Global description of bottomonium suppression in proton-nucleus and nucleus-nucleus collisions at LHC energies

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arXiv:1804.04474

Motivation: the cold nuclear matter effects

Quarkonium production in nucleus-nucleus:

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

Motivation: the intriguing suppression of excited states in pA

- PHENIX found out a relative ψ(2S)/J/ψ suppression in dAu collisions @ 200 GeV
- ALICE also found a relative ψ(2S)/J/ψ suppression in pPb collisions @ 2.76 TeV
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- **At low E:** the relative suppression can be explained by nuclear abs. $\sigma_{\text{breakup}} \propto r^2_{\text{meson}}$
- **At high E:** too long formation times

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

$\gamma_{\text{LHC}}=2660$ (at y=0) => $t_f > 1000$ fm/c @ LHC

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Time for a quarkonium to form and be distinguishable from its excited states: $t_f >> R$

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A natural explanation would be a final-state effect acting over sufficiently long time => **interaction with a comoving medium**

Comover-interaction model CIM

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

- Stronger suppression where the comover densities (multiplicities) are larger

- Rate equation governing the quarkonium density:

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

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

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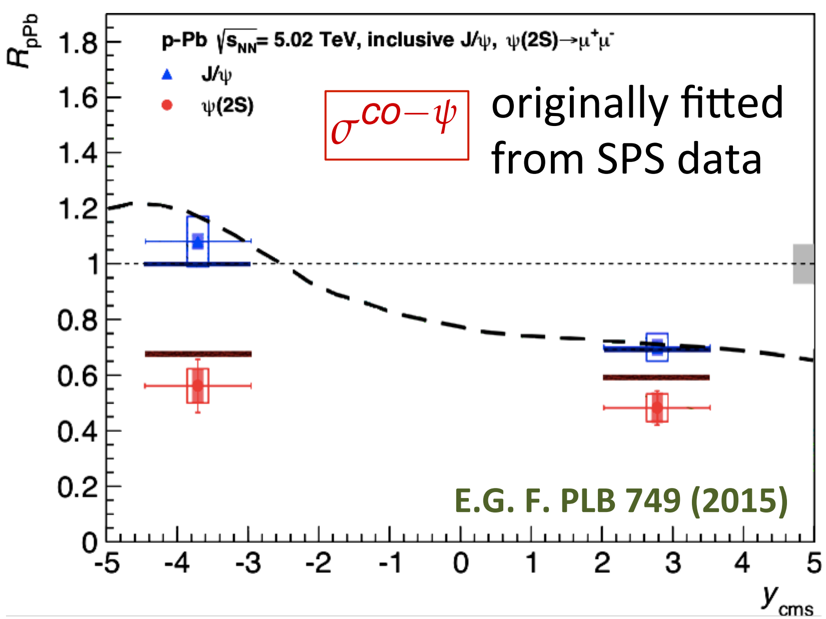

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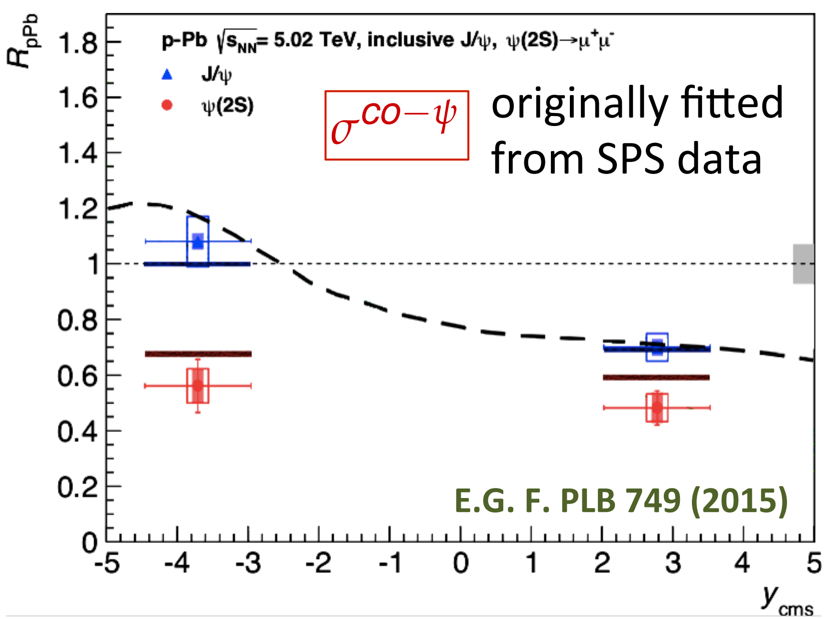

Our aim:

- to investigate if the relative suppression for Υ states can be explained by CIM
- to apply CIM to pPb and PbPb
- to investigate the nature of the comovers

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 breakup

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	$0.21 \pm 0.07\,(\text{stat.}) \pm 0.02\,(\text{syst.})$	$0.06 \pm 0.06\,(\text{stat.}) \pm 0.06\,(\text{syst.})$

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*p*Pb	0.83 ± 0.05 (stat.) ± 0.05 (syst.)	0.71 ± 0.08 (stat.) ± 0.09 (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 the Υ family and its feed down structure

