Excited quarkonia and nuclear matter : pA and AA theories (comovers and QGP effects)

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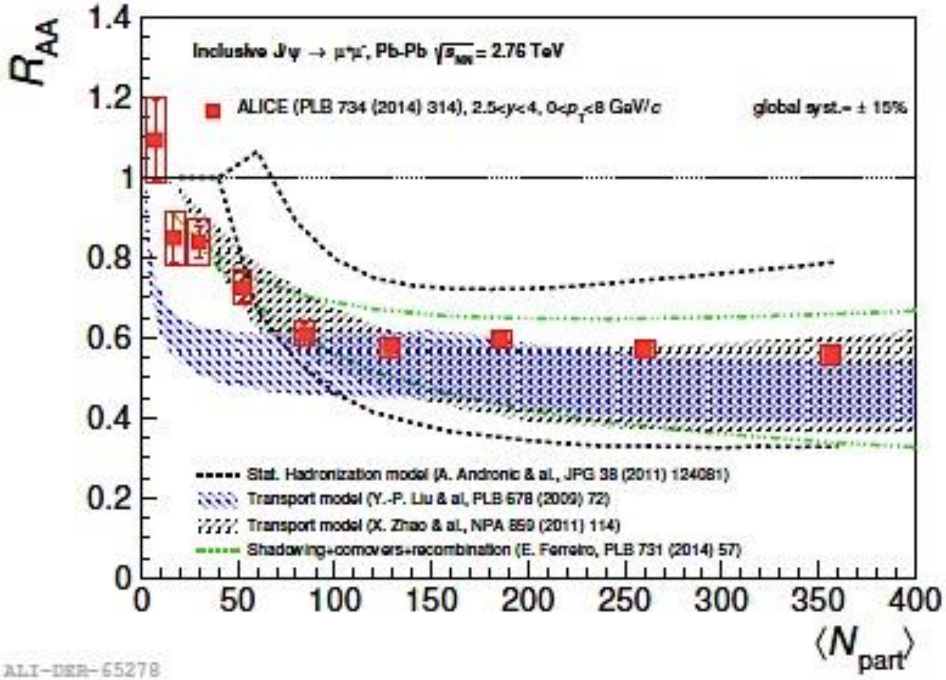
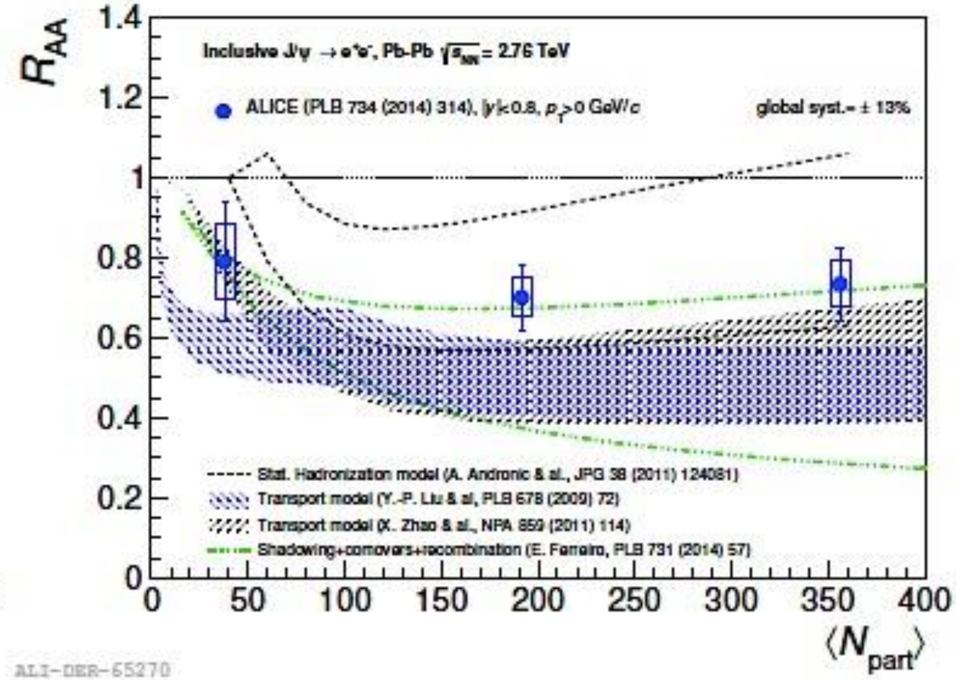
Introduction: J/ψ production

The originally proposed J/ψ suppression signature of QGP formation has evolved into a more complex problem where both suppression & regeneration (or statistical hadronization) mechanisms need to be considered

Main ingredients:
- suppression (either color screening, or in-medium dissociation)
- recombination (either in-medium or at phase boundary)
- Initial cold nuclear matter effects (shadowing and/or energy loss)





Inclusive J/ψ R_{PbPb} versus Event Centrality @ LHC

J/ψ production seems at least qualitatively understood

Theoretical models

Statistical hadronization model

Braun-Munzinger, Stachel, PLB 490 (2000) 196; NPA 789 (2006) 334, PLB 652 (2007) 259

all charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)
thermalized in QGP (thermal, but not chemical equilibrium)
charmed hadrons are formed at chemical freeze-out together with all hadrons ("generation") . ..
no J/ψ survival in QGP (full screening)

if supported by data, J/ψ looses status as "thermometer" of QGP

Transport models Ralf Rapp et al

implement screening picture with space-time evolution of the fireball (hydro-like)

continuous destruction and "(re)generation" ("recombination")

Thews et al., PRC 63 (2001) 054905 ...
"TAMU", PLB 664 (2008) 253, NPA 859 (2011) 114, EPJA 48 (2012) 72
"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, arXiv:1401.5845

Comover model

Capella et al., PLB 393 (1997) 431; PLB 430 (1998) 23; PRC 59 (1999) 395;
PRL 85 (2000) 2080; EPJC 42 (2005) 419; EPJC 61 (2009) 865; PLB 731 (2014) 57

Similar to transport model
Hadronic and partonic comovers contribute
to suppression and recombination
No thermalization

Theoretical models

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"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, arXiv:14

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_{\mathrm{F}} N_c N_{\bar{c}} [V(\tau)]^{-1} - \lambda_{\mathrm{D}} N_{J/\psi}\, \rho_g$$

Similar gain and loss diferential eqs.

Comover model

Capella et al., PLB 393 (1997) 431; PLB 430 (1998) 23; PRC 59 (1999) 395;
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Similar to transport model

Hadronic and partonic comovers contribute

to suppression and recombination

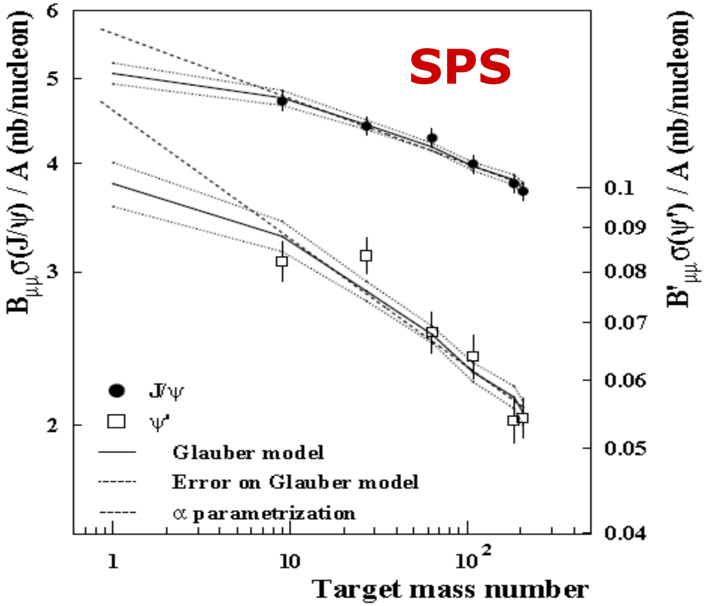
No thermalization

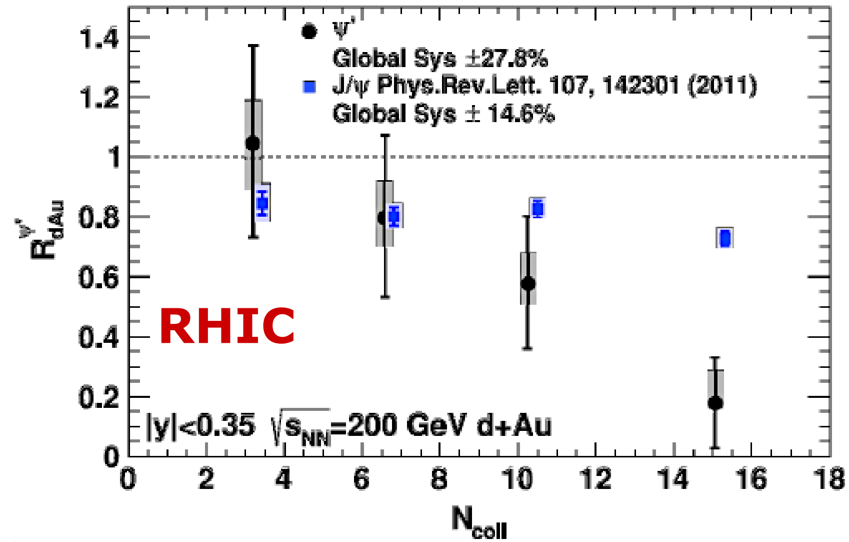
$$\tau \frac{dN^{J/\psi}}{d\tau}(b,s,y) = -\sigma \left\{ N_{J/\psi} N^{co} - N_D N_{\bar{D}} \right\}$$

State of the art for ψ(2S)

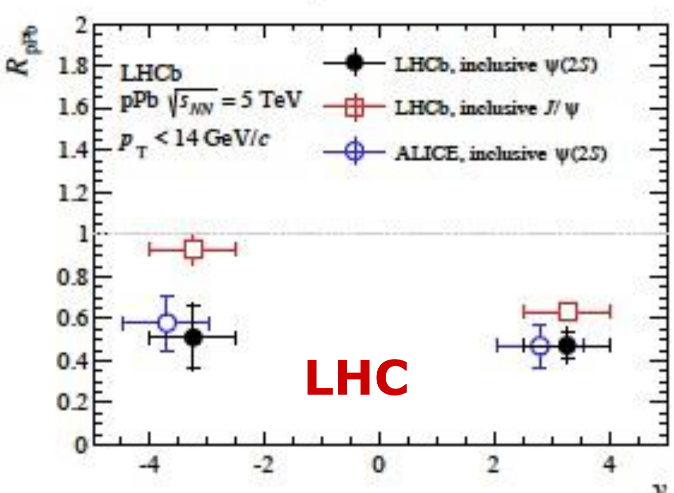
Much less is known about the 2S excited state: unknown in-medium properties

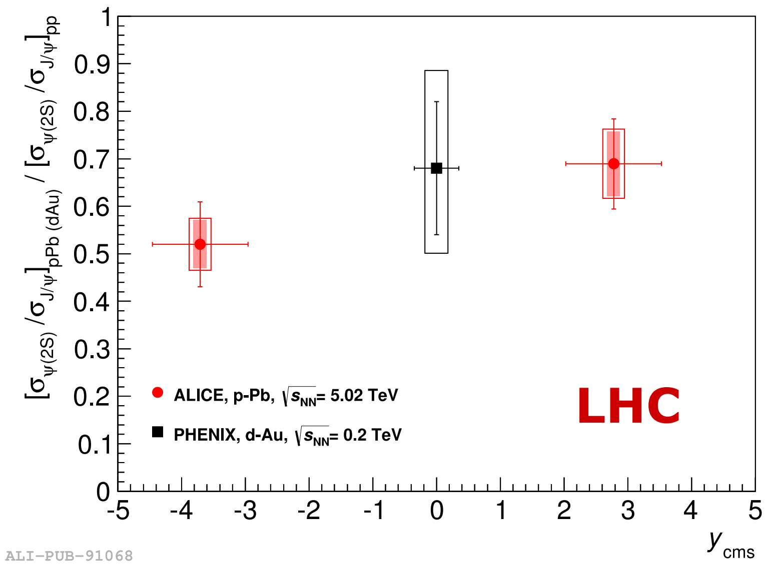
Experimentally: Stronger suppression of ψ(2S) than J/ψ at SPS, RHIC and LHC in pA





