Quarkonium suppression in medium: coherent description in proton-nucleus and nucleus-nucleus collisions

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Work (in progress) done in collaboration with J.-P. Lansberg

Motivations

Quarkonium production in nucleus-nucleus:

- Since the 80's, quarkonium suppression is considered to be a signature of QGP
- Different states sequentially melt at different T due to different binding E

Quarkonium production in proton-nucleus:

no QGP expected, but cold nuclear matter effects are present

- Modification of the gluon flux — *initial-state effect*
  - Modification of PDF in nuclei
  - Gluon saturation at low x
- Parton propagation in medium — *initial/final effect*
  - Energy loss, Cronin effect
- Quarkonium-hadron interaction — *final-state effect*
  - Break up in the nuclear matter
  - Break up by comoving medium

Obviously relevant if one wishes to use quarkonia as a probe of the QGP => baseline

Excited states: An intriguing relative suppression in pA

- ALICE found out a relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 2.76 TeV
- PHENIX also found a relative $\psi(2S)/J/\psi$ suppression in dAu collisions @ 200 GeV
- CMS reported relative suppression of $\Upsilon(2S,3S)$ w.r.t. $\Upsilon(1S)$ in pPb @ 2.76 and 5 TeV

- Initial-state effects –modification of nPDFs / parton E loss- identical for the family
- Any difference among the states should be due to final-state effects

- At low energy, the relative suppression pattern can be explained by $\sigma_{\text{breakup}} \propto r^2_{\text{meson}}$
- At high energies this is irrelevant: too long formation times

$\tau_f^{onia} \approx 0.4$ fm (meson rest frame) => $t_f = \gamma\, \tau_f$ (target rest frame)

$\gamma = \cosh(y - y^A_{\text{beam}})$ => $\gamma_{\text{RHIC}}=107$ and $\gamma_{\text{LHC}}=2660$ (at y=0)

It takes $t_f > 40$ fm/c at RHIC and $t_f > 1000$ fm/c at LHC for a quarkonium to form and to become distinguishable from its excited states $t_f >> R$

Consensus: $\sigma_{\text{break-up}}$ is getting small at high energies and may be the same for ground and excited states

- A natural explanation would be a final-state effect acting over sufficiently long time in order to impact different states with a different magnitude=>

interaction with a comoving medium

Comover-interaction model CIM

- In a comover model: suppression from scatterings of the nascent ψ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)**

- Stronger comover suppression where the comover densities are larger. For asymmetric collisions as proton-nucleus, stronger in the nucleus-going direction

- Rate equation governing the quarkonium density:

$$\tau \frac{d\rho^{\mathcal{Q}}}{d\tau}(b,s,y) = -\sigma^{co-\mathcal{Q}} \rho^{co}(b,s,y)\, \rho^{\mathcal{Q}}(b,s,y)$$

$\sigma^{co-\mathcal{Q}}$ cross section of quarkonium dissociation due to interactions with comoving medium

$\rho^{co}(b,s,y)$ connected to the number of binary collisions and dN^{pp}_{ch}/dy

- Survival probability from integration over time (with $\tau_f/\tau_0 = \rho^{co}(b,s,y)/\rho_{pp}(y)$)

By essence of their comoving character, these can interact with the fully formed states after 0.3 ÷0.4 fm/c

$$S^{co}_{\mathcal{Q}}(b,s,y) = \exp\left\{-\sigma^{co-\mathcal{Q}} \rho^{co}(b,s,y) \ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

Our aim is to investigate if the relative suppression in pPb can be explained by the comover model and what could the impact on the PbPb data be

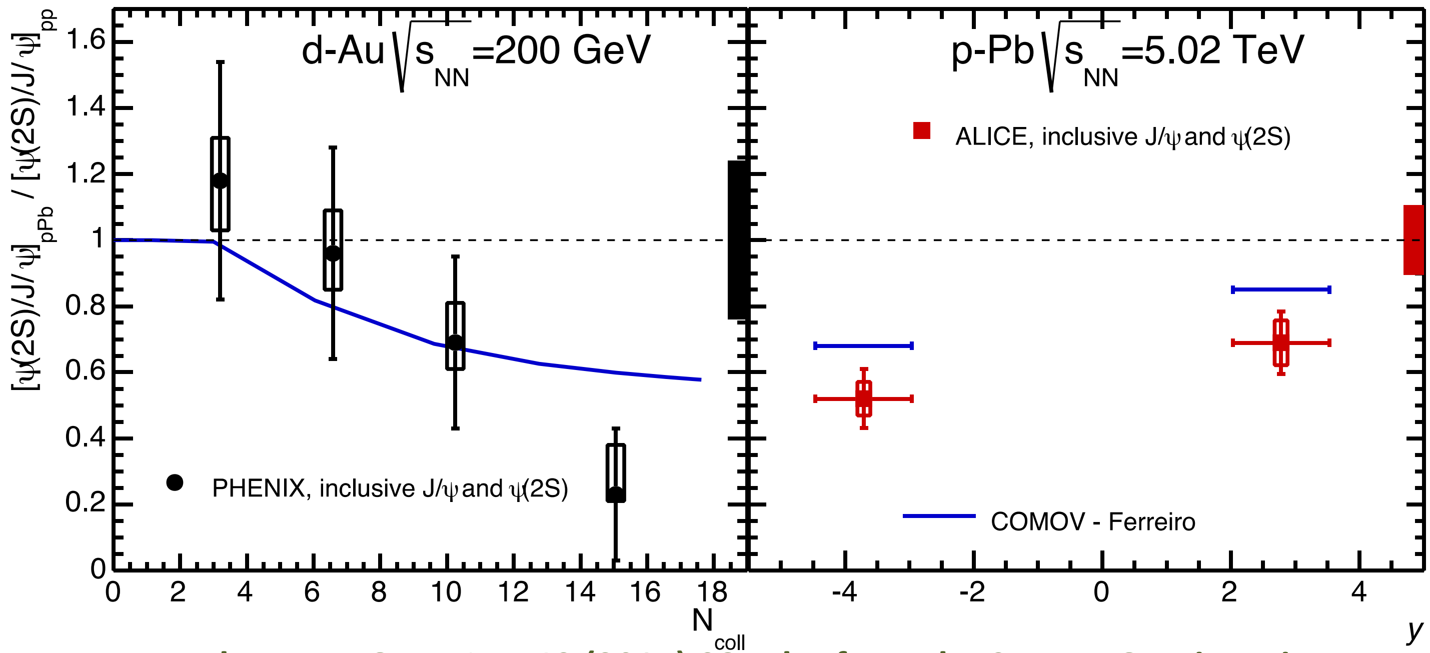
Stronger suppression in nucleus-nucleus collisions

Past CIM results for charmonia at RHIC and LHC

- Extensive phenomenology for SPS: σ^{co-Q} fixed from fits to low-energy AA data

N. Armesto, A. Capella, PLB 430 (1998) 23

$$\sigma^{co-J/\psi} = 0.65 \text{ mb for the } J/\psi \text{ and } \sigma^{co-\psi'} = 6 \text{ mb for the } \psi'$$



Theory: E.G. F. PLB 749 (2015) 98; Plot from the Sapore Gravis review

- Pretty encouraging since the data were not fit and CIM has the good rapidity trend

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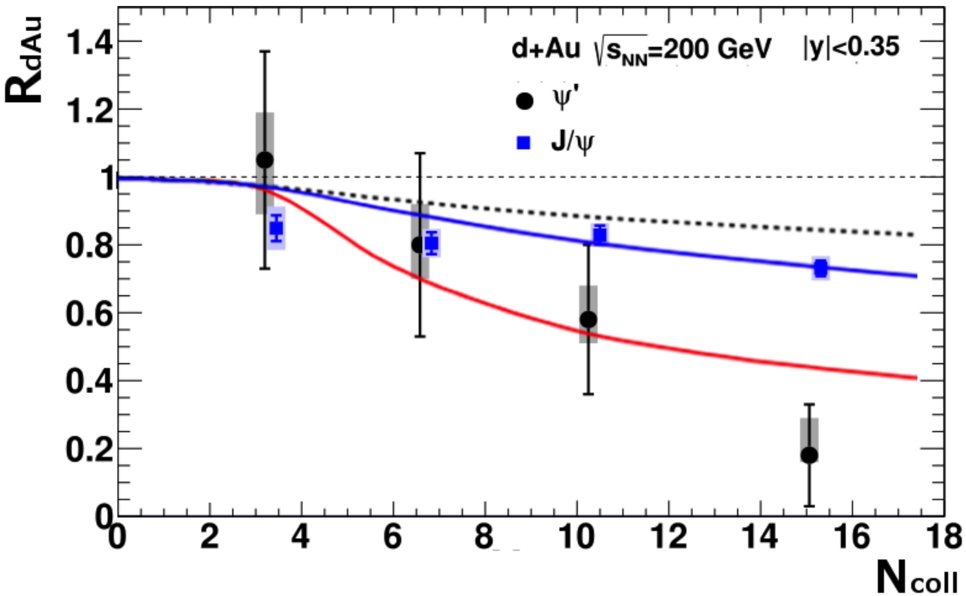