- 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)
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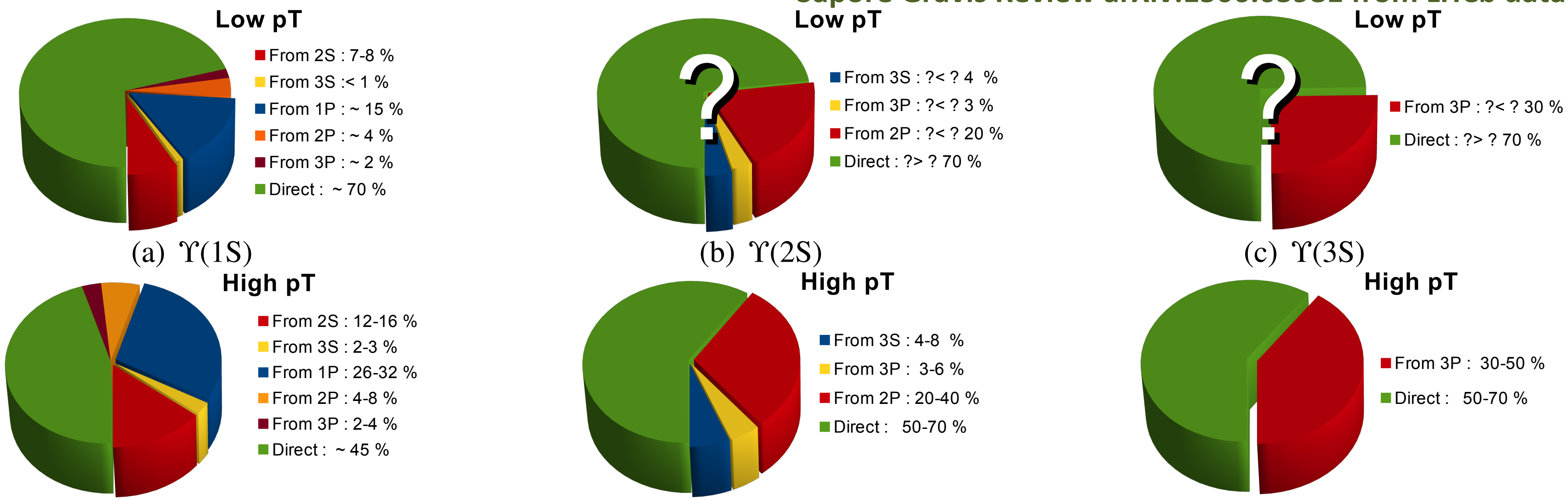
Feed-down structure at low p_T is quite different than CDF measurement at p_T>8GeV

Sapore Gravis Review arXiv:1506.03981 from LHCb data



- **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**

Setting the scene for the bottomonium family

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- We take:

$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{\text{geom}}\left(1 - \frac{E_{\text{Binding}}}{E_{co}}\right)^n$$

E. G. F., J.P. Lansberg, arXiv:1804.04474

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

$E_{\text{Binding}} \equiv 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$, *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 $1/(e^{E^{co}/T_{eff}} - 1)$

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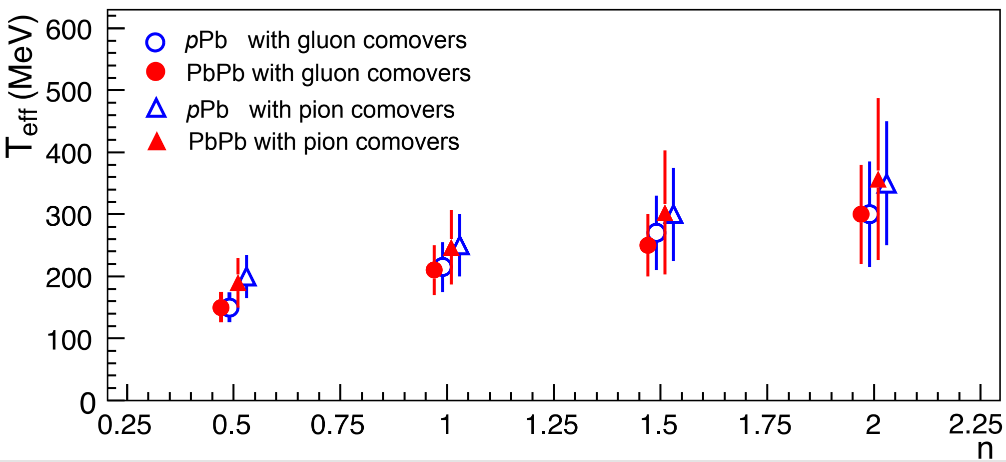
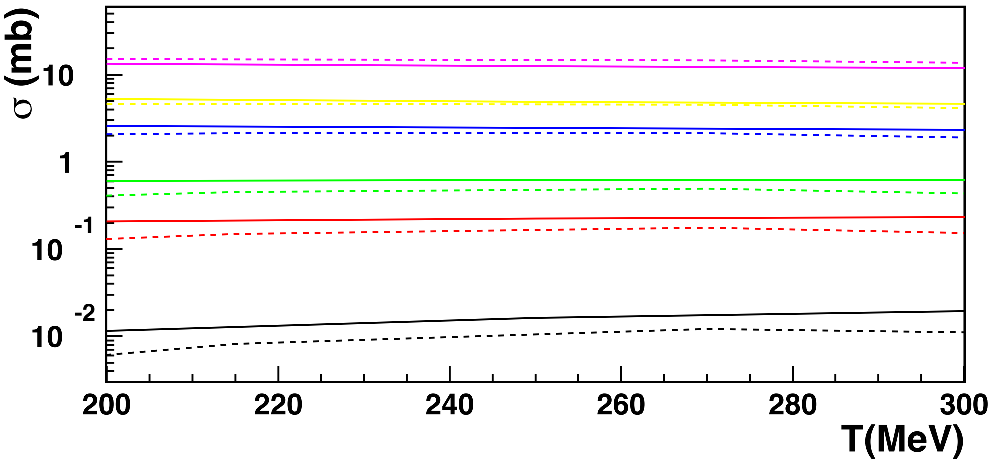


