1.7.09

Heavy Quark Interactions in Deconfined Media

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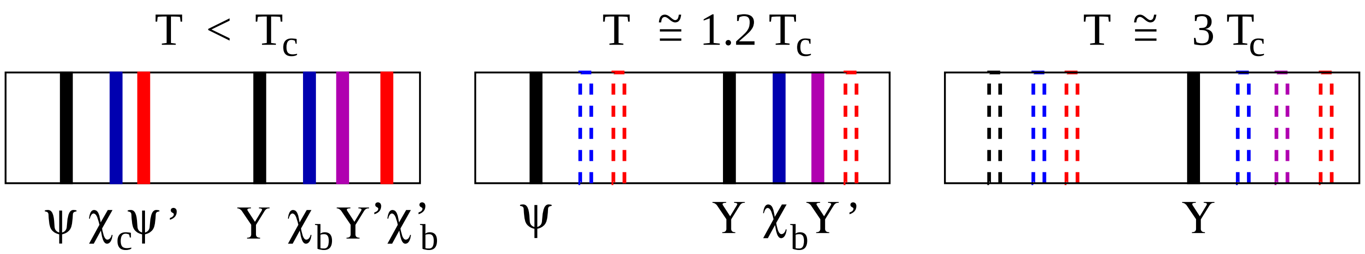
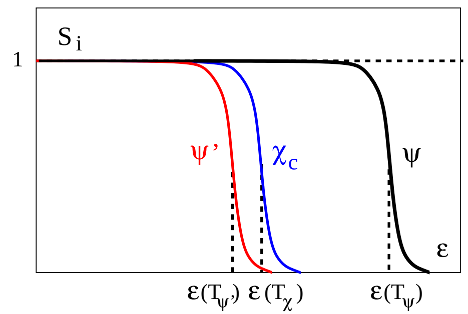
Spectral Analysis of QGP: Theoretical Basis

- QGP consists of deconfined colour charges, hence
  $\exists$ colour charge screening for $Q\bar{Q}$ probe
- screening radius $r_D(T)$ decreases with temperature T
- if $r_D(T)$ falls below binding radius r_i of $Q\bar{Q}$ state i,
  Q and $\bar{Q}$ cannot bind, quarkonium i cannot exist
- quarkonium dissociation points T_i, from $r_D(T_i) = r_i$,
  specify temperature of QGP



Spectral Analysis of QGP: Experimental Basis

- measure quarkonium production in AA collisions as function of collision energy, centrality, A
- determine onset of (anomalous) suppression for the different quarkonium states
- correlate experimental onset points to thermodynamic variables (temperature, energy density)
- compare thresholds in survival probabilities S_i of states i to QCD predictions



⇒ direct comparison:

experimental results vs. quantitative QCD predictions

In-Medium Behaviour of Quarkonia: Theory

Quarkonia:
heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV), beauty ($m_b \simeq 4.7$ GeV)
stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks ⇒ quarkonium spectroscopy via
non-relativistic potential theory

Schrödinger equation

$$\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\ \Phi_i(r)$$

confining ("Cornell") potential $\quad V(r) = \sigma\ r - \frac{\alpha}{r}$

string tension $\sigma \simeq 0.2$ GeV^2, coupling $\alpha \simeq \pi/12$, charm
quark mass $m_c = 1.3$ GeV

$\Rightarrow$ **good account of quarkonium spectroscopy**

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	**3.10**	**3.53**	**3.68**	**9.46**	**9.99**	**10.02**	**10.26**	**10.36**
ΔE [GeV]	**0.64**	**0.20**	**0.05**	**1.10**	**0.67**	**0.54**	**0.31**	**0.20**
ΔM [GeV]	**0.02**	**-0.03**	**0.03**	**0.06**	**-0.06**	**-0.06**	**-0.08**	**-0.07**
radius [fm]	**0.25**	**0.36**	**0.45**	**0.14**	**0.22**	**0.28**	**0.34**	**0.39**

NB: error in mass determination ΔM is less than 1 %

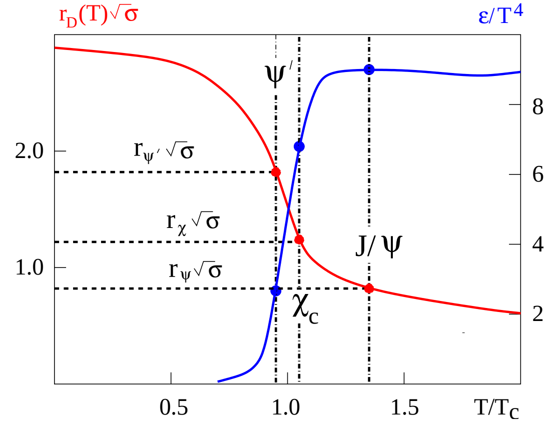
Ground states:

tightly bound $\Delta E = 2M_{D,B} - M_0 \gg \Lambda_{QCD}, \quad r_0 \ll r_h$

What happens to binding in QGP?

Colour screening ⇒ binding weaker and of shorter range

when force range/screening radius become less than binding radius, Q and $\bar{Q}$ cannot "see" each other



⇒ quarkonium dissociation points

determine temperature, energy density of medium

How to calculate quarkonium dissociation temperatures?

