Quarkonium results: introduction for non-believers and lessons from LHC run-1

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INCONTRO SULLA FISICA CON IONI PESANTI A LHC

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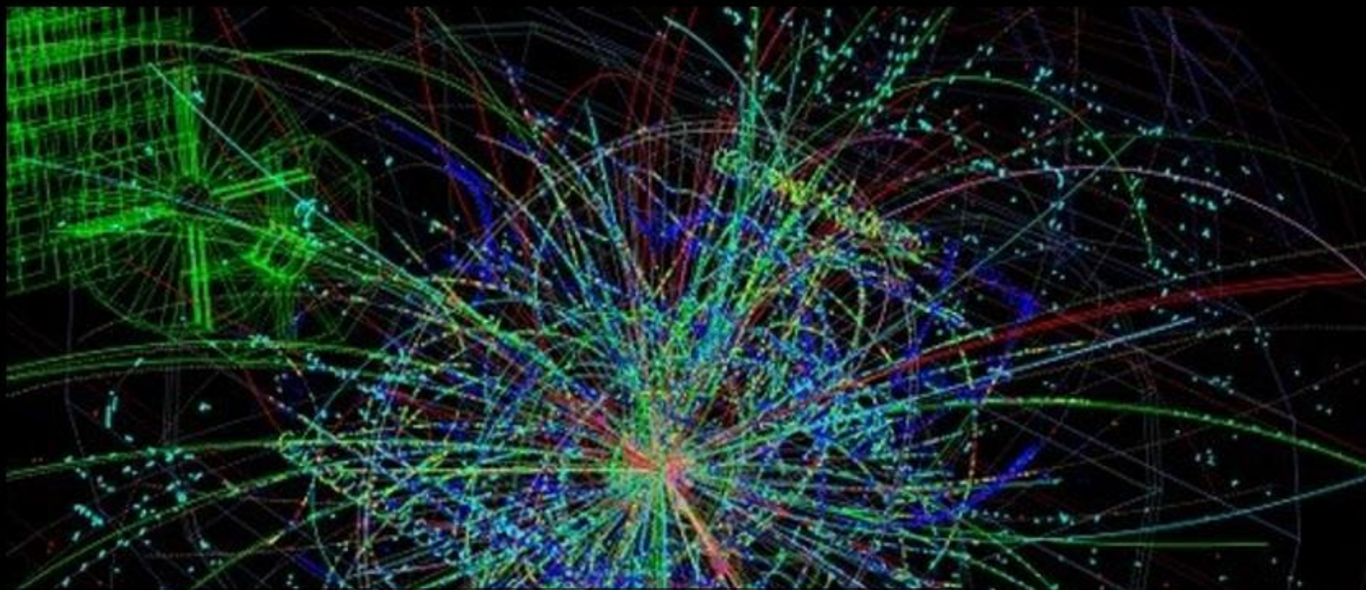
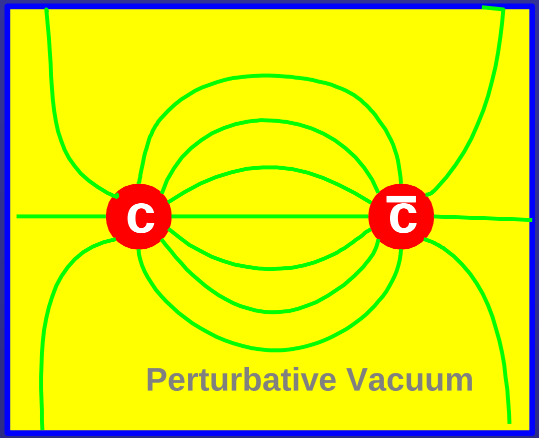
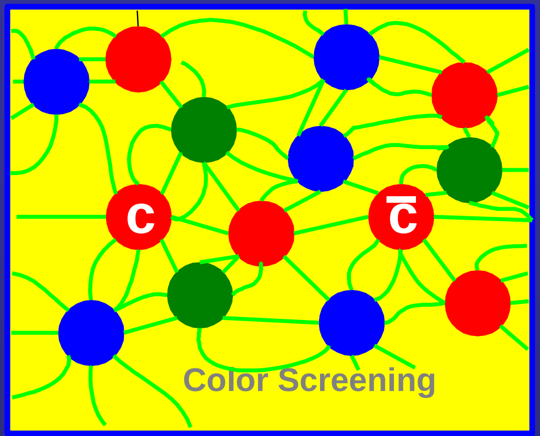


- Short introduction (color screening, regeneration…)
- Flashing results from LHC run-1
- Open points and prospects for run-2

Quarkonia: from color screening…

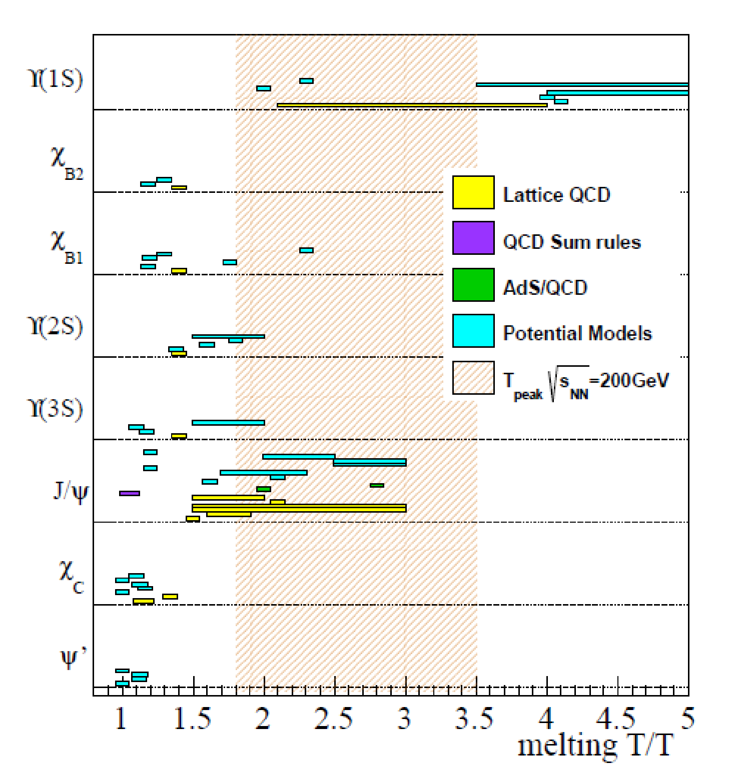
Screening of strong interactions in a QGP





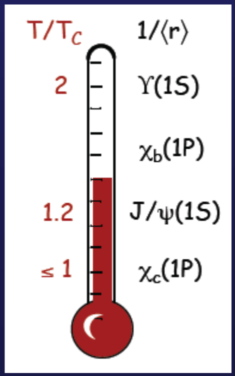
T. Matsui and H. Satz, PLB178 (1986) 416

- Screening stronger at high T
- λ_D → maximum size of a bound state, decreases when T increases
- Different states, different sizes



Resonance melting

QGP thermometer

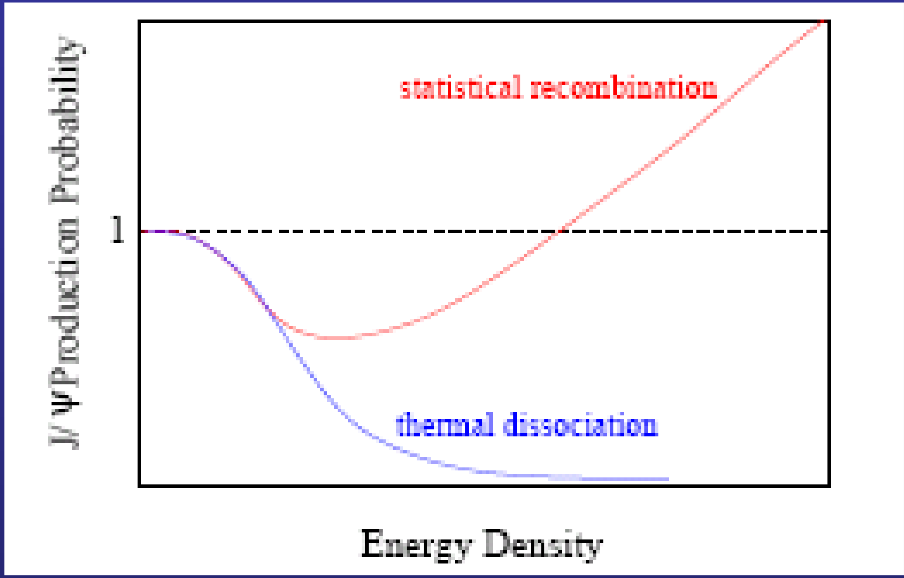


A. Adare et al. (PHENIX), arXiv:1404.2246

...to regeneration (for charmonium!)

