ÉCOLE DE PHYSIQUE
LES HOUCHES

Charmonium production from SPS to LHC

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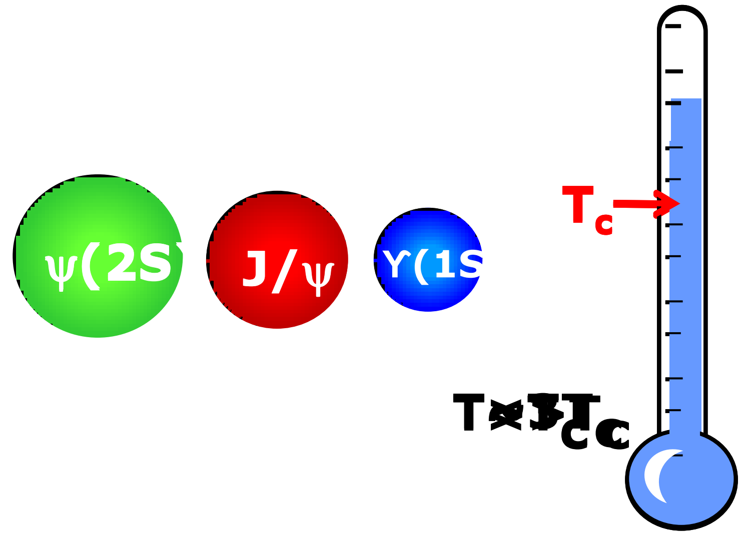
Probing the strong interaction at A Fixed Target ExpeRiment with LHC beams

Les Houches, 12-17 January 2014

From suppression…to (re)combination

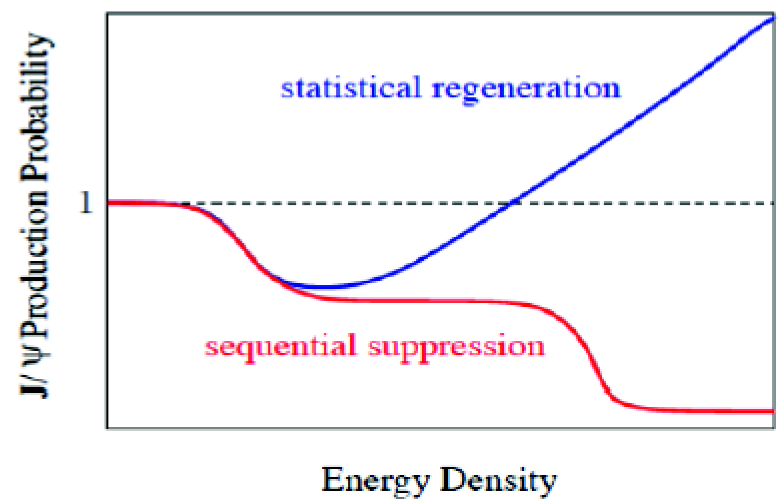
- Differences in the binding energies of the quarkonium states lead to a sequential melting of the states with increasing temperature
  (Digal,Petrecki,Satz PRD 64(2001) 0940150)

  → thermometer of the initial QGP temperature



- Increasing the energy of the collision the $c\bar{c}$ pair multiplicity increases

In most central AA collisions	SPS 20 GeV	RHIC 200GeV	LHC 2.76TeV
N_{ccbar}/event	~0.2	~10	~75



An enhancement via (re)combination of cc pairs producing quarkonia can take place at hadronization or during QGP stage

P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196, R. Thews et al, Phys.ReV.C63:054905(2001)

How can we measure medium effects?

Nuclear modification factor R_{AA}:

compare quarkonium yield in AA with the pp one, scaled by a geometrical factor (from Glauber model)

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle \sigma_{pp}^{J/\psi}}$$

- If yield scales with the number of binary collisions
  → $R_{AA} = 1$

- If there are medium effects
  → $R_{AA} \neq 1$

Cold Nuclear Matter effects (CNM):
- Nuclear parton shadowing
- Parton energy loss
- $c\bar{c}$ in medium dissociation

Hot Medium effects:
- quarkonium suppression
- enhancement due to recombination

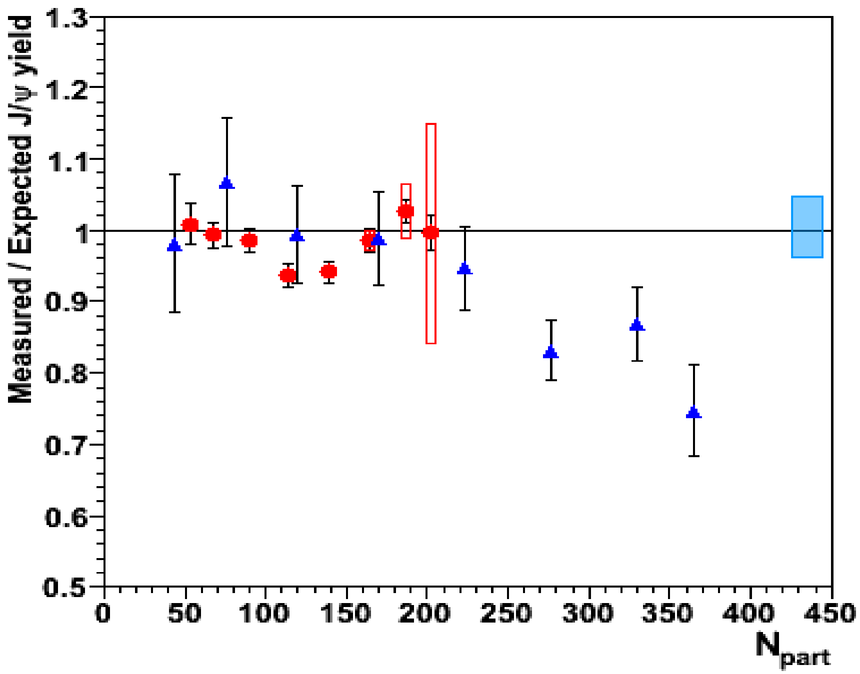
- knowledge of CNM effects fundamental to disentangle genuine QGP induced suppression in AA

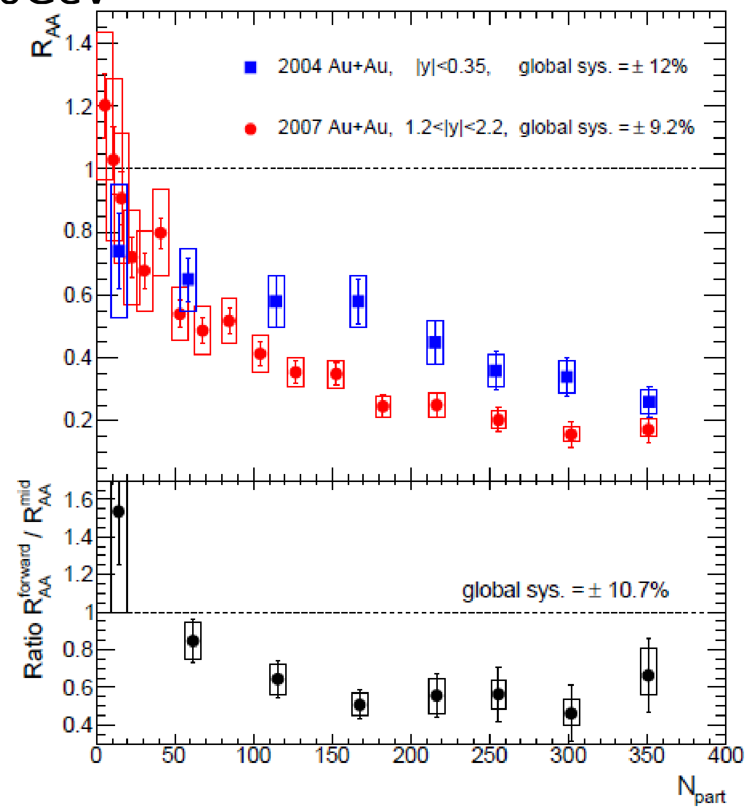
  → need infos on quarkonium production in pA (dA) collisions!

"Low energy" experiments…

Charmonium production deeply investigated at

- SPS (NA50, NA60) $\sqrt{s_{NN}}$ = 17 GeV
- RHIC (PHENIX,STAR) $\sqrt{s_{NN}}$ =39,62.4,200GeV





SPS: first evidence of anomalous suppression (i.e., beyond CNM expectations) in Pb-Pb at $\sqrt{s}$= 17 GeV

RHIC: suppression, strongly y-dependent, in Au-Au at $\sqrt{s}$= 200 GeV

"Low energy" experiments…

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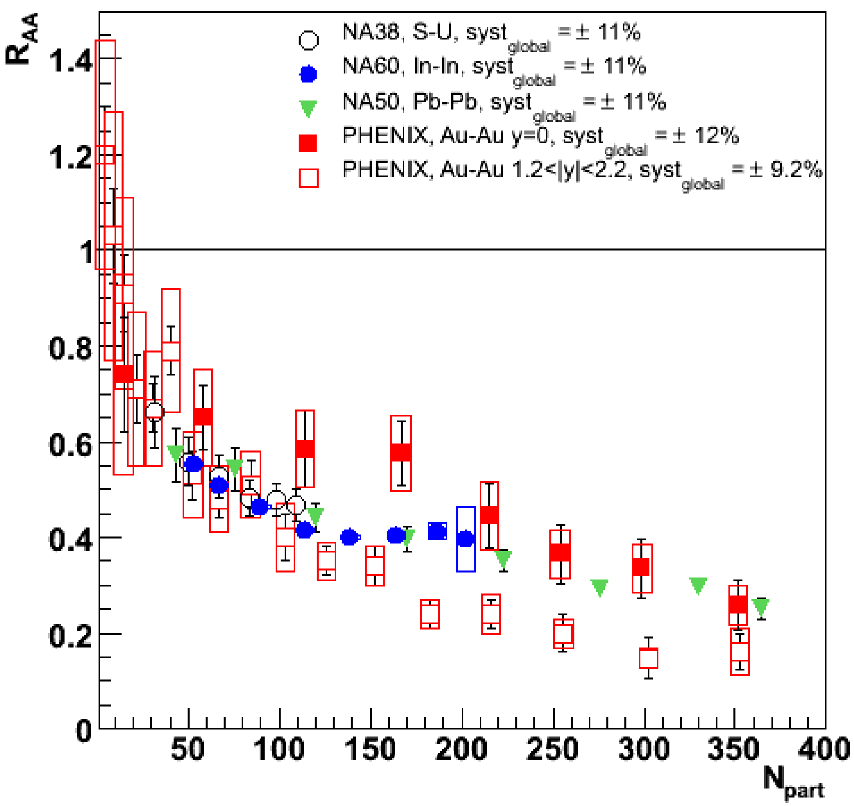


Eur.Phys.J.C71:1534,2011

Puzzles from SPS and RHIC

- RHIC: stronger suppression at forward rapidities
- SPS vs. RHIC: similar R_{AA} pattern versus centrality

Hint for (re)combination at RHIC?

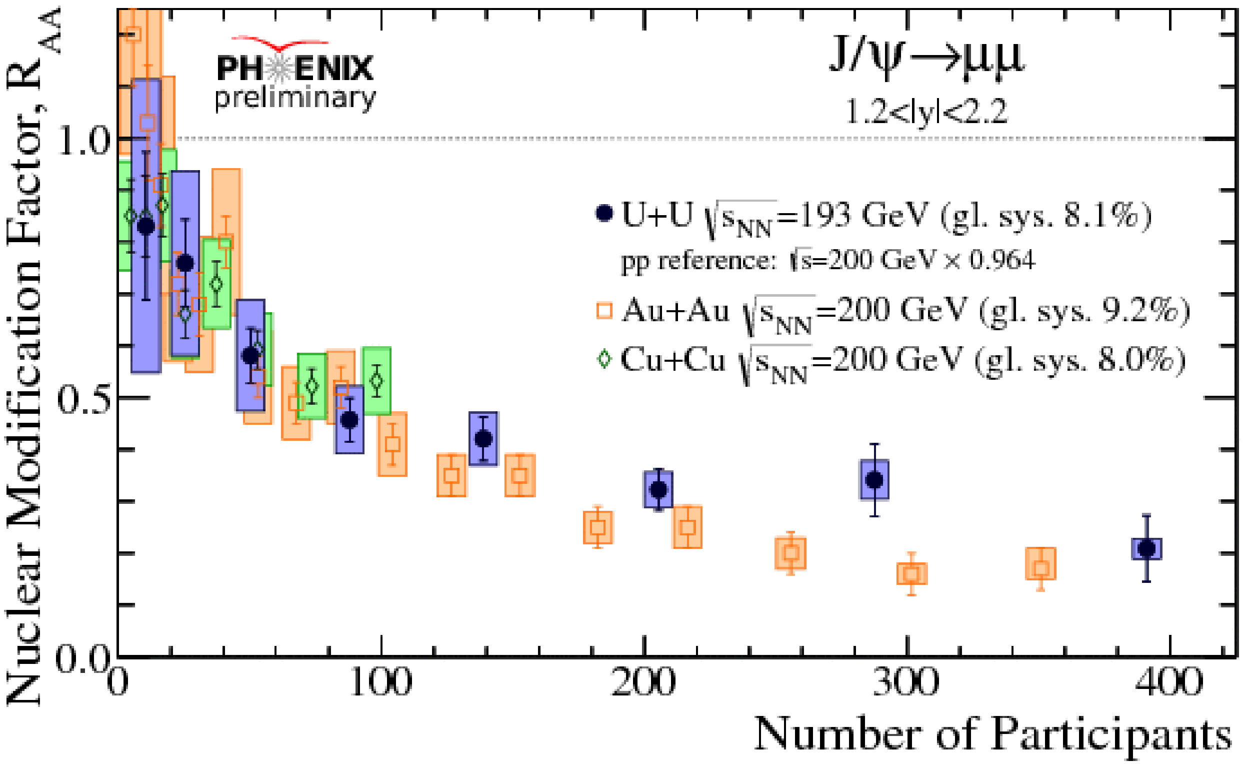
No final theoretical explanation

Decisive inputs expected from LHC results, having access to:

- higher energy
- larger cc multiplicity
- other quarkonium states (bottomonium)

RHIC: results from different AA systems

RHIC: quarkonium measurements done over a wide range of energies and collision species



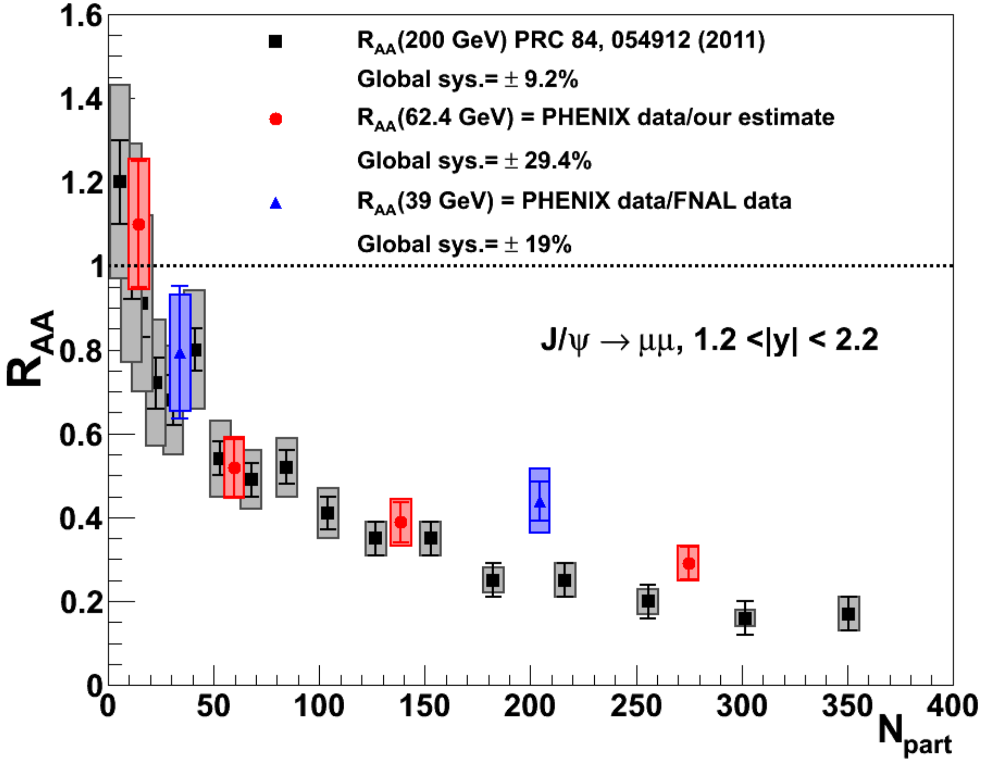
Au+Au
Cu+Cu
U+U

Similar suppression across the different ion-ion collisions

RHIC: results from different collision energy

- J/ψ R_{AuAu} has been studied as a function of the collision energy, at $\sqrt{s_{NN}}$ = 200, 62 and 39 GeV

Phys. Rev C 86 064901 (2012)



- Rather similar pattern observed in Au-Au at different energies

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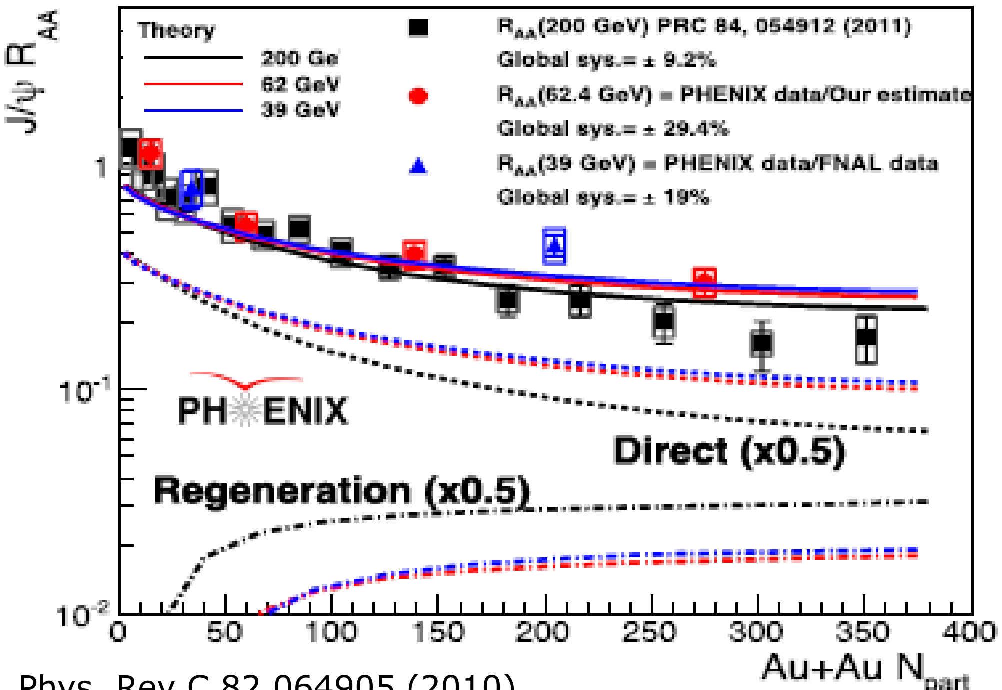


