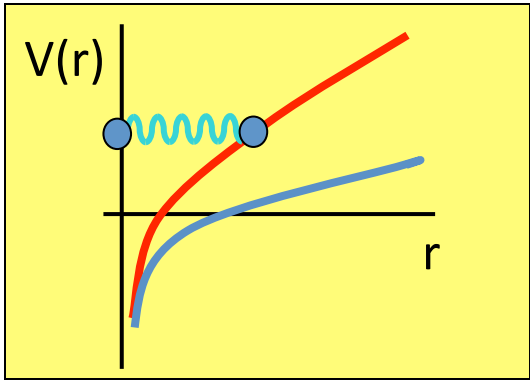
Understanding the J/ψ and ϒ suppression (and enhancement) at LHC and RHIC

Elena G. Ferreiro
Universidade de Santiago de Compostela, Spain

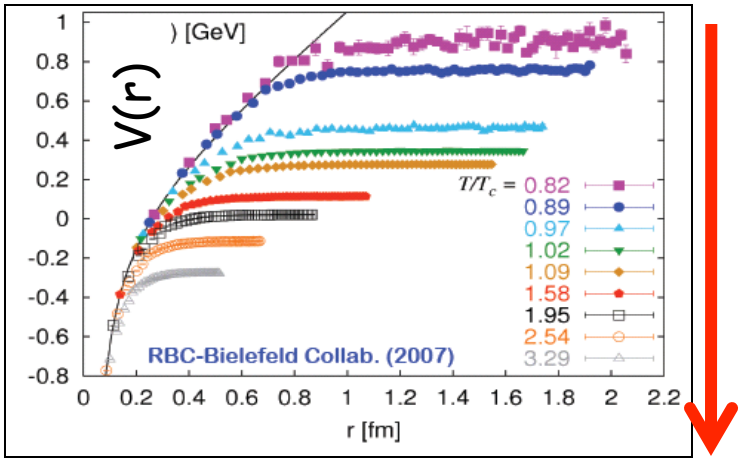
Quarkonium production: the typical introduction….

Potential between q-anti-q pair grows linearly at large distances

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$



Screening of long range confining potential at high enough temperature or density.



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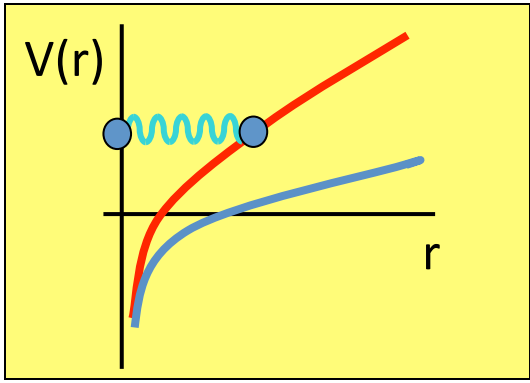

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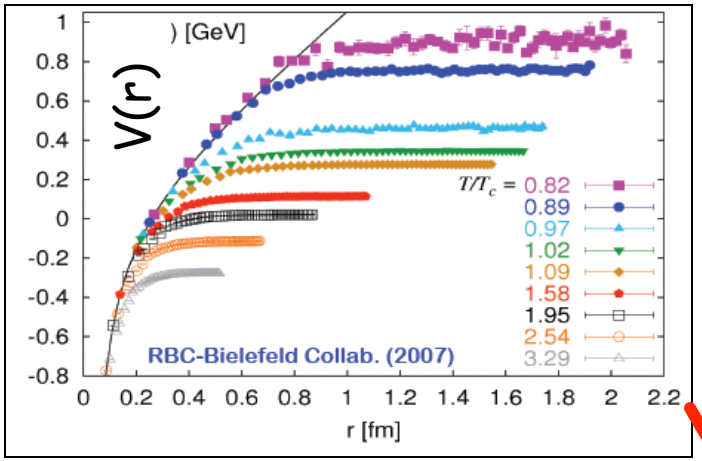
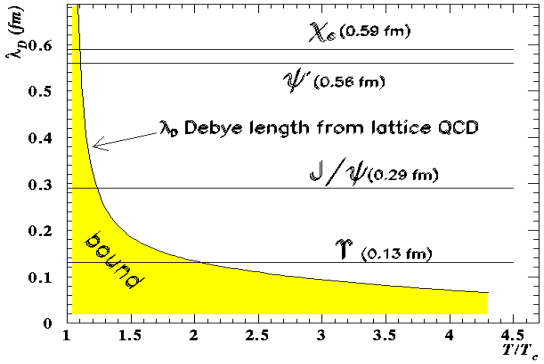


What happens when the range of the binding force becomes smaller than the radius of the state?

different states "melting" at different temperatures due to different binding energies.



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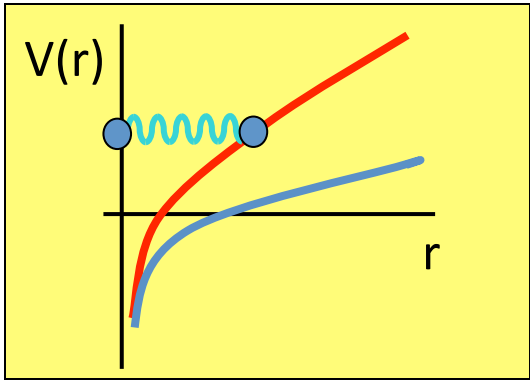

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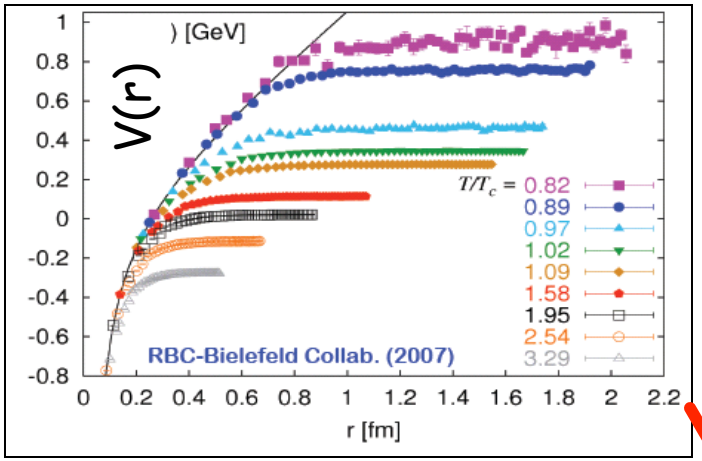

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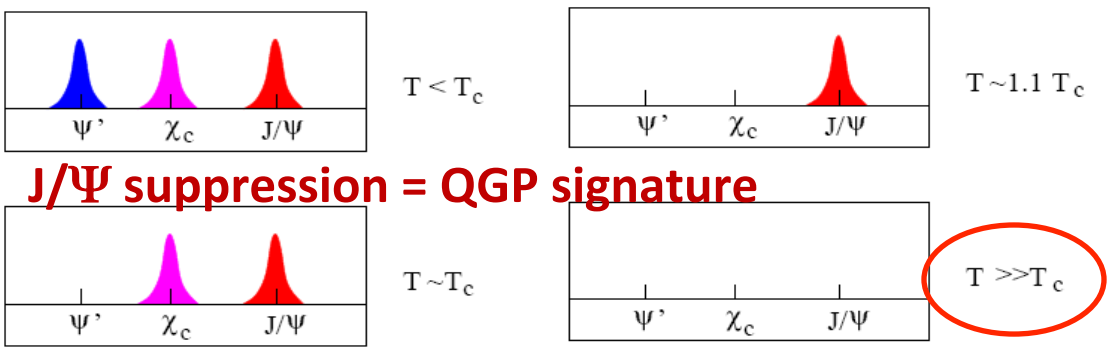
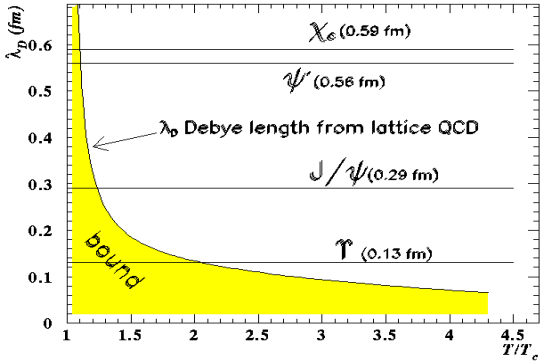
Matsui and Satz:

J/ψ destruction in a QGP by Debye screening



J/Ψ suppression = QGP signature



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- Do we understand charmonium production in elementary p+p collisions?
- Do experimental observations fit in a coherent picture ?

Charmonia/bottomonia topics

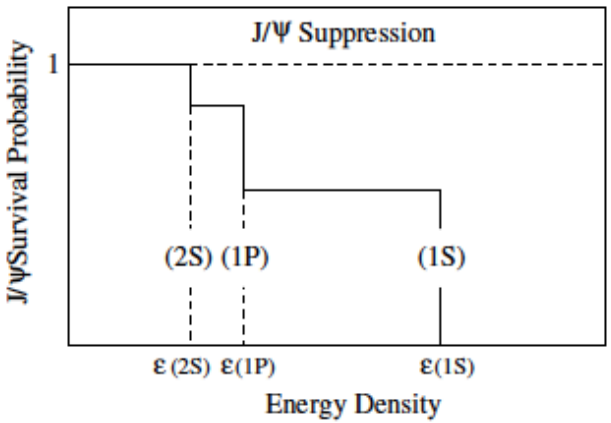
Three main topics

Sequential suppression

Charmonium → J/χ ,ψ_c, $\psi(2S)$

Bottomonium Υ →(1S), Υ(2S), Υ(3S), χ_b

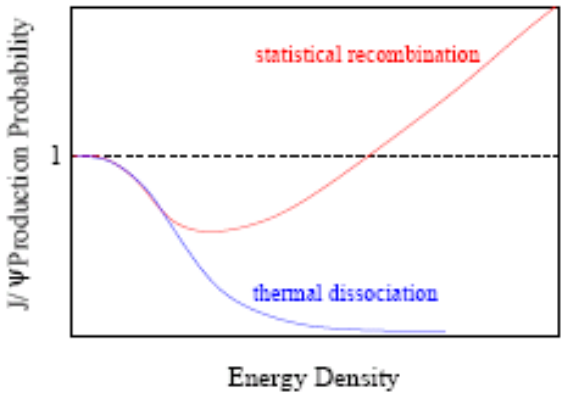
Relying on theory for connection with temperature



Two competing mechanisms

Color screening → suppression

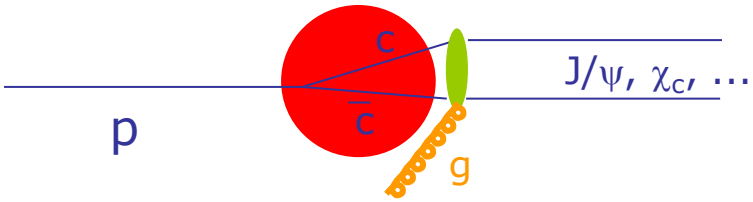
(Re)-combination →enhancement



Cold nuclear matter effects

Shadowing, absorption, comovers

Description/understanding of underlying mechanisms difficult



Scomparin, QM2014

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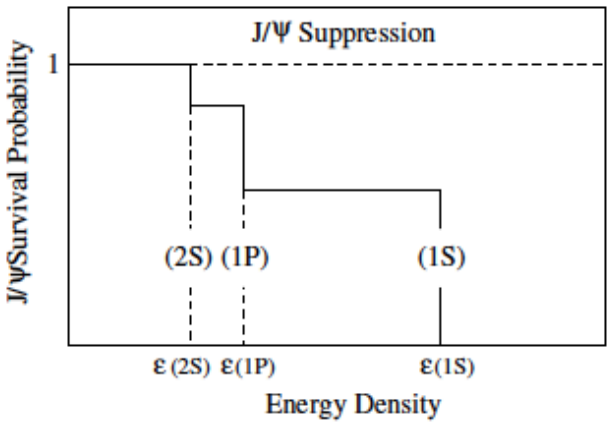