At sufficiently high energy, the cc pair multiplicity becomes large

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60



P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196

Statistical approach:

- Charmonium fully melted in QGP
- Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

Kinetic recombination:

- Continuous dissociation/regeneration over QGP lifetime

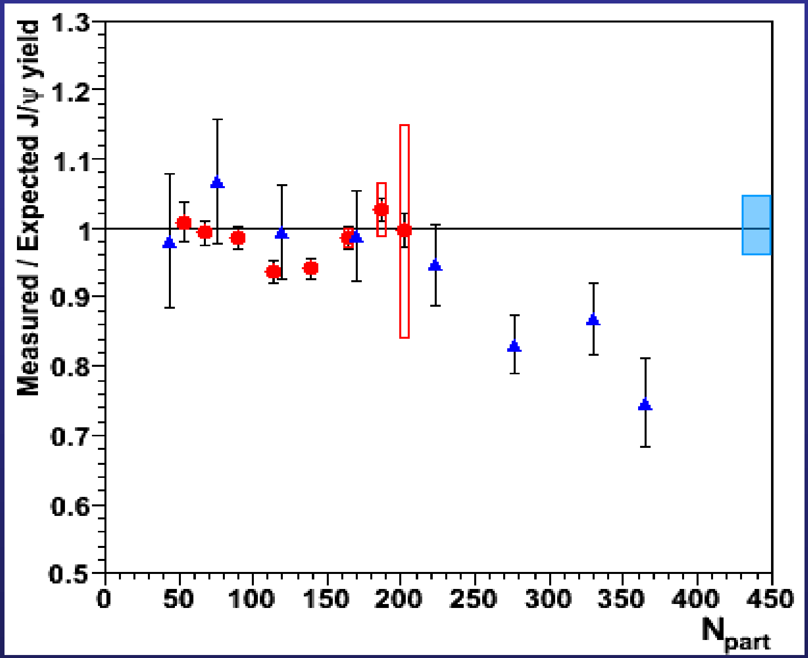
Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

if supported by data, charmonium looses status as "thermometer" of QGP
...and gains status as a powerful observable for the phase boundary

Low energy results: J/ψ from SPS & RHIC

SPS (NA38, NA50, NA60)
$\sqrt{s_{NN}}$ = 17 GeV

R.Arnaldi et al.(NA60) NPA830 (2009) 345c

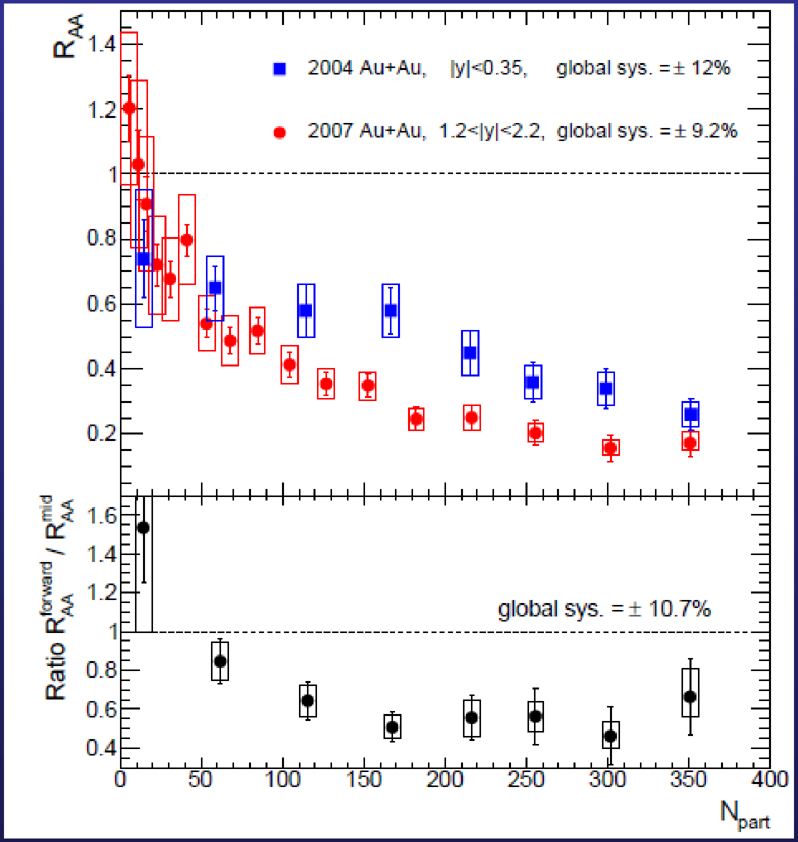


First evidence of anomalous suppression (i.e. beyond CNM expectations) in Pb-Pb collisions

~30% suppression compatible with ψ(2S) and χ_c decays

RHIC (PHENIX, STAR)
$\sqrt{s_{NN}}$ = 39, 62.4, 200 GeV

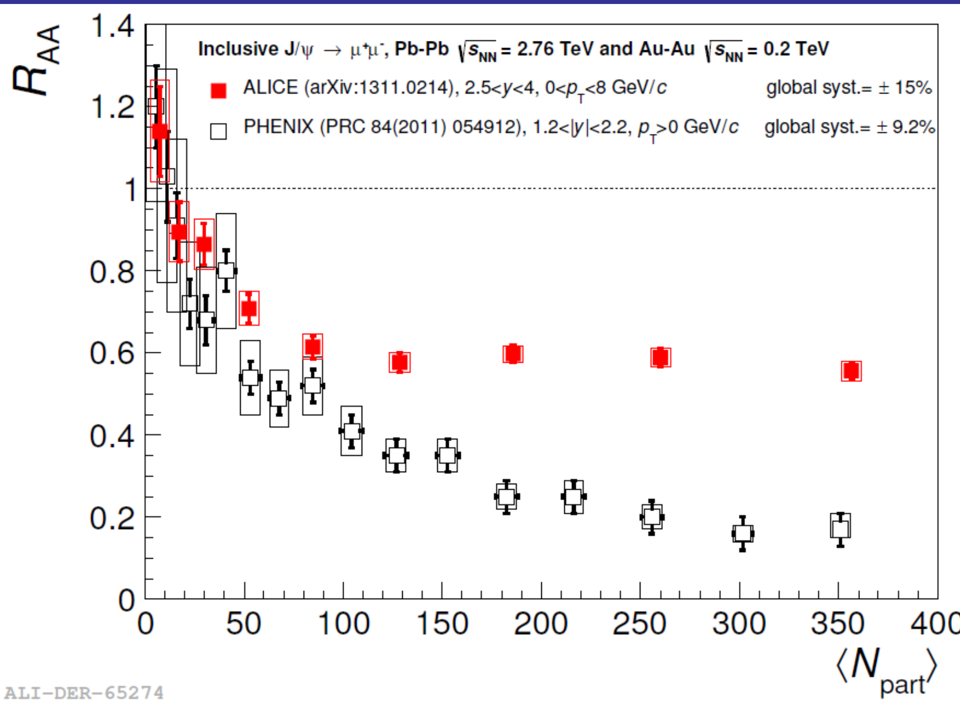
A. Adare et al. (PHENIX) PRC84(2011) 054912