Phys. Rev C 82 064905 (2010)

- Rather similar pattern observed in Au-Au at different energies

- Data can provide constraints for theoretical models

Similarity of R_{AA} at different $\sqrt{s_{NN}}$ may originate from interplay of suppression and regeneration contributions (direct suppression changes by ~50%)

- pp and pA data at the same energies are needed for more quantitative conclusions

LHC experiments

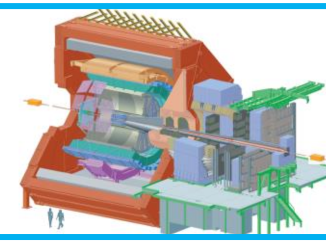
Currently available AA and pA results:

ALICE

J/ψ, $\psi(2S)$, $\Upsilon \rightarrow \mu^+\mu^-$ $2.5<y<4$

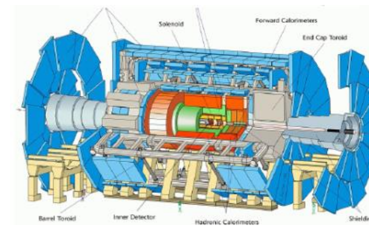
$J/\psi \rightarrow e^+e^-$ $|y|<0.9$

p_T coverage down to $p_T \sim 0$



ATLAS

$J/\psi \rightarrow \mu^+\mu^-$ $|y|<2.4$ p_T $J/\psi > 6.5$ GeV/c

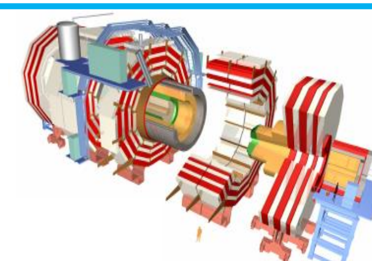


CMS

J/ψ, $\psi(2S) \rightarrow \mu^+\mu^-$ $|y|<2.4$ $p_T > 6.5$ GeV/c

$\Upsilon \rightarrow \mu^+\mu^-$ $|y|<2.4$ $p_T > 0$

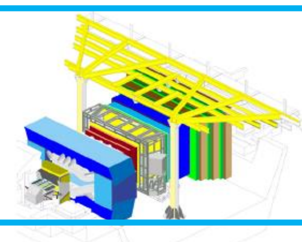
(J/ψ p_T coverage depends on y)



LHCb

$J/\psi \rightarrow \mu^+\mu^-$ $2<y<4.5$ p_T coverage down to $p_T \sim 0$

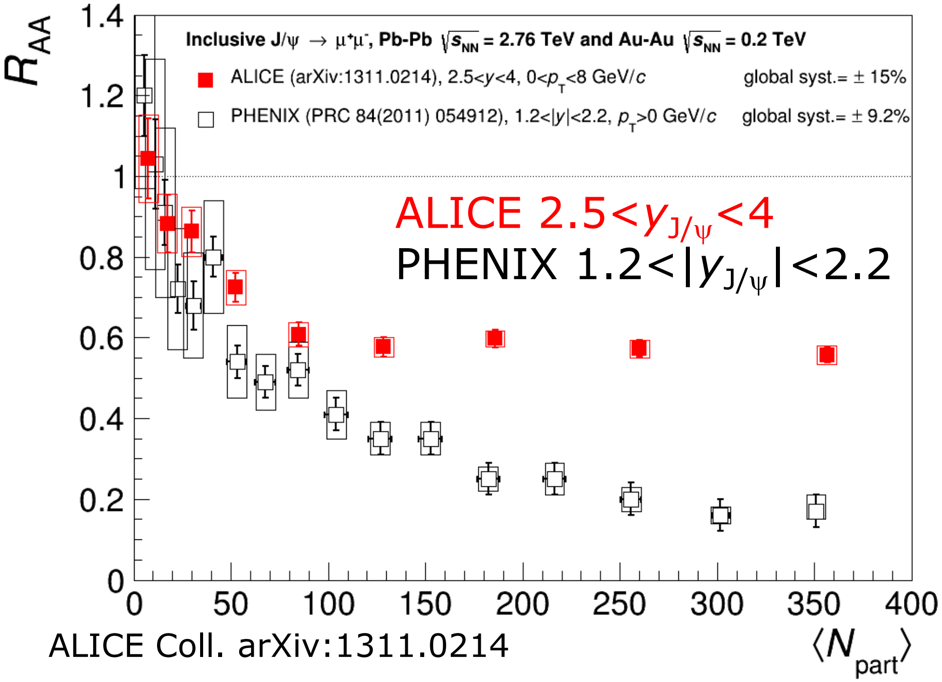
(no heavy ion physics program)



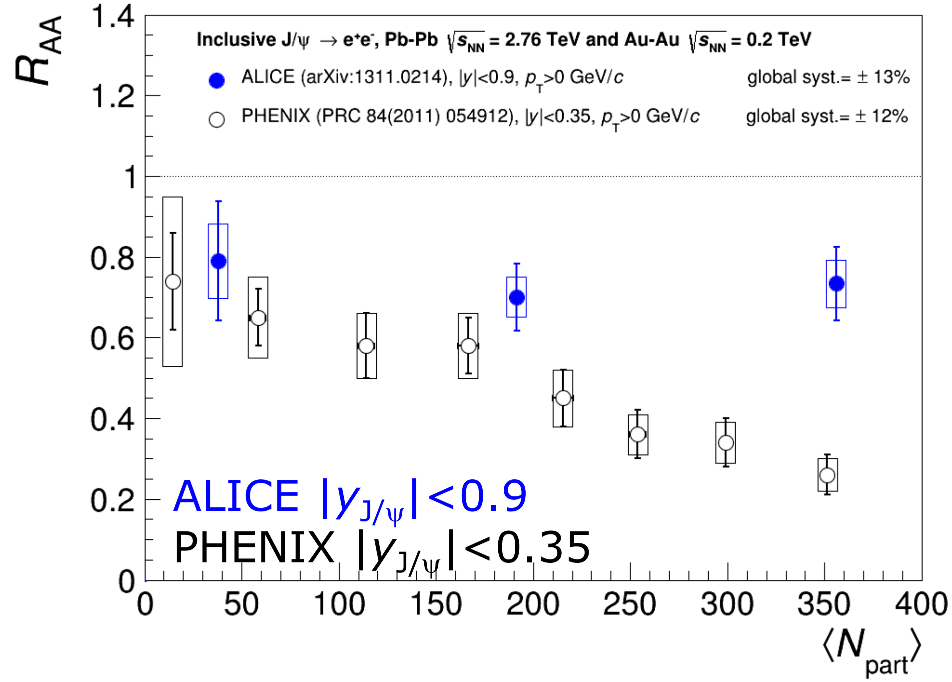
Complementary quarkonium results from LHC experiments

ALICE: low p_T J/ψ

How does RHIC suppression compare to LHC results?



ALICE Coll. arXiv:1311.0214



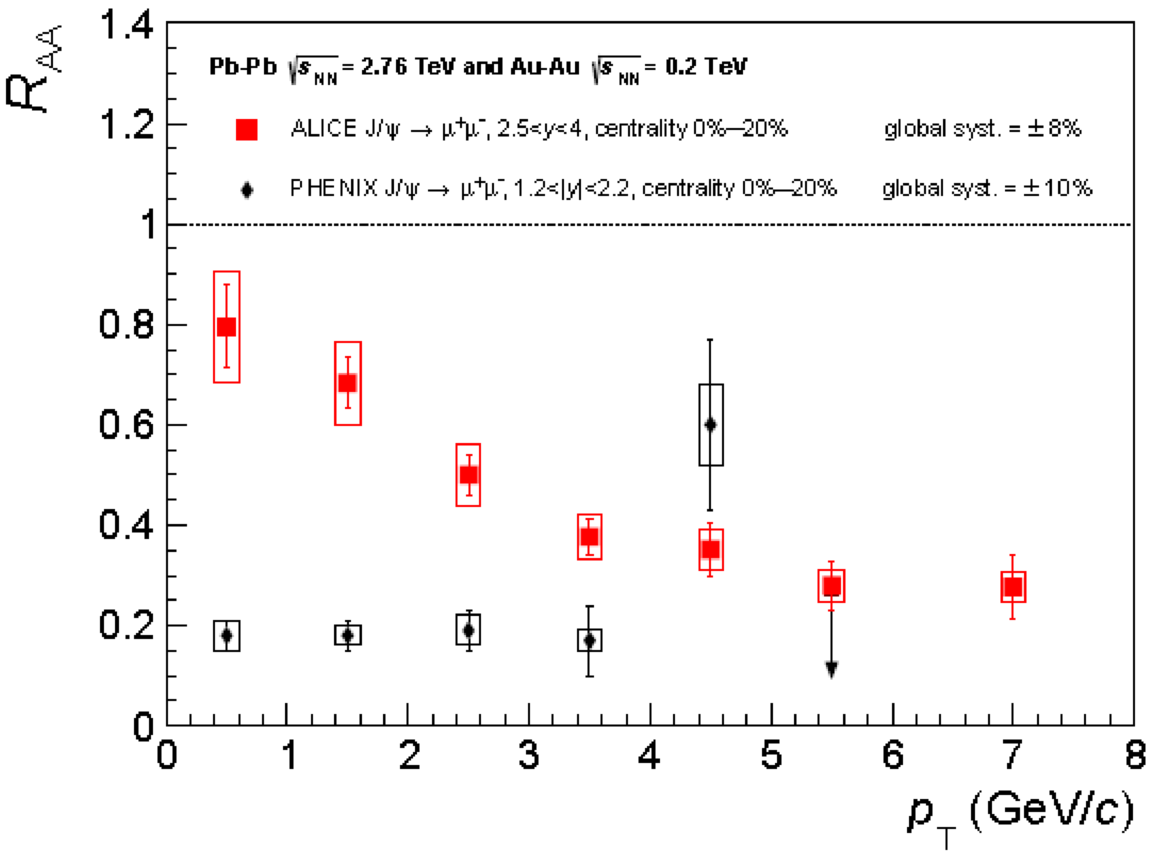
- Clear J/ψ suppression with almost no centrality dependence above N_{part}~100
- Less J/ψ suppression at mid-rapidity wrt forward y for central events

- Comparison with PHENIX: ALICE results show weaker centrality dependence and smaller suppression for central events

Is this the expected signature for (re)combination ?

ALICE R_{AA} vs p_T

J/ψ production via (re)combination should be more important at low transverse momentum → p_T region accessible by ALICE



- Different suppression for low and high p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ

→ Striking difference between the PHENIX and ALICE patterns, in particular at low p_T

ALICE R_{AA} vs p_T

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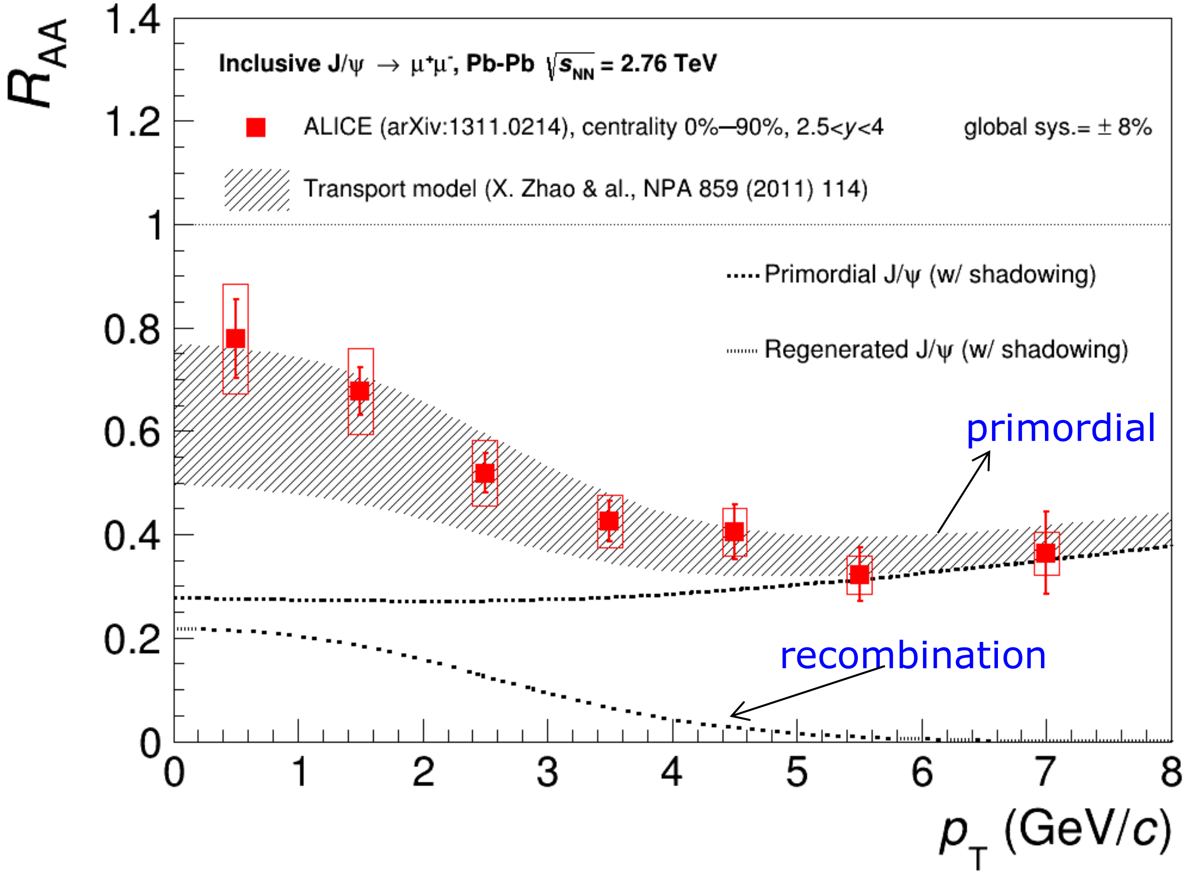
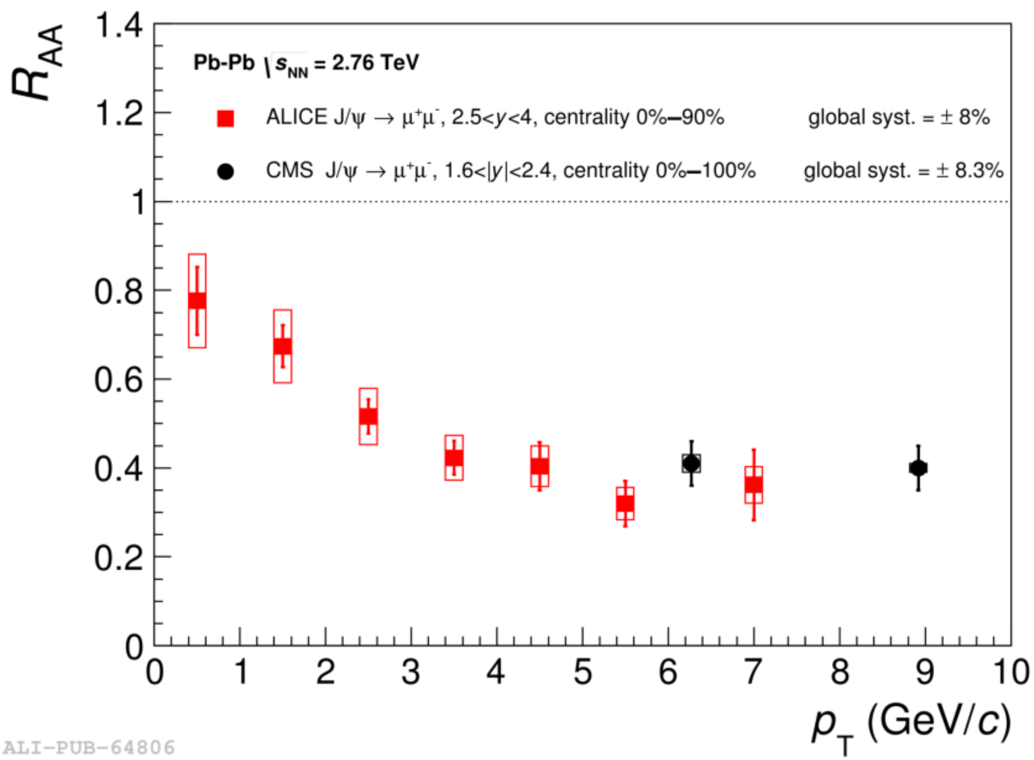


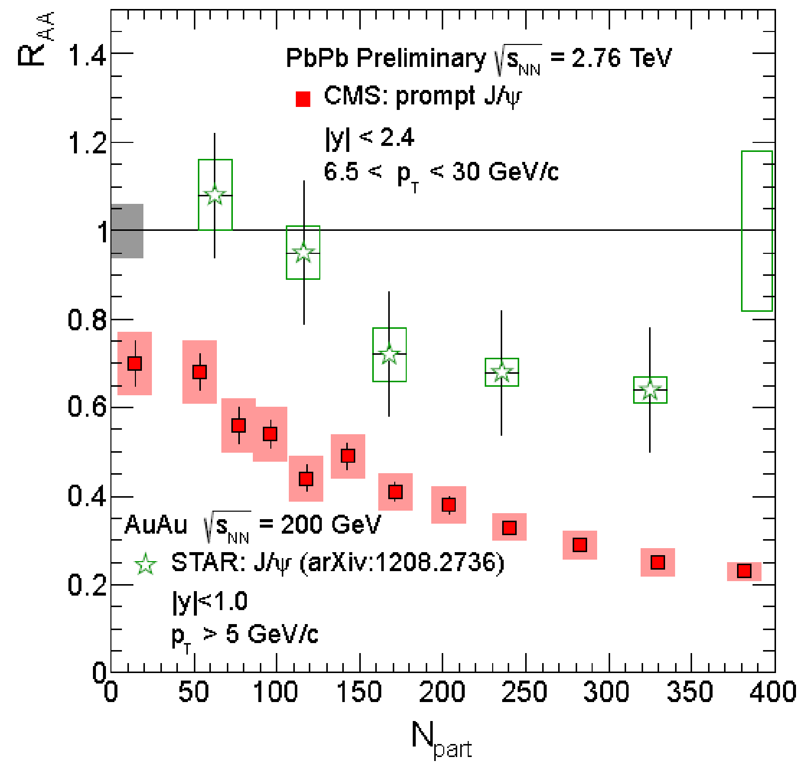
- Different suppression for low and high p_T J/ψ
- Smaller R_{AA} for high p_T J/ψ

- Models: ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible

CMS: high p_T J/ψ

➡ The high p_T region can be investigated by CMS!



