

# Quarkonium production in AA (pA) collisions

E. Scomparin (INFN-Torino)

- ❑ A short introduction
  - 30 years ago at Quark Matter
- ❑ RHIC and LHC at work
  - New discoveries, better understanding
- ❑ Open points and prospects
  - Where do we stand ? Is the future bright ?

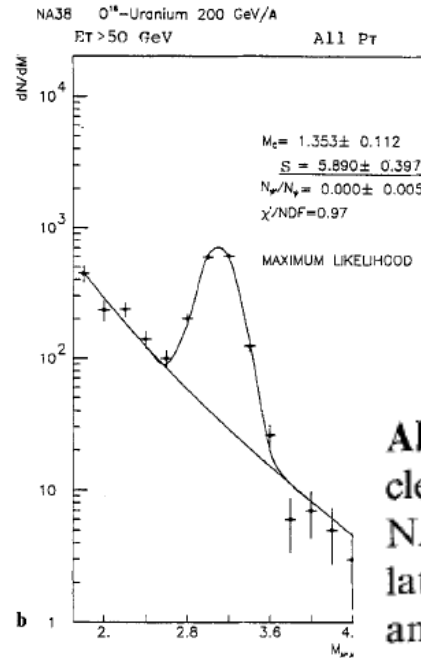
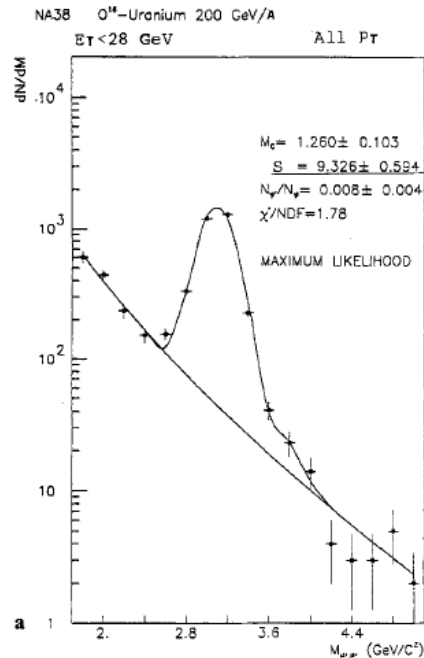


The bottom of the slide features a composite image. On the left, there is a stylized logo for 'Quark Matter 2017'. The word 'Quark' is in red, and 'Matter' is in white. The 'Q' in 'Quark' is large and red, with a grid of colored dots (red, orange, yellow, green) forming its shape. Below 'Matter' is the year '2017' in red. To the right of the logo is a silhouette of a city skyline at night, with various skyscrapers. The background of the entire slide is a dark blue night sky filled with stars.

Quark  
Matter  
2017

# The beginning...

- “If high-energy heavy ion collisions lead to the formation of a quark-gluon plasma, then **color screening prevents cc binding** in the deconfined interior of the interaction region” (Matsui, Satz, 1986)



- NA38, O-U collisions at the **CERN SPS**
- 200 GeV/nucleon (lab system!  $\sqrt{s_{NN}} = 19.4$  GeV)

## Quark Matter 87

First evidence for  $J/\psi$  suppression in nuclear collisions!

**Abstract.** The dimuon production in 200 GeV/nucleon oxygen-uranium interactions is studied by the NA38 Collaboration. The production of  $J/\psi$ , correlated with the transverse energy  $ET$ , is investigated and compared to the continuum, as a function of the dimuon mass  $M$  and transverse momentum  $PT$ . A value of  $0.64 \pm 0.06$  is found for the ratio  $(\Psi/\text{Continuum at high } ET)/(\Psi/\text{Continuum at low } ET)$ , from which the  $J/\psi$  relative suppression can be extracted. This suppression is enhanced at low  $PT$ .

# ...and the feedback of the audience....

From the QM87 summary talk

The most provocative observation, reported by NA 38 [13], was that  $J/\psi$  production seems to be suppressed by  $\sim 30\%$  in high  $E_T$  events. The second provocative

## 3 Puzzles

$$N_{\psi}/N_c = \begin{cases} 9.3 \pm 0.6 & \text{for } E_T < 28 \text{ GeV} \\ 5.9 \pm 0.4 & \text{for } E_T > 50 \text{ GeV.} \end{cases}$$

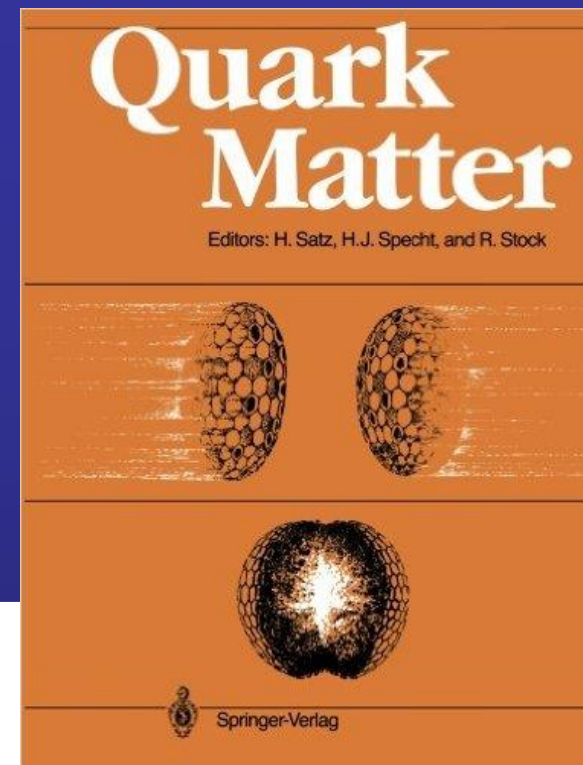
### 3.1 $J/\psi$ suppression

This 30% reduction of  $\psi$  production caused the most controversy at Quark Matter '87.

There are naturally several caveats that need further consideration. First, there is the problem of pro-

- ❑ Competing sources of  $J/\psi$  dissociation involving hadronic interactions (with cold nuclear matter and/or hadronic medium) can reproduce the observations if  $\sigma_{\text{diss}} \sim 1\text{-}2 \text{ mb}$

A **signature of deconfinement**,  
or just a **generic signature** for dense matter formation?

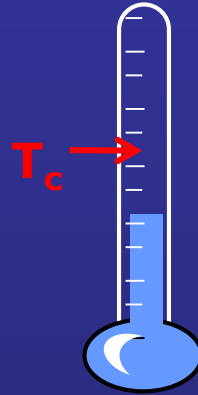
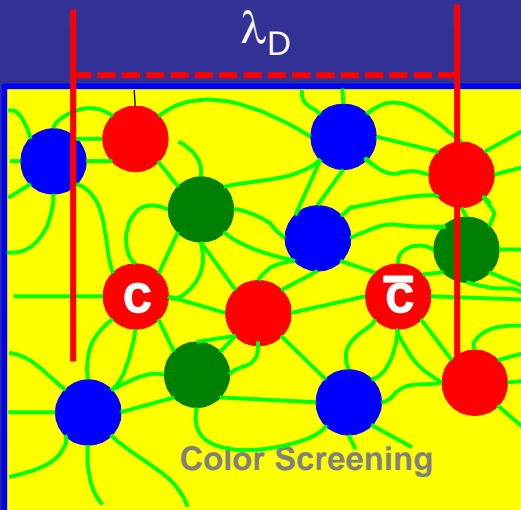


# Where do we stand, after 30 years ?

- ❑ A wealth of high-quality data have been accumulated, at various facilities (SPS, RHIC, LHC) for various collision systems
- ❑ Do experimental results allow us to
  - 1) Understand the phenomenology of quarkonium in HI ?
  - 2) Extract quantitative/detailed information on the QGP features ?
- ❑ In this talk
  - **The “push” from experiments is very strong**
  - Let’s discuss lots of high quality new data**
- ❑ As for all observables in HI, interaction with theory is mandatory → see next talk



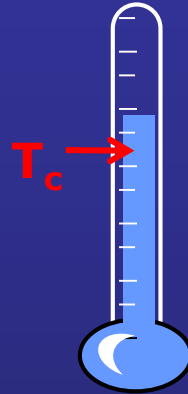
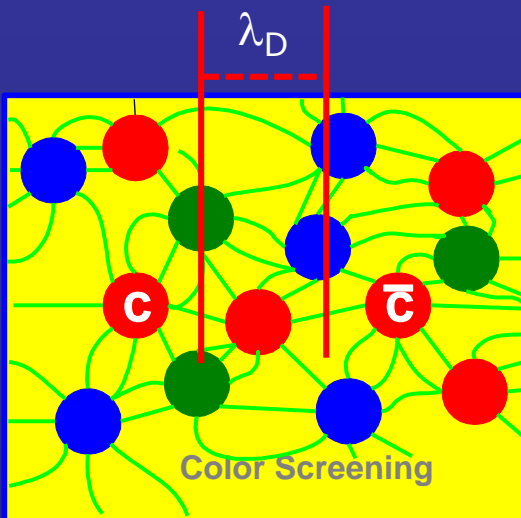
# $J/\psi$ in AA collisions



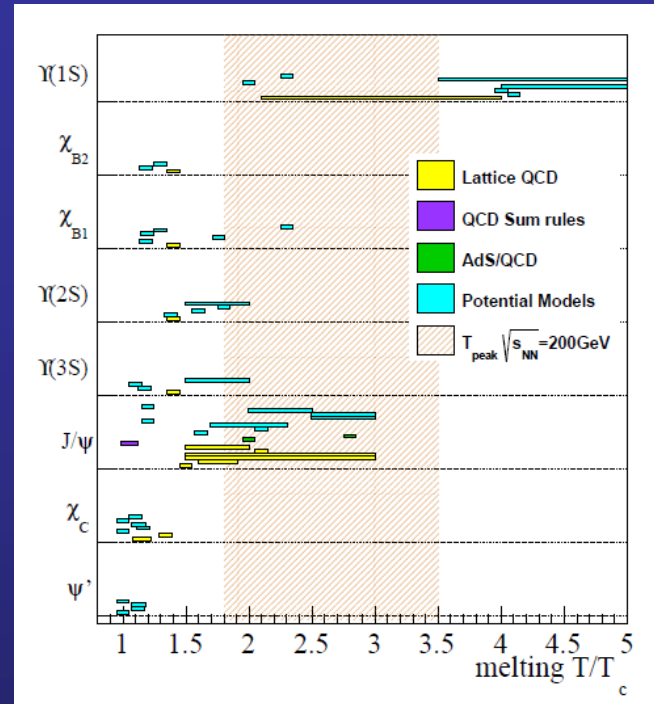
**From  
color  
screening**

Quarkonium melting  
→ QGP thermometer

# J/ψ in AA collisions

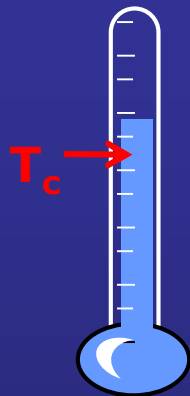
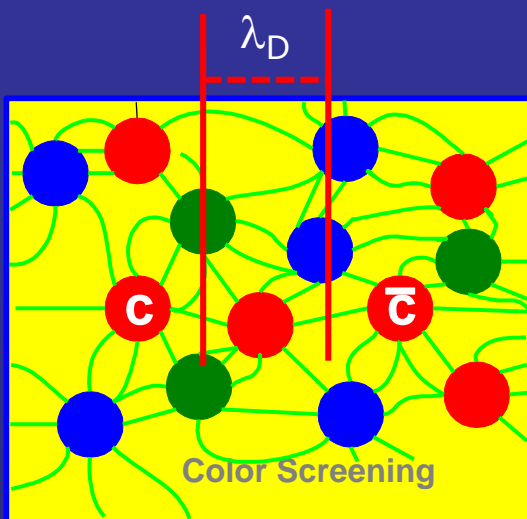


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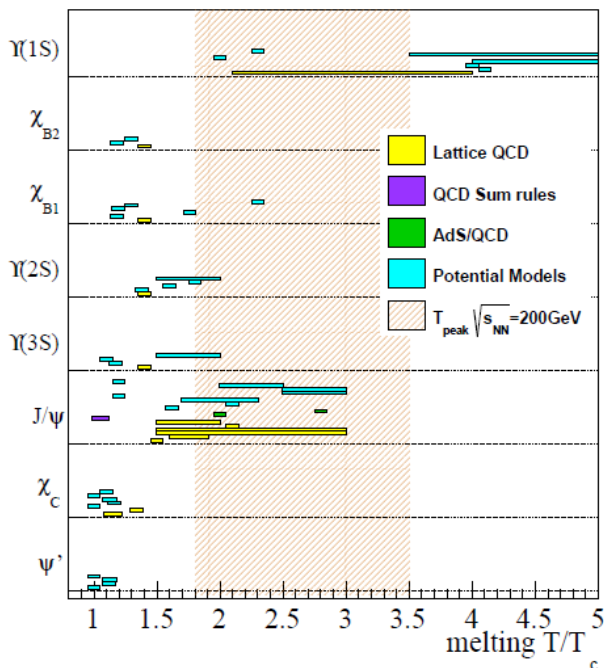


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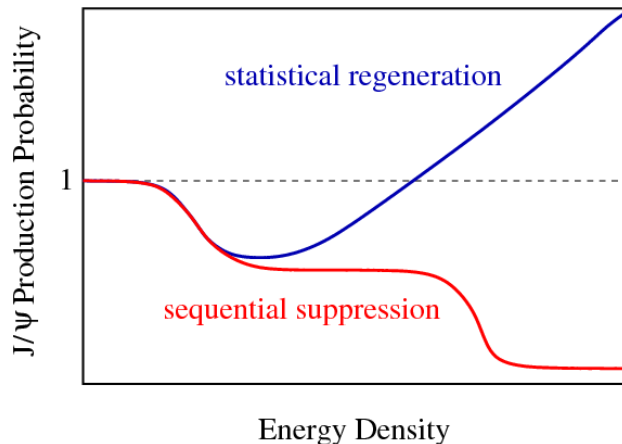
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From  
color  
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Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5 TeV
$N_{c\bar{c}bar}/\text{event}$	$\sim 0.2$	$\sim 10$	$\sim 115$

Quarkonium (re)generation  
→ Heavy quark dynamics in QGP



to  
quark  
(re)  
combination

# Disclaimer

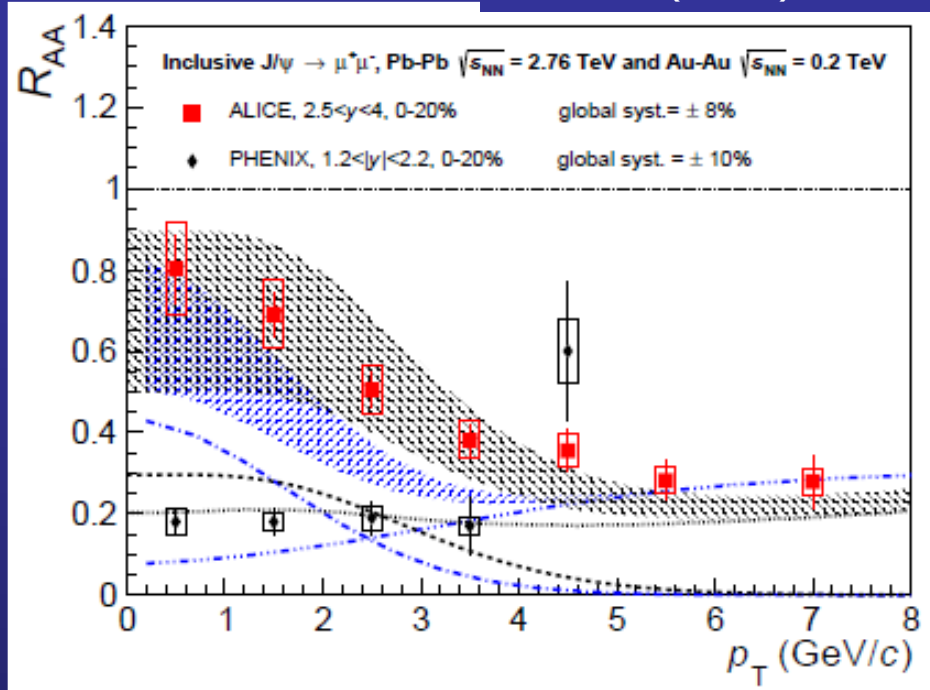
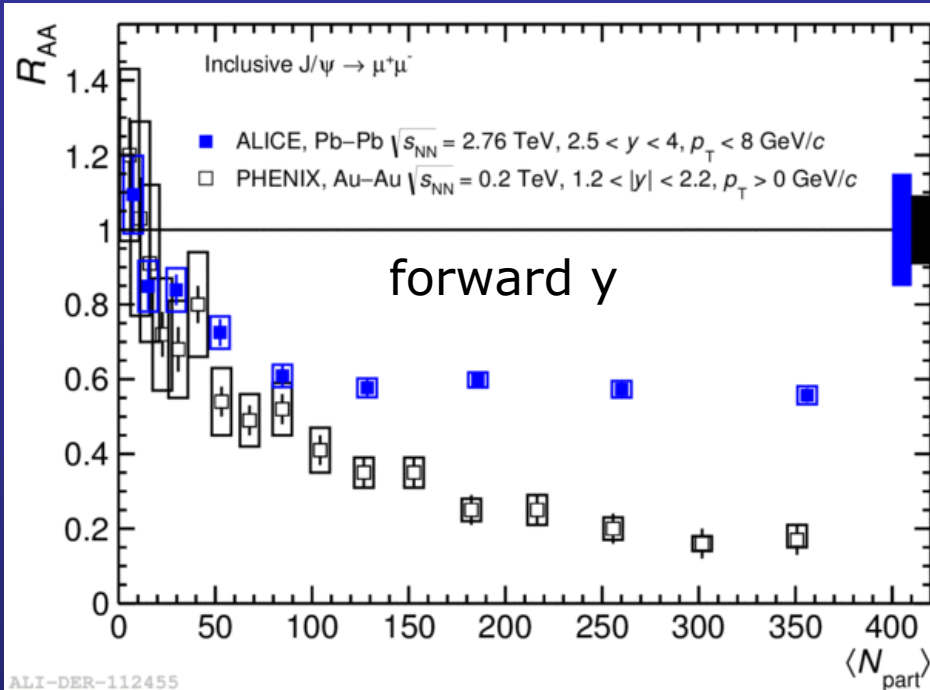


- ❑ Although the “**screening+recombination**” picture is conceptually simple and attractive, a realistic description implies a sophisticated treatment
- ❑ Some examples
  - ❑ At high-energy the QGP thermalization times can be very short
    - **In-medium formation of quarkonium** rather than suppression of already formed states
    - **Heavy quark diffusion** is relevant for quarkonium production
- ❑ Need
  - ❑  $T_D, M_\psi(T), \Gamma_\psi(T)$  from QCD calculations (using spectral functions from **EFT/LQCD**)
  - ❑ **Fireball evolution** from microscopic calculations
  - ❑ Precise determination of the **total open charm cross section**

Impressive advances on theory side but the availability of data for various colliding systems and energy remains a must!

# Low- $p_T$ $J/\psi$ : ALICE (vs PHENIX)

B. Abelev et al., ALICE  
PLB 734 (2014) 314



□ Results vs centrality dominated by low- $p_T$   $J/\psi$

□ Systematically **larger  $R_{AA}$  values** for **central** events at LHC

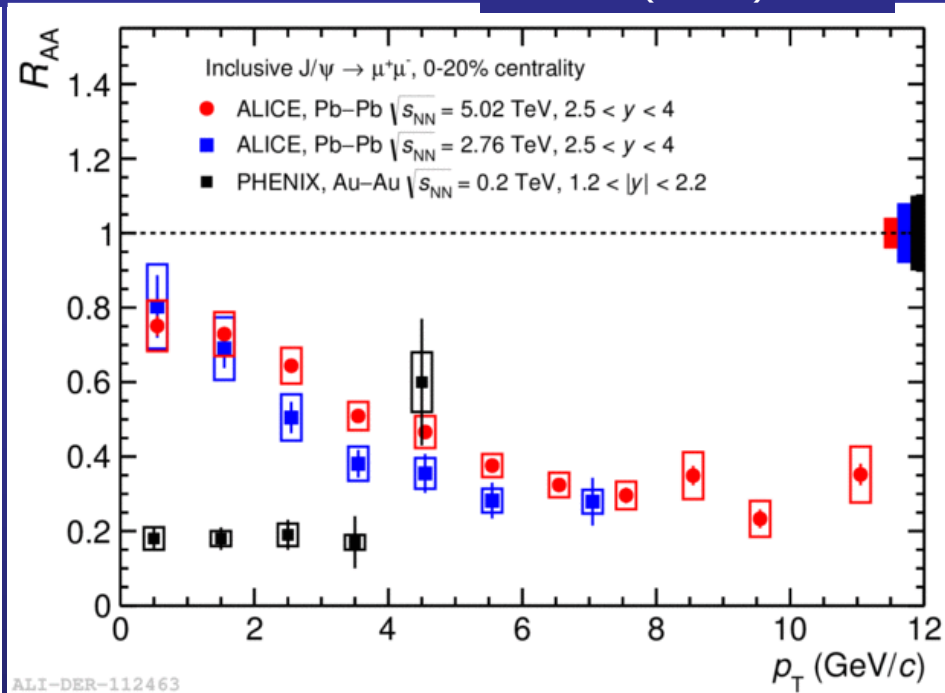
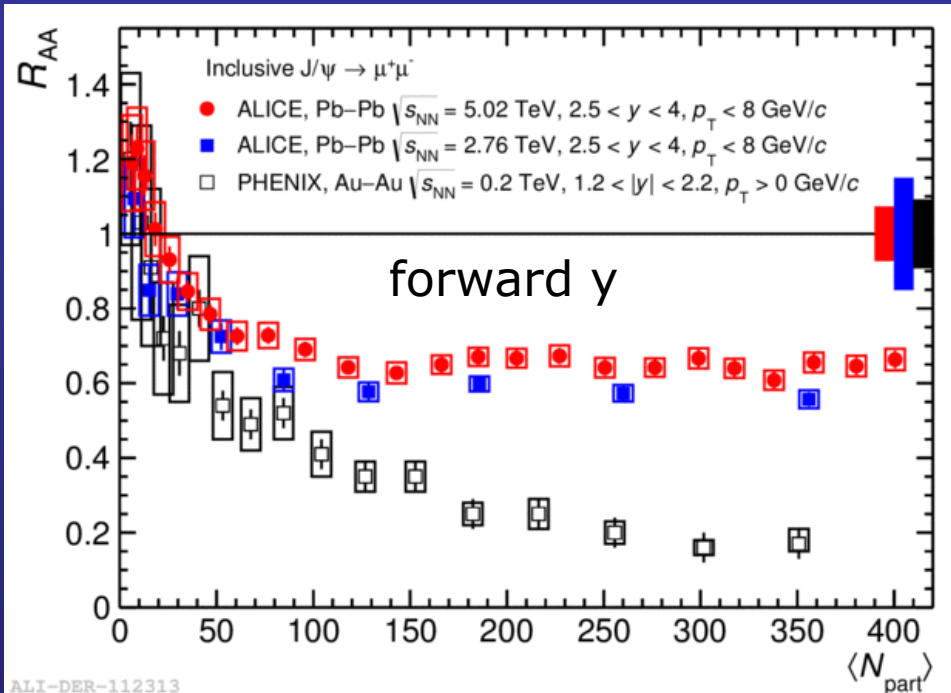
□  **$R_{AA}$  increases at low  $p_T$**  at LHC

□ **Precise results at  $\sqrt{s_{NN}} = 5.02$  TeV**, compatible with  $\sqrt{s_{NN}} = 2.76$  TeV

Possible interpretation: { **RHIC** energy  $\rightarrow$  **suppression** effects dominate  
**LHC** energy  $\rightarrow$  **suppression + regeneration**

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J.Adam et al, ALICE  
PLB766(2017) 212



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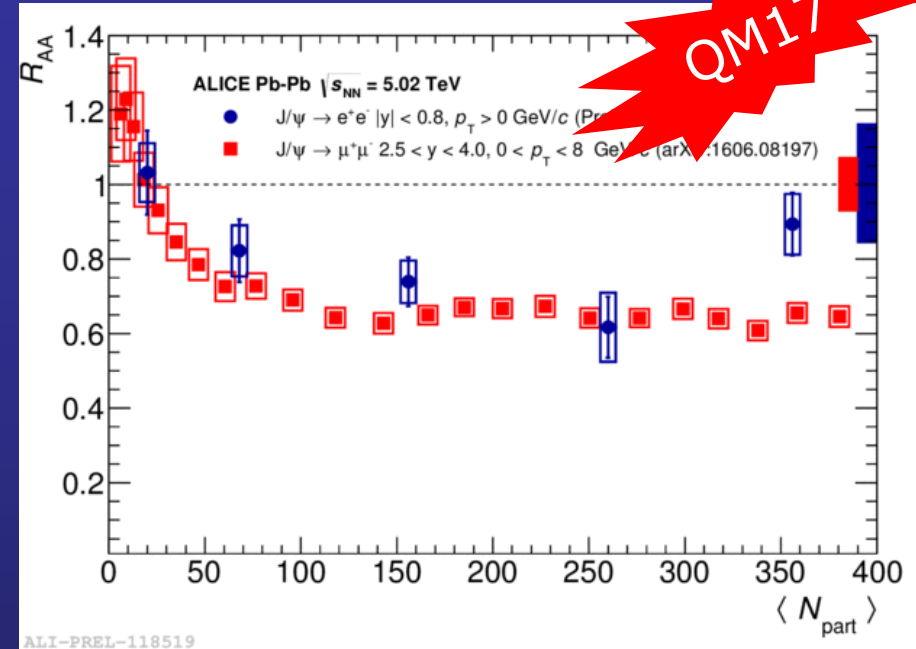
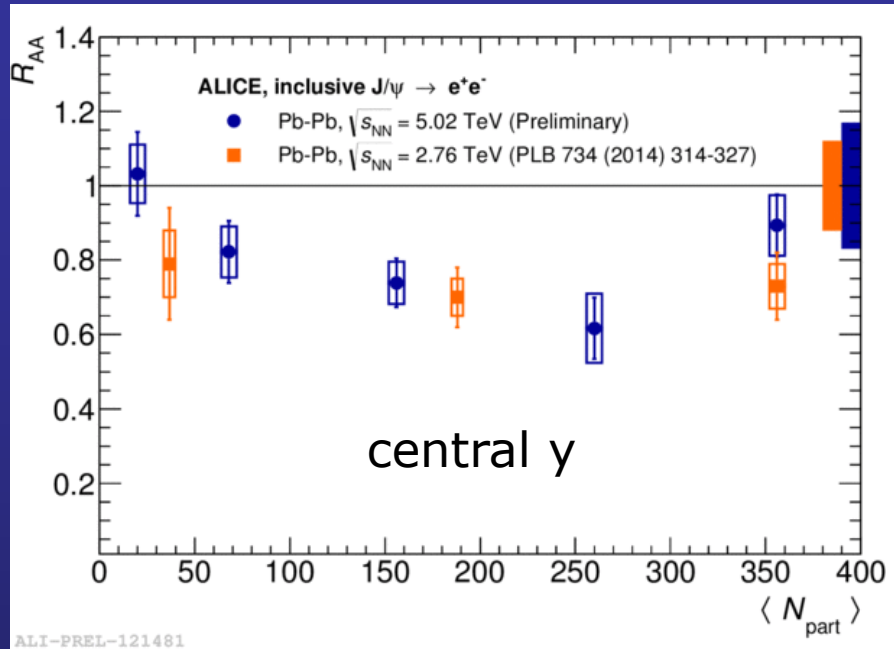
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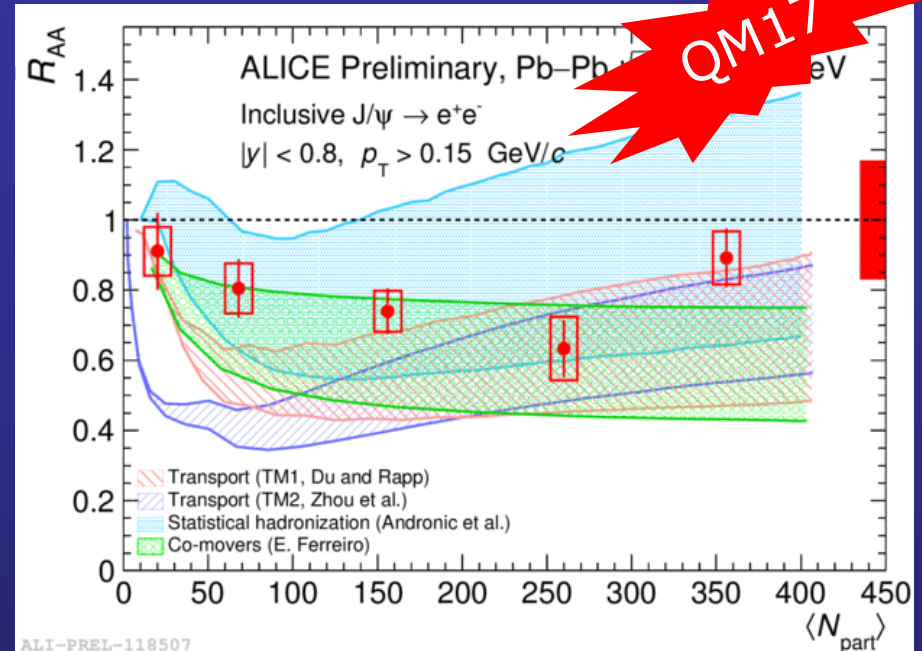
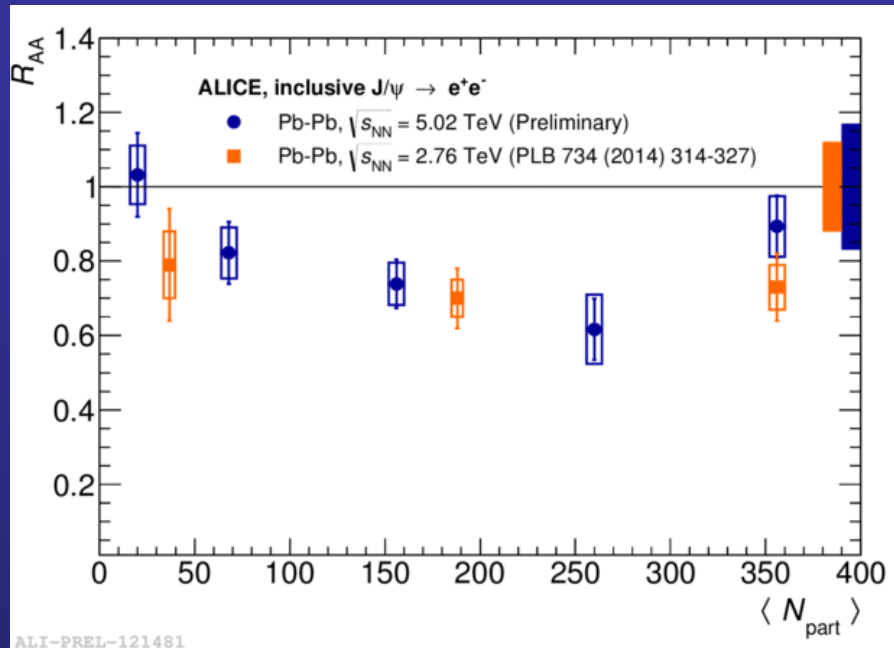
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# Low- $p_T$ $J/\psi$ : central vs forward-y



- Central Pb-Pb: **hints for a weaker suppression at  $y \sim 0$**  with respect to forward-y results at  $\sqrt{s_{NN}} = 5.02$  TeV  
→ expected in a (re)generation scenario (fluctuation cannot be excluded)
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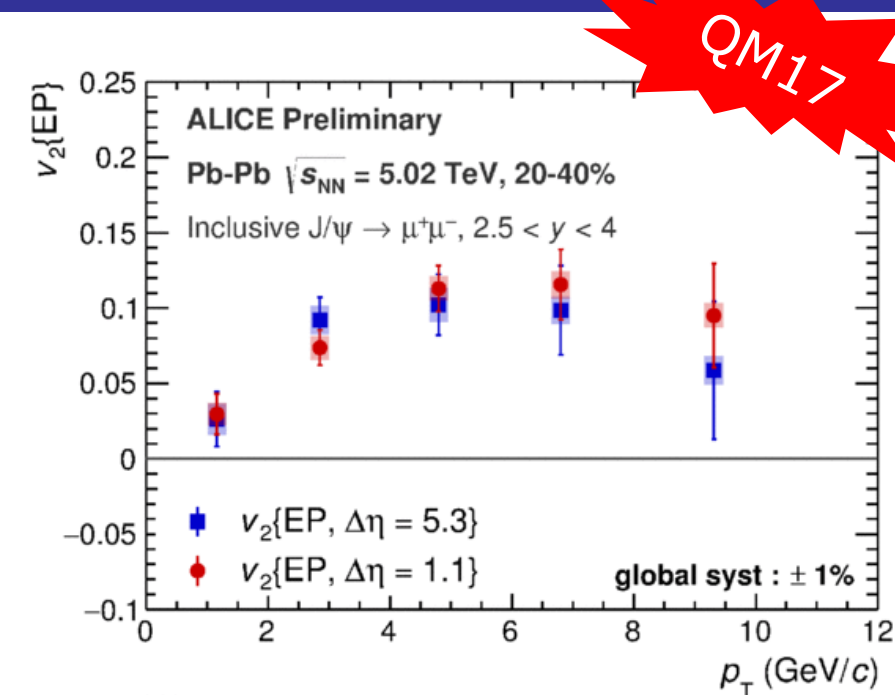


QM17

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 $\rightarrow$  expected in a (re)generation scenario (fluctuation cannot be excluded)
- No significant  $\sqrt{s_{NN}}$ -dependence** of  $R_{AA}$  (5.02 vs 2.76 TeV), confirming forward-y observations
- Transport and statistical models have large uncertainties**  
 (shadowing+open charm cross section)

# New $J/\psi$ $v_2$ results

- The contribution of  $J/\psi$  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

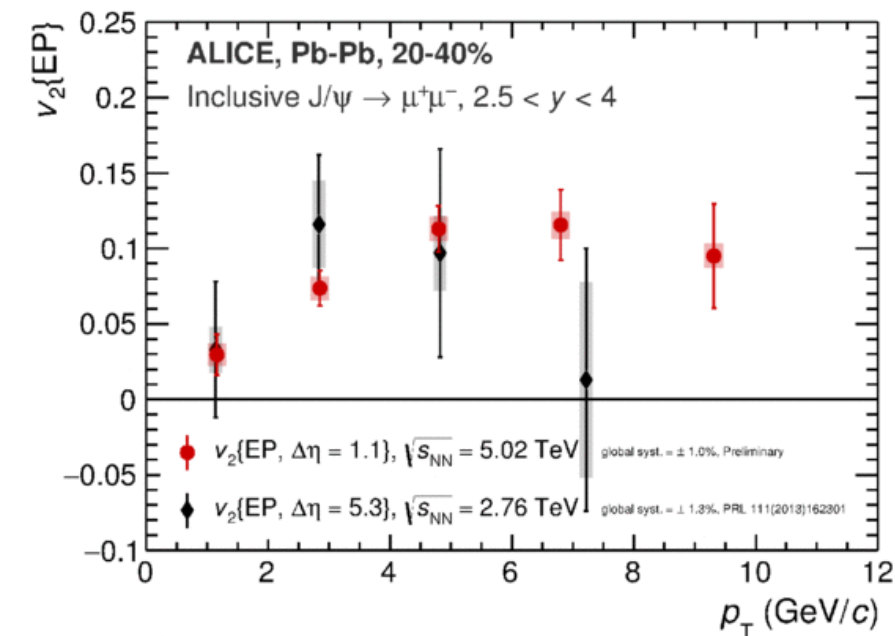


$p_T$ (GeV/c)	0-2	2-4	4-6	6-8	8-12
$\Delta\eta=1.1$	$2.2\sigma$	$6.3\sigma$	$7.4\sigma$	$5.0\sigma$	$2.8\sigma$
$\Delta\eta=5.3$	$1.4\sigma$	$6.2\sigma$	$5.0\sigma$	$3.3\sigma$	$1.3\sigma$

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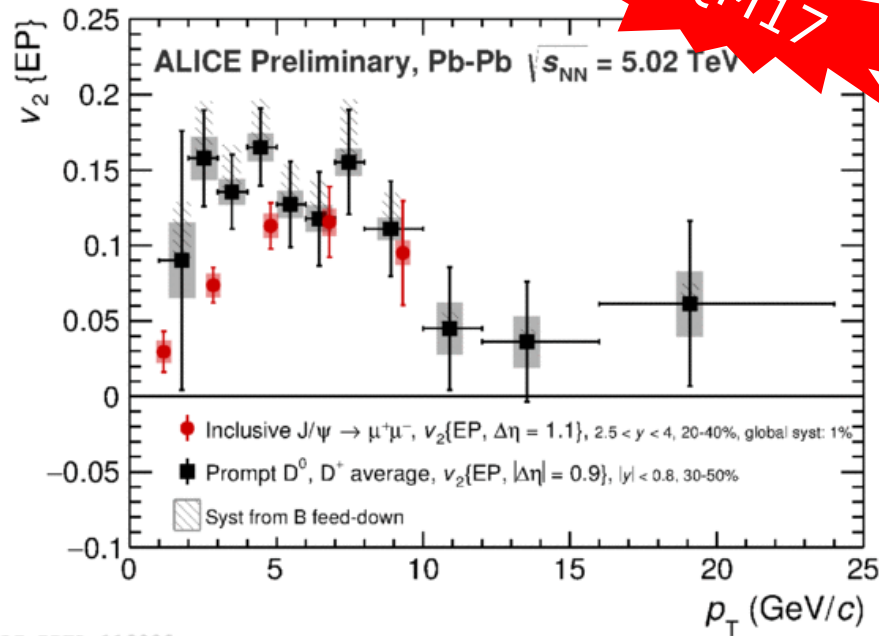
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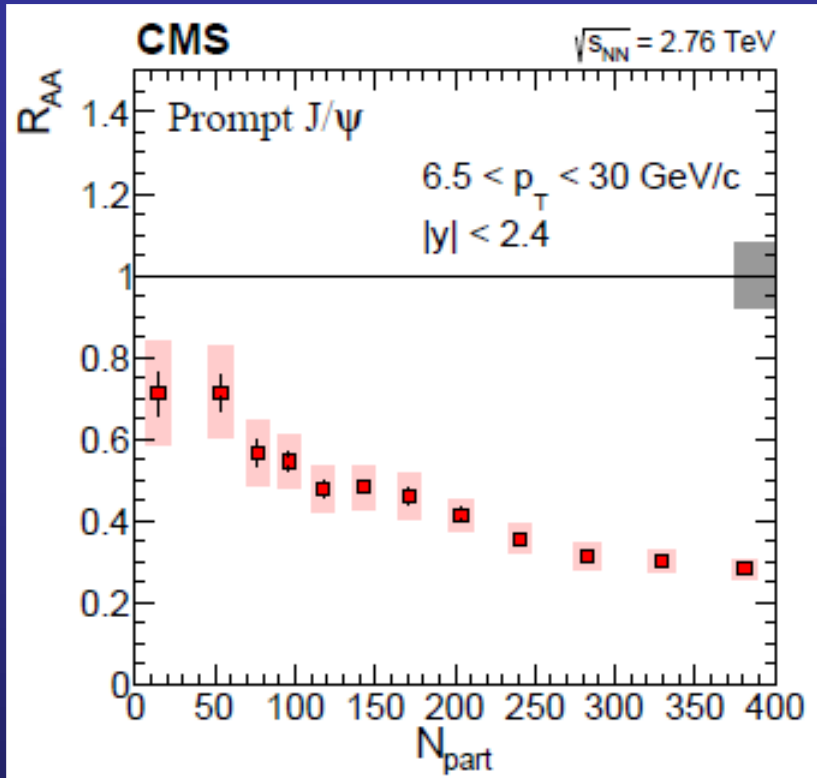


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- **From hint to evidence for a non-zero  $v_2$  signal**, maximum for  $4 < p_T < 6$  GeV/c, 20-40% centrality
- Agreement, within uncertainties, with run-1 results
- Comparison closed vs open charm  
→ Learn about **light vs heavy quark flow**

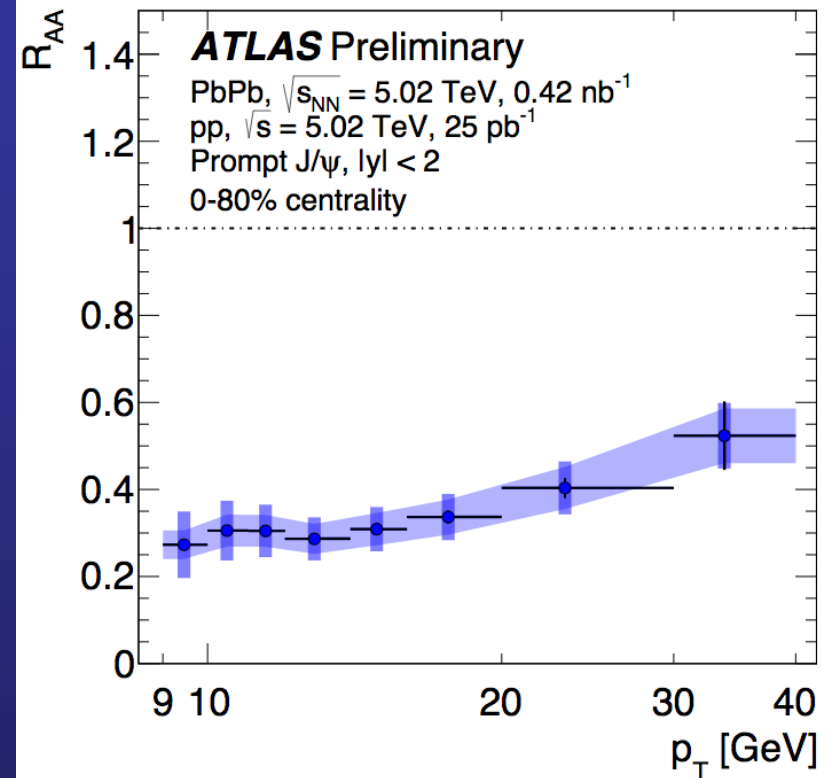
ALI-PREL-119009

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- A significant fraction of observed  $J/\psi$  comes from charm quarks which thermalized in the QGP



- ❑ Striking difference with respect to low- $p_T$   $J/\psi$
- ❑ **Suppression increases with centrality** at high  $p_T$ , **down to  $R_{AA} \sim 0.3$**

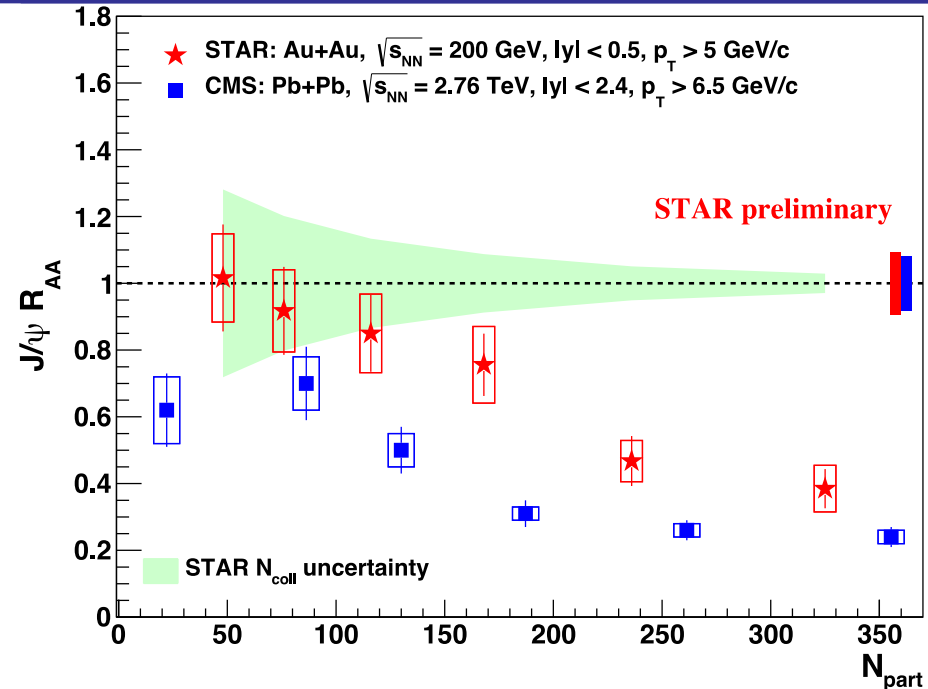
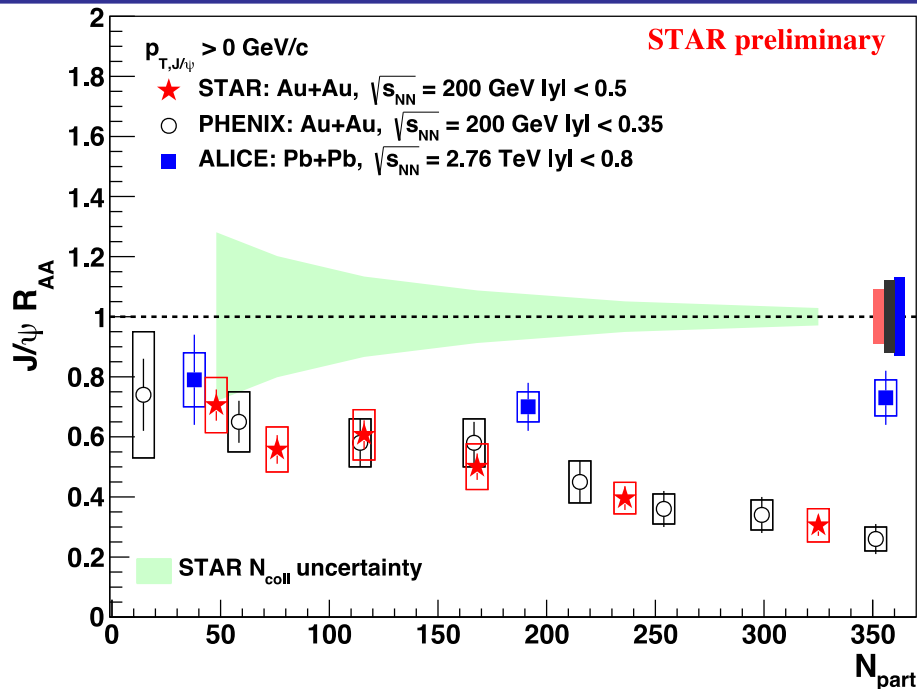


- ❑  **$R_{AA}$  increases for  $p_T > 20$  GeV/c**
- ❑ Related to energy loss effects, rather than dissociation ?

# J/ψ - RHIC energy

□ Recent highlights by STAR

□ **Low vs high  $p_T$  J/ψ suppression**



□ **Low  $p_T$  J/ψ,  $R_{AA}^{LHC} > R_{AA}^{RHIC}$**

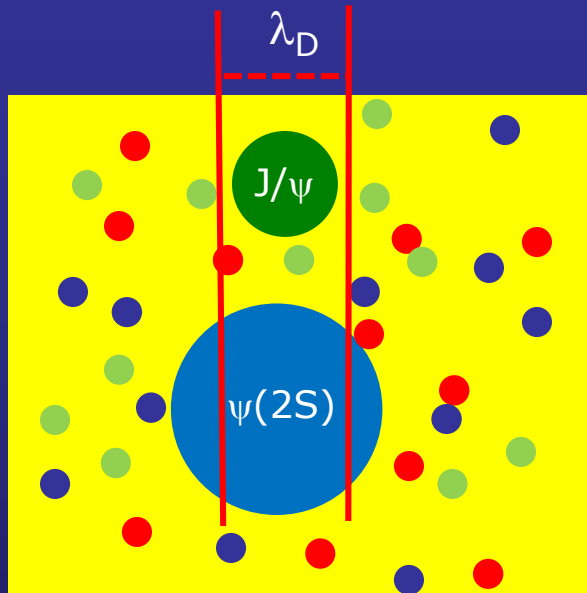
□ **High  $p_T$  J/ψ,  $R_{AA}^{LHC} < R_{AA}^{RHIC}$**

← strong regeneration

← weak (or no) regeneration

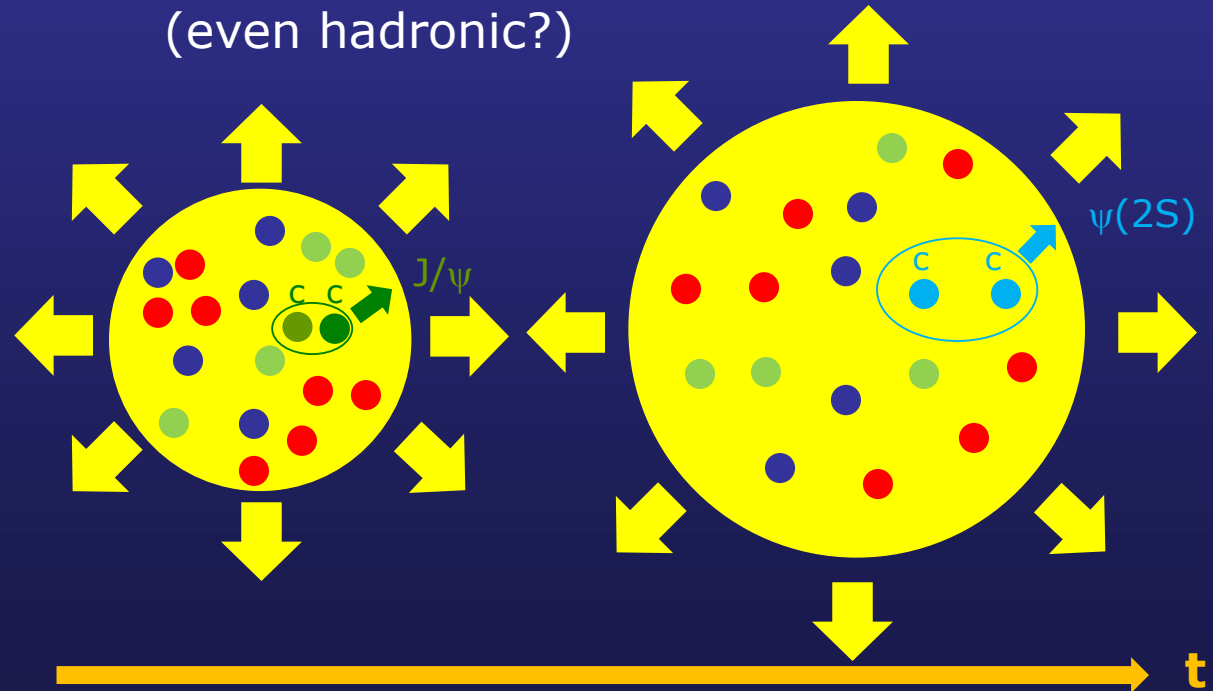
# $\psi(2S)$ in Pb-Pb

□ Binding energy  $\sim (2m_D - m_\psi) \rightarrow \psi(2S) \sim 60 \text{ MeV}, J/\psi \sim 640 \text{ MeV}$



□ Expect **much stronger dissociation effects** for the weakly bound  $\psi(2S)$  state

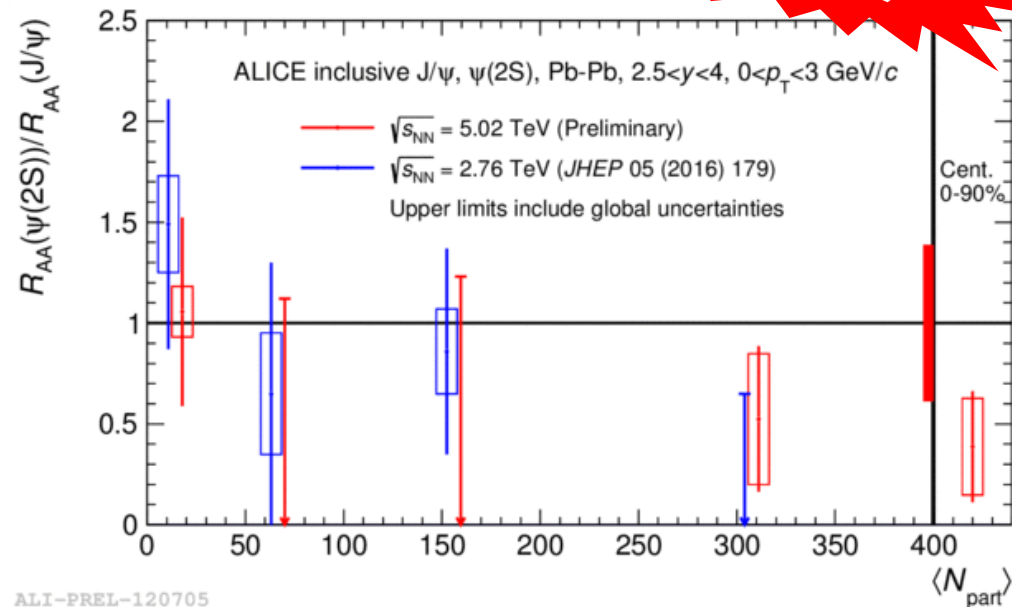
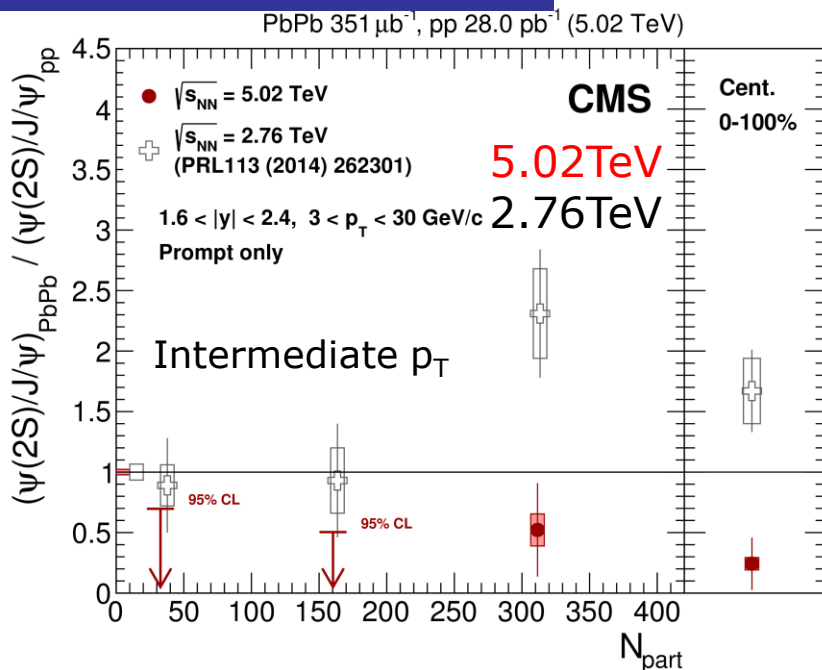
□ Effect of re-combination on  $\psi(2S)$  more subtle  $\rightarrow$  important when the system is **more diluted** (even hadronic?)



Important test  
for models!