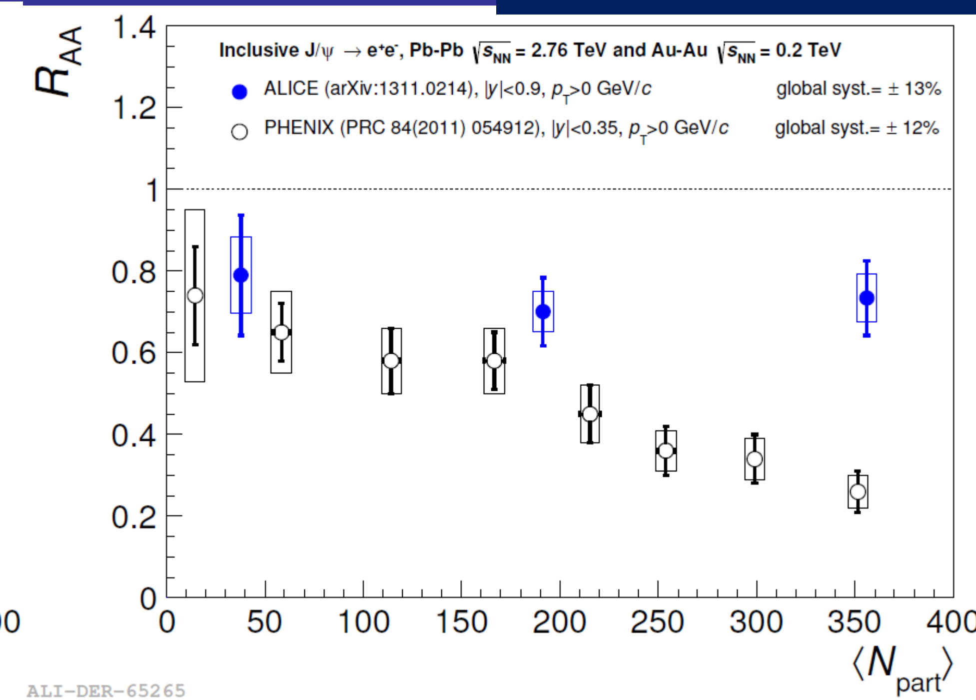


suppression, with strong rapidity dependence, in Au-Au at $\sqrt{s}$= 200 GeV

Low p_T J/ψ: ALICE

B. Abelev et al., ALICE arXiv:1311.0214.



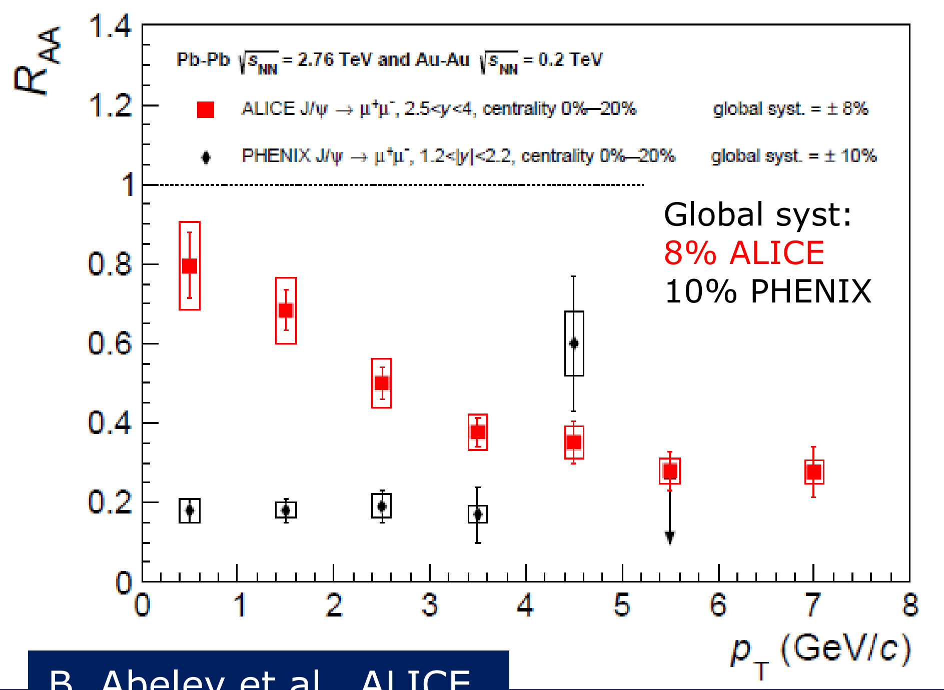


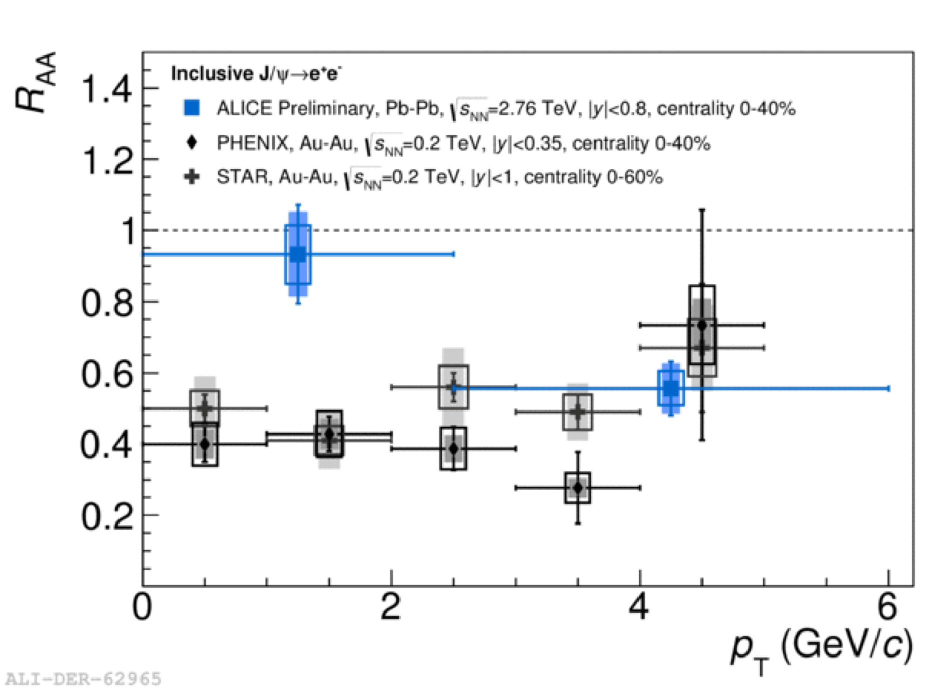
- Compare J/ψ suppression, RHIC ($\sqrt{s_{NN}}$=0.2 TeV) vs LHC ($\sqrt{s_{NN}}$=2.76 TeV)
- Results dominated by low-p_T J/ψ
  - Stronger centrality dependence at lower energy
  - Systematically larger R_{AA} values for central events in ALICE

Possible interpretation:
- RHIC energy → suppression effects dominate
- LHC energy → suppression + regeneration

How can this picture be validated?

R_{AA} vs p_T

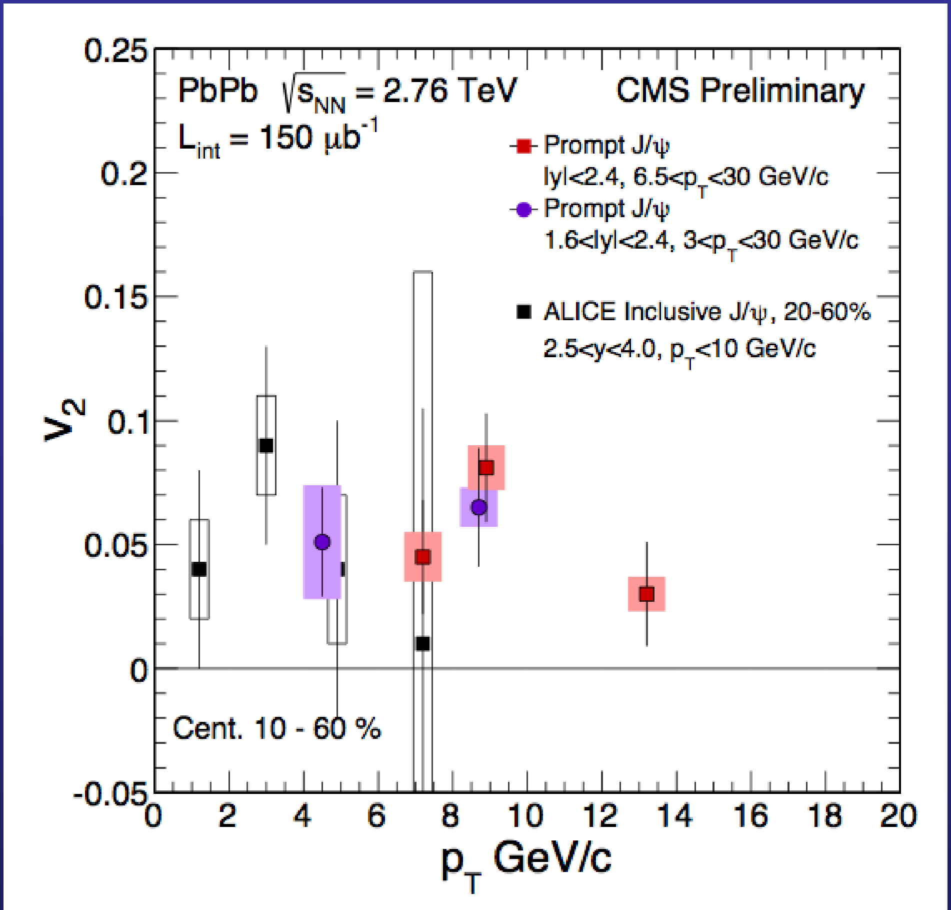




B. Abelev et al., ALICE arXiv:1311.0214.

- Charm-quark transverse momentum spectrum peaked at low-p_T
- Recombination processes expect to mainly enhance low-p_T J/ψ
  → Expect smaller suppression for low-p_T J/ψ → observed!
- Opposite trend with respect to lower energy experiments
- Fair agreement with transport and statistical models (not shown)

Non-zero v_2 for J/ψ at the LHC

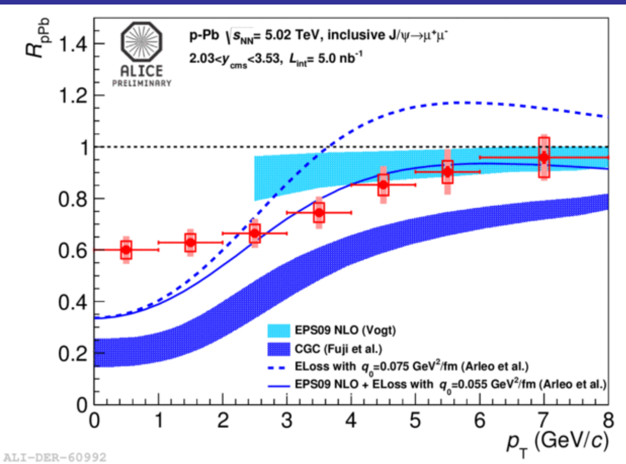


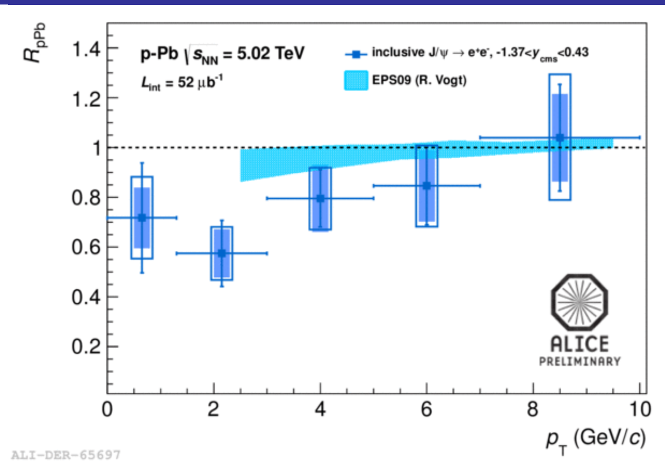
E.Abbas et al. (ALICE), PRL111(2013) 162301

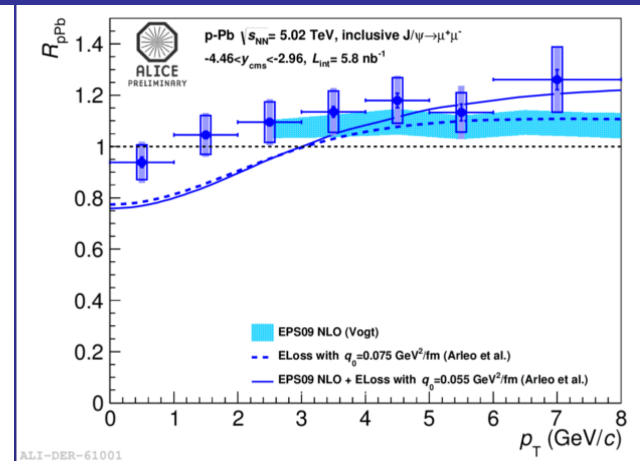
- The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy

- A significant v_2 signal is observed by BOTH ALICE and CMS
- The signal remains visible even in the region where the contribution of (re)generation should be negligible
- Due to path length dependence of energy loss ?
- In contrast to these observations STAR measures v_2=0

CNM effects are not negligible!