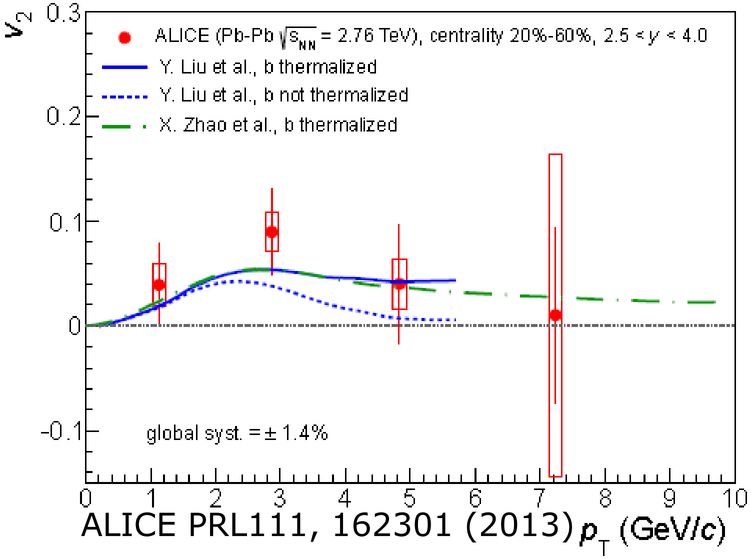


➡ Good agreement with ALICE (at high p_T) in spite of the different rapidity range

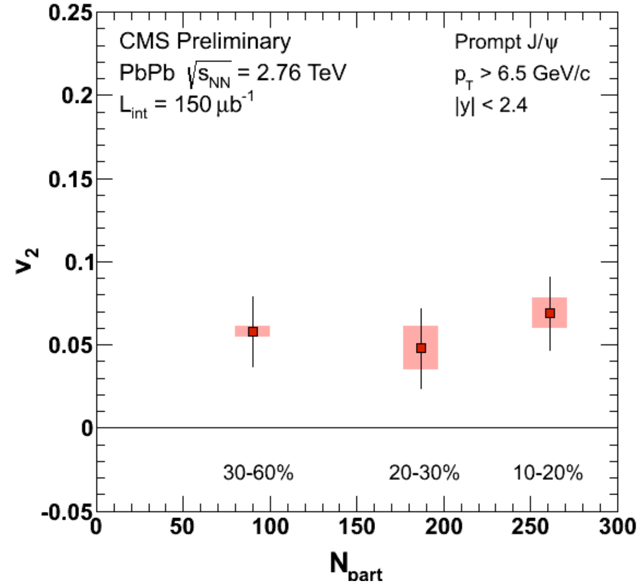
➡ High p_T: stronger J/ψ suppression at LHC wrt to RHIC (re-combination should not play a role)

J/ψ flow

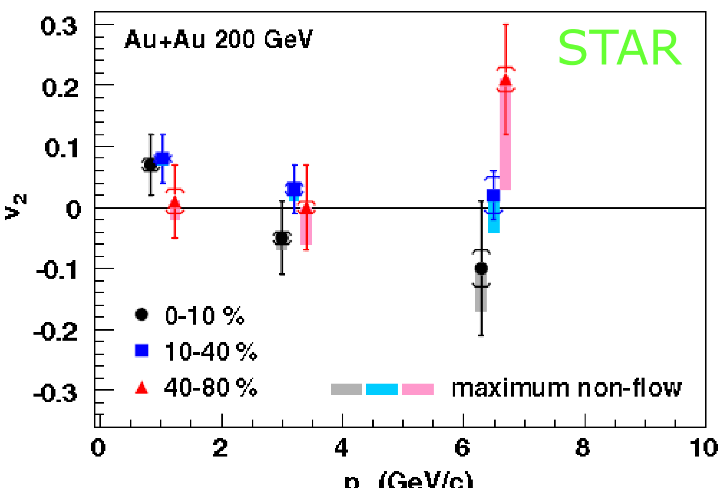
- The contribution of J/ψ from (re)combination should lead to a significant elliptic flow signal at LHC energy



ALICE PRL111, 162301 (2013)



D.Moon, HP2013



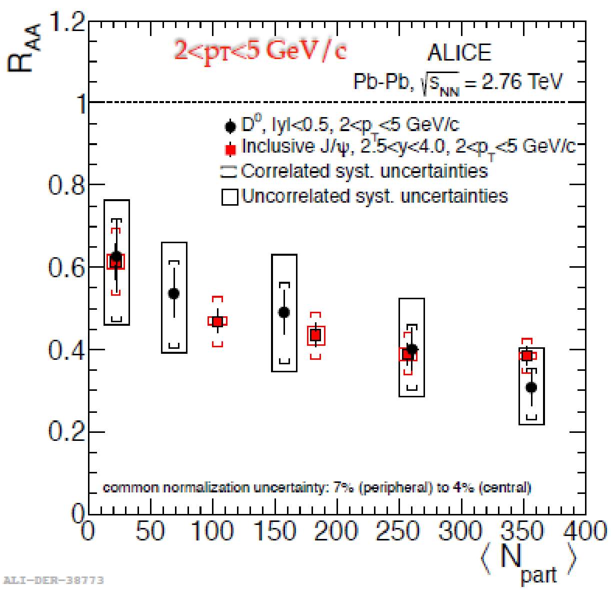
STAR, PRL 052301(2013)

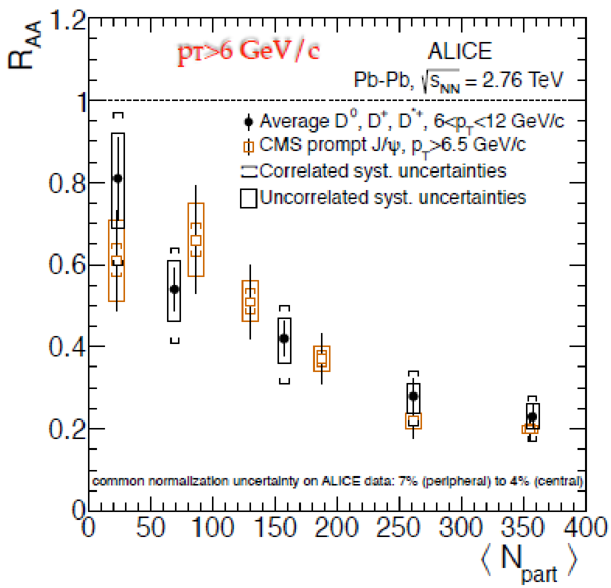
> Hint for J/ψ flow in heavy-ion collisions (LHC), contrary to v_2~0 observed at RHIC!

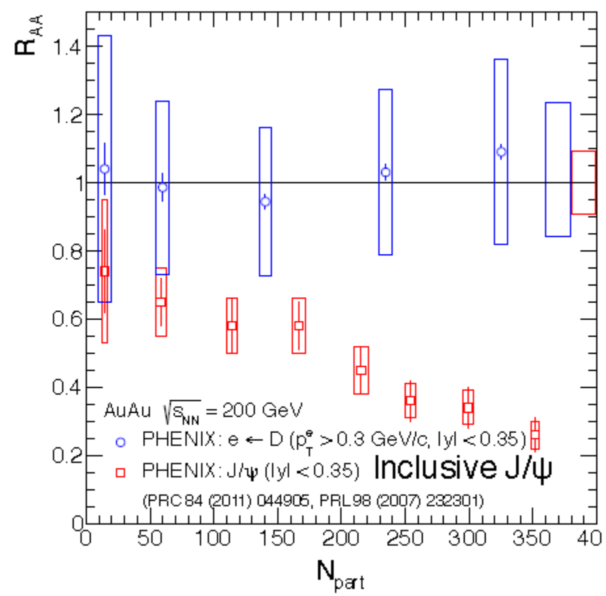
- ALICE: qualitative agreement with transport models including regeneration
- CMS: path-length dependence of energy loss?

J/ψ vs D in AA collisions

- Open charm should be a very good reference to study J/ψ suppression (a` la Satz)







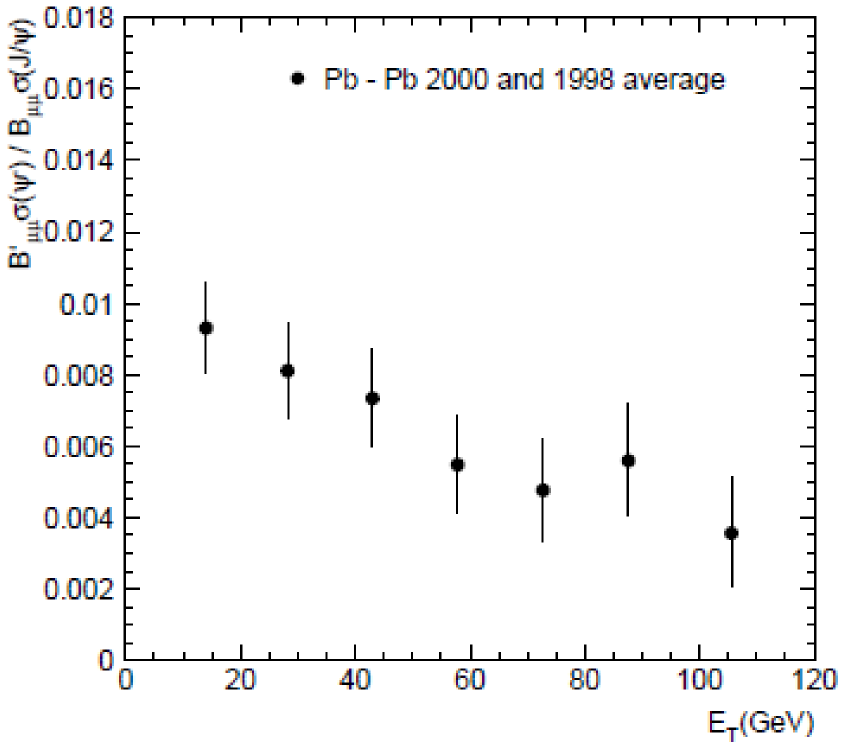
- **Interesting comparison between ALICE and CMS J/ψ compared to D**

Caveat:
complicate to compare J/ψ and D R_{AA} at LHC because of restricted kinematic regions.
Low p_T D not accessible for the moment

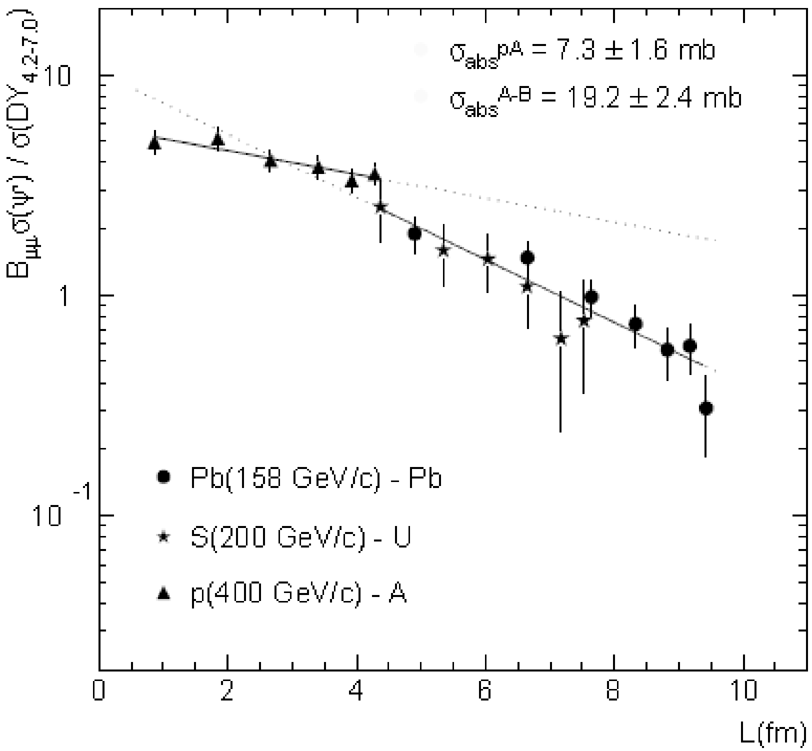
- Different trend observed at low p_T at RHIC.
At high p_T trend is similar to the LHC one

ψ(2S) in AA at lower energy exp.

- Study of other charmonium states can help constraining theoretical models
  - ψ(2S) much less bound than J/ψ



B. Alessandro et al.(NA50),EPJC49 (2007) 559

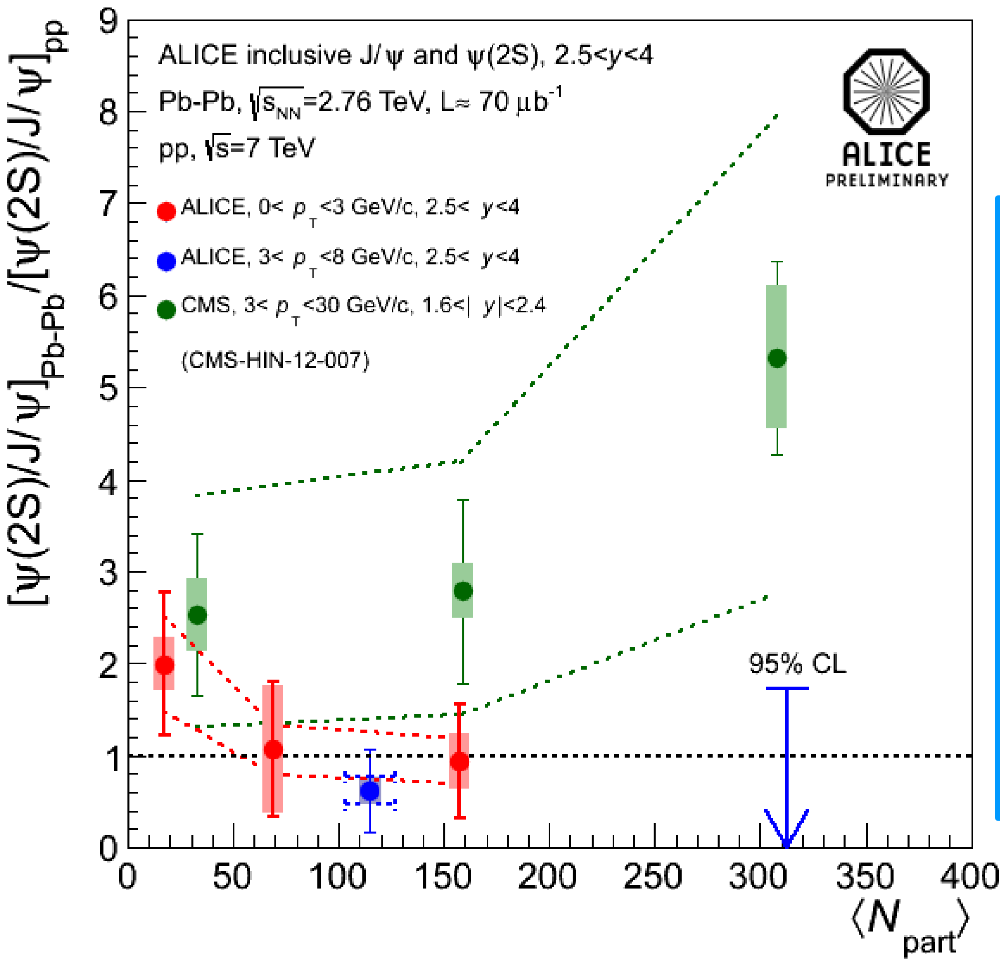


- At SPS, ψ(2S) is more suppressed than J/ψ and the suppression increases with centrality

- Stronger suppression already for peripheral events (compared to J/ψ, where the anomalous suppression sets in at higher L)

ψ(2S) in Pb-Pb at LHC

- ψ(2S) studied by both CMS and ALICE (different kinematics) comparing the ψ(2S) yield to the J/ψ one in Pb-Pb and in pp



- Difference trend in ALICE and CMS:

  Strong centrality enhancement excluded in ALICE data

  large statistics and systematic errors prevent a firm conclusion on the ψ(2S) enhancement or suppression versus centrality

Nucl.Phys.A 19 (2013), pp. 595-598
CMS PAS HIN-12-007

Where are we?

➡ 28 years after first suppression prediction, this is observed in the charmonium (and bottomonium) sector with very good accuracy!

➡ Two main mechanisms at play:

1. Suppression in a deconfined medium
2. Re-combination (for charmonium) at high $\sqrt{s}$

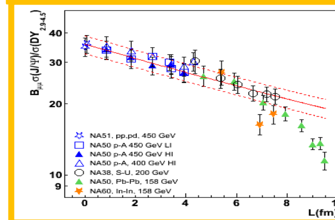
can qualitatively explain the main features of the results

➡ To move towards a more quantitative understanding, a precise knowledge of cold nuclear matter effects is crucial!