# Double ratios $\psi(2S)/J/\psi$

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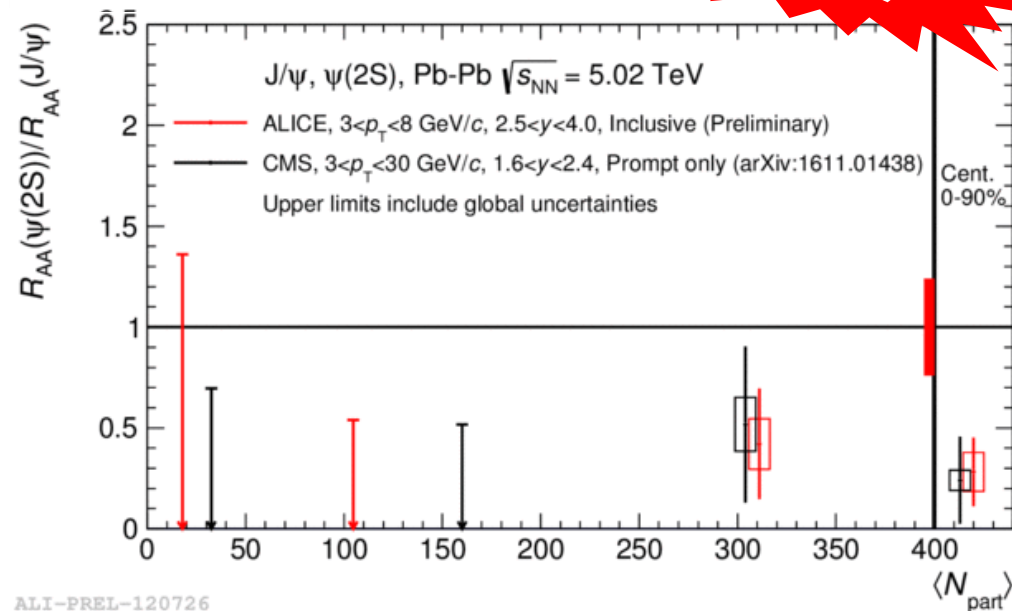
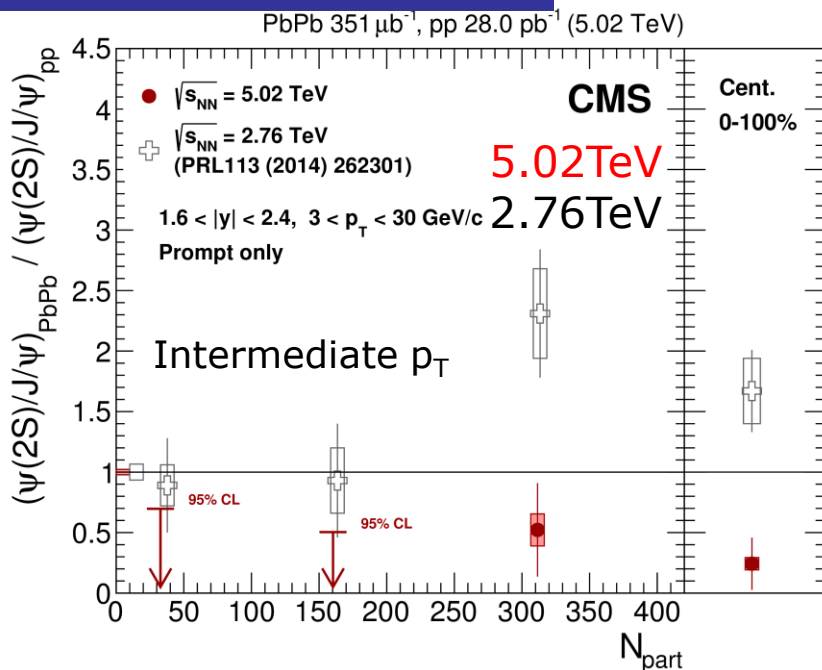


- $(\psi(2S)/J/\psi)_{\text{PbPb}} / (\psi(2S)/J/\psi)_{\text{pp}} \rightarrow \ll 1$  in a dissociation scenario
- CMS (intermediate  $p_T$ ), **enhancement** to **suppression** for increasing  $\sqrt{s_{NN}}$
- ALICE extends down to  $p_T=0$ , suppression is seen

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

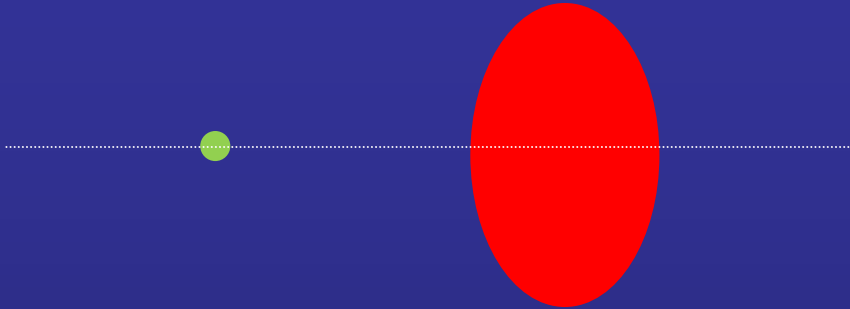
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- CMS (intermediate  $p_{\text{T}}$ ), **enhancement** to **suppression** for increasing  $\sqrt{s_{\text{NN}}}$
- ALICE extends down to  $p_{\text{T}}=0$ , suppression is seen
- Good compatibility at  $\sqrt{s_{\text{NN}}}=5.02 \text{ TeV}$  in the common  $p_{\text{T}}$  range
- Proposed mechanism (Rapp) for enhancement:  **$\psi(2S)$  regeneration** **mainly occurring later**, when radial flow is already built-up

# p-A results and CNM effects



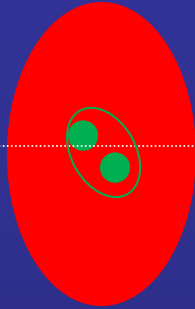
## Low-energy collisions

cc pair may form inside nucleus

→ can be dissociated

→ low hadronic multiplicity

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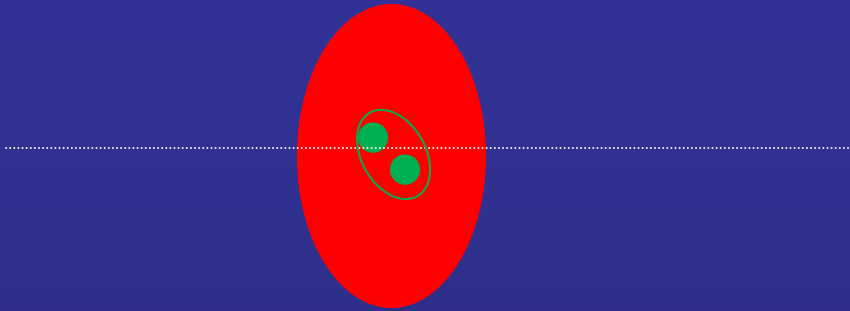
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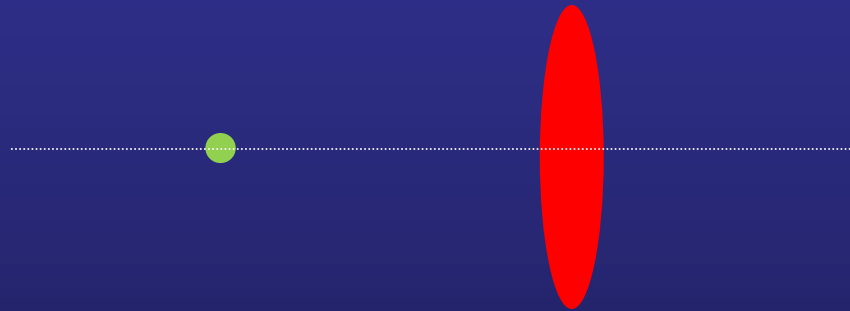
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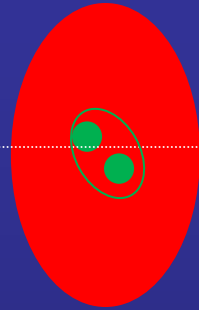
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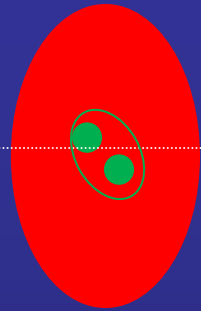
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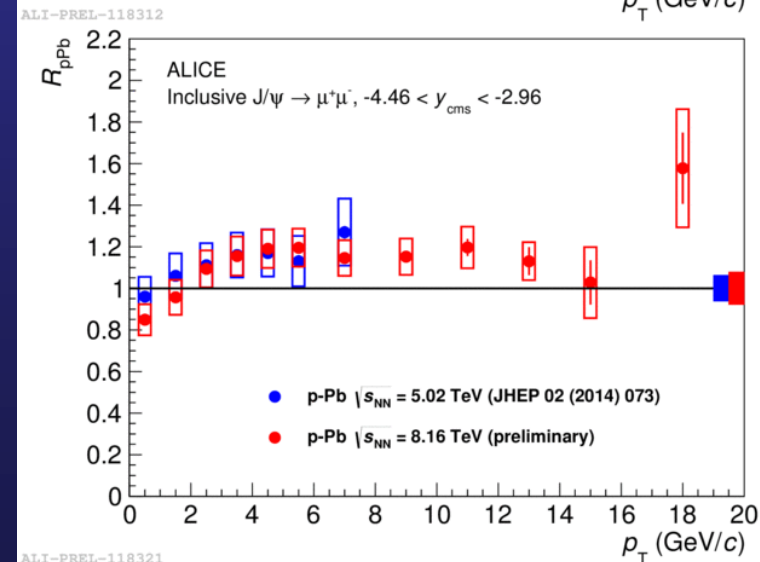
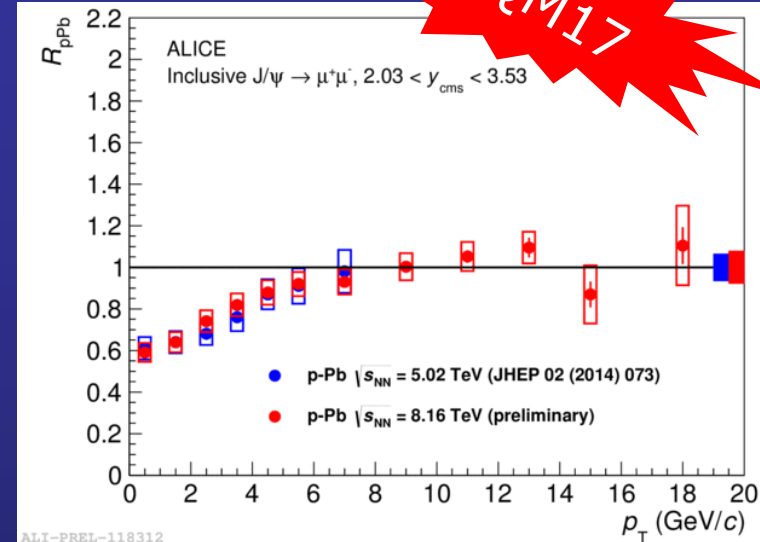
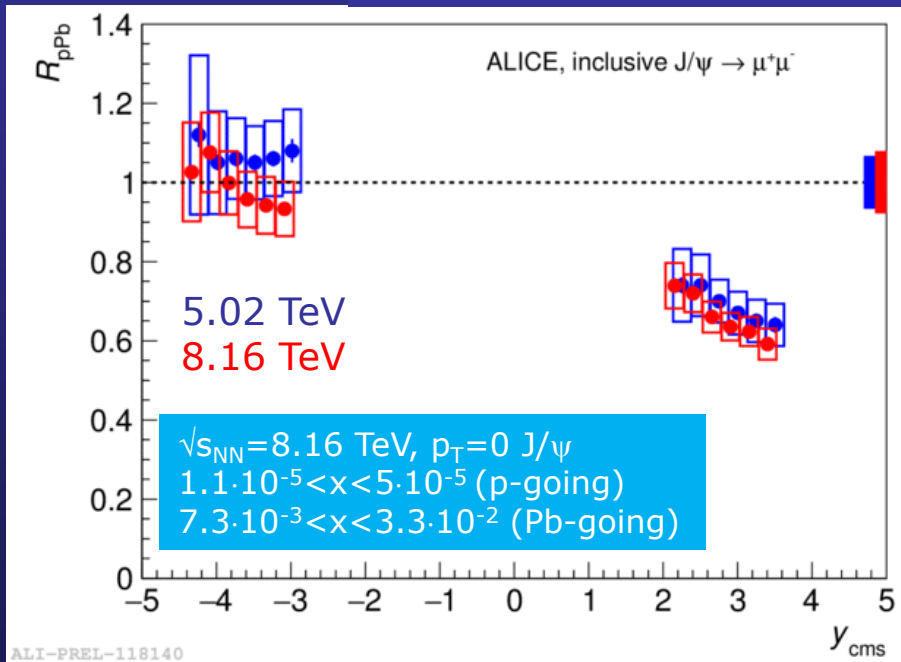
- ❑ Important ingredient for the interpretation of A-A results
- ❑ Study of various QCD-related mechanisms  
(shadowing, coherent parton energy loss, CGC, ...)

# ALICE results from the recent p-Pb LHC run ( $\sqrt{s_{NN}}=8.16$ TeV)

- Extend kinematic coverage ( $p_T=20$  GeV/c)
- Different (higher) energy  
→ slightly different x-region

□ **Results at  $\sqrt{s_{NN}}=5.02$  and 8.16 TeV compatible**

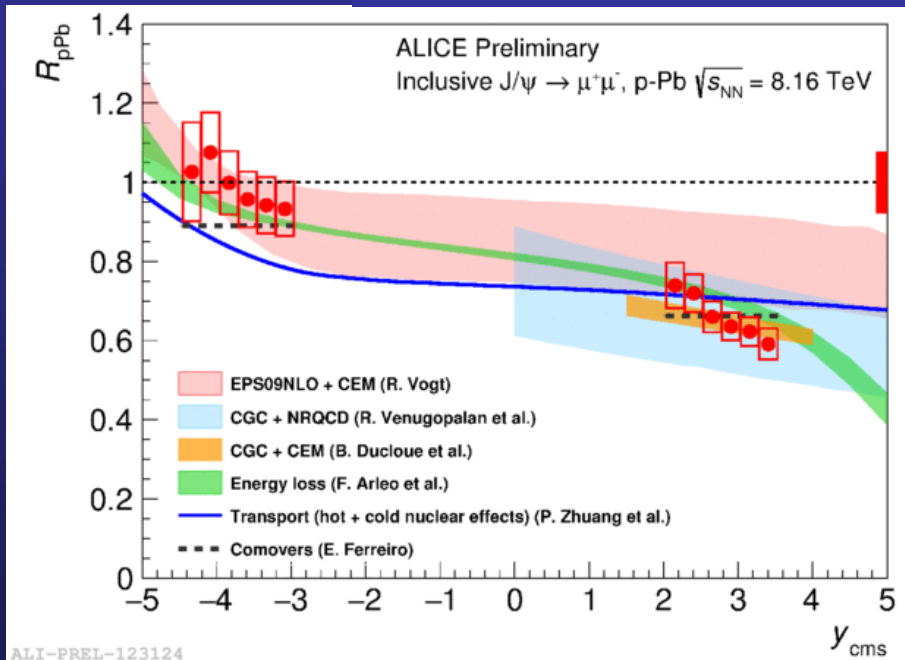
CERN-ALICE-PUBLIC-2017-001



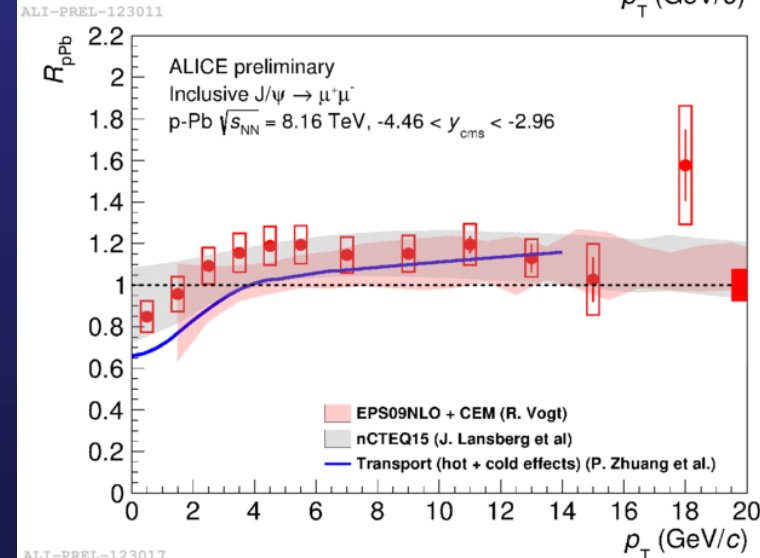
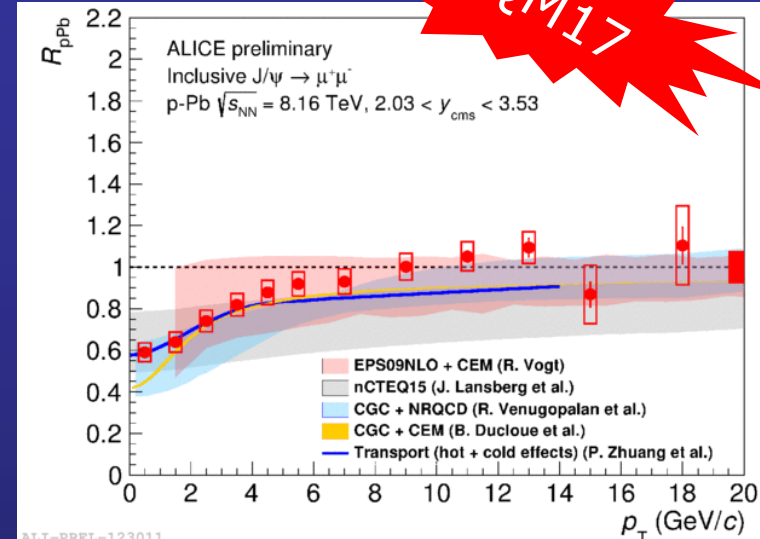
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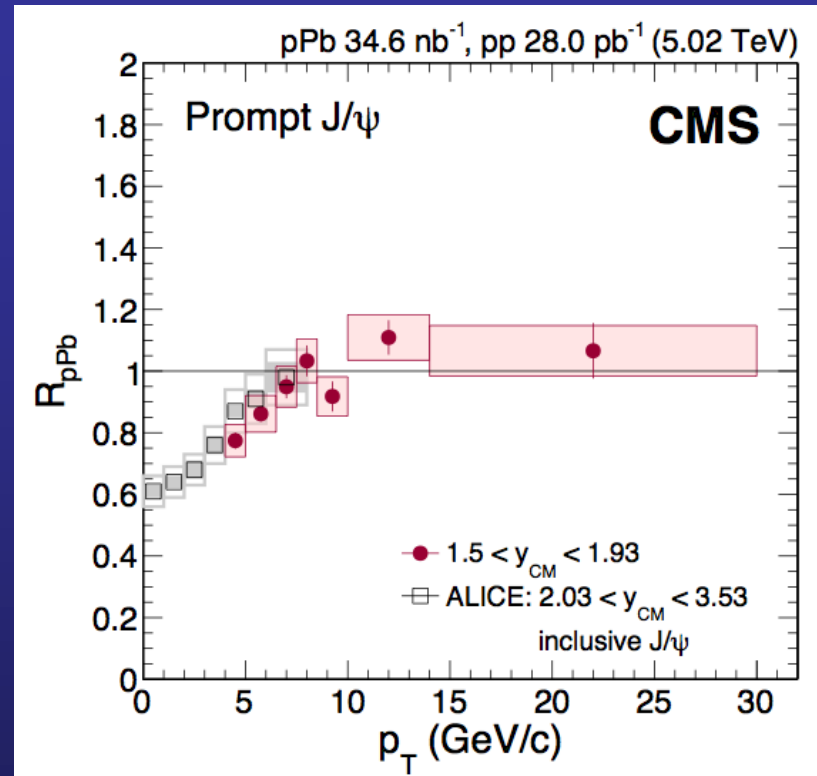
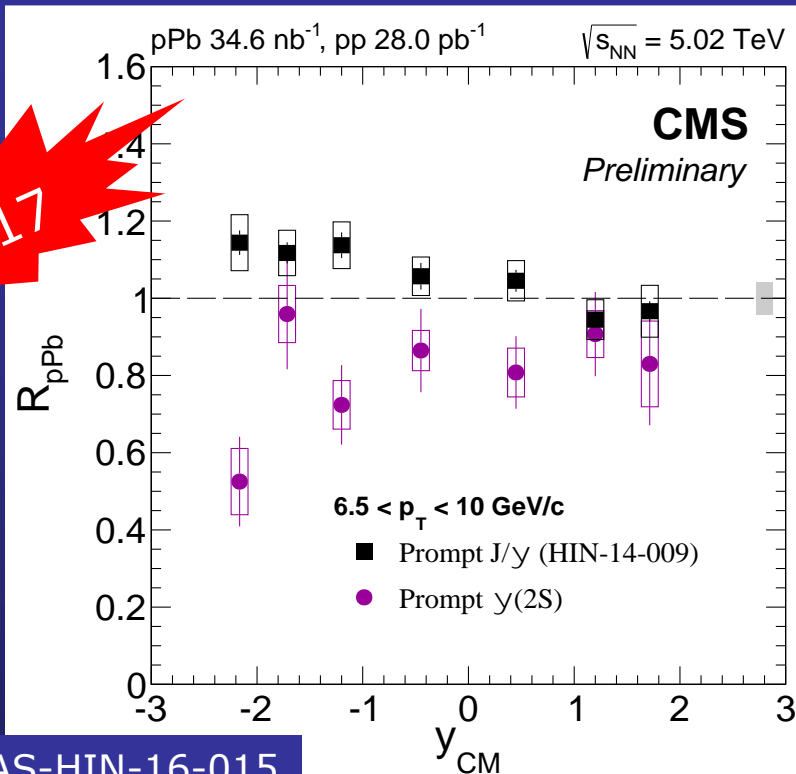


□ **Good agreement with models (shadowing, energy loss, CGC)**



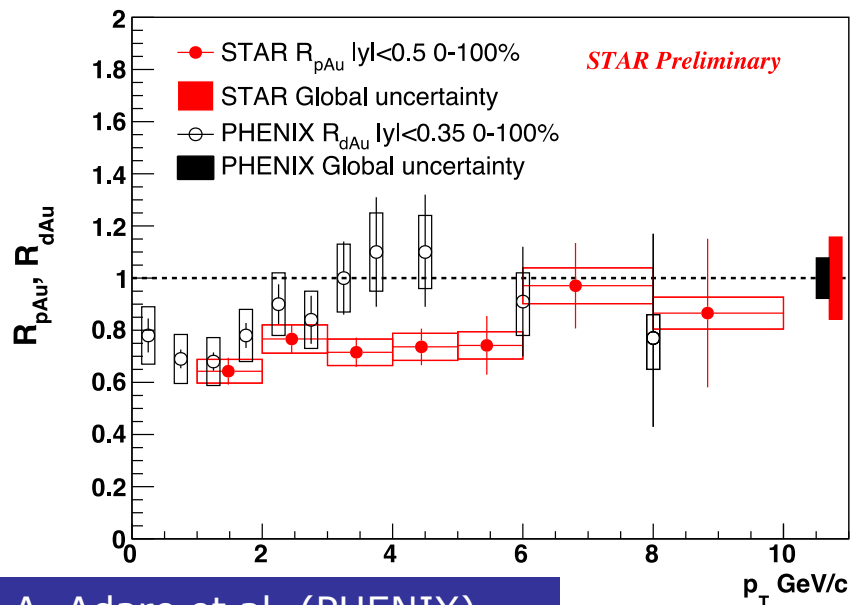
# New p-Pb results at central-y from CMS ( $\sqrt{s_{NN}}=5.02$ TeV)

A.M.Syranian et al. (CMS),  
arXiv:1702.01462

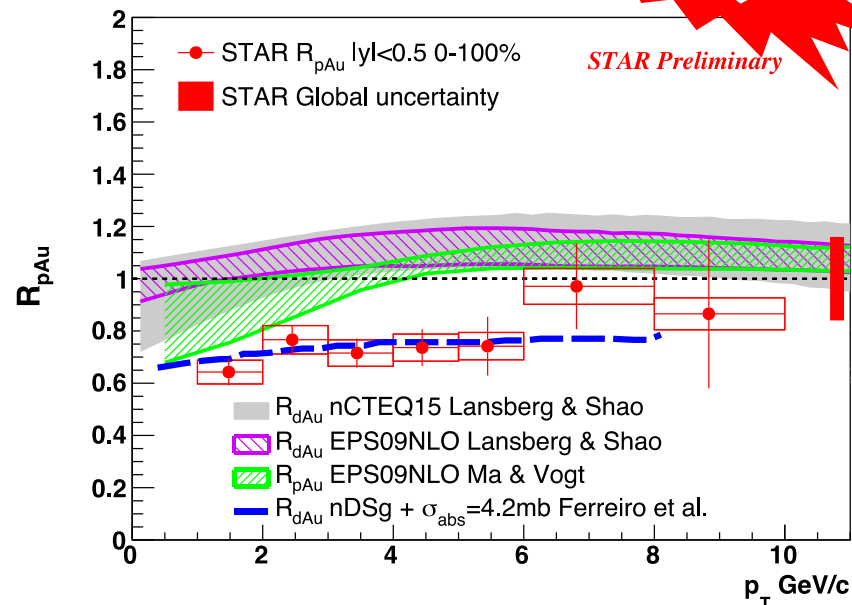


- High- $p_T$  **CNM effects weak**
- Compatible with ALICE in the common  $p_T$  range (different  $y$ )
- The **strong J/ψ suppression in high- $p_T$  Pb-Pb is NOT a CNM effect**

# New p-A data from STAR



A. Adare et al. (PHENIX),  
PRC 87 (2012) 034903



□ STAR  $R_{pAu}$  from RHIC run 15

□ **From strong to no suppression for increasing  $p_T$**

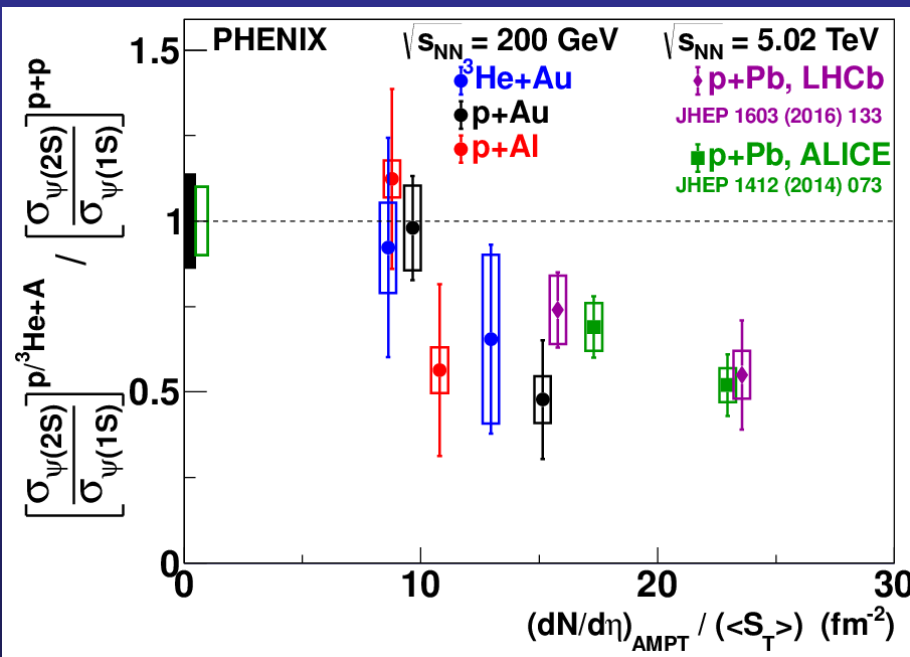
→ confirms d-Au results from PHENIX, within uncertainties

□ Final state effects? Shadowing alone likely not enough at  $p_T \sim 5$  GeV/c

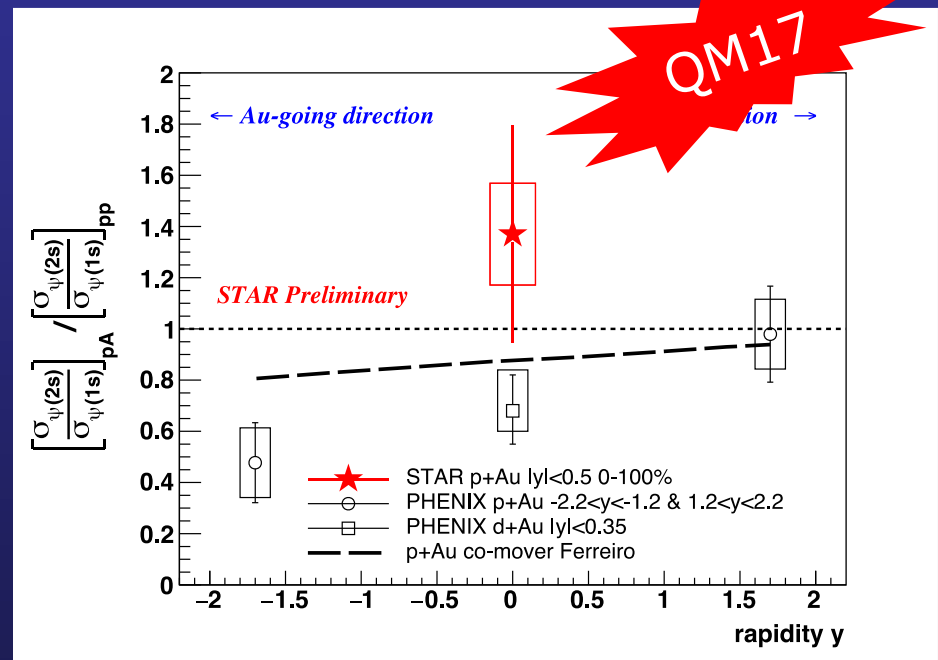
□ Good agreement with model including nuclear absorption ( $\sigma_{abs} = 4.2$  mb)

# $\psi(2S)$ in p-A

- $\psi(2S)$  binding energy very low
- Might be sensitive not only to QGP effects but **also to hadronic medium**  
→ **Even to the one produced in p-A**
- Effects **first seen by PHENIX** and confirmed by ALICE/LHCb

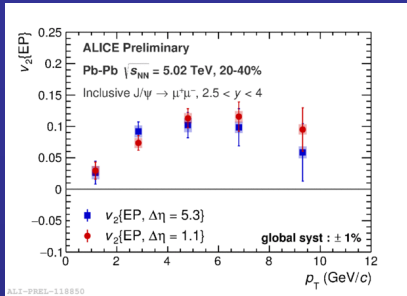


A. Adare et al. (PHENIX),  
arXiv:1609.06550

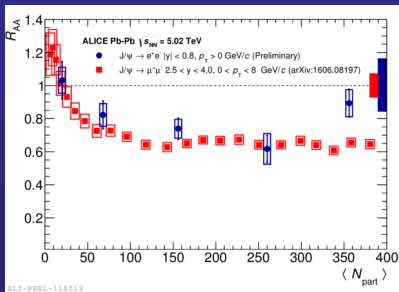


New **STAR result** agrees within uncertainties with PHENIX d-Au

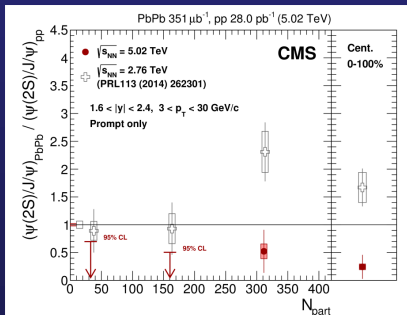
# Charmonia – Highlights!



**The  $J/\psi$  flows!**  $\rightarrow$  Heavy quarks thermalize in the QGP and can (re)create charmonia (ALICE)



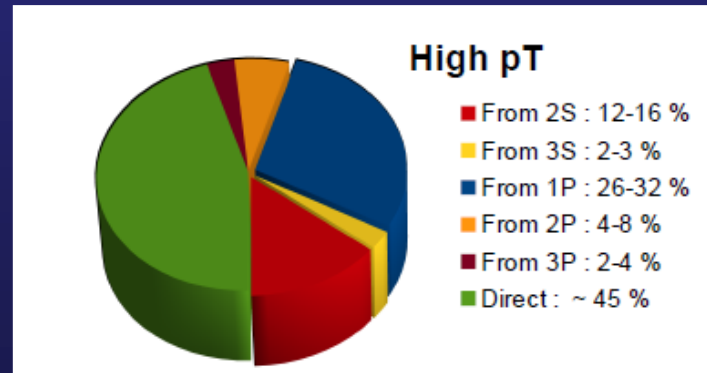
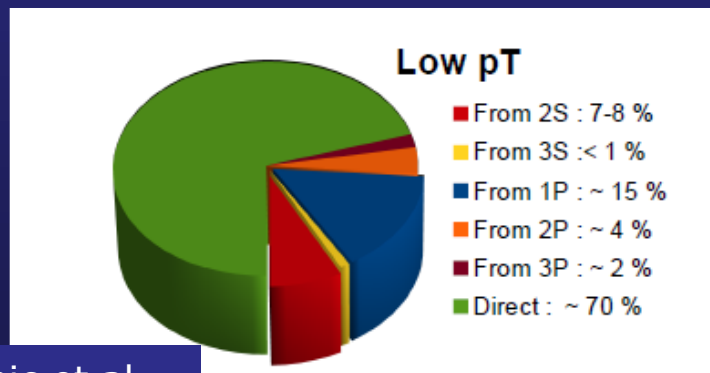
Precise new data on  **$J/\psi$  suppression and regeneration!**  $\rightarrow R_{AA}$  at  $\sqrt{s_{NN}} = 5.02$  TeV (ALICE)



Complete set of  **$\psi(2S)$  results** (complex  $\sqrt{s_{NN}}$ -dependence)  
Deeper insight on charmonia in medium (CMS+ALICE)

# Bottomonium in A-A

- For high-energy collisions, several appealing features
    - **Re-combination effects not strong** → simpler interpretation?
    - **$\Upsilon(1S)$  very strongly bound**,  $E_b = (2m_B - m_{\Upsilon(1S)}) \sim 1100$  MeV  
→ probe of hot QGP
  - Together with  $\Upsilon(2S)$  ( $E_b \sim 500$  MeV) and  $\Upsilon(3S)$  ( $E_b \sim 200$  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 results

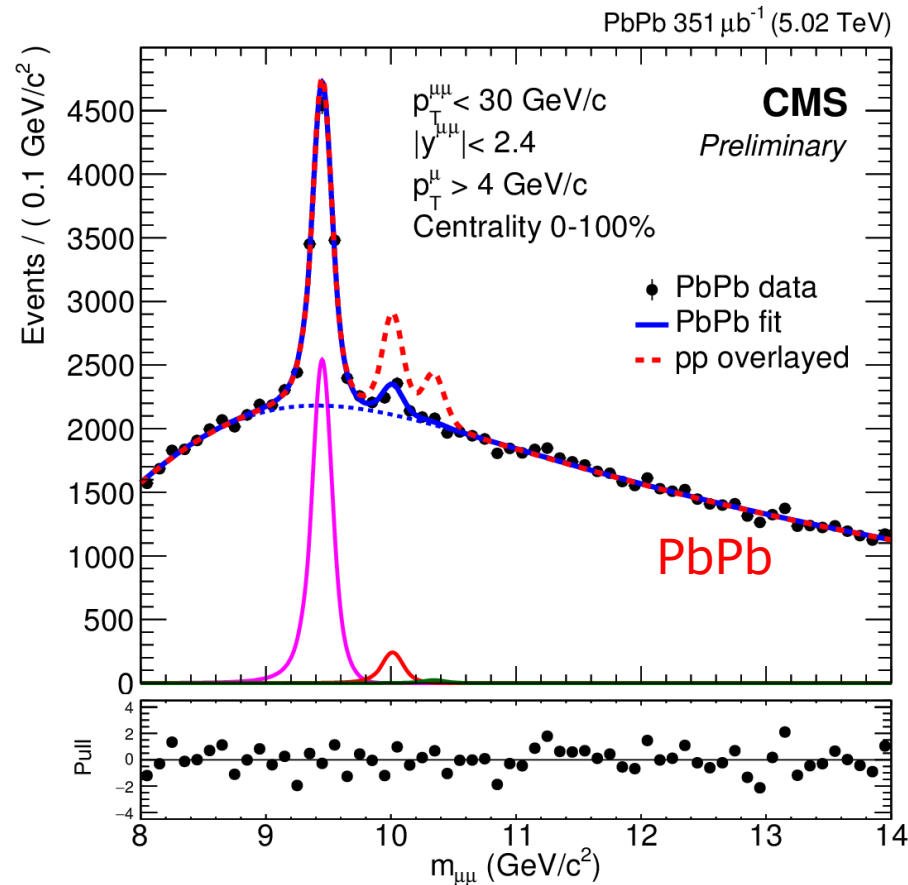
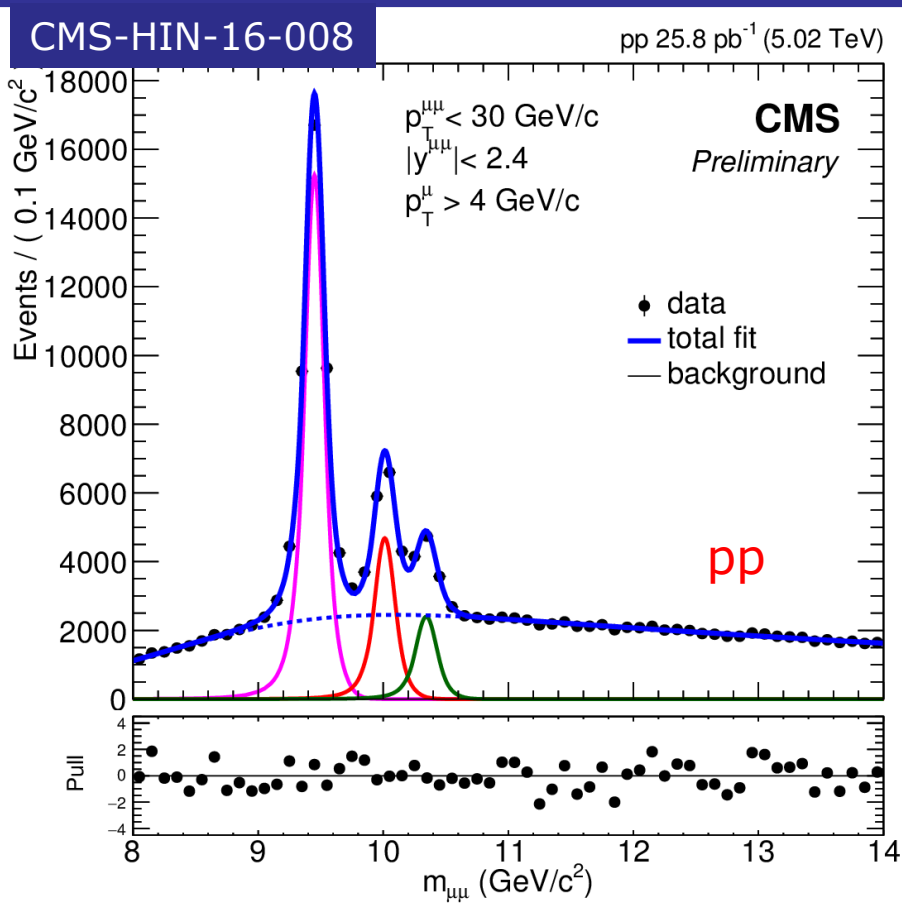


A. Andronic et al.,  
EPJC 76 (2016) 107

Recent improvements thanks in particular to LHCb data!

# Bottomonium (sequential) suppression

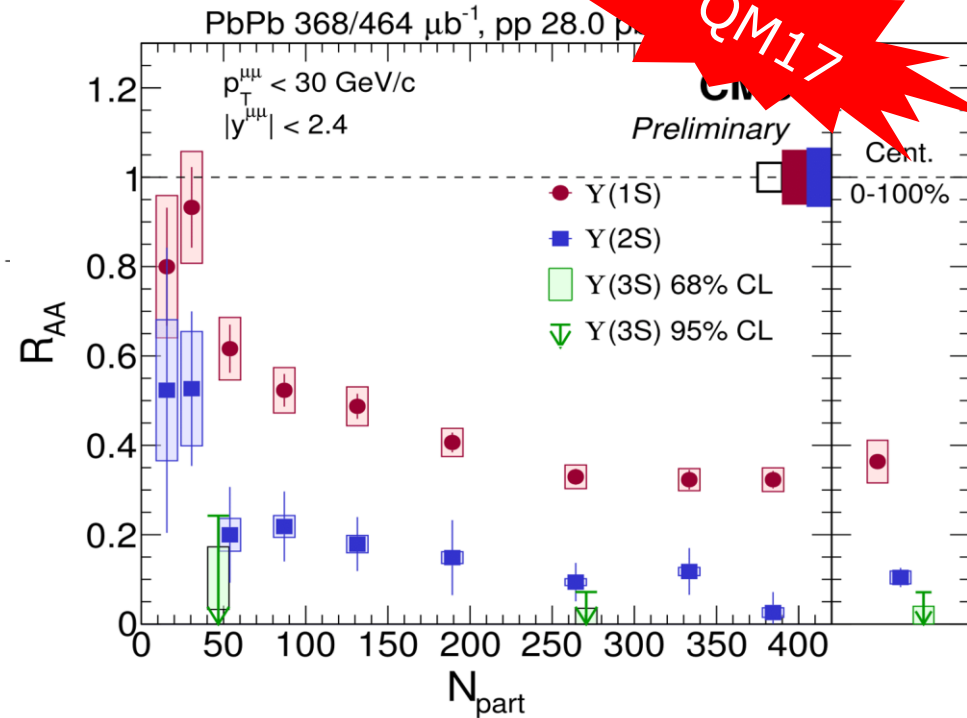
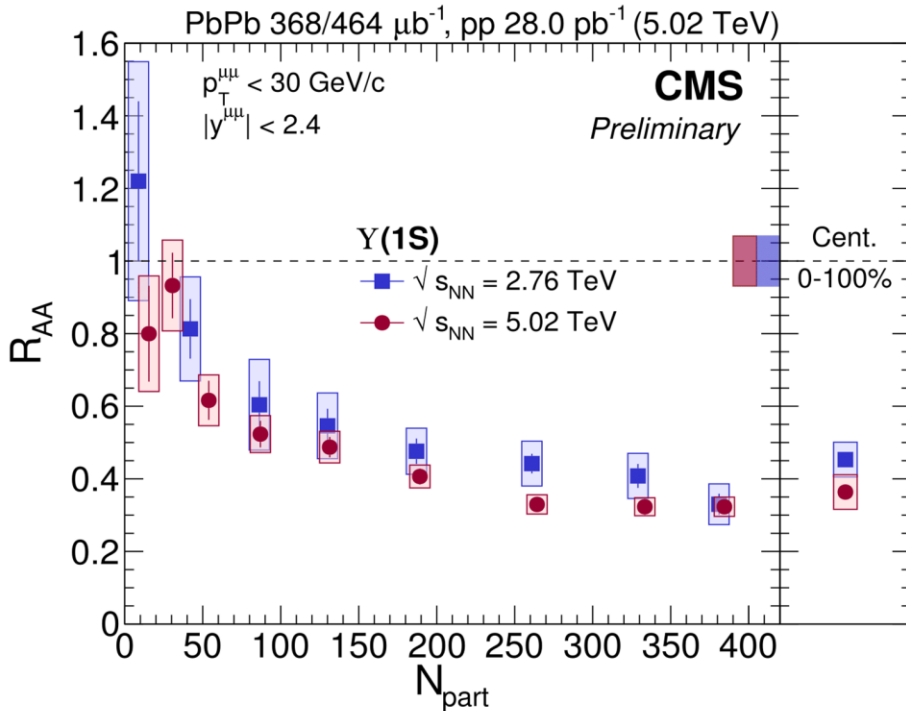
□ Probably the **most spectacular result** from quarkonia in HI at the LHC



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

# New $R_{AA}$ results

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



QM17

CMS-PAS-HIN16-023

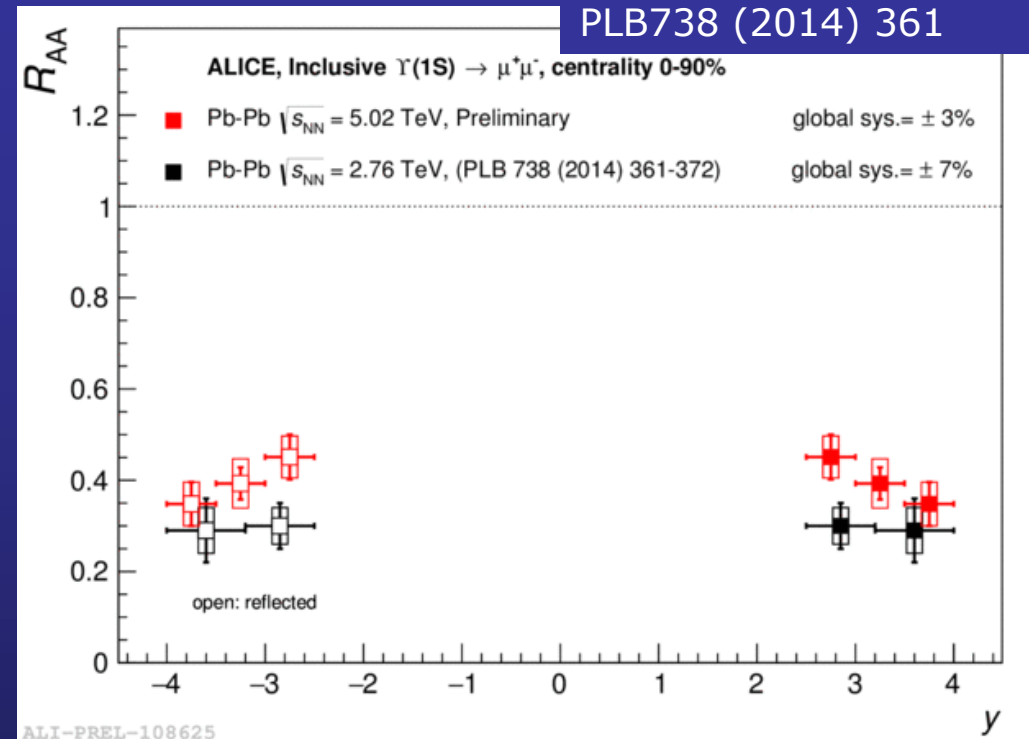
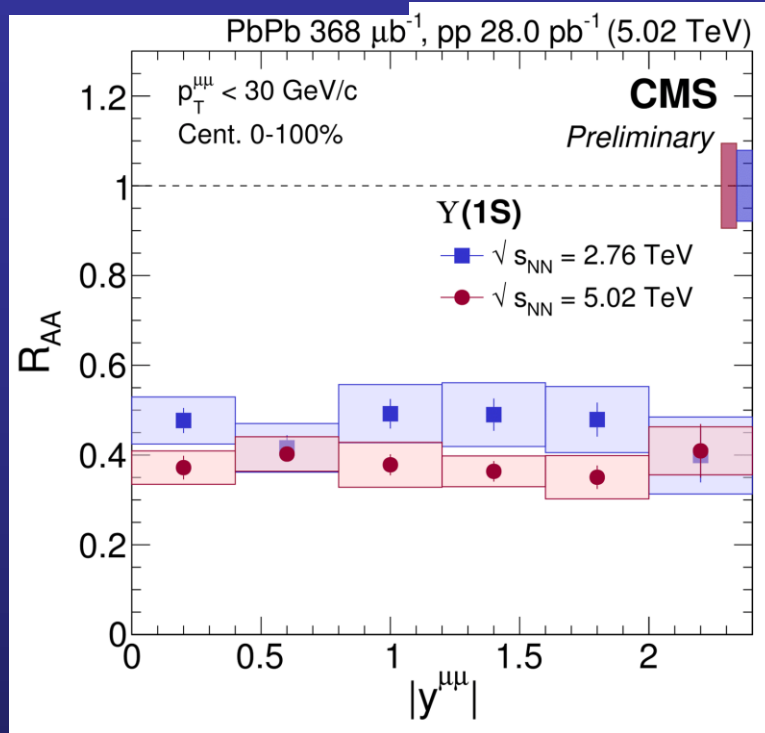
V. Khachatryan et al., CMS  
 arXiv:1611.01510

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

# $R_{AA}$ vs $y$ : ALICE and CMS $\Upsilon(1S)$

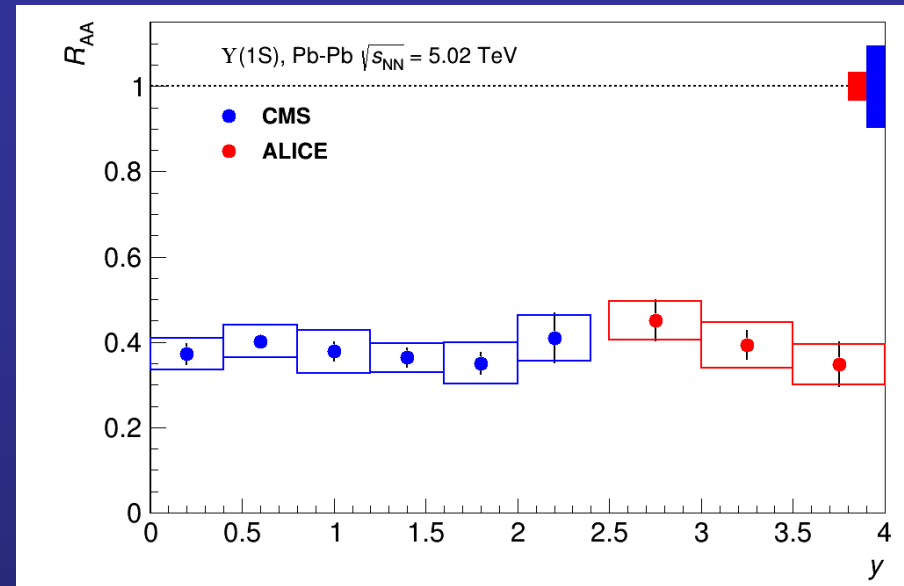
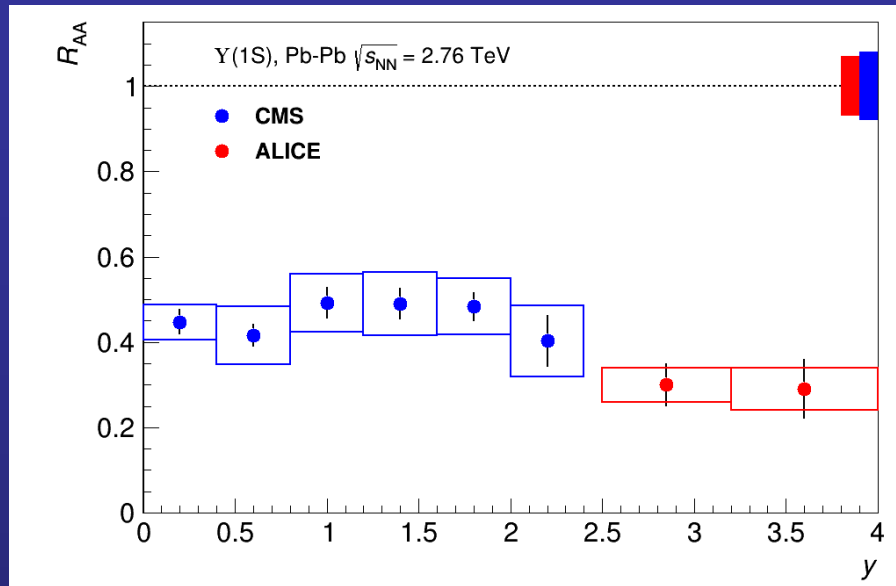
CMS-PAS-HIN16-023

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



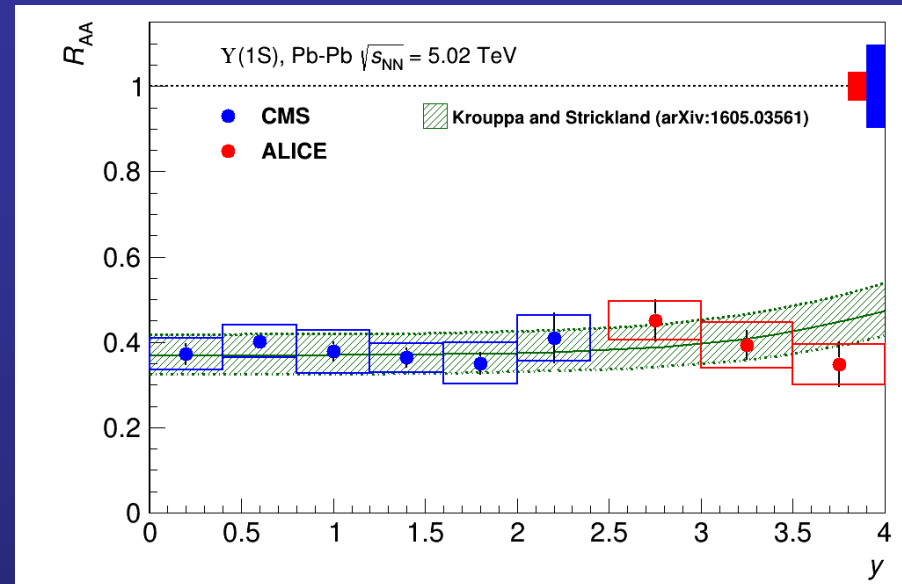
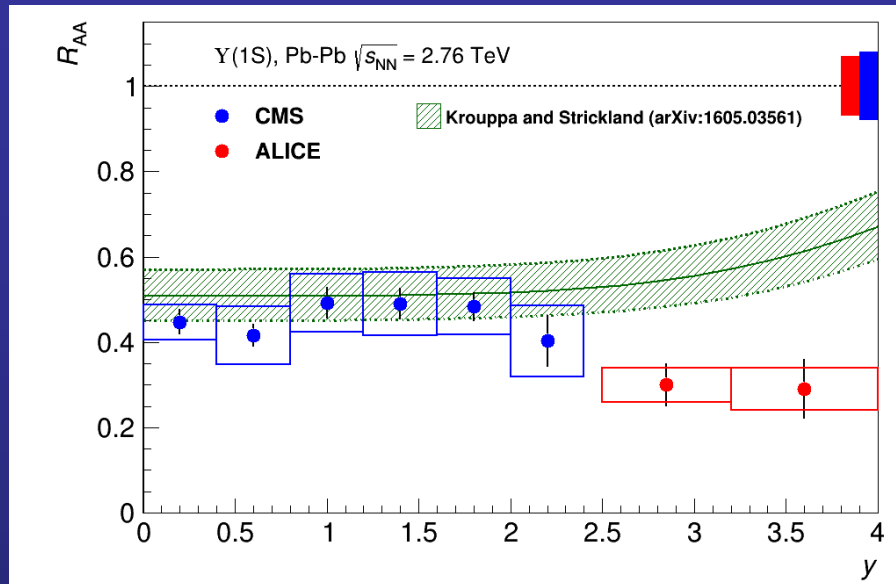
- ❑ ALICE → hints for **less suppression** at  $\sqrt{s_{NN}} = 5.02$  TeV
- ❑ CMS → hints for **more suppression** at  $\sqrt{s_{NN}} = 5.02$  TeV
- ❑ Compare  $R_{AA}$  vs  $y$  for the two experiments in a single plot

# $R_{AA}$ vs $y$ : ALICE and CMS $\Upsilon(1S)$



- ❑ Suppression **increases** with  $y$  at  $\sqrt{s_{NN}}=2.76$  TeV
- ❑ Suppression **constant** vs  $y$  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
- ❑ Can the  $y$ -dependence of CNM effects play a role? Not likely

# $R_{AA}$ vs $y$ : ALICE and CMS $\Upsilon(1S)$

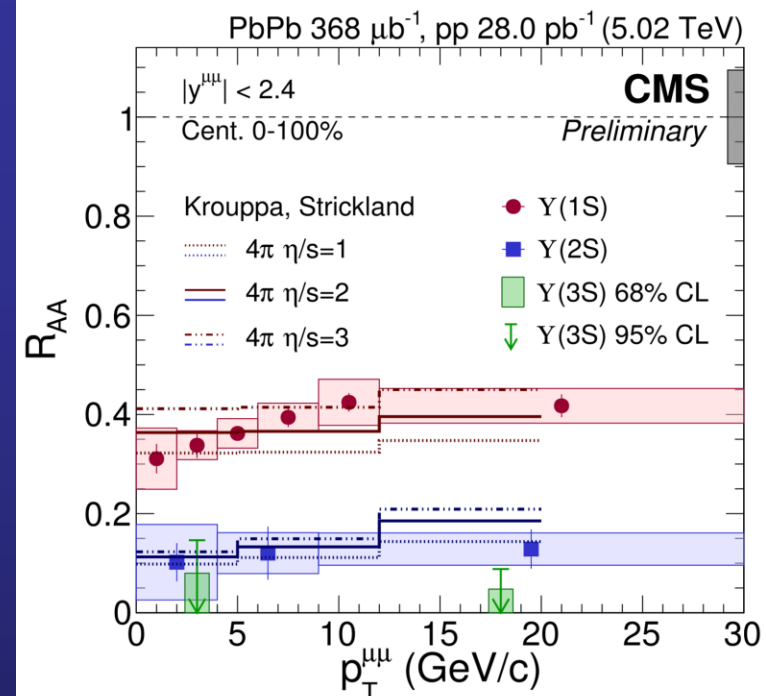
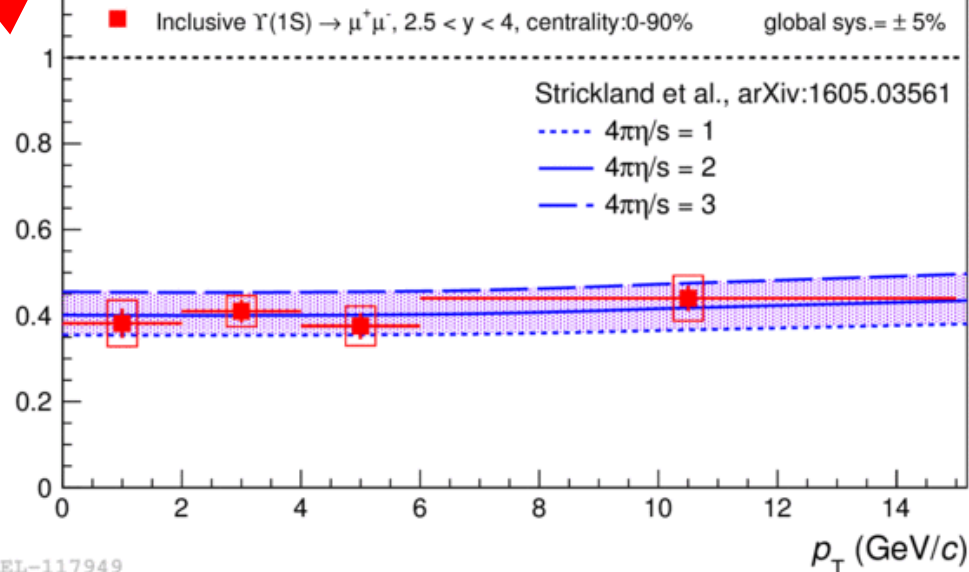


- ❑ Suppression **increases** with  $y$  at  $\sqrt{s_{NN}} = 2.76$  TeV
- ❑ Suppression **constant** vs  $y$  at  $\sqrt{s_{NN}} = 5.02$  TeV
- ❑  $\sqrt{s_{NN}} = 2.76$  TeV: typical features of a **(re)generation pattern**, which seems to vanish at  $\sqrt{s_{NN}} = 5.02$  TeV
- ❑ Systematic uncertainties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

# $R_{AA}$ vs $p_T$ : ALICE and CMS $\Upsilon(1S)$

QM17

ALICE Preliminary, Pb-Pb  $\sqrt{s_{NN}} = 5.02$  TeV

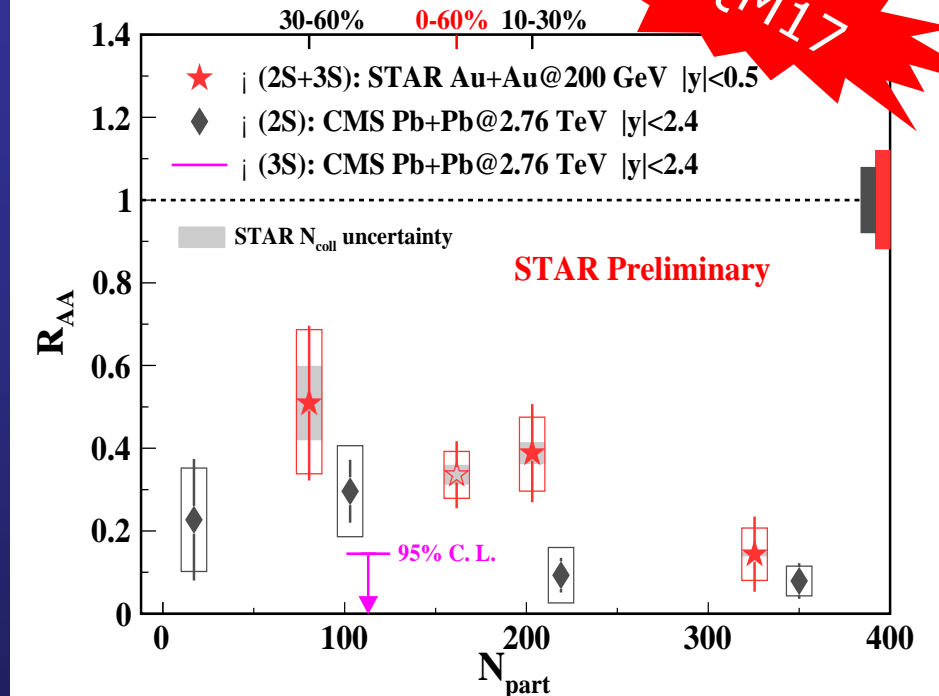
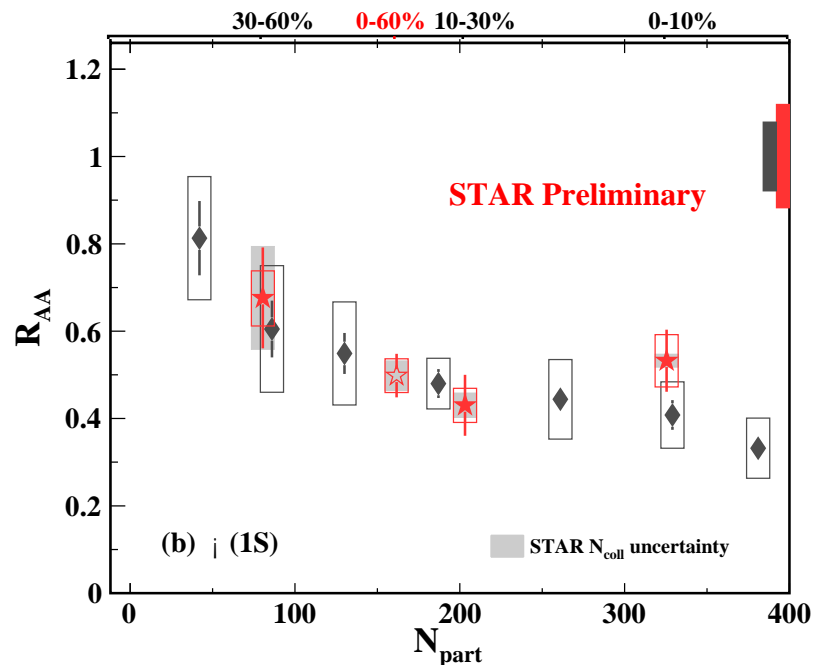


V. Khachatryan et al.,  
CMS arXiv:1611.01510  
CMS-PAS-HIN16-023

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

# First precision results from STAR

- New pp reference (run-15) AND combination of  $\mu^+\mu^-$  (run 14) and  $e^+e^-$  (run 11) Au-Au data samples



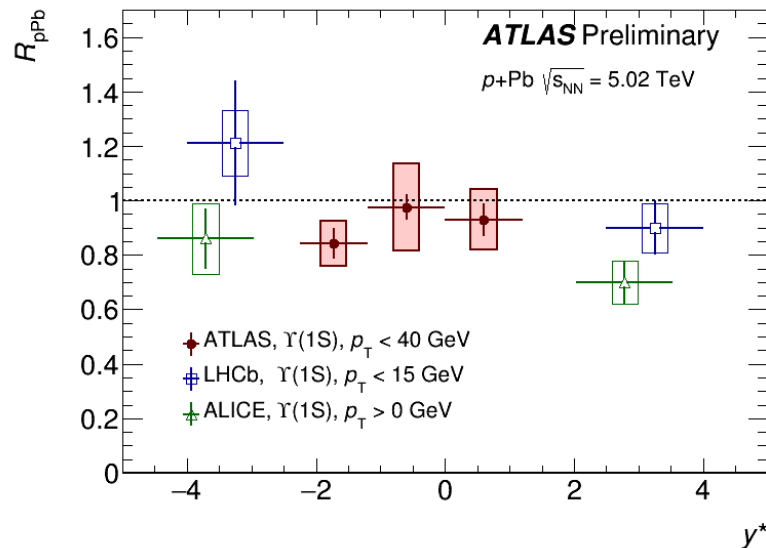
## □ Evidence for suppression of the 3 $\Upsilon$ states ALSO at RHIC energy

- Hints for  $\Upsilon(2S)+\Upsilon(3S)$  less suppressed up to semi-central events and then compatible with CMS for central  $\rightarrow$  effect related to energy density ?
- $\Upsilon(1S)$  identical at RHIC and LHC  $\rightarrow$  dominated by feed-down ?

