Quarkonium Production in Nucleus-nucleus Collisions at LHC

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OUTLINE

- **Why Quarkonium in heavy-ion physics**

- **Quarkonium results in Pb-Pb collisions at the LHC**
  - **Charmonium**
  - **Bottomonium**

- **Summary**

Quarkonium at LHC

Where do we stand after 30 years?

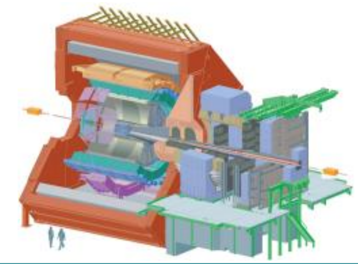
A wealth of high-quality data have been accumulated,
at various facilities (SPS, RHIC, LHC) for various collision systems

Decisive inputs from LHC results, having access to:

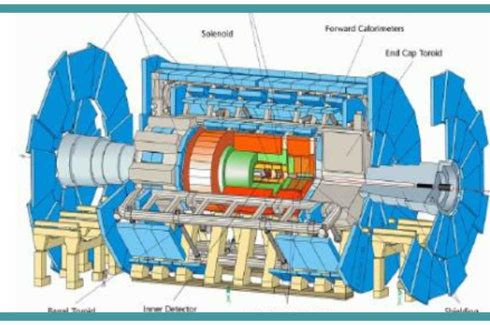
- Higher energies
  - stronger quarkonium suppression?
- More charm
  - larger (re)combination?
- More bottom
  - Υ can be investigated

Quarkonium at LHC

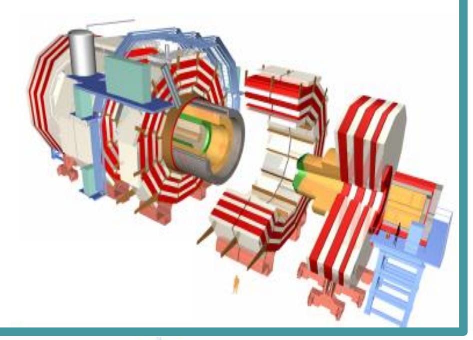
ALICE $J/\psi,\ \psi(2S) \rightarrow \mu^+\mu^-$
$\Upsilon \rightarrow \mu^+\mu^-$
$J/\psi \rightarrow e^+e^-$



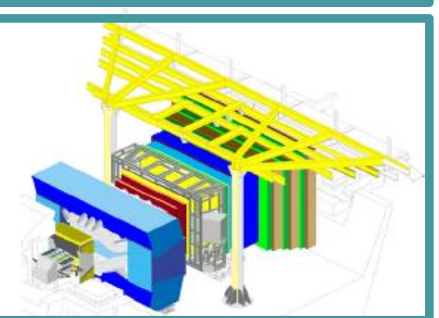
ATLAS $J/\psi \rightarrow \mu^+\mu^-$



CMS $J/\psi,\ \psi(2S) \rightarrow \mu^+\mu^-$
$\Upsilon \rightarrow \mu^+\mu^-$

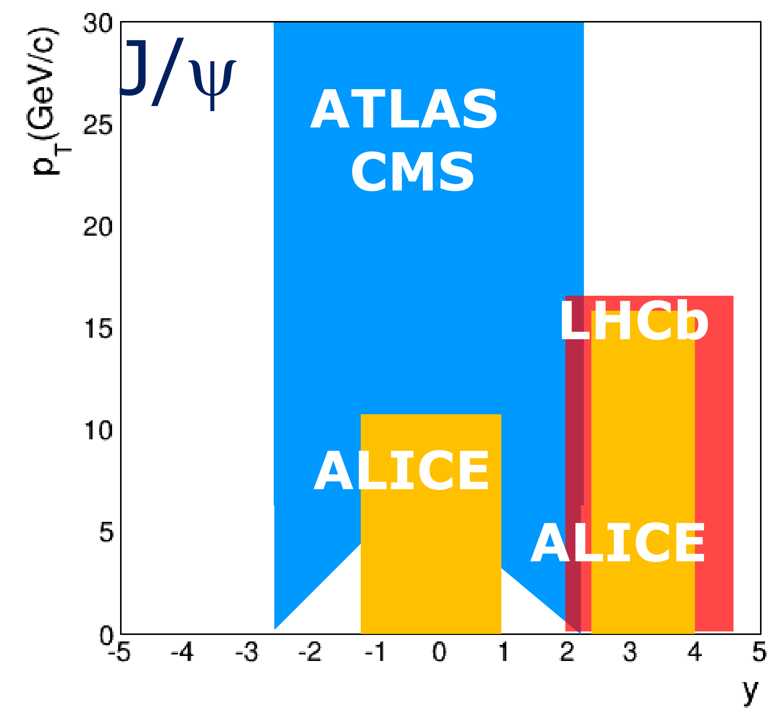


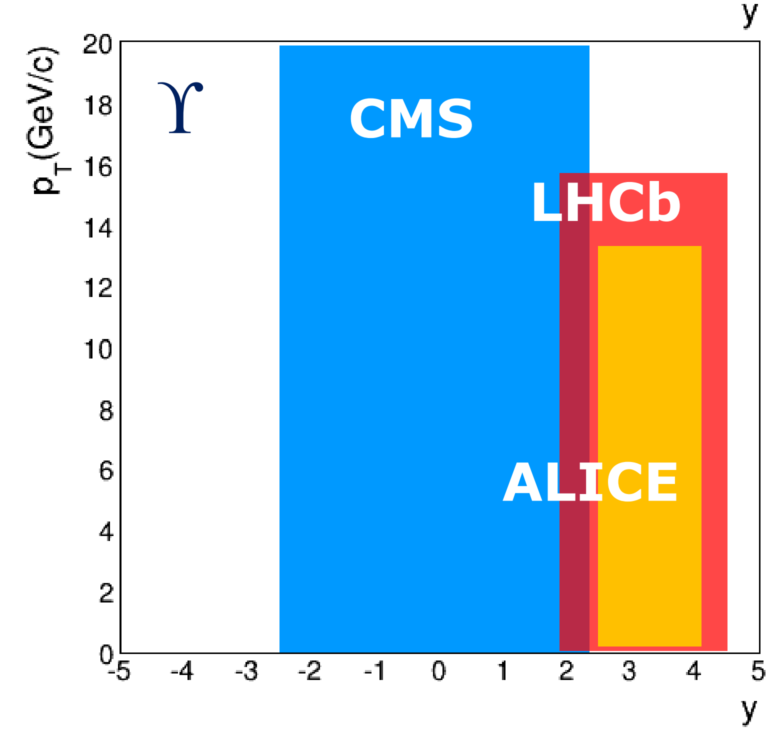
LHCb $J/\psi,\ \Upsilon \rightarrow \mu^+\mu^-$



Complementary quarkonium results from LHC experiments

Kinematic coverage of quarkonium measurements

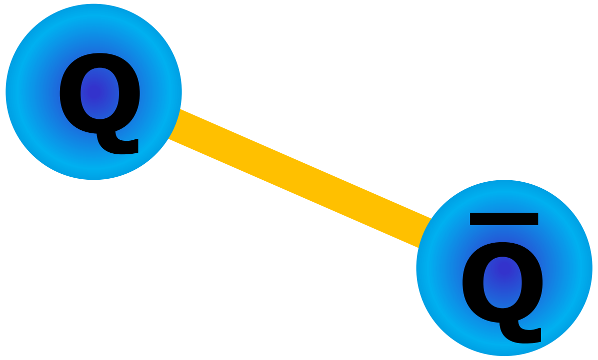




Quarkonium

Quarkonium is a bound state of Q and $\bar{Q}$ with $m_{QQ}<2m_D(m_B)$

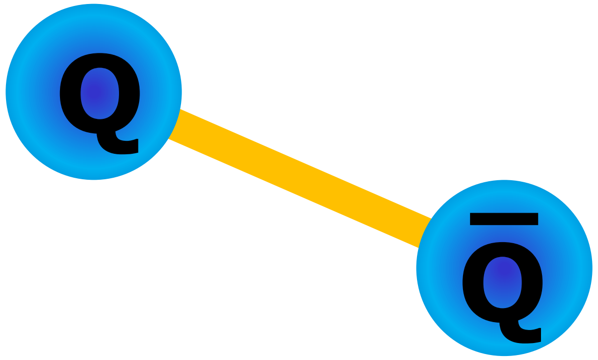
→ Several quarkonium states exists, characterized by different quantum numbers



Quarkonium at T=0

At T=0, the binding of the Q and $\bar{Q}$ quarks can be expressed using the Cornell potential:

$$V(r) = -\frac{\alpha}{r} + kr$$



Quarkonium in a QGP

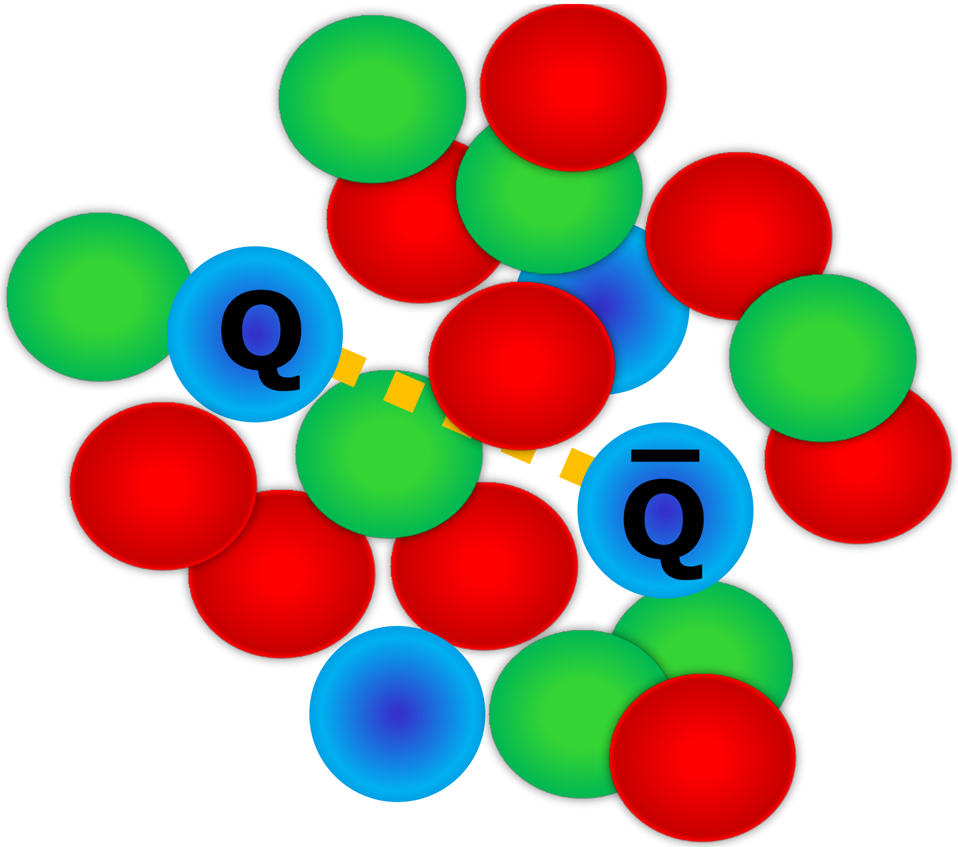
What happens to a $Q\bar{Q}$ pair placed in the QGP?

$$V(r) = -\frac{\alpha}{r} + kr$$

↓

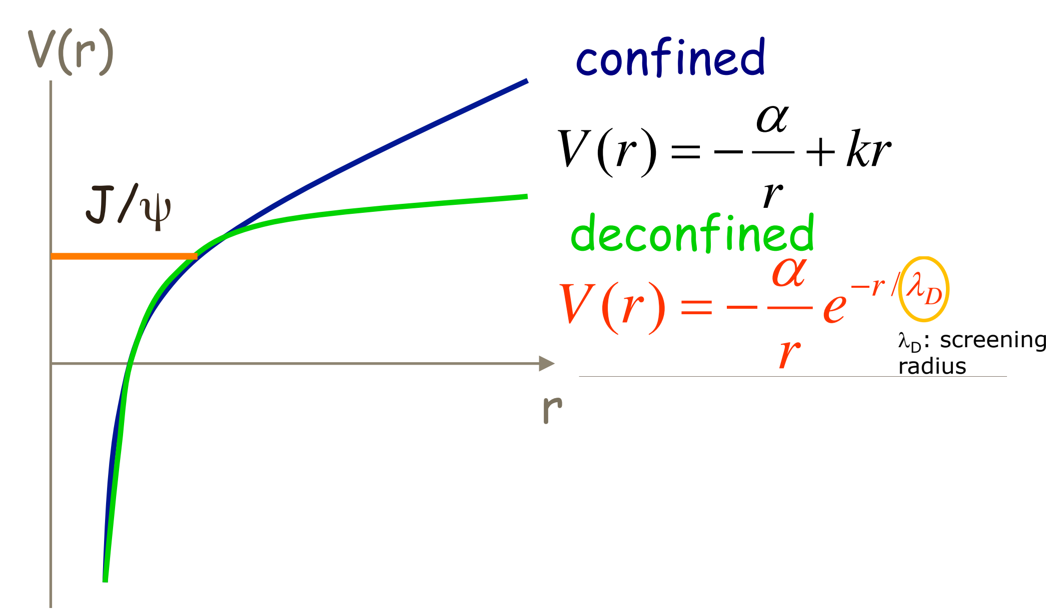
$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

λ_D: screening radius



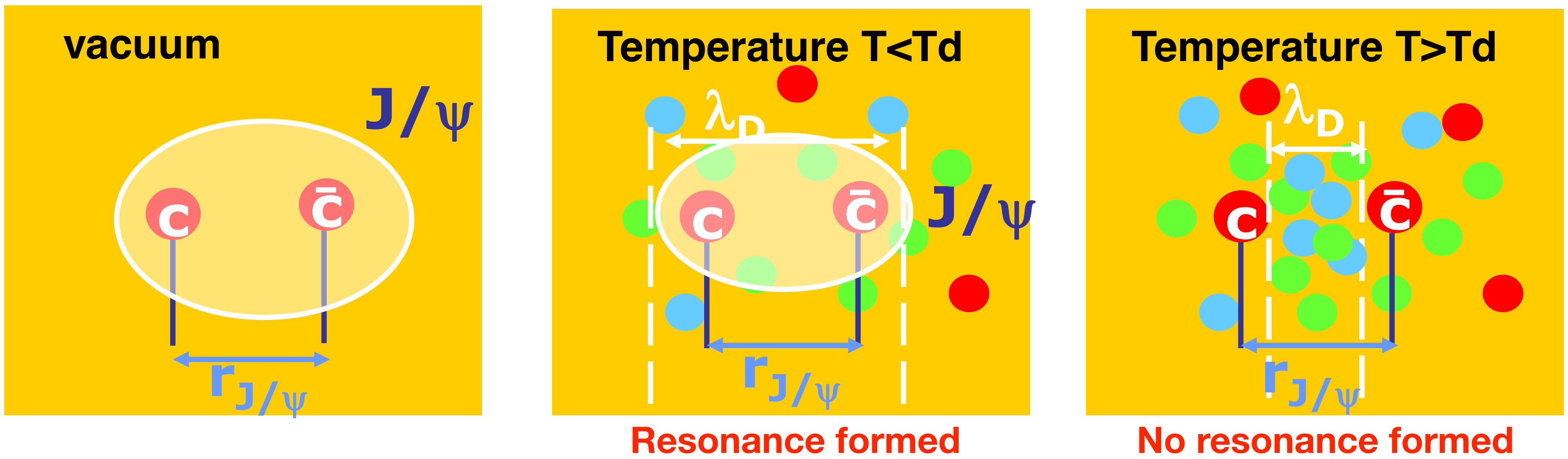
The QGP consists of deconfined colour charges → the binding of a $Q\bar{Q}$ pair is subject to the effects of colour screening

- The "confinement" contribution disappears
- The high color density induces a screening of the coulombian term of the potential



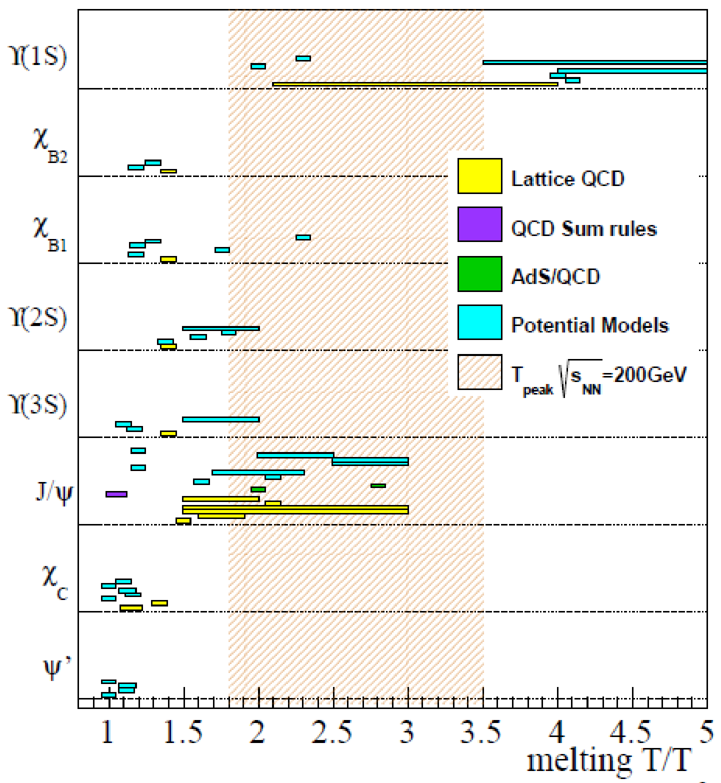
Debye Screening

The screening radius $\lambda_D(T)$ (i.e. the maximum distance which allows the formation of a bound $Q\bar{Q}$ pair) decreases with the temperature T



Quarkonium dissociation when

$r_{Debye} < r_{Quarkonium}$

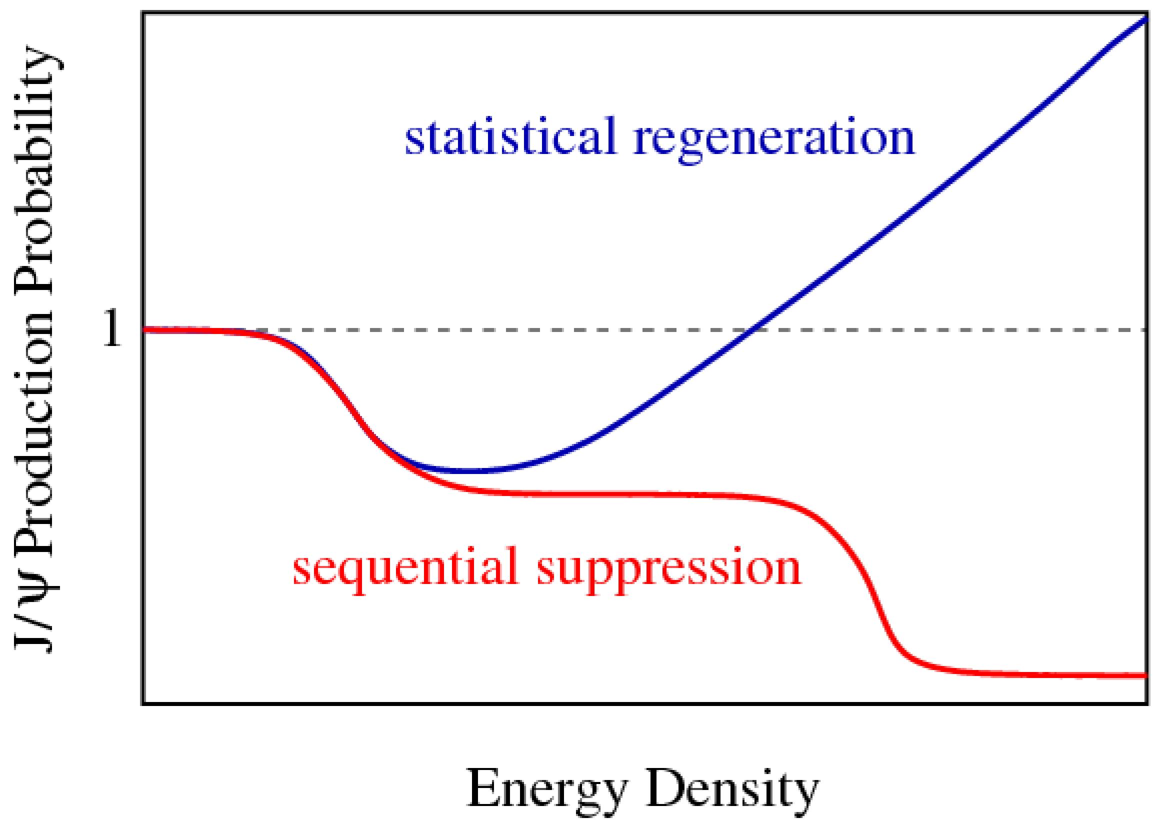


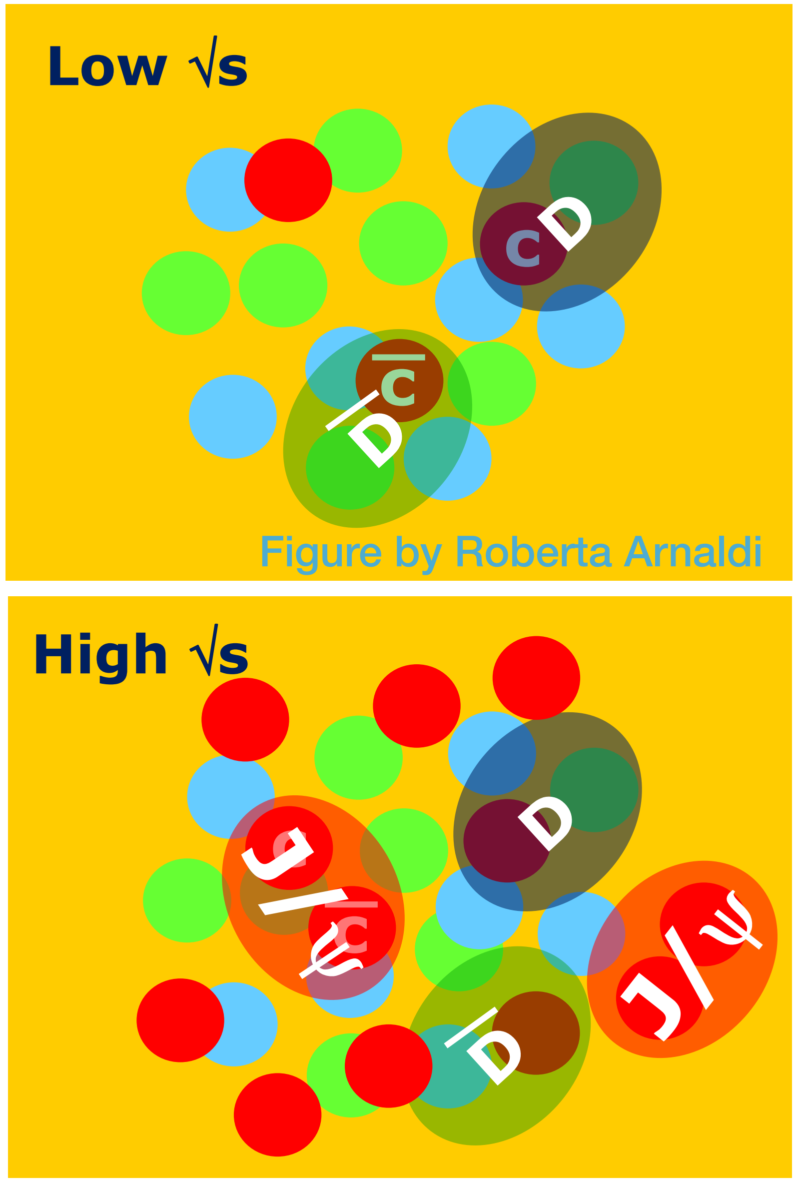
Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature

Thermometer of the initial QGP temperature

From suppression to regeneration

Central AA	SPS 20 GeV	RHIC 200 GeV	LHC 2.76 TeV	LHC 5 TeV
$N_{c\bar{c}}$/event	~0.2	~10	~75	~115

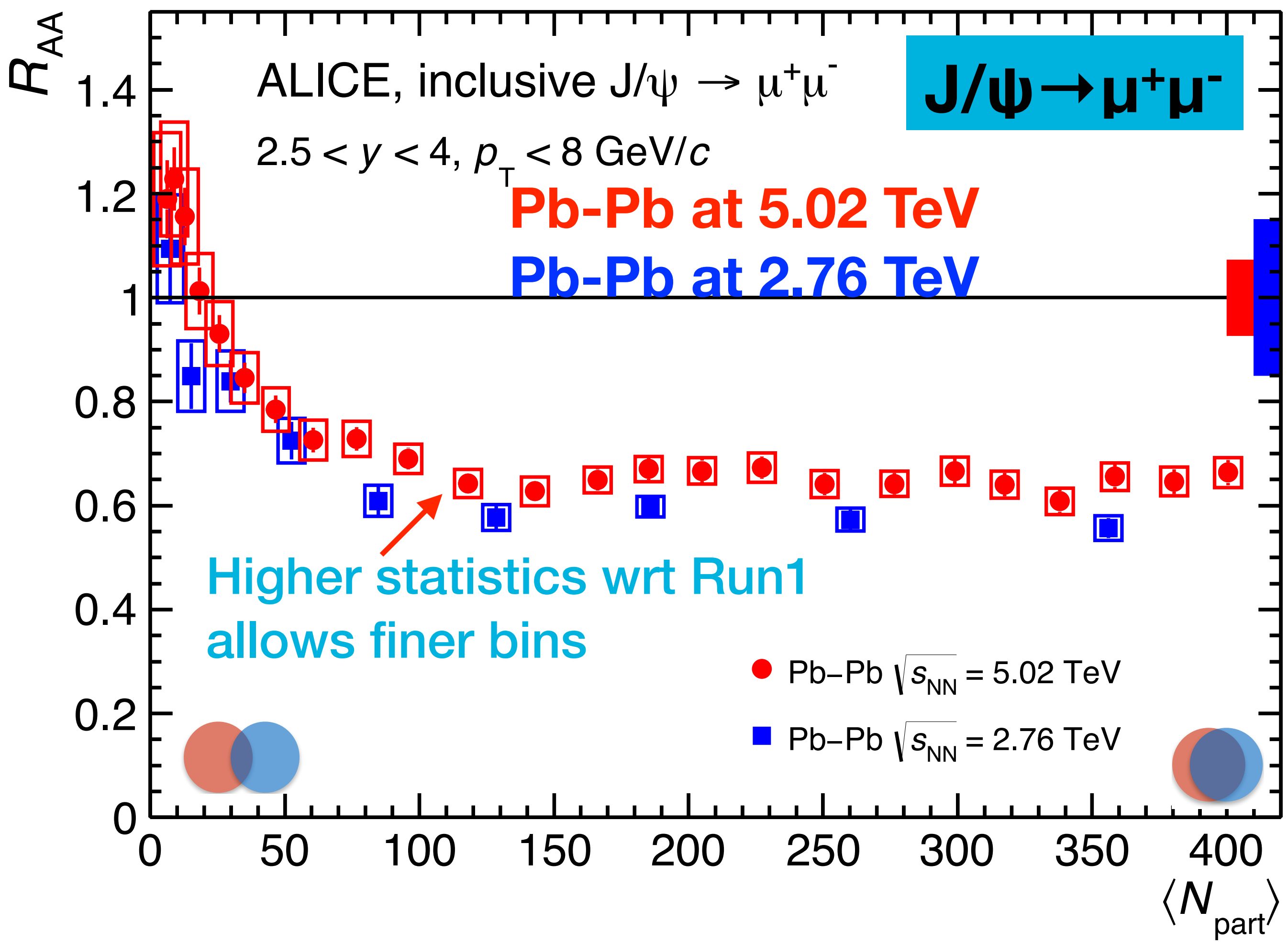


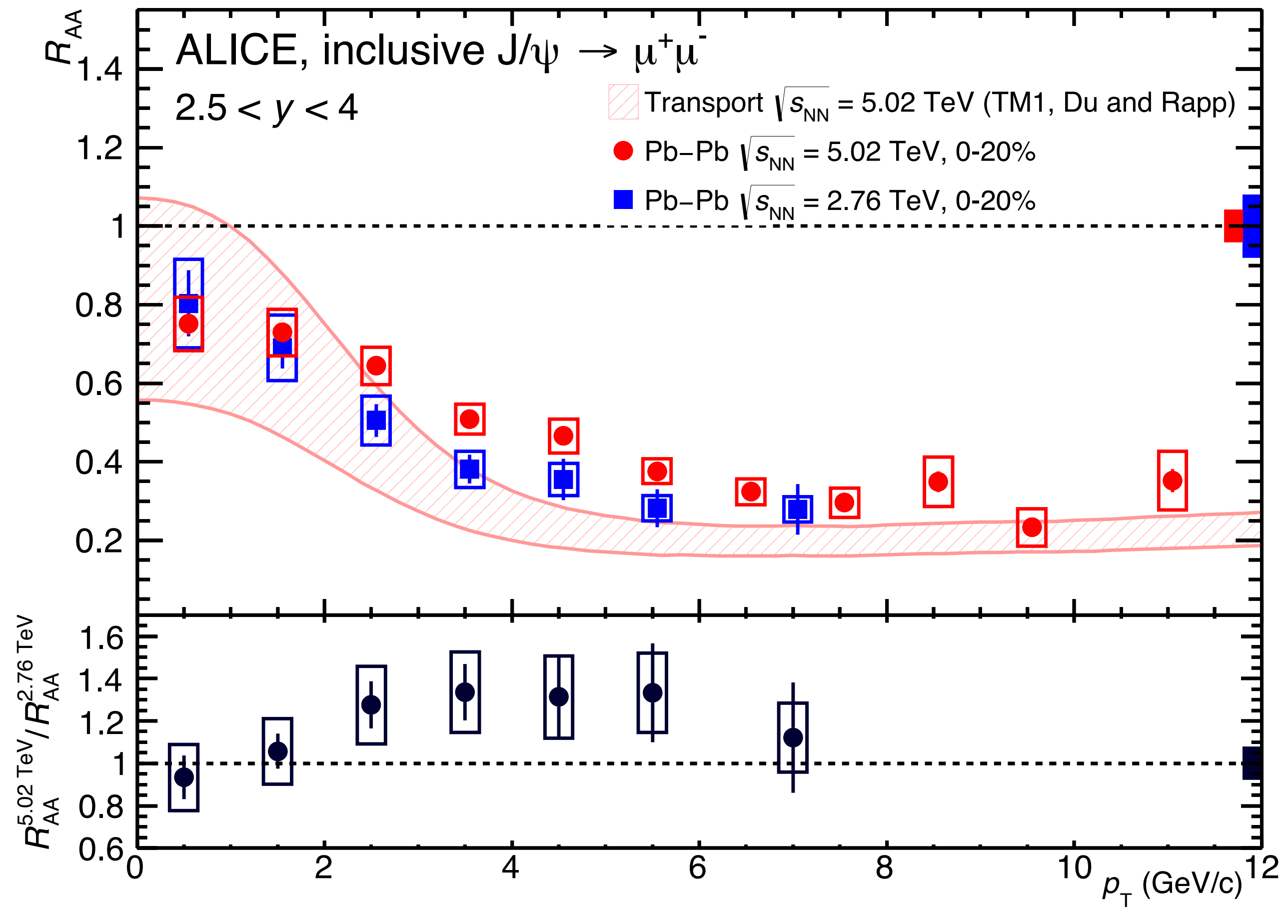


An enhancement via (re)combination of $c\bar{c}$ pairs producing quarkonia can take place at hadronization or during QGP stage

Although the "screening+recombination" picture is conceptually simple and attractive, a realistic description implies a sophisticate treatment (ex. In-medium formation of quarkonium, Heavy quark diffusion, …)

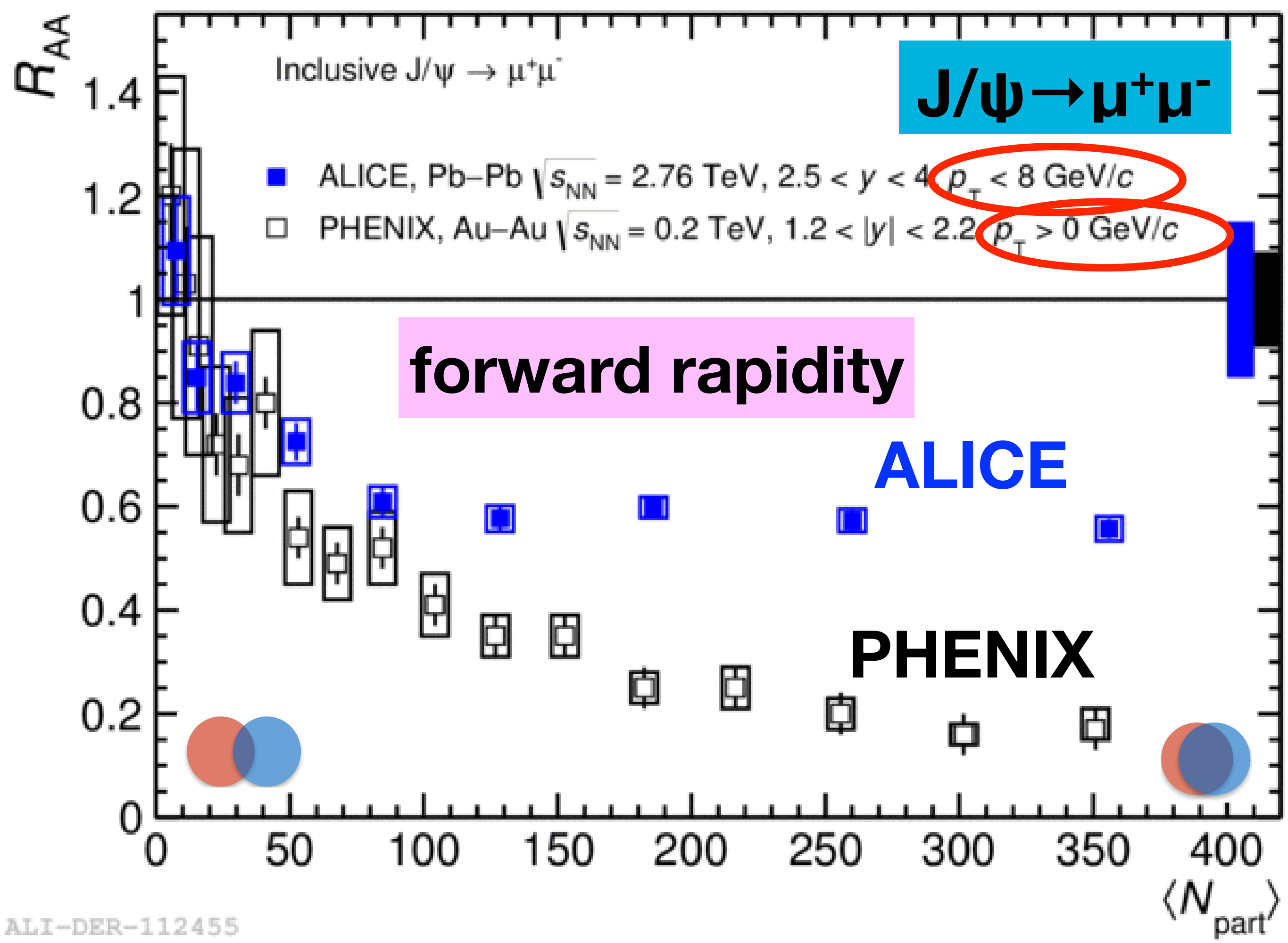
Low-p_T J/ψ : ALICE

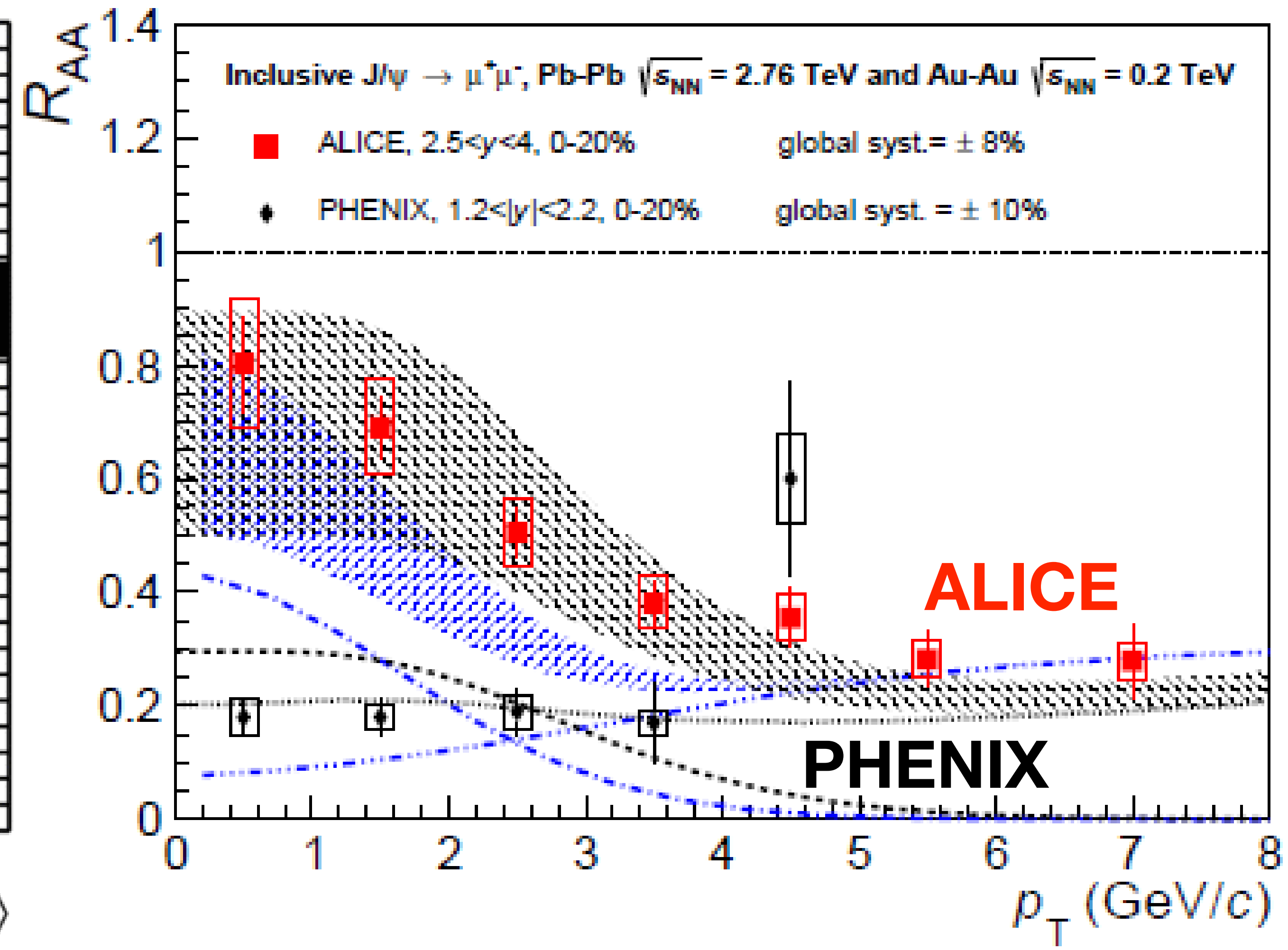




- Clear J/ψ suppression with almost no centrality dependence above N_{part} ~ 100
  - Suppression insensitive to the collision centrality in semi-central and central collisions → indication of regeneration
- Hint of an increase of R_{AA} at 5.02 TeV wrt 2.76 TeV is observed between 2-6 GeV/*c*
- J/ψ is less suppressed at low p_T than at high p_T → hint of the $c\bar{c}$ recombination?
  (as expected in regeneration models: regeneration contribution important at low p_T)