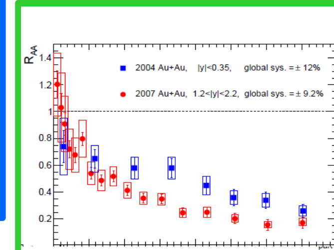
➡ pA/dA results, where no hot medium should be formed, are needed to:

1. investigate initial/final state CNM effects on J/ψ: shadowing, energy loss, parton saturation effects, cc break-up in the medium…
2. build a reference for AA collisions

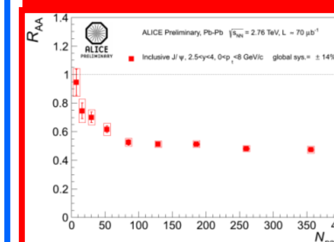
SPS



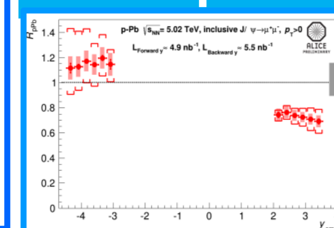
RHIC dA, AA



LHC AA



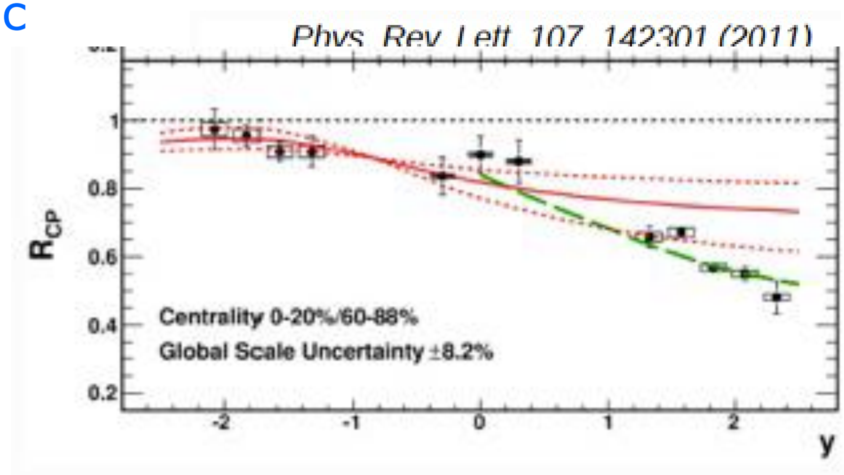
LHC pA

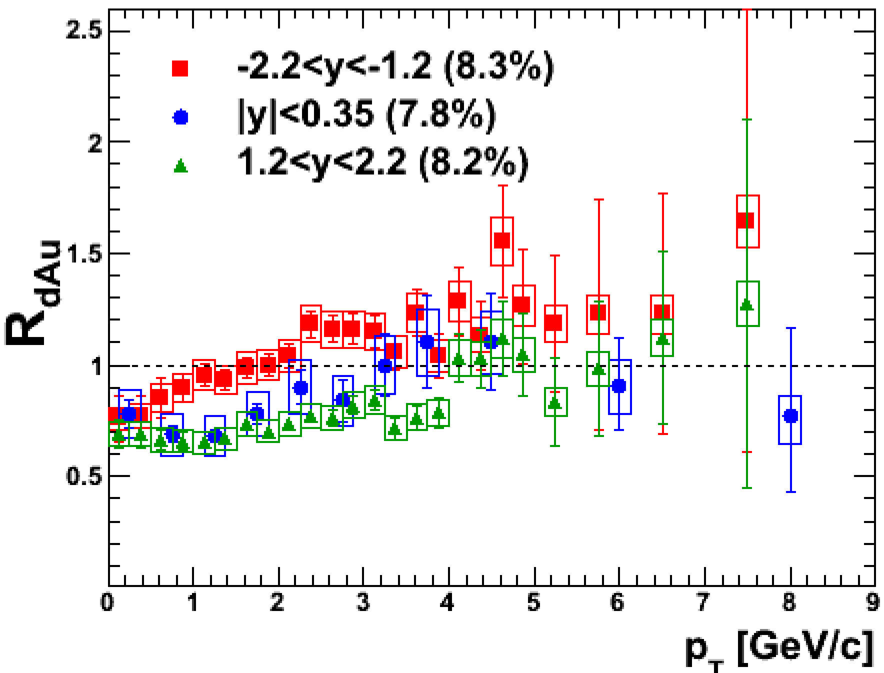


J/ψ production in d-Au

- CNM effects studied in a large kinematic range
  → different mechanisms playing a role

Strong centrality dependence, not expected from EPS09 with linear dependence on nuclear thickness +break-up σ





Phys. Rev. C 87 034904 (2013)

J /ψ R_{dAu} vs p_T:
shape is similar at forward and mid-*y*
→ shadowing+Cronin+break-up contributions might explain the pattern

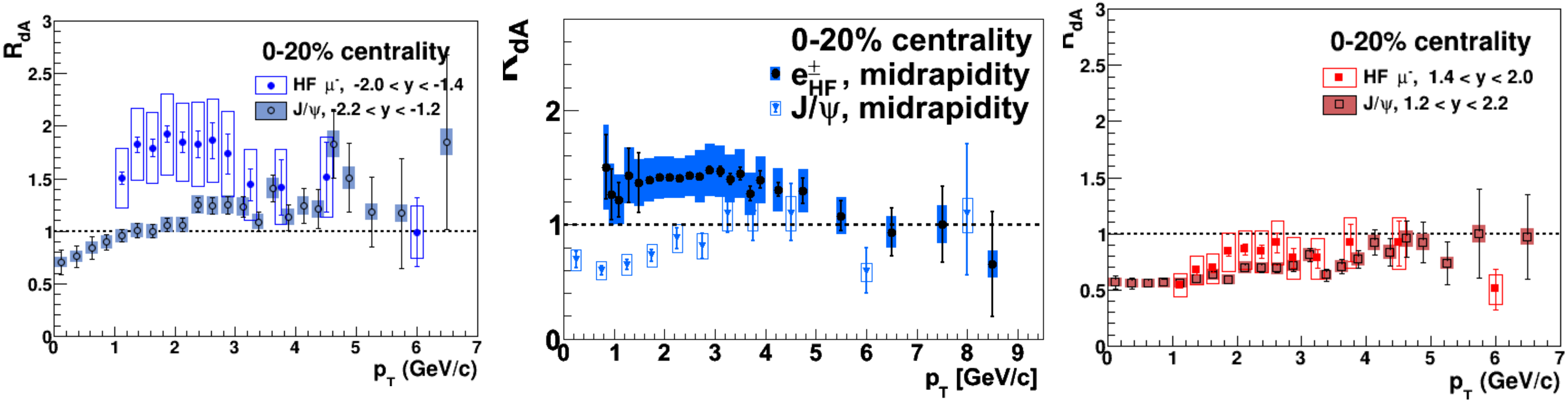
different shape at backward *y*
→ not easy to be explained by models

- No models describes simultaneously *y*, p_T and centrality dependence

J/ψ and HF in d-Au

- HF and quarkonia are sensitive to similar initial state effects, apart from charmonium in medium break-up
  - Can further constraints on charmonium break-up be inferred from the comparison to HF R_{AA} ?

PHENIX: arXiv:1310.1005

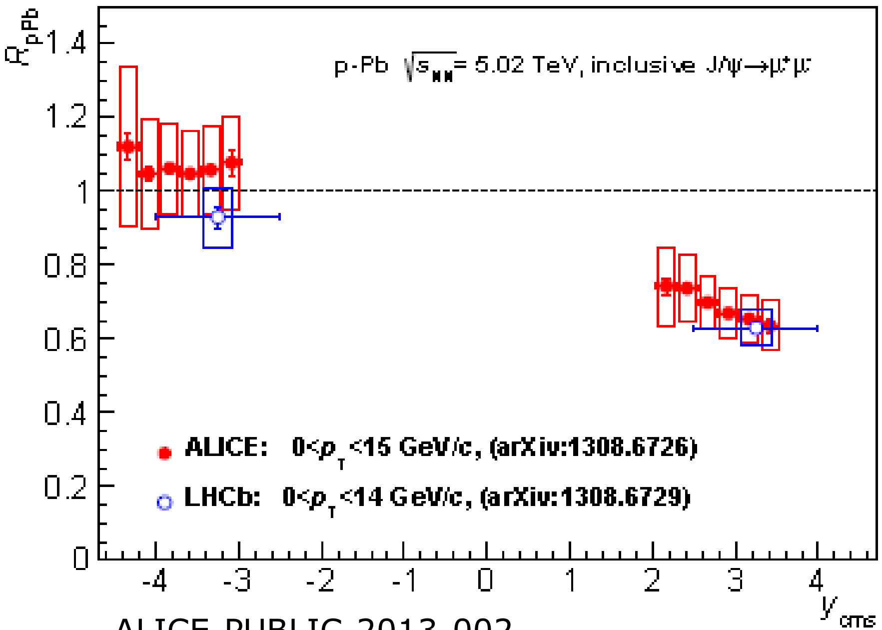


- Mid and backward rapidity: different pattern → enhanced HF versus suppressed J/ψ Additional J/ψ break-up due to longer cc medium crossing time?

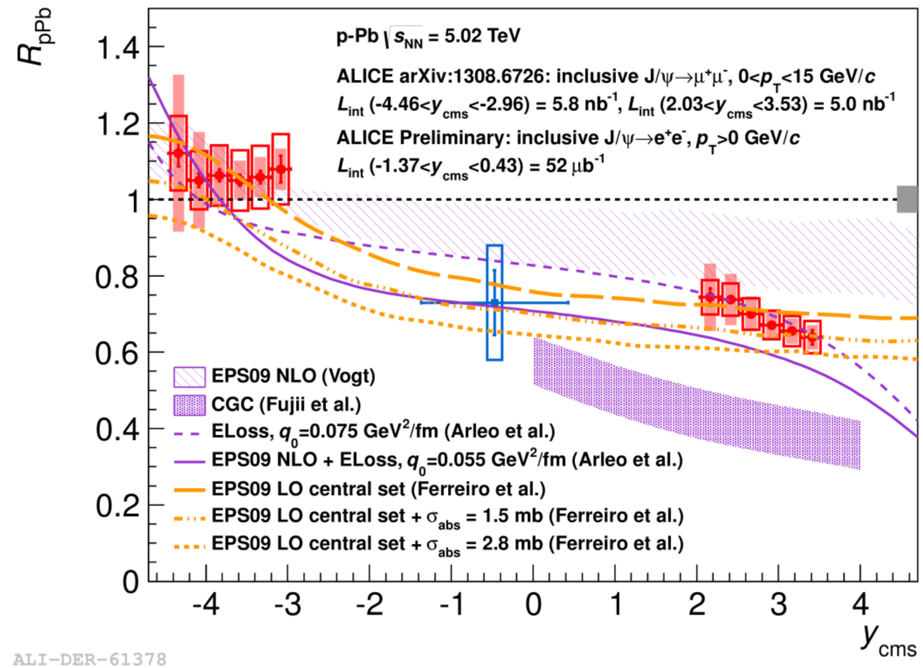
- Forward *y*: similar R_{AA} pattern for J/ψ and HF

Caveat: different kinematic

pA: J/ψ R_{pA} vs y



ALICE-PUBLIC-2013-002,
LHCb-CONF-2013-013



➡ R_{pA} decreases towards forward y

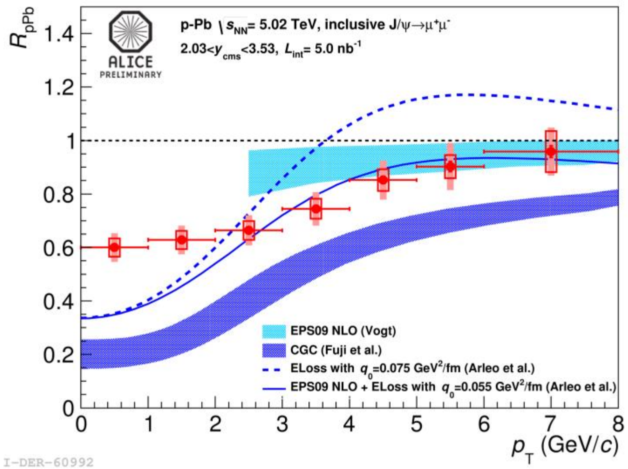
➡ Theoretical predictions: reasonable agreement with
- shadowing EPS09 NLO calculations (R. Vogt) or EPS09 LO (E. Ferreiro et al)
- models including coherent parton energy loss contribution (F. Arleo et al)

CGC description (H. Fujii et al) seems not to be favoured

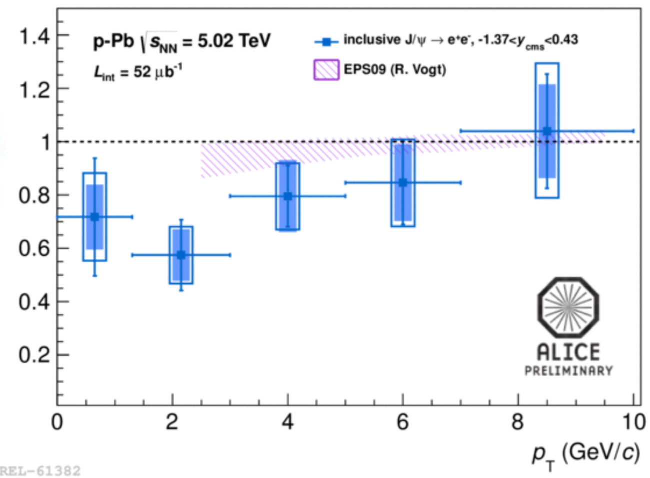
➡ Very good agreement between ALICE vs LHCb results

J/ψ nuclear modification factor R_{pA} vs p_T

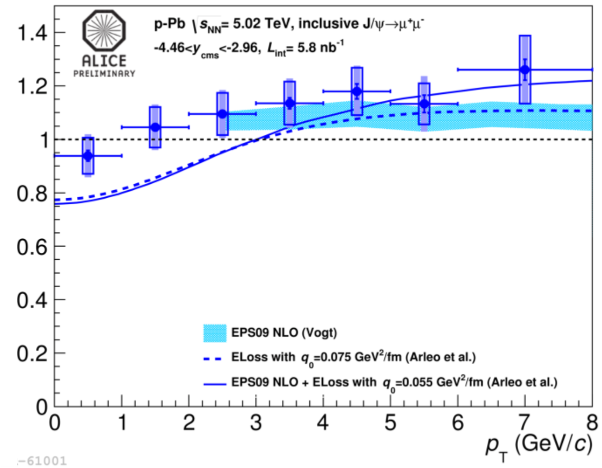
Forward rapidity



Mid-rapidity



Backward rapidity

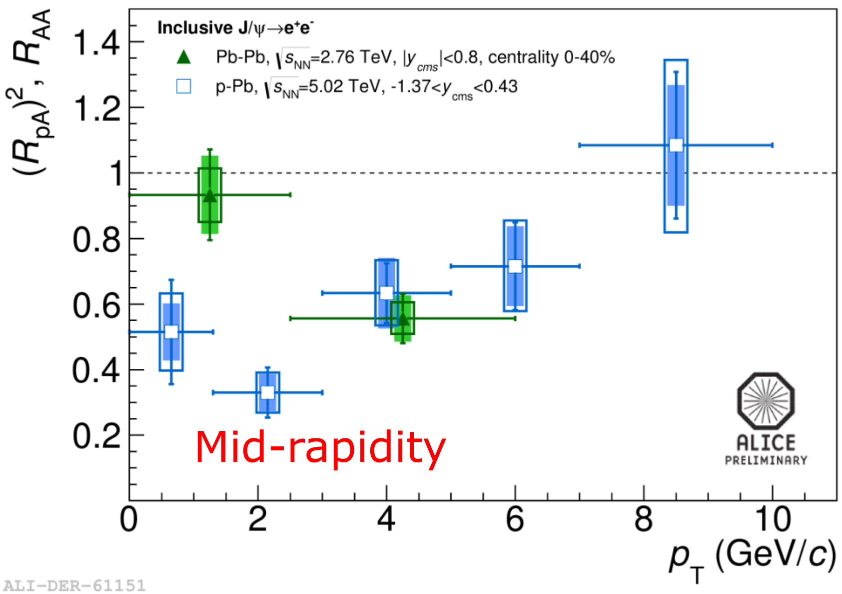


- Forward *y:* R_{pA} increases towards high p_T
- Mid-rapidity: R_{pA} tends to increase vs p_T
- Backward *y:* R_{pA} is rather flat and close to unity

- Theoretical predictions: reasonable agreement with
  - shadowing EPS09 NLO calculations (R. Vogt)
  - models including coherent parton energy loss contribution (F. Arleo et al)

  CGC description (H. Fujii et al) seems not to be favoured

J/ψ $R_{pPb}(p_T)$ vs $R_{PbPb}(p_T)$



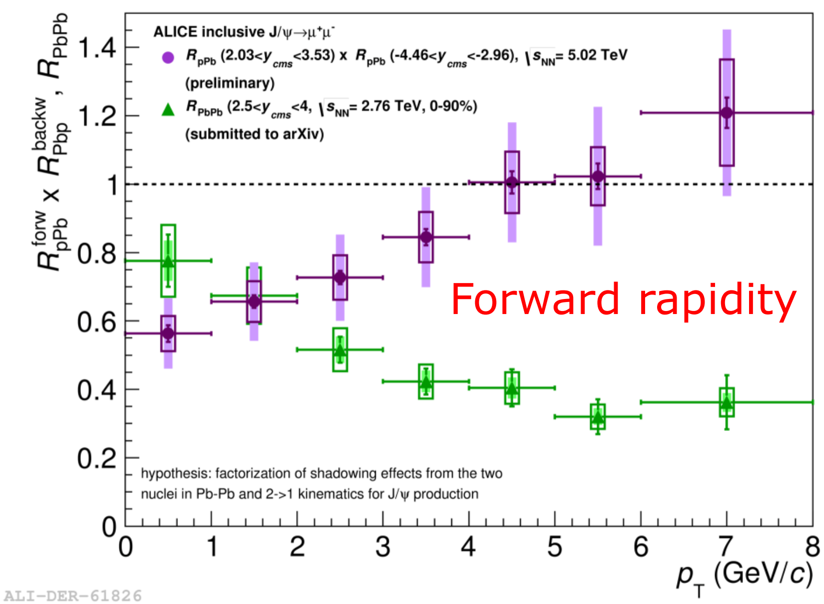
Hypothesis:

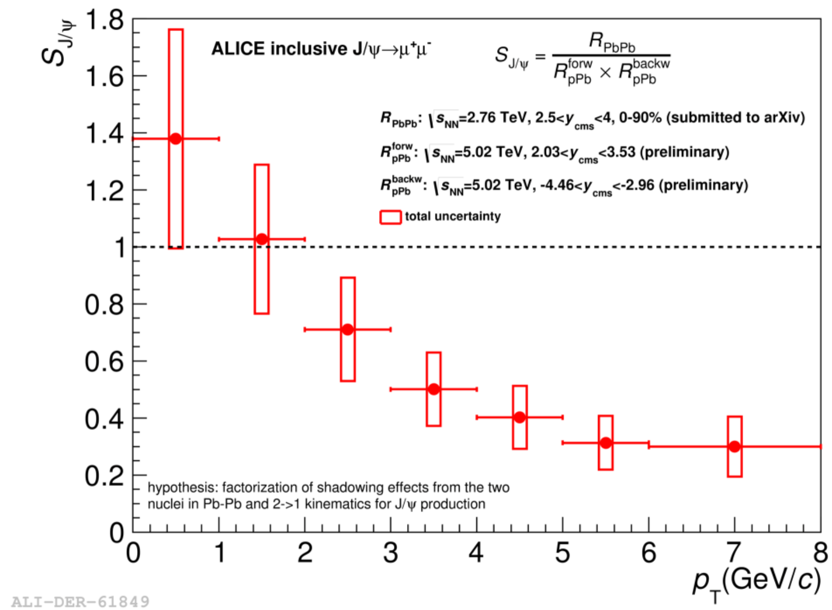
2→1 kinematics for J/ψ production

→ similar x_g in spite of different $\sqrt{s}$ and y

factorization of shadowing effects in p-Pb and Pb-Pb:

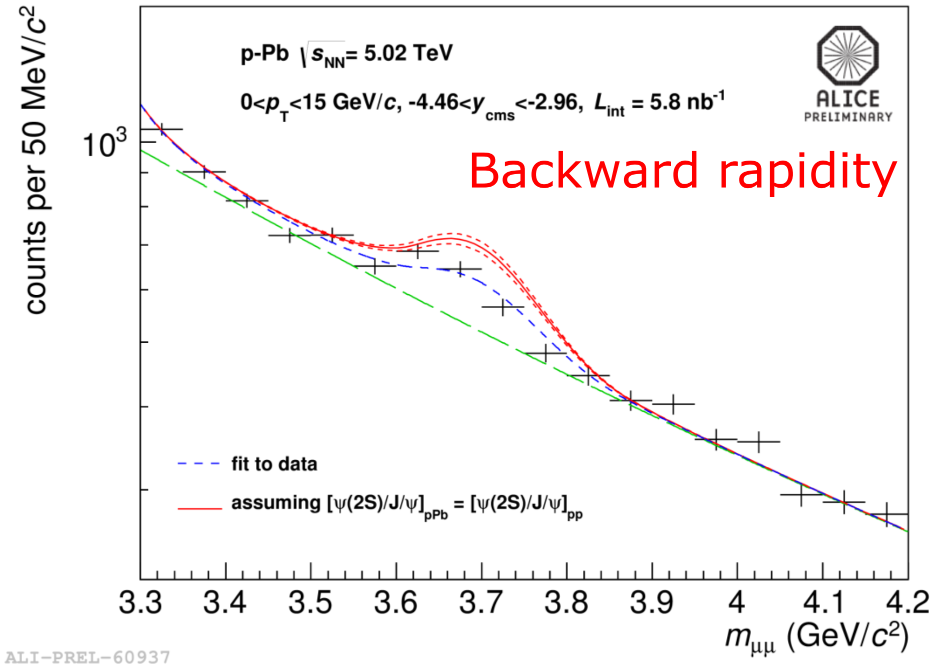
$$R^{shad}_{PbPb} = R_{pPb} \times R_{Pbp}$$

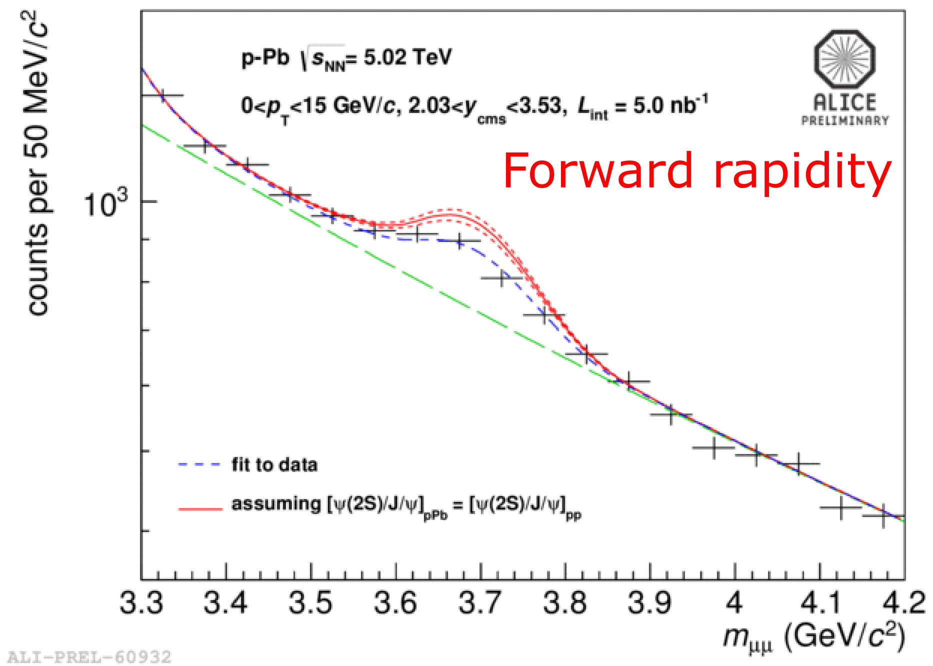




➡ R_{PbPb} enhanced at low p_T when corrected by this shadowing evaluation

ψ(2S) measurements in p-A

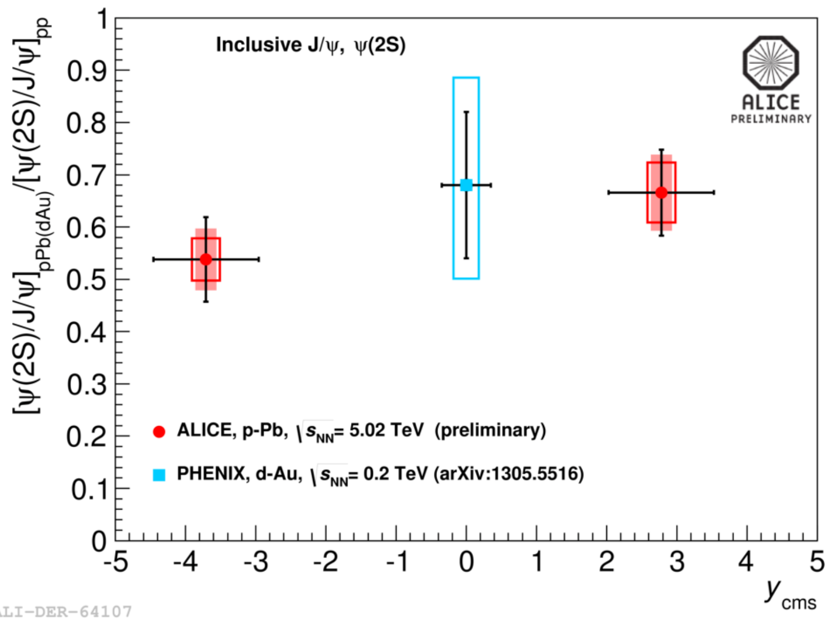


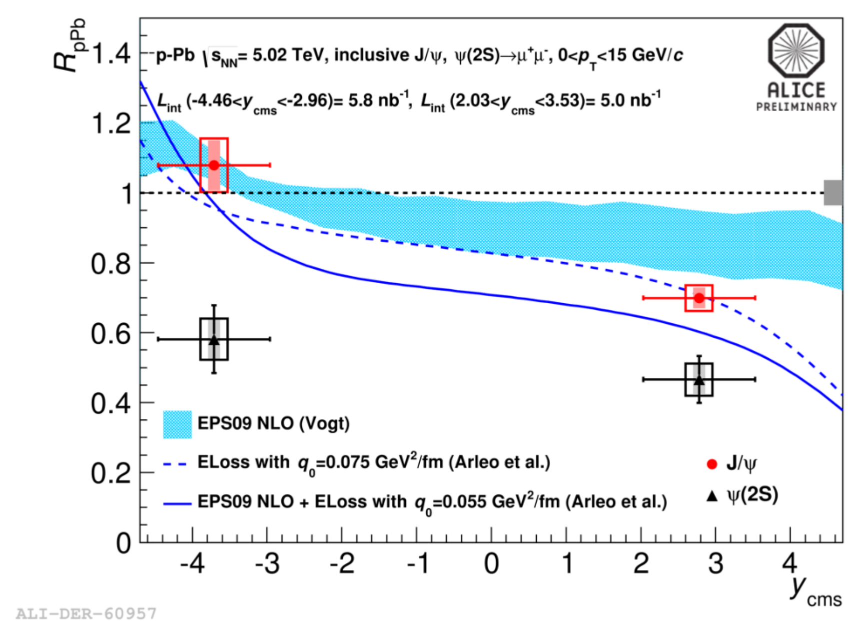


➡ ψ(2S) is clearly suppressed in p-A wrt pp (at √s=7TeV)

ψ(2S) measurements in p-A

- ψ(2S)/J/ψ strongly decreased from pp to p-Pb

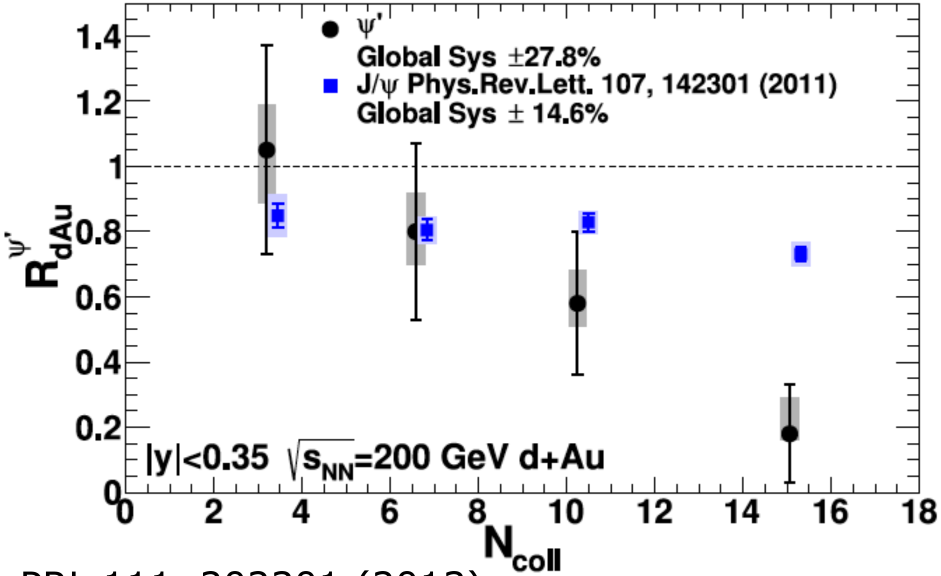




- ψ(2S)/J/ψ suppression is observed also in mid-rapidity d-Au results at √s=200GeV

- Shadowing and/or coherent energy loss don't explain the stronger ψ(2S) suppression (same treatment for ψ(2S) and J/ψ)
- Hot medium effects?

ψ(2S) measurements in d-Au



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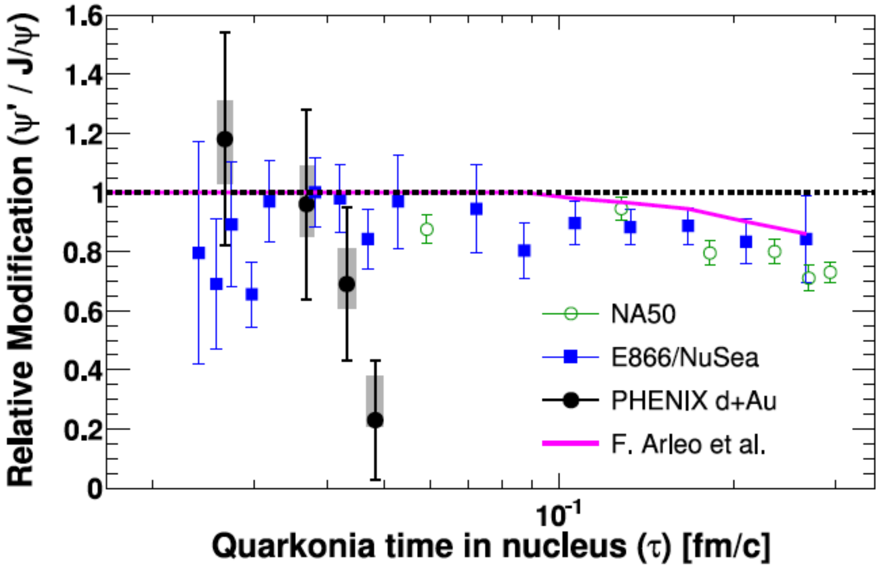


- ψ(2S) ~ 3 times more suppressed than J/ψ in central events
- If ψ(2S) suppression is due to the break-up of the pre-resonant state, it should be identical to J/ψ
- Near future: p-Cu, p-Si, p-Au in 2015 at RHIC!

Conclusions

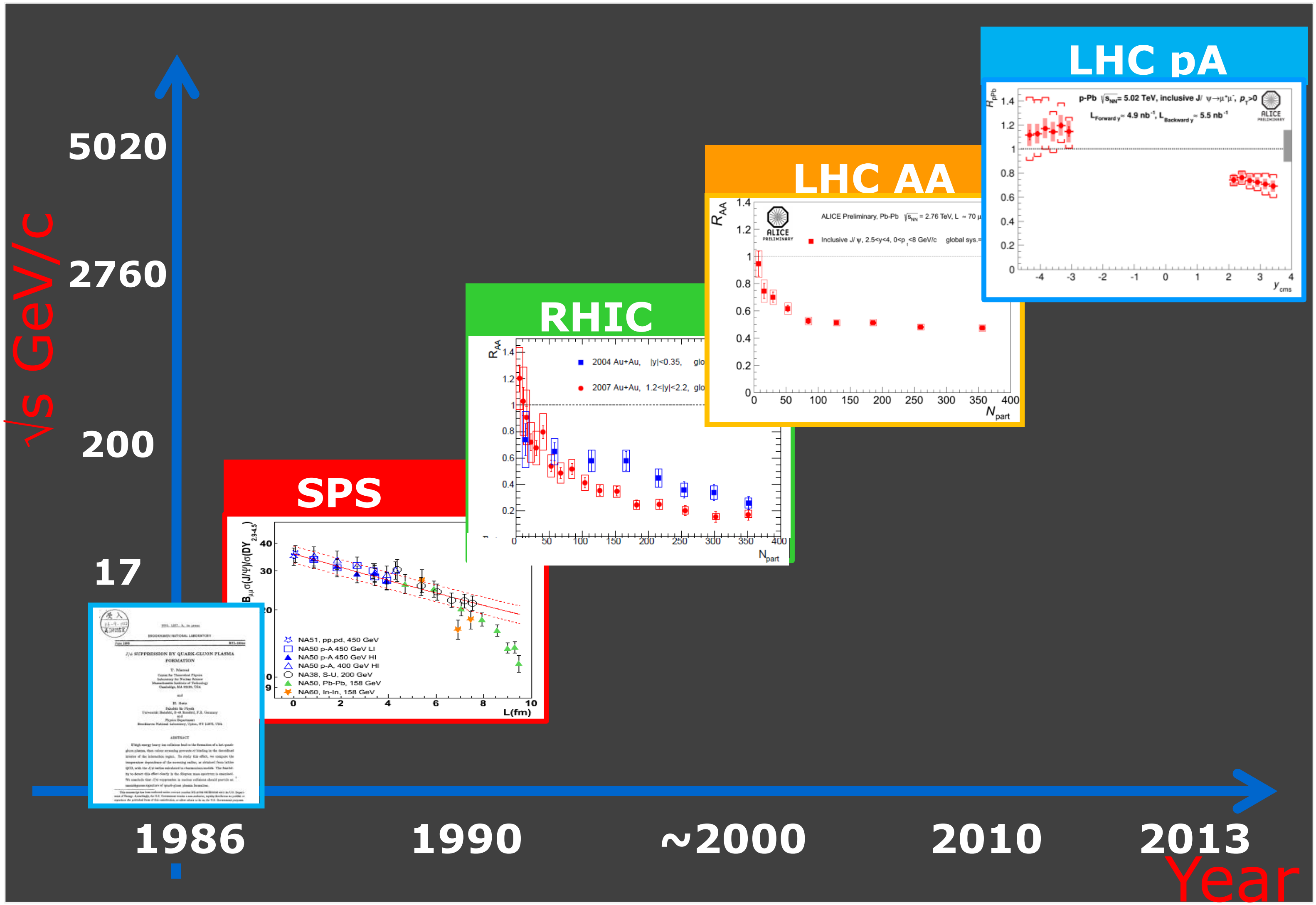
- Quarkonia study in heavy ion collisions is already a 25 years long story!
  - First LHC run has now provided a large wealth of charmonium and bottomonium results to complement results from SPS and RHIC!
    - not only J/ψ, but also ψ(2S) (and Υ) are now accessible in various kinematic regions
    - complicate picture in AA because of the interplay of many mechanisms: scenario qualitatively understood as a combination of suppression and (re)combination processes
    - pA and dA data now available: crucial to define cold nuclear matter effects …but non trivial effects observed on excited quarkonium states!

Thank you!

