Quark-Gluon Plasma Physics

10. Quarkonia

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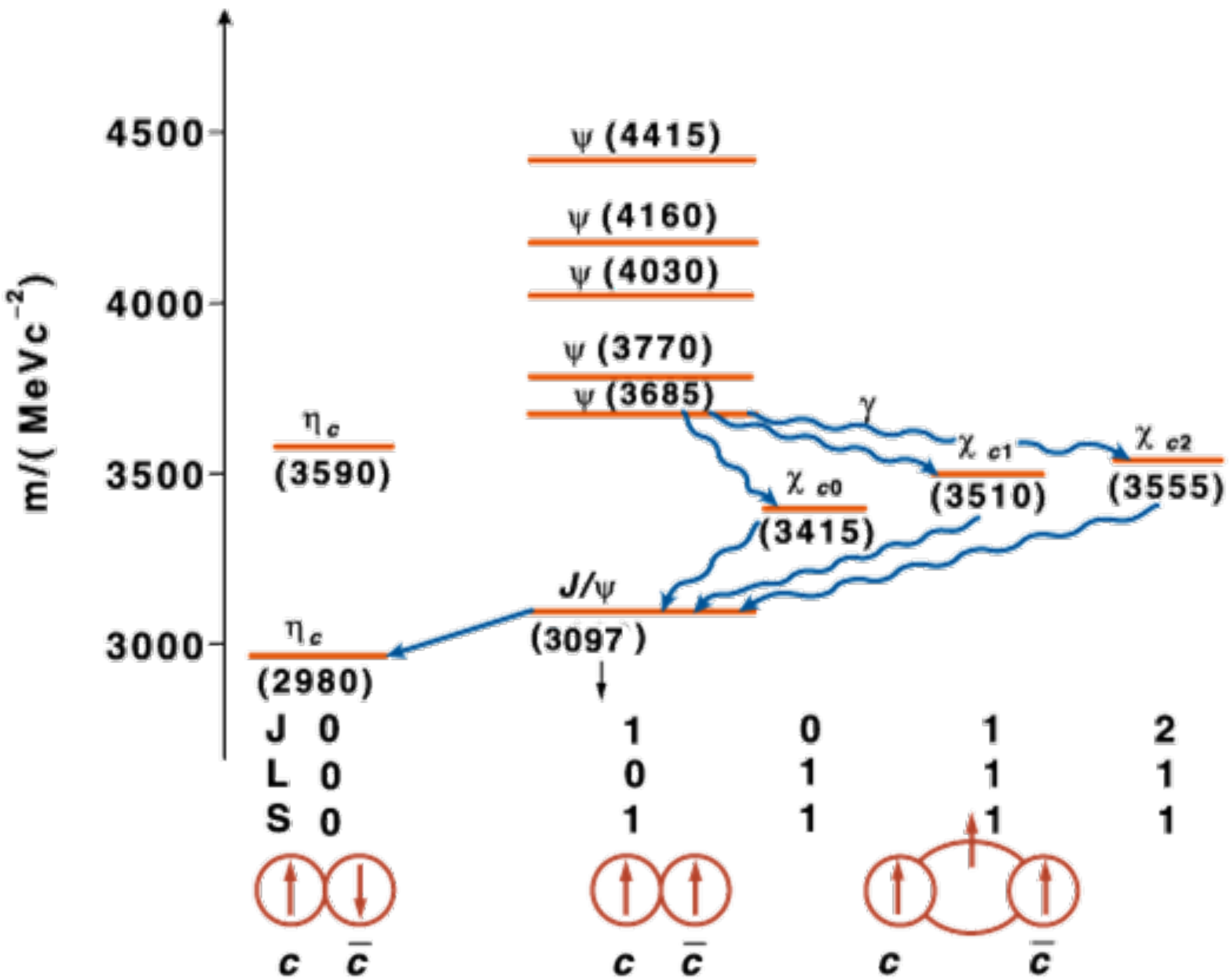
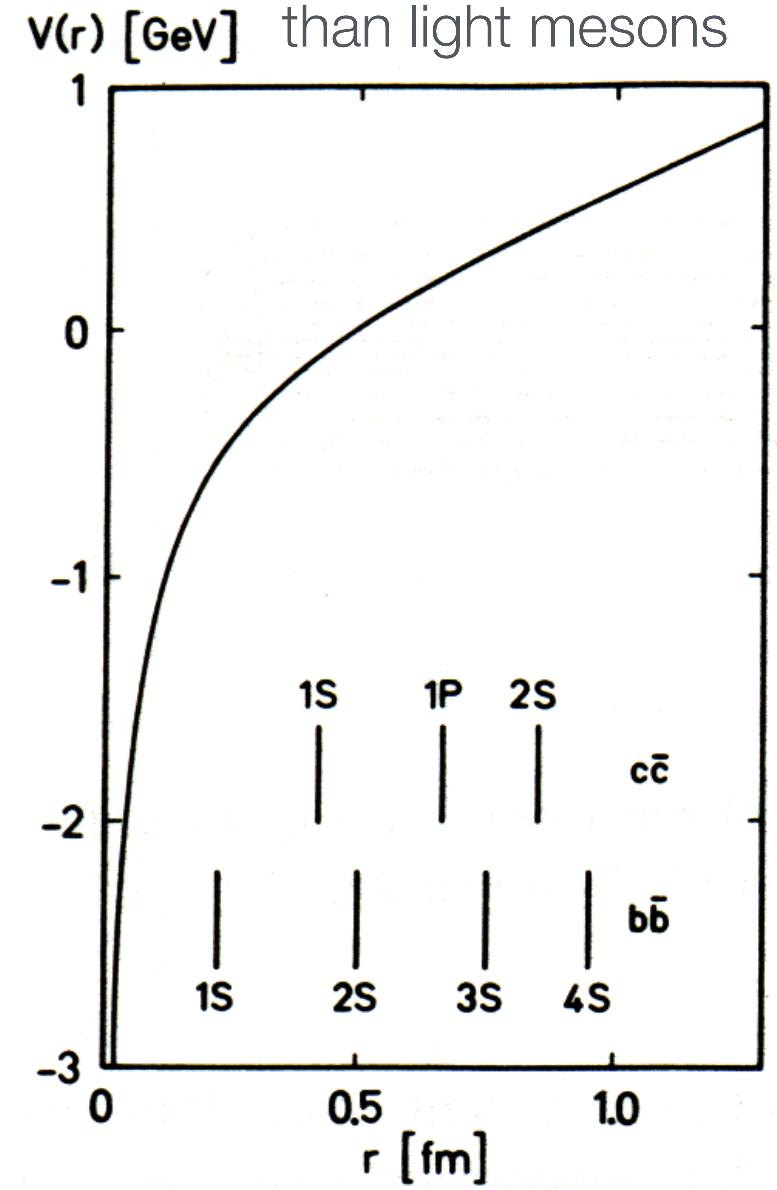
Charmonium and bottomium



Quarkonia: tightly bound, smaller radius than light mesons



- Non-relativistic treatment for heavy quarks ($m_c \approx 1.3$ GeV, $m_b \approx 4.7$ GeV)
- Charmonium and bottomium states reproduced by solving Schrödinger equation using Cornell potential:

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

σ ≈1 GeV/fm, α ≈ π/12

Debye screening in the QGP

- Matsui, Satz (Phys. Lett. B 178 (1986)):
  - Potential between two heavy quarks is modified in the QGP, preventing initially produced charm anticharm quarks to form a J/ψ
  - J/ψ suppression is a QGP signal