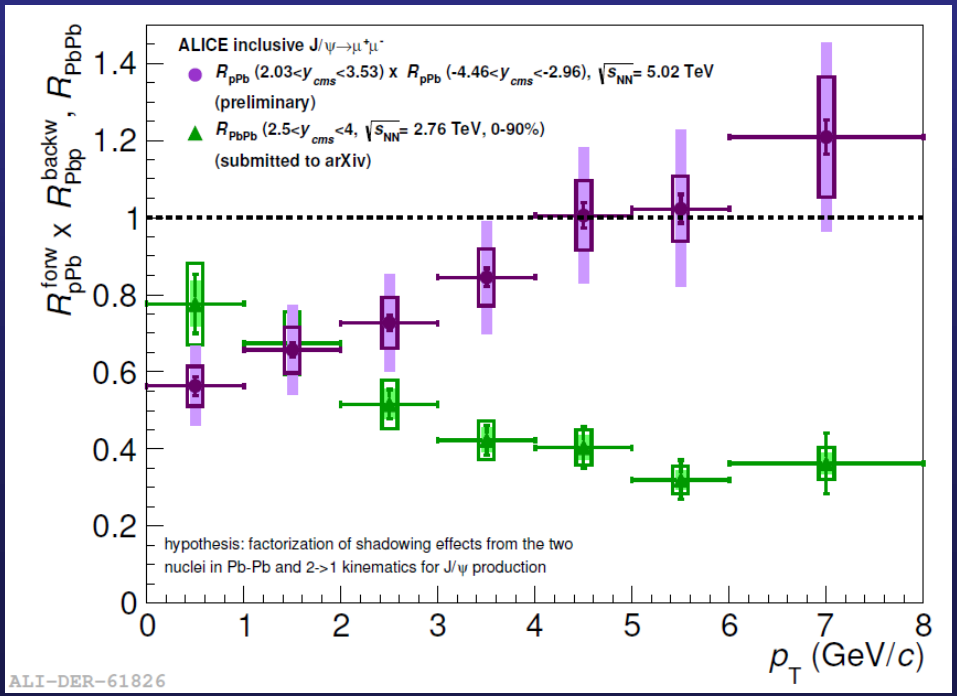




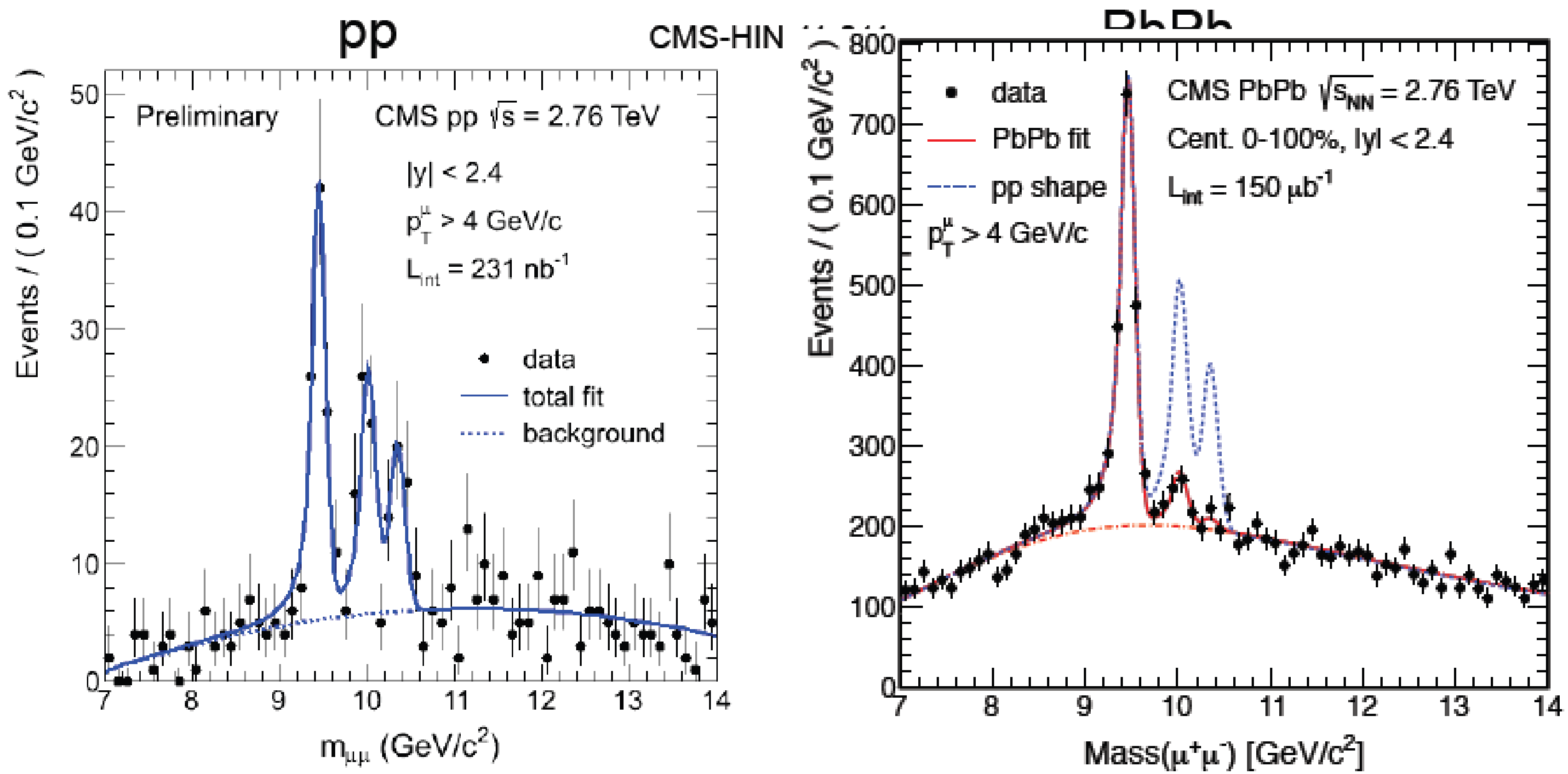


- ❑ Suppression at backward + central rapidity
- ❑ No suppression (enhancement?) at forward rapidity
- ❑ Fair agreement with models (shadowing + energy loss)

- ❑ (Rough) extrapolation of CNM effects to Pb-Pb → evidence for hot matter effects!



Υ suppression: CMS results



$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$

$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$

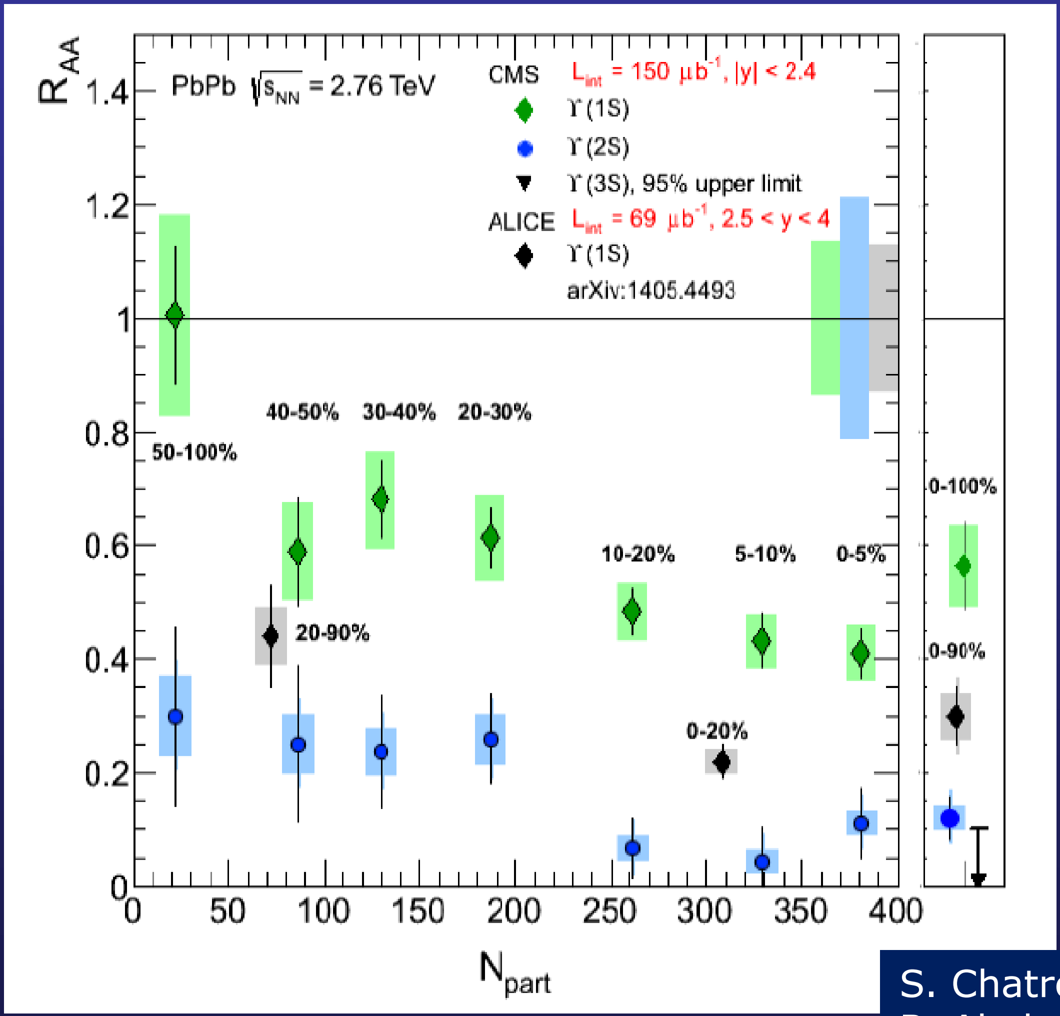
$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$

$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$

S. Chatrchyan et al.(CMS), PRL 109 (2012) 222301

- More weakly bound states (Υ(2S), Υ(3S)) show strong suppression in Pb-Pb, compared to Υ(1S)
- Expected signature for QGP-related suppression
- Regeneration effects expected to be negligible for bottomonia