Backup

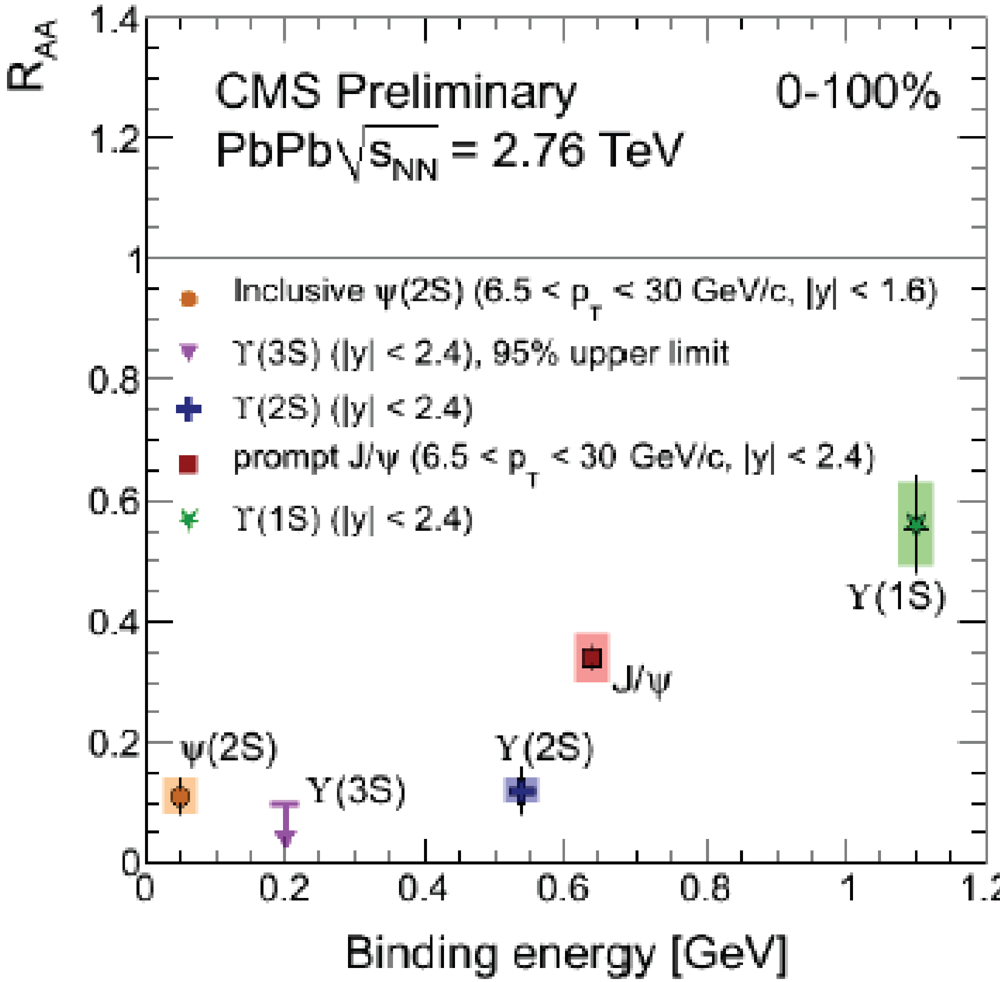
History of heavy-ion quarkonium studies

- Quarkonium suppression is, since 25 years, one of the most striking signatures for QGP formation in AA collisions



Where are we?

- 27 years after first suppression prediction, this is observed in the charmonium and bottomonium sector with very good accuracy!



Nucl.Phys.A 904-905 (2013) 194c-201c

- Two main mechanisms at play:
  1. Suppression in a deconfined medium
  2. Re-combination (for charmonium) at high √s

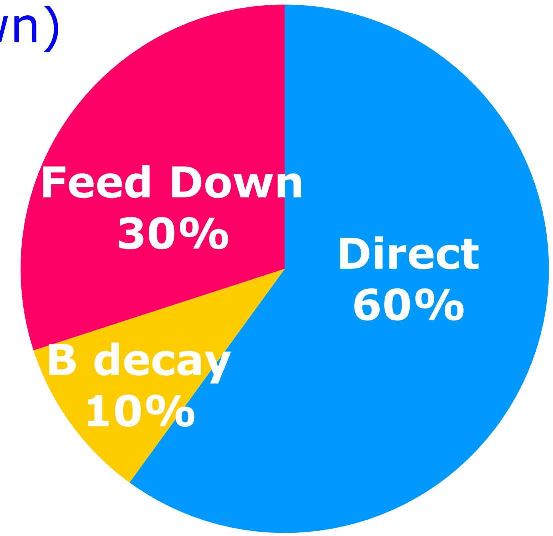
  can qualitatively explain the main features of the results

- R_{AA} vs binding energy: looser bound states more suppressed than the tighter ones

- however hot and cold effects not yet disentangled…need pA/dA results where no hot medium should be formed!

Quarkonium production

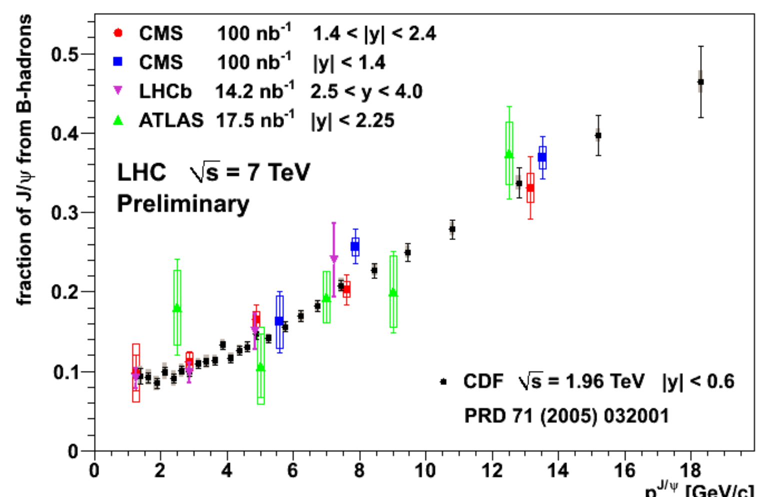
- Quarkonium production can proceed:
  - directly in the interaction of the initial partons
  - via the decay of heavier hadrons (feed-down)



- For J/ψ (at CDF/LHC energies) the contributing mechanisms are:

Prompt
- Direct production
- Feed-down from higher charmonium states:
  ~ 8% from ψ(2S), ~25% from χ_c

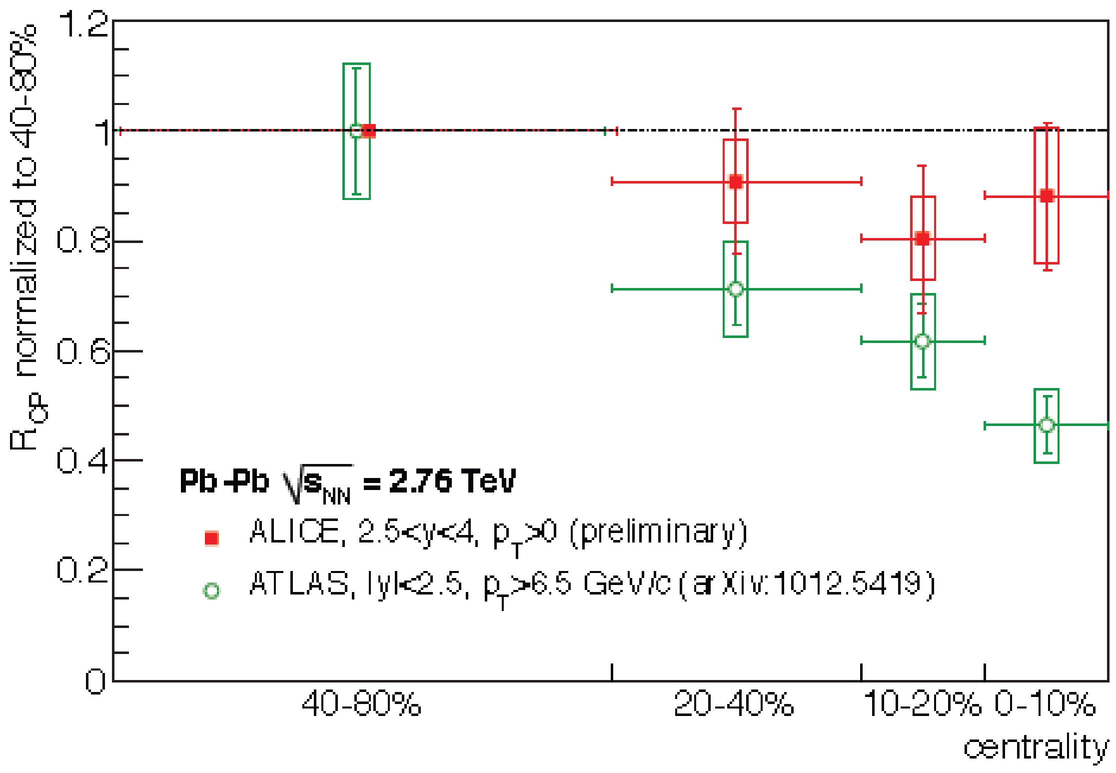
Displaced
- B decay
  contribution is p_T dependent
  ~10% at p_T~1.5GeV/c



- Feed down and J/ψ from B, if not properly taken into account, may affect physics conclusions

ALICE and ATLAS J/ψ

Statistical and systematic uncertainties have not been propagated for ATLAS



ALICE:

- 2.5<y<4
- $p_T > 0$

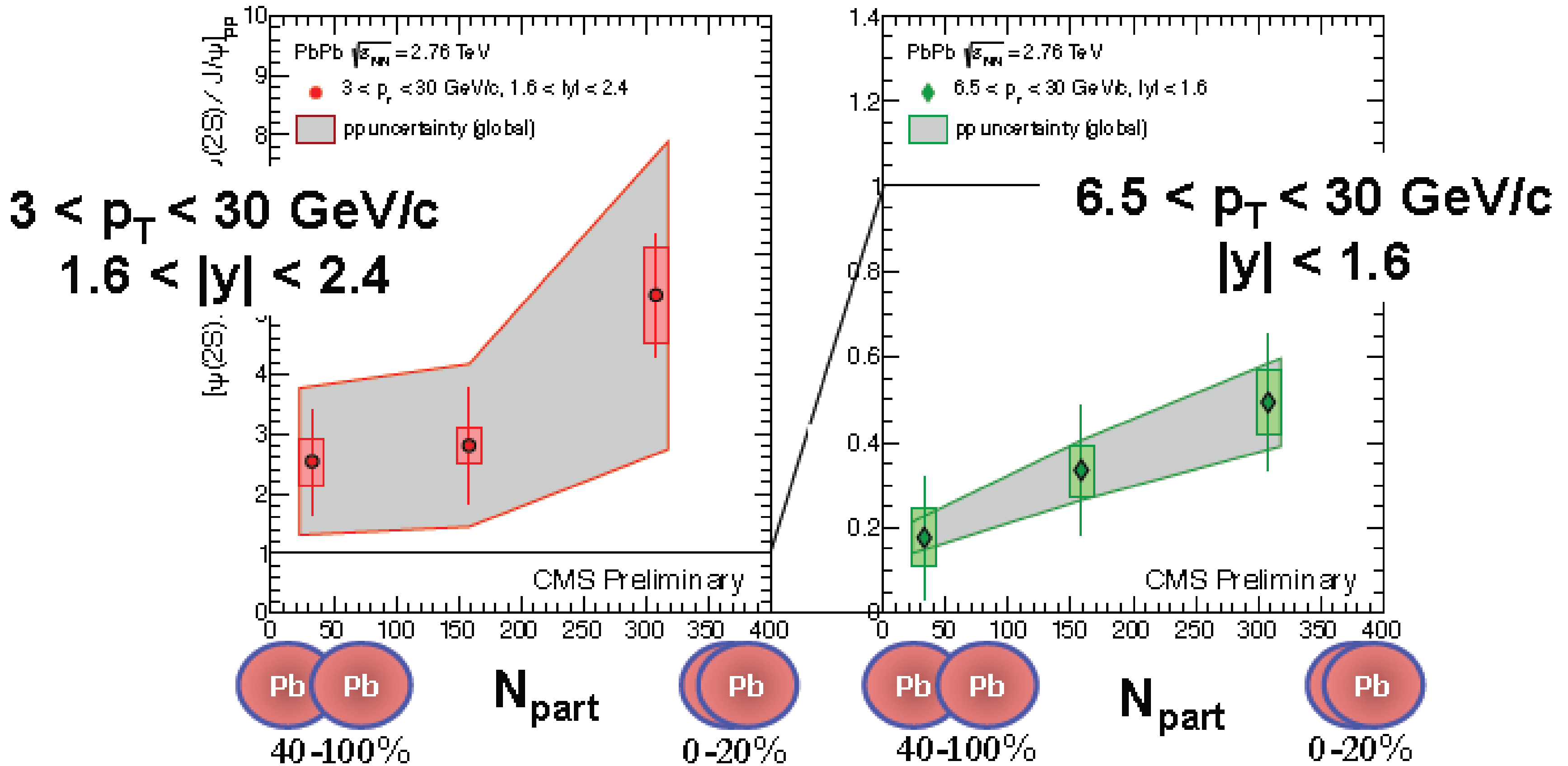
ATLAS:

- |y|<2.5
- 80% of J/ψ with $p_T > 6.5$ GeV/c

J/ψ R_{CP} larger for ALICE than for ATLAS in the most central collisions…

… But different rapidity and p_T coverage

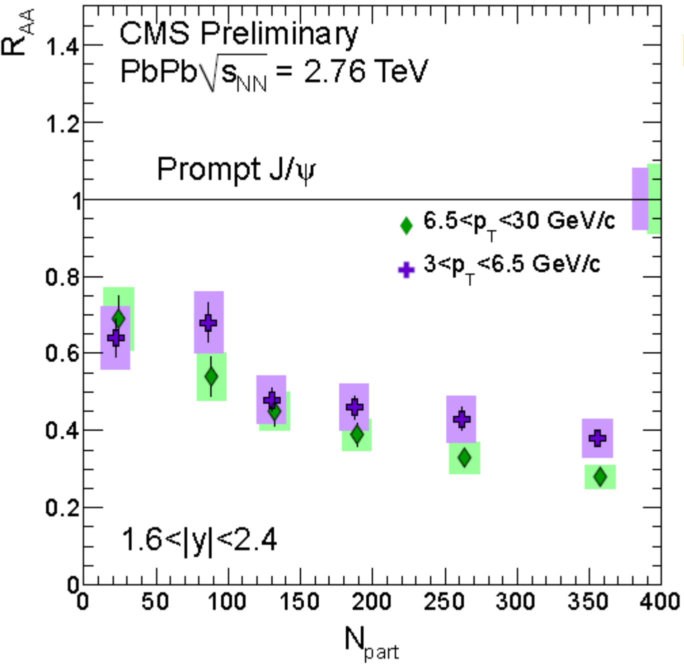
ψ(2S)/ ψ



$$\frac{N_{\psi(2S)}/N_{J/\psi}|_{PbPb}}{N_{\psi(2S)}/N_{J/\psi}|_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$

- **High-p_T:** $R_{AA}^{0-100\%}(\psi(2S)) = 0.11 \pm 0.03(\text{stat}) \pm 0.02(\text{syst}) \pm 0.02(\text{pp})$
- **Low-p_T (<2σ):** $R_{AA}^{0-100\%}(\psi(2S)) = 1.54 \pm 0.32(\text{stat}) \pm 0.22(\text{syst}) \pm 0.76(\text{pp})$

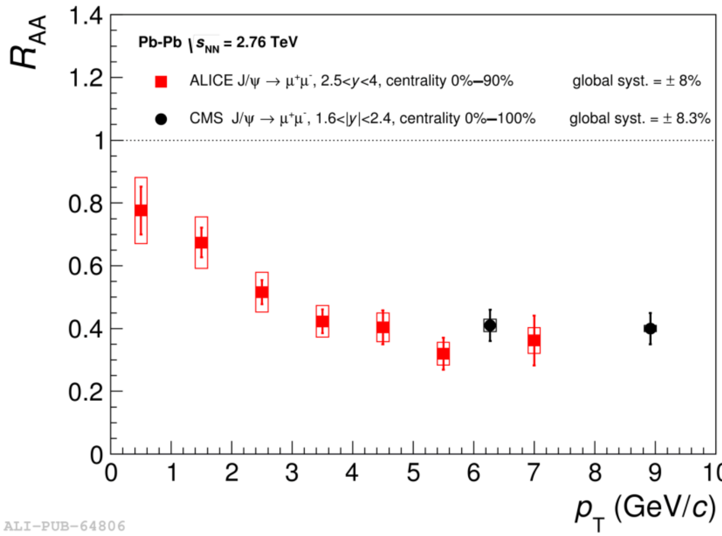
CMS: high p_T J/ψ



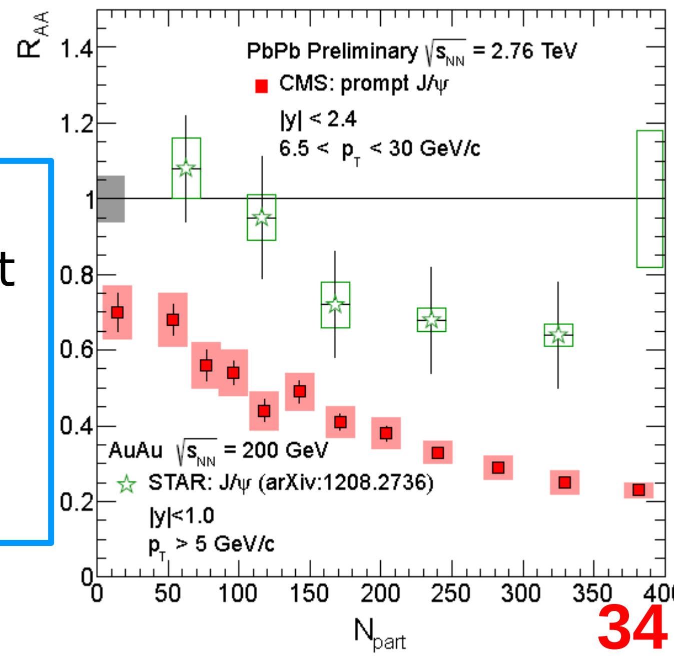
The high p_T region can be investigated by CMS!