Using pPb CMS and ATLAS data at 5.02 TeV we fit T_{eff} and n. Also with PbPb CMS data

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 range with running *n*



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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

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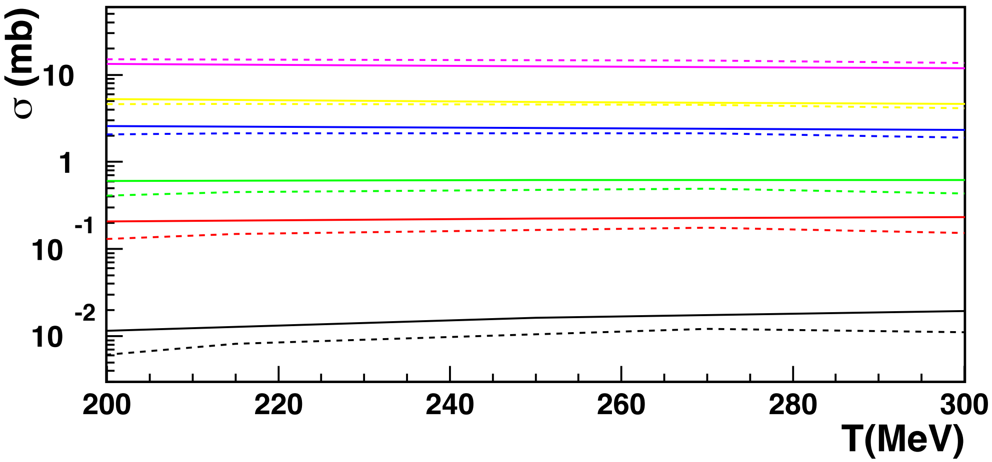

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low P_T	direct	from χ_b	from Υ'	from χ'_b	from Υ''	from χ''_b
Υ	~ 70%	~ 15%	≃ 8%	~ 5%	≃ 1%	~ 1%
Υ'	~ 63%	–	–	~ 30%	≃ 4%	~ 3%
Υ''	~ 60%	–	–	–	–	~ 40%

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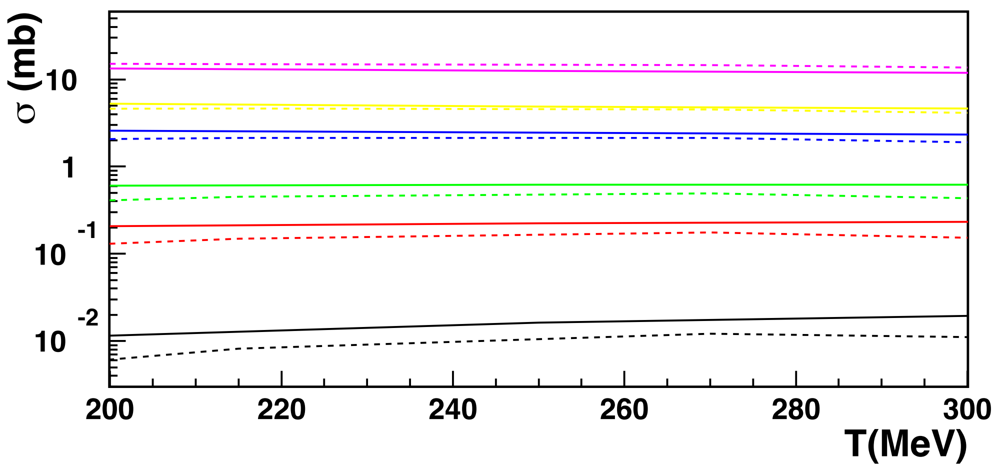

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- Varying the feed-down fractions for 2 limiting cases does not change the results 80% of direct 1S and 50% of direct 3S or 60% of direct 1S and 70% of direct 3S

Double ratio Υ(nS)/Υ(1S) in pPb & PbPb @ 2.76 & 5.02 TeV

For n=1 and T=250 ± 50 MeV:

	$E_{Binding}$	$r_{Q_{b\bar{b}}}$	$\sigma^{co-Q_{b\bar{b}}}$
$\Upsilon(1S)$	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
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χ_{B3}	50 MeV	0.45 fm	$12.55^{+1.53}_{-1.88}$ mb

Υ pPb at 5.02 TeV

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$\Upsilon(2S)/\Upsilon(1S)$	0.91 ± 0.03	0.83 ± 0.05 (stat.) ± 0.05 (syst.)
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	$-2.0 < y < 1.5$	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.)