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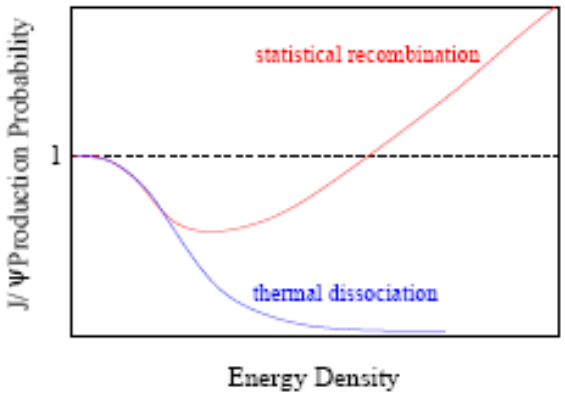

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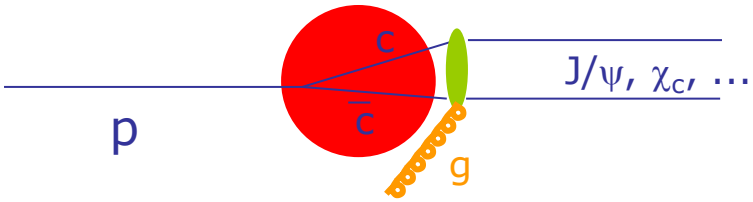

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Quarkonium and the QGP - “sequential suppression”

H.Satz, arXiv:1310.1209

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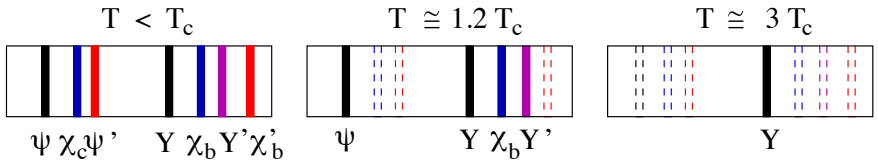

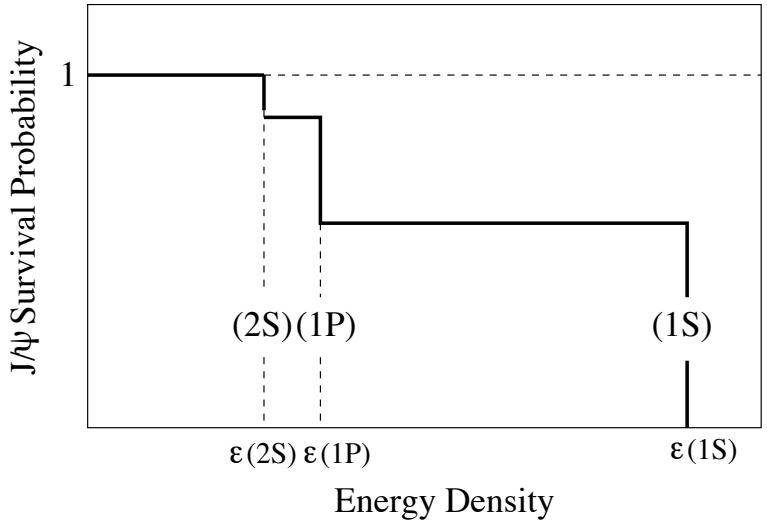

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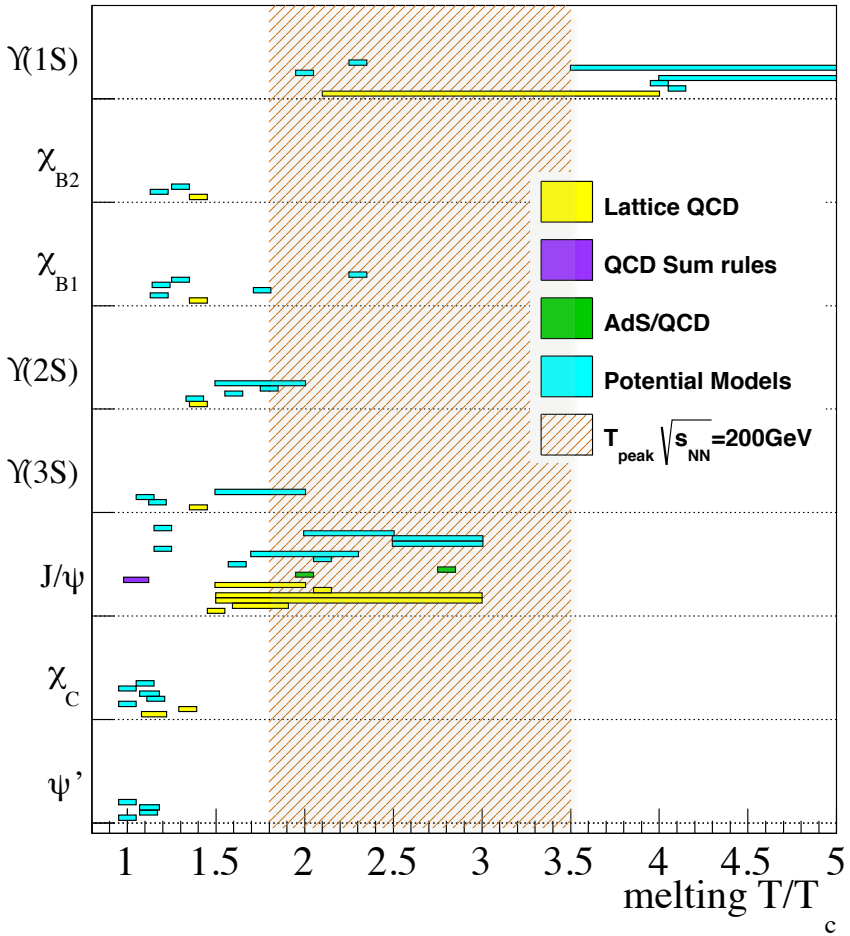

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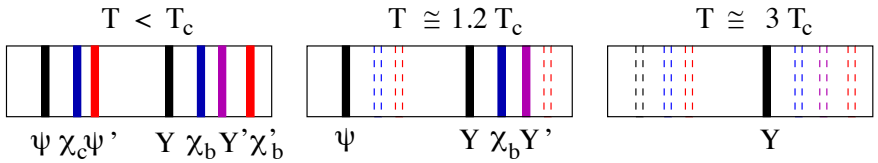

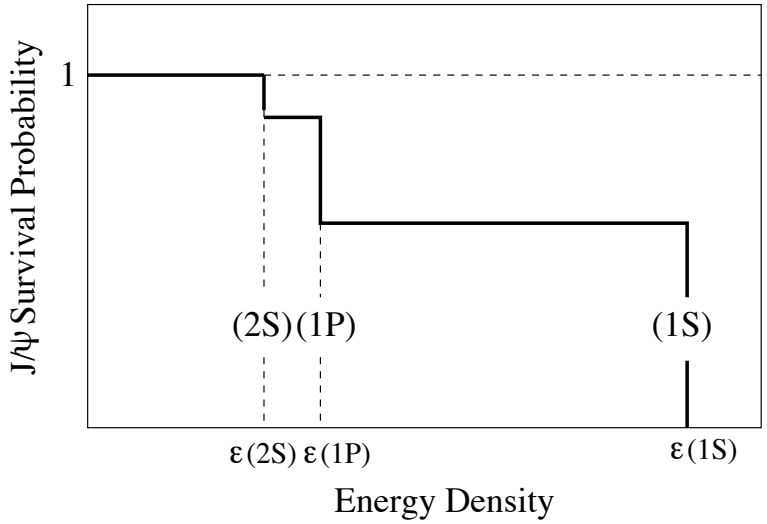

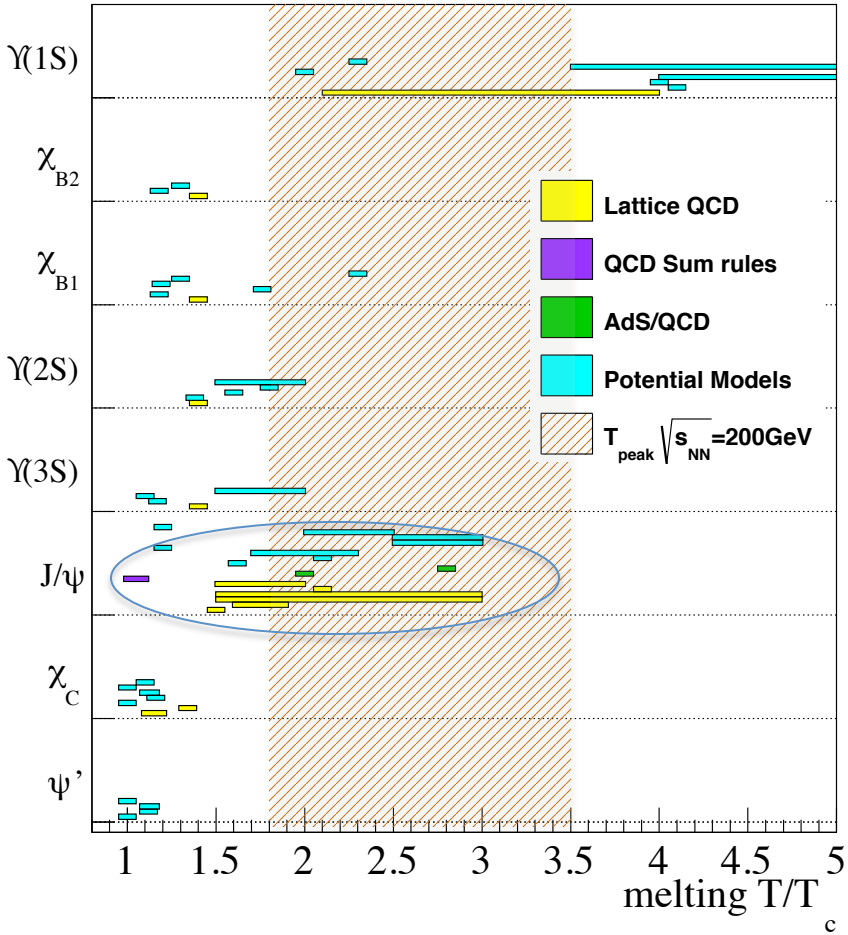

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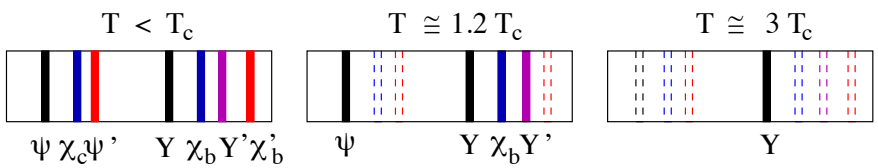