Small hint of p_T dependent suppression even in the CMS p_T range

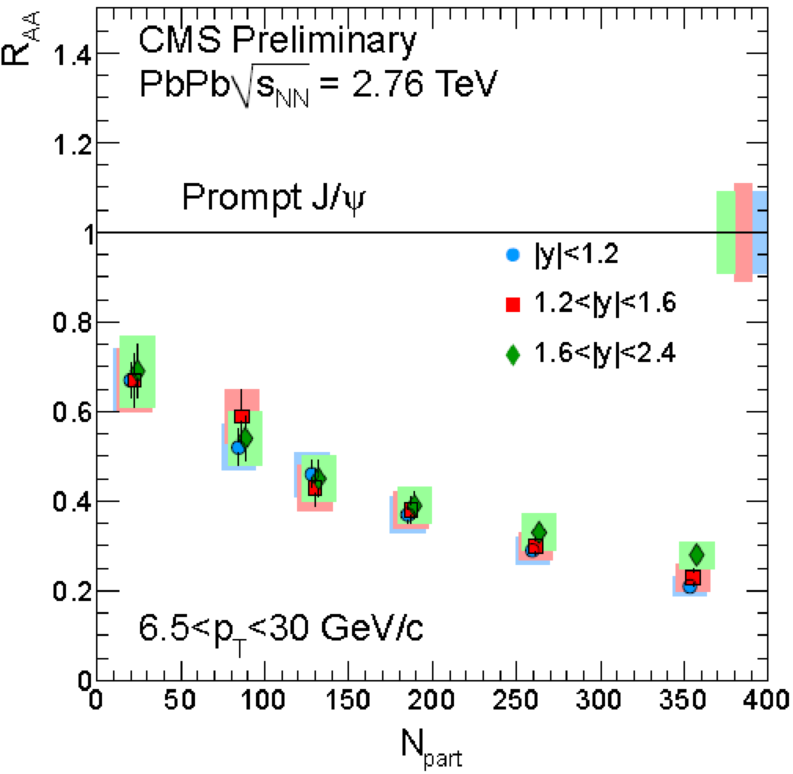
Good agreement with ALICE (high p_T) in spite of the different rapidity range



High p_T: stronger J/ψ suppression at LHC wrt to RHIC (re-combination should not play a role)

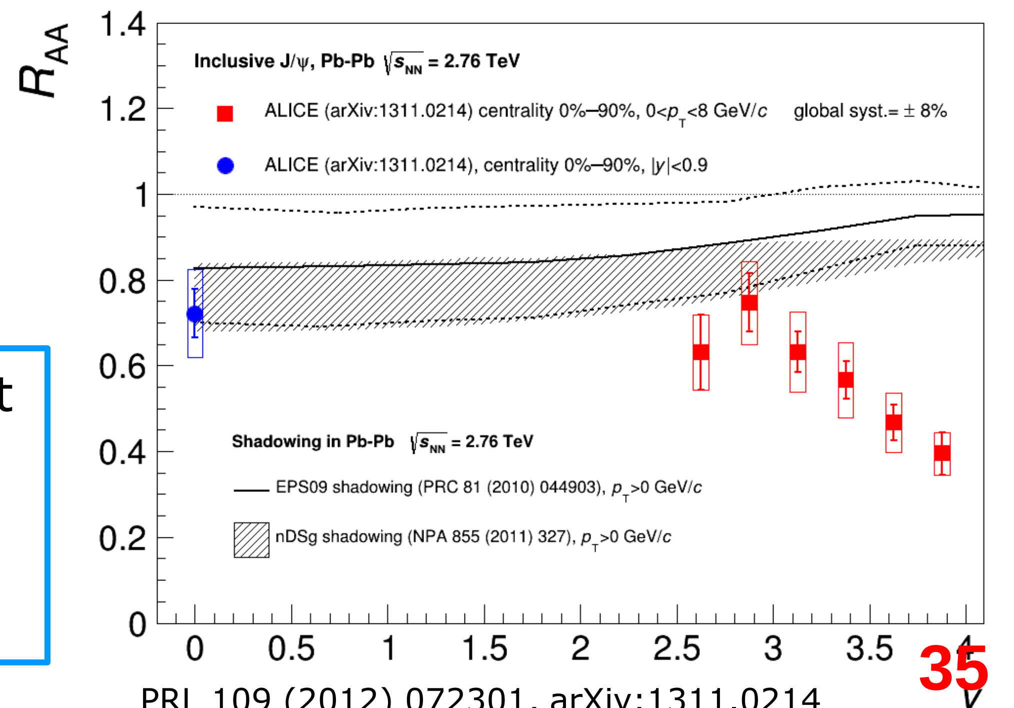


J/ψ R_{AA} vs rapidity



➡ R_{AA} y pattern depends on the J/ψ p_T

- At high p_T (CMS) almost no y dependence in the range $|y|<2.4$
- At low p_T (ALICE) R_{AA} decreases by 40% from y=2.5 to y=4



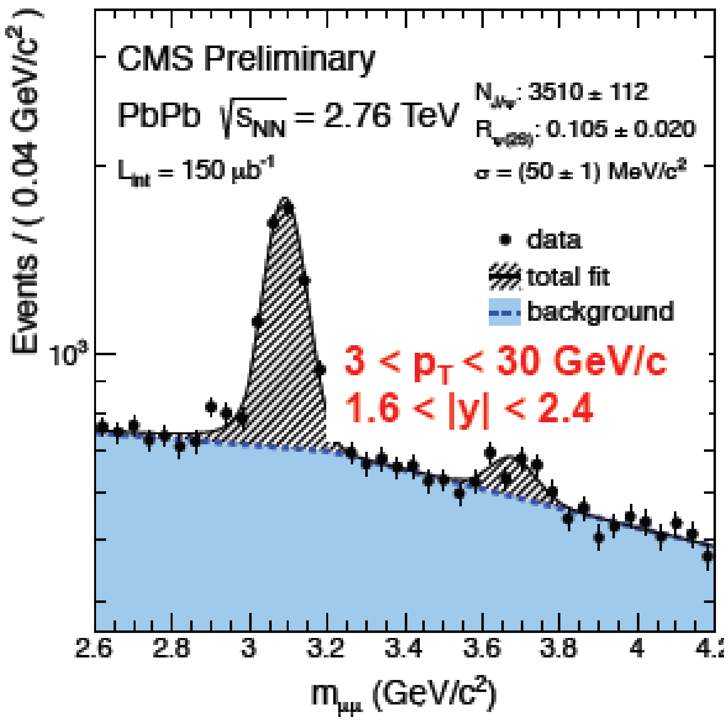
- Suppression beyond the current shadowing estimates. Important to quantify cold nuclear matter effects in p-A collisions

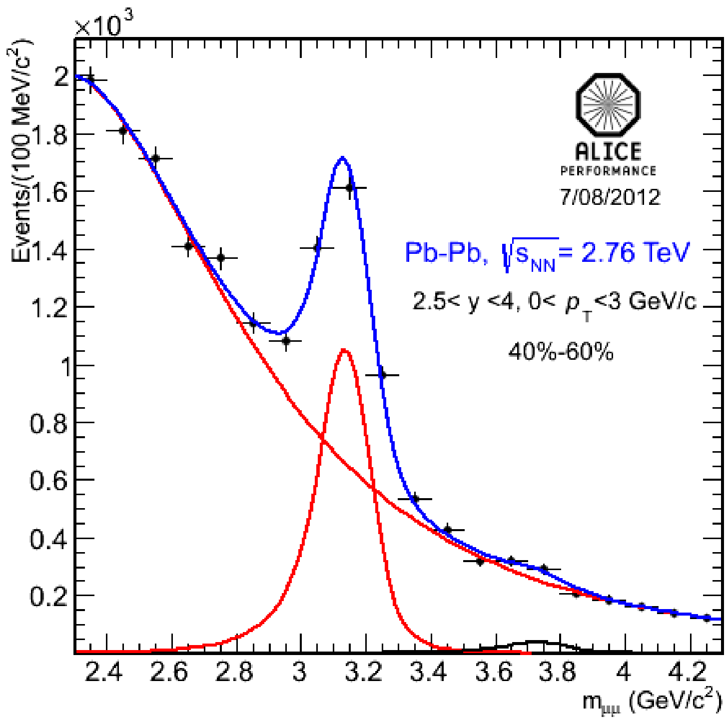
JHEP05 (2012) 063, CMS PAS HIN-12-014

PRL 109 (2012) 072301, arXiv:1311.0214

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

- Study of other charmonium resonances can help constraining theoretical models
  - $\psi(2S)$ much less bound than J/ψ
  - Results from the SPS showed a suppression larger than the J/ψ one

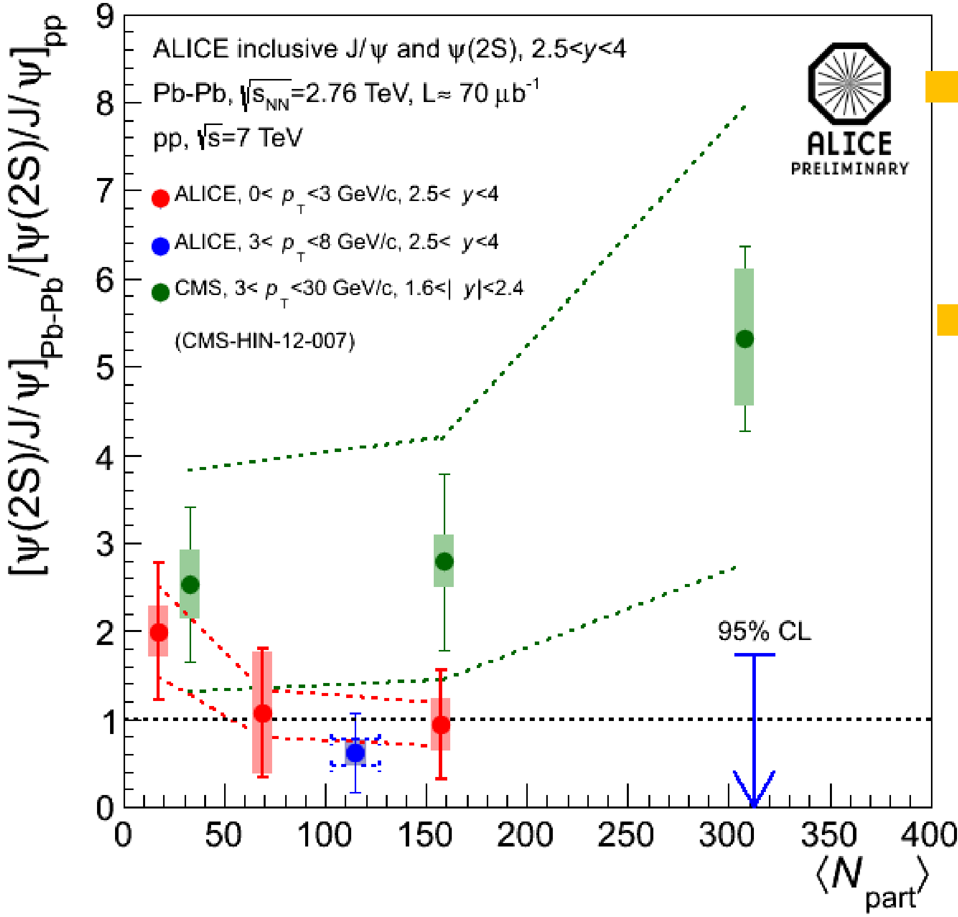




- $\psi(2S)$ studied by both CMS and ALICE, different kinematics

ψ(2S) in Pb-Pb

- The ψ(2S) yield is compared to the J/ψ one in Pb-Pb and in pp



- At SPS, the ψ(2S)/J/ψ suppression increased with centrality
- Overall interpretation is challenging

ALICE excludes a large enhancement

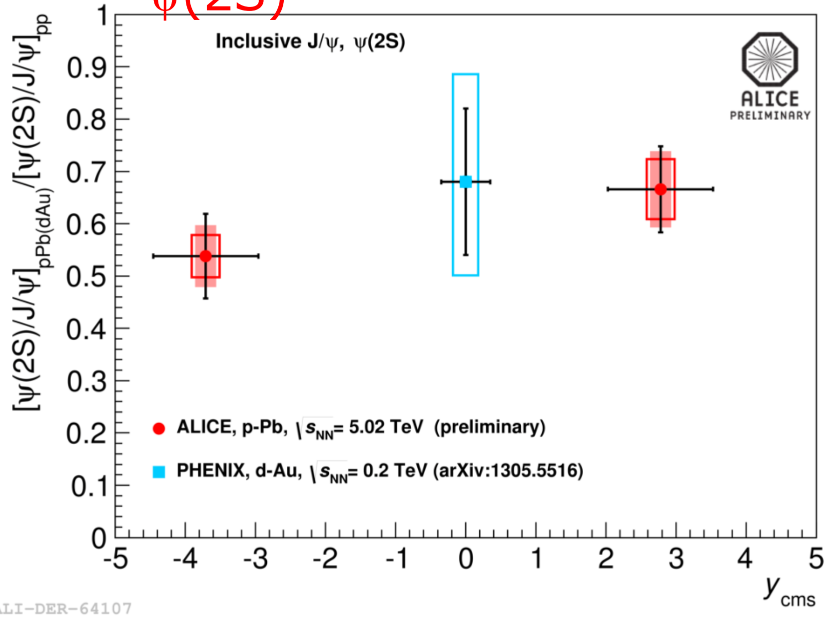
- Difference trend in ALICE and CMS: large statistics and systematic errors prevent a firm conclusion on the ψ(2S) enhancement or suppression versus centrality

Nucl.Phys.A 19 (2013), pp. 595-598
CMS PAS HIN-12-007

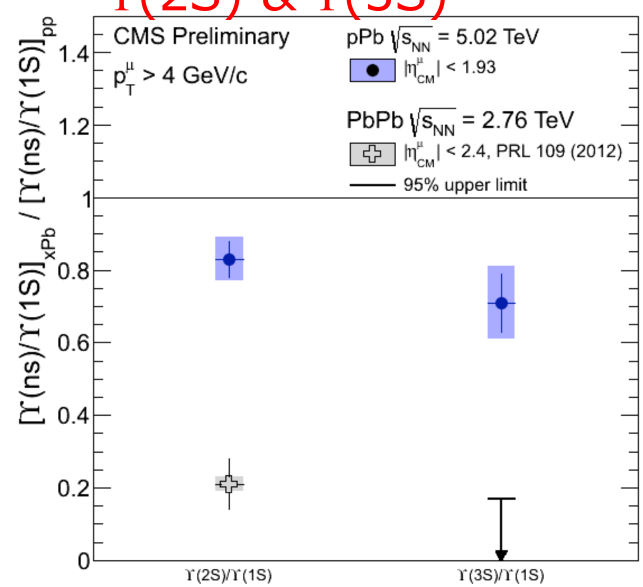
Excited quarkonia states in p-A

- Excited states suppressed relative to ground states

ψ(2S)



ϒ(2S) & ϒ(3S)



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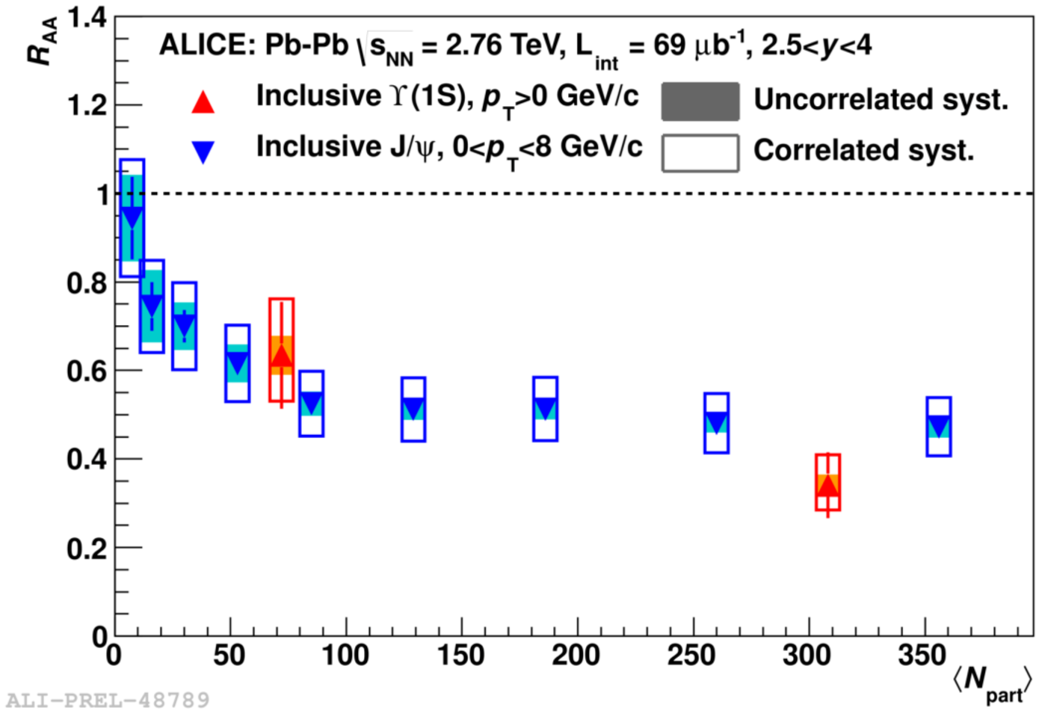
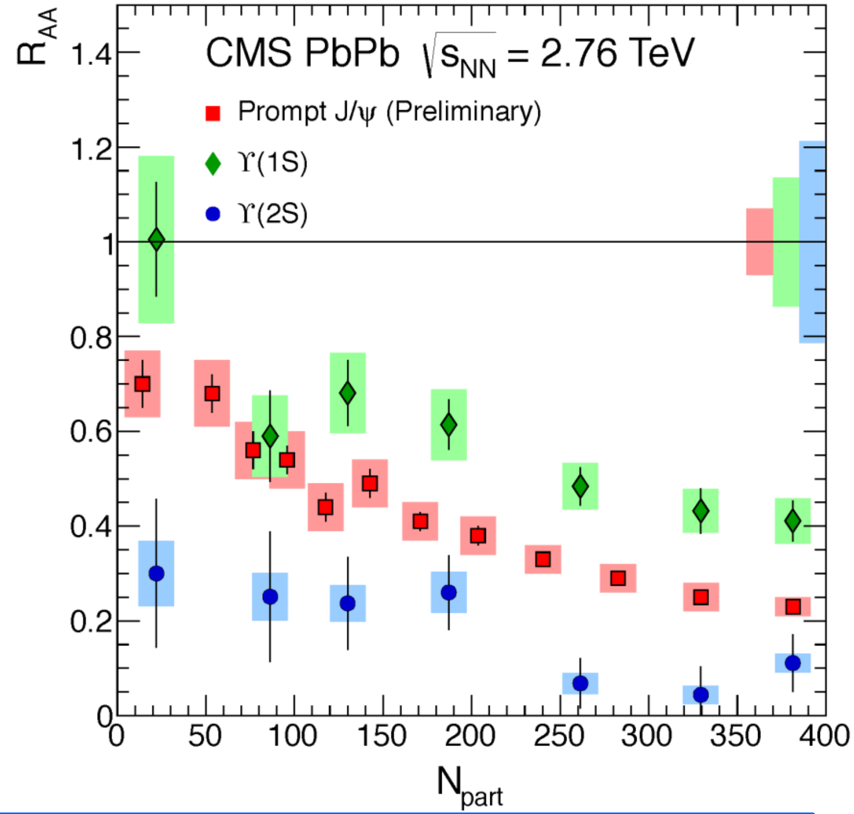
- ψ(2S) is clearly suppressed in p-A wrt pp (at √s=7TeV)
- Similar suppression observed also in d-Au at √s=200GeV
- Shadowing and/or coherent energy loss don't explain the stronger ψ(2S) suppression. Hot medium effects?