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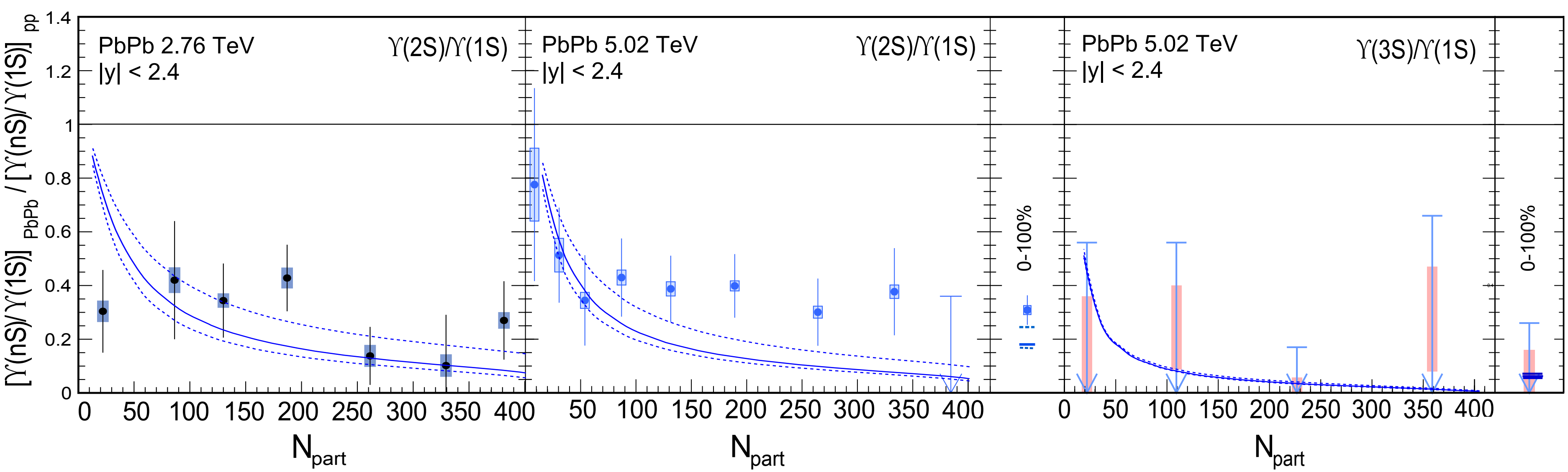


ϒ(nS)/ϒ(1S) well reproduced in PbPb collisions without any other phenomena needed

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

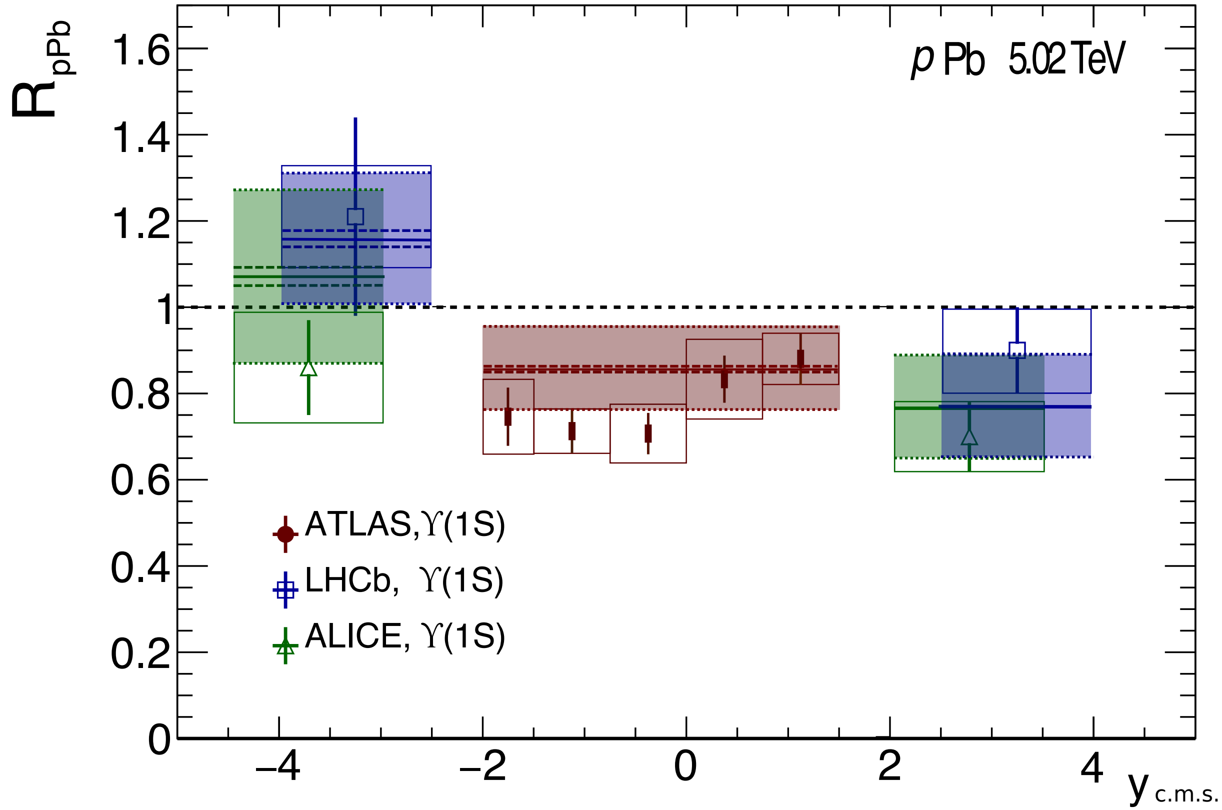
- Now that the $\sigma^{co-\mathcal{Q}_{b\bar{b}}}$ are fixed, we need to check the consistency with the absolute suppression of Υ(1S)