In pA collisions at all energies: $R_{pA}^{J/\psi} > R_{pA}^{\psi'}$



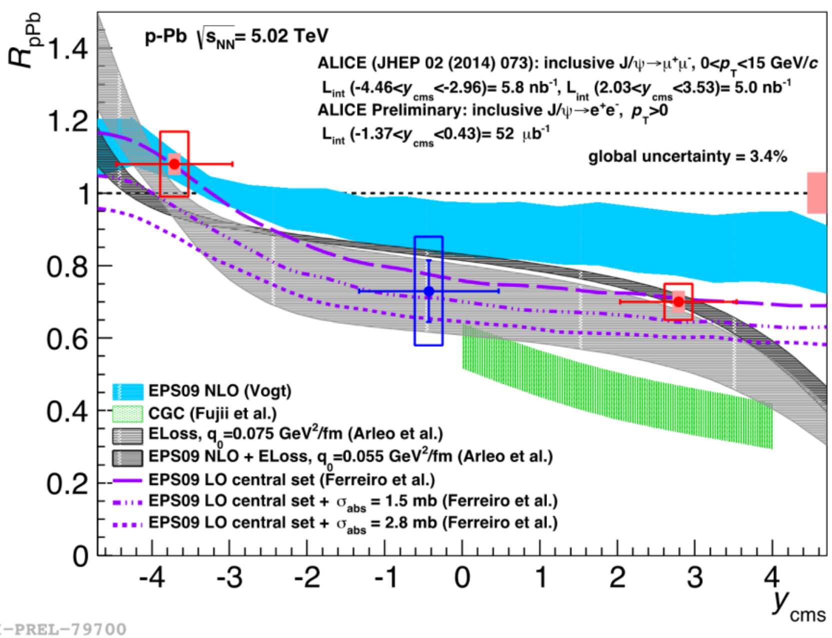


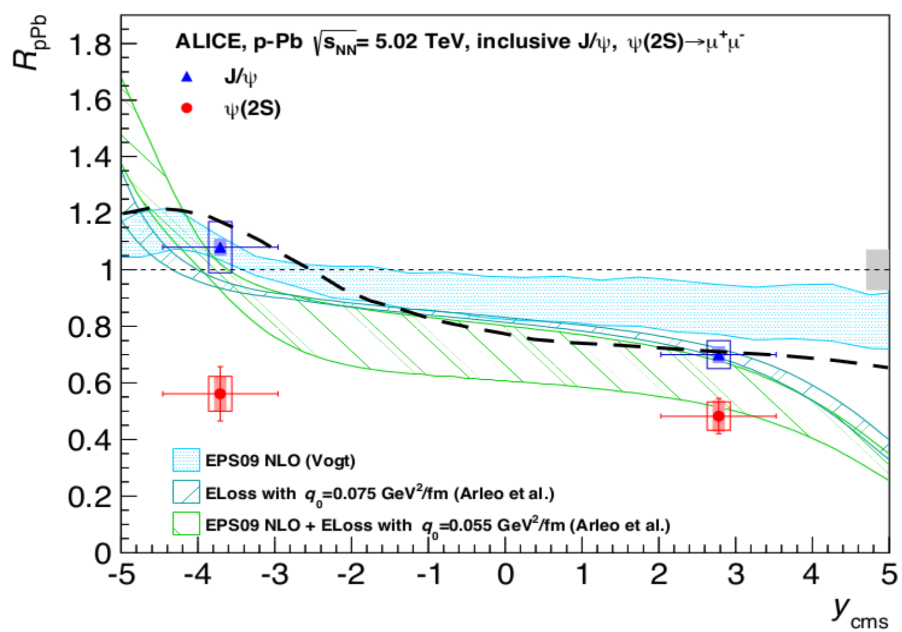
ψ(2S) suppression in pA collisions

- pA @ SPS: Nuclear breakup effect => Stronger suppression of the larger ψ(2S)
  charmonium formation times < nuclear radius

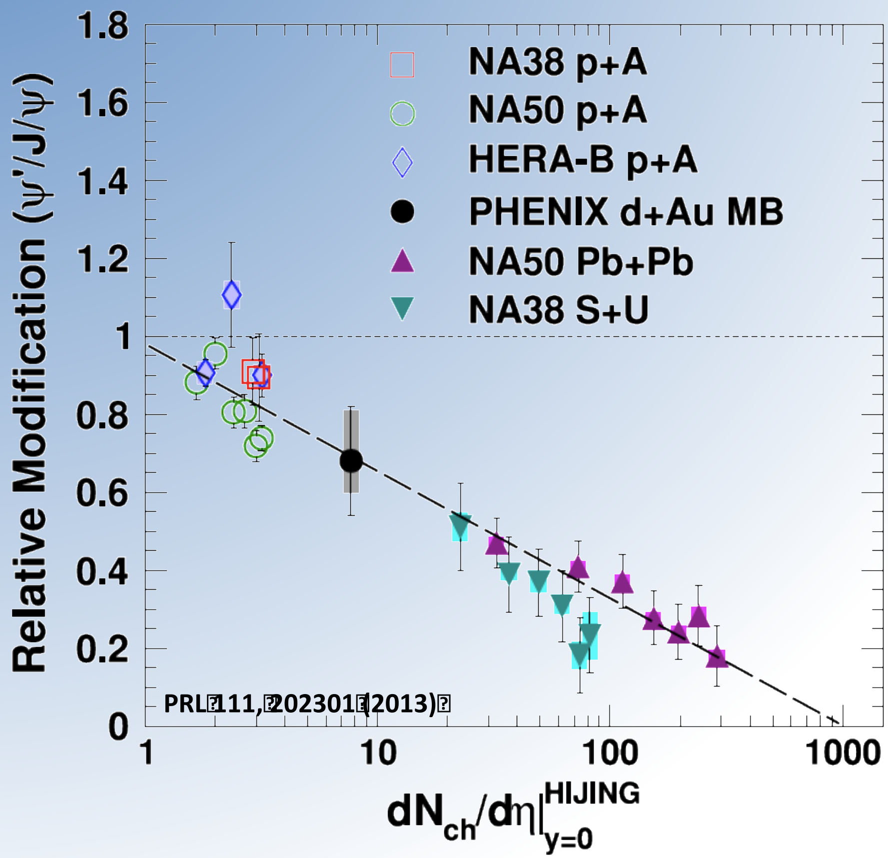
- dA @ RHIC: Charmonium formation times $t_f = \gamma\,\tau.$ > R_A nuclear radius =>
  pA @ LHC: nuclear absorption cannot be invoked
  (identical for ψ(2S) and J/ψ since they cannot be distinguished)

Same initial CNM effects (shadowing –similar m_T-, energy loss) for both J/ψ and ψ(2S)
=> theoretical predictions in disagreement with ψ(2S) results





Relative Modification of ψ(2s)/ψ(1s) – particle density



Relative modification in *all* systems follows common trend with increasing produced particle density.

Co-mover (or medium?) density seems to be the relevant quantity.

M. Durham QM2014

Final state effects related to the co-moving medium

ψ(2S) and J/ψ in dAu @ RHIC & pPb @ LHC: Comover scenario

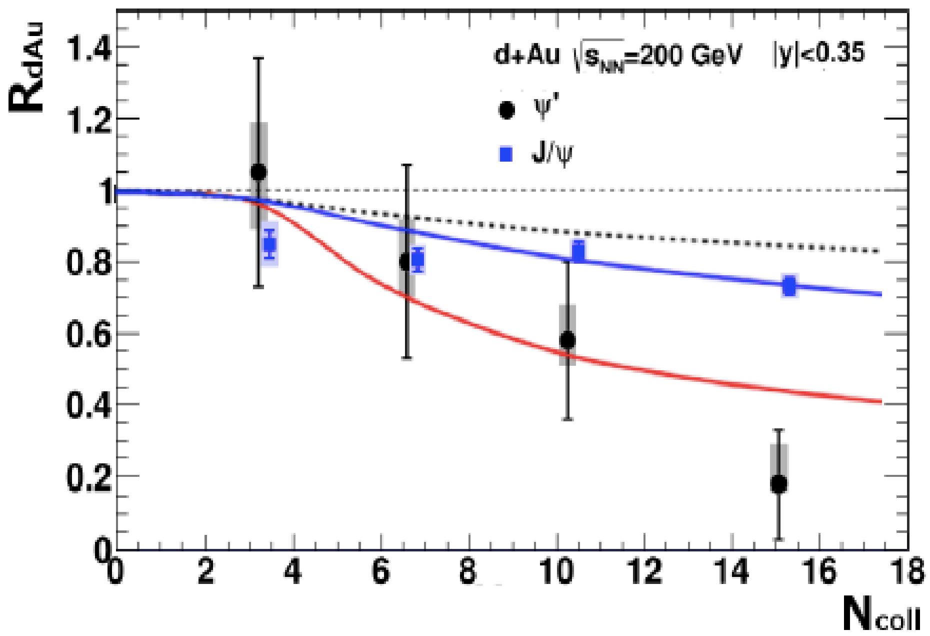
Charmonium interaction with comoving particles

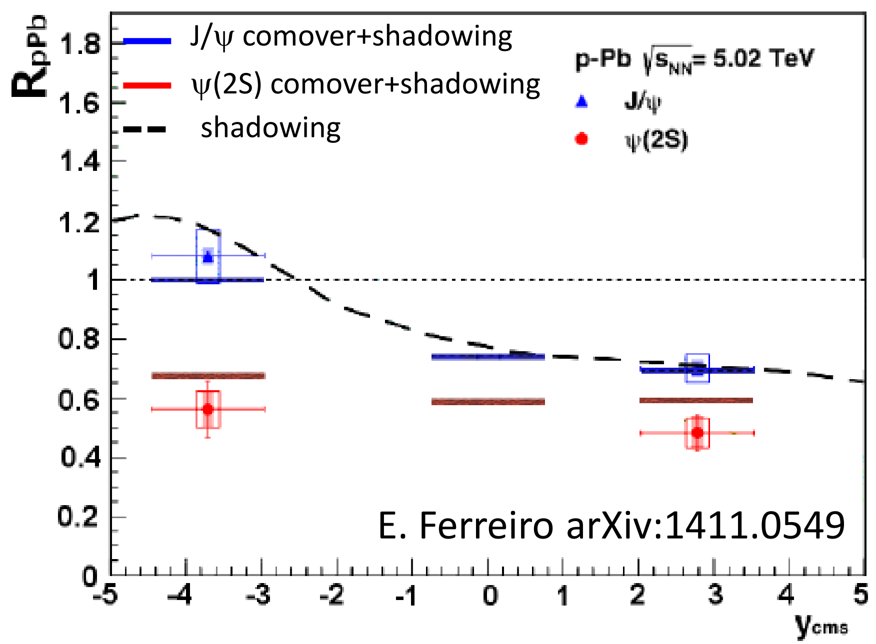
$$\tau \frac{dN_{J/\psi}}{d\tau}(b,s,y) = -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$

- Identical shadowing for ψ(2S) and J/ψ
- J/ψ suppression due to the combined effect of shadowing and comover dissociation
- ψ (2S) suppression due to the combined effect of shadowing and stronger comover dissociation

$\sigma_{co-\psi(2S)} > \sigma_{co-J/\psi}$ $\sigma_{co-\psi(2S)}$ = 6 mb, $\sigma_{co-J/\psi}$ = 0.65 mb identical to the ones used at SPS