First accurate determination of ϒ suppression



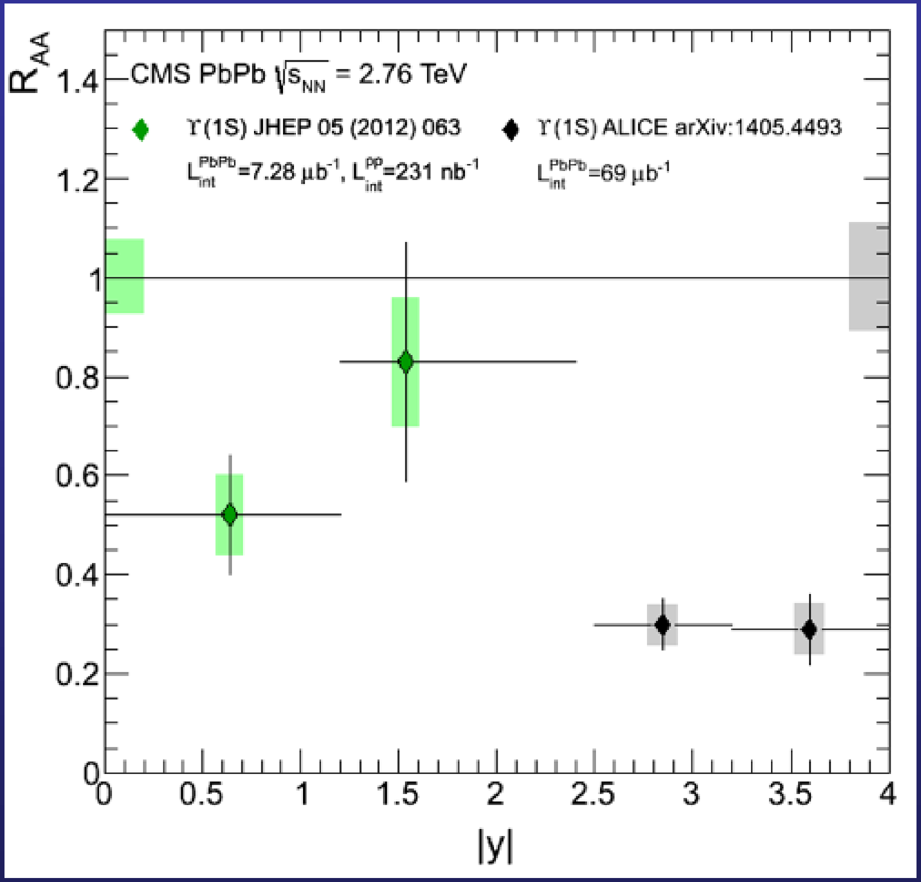
- Suppression increases with centrality
- First determination of ϒ(2S) R_{AA}: already suppressed in peripheral collisions
- ϒ(1S) (see also ALICE) compatible with suppression of bottomonium states decaying to ϒ(1S)

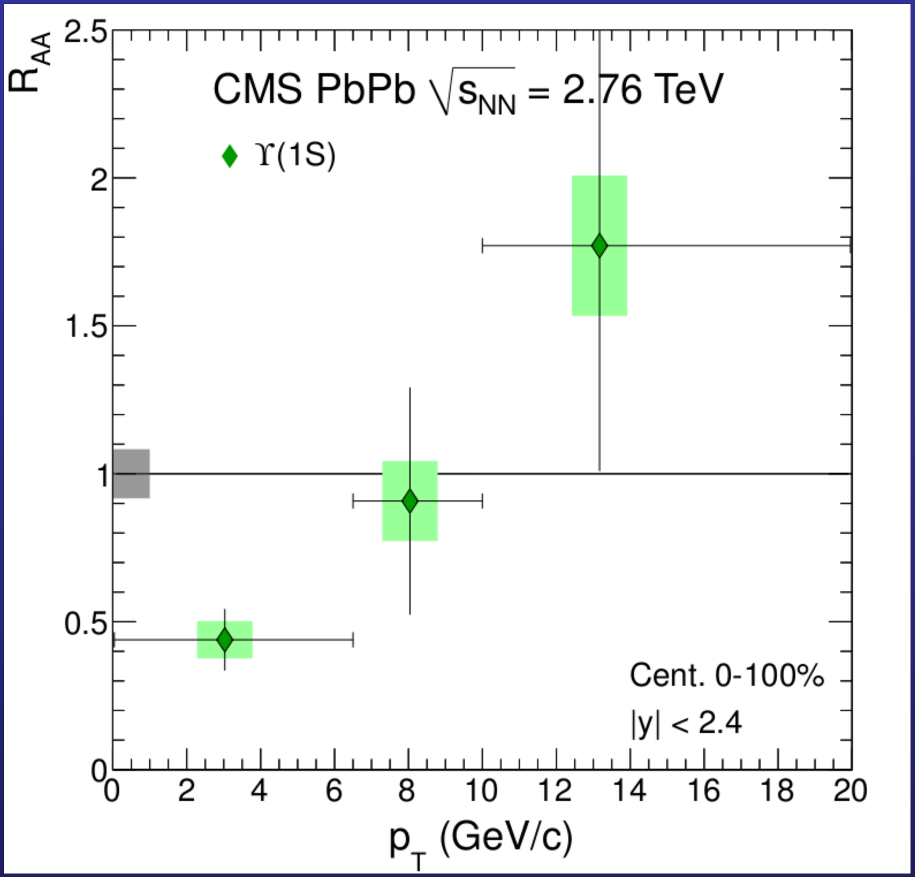
→ Probably yes, also taking into account the normalization uncertainty

S. Chatrchyan et al.(CMS), PRL 109 (2012) 222301
B. Abelev et al. (ALICE), arXiv:1405.4493

Is ϒ(1S) dissoc. threshold still beyond LHC reach ? → Run-II

Υ(1S) vs y and p_T from CMS+ALICE





- Start to investigate the kinematic dependence of the suppression
- Suppression concentrated at low p_T (opposite than for J/ψ, no recombination here!)
- Suppression extends to large rapidity (puzzling y-dependence?)

From run-1 ro run-2

- Charmonium highlight → evidence for a new mechanism which enhances the J/ψ yield, in particular at low p_T, with respect to low-energy experiments

- In addition
  - Indications for J/ψ azimuthal anisotropy (non-zero v_2)
  - Significant final state effects on ψ(2S) in p-Pb (not discussed here!), likely related to the (hadronic) medium created in the collision

- Bottomonium highlight → evidence for a stronger suppression of 2S and 3S states compared to 1S. Effect not related to CNM (not discussed here!) and compatible with sequential suppression of "bottomonium" states

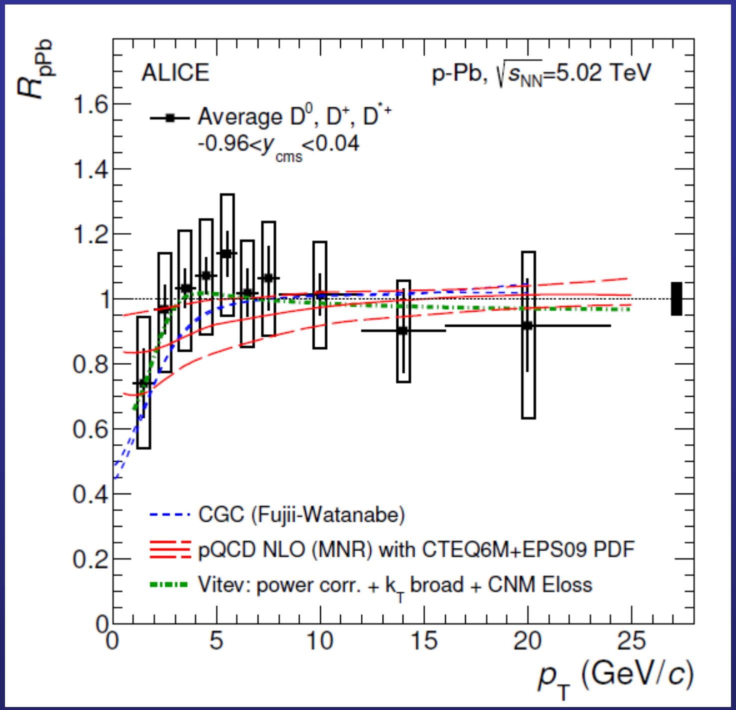
- In addition
  - 1S is also suppressed (~50%). Feed-down effect only?
  - y-dependence of 1S suppression to be understood

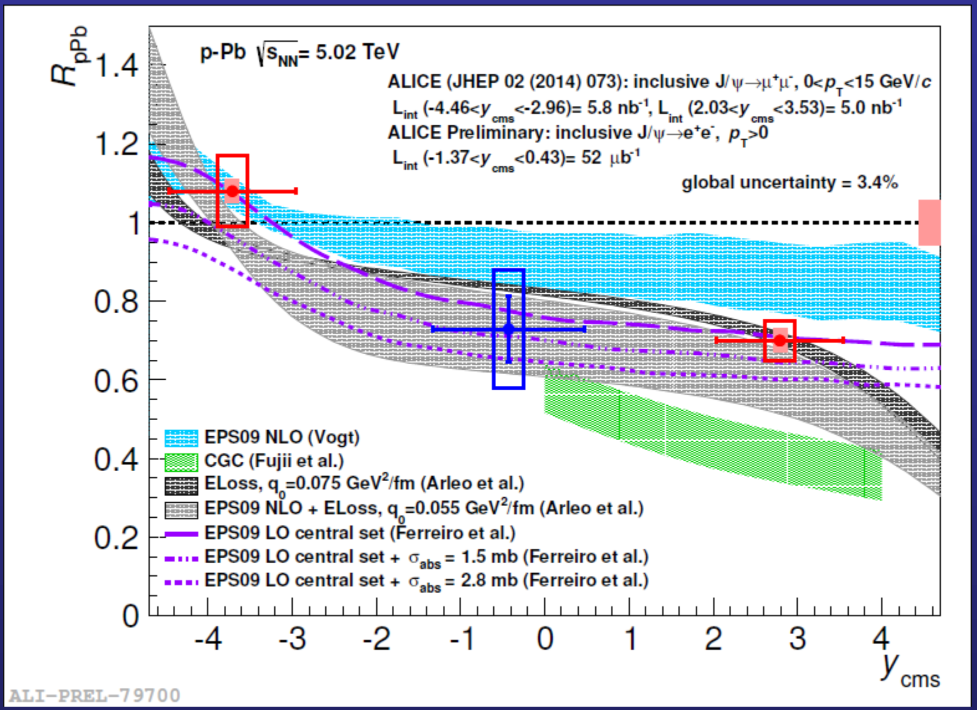
From run-1 to run-2

- Prospects for run-2
  - → Collect a ~1 order of magnitude larger integrated luminosity
- High-statistics J/ψ sample
  - → Comparison with run-1 AND with theoretical predictions crucial to confirm/quantify our understanding in terms of regeneration
  - → more precise v_2 results also needed
- Significant $\psi(2S)$ sample
  - → Crucial: run-1 results "exploratory" (and interpretation not clear)
- High-statistics $\Upsilon(1S)$ sample
  - → A significant increase in 1S suppression with respect to run-1 might imply that a high-T QGP is formed ("threshold" scenario)
- Differential $\Upsilon(2S)$ and $\Upsilon(3S)$ results from run-1 are limited by statistics
  - → Centrality and p_T-dependent studies important to assess details of sequential suppression