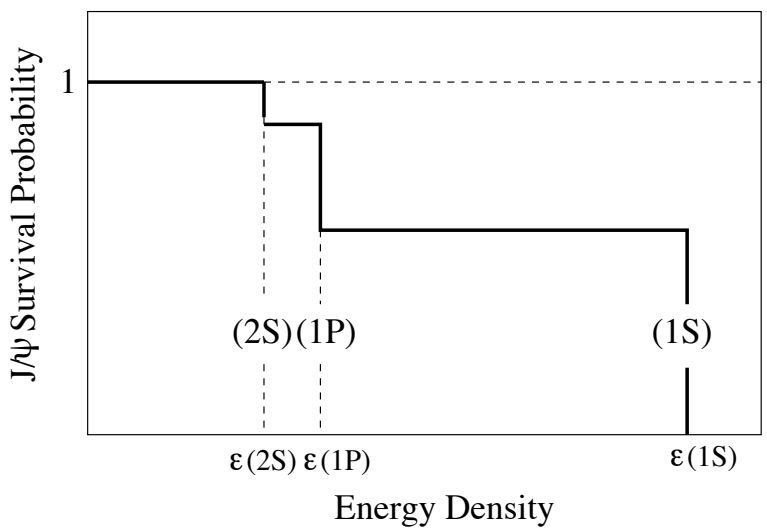

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Dissociation temperatures T_{diss}/T_c

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$
$V(r,T) = U(r,T)$	2.1	1.2	1.1
$V(r,T) = F(r,T)$	1.2	1.0	1.0

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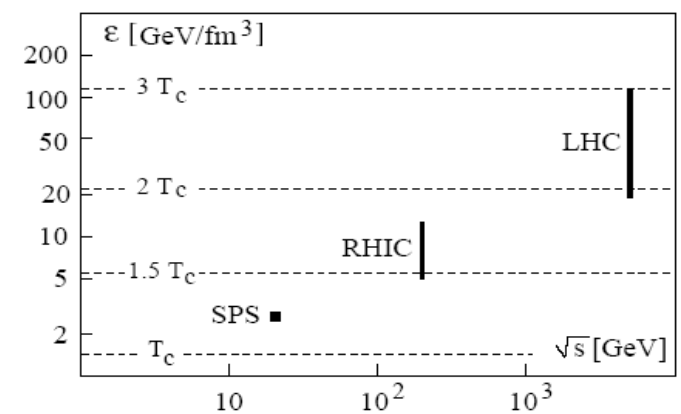

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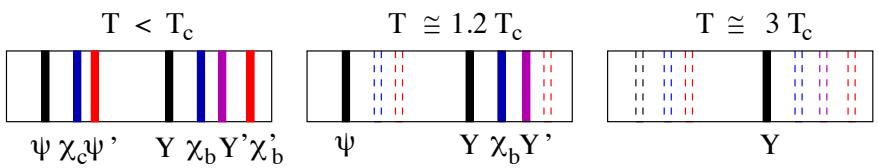

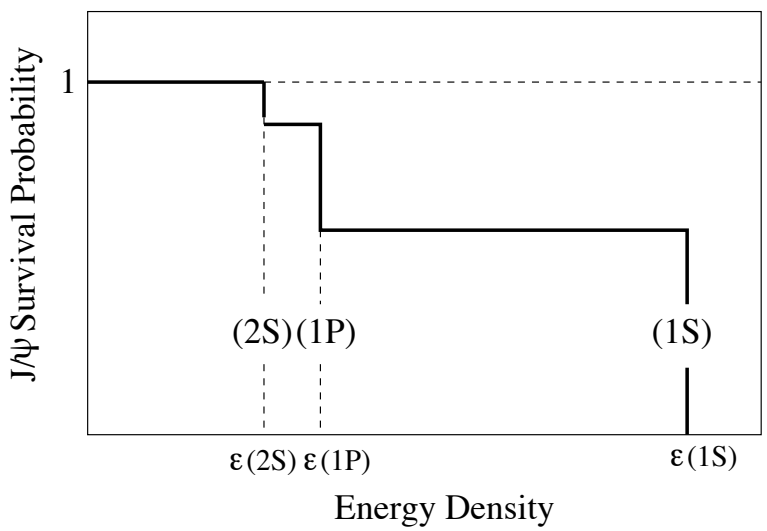

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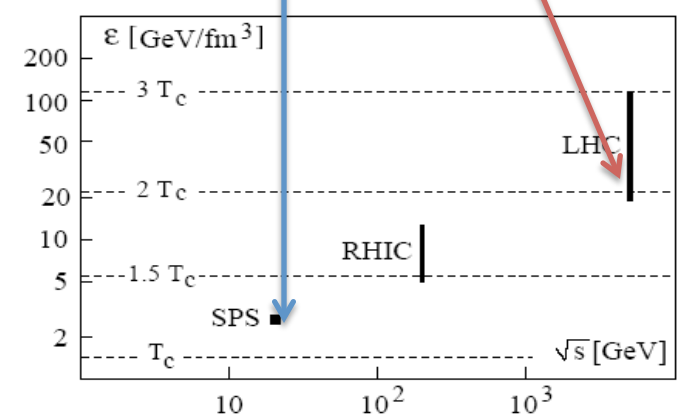


Present situation: Bottomonia in AA at RHIC and LHC

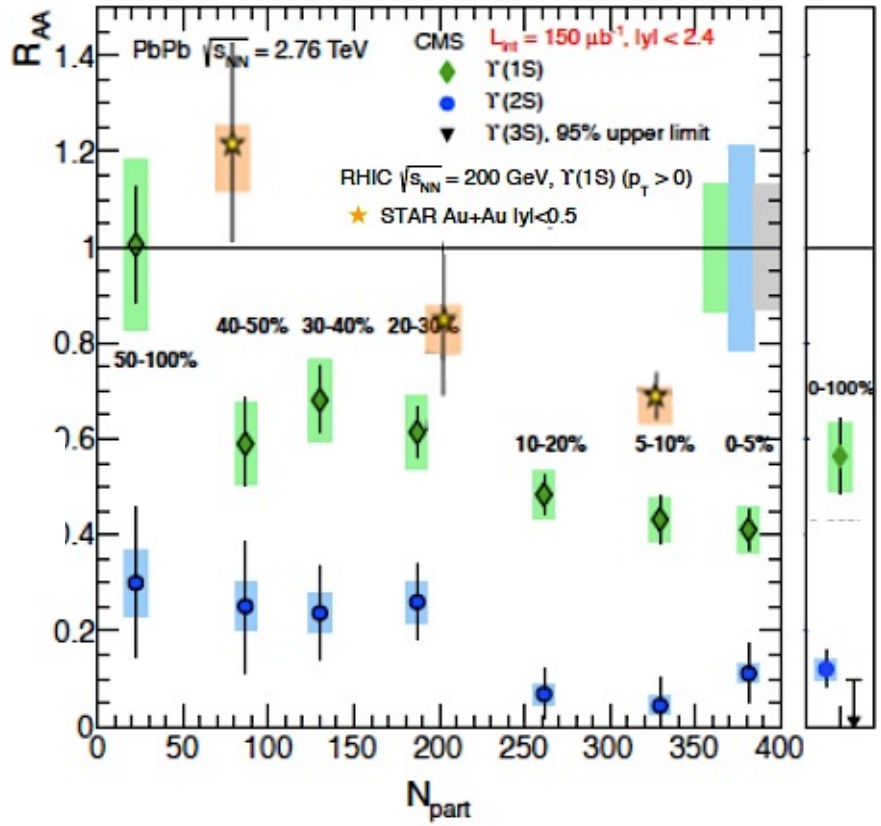
LHC | RHIC

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

- **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



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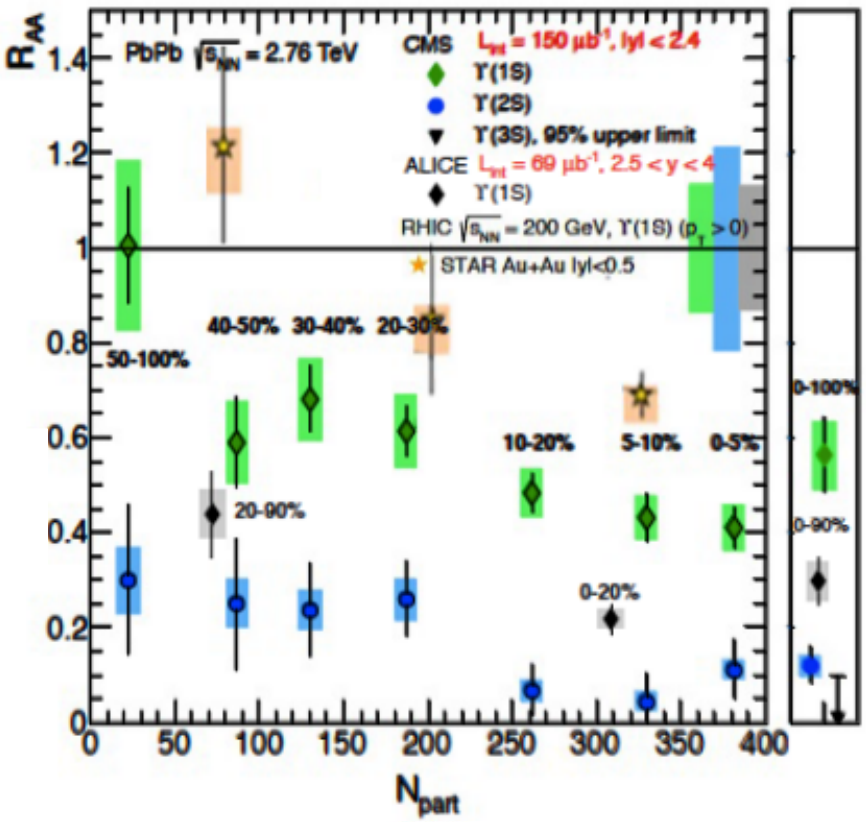

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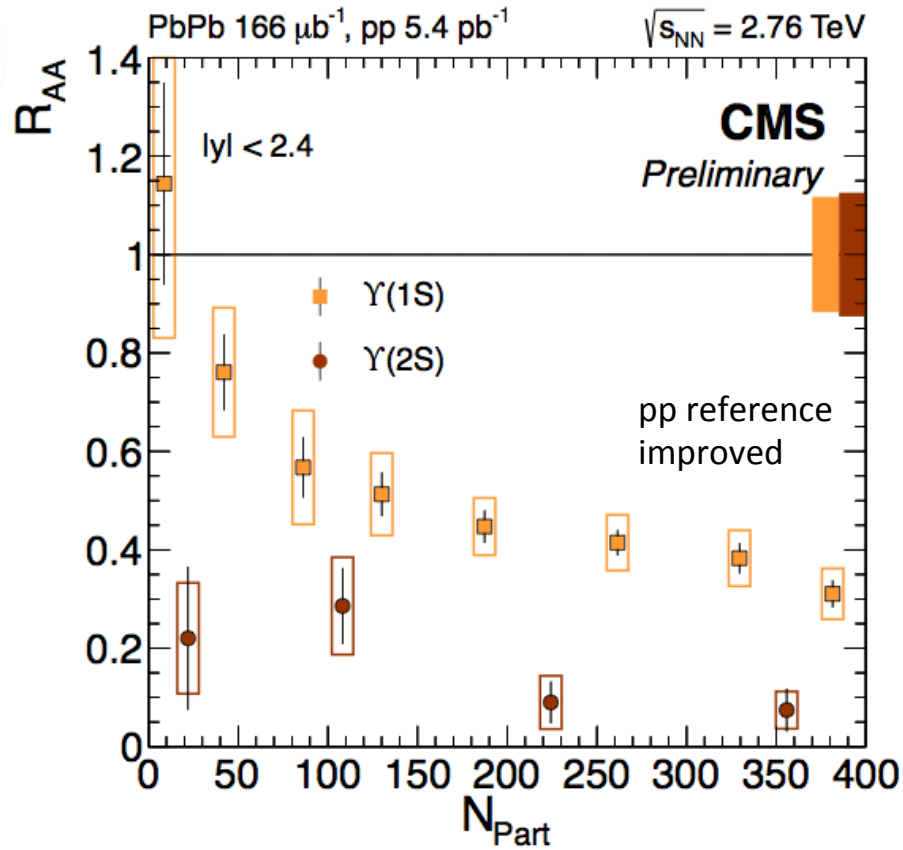

