Nuclear effects in charmonium production

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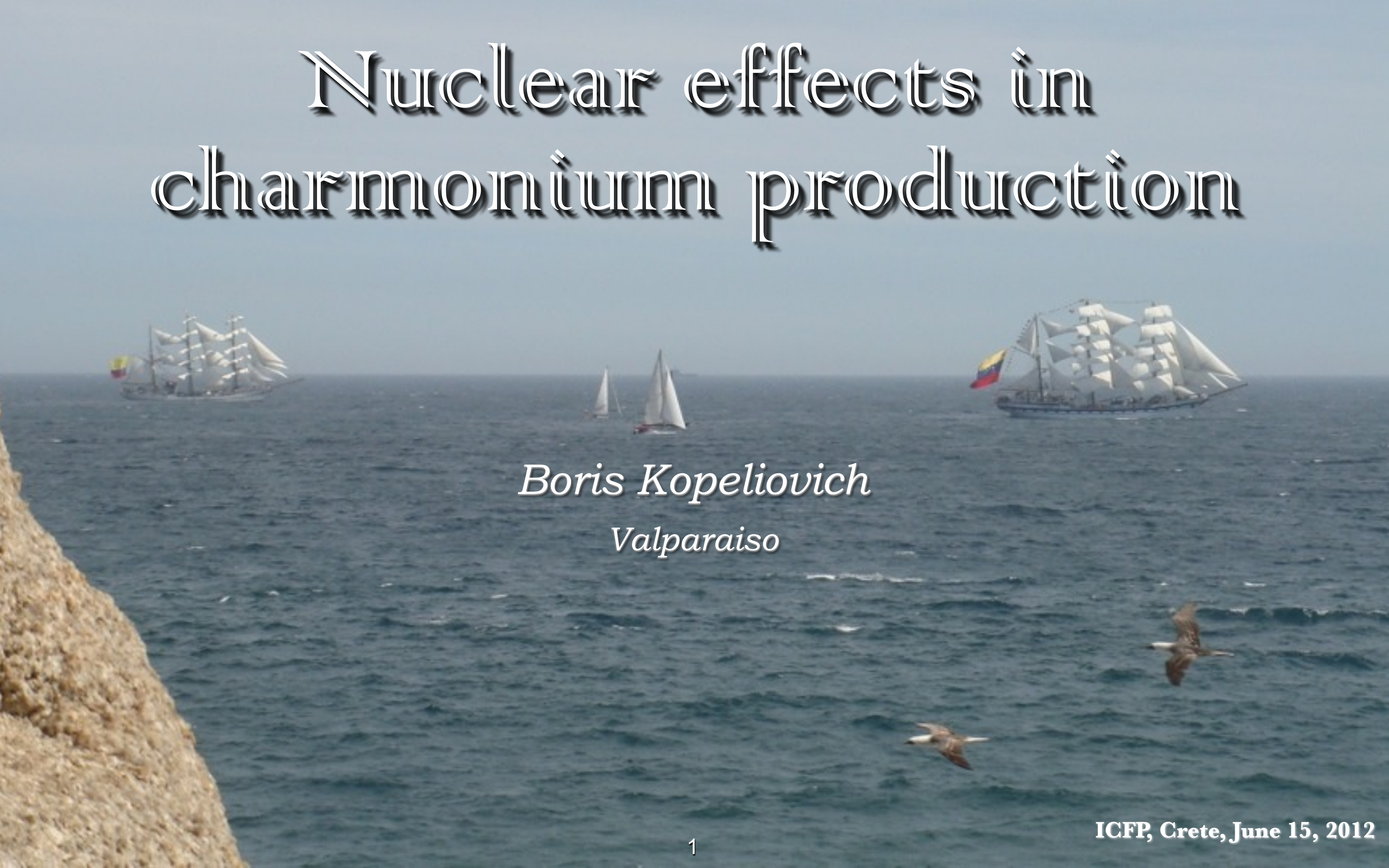
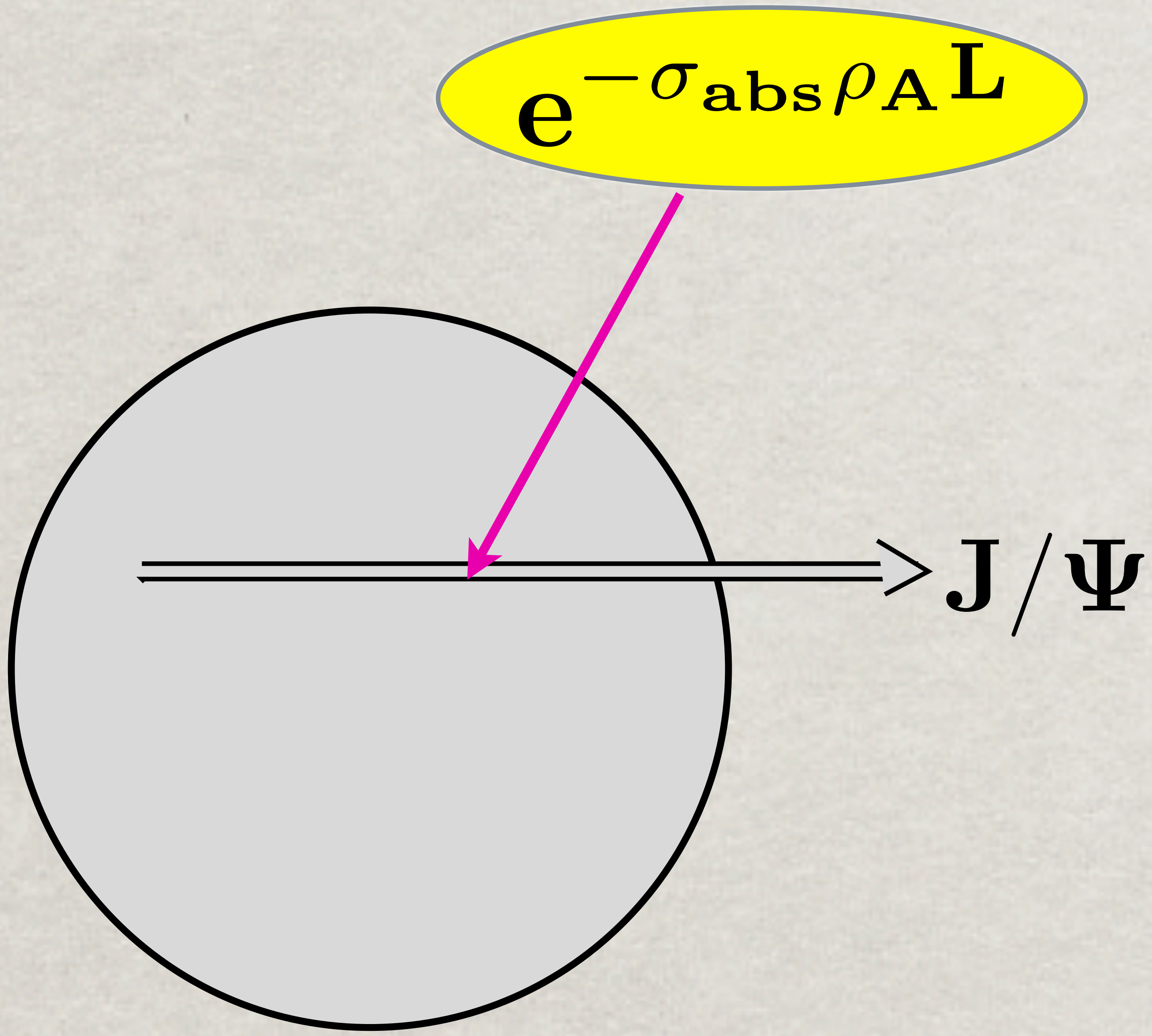
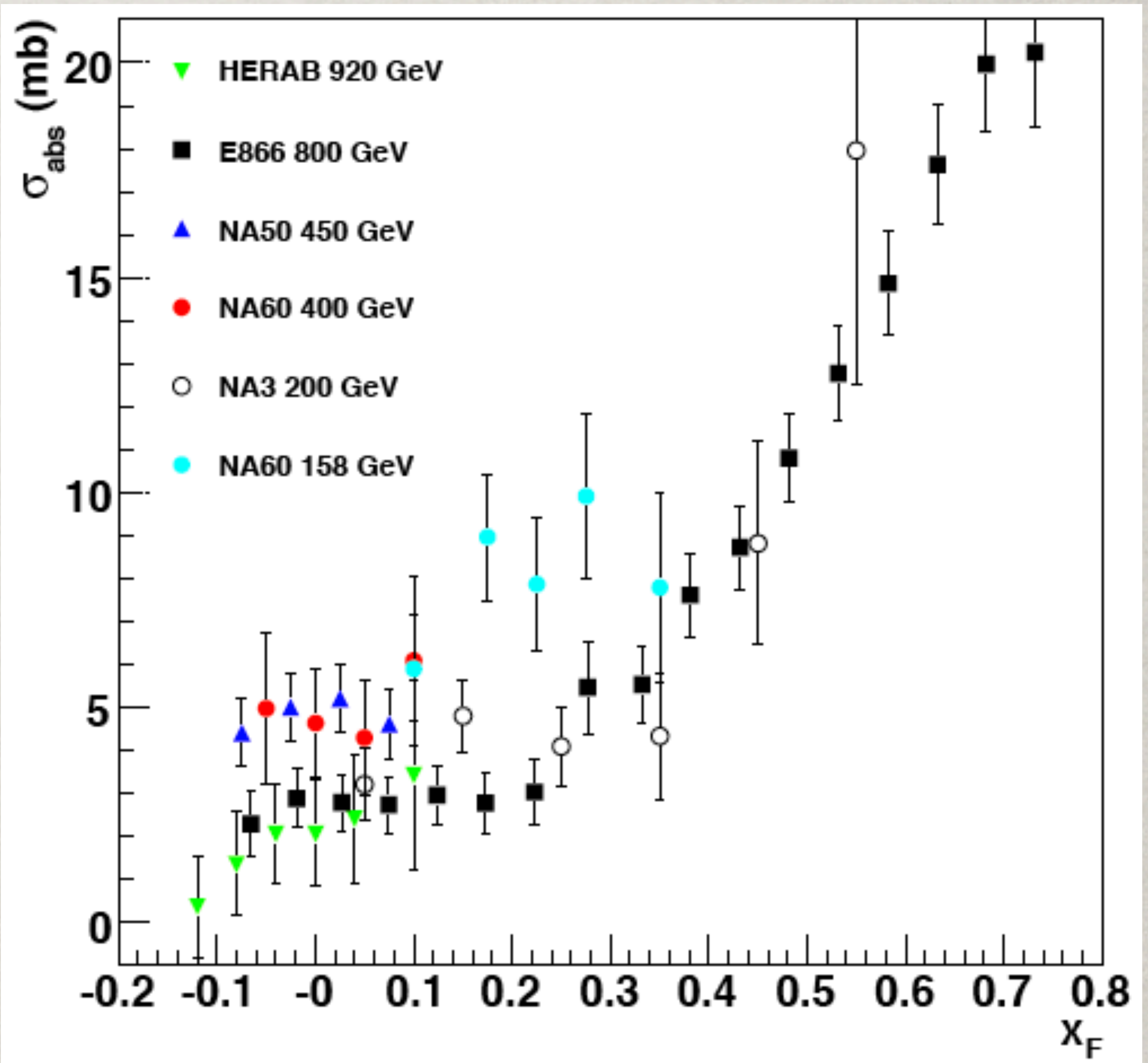
Valparaiso



ICFP, Crete, June 15, 2012

Energy dependence of σ_{abs}





¿ **NA60**: why does σ_{abs} decrease with energy ?

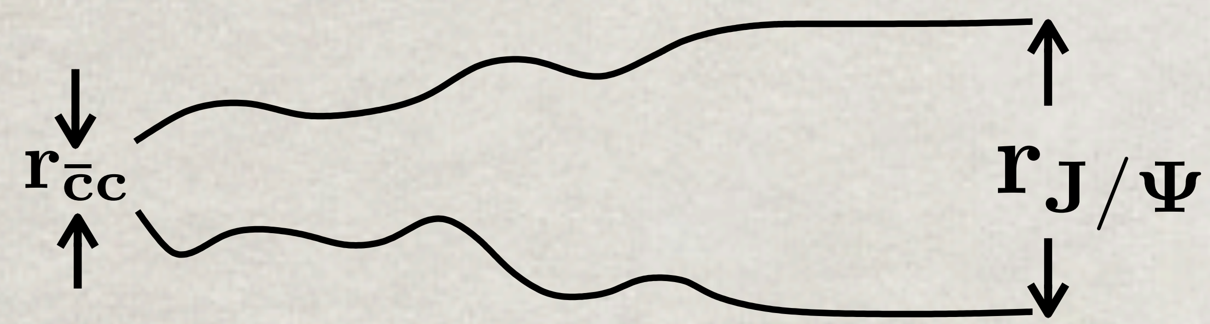
pA: J/Ψ formation and color transparency

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

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

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

Perturbative expansion



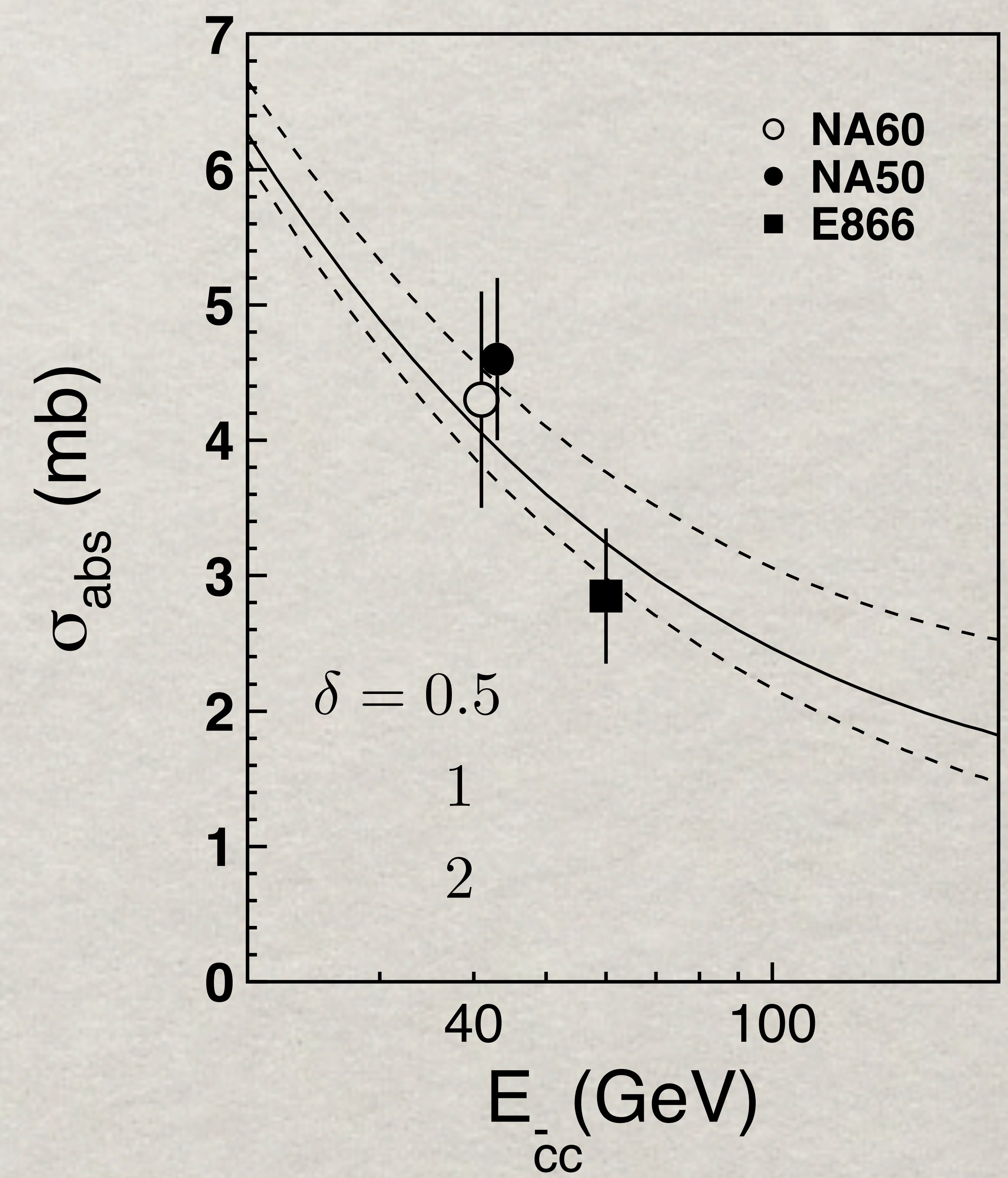
$$\frac{dr_T}{dt} = \frac{4p_T}{E_{\bar{c}c}}$$