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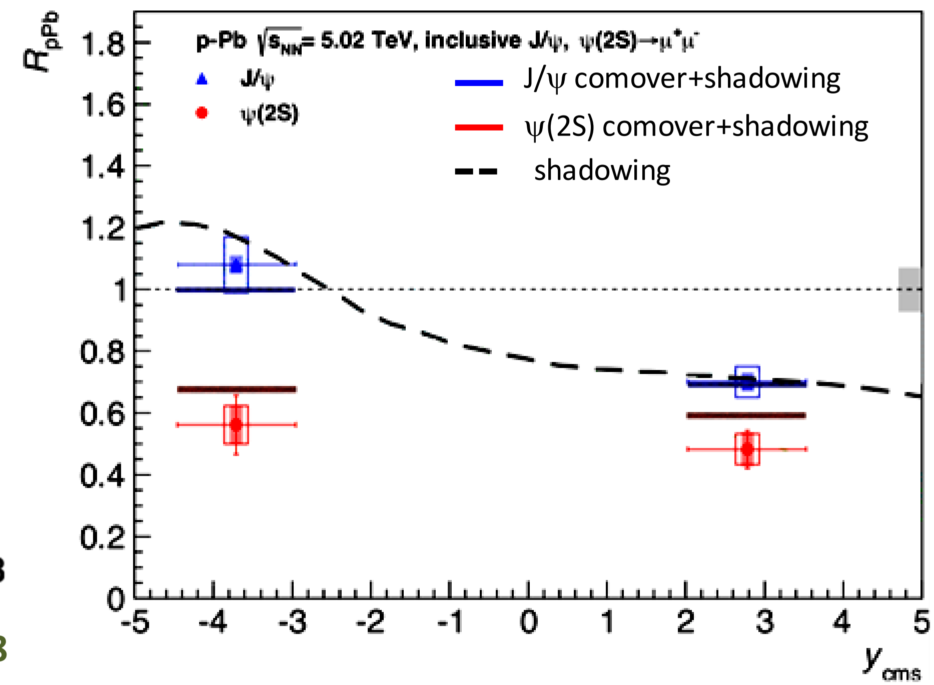


Charmonium interaction with comoving particles:

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

Upsilon CMS suppression in pPb

At the time of the CMS Υ PbPb analysis, no nuclear effects were expected to apply differently to different states, in particular nuclear break-up

Selected for a Viewpoint in Physics
PRL 109, 222301 (2012) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2012

Observation of Sequential Υ Suppression in PbPb Collisions

S. Chatrchyan et al.*
(CMS Collaboration)

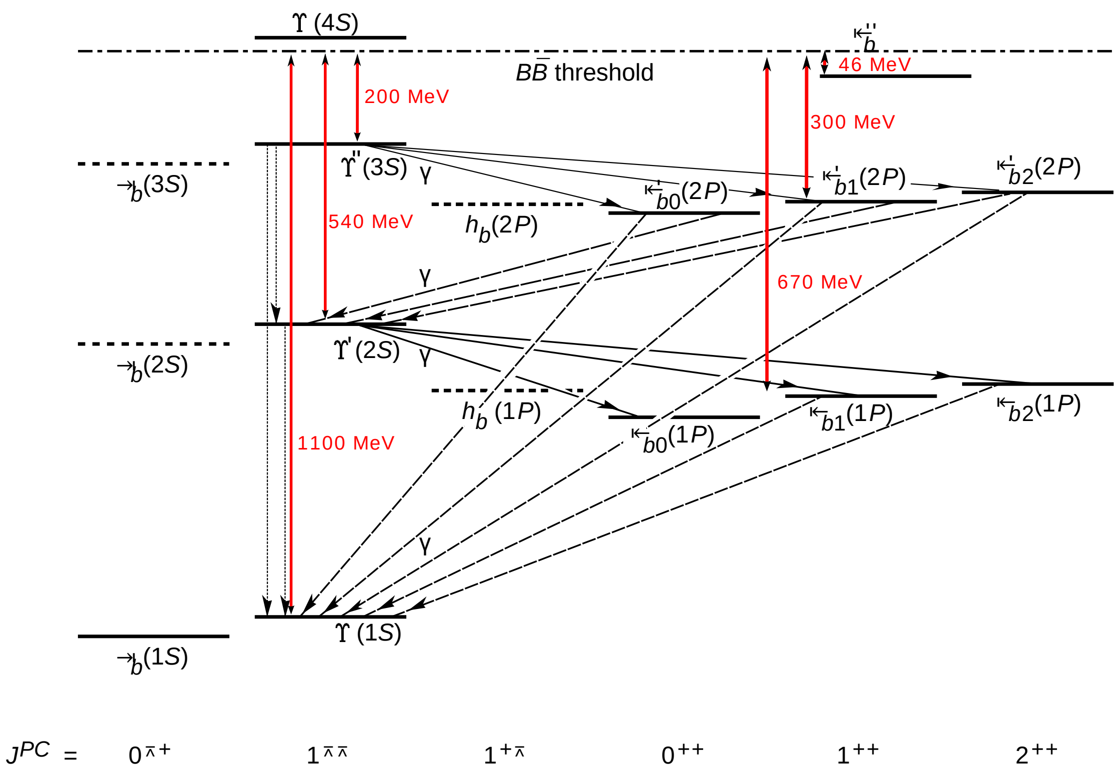
In addition to QGP formation, differences between quarkonium production yields in PbPb and pp collisions can also arise from cold-nuclear-matter effects [21]. However, such effects should have a small impact on the double ratios reported here. Initial-state nuclear effects are expected to affect similarly each of the three Υ states, thereby canceling out in the ratio. Final-state "nuclear absorption" becomes weaker with increasing energy [22] and is expected to be negligible at the LHC [23].

$\frac{[\Upsilon(nS)/\Upsilon(1S)]_{ij}}{[\Upsilon(nS)/\Upsilon(1S)]_{pp}}$	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	$0.83 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	$0.71 \pm 0.08\,(\text{stat.}) \pm 0.09\,(\text{syst.})$

- CMS assumption contradicted by their pPb data CMS JHEP04(2014)103
- If this relative suppression can be attributed to comover effects, how does that translate to PbPb collisions? [comover suppression is related to the multiplicity]

A closer look into Υ states

- The bottomonium family is much richer than the charmonium one
- χ_b'' first particle discovered at the LHC **ATLAS PRL 108 (2012) 152001**
- It allows for a much finer studies with 3 Υ states (decaying into dimuons)
- It comprises excited states which are not too fragile [as opposed to e.g. the ψ□]