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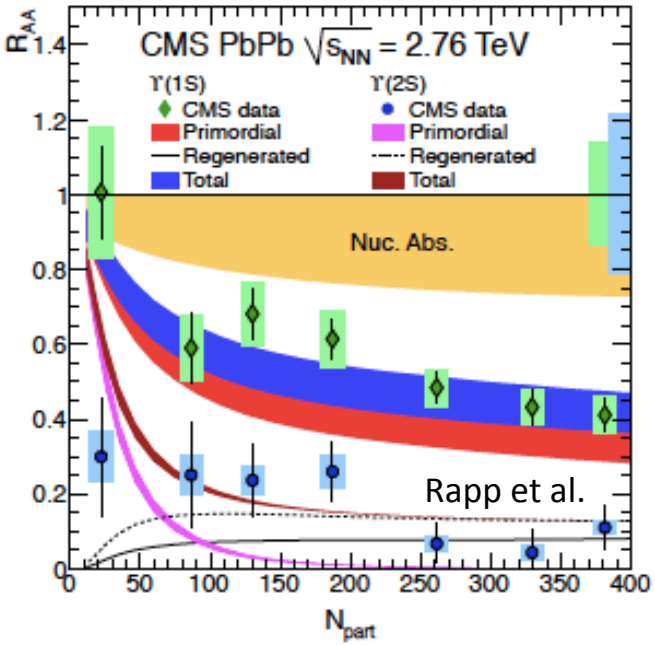
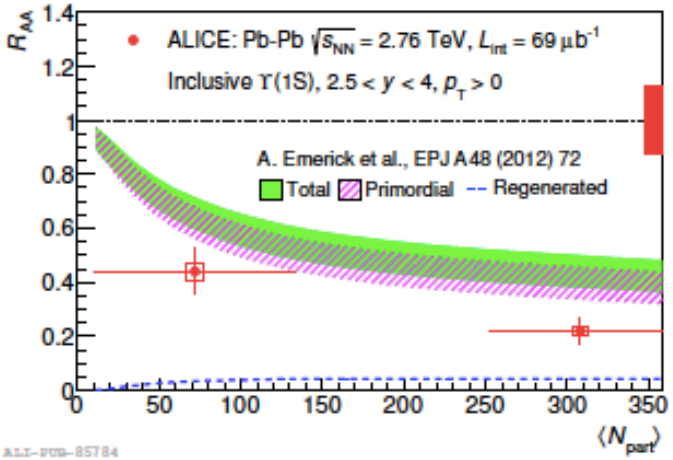
ϒ(1S), ϒ(2S), ϒ(3S) in PbPb @ LHC





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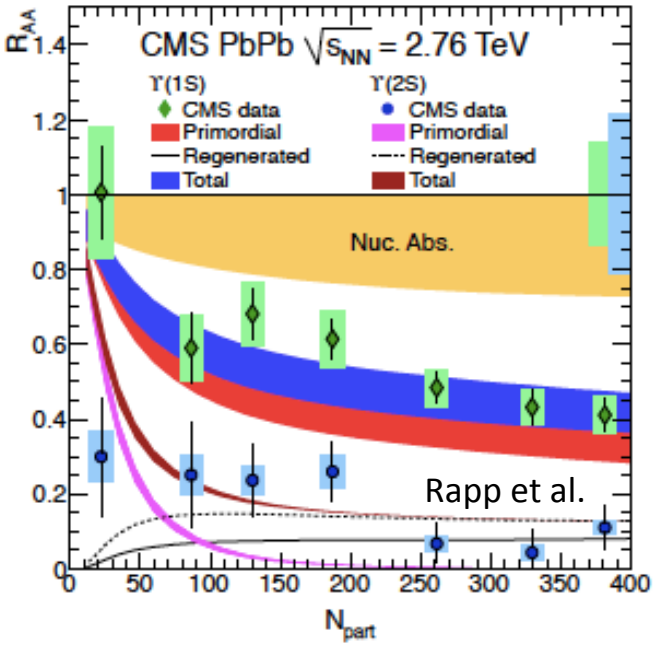

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Dynamical aHYDRO
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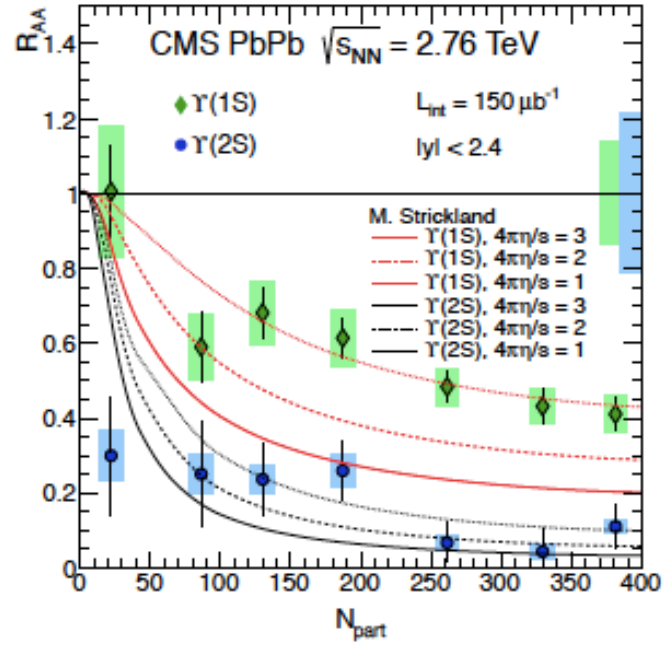

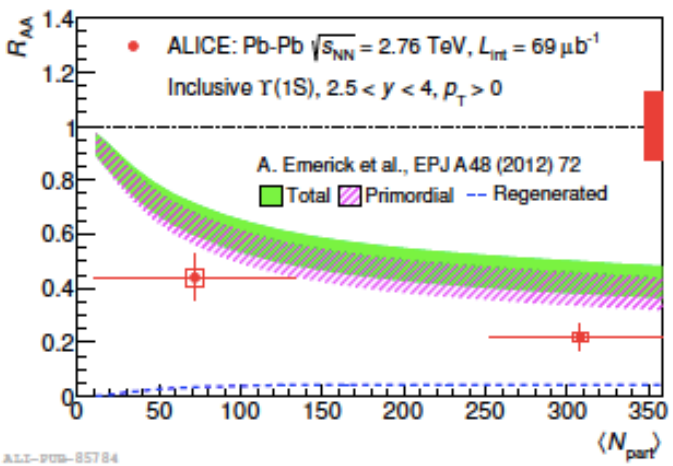

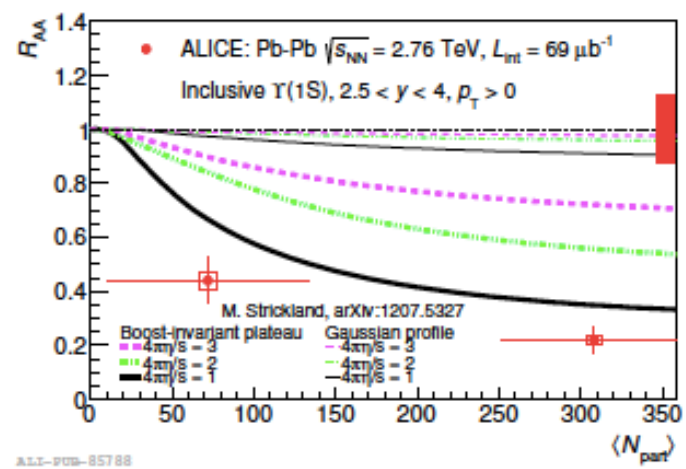

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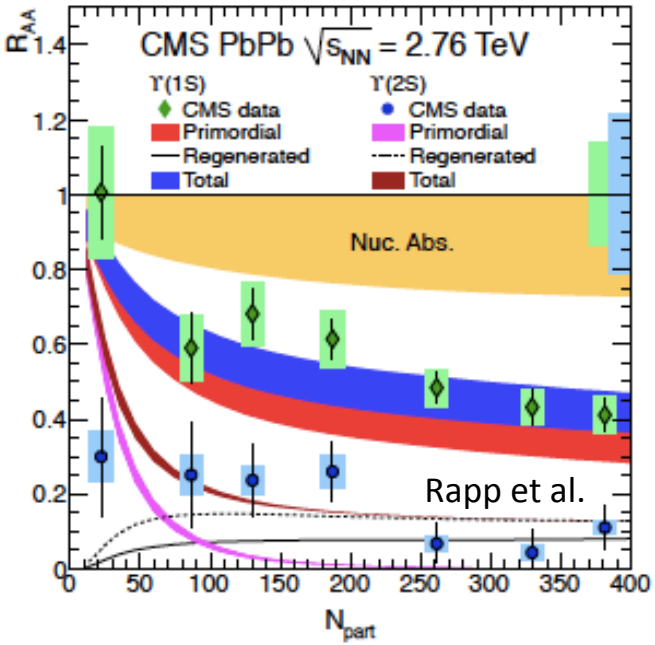