PLB430 (1998), PRL 85 (2000) 2080, PLB731 (2014) 57





- Comovers dissociation affects more strongly the loosely bound ψ(2S) than the J/ψ
- Comovers density larger at backward rapidity

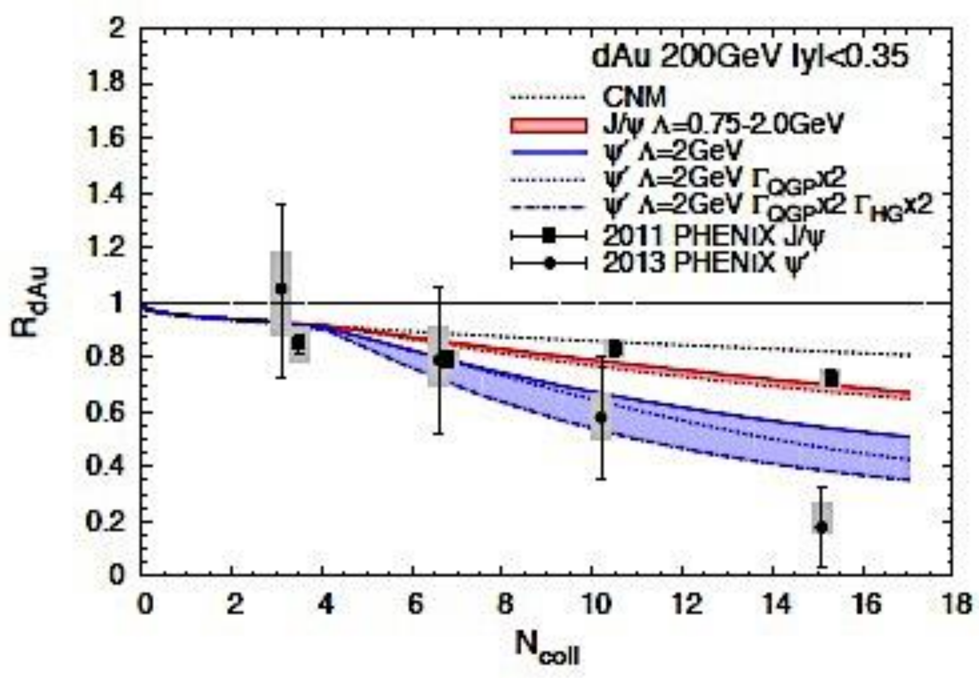
ψ(2S) and J/ψ in dAu @ RHIC & pPb @ LHC: Transport model

- Thermal-rate equation framework $$\Gamma^{\text{diss}}_{X+J/\psi}(T) = \int \frac{d^3k}{(2\pi)^3} f^X(E_X(k);T)\,\sigma^{\text{in}}_{X+J/\psi}(s, s^X_{\text{thr}})\,v_{\text{rel}}$$

- The fireball evolution includes the transition from a short(quasiparticle) QGP phase into the hadron resonance gas, through a mixed phase

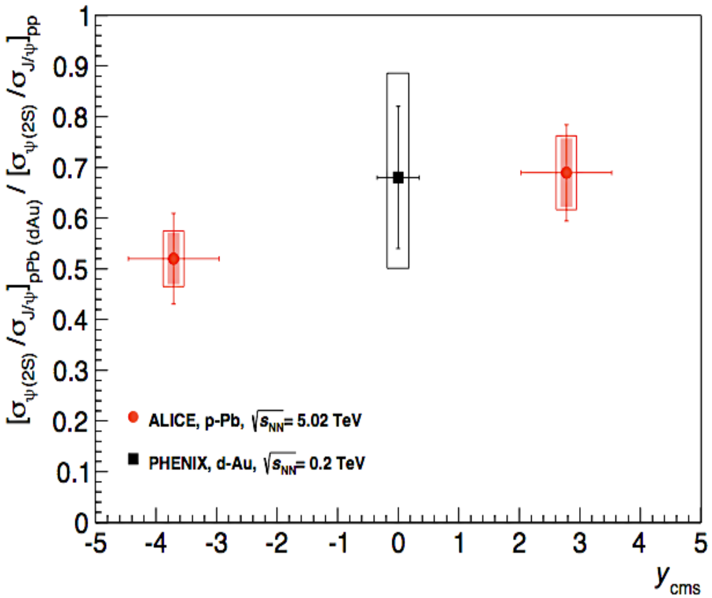
- Dissociation of charmonia in a hadron resonance gas

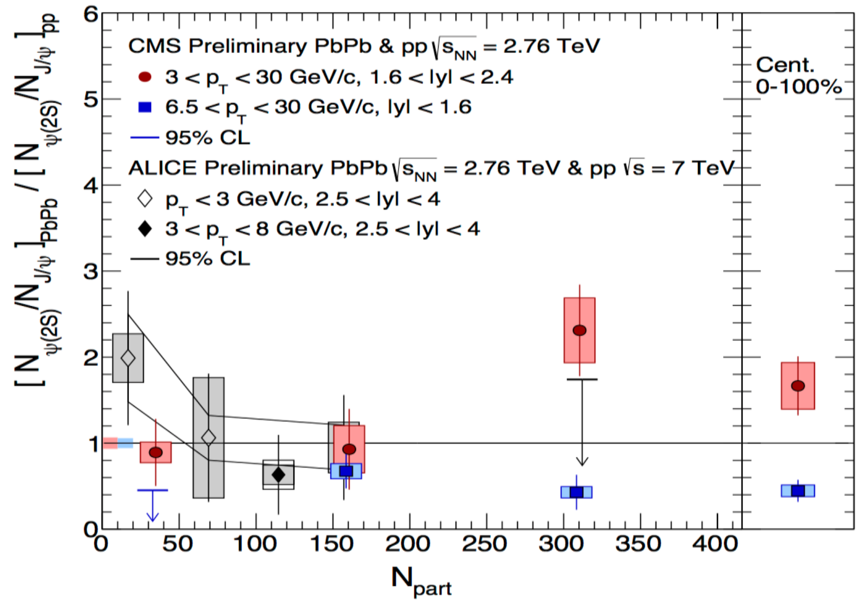
- Large hadronic dissociation reactions leads to appreciable suppression in the hadronic medium of an expanding fireball background for d-Au collisions.



Xiaojian Du and Ralf Rapp
arXiv:1504.00670

From pA to AA: R_{pPb} (2S)/R_{pPb}(1S) vs R_{PbPb} (2S)/R_{PbPb}(1S)



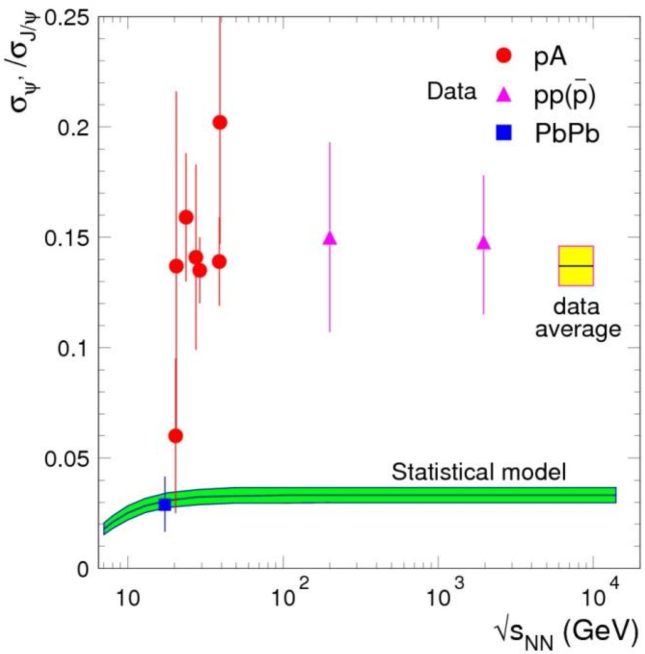


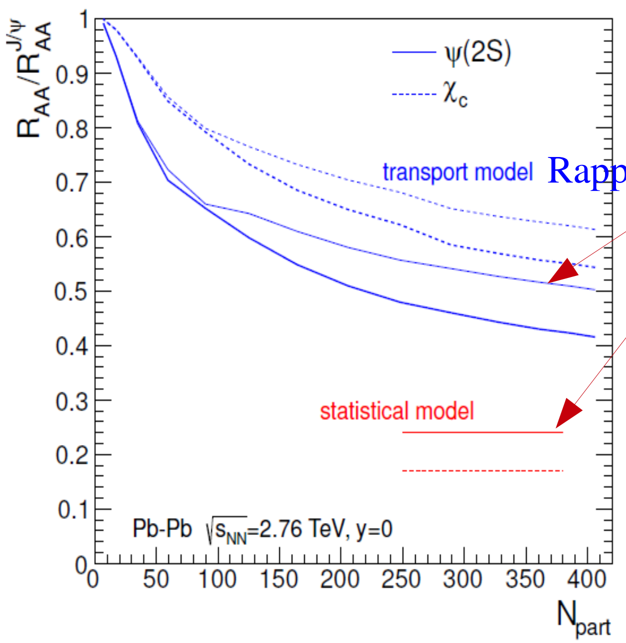
2S more supressed than 1S in pPb

2S less supressed than 1S in PbPb or ….
Suppression + recombination at low p_T?

- At mid-rapidity and **high p_T**: R_{pPb} (2S)/R_{pPb}(1S) < 1 as expected from sequential melting
- At forward rapidity and **low p_T**: R_{pPb} (2S)/R_{pPb}(1S) > 1 => larger 2S than 1S, regeneration ?
- Peripheral and semi-central collisions show a double ratio consistent with 1 at forward y, whereas the most central bin shows an increase of the double ratio (low to moderate p_T)
- The suppression of the double ratio at mid-y appears to be independent of centrality (high p_T)