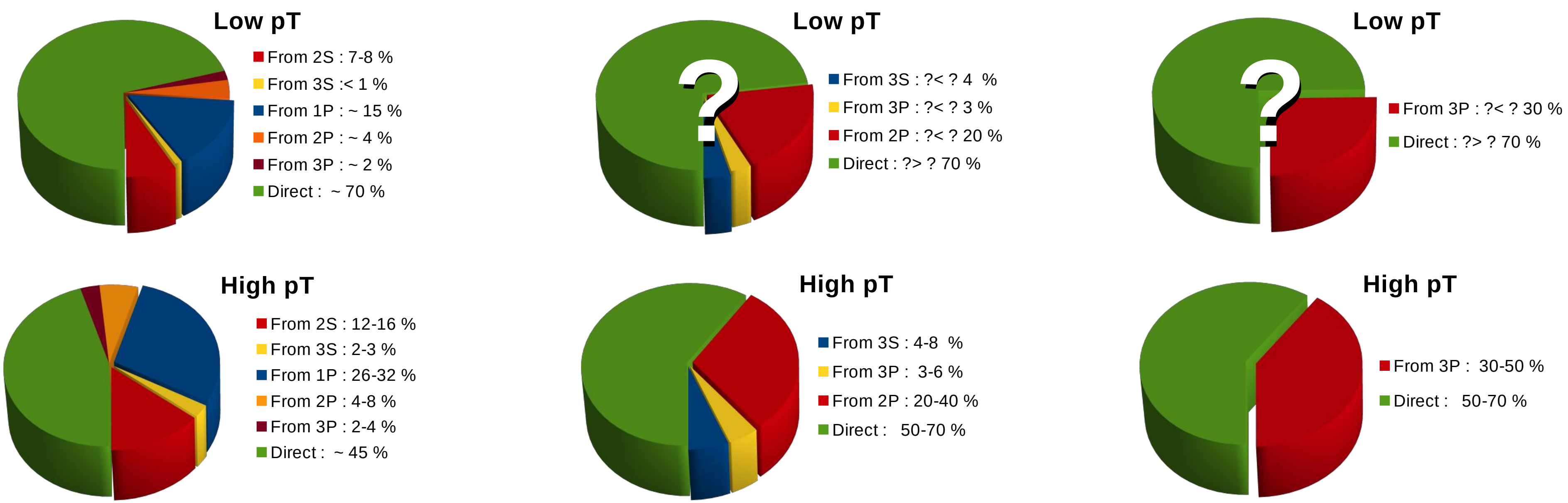


	Binding Energy [MeV]	Radius [fm]
Υ	1100	0.14
χ_b	670	0.22
Υ′	540	0.28
χ_b'	300	0.34
Υ″	200	0.39
χ_b''	50	0.45 (?)

The bottomonium family and its feed down structure

Feed-down structure at low p_T -where quarkonium heavy-ion measurements are mostly carried out- is quite different than that commonly accepted ten years ago based on the CDF measurement, with a p_T>8 GeV

Sapore Gravis Review arXiv:1506.03981 from LHCb data



(a) Υ(1S) (b) Υ(2S) (c) Υ(3S)

- **Υ(3S) is far from being 100% direct**
- **In the region of the Υ PbPb and pPb data, the Υ(1S) is not 50% direct**

This information is fundamental to use bottomonia as probes of QGP, especially for the interpretation of their possible sequential suppression

Setting the scene for the bottomonium family

- Unlike ψ, no such AA data exist at low energies **E. G. F., J.P. Lansberg, work in progress**

In fact, the CIM was never applied to bottomonia

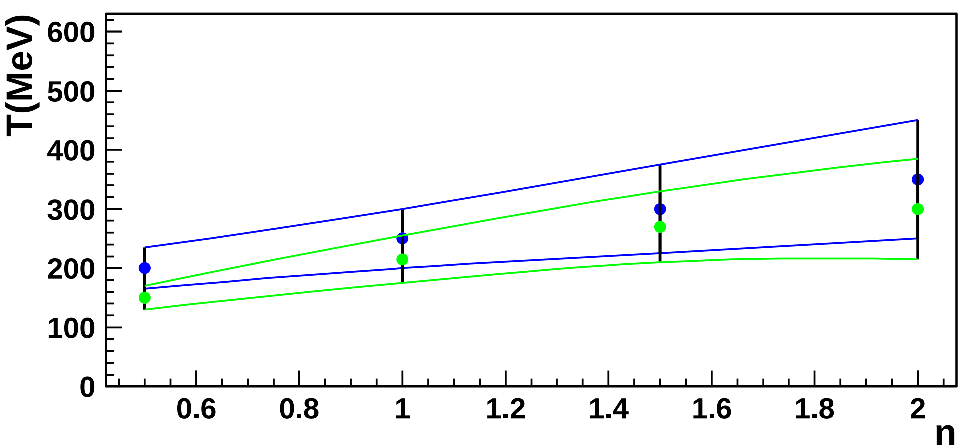
- The relative suppression of the excited Υ is probably the cleanest observable to fix the comover suppression magnitude [without interference with other nuclear effect]
- However, not enough data to fit all the 6 $\sigma^{co-\mathcal{Q}_{b\bar{b}}}$ [the feed-downs discussed above were used]
- We take: $$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\text{geom}}\left(1 - \frac{E_{\text{Binding}}}{E_{co}}\right)^n$$

$\sigma_{\text{geom}} \equiv \pi r^2_{\mathcal{Q}_{b\bar{b}}}$

$E_{\text{Binding}} \equiv 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$, i.e. the threshold energy to break the bound state

$E^{co} = \sqrt{p^2 + m^2_{co}}$ the average energy of the comovers in the quarkonium rest frame

- We average over B-E phase space distribution of the comovers $1/(e^{E^{co}/T_{eff}} - 1)$

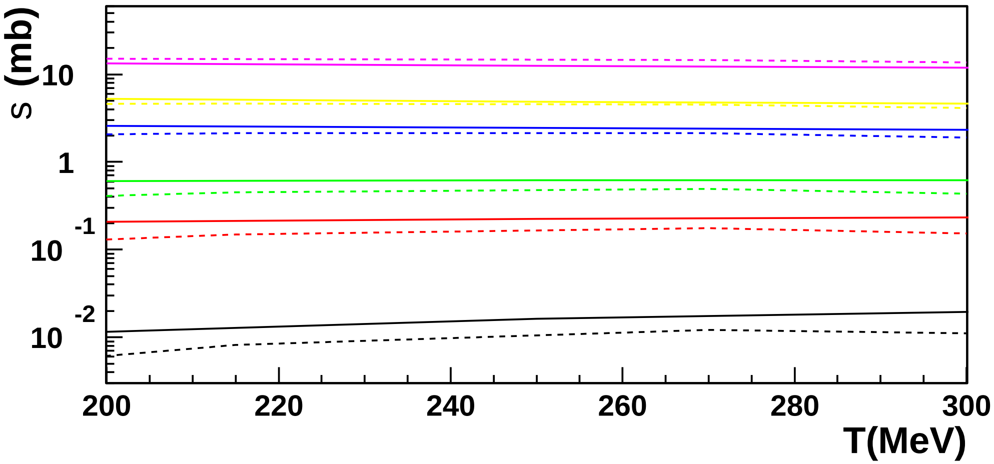


Using pPb CMS and ATLAS data at 5.02 TeV we fit T_{eff} and n

By varying n between 0.5 and 2, we obtain T_{eff} in the range from 200 to 300 MeV both for partons or hadrons

Setting the scene for the bottomonium family

- High stability in the mentioned temperature and *n* ranges



E. G. F., J.P. Lansberg, work in progress

The mean values for the dissociation cross-sections for the bottomonium family in a comover medium made of pions (continuous line) or gluons (discontinuous line).
From down to up: 1S, 1P, 2S, 2P, 3S, 3P

- The feed-downs discussed above were used:

low P_T	direct	from χ_b	from Υ'	from χ_b'	from Υ''	from χ_b''
Υ	$\sim 70\%$	$\sim 15\%$	$\simeq 8\%$	$\sim 5\%$	$\simeq 1\%$	$\sim 1\%$
Υ'	$\sim 63\%$	–	–	$\sim 30\%$	$\simeq 4\%$	$\sim 3\%$
Υ''	$\sim 60\%$	–	–	–	–	$\sim 40\%$

- Varying the feed-down fractions for 2 limiting cases does not change the results 80% of direct 1S and 50% of direct 3S or 60% of direct 1S and 70% of direct 3S on

Double ratio $\Upsilon(nS)/\Upsilon(1S)$ in pPb @ 5.02 TeV

Taking into account the temperature uncertainty, T=250 ± 50 MeV, we obtain, for n=1, the following values for the cross-sections:

	$E_{Binding}$	$r_{Q_{b\bar{b}}}$	$\sigma^{co-Q_{b\bar{b}}}$
$\Upsilon(1S)$	1100 MeV	0.14 fm	$0.02^{+0.020}_{-0.010}$ mb
χ_{B1}	670 MeV	0.22 fm	$0.23^{0.14}_{-0.12}$ mb
$\Upsilon(2S)$	540 MeV	0.28 fm	$0.61^{+0.33}_{-0.28}$ mb
χ_{B2}	300 MeV	0.34 fm	$2.44^{+0.76}_{-0.79}$ mb
$\Upsilon(3S)$	200 MeV	0.39 fm	$4.92^{+1.11}_{-1.29}$ mb
χ_{B3}	50 MeV	0.45 fm	$12.55^{+1.53}_{-1.88}$ mb

which correspond to the double ratios:

Υ pPb at 5.02 TeV

	CIM	Exp
	$-1.93 < y < 1.93$	CMS data
$\Upsilon(2S)/\Upsilon(1S)$	0.91 ± 0.03	0.83 ± 0.05 (stat.) ± 0.05 (syst.)
$\Upsilon(3S)/\Upsilon(1S)$	0.72 ± 0.02	0.71 ± 0.08 (stat.) ± 0.09 (syst.)
	$-2.0 < y < 1.5$	ATLAS data
$\Upsilon(2S)/\Upsilon(1S)$	0.90 ± 0.03	0.76 ± 0.07 (stat.) ± 0.05 (syst.)
$\Upsilon(3S)/\Upsilon(1S)$	0.71 ± 0.02	0.64 ± 0.14 (stat.) ± 0.06 (syst.)