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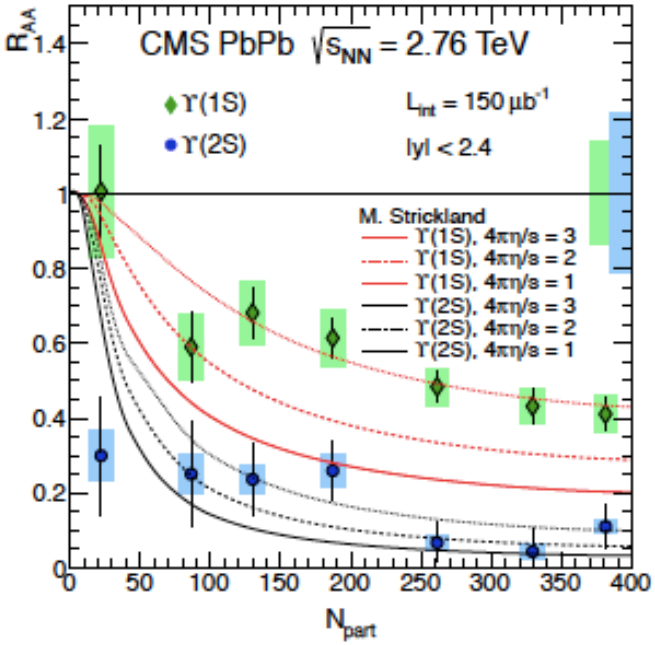
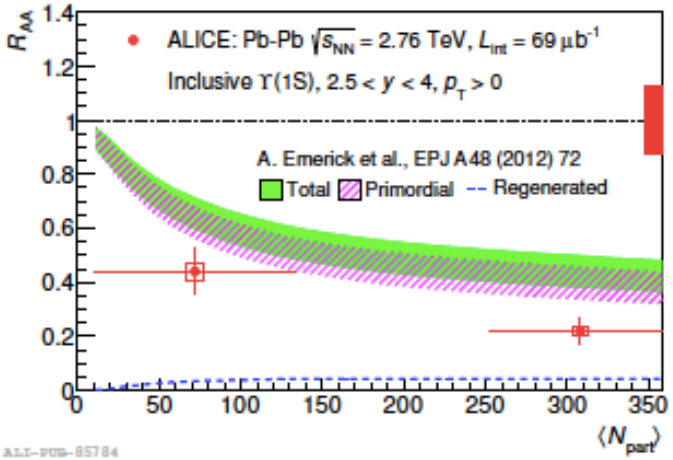
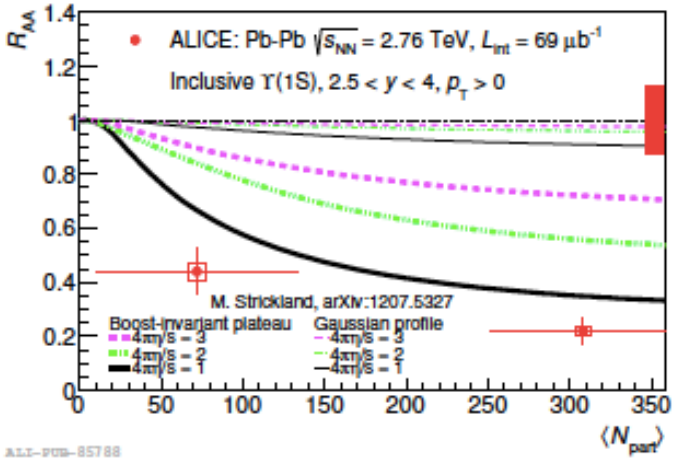




Resonable description of data

Precise measurement of feed-down needed
(ϒ(1S) from feed-down between 30%-50%)



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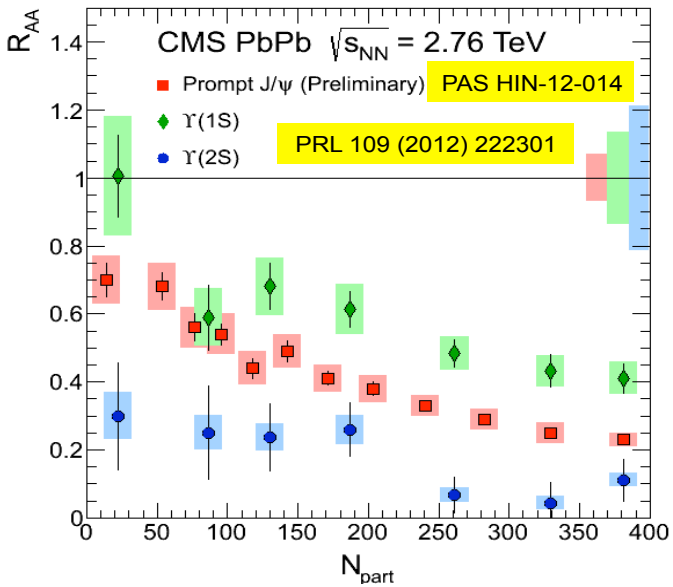
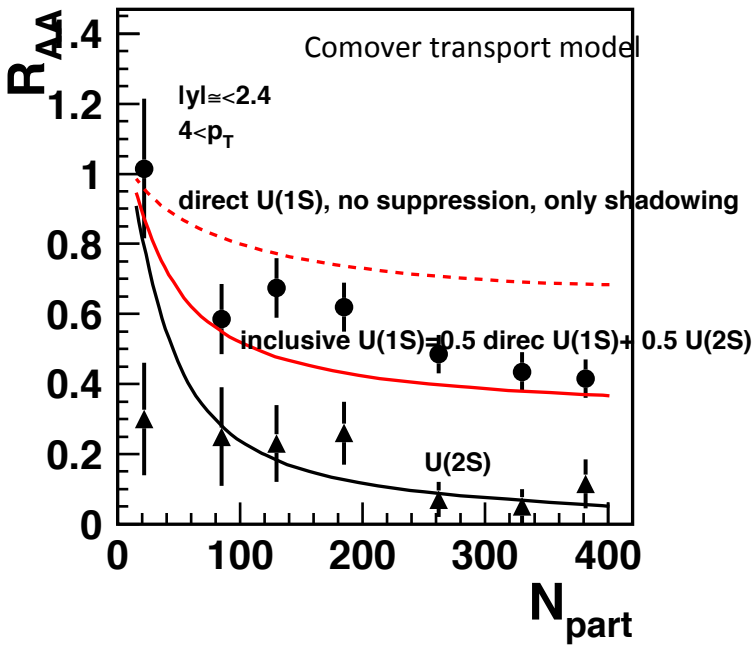


Clear suppression of ϒ(2S)

ϒ(1S) suppression consistent with excited state suppresion (≈ 50% feed down)



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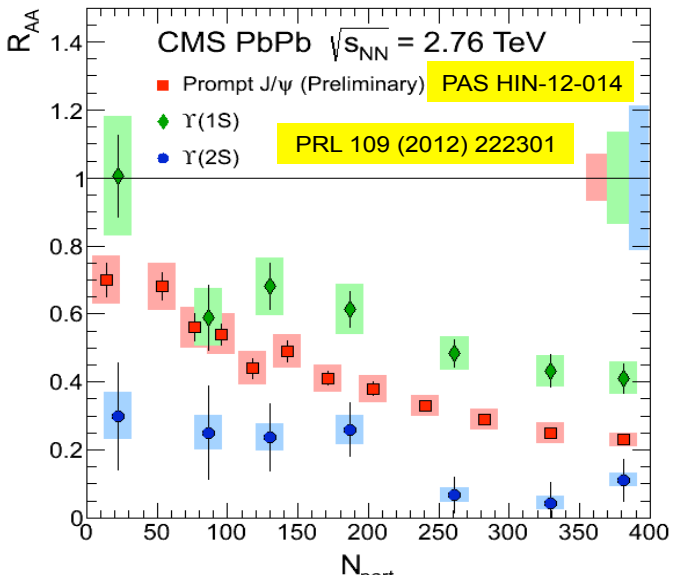
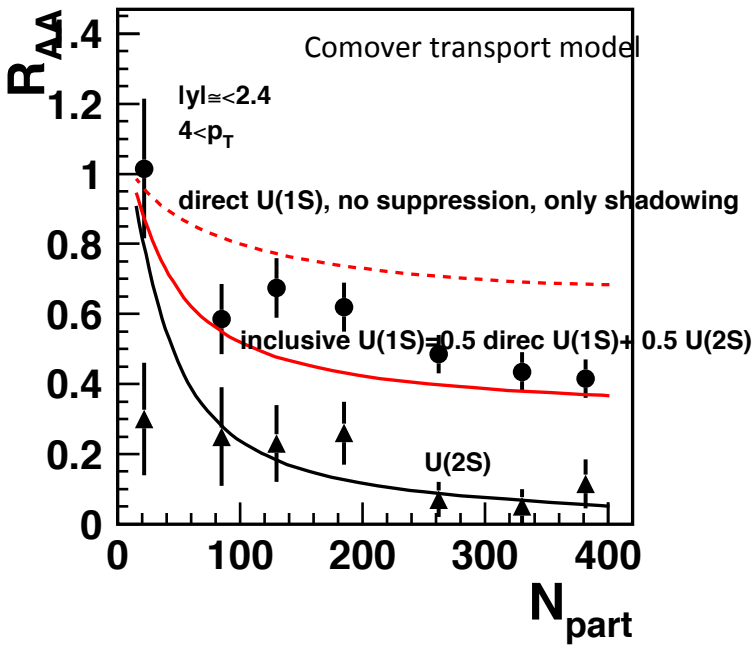
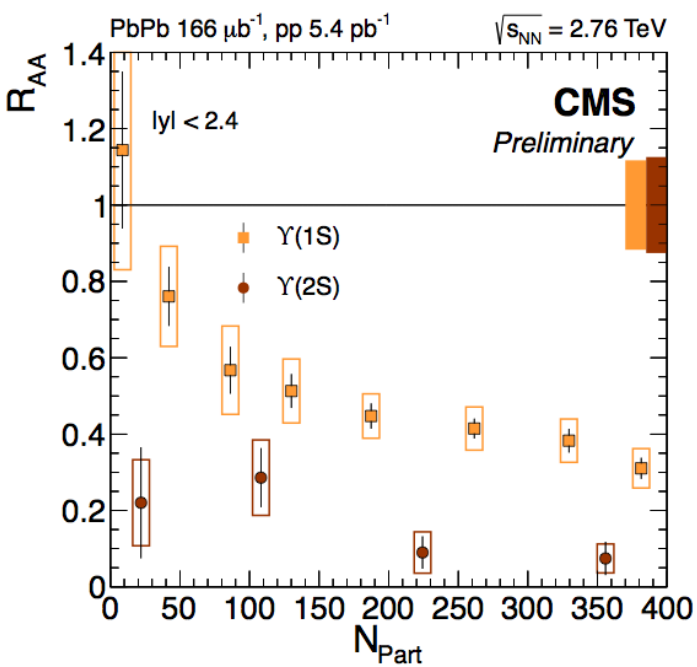


Clear suppression of ϒ(2S)

ϒ(1S) suppression consistent with excited state suppresion (≈ 50% feed down)





Updated CMS results: Improved pp reference & PbPb data sample

ϒ(1S) RAA decreases with centrality down to 0.3
Ground state suppressed?

Precise measurement of feed-down needed (ϒ(1S) from feed-down between 30%-50%)

Present situation: Charmonia in AA at RHIC and LHC

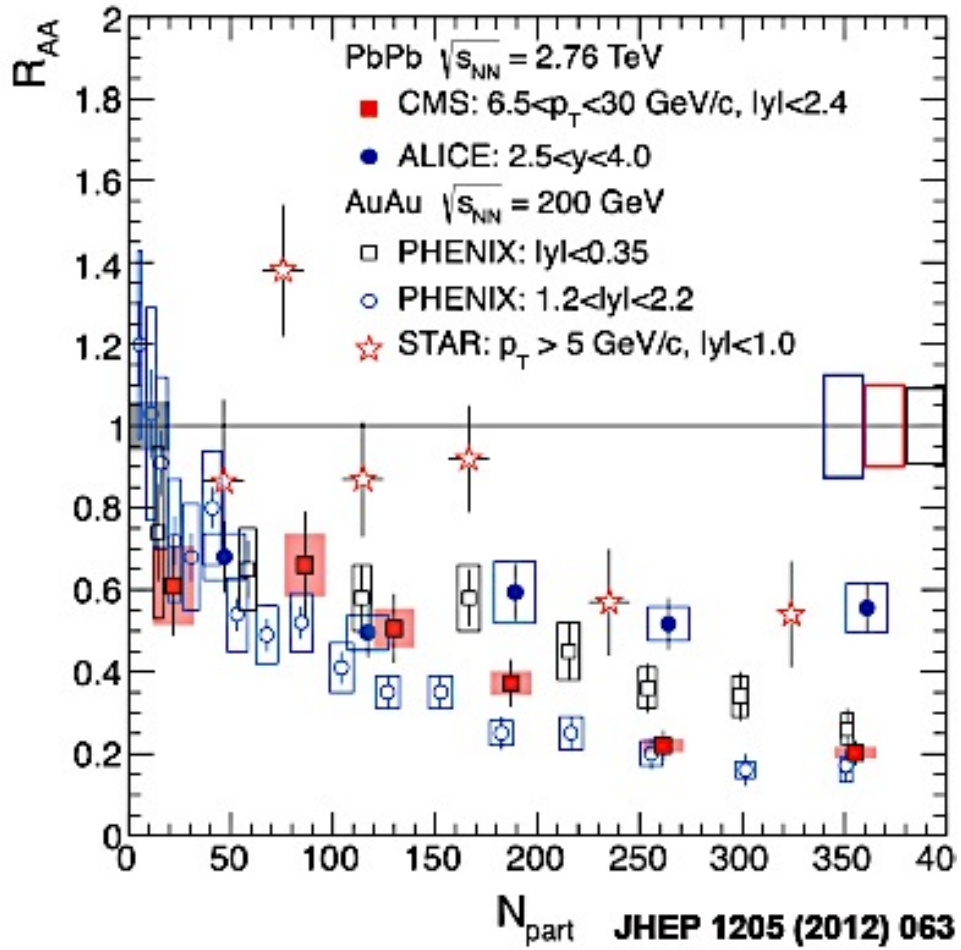
- **Suppression**, but not clear pattern/picture

- **Interplay** of **hot** and **cold** medium effects:

  shadowing, nuclear absorption, energy loss, comovers, colour screening, regeneration

- **Quarkonium in p+p** still not fully controlled theoretically

  CSM, COM, polarization..