$$r^2_T(t) = \frac{8t}{E_{\bar{c}c}} + \frac{\delta}{m^2_c}$$

The mean cross section is L- and Edependent

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

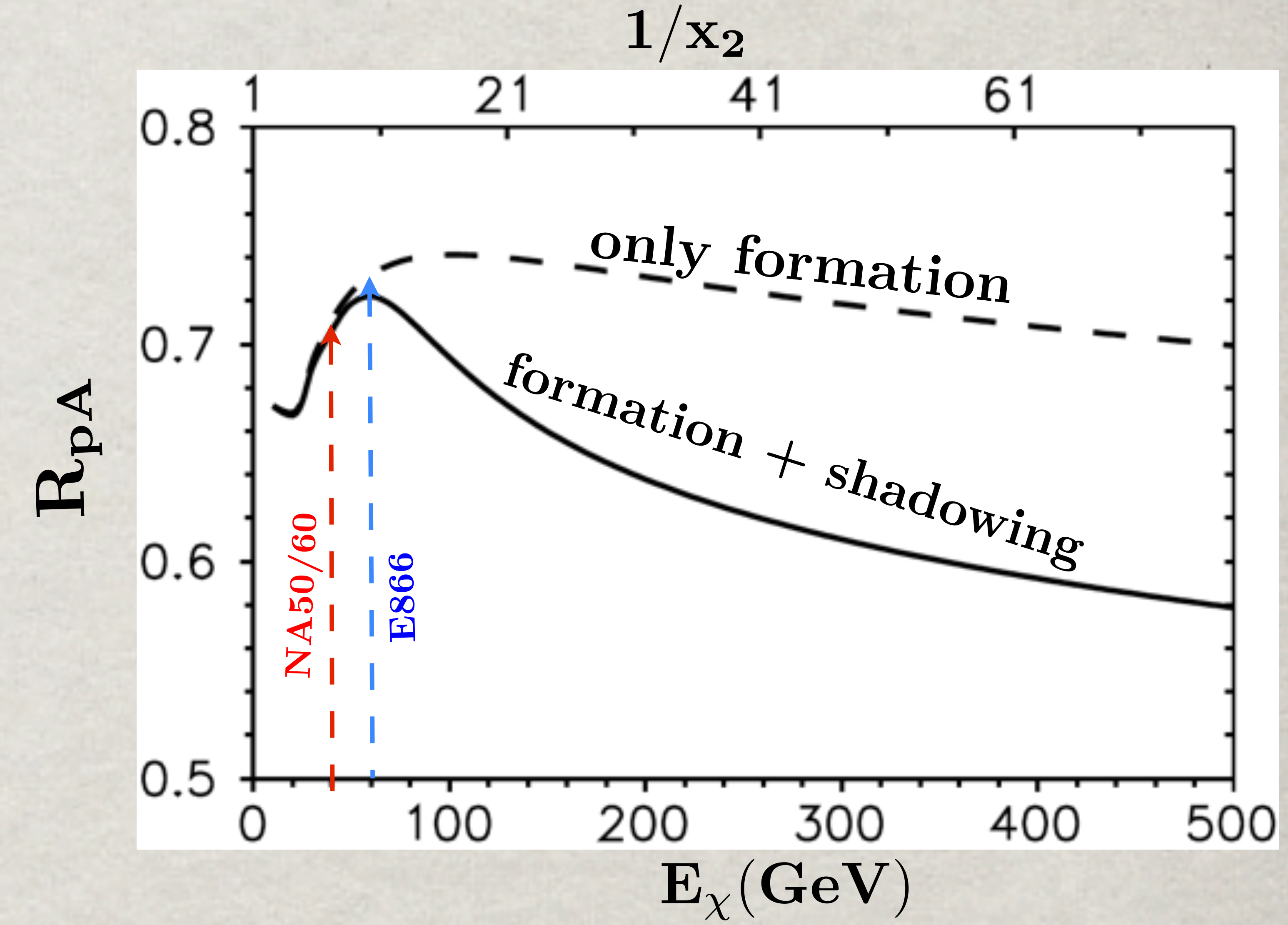
$$R_{pA} = \frac{1}{A\sigma_{abs}}\int d^2b\left[1 - e^{-\sigma_{abs}T_A(b)}\right]$$



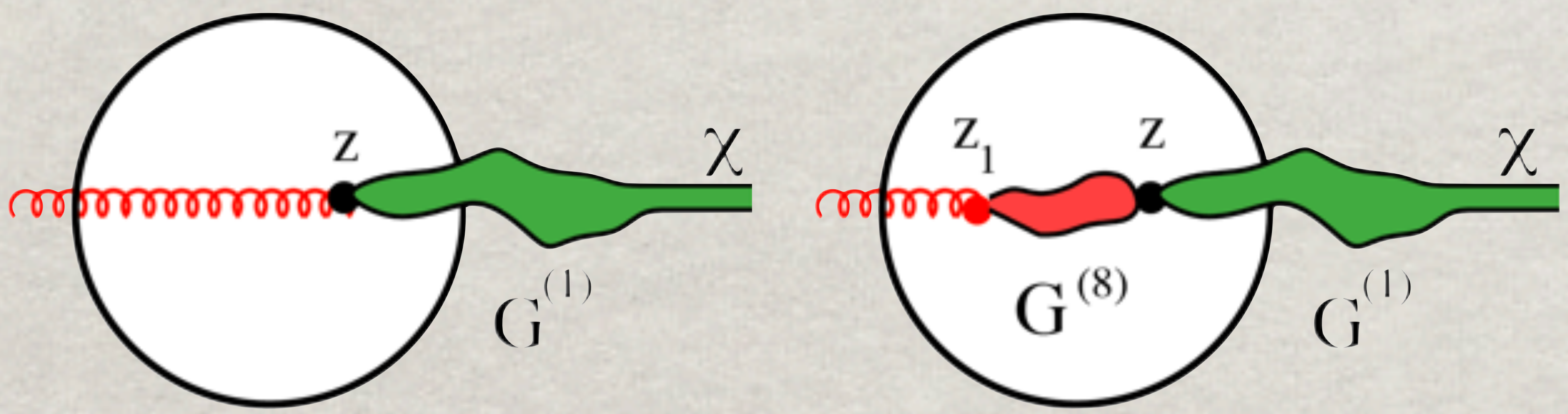
pA: Higher twist c-quark shadowing

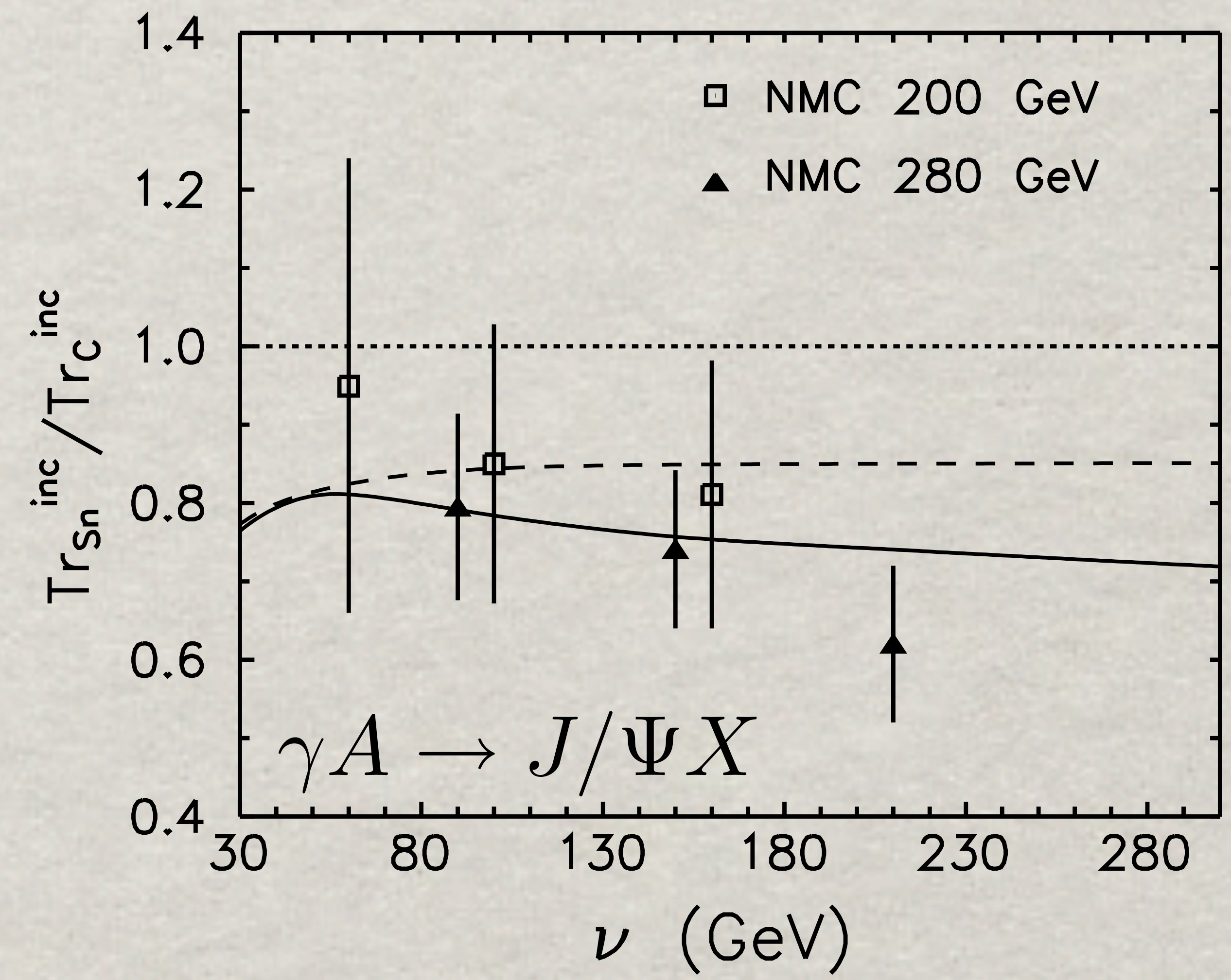
At higher energies $\bar{\sigma}_{abs}$ is affected by another time scale, the lifetime of a $c\bar{c}$ fluctuation

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



If $t_p \gtrsim R_A$ the initial state fluctuation $g \to \bar{q}q$ 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.

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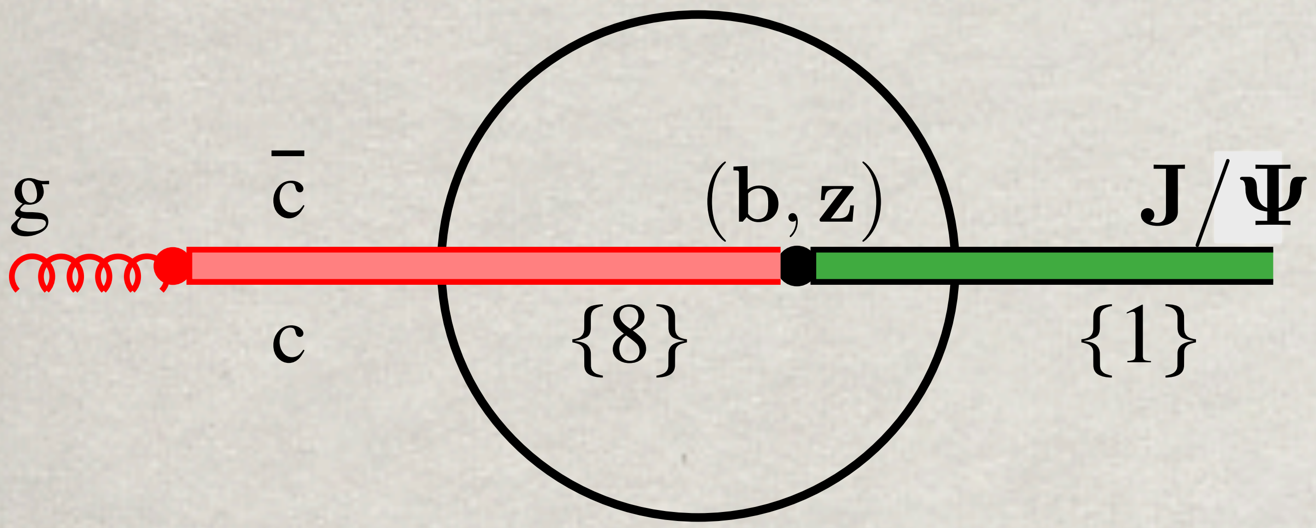
pA: Charmonium suppression at RHIC/LHC



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

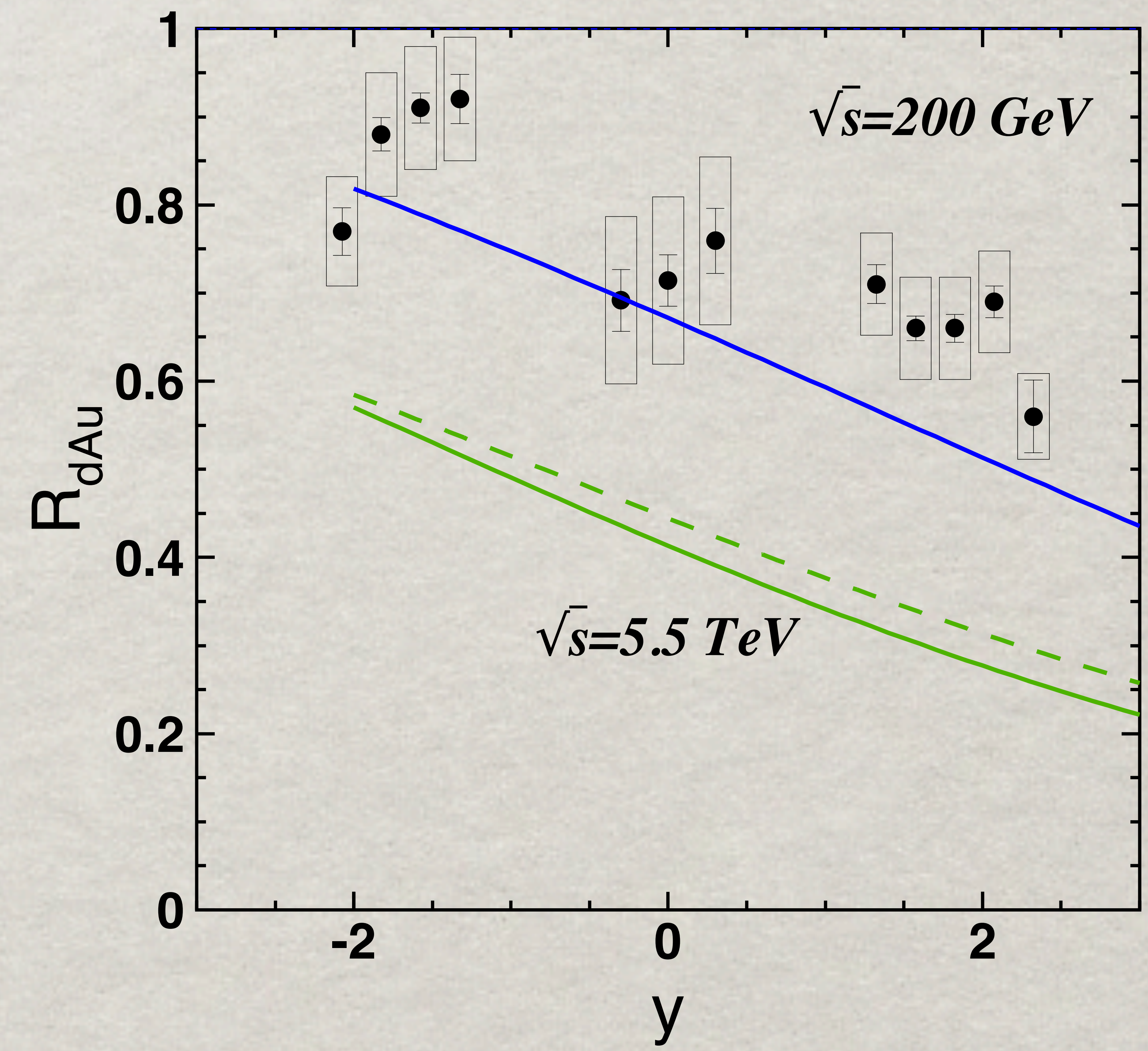
$$S_{pA}(b,z) = \int d^2r_T\, K_0(m_c r_T)\, r_T^2\, \Psi_{J/\Psi}(r_T) e^{-\frac{1}{2}\sigma_{\bar{c}cg}(r_T)T_-(b,z)-\frac{1}{2}\sigma_{\bar{c}c}(r_T)T_+(b,z)}$$

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

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

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

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



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.