# Experimental evidence for direct $\Upsilon(1S)$ suppression ?

- Direct  $\Upsilon(1S)$  suppression implies **QGP temperatures at least  $\sim 2 T_c$** ,
- **Experimental** evidence for direct  $\Upsilon(1S)$  suppression needs control over
  - **Feed-down** from S and P bottomonium states
  - Recent LHCb results imply a  **$\sim 30\%$  effect at (fairly) low  $p_T$  in pp**
  - Size of **CNM effects  $\rightarrow$  weak but not precisely known**

ATLAS-CONF-2015-050



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

$$R_{AA}^{\text{incl } \Upsilon(1S)} \sim 0.36$$

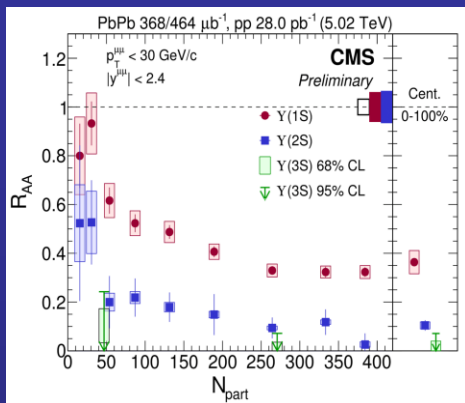
$$R_{AA}^{\text{direct } \Upsilon(1S)} \sim 0.36/0.7 = 0.51$$

CNM effects ( $-1\sigma$  level)

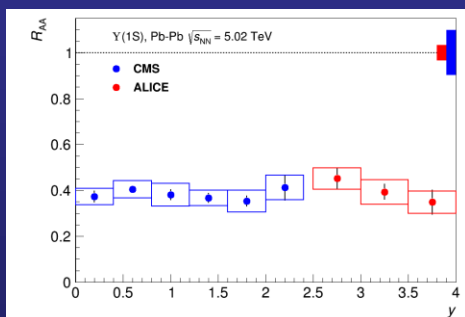
$$\rightarrow (R_{pA} - 1\sigma)^2 \sim 0.8^2 = 0.64$$

- **Experimental indication for direct  $\Upsilon(1S)$  suppression!**

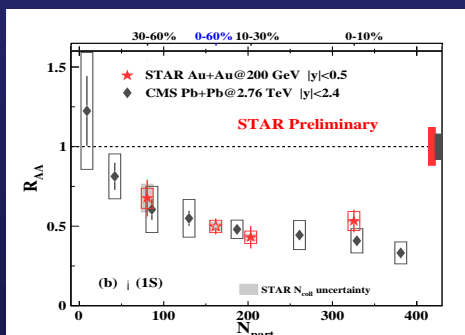
# Bottomonia – Highlights!



Full information on  $\Upsilon(1\text{S})$  and  $\Upsilon(2\text{S})$   $R_{\text{AA}}$  available at BOTH  $\sqrt{s_{\text{NN}}}=2.76$  and 5.02 TeV (CMS)  
**→ Evidence for hierarchy of suppression!**



Understand the **y-dependence of  $\Upsilon(1\text{S})$  suppression**  
**→ Intriguing effect or trivially within uncertainty ?**



First set of **precise results from RHIC** now available!  
**→ Look for a unified description from low to high energy**

# Conclusions

- ❑ **Lots of high-quality new results have become available at QM2017**
- ❑ **Charmonia (  $J/\psi$ ,  $\psi(2S)$  )**
  - Firm evidence for  $J/\psi$  elliptic flow and strong re-generation effects**
  - Charm quarks thermalize in the deconfined medium**
- ❑ **Bottomonia (  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  )**
  - Suppression effects strongly correlated with binding energy**
  - Evidence for resonance melting in a hot QGP**



# Thanks to all the speakers!

- ☐ Measurements of charmonium production in p+p, p+Au, and Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV with the STAR experiment, **Takahito Todoroki**
- ☐ ALICE Measurement of the  $J/\psi$  Nuclear Modification Factor  $R_{AA}$  at Mid-Rapidity in Pb-Pb Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, **Tonatiuh Jimenez**
- ☐  $\psi(2S)$  and  $J/\psi$  modification in pPb and PbPb collisions at 5.02 TeV with CMS, **Javier Martin Blanco**
- ☐ Measurement of charmonia production in heavy-ion collisions with the ATLAS detector, **Jorge Andres Lopez**
- ☐ Measurement of charmonium production at forward rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV with ALICE, **Mohamad Tarhini**
- ☐ Bottomonium measurements at forward rapidity in Pb-Pb and p-Pb collisions with ALICE at LHC, **Indranil Das (Antoine Lardeux)**
- ☐ Bottomonia results from the LHC Run 1 and 2 with CMS, **Chad Steven Flores**
- ☐ Heavy flavour production in proton-lead and lead-lead collisions with LHCb, **Michael Winn**
- ☐  $\Upsilon$  measurements in p+p, p+Au and Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV with the STAR experiment, **Zaochen Ye**
- ☐ PHENIX measurements of open and hidden heavy-flavor in p+p, p+Al, and p/d/ $^3\text{He}$ +Au collisions across a wide range of rapidity, **Sanghoon Lim**

# Backup

# J/ψ - RHIC energy

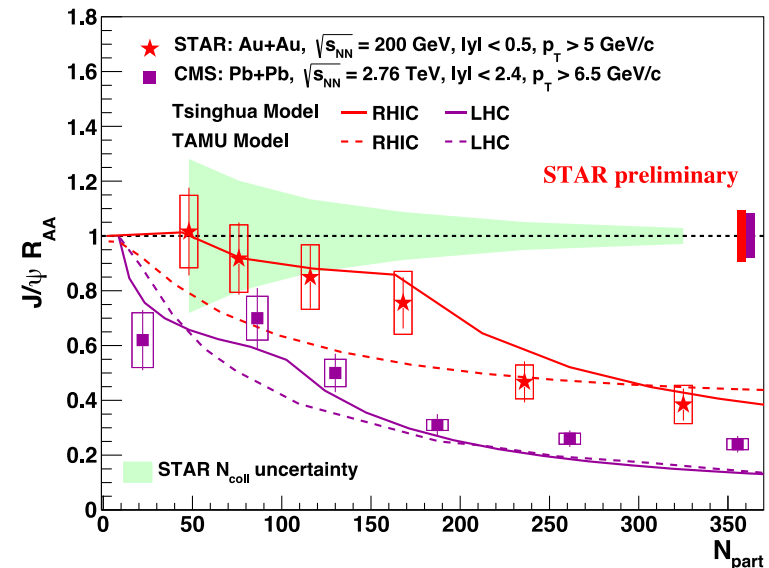
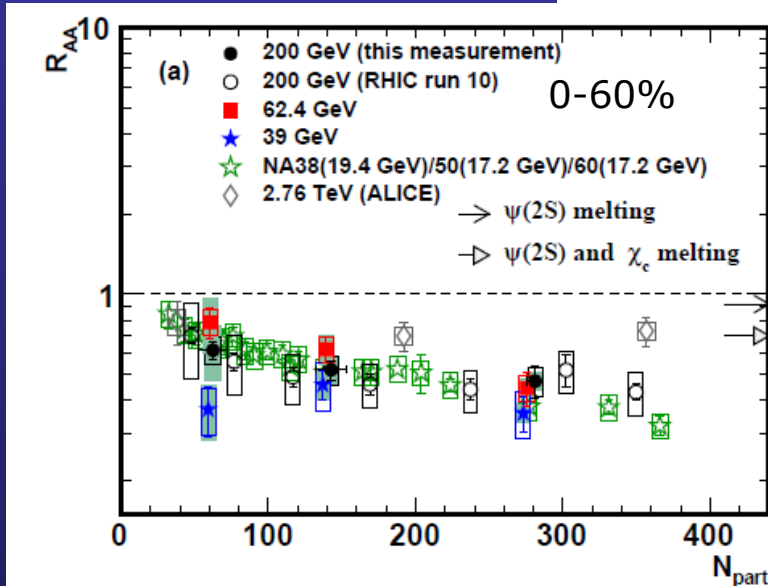
- Recent highlights by STAR
- Systematic exploration of **J/ψ suppression at lower energies**
- High  $p_T$  J/ψ suppression**

L. Adamczyk et al. (STAR),  
arXiv:1607.07517

Reference  
cross section  
at low RHIC  
energy



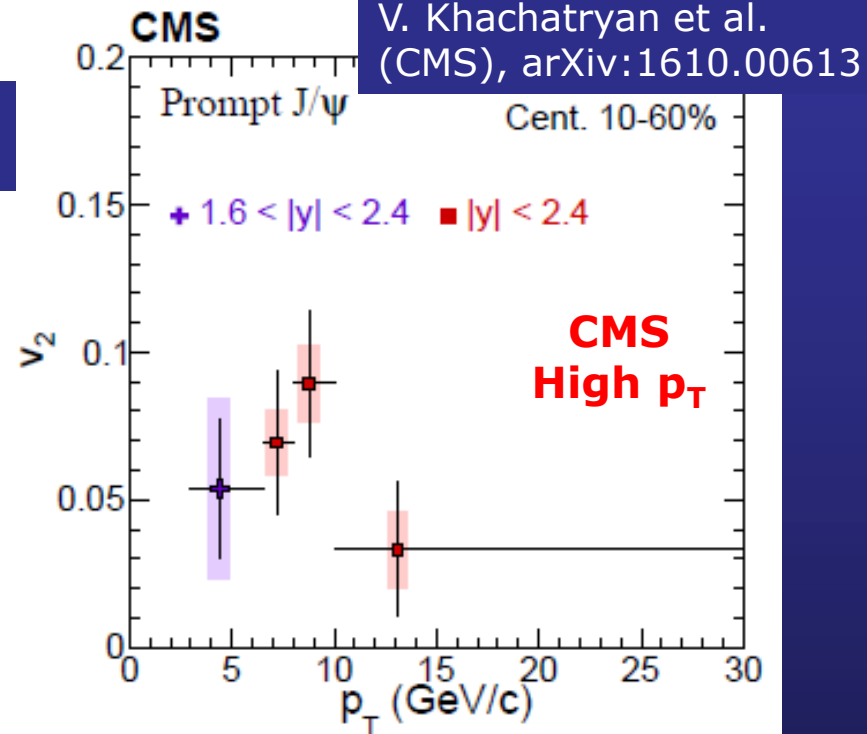
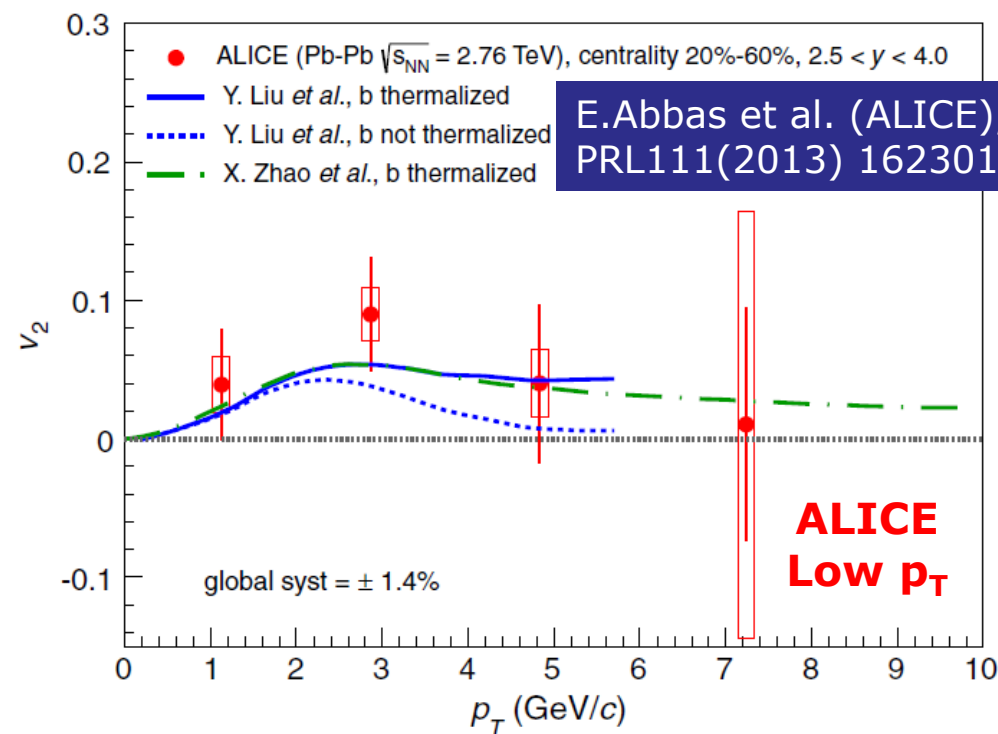
Interpolation  
of SPS/FNAL  
results



- No significant energy dependence of  $R_{AA}$  up to  $\sqrt{s_{NN}}=200$  GeV**  
 $\rightarrow$  (Almost) exact compensation of suppression and (re)combination
- High  $p_T$  J/ψ,  $R_{AA}^{LHC} < R_{AA}^{RHIC}$**  (opposite behavior at low  $p_T$ )

# J/ψ v<sub>2</sub>

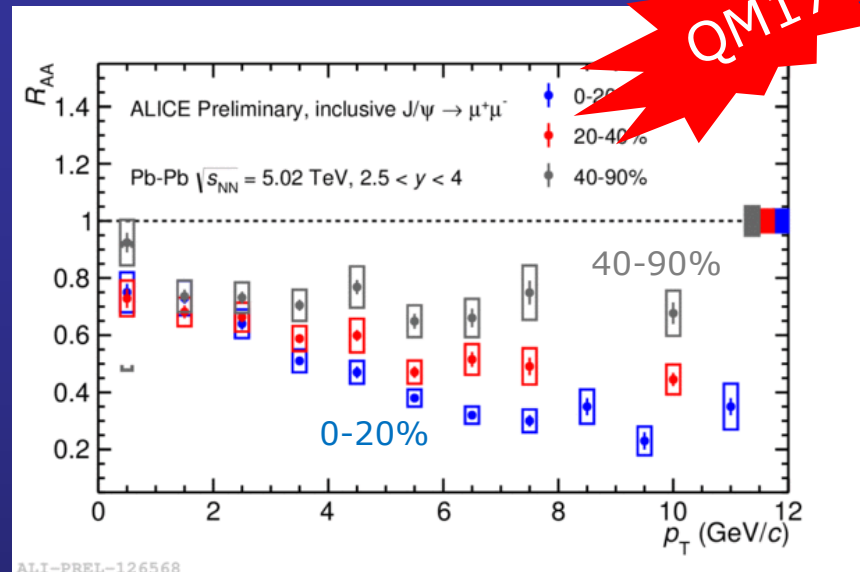
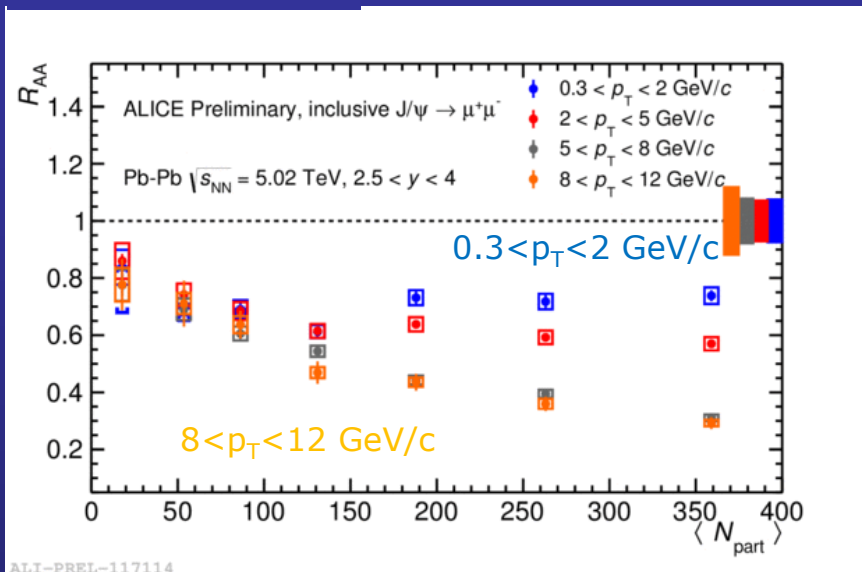
- The contribution of J/ψ from (re)combination could lead to an **elliptic flow** signal at LHC energy → hints observed in run-1 results



- $v_2$  remains significant **at large p<sub>T</sub> ( $\sim 10$  GeV/c)** where the contribution of (re)generation should be negligible  
→ Likely due to **path length dependence of energy loss**

# Multi-differential $J/\psi$ $R_{AA}$ (forward $y$ )

$\sqrt{s_{NN}} = 5.02$  TeV

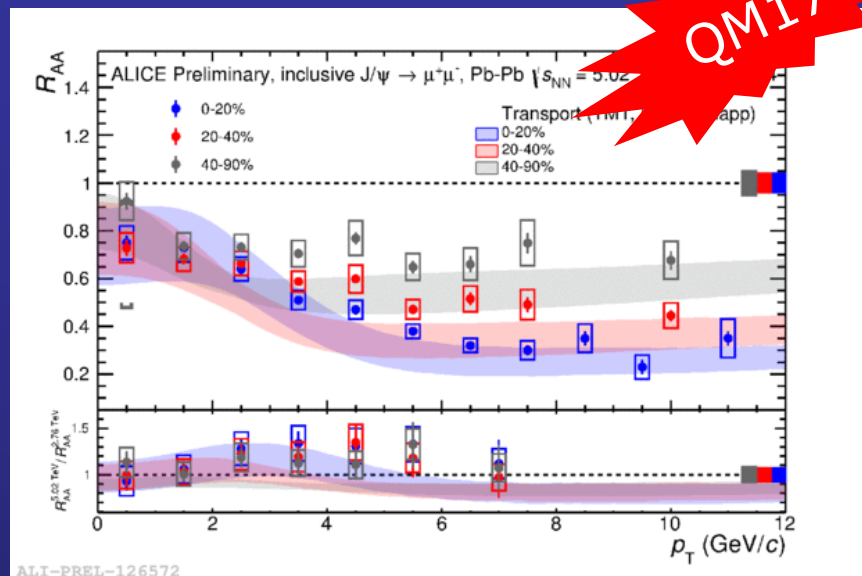
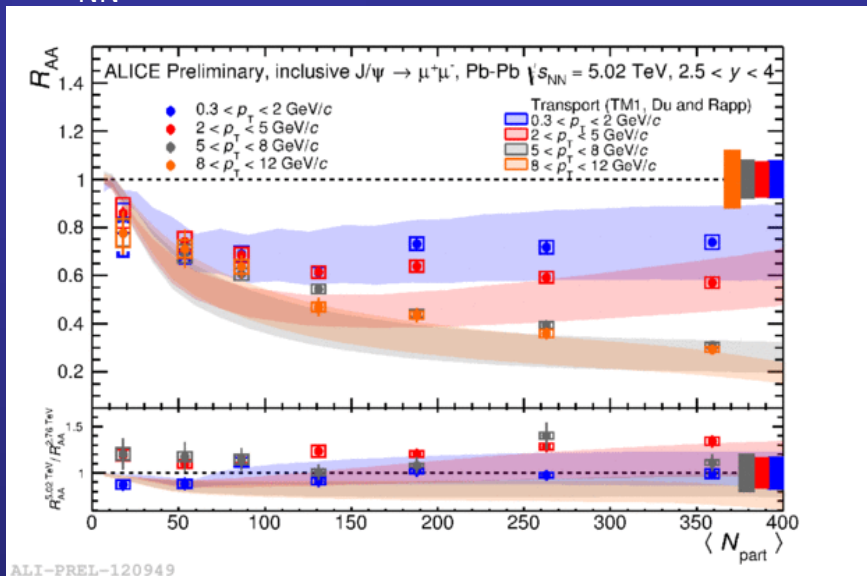


QM17

- ❑  $R_{AA}$  vs  $p_T$  for different centrality bins (and viceversa) at  $\sqrt{s_{NN}} = 5.02$  TeV
- ❑ Features seen in LHC run-1 results are confirmed
- ❑ New results include
  - Smaller statistical AND systematical uncertainties
  - Increase of the  $p_T$  reach up to 12 GeV/c
- ❑ **Striking features observed**
  - **$R_{AA}$  vs centrality (almost) flat in  $0 < p_T < 2$  GeV/c**
  - **$\sim 80\%$  suppression for central events at  $p_T \sim 10$  GeV/c**
- ❑ Precise results open up the way to discriminating comparisons with models

# Multi-differential $J/\psi$ $R_{AA}$ (forward $y$ )

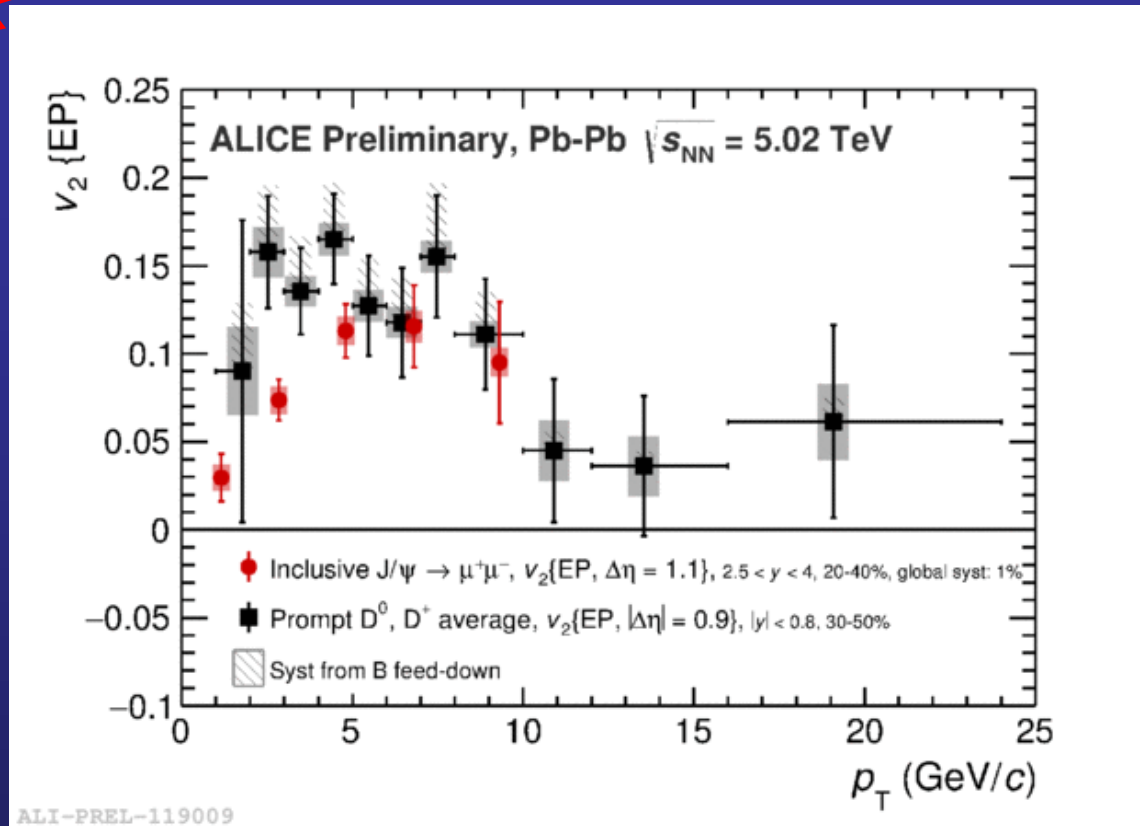
$\sqrt{s_{NN}} = 5.02$  TeV



QM17

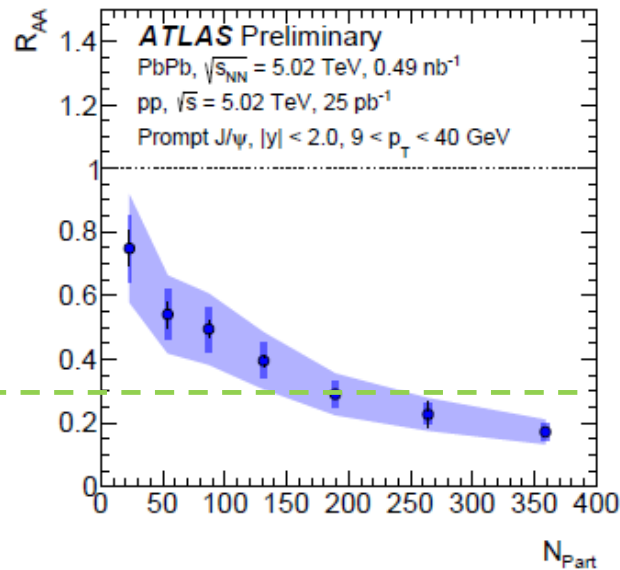
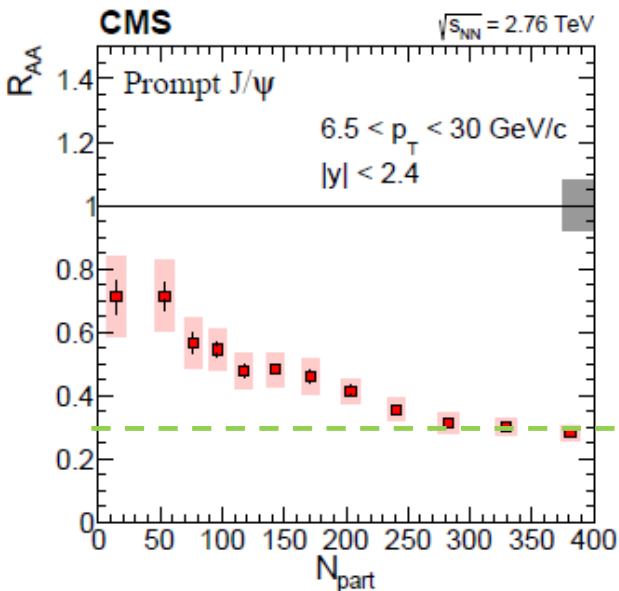
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- ❑ Precise results open up the way to discriminating comparisons with models

# Elliptic flow- closed vs open charm

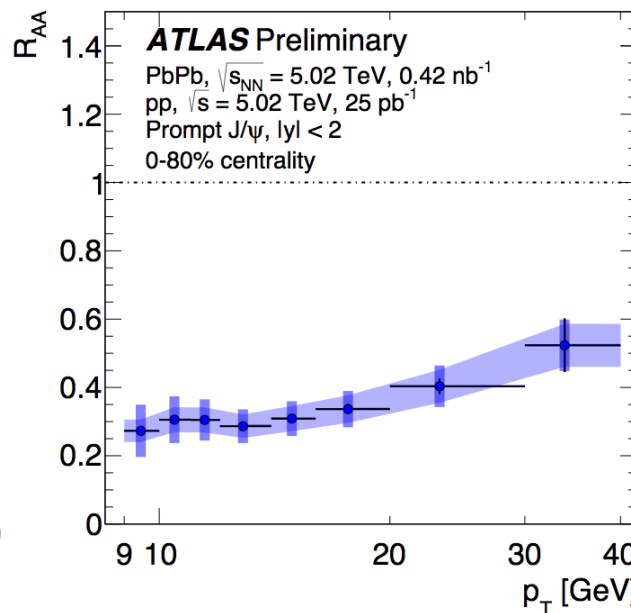
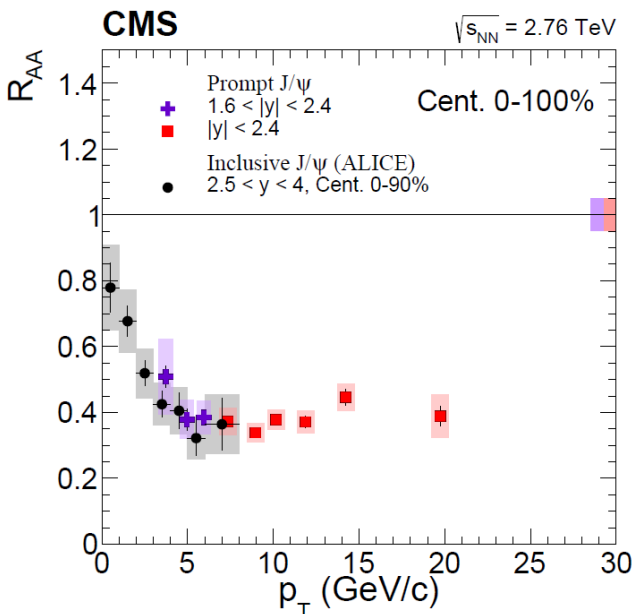


- At  $p_T \sim 5$  GeV/c,  **$v_2^{J/\psi}$  and  $v_2^D$  are compatible**
- Note different  $y$ -region ( $2.5 < y < 4$  for  $J/\psi$ ,  $|y| < 0.8$  for  $D^0$ ) and slightly different centrality selection (20-40% vs 30-50%)
- Charm quarks strongly interact with the medium

# High- $p_T$ $J/\psi$

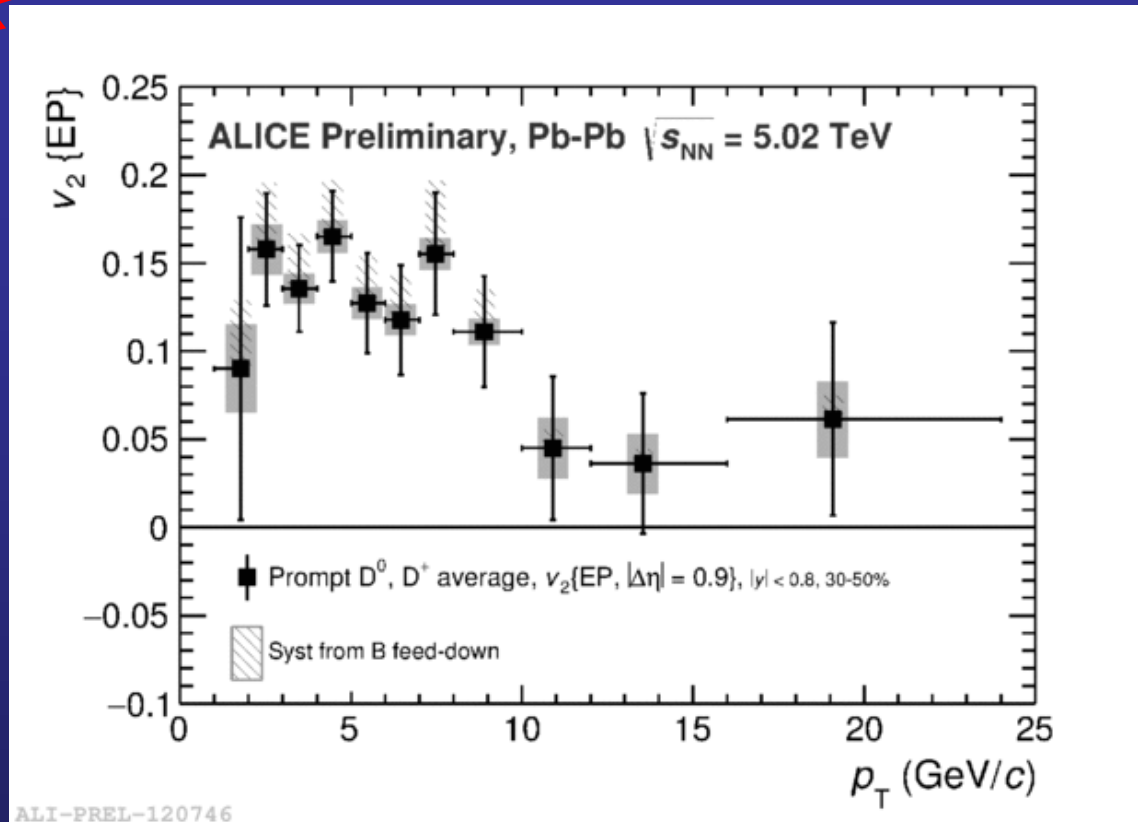


- Fine centrality binning
- Striking difference with respect to low- $p_T$   $J/\psi$
- **Suppression increases with centrality at high  $p_T$ , down to  $R_{AA} \sim 0.2$**
- **$\sqrt{s_{NN}}$ -dependent effects are weak**



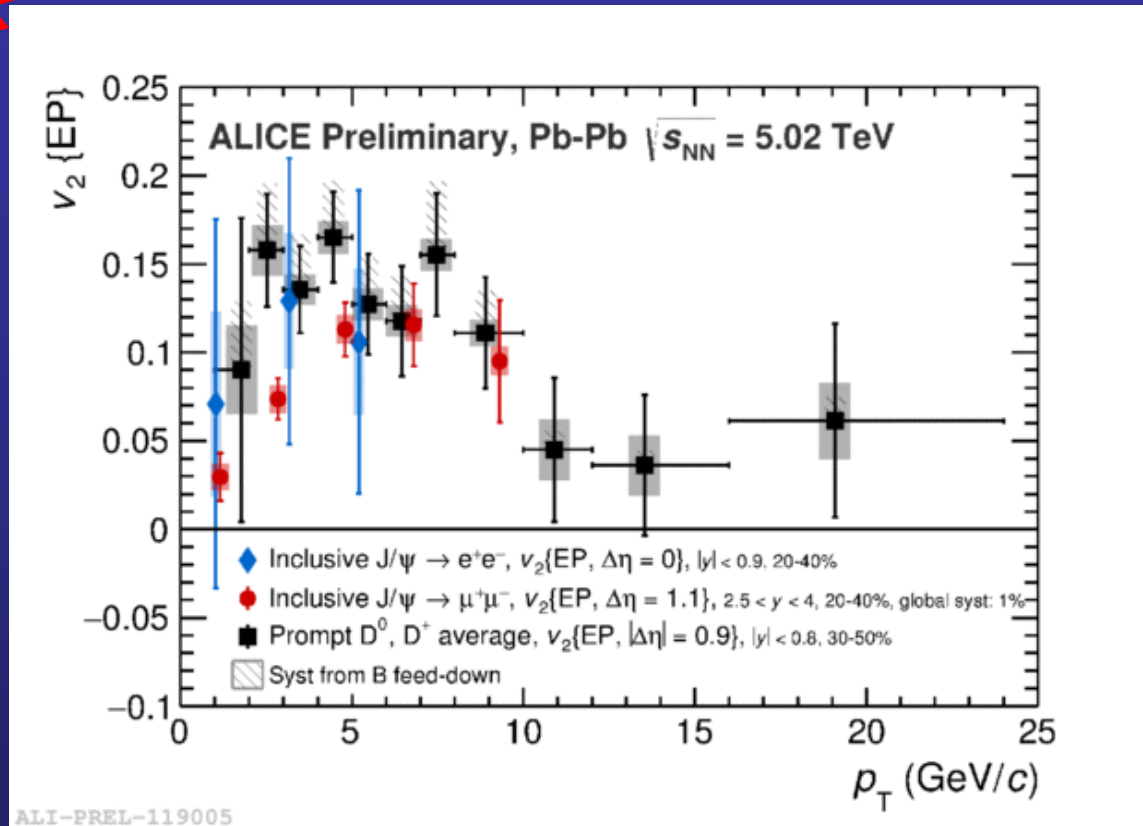
- **$R_{AA}$  increases for  $p_T > 20$  GeV/c**
- Related to energy loss effects, rather than dissociation ?

# Elliptic flow- closed vs open charm



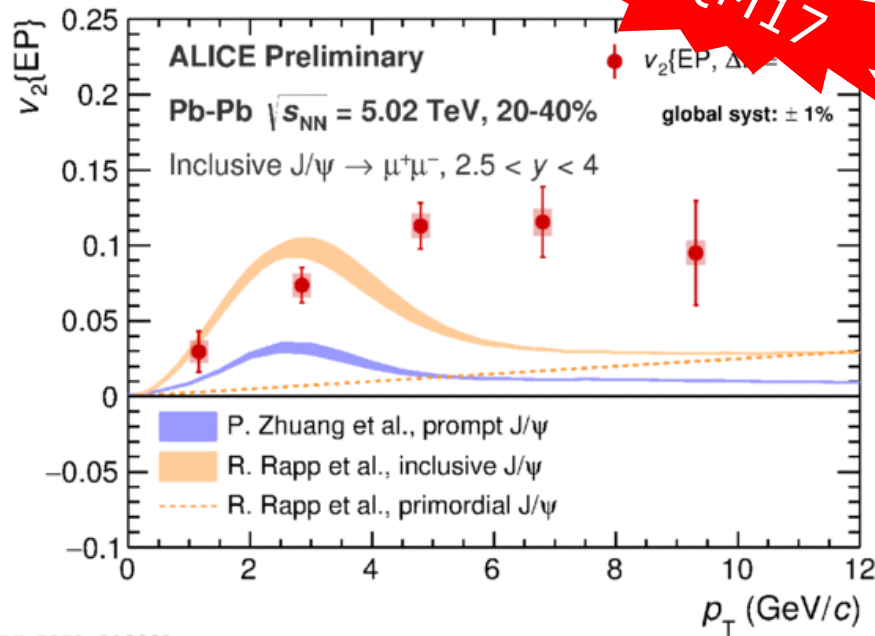
- At  $p_T \sim 5$  GeV/c,  **$v_2^{J/\psi}$  and  $v_2^D$  are compatible**
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# Elliptic flow- closed vs open charm



- At  $p_T \sim 5$  GeV/c,  **$v_2^{J/\psi}$  and  $v_2^D$  are compatible**
- Note different  $y$ -region ( $2.5 < y < 4$  for  $J/\psi$ ,  $|y| < 0.8$  for  $D^0$ ) and slightly different centrality selection (20-40% vs 30-50%)
- ALICE results at midrapidity confirm the observed signal
- Charm quarks strongly interact with the medium

# New $J/\psi$ $v_2$ results



- The contribution of  $J/\psi$  from (re)combination could lead to an **elliptic flow** signal at LHC energy  $\rightarrow$  hints observed in run-1 results

- ALICE results at  $\sqrt{s_{NN}}=5.02$  TeV, corresponding to  $L_{int} \sim 225 \mu b^{-1}$  (was  $L_{int} \sim 70 \mu b^{-1}$  at  $\sqrt{s_{NN}}=2.76$  TeV)

- **From hint to evidence for a non-zero  $v_2$  signal**, maximum for  $4 < p_T < 6$  GeV/c, 20-40% centrality

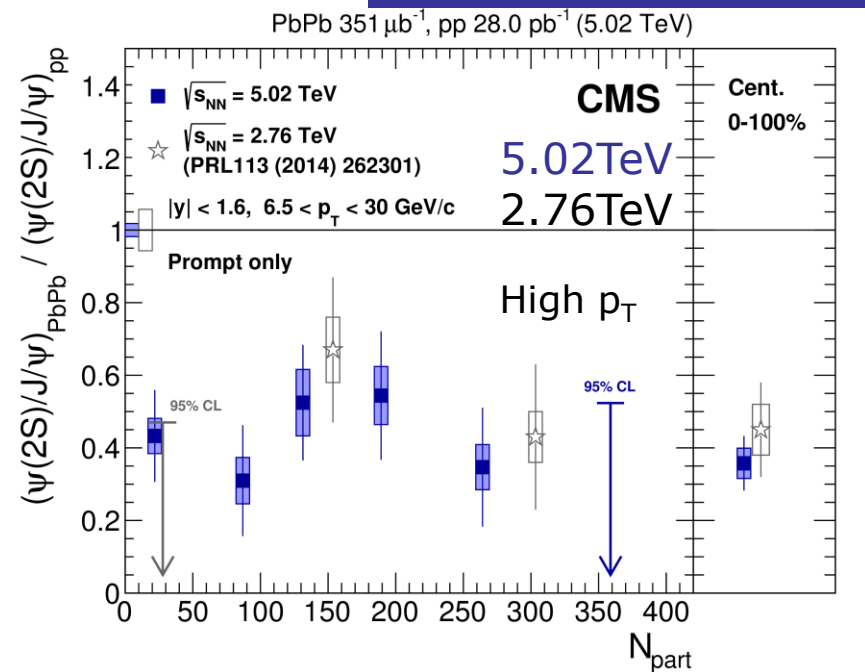
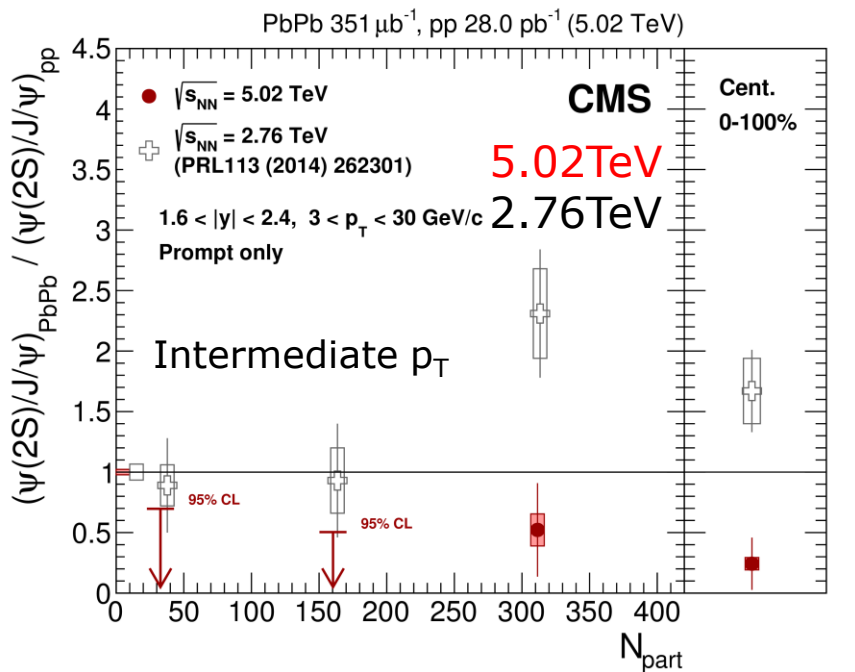
- Agreement, within uncertainties, with run-1 results

$p_T$ (GeV/c)	0-2	2-4	4-6	6-8	8-12
$\Delta\eta=1.1$	$2.2\sigma$	$6.3\sigma$	$7.4\sigma$	$5.0\sigma$	$2.8\sigma$
$\Delta\eta=5.3$	$1.4\sigma$	$6.2\sigma$	$5.0\sigma$	$3.3\sigma$	$1.3\sigma$

- A significant fraction of observed  $J/\psi$  comes from charm quarks which thermalized in the QGP

# Double ratios $\psi(2S)/J/\psi$

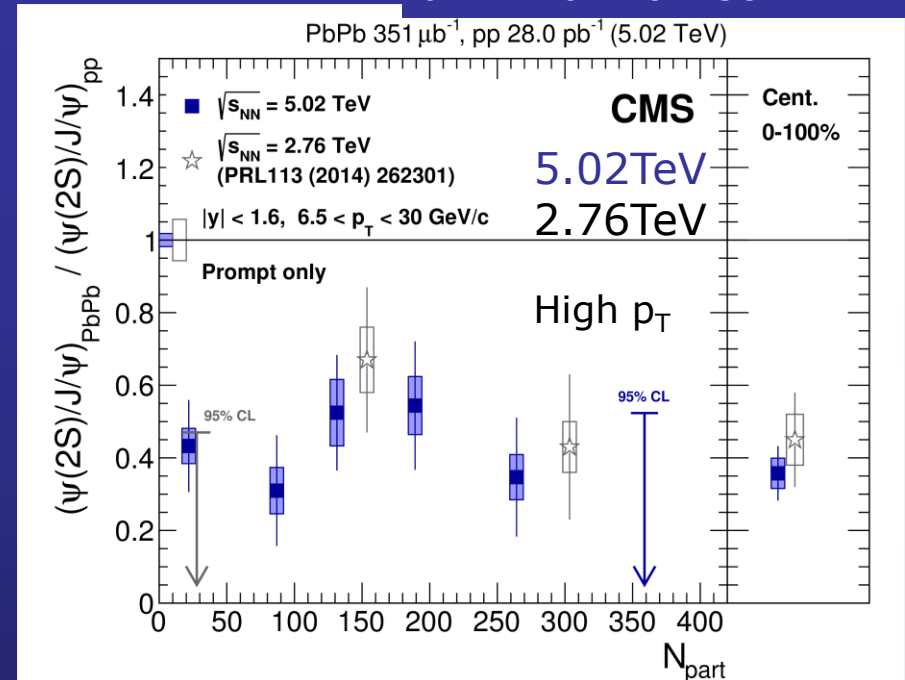
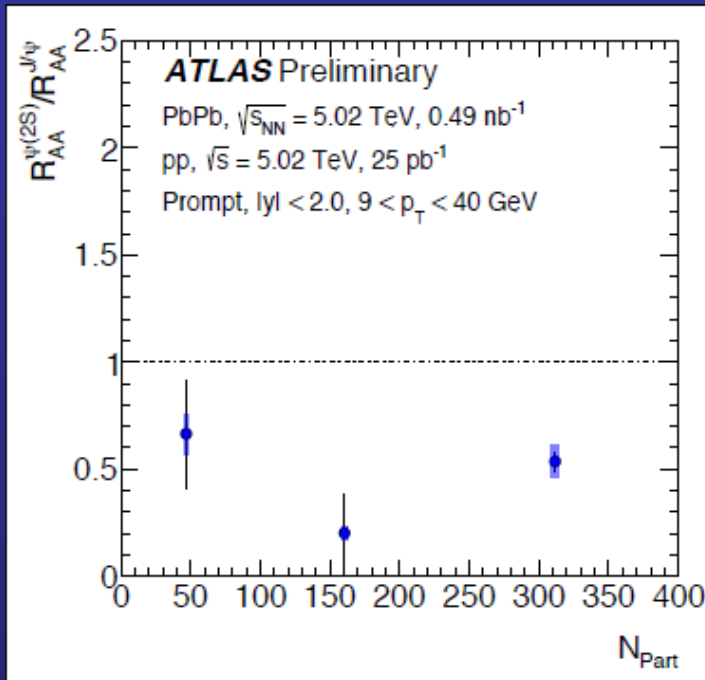
V. Khachatryan et al. (CMS),  
arXiv:1611.01438



- ❑ Ratio  $(\psi(2S)/J/\psi)_{\text{PbPb}} / (\psi(2S)/J/\psi)_{\text{pp}} \rightarrow \ll 1$  in a dissociation scenario
- ❑ **Suppression** seen by CMS at intermediate and high  $p_T$ , but...
- ❑ **Enhancement** seen at 2.76 TeV intermediate  $p_T$  for central events
- ❑ ATLAS confirms suppression in the high- $p_T$  region
- ❑ Proposed mechanism (Rapp) for enhancement:  **$\psi(2S)$  regeneration** **mainly occurring later**, when radial flow is already built-up
- ❑  $\sqrt{s_{NN}}$  dependence of the effect not easy to explain, though

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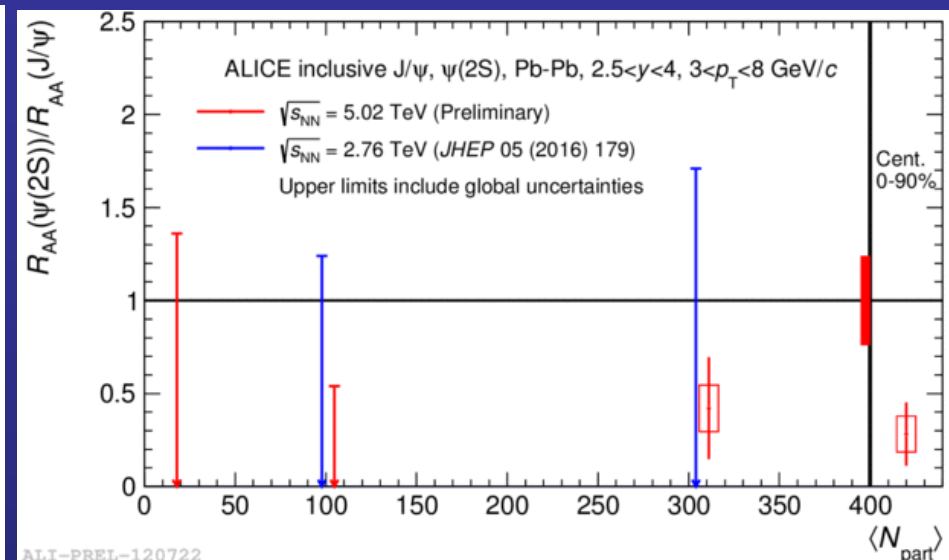
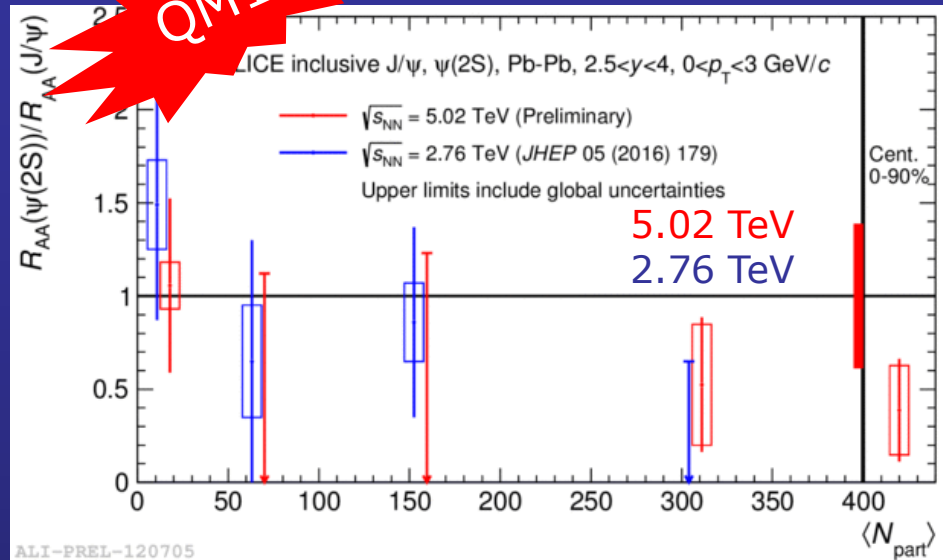
V. Khachatryan et al. (CMS),  
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# New $\psi(2S)$ results from ALICE

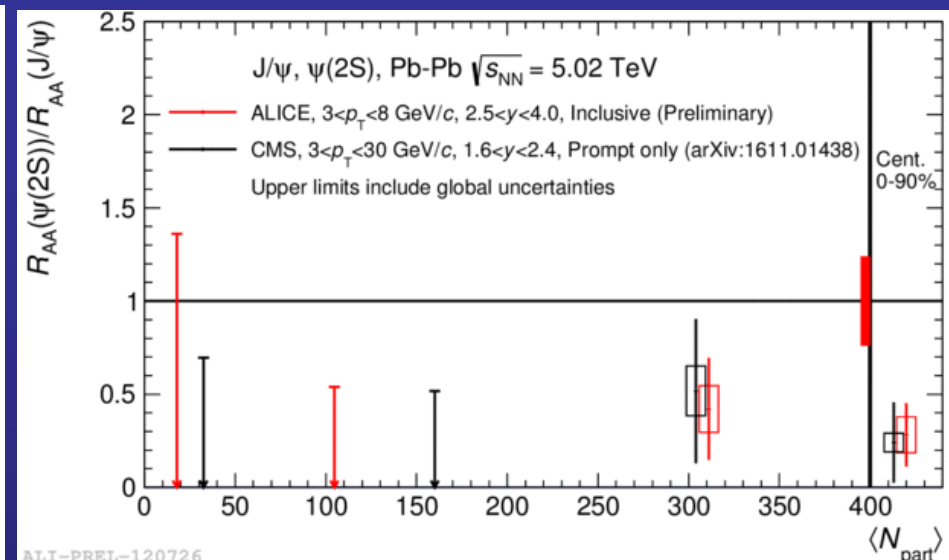
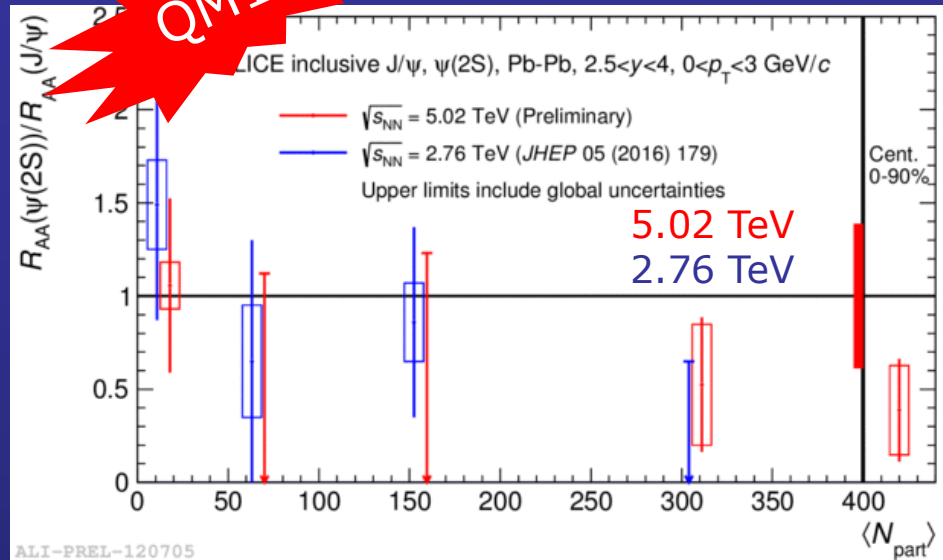
QM17



- ALICE accesses forward  $y$  and extends coverage **down to  $p_T = 0$**
- Uncertainties are generally rather large (S/B sub-optimal)
- $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV result are compatible
- Indications for **suppression at low AND intermediate  $p_T$**
- Enhancement seen by CMS at  $\sqrt{s_{NN}} = 2.76$  TeV remains somewhat “isolated”
- General comment:  $\psi(2S)$  can be **heavily affected by the hadronic medium**, do we have a quantitative understanding of processes occurring at (very) late stages?
- Should  $\psi(2S)$  be treated together with (light) hadronic resonances ?