formation of charmonia from deconfined quarks: psi' is crucial cornerstone

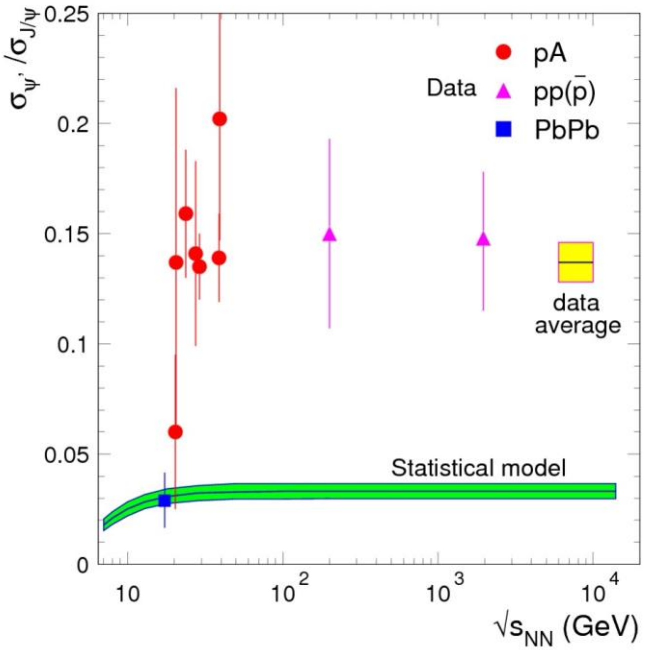


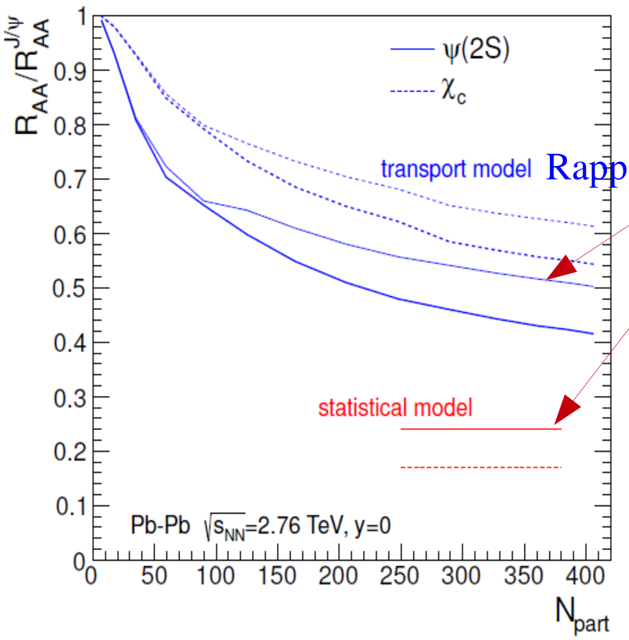


in fact: here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

for statistical hadronization need to see suppression by Boltzmann factor

formation of charmonia from deconfined quarks: psi' is crucial cornerstone

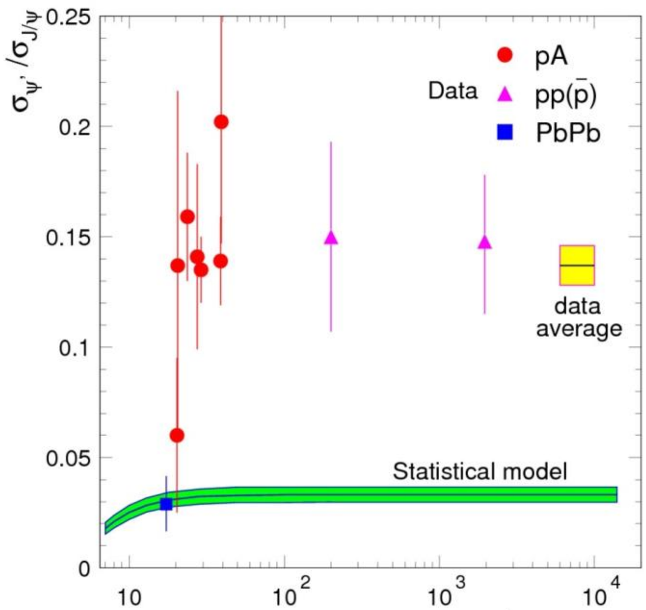


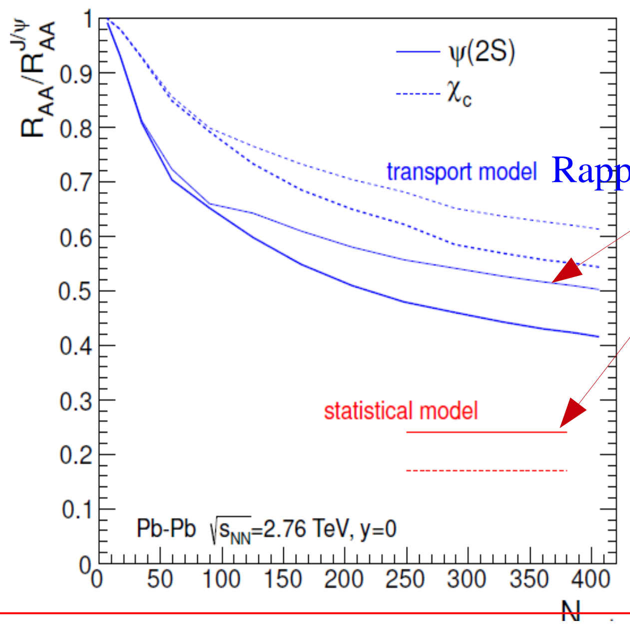


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

- The statistical hadronisation model predicts a pT -integrated double-ratio of 0.2, contray to data
- It remains to be seen which effects can explain these results, e. g. if regeneration of (2S) can be enhanced relative to J/ψ due to the larger binding radius
- Attempts are made to explain this observation, arguing that (2S) are regenerated at later stages than J/ψ and/or with larger interaction cross section: Comover and transport models

formation of charmonia from deconfined quarks: psi' is crucial cornerstone





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4 Conclusions **Peter Braun-Munzinger, Krzysztof Redlich EPJC16 (2000) 519**

We have considered the possibility of the secondary charmonium production in ultrarelativistic heavy ion collisions at LHC energy. Admitting thermalization of a partonic medium crated in a collision and the subsequent first order phase transition to a hadronic matter we have shown that the secondary charmonium production appears almost entirely during the mixed phase. The yield of secondarily produced ψ mesons is very sensitive to the hadronic absorption cross section. Within the context of the short distance QCD approach this leads to negligible values for J/ψ regeneration. The ψ' production, however, can be large and may even exceed the initial yield from primary hard scattering. Thus it is conceivable that at LHC energy the ψ' charmonium state can be seen in the final state whereas J/ψ production can be entirely suppressed. The appearance of the ψ' in the final state could be thus considered as an indication for the charmonium production from the secondary hadronic rescattering.

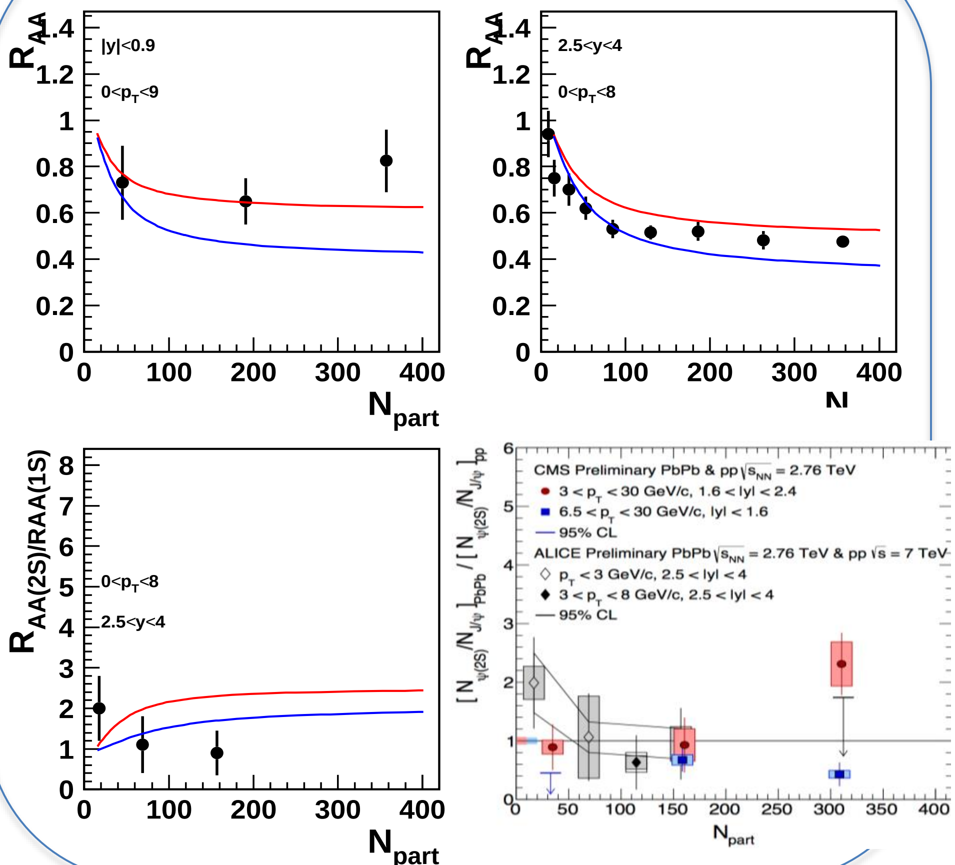
Comover dissociation + recombination in PbPb at LHC?

Double ratio $R_{PbPb}(2S)/R_{PbPb}(1S)$ @ LHC: Comover results

$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}(b,s,y) = -\sigma_{co}\left[N^{co}(b,s,y)N_{J/\psi}(b,s,y) - N_c(b,s,y)N_{\bar{c}}(b,s,y)\right]$$

$$S^{co}(b,s,y) = \exp\left\{-\sigma_{co}\left[N^{co}(b,s,y) - \frac{N_c(b,s,y)N_{\bar{c}}(b,s,y)}{N_{J/\psi}(b,s,y)}\right]\ln\left[\frac{N^{co}(b,s,y)}{N_{pp}(0)}\right]\right\}$$

p_T integrated results



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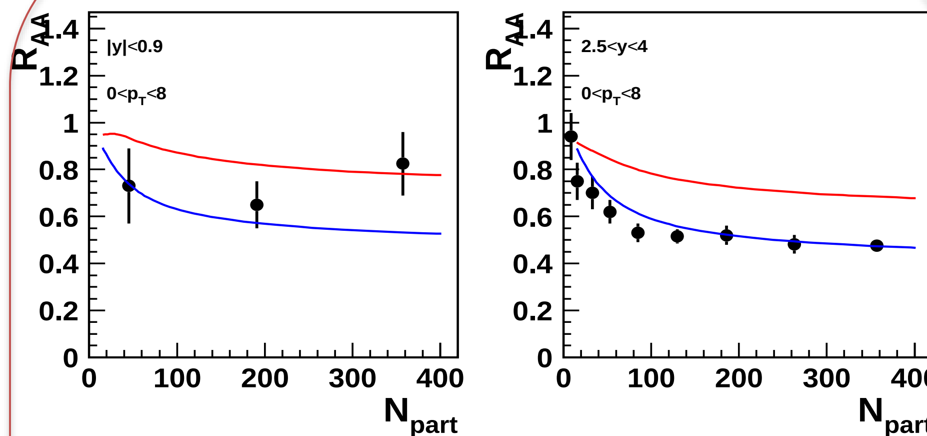
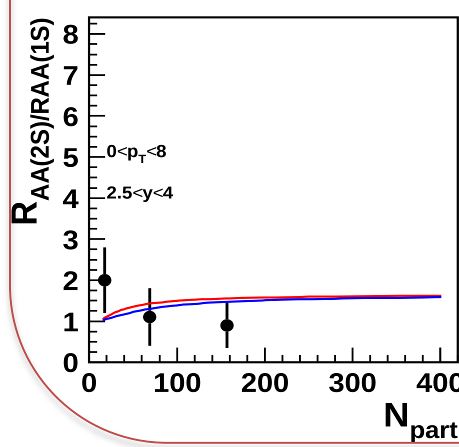


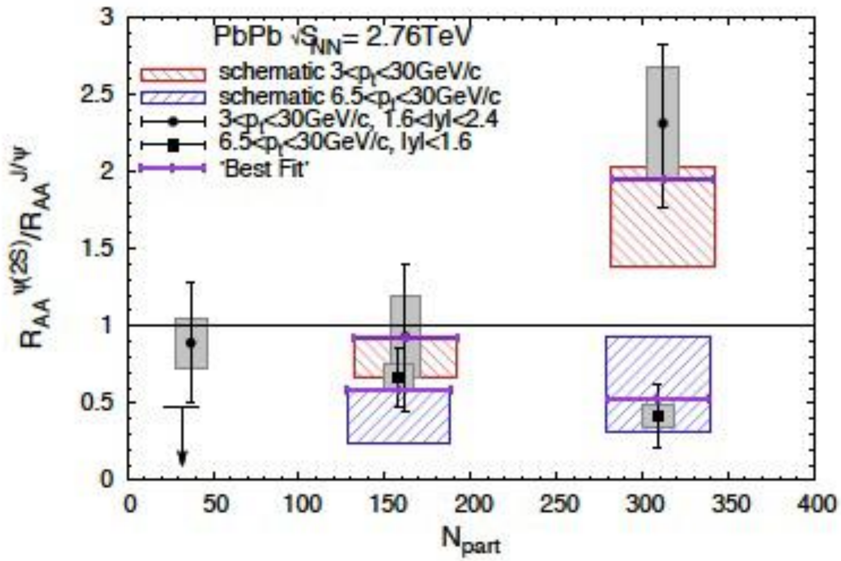


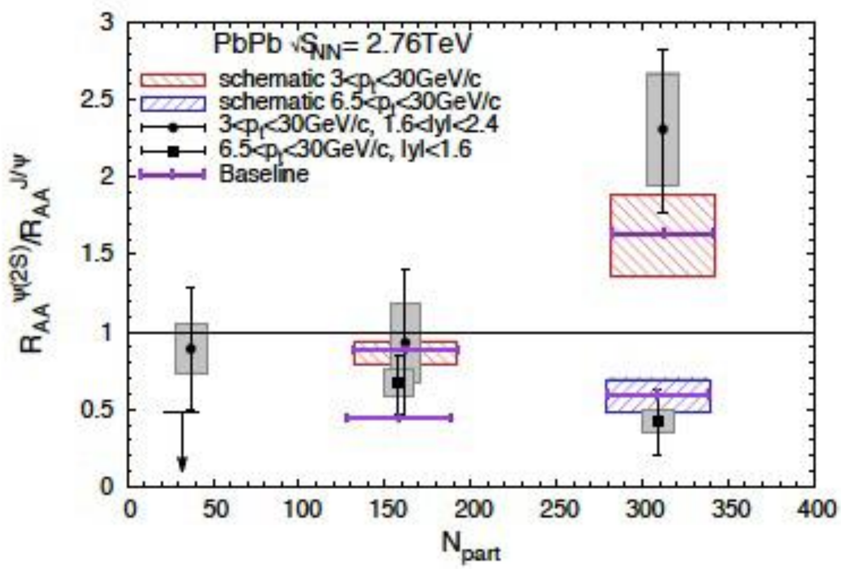
Feed down taken into account:

Inclusive 1S = 0.4 direct 1S + 0.6 2S

WIP

Double ratio $R_{PbPb}(2S)/R_{PbPb}(1S)$ @ LHC: Transport model





Sequential Regeneration of Charmonia in Heavy-Ion Collisions

Xiaojian Du and Ralf Rapp arXiv:1504.00670

In the present paper we put forward a potential mechanism to (partially) resolve the above "puzzle". Based on the rather large inelastic reaction rates for the ψ' in hadronic matter that we deduce from its suppression in d-Au (also in line with the aforementioned SPS data), we argue that the inverse reactions of ψ' formation in Pb-Pb collisions must also happen in the later, hadronic stages of the fireball evolution. In particular, the ψ' regenera-

Models that can explain an increase of the doble ratio asume **stronger regeneration of the 2S compared to 1S state as final state effect of "*hadronic*"** origin

What is the medium made of? What is a comover?

- Our initial comover densities are proportional to the number of created hadrons (parton hadron duality)
- A large contribution to the integral comes from the few first fm/c after the collision
- Interaction of comovers at the early time τ_0 (1 fm) involves large densities which appear high for free mesons (partons/pre-hadrons/dressed mesons/hadron)
- Hadronic matter in this situation is certainly far away from the ideal pion gas, but can be approximated as pre-hadrons or dressed mesons (spectral densities with the quantum numbers of the hadronic states that show up at high energy density)
- Actually, Brodsky and Mueller introduced the comover interaction as a coalescence phenomenon at the partonic level
- When the volume increases (i.e., the time passes), the densities dilute

parton=>hadron

Dense medium, not necessarily thermalized nor deconfined

Bottomonia in AA at RHIC and LHC

LHC **RHIC**

$$R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)} < R_{AA}^{\Upsilon(1S)}$$

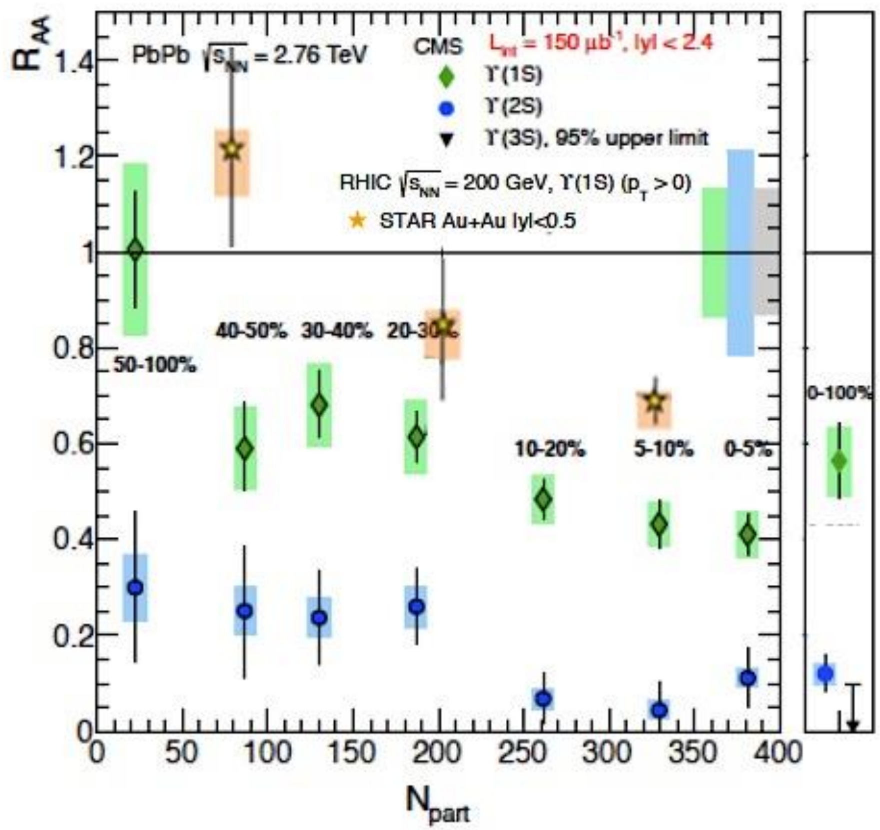
- **Centrality integrated:**

LHC

- $\Upsilon(1S)$: $0.56 \pm 0.08 \pm 0.07$
- $\Upsilon(2S)$: $0.12 \pm 0.04 \pm 0.02$
- $\Upsilon(3S)$: <0.10 at 95% CL

- Ordered suppression
  => **Sequential melting**

- **The situation seems clear for Υ…**
  BUT

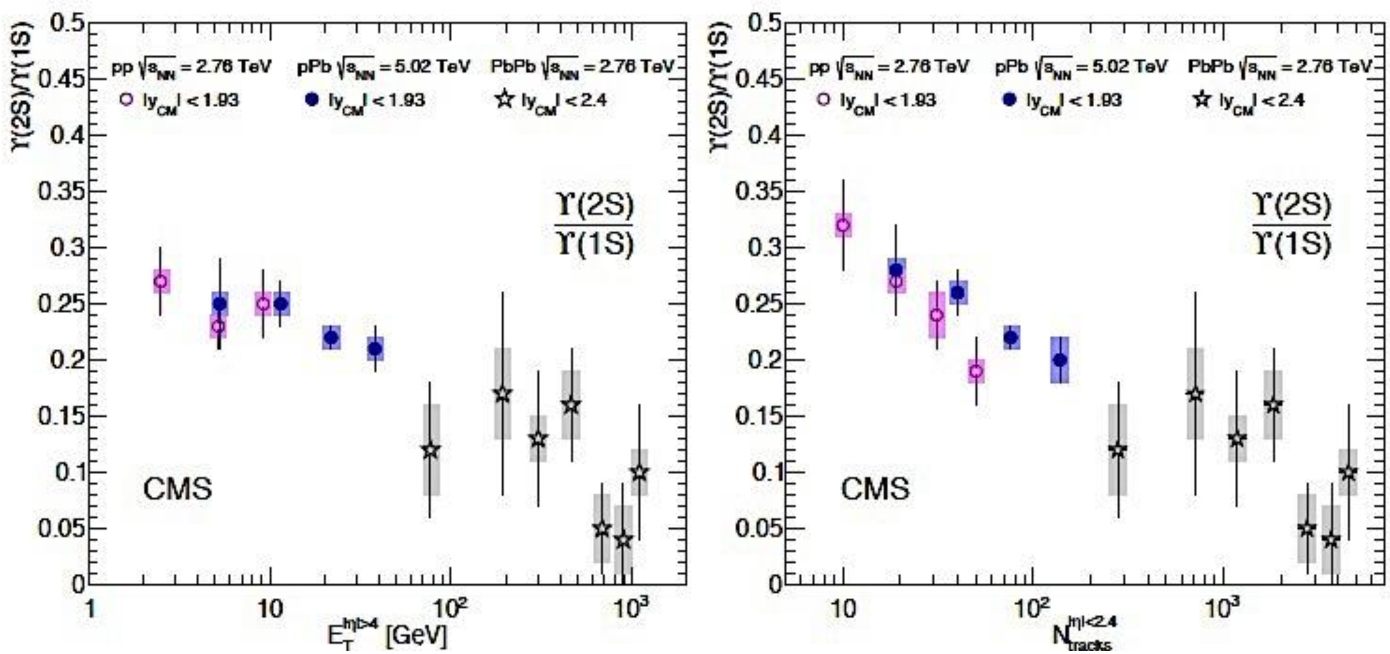


Bottomonia in pA at LHC

$\frac{[\Upsilon(nS)/\Upsilon(1S)]_{ij}}{[\Upsilon(nS)/\Upsilon(1S)]_{pp}}$	$2S$	$3S$
PbPb	$0.21 \pm 0.07\,(\text{stat.}) \pm 0.02\,(\text{syst.})$	$0.06 \pm 0.06\,(\text{stat.}) \pm 0.06\,(\text{syst.})$
pPb	$0.83 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	$0.71 \pm 0.08\,(\text{stat.}) \pm 0.09\,(\text{syst.})$

- Significant relative suppression of the 2S and 3S states with respect to the 1S state
- If the effects responsible for the relative nS/1S suppression in pPb collision factorise
  => responsible for half of the PbPb relative suppression!
- The **differential suppression of the excited states is found to be stronger for events with larger particle production**, suggesting that the larger number of particles in the final state has a stronger effect on the more weakly bound states