- **obtain heavy quark potential $V(r,T)$ from finite temperature lattice studies, solve Schrödinger equation**
- **calculate in-medium quarkonium spectrum $\sigma(\omega,T)$ directly in finite temperature lattice QCD**

Heavy Quark Interactions in Finite T Lattice QCD

[Karsch, Kaczmarek, HS - in progress]

Consider free energy with and without color singlet $Q\bar{Q}$ pair

Hamiltonian $\mathcal{H}_Q$ for QGP with $Q\bar{Q}$:

$$F_Q(r,T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_Q/T\}$$

Hamiltonian $\mathcal{H}_0$ for QGP without $Q\bar{Q}$:

$$F_0(T) = -T \ln \int d\Gamma \exp\{-\mathcal{H}_0/T\}$$

lattice QCD: free energy difference $F(r,T) = F_Q(r,T) - F_0(T)$

internal energy difference $U(r,T)$ & entropy difference $S(r,T)$

$$U(r,T) = -T^2 \left(\frac{\partial [F(r,t)/T]}{\partial T} \right) = F(r,T) + TS(r,T)$$

Internal energy (derivative of $Z(\beta)$ re β)

$$U(r,T) = \langle \mathcal{H}_Q(r,T) \rangle - \langle \mathcal{H}_0(T) \rangle$$

for static heavy quarks, H_Q contains no kinetic term, so $U(r,T)$ gives change in potential energy due to presence of $Q\bar{Q}$ pair

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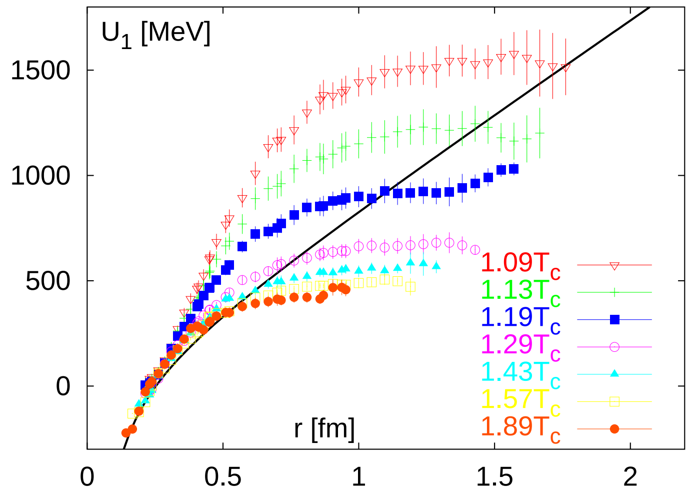
at $T = 0$: $$U(r, T=0) = F(r, T=0) = \sigma r - \frac{\alpha}{r}$$

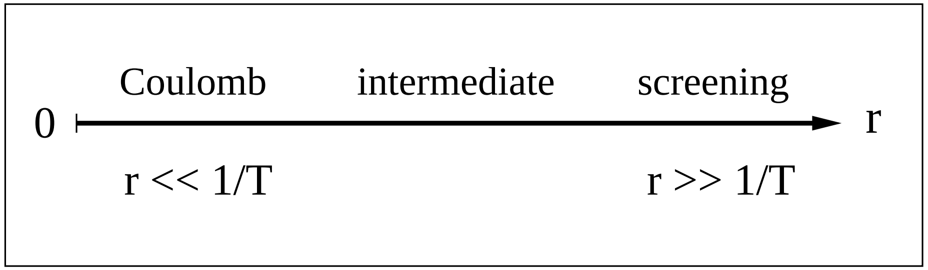
for $T > T_c$ & two flavor QCD, very much stronger interaction potential in the region $0.3 \leq r \leq 1.5$ fm

why?



for static $Q\bar{Q}$ pair in a hot QGP (above T_c)

$\exists$ three interaction ranges



- Coulomb regime: $r^{-1} \gg T$
  Coulomb binding much stronger than kinetic energy of medium

- screening regime: $r \gg T^{-1} \sim \xi(T)$
  separation of $Q\bar{Q}$ is much greater than correlation length $\xi(T)$ of medium

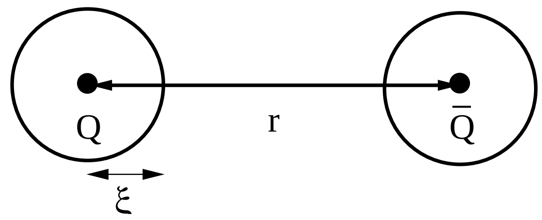
- intermediate regime: $r \sim \xi(T)$
  complex interactions

- <u>large distance limit</u>

  for $r \longrightarrow \infty$ ($r \gg T^{-1}$):

  $\exists$ well-separated polarization clouds,

  of radius correlation length $\xi(T)$



- <u>short distance limit</u>

  for $r \longrightarrow 0$ ($r \ll T^{-1}$):

  – $Q\bar{Q}$ neutralizes itself & does not see medium

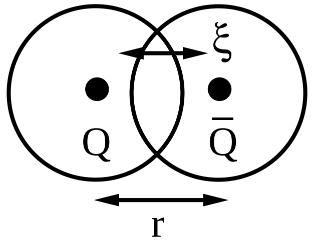
  – medium does not see color-neutral $Q\bar{Q}$;

  – hence effectively $T = 0$ and

$$U_{Q\bar{Q}}^{(1)}(r,T) = F_{Q\bar{Q}}^{(1)}(r,T) = -\frac{4}{3}\frac{\alpha(r)}{r}$$

- <u>intermediate separation regime</u>

  at small r, polarization clouds overlap



  how does this affect binding?

  $U(r,T)$ is sum of $Q\bar{Q}$ interaction and "cloud" energy

concentrate on binding (remove constant $U(r \to \infty, T)$),

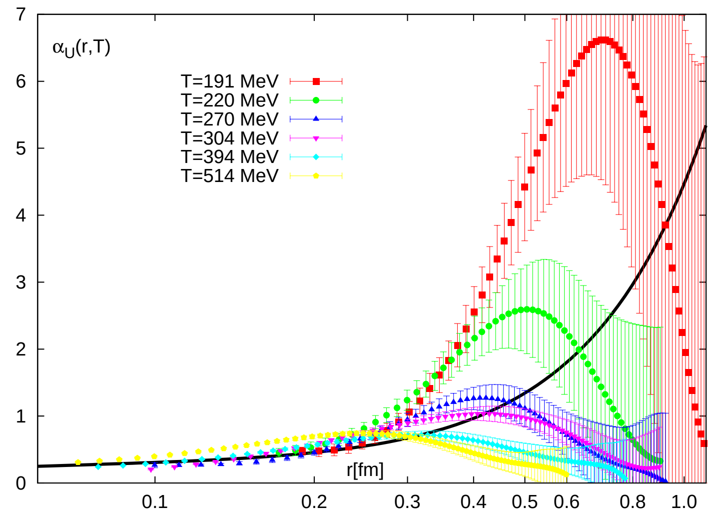
consider effective coupling $$\alpha(r,T) = \frac{3}{4} r^2 \left(\frac{\partial U(r,T)}{\partial r}\right)$$

at $T\!=\!0$: $$\alpha(r, T=0) = \alpha + \sigma r^2$$

in QGP:

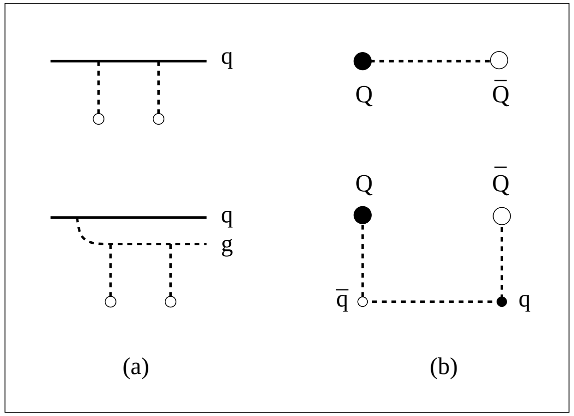
for $T_c < T < 2\ T_c$, $\exists$ strong enhancement of α

effective binding in medium
is stronger than in vacuum

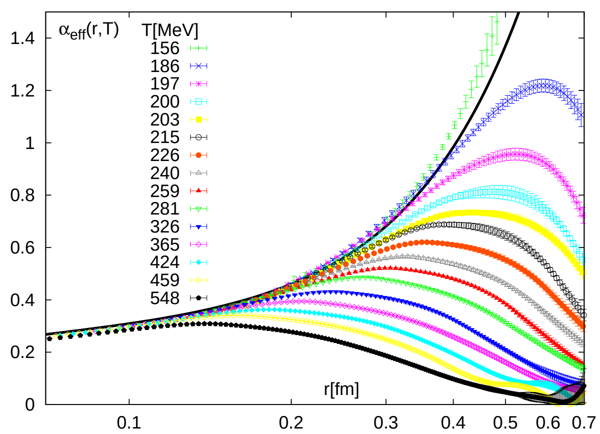


when polarization clouds overlap
∃ "cloud-cloud" binding
in addition to direct $Q\bar{Q}$ binding

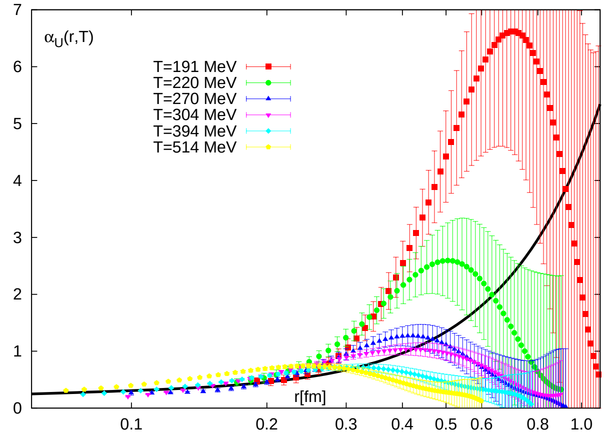
similar to parton energy loss
in dense QGP [GW vs. BDMPS]



to include cloud-cloud binding, must use $U(r,T) = V(r,T)$ in Schrödinger equation; compare to $\alpha_F(r,T)$ to $\alpha_U(r,T)$:



bare $Q\bar{Q}$ interaction



$Q\bar{Q}$ and cloud interactions

illustrate: dissociation in semi-classical approximation

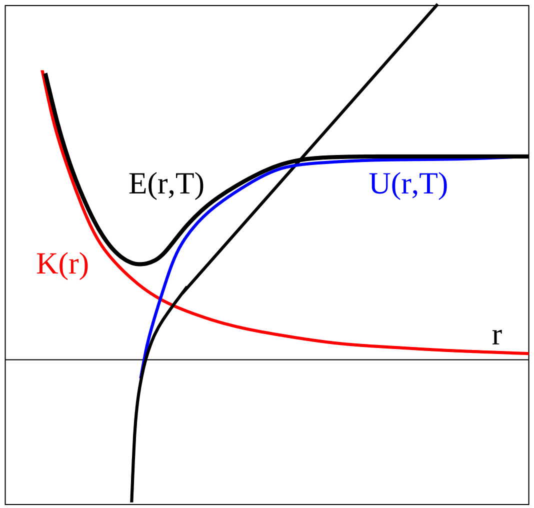
$$2m_c + \frac{p^2}{m_c} + U(r,T) = M(r,T)$$

uncertainty relation $\Rightarrow p^2 \simeq c/r^2$,

$$\frac{c}{m_c r^2} + U(r,T) = K(r) + U(r,T) = E(r,T)$$

minimize

$$E(r,T) = \frac{c}{m_c r^2} + U(r,T)$$



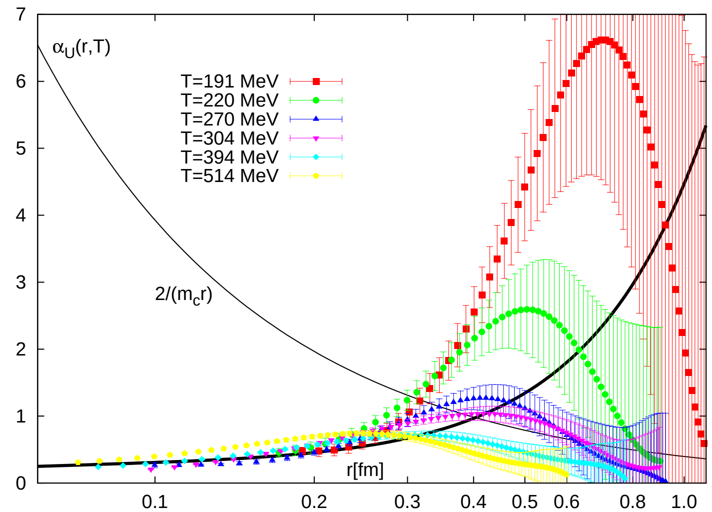
to get

$$\frac{2c}{m_c r_0} = r_0^2 \left(\frac{\partial V(r_0,T)}{\partial T} \right) = \frac{4}{3}\alpha(r_0,T)$$

fix c by $M(r_0, T=0) = M_{J/\psi}$, solve graphically compare kinetic term $2c/m_c r$ to potential term $\alpha_U(r,T)$

$\Rightarrow J/\psi$ dissociation
at about 1.5 - 2 T_c

Digal et al. 2001
Shuryak & Zahed 2004
Wong 2004,...
Alberico et al. 2005,...
Digal et al. 2005
Mocsy & Petreczky 2005,...



• with full cloud-cloud interaction

state	J/ψ	χ_c	ψ'
T_d/T_c	$1.5 - 2.2$	$1.1 - 1.2$	$1.0 - 1.1$

• less cloud interaction weakens binding, reduces dissociation temperatures

Lattice Studies of Quarkonium Spectrum

Calculate correlation function $G_i(\tau, T)$ for mesonic channel i determined by quarkonium spectrum $\sigma_i(\omega, T)$

$$G(\tau, T) = \int d\omega \ \sigma_i(\omega, T) \ K(\omega, \tau, T)$$

relates imaginary time τ and $c\bar{c}$ energy ω through kernel

$$K(\omega, \tau, T) = \frac{\cosh[\omega(\tau - (1/2T))]}{\sinh(\omega/2T)}$$

invert $G(\tau, T)$ by Maximum Entropy Method (MEM) to get $\sigma(\omega, T)$

Asakawa and Hatsuda 2004

Basic Problem:

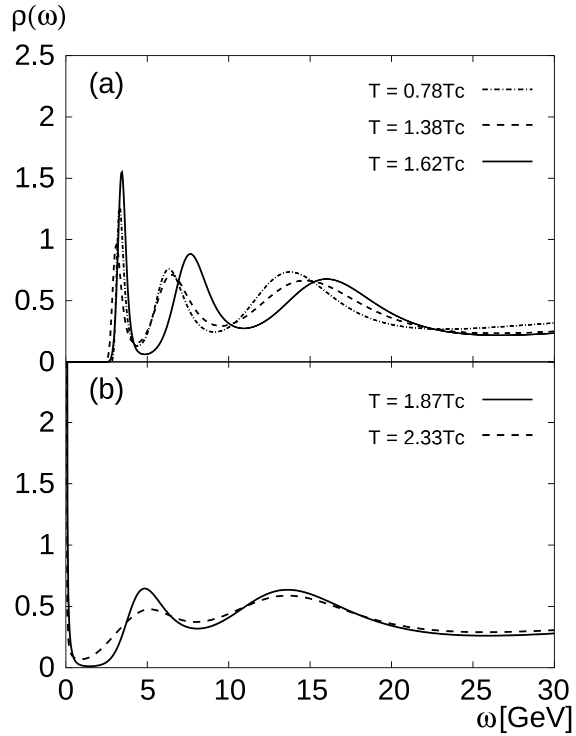
correlator given at discrete number of lattice points with limited precision ("mosaic fragments") charmonia quenched:

Umeda et al. 2001
Asakawa & Hatsuda 2004
Datta et al. 2004
Iida et al. 2005
Jakovac et al. 2005

charmonia unquenched:

Aarts et al. 2005, 2007

$\Longrightarrow$



Present status:

- ground state peak position OK, widths & continuum not, higher resonances averaged into ground state, continuum

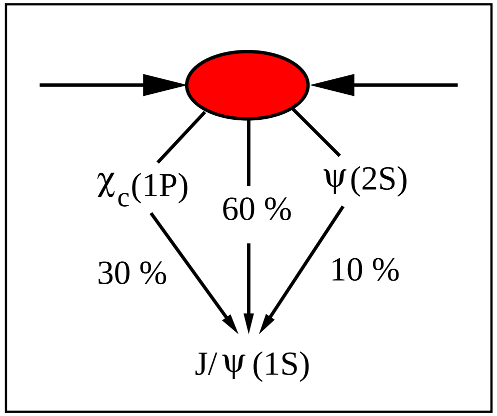
Tentative present summary:

- J/ψ survives up to $T \simeq 1.5 - 2.0\ T_c$
- χ_c dissociated at or slightly above T_c

Experimental Consequence: Sequential J/ψ Suppression

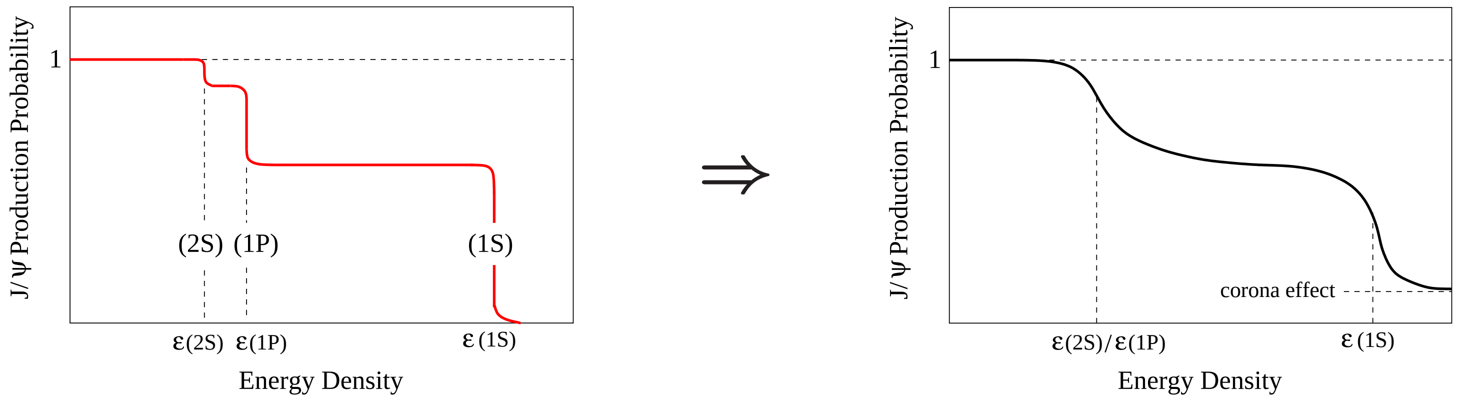
Karsch & HS 1991; Gupta & HS 1992; Karsch, Kharzeev & HS 2006

- measured J/ψ's are about 60% direct 1S, 30% χ_c decay, 10% ψ' decay
- narrow excited states $\rightarrow$ late decay; medium affects excited states



- remove effects of cold nuclear matter (shadowing, initial state energy loss, nuclear absorption)

• remaining J/ψ survival rate should show a sequential reduction: first due to ψ' and χ_c melting, then later direct J/ψ dissociation; experimental smearing of steps



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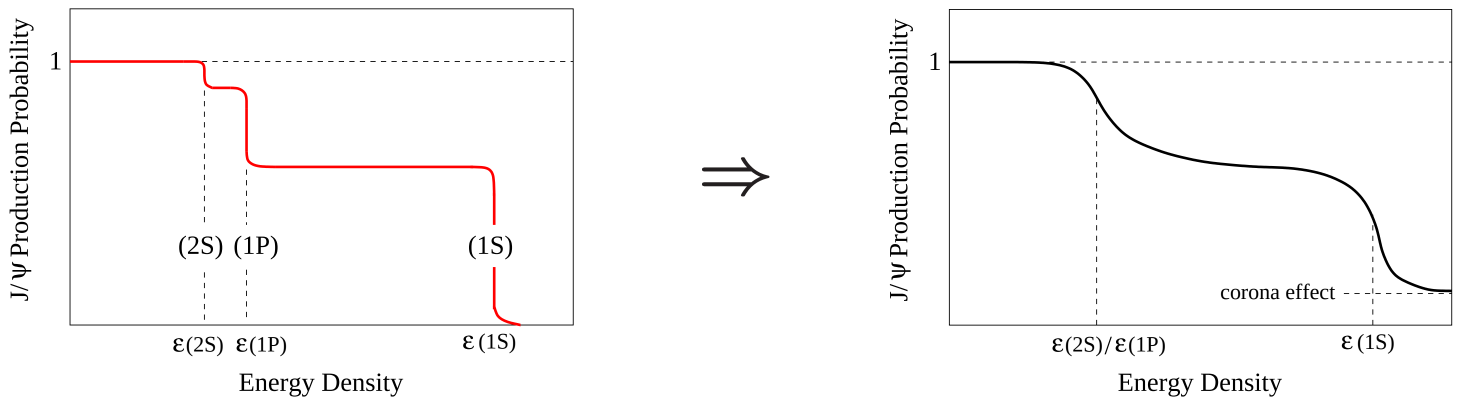
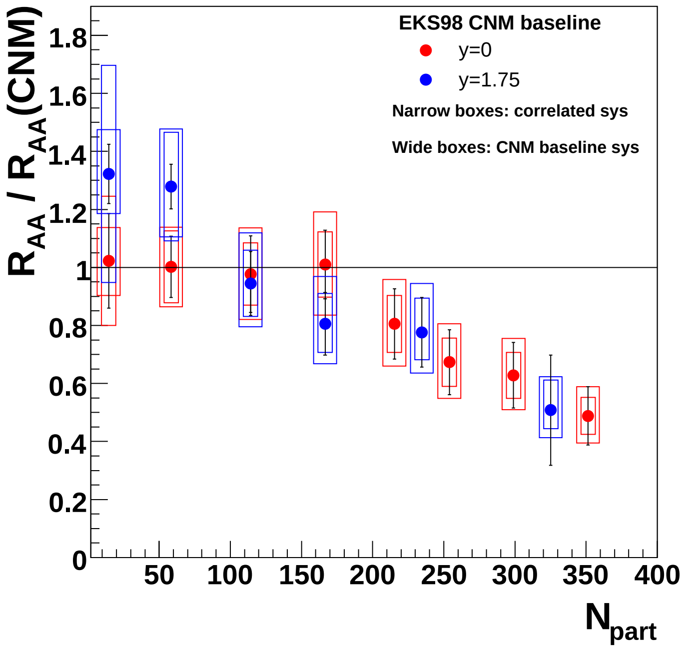


Data

- **SPS: Pb-Pb (NA50) and In-In (NA60) at $\sqrt{s} \simeq 16$ GeV; CNM reference pA at $\sqrt{s} \simeq 16$ GeV** [R. Arnaldi 2009]

- **RHIC: Au-Au (Phenix) at $\sqrt{s} \simeq 200$ GeV; CNM reference dAu at $\sqrt{s} \simeq 200$ GeV (run 8)** [A. Frawley 2009]


EKS98 CNM baseline
y=0
y=1.75
Narrow boxes: correlated sys
Wide boxes: CNM baseline sys
R_{AA} / R_{AA}(CNM)
N_{part}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
50
100
150
200
250
300
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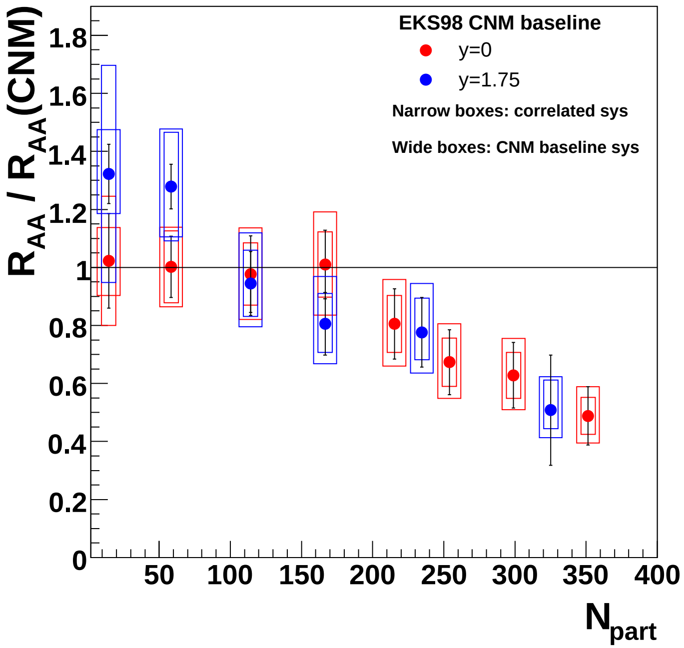
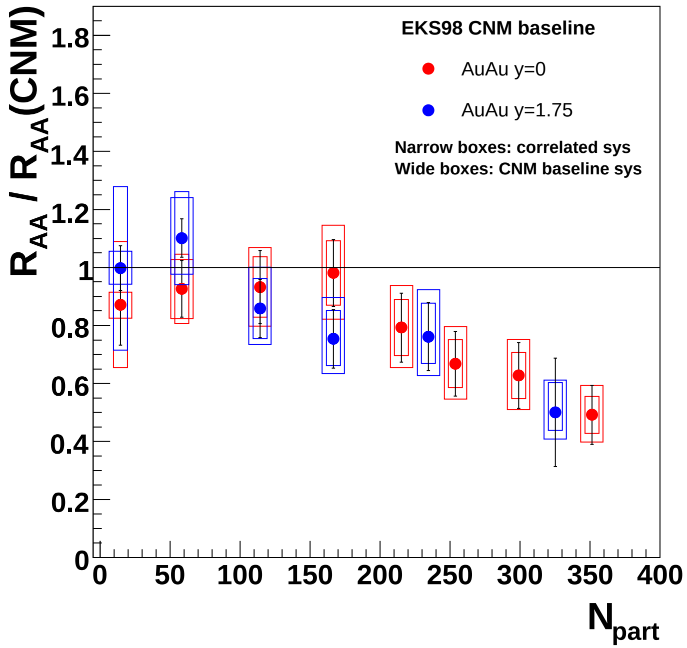
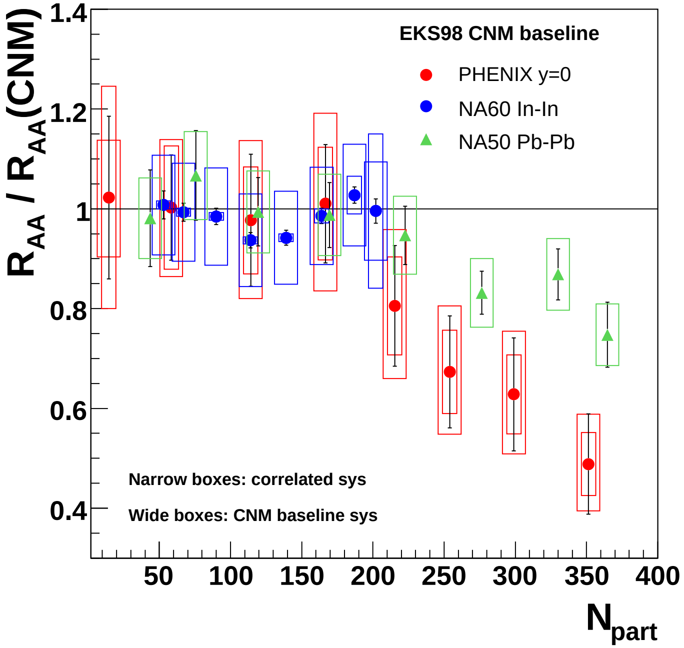




A. Frawley, PHENIX

ECT*/Trento, INT/Seattle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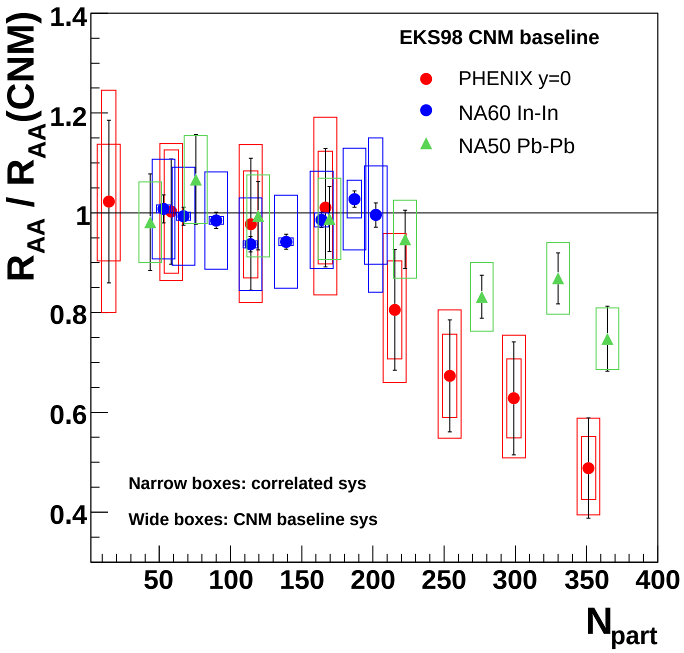
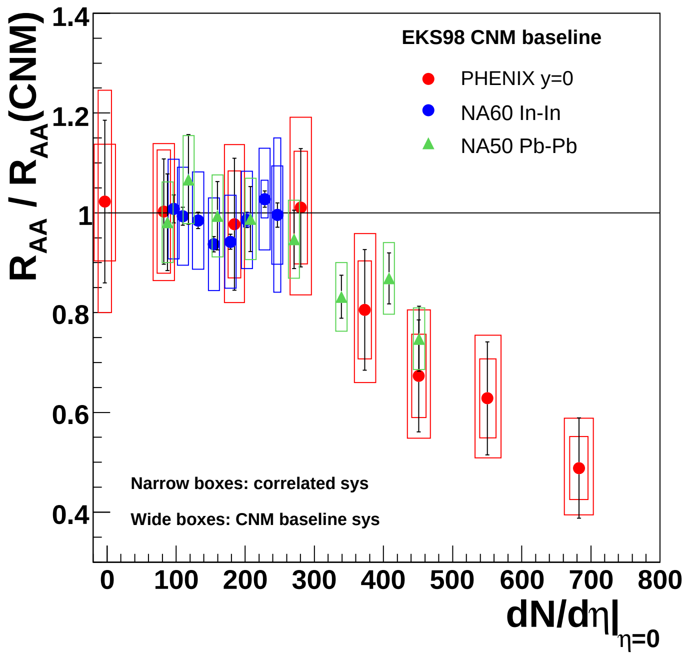
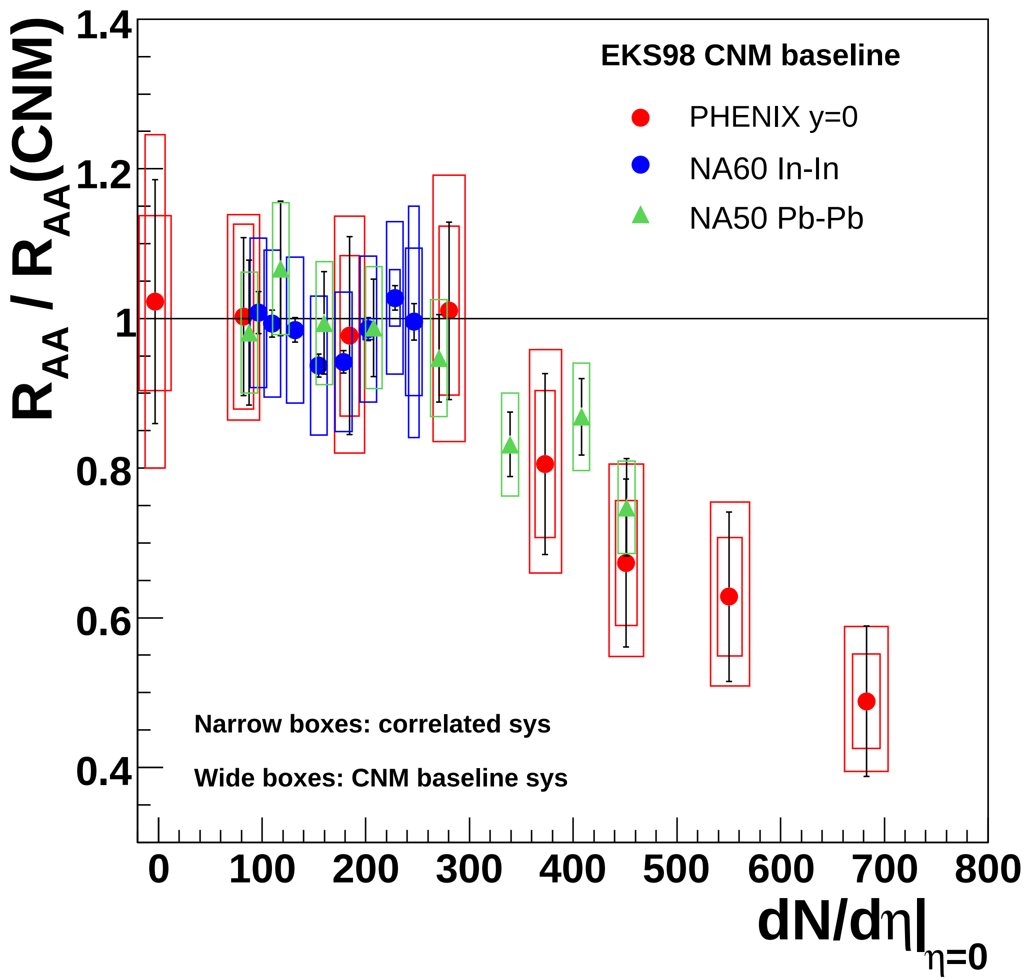




R. Arnaldi, NA60 ECT*/Trento

Conclusions

- with caveats, potential model studies and direct lattice studies seem to indicate J/ψ survival up to 1.5 - 2 T_c, dissociation of χ_c and ψ' just above T_c.
- J/ψ survival is due to stronger $c\bar{c}$ binding at radii around 0.5 fm, coming from polarization cloud interactions.
- using new cold nuclear matter data, experimental J/ψ survival seems consistent from SPS to RHIC, for all data (Pb-Pb, In-In and Au-Au). No suppression up to about $(dN/d\eta)_{y=0} \simeq 200$, or $\epsilon_0 \simeq 1$ GeV/fm^3, then uniform decrease to about 0.5-0.6
- decisive role of forthcoming LHC data...



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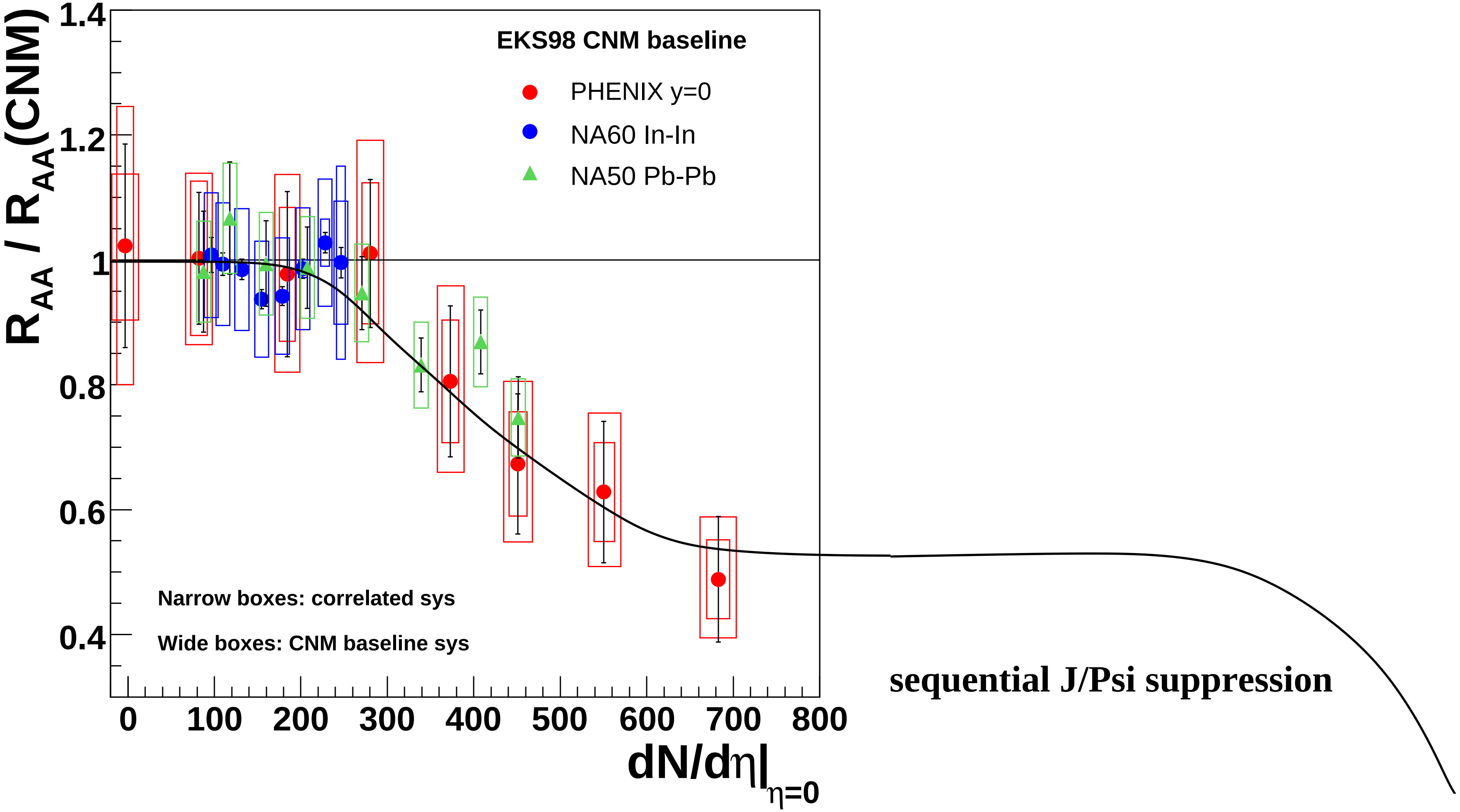
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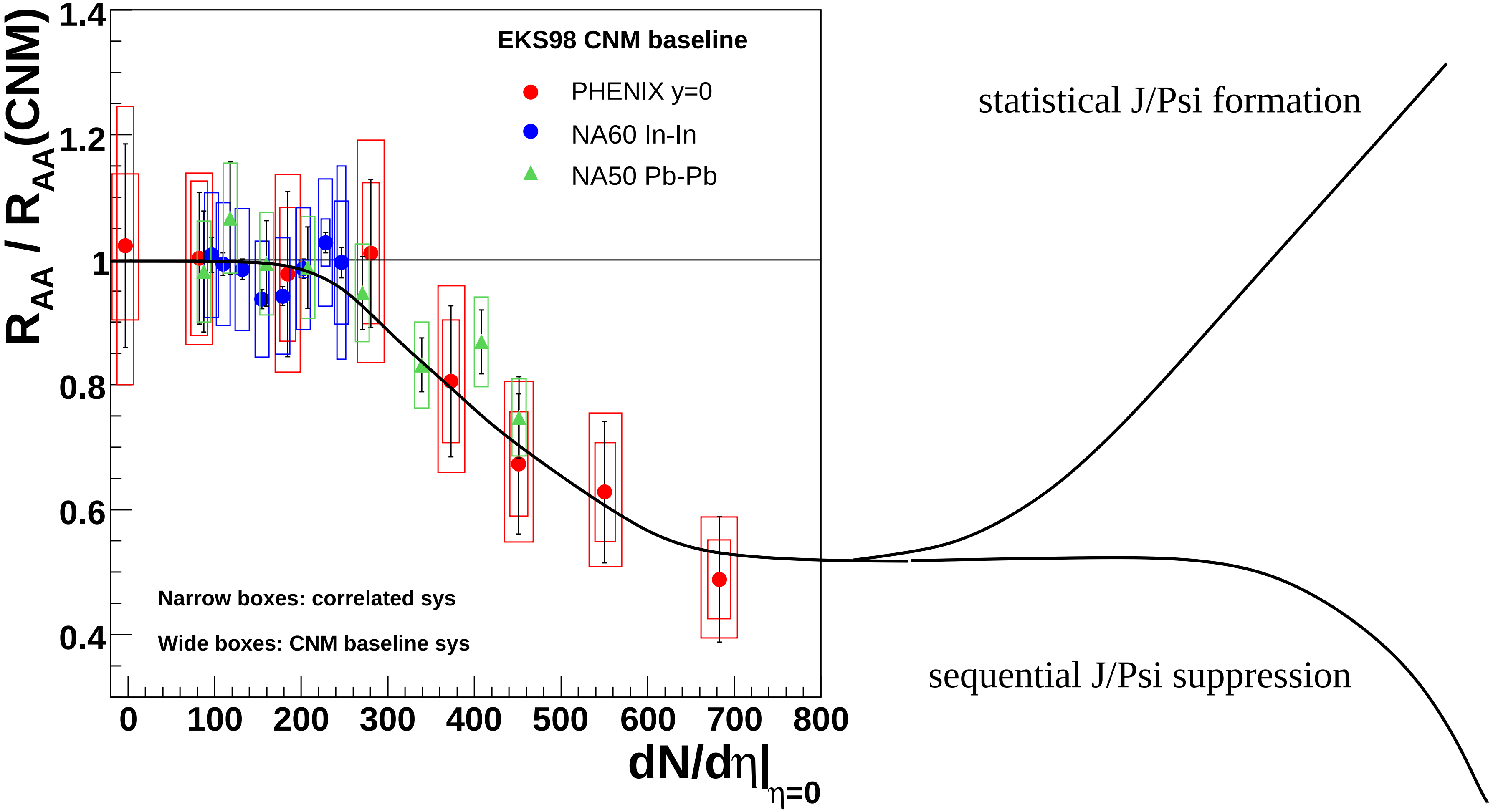
$dN/d\eta|_{\eta=0}$
sequential J/Psi suppression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