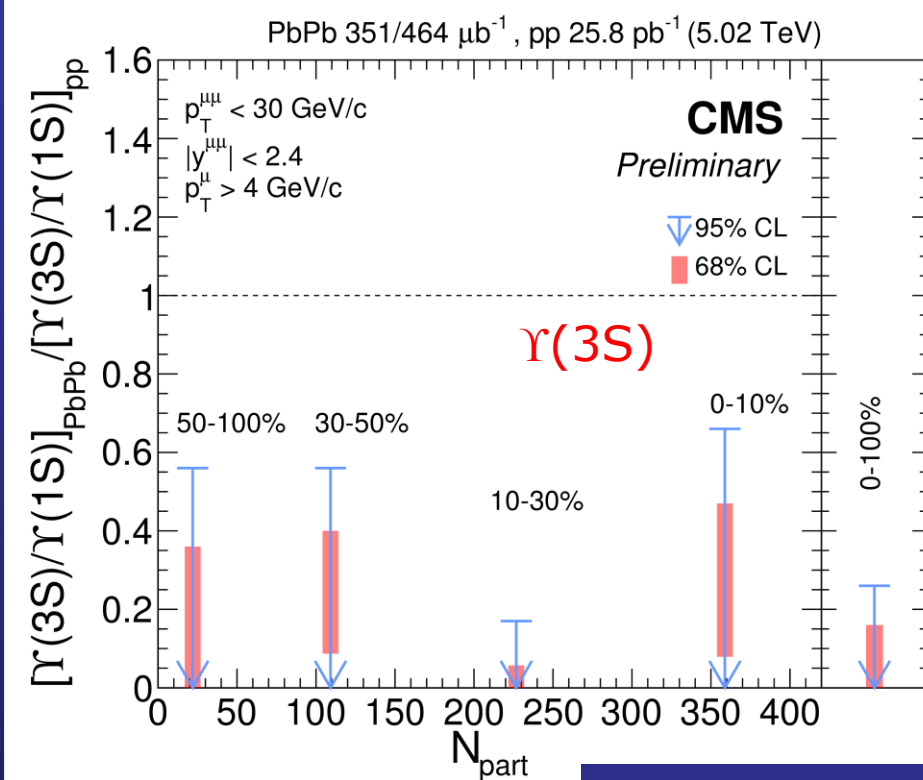
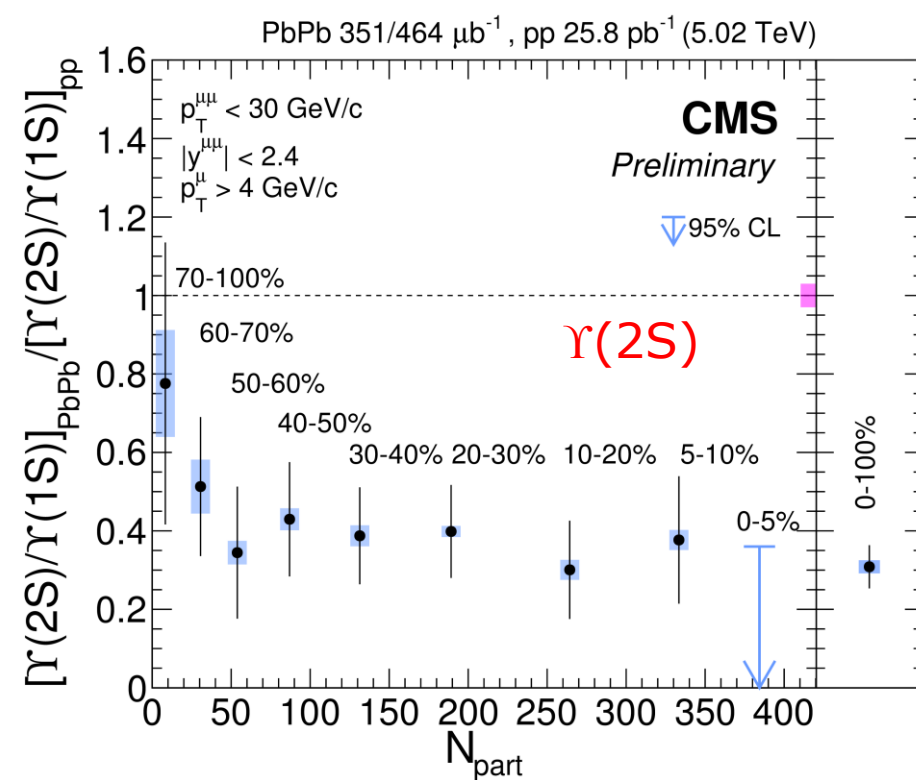
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QM17



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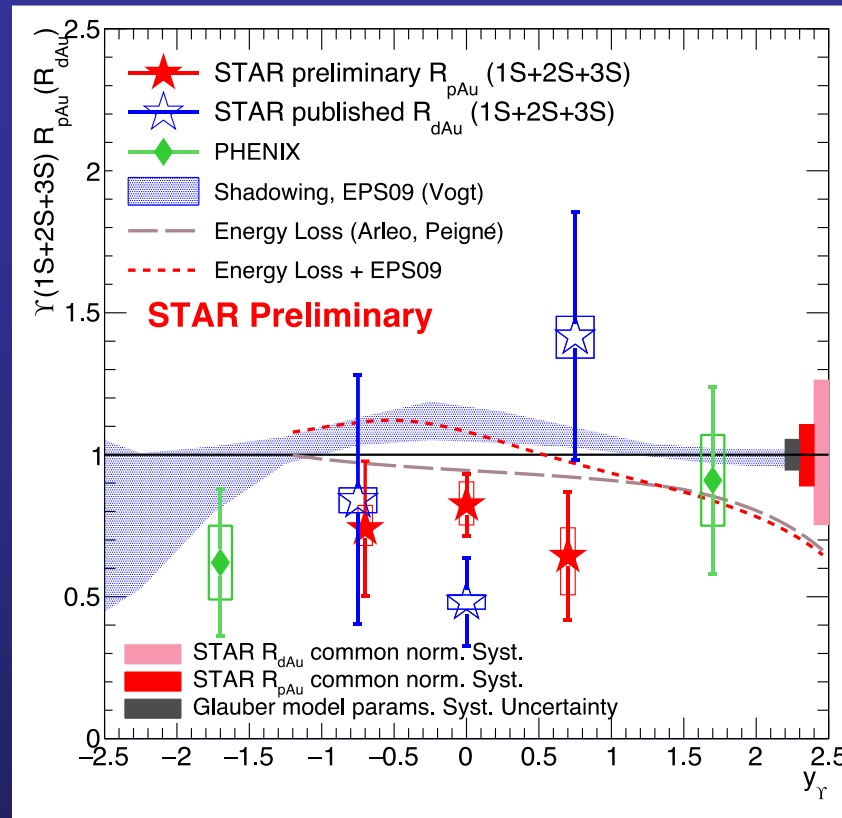
# $\Upsilon(2S)$ and $\Upsilon(3S)$ suppression relative to $\Upsilon(1S)$



CMS-HIN-16-008

- $\Upsilon(2S)/\Upsilon(1S)$  integrated double ratios:  
 $\sqrt{s_{\text{NN}}} = 5 \text{ TeV} \rightarrow 0.308 \pm 0.055 \pm 0.017$ ,  $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \rightarrow 0.21 \pm 0.07 \pm 0.02$
- The  $\Upsilon(2S)$  relative suppression already **saturates for semi-peripheral collisions**

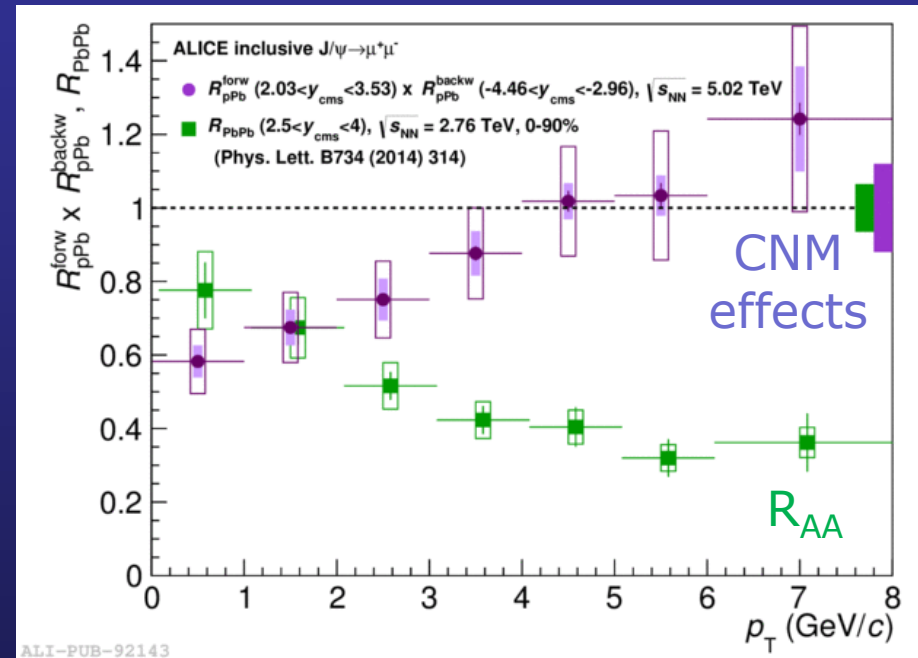
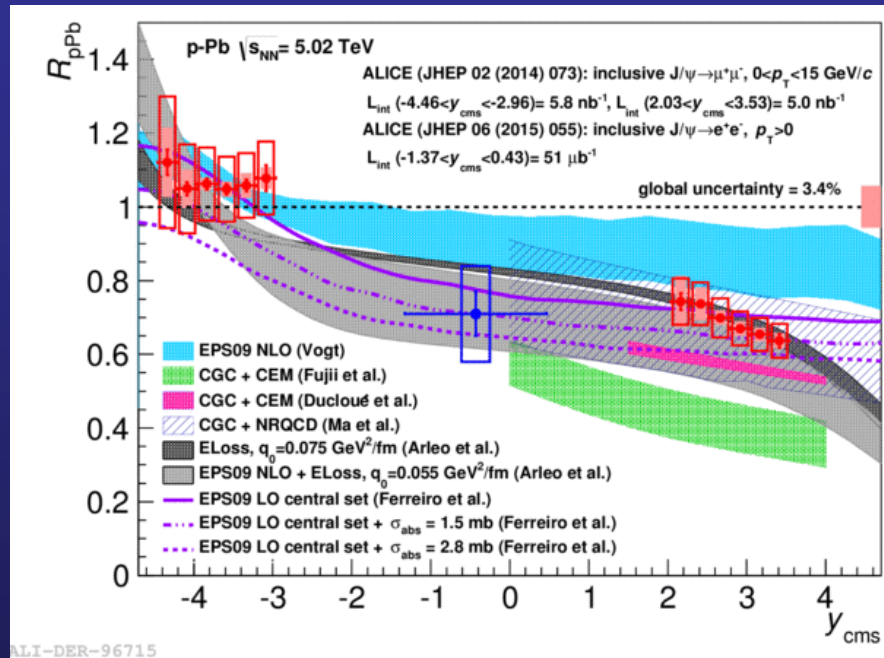
# $R_{pAu}$ at RHIC, new STAR result



- ❑ Strong improvement with respect to previous d-Au results
- ❑ Hint of  $\gamma(1S+2S+3S)$  suppression in p+Au collisions:  
 $\rightarrow R_{pA} (|y| < 0.5): 0.82 \pm 0.10_{-8.8\%}^{+8.8\%}$
- ❑ Shadowing calculations give  $R_{pAu} > 1$  at midrapidity

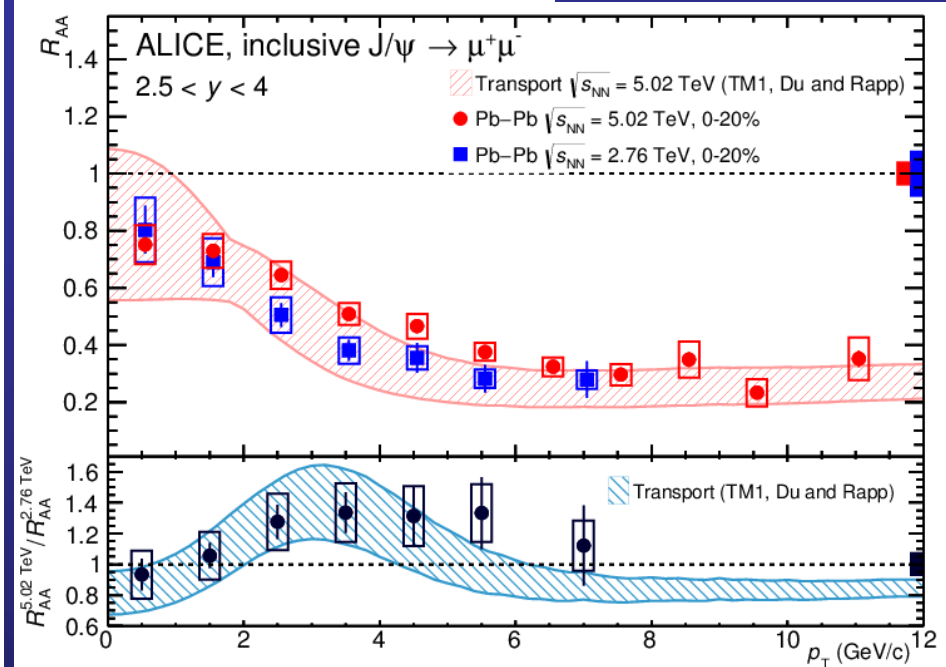
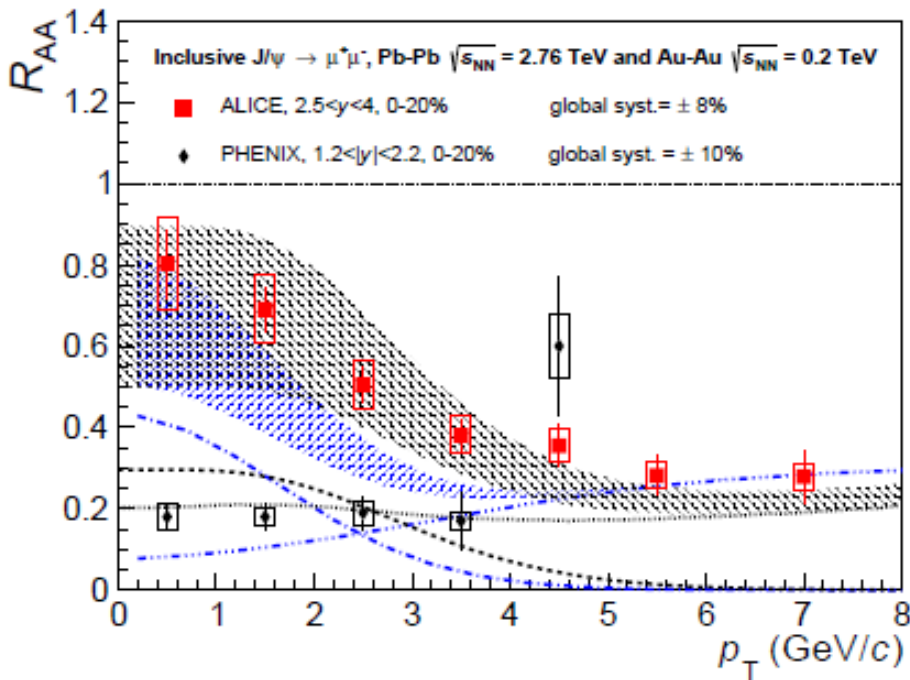
# CNM effects - charmonia

- LHC energy → **Strong CNM effects** observed at **forward-y and low  $p_T$**
- Can be described via **shadowing + coherent energy loss** and also via a **ColorGlassCondensate** approach



- Qualitative extrapolations of CNM effects to Pb-Pb imply **strong high  $p_T$  suppression** and hints for  **$J/\psi$  enhancement at low  $p_T$**

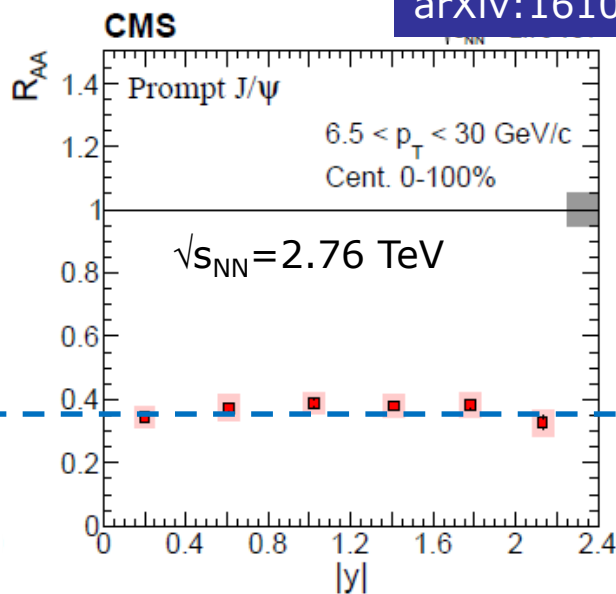
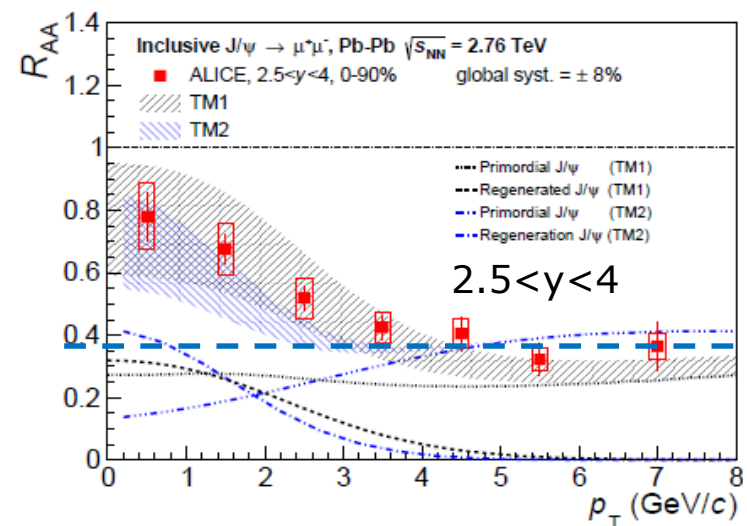
# J/ψ R<sub>AA</sub> vs p<sub>T</sub> (at low p<sub>T</sub>)



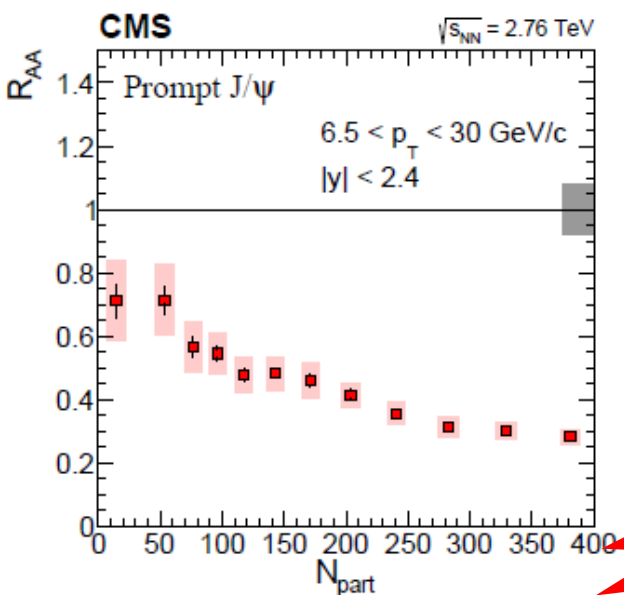
- Typical feature at both  $\sqrt{s_{NN}} = 2.76$  and  $5.02$  TeV → **reduced suppression at low  $p_T$**  (where the bulk of charm quarks is produced)
- Effect not visible at RHIC
- Fair agreement with theory calculations including (re)generation
- Comparison still suffers from **non-negligible uncertainties in the model inputs** → role of cold nuclear matter, open charm cross section

# High- $p_T$ $J/\psi$ at LHC

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



**J/ $\psi$  suppression stronger at high- $p_T$ , with no significant  $y$  dependence (ALICE vs CMS)**



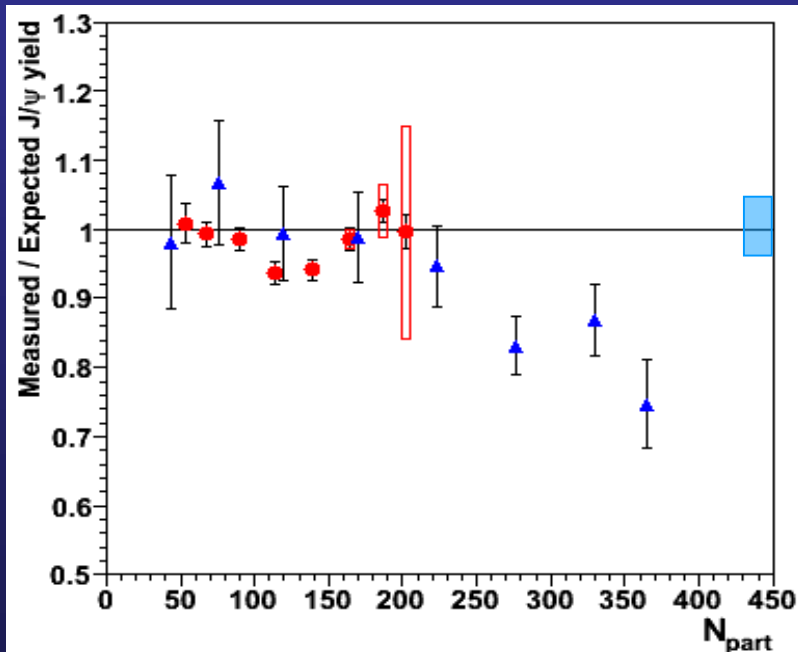
- New high statistics result from CMS from round-2  $\rightarrow R_{AA}$  in fine centrality bins
- Striking difference with respect to low- $p_T$   $J/\psi$  results  $\rightarrow$  **Continuously increasing suppression (high  $p_T$ ) vs saturation (low  $p_T$ )**

QM17

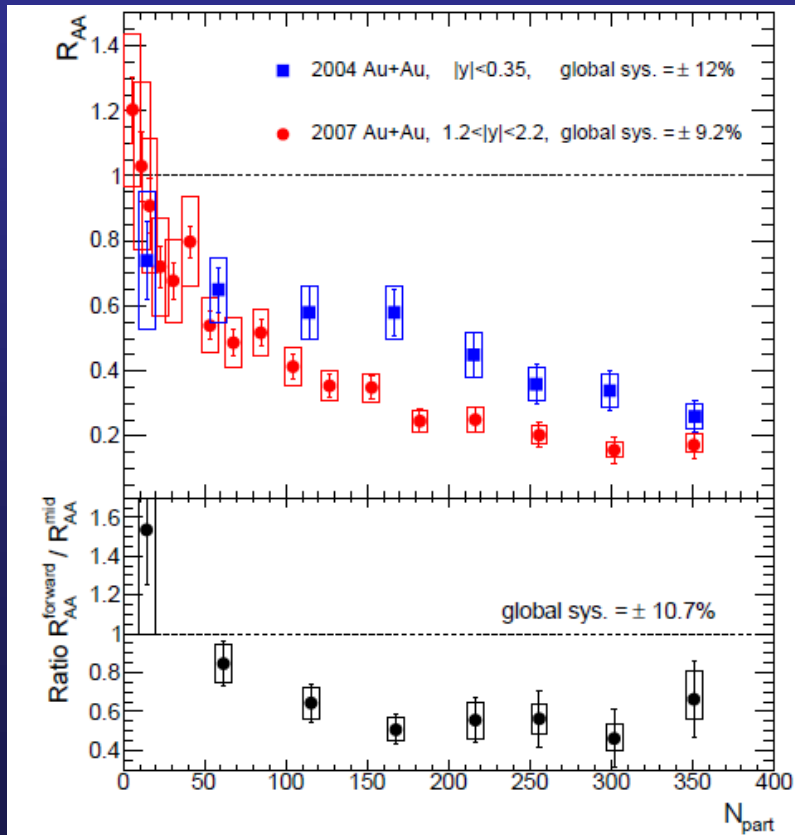
Up to a factor  $\sim 5$  for central events

# The legacy of SPS/RHIC

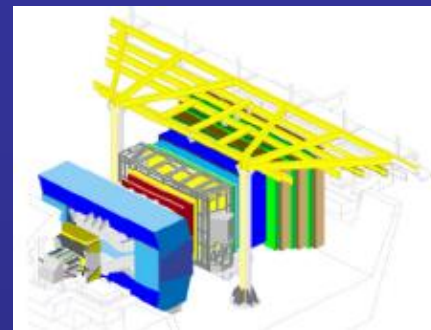
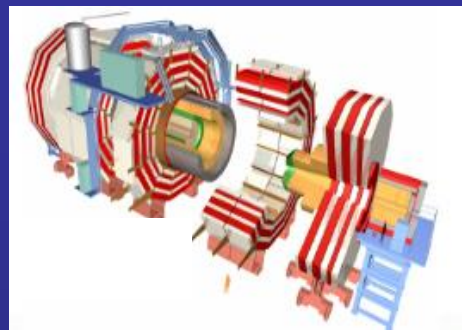
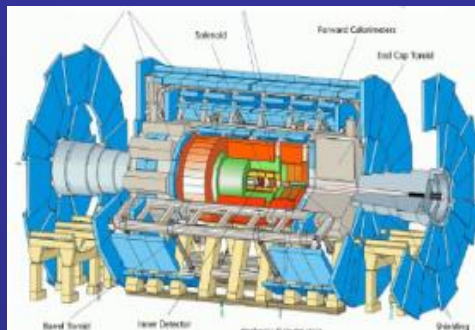
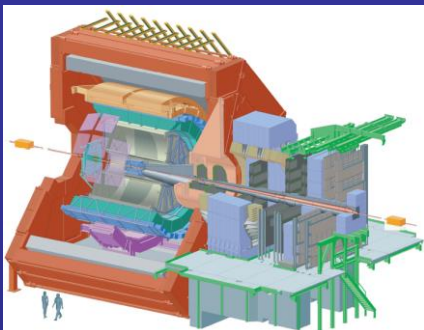
- ❑ Several landmarks were established
  - ❑  $J/\psi$  suppression beyond CNM effects at SPS  
(maximum suppression compatible with  $\chi_c + \psi(2S)$  melting)
  - ❑ Much stronger  $\psi(2S)$  suppression relative to  $J/\psi$  at SPS
  - ❑ Strong  $y$ -dependence of  $J/\psi$  suppression at RHIC  
(possible indication of recombination)



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



# Quarkonium at LHC



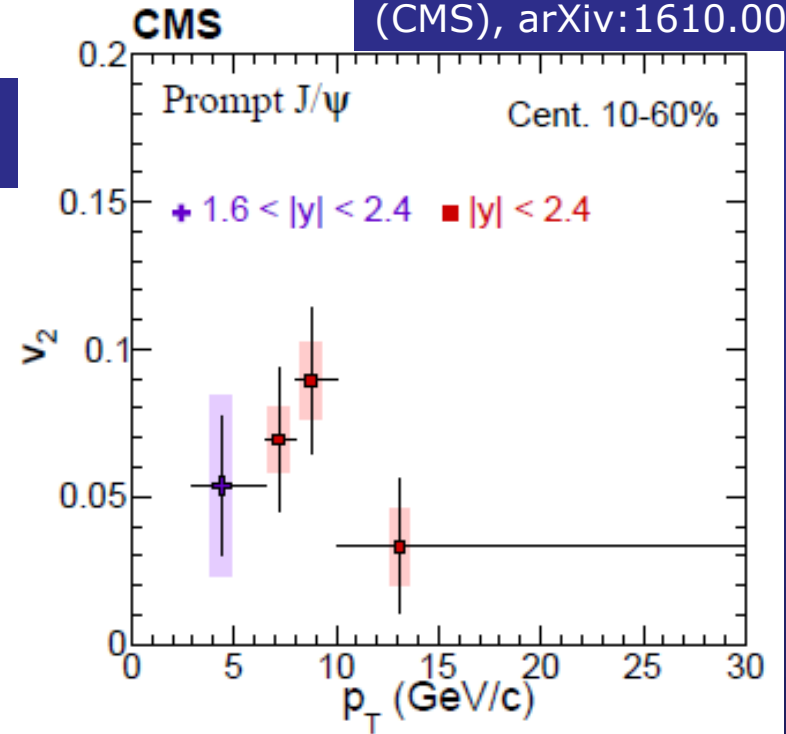
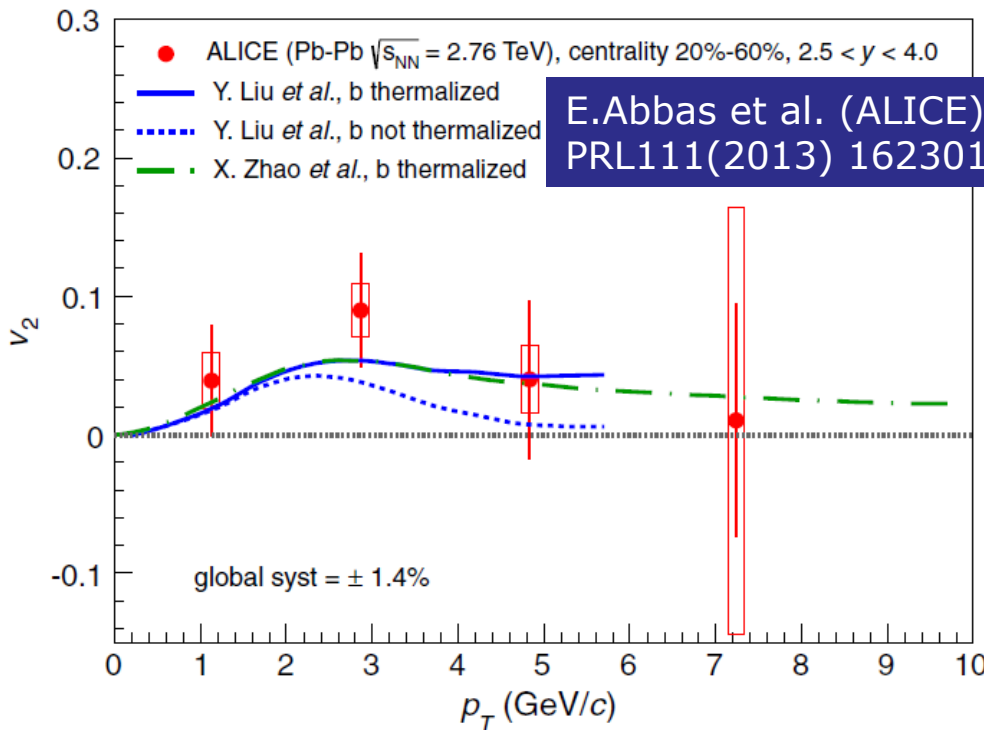
- All the four experiments have investigated quarkonium production
    - **Pb-Pb** → mainly ALICE + CMS, **p-Pb** → all the 4 experiments
  - Complementary kinematic ranges → **excellent phase space coverage**
    - ALICE** → forward-y ( $2.5 < y < 4$ , dimuons) and mid-y ( $|y| < 0.9$ , electrons)
    - LHCb** → forward-y ( $2 < y < 4.5$ , dimuons)
    - CMS** → mid-y ( $|y| < 2.4$ , dimuons)
    - ATLAS** → mid-y ( $|y| < 2.25$ , dimuons)
- (N.B.: y-range refers to symmetric collisions →rapidity shift in p-Pb!)

Data samples	<b>Pb-Pb</b> , $\sqrt{s_{NN}} = 2.76$ TeV, 2010 ( $9.7 \mu\text{b}^{-1}$ ) + 2011 ( $184 \mu\text{b}^{-1}$ )	Run 1
	<b>p-Pb</b> , $\sqrt{s_{NN}} = 5.02$ TeV, 2013 ( $36 \text{ nb}^{-1}$ )	
	ref. <b>p-p</b> , $\sqrt{s} = 2.76$ TeV, 2011 ( $250 \text{ nb}^{-1}$ ) + 2013 ( $5.6 \text{ pb}^{-1}$ )	
	<b>Pb-Pb</b> , $\sqrt{s_{NN}} = 5.02$ TeV, 2015 ( $600 \mu\text{b}^{-1}$ )	Run 2
	<b>p-Pb</b> , $\sqrt{s_{NN}} = 8.16$ TeV, 2016 ( $194 \text{ nb}^{-1}$ )	
	ref. <b>p-p</b> , $\sqrt{s} = 5.02$ TeV, 2015 ( $30 \text{ pb}^{-1}$ )	

# Non-zero $v_2$ for $J/\psi$ at the LHC

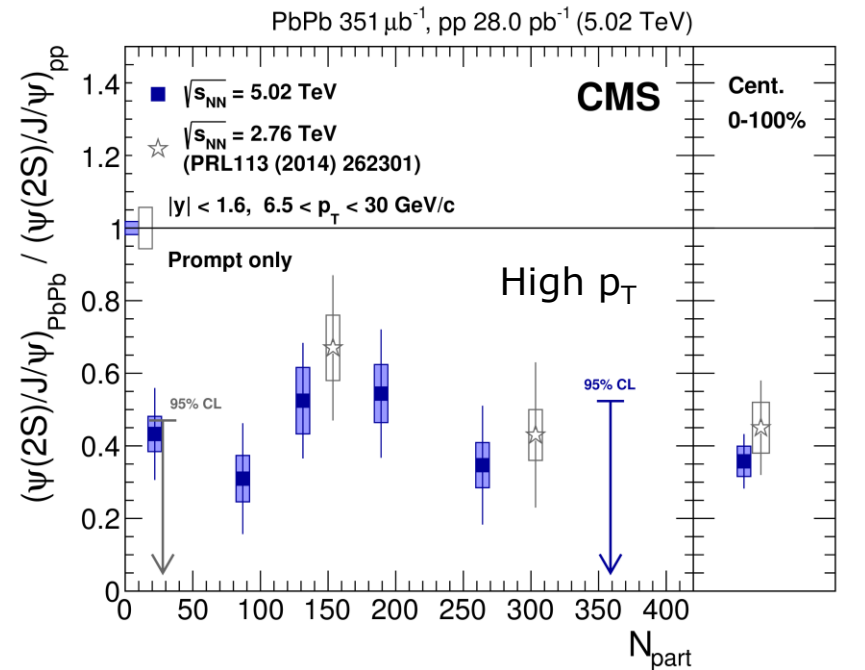
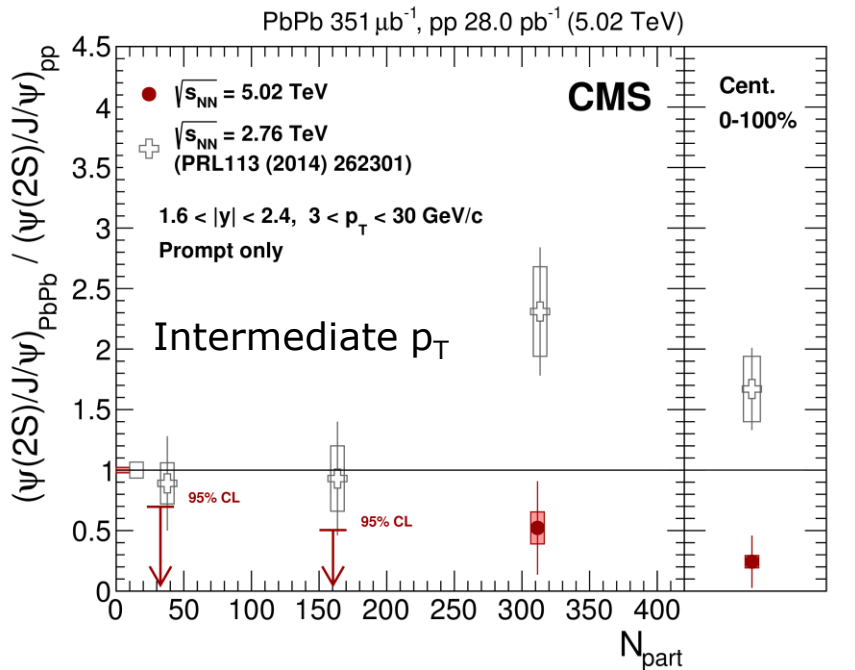
- The contribution of  $J/\psi$  from (re)combination could lead to a significant elliptic flow signal at LHC energy → observed!

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



- A significant  $v_2$  signal is observed at LHC (no evidence at RHIC)
- $v_2$  remains significant even in the region where the contribution of (re)generation should be negligible  
→ Likely due to path length dependence of energy loss

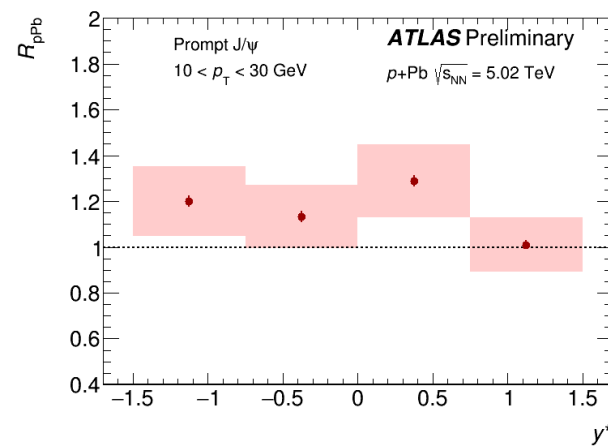
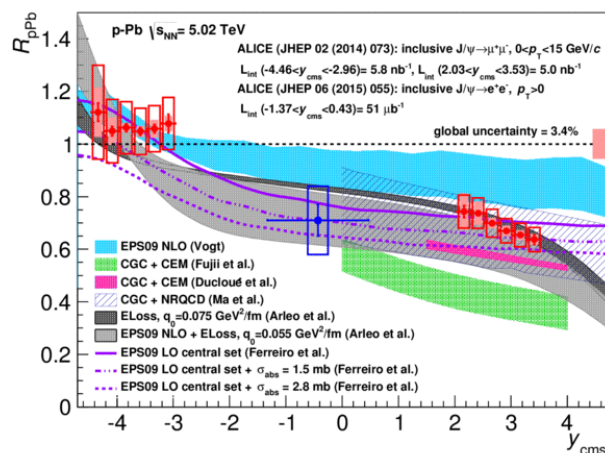
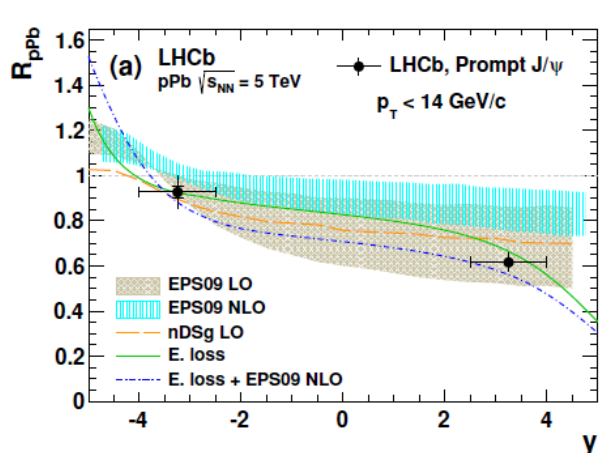
# $\psi(2S)$ in Pb-Pb collisions



- Ratio  $(\psi(2S)/J/\psi)_{\text{PbPb}} / (\psi(2S)/J/\psi)_{\text{pp}} \rightarrow$  naïve expectation  $< 1$
- Enhancement seen at 2.76 TeV, but not at 5.02 TeV
- ATLAS (not shown) confirms suppression in the high- $p_T$  region
- Proposed mechanism (Rapp) for enhancement:  $\psi(2S)$  regeneration occurring later, when radial flow is already built-up.  $\sqrt{s_{NN}}$  dependence of the effect not easy to explain

# CNM effects: $J/\psi$ in p-Pb collisions

- p-Pb collisions,  $\sqrt{s_{NN}}=5.02$  TeV,  $R_{pPb}$  vs  $p_T$
- $R_{pPb}$  vs  $y \rightarrow$  fair **agreement** ALICE vs LHCb, ATLAS refers to  $p_T > 10$  GeV/c

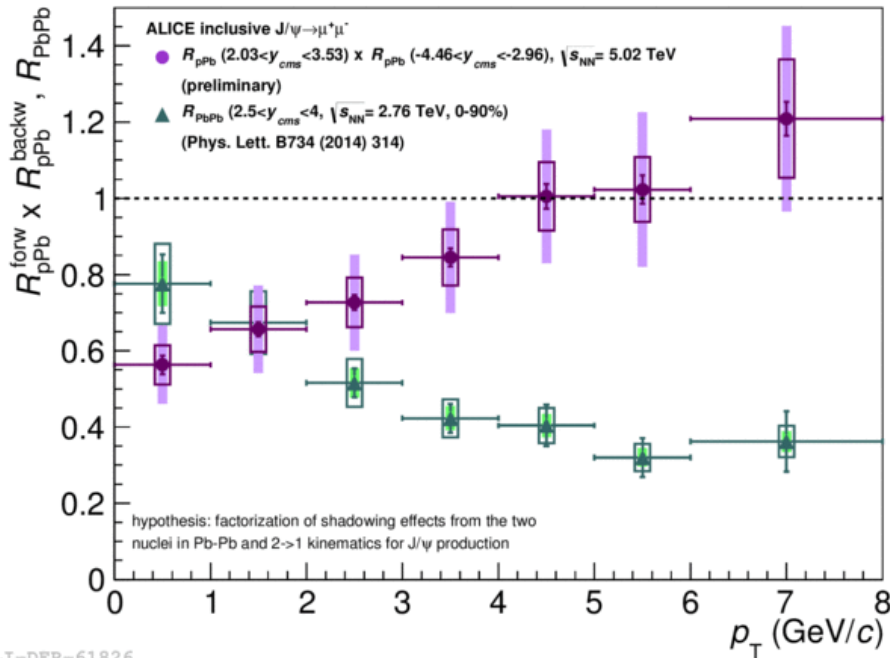


LHCb, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73

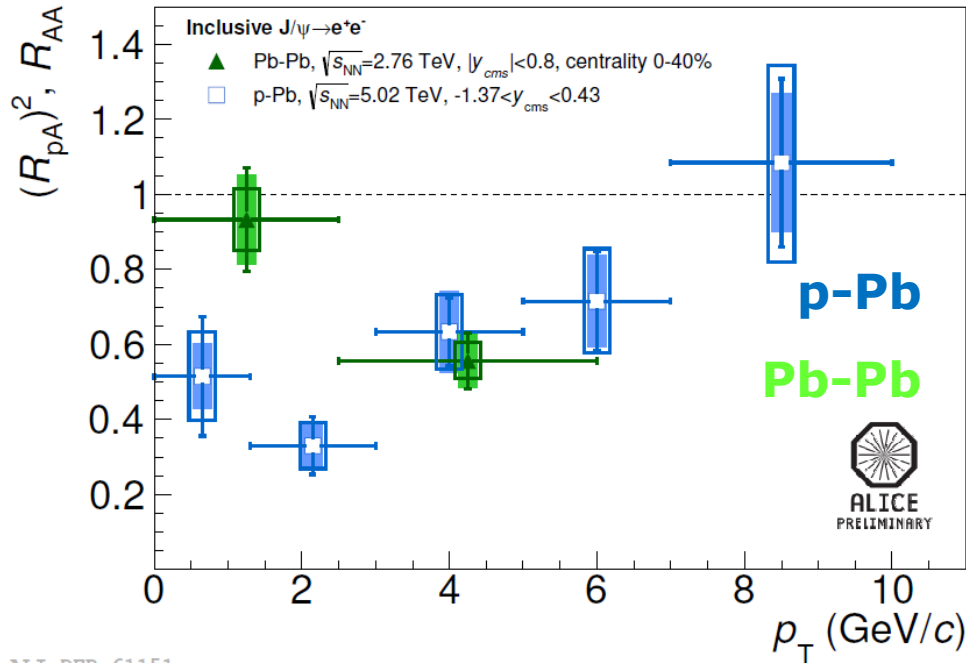
- LHC results can be described in terms of
  - shadowing
  - coherent energy loss
  - CGC approaches
- **Suppression effects can be strong**, in particular for  $y > 0$  and low  $p_T$
- Investigation of CNM effects **interesting**
  - To learn about **heavy quark behavior** in cold matter
  - As a **"background"** for hot matter effects

# CNM effects: from p-Pb to Pb-Pb

- If shadowing is the main CNM source  $\rightarrow R_{\text{PbPb}}^{\text{CNM}} = R_{\text{pPb}} \times R_{\text{pPb}}$   
(not quantitatively true for coherent energy loss, but  $\sqrt{s_{\text{NN}}}$  dependence weak)



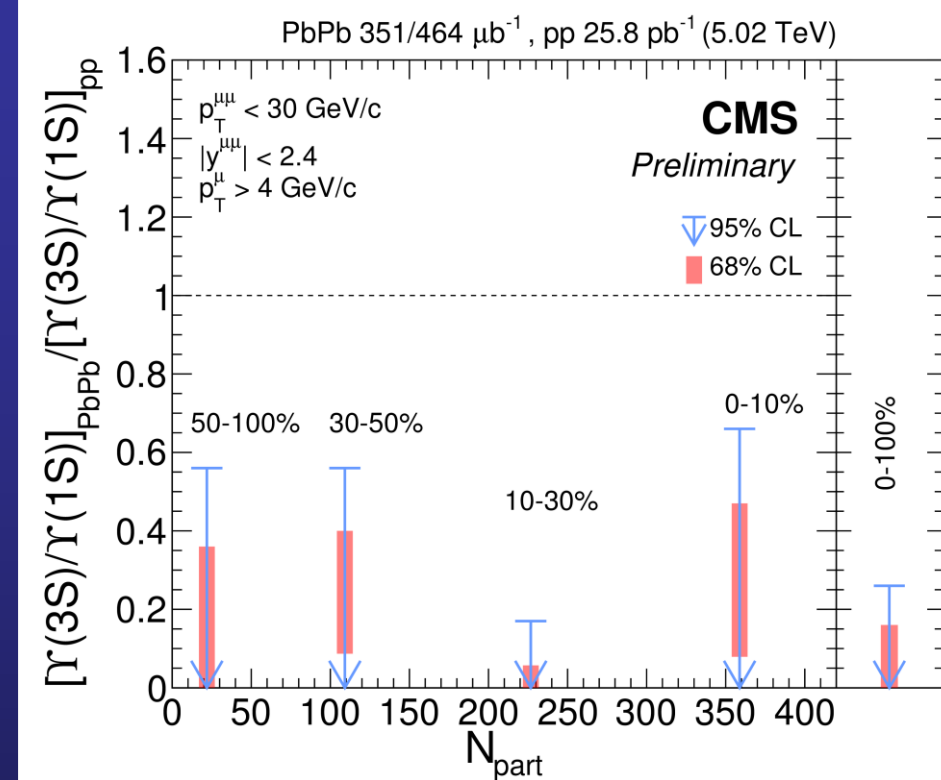
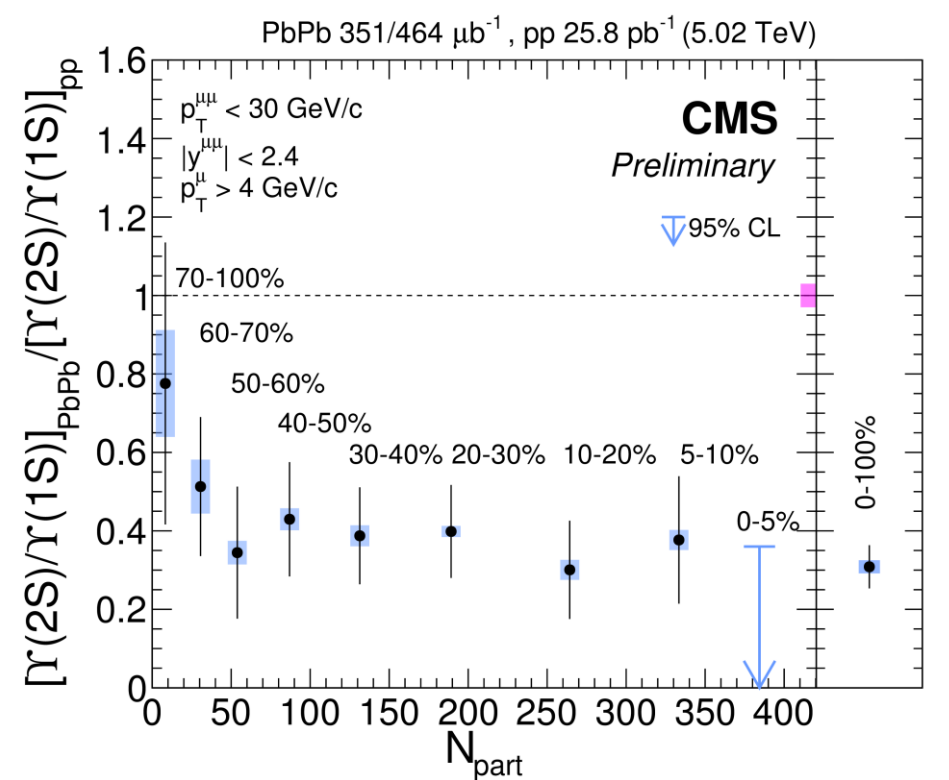
ALI-DER-61826



ALI-DER-61151

- This (cautious) exercise confirms that
  - $\rightarrow$  high  $p_T$   $J/\psi$  suppression is not a CNM effect
  - $\rightarrow$  at low  $p_T$  the observed suppression is consistent with CNM (i.e. there is a balance of suppression+recombination in hot matter)

# $\Upsilon(2S)$ and $\Upsilon(3S)$ suppression relative to $\Upsilon(1S)$



- $\Upsilon(2S)/\Upsilon(1S)$  integrated double ratios:  
 $\sqrt{s_{\text{NN}}} = 5 \text{ TeV} \rightarrow 0.31 \pm 0.06 \pm 0.02$ ,  $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \rightarrow 0.21 \pm 0.07 \pm 0.02$
- The suppression already saturates for semi-peripheral collisions