Low-p_T J/ψ : ALICE vs PHENIX

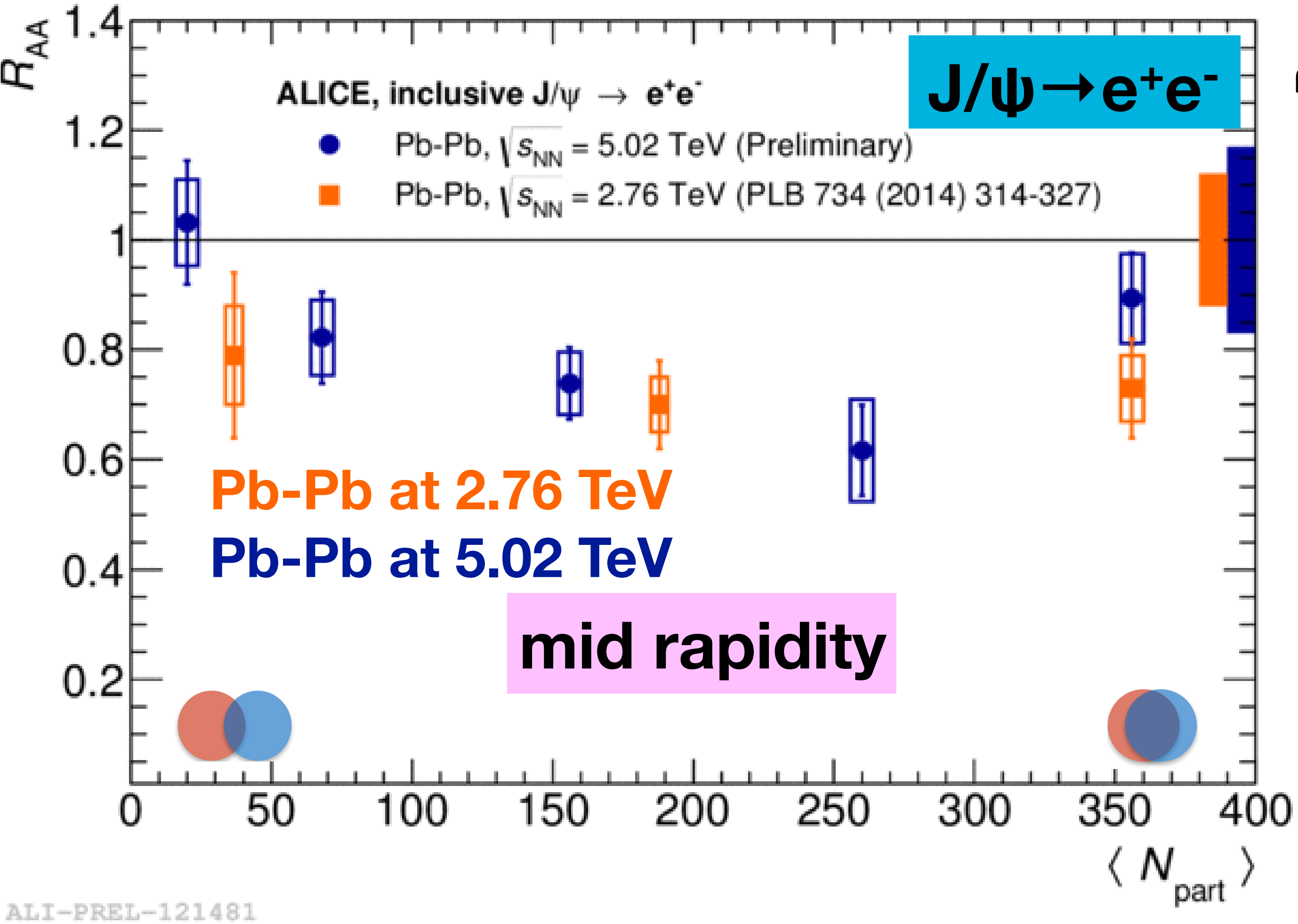


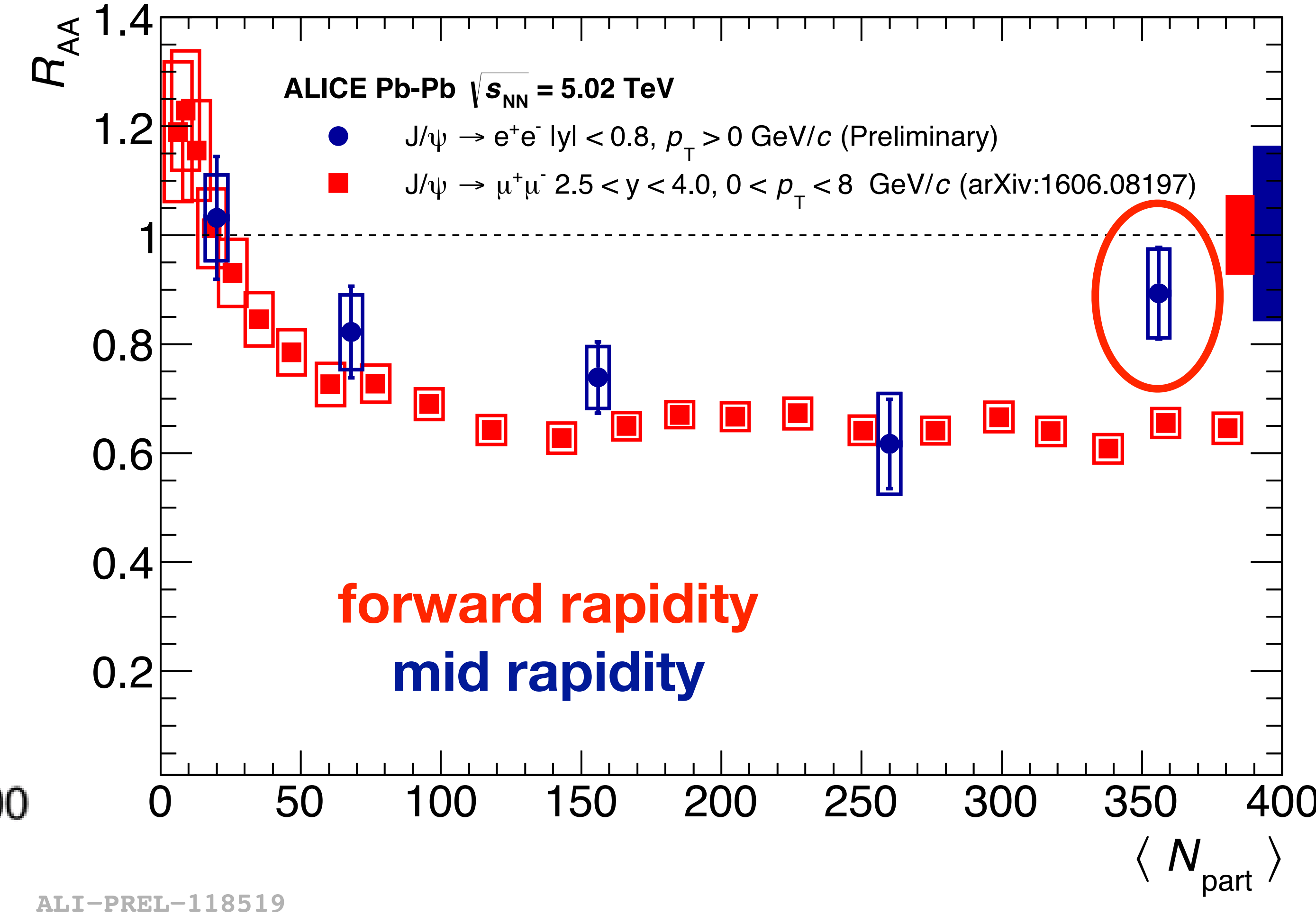


- Results vs centrality dominated by low-p_T J/ψ
  - Systematically larger R_{AA} values for central events at LHC
  - R_{AA} increases at low-p_T at LHC

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

Low-p_T J/ψ : central vs forward rapidity





- **No significant $\sqrt{s_{NN}}$-dependence** of R_{AA} (5.02 vs 2.76 TeV) as the observations at forward-rapidity
- Central Pb-Pb: **hints for a weaker suppression at mid-rapidity** with respect to forward-rapidity results at $\sqrt{s_{NN}}$=5.02 TeV→ expected in a (re)generation scenario (fluctuation cannot be excluded)

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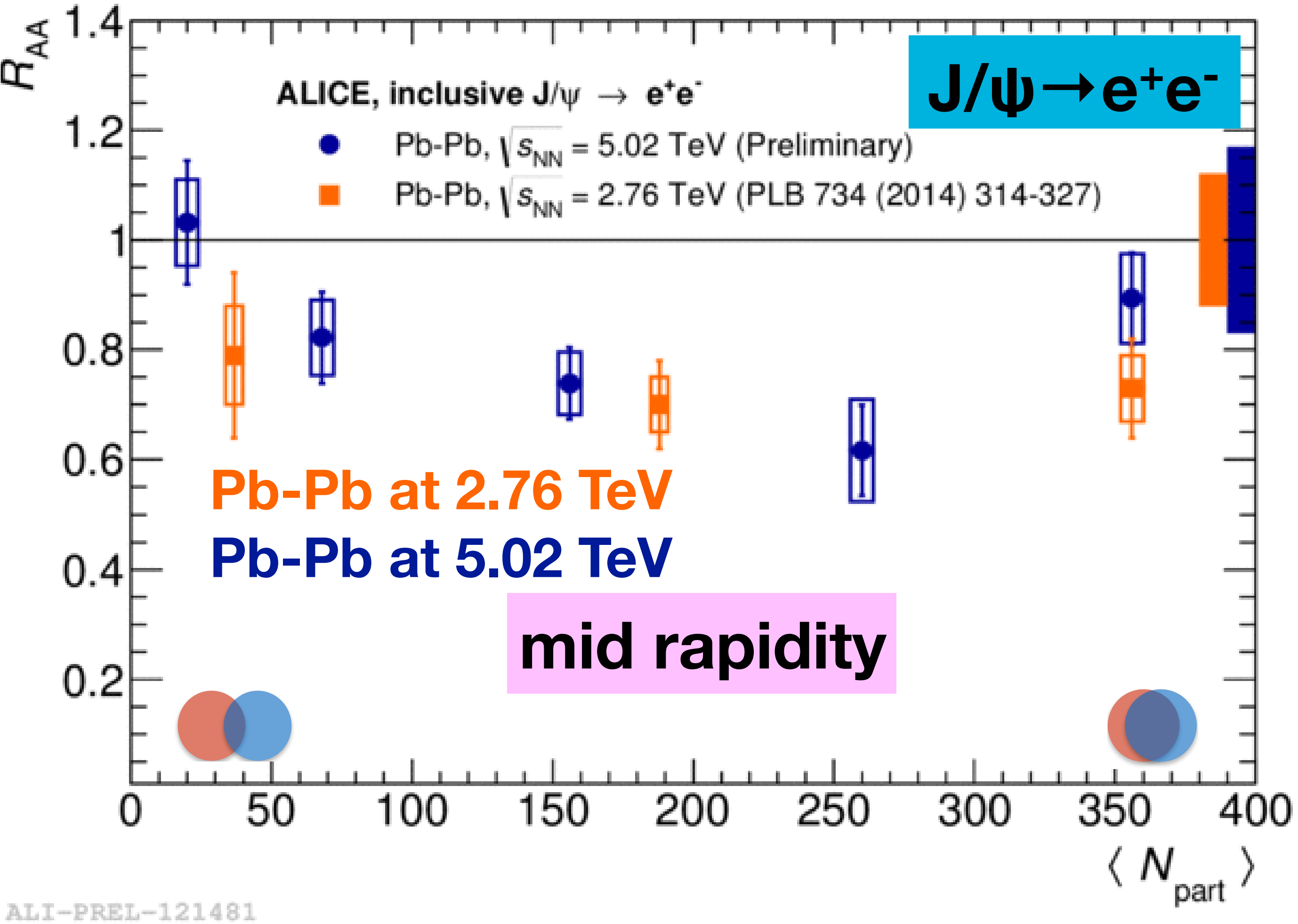

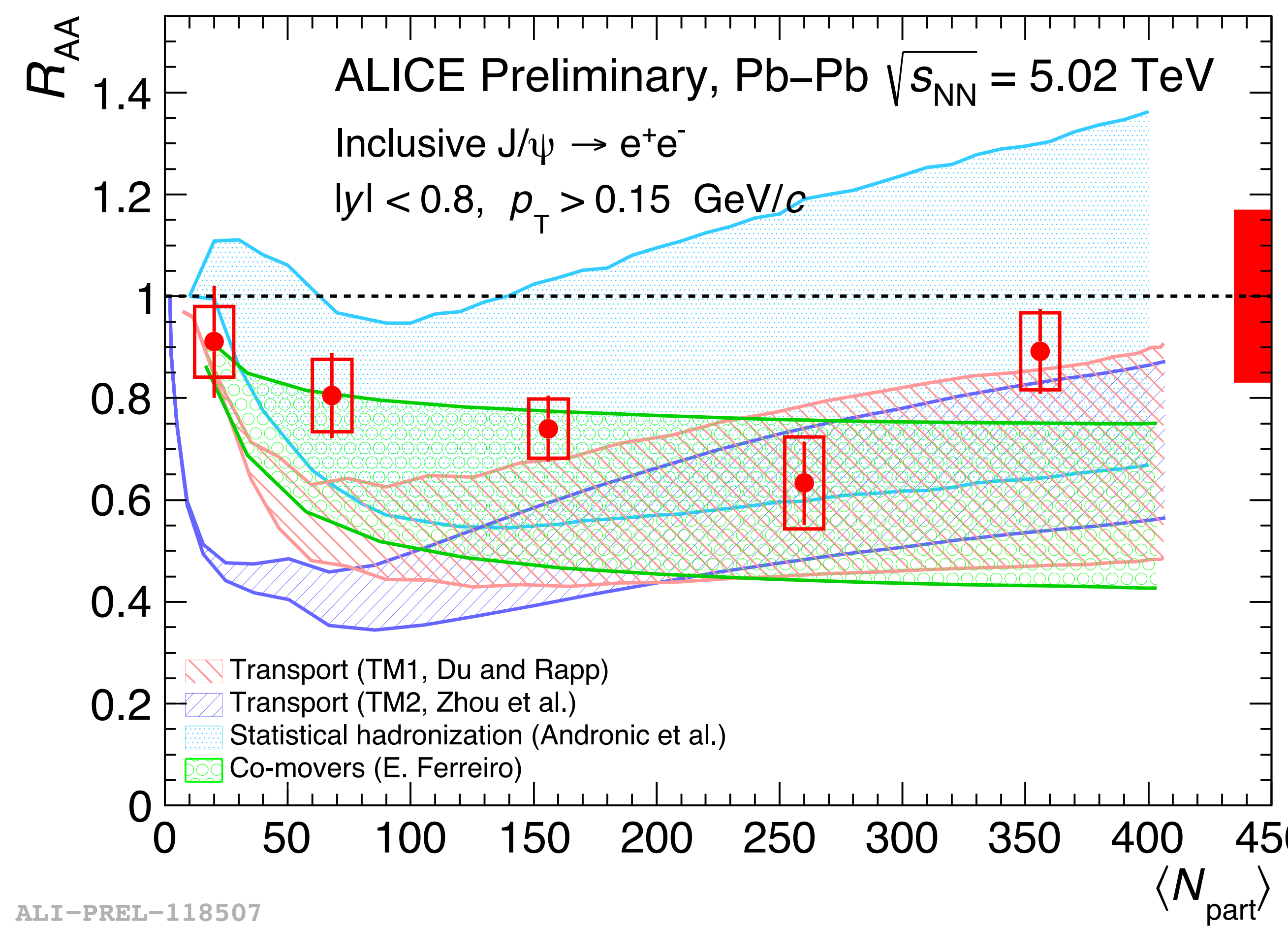

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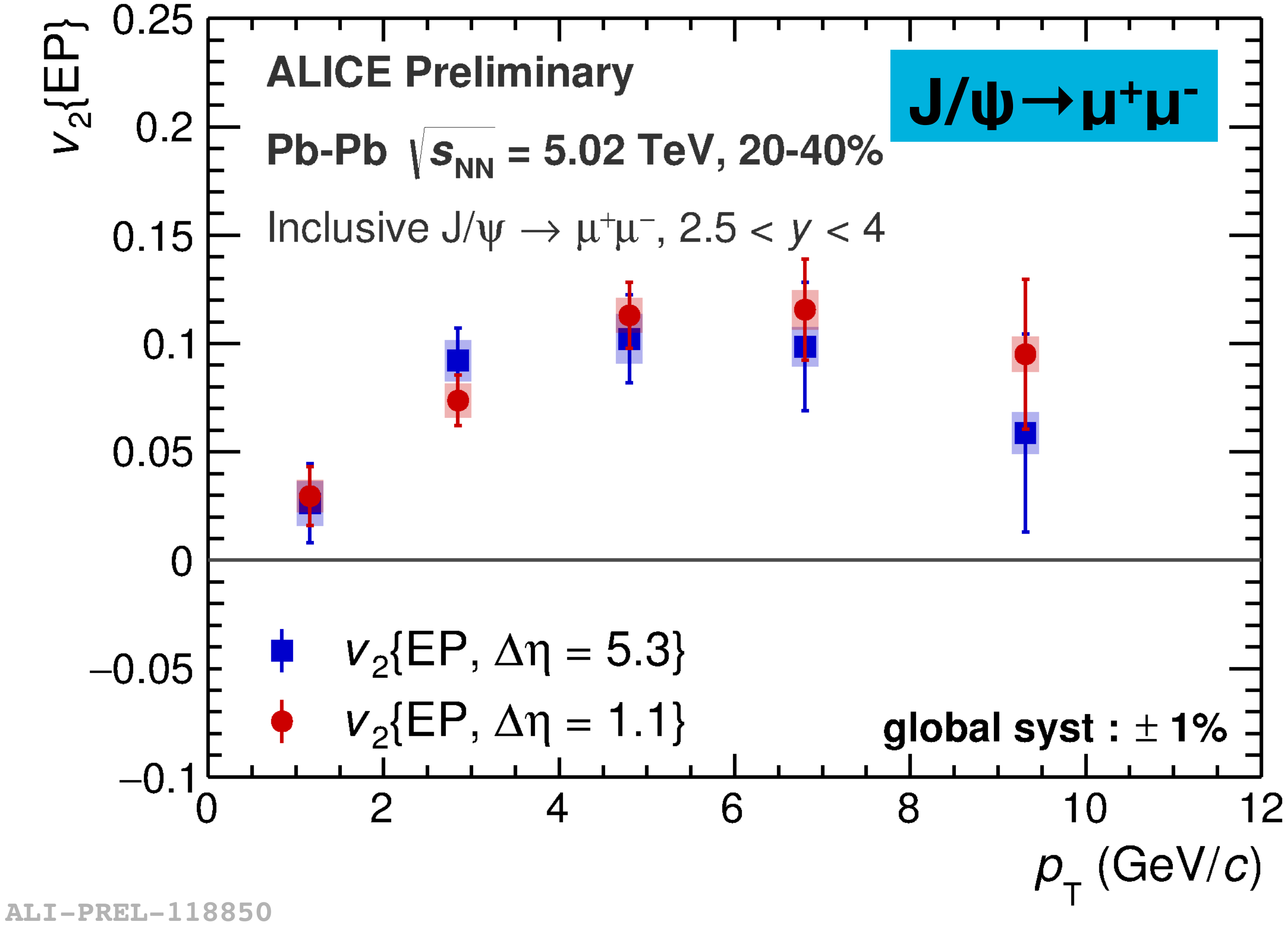
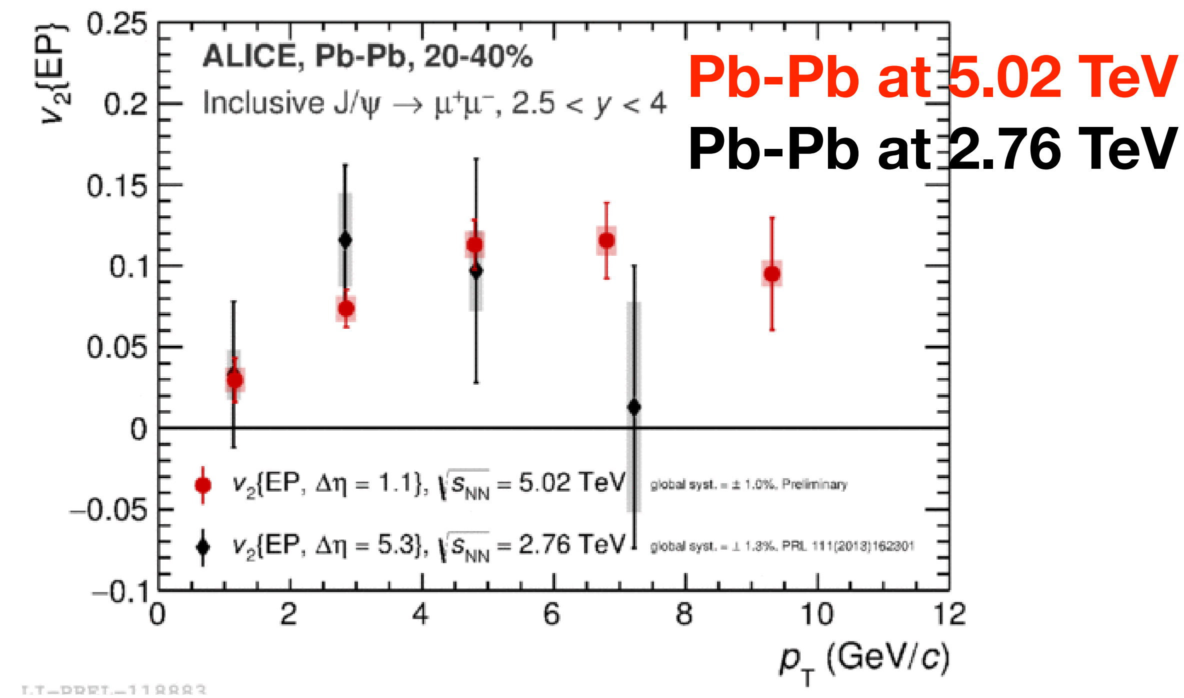
- **Transport and statistical models have large uncertainties** (shadowing +open charm cross section)

J/ψ v_2 results

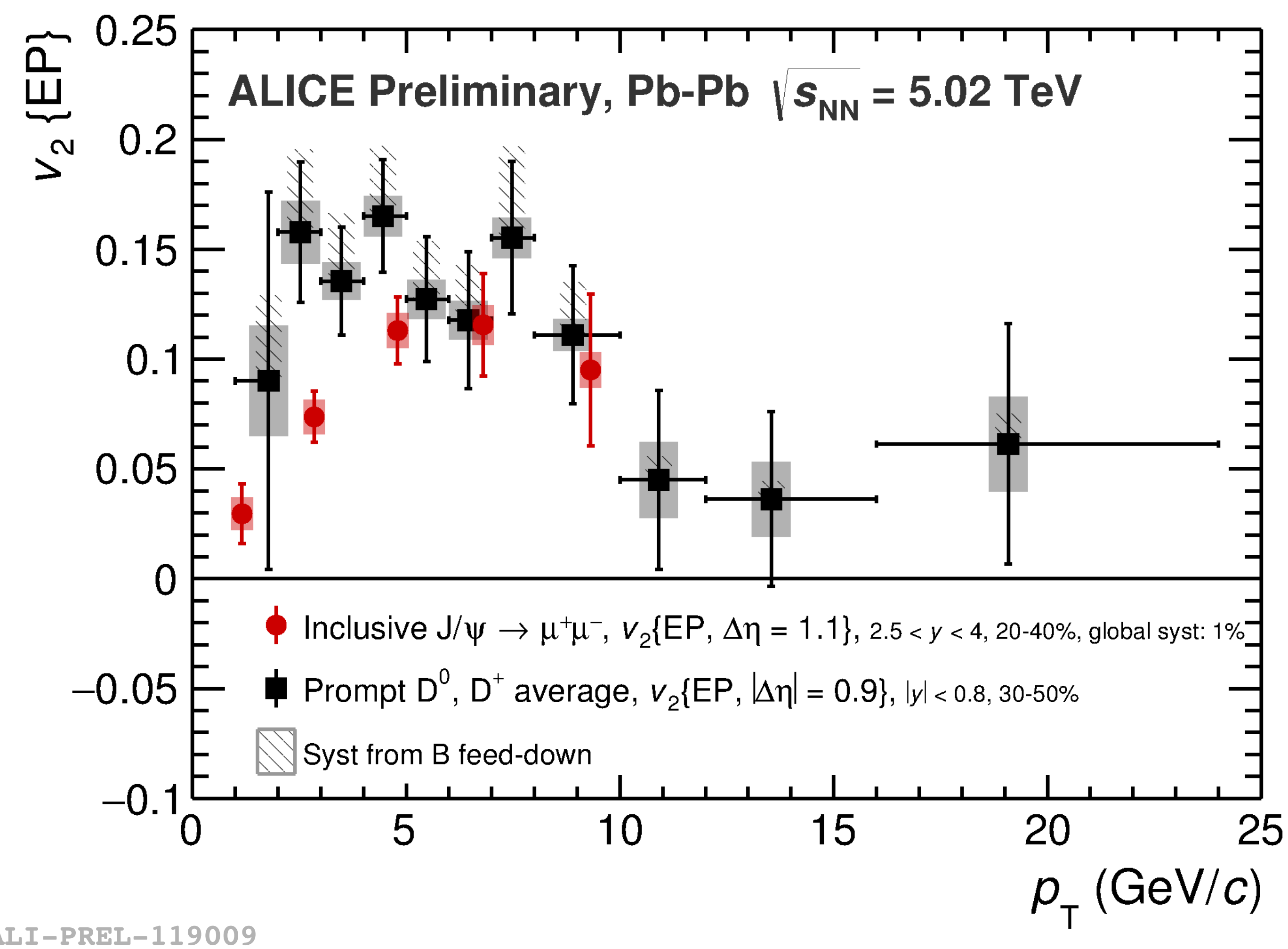


p_T (GeV/c)	0-2	2-4	4-6	6-8	8-12
Δη=1.1	2.2σ	6.3σ	7.4σ	5.0σ	2.8σ
Δη=5.3	1.4σ	6.2σ	5.0σ	3.3σ	1.3σ