Consistency check: Υ(1S) nuclear modification factor in pPb

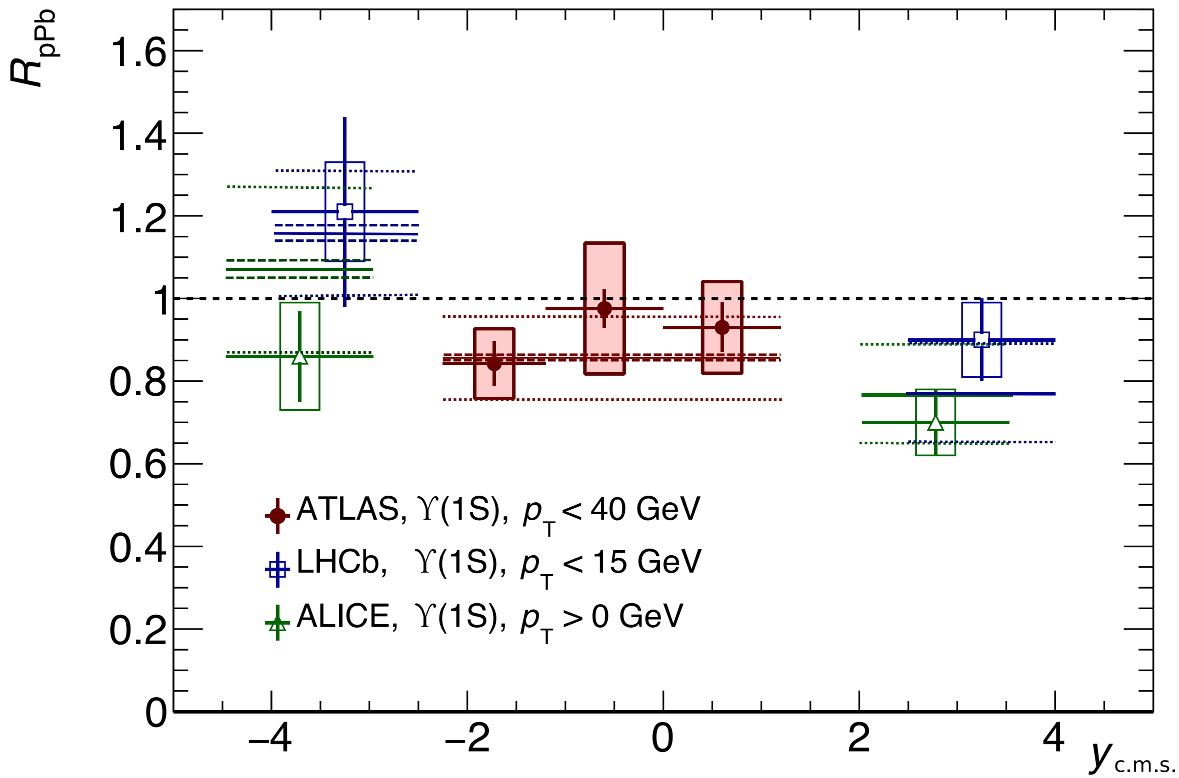
- Now that the $\sigma^{\infty - Q_{b\bar{b}}}$ are fixed, we need to check the consistency with the absolute suppression of Υ(1S)

- Other nuclear effects which cancel in the double ratio, do not cancel anymore, i.e. shadowing

- We take into account nCTEQ15

- Comovers damp down the antishadowing peak

=> better agreement with ALICE



E. G. F., J.P. Lansberg, work in progress

Consistency check: Υ(1S) nuclear modification factor in pPb

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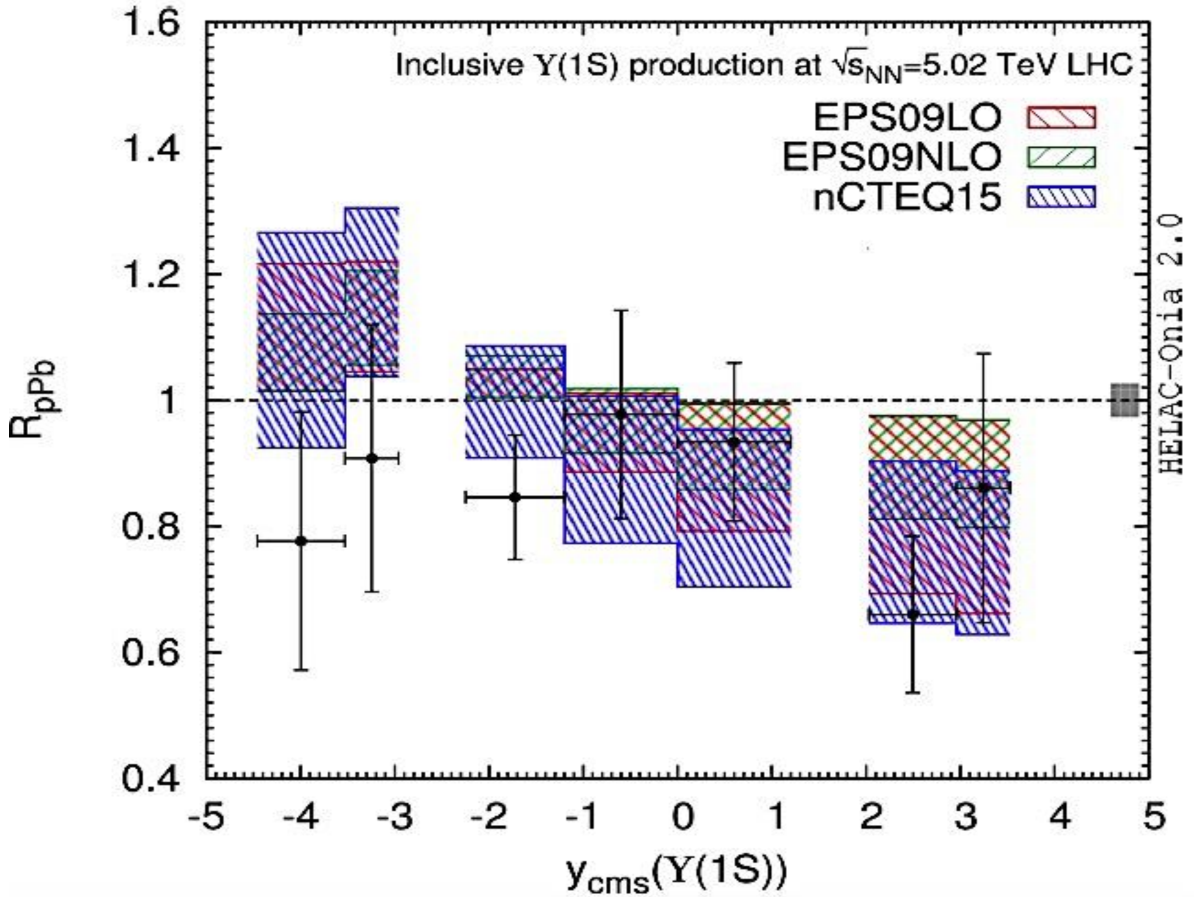

