -pair is produced at the time

$$t_p^* \sim \frac{1}{\sqrt{4m_c^2 + p_T^2}} < 0.07 \text{ fm}$$

which is much shorter than the time scale of medium creation, $t_p \ll t_0$

! However, t_p is $\sqrt{s}/2m_N$ longer in the rest frames of colliding nuclei

★ Formation time:

The time of formation of the J/Ψ wave function is also short

$$t_f^* = \frac{\sqrt{p_T^2 + M_{J/\Psi}^2}}{(m_{\Psi'} - m_{J/\Psi})m_{J/\Psi}} \lesssim 0.5 \text{ fm}$$

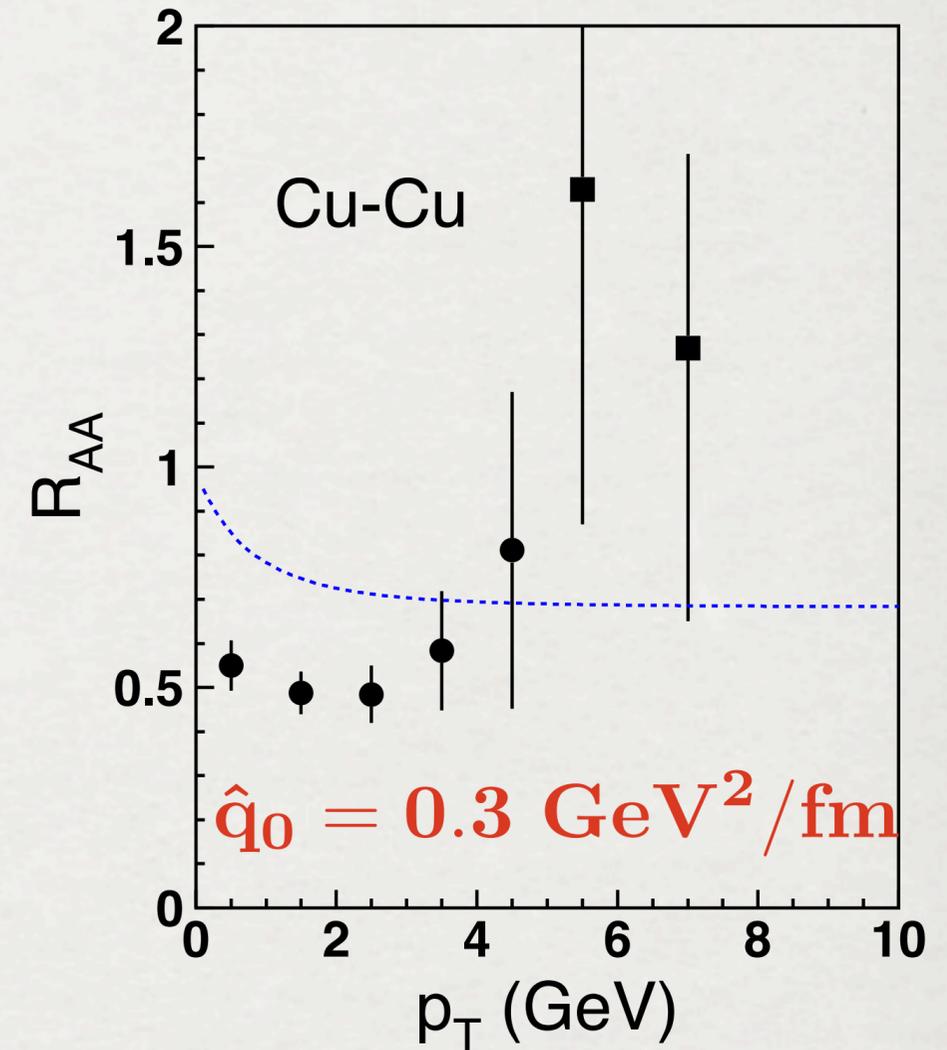
★ Not a $\bar{c}c$ dipole, but a fully formed J/Ψ propagates through the medium



The absorption cross section for a dipole propagating through a medium is related to the parton broadening, i.e. to the transport coefficient \hat{q}

$$\hat{q} = 2\rho \left. \frac{d\sigma(\mathbf{r})}{dr^2} \right|_{r=0} \xrightarrow{\text{absorption rate}} \frac{dS(\mathbf{r}, l)}{dl} = -\frac{1}{2} \hat{q} r^2$$

$$R(s, p_T) = \frac{1}{\pi} \int_0^\pi d\phi \exp \left[-\frac{1}{2} \langle r_{J/\Psi}^2 \rangle \int_{l_0}^\infty dl \hat{q}(\vec{s} + \vec{l}) \right]$$



J/Ψ breakup is controlled by the same transport coefficient as the energy loss.