- The contribution of J/ψ from (re)combination could lead to an **elliptic flow** signal at LHC → hints observed in run-1 results
- From hint to evidence for a non-zero v_2 signal, maximum for $4<p_T<6$ GeV/c 20-40% centrality
- A significant fraction of observed J/ψ comes from charm quarks which thermalized in the QGP

J/ψ v_2 results



Comparison closed vs open charm
→ Learn about light vs heavy quark flow

- The contribution of J/ψ from (re)combination could lead to an elliptic flow signal at LHC → hints observed in run-1 results
- From hint to evidence for a non-zero v_2 signal, maximum for $4<p_T<6$ GeV/c 20-40% centrality
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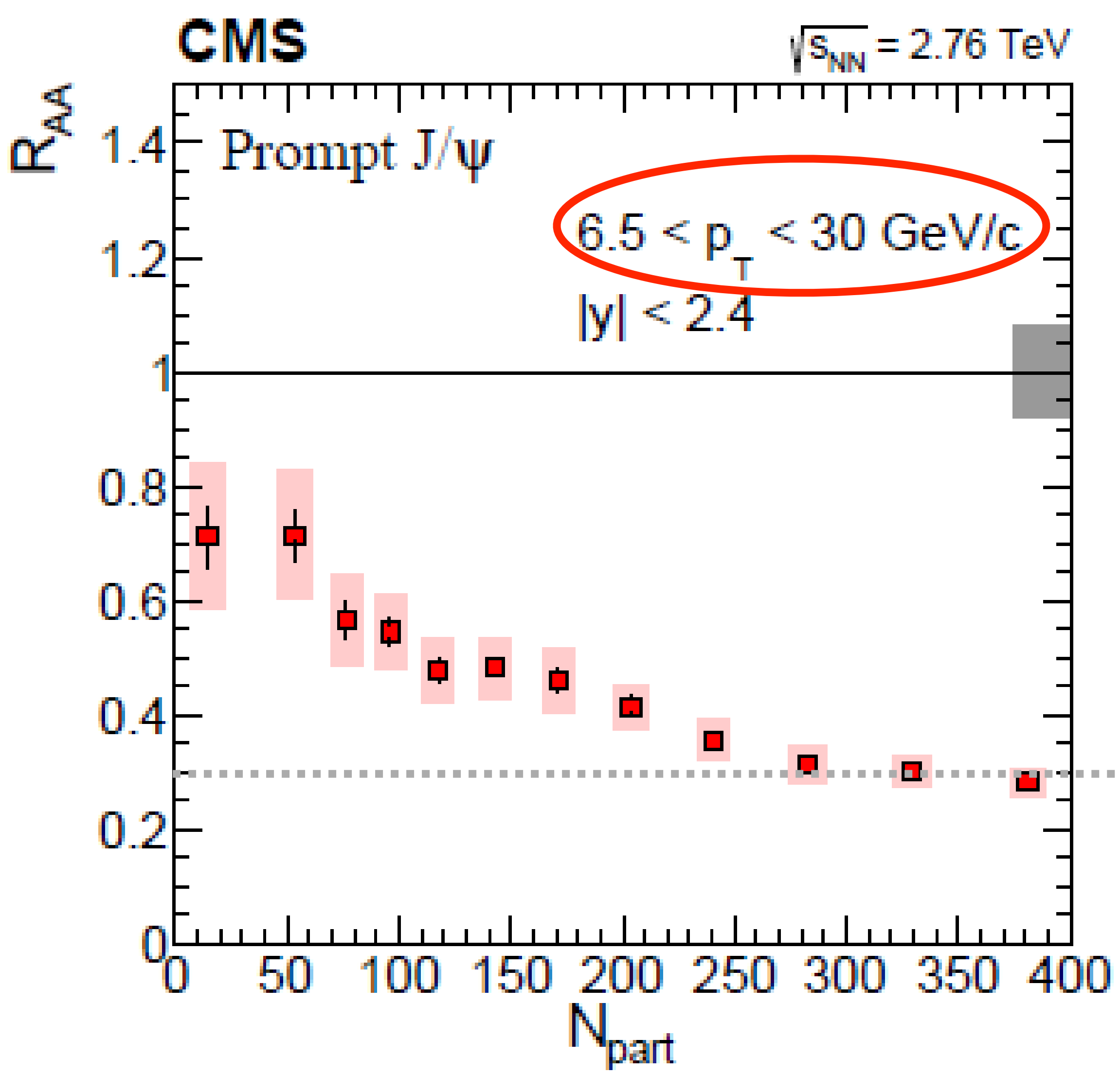
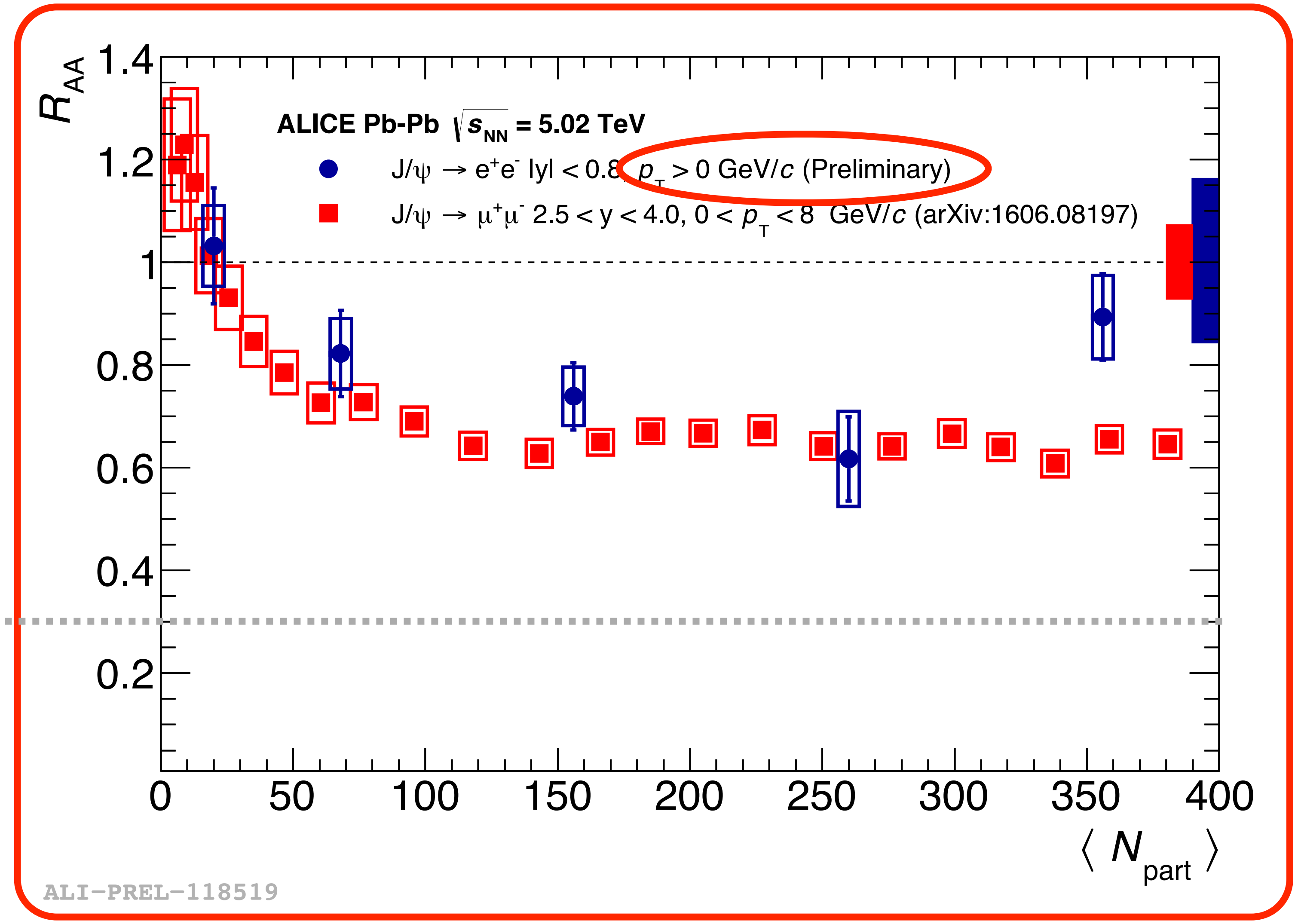
High-p_T J/ψ

V. Khachatryan et al. (CMS), arXiv: 1610.00613





- Striking difference with respect to low-p_T J/ψ
- Suppression increases with centrality at high p_T, down to R_{AA}~0.3

High-p_T J/ψ

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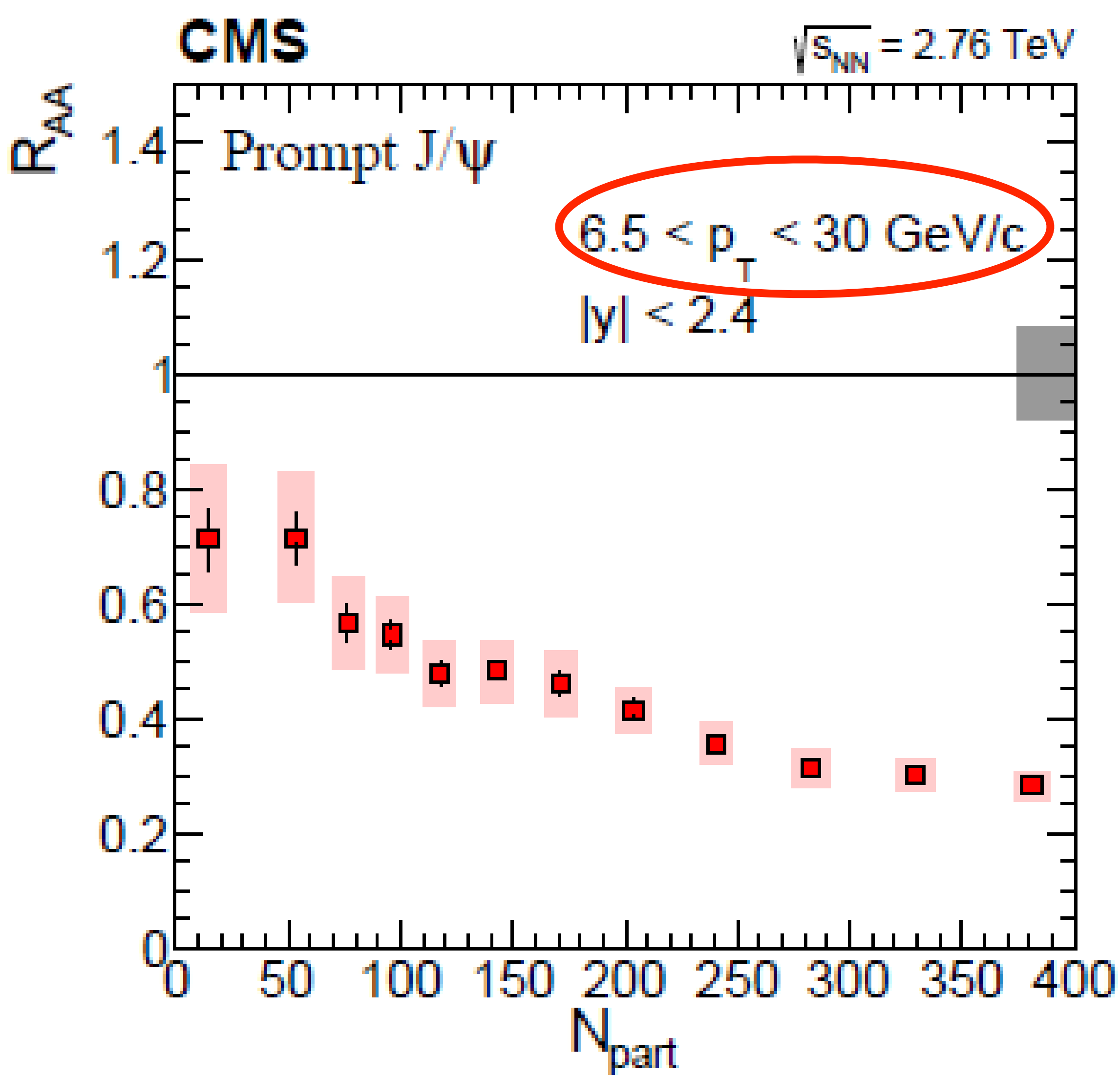
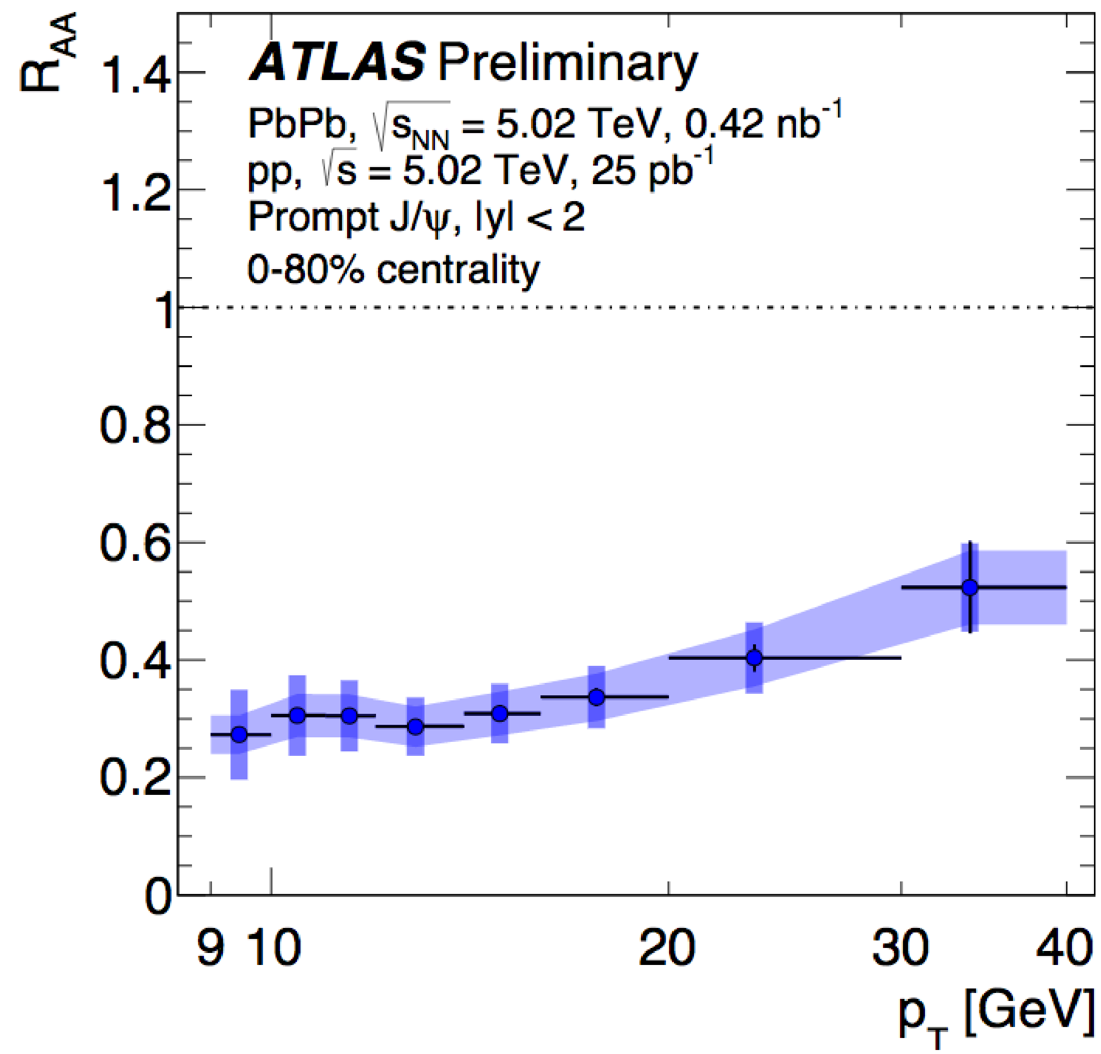


ATLAS-CONF-2016-109



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- Suppression increases with centrality at high p_T, down to R_{AA}~0.3

- R_{AA} increases for p_T > 20 GeV/c
- Related to energy loss effects, rather than dissociation?

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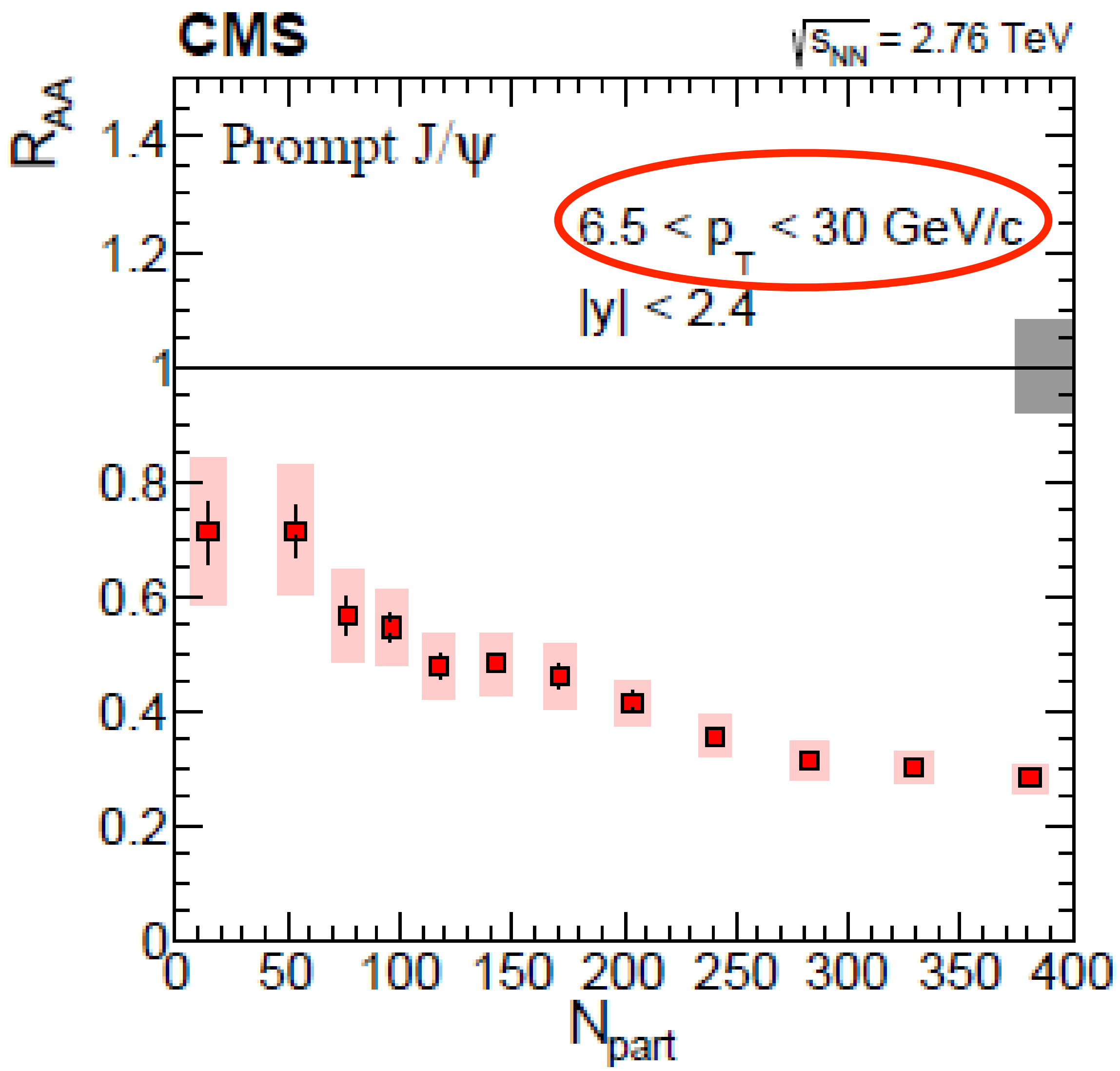