Bottomonia in pA and AA at LHC

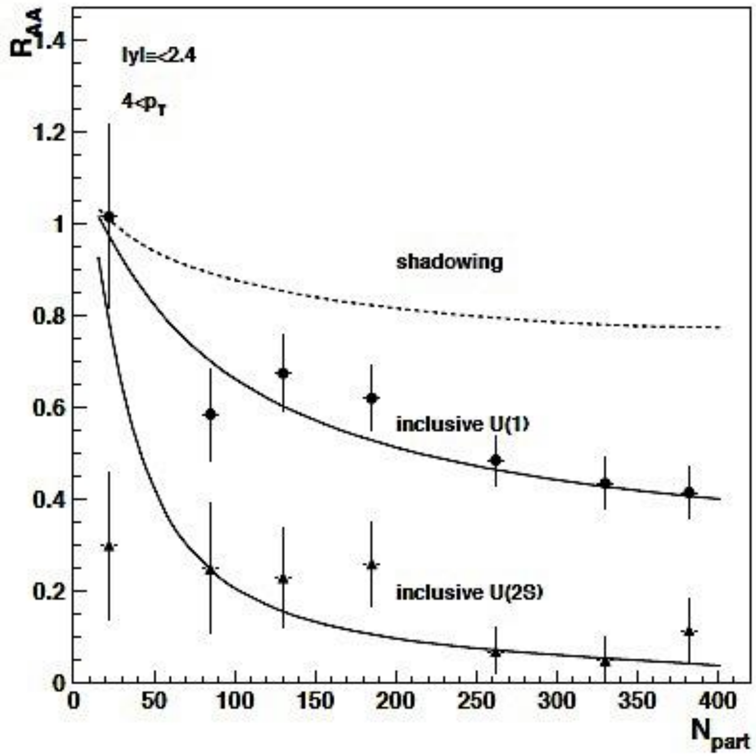


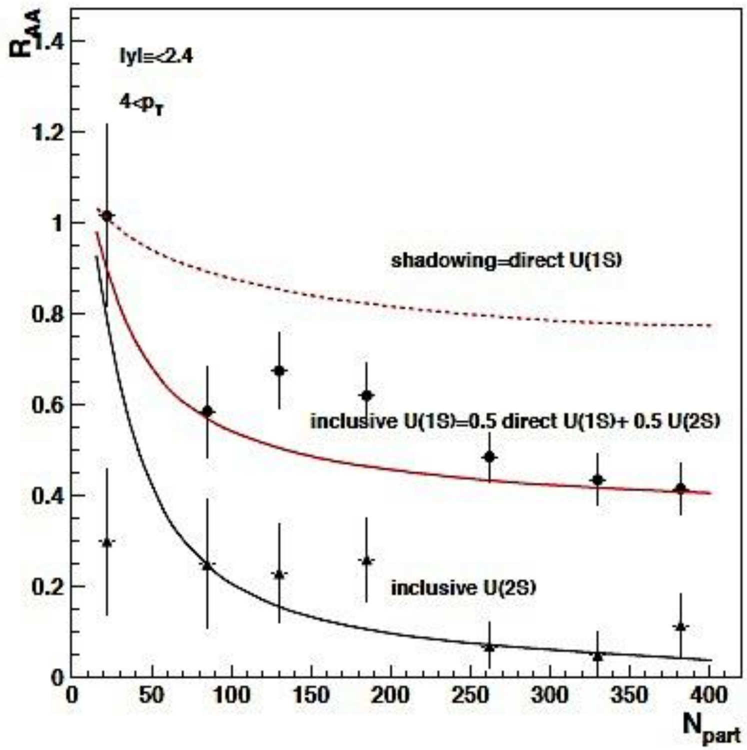
From CMS arXiv:1312.6300

- The **excited-to-ground-states cross section ratios**, U(nS)/U(1S), are found to **decrease with increasing charged-particle multiplicity**
- **Initial effects** -modification of nPDFs the incoming nuclei, parton energy loss, and the Cronin effect-, are expected to **affect the members of the Y family in the same way**
- Consequently, **any difference among the states is likely due to phenomena occurring after the bb production, during or after the Y formation**. Examples of final-state effects that might play a role include **collisions with comoving hadrons or surrounding partons**

Double ratio $R_{PbPb}(2S)/R_{PbPb}(1S)$ @ LHC: Comover results

	Υ(1S)	Υ(2S)	Υ(2S)/Υ(1S)	Υ(2S)/Υ(1S)exp
pPb @ 5.02 TeV	0.88	0.77	0.87	0.83±0.05±0.05
PbPb @ 2.76 TeV	0.54	0.14	0.26	0.21±0.07±0.02





WIP

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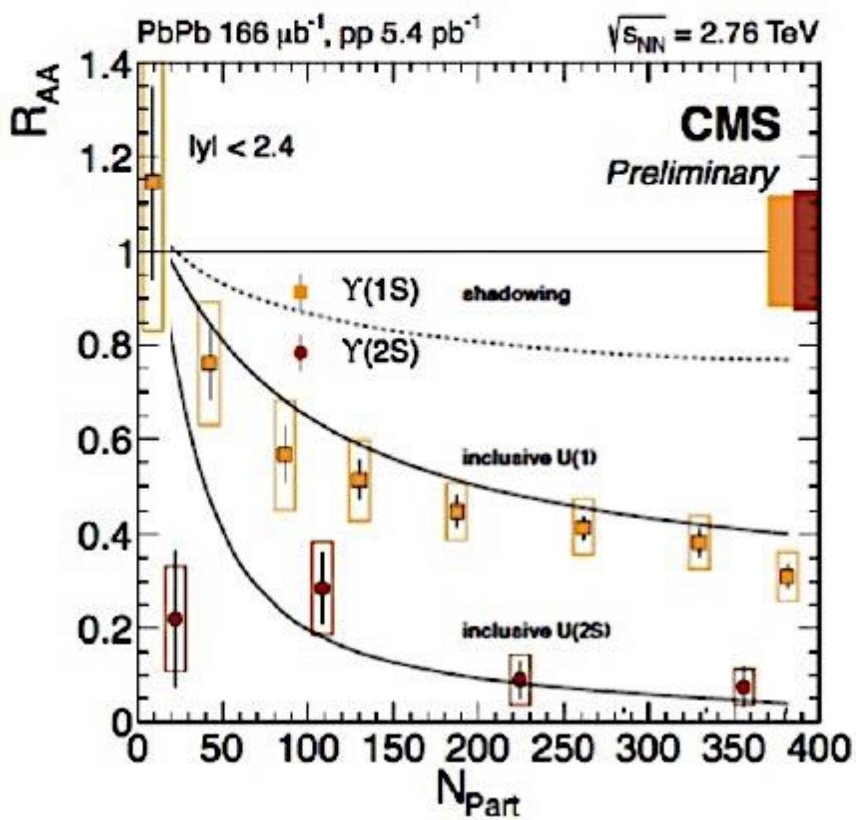
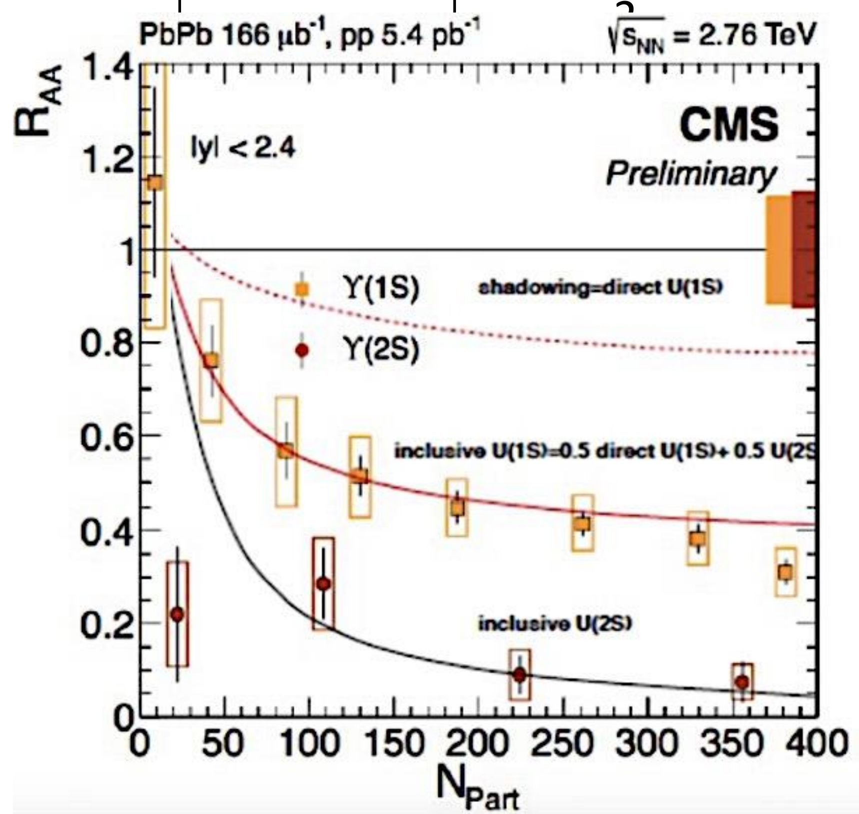
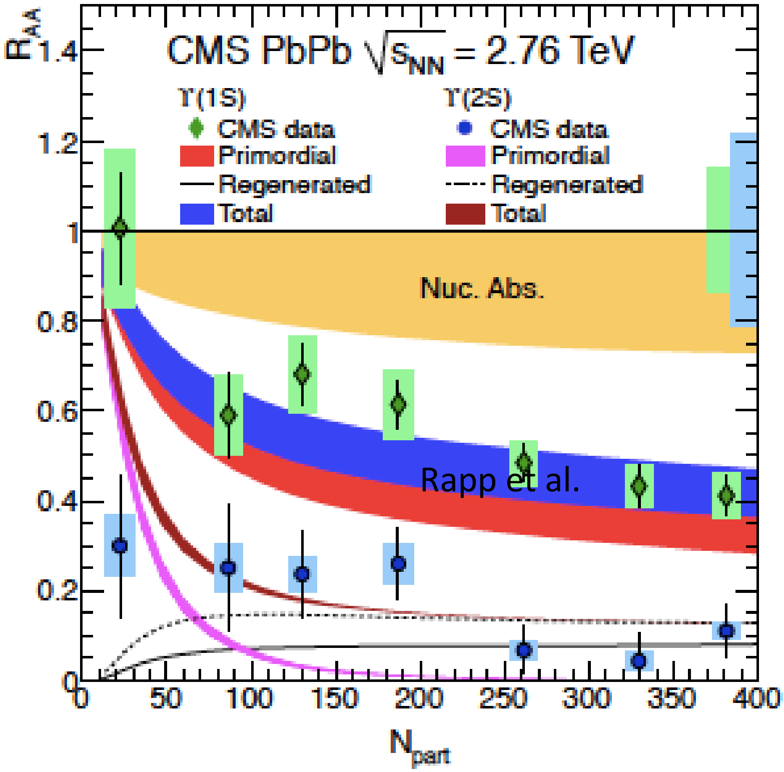




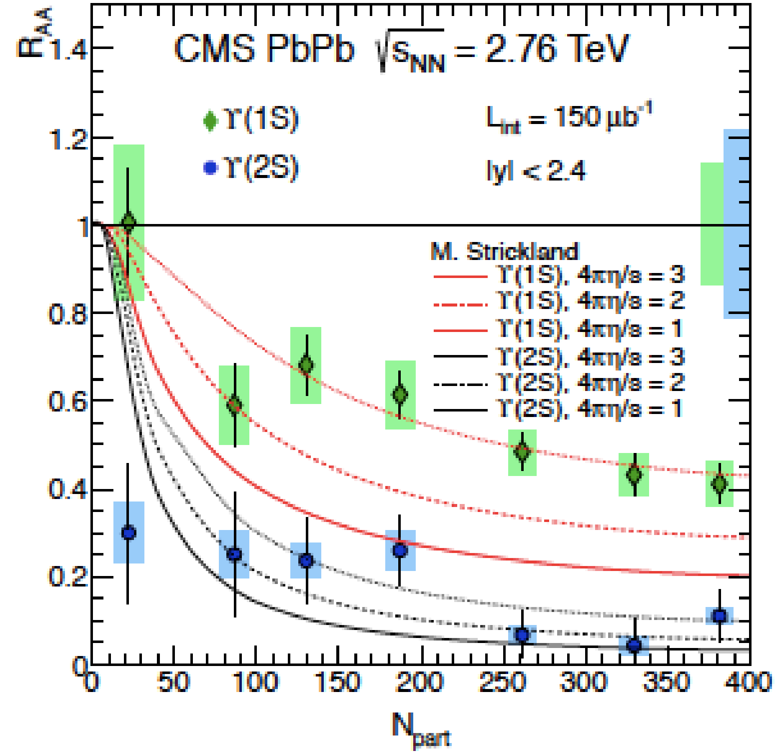
WIP

Bottomonia in PbPb @ LHC: Other models



Transport models
(Rapp et al., Emerirck et al)
with small or none
regeneration/CNM effects

Reasonable description of data



Dynamical aHYDRO
(Strickland)
model without
regeneration/CNM effects

Some tension to describe Y(1S) and Y(2S) with the same η/s value

What have we learnt from quarkonia production @ LHC?

J/ψ production seems at least qualitatively understood

Initial cold nuclear matter effects can be described with shadowing and/or energy loss

Production in HI collisions is described by a combination of

- **suppression** (either color screening, or in-medium dissociation)
- **recombination** (either in-medium or at phase boundary)

High density medium, Not necessairly thermalized

Challenge will be to discriminate between these possible scenarios

What is the state of the art for ψ(2)?