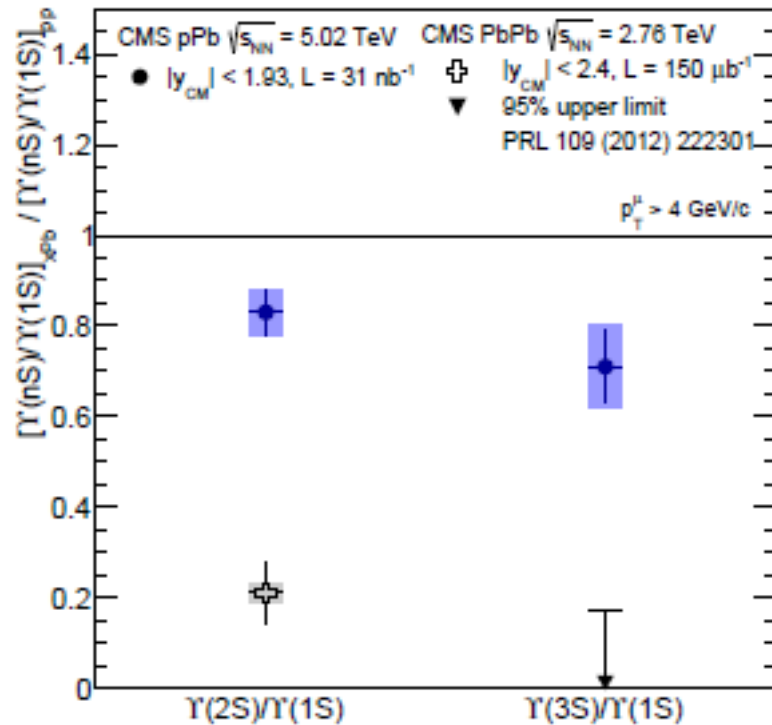
# CNM effects: the $\Upsilon$ family

□ **ALICE** has, for p-Pb collisions at  $\sqrt{s_{NN}}=5.02$  TeV

$$\Upsilon(2S)/\Upsilon(1S)=0.27 \pm 0.08 \pm 0.04 \quad (2.03 < y < 3.53)$$

$$\Upsilon(2S)/\Upsilon(1S)=0.26 \pm 0.09 \pm 0.04 \quad (-4.46 < y < -2.96)$$

to be compared with  $\Upsilon(2S)/\Upsilon(1S)=0.26 \pm 0.08$  in pp at  $\sqrt{s}=7$  TeV ( $2.5 < y < 4$ )  
→ No indication for different effects on  $\Upsilon(2S)$  and  $\Upsilon(1S)$

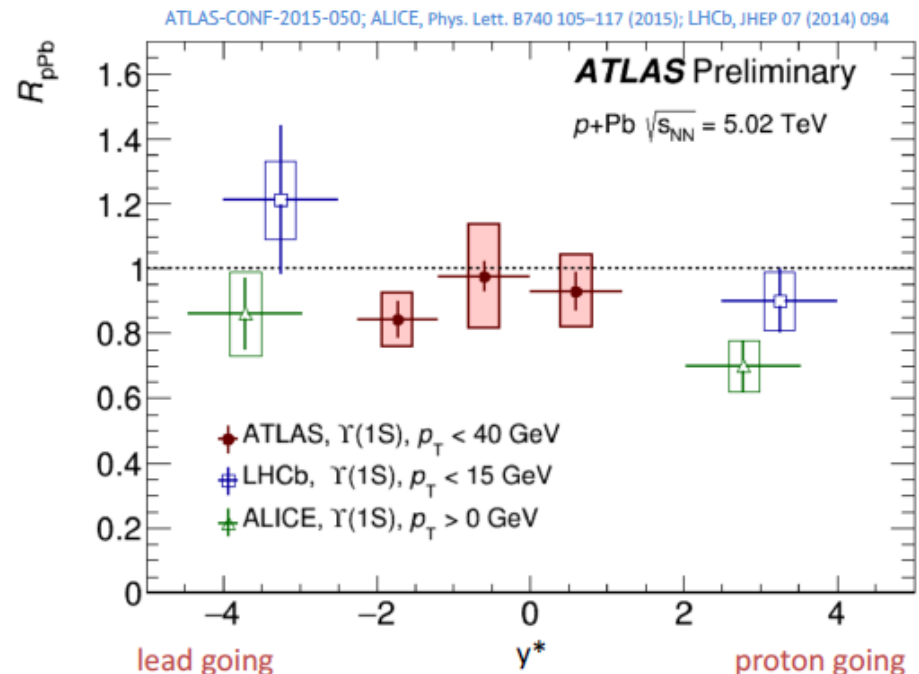
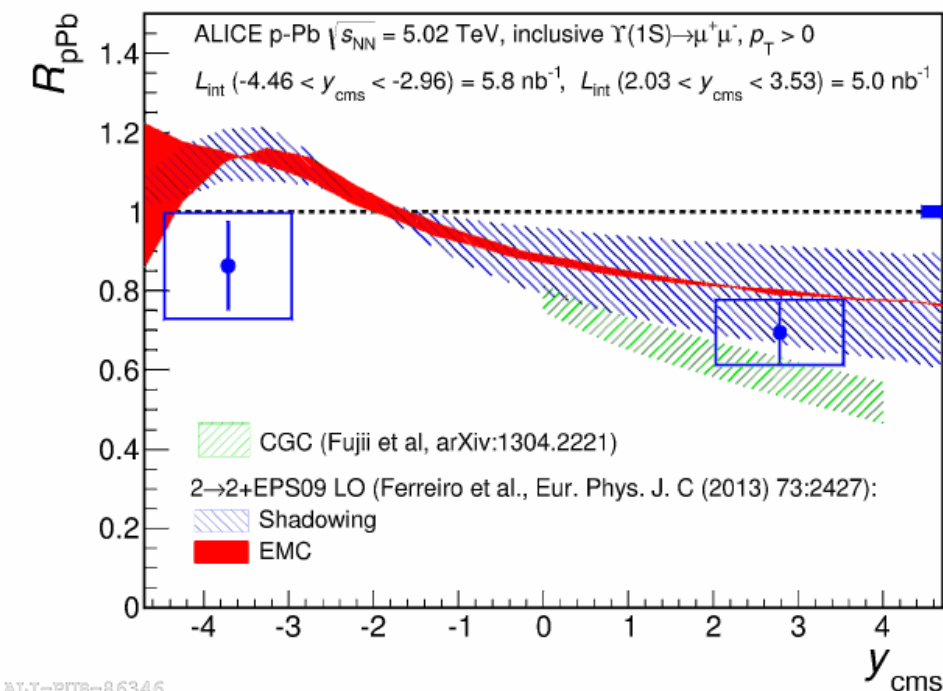


□ **CMS results have smaller uncertainties and show a stronger CNM effects on  $\Upsilon(2S)$  with respect to  $\Upsilon(1S)$**

□ Still, the result shows that only a (small) fraction of the suppression observed for  $\Upsilon(2S)$  with respect to  $\Upsilon(1S)$  can be ascribed to CNM

S. Chatrchyan et al. (CMS),  
JHEP04(2014) 103

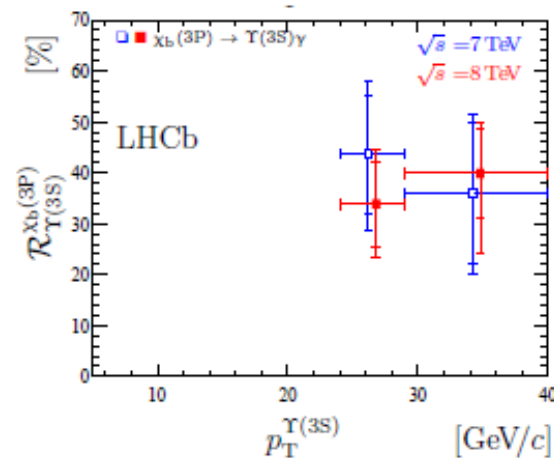
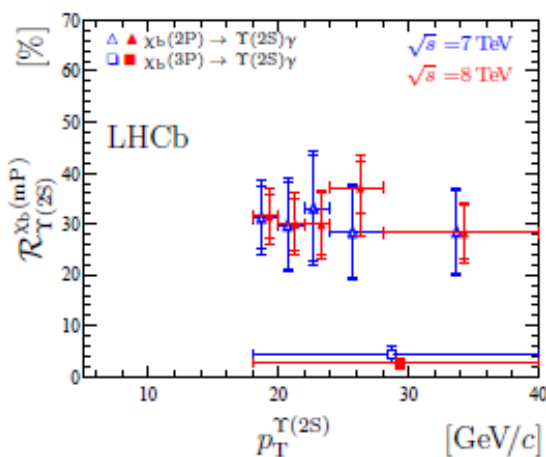
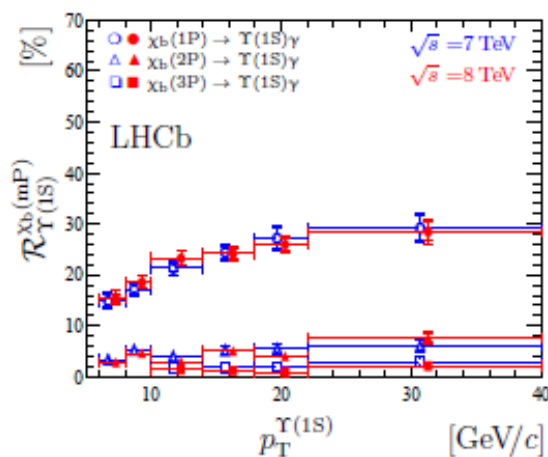
# $\Upsilon(1S)$ suppression in p-Pb



- ❑ Uncertainties are still not negligible → LHC **run-2**
- ❑ No real tension between ALICE and LHCb but the **range of “allowed” values is clearly rather large**
- ❑ CNM effect generally smaller than for charmonia, but not negligible  
 → applying the  $R_{pPb}^{CNM} = R_{pPb} \times R_{pPb}$  prescription on ALICE results may give a sizeable effect ( $0.70 \times 0.86 \sim 0.60$ !)

# Feed-down

- Systematic measurements by LHC pp experiments have **enormously improved the situation**



## Recent news

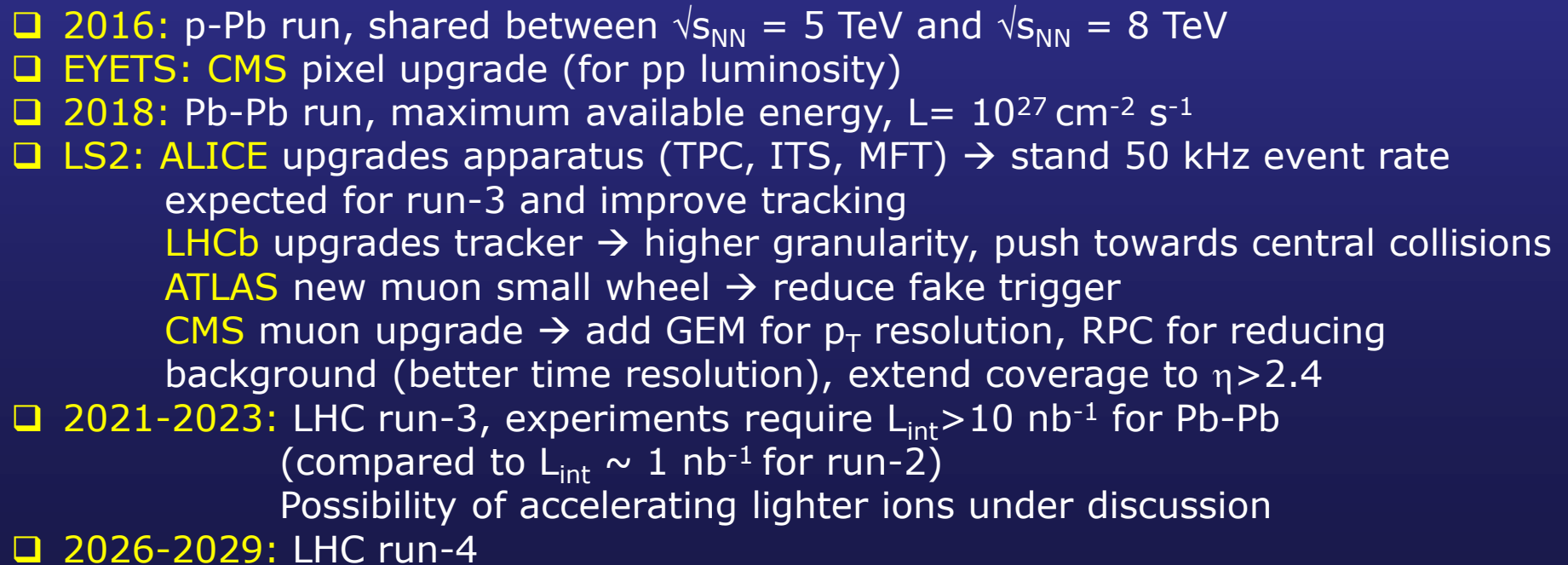
- Feed-down to  $\Upsilon(1S)$  is **smaller** than believed ( $\sim 50\% \rightarrow \sim 30\%$ )
- Feed-down to  $\Upsilon(3S)$  (unseen in PbPb!) is **very strong** ( $\sim 40\%$ )

low $P_T$	direct	from $\chi_b$	from $\Upsilon'$	from $\chi'_b$	from $\Upsilon''$	from $\chi''_b$
$\Upsilon$	$\sim 70\%$	$\sim 15\%$	$\simeq 8\%$	$\sim 5\%$	$\simeq 1\%$	$\sim 1\%$
$\Upsilon'$	$\sim 63\%$	—	—	$\sim 30\%$	$\simeq 4\%$	$\sim 3\%$
$\Upsilon''$	$\sim 60\%$	—	—	—	—	$\sim 40\%$

(HP2016, Lansberg)

- Can CMS “correct” their  $\Upsilon(1S)$   $R_{AA}$  for  $\Upsilon(2S)$  feed-down?

↓ (today)



# Prospects for quarkonium studies

- ❑ Factor  $\sim 10$  gain in run-3 surely beneficial for  $\psi(2S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  studies and for all non- $R_{AA}$  analyses (see next slide)
  - Possibility of investigating (very) peripheral collisions
- ❑ Possibility of accelerating lighter ions
  - ❑ Once considered very useful in the frame of detecting “threshold” effects and/or scaling behaviors for various observables
  - ❑ ...but we have now extensively seen that threshold effects are not really detectable
  - ❑ Asymmetric collisions (see Cu+Au @RHIC) are in principle interesting, but admittedly it is not easy to extract physics out of it

# Prospects for quarkonia studies

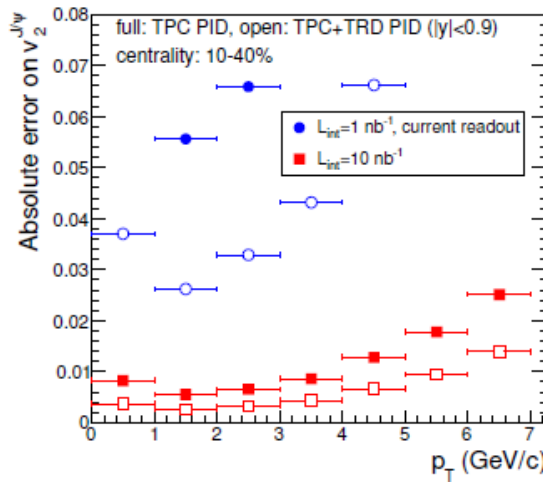
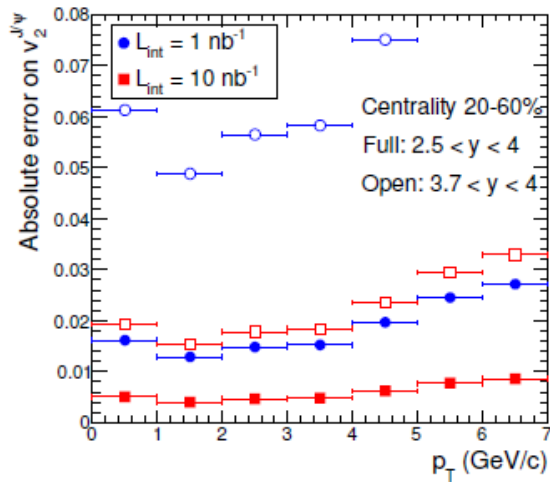
## □ CMS prospects for run-3 (CMS-PAS-FTR-13-025)

$\sqrt{s_{NN}}$	2.76 TeV	5.5 TeV						
$L_{int}$	$150 \mu b^{-1}$	$10 nb^{-1}$						
Centrality(%)	0-100	0-100	50-100	60-100	70-100	80-100	90-100	0-100
Signal	$p_T$ -inclusive raw yields							( $p_T > 30$ GeV)
$B \rightarrow J/\psi$	2 250	300 000	12 400	6 150	2 350	810	215	5500
Prompt $J/\psi$	9 000	1 200 000	49 500	24 500	9 420	3 240	860	4400
$\psi(2S)$	200	26 600	1 100	547	210	70	20	100
$Y(1S)$	2 000	266 000	11 000	5 460	2 090	720	191	267
$Y(2S)$	300	40 000	1650	820	314	108	29	80
$Y(3S)$	50	6 700	275	137	52	18	5	20

## □ ALICE prospects for run-3 (Upgrade Letter of Intent)

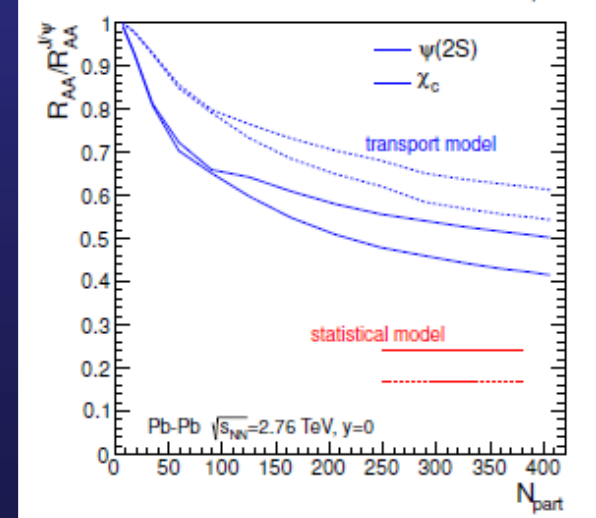
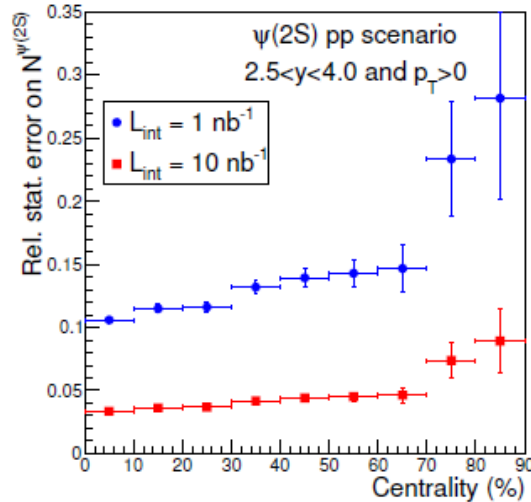
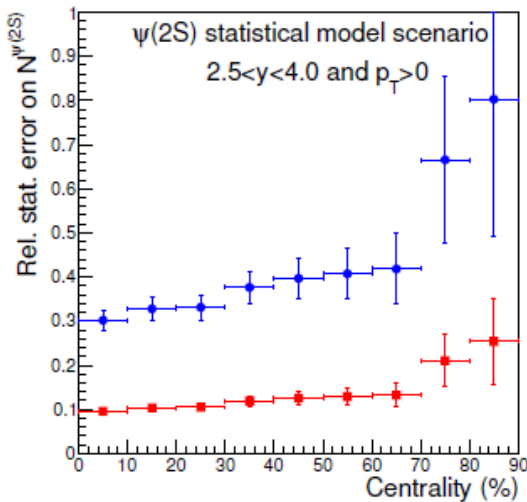
Observable	Approved		Upgrade	
	$p_T^{Amin}$ (GeV/c)	statistical uncertainty	$p_T^{Umin}$ (GeV/c)	statistical uncertainty
Charmonia				
$J/\psi R_{AA}$ (forward rapidity)	0	1 % at 1 GeV/c	0	0.3 % at 1 GeV/c
$J/\psi R_{AA}$ (mid-rapidity)	0	5 % at 1 GeV/c	0	0.5 % at 1 GeV/c
$J/\psi$ elliptic flow ( $v_2 = 0.1$ )	0	15 % at 2 GeV/c	0	5 % at 2 GeV/c
$\psi(2S)$ yield	0	30 %	0	10 %

# ALICE projected highlights



$v_2$  measurement for  $J/\psi$  at mid- and forward- $y$

$\psi(2S)$  precision measurement only in run-3



# LHCb highlights

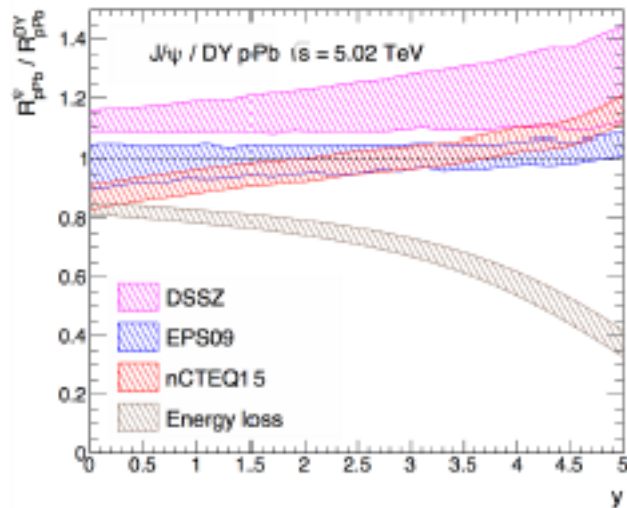
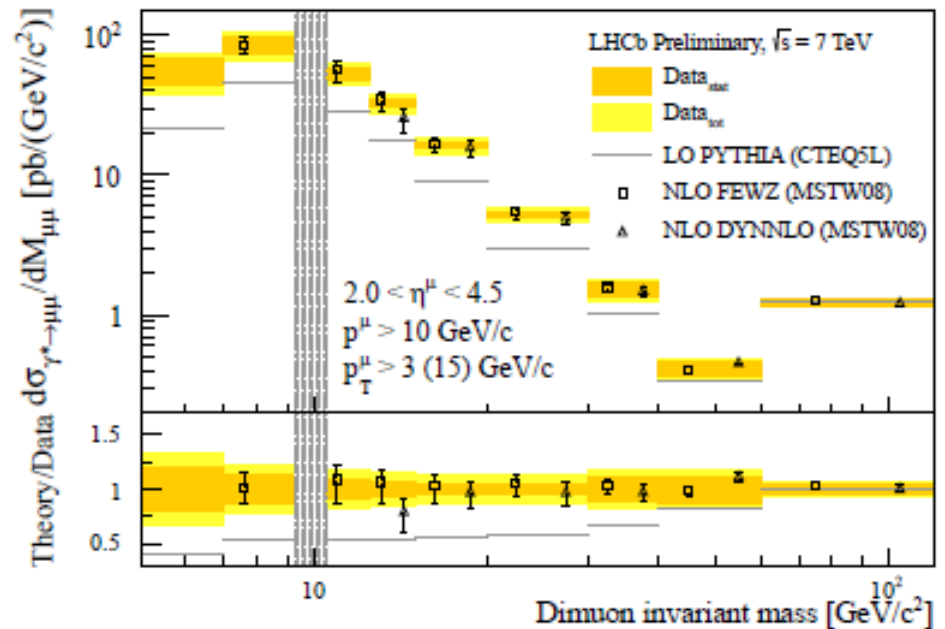


Figure 3: Double ratio  $R_{pPb}^{\psi/DY}$  in p-Pb collisions at  $\sqrt{s} = 5.02$  TeV for the various nPDF sets and in the coherent energy loss model.

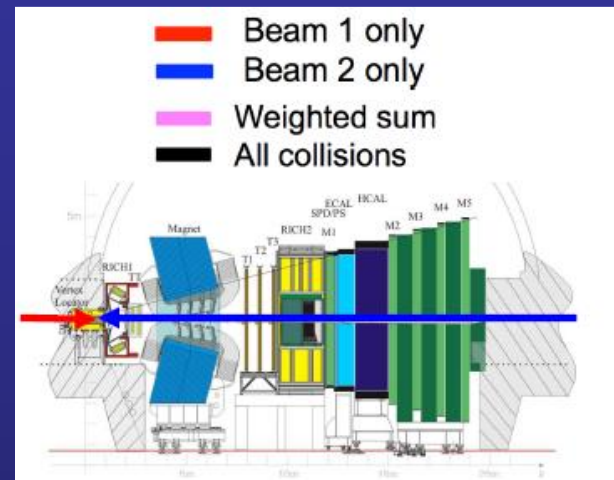
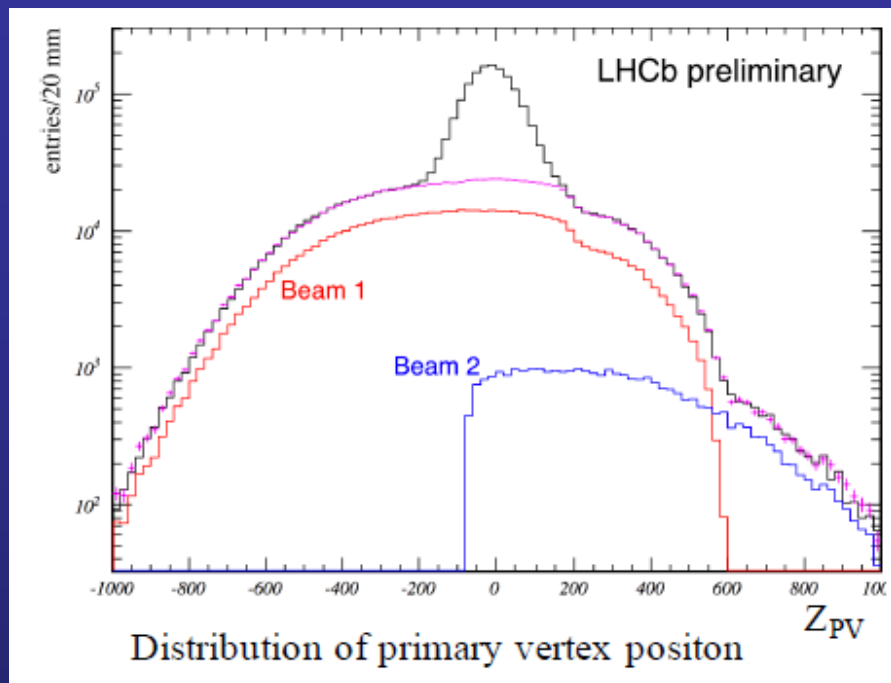
- Measured in **pp collisions**, via fits to the muon isolation distributions

- Possibility of measuring **Drell-Yan production** in p-Pb collisions  
 → (decisive) test of the **energy loss picture**  
 → Good handle on **nPDF**
- Reference for quarkonium production in Pb-Pb collisions, as in very old times ?



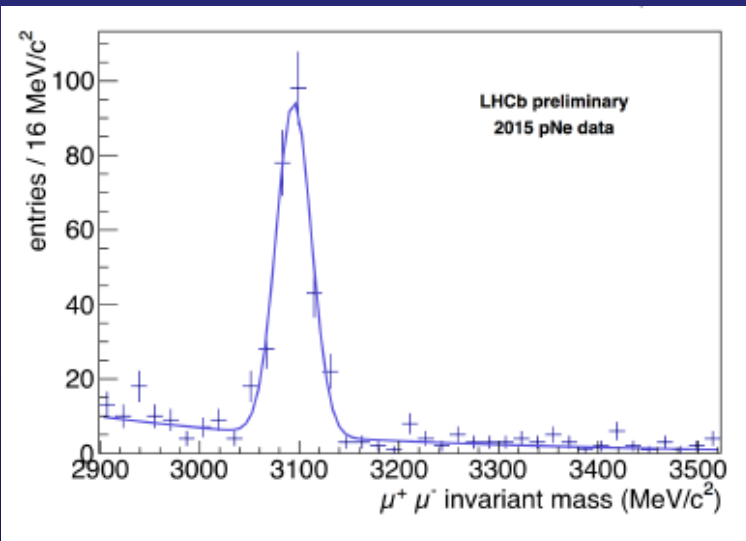
# LHCb fixed target

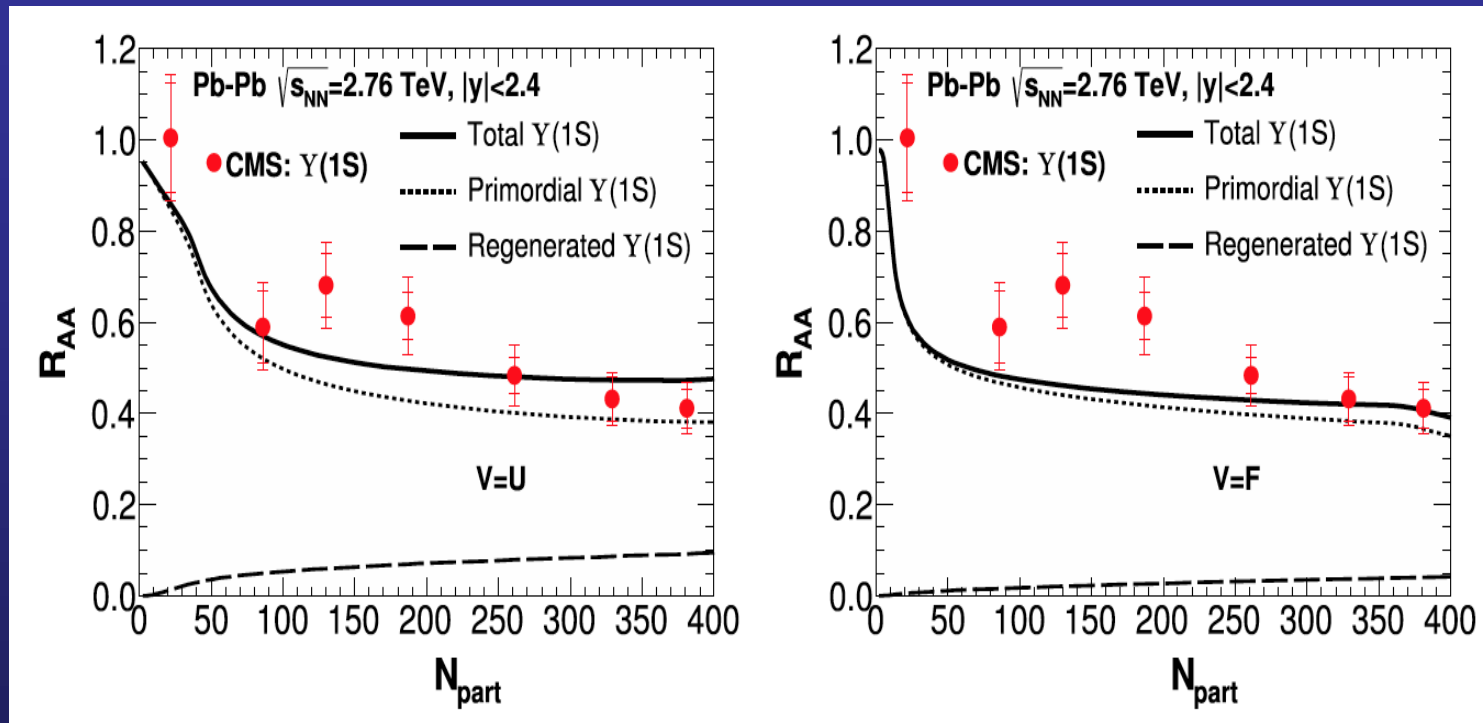
SMOG (System for Measuring the Overlap with Gas)



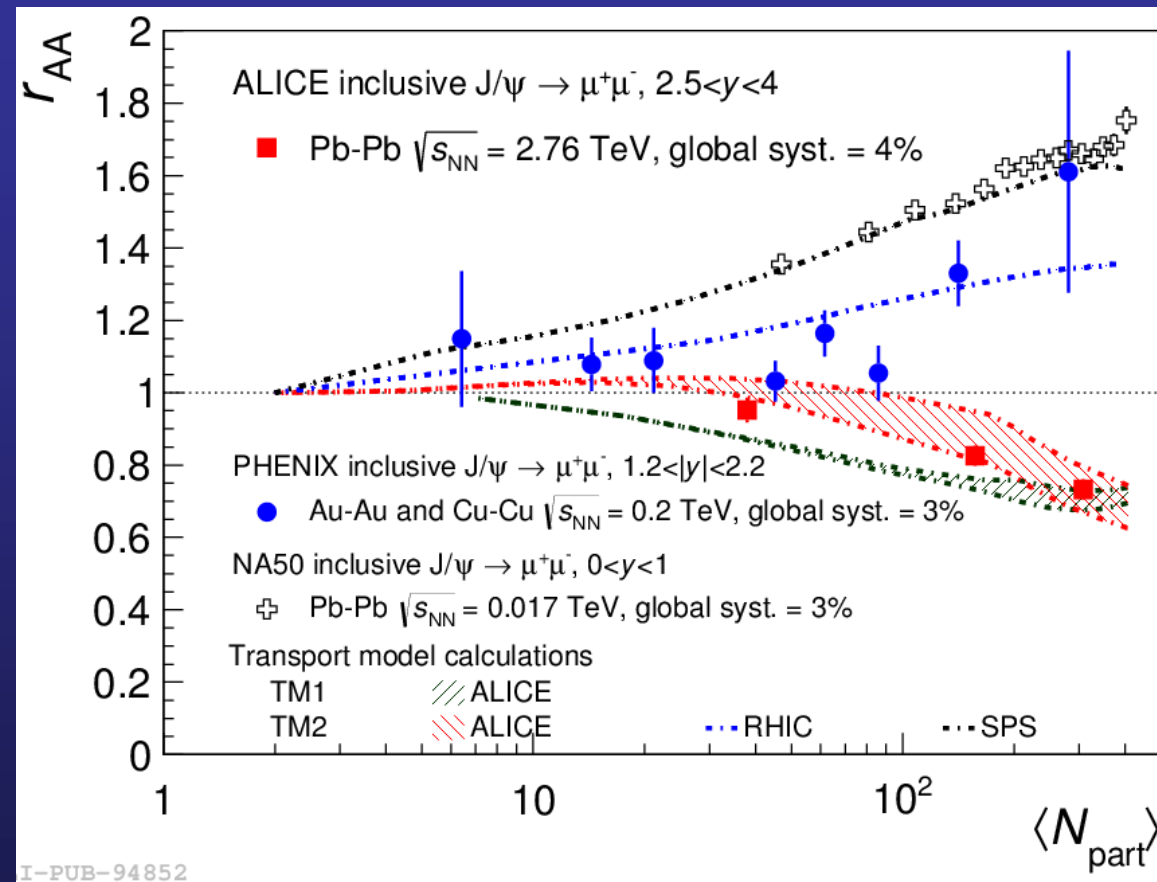
- pHe at  $\sqrt{s_{NN}} = 110$  GeV
- pNe at  $\sqrt{s_{NN}} = 87$  GeV, 110 GeV
- pAr at  $\sqrt{s_{NN}} = 69$  GeV, 110 GeV
- PbNe at  $\sqrt{s_{NN}} = 54$  GeV
- PbAr at  $\sqrt{s_{NN}} = 69$  GeV

❑ Further measurements in 2016, during p-Pb @  $\sqrt{s_{NN}} = 5$  TeV data taking





$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$



→  $r_{AA}$  centrality evolution strongly depends on  $\sqrt{s}$

→ decreasing  $r_{AA}$  trend, observed at LHC

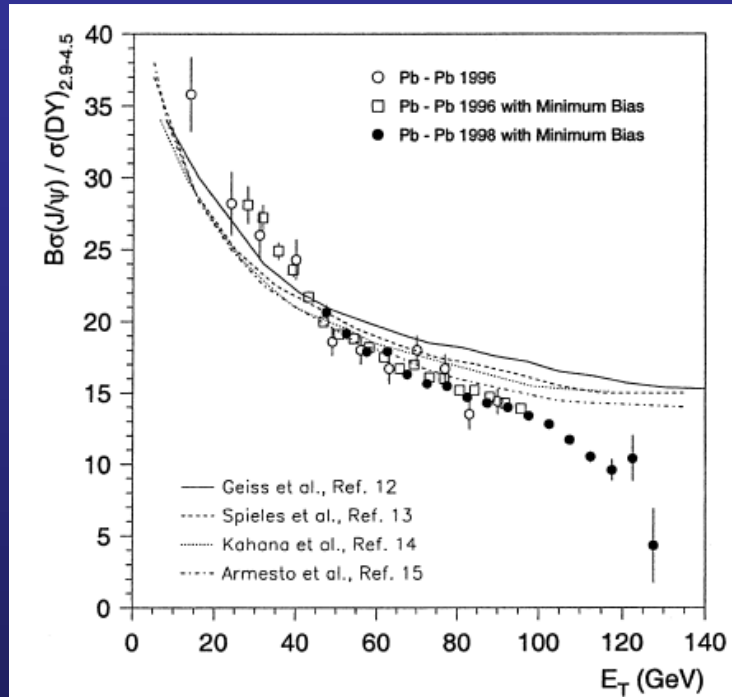
→ due to (re)combination, which dominates  $J/\psi$  production at low

→ transport models, already describing  $J/\psi R_{AA}$ , also reproduce the  $r_{AA}$  evolution

# More accurate data allowed more stringent conclusions...

1994-2000: really “heavy” ions in the SPS (Pb-Pb collisions)

February 2000 → “New state of matter created at CERN” press release

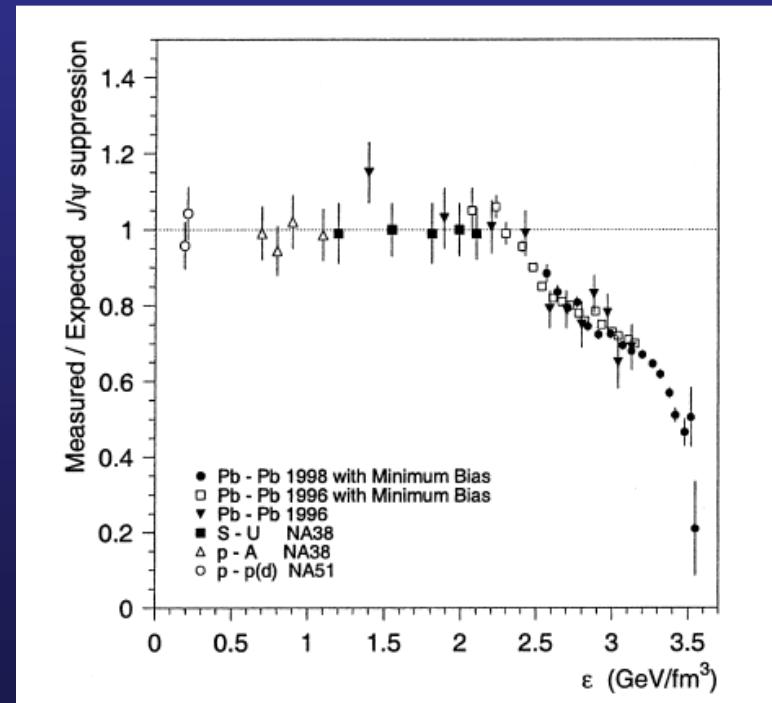


□ Clear suppression beyond CNM effects measured by NA50

- 1) Sharp onset of suppression
- 2) “Conventional” models found to disagree with data

Evidence for deconfinement of quarks and gluons  
from the  $J/\psi$  suppression pattern  
measured in Pb-Pb collisions at the CERN-SPS

NA50 Collaboration



...leaving a well-traced path for the following collider studies..



Collider	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
RHIC	PHENIX STAR	Au-Au, Cu-Cu, Cu-Au, U-U	200, 193, 62, 39	2000-2015
		p-A, d-Au	200	
		pp	200-500	
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760 5020	2010/2011 2015
		p-Pb	5020	2013
		pp	2760, 7000, 8000, 13000	2010-2015

...that continue up to now

# Still a bit of history....

- The possibility of an **enhancement of charmonium production** in nuclear collisions was considered from the very beginning!

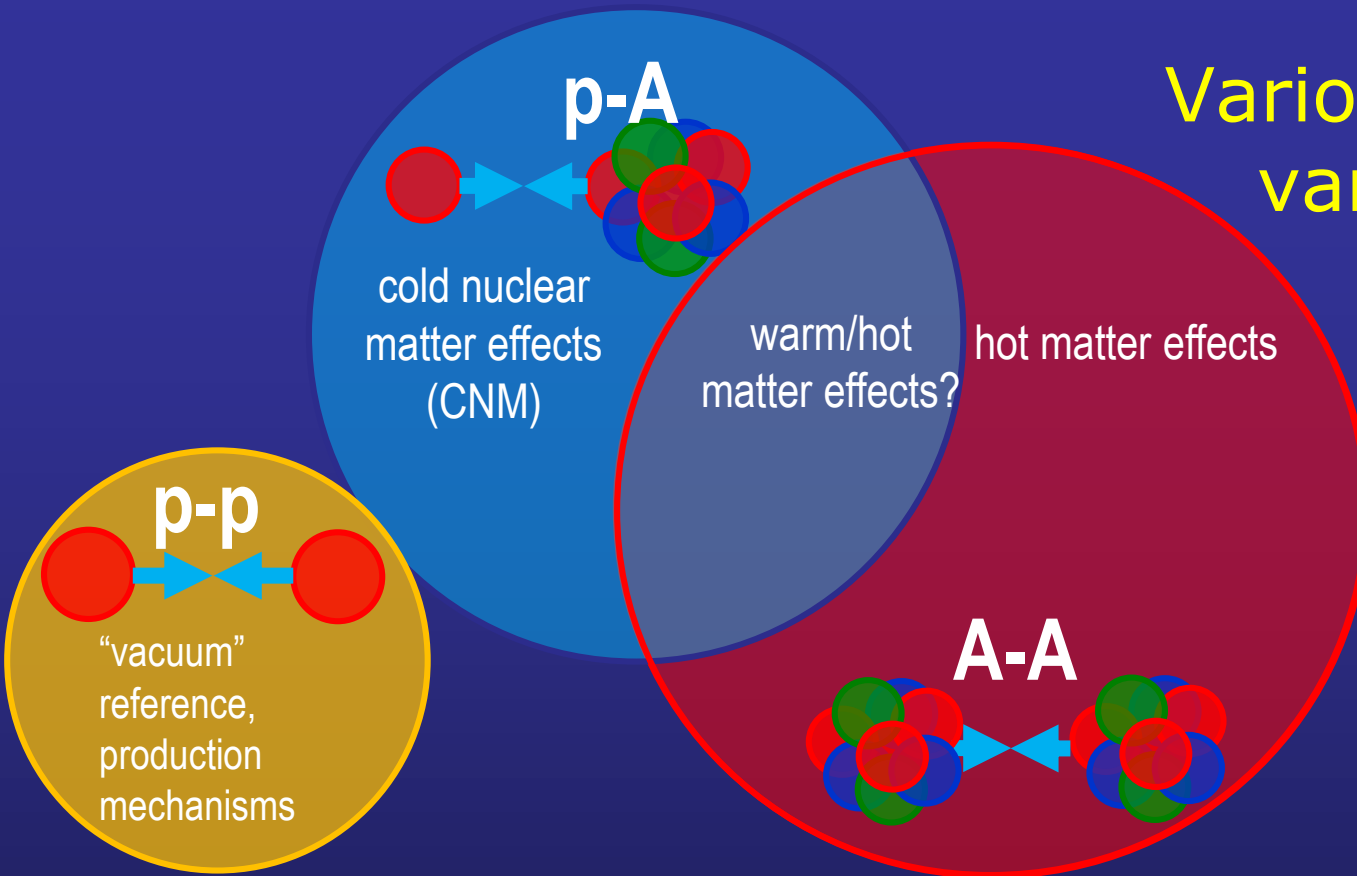
From T.Matsui QM87 proceedings

*Q3. Could  $J/\psi$  suppression be compensated at the hadronization stage?*

– This is very unlikely from our consideration on the charm production mechanism. One should check, however, both experimentally and theoretically whether there is no anomalous enhancement in the charm production cross section which could lead to large recombination probability of  $c\bar{c}$  into  $J/\psi$  during the hadronization stage.

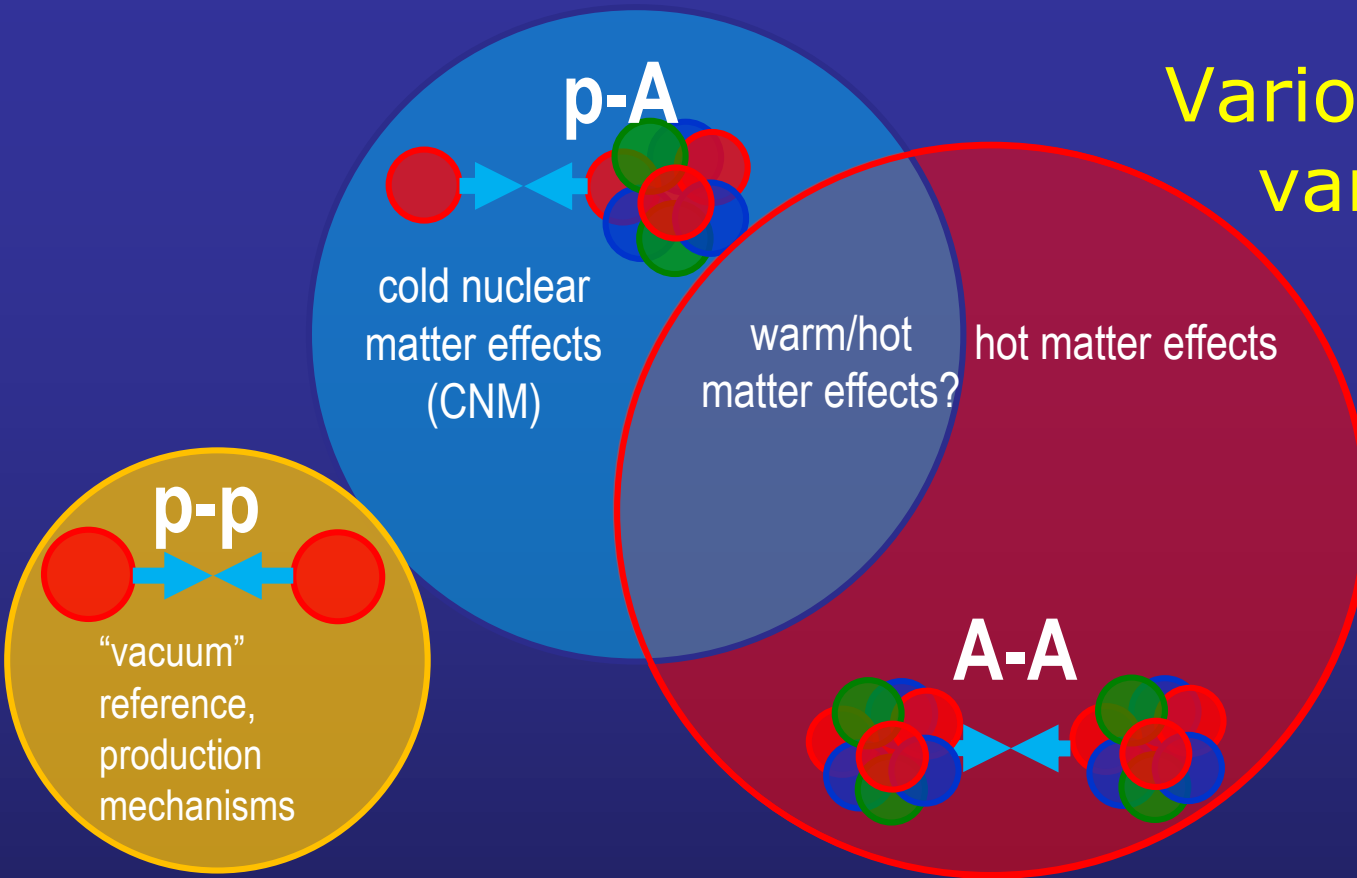
(even if, at that time, correctly discarded because of the small open charm cross section at the energies then available)

# Various systems, various effects



- ❑ CNM: nuclear shadowing, color glass condensate, parton energy loss, resonance break-up (RHIC energy)
- ❑ Hot matter effects: suppression vs re-generation
- ❑ “Warm” matter effects: hadronic resonance gas

# Various systems, various effects



Quantify the yield modifications via the nuclear modification factor  $R_{AA}$

$$R_{AA} = \frac{dN_{AA}^P}{\langle N_{coll} \rangle dN_{pp}^P}$$

**$R_{AA} < 1$  suppression**  
 **$R_{AA} > 1$  enhancement**

# Sources of heavy quarkonia

➔ Quarkonium production can proceed:

- directly in the interaction of the initial partons
- via the decay of heavier hadrons (feed-down)

➔ For  $J/\psi$  (at CDF/LHC energies) the contributing mechanisms are:

Prompt

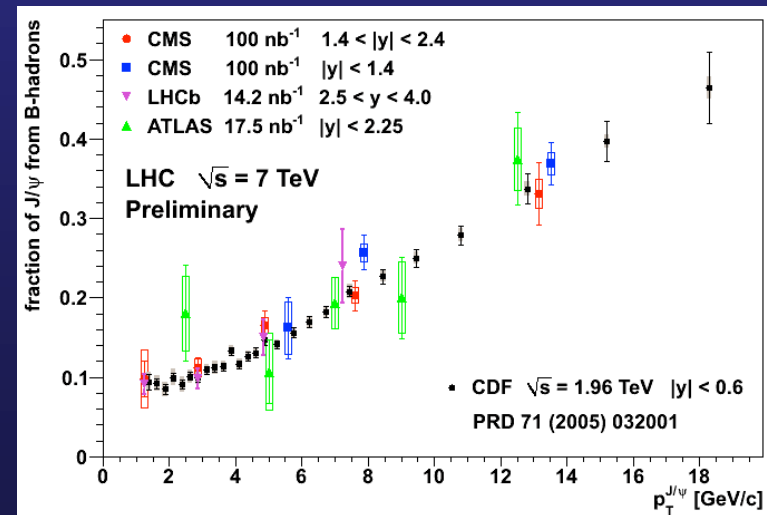
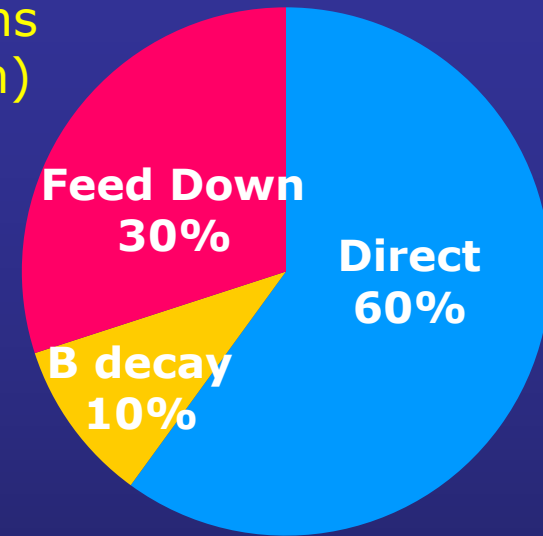
- ➔ Direct production
- ➔ Feed-down from higher charmonium states:  
 $\sim 8\%$  from  $\psi(2S)$ ,  $\sim 25\%$  from  $\chi_c$

Non-prompt

- ➔ B decay  
contribution is  $p_T$  dependent  
 $\sim 10\%$  at  $p_T \sim 1.5 \text{ GeV}/c$

➔ B-decay component “easier” to separate  $\rightarrow$  displaced production

Low  $p_T J/\psi$

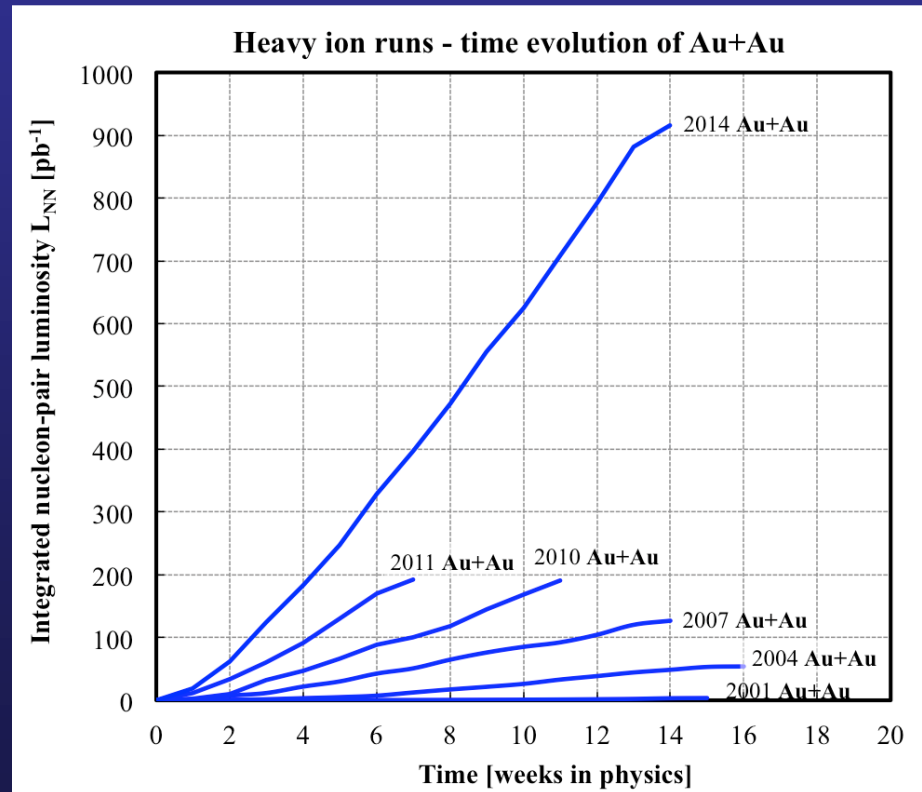
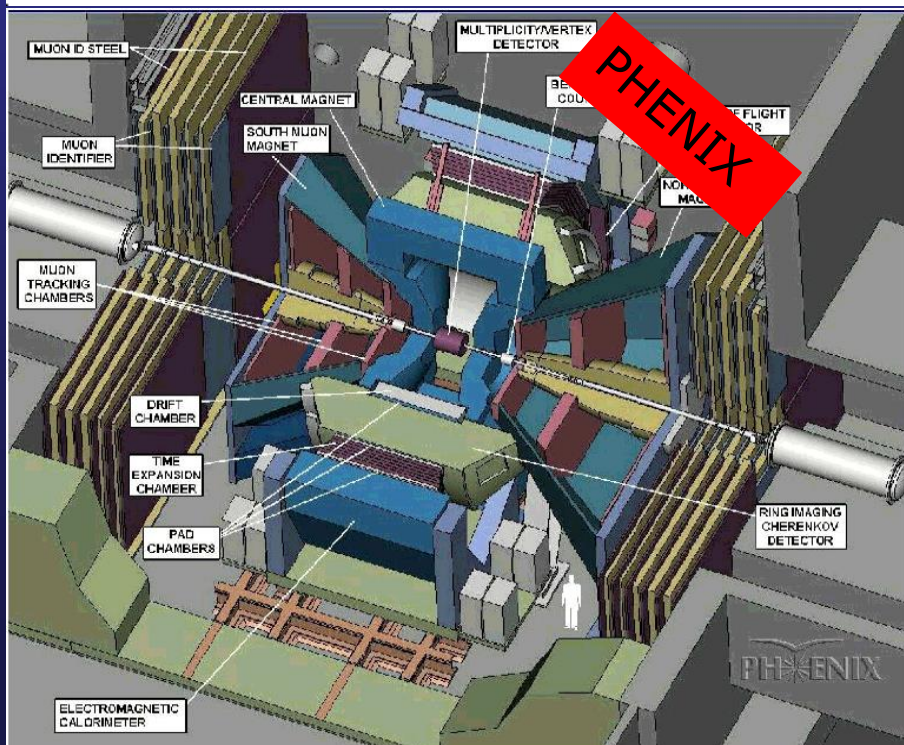
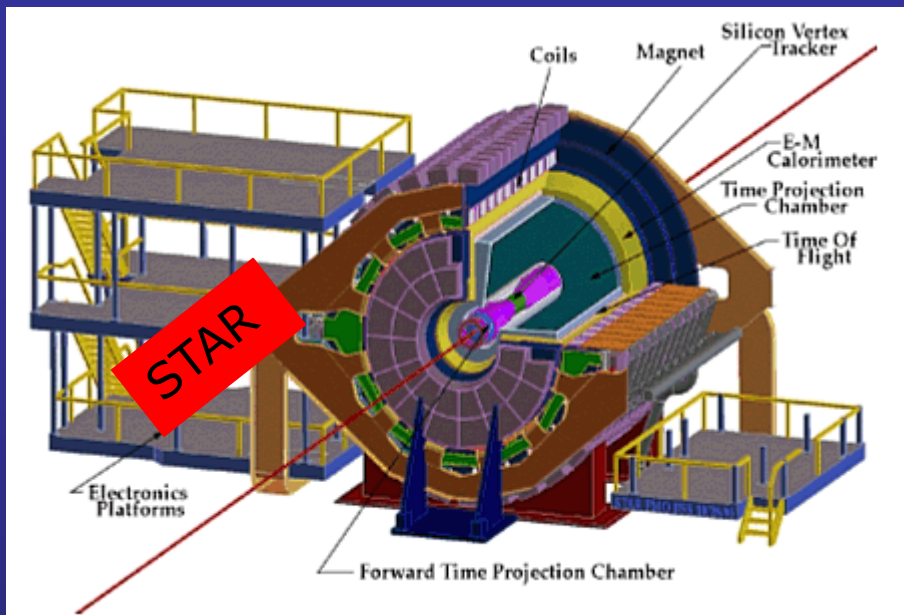