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pA: Cronin effect

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

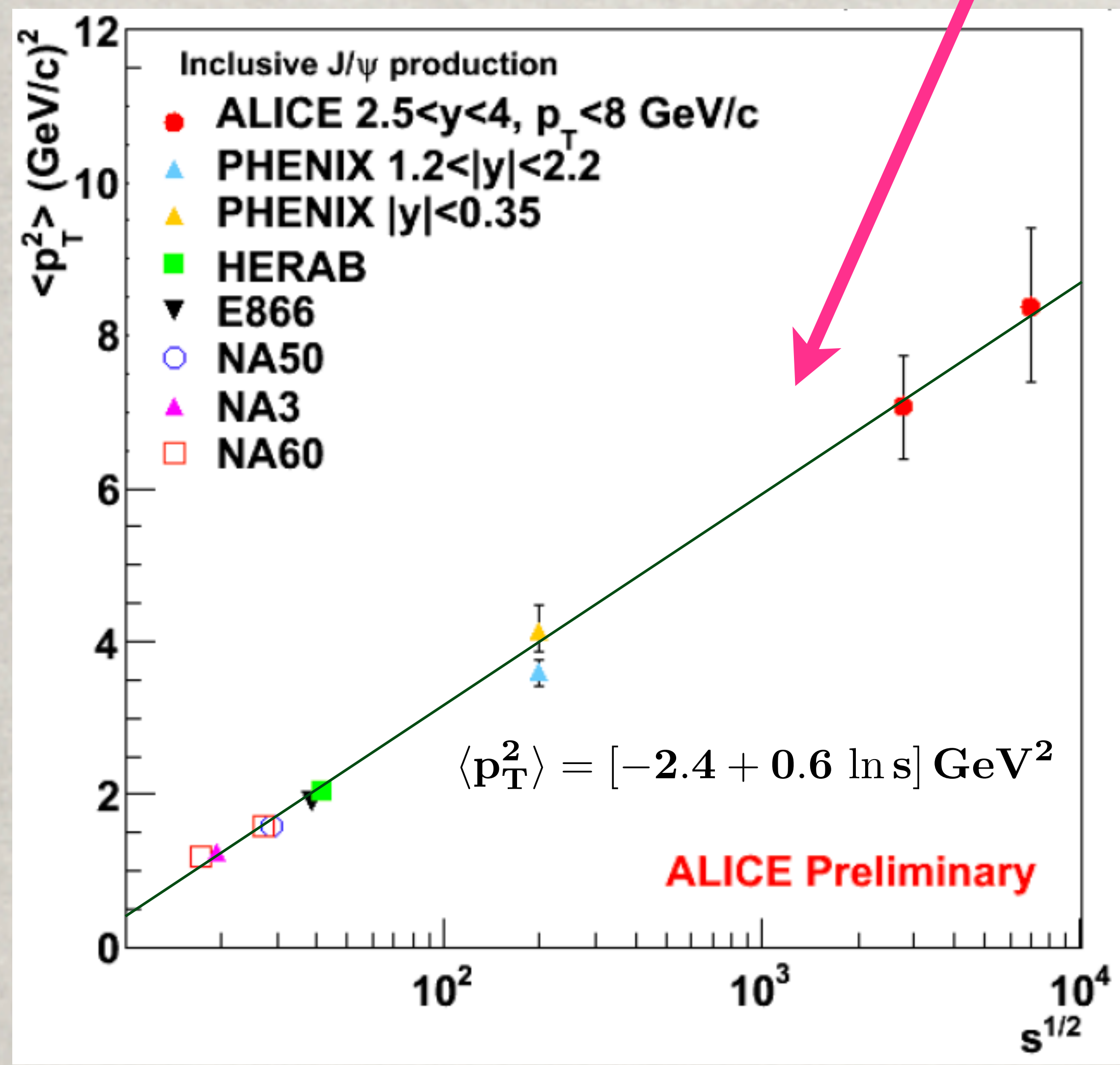
$$\frac{d\sigma_{pp}(J/\Psi)}{dp_T^2} \propto \left(1 + \frac{p_T^2}{6\langle p_T^2\rangle}\right)^{-6}$$

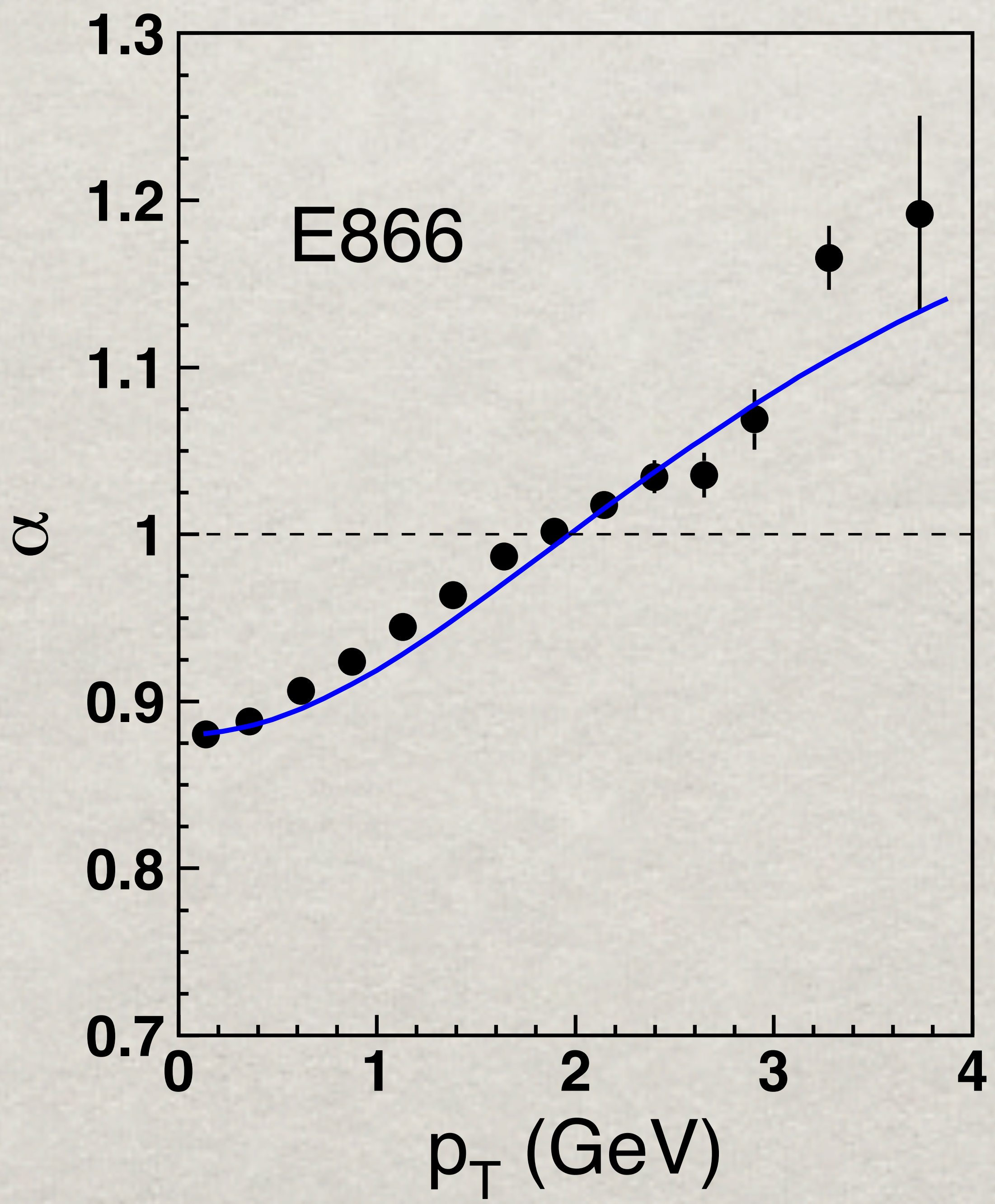
In pA collisions $\langle p_T^2\rangle$ is increased

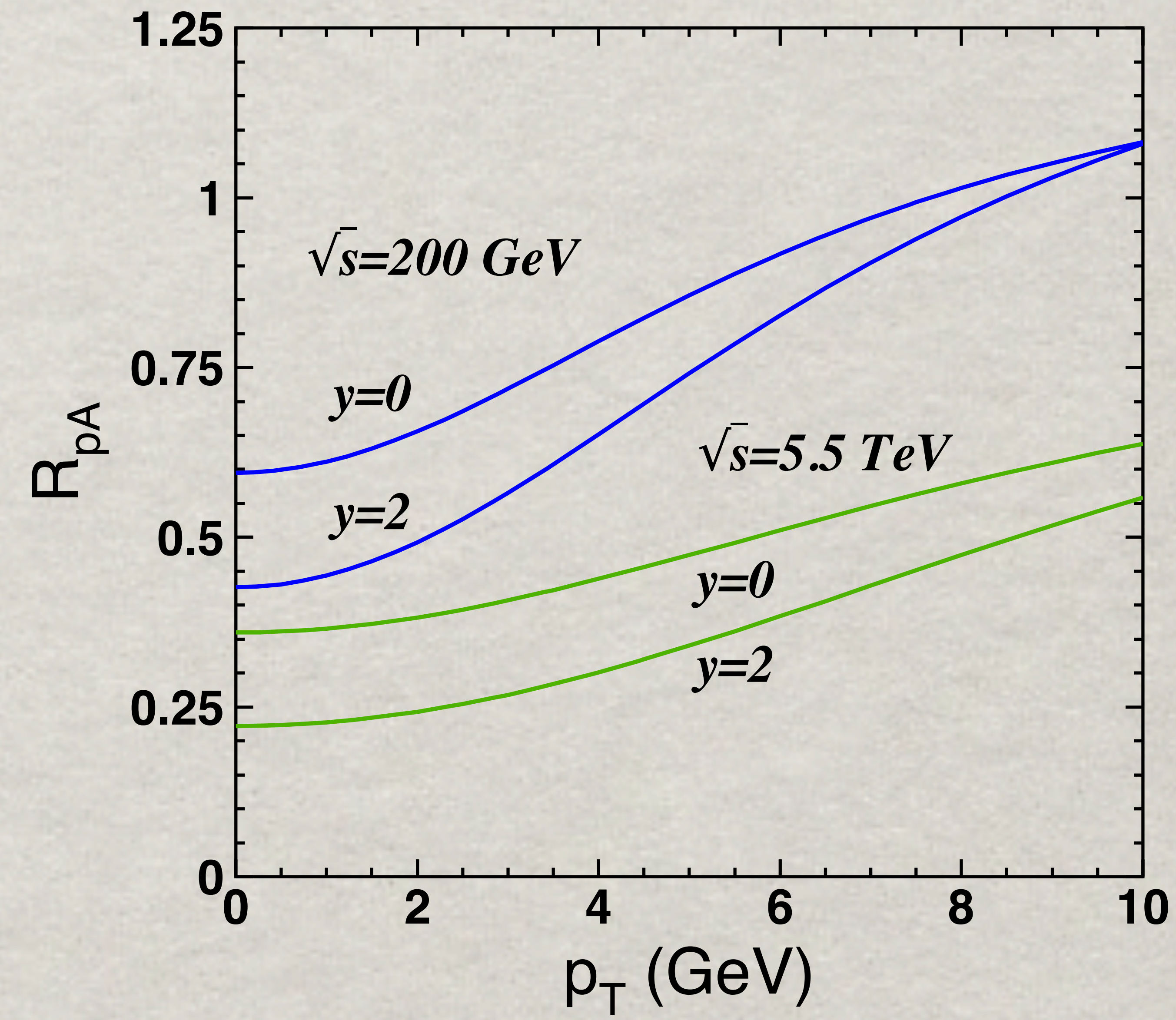
$$\langle p_T^2\rangle_{pA} = \langle p_T^2\rangle_{pp} + Q_s^2$$

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

$$Q_{sA}^2(b) = \vec{\nabla}_{r_T}^2\, \sigma_{dip}(r_T)\Big|_{r_T=0} T_A(b)$$







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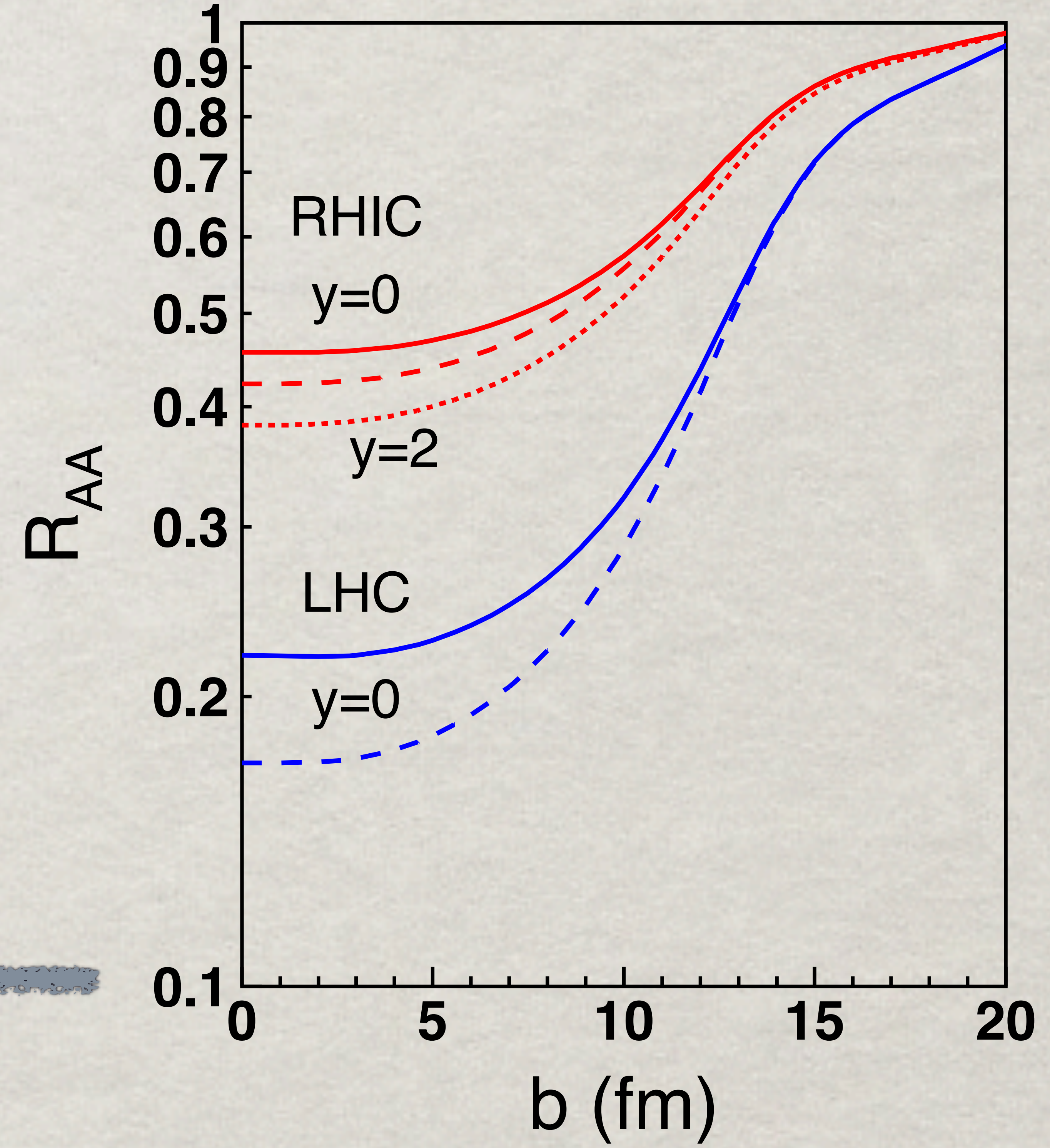
B.Z. Kopeliovich, Crete, June 15, 2012

pA-AA (ISI): Double color filtering

Survival probability of a dipole in a medium:

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

$\sigma_{\mathbf{abs}}$ **is the break-up cross section**



Color transparency makes the medium more transparent

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

Simultaneous propagation through two nuclei

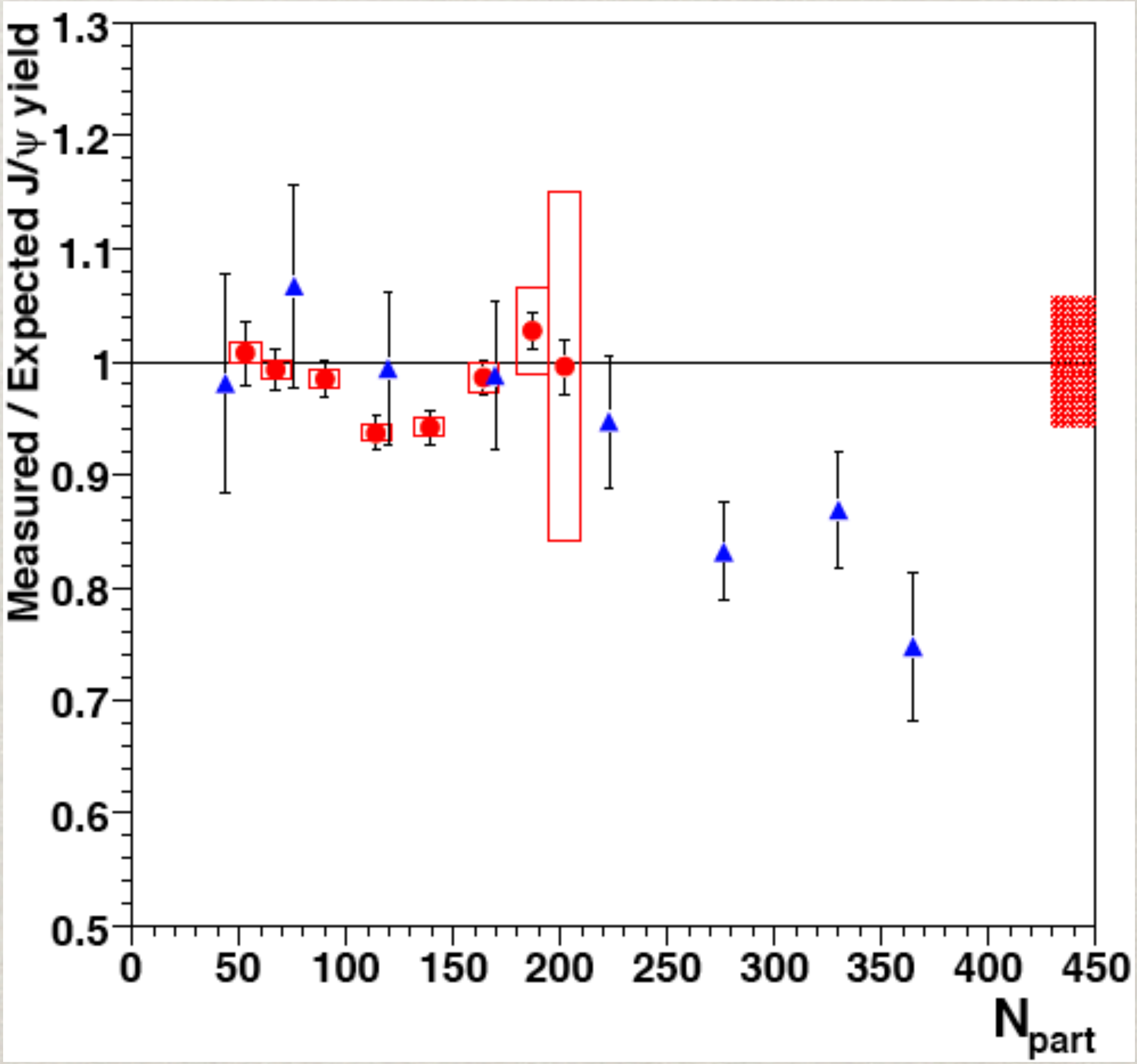
Naive: $$\mathbf{P(L_A, L_B) = P(L_A)P(L_B) = \frac{1}{(1 + \sigma_{abs}\rho L_A)(1 + \sigma_{abs}\rho L_B)}}$$

Double color filtering: $$\mathbf{P(L_A, L_B) = \frac{1}{1 + \sigma_{abs}\rho(L_A + L_B)}}$$

NA50: J/Ψ probes the QGP.

¡ Anomalous suppression in central AA collisions !

¿ Why does the "anomalous" J/Ψ suppression signal about QGP at SPS, but the jet quenching doesn't ?



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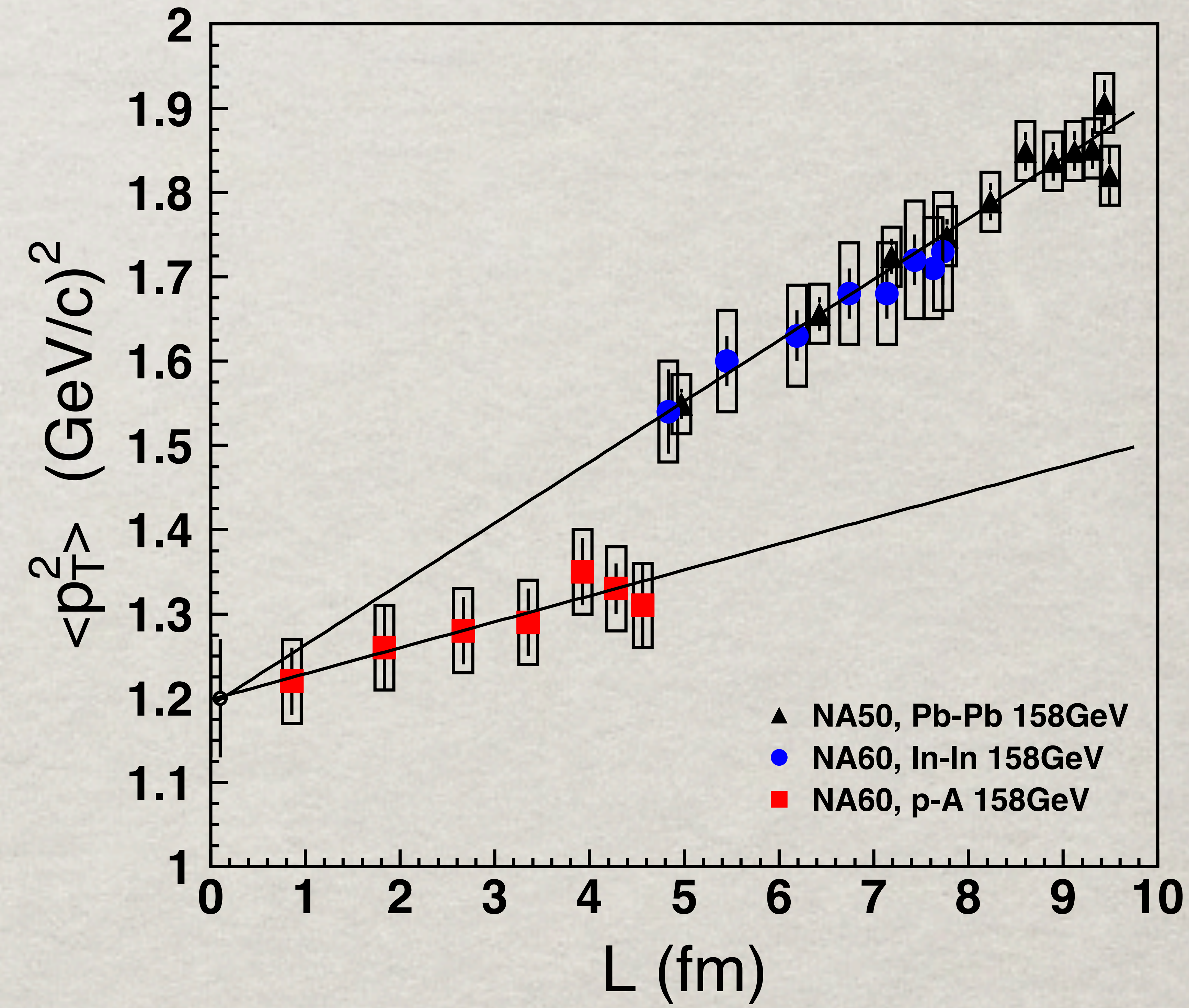
B.Z. Kopeliovich, Crete, June 15, 2012

Broadening of J/Ψ in pA and AA collisions

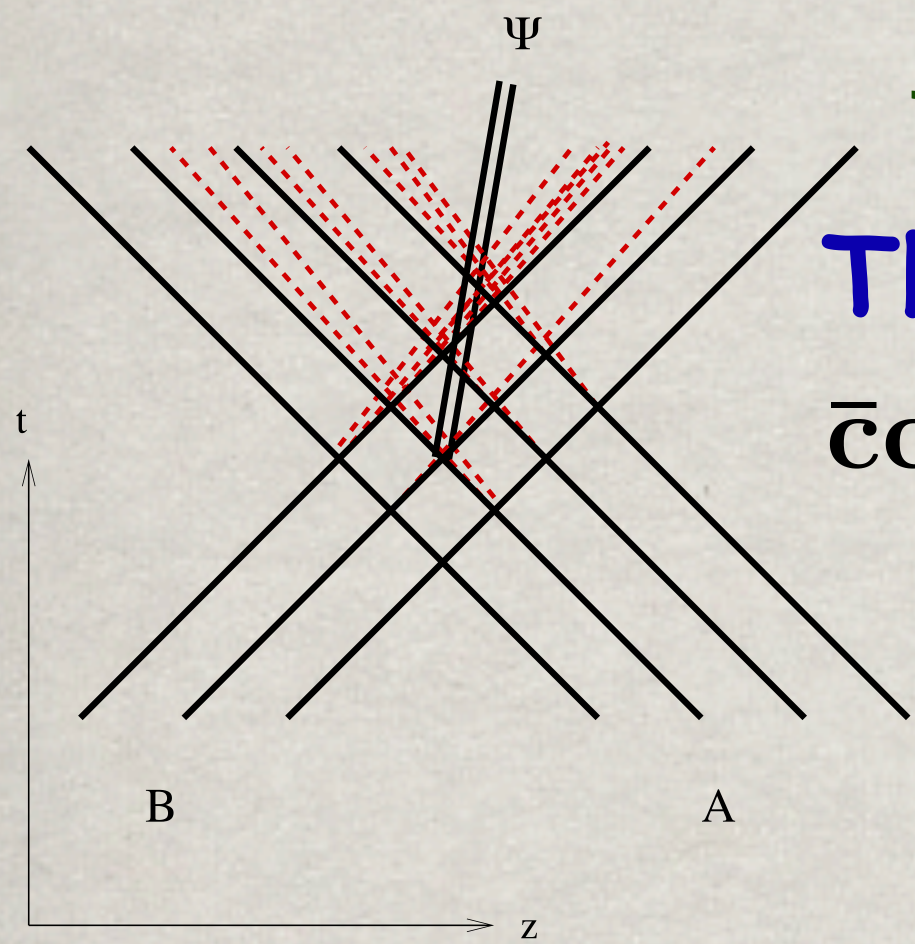
Broadening is an ISI effect, it is not affected by the QGP

NA50/60: why broadening in pA is twice smaller than in AA?



¿ Is the "cold" nuclear matter really cold ?