- 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



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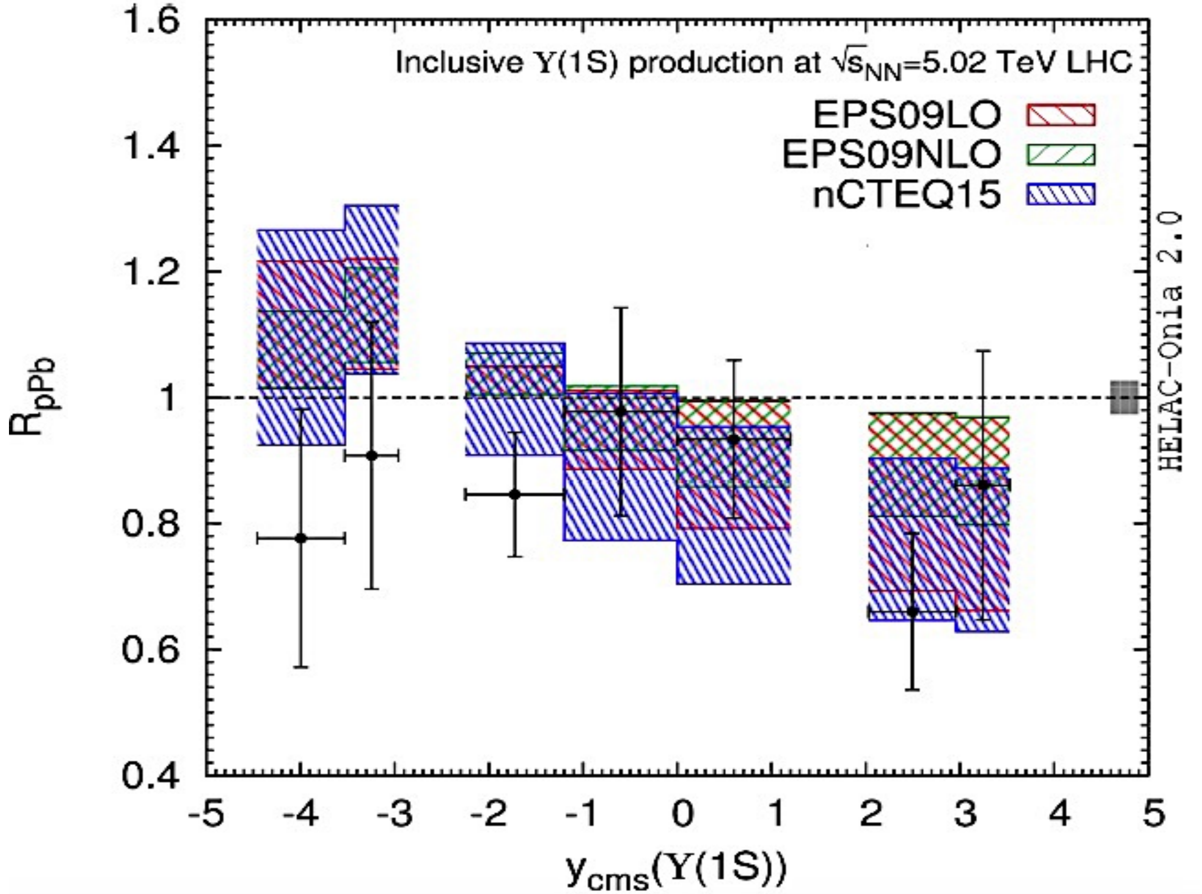
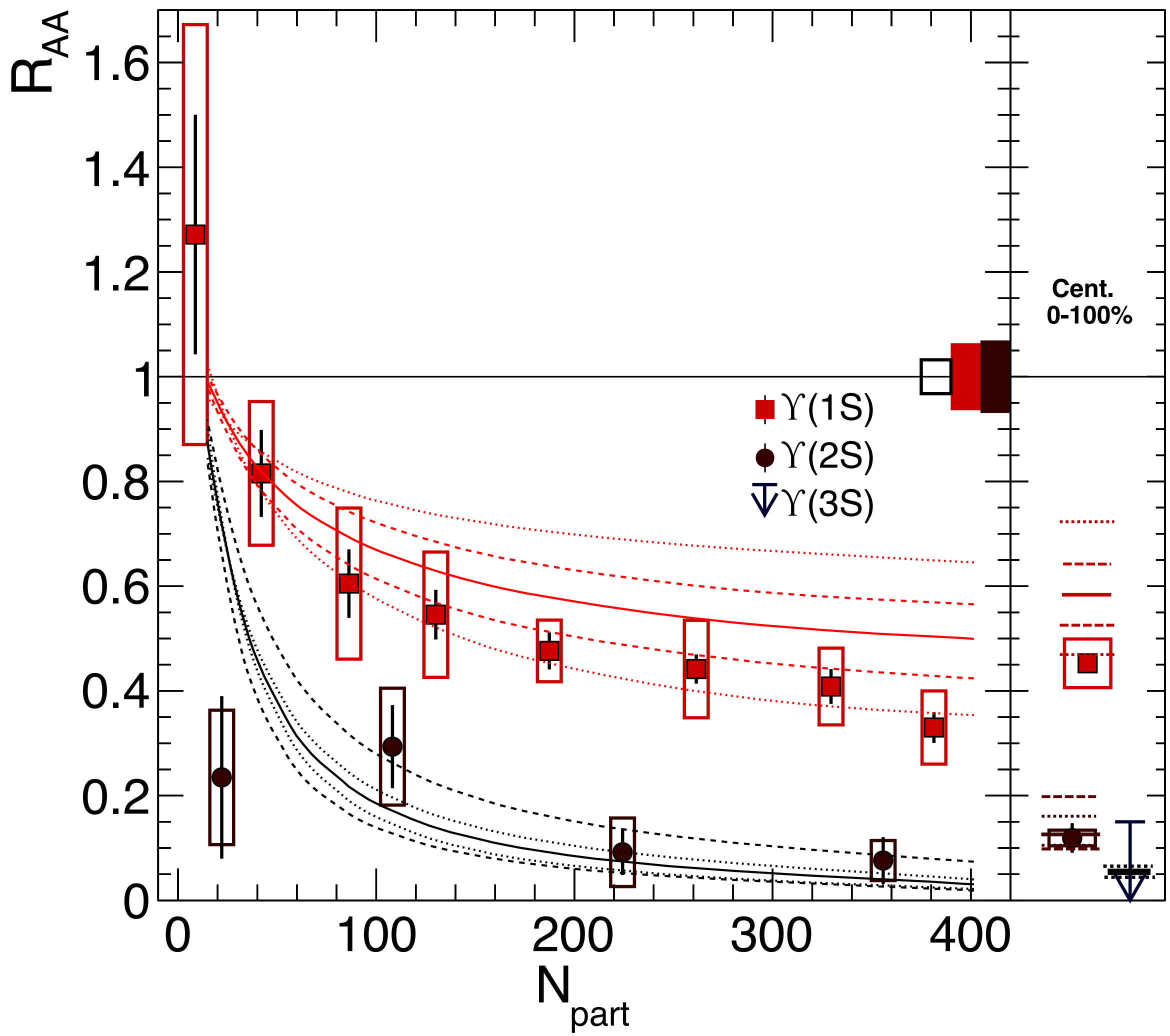