# Quarkonium at RHIC

## □ Kinematic coverage

□ PHENIX  $1.2 < |y| < 2.2$  ( $\mu^+\mu^-$ ),  
 $|y| < 0.35$  ( $e^+e^-$ )

□ STAR  $|y| < 1$  ( $e^+e^-$ )  
 (recently  $|y| < 0.5$   $\mu^+\mu^-$ )



$$L = L_{NN} / (197)^2$$

# Quarkonium at RHIC

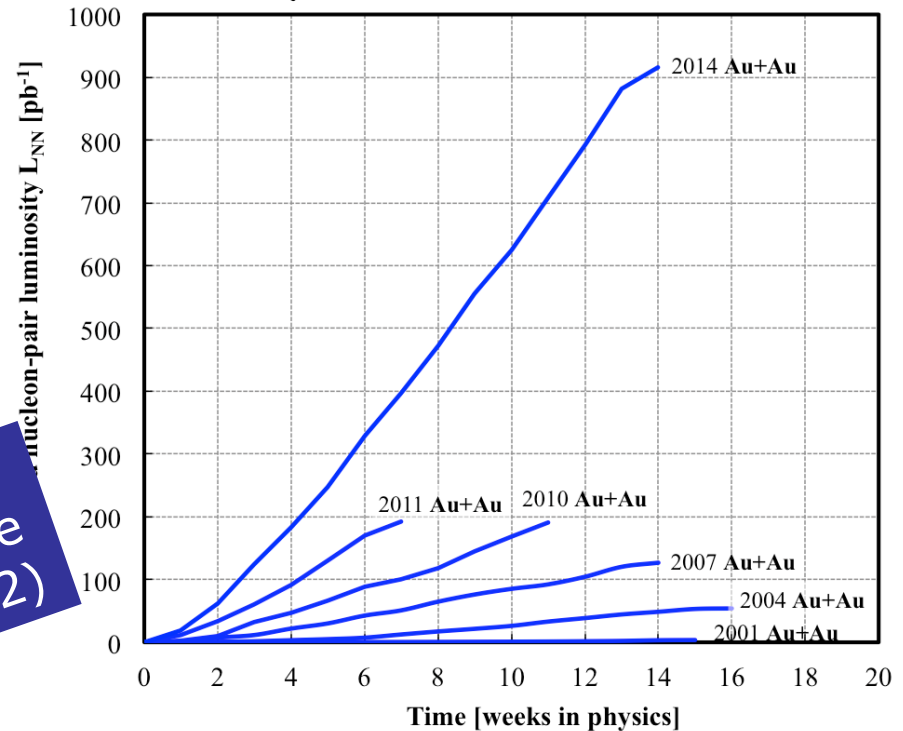
## □ Kinematic coverage

□ PHENIX  $1.2 < |y| < 2.2$  ( $\mu^+\mu^-$ ),  
 $|y| < 0.35$  ( $e^+e^-$ )

□ STAR  $|y| < 1$  ( $e^+e^-$ )  
 (recently  $|y| < 0.5$   $\mu^+\mu^-$ )

MTD → trigger on and identify muons (2014)  
 - precise timing measurement ( $\sigma \sim 100$  ps)

Heavy ion runs - time evolution of Au+Au



$$L = L_{NN} / (197)^2$$

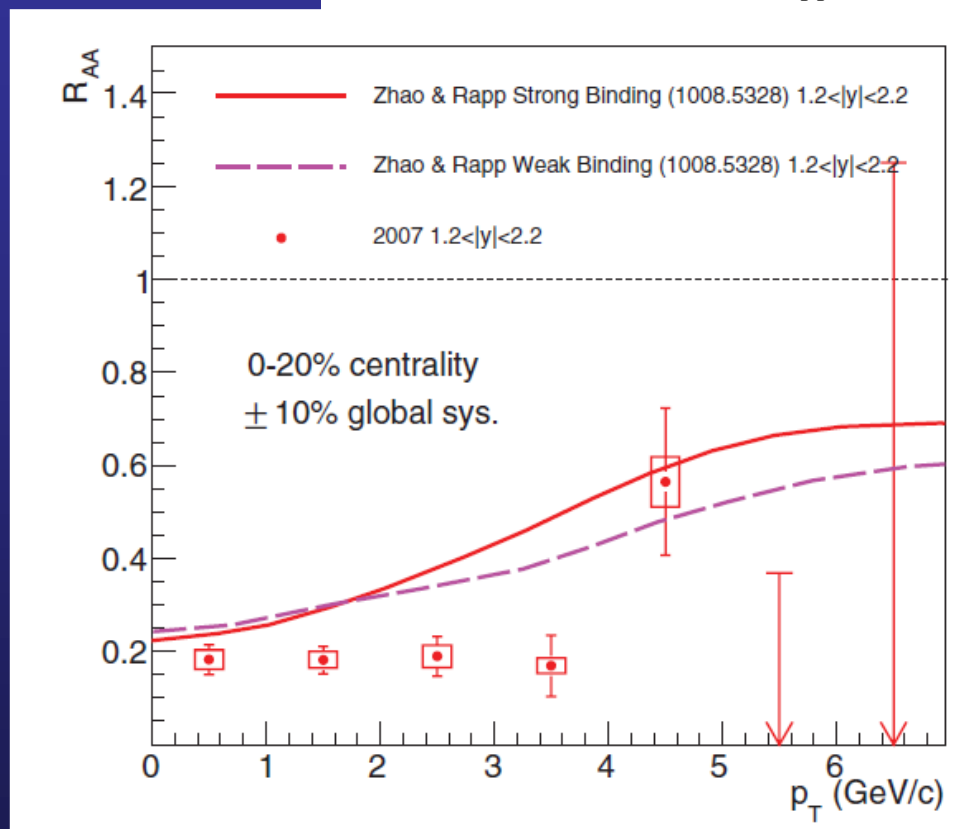
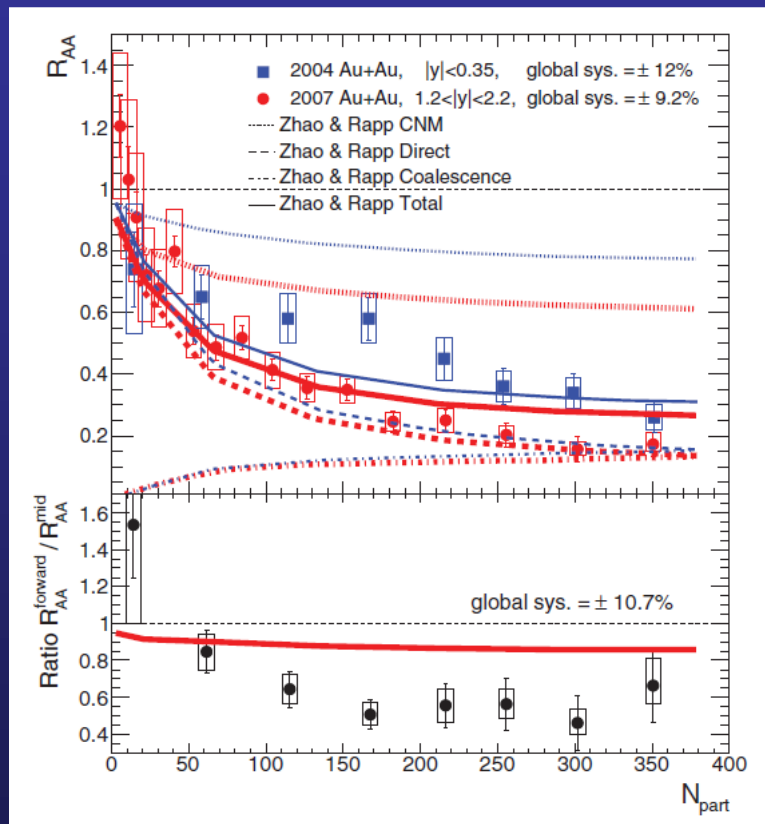
FVTX → improve  $\mu\mu$  mass resolution by measuring opening angle before absorber (from 2012)

# Selected RHIC results

PHENIX,  $\sqrt{s_{NN}} = 200$  GeV

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

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$

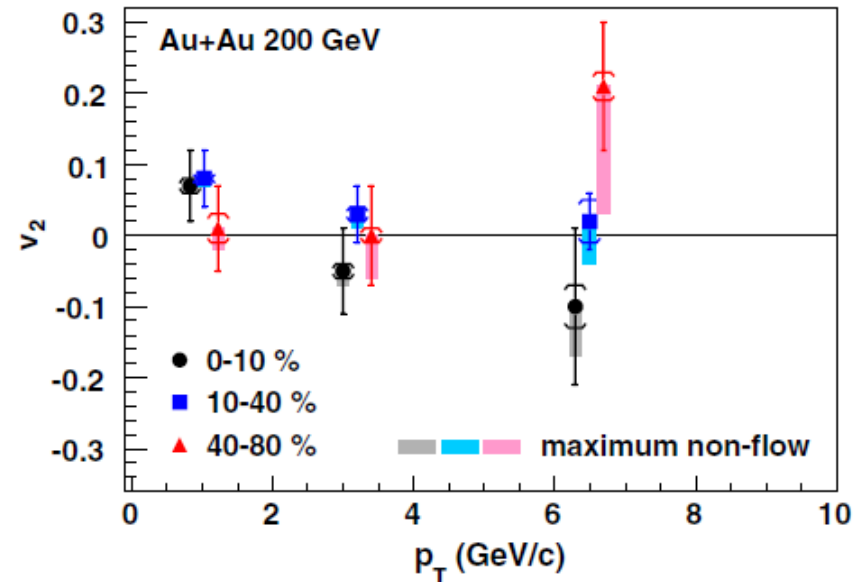
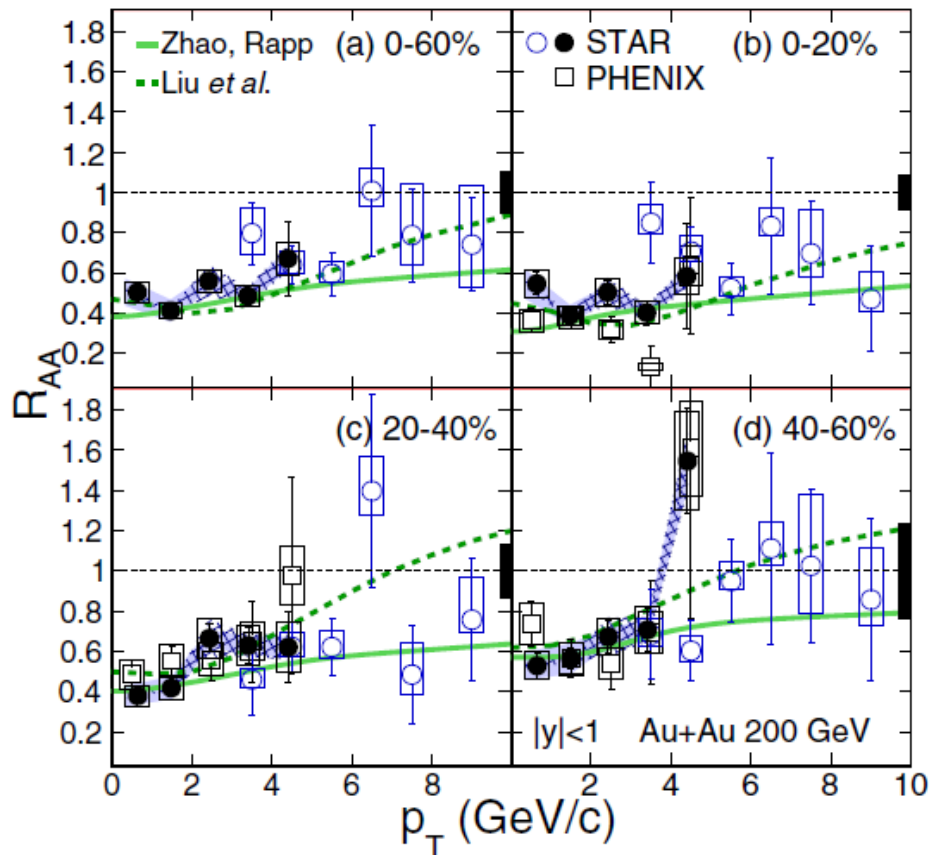


- Suppression, with strong rapidity dependence, in Au-Au at  $\sqrt{s} = 200$  GeV
- Qualitatively, but not quantitatively in agreement with models

# Selected RHIC results

STAR,  $\sqrt{s_{NN}} = 200$  GeV

Adamczyk et al. (STAR), PRC90 (2014) 024906  
Adamczyk et al. (STAR), PRL111 (2013) 052301

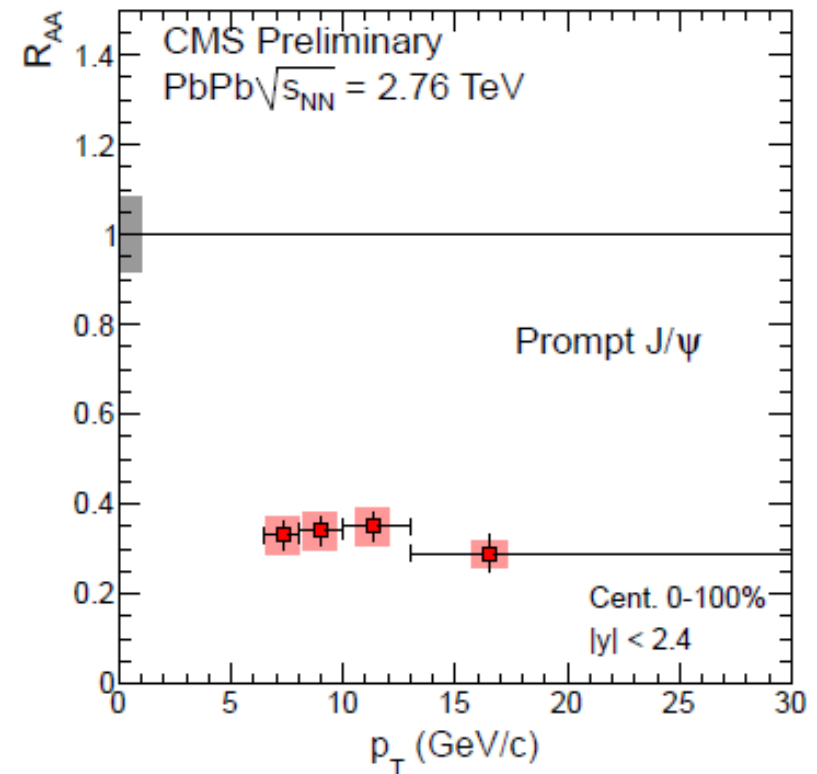
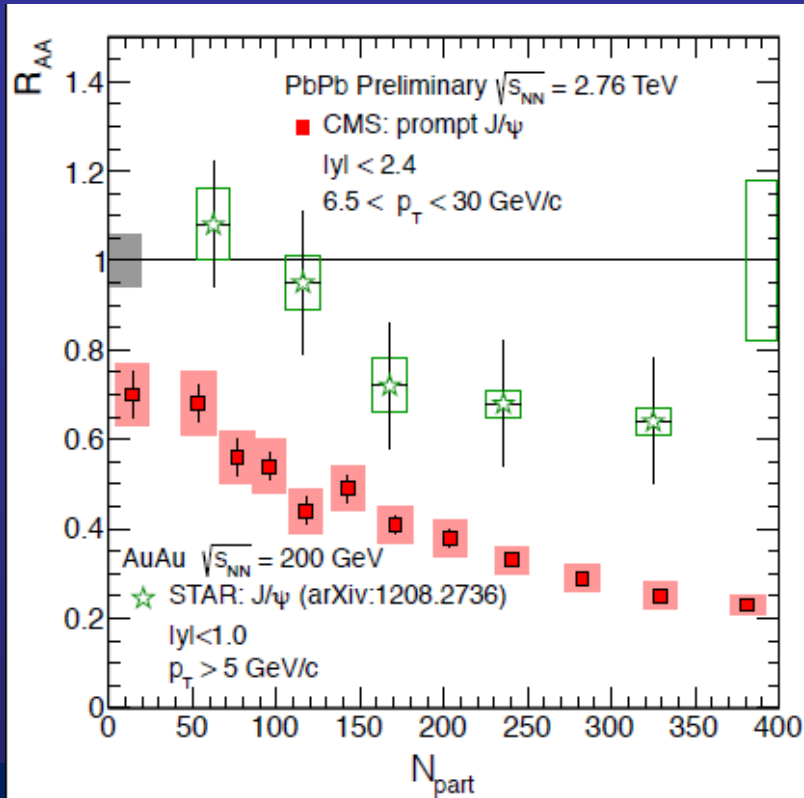


- Good coverage from low to high  $p_T$
- $R_{AA}$  increases with  $p_T$
- No significant  $J/\psi$  elliptic flow

Re-generation expected to enhance low- $p_T$  production  
Re-generated  $J/\psi$  should inherit charm quark flow

} not seen

# CMS results: prompt $J/\psi$ at high $p_T$



CMS-PAS HIN-12-2014

- Striking **difference** with respect to “ALICE vs PHENIX”
  - No saturation of the suppression vs centrality
  - High- $p_T$  RHIC results show **weaker** suppression
- No significant  **$p_T$  dependence** from 6.5 GeV/c onwards
- **(Re)generation** processes expected to be negligible

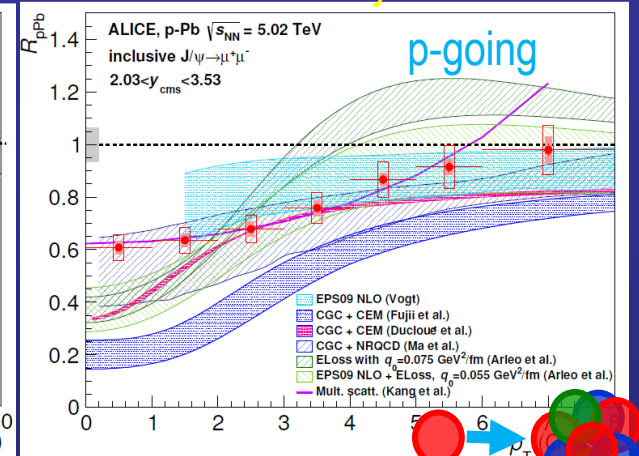
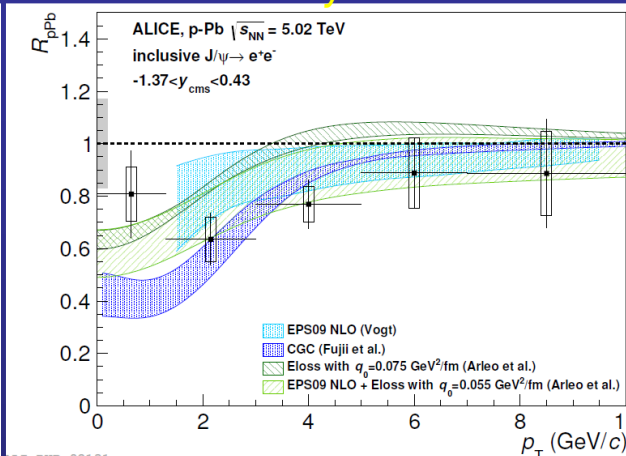
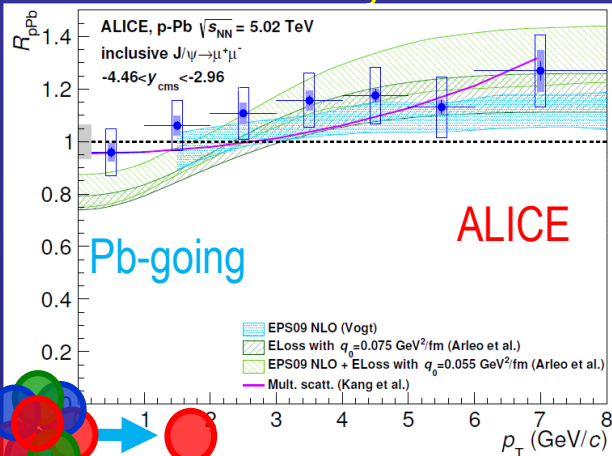
# CNM effects are not negligible!

□ p-Pb collisions,  $\sqrt{s_{NN}}=5.02$  TeV,  $R_{pPb}$  vs  $p_T$

backward-y

mid-y

forward-y



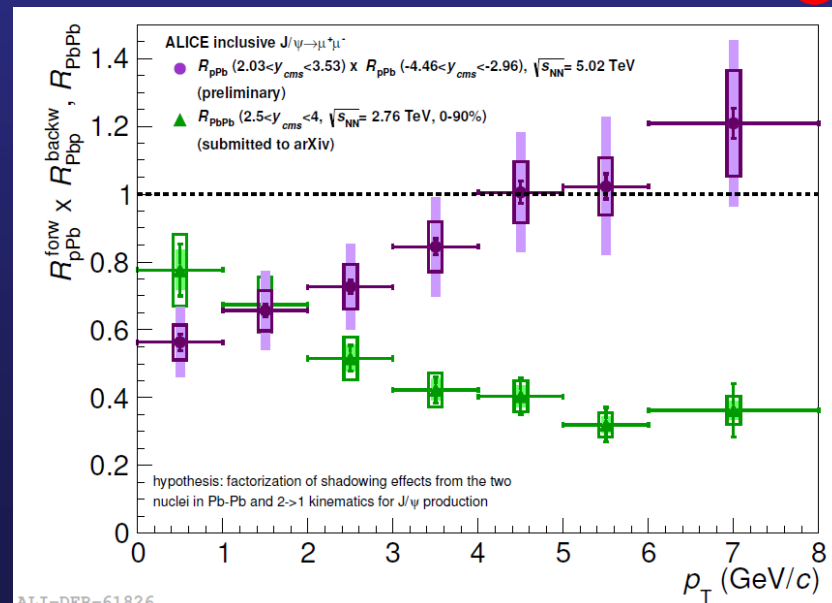
ALICE, JHEP 1506 (2015) 055

□ Fair **agreement with models**  
(shadowing/CGC + energy loss)

□ (Rough) **extrapolation of CNM**  
effects to Pb-Pb

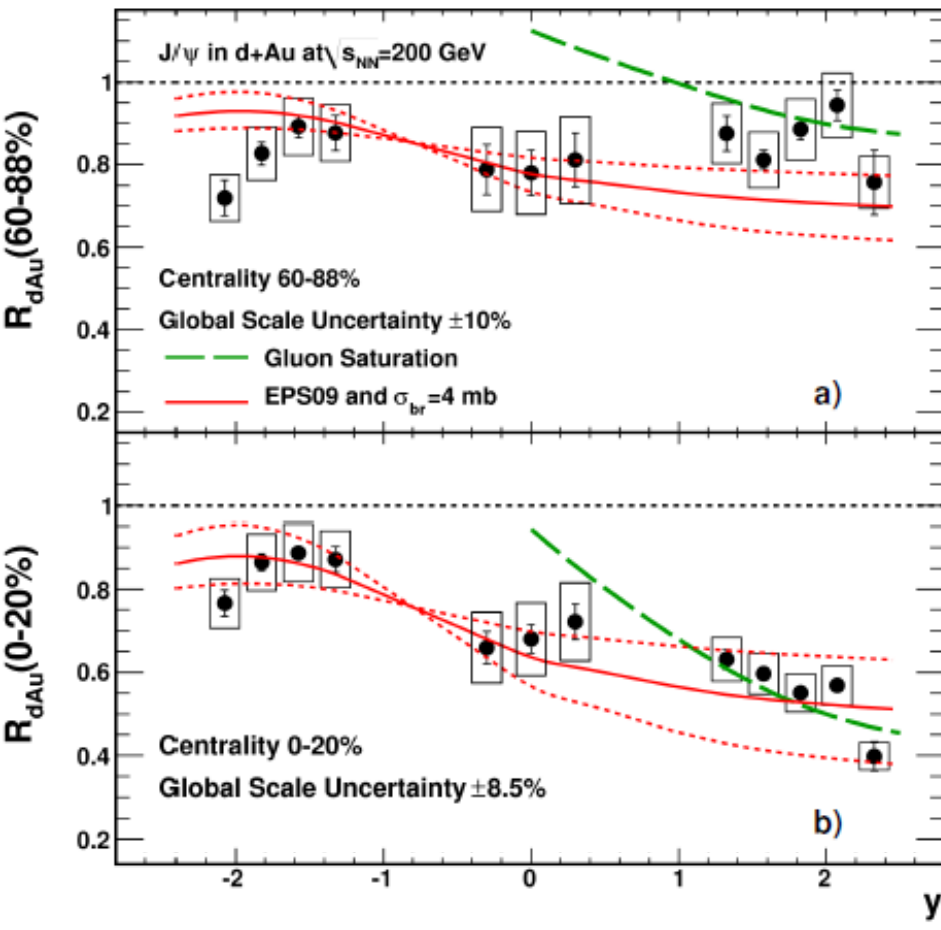
$$R_{PbPb}^{cold} = R_{pPb} \times R_{pPb}$$

→ **Evidence for hot matter effects!**



ALI-DER-61826

# CNM at RHIC energy

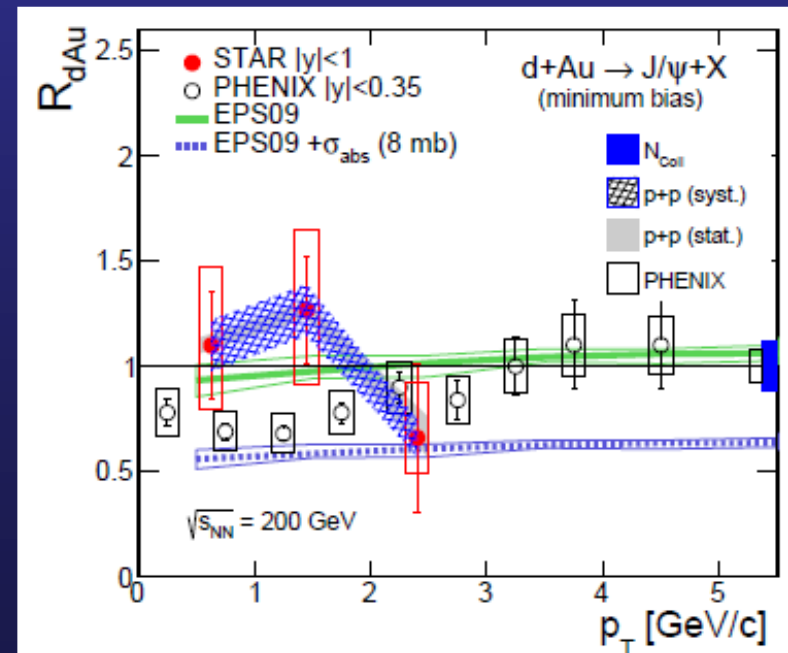


PHENIX, PRL107 (2011) 142301

- Transverse momentum dependence more difficult to reproduce

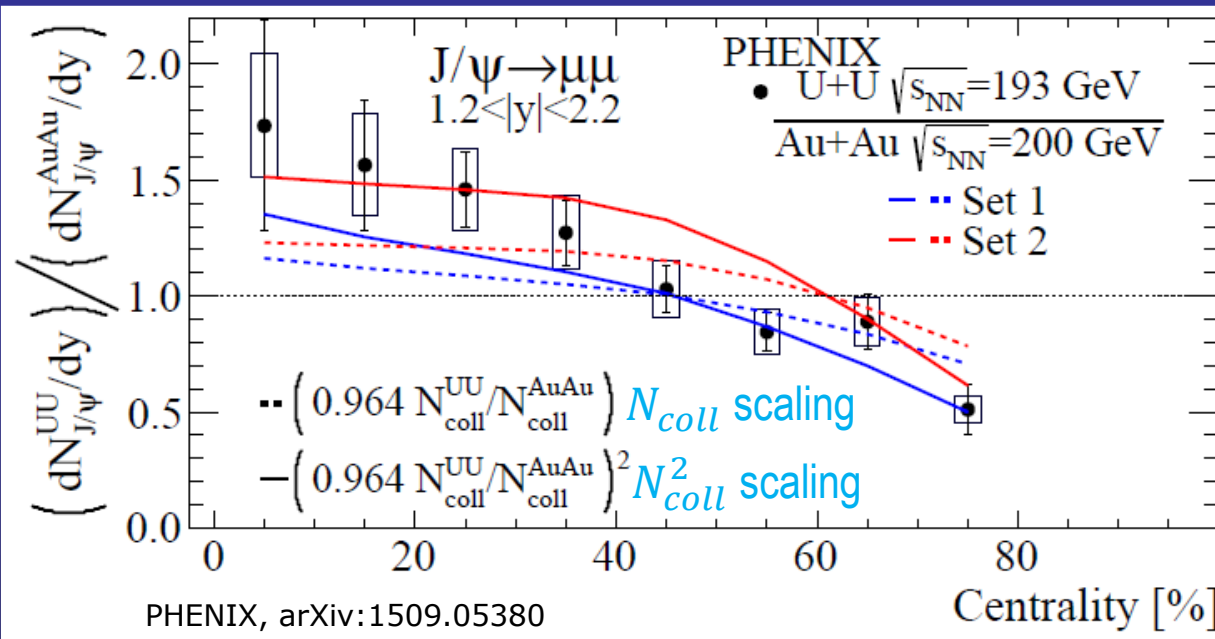
- Significant CNM effects also at RHIC energy
- Contrary to LHC results, J/ψ data allow (need) a contribution from J/ψ breakup in nuclear matter ( $\sigma_{J/\psi-N} \sim 4$  mb)

STAR, arXiv:1602.02212



# Recent RHIC results: U-U!

➔ (re)combination/suppression role investigated comparing U-U and AuAu



in central U-U wrt Pb-Pb

1) stronger suppression due to color screening

$$\varepsilon_{AuAu} \sim 80-85\% \varepsilon_{UU}$$

2)  $J/\psi$  recombination favoured by 25% larger  $N_{coll}$  in UU

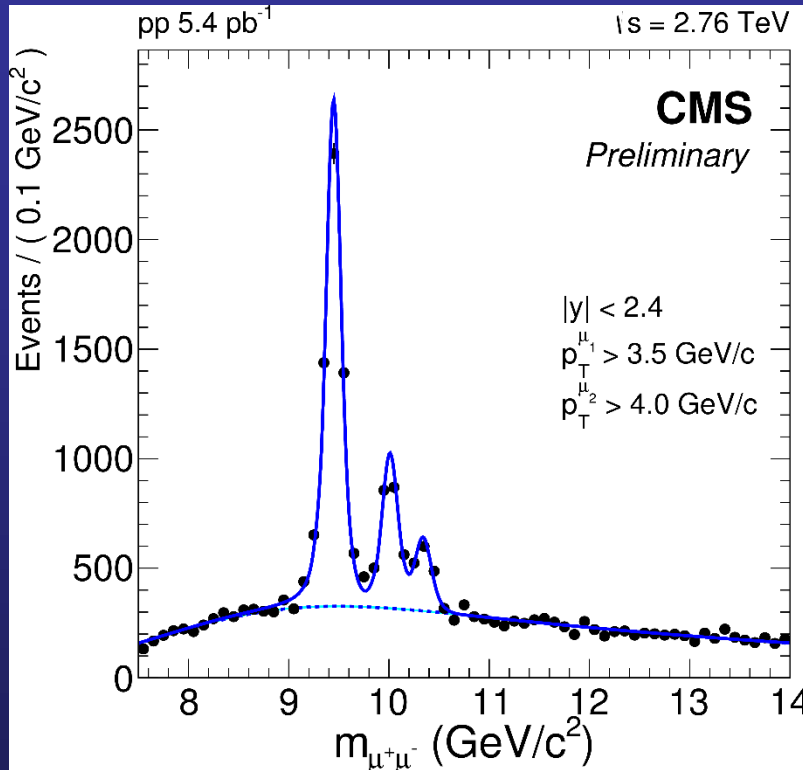
$$N_{J/\psi}^{stat} \sim N_c^2 \sim N_{coll}^2$$

➔ results slightly favour  $N_{coll}^2$  scaling → (re)combination wins over suppression when going from central U-U to Au-Au collisions

➔ quantitative comparison depends on the choice of the uranium Woods-Saxon parametrizations

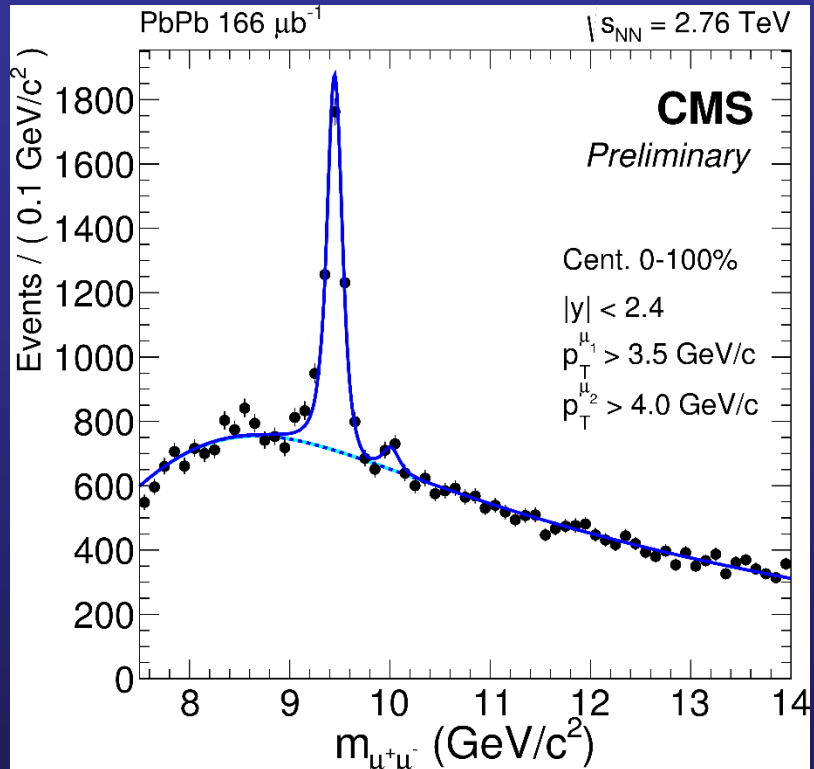
# $\Upsilon$ suppression in Pb-Pb collisions

- Relatively low beauty cross section  $\rightarrow$  weak regeneration effects
- Kinematic coverage down to  $p_T=0$  for all LHC experiments



CMS-HIN-15-001

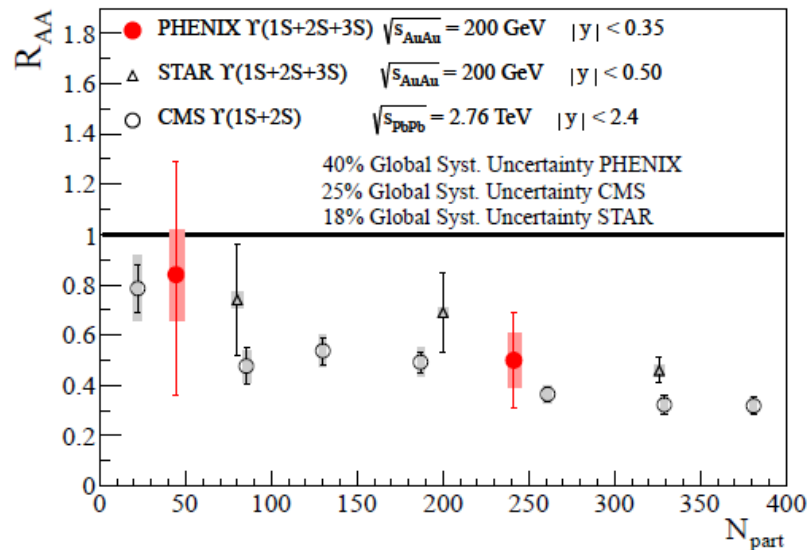
Strong relative suppression  
of more loosely bound states



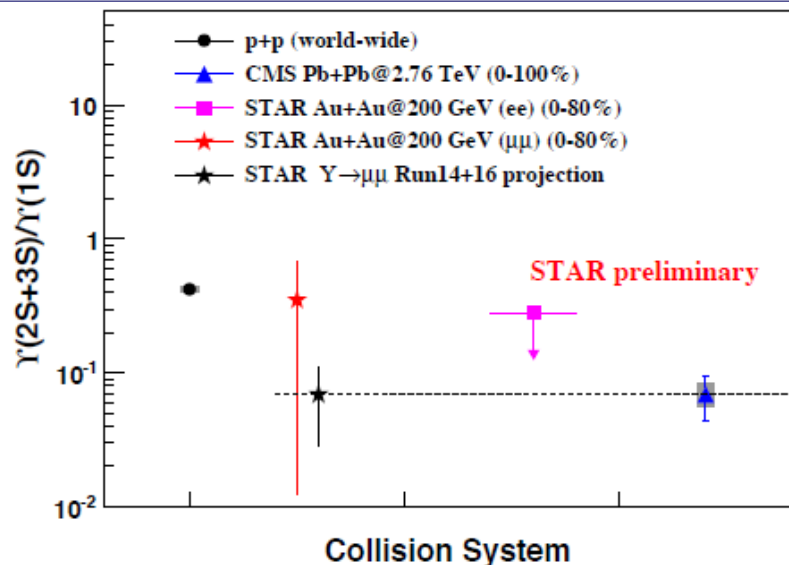
$$\begin{aligned} R_{AA}(\Upsilon(1S)) &= 0.43 \pm 0.03 \pm 0.07 \\ R_{AA}(\Upsilon(2S)) &= 0.13 \pm 0.03 \pm 0.02 \\ R_{AA}(\Upsilon(3S)) &< 0.14 \text{ at 95\% CL} \end{aligned}$$

95

# Bottomonium results at RHIC

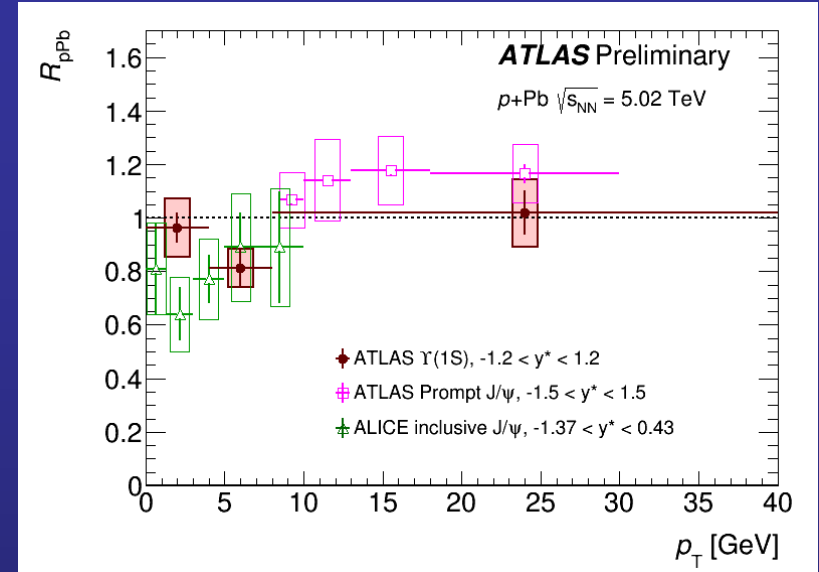
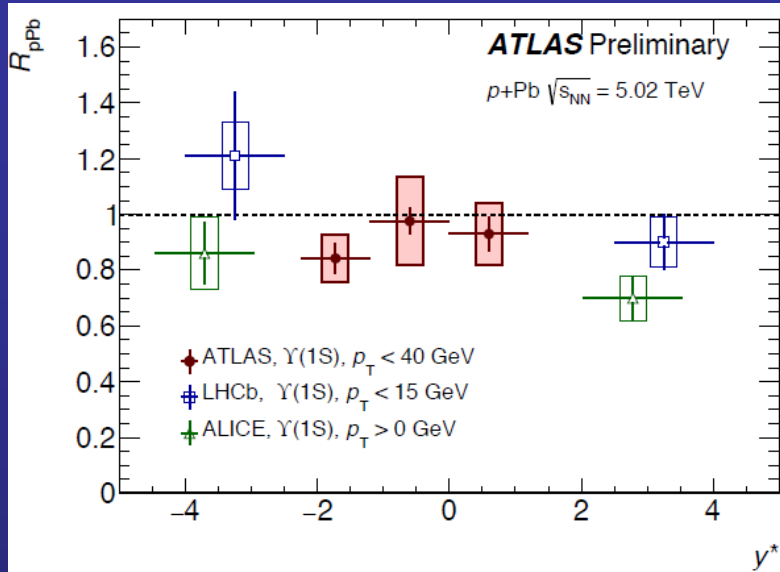


- Both PHENIX/STAR have published results on  $\Upsilon$
- Mutual agreement between experiments but **still large stat+syst uncertainties**  
→ Need **upgraded** detectors and **higher** luminosity



- Recent results with the STAR MTD on the ratio excited/ground state
- Consistent with dielectron measurement within large uncertainties
- Factor 7 more statistics on this measurement with full Run14+Run16 data

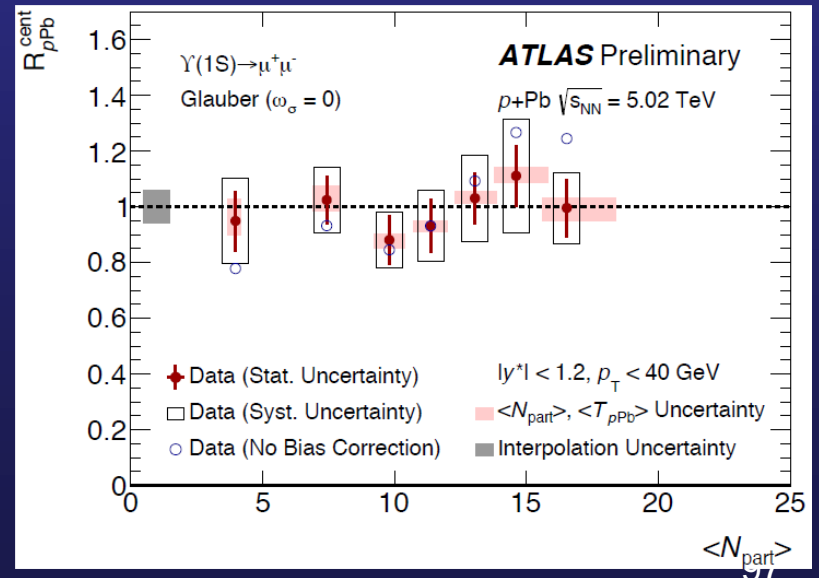
# Weak CNM effects for bottomonium



□  $R_{p\text{Pb}}$  close to 1 and with no significant dependence on  $y$ ,  $p_{\text{T}}$  and centrality

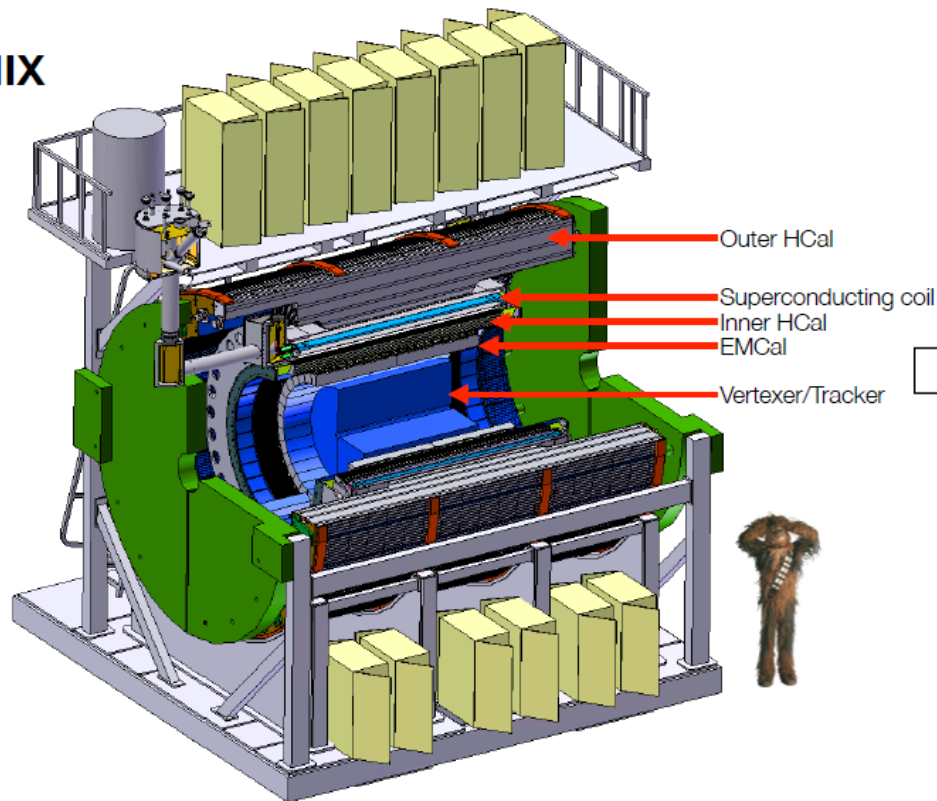
□ Fair agreement ALICE vs LHCb (within large uncertainties)

ALICE, PLB 740 (2015) 105  
 ATLAS-CONF-2015-050  
 LHCb, JHEP 07(2014)094



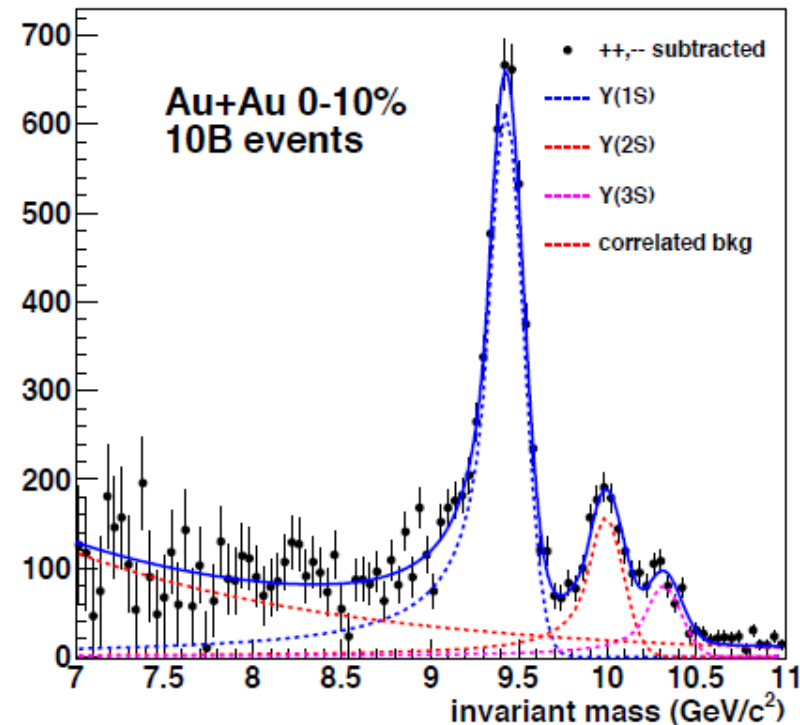
# The future of RHIC - sPHENIX

## sPHENIX



- BaBar 1.5 T superconducting solenoid
- Full em/hadronic calorimetry
- Precision tracking/vertexing

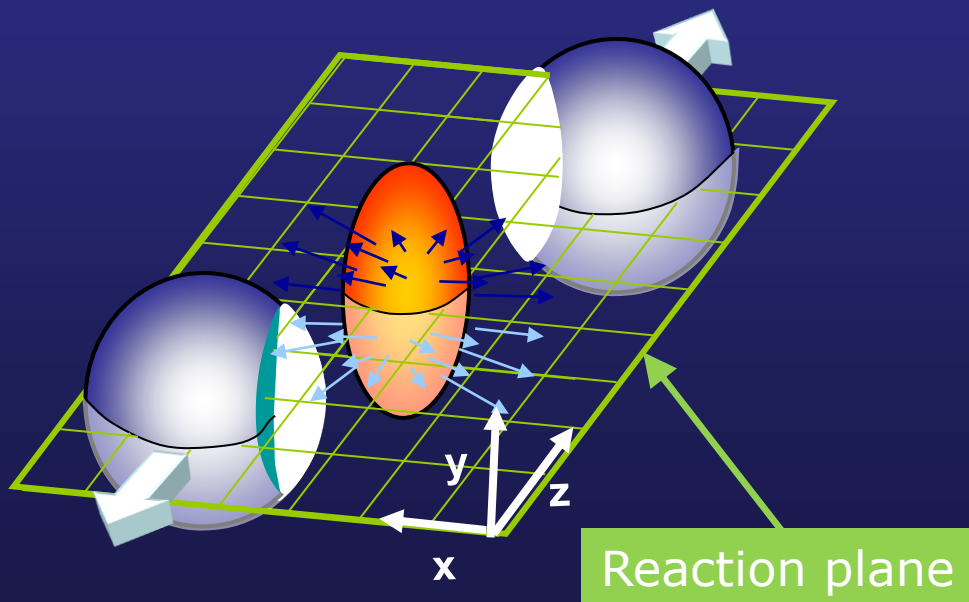
$\Upsilon(1S, 2S, 3S)$



- Physics program  
→ Light and HF jets, photons, upsilons and their correlations

# Anisotropic transverse flow

- ❑ In collisions with  $b \neq 0$  (non central) the fireball has a **geometric anisotropy**, with the overlap region being an ellipsoid
- ❑ Macroscopically (hydrodynamic description)
  - ❑ The **pressure gradients**, i.e. the forces “pushing” the particles are anisotropic ( $\phi$ -dependent), and **larger in the x-z plane**
  - ❑  $\phi$ -dependent velocity  $\rightarrow$  **anisotropic azimuthal distribution** of particles



- ❑ Microscopically
  - ❑ **Interactions** between produced particles (if strong enough!) can convert the **initial geometric anisotropy** in an **anisotropy in the momentum** distributions of particles, which can be measured

# Anisotropic transverse flow

- Starting from the azimuthal distributions of the produced particles with respect to the reaction plane  $\Psi_{RP}$ , one can use a Fourier decomposition and write

$$\frac{dN}{d(\varphi - \Psi_{RP})} = \frac{N_0}{2\pi} \left( 1 + 2v_1 \cos(\varphi - \Psi_{RP}) + 2v_2 \cos(2(\varphi - \Psi_{RP})) + \dots \right)$$

- The terms in  $\sin(\varphi - \Psi_{RP})$  are not present since the particle distributions need to be symmetric with respect to  $\Psi_{RP}$
- The coefficients of the various harmonics describe the deviations with respect to an isotropic distribution
- From the properties of Fourier's series one has

$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

# On feed-down fractions

- Usually they are not supposed to vary strongly with  $\sqrt{s}$  (or  $y$ )
- New LHCb pp results could alter the picture inherited by CDF (relative to  $p_T^Y > 8$  GeV/c)

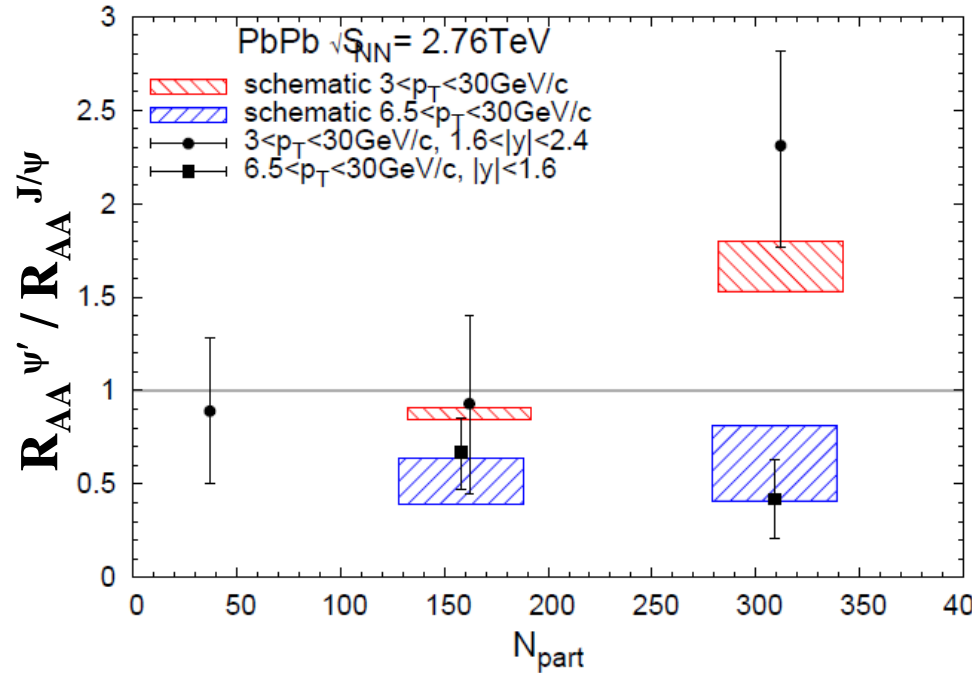
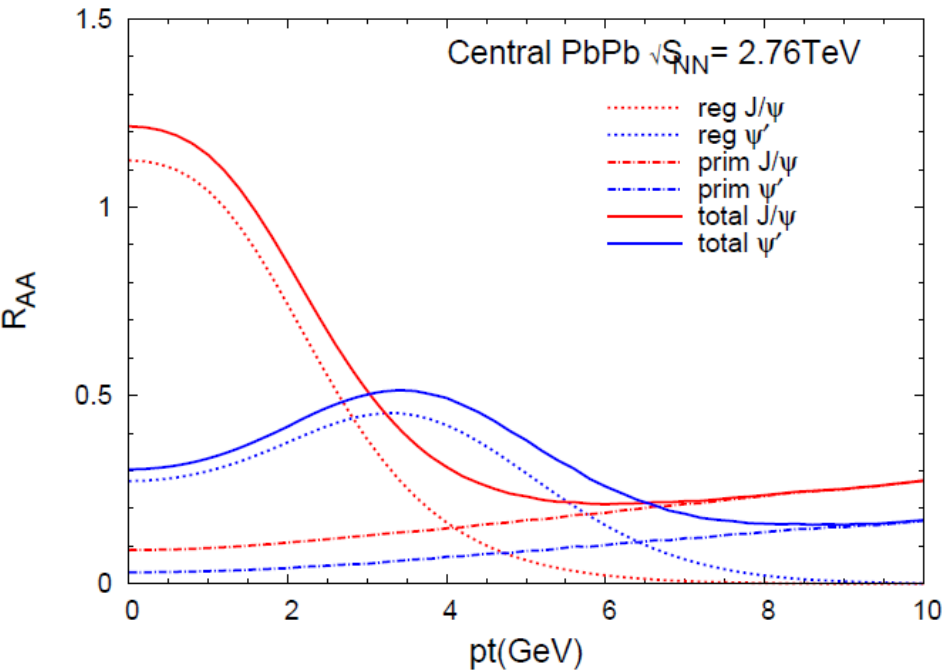
	$p_T^Y$ (GeV/c)	$\mathcal{R}_{Y(nS)}^{\chi_b(1P)}$	$\mathcal{R}_{Y(nS)}^{\chi_b(2P)}$
Y(1S)	6–8	$14.8 \pm 1.2 \pm 1.3$	$3.3 \pm 0.6 \pm 0.2$
	8–10	$17.2 \pm 1.0 \pm 1.4$	$5.2 \pm 0.6 \pm 0.3$
	10–14	$21.3 \pm 0.8 \pm 1.4$	$4.0 \pm 0.5 \pm 0.3$
	14–18	$24.4 \pm 1.3 \pm 1.2$	$5.2 \pm 0.8 \pm 0.4$
	18–22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