JHEP 1205 (2012) 063
JHEP 1205 (2012) 063
PRL 98 (2007) 232301
PRC 84 (2011) 054912

Quarkonium supression in p+A collisions: CNM effects

Quarkonium production is suppressed in nuclear collisions ...but for a variety of reasons

- dissociation by screening ("melting") and/or collisions in hot QGP

QGP effects
A+A collisions

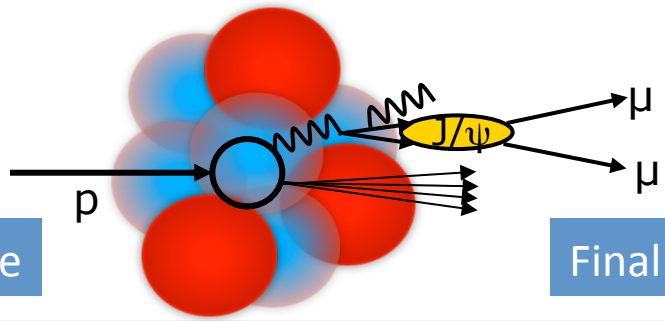
Quarkonium supression in p+A collisions: CNM effects

Quarkonium production is suppressed in nuclear collisions ...but for a variety of reasons

- dissociation by screening ("melting") and/or collisions in hot QGP

QGP effects
A+A collisions

- shadowing,
- saturation
- intrinsic charm



Initial state

Final state

- nuclear absorption
- energy loss
- comovers

CNM effects
p+A and A+A collisions

Quarkonium supression in p+A collisions: CNM effects

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QGP effects
A+A collisions

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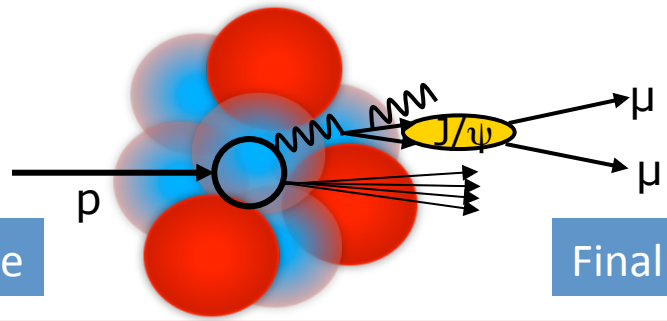
- intrinsic charm



Initial state

Final state

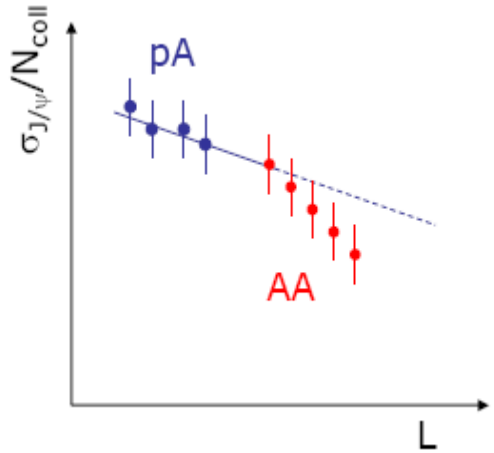
- nuclear absorption
- energy loss
- comovers

CNM effects
p+A and A+A collisions

To understand quarkonium behaviour in the hot medium, it's important to know its behaviour in the cold nuclear matter. This information can be achieved studying pA collisions

The cold nuclear matter effects present in pA collisions are of course present also in AA and can mask genuine QGP effects

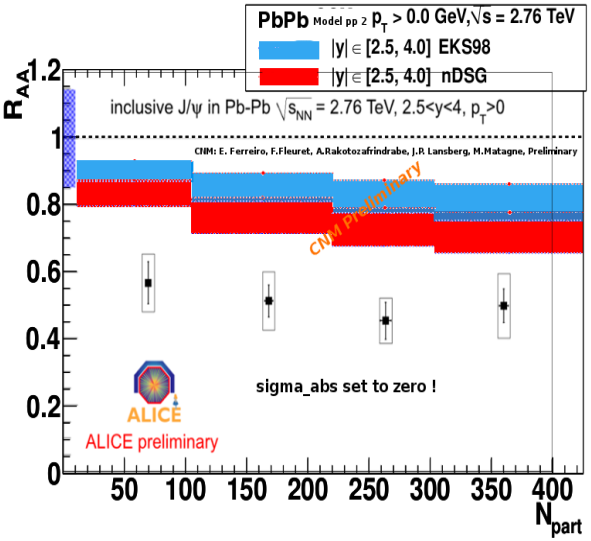
CNM, evaluated in pA, are extrapolated to AA, in order to build a reference for the J/Ψ behaviour in hadronic matter



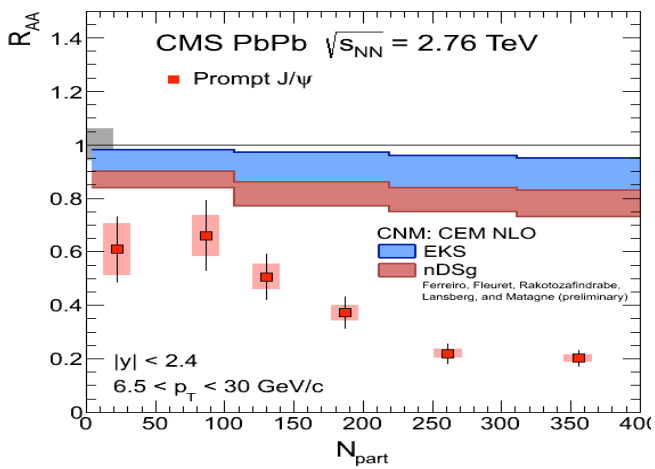
Initial shadowing effects are important: J/ψ production in PbPb @ LHC

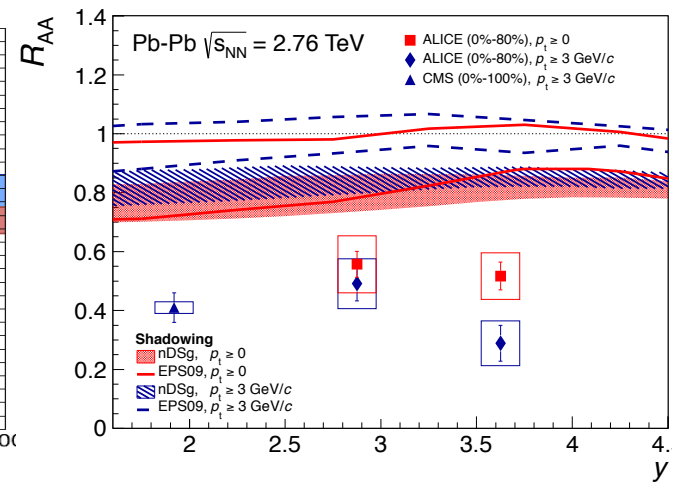
- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
- PDFs in nuclei different from the superposition of PDFs of their nucleons

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



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

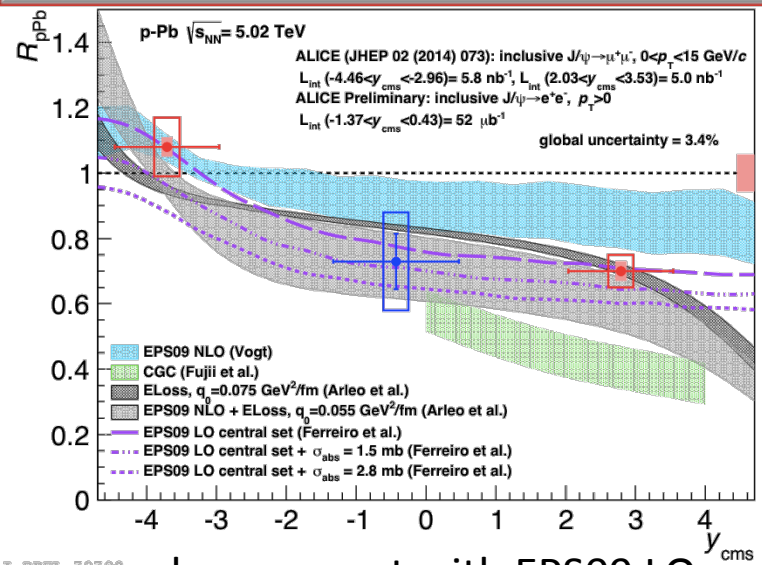


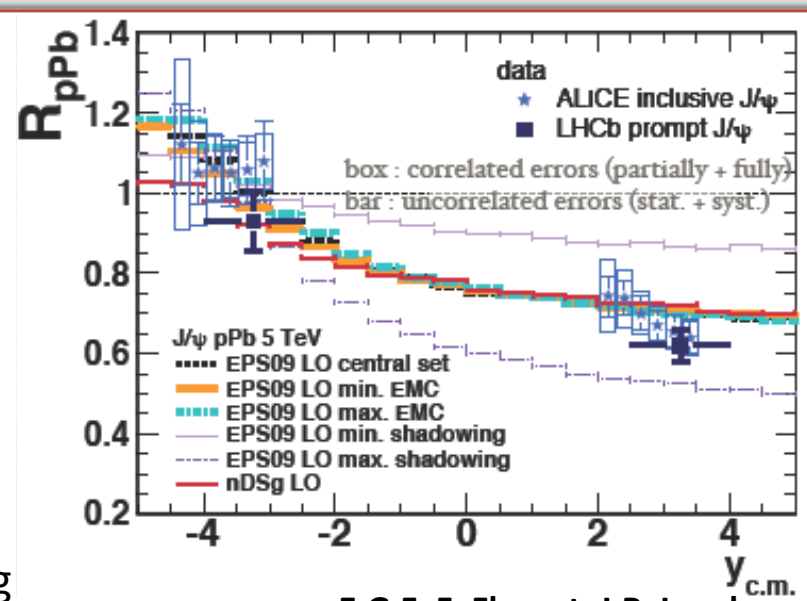


Production mechanism affects CNM effects intimately:

- 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

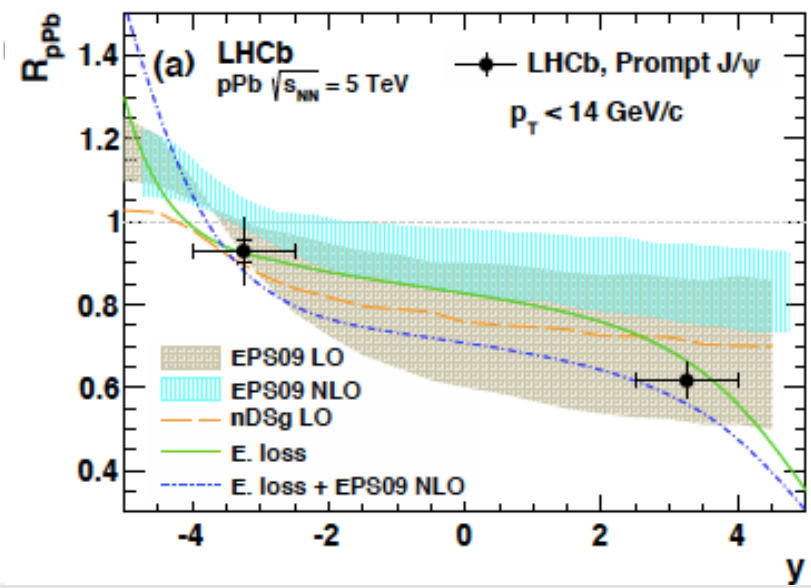
Cross check: J/ψ production in pPb @ LHC

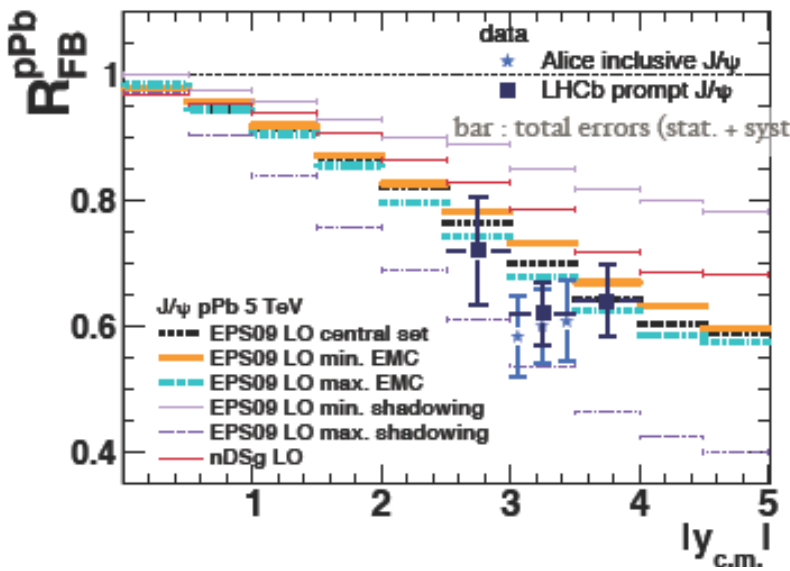




good agreement with EPS09 LO and nDSg shadowing
also consistent w energy loss models w/wo EPS09NLO shadowing
EPS09 NLO and CGC calculation disfavored

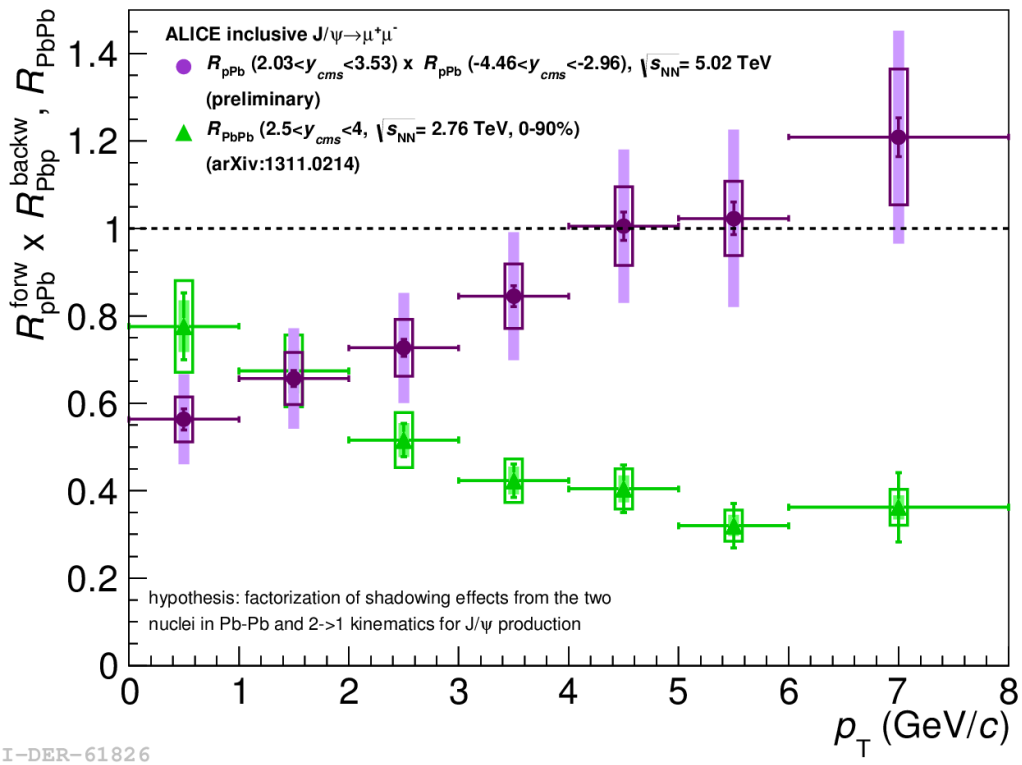
E.G.F, F. Fleuret, J.P. Lansberg, A.Rakotozafindrabe
Phys.Rev. C88 (2013) 4, 047901





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

Theoretical models on recombination

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

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c N_{\bar{c}} [V(\tau)]^{-1} - \lambda_D N_{J/\psi} \rho_g$$

Similar gain and loss diferential eqs.

Comover model

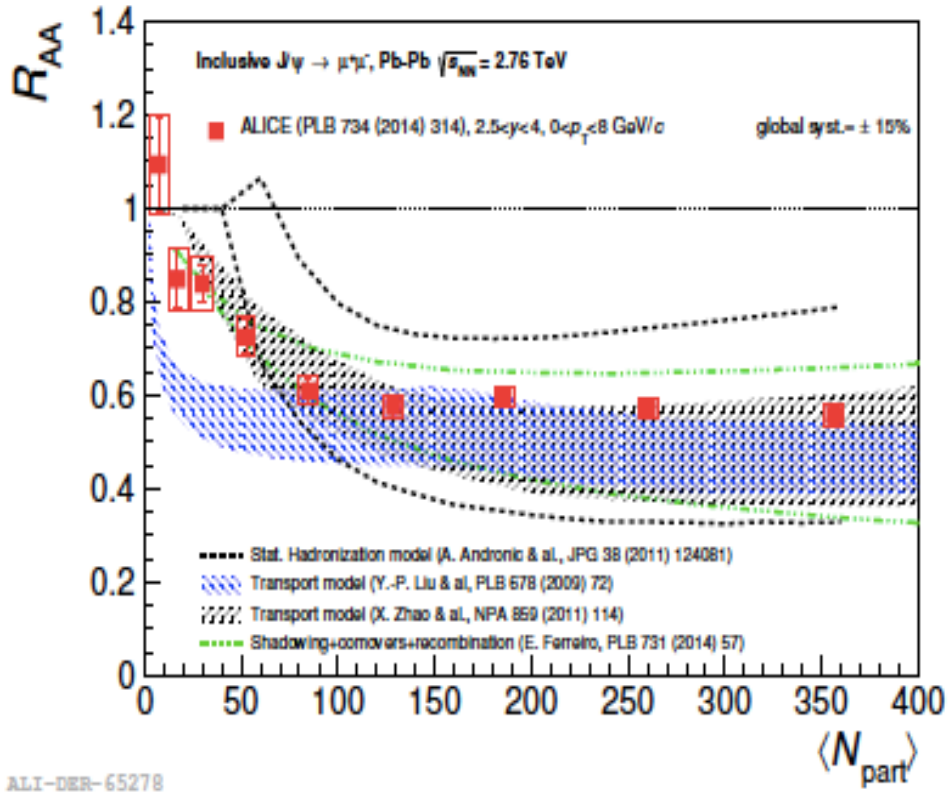
Capella et al., PLB 393 (1997) 431; PLB 430 (1998) 23; PRC 59 (1999) 395;
PRL 85 (2000) 2080; EPJC 42 (2005) 419; EPJC 61 (2009) 865; PLB 731 (2014) 57

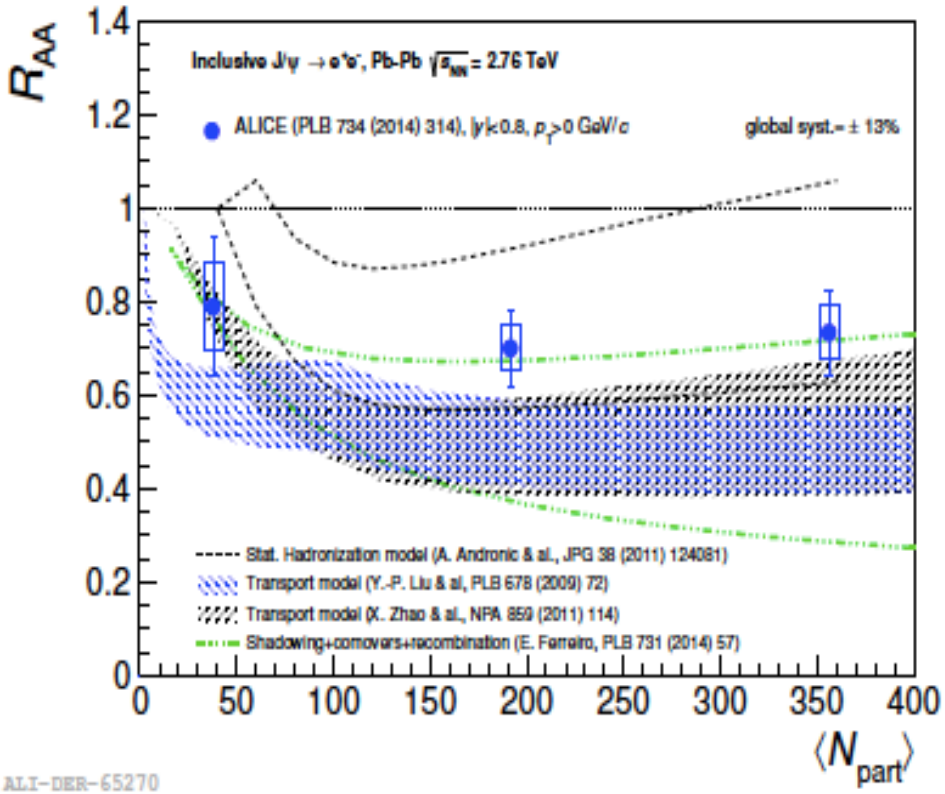
Similar to transport model
Hadronic and partonic comovers contribute
to suppression and recombination
No thermalization