Consistency check: R_{PbPb} for $\Upsilon(1S)$ and $\Upsilon(2S)$ @ 2.76 TeV

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



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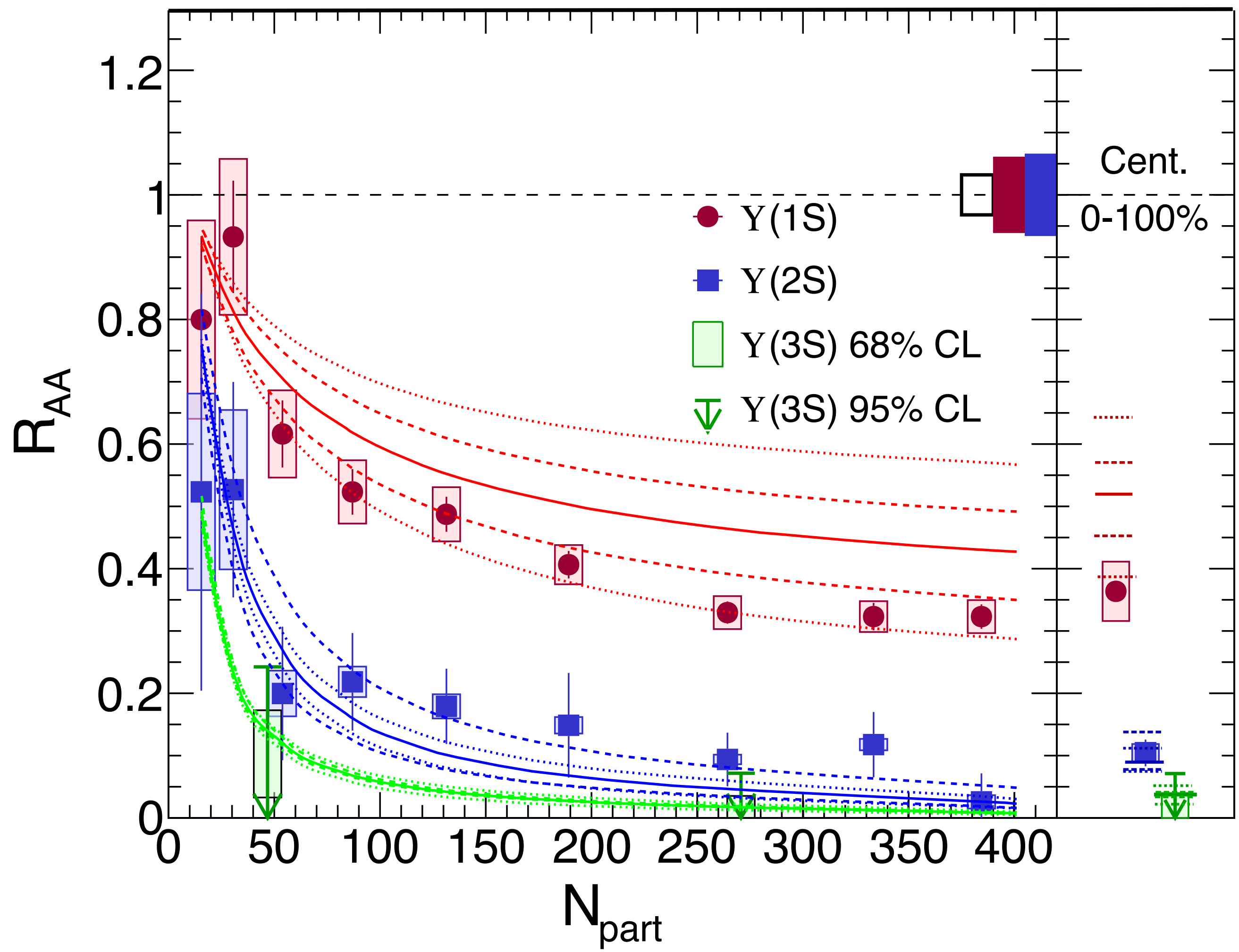