A couple of more specific issues

- Open charm as a normalization for J/ψ suppression/enhancement





$R_{pPb}^{D} = 0.85 \pm 0.05 \pm 0.11$

(weighted average of p_T differential points using FONLL cross section (no FONLL unc.) and $R_{pPb}(0\text{-}1)=R_{pPb}(1\text{-}2)$)
Assuming $R_{pPb}(0\text{-}1) = 0.4$

$R_{pPb}^{D} = 0.82 \pm 0.05 \pm 0.11$

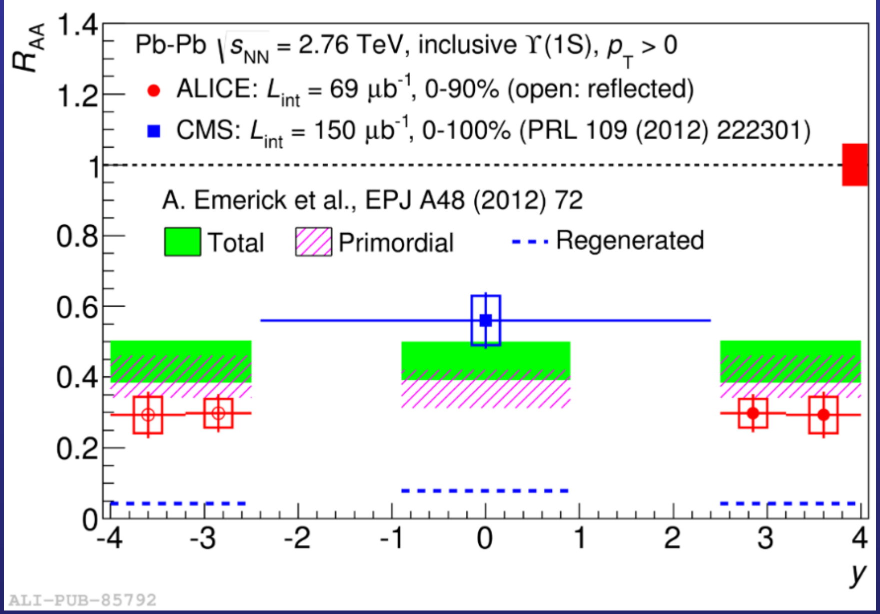
$R_{pPb}^{J/\psi} = 0.73 \pm 0.08 \pm 0.15$

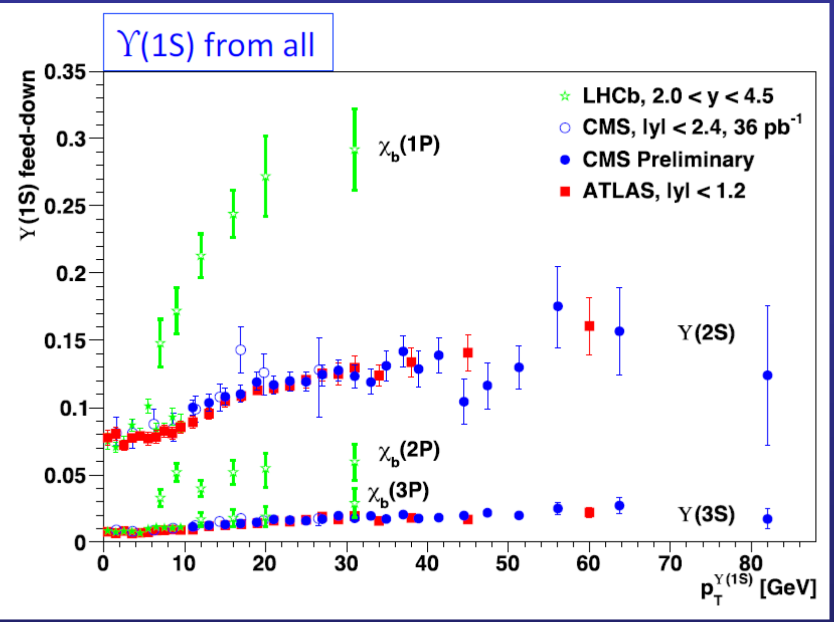
Within uncertainties (and with reasonable extrapolations to p_T=0), CNM effects on integrated J/ψ and D-mesons production have the same size

- Can we go beyond this relevant but somewhat limited statement ?

Bottomonium at the LHC: open issues

- Is the y-distribution of $\Upsilon(1S)$ understood ?





- Data show evidence for larger suppression at forward-y
  → In contrast with sequential suppression interpretation

- New LHC results on feed-down fractions may imply lower values wrt to the older CDF result (50.9 ± 8.2 ± 9.0 % from $\Upsilon(2S)+\Upsilon(3S)+\chi_b(1P)+\chi_b(2P)$)
→ may question the interpretation of observed $\Upsilon(1S)$ suppression coming purely from feed-down

More info

Charmonium vs open charm

- In p-Pb

- Are we so far from exploring the integrated cross section ?
  - Data are now available down to 1 GeV/c for D^0, D^+, D^*
    - → Extrapolation is not so large here
    - → Situation “worse” for single-lepton studies

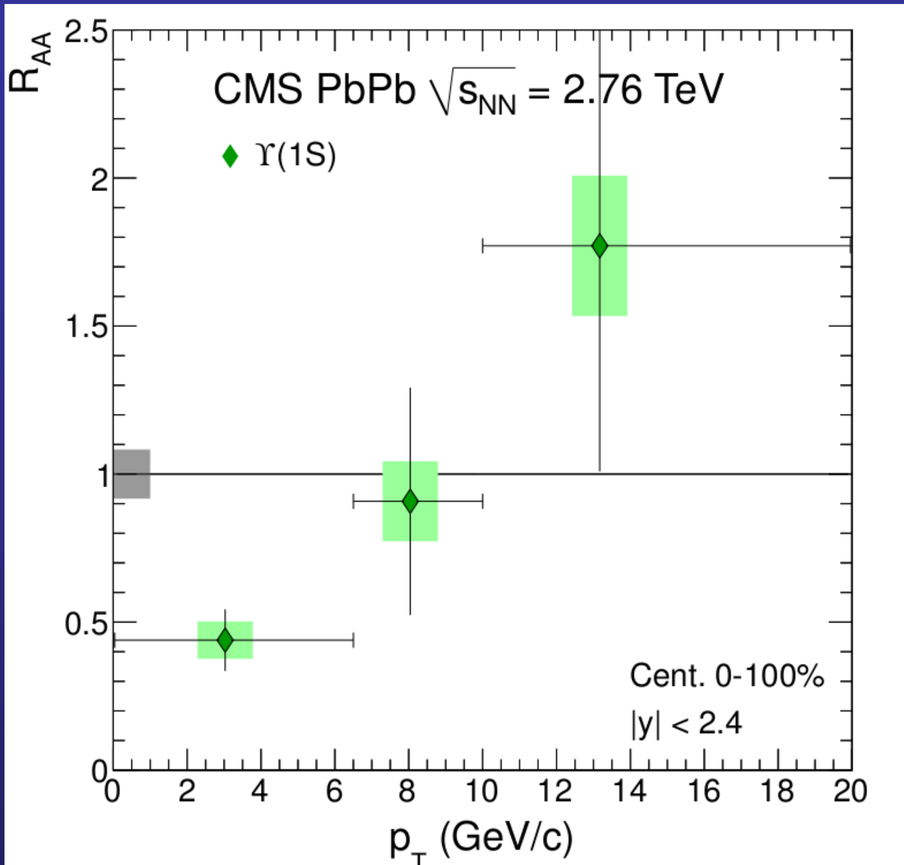
- Uncertainties are not negligible though (~15% now)
  - Is there a reasonable hope for a significant improvement ? Run-2 ?
  - Now dominated by
    - Signal extraction
    - $\sqrt{s}$-rescaling of reference (from 7 to 5.02 TeV, not too large)
    - Contribution from B-decays

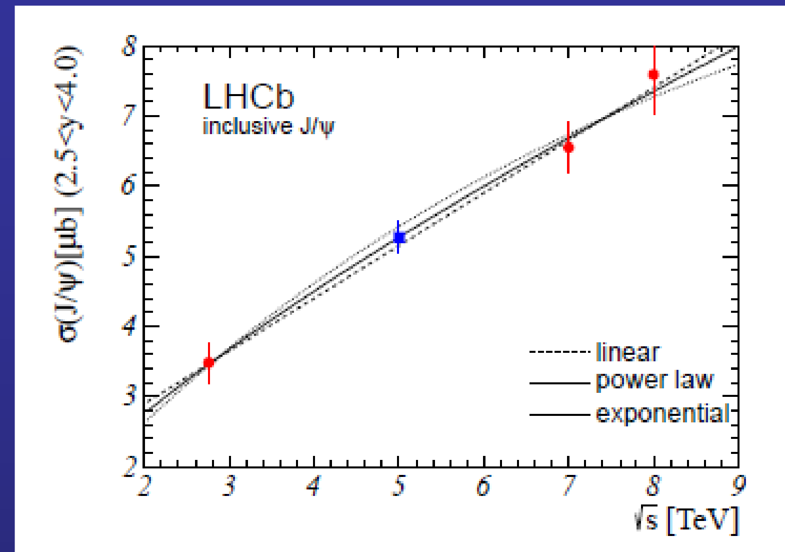
- Qualitative agreement between integrated R_{AA}^{D} and $R_{AA}^{J/\psi}$ is reassuring, but is there (will there be) a recipe for a differential comparison ?