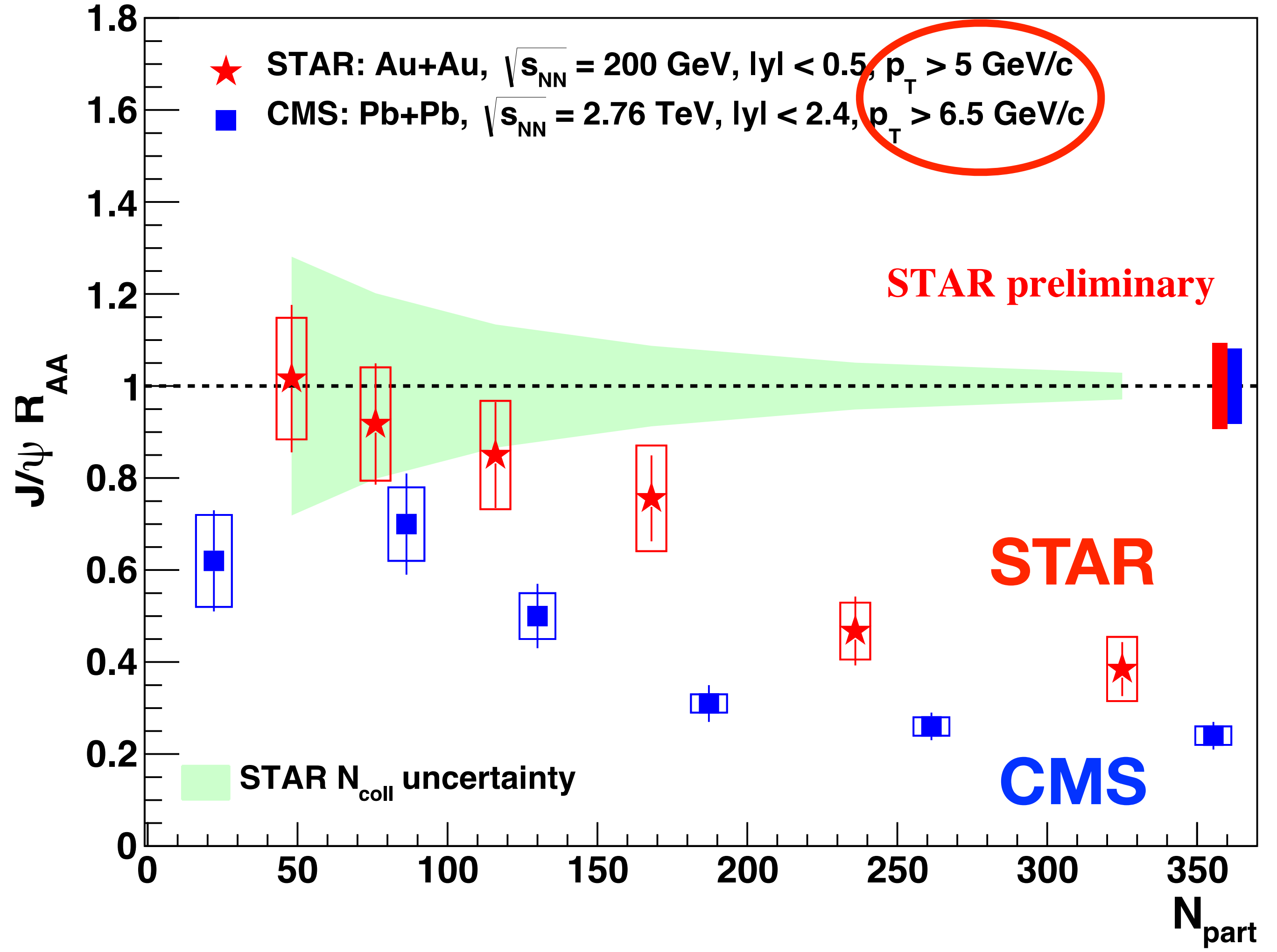

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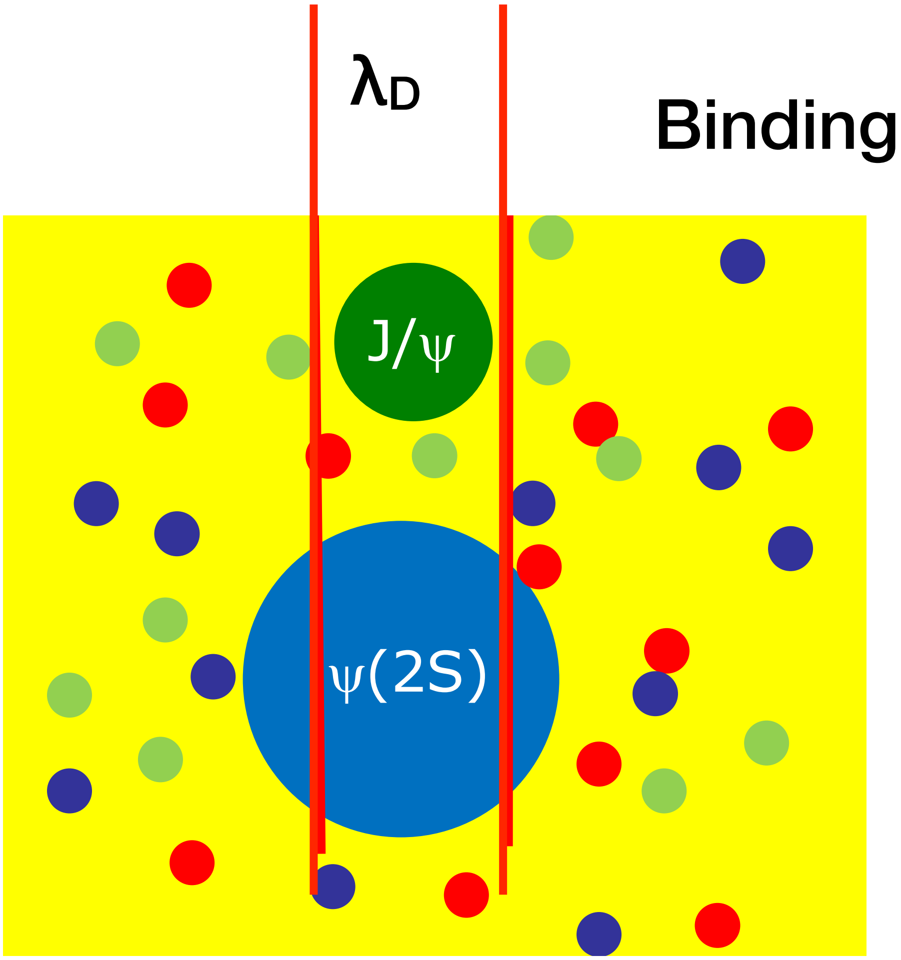
- Suppression increases with centrality at high p_T, down to R_{AA}~0.3

- R_{AA} increases for p_T > 20 GeV/c
- Related to energy loss effects, rather than dissociation?
- $R_{AA}^{LHC} < R_{AA}^{RHIC}$ → weak regeneration?

ψ(2s) in Pb-Pb



Binding energy ~$(2m_D - m_\psi)$ → ψ(2S) ~ 60 MeV, J/ψ ~ 640 MeV

- Expect **much stronger dissociation** effects for the **weakly bound ψ(2S) state**
- Effect of re-combination on ψ(2S) more subtle
  → important when the system is more diluted
  ⇒**Important to test models!**

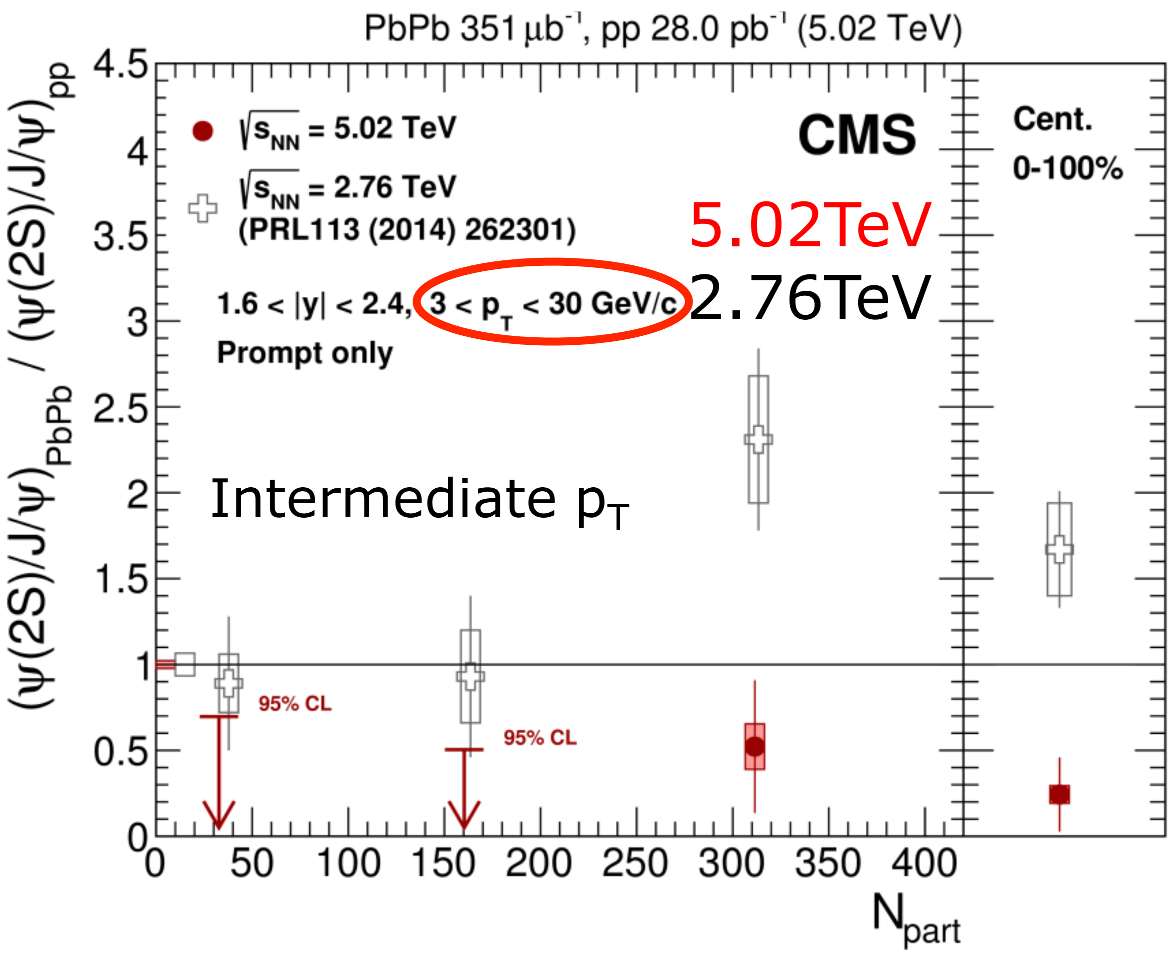
state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.51	3.69
ΔE (GeV)	0.64	0.22	0.05
r_o(fm)	0.50	0.72	0.90

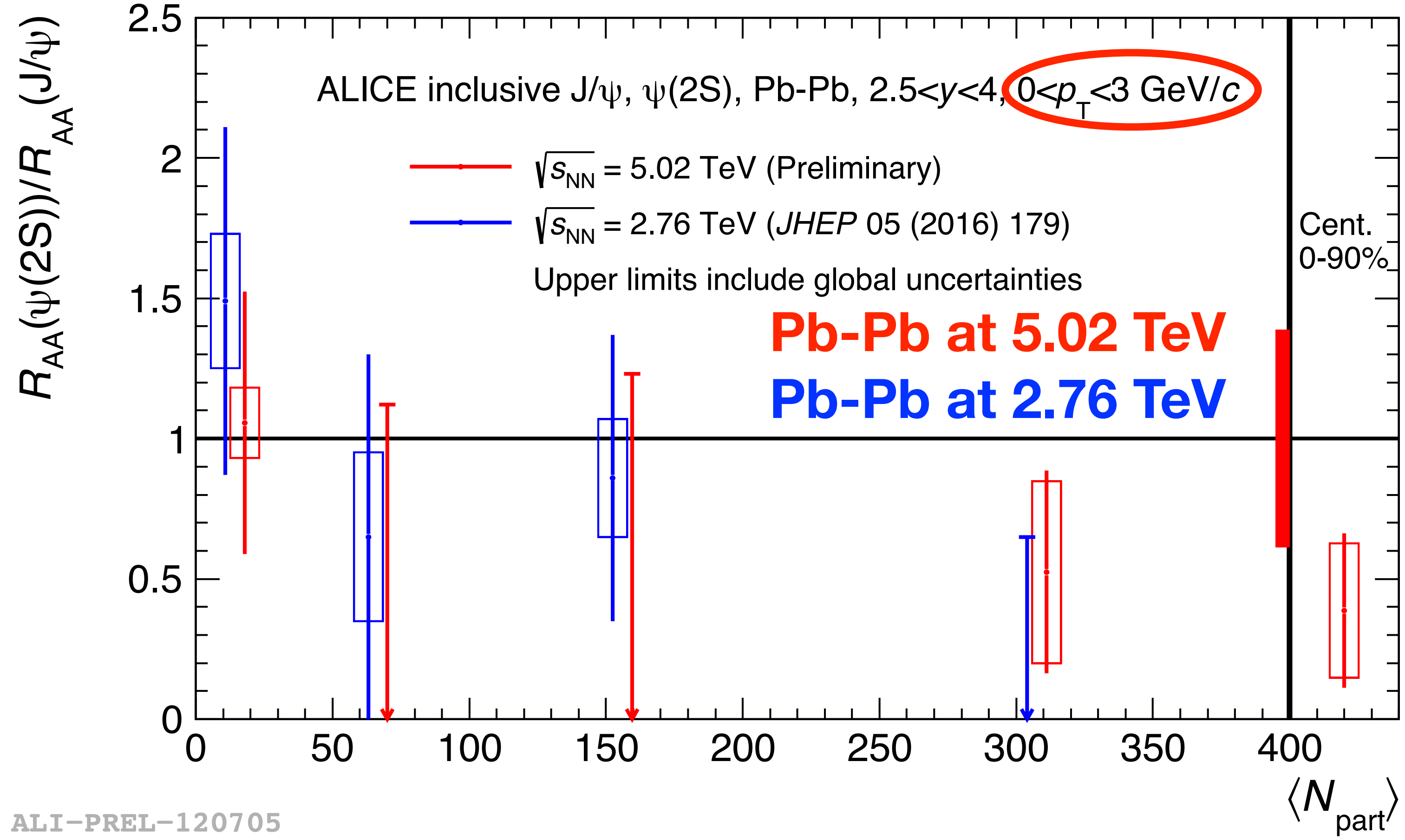
state	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

(Digal,Petrecki,Satz PRD 64(2001) 0940150)

Double ratios ψ(2s)/J/ψ

V. Khachatryan et al. (CMS), arXiv: 1611.01438





- $(\psi(2S)/J/\psi)_{PbPb} / (\psi(2S)/J/\psi)_{pp} \rightarrow \ll 1$ in a dissociation scenario
- CMS (intermediate p_T), **enhancement** to **suppression** for increasing $\sqrt{s_{NN}}$
- ALICE extends down to p_T=0, suppression is seen

- Proposed mechanism (Rapp arXiv:1609.04868) for enhancement: **ψ(2S) regeneration mainly occurring later**, when radial flow is already built-up

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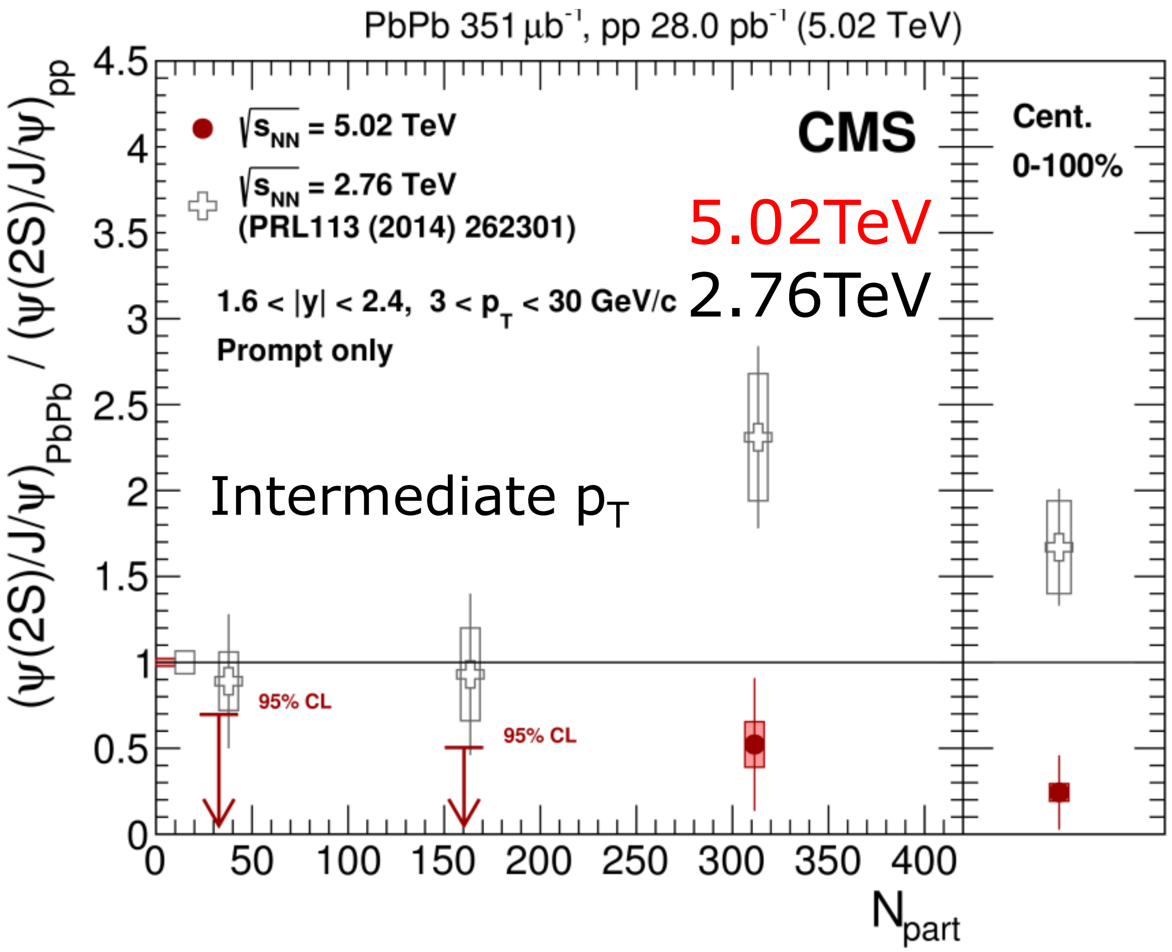
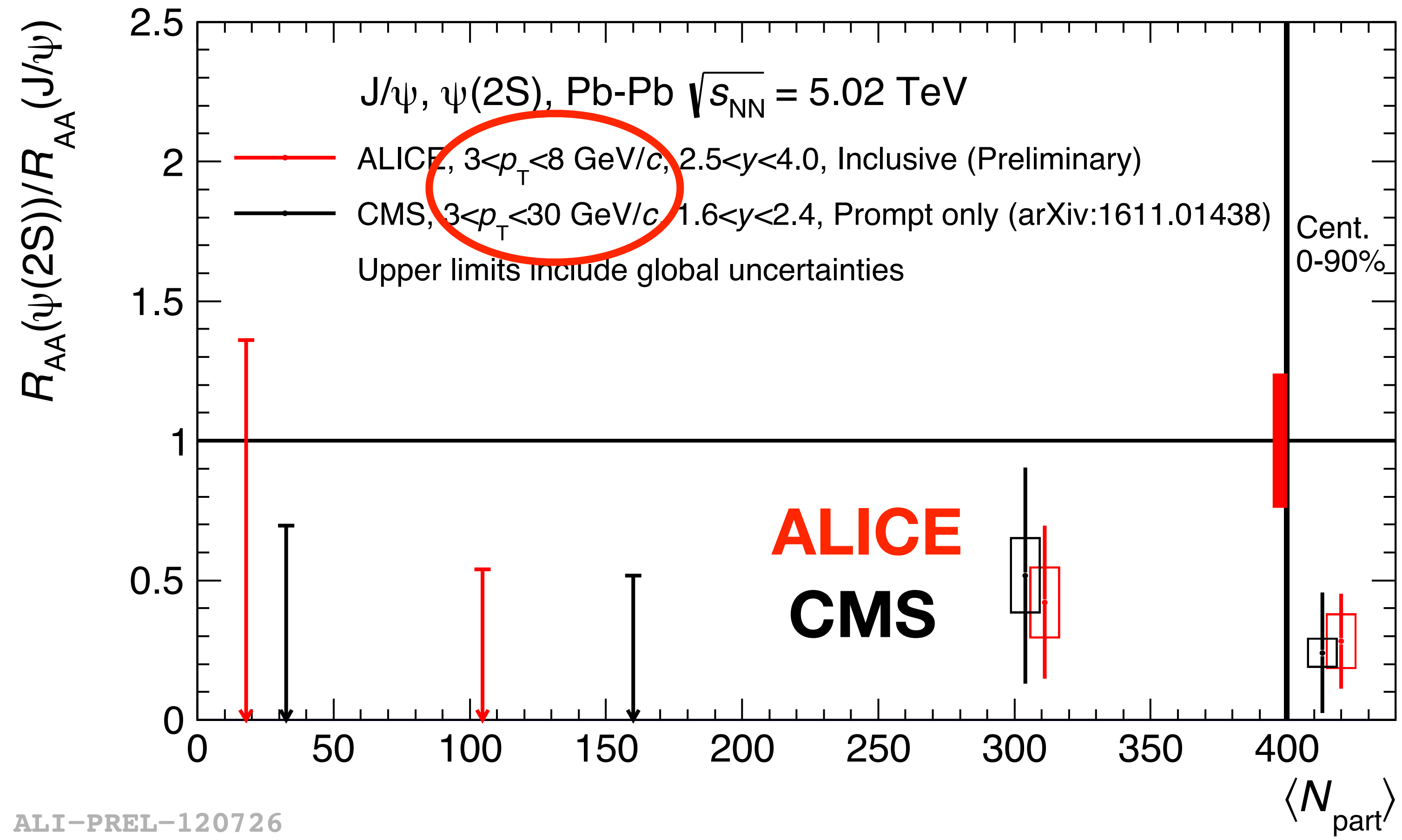




- $(\psi(2S)/J/\psi)_{PbPb}/\ (\psi(2S)/J/\psi)_{pp}$ → ≪ 1 in a dissociation scenario
- CMS (intermediate p_T), **enhancement** to **suppression** for increasing $\sqrt{s_{NN}}$
- ALICE extends down to p_T=0, suppression is seen
- Good compatibility at $\sqrt{s_{NN}}$ =5.02 TeV in the common p_T range

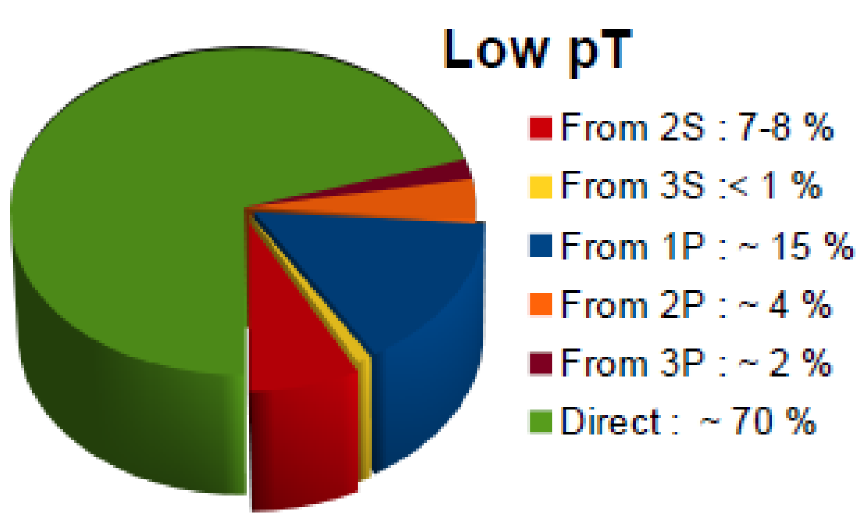
- Proposed mechanism (Rapp arXiv:1609.04868) for enhancement: **ψ(2S) regeneration mainly occurring later**, when radial flow is already built-up