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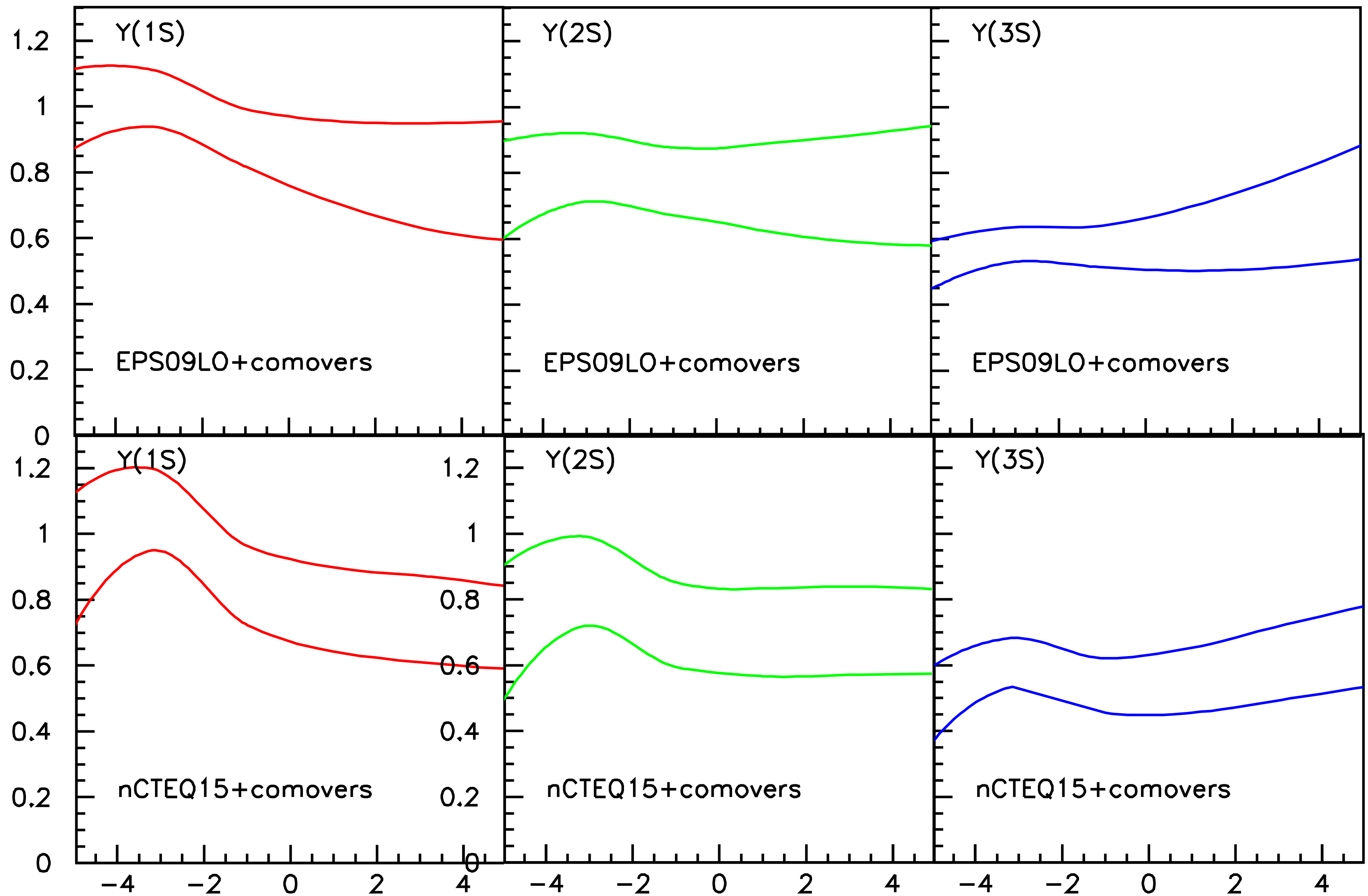
Predictions: R_{pPb} for Υ(1S), Υ(2S) and Υ(3S) @ 8.16 TeV



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 and ATLAS pPb double ratios in a coherent way
- A fit to the CMS PbPb double ratios at 2.76 and 5.02 TeV gives similar results
- 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)
- 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 in PbPb collisions without the need to invoke any other phenomena

Physical interpretation: what the nature of the comovers is

- Case I: The medium is hadronic in pPb collisions, while it is gluonic in PbPb
  - The most common expectation: The relevant d.o.f. are hadrons in pPb collisions where the QGP is not produced whereas the gluons become relevant in the hotter PbPb environment with the presence of QGP