Going to AA: Double ratio Υ(2S)/Υ(1S) in PbPb @ 2.76 TeV

We use the CIM out-of-box (no tuning) with

	$\sigma^{co-Q_{b\bar{b}}}$
$\Upsilon(1S)$	$0.02^{+0.020}_{-0.010}$ mb
χ_{B1}	$0.23^{0.14}_{-0.12}$ mb
$\Upsilon(2S)$	$0.61^{+0.33}_{-0.28}$ mb
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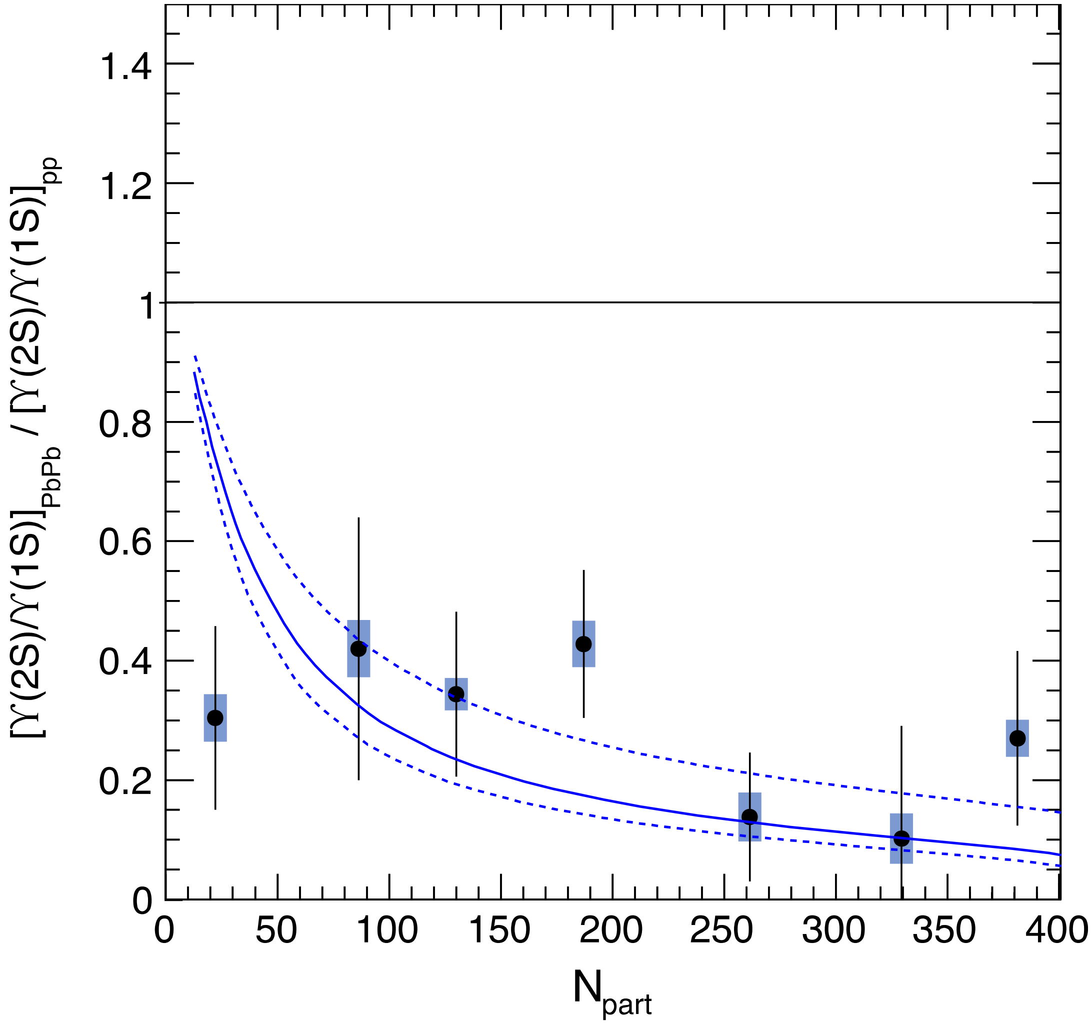

Double ratio Υ(2S)/Υ(1S) -insensitive to shadowing- is well reproduced without the need to invoke any other phenomena

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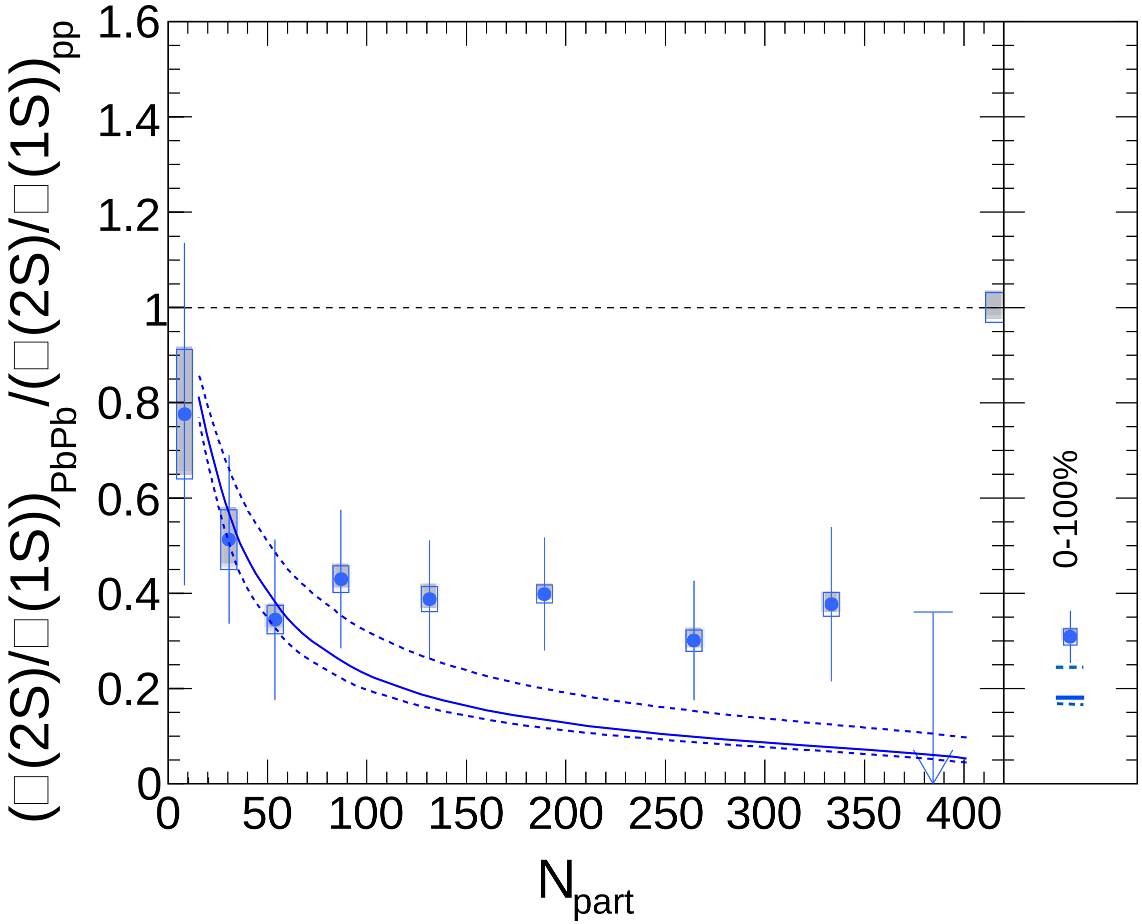

Double ratio Υ(2S)/Υ(1S) -insensitive to shadowing- is well reproduced without the need to invoke any other phenomena