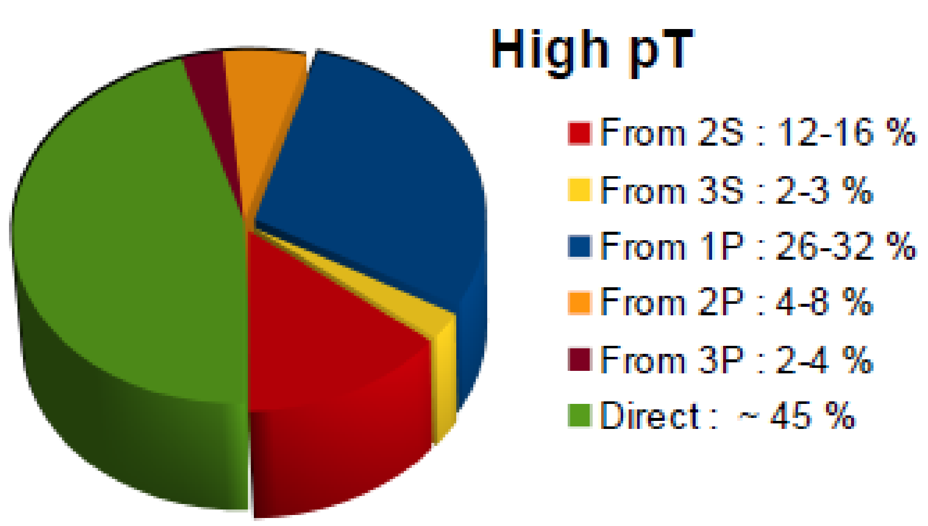
Bottomonium in A-A

- Re-combination effects not strong → simpler interpretation?
- Υ(1S) very strongly bound, $E_b=(2m_B-m_{\Upsilon(1S)})$ ~ 1100 MeV → probe of hot QGP
- Together with Υ(2S) (E_b~500 MeV) and Υ(3S) (E_b~200 MeV) → provide (very) different sensitivity to the medium
- Caveats

1) Realistic theory description anyway not straightforward

2) The feed-down structure of the bottomonium sector is not trivial → has an impact on the interpretation of the result

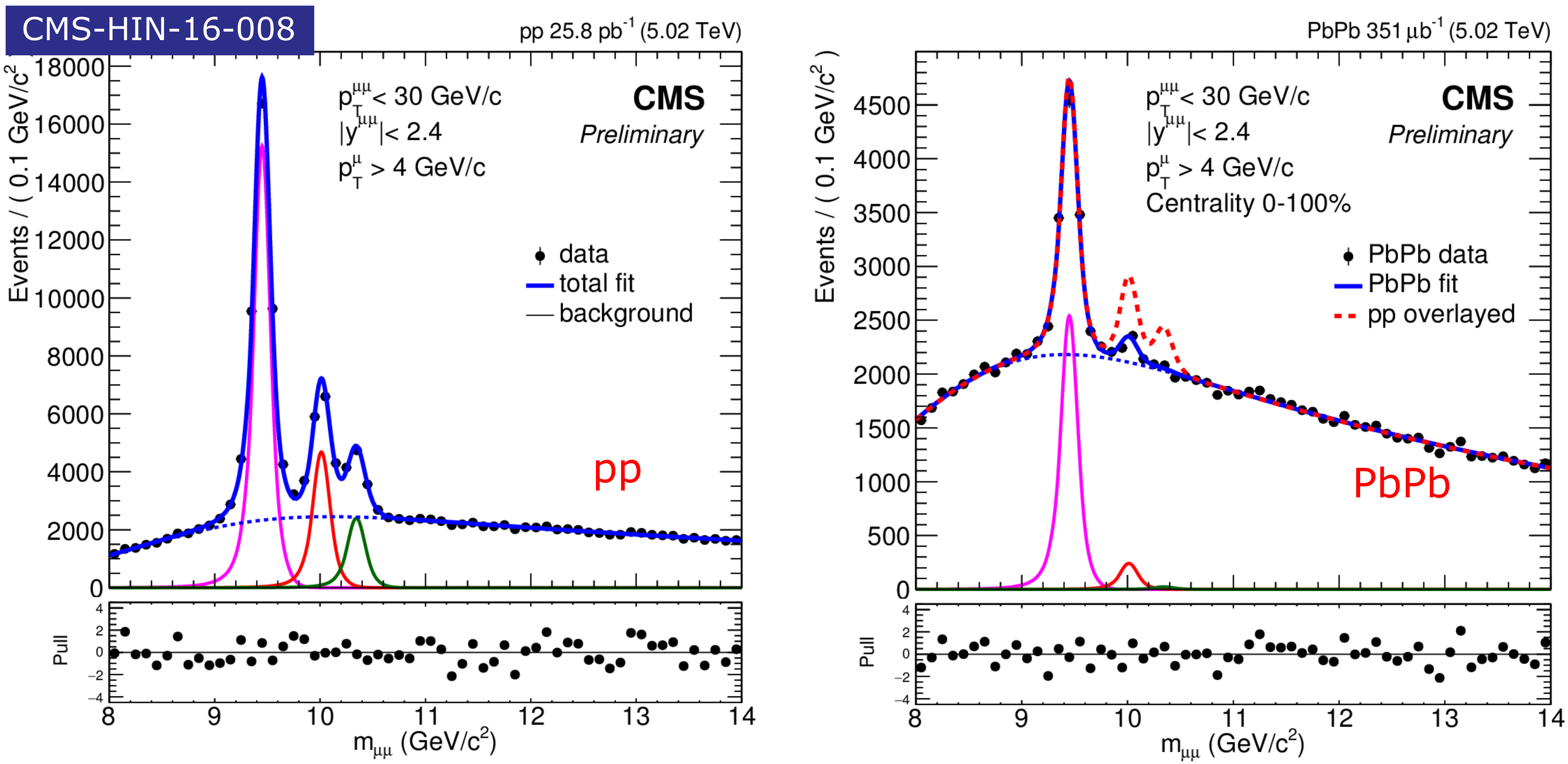




A. Andronic et al., Eur. Phys. J. C 76 (2016) 107

Bottomonium (sequential) suppression

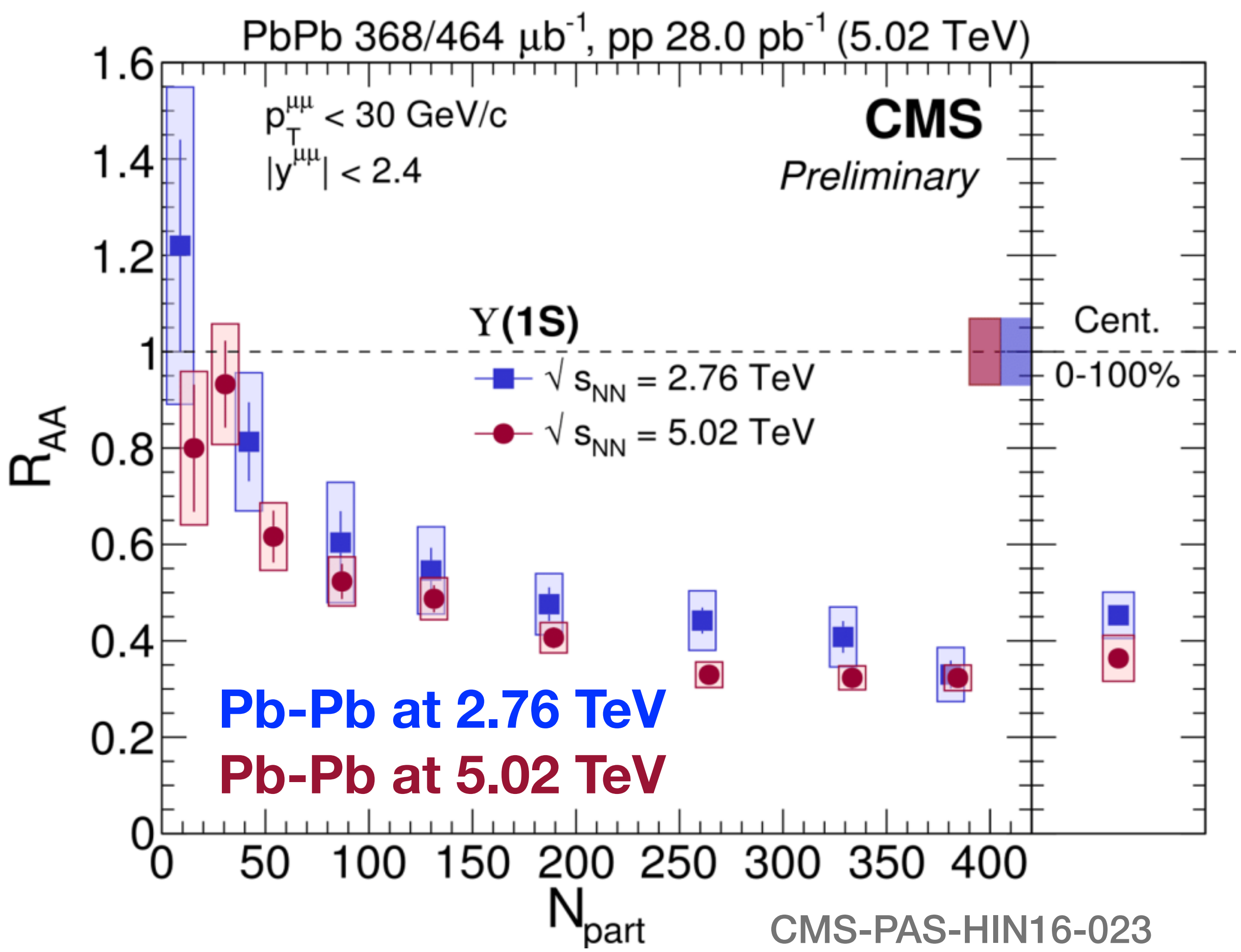
- Quarkonia in HI at the LHC - Sequential suppression?

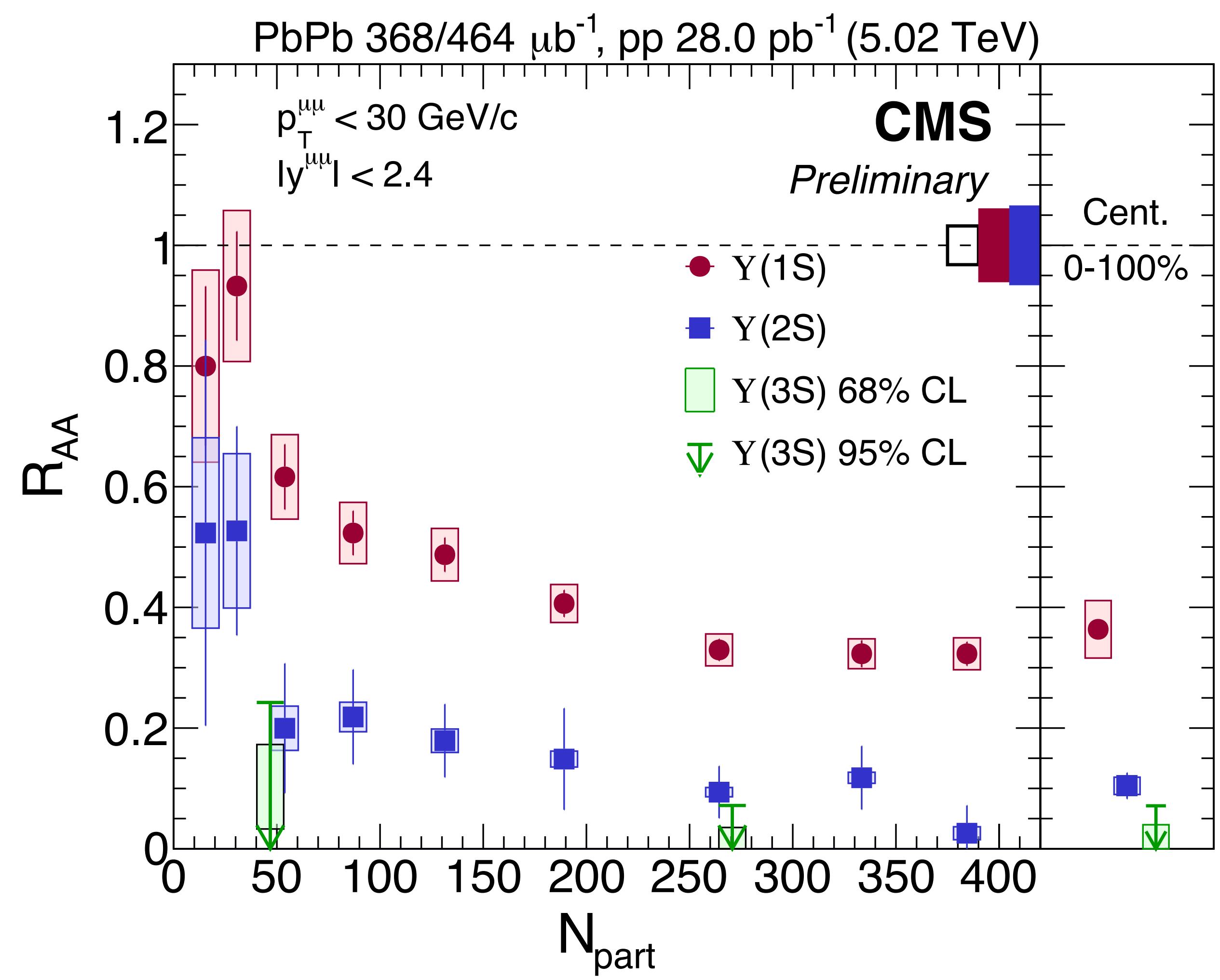


- Recent **CMS results at $\sqrt{s}$=5.02** TeV confirm the Υ(2S,3S) suppression relative to the strongly bound Υ(1S)!

R_{AA} of Υ(1S) and Υ(2S)

- $\sqrt{s_{NN}}$ =2.76 TeV, strong centrality dependence, up to factor ~2 and ~8 suppression for Υ(1S) and Υ(2S), respectively





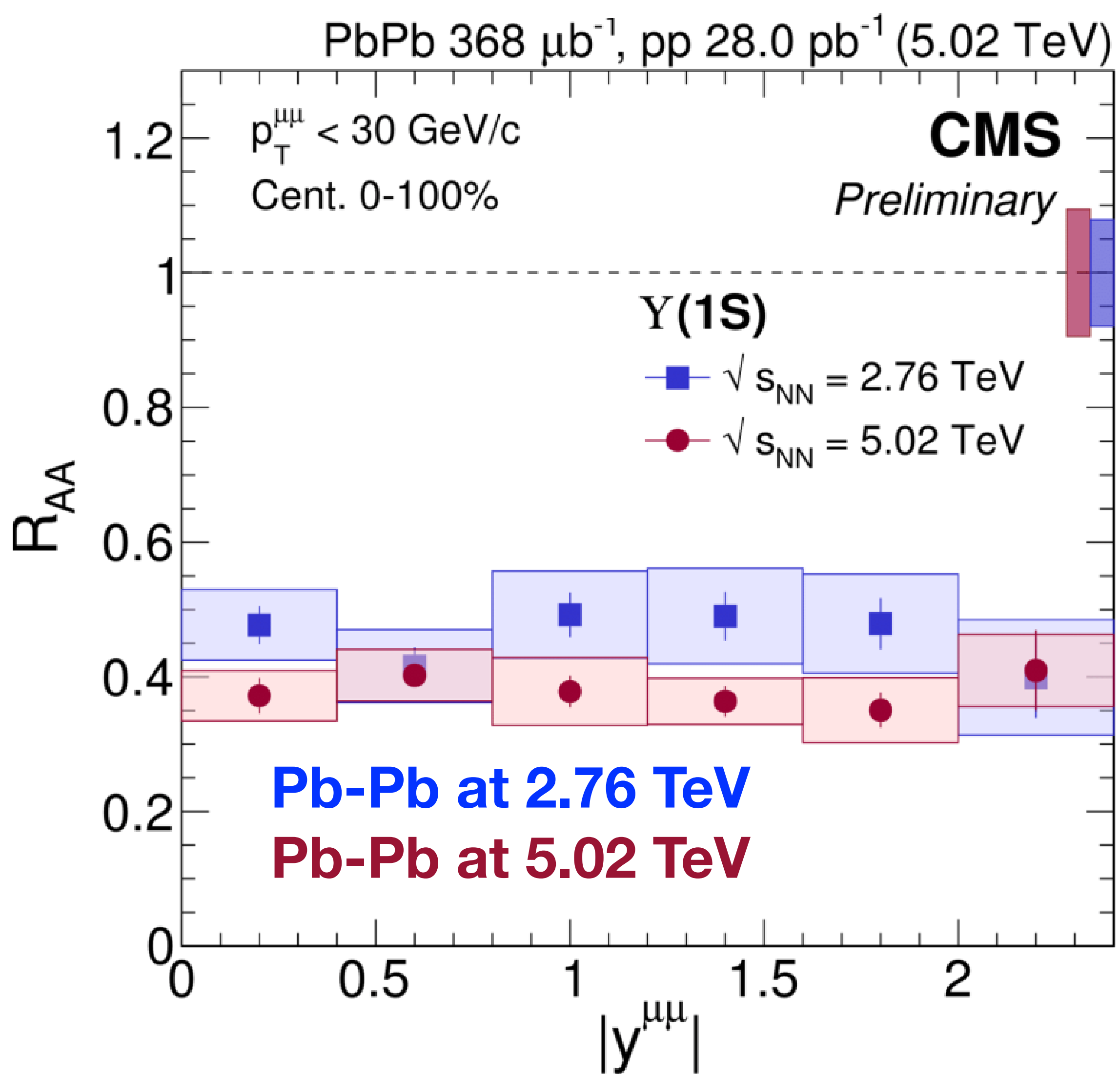
CMS-PAS-HIN16-023

V. Khachatryan et al. (CMS), arXiv: 1611.01510

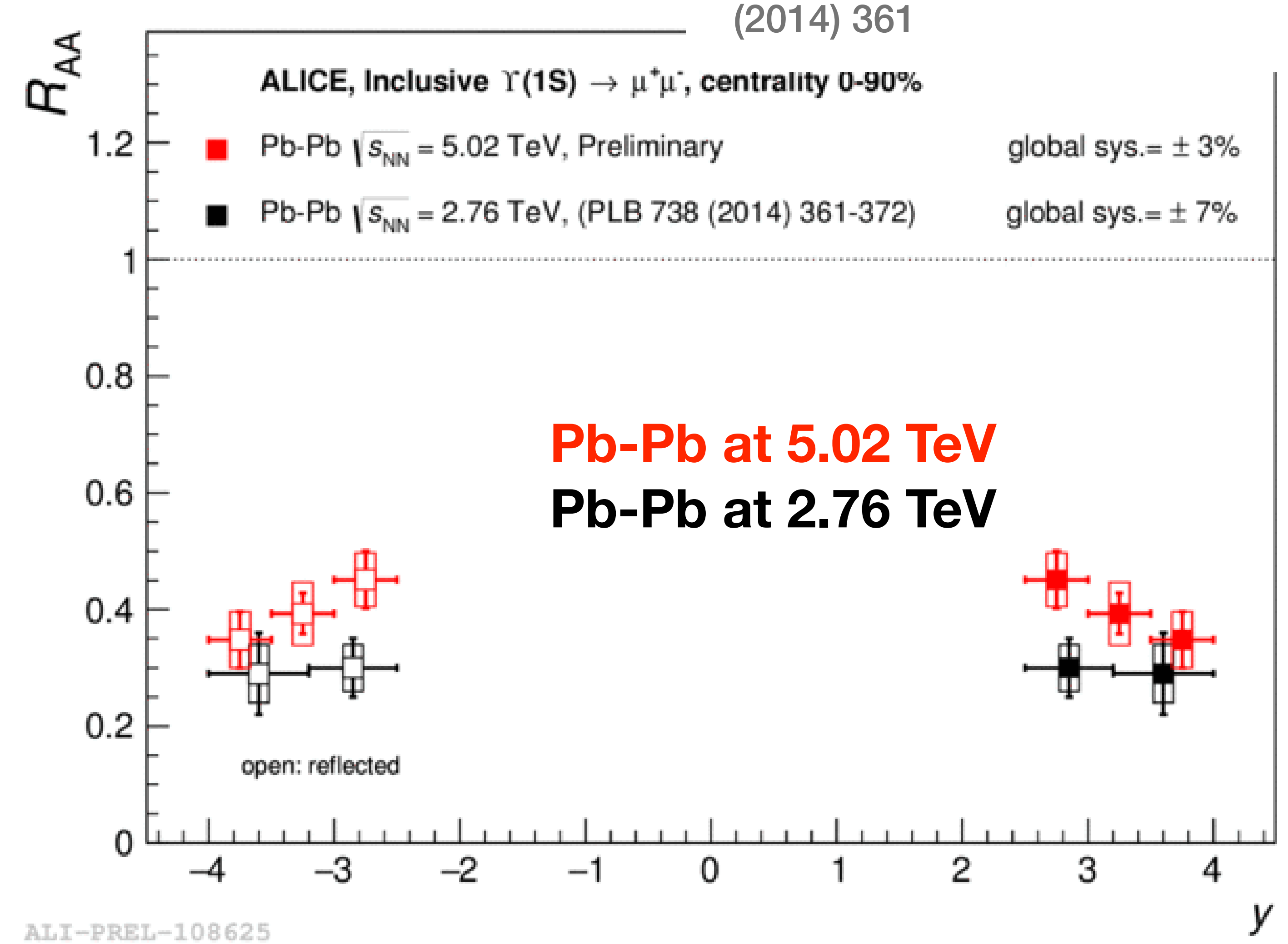
- New CMS results at $\sqrt{s_{NN}}$ =5.02 TeV
  → Indications for slightly stronger suppression