pA- 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

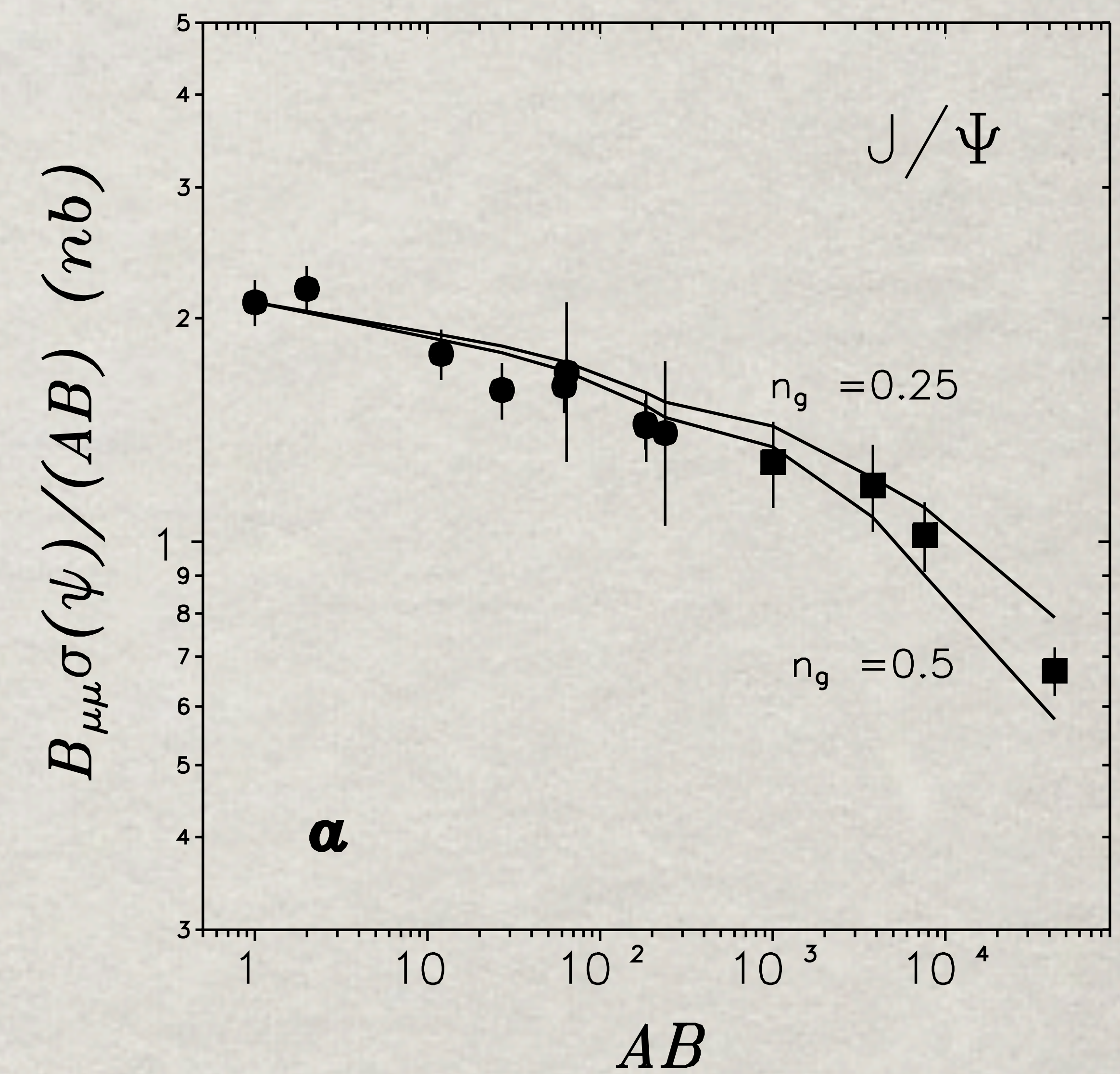
Gluon radiation time

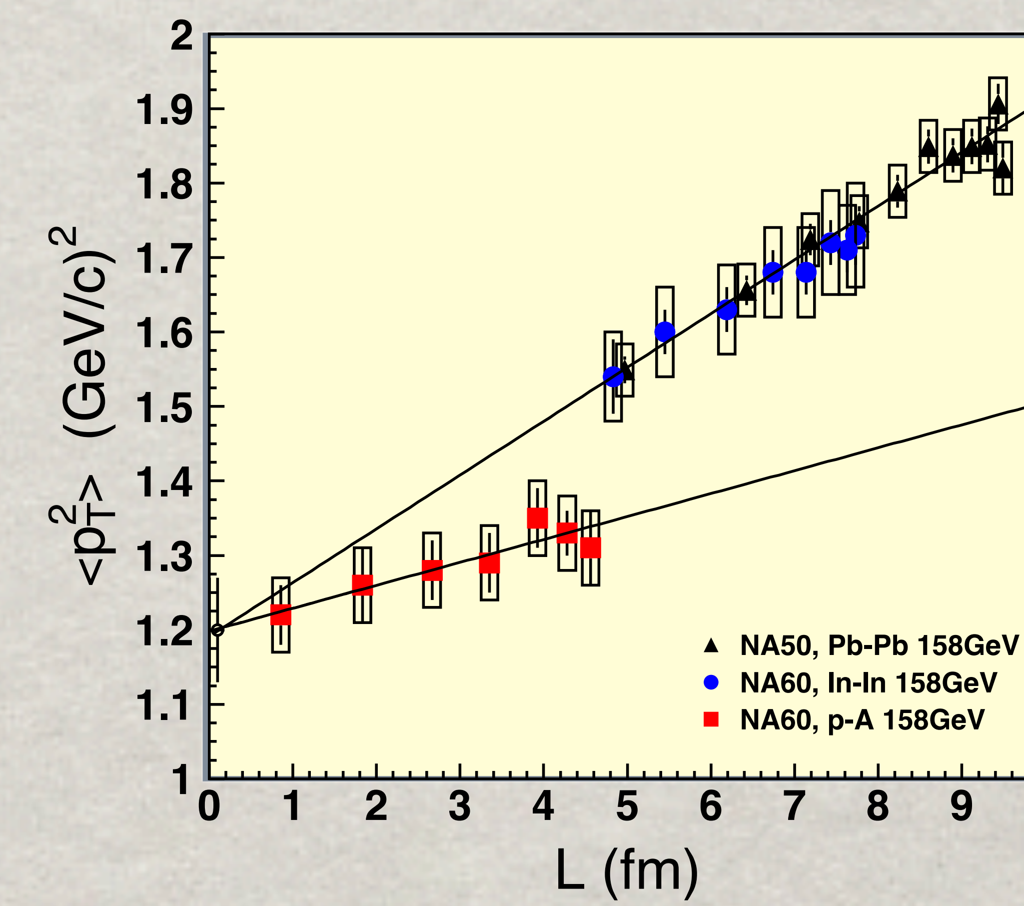
$$l_f^g = \frac{2\,E_q\,\alpha(1-\alpha)}{\alpha^2 m_q^2 + k^2}$$

$$\langle n_g \rangle = \frac{3}{\sigma_{in}(NN)} \int\limits_{k^2_{min}}^{\infty} dk^2 \int\limits_{\alpha_{min}}^{1} d\alpha\, \frac{d\sigma(qN\to gX)}{d\alpha\, dk^2}\, \Theta(\Delta z - l_f^g)$$

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

The effect vanishes at the energies of RHIC and LHC.





Broadening is not additive

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pA- AA (ISI): Excitation of higher Fock components

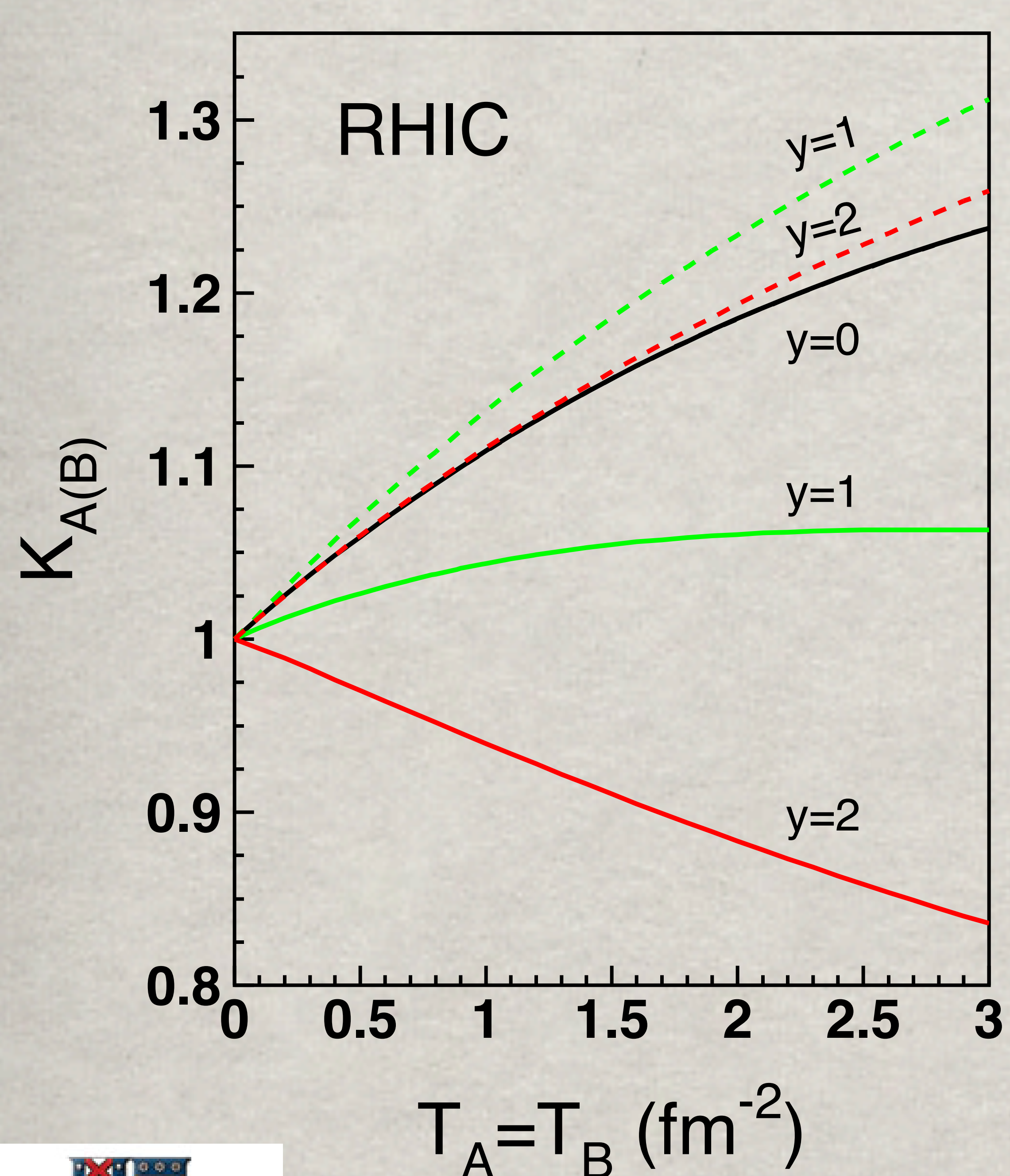
Like at low energies, broadening in AA collision should be enhanced compared to pA, but for another reason: boosted saturation scale.

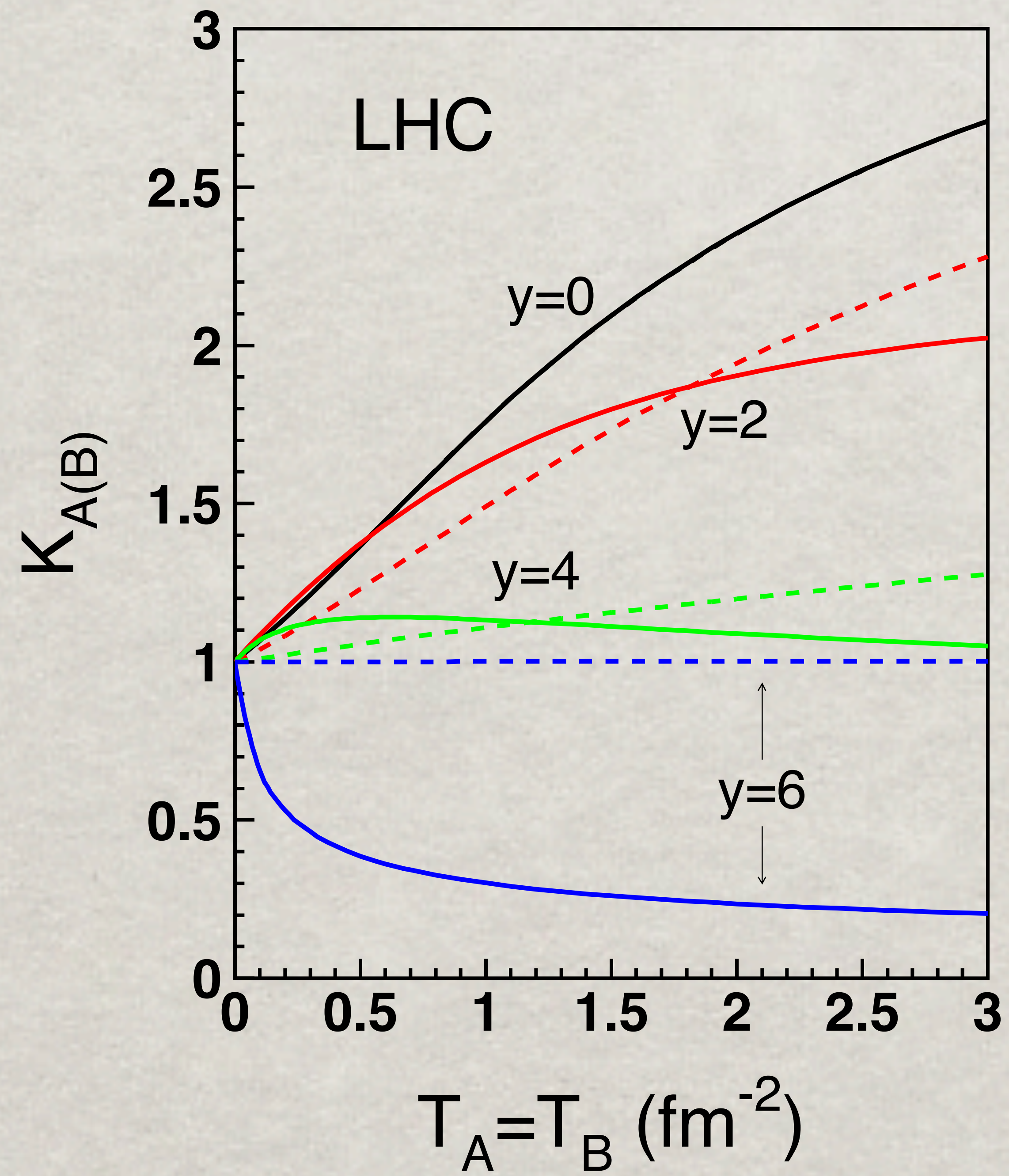
Mutual multiple interactions of the nucleons enhance the higher Fock states, containing more gluons at small x.

$$\tilde{Q}^2_{sB}(x_B) = \frac{3\pi^2}{2}\alpha_s(\tilde{Q}^2_{sA} + Q^2_0)x_B g_N(x_B, \tilde{Q}^2_{sA} + Q^2_0)\,T_B$$

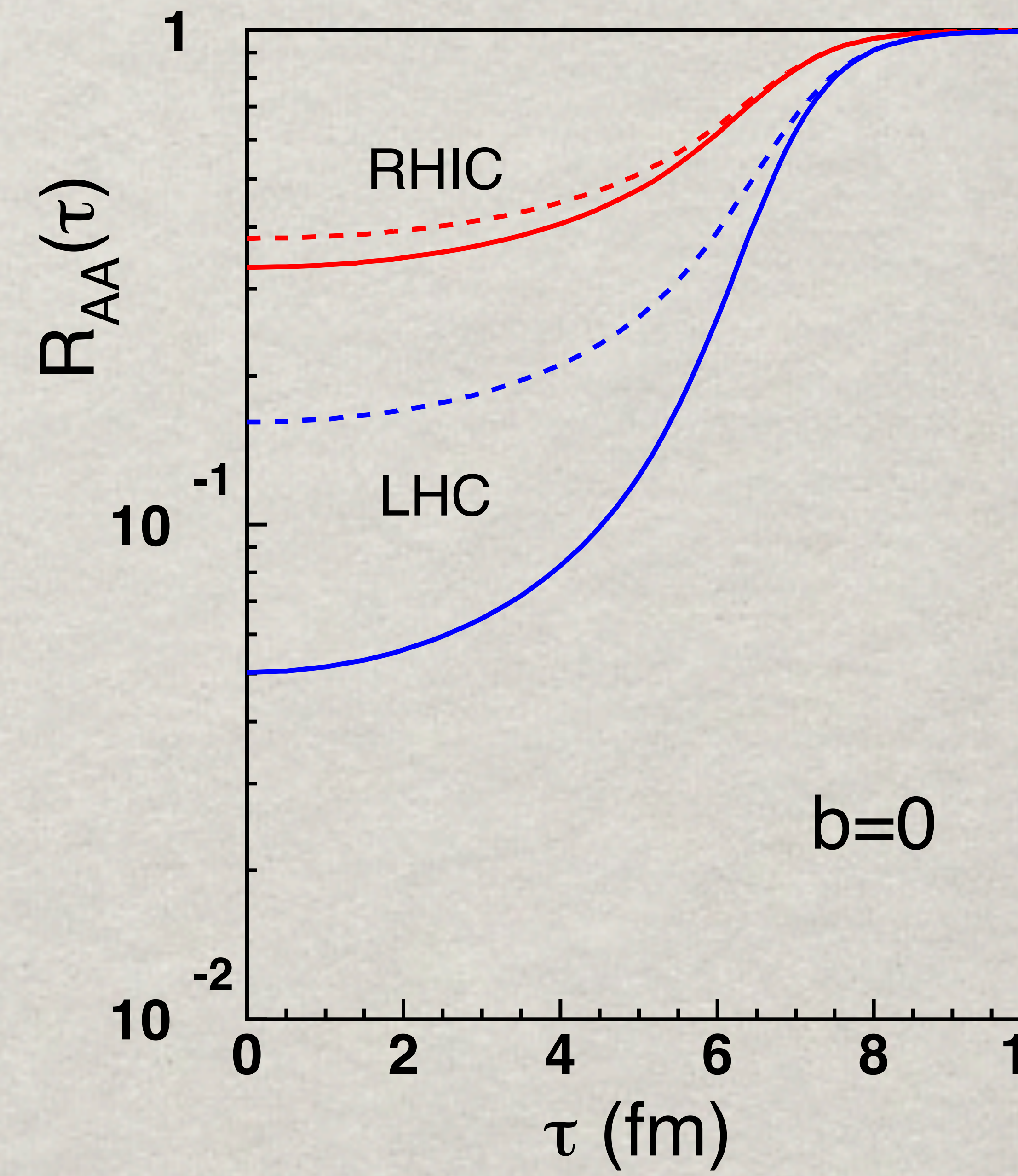
$$\tilde{Q}^2_{sA}(x_A) = \frac{3\pi^2}{2}\alpha_s(\tilde{Q}^2_{sB} + Q^2_0)x_A g_N(x_A, \tilde{Q}^2_{sB} + Q^2_0)\,T_A$$