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

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

Comparison to theory calculations

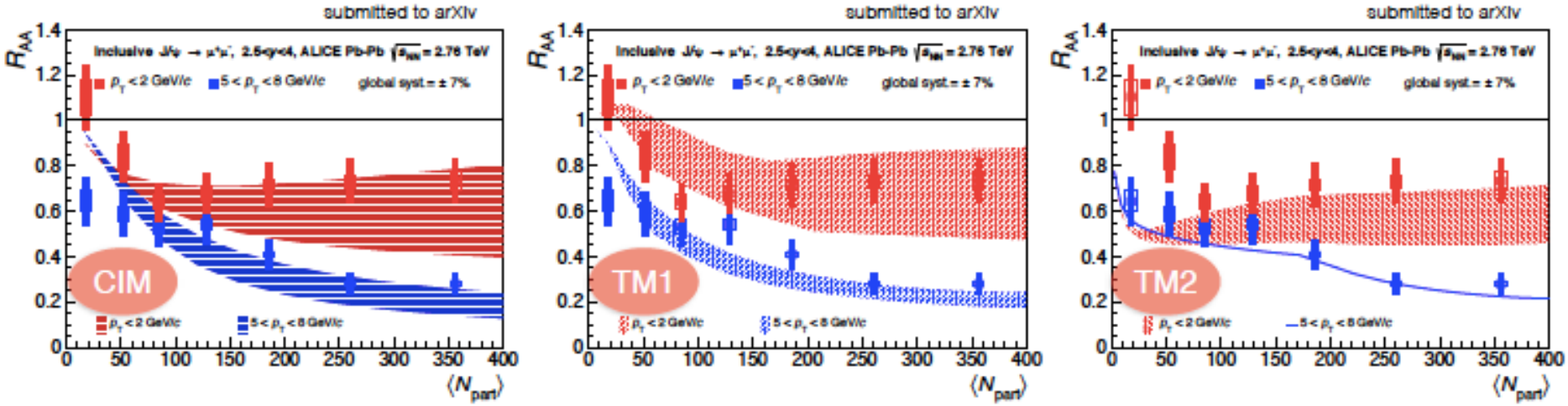




Statistical hadronization, transport and comover models with **recombination component can describe the trend in data**

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

Comparisons with models



CIM: Comover Interaction Model
PLB 731,57 (2014)

Shadowing, interaction with co-moving dense partonic medium, recombination effects.

TM1: Transport Model from Zhao
Nucl. Phys. A859, 114 (2011)

TM2: Transport Model from Zhou
Phys. Rev. C89, 054911 (2014)

Shadowing, transport approach accounting for both suppression and regeneration mechanisms, beauty-meson decays. Mainly differ in the rate equation.

To match our J/ψ R_{AA} results, all models need to include a sizable J/ψ production from regeneration

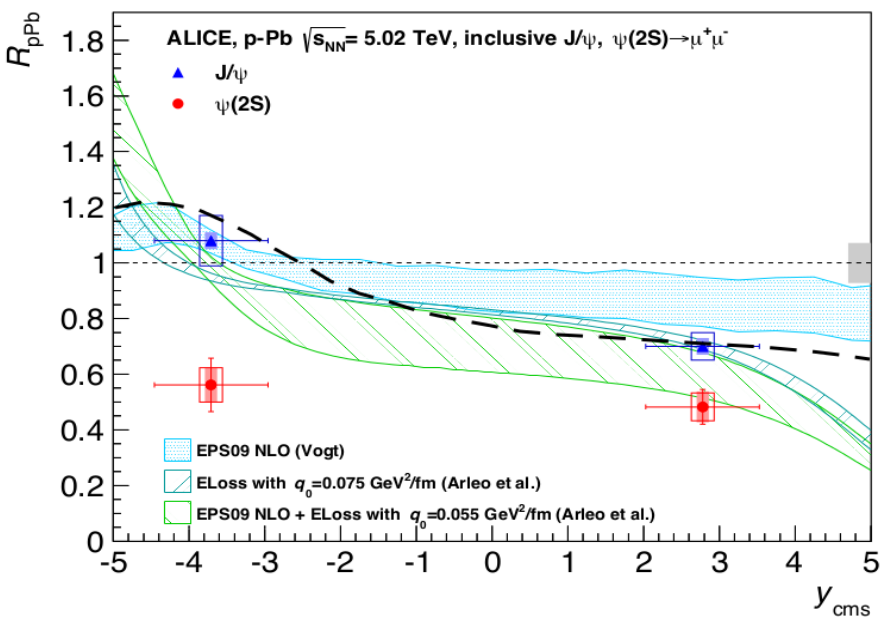
Lardeux, HP2015

Within the large uncertainties on the shadowing and the charm cross section, all models reproduce reasonably well our measurement for $\langle N_{part} \rangle > 70$

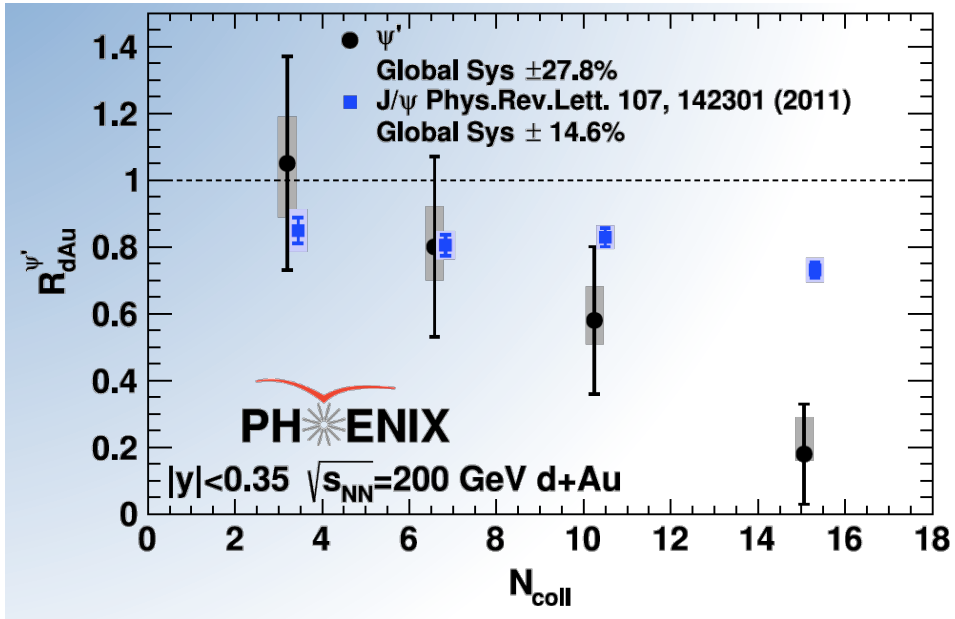
A surprise: ψ(2S) in dAu @ RHIC and pPb @LHC

- A strong decrease of the ψ(2S) production, relative to J/ψ, is observed in

p+Pb at LHC



d+Au at RHIC



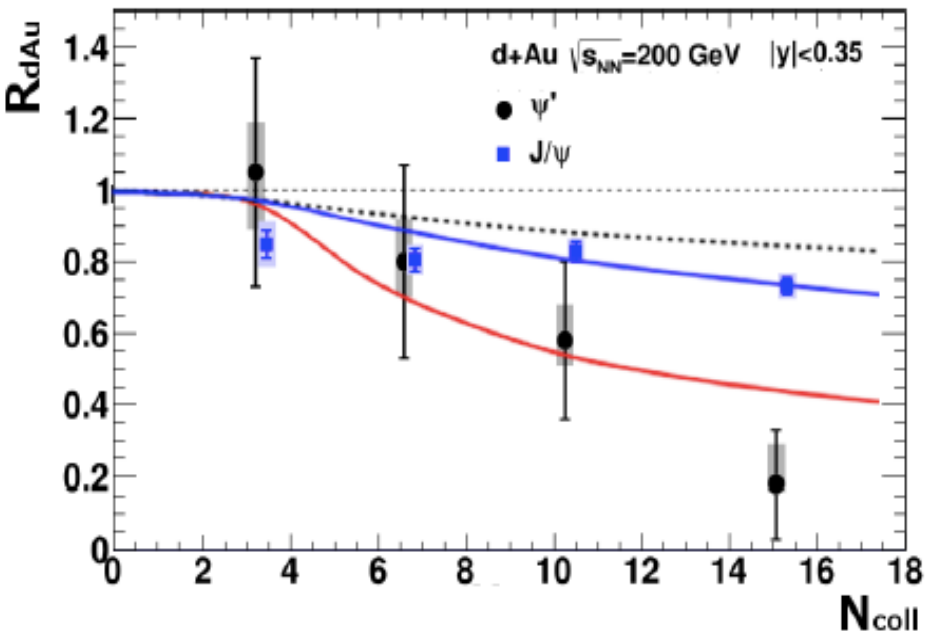
Same initial CNM effects (shadowing –similar m_T-, energy loss, nuclear absorption - charmonium formation time $t_f = \gamma \tau$. > R_A -) for both J/ψ and ψ(2S)
=> theoretical predictions in disagreement with ψ(2S) results

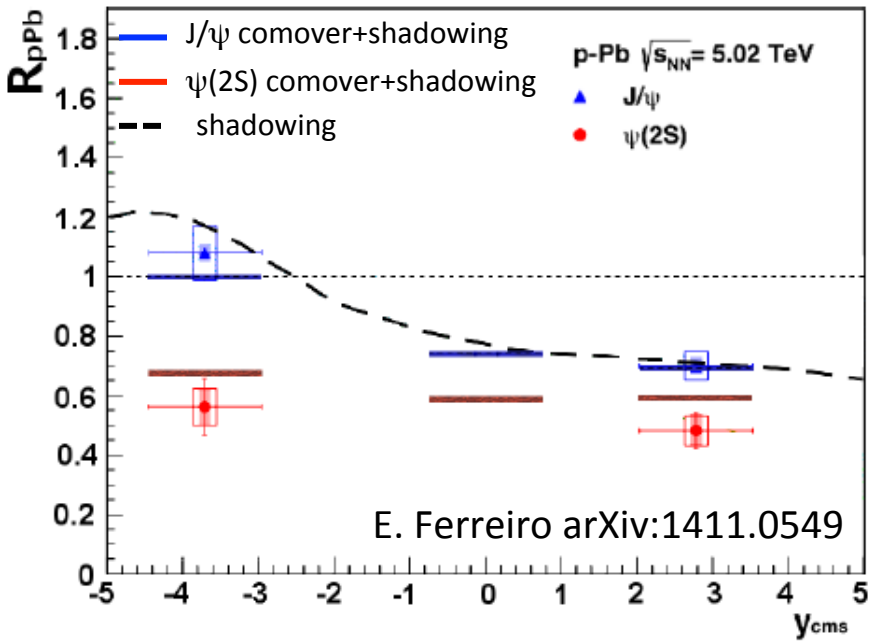
Final state effects related to the medium created in the p-Pb collisions?: co-moving medium

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

Charmonium interaction with comoving particles:

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





What have we learnt from quarkonia production @ LHC?

ϒ(nS): Sequential suppression of the three states in order of their binding energy

- ϒ(2S) and (3S) are strongly suppressed at LHC, ϒ(1S) suppression consistent with higher mass excited states suppression?
- Small room for recombination, some shadowing effects

J/ψ production seems at least **qualitatively understood**

- **Initial cold nuclear matter** effects can be described with shadowing/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)

Challenge will be to discriminate between these possible scenarios

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

- **Initial cold nuclear matter effects** (shadowing/ energy loss) are considered to be the same for than for the J/ψ
- **In-medium effects** depending on density (comovers) are able to distinguish between J/ψ and ψ(2S)