Going to AA: Double ratio Υ(3S)/Υ(1S) in PbPb @ 5.02 TeV

We use the CIM out-of-box (no tuning) with

	$\sigma^{co-Q_{b\bar{b}}}$
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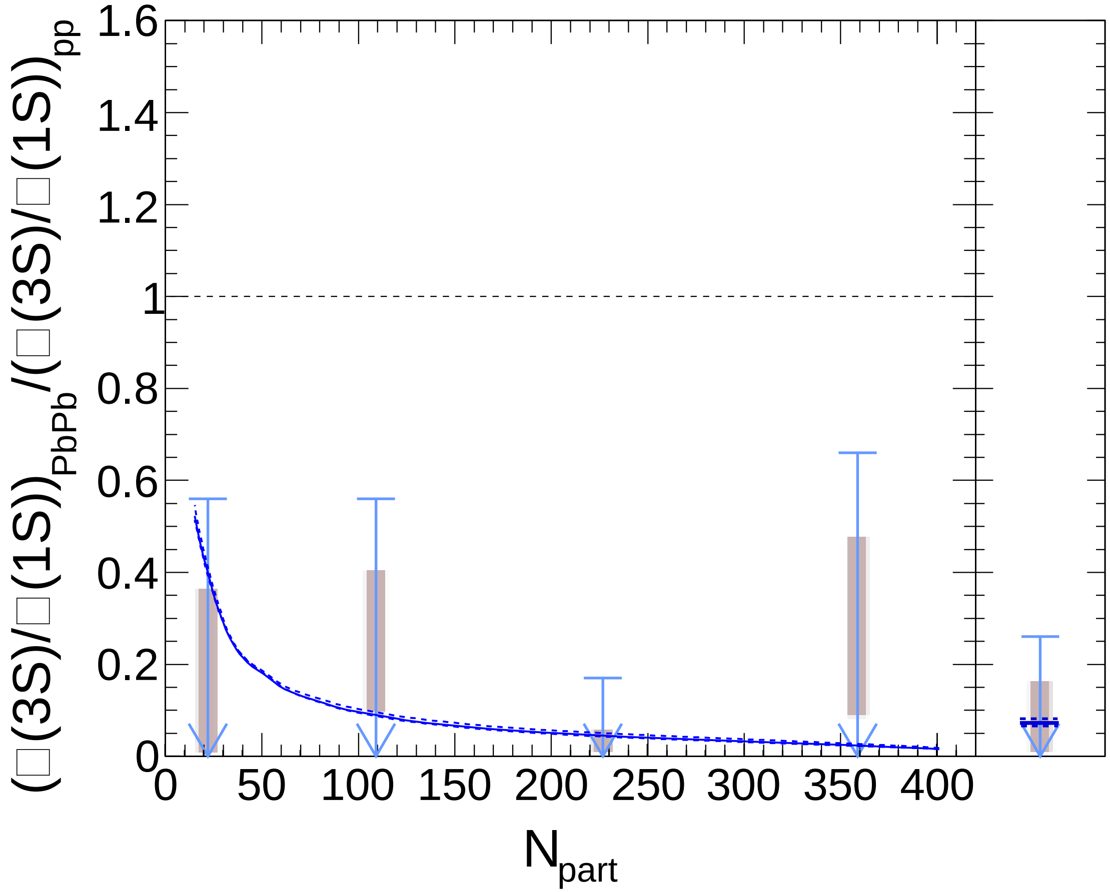
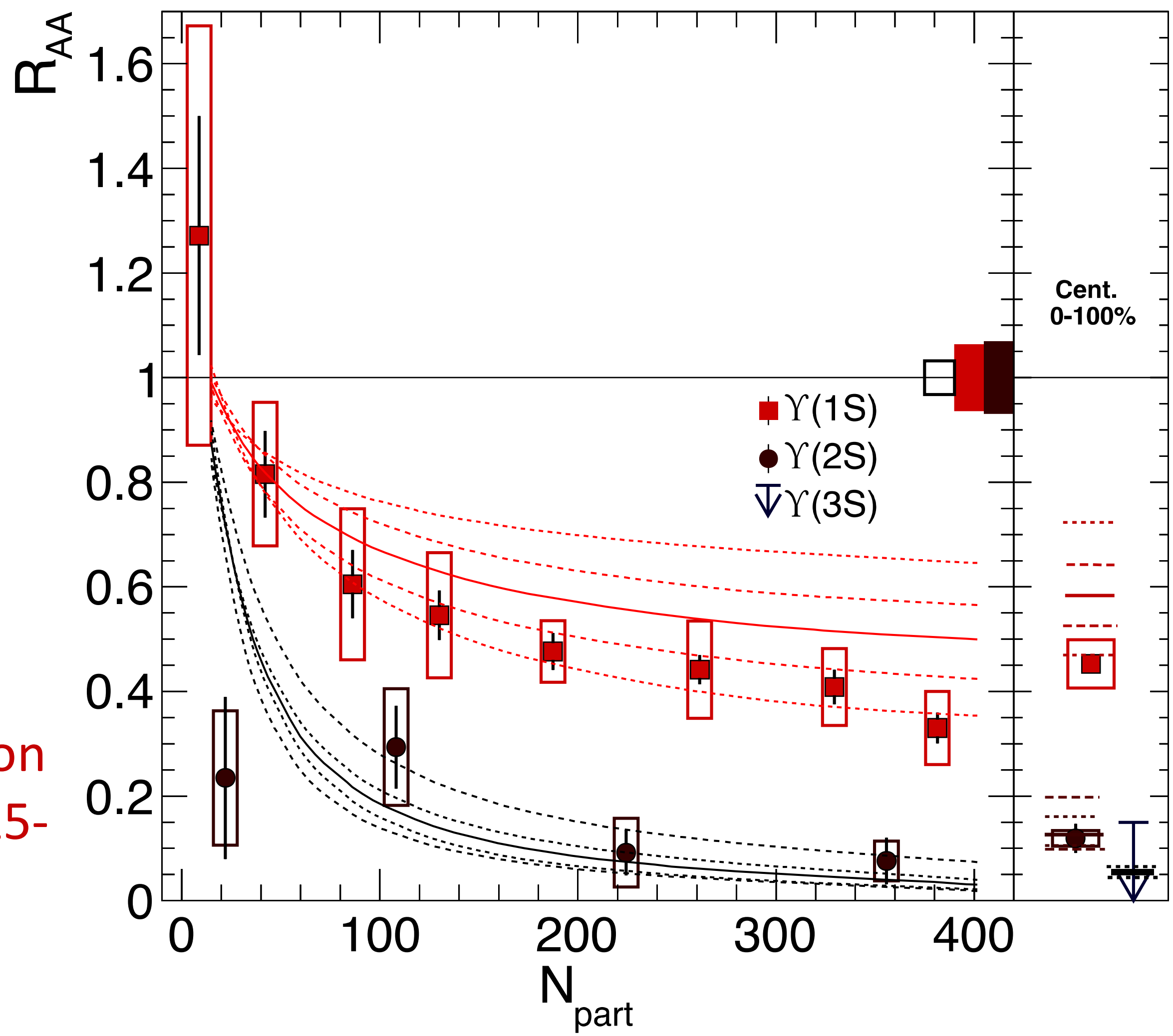


Double ratio Υ(3S)/Υ(1S) -insensitive to shadowing- is well reproduced without the need to invoke any other phenomena

Consistency check: R_{PbPb} for $\Upsilon(1S)$ and $\Upsilon(2S)$ @ 2.76 TeV

- We got the ratio right out-of-the box
- We take into account nCTEQ15 (as for R_{pPb})
- We do show the **signicant uncertainty** of the barely known gluon nPDFs

The magnitude of suppression -taking into account nCTEQ15- is well reproduced without the need to invoke any other phenomena