- p-Pb vs Pb-Pb: additional final state effects in Pb-Pb affecting the excited states more than the ground state
- p-Pb vs pp: suppression increases with increase of charged particle multiplicity

Comparison Υ and J/ψ





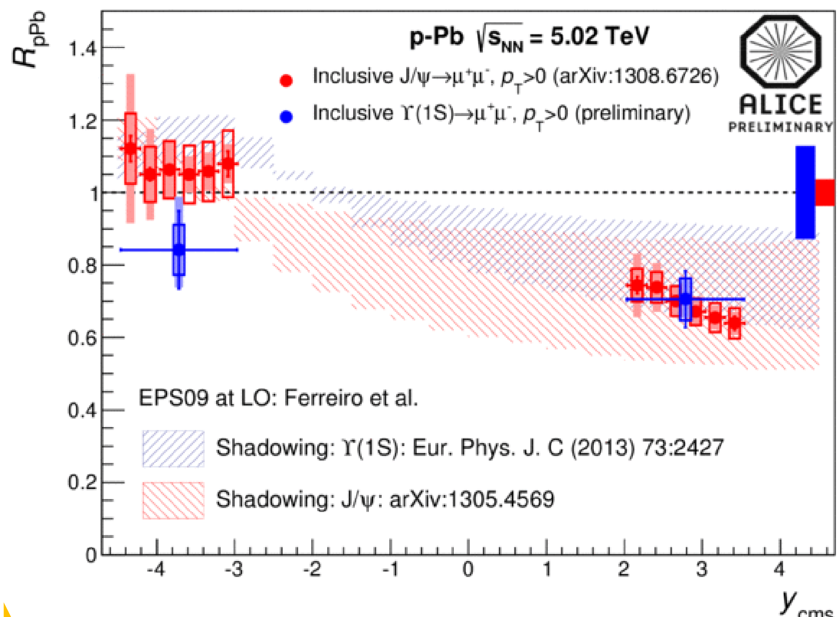
- Similar R_{AA} for low p_T inclusive J/ψ and $\Upsilon(1S)$
- Sequential suppression observed for prompt J/ψ and $\Upsilon(nS)$ at high p_T

- interplay of the competing mechanisms for J/ψ and Υ can be different and dependent on kinematics!

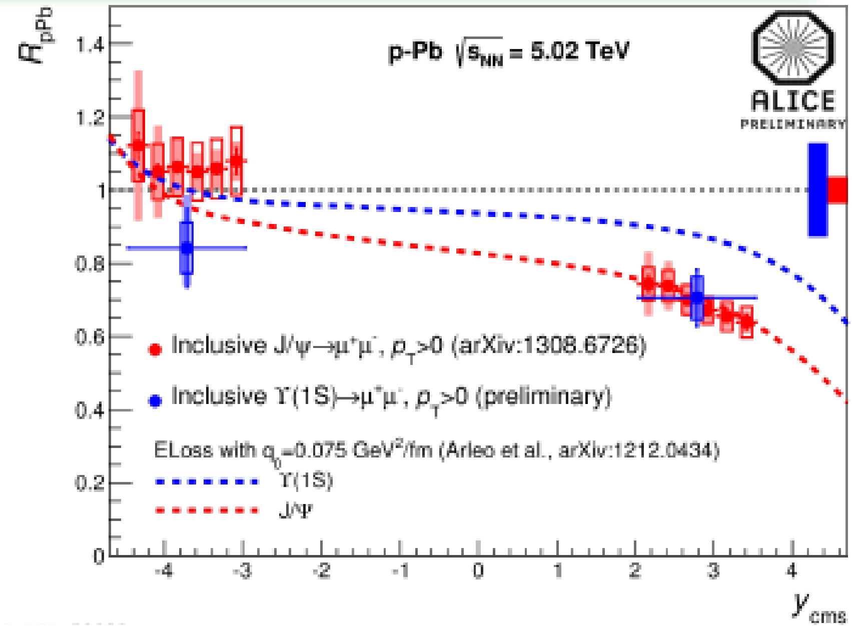
Υ(1S) measurements in p-A

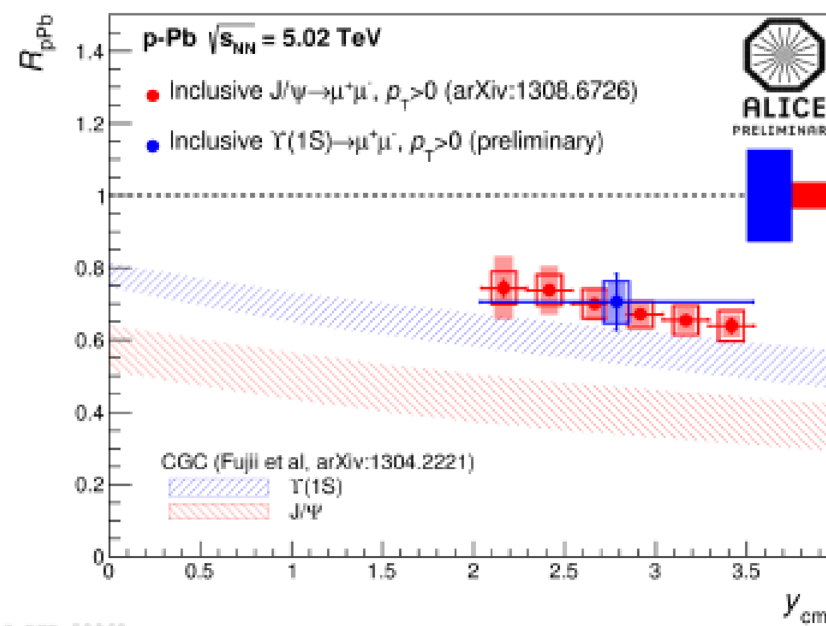
- Hint for Υ(1S) R_{pPb} suppression at forward rapidity. Smaller effect at backward *y*

- R_{pPb} comparable for J/ψ and Υ(1S)

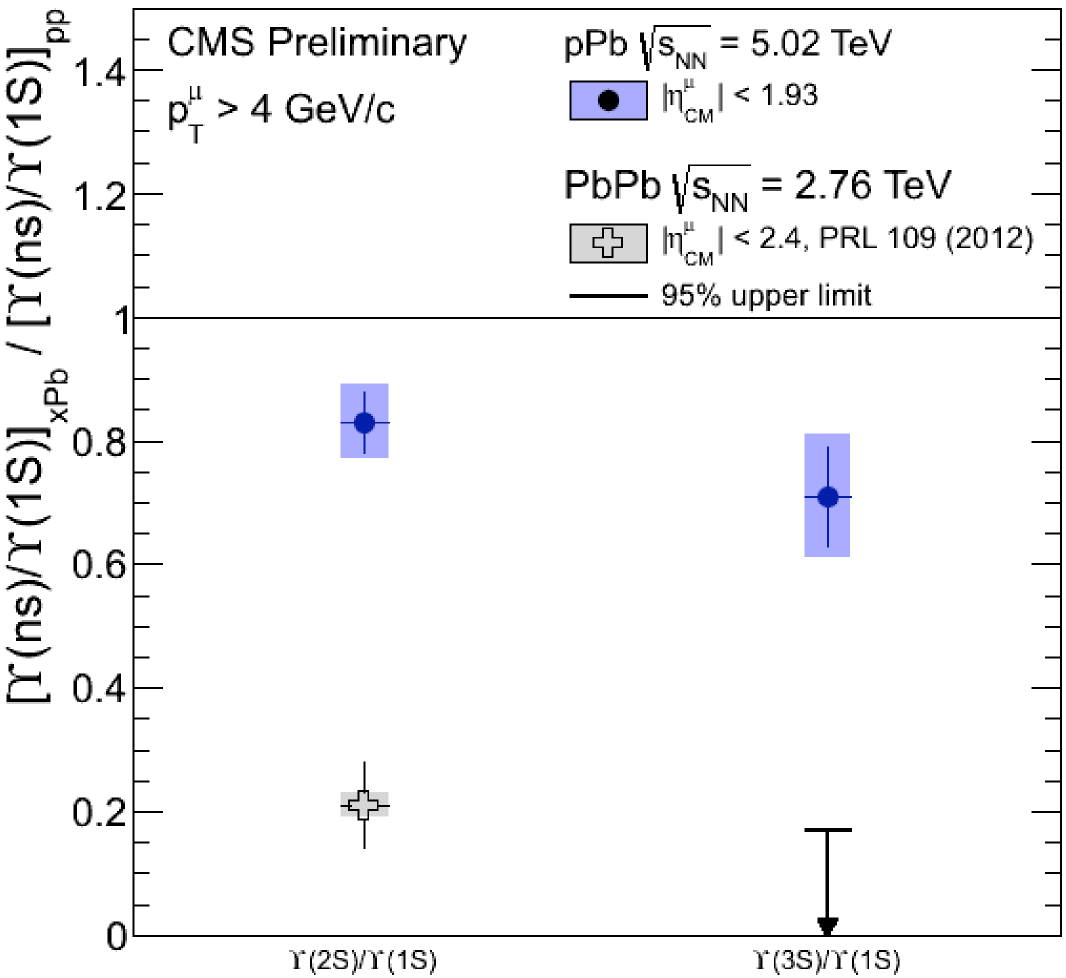


- EPS09 shadowing models, CGC and coherent energy loss in fair agreement with Υ(1S) R_{pA} result





Υ(2S) & Υ(3S) measurements in p-A



- **p-Pb vs PbPb**: additional final-state effects in Pb-Pb affecting the excited states more than the ground state
- **p-Pb vs pp**: excited states more suppressed than the ground states. Suppression increases with increase of charged particle multiplicity

L. Benhabib, HP2013

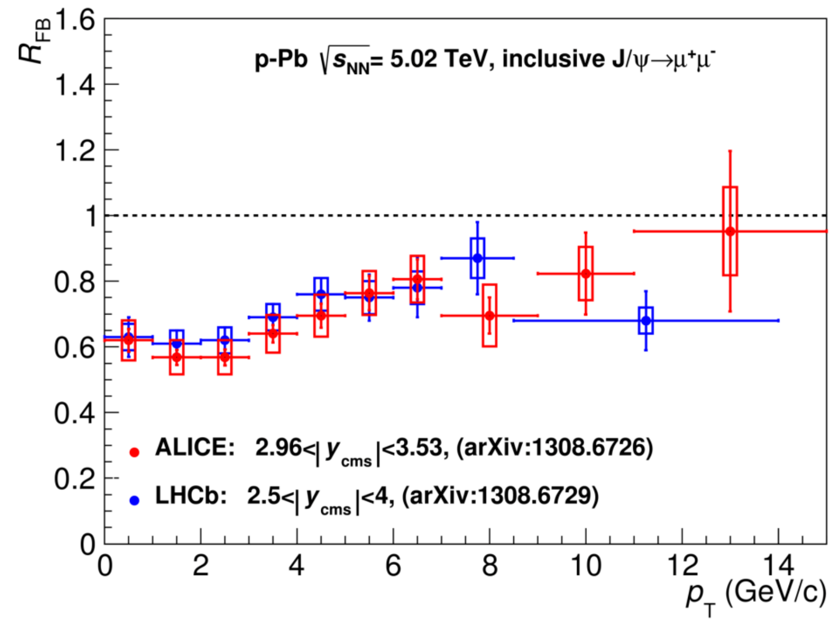
Ratio forward to backward yields: R_{FB}

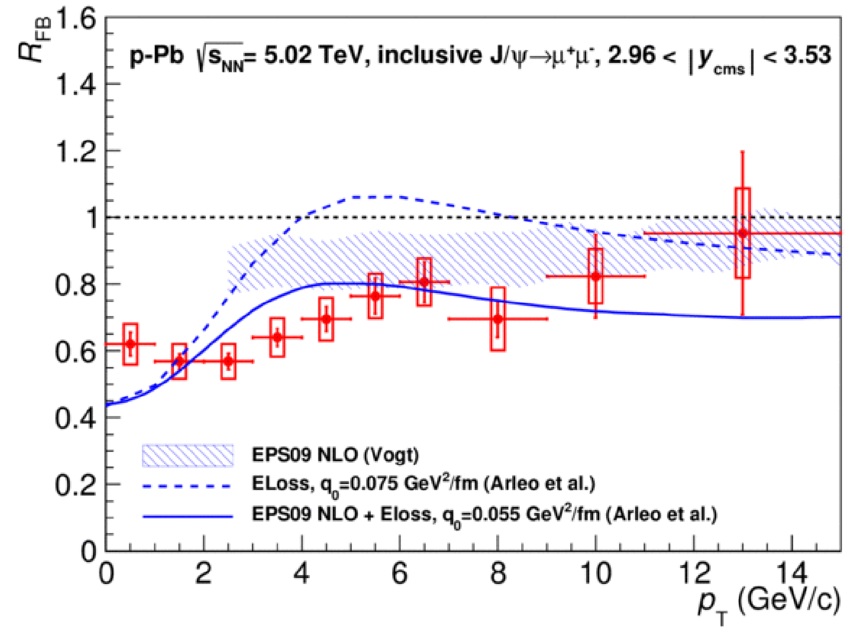
- R_{FB}: free from uncertainties on the pp reference

$$R_{FB} = \frac{Y_{J/\psi}^{Forward}}{Y_{J/\psi}^{Backward}}$$

- The R_{FB} ratio shows a rather flat y dependence and a p_T dependence with stronger forward to backward suppression at low p_T

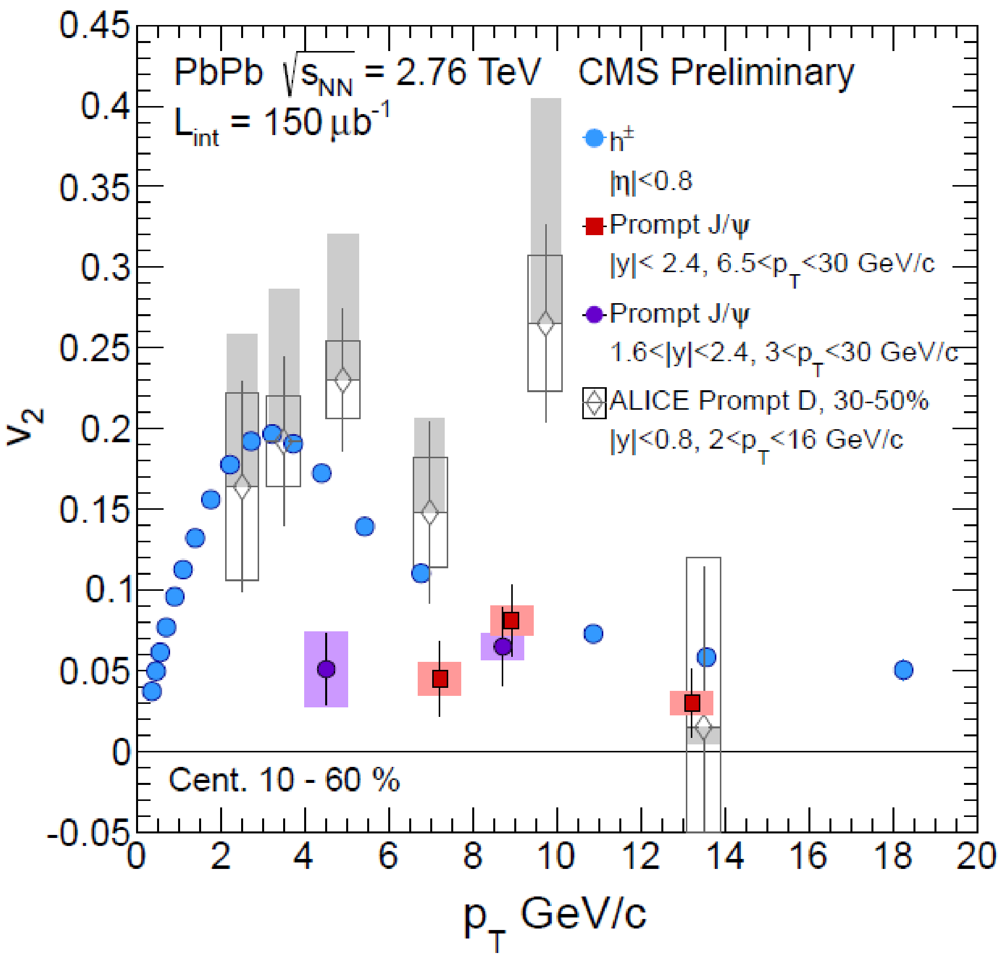
- Less stringent comparison to theory wrt R_{pA}: however theoretical predictions including energy loss show strong nuclear effects at low p_T, in fair agreement with the data





J/ψ vs open HF v_2

CMS HIN-2012-001



- J/ψ elliptic flow should be directly related to HF v_2
- Smaller values for J/ψ in the region where (re)generation should play a role
- Simply a reflection of the fraction of J/ψ due to (re)generation?

- Similar values at very high p_T (uncertainties!) for all particles