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



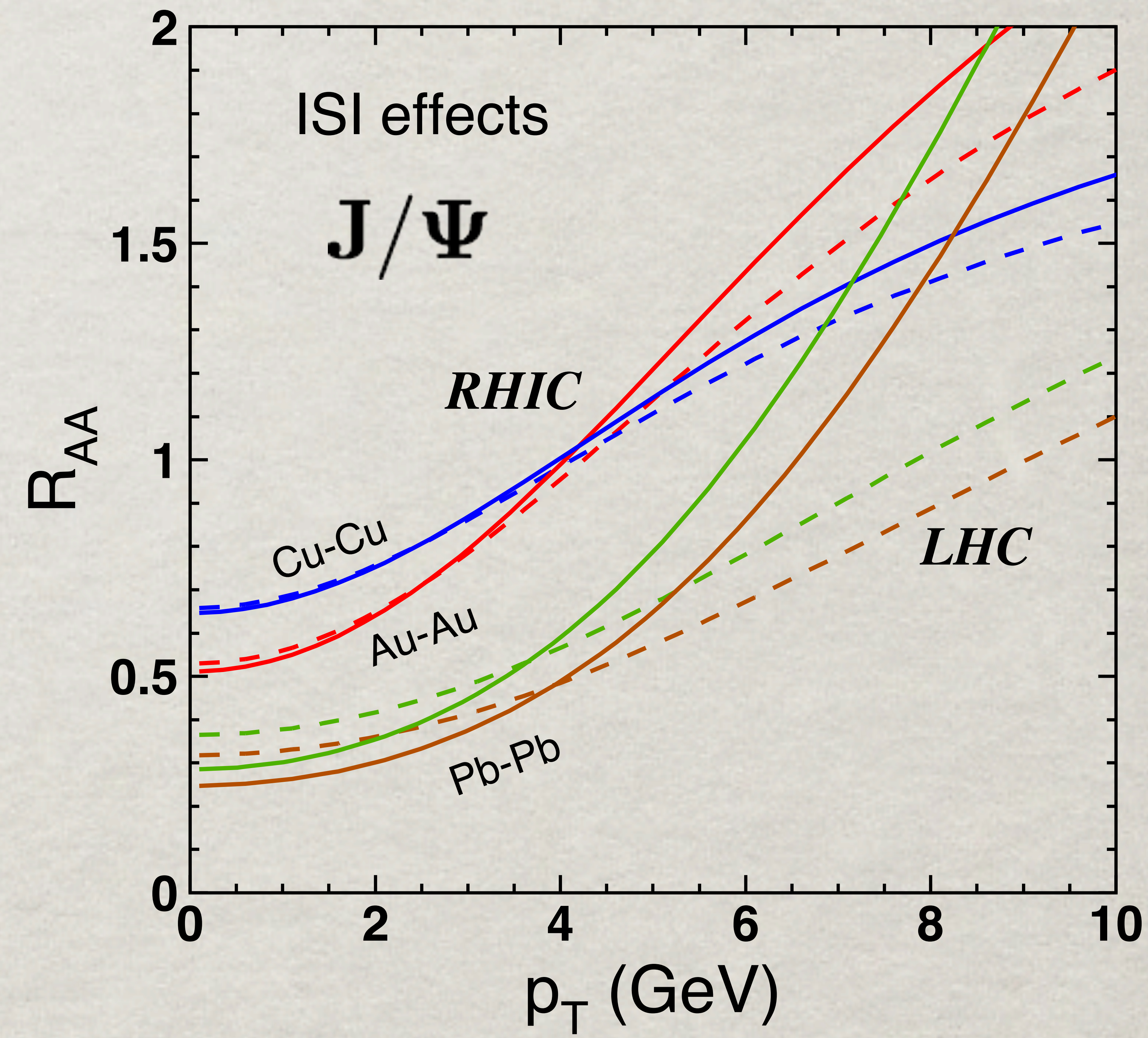


Cold nuclear matter is not cold



pA- 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 $p_T > 5\text{GeV}$

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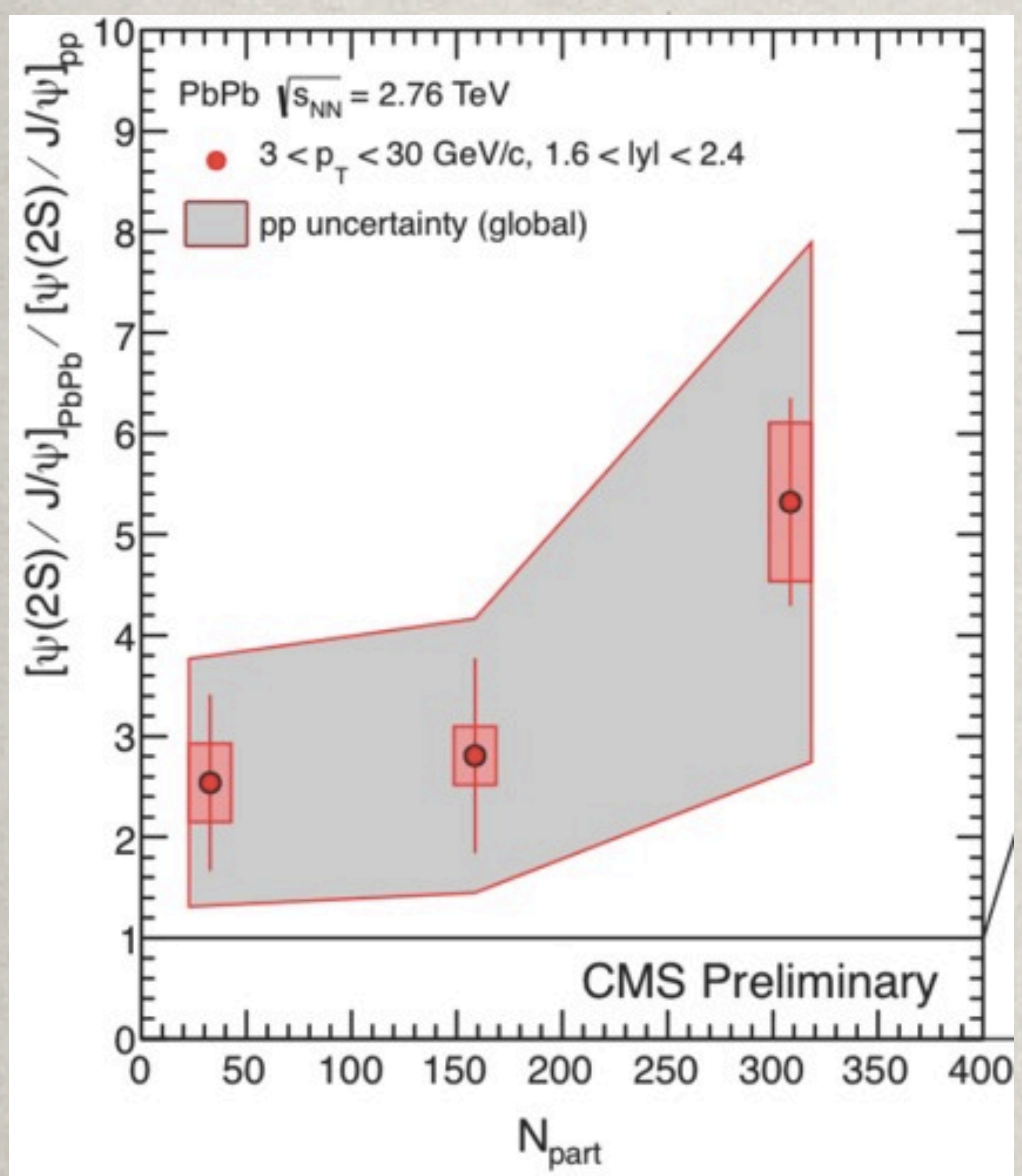
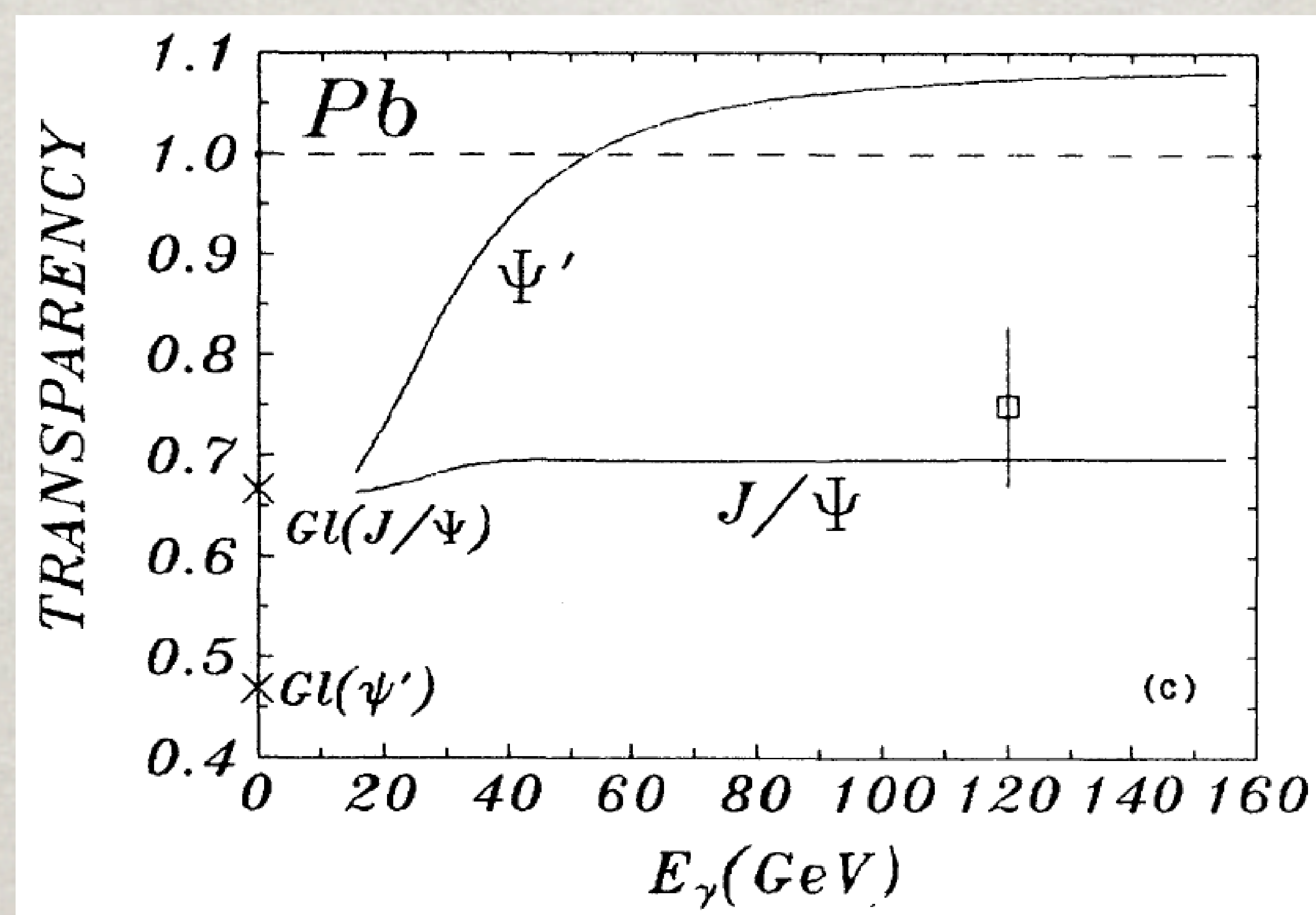
Nuclear enhancement of Ψ'

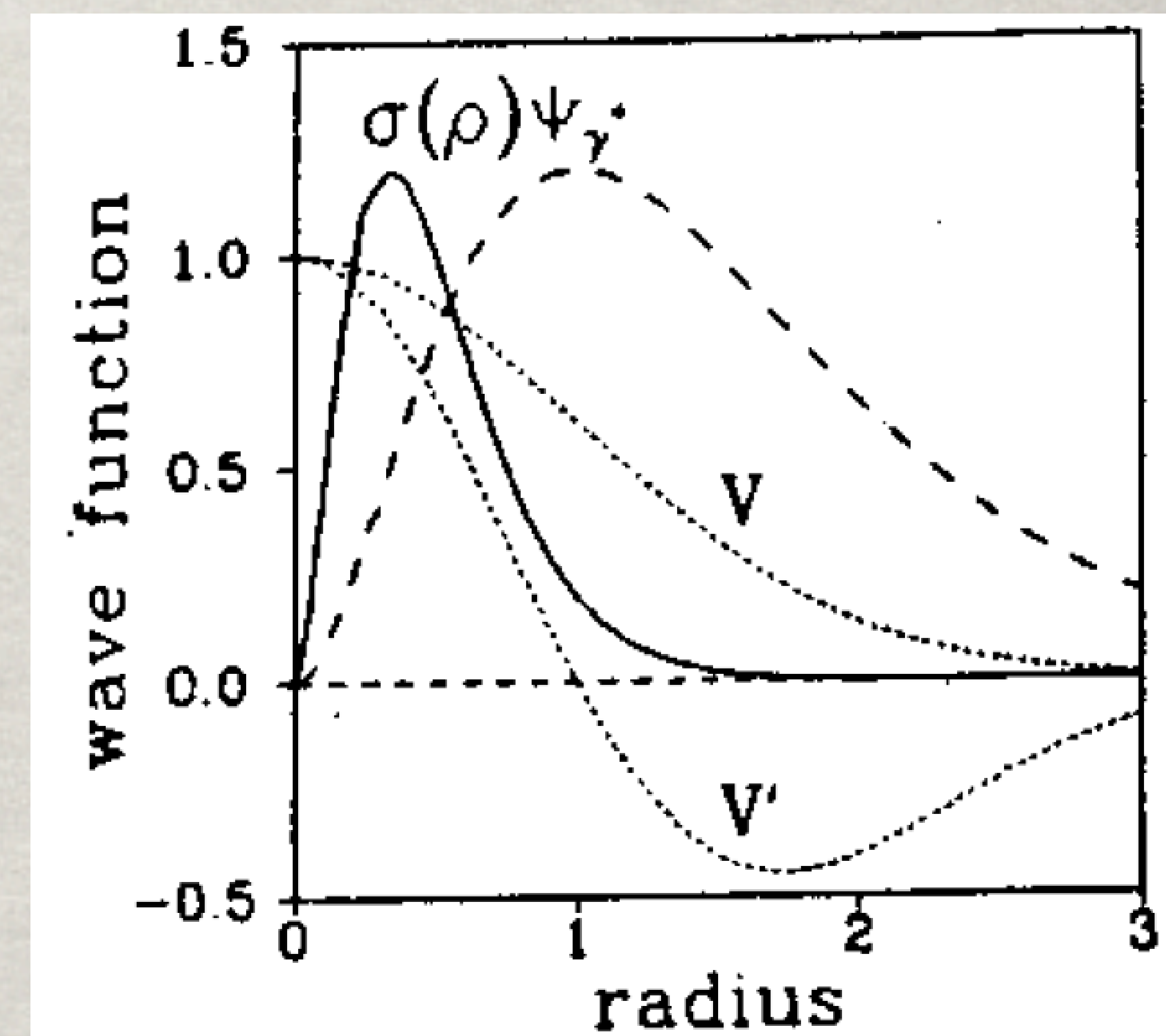
$$\gamma + \mathbf{A} \rightarrow \mathbf{\Psi} + \mathbf{X}$$

$$\mathbf{R_{A/p}} = \frac{\mathbf{1}}{\mathbf{A}} \int \mathbf{d^2b\, T_A(b)} \left\langle \mathbf{\Psi} \right| \exp[-\sigma(\mathbf{r})\mathbf{T_A(b)/2}] \left| \gamma \right\rangle^{\mathbf{2}}$$