R_{AA} vs y of Υ(1S)

CMS-PAS-HIN16-023

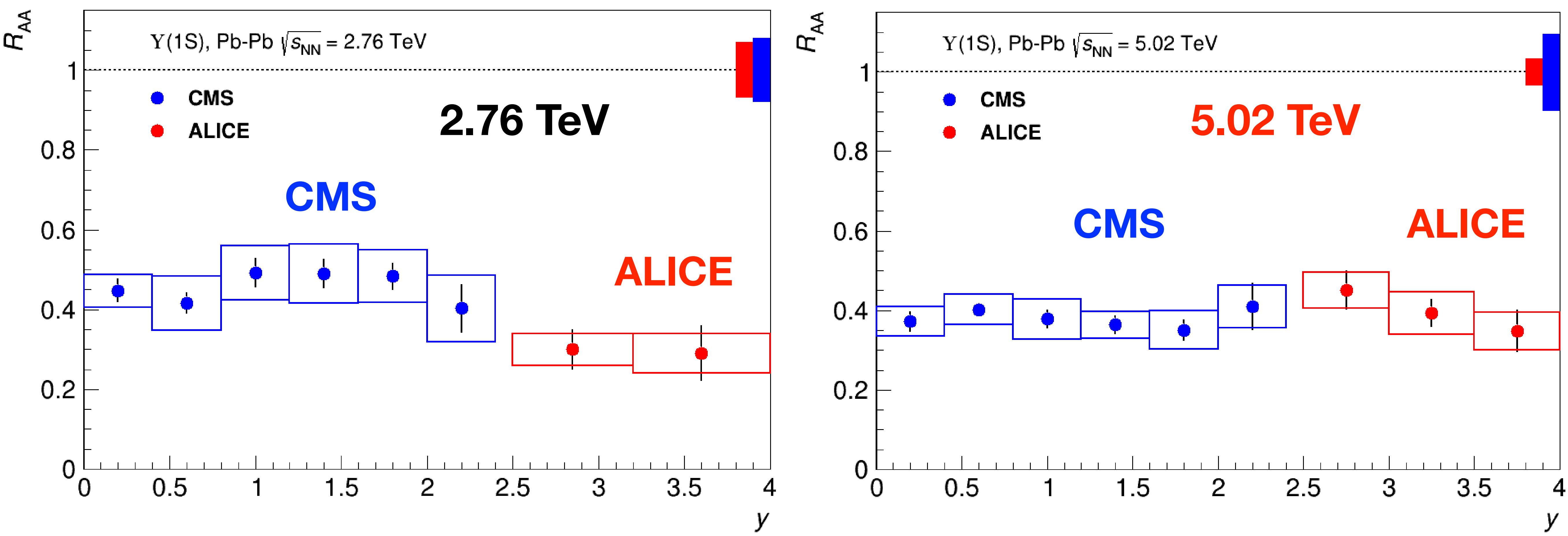


B. Abelev et al., (ALICE) PLB738 (2014) 361



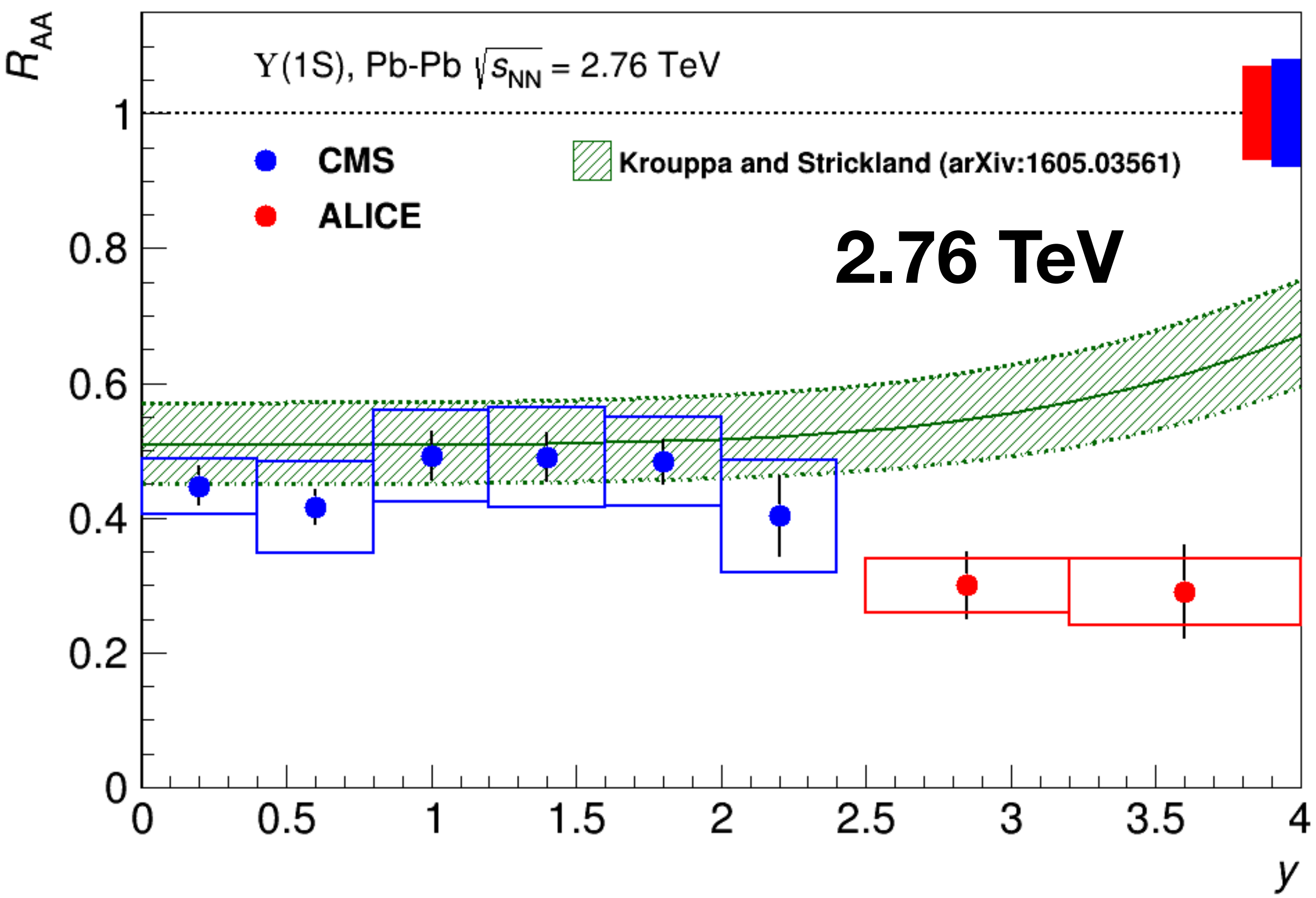
- CMS → hints for more suppression at $\sqrt{s_{NN}}$ =5.02 TeV
- ALICE → hints for less suppression at $\sqrt{s_{NN}}$ =5.02 TeV
- Compare R_{AA} vs y for the two experiments in a single plot

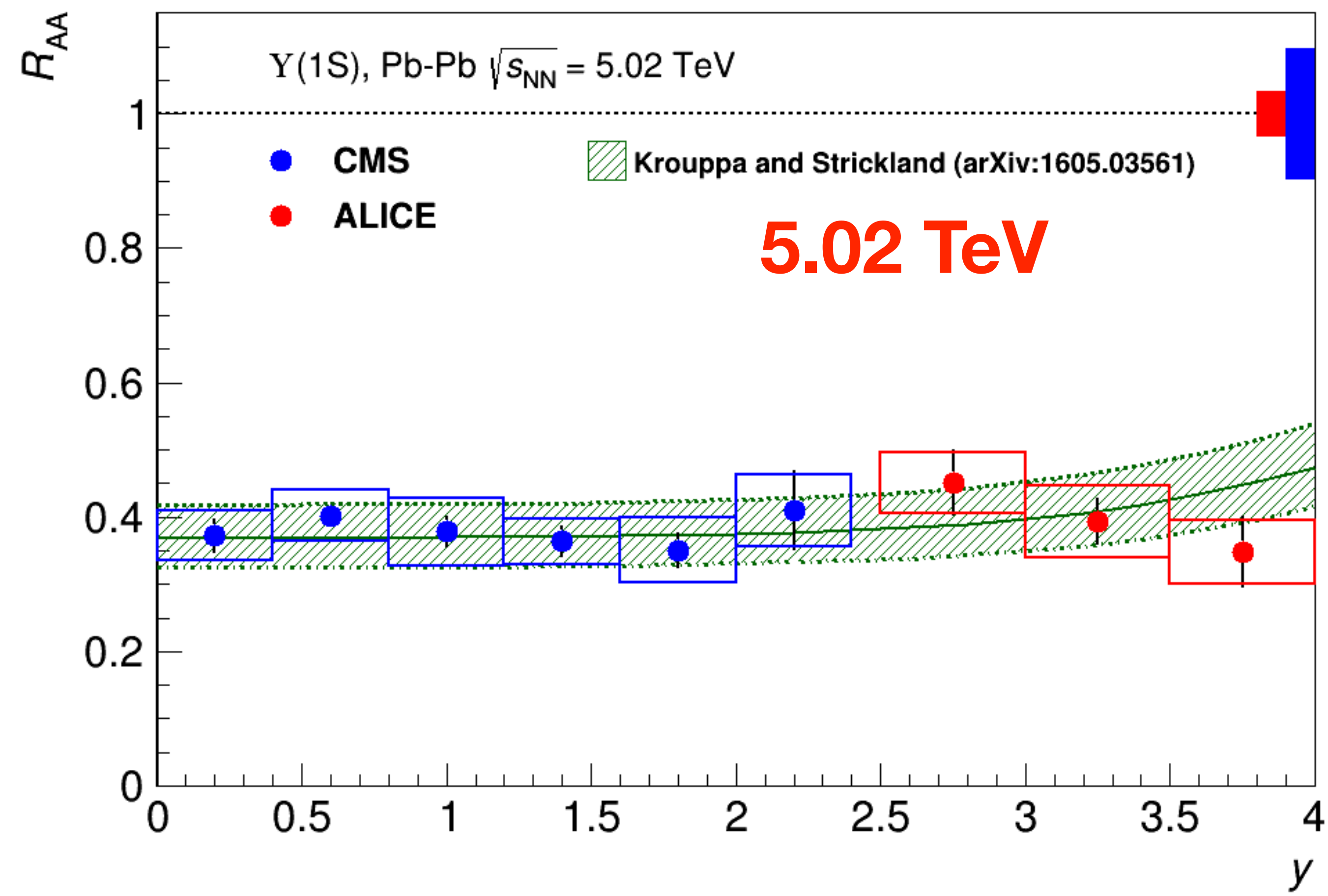
R_{AA} vs y of Υ(1S)



- Suppression **increases** with rapidity at $\sqrt{s_{NN}}$=**2.76 TeV**
- Suppression **constant** vs rapidity at $\sqrt{s_{NN}}$=**5.02 TeV**
- $\sqrt{s_{NN}}$=2.76 TeV: typical features of a **(re)generation pattern,** which seems to vanish at $\sqrt{s_{NN}}$=5.02 TeV
- Systematic uncertainties not negligible

R_{AA} vs y of Υ(1S)





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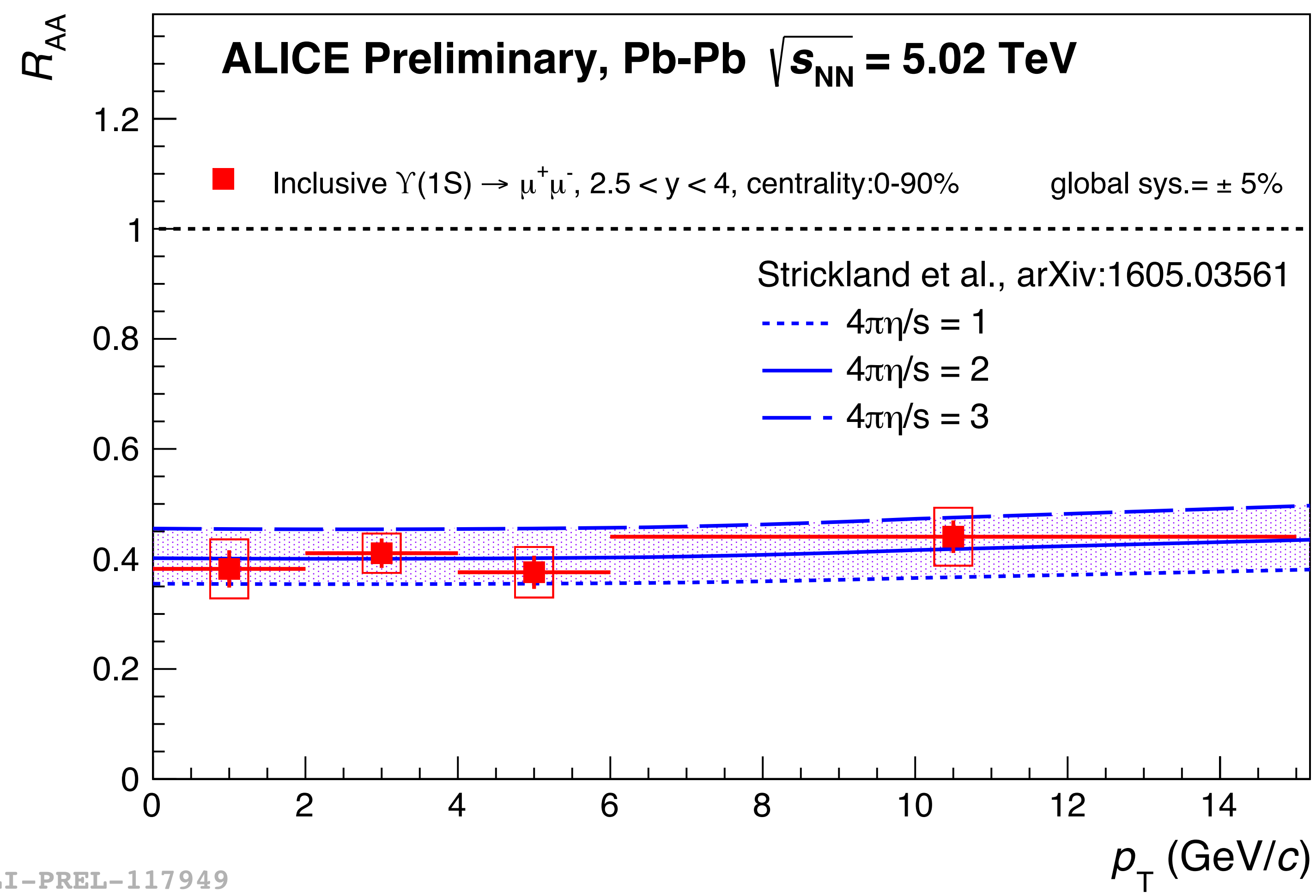
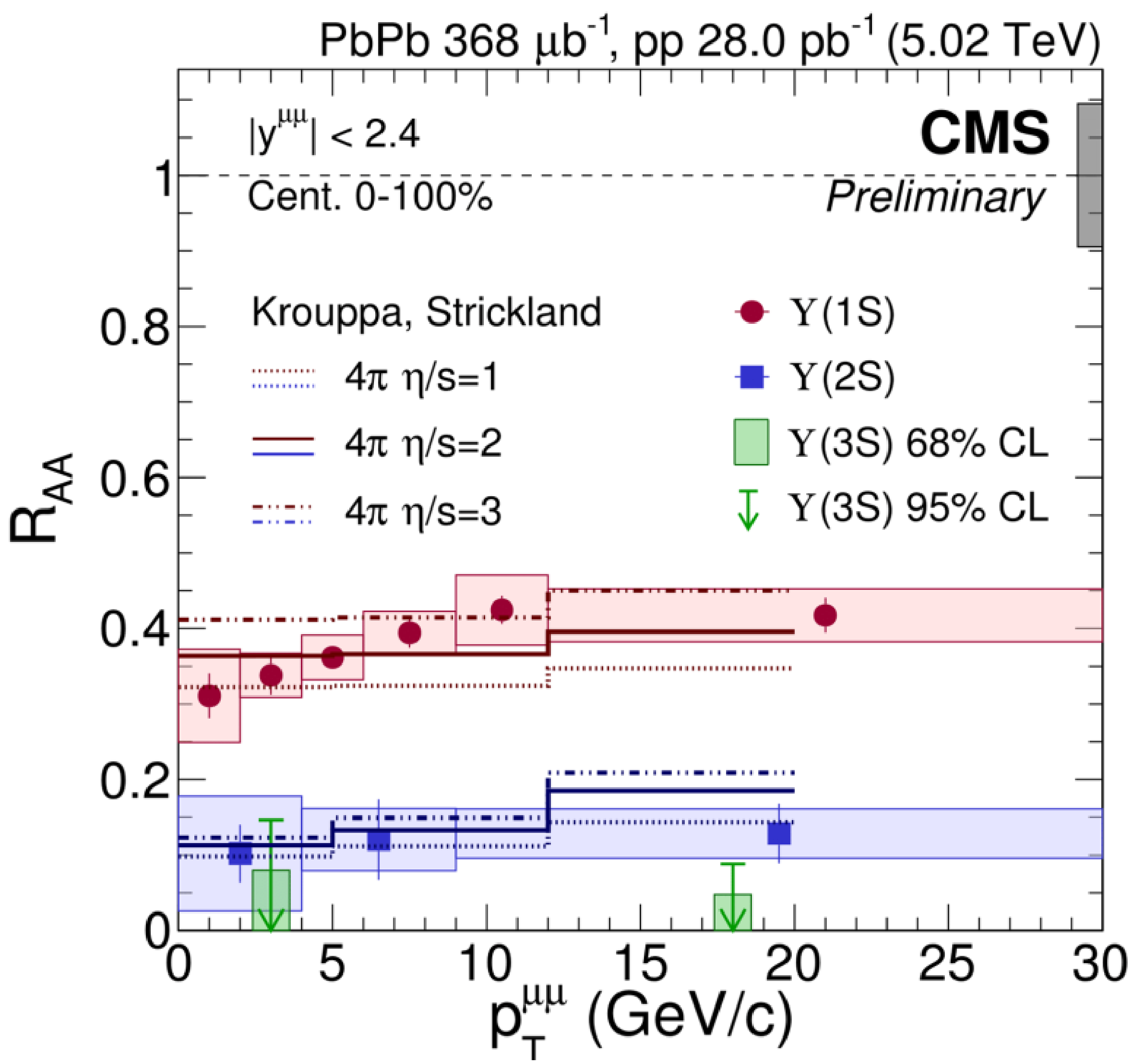
- $\sqrt{s_{NN}}$=2.76 TeV: typical features of a **(re)generation pattern,** which seems to vanish at $\sqrt{s_{NN}}$=5.02 TeV
- Systematic uncertainties not negligible
- Can the rapidity-dependence of CNM effects play a role? Not likely

R_{AA} vs p_T of Υ(1S)





CMS-PAS-HIN16-023

- **Both CMS and ALICE measure weak or no dependence of R_{AA} vs p_T**
- **Fair agreement with theoretical model (Strickland)**

Summary

- Charmonia (J/ψ, ψ(2S))

  Firm evidence for J/ψ elliptic flow and strong re-generation effects

  → Charm quarks thermalization in the deconfined medium

- Bottomonia (Υ(1S), Υ(2S), Υ(3S))

  Suppression effects strongly correlated with binding energy

  → Evidence for resonance melting in a hot QGP

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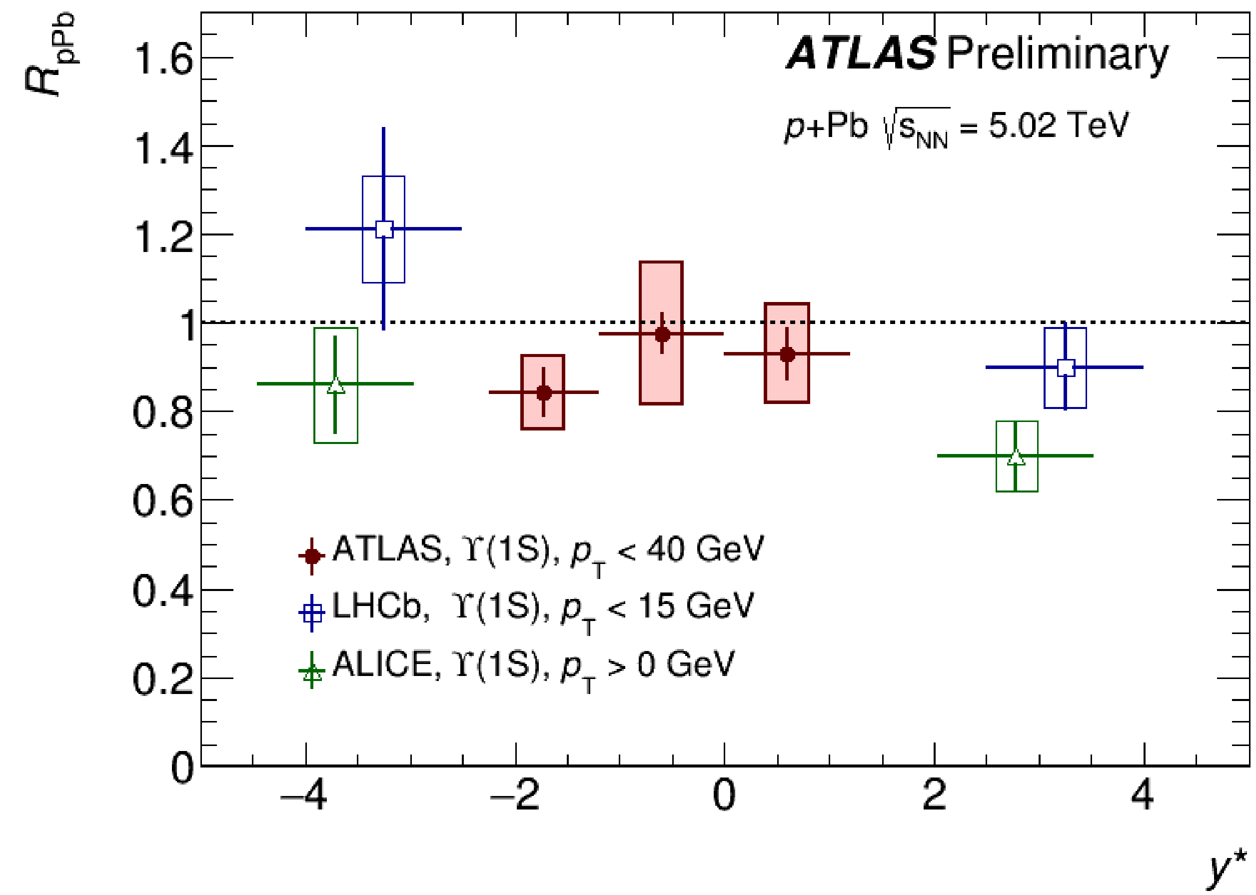
Thank you for your attention!