Consistency check: R_{PbPb} for Υ(1S), Υ(2S) and Υ(3S) @ 5.02 TeV

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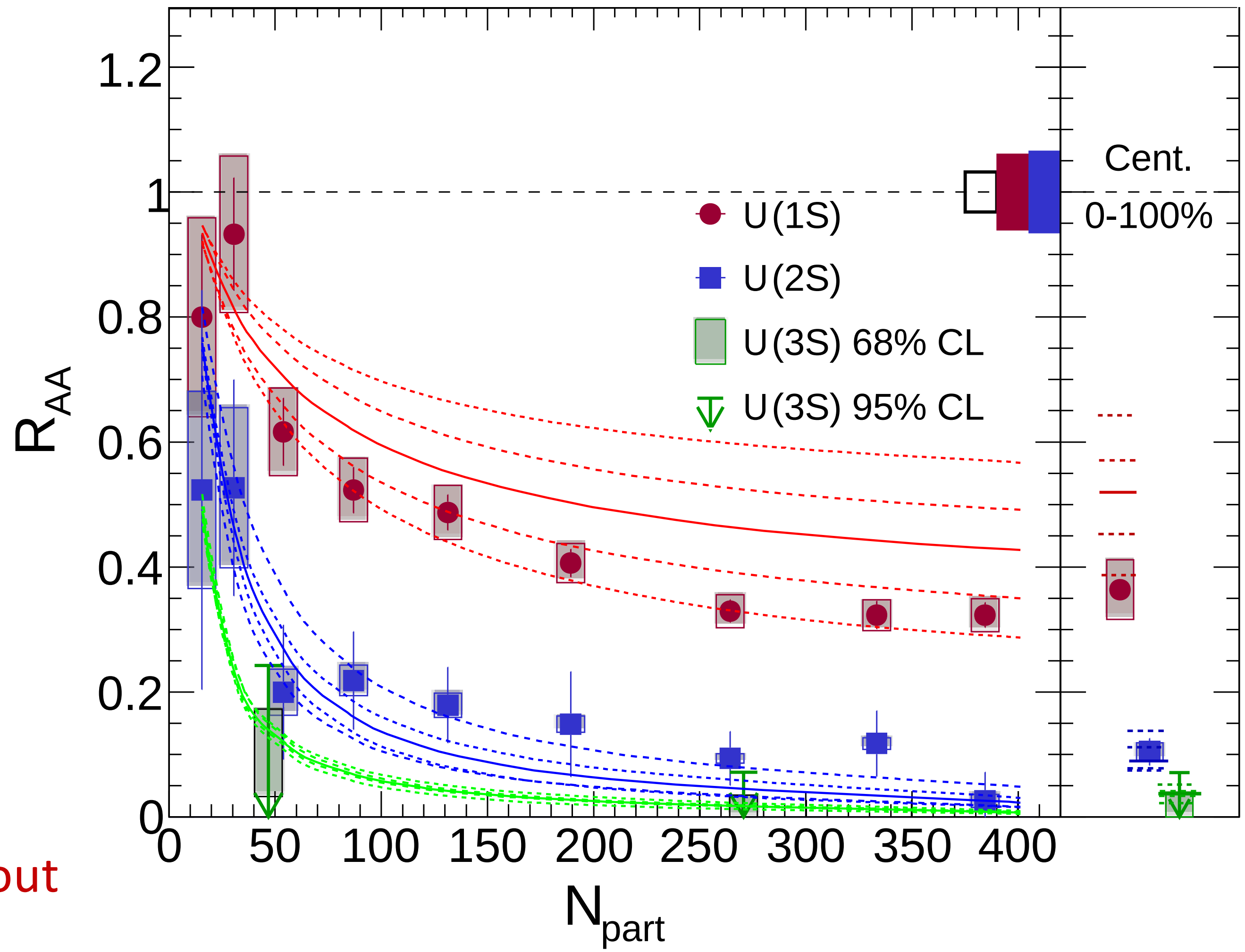


Conclusions

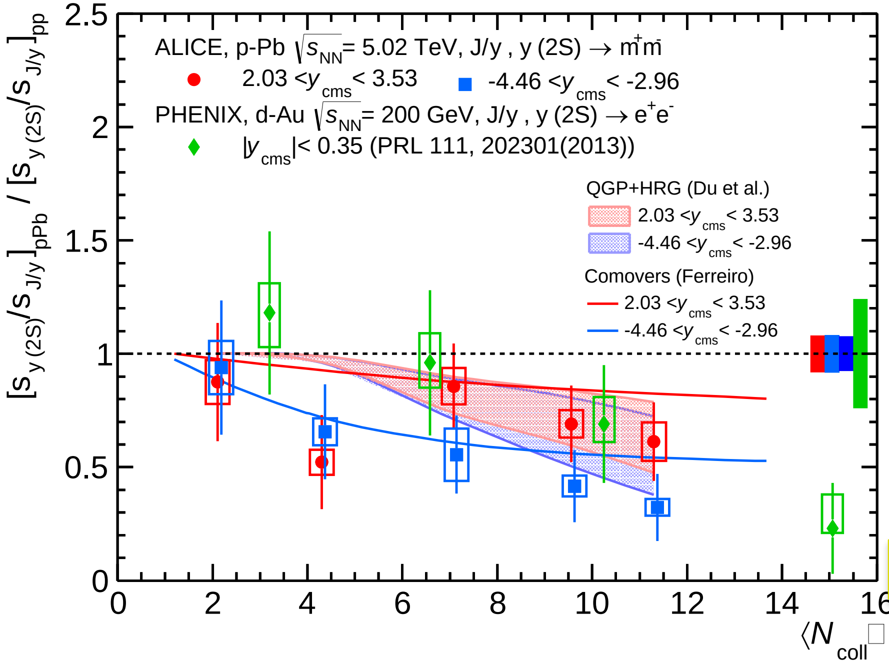
- We have updated our understanding of the feed-down pattern within the bottomium family close to <p_T> where it matters for heavy-ion studies
- In the absence of any other explanation for the relative suppression of excited quarkonia in pA collisions (and its rapidity dependence), we have assumed that the reinteraction with comovers explains it all
- This allowed us to fit all the comover-bottomonium-interaction cross sections from the CMS pPb double ratios in a coherent way
- We have checked that it yields a consistent magnitude for the Υ suppression as mesured by ATLAS, ALICE and LHCb in pPb collisions when combined with nCTEQ15 shadowing (which does not affect the double ratio)
- In turn, we computed double ratio in PbPb collisions at 2.76 and 5.02 TeV
- Both the double ratios of Υ(2S)/Υ(1S) & Υ(3S)/Υ(1S) (insensitive to shadowing) and the magnitude of the suppression (with nCTEQ15) of Υ(1S) & Υ(2S) are well reproduced without the need to invoke any other phenomena

Conclusions

- Physical interpretation: what the nature of the comovers is
- Case I: comovers are partons
  - comovers are to be considered as partons in a (deconfined) medium
  - CIM: effective modelling of bottomonium dissociation in the QGP
- Case II: comovers are hadrons
  - both in pA and AA collisions, Υ not affected by the hot (deconfined) medium
  - Bottomonia unaffected by the presence of a possible QGP => they do not melt
  - Trivial coherence of the description of pA and AA collisions: in both cases, their suppression follows from scattering with the hadron produced in the collision
- Intermediate scenarios: suppression can occur both with partons and hadrons.

QGP-like effects in pA? … in fact not quite

ALICE 1603.02816 Prediction: Ferreiro arxiv:1411.0549 Postdiction: Du & Rapp, private communication