LHCb

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

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

# Charmonium: the $\psi(2S)$ puzzle



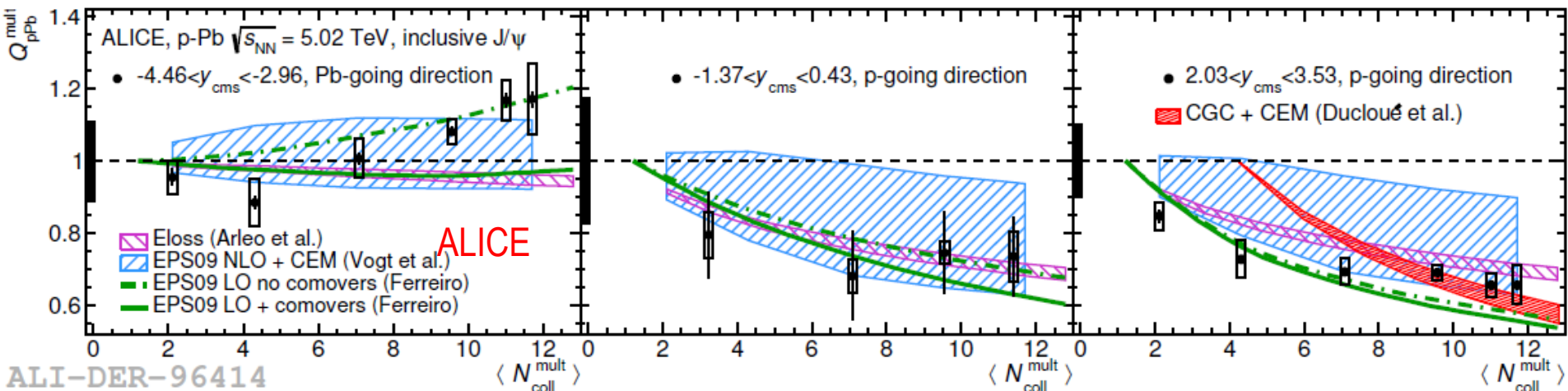
- ❑ The regeneration of  $\psi'$  mesons occurs significantly later than for  $J/\psi$ 's
- ❑ Despite a smaller total number of regenerated  $\psi'$ , the stronger radial flow at their time of production induces a marked enhancement of their  $R_{AA}$  relative to  $J/\psi$ 's in a momentum range  $pt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

# $J/\psi$ $R_{pPb}$ : centrality dependence

backward-y

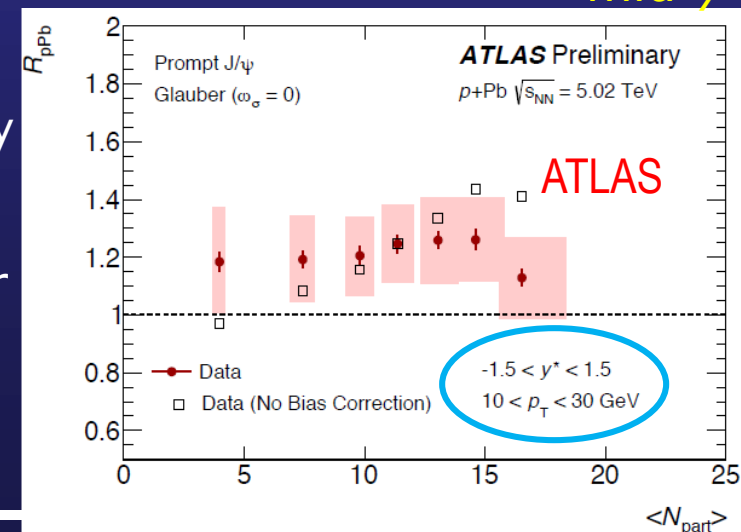
mid-y

forward-y

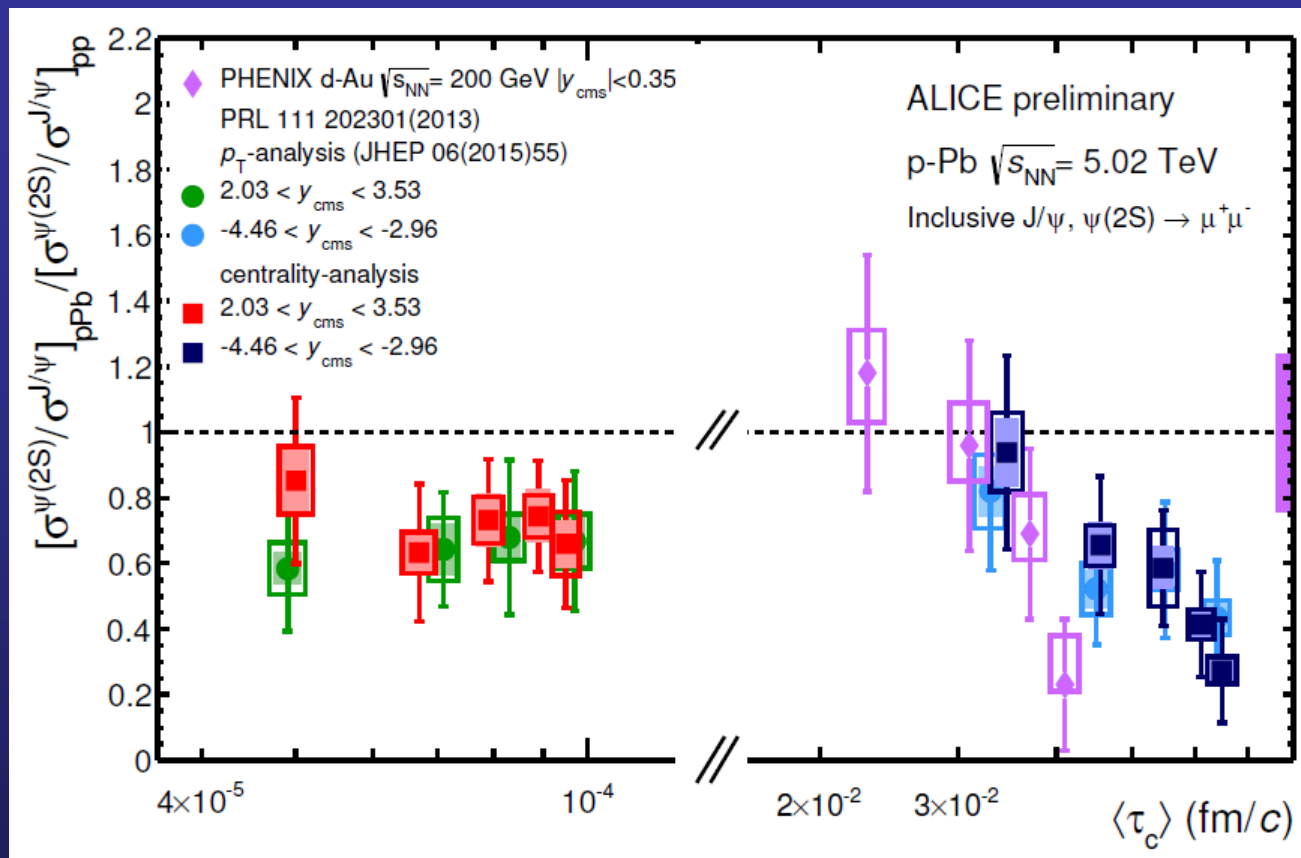


mid-y

- ALICE:
- mid and fw-y: suppression increases with centrality
- backward-y: hint for increasing  $Q_{pA}$  with centrality
- Shadowing and coherent energy loss models in fair agreement with data
- ATLAS
- Flat centrality dependence in the high  $p_T$  range



# Dependence of suppression on $\tau_c$

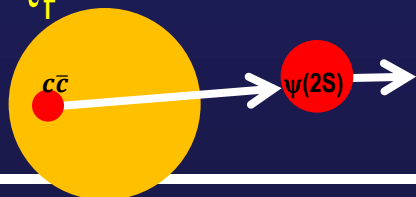


$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

D. McGlinchey, A. Frawley and R. Vogt, PRC 87,054910 (2013)

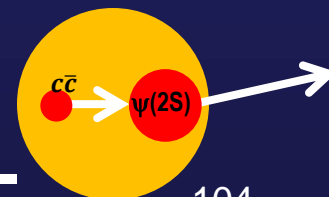
Forward- $y$ :  $\tau_c \ll \tau_f$

interaction with  
nuclear matter  
cannot play a role

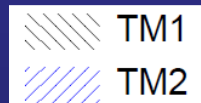
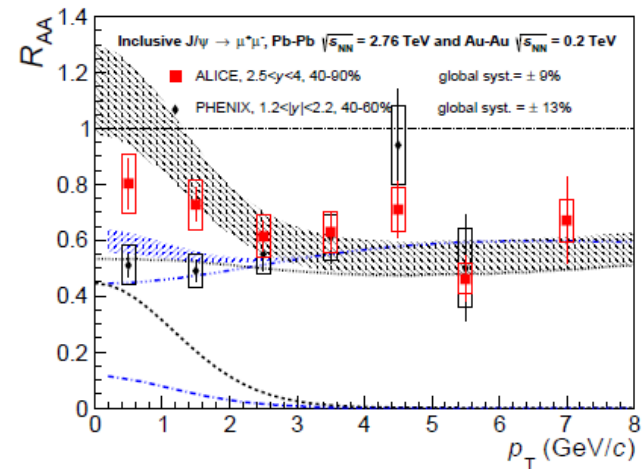
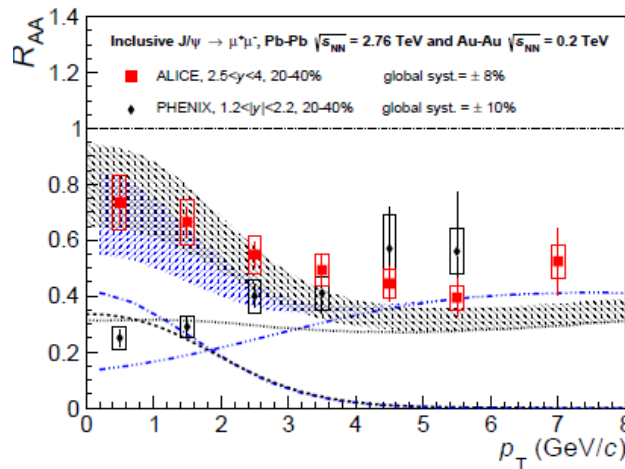
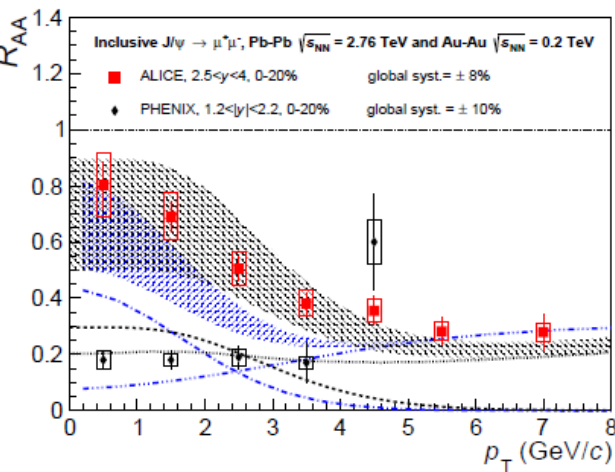


Backward- $y$ :  $\tau_c \gtrsim \tau_f$

indication of effects  
related to break-up in  
the nucleus?



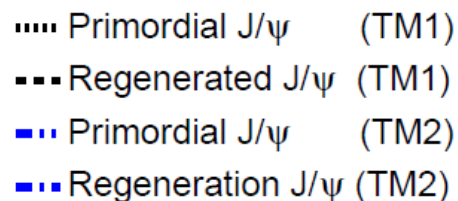
# $R_{AA}$ vs $p_T$



Zhao et al., Nucl.Phys.A859 (2011) 114

Zhou et al. Phys.Rev.C89 (2014)054911

ALICE, arXiv:1506.08804



□ Models provide a fair description of the data, even if with different balance of primordial/regeneration components

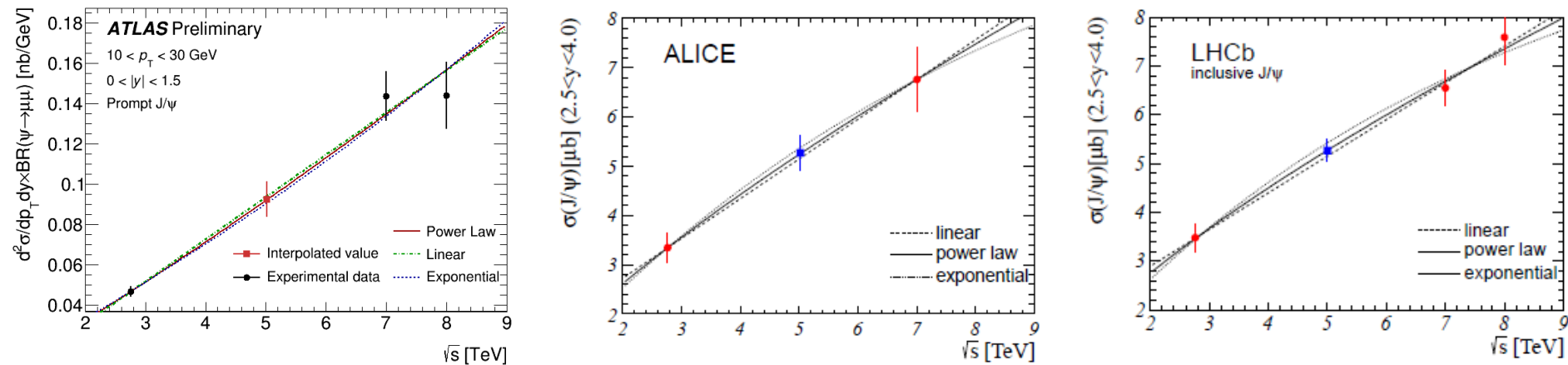
Still rather large theory uncertainties: models will benefit from precise measurement of  $\sigma_{cc}$  and CNM effects

□ Opposite trend with respect to lower energy experiments

# Building a reference $\sigma_{pp} \rightarrow$ interpolation

- Simple **empirical approach** adopted by ALICE, ATLAS and LHCb

CERN-LHCb-CONF-2013-013; ALICE-PUBLIC-2013-002.



Example: ALICE result

$$\sigma_{\text{incl}} = 5.28 \pm 0.40_{\text{exp}} \pm 0.10_{\text{inter}} \pm 0.05_{\text{theo}} \mu\text{b} = 5.28 \pm 0.42 \mu\text{b}.$$

inter: spread of interp. with empirical functions  
theo: spread of interp. with theory estimates

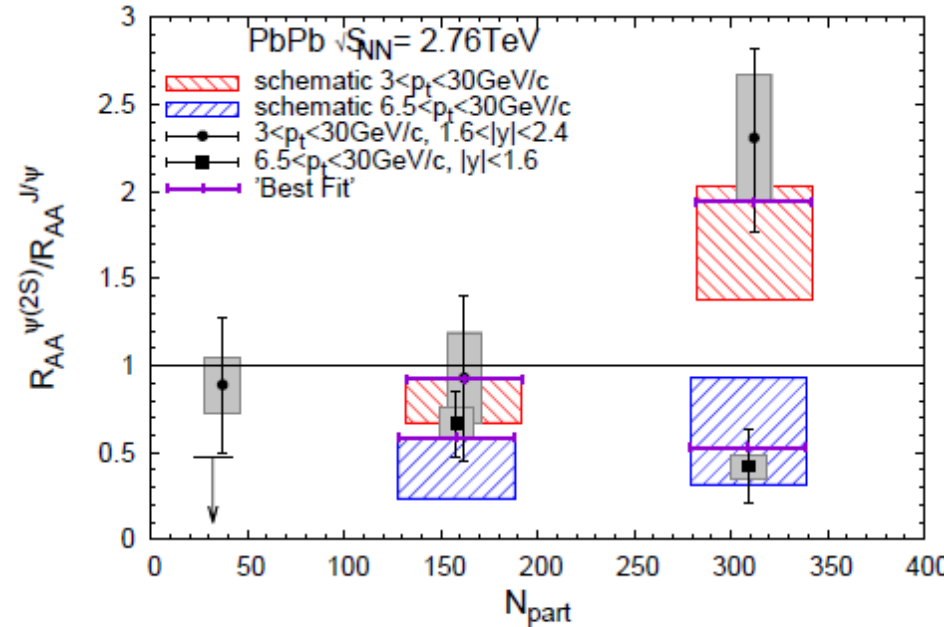
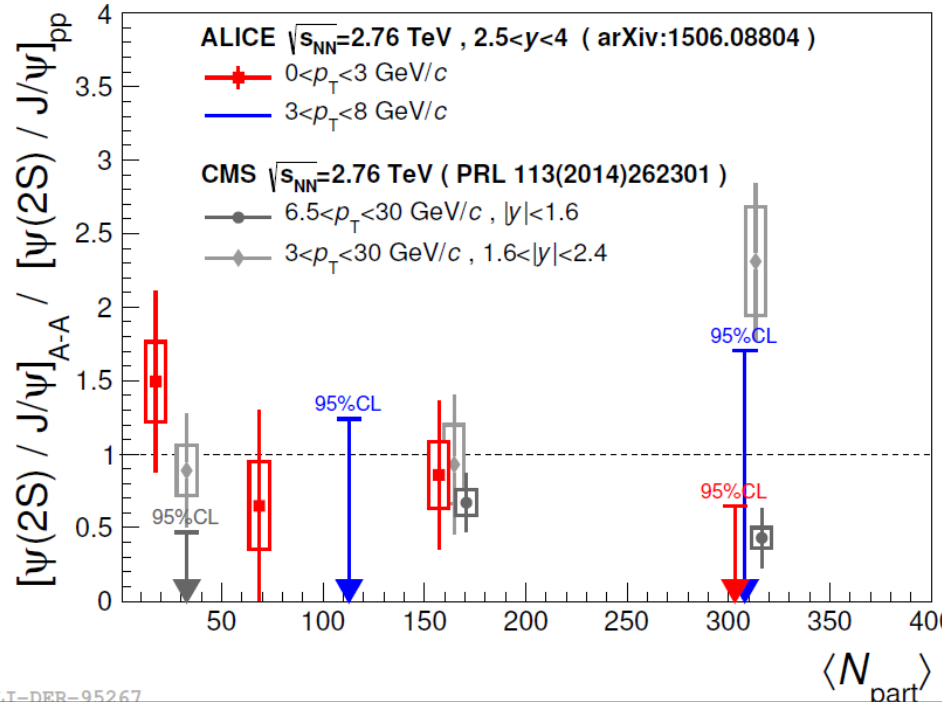
- $\psi(2S) \rightarrow$  interpolation difficult, small statistics at  $\sqrt{s}=2.76$  TeV
- Ratio  $\psi(2S) / J/\psi \rightarrow$  **ALICE uses  $\sqrt{s}=7$  TeV pp values** (weak  $\sqrt{s}$ -dependence)

$$R_{pA}^{\psi(2S)} = R_{pA}^{J/\psi} \times \frac{\sigma_{pA}^{\psi(2S)}}{\sigma_{pA}^{J/\psi}} \times \frac{\sigma_{pp}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}}$$

ALICE estimate (conservative)  
 $\rightarrow$  **8% syst. unc.** due to different  $\sqrt{s}$   
(using CDF/ALICE/LHCb results)

# $\psi(2S)$ in Pb-Pb: ALICE "vs" CMS

- $\psi(2S)$  production modified in Pb-Pb with a strong kinematic dependence
- CMS  $\rightarrow$  suppression at high  $p_T$ , enhancement at intermediate  $p_T$



Du and Rapp arXiv:1504.00670

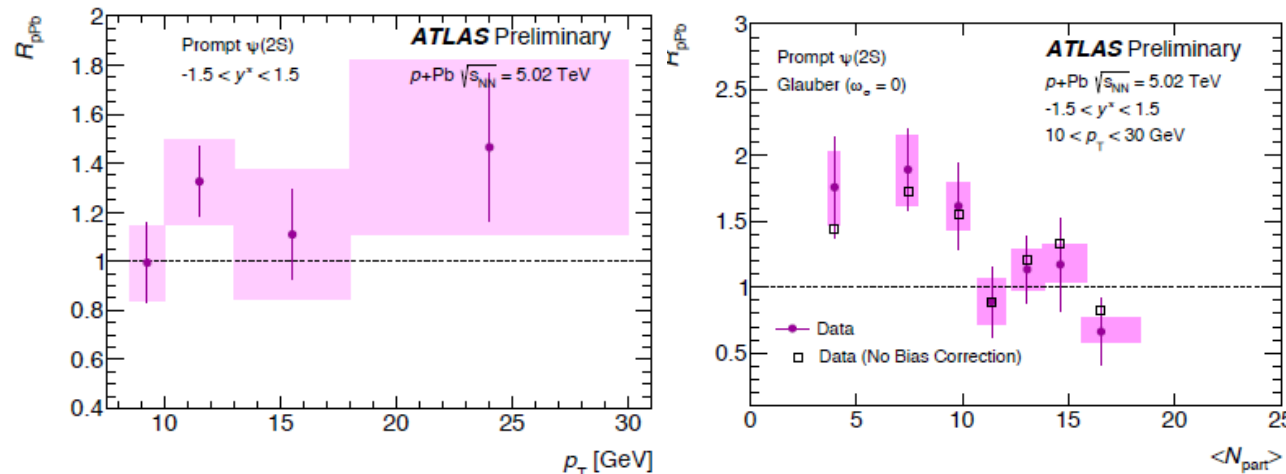
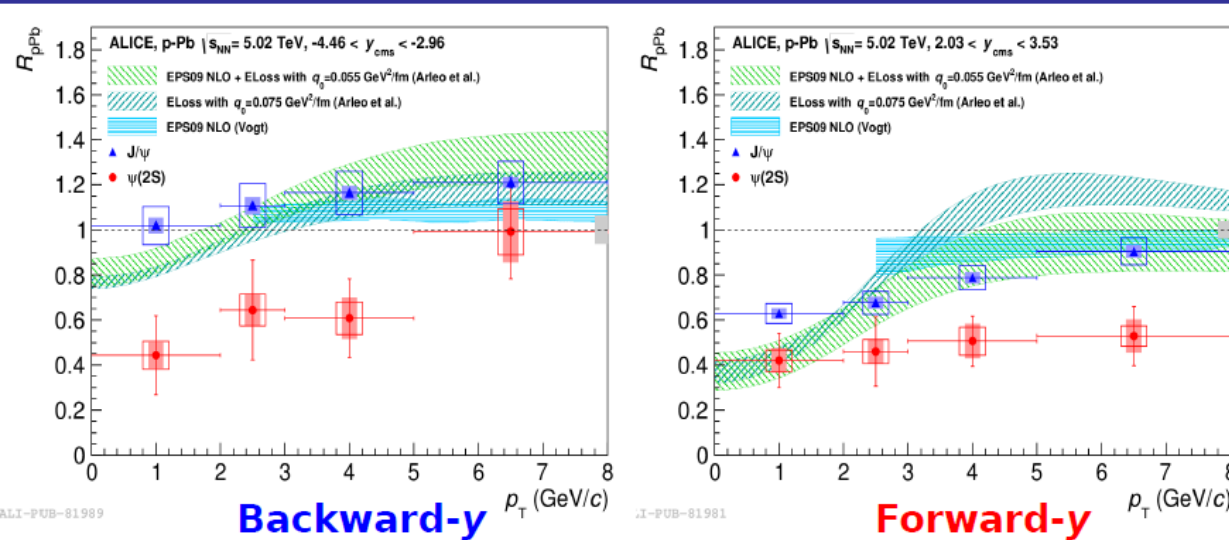
CMS, PRL113 (2014) 262301  
ALICE, arXiv:1506.08804

- Possible interpretation (Rapp et al.)  $\rightarrow$  Re-generation for  $\psi(2S)$  occurs at later times wrt  $J/\psi$ , when a significant radial flow has built up, pushing the re-generated  $\psi(2S)$  at a relatively larger  $p_T$

# $\psi(2S)$ in p-Pb: $p_T$ dependence

ALICE, JHEP 12 (2014) 073

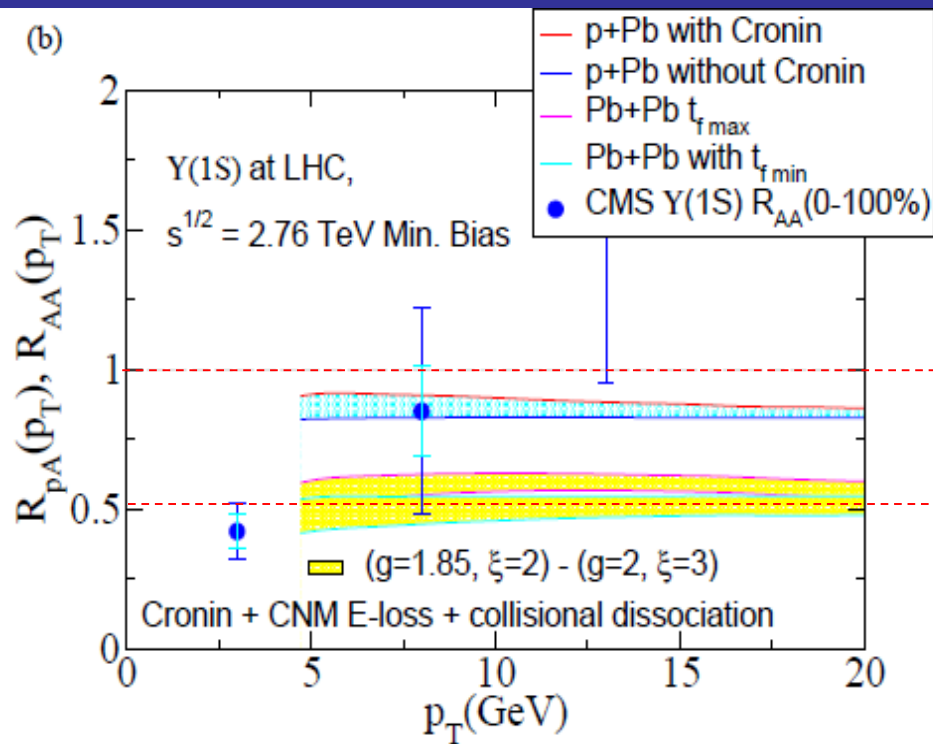
- ALICE (low  $p_T$ ) : rather **strong suppression**, possibly vanishing at backward  $y$  and  $p_T > 5$  GeV/c



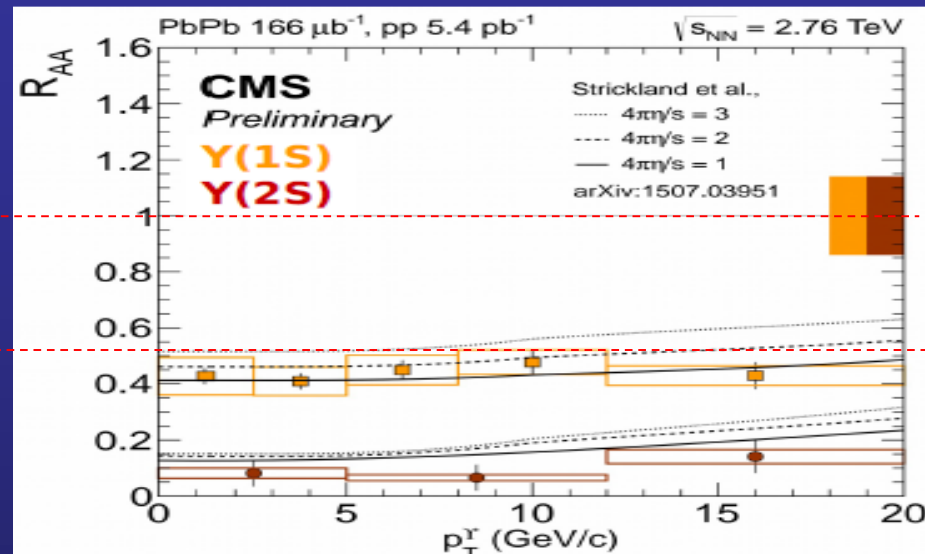
ATLAS-CONF-2015-023

- Possible **tension** between ALICE and ATLAS results ? Wait for final results

# High $p_T$ $\Upsilon$ : model comparison

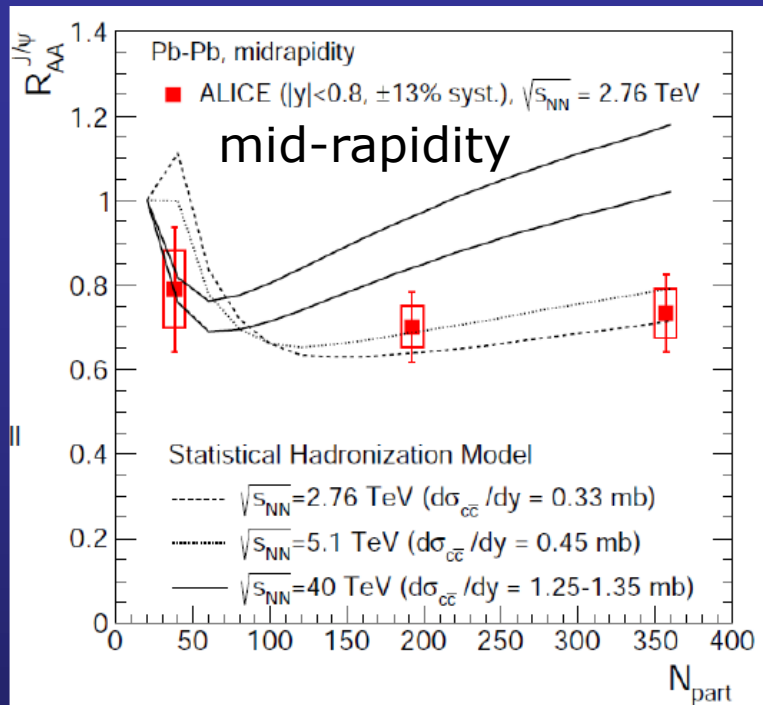


Sharma and Vitev,  
Phys. Rev. C 87, 044905 (2013)



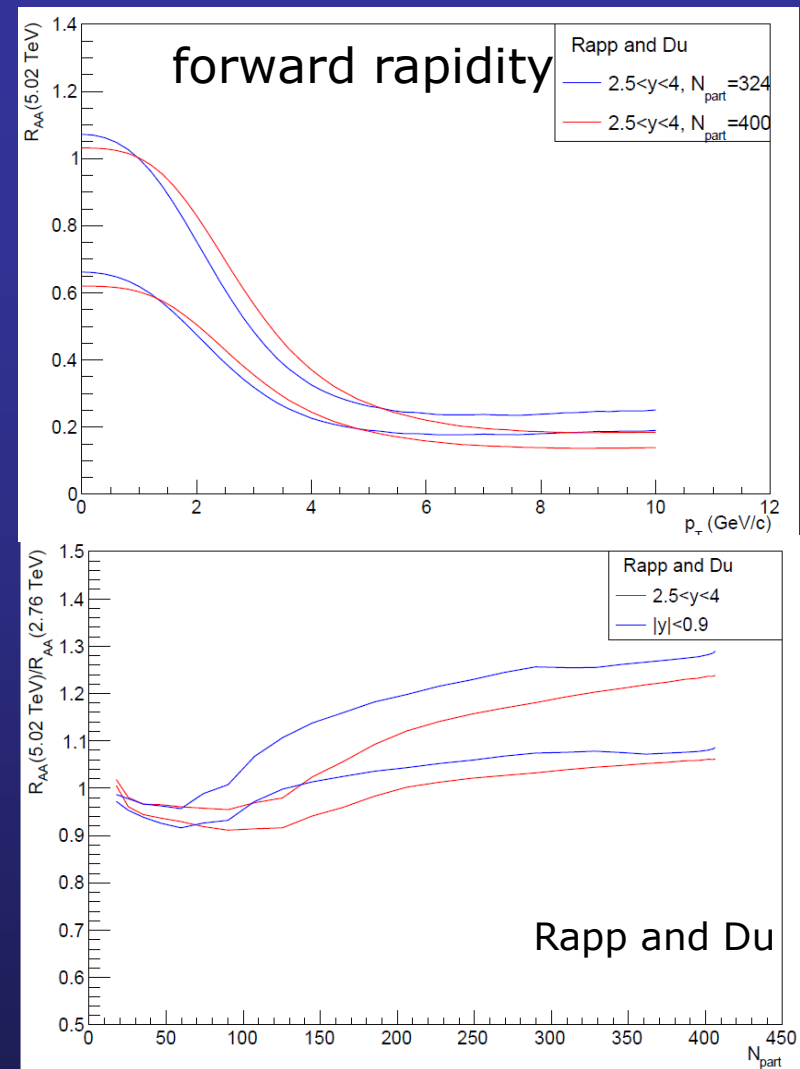
- ❑ High  $p_T$   $\Upsilon$  suppression
- ❑ Propagation effects through QGP
  - ❑ Quenching of the color octet component
  - ❑ Collisional dissociation model
- ❑ Approximation: initial wave function of the quarkonia well approximated by vacuum wavefunctions in the short period before dissociation
- ❑ CNM effects accounted for (shadowing + Cronin)

# Some $J/\psi$ predictions for run-2



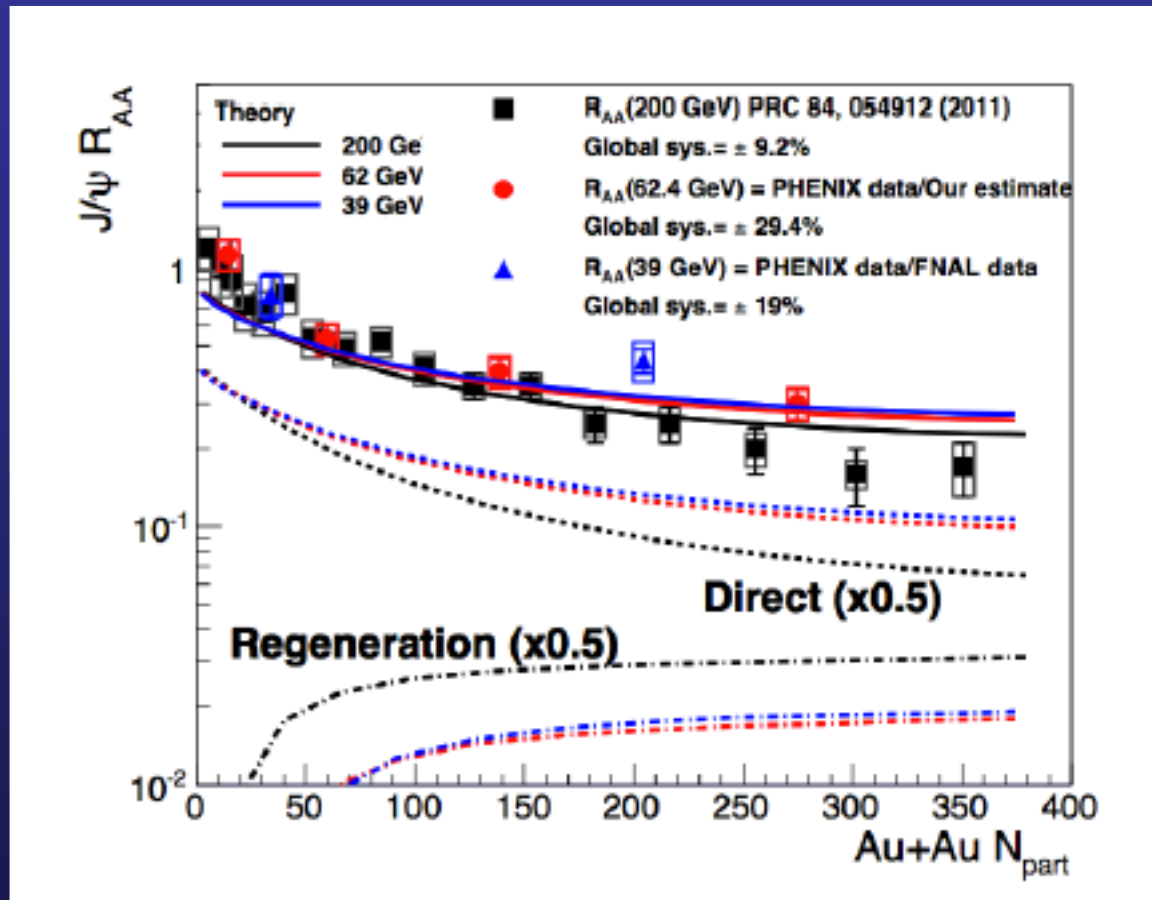
PBM, Andronic, Redlich and Stachel

- ❑ First **predictions** for (both statistical and transport models) indicate a **moderate increase** in  $R_{AA}$ , when comparing  $\sqrt{s_{NN}} = 5.02$  and 2.76 TeV
- ❑ **Theoretical uncertainties are larger than the predicted increase**
  - Provide quantities where at least partial cancellation of uncertainties takes place (double ratios of  $R_{AA}$ )

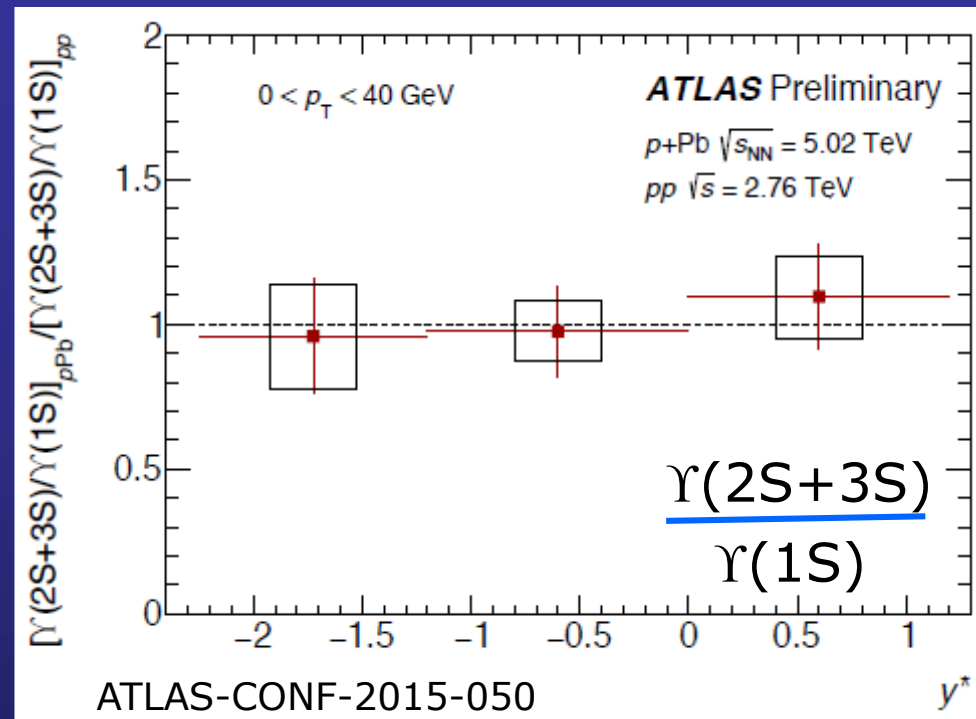
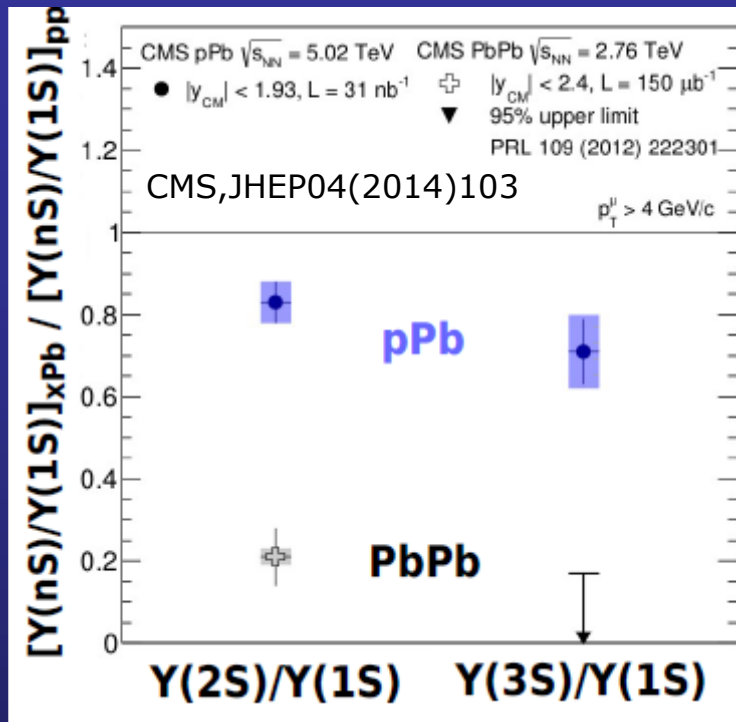


# Suppression vs $\sqrt{s_{NN}}$ (RHIC)

- At RHIC 39 GeV, 62 GeV, 200 GeV all show similar suppression



# Yield ratios for bottomonium in p-Pb



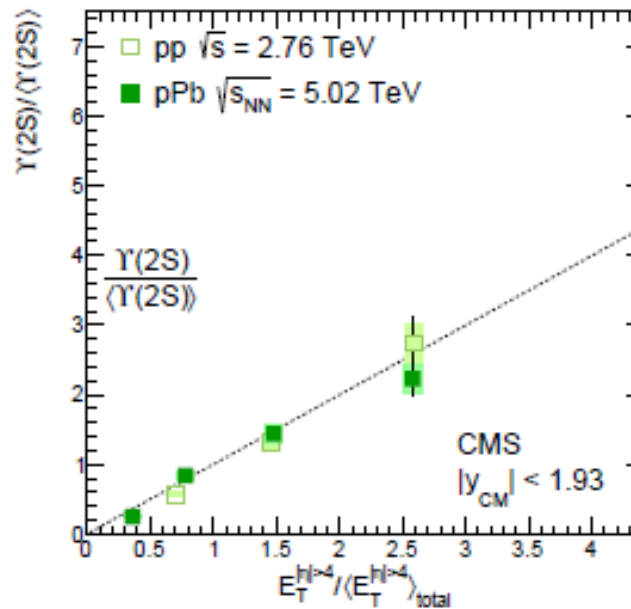
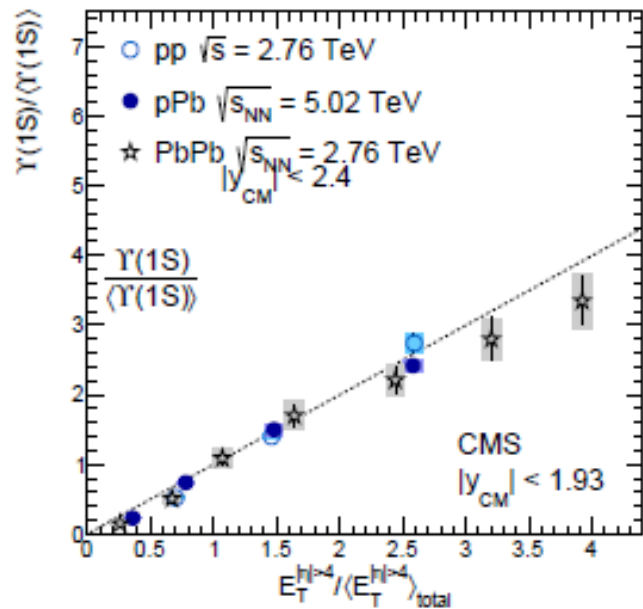
## CMS

- ❑ Excited states suppressed with respect to  $\Upsilon(1S)$
- ❑ Initial state effects similar for the various  $\Upsilon(ns)$  states
- Final states effects at play?

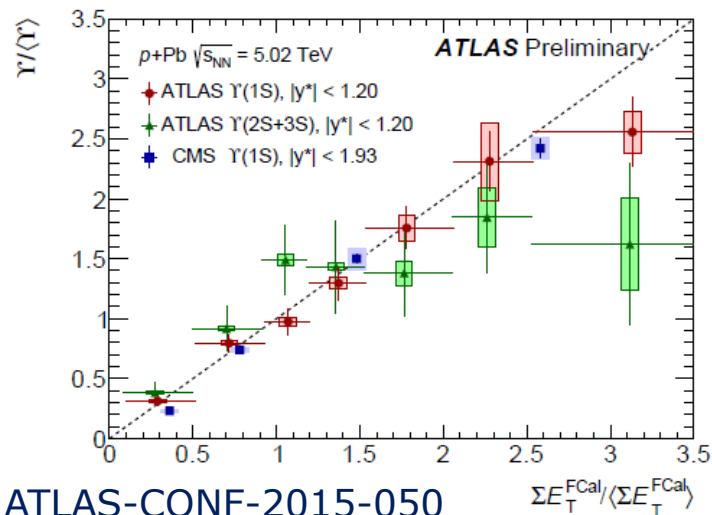
## ATLAS

- ❑ no strong  $y$  (and  $p_T$ ) dependence
- ❑ agreement with CMS within uncertainties

# Self-normalized $\Upsilon$ cross sections



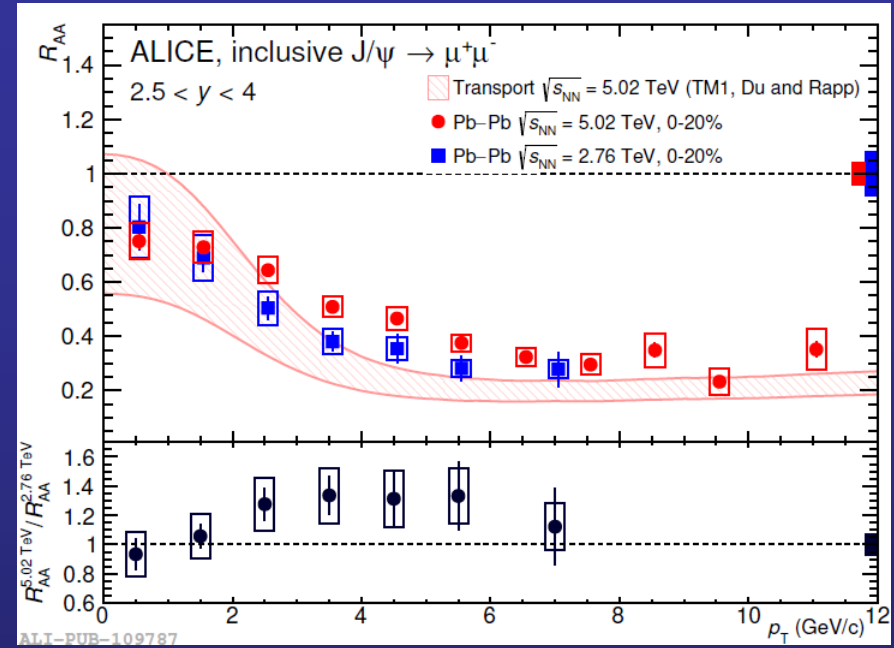
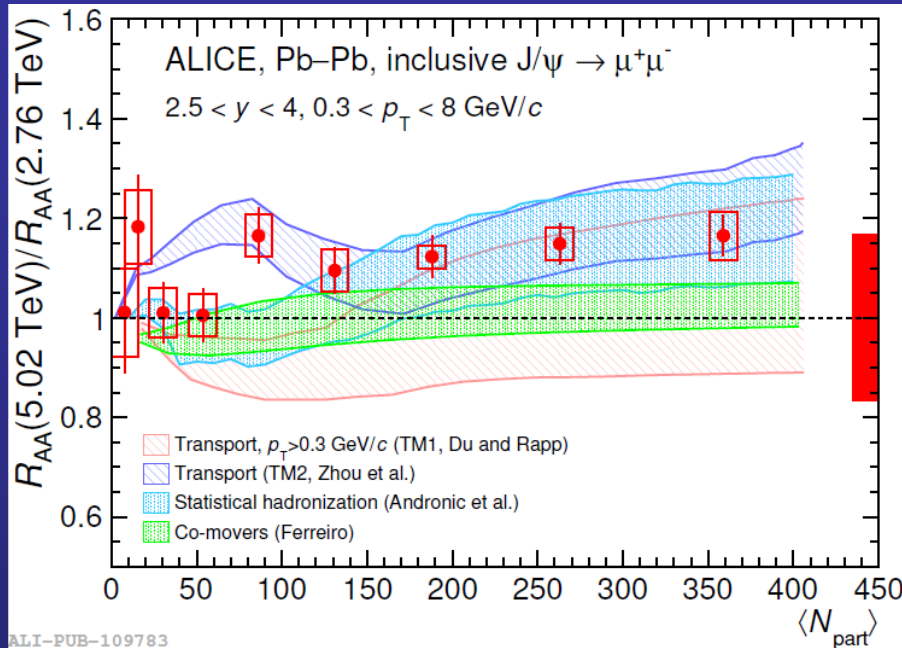
Similar behaviour  
observed for  
 $J/\psi$  (ALICE)  
(PLB712 (2012) 165-175)



CMS, JHEP 04 (2014) 103

- All the **ratios increase** with increasing forward transverse energy
- When Pb nuclei are involved  
→ Increase partly due to larger number of N-N collisions
- Increase observed also in pp collisions  
→ **multiple partonic interactions** ?