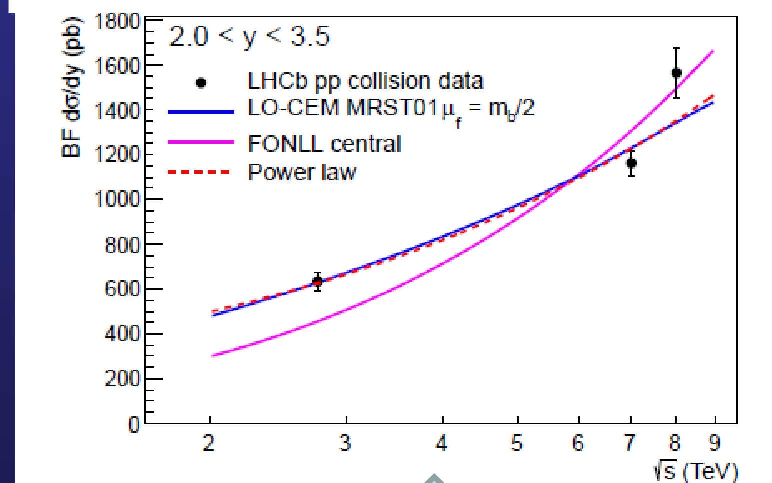
- In Pb-Pb

- Most p-Pb considerations apply, plus
  - The contribution of D_s and Λ_c may have a significant impact ?
  - $\sqrt{s}$-rescaling of reference → more important uncertainty

Other ingredients/caveats to the "puzzle"







- ❑ p_T dependence of R_{AA} from CMS exhibits features different from J/ψ with maximal suppression at low p_T (No equivalent plot from ALICE)

- ❑ Caveat: ALICE takes reference data from LHCb measurements Contrary to J/ψ, these exhibit a √s-dependence which disagrees with FONLL expectations, and even with (usual) empirical shapes

On feed-down fractions

- Usually they are not supposed to vary strongly with √s (or y)
- New LHCb pp results could alter the picture inherited by CDF (relative to p_{Υ}>8 GeV/c)

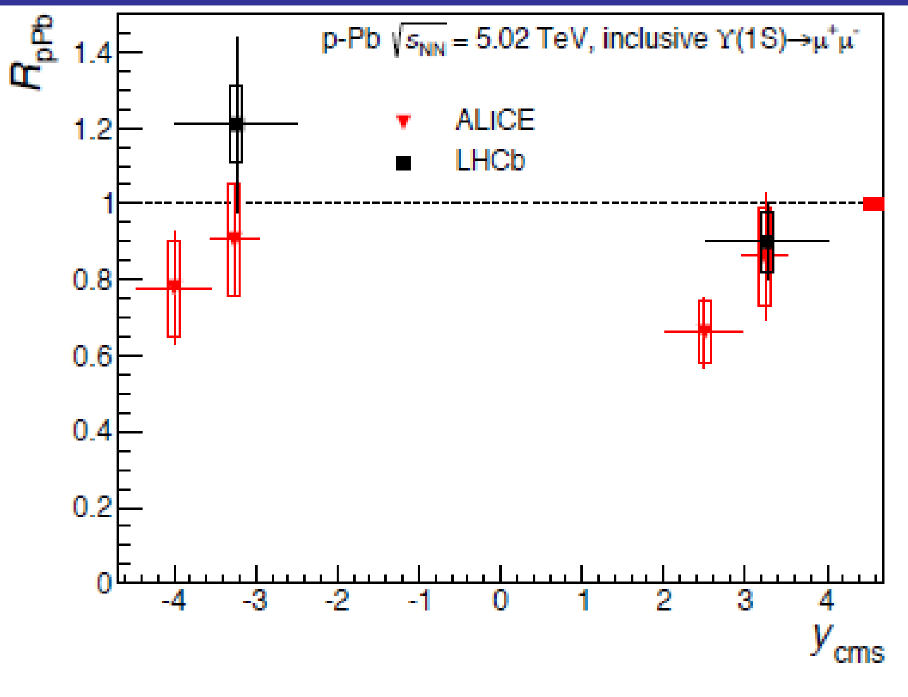
	p_T^{Υ} (GeV/c)	$\mathcal{R}^{\chi_b(1P)}_{\Upsilon(nS)}$	$\mathcal{R}^{\chi_b(2P)}_{\Upsilon(nS)}$
Υ(1S)	6–8	$14.8 \pm 1.2 \pm 1.3$	$3.3 \pm 0.6 \pm 0.2$
	8–10	$17.2 \pm 1.0 \pm 1.4$	$5.2 \pm 0.6 \pm 0.3$
	10–14	$21.3 \pm 0.8 \pm 1.4$	$4.0 \pm 0.5 \pm 0.3$
	14–18	$24.4 \pm 1.3 \pm 1.2$	$5.2 \pm 0.8 \pm 0.4$
	18–22	$27.2 \pm 2.1 \pm 2.1$	$5.5 \pm 1.0 ^{+0.4}_{-1.0}$
	22–40	$29.2 \pm 2.5 \pm 1.7$	$6.0 \pm 1.2 ^{+0.4}_{-0.7}$

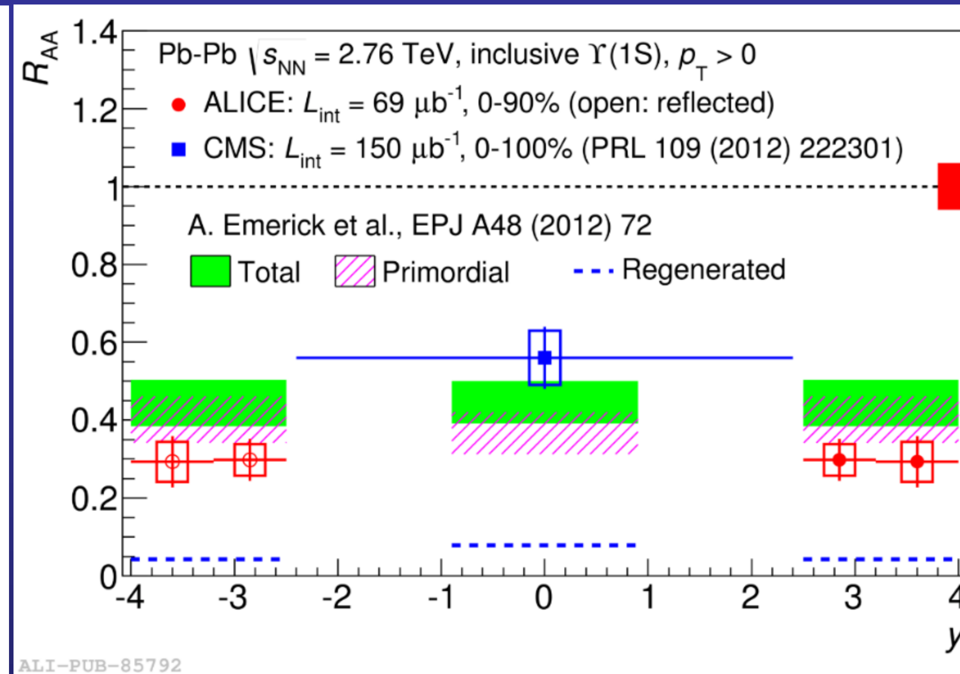
LHCb

We have reconstructed the radiative decays $\chi_b(1P) \to \Upsilon(1S)\gamma$ and $\chi_b(2P) \to \Upsilon(1S)\gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, and measured the fraction of $\Upsilon(1S)$ mesons that originate from these decays. For $\Upsilon(1S)$ mesons with $p_T^{\Upsilon} > 8.0$ GeV/c, the fractions that come from $\chi_b(1P)$ and $\chi_b(2P)$ decays are [27.1 ± 6.9(stat) ± 4.4(syst)]% and [10.5 ± 4.4(stat) ± 1.4(syst)]%, respectively. We have derived the fraction of directly produced $\Upsilon(1S)$ mesons to be [50.9 ± 8.2(stat) ± 9.0(syst)]%.

- At the limit of uncertainties or do we have a problem here ?
- Difficult to reach 50% including 2S and 3S

Can we take CNM into account ?





- Apply the simple $R_{pPb} \times R_{Pbp}$ recipe on ALICE pPb
- Would give $0.78 \times 0.86 = 0.67$ for $3.25<y<4$
  $0.91 \times 0.66 = 0.60$ for $2.5<y<3.25$
  (but see also LHCb result)

⇒ ~0.5 "anomalous" suppression at forward-y

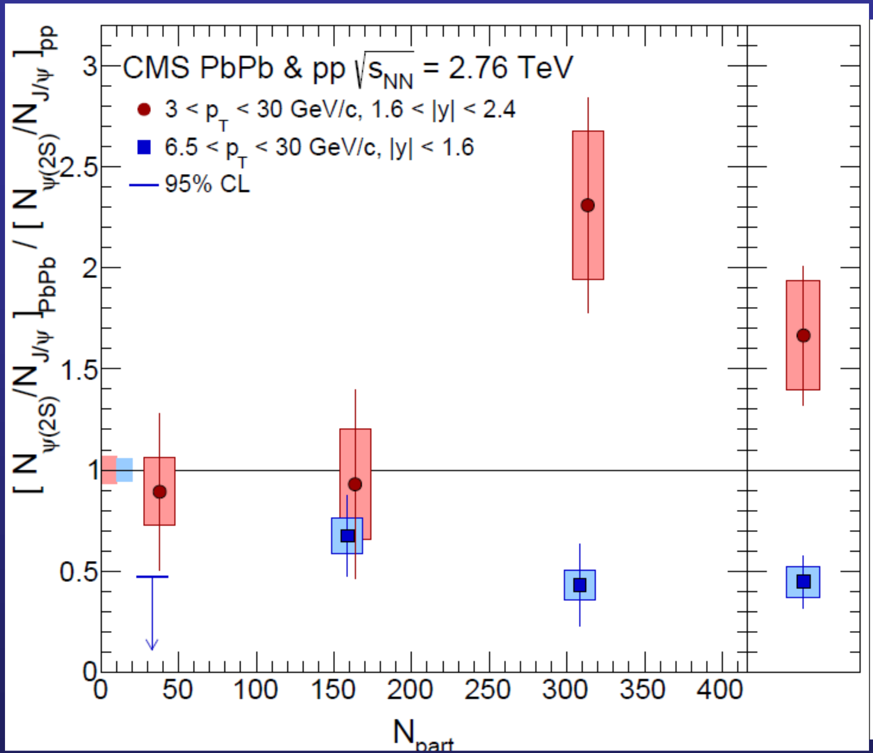
- No results from CMS (for the moment ?)
- Assuming a "smooth" y-interpolation of CNM

