Quarkonium production in Pb-Pb collisions

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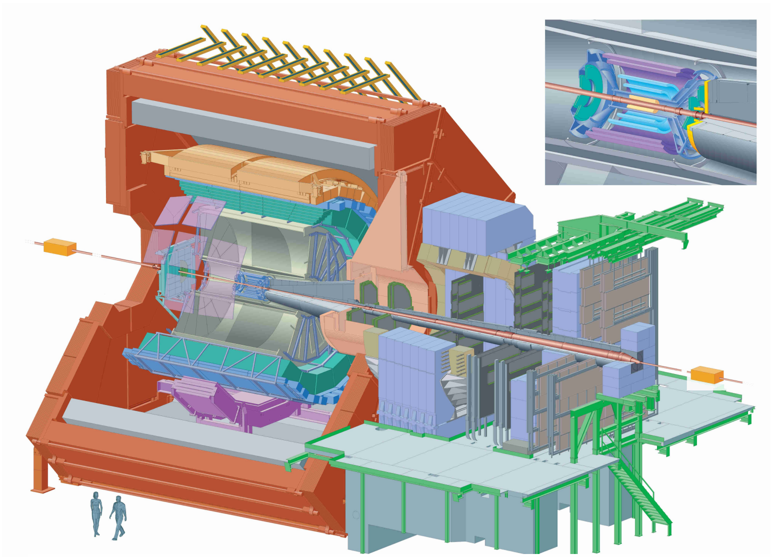
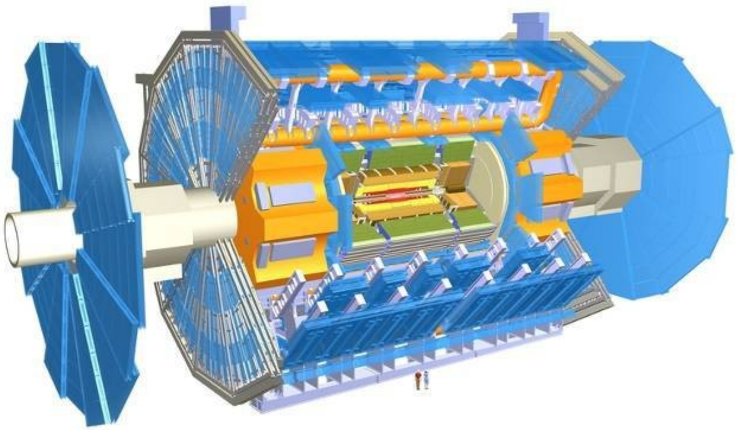
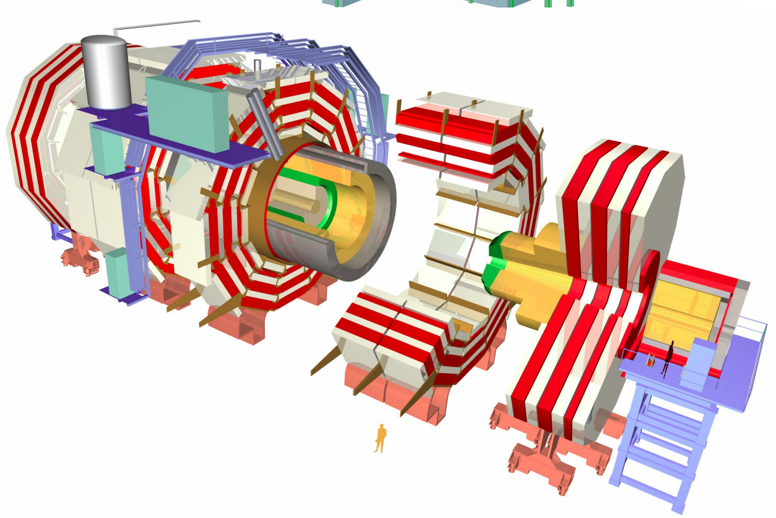
Outline

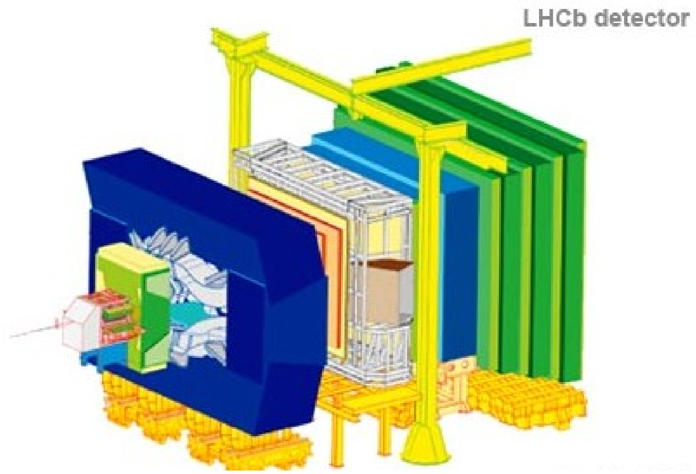
- Heavy ion collisions lore
- Charmonium
  - J/ψ, ψ'
- Bottomonium
  - Y(1S), Y(2S), Y(3S)
- Summary & Conclusions

Relativistic heavy ion collisions



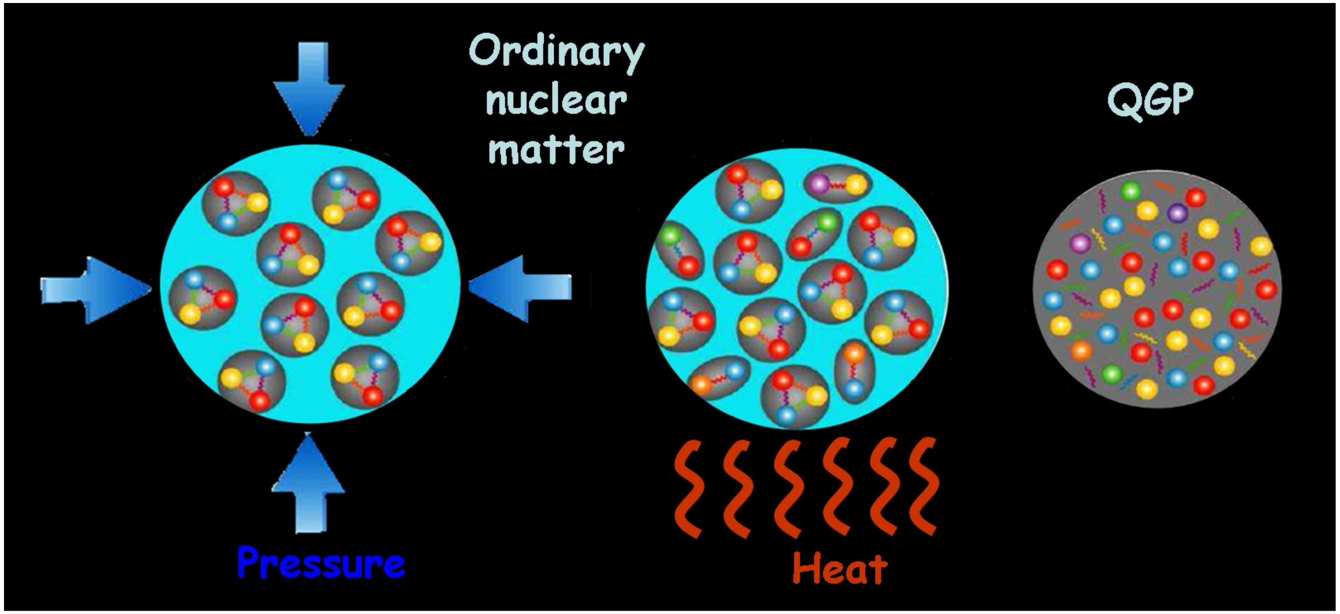






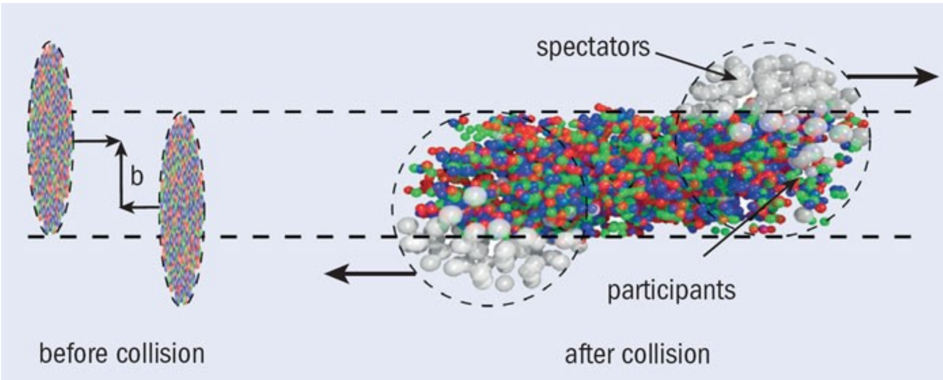
- CERN-LHC: Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
- Three heavy ion experiments: ALICE, ATLAS and CMS
- LHCb joined the p-Pb run

The medium in nucleus-nucleus collisions

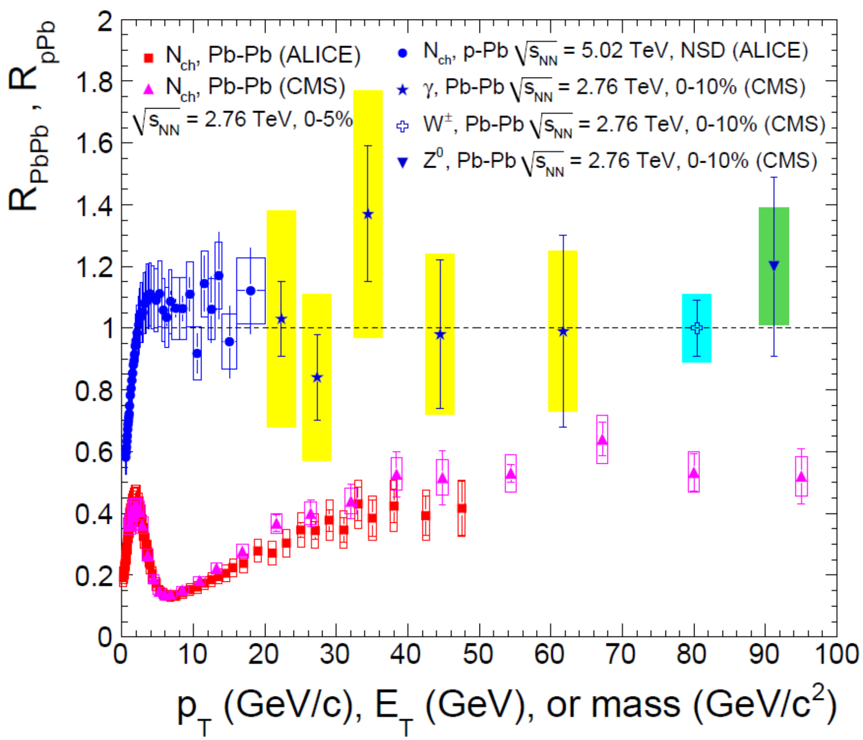


- In a nucleus-nucleus collision, ordinary nuclear matter is compressed and heated leading to the formation of a deconfined state of matter, dubbed Quark-Gluon Plasma (QGP)
- Heavy quarkonia is one of the prime probes for studying QGP

Quantifying medium effects -nuclear modification factor-



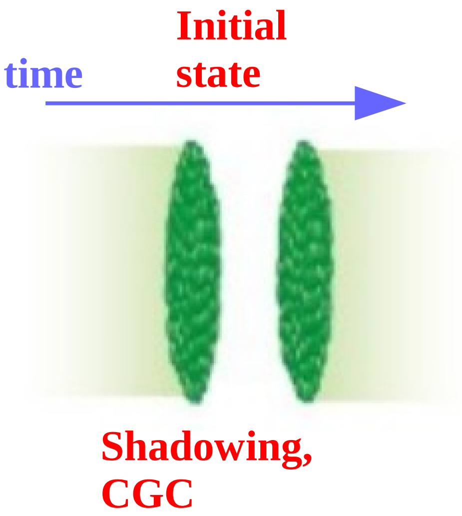
$$R_{AA} = \frac{d^2 N_{AA} / dp_T\, dy}{N_{coll} \times d^2 N_{pp} / dp_T\, dy}$$

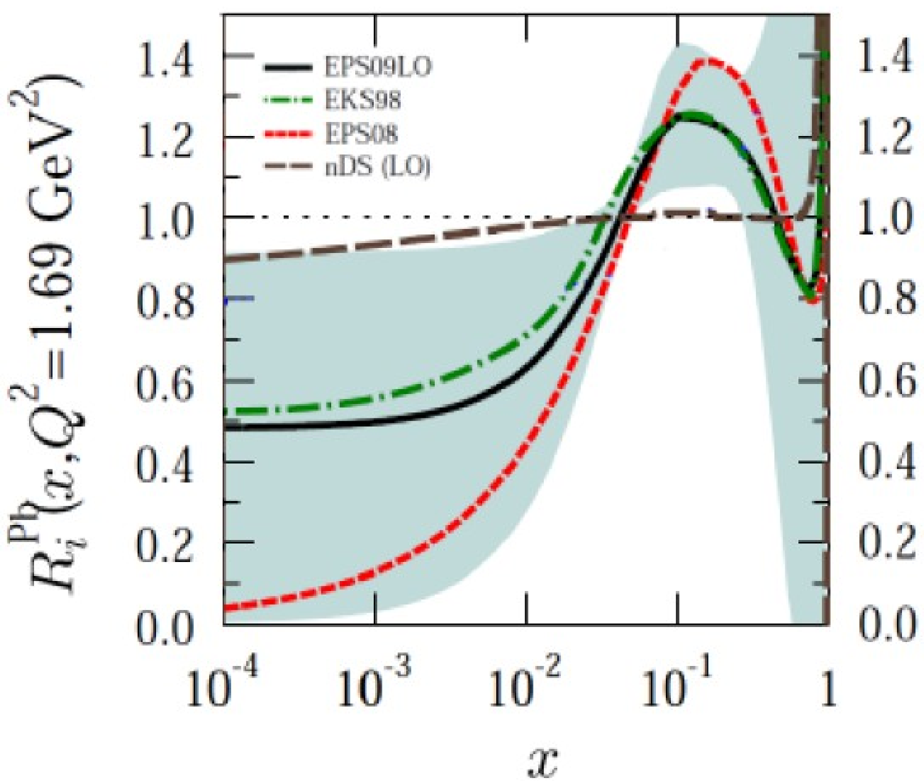


- Superposition of NN collisions → R_{AA}=1
- Strong suppression for light hadrons observed at LHC in Pb-Pb collisions
- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 bosons R_{AA} are compatible with 1

p-Pb, ALICE PRL110(2013)082302
Pb-Pb, ALICE, Phys.Lett.B720 (2013)52
Pb-Pb, CMS, EPJC (2012) 72
γ, CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB715 (2012) 66
Z^0, CMS, PRL106 (2011) 212301

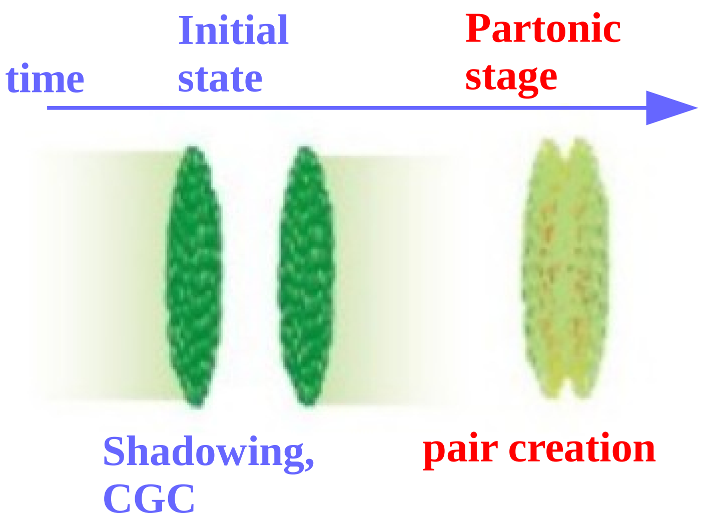
Quarkonia in AA collisions





- Cold nuclear matter (CNM) effects
  - Gluon shadowing or gluon saturation expected to play an important role in the small-*x* region at LHC
  - Initial state parton energy loss
- Cold nuclear matter effects currently studied in p-Pb collisions at 5 TeV

Quarkonia in AA collisions

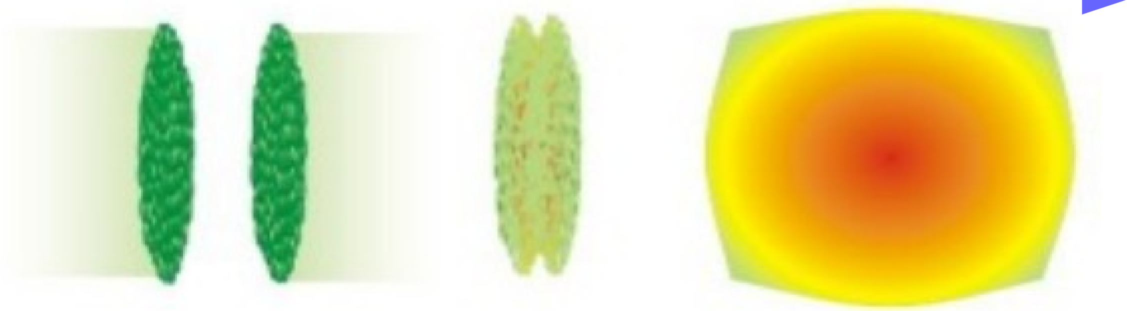


- Charm and beauty quarks produced via pair creation
- Pair production in pp
  - σ_{inel}(pp @ 7TeV) ~ 73mb
  - $\sigma_{c\bar{c}}$(pp @ 7TeV) = 8.5mb   ALICE JHEP 1207 (2012) 191
  - $\sigma_{b\bar{b}}$(pp @ 7TeV) = 0.28mb   ALICE JHEP 1211 (2012) 06
- Central Pb-Pb collision at LHC have ~1500 nucleon-nucleon collisions:
  - ~100 $c\bar{c}$ pairs
  - 5-6 $b\bar{b}$ pairs

- Nuclear absorption negligible at LHC:
  - Quarkonia formation time >> collision time
- Number of charm and beauty quarks conserved throughout the collision → well calibrated probe

Quarkonia in AA collisions

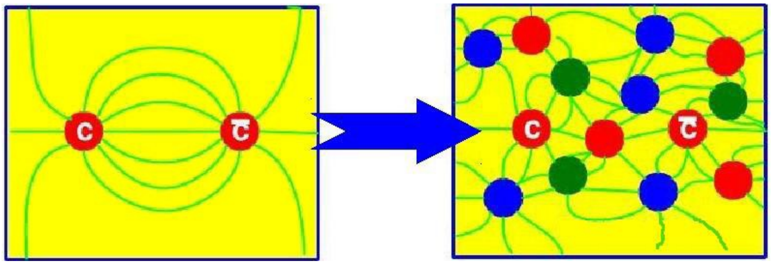
time — Initial state — Partonic stage — QGP hydro evolution



Shadowing, CGC

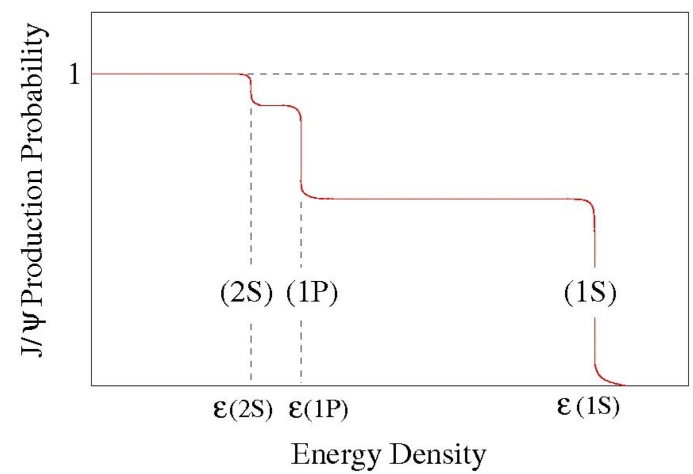
pair creation: ~100 ccbar 5-6 bbar

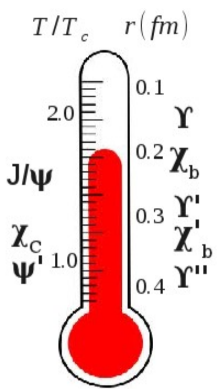
Melting <-> formation of quarkonium states
Thermalization
Flow of heavy quarks



- Colour screening
  - Matsui and Satz, PLB 178 (1986) 416

- Sequential suppression depending on binding energy
  - Digal, Petreczky, Satz, PRD (2001) 0940150

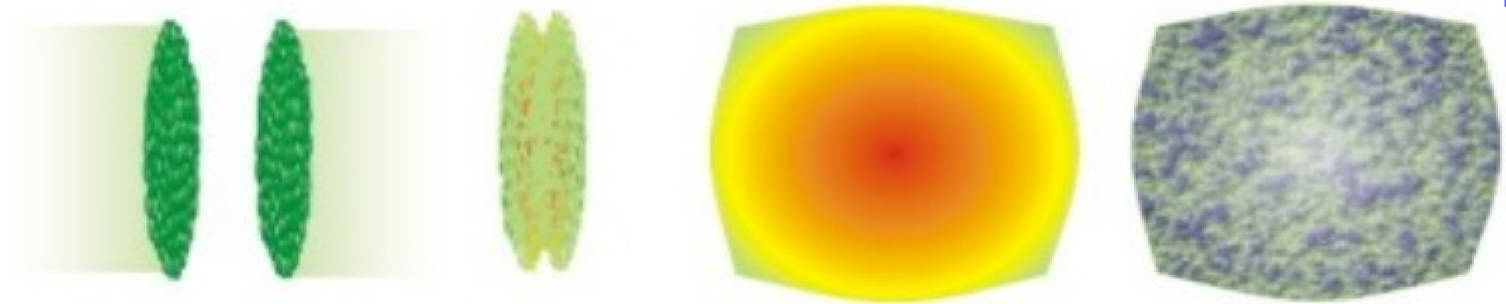




- Melting ↔ formation of quarkonium states
  - Thews et al., PRC 63 (2001) 054905
  - Transport models

Quarkonia in AA collisions

time | Initial state | Partonic stage | QGP hydro evolution | **Chemical freeze-out**



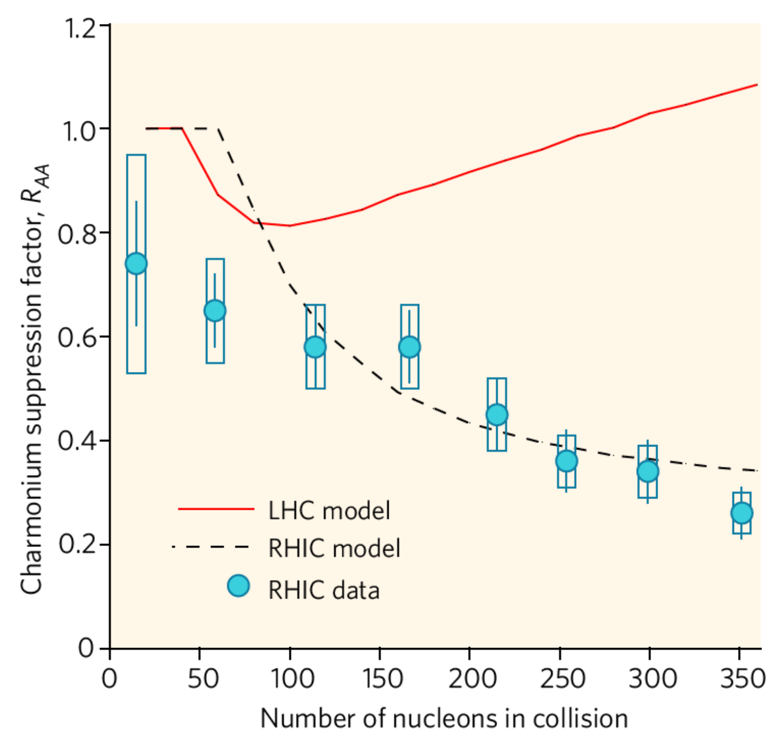
Shadowing, CGC

pair creation: ~100 ccbar 5-6 bbar

Melting <-> formation of quarkonium states Thermalization Flow of heavy quarks

Quarkonia formed via statistical hadronization ?

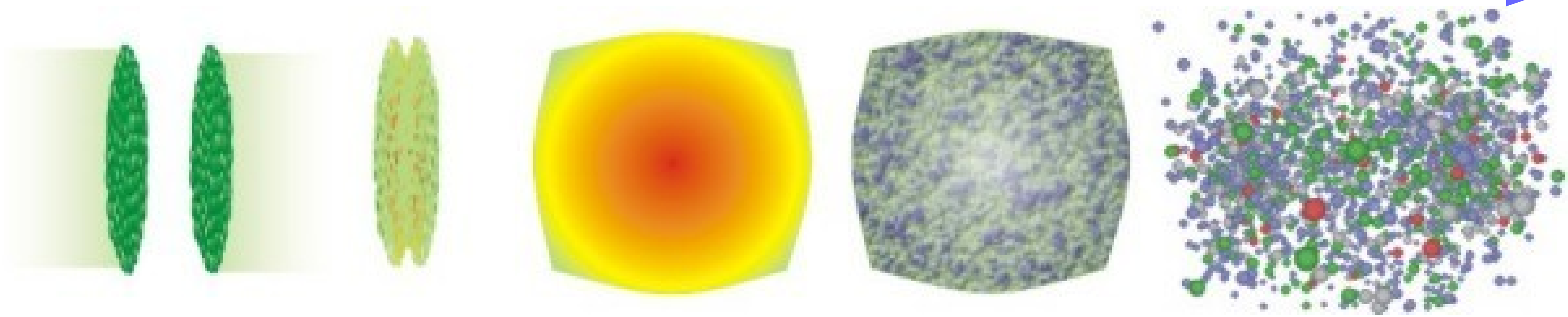
- Enhancement of quarkonia states from qqbar pairs at the chemical freeze-out
- Open charm and quarkonia abundancies calculated assuming statistical hadronization.
  - Braun-Munzinger and Stachel, PLB 490 (2000) 196



Quarkonia in AA collisions

time

Initial state | **Partonic stage** | **QGP hydro evolution** | **Chemical freeze-out** | **Kinetic freeze-out**



Shadowing, CGC

pairs creation:
~100 ccbar
5-6 bbar

Melting <-> formation of quarkonium states
Thermalization
Flow of heavy quarks

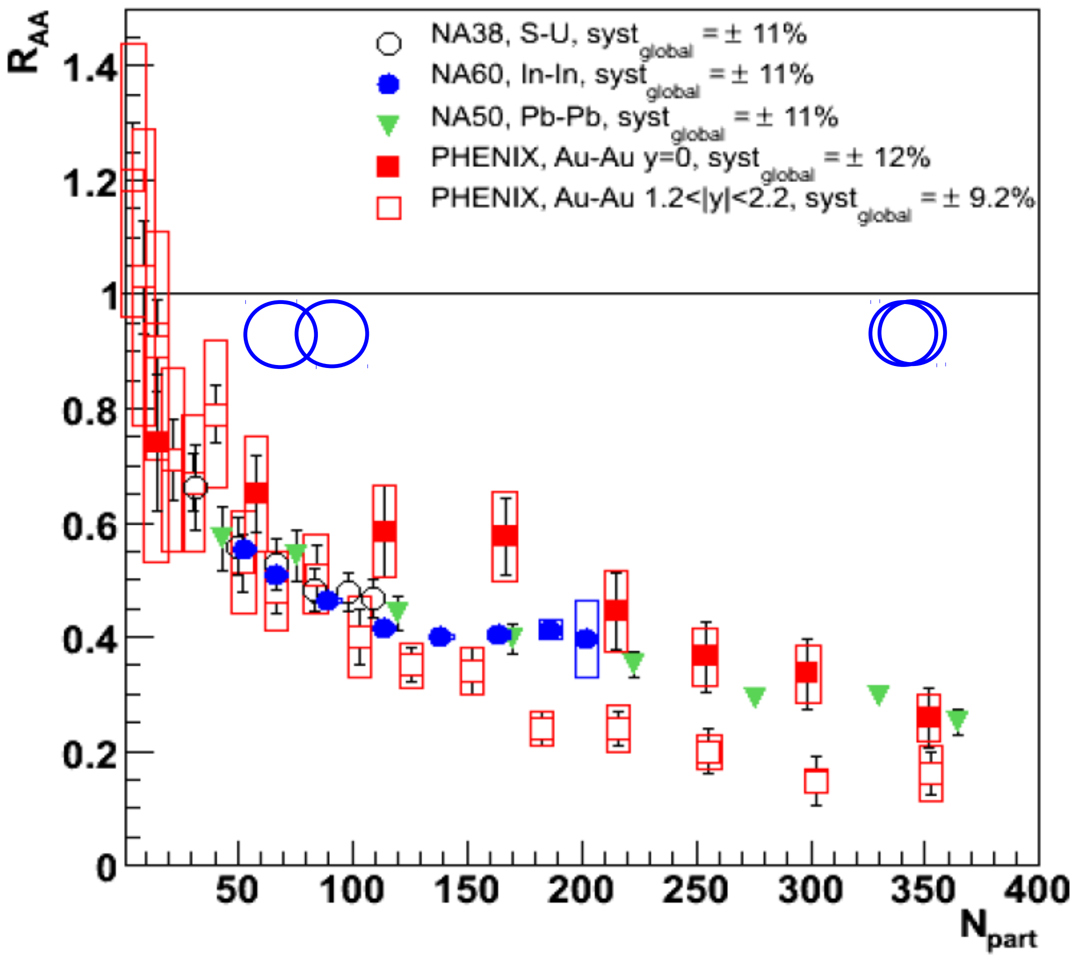
Quarkonia formed via statistical hadronization ?

Free streaming, decays

- A large variety of results already available from Pb-Pb at the LHC:
  - J/ψ vs. centrality, rapidity and p_T
  - ψ'
  - Υ family vs centrality and rapidity
- Results from p-Pb collisions:
  - J/ψ, Υ(1S)

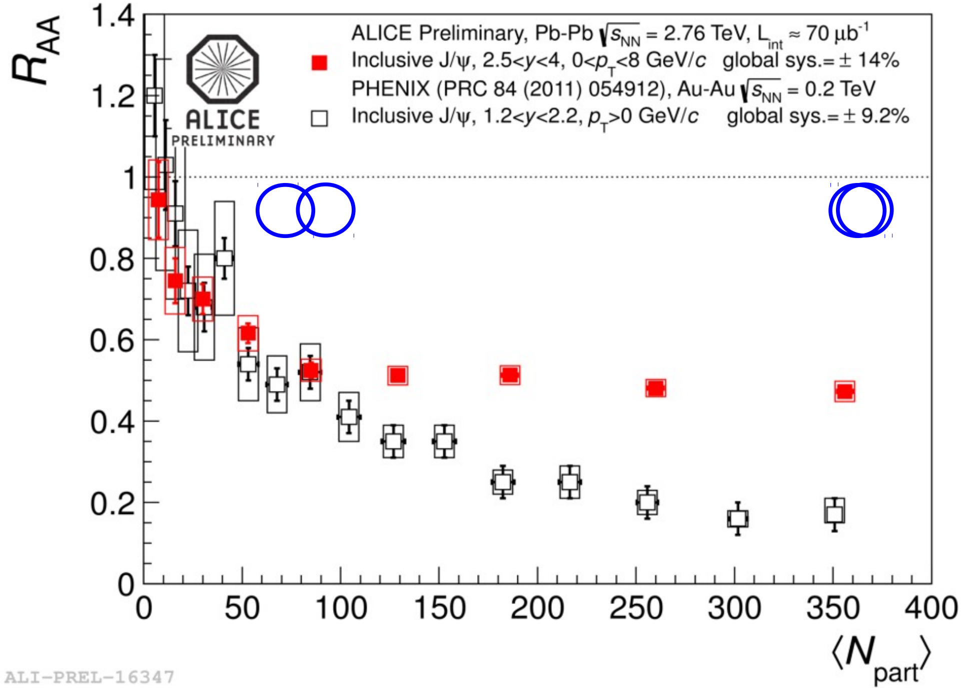
Charmonia

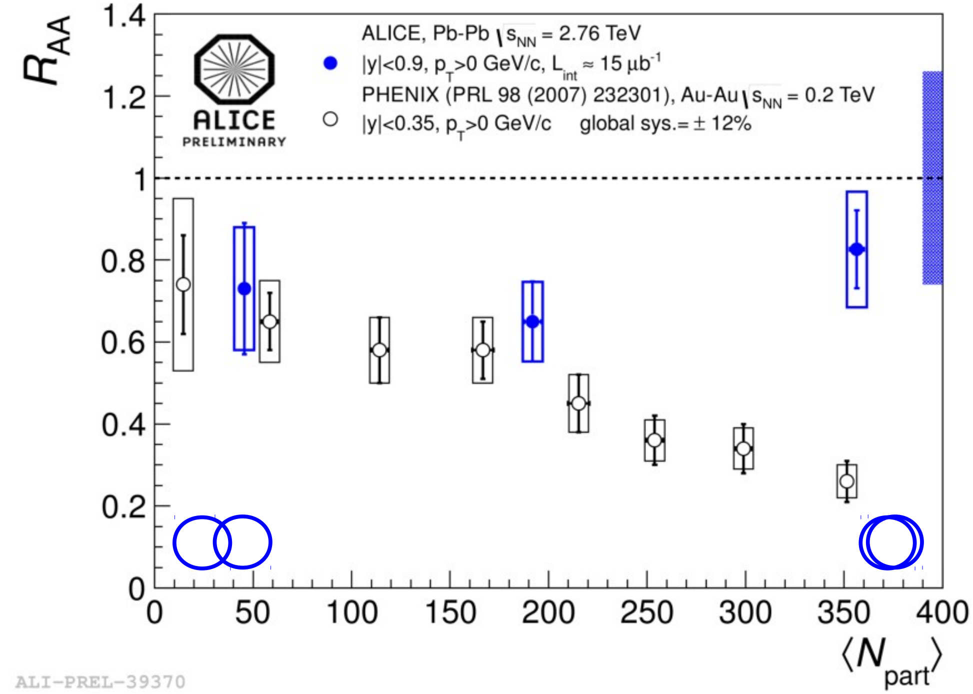
Charmonium at lower energy experiments



- Puzzles:
  - Observation: Similar suppression factor vs centrality observed at mid-rapidity at SPS and RHIC.
    Explanation: Charmonia created from uncorrelated $c\bar{c}$ pairs during fireball evolution or at freeze-out, aka (re)combination
  - Observation: At RHIC, more suppression at forward than at mid-rapidity
    Explanation: (Re)combination and shadowing/saturation effects should depend on rapidity

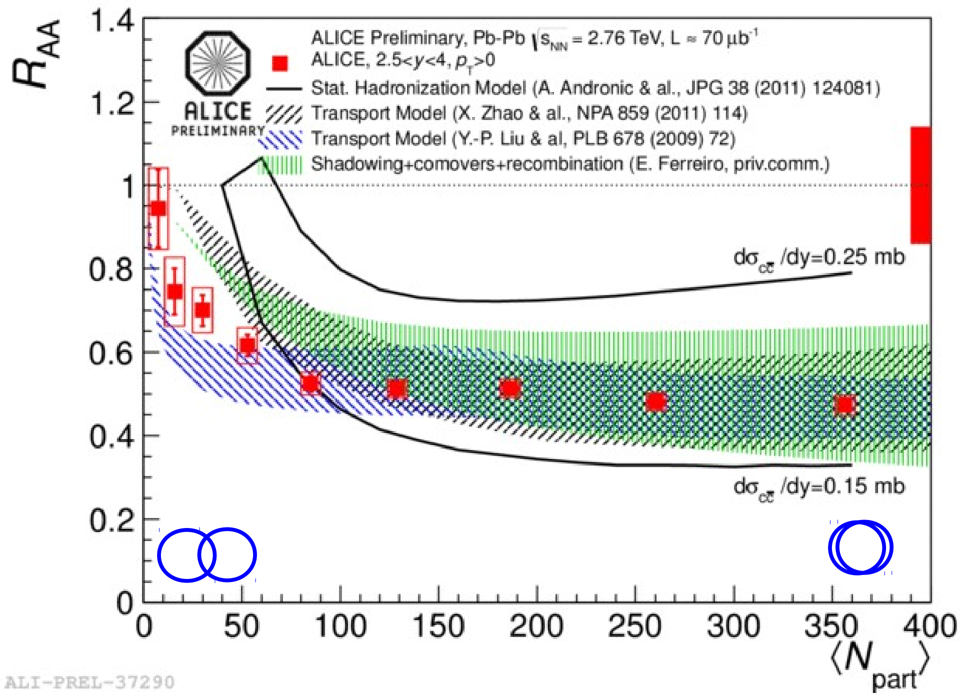
Inclusive J/ψ at the LHC

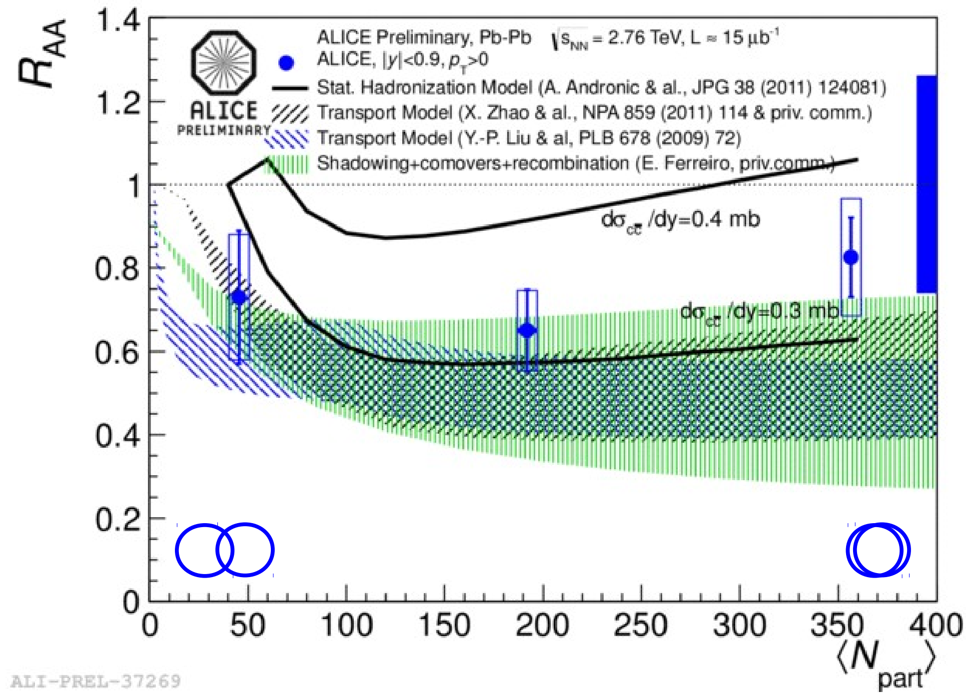




- Clear J/ψ suppression seen for all centralities
- Indication of less suppression at mid-rapidity
- ALICE results show smaller suppression compared to lower energies (PHENIX) in central collisions

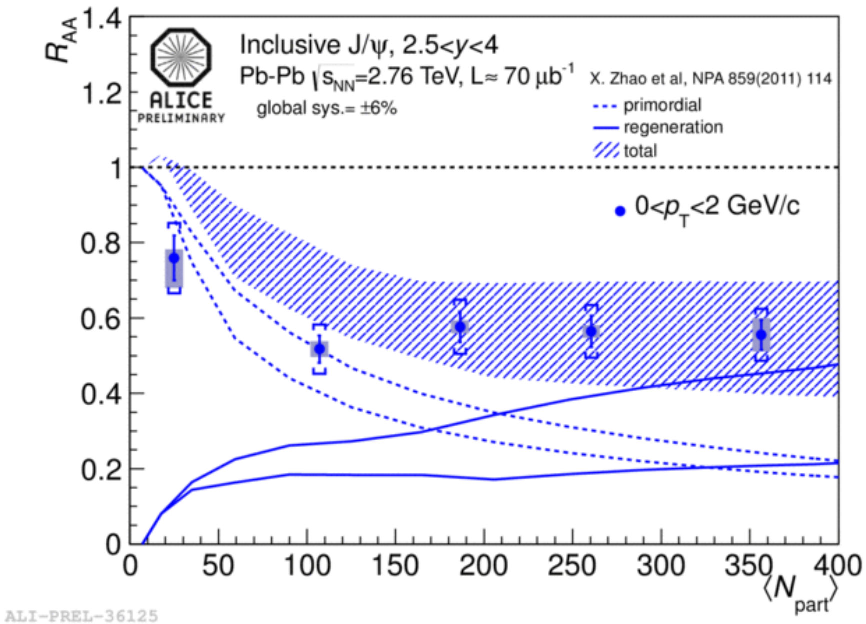
Inclusive J/ψ at the LHC

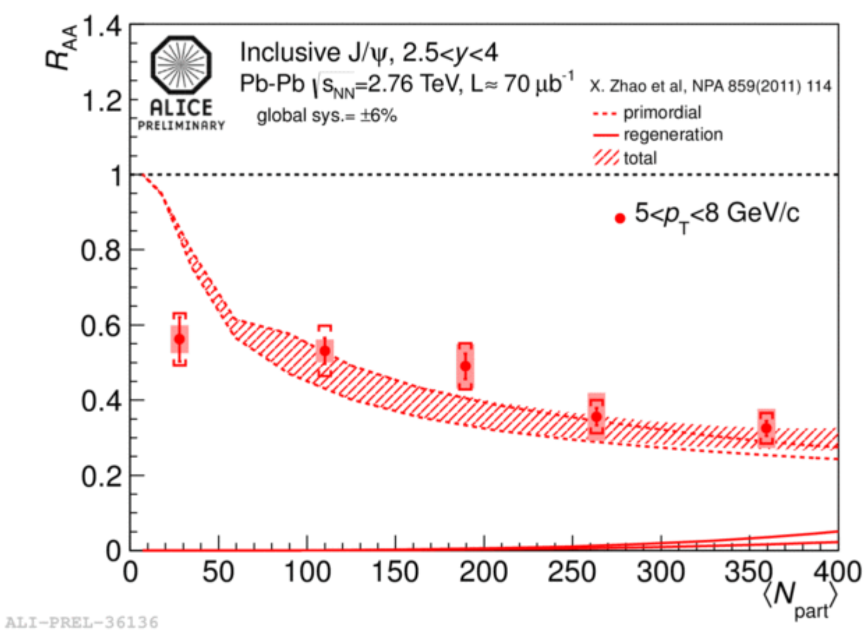


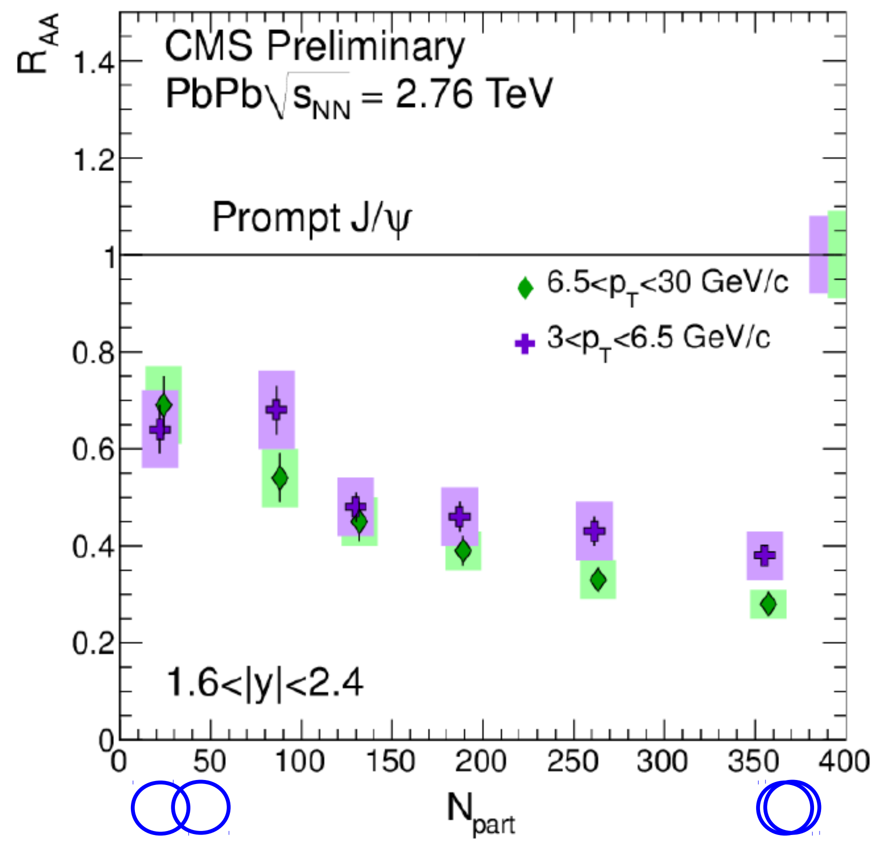


- Models which include (re)combination agree with the data.
- Uncertainties on the total $c\bar{c}$ cross-section and CNM need to be improved to fully constrain models

J/ψ as a function of p_T

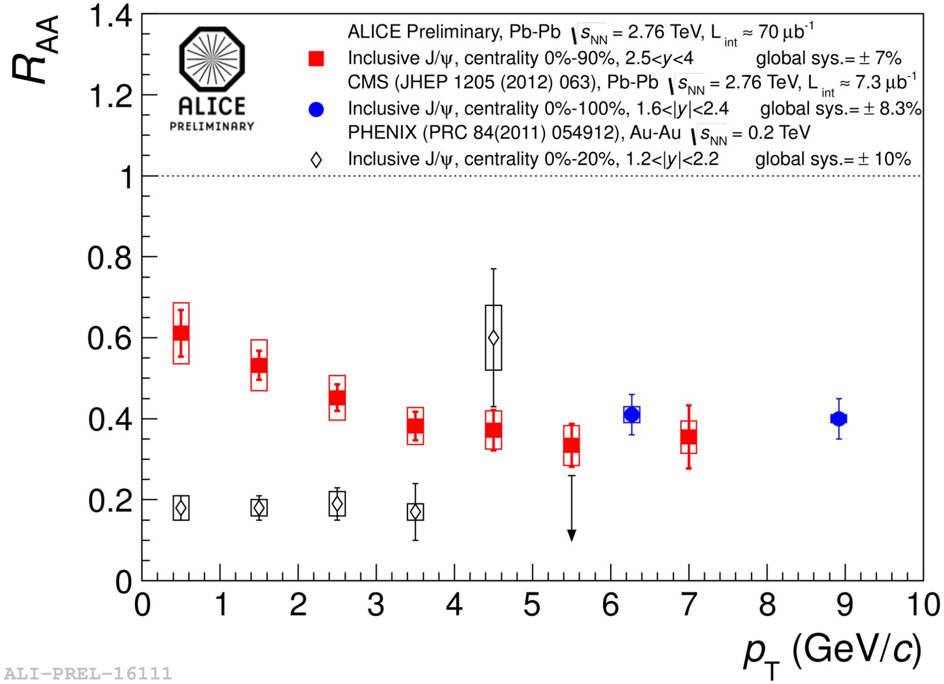




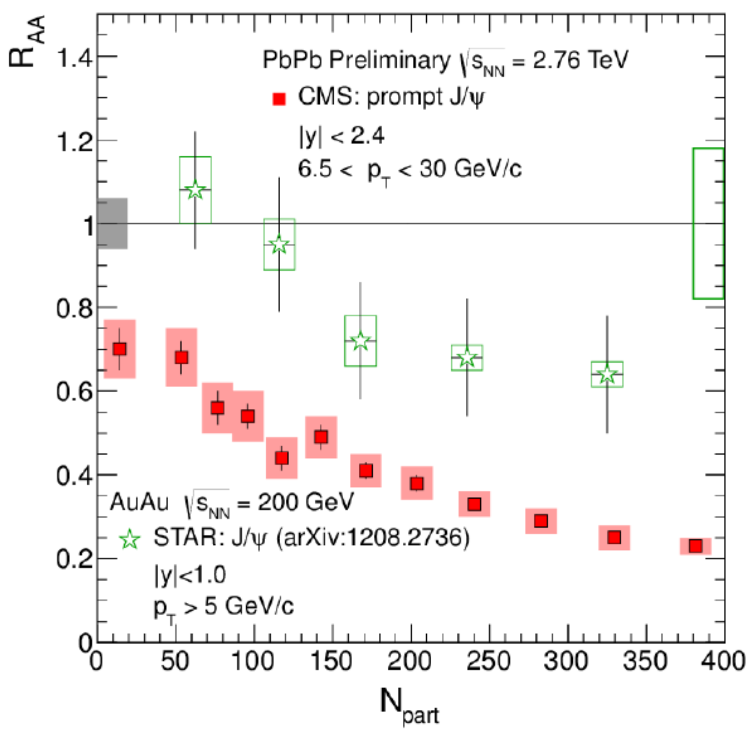


- Less suppression observed at low p_T (ALICE)
  - 50% of the J/ψ yield produced via (re)combination in transport models
- Stronger suppression and centrality dependence at high p_T (CMS, ALICE)

J/ψ as a function of p_T

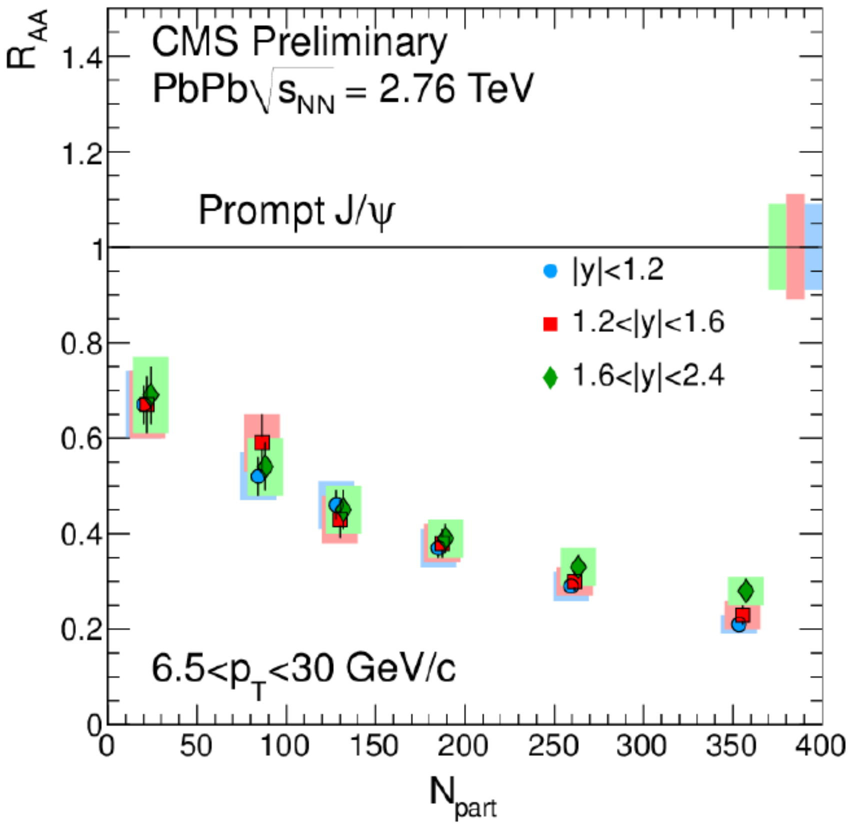


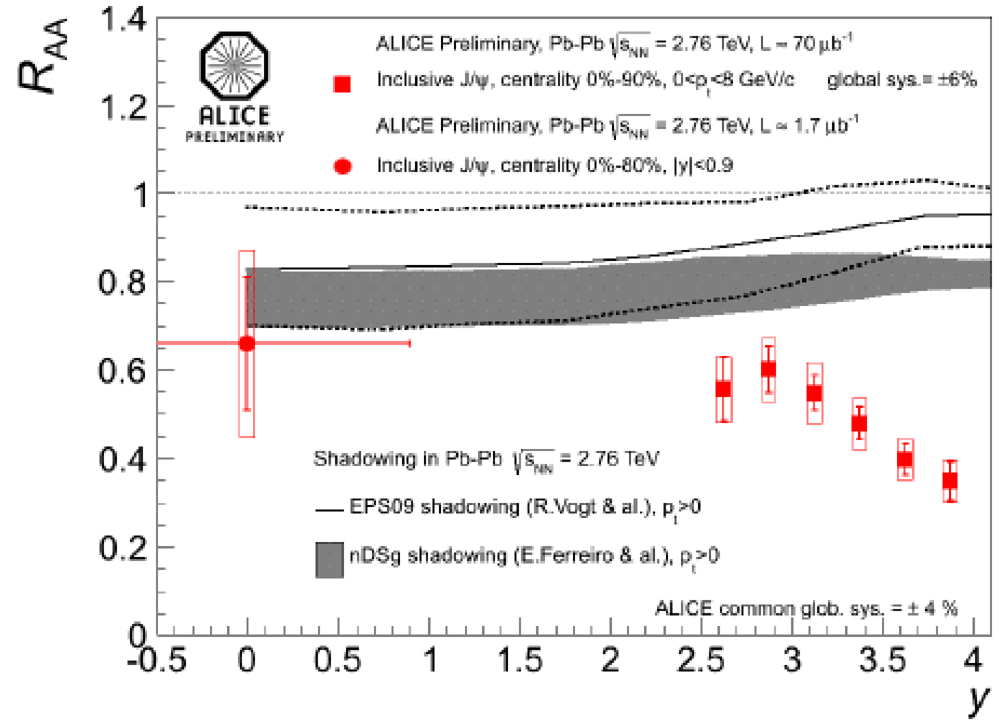
- Striking difference between LHC and RHIC at low-p_T
  - "Smoking gun" for (re)combination ?
- Good agreement between ALICE and CMS data



- Stronger suppression at LHC for high-p_T J/ψ's
  - Negligible (re)combination expected in this kinematic range
  - Higher energy density at LHC at play

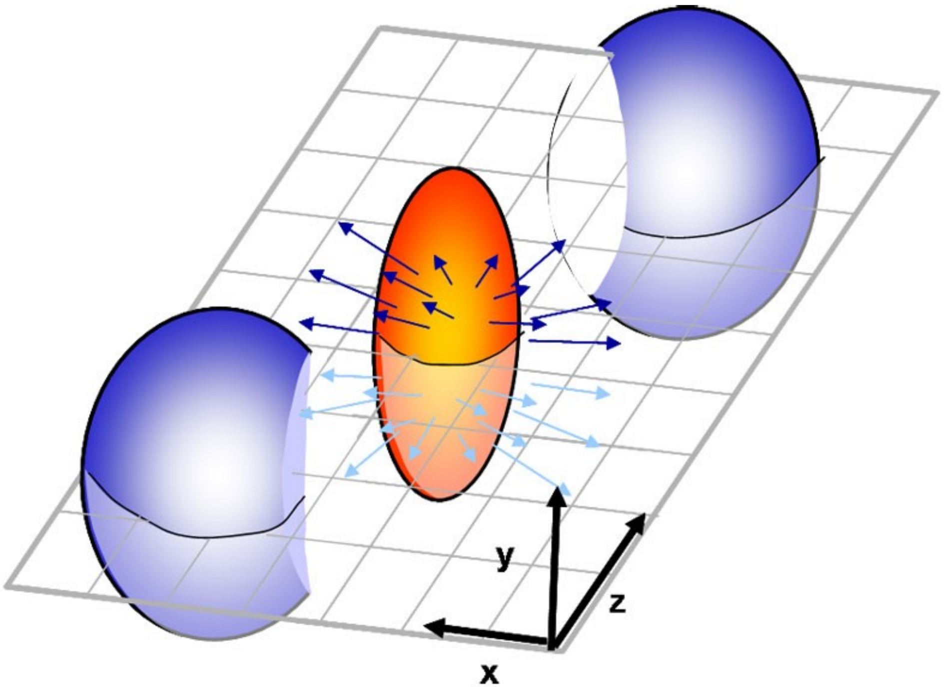
J/ψ as a function of rapidity



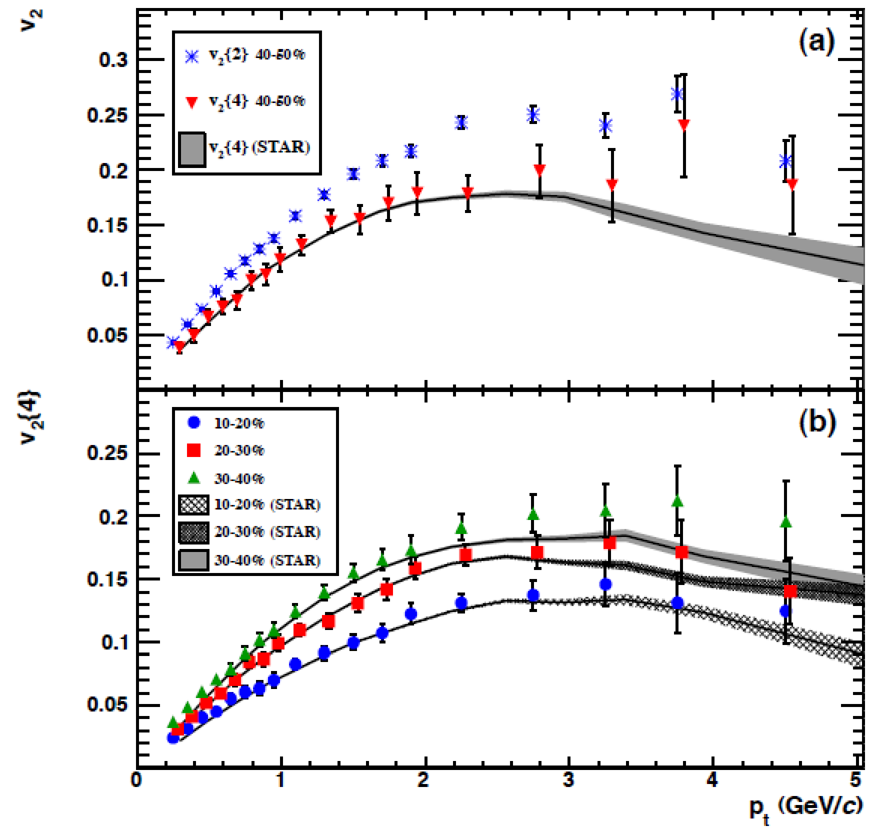


- No significant rapidity dependence seen at high-p_T (CMS)
- Strong rapidity dependence for low-p_T (ALICE)
  - CNM effects, (re)combination ?

Elliptic flow

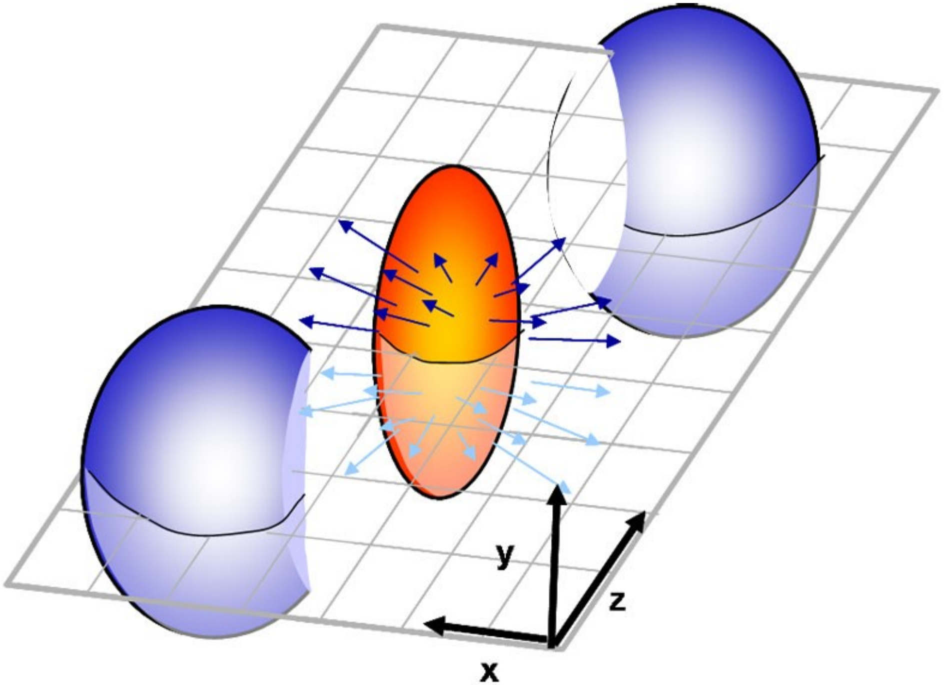