# Comparison with models



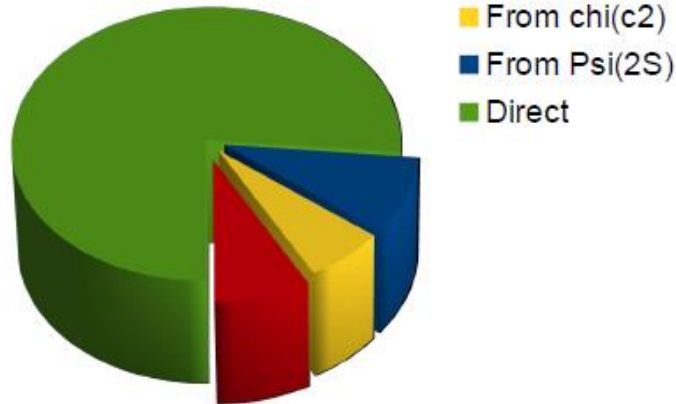
- ❑ Theoretical and experimental uncertainties reduced in the  $R_{AA}$  double ratio
- ❑ Centrality dependence of the  $R_{AA}$  ratio is rather flat

- ❑  $R_{AA}$  increases at low  $p_T$ , at both energies, as expected in a regeneration scenario
- ❑ Hint for an increase of  $R_{AA}$ , at 5.02 TeV, in  $2 < p_T < 6 \text{ GeV}/c$

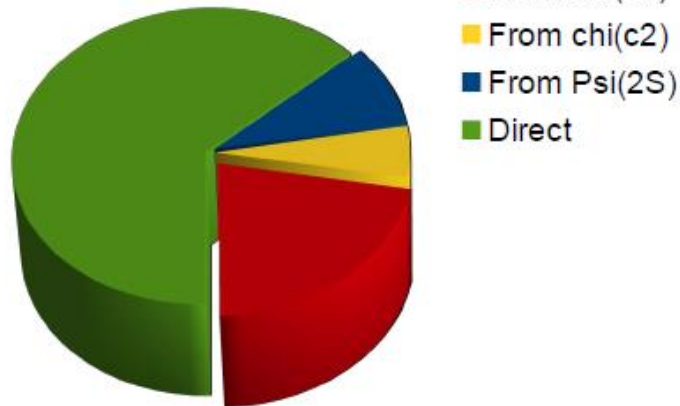
→ Also  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  results support a picture where a combination of  $J/\psi$  suppression and (re)combination occurs in the QGP

# Feed-down

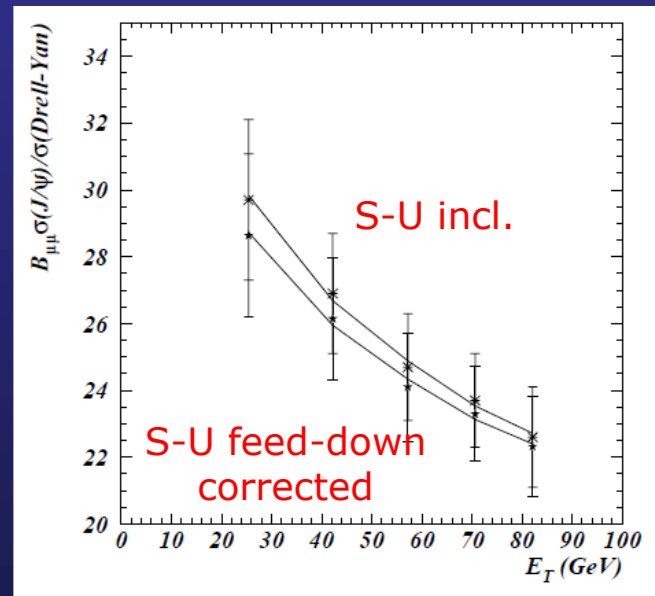
Low transverse momentum



High transverse momentum

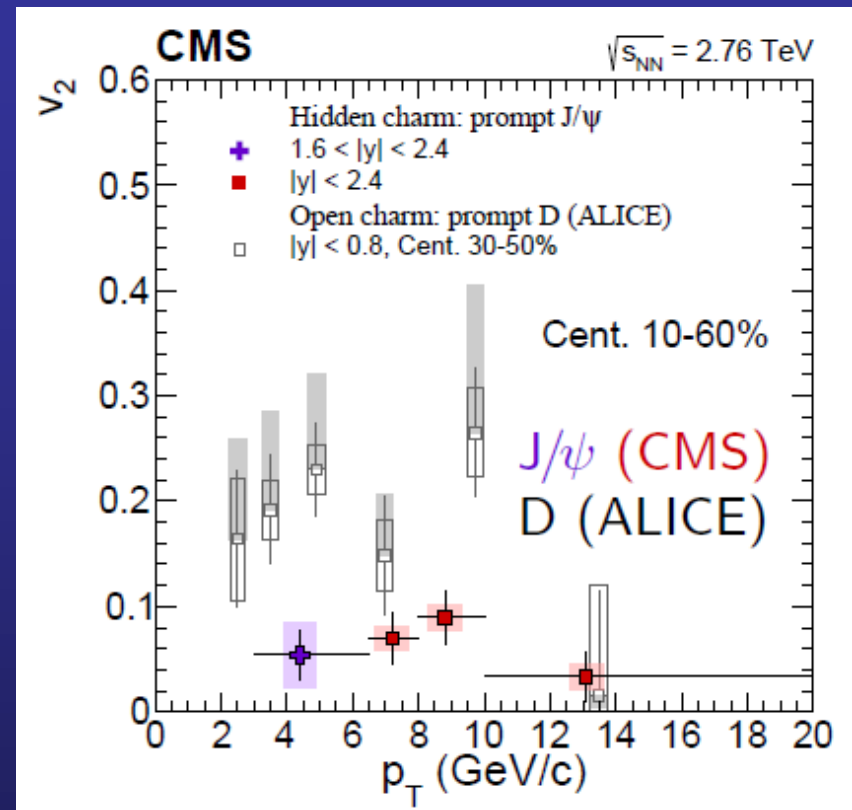
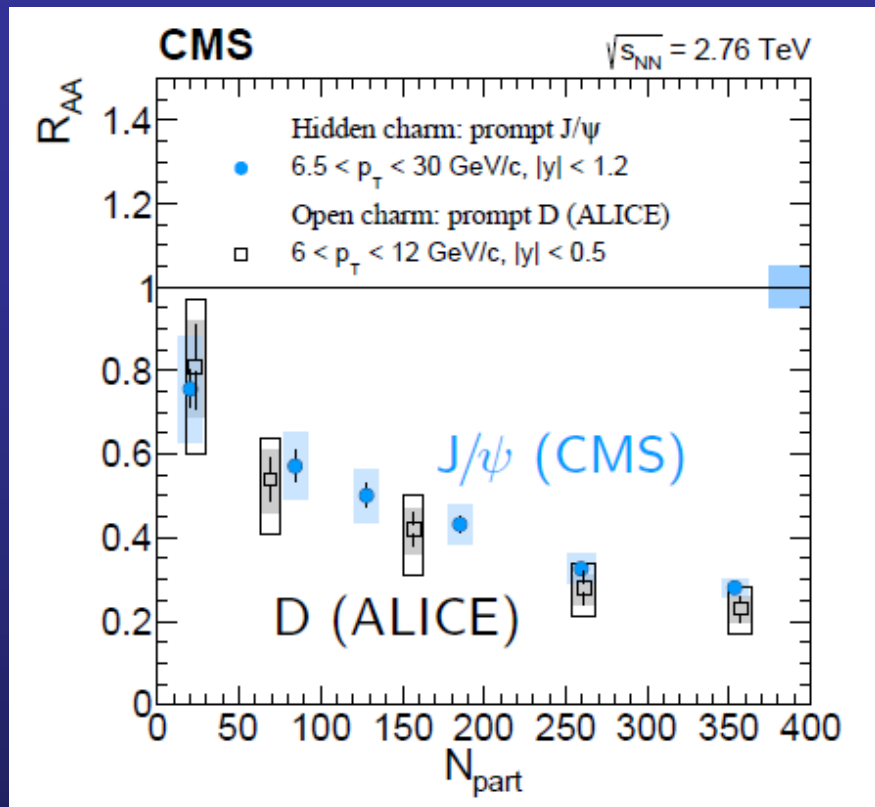


- ❑ Cannot be addressed precisely until today!
- ❑ If  $\psi(2S)$  and  $\chi_c$  were precisely measured in Pb-Pb their contribution could be subtracted out and obtain **direct**  $J/\psi$
- ❑ Explicitly done (only ?) by NA50, for  $\psi(2S)$  when comparing p-A and S-U data



- ❑ We are still very far at the LHC! Needed for a quantitative understanding

# Comparing $R_{AA}$ and $v_2$ for closed/open charm



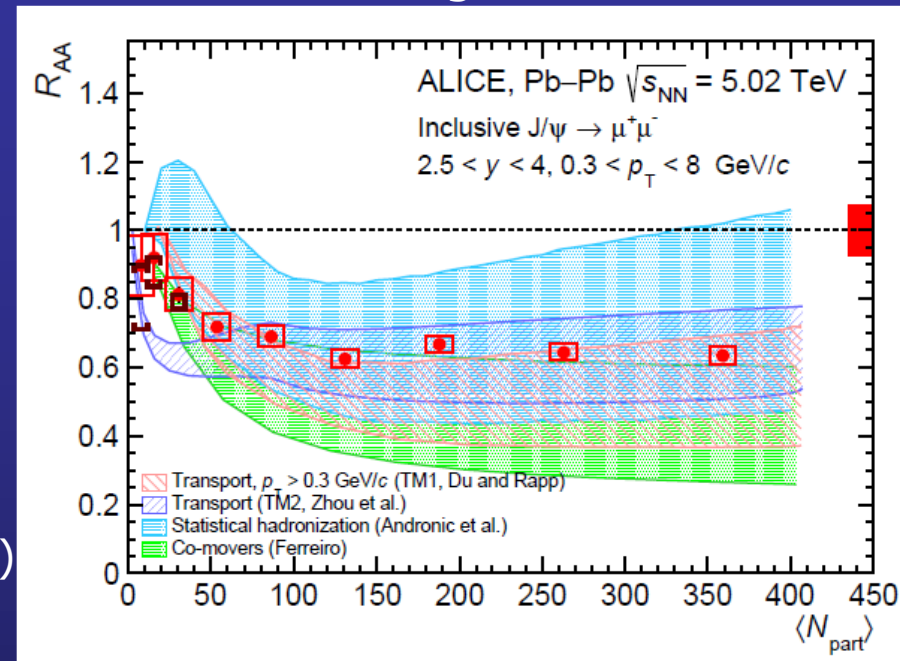
- CMS final results from HP2016
- Striking similarity for  $R_{AA}$ ,  $v_2$  systematically lower for  $J/\psi$
- Interesting but **not trivial comparison** (same- $p_T$  comparison can probe different HQ kinematics, ...)
- Need a solid theory support

# Low- $p_T$ $J/\psi$ : open questions

Reasonably **good set of data**  $\rightarrow$  fundamental to investigate re-combination issues

**Quantitative interpretation** made difficult by the significant **spread in crucial quantities of the models**, such as ( $\sqrt{s}=5$  TeV)

$$(d\sigma/dy)_{cc} \begin{cases} 0.42 \text{ mb (Statistical, Andronic)} \\ 0.57 \text{ mb (Transport, Du/Rapp)} \\ 0.82 \text{ mb (Transport, Zhou et al.)} \\ 0.45\text{-}0.70 \text{ mb (Comover, Ferreiro)} \end{cases}$$



Recent **LHCb estimates** (LHCb-CONF-2016-003) suggest values on the low-side of this range (caveat, extrapolation, to be updated with their  $\sqrt{s}=5$  TeV data)

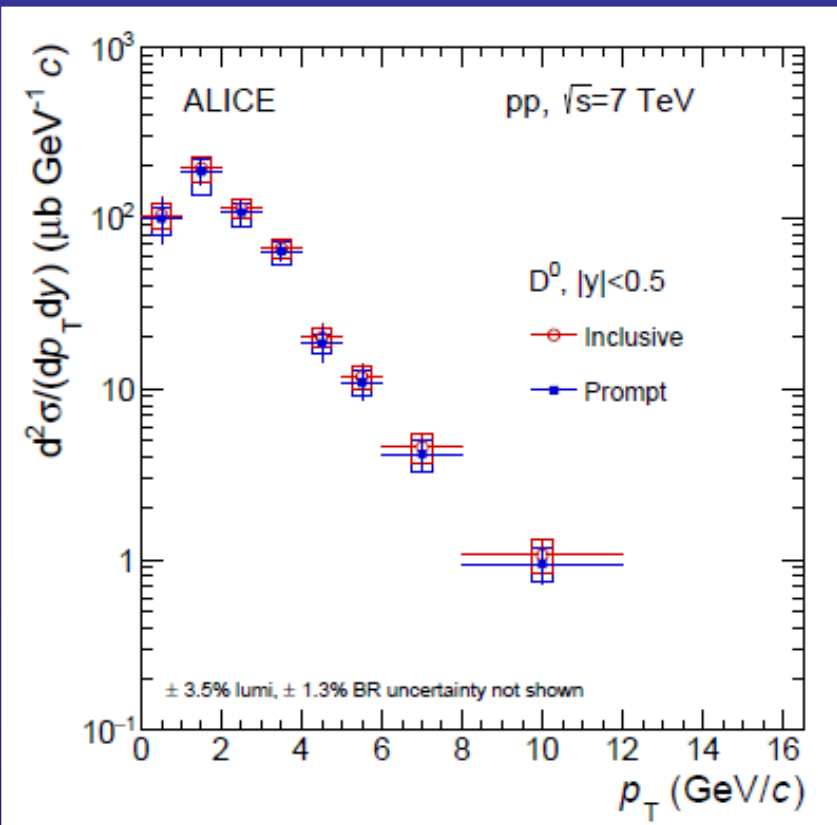
Starting from their

$$\sigma_{D0}(p_T < 8 \text{ GeV}/c, 2.5 < y < 4) = 713 \pm 95(\text{LHCb}) \pm 47(\text{interp.}) \mu\text{b}$$

one gets

$$(d\sigma/dy)_{cc} = 0.44 \pm 0.06(\text{LHCb}) \pm 0.03(\text{interp.}) \pm 0.02(\text{FF}) \text{ mb} = 0.44 \pm 0.07 \text{ mb}$$

# Low- $p_T$ $J/\psi$ : open questions



- ❑ Precise measurements of open charm cross section are mandatory
- ❑ Best results available today (ALICE, LHCb) have uncertainties of about 20%
- ❑ If there is no space for a significant improvement, model uncertainties are not getting smaller
- ❑ Theorists, please, agree on using the same input values !

$$d\sigma_{pp, 7\text{TeV}}^{c\bar{c}}/dy = 988 \pm 81 (\text{stat.})^{+108}_{-195} (\text{syst.}) \pm 35 (\text{lumi.}) \pm 44 (\text{FF}) \pm 33 (\text{rap. shape}) \mu\text{b}.$$

- ❑ CNM (shadowing) is the other main source of uncertainty (see later)

# Prompt $D^0$ nuclear modification factor in pPb

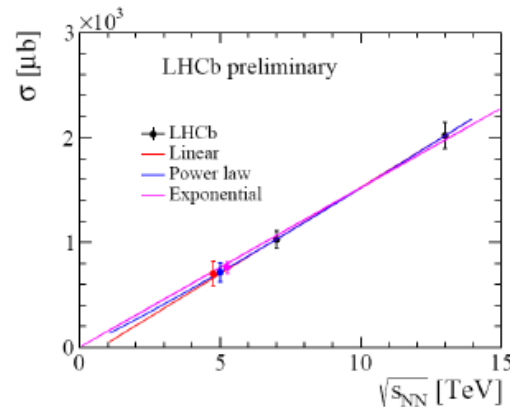


- $R_{pPb}(y^*, p_T) = \frac{1}{A} \times \frac{\sigma_{pPb}(y^*, p_T, \sqrt{s_{NN}})}{\sigma_{pp}(y^*, p_T, \sqrt{s_{NN}})}, A=208$

*LHCb-CONF-2016-003*

- Prompt  $D^0$  cross-section in  $pp$  collisions at  $\sqrt{s} = 5$  TeV was extrapolated using LHCb measurements at 7 and 13 TeV

*Nucl. Phys. B871 (2013) 1;*  
*JHEP 03 (2016) 159,*  
*Erratum-ibid 09 (2016) 013*



$$\sigma(\sqrt{s}) = \begin{cases} p_1(\sqrt{s})^{p_0} & \text{power law,} \\ p_1 + p_0\sqrt{s} & \text{linear,} \\ p_1(1 - \exp(-\sqrt{s}/p_0)) & \text{exponential.} \end{cases}$$

**CAUTION:** Preliminary  $R_{pPb}$  uses extrapolated  $pp$  cross-sections for reference! will be updated soon with the measured  $pp$  values!

**Extrapolated:**  $\sigma_{pp}(p_T < 8 \text{ GeV}/c, 2.5 < |y^*| < 4.0) = 713 \pm 95(\text{LHCb}) \pm 47 \text{ (fit model)} \mu\text{b}$

- Prompt  $D^0$  in  $pp$  at  $\sqrt{s} = 5$  TeV was measured recently! *LHCb-PAPER-2016-042*

**Measured:**  $\sigma_{pp}(p_T < 8 \text{ GeV}/c, 2.5 < |y^*| < 4.0) = 943 \pm 2 \pm 49 \mu\text{b}$

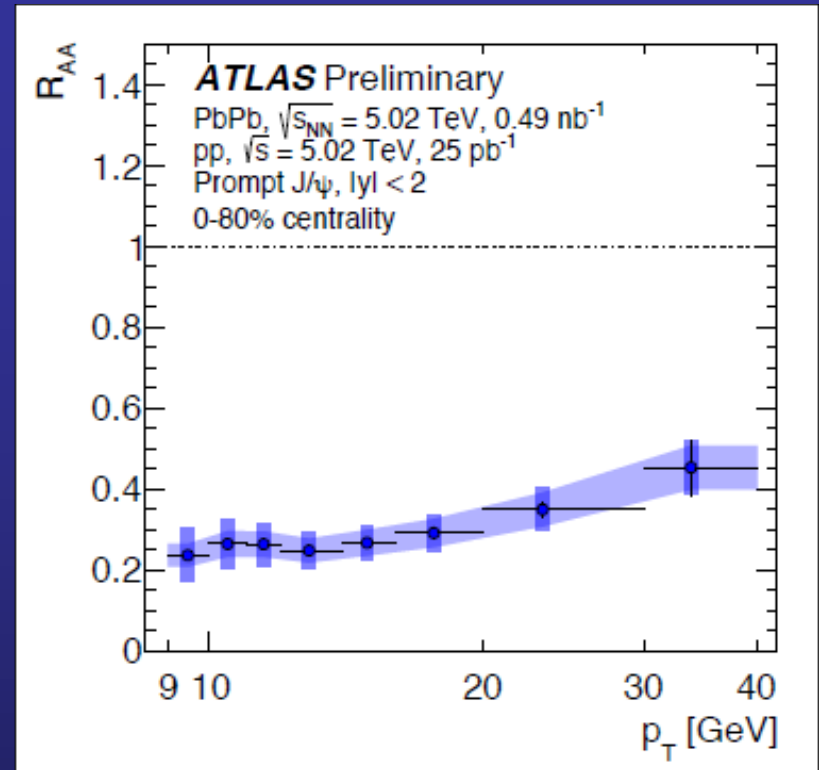
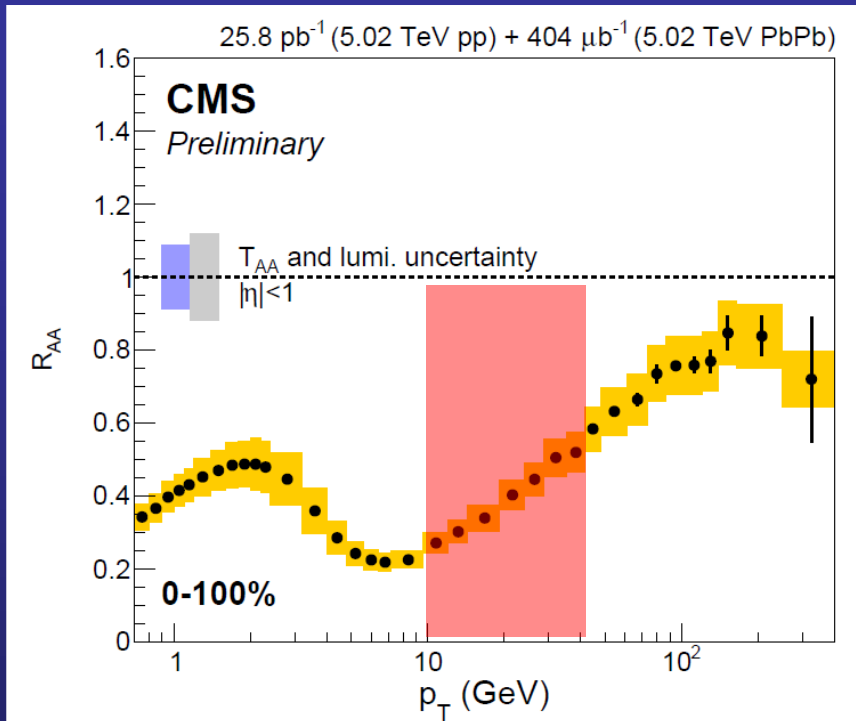
2016/09/24

X. Zhu,  $D^0$  production in LHCb, HP2016

10

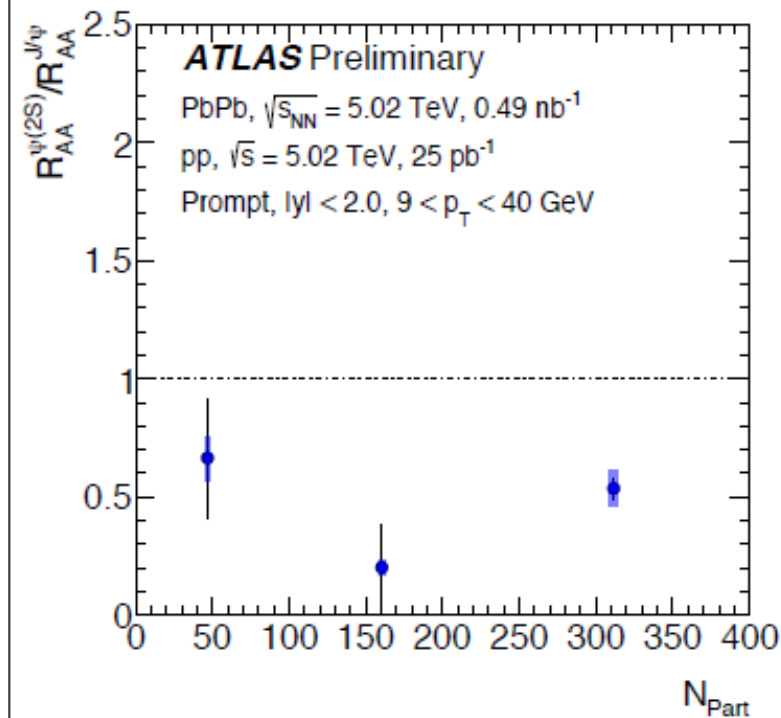
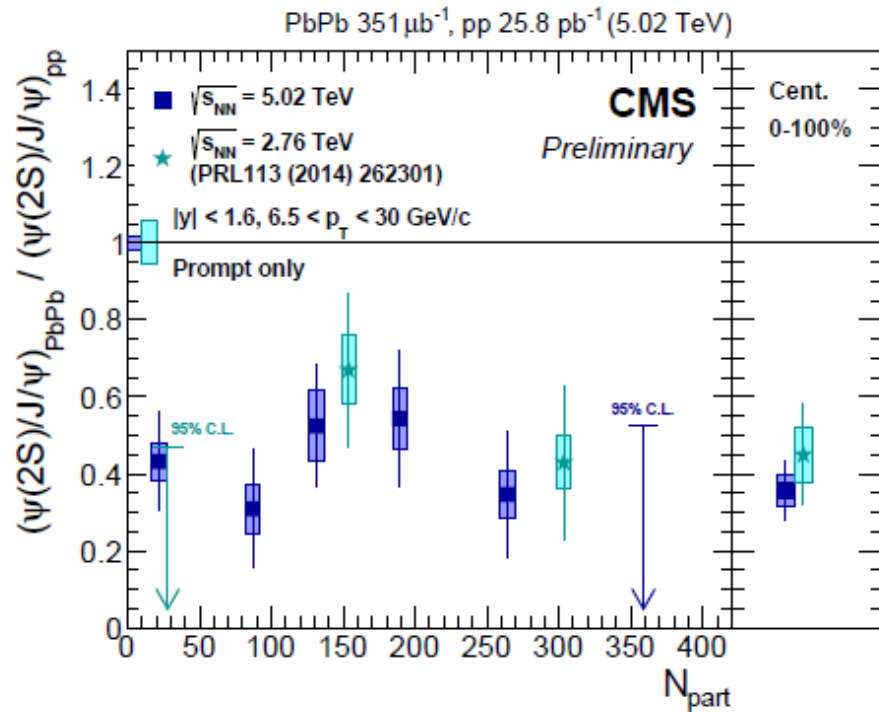
Fresh news  $\rightarrow$  LHCb cross section updated  
 Brings to  $(d\sigma/dy)_{cc} = 0.58 \text{ mb}$ , with rather small uncertainties!

# High- $p_T$ $J/\psi$ : CMS (+ATLAS)



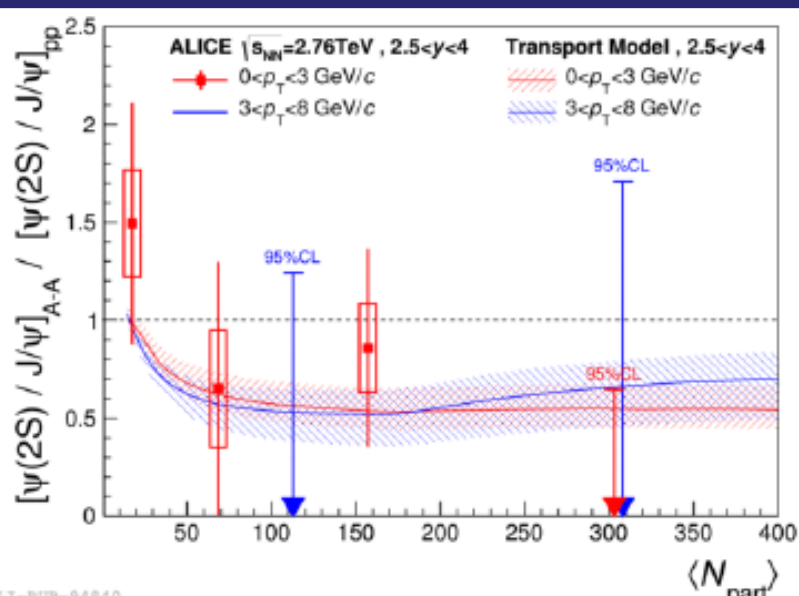
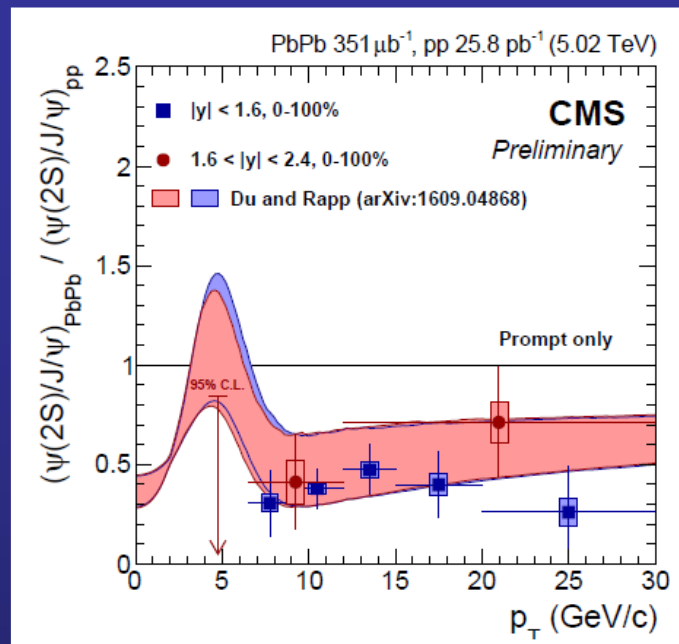
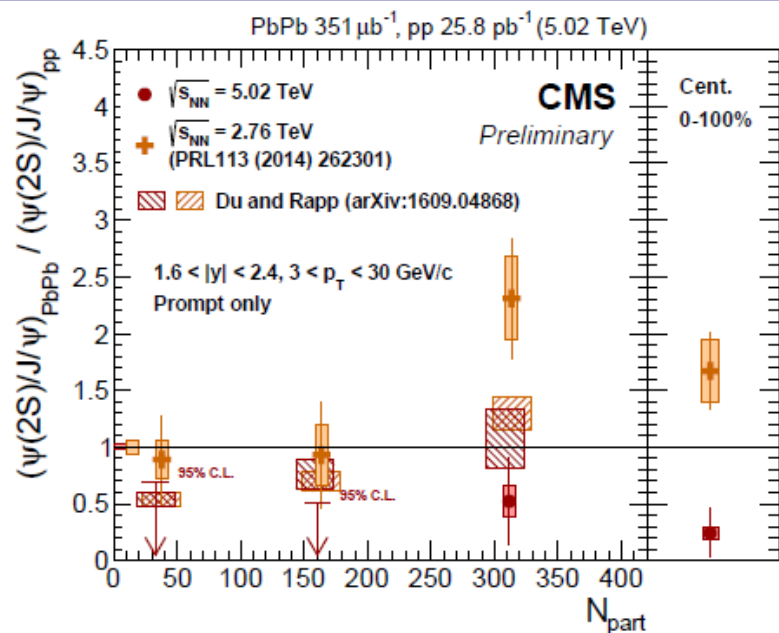
- ❑ Maximum  $J/\psi$  suppression, then **increase beyond  $p_T=20$  GeV/c**
- ❑ Similar behavior as for hadrons ?
- ❑ Is a model description in terms of **energy loss** needed?
- ❑ Compatibility ATLAS vs CMS: factor  $\sim 2$  more suppression for ATLAS
- ❑ Could it be an **effect of the different  $\sqrt{s}$**  ? Wait for CMS run-2 results

# $\psi(2S)$ : 5.02 vs 2.76 TeV



- ❑ CMS preliminary results
- ❑ Larger  $\psi(2S)$  suppression confirmed at high  $p_T$
- ❑ Has the anomalous bump seen at 2.76 TeV disappeared ?
- ❑ Or is this one of the few observables sensitive to the LHC energy increase ?
- ❑ ATLAS confirms suppression in the high- $p_T$  region

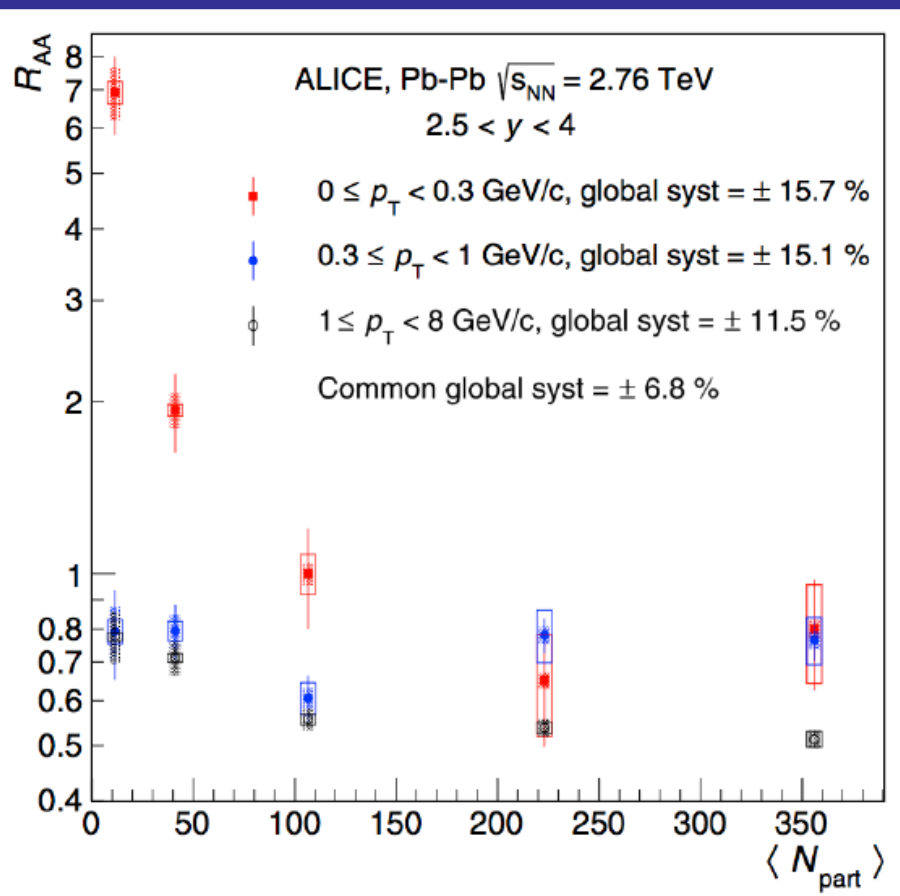
# $\psi(2S)$ : 5.02 vs 2.76 TeV



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

# Photonuclear production: LHC

- A new source of  $J/\psi$  in hadronic Pb-Pb collision
- Low  $p_T$  “excess” (huge  $R_{\text{PbPb}}$  values for  $p_T < 0.3$  GeV/c)



- Likely due to photoproduction in events with  $b > 2R$  (recently observed at RHIC too!)
- $\sim 75\%$  of the signal expected for  $p_T < 0.3$  GeV/c
- ALICE peripheral  $R_{\text{AA}}$  lowers by max 20% when photoproduction removed
- At the same time
  - A “background” for hadronic  $R_{\text{PbPb}}$  studies (anyway concentrated in peripheral events, where theory calculations are less reliable)
  - A “signal” of a known process in a “non-standard” environment

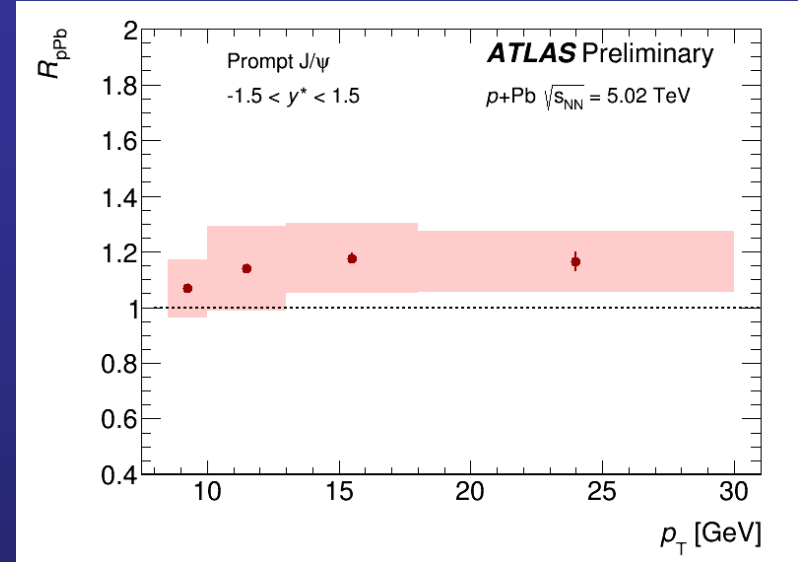
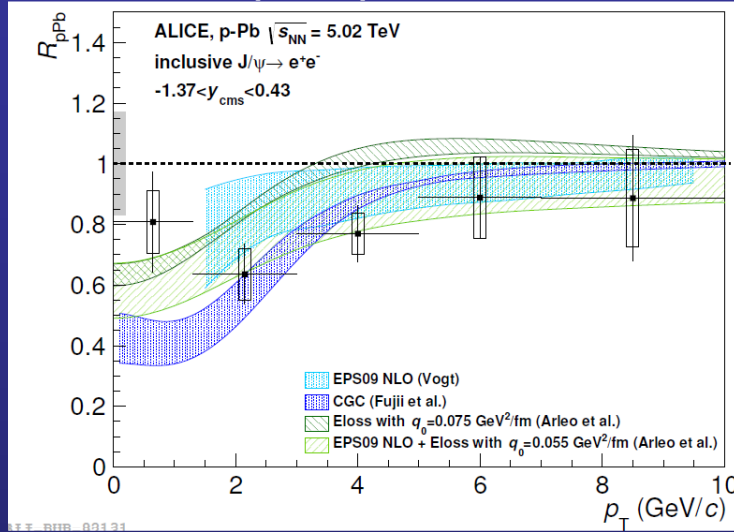
If under theory control, could it be used as a probe of hot matter ?

# J/ψ R<sub>pPb</sub>: ATLAS "vs" ALICE "vs" LHCb

□ R<sub>pPb</sub> vs p<sub>T</sub> at y~0 → fair **agreement** ALICE vs ATLAS (extends to high p<sub>T</sub>)

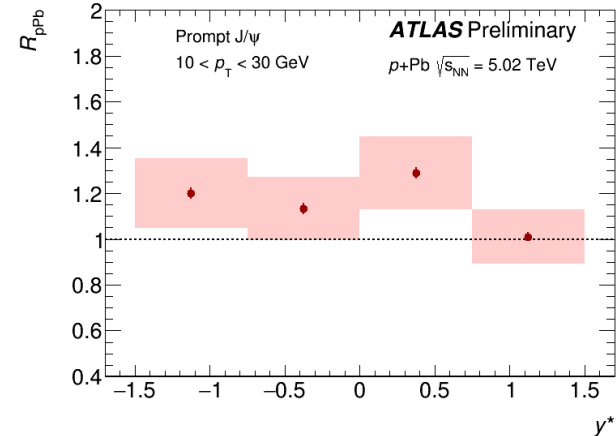
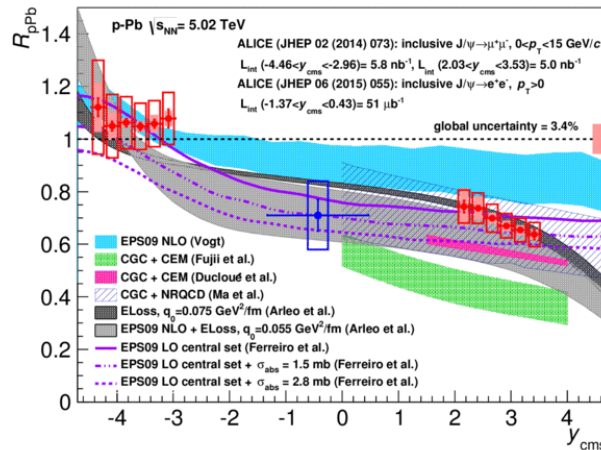
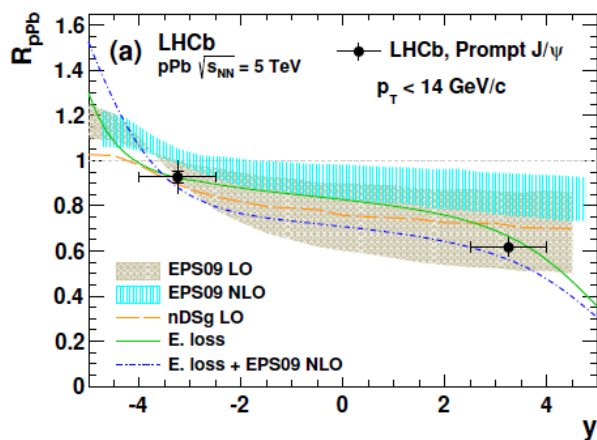
ALICE, JHEP 1506 (2015) 055

ATLAS-CONF-2015-023

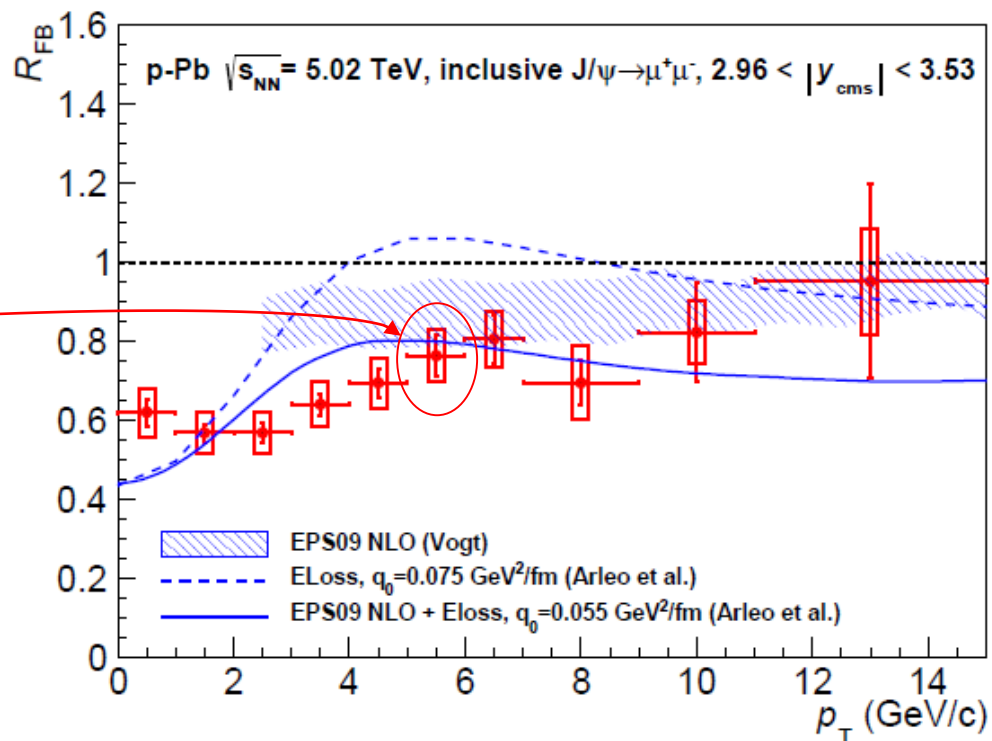
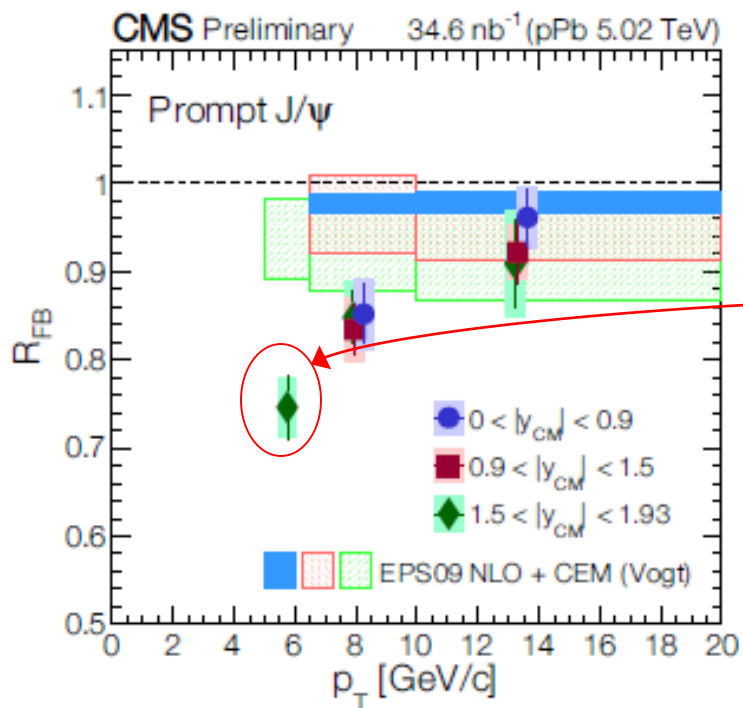


□ R<sub>pPb</sub> vs y → fair **agreement** ALICE vs LHCb, ATLAS refers to p<sub>T</sub>>10 GeV/c

LHCb, JHEP 02 (2014) 72, ALICE, JHEP 02 (2014) 73



# $R_{FB}$ from CMS



- ❑ Comparing  $R_{FB}$  from ALICE and CMS
- ❑ Good compatibility at forward y (slightly more forward for ALICE)
- ❑ Check shadowing (y-effect or different calculation?)
- ❑  $R_{FB}$  pros/cons: reduced uncertainties vs less sensitivity to models

# CNM effects: from p-Pb to Pb-Pb

- x-values in Pb-Pb  $\sqrt{s_{NN}}=2.76$  TeV,  $2.5 < y_{cms} < 4$  {  $2 \cdot 10^{-5} < x < 9 \cdot 10^{-5}$   
 $1 \cdot 10^{-2} < x < 6 \cdot 10^{-2}$
- x-values in p-Pb  $\sqrt{s_{NN}}=5.02$  TeV,  $2.03 < y_{cms} < 3.53 \rightarrow 2 \cdot 10^{-5} < x < 8 \cdot 10^{-5}$
- x-values in p-Pb  $\sqrt{s_{NN}}=5.02$  TeV,  $-4.46 < y_{cms} < -2.96 \rightarrow 1 \cdot 10^{-2} < x < 5 \cdot 10^{-2}$

→ Partial **compensation** between  $\sqrt{s_{NN}}$  shift and y-shift

- If CNM effects are dominated by shadowing

$$\square R_{PbPb}^{CNM} = R_{pPb} \times R_{Pbp} = 0.75 \pm 0.10 \pm 0.12$$

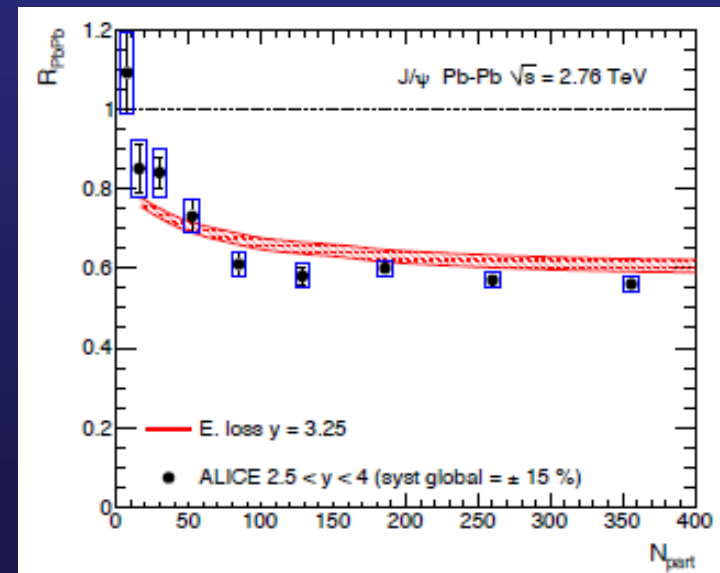
$$\square R_{PbPb}^{meas} = 0.57 \pm 0.01 \pm 0.09$$

} “compatible”  
within  $1-\sigma$

- Same kind of “agreement” in the energy loss approach (Arleo)

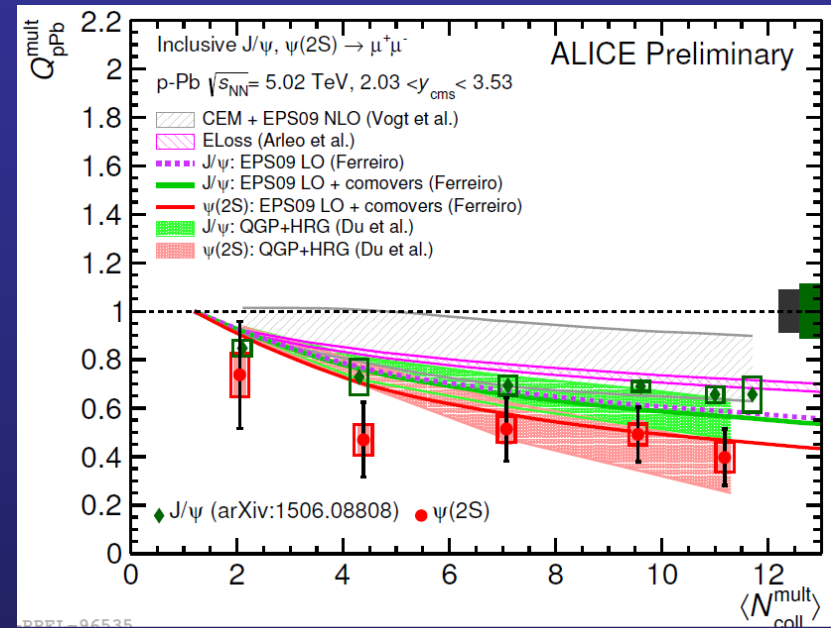
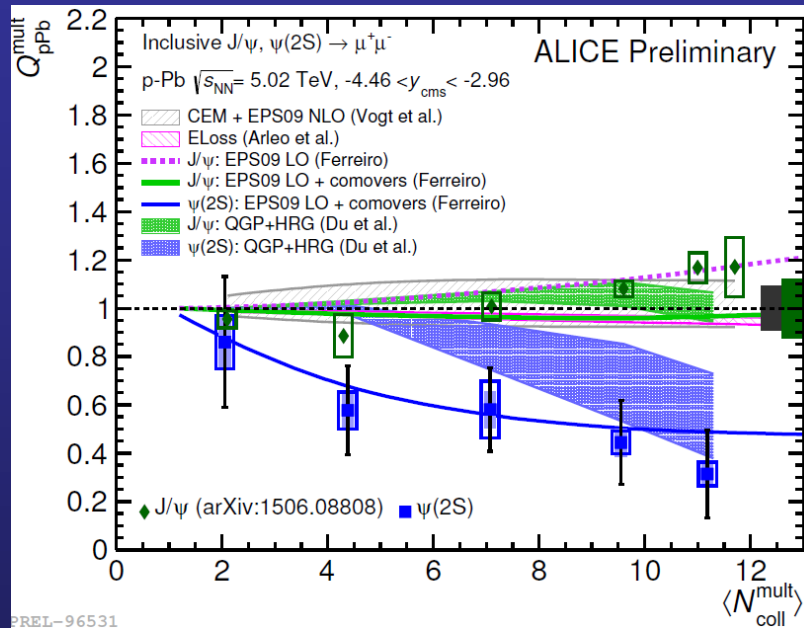
...which does not exclude **hot matter effects** which partly compensate each other

F. Arleo and S. Peigne, arXiv:1407.5054



# Cold nuclear matter: the $\psi(2S)$

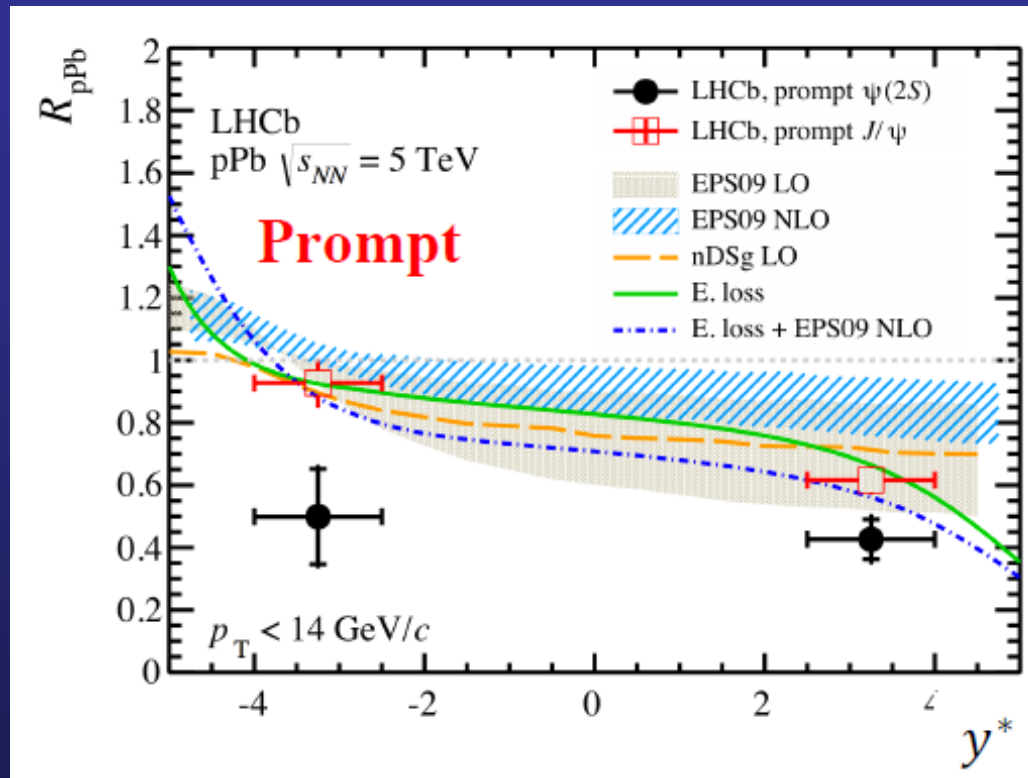
- ❑ In principle should be affected by CNM in the same way as the  $J/\psi$
- ❑ Formation times should prevent any “nuclear absorption”
- ❑ Shadowing/energy loss cancel, at least at first order



- ❑ Results show a (much) **stronger  $\psi(2S)$  suppression**
- ❑ Not a “real” surprise, already seen by PHENIX even if with large uncertainties
- ❑ Very **strong rapidity dependence**, compatible with an effect related with the hadronic activity (not so strange, seen the weak binding)

# Cold nuclear matter: the $\psi(2S)$

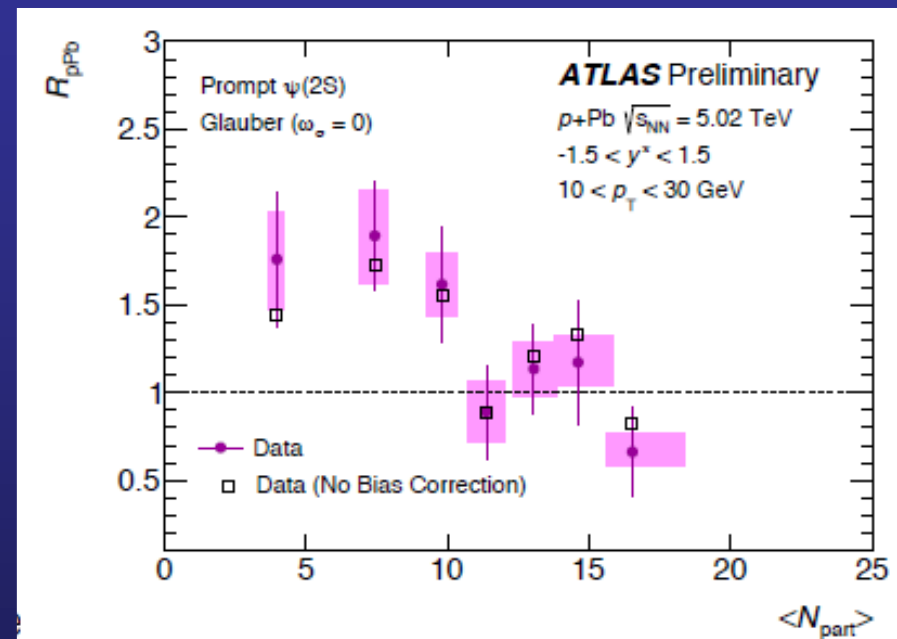
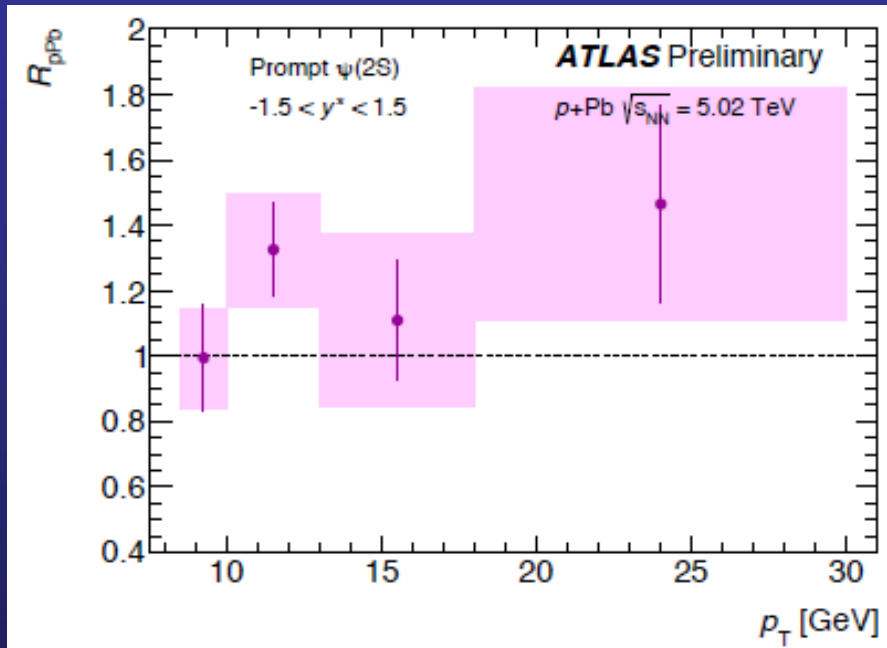
- In principle should be affected by CNM in the same way as the  $J/\psi$
- Formation times should prevent any “nuclear absorption”
- Shadowing/energy loss cancel, at least at first order



Nicely confirmed by LHCb!

# ATLAS on $\psi(2S)$ in p-Pb

- High  $p_T$ , rather large uncertainties
- Hints for **strong enhancement**, concentrated in **peripheral events**



ATLAS-CONF-2015-023

- Possible tension with ALICE results (sees  $R_{pPb} < 1$  at forward- $y$  up to  $p_T = 8 \text{ GeV}/c$ ), even if it is difficult to conclude
- Issues with the centrality assignment ?

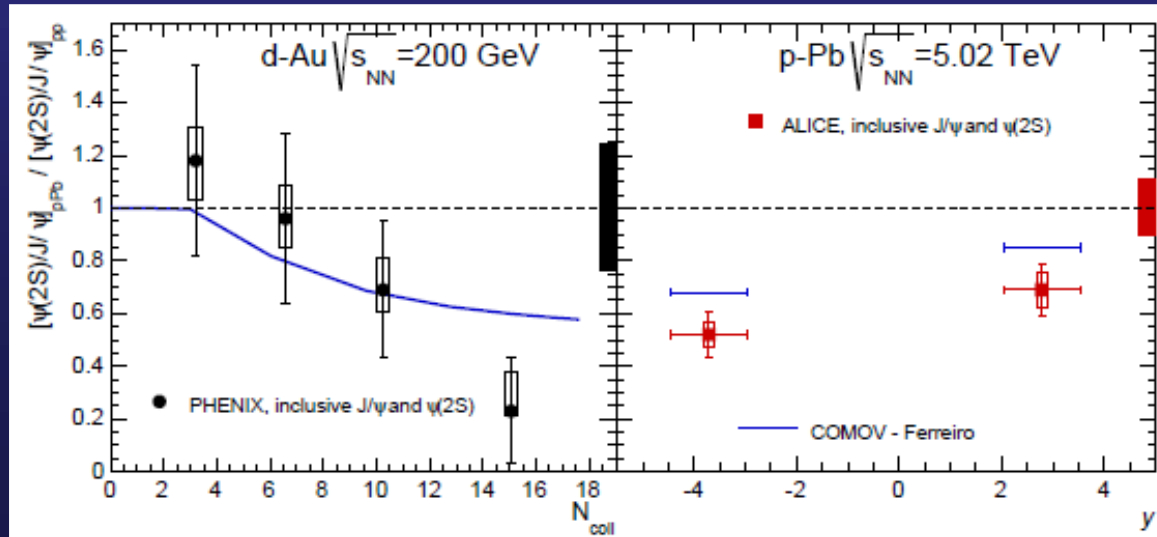
# The comovers are back again

- ❑ A subject of “epic” battles in the ‘90s (comovers vs QGP!)
- ❑ Entered a “dormant” state in RHIC years, now re-proposed for the  $\Upsilon$
- ❑ Old survival probability formula

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

which gave fair results at SPS with  $\sigma^{co-J/\psi} = 0.65$  mb and  $\sigma^{co-\psi(2S)} = 6$  mb

- ❑ Also does well at RHIC and LHC (2S/1S ratio), same parameters (?!)



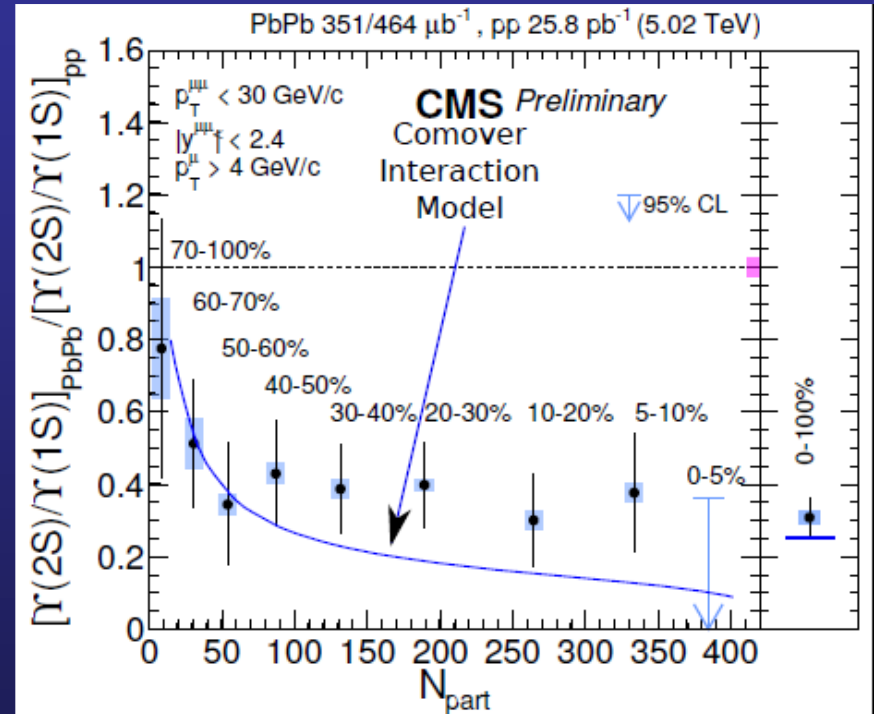
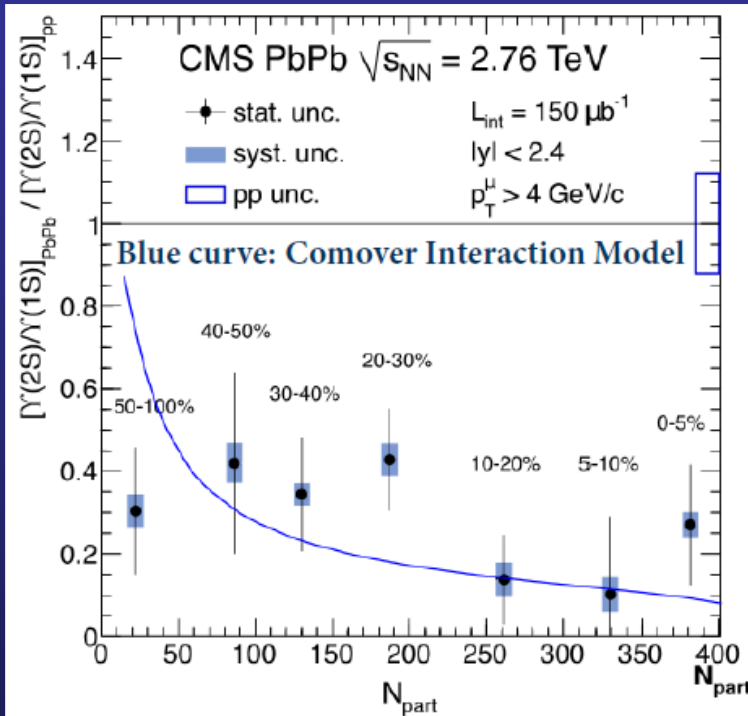
p-Pb only!

# The comovers are back again

- Refining the comover cross section (and fixing parameters on CMS double ratios for pPb)



$$\sigma^{co-Q_{bb}} = \sigma_{\text{geom}} \left( 1 - \frac{E_{\text{Binding}}}{\langle E_{co} \rangle} \right)^n$$



- (Surprisingly), a qualitative agreement is found
- Is the physics of bottomonia simply “driven” by  $dN_{ch}/d\eta$  ??