B.K. & B.G.Zakharov (1991)





AA (FSI): Relevant time scales

★ **Production time:**

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

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

which is much shorter that 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

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

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

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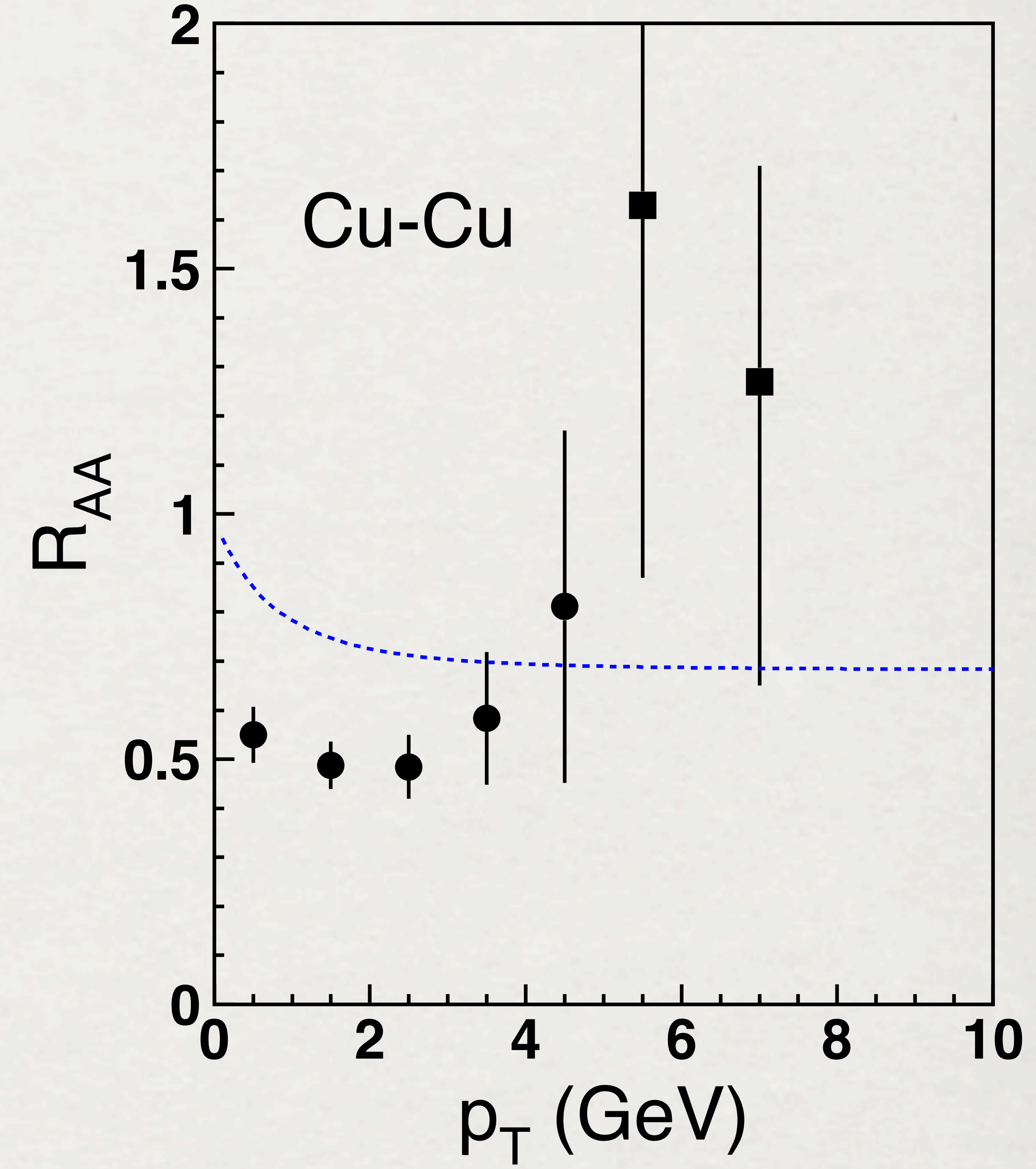
AA (FSI): Attenuation in the dense medium

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

$$\hat{q} = 2\,\rho\,\frac{d\sigma(r)}{dr^2}\Big|_{r=0} \quad \Rightarrow \quad \frac{dS(r,l)}{dl} = -\frac{1}{2}\,\hat{q}\,r^2$$

absorption rate

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



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

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

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

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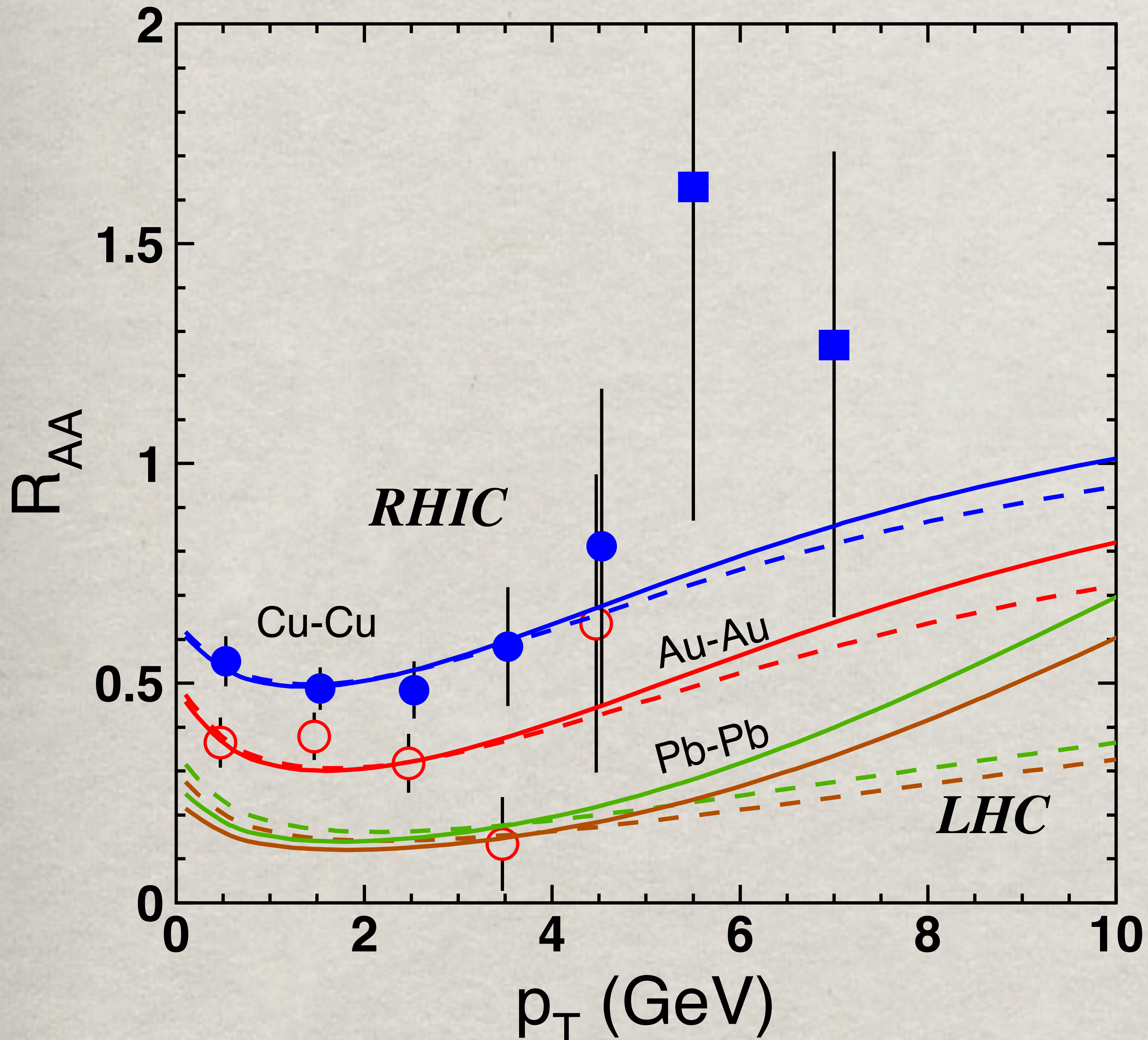
AA (FSI): Attenuation in the dense medium

The combined ISI and FSI effects



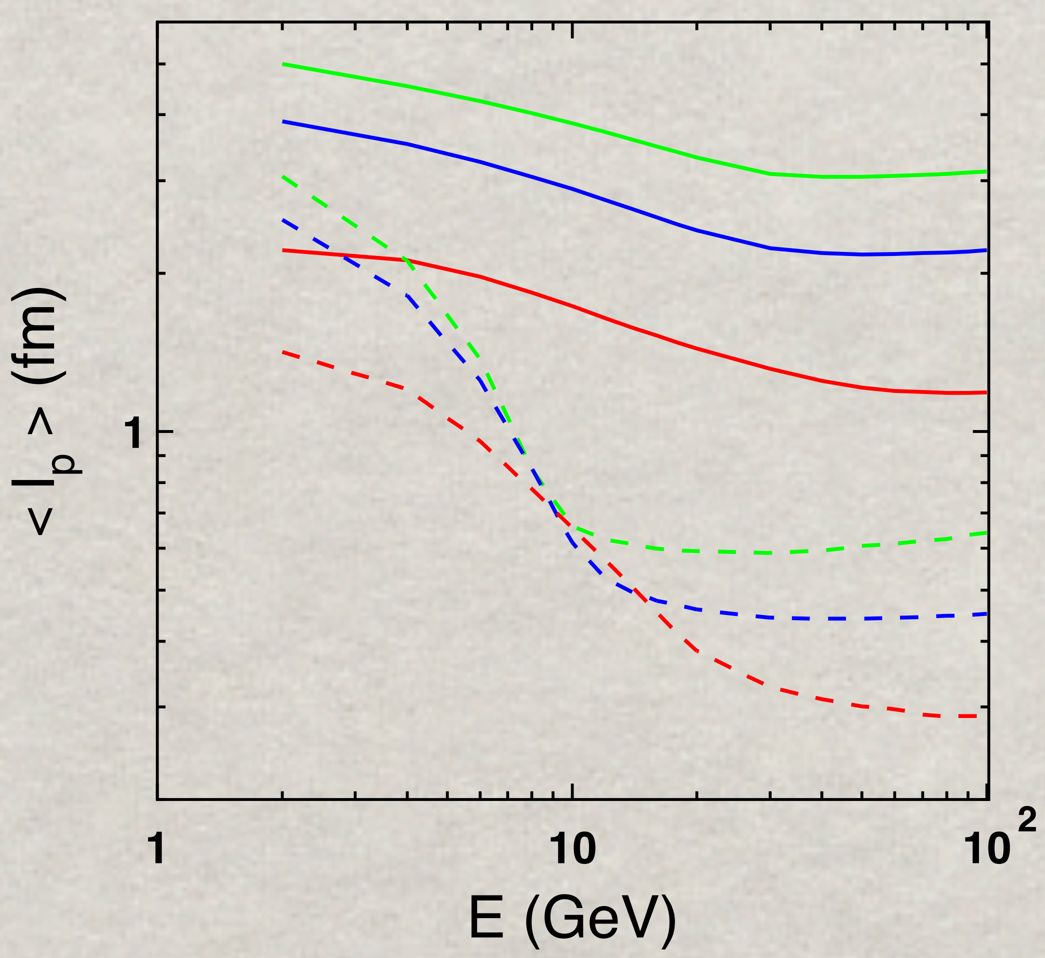
The $\mathbf{p_T}$-integrated ratio

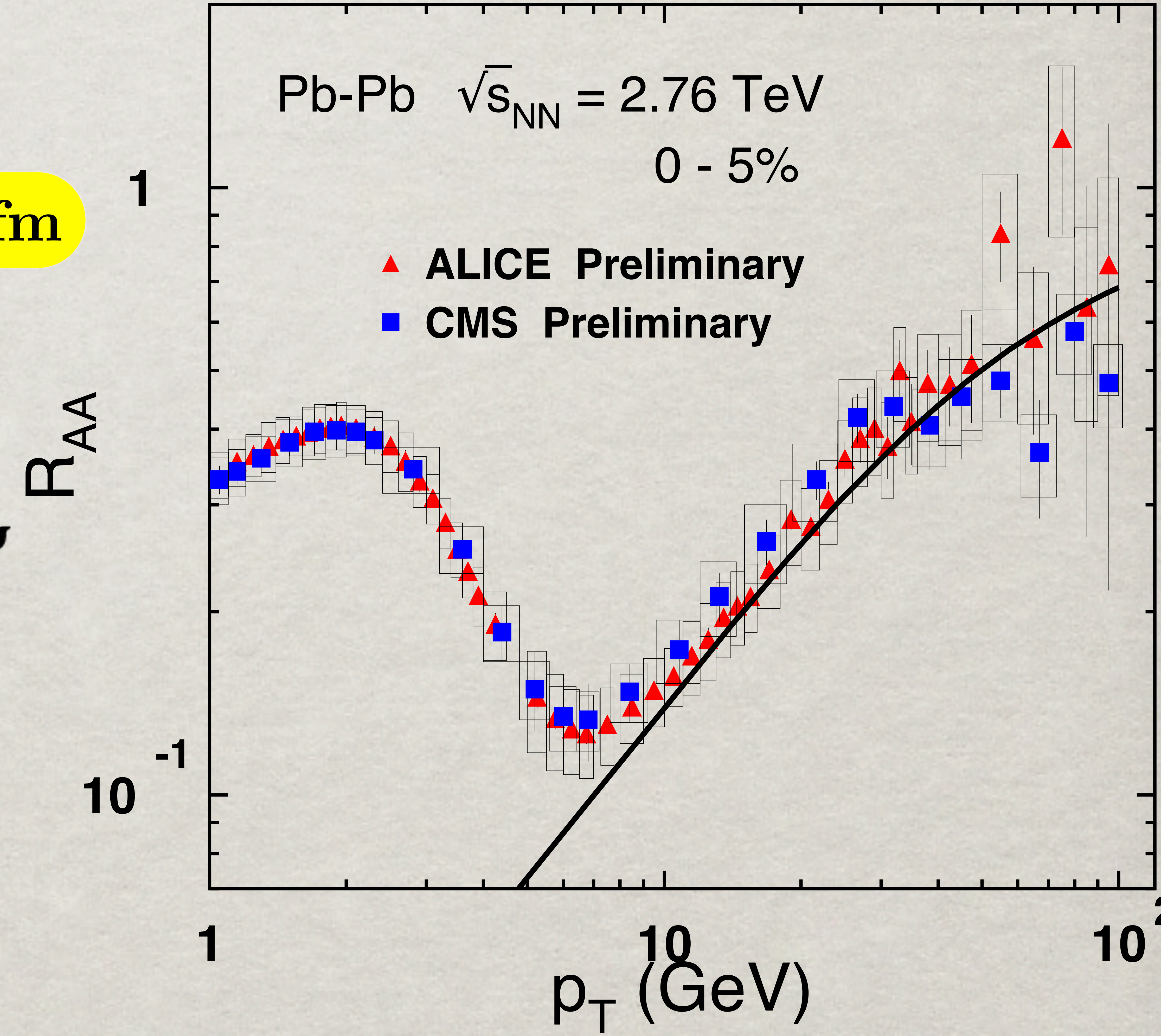
Cu-Cu	$\sqrt{s} = 200\,\mathrm{GeV}$	$R_{AA} = 0.54$
Au-Au	$\sqrt{s} = 200\,\mathrm{GeV}$	$R_{AA} = 0.34$
Pb-Pb	$\sqrt{s} = 2.76\,\mathrm{TeV}$	$R_{AA} = 0.18$
Pb-Pb	$\sqrt{s} = 5.50\,\mathrm{TeV}$	$R_{AA} = 0.16$

Test with jet quenching

The main result, smallness of $\hat{q}_0$, is confirmed by comparison with the analysis of high-pT hadron suppression at LHC: $\hat{q}_0 \approx 0.8\,\mathrm{GeV}^2/\mathrm{fm}$

Shortness of the production length for a light-quark dipole makes pion quenching similar to J/Ψ





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Summary

- J/Ψ production offers an alternative way to probe the transport coefficient of the medium created in HI collisions.