- Simple parameterization of the screened potential ("Debye screening")

$$V(r,T) = -\frac{\alpha}{r} e^{-\mu r} + \sigma r \frac{1 - e^{-\mu r}}{\mu r}$$

screening radius depends on temperature:

$$r_D = 1/\mu$$ ← Debye mass

$$\mu = \mu(T) \propto g(T) T$$

- Basic idea: heavy-quark bound state melts in the QGP if $r_{Q\bar{Q}} \gtrsim r_D$

- There is a dissociation temperate T_d for each state ("sequential melting"):

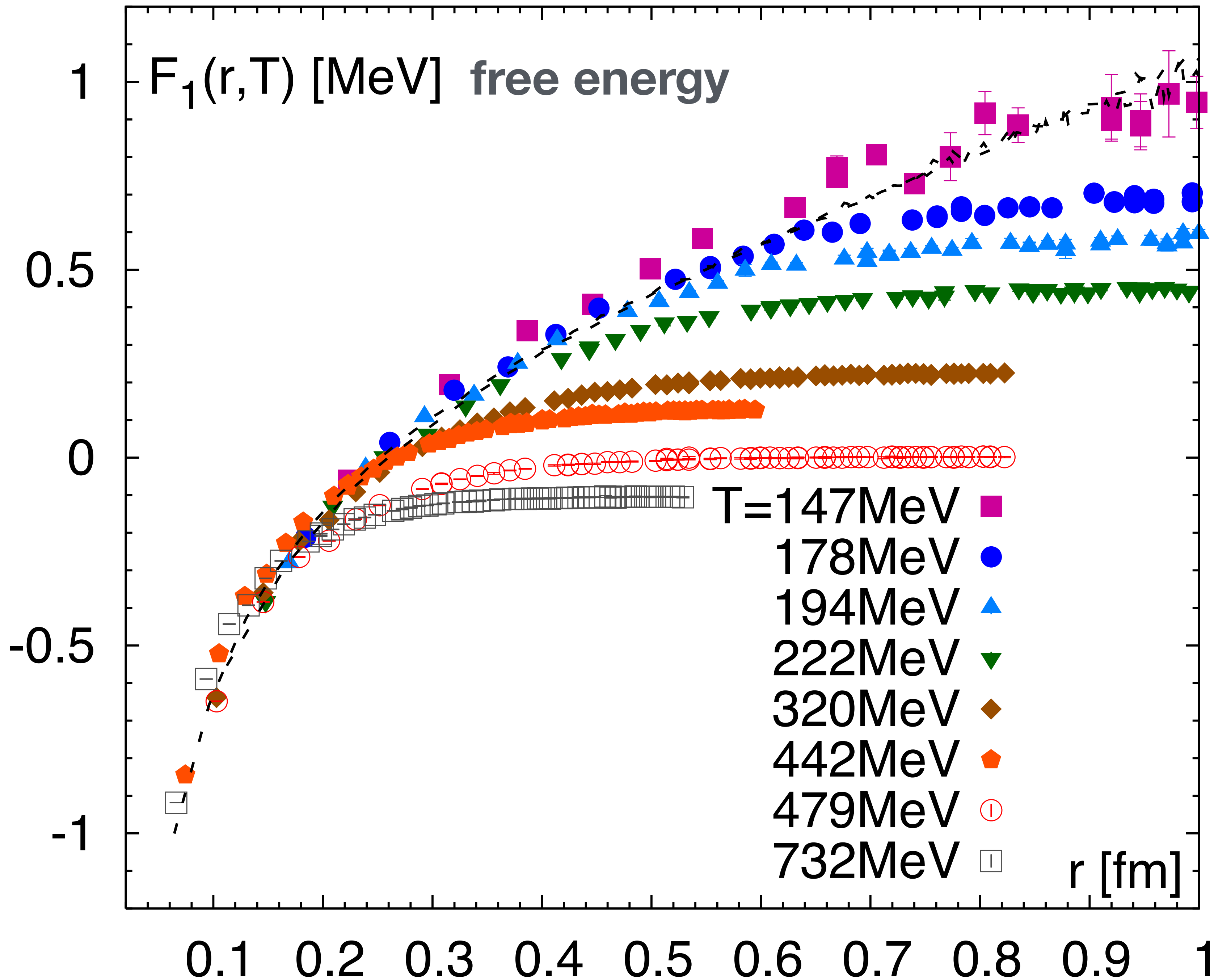
Can the different T_d's serve as a QGP thermometer?

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

arXiv:0706.2183

Heavy quark potential for different temperatures from lattice QCD

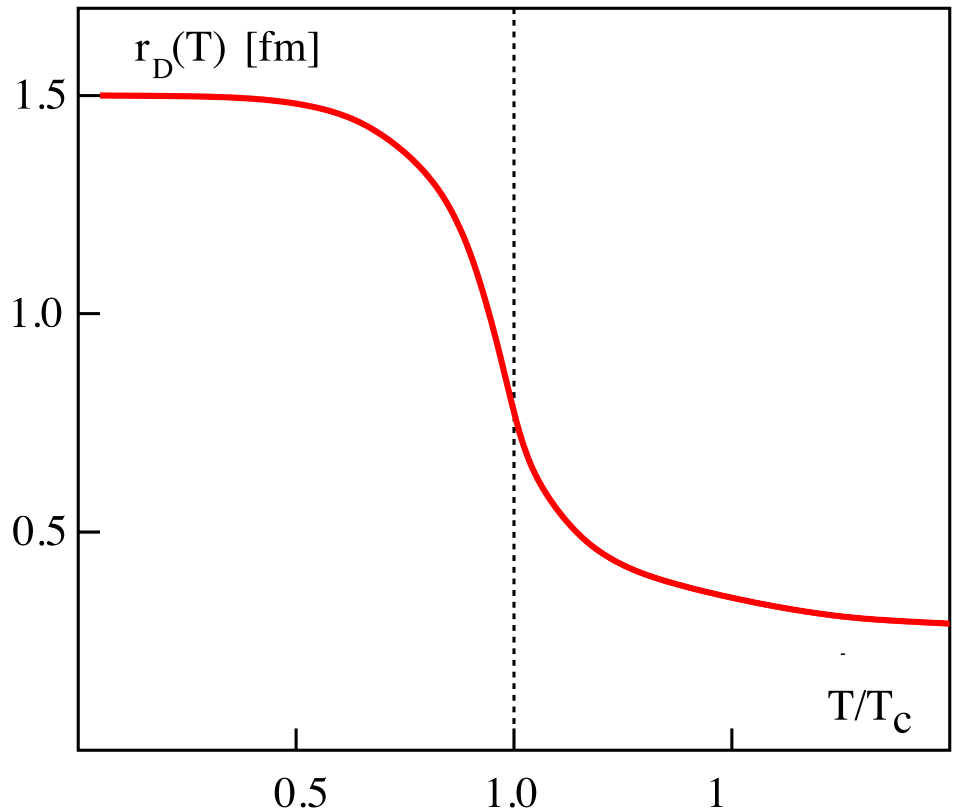
arXiv:1302.2180v1



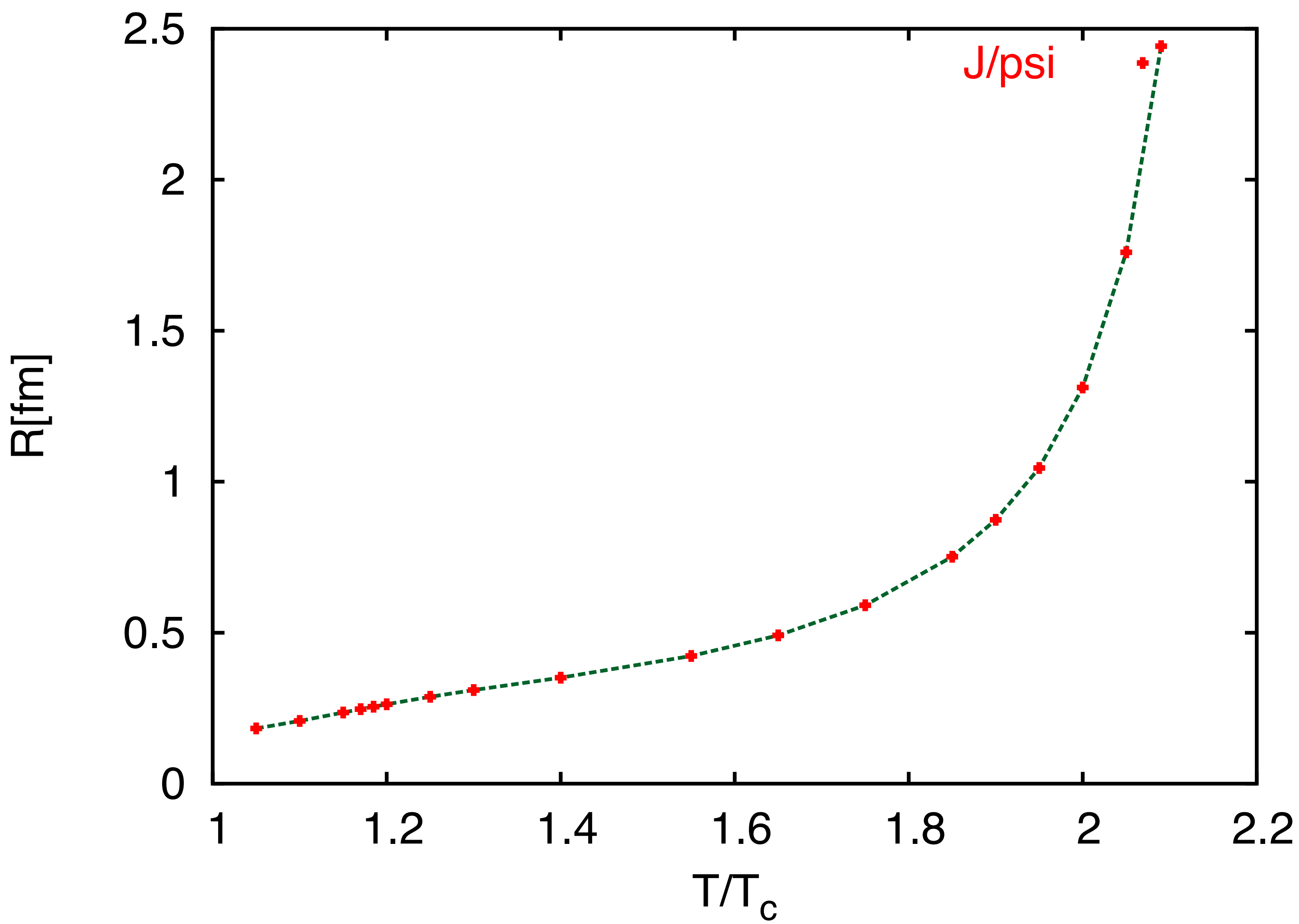
Interaction range and J/ψ radius in the medium as a function of the temperature

H. Satz, hep-ph/0512217

Interaction range vs *T*



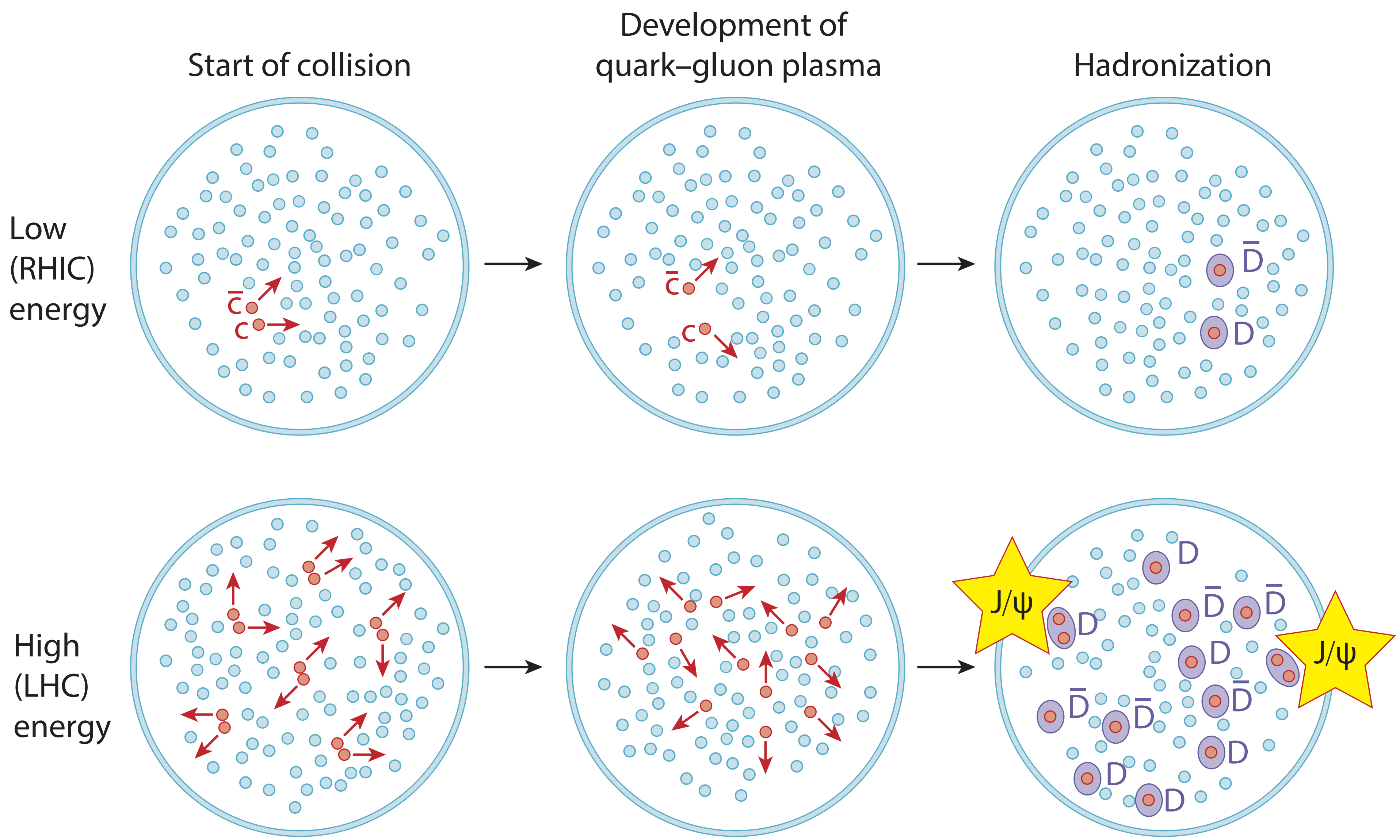
J/ψ radius vs. *T*



- J/ψ radius becomes larger with increasing T
- No bound state anymore for $T \gtrsim 2\ T_c$

A new twist:
J/ψ might form again from deconfined charm

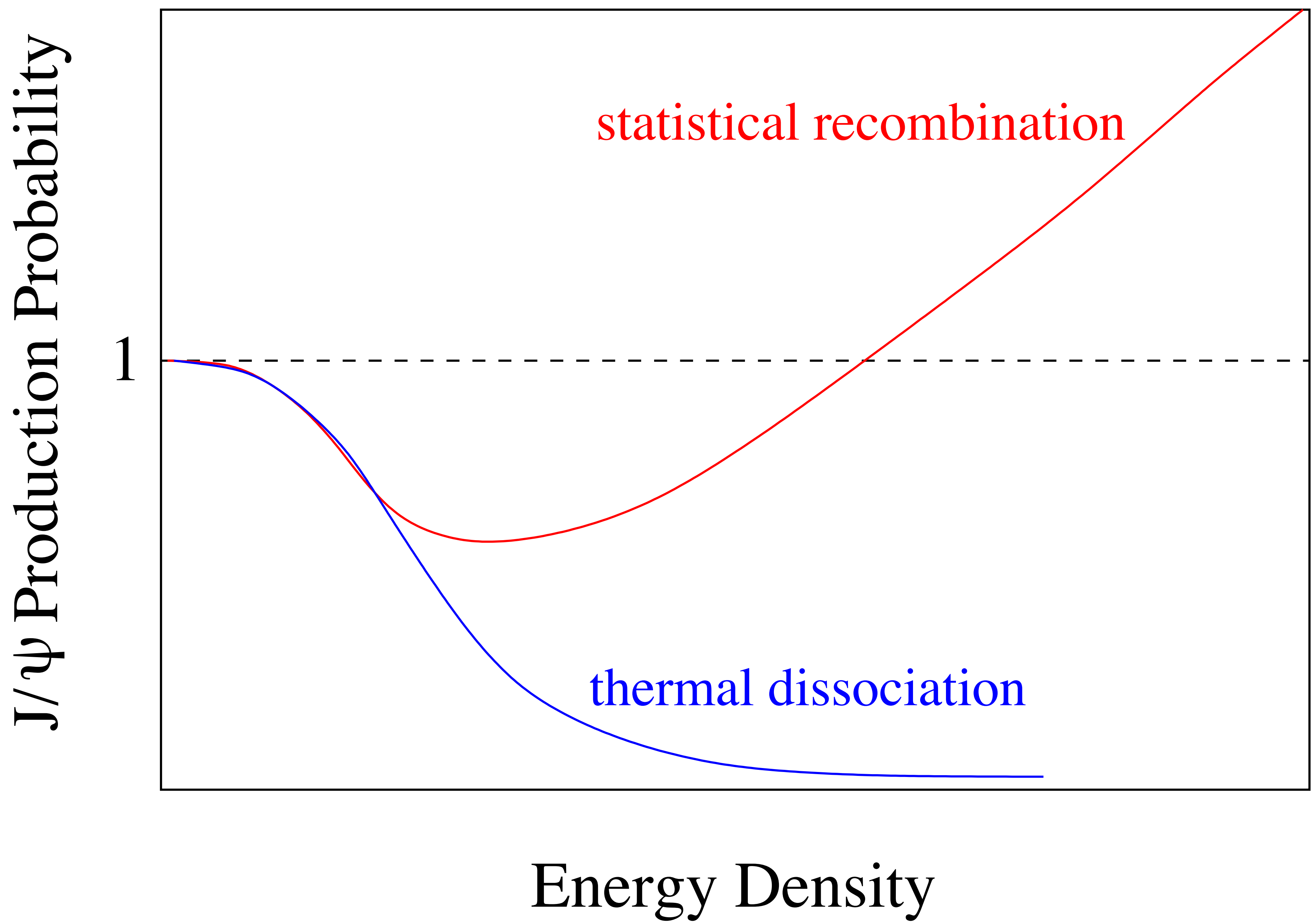
Braun-Munzinger, Stachel, Nature 448 (2007) 302



- Requires large number of initially produced c cbar pairs: $N_{J/\psi} \propto N_{c\bar{c}}^2$
- Expect J/ψ suppression at SPS, RHIC and J/ψ enhancement at high energies (LHC)

Expected J/ψ signal with or without statistical recombination of charm quarks

Kluberg, Satz, 0901.3831



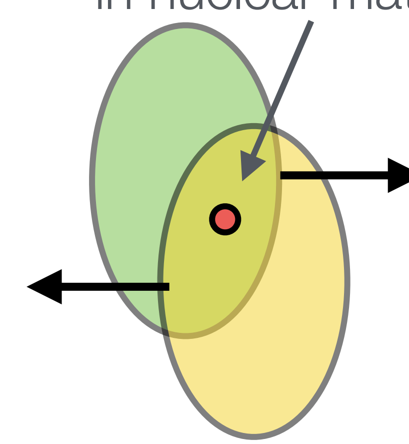
Time scales

Collision time: $t_{\text{coll}} = 2R/\gamma_{cm}$ (RHIC: $0.1\,\text{fm}/c$, LHC: $5 \cdot 10^{-3}\,\text{fm}/c$)

Charm pair formation: $\tau_{c\bar{c}} = \frac{1}{2m_c} \approx 0.08\,\text{fm}/c$

QGP formation: $\tau_{\text{QGP,SPS}} \approx 1\,\text{fm}/c,\ \tau_{\text{QGP,SPS}} < 0.5\,\text{fm}/c,\ \tau_{\text{QGP,LHC}} < 0.1\,\text{fm}/c$

Hadron formation time: $\tau_{\text{hadron}} \approx 1\,\text{fm}/c$



CERN SPS energies and below: $t_{\text{coll}} \simeq \tau_{\text{QGP}} \simeq \tau_{\text{hadron}}$

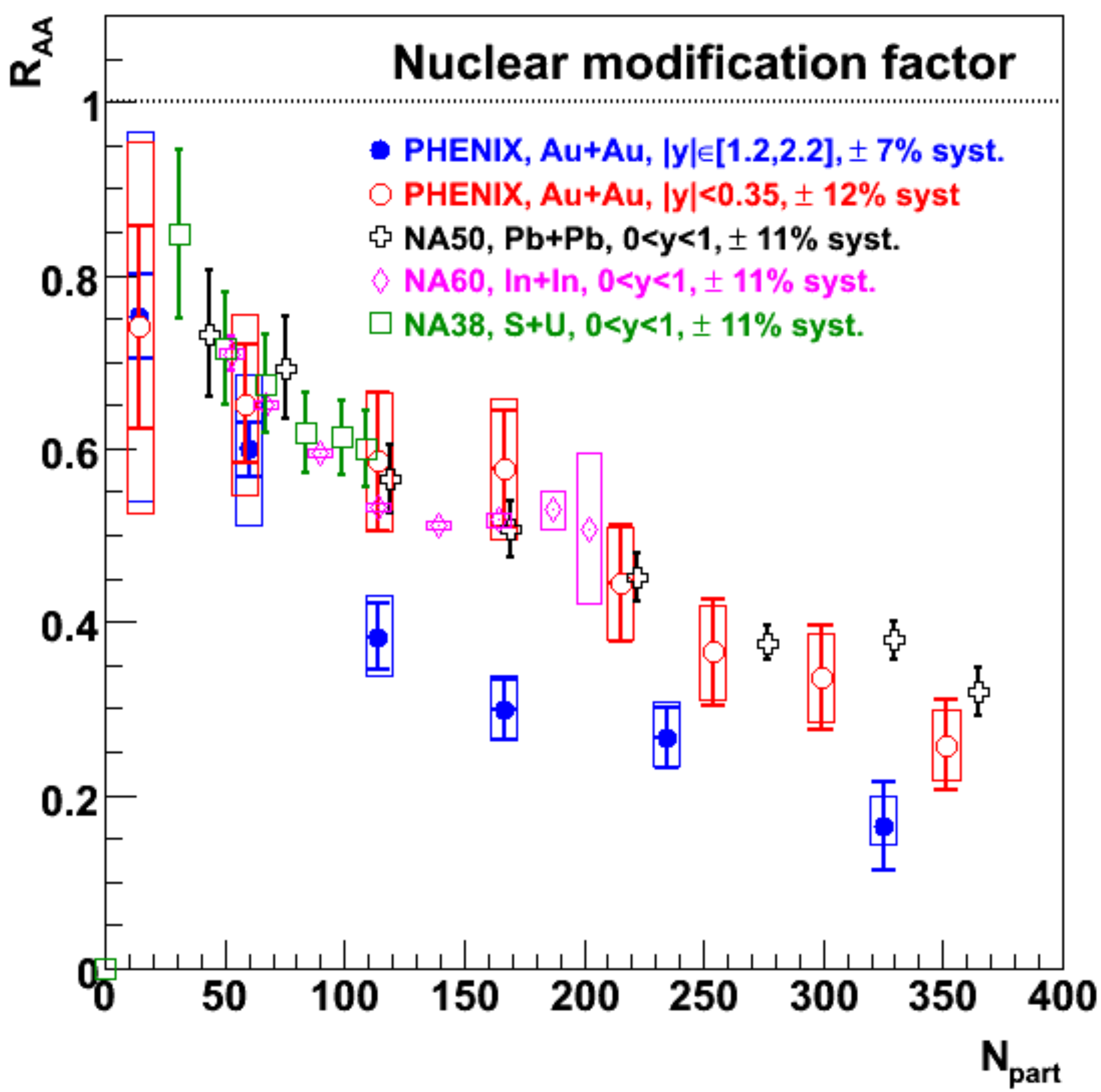
→ pre-resonant state can be absorbed in cold nuclear matter

Separation of scales at the LHC (and also RHIC):

$$t_{\text{coll}} \ll \tau_{\text{QGP}} < \tau_{\text{hadron}}$$

Interpretation of the J/ψ signal easier at the LHC (and at RHIC) as absorption in cold nuclear matter should not be irrelevant

J/ψ suppression at the CERN SPS and at RHIC

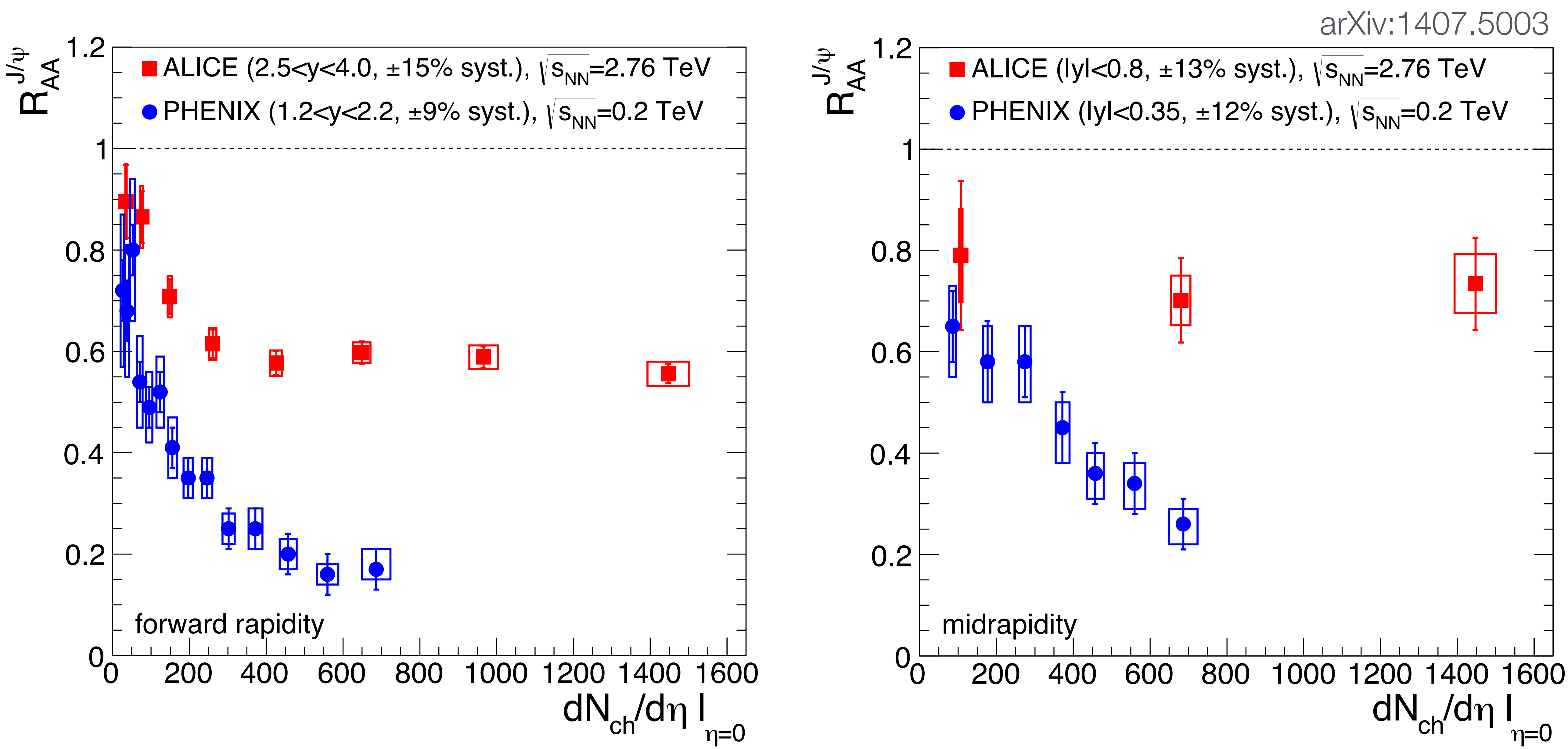


- Same suppression at midrapidity at the CERN SPS and at RHIC, in spite of larger energy density at RHIC
- RHIC: suppression large at forward rapidity, in spite of larger energy density at mid-rapidity
- Not easy to explain in pure dissociation picture

$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

where $\langle T_{\mathrm{AB}}\rangle = \langle N_{\mathrm{coll}}\rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$

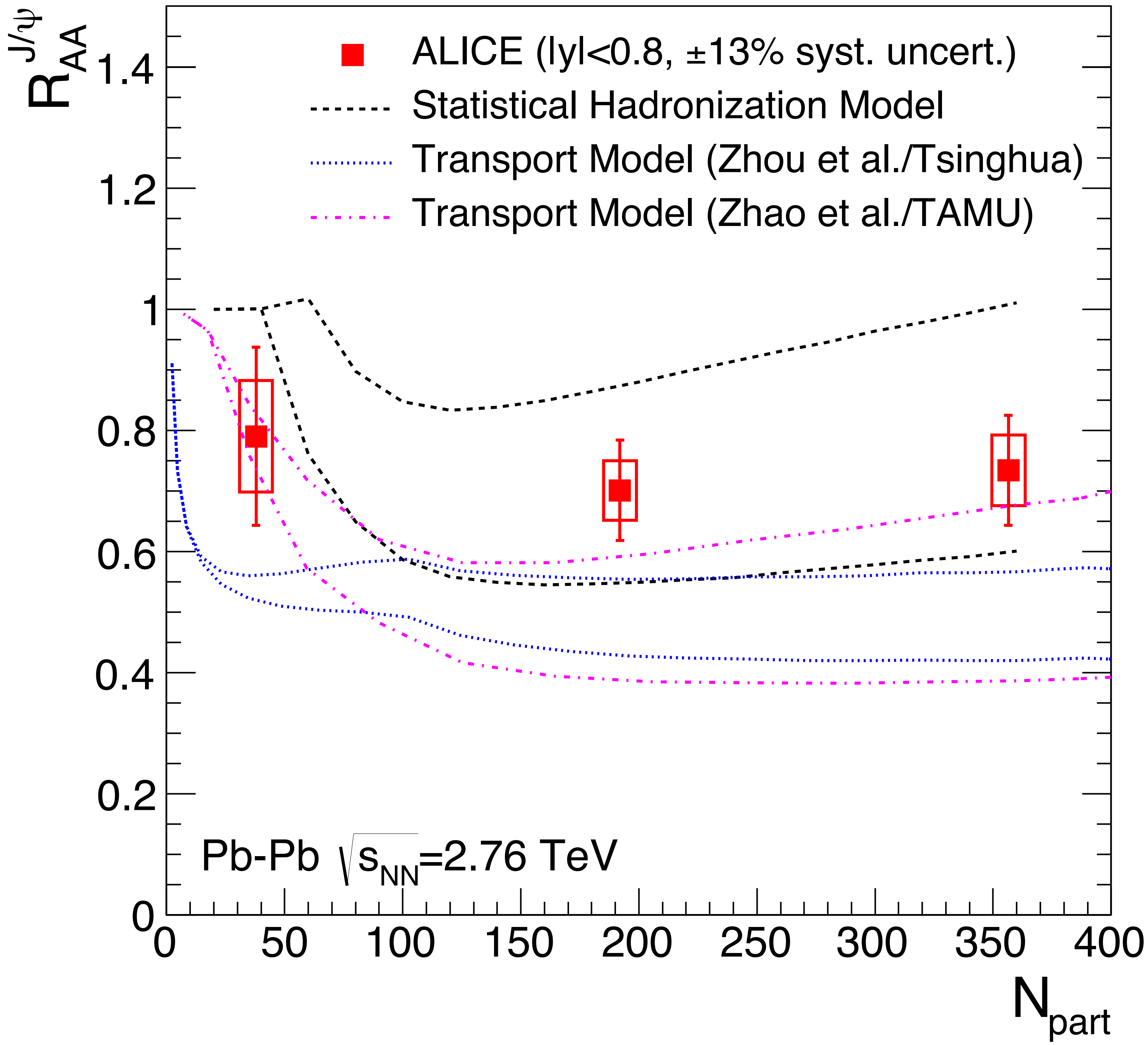
J/ψ suppression at RHIC and the LHC



Much less suppression at the LHC in spite of larger energy density

J/ψ R_{AA} at the LHC is reproduced by models based on the regeneration mechanism

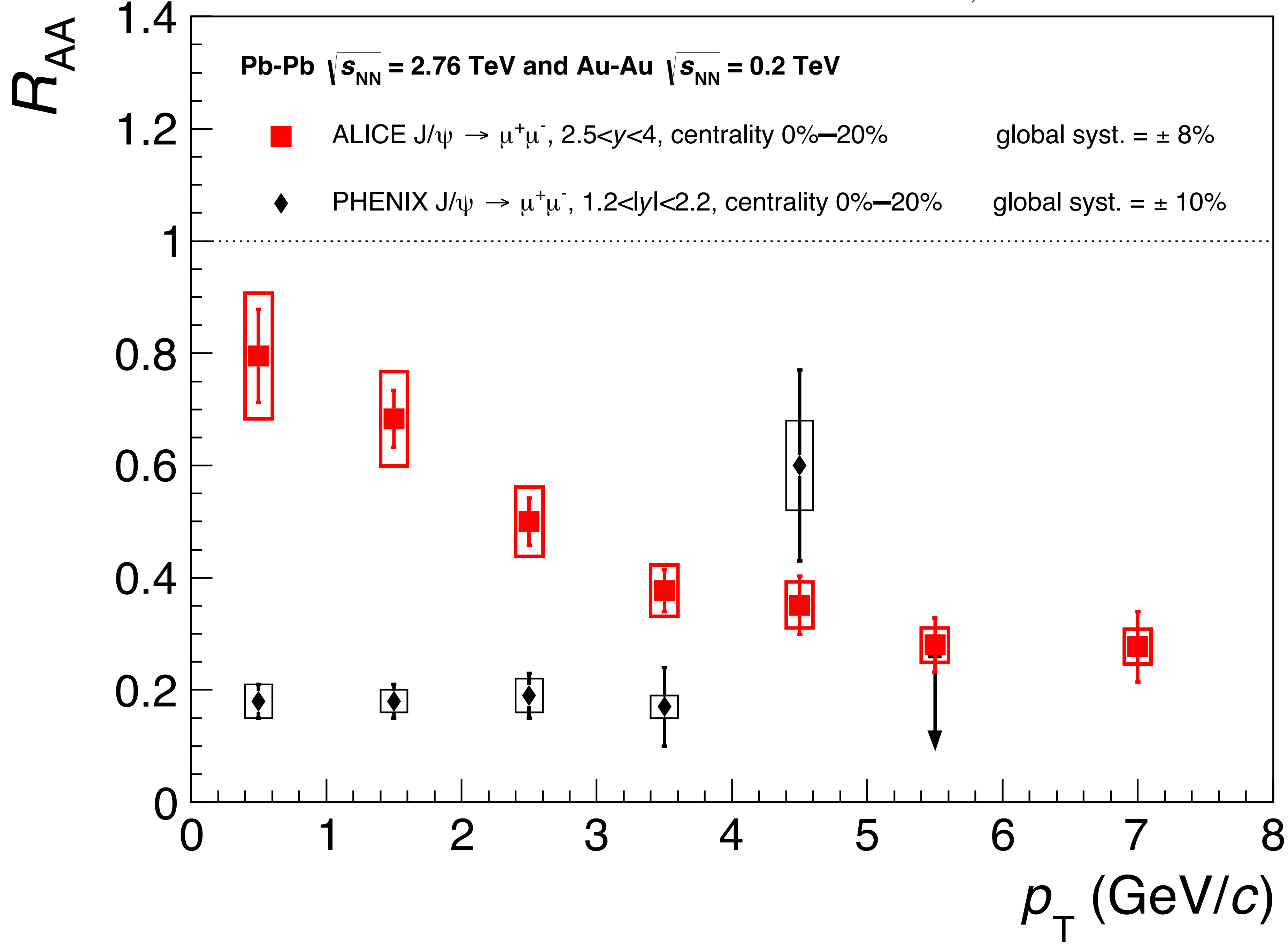
arXiv:1510.00442



- Two different approaches
  - Statistical hadronization at the phase boundary
  - Kinetic recombination of charm and anti-charm quarks in the QGP (hep-ph/0007323)
- Important model input: number of initial charm quark pairs

J/ψ R_{AA} vs p_T at RHIC and the LHC (0-20%)

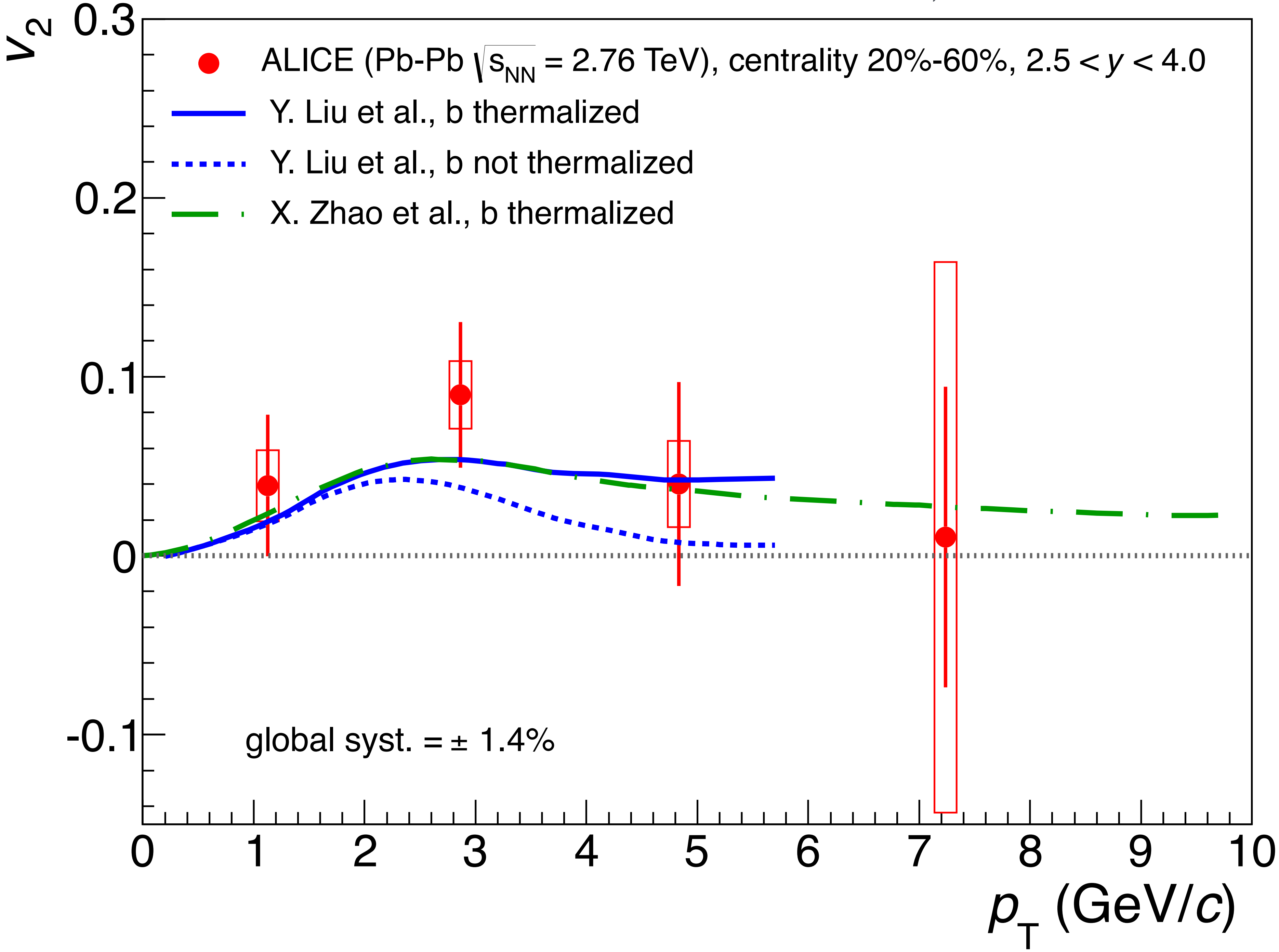
ALICE, arXiv:1510.00442



Much less suppression at low p_T, consistent with regeneration picture

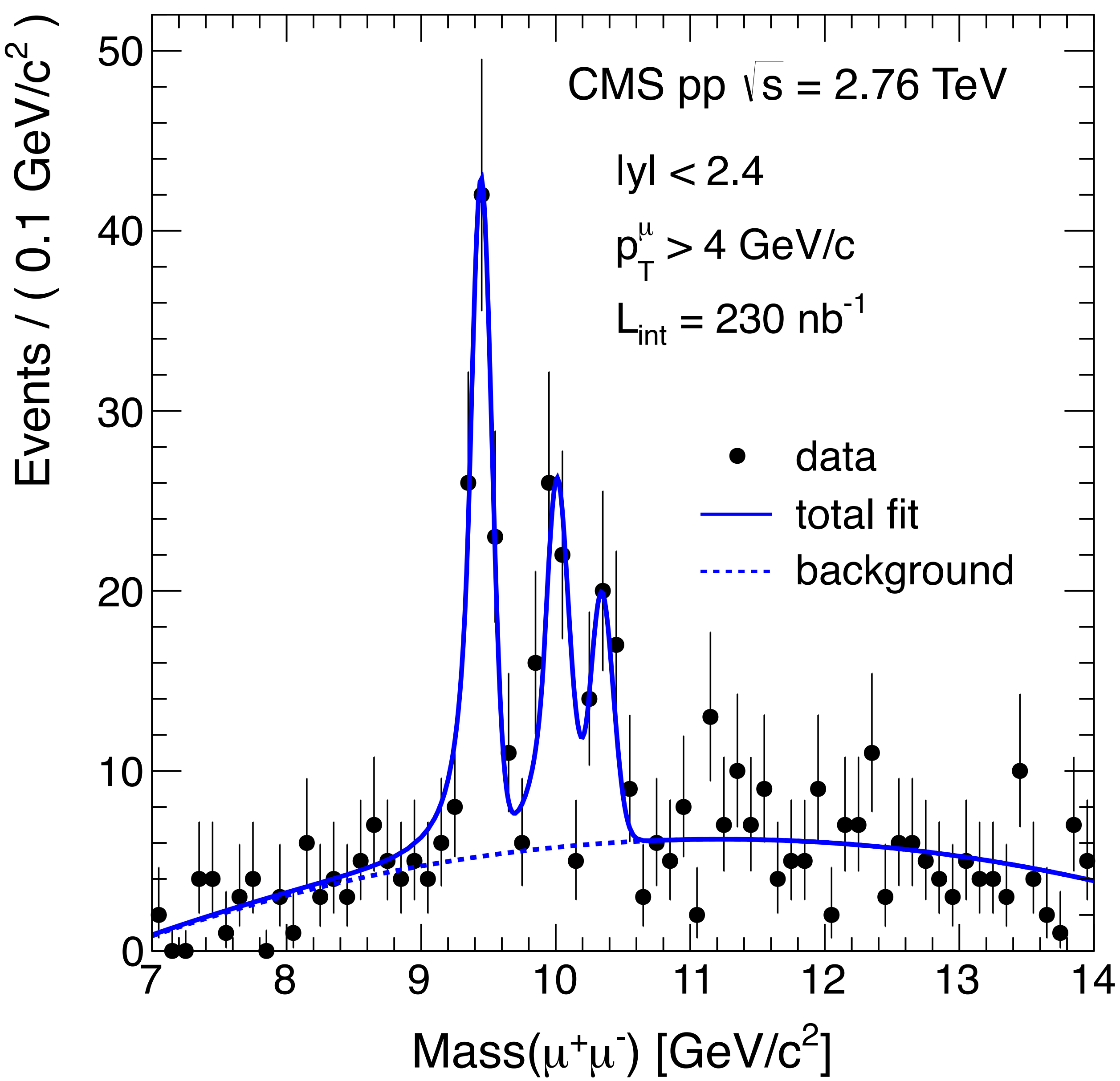
J/ψ seems to flow, too — Support for thermalization of charm quarks in the QGP

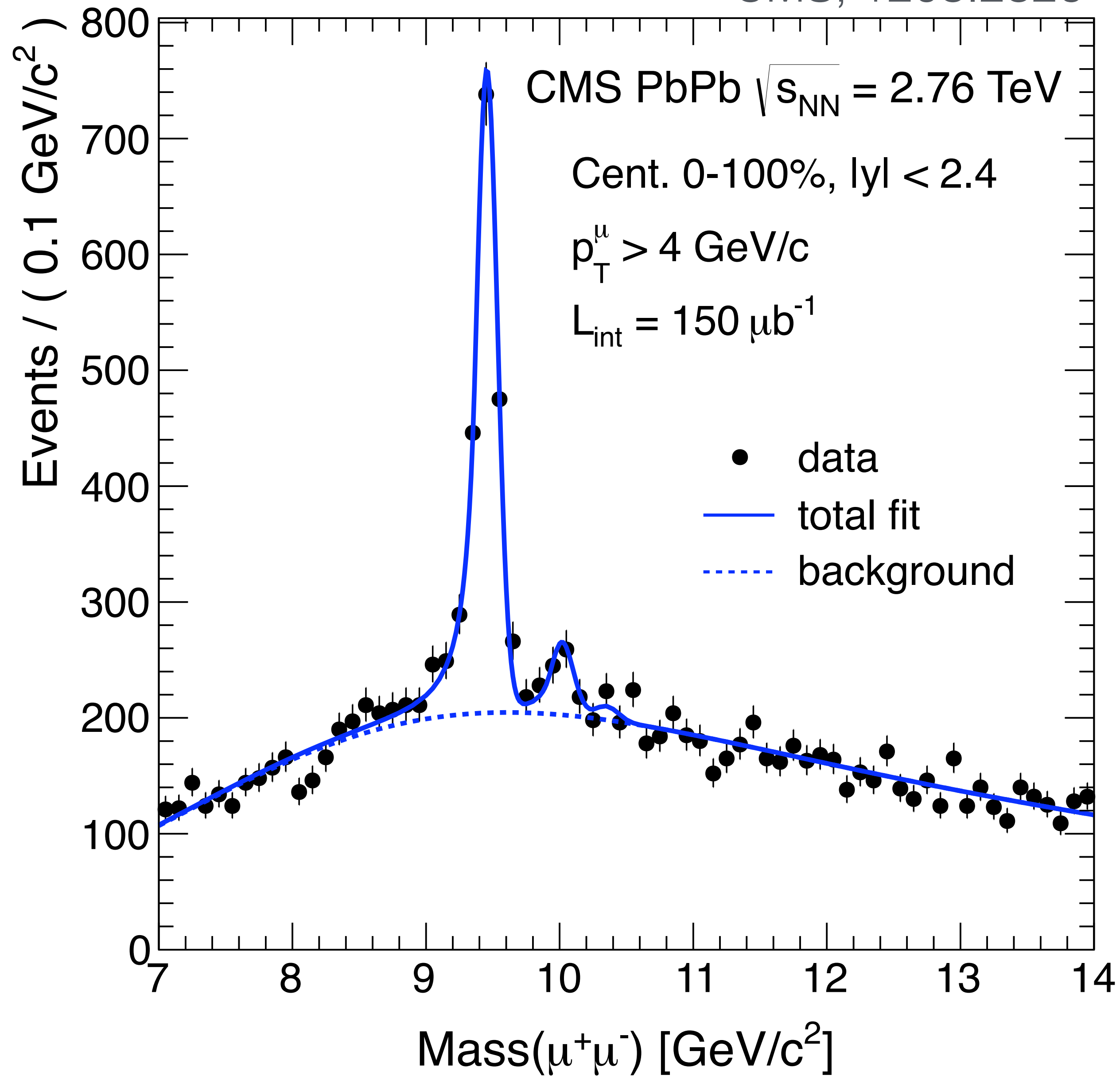
ALICE, arXiv:1303.5880v4



Υ at the LHC:
Υ(2s) and Υ(3s) more suppressed in Pb-Pb than Υ(1s)

CMS, 1208.2826

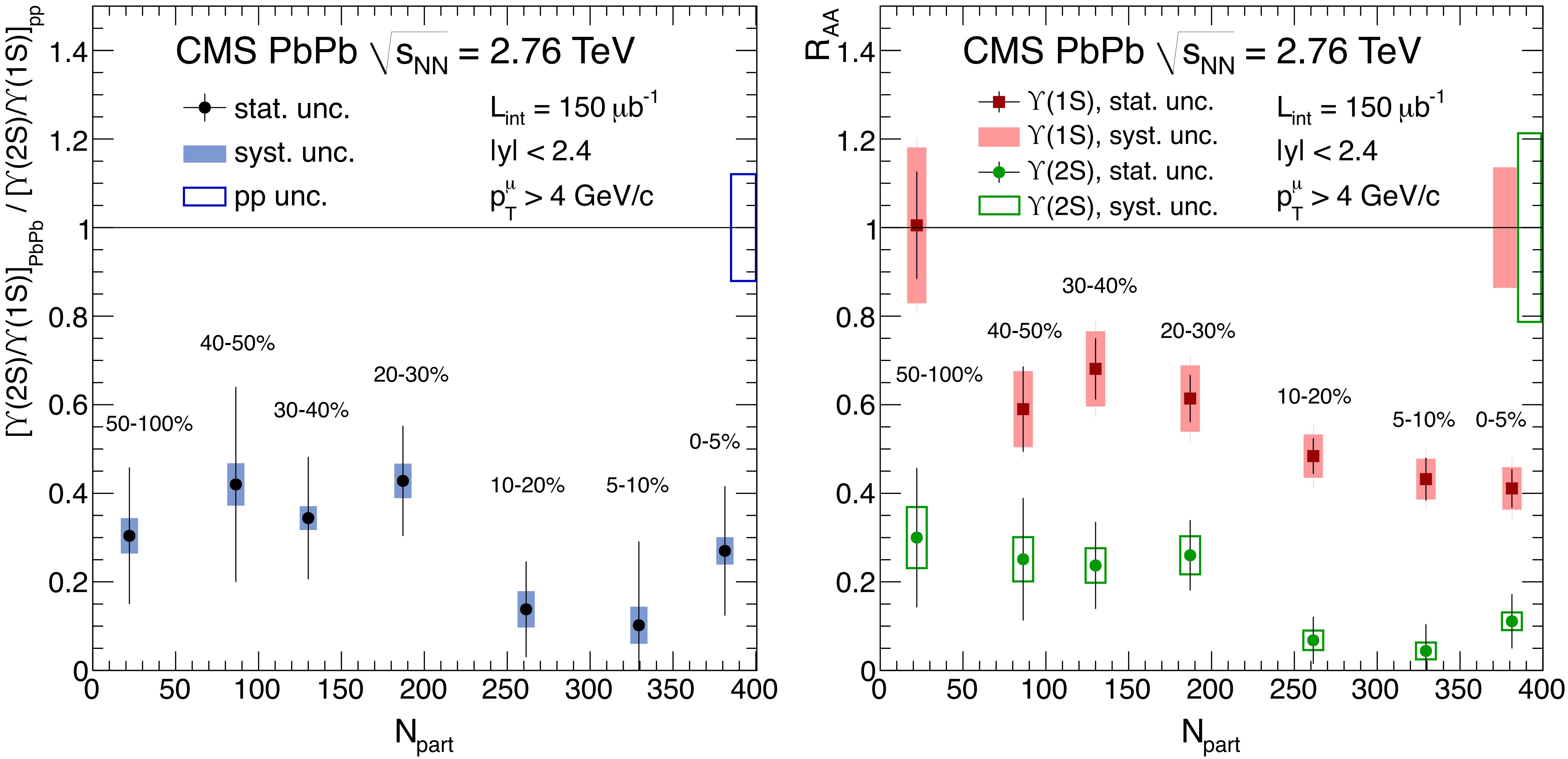




Qualitatively consistent with sequential melting for the Υ states

Υ at the LHC: R_{AA} vs N_{part}

CMS, arXiv:1208.2826



Υ(1S) appears to be suppressed stronger than one would expect from the Υ(2S) and Υ(3S) suppression alone (feeddown)

Summary/questions quarkonia

- Two main effects discussed in A-A collisions
  - Suppression due to color screening in the QGP
  - Regeneration of quarkonia for sufficiently large numbers of deconfined c quarks
- $\sqrt{s_{NN}}$ dependence of J/ψ production consistent with regeneration picture (at RHIC and, more pronounced, at the LHC)
  - However, need stronger constraints on initial number of charm quarks from hard scattering
- What is the appropriate description of the J/ψ regeneration?
- Does the melting scenario hold for Y production at the LHC?
- Can yields of Y states serve as a QGP thermometer?