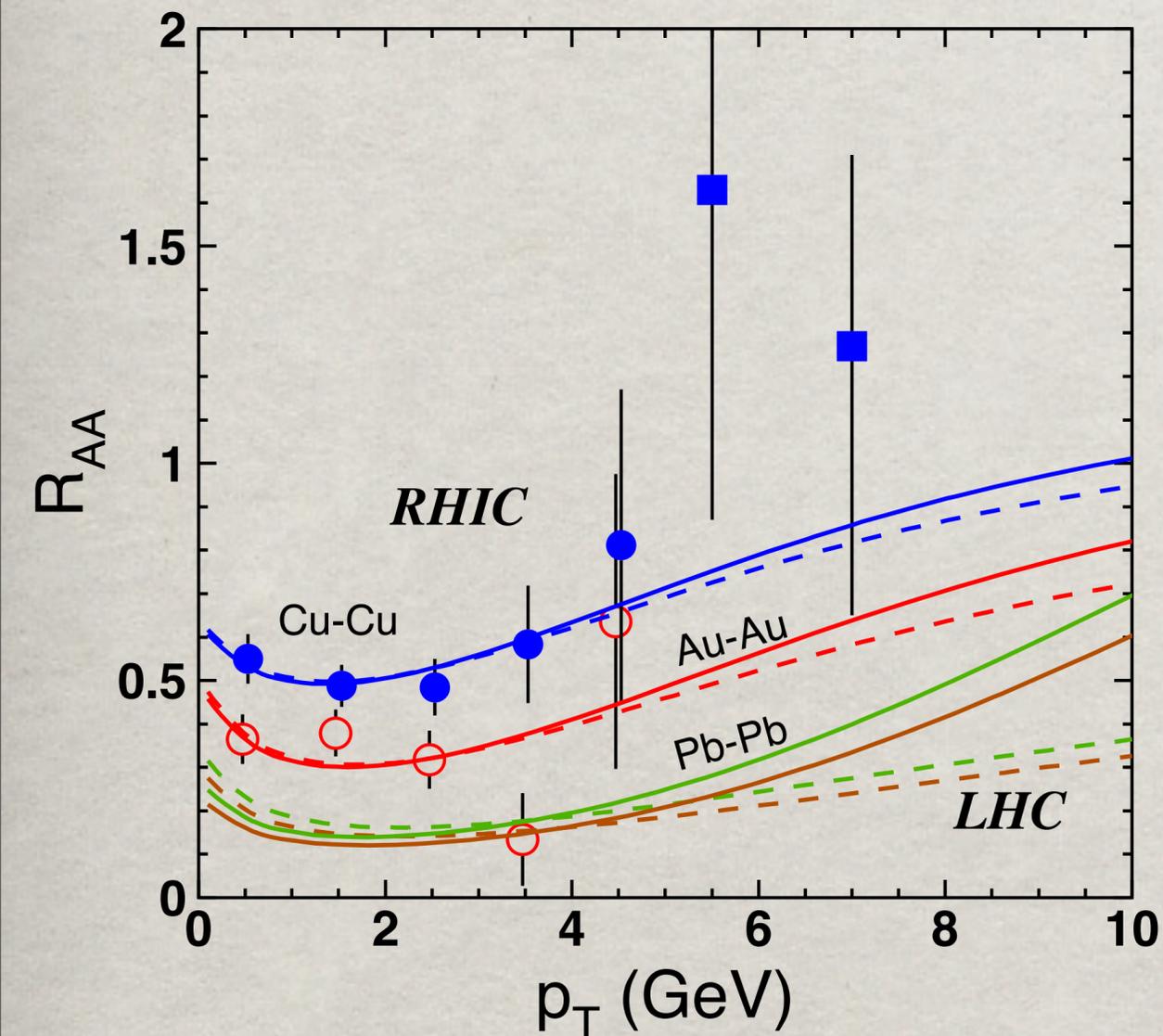
We relied on the popular model $\hat{q}(b, s, t) = \frac{\hat{q}_0 t_0}{t} \frac{n_{\text{part}}(b, s)}{n_{\text{part}}(0, 0)}$, fixed $t_0 = 0.5 \text{ fm}$

and adjusted $\hat{q}_0 \sim 0.5 \text{ GeV}^2/\text{fm}$ to reproduce the data

AA (FSI): Attenuation in the dense medium

The combined ISI and FSI effects

The p_T -integrated ratio



<i>Cu-Cu</i>	$\sqrt{s} = 200 \text{ GeV}$	$R_{AA} = 0.54$
<i>Au-Au</i>	$\sqrt{s} = 200 \text{ GeV}$	$R_{AA} = 0.34$
<i>Pb-Pb</i>	$\sqrt{s} = 2.76 \text{ TeV}$	$R_{AA} = 0.18$
<i>Pb-Pb</i>	$\sqrt{s} = 5.50 \text{ TeV}$	$R_{AA} = 0.16$

Summary

Charmonium production offers a novel clean (a different kind of dirt) probe for the medium created in heavy ion collisions:

no energy loss, but rather complicated ISI effects, which explain a substantial part of the observed suppression.

The ISI effects include: (i) coherence effects for interaction of $|\bar{c}c\rangle$ (c-quark shadowing) and $|\bar{c}c g\dots\rangle$ (gluon shadowing) Fock components of projectile gluons; (ii) color transparency; (iii) double color filtering; (iv) Cronin effect; (v) boosting of the saturation scale.

While (i), (ii) and (iv) are well confirmed by data on pA, (iii) and (v) need further experimental tests

Attenuation is controlled by the same transport coefficient as parton broadening and energy loss, which is found from J/Ψ data to be rather small, $\hat{q}_0 \sim 0.5 \text{ GeV}^2/\text{fm}$, compared to the results of jet quenching analyses based on the energy loss scenario.