- Case II: Both in pPb and PbPb collisions, the medium is made of hadrons, i.e. the comovers can be identified with pions
  - Both in pA and AA collisions, Υ not affected by the hot (deconfined) medium
  - Possible interpretation: melting temperature of the Υ(1S) and Υ(2S) is too high to be observed and the Υ(3S) is fragile enough to be entirely broken by hadrons. Bottomonia unaffected by the presence of a possible QGP

- Case III: Both in pPb and PbPb collisions, the medium is made of partons, i.e. the comovers can be identified with gluons
  - Comovers are to be considered as partons in a (deconfined) medium
  - A QGP-like medium is formed following pPb collisions at LHC energies
  - CIM: effective modelling of bottomonium dissociation in the QGP

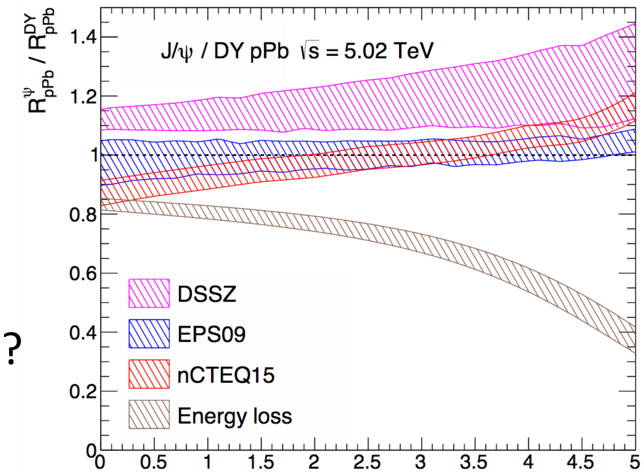
Summarizing on proton-nucleus collisions:

- 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

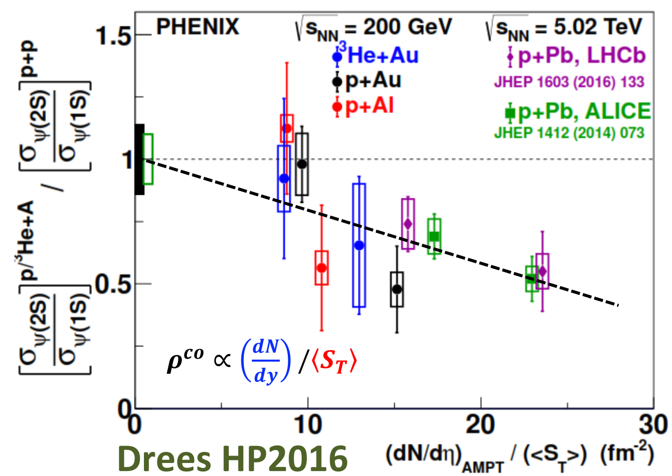
Possibility to distinguish bewteen them?



Arleo (2016)

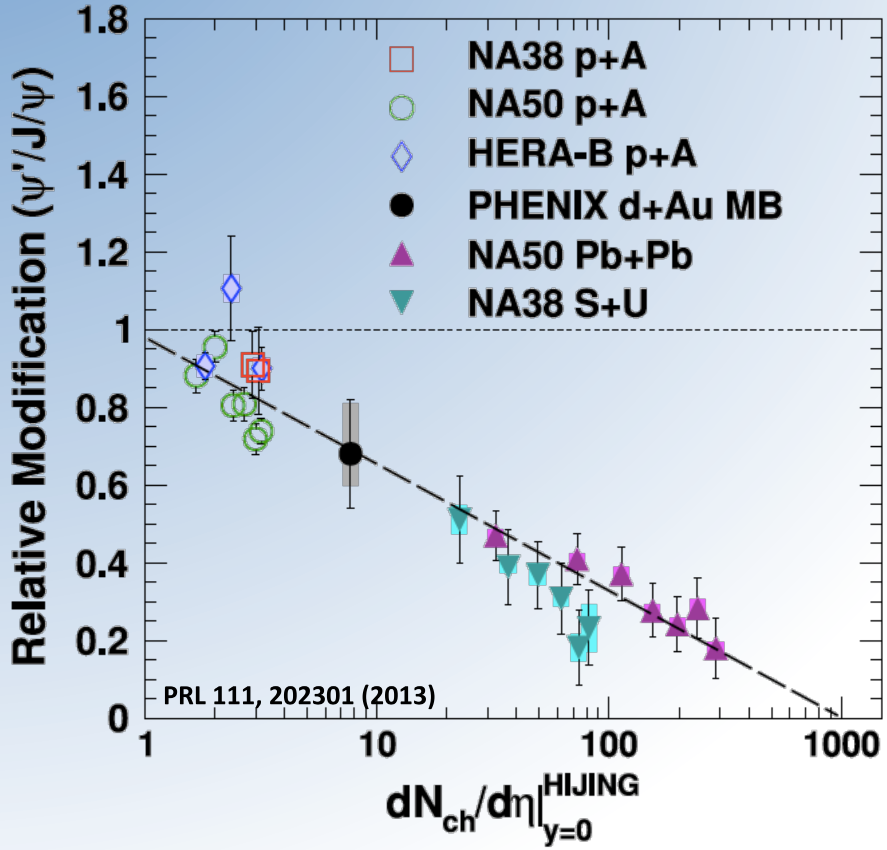
- Coherent Eloss mechanism can also reproduce **ground state** data

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



Drees HP2016

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