Extra Slides

Experimental evidence for direct Υ(1S) suppression?

- Direct Υ(1S) suppression implies QGP temperatures at least ~2 T_C
- Experimental evidence for direct Υ(1S) suppression needs control over
  - Feed-down from S and P bottomonium states

    Recent LHCb results imply a ~ 30% effect at (fairly) low p_T in pp
  - Size of CNM effects → weak but not precisely known



- Starting from CMS results and assuming all the remaining Pb-Pb Υ(1S) are direct

  R_{AA}^{incl} Υ(1S) ~ 0.36

  R_{AA}^{direct} Υ(1S) ~ 0.36/0.7 = 0.51

  CNM effects (-1σ level)

  → $(R_{pA} - 1\sigma)^2 \sim 0.8^2 = 0.64$

- Experimental indication for direct Υ(1S) suppression!

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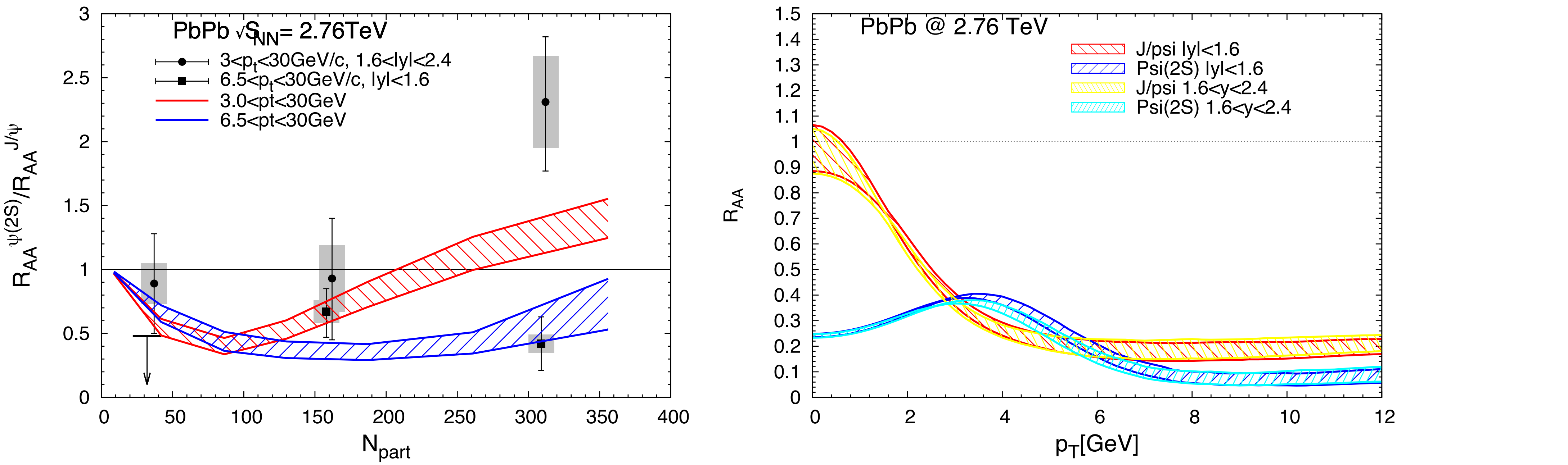


Figure 1. Charmonium production in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV within the kinetic rate equation approach. Left panel: centrality dependence of the double ratio $R_{\rm AA}(\psi(2S))/R_{\rm AA}(J/\psi)$ for p_T>6.5 GeV and $|y|$<1.6 (blue band) as well as p_T>3 GeV and 1.6<$|y|$<2.4 (red band), compared to CMS data [7]. Right panel: p_T dependence of the individual J/ψ and $\psi(2S)$ $R_{\rm AA}$'s for central collisions. A 10 % shadowing is assumed in the p_T-spectra according to EPS09 NLO [12].

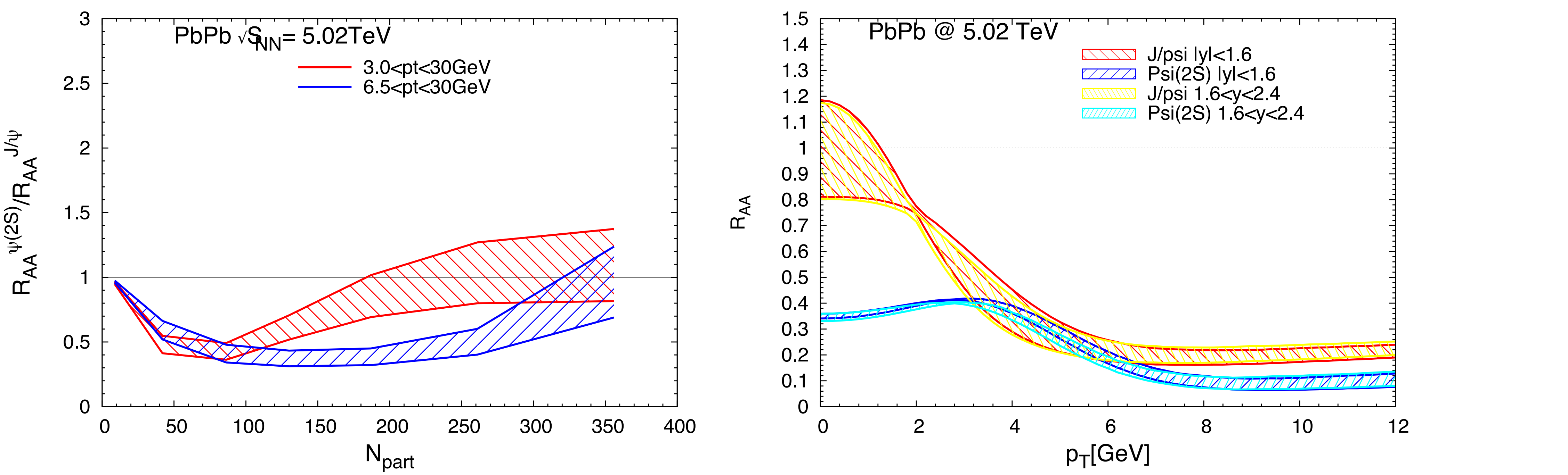
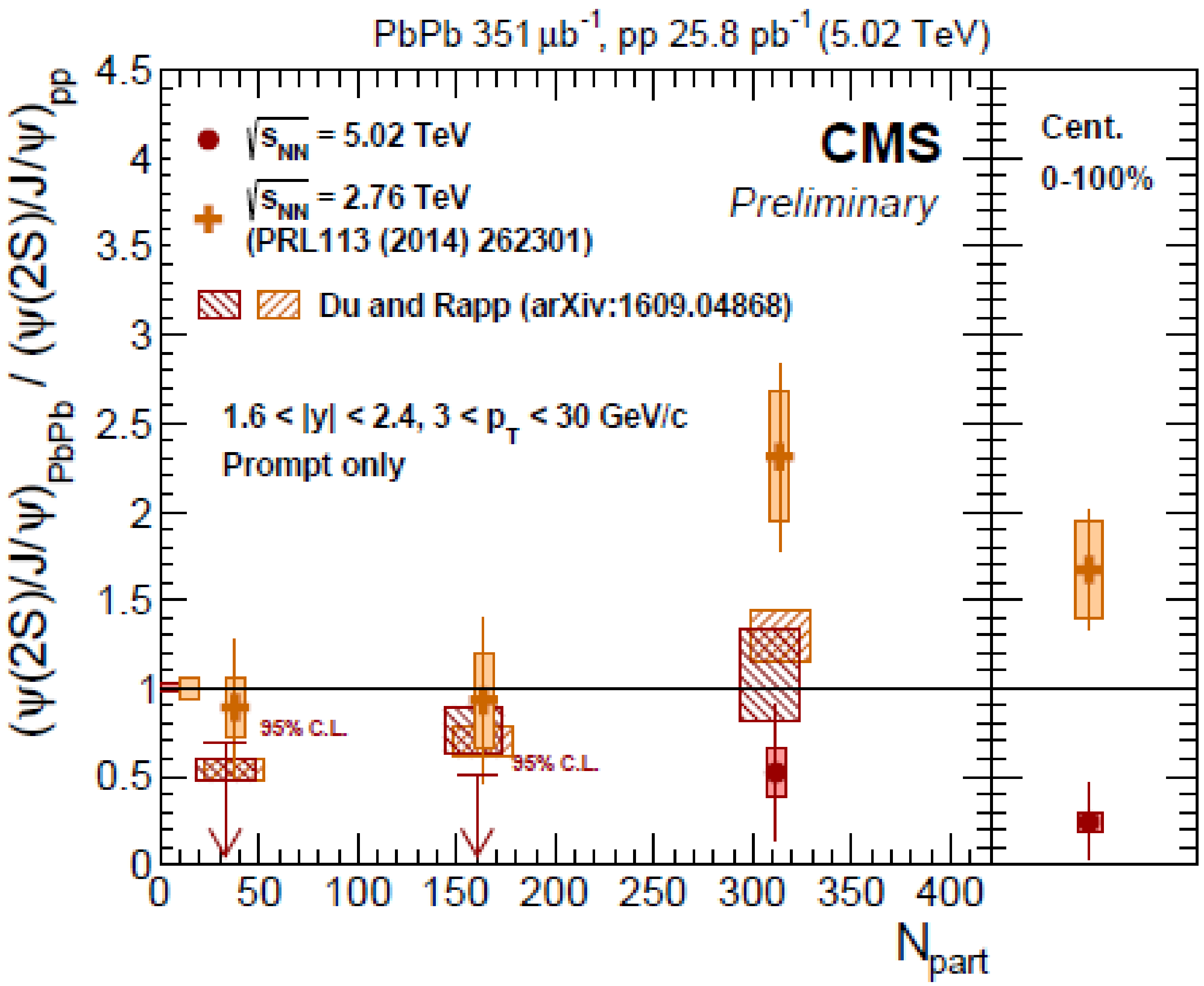
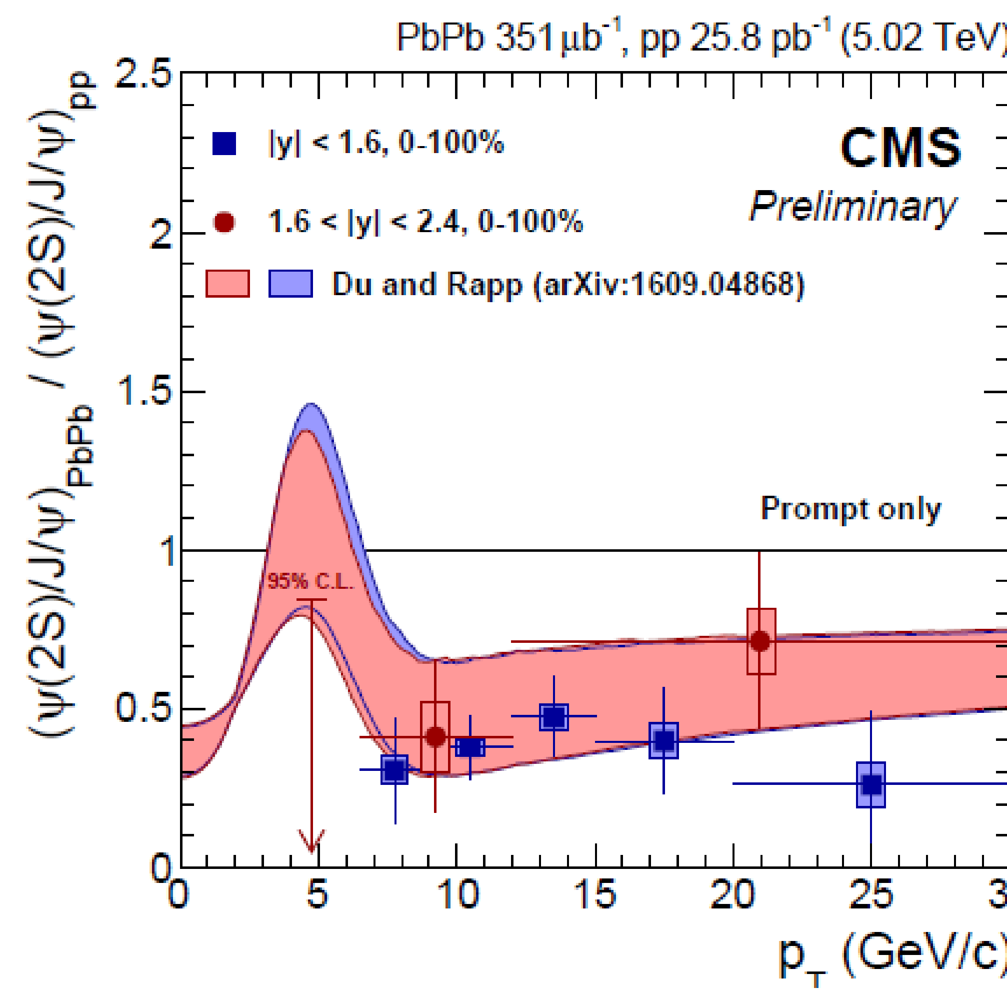
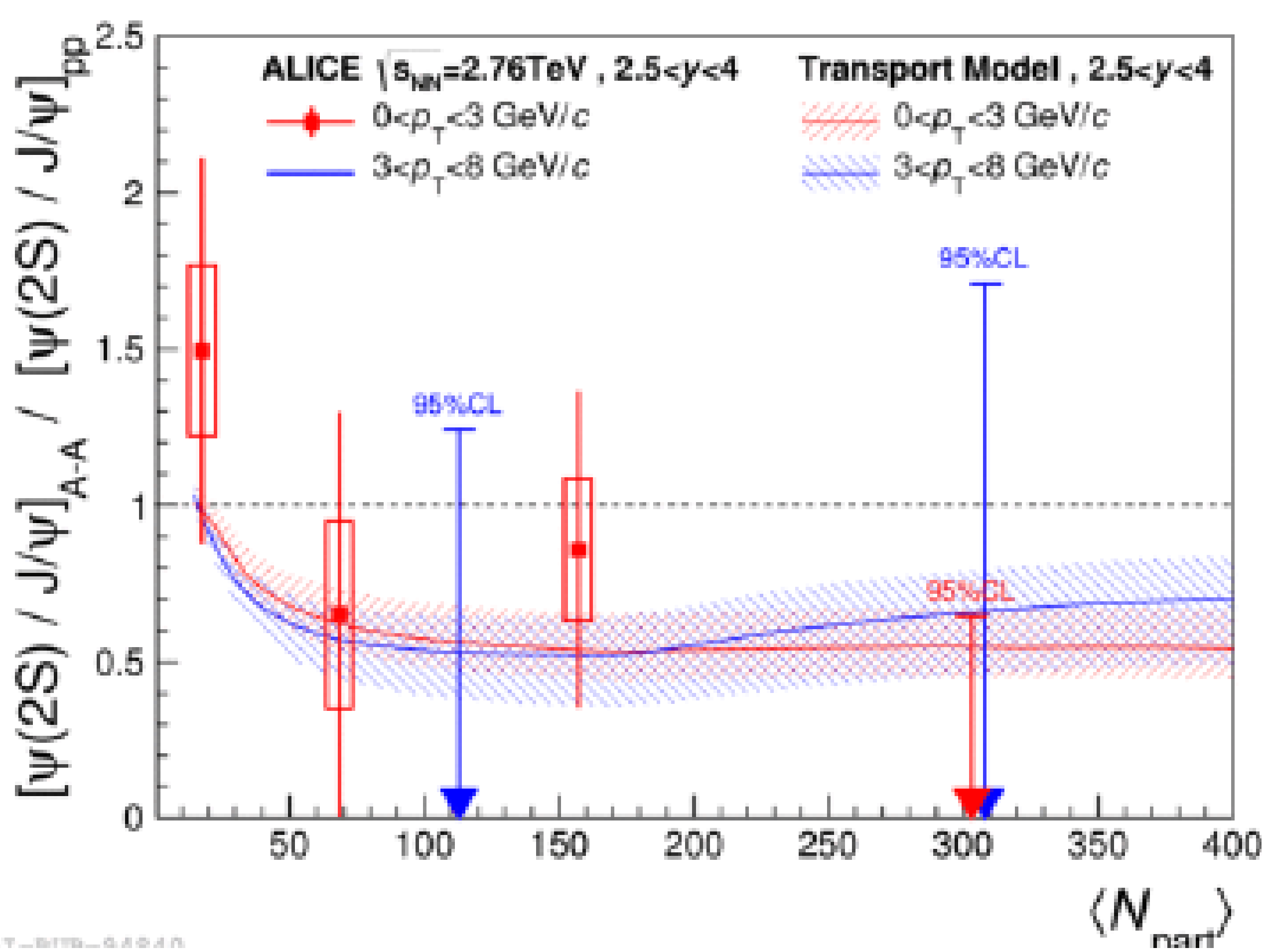


Figure 2. Same as Fig. 1 but for Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV.







- ψ(2S) regeneration occurring at higher p_T due to larger flow push
- Smart ad-hoc explanation for the enhancement at 2.76 TeV, still needed?
- Quality of ALICE results should improve in run-2 in order to give valuable input

increase in suppression for forward rapidities, which is due to the increased plateau halfwidth used in the initial conditions.

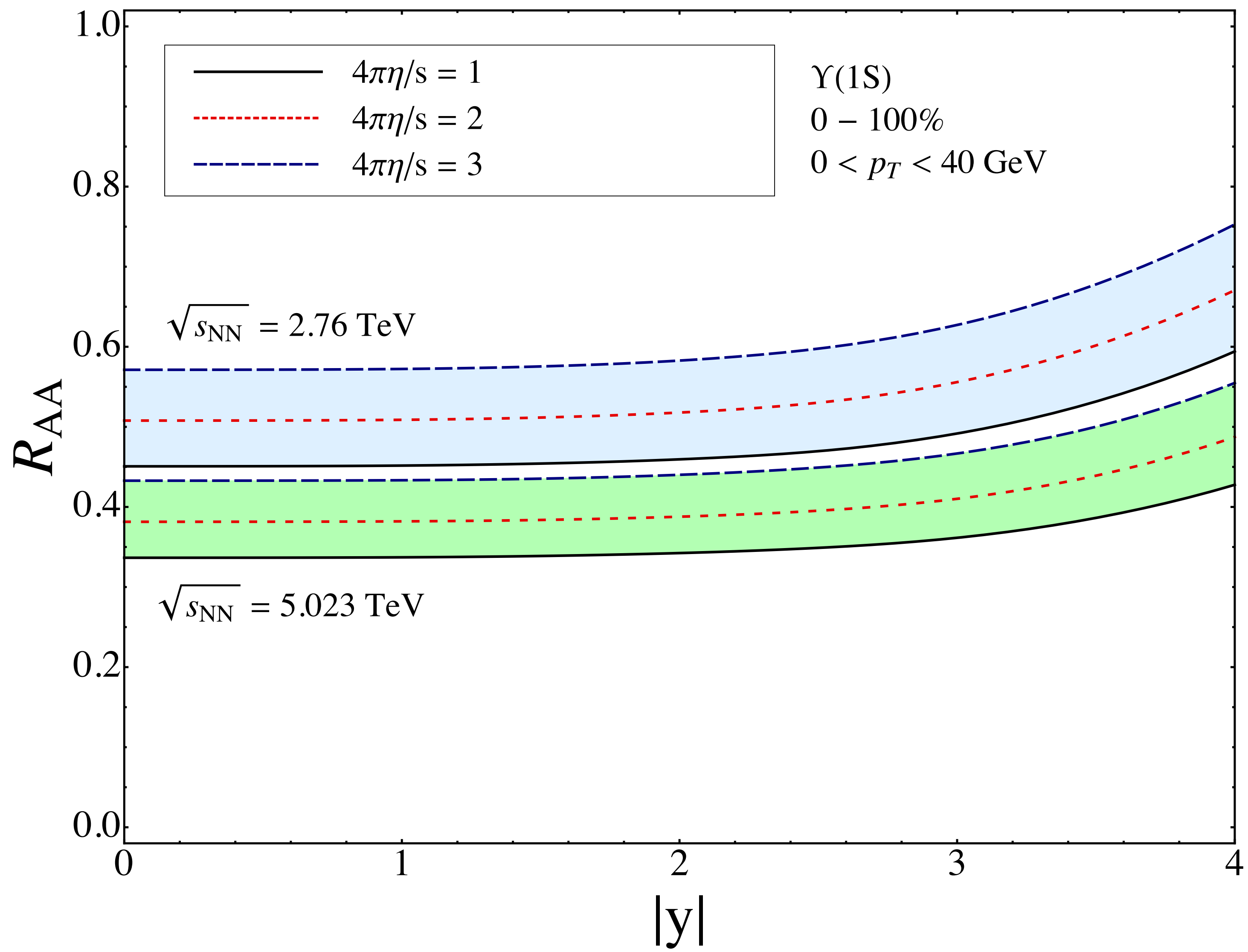


Figure 4. (Color online) Inclusive $\Upsilon(1S)$ state calculated with feed down contributions from excited states. Here we show a comparison between $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.023$ TeV collision energies.