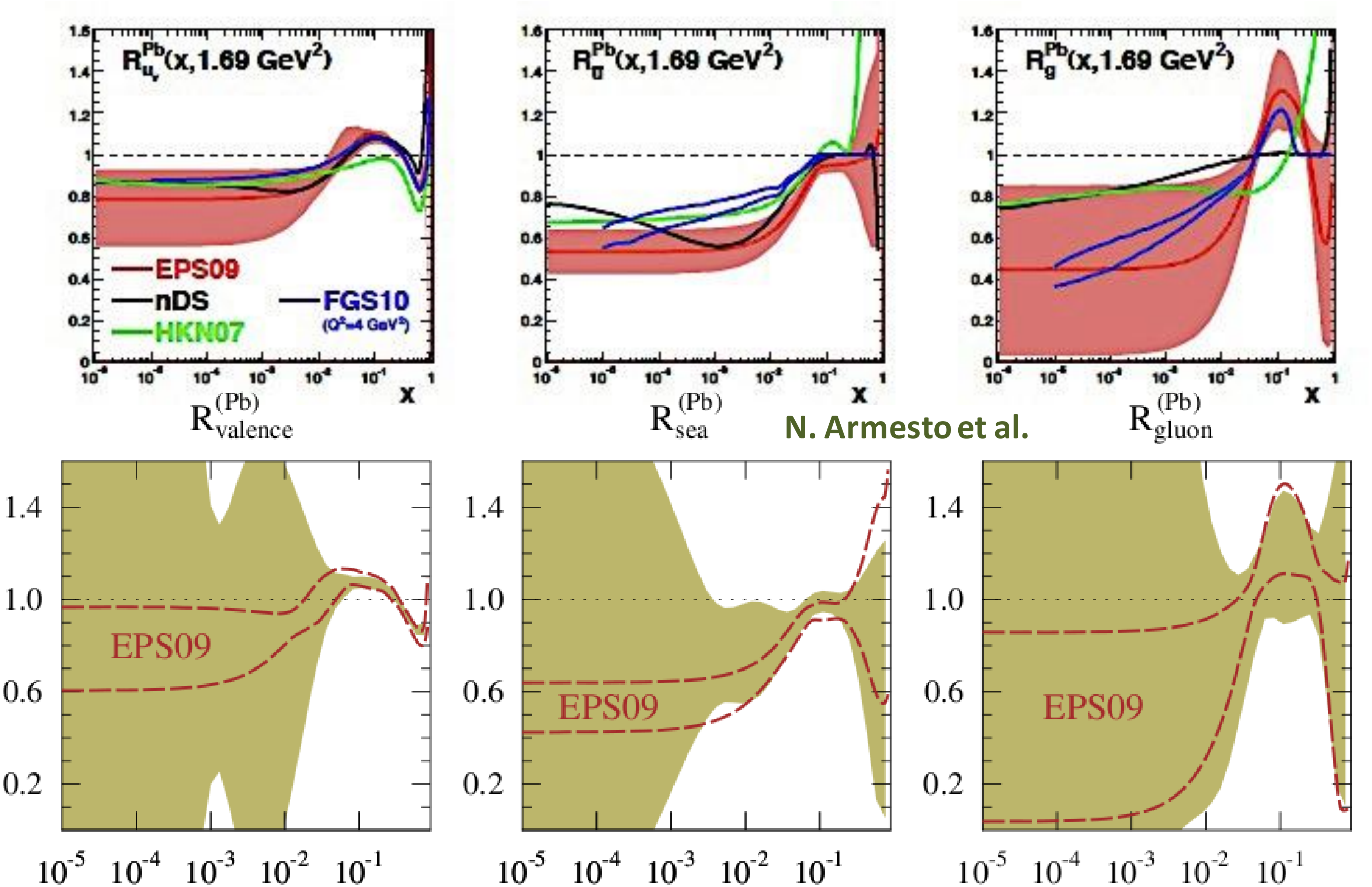


Du & Rapp 1504.00670

In the present work, we have investigated the production systematics of ψ' mesons in URHICs. We first revisited the problem of hadronic ψ' dissociation and found that a more complete inclusion of hadronic states in a resonance gas suggests a marked increase of its inelastic reaction rates. When implementing these rates into an expanding fireball for d-Au collisions at RHIC, we found a much improved description of the rather strong suppression of ψ' mesons observed in these reactions. This is similar in spirit to, and thus supports, the recently suggested comover suppression effects [16] in dA and pA reactions at RHIC and LHC.

- The transport model (QGP+HRG) is based on a thermal-rate equation framework which also implements the dissociation of charmonia in a hadron resonance gas
- The fireball evolution includes the transition from a short QGP phase into the hadron resonance gas, through a mixed phase
- Most of the effect in pA collisions comes from hadronic final-state interactions=> Similar in spirit to the comover suppression effects

A look on uncertainty: EPS09 shadowing model



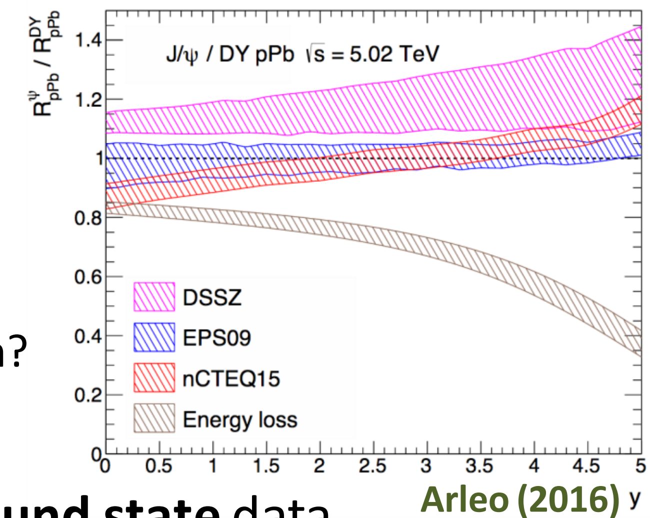
Large uncertainties for gluons, in particular if one takes more flexible low-x parametrization

Summarizing on proton-nucleus collisions:

- Initial-state effects are required to explain pA data from RHIC and LHC => Modification of the gluon flux, either by modified nPDF **or** CGC, needs to be taken into account

  Issues:
  - Huge incertainty of nPDFS
  - Widespread CGC results

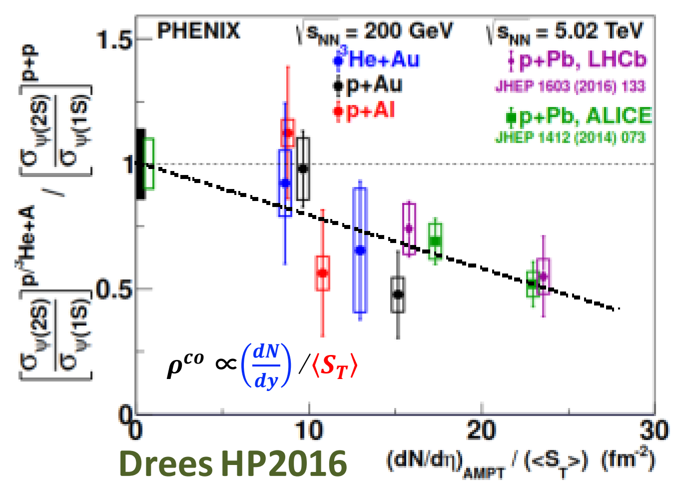
  Possibility to distinguish bewteen them?



Arleo (2016)

- Coherent Eloss mechanism can also reproduce **ground state** data

- Final-state effects as comover interaction, are good candidates to reproduce **excited to ground state** data.
  Comover interaction similar to **transport model**

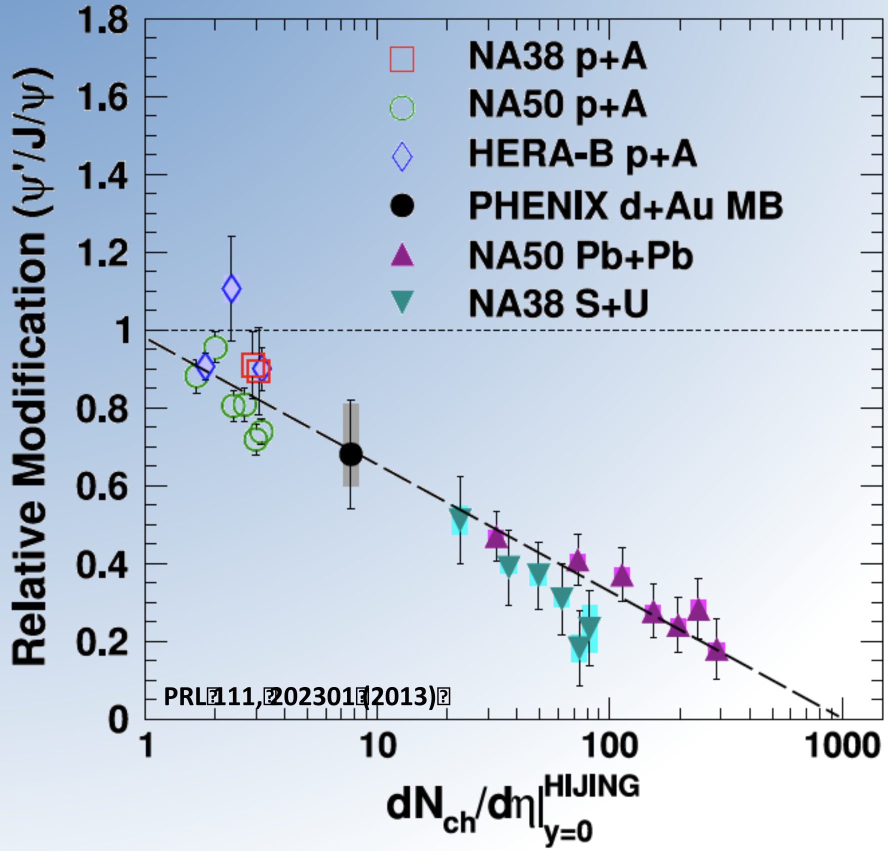


Drees HP2016

PHENIX

Relative Modification of $\psi(2s)/\psi(1s)$ – particle density

Los Alamos NATIONAL LABORATORY EST. 1943



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

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

Matt Durham – Quark Matter 2014   16

M. Durham QM2014