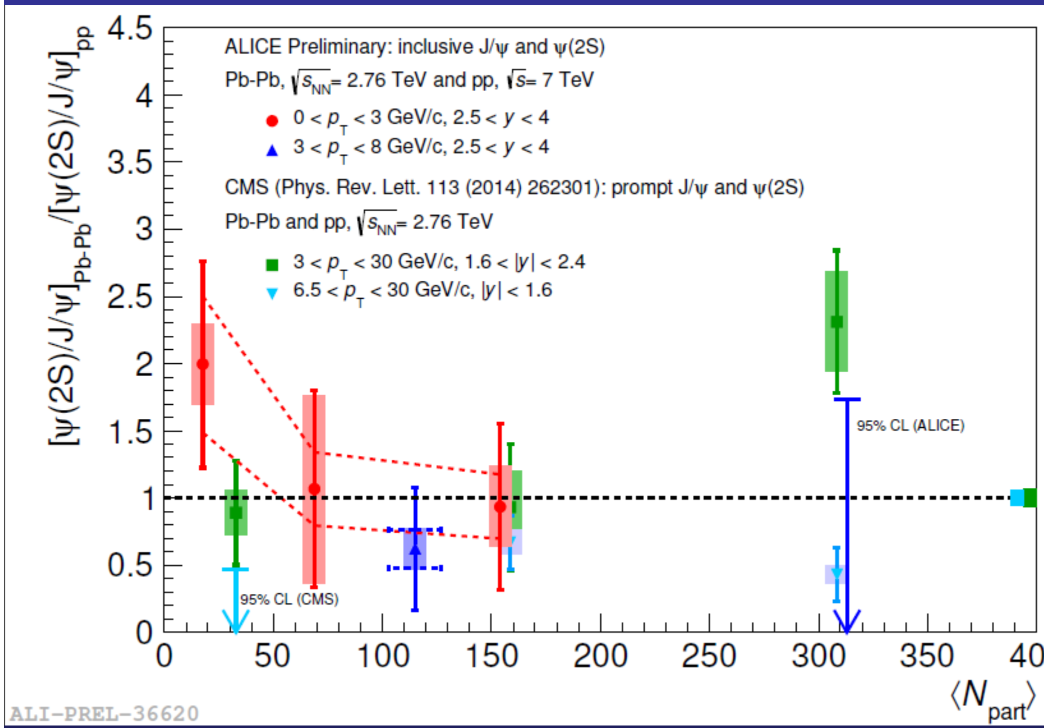
⇒ ~0.8-0.9 "anomalous" suppression at central-y

→ Need new/better pPb data ?

Charmonium: the ψ(2S) puzzle

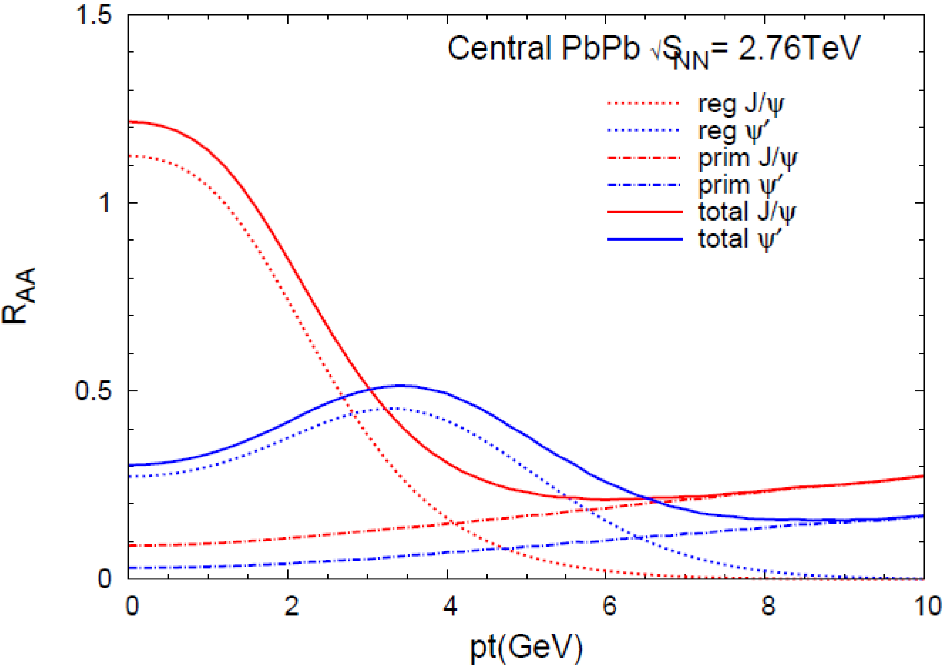
- ❑ At the end of run-1 results are still limited by statistics

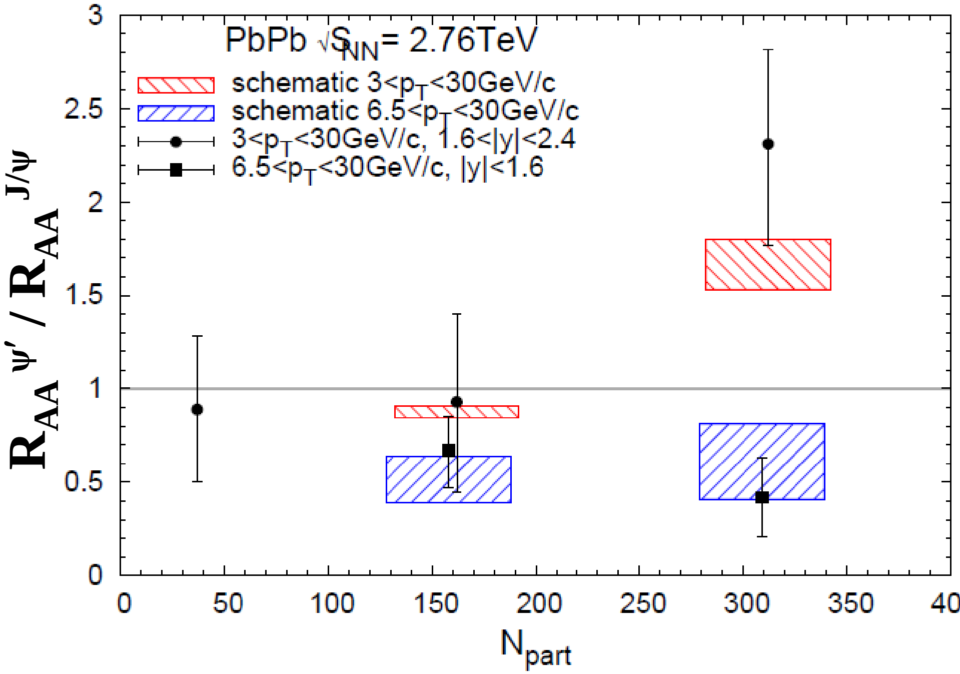




- ❑ From enhancement at intermediate p_T to suppression at large p_T
- ❑ Is there a discrepancy with ALICE at intermediate p_T?
- ❑ First recent proposals (Rapp, arXiv:1504.00670) on how interpreting the result

Charmonium: the ψ(2S) puzzle





- The regeneration of ψ′ mesons occurs significantly later than for J/ψ's
- Despite a smaller total number of regenerated ψ′, the stronger radial flow at their time of production induces a marked enhancement of their R_{AA} relative to J/ψ's in a momentum range pt ≃ 3-6 GeV/c.

J/ψ in Pb-Pb: from run-1 to run-2

- Evidence for smaller suppression compared to RHIC
  → Occurrence of recombination is at present the only explanation
- p_T-dependence of R_{PbPb} also compatible with recombination

- Although qualitative interpretation looks unambiguous, the quantitative assessment of the effects at play needs refinement
- Values for $d\sigma_{cc}/dy$ evolved. At present, in the forw.-y ALICE domain:
  - SHM → 0.15 – 0.25 mb (y=4 and y=2.5) – no shadowing
  - Zhao and Rapp → 0.5 mb – "empirical" shad. vs no shad.
  - Zhuang et al. → 0.4 – 0.5 mb – EKS98 shadowing
  - Ferreiro et al. → 0.4 – 0.6 mb + Glauber-Gribov shad. ~ nDSG(min.) > EKS98

- LHC run-2 → (almost) a factor 2 gain in $\sqrt{s}$
  → would it be possible to extract $d\sigma_{cc}/dy$ which gives the best fit to run-1 results, extrapolate to run-2 energy (FONLL?) and give predictions ?

- Suppression persists up to the largest investigated p_T
  - Higher p_T reach in run-2 → increase of R_{PbPb} ? Predictions ?

- Interesting indication for azimuthal anisotropies. Run-2 needs
  - Experiment → (much) larger statistics
  - Theory → solid predictions

J/ψ in p-Pb: run-1 summary

- p-Pb data: characterization of CNM effects in terms of shadowing plus coherent energy loss (no break-up) looks satisfactory

- Uncertainties on shadowing calculations are large, could one use the LHC data to better constrain shadowing ?

- Effects are strong, $R_{pPb}\sim 0.6$ at low p_T and central to forward rapidity
  → Strong influence of CNM effects in Pb-Pb in the corresponding kinematic region

- The simple estimate $R_{PbPb}^{CNM}=R_{pPb}\times R_{Pbp}$ (inspired to a shadowing scenario) leads, once this effect is factorized out, to an even steeper p_T-dependence of R_{PbPb}

- Also for p-Pb, run-2 energy predictions ($\sqrt{s}\sim 8$ TeV), with parameters TUNED on run-1 results, would allow a crucial test of our understanding of the involved mechanisms