- pA -> AA transition is nontrivial and model dependent

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

- 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, $\hat{q}_0 \sim 0.5\ \mathrm{GeV}^2/\mathrm{fm}$, compared to the results of jet quenching analyses based on the energy loss scenario.

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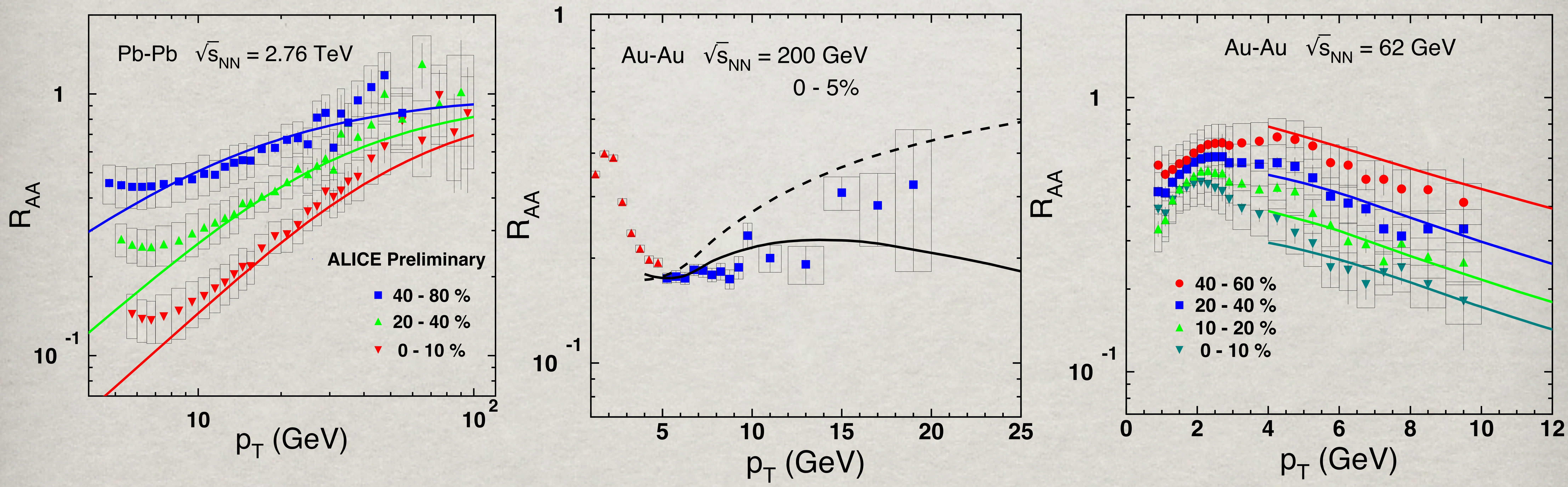
Backups



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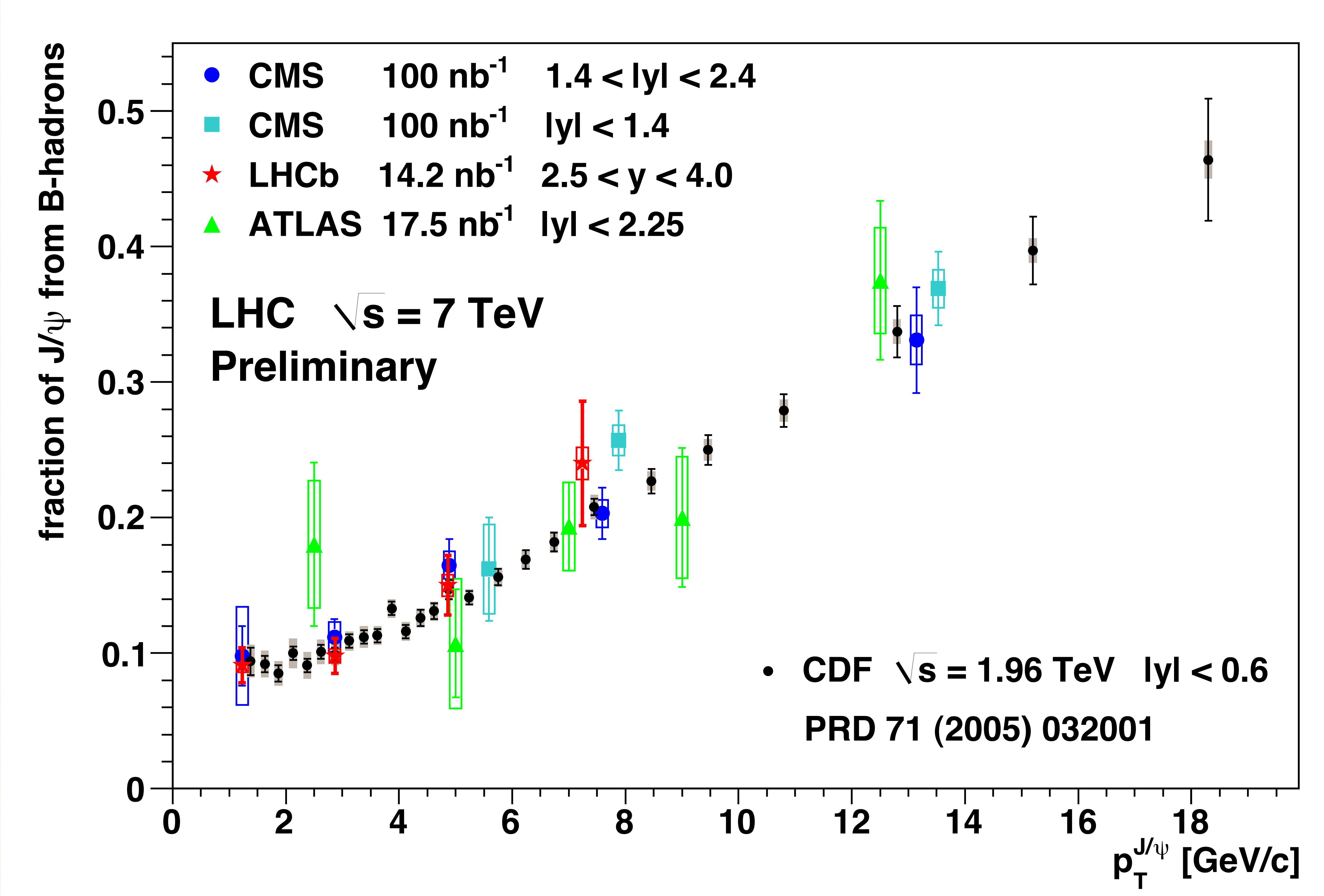


fraction of J/ψ from B-hadrons
CMS 100 nb^{-1} 1.4 < lyl < 2.4
CMS 100 nb^{-1} lyl < 1.4
LHCb 14.2 nb^{-1} 2.5 < y < 4.0
ATLAS 17.5 nb^{-1} lyl < 2.25
LHC √s = 7 TeV
Preliminary
CDF √s = 1.96 TeV lyl < 0.6
PRD 71 (2005) 032001
$p_T^{J/\psi}$ [GeV/c]

pA: Leading twist gluon shadowing

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

$$l_c^g = \frac{P^g}{\tilde{x}_2\, m_N}$$

where $\tilde{x}_2 = x_2/(1-x_1)$; $P^g \approx 0.1$ is scale independent.

This is why there is no shadowing above $\tilde{x}_2 \gtrsim 0.01$

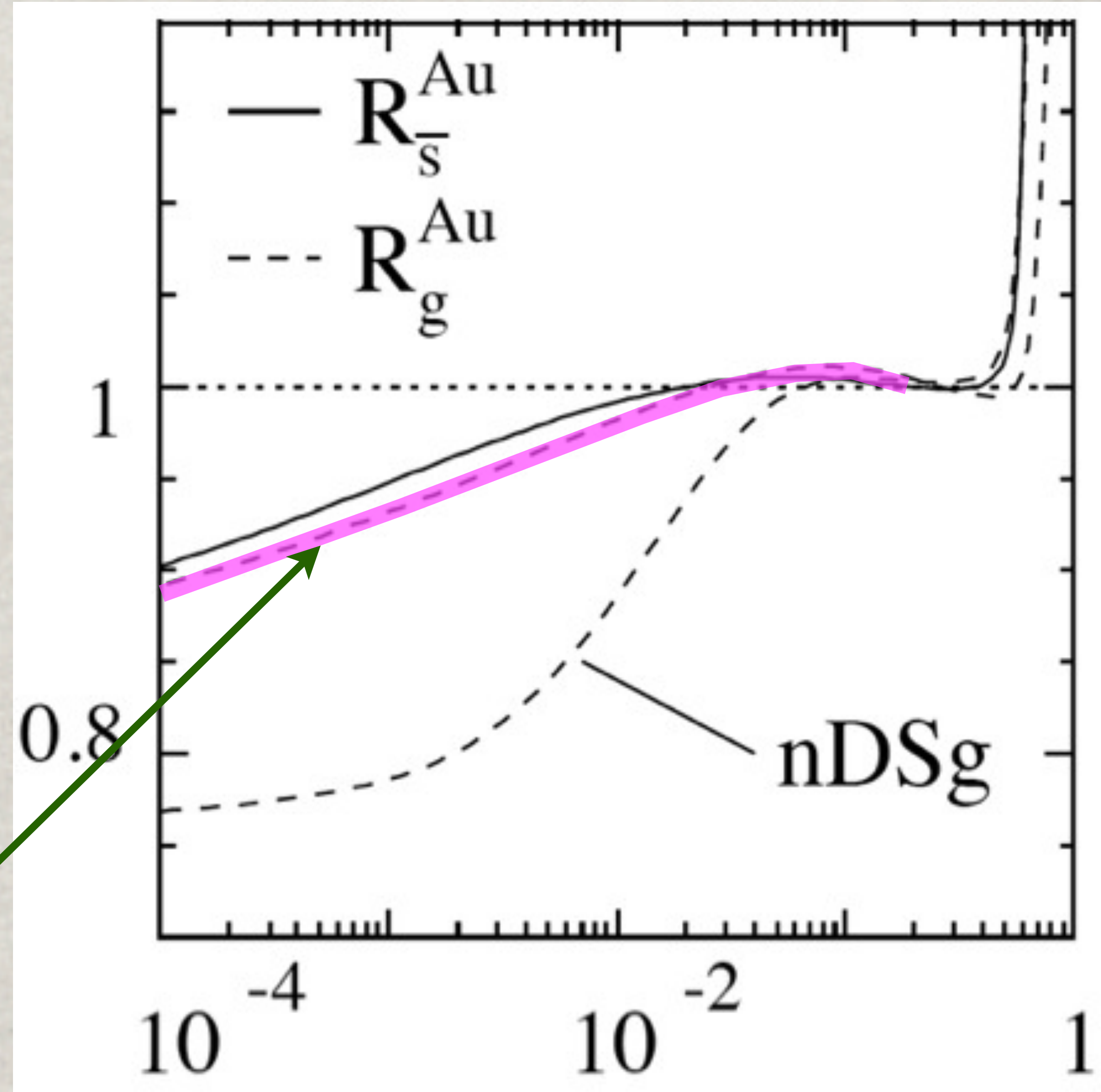
in particular, gluon shadowing should not affect any of the fixed-target experiments $l_c^g < 1\ \mathrm{fm}$

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

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

Still gluon shadowing is very weak



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

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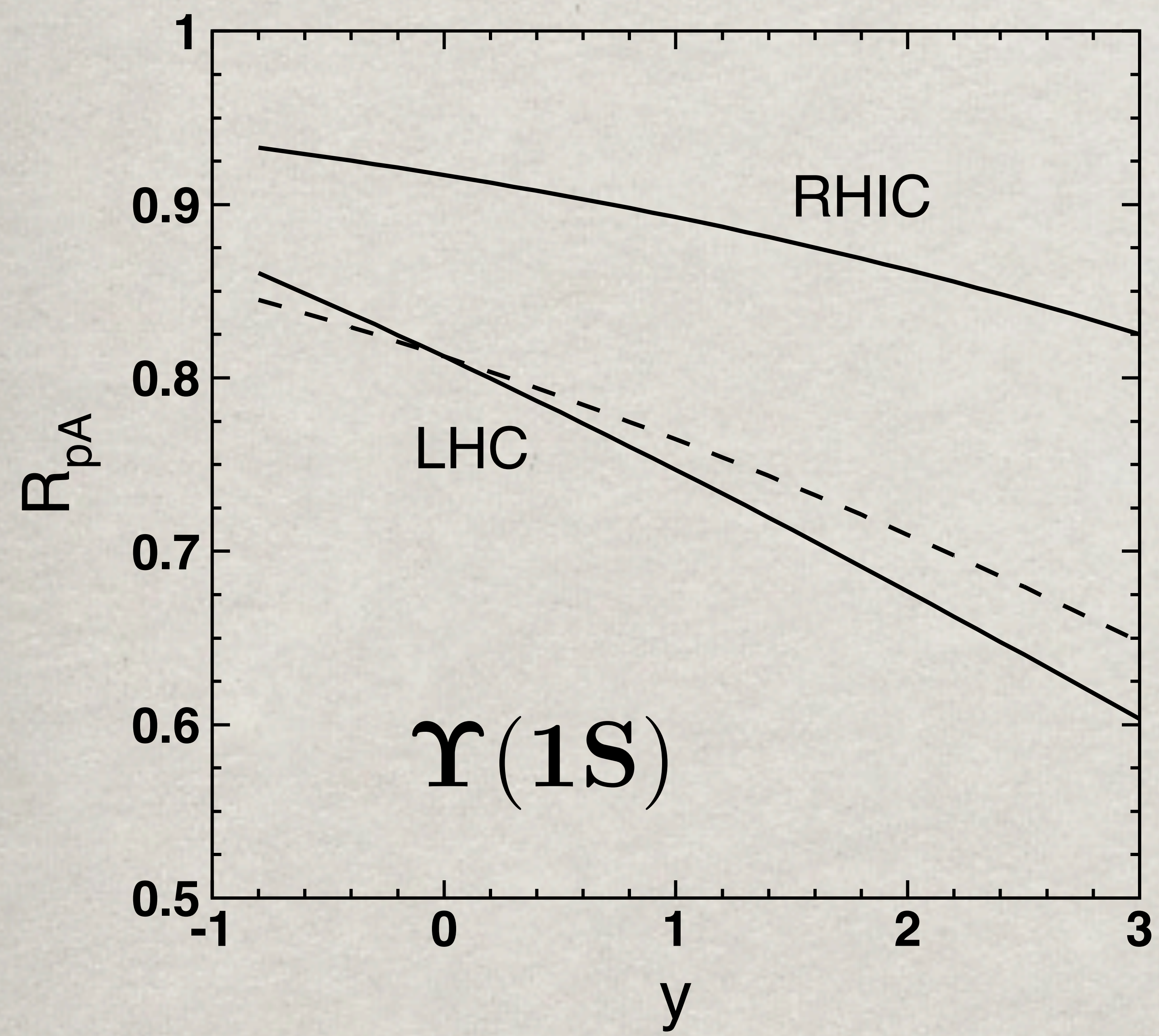
pA: Bottomium

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

Υ(1S) *RAA* in the most central 20%
0.60 ± 0.12(stat.) ± 0.10(syst.)

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