Crucial to distinguish among the models

Note that **initial cold nuclear matter effects** (shadowing and/or energy loss) are considered to be the same for than for the J/ψ

Nevertheless, **in-medium effects** depending on density (comovers) would be able to distinguish between them

ϒ(nS): Sequential suppression of the 3 states in pA and AA

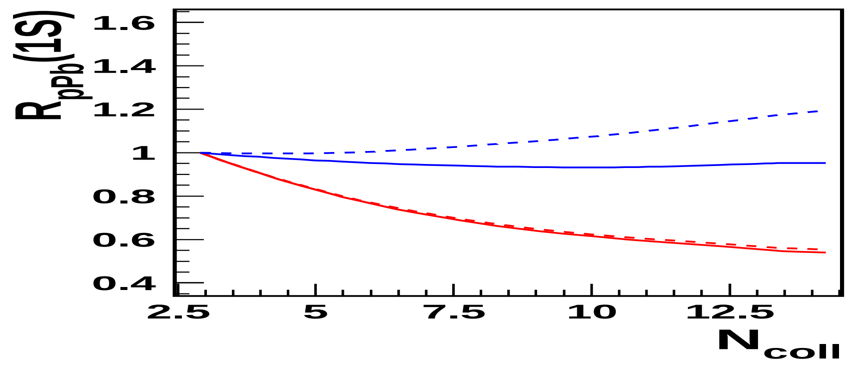
ϒ(2S) and (3S) are strongly suppressed at LHC

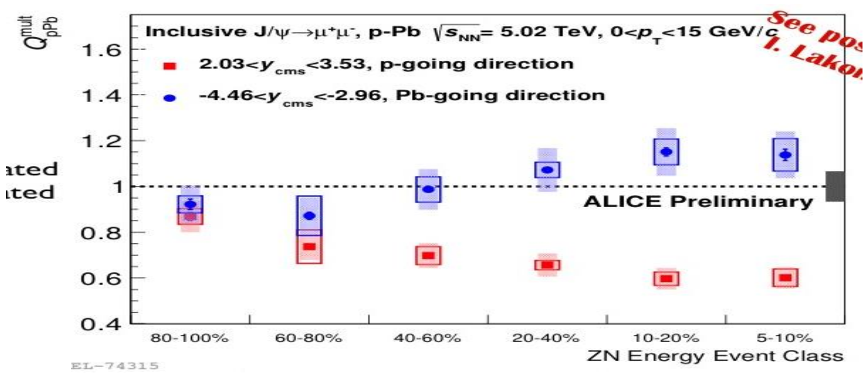
ϒ(1S) suppression consistent with higher mass excited states suppression

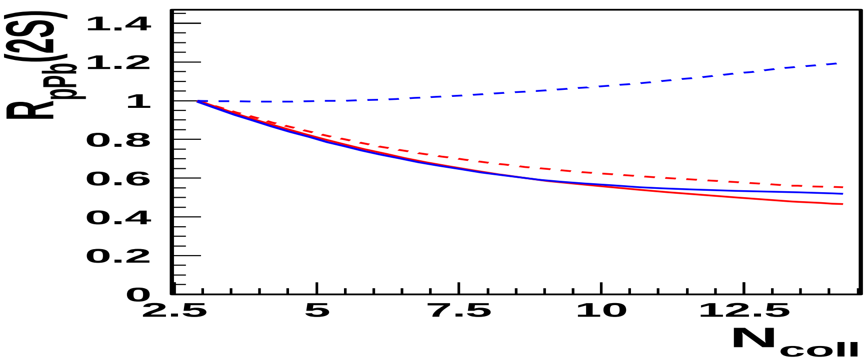
No recombination, but some shadowing effects

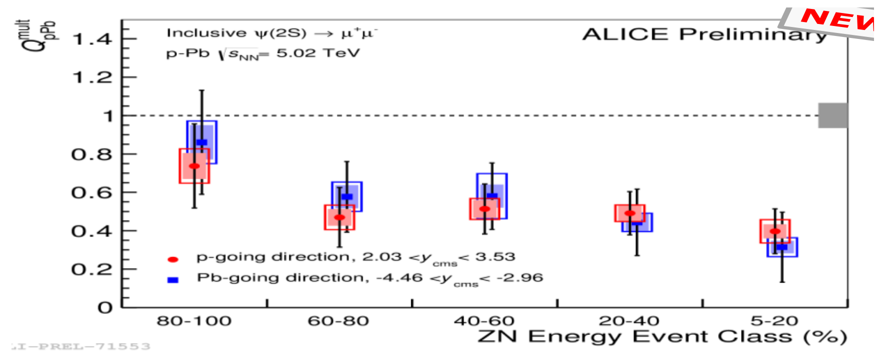
BACKUP

ψ(2S) and J/ψ in pPb @ LHC: Comover scenario









- shadowing suppression in the forward y --------- • antishadowing in the backward y -----------
- Comover suppression very small in the forward y due to small medium density

⇒ **Total effect mostly due to shadowing in the forward region** ____________________

- Comover suppression important in the backward y due to larger medium density

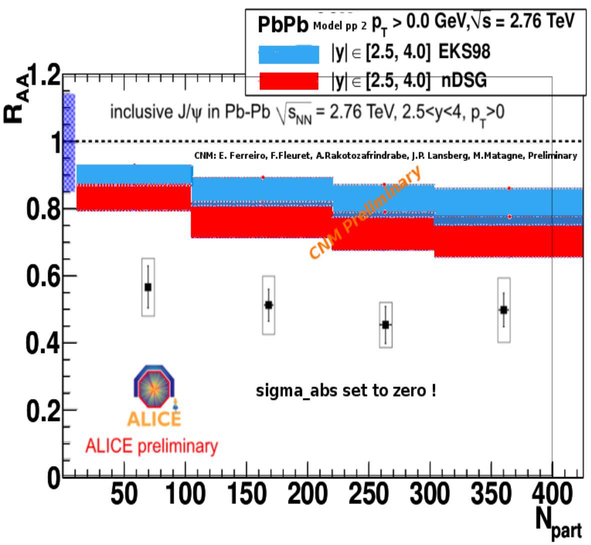
=> **Combined effect of antishadowing and comover suppression in the backward region** ______

Identical shadowing on J/ψ and ψ(2S), stronger comover suppression on ψ(2S) due to larger σ_{co}

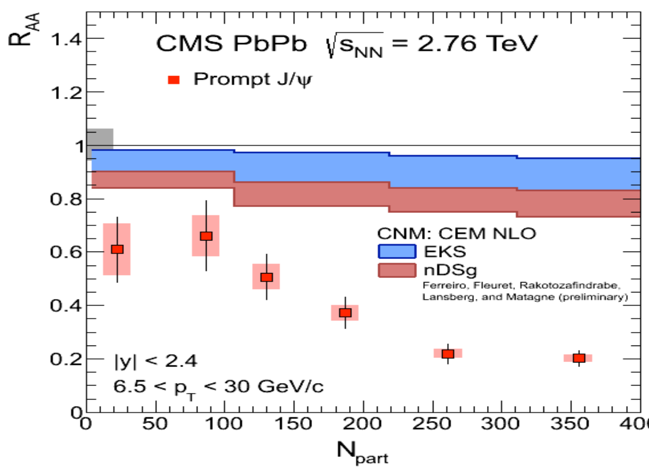
Initial shadowing effects are important: J/ψ production in PbPb @ LHC

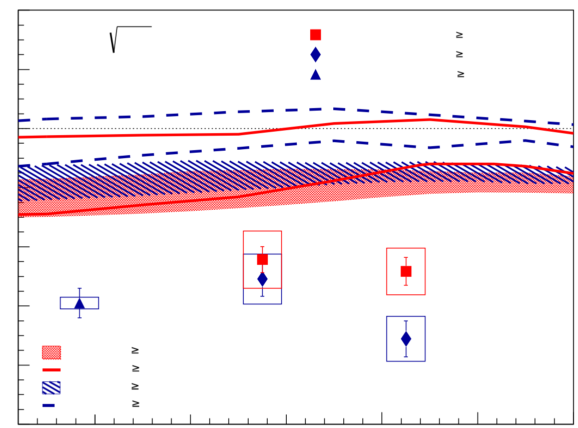
- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
- PDFs in nuclei different from the superposition of PDFs of their nucleons

Shadowing effects increases with energy (1/x) and decrease with Q^2 (m_T)



Rakotozandrabe, Ferreiro, Fleuret, Lansberg , Matagne Nucl. Phys. A855, 327 (2011)



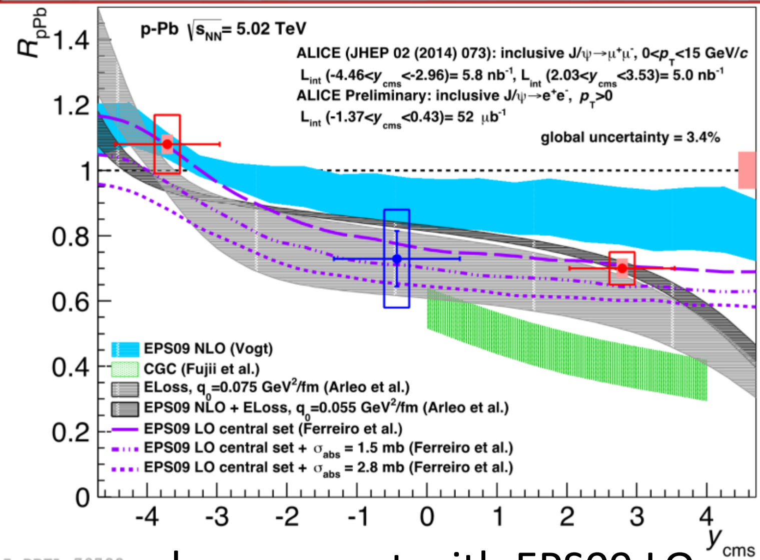


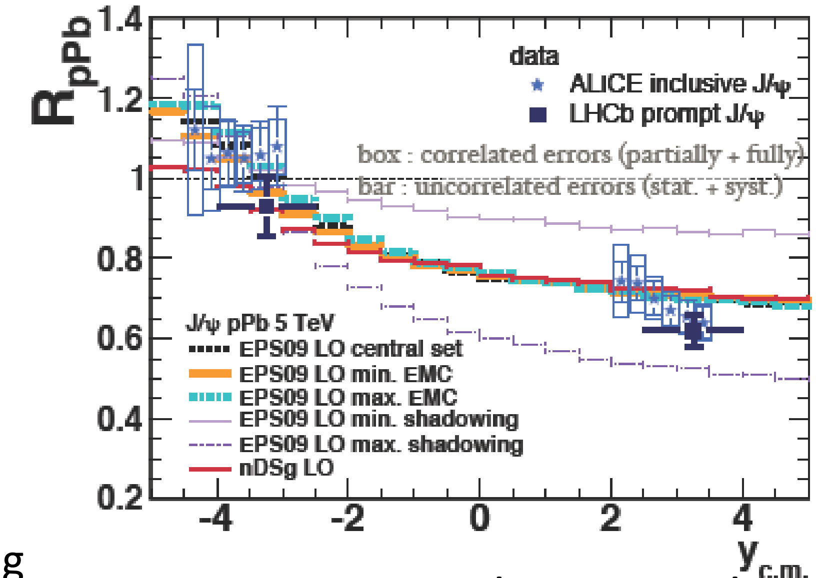
Production mechanism affects CNM effects intimately:

- Shadowing depends on momentum fraction x of the target (and projectile in AA) which is influenced by how the state was produced: 2 → 1 or 2 → 2 process
- Production can also affect other CNM effects,

since singlet and octet states can be absorbed differently

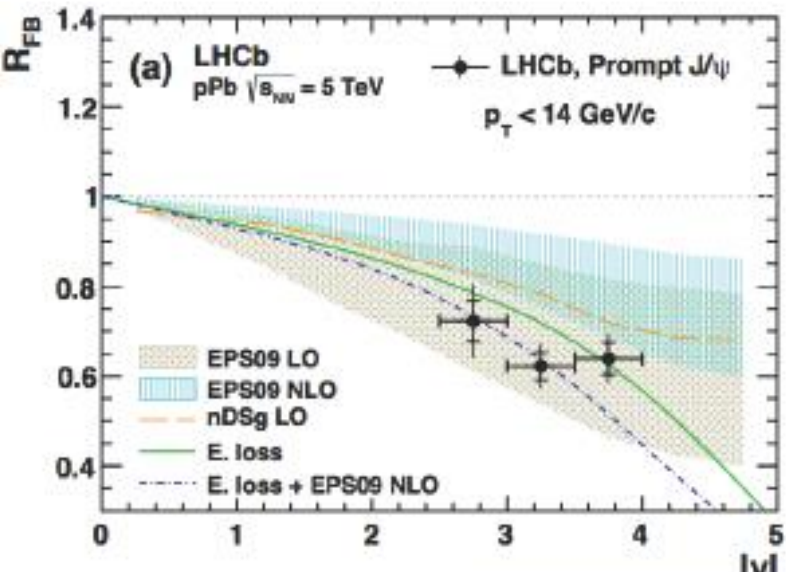
Cross check: J/ψ production in pPb @ LHC

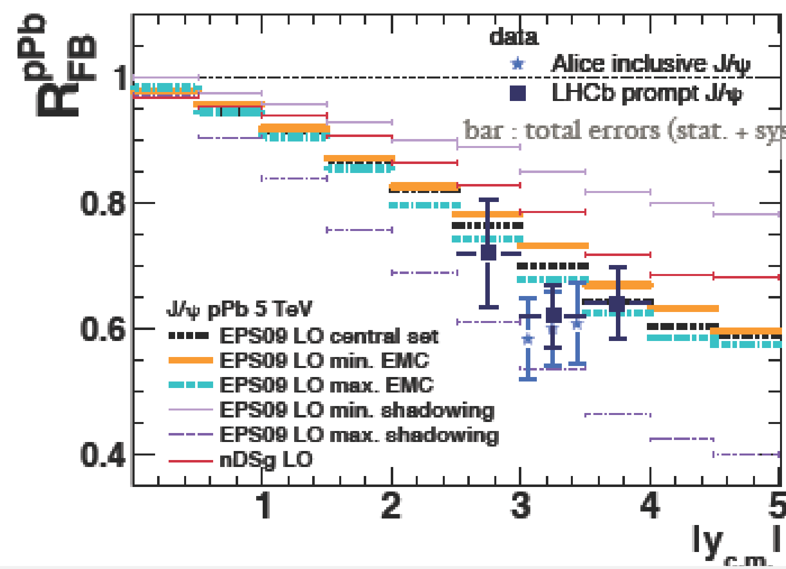




- good agreement with EPS09 LO and nDSg shadowing
- also consistent w energy loss models w/wo EPS09NLO shadowing
- EPS09 NLO and CGC calculation disfavored

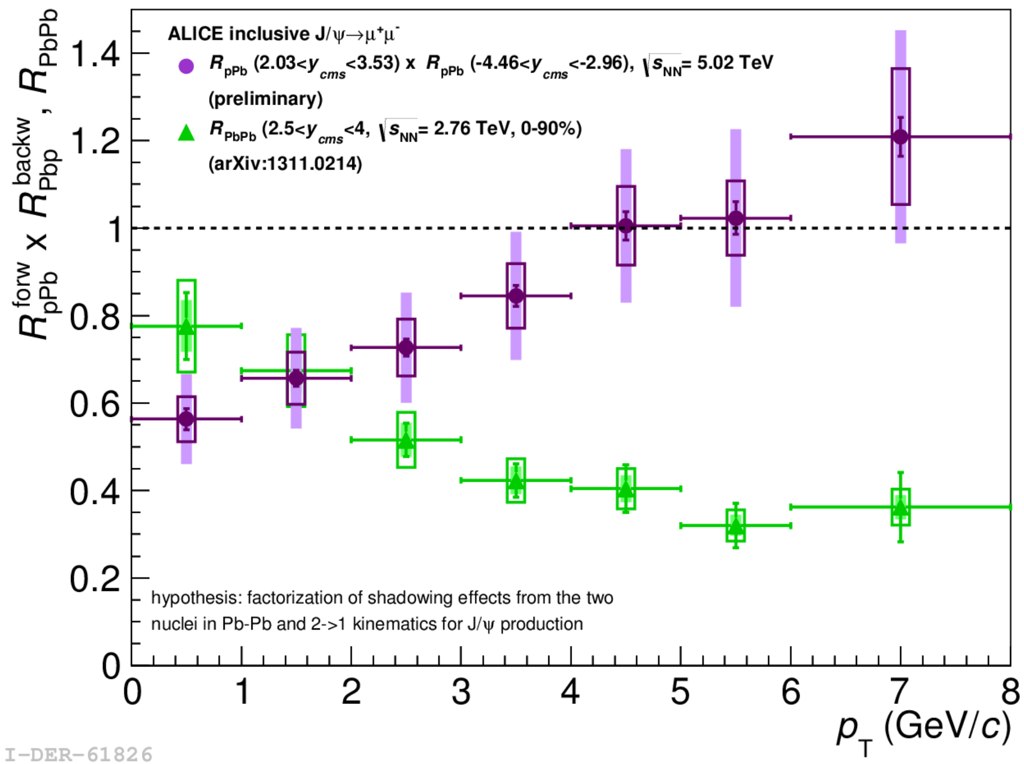
E.G.F, F. Fleuret, J.P. Lansberg, A.Rakotozafindrabe
Phys.Rev. C88 (2013) 4, 047901





CNM effects from p-Pb to Pb-Pb

Once CNM effects are measured in pA,
what can we learn on J/ψ production in PbPb?



Sizeable p_T dependent suppression still visible

→ CNM effects not enough to explain AA data at high p_T

From enhancement to suppression increasing p_T

→ hint for recombination

Some words about comover scenario

$$\tau \frac{d\rho^{J/\psi}(b,s,y)}{d\tau} = -\sigma_{co}\ \rho^{J/\psi}(b,s,y)\ \rho^{medium}(b,s,y)$$

- Our equations have to be integrated between initial time τ_0 and freeze-out time τ_f.

- The solution depends only on the ratio τ_f/τ_0.

- We use the inverse proportionality between proper time and densities, $\tau_f/\tau_0 = \rho(b,s,y)/\rho_{pp}(y)$

$\rho_{pp}(y)$= density per unit rapidity for mb pp collisions

$\rho(b,s,y)$ = density produced in the primary collisions

- Our densities can be either hadrons or partons:

σ_{co}: **effective cross-section averaged over the interaction time**

- **Survival probability $S_{co}(b,s)$ of the J/ψ due to comovers interaction:**

$$S^{co}(b,s) \equiv \frac{N^{J/\psi(final)}(b,s,y)}{N^{J/\psi(initial)}(b,s,y)} = \exp\left[-\sigma_{co}\ \rho^{co}(b,s,y)\ell n\left(\frac{\rho^{co}(b,s,y)}{\rho_{pp}(0)}\right)\right]$$

Some words about comover scenario

σ_{co} is the effective comover cross-section averaged from time τ_0 to freeze-out

A large contribution to the integral comes from the few first fm/c after the collision, where the system is in a pre-hadronic stage.

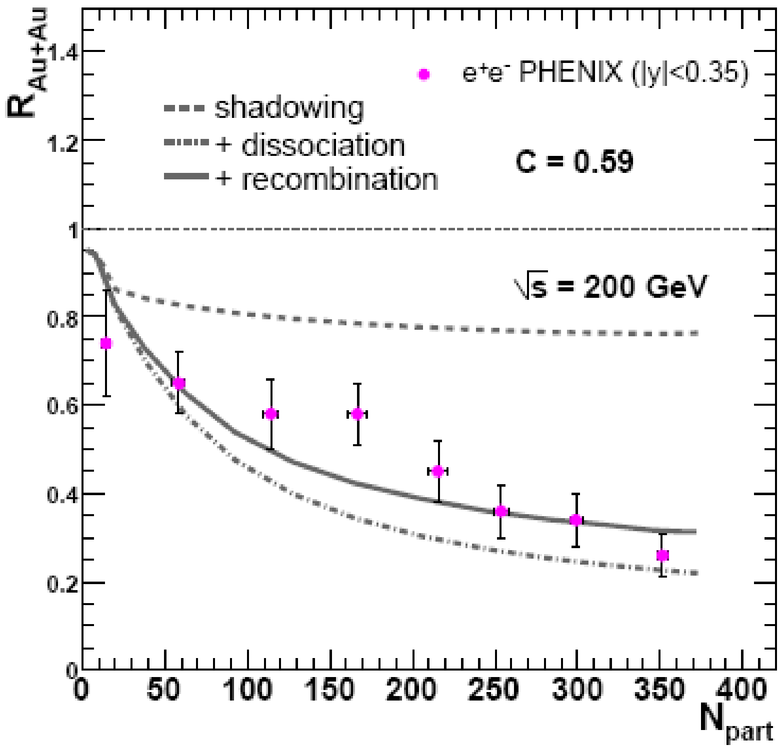
Actually, Brodsky and Mueller introduced the comover interaction as a coalescence phenomenon at the partonic level.

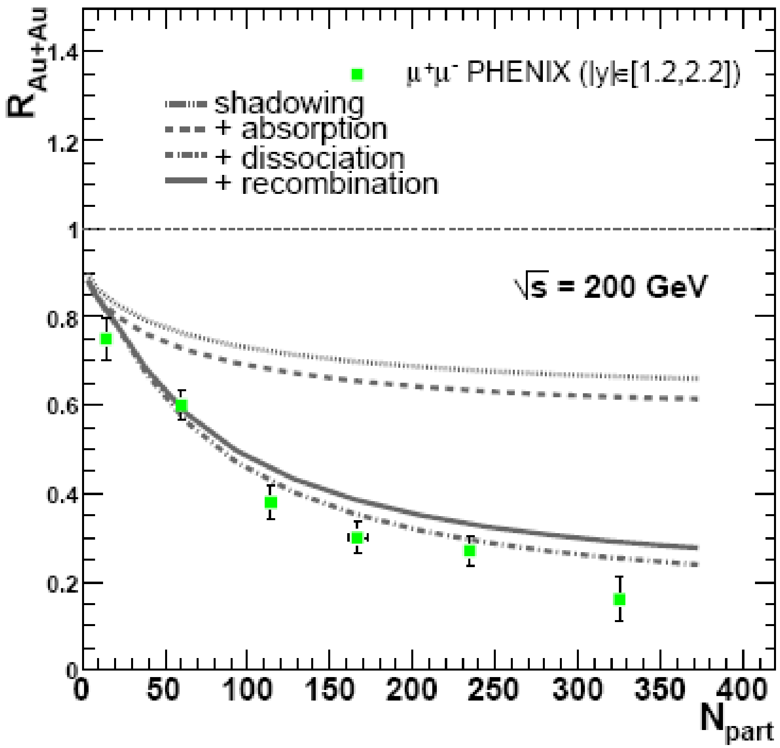
For times close to τ_0, one is dealing with a dense interacting parton system and thus the precise relation between σ_{co} and the J/ψ (ψ') hadron cross-section is not established

Geometrical considerations, together with different theoretical calculations (multipole expansion in QCD , non-perturbative effects…) $\sigma_{co-\psi(2S)} / \sigma_{co-J/\psi} \approx 10$

CIM: Comover suppression and recombination
Comparation to Au+Au @ RHIC data

Capella, Bravina, Ferreiro, Kaidalov, Tywoniuk, Zabrodin **Eur. Phys. J. C58 (2008) 437**





C=0.59 $\frac{d\sigma_{pp}^{c\bar{c}}}{dy}$ $123 \pm 12 \pm 45\ \mu b$

C=0.32 $\frac{d\sigma_{pp}^{c\bar{c}}}{dy}$ $70.9 \pm 14\ \mu b$

CIM describes properly the rapidity dependence of the suppression @ RHIC

Regeneration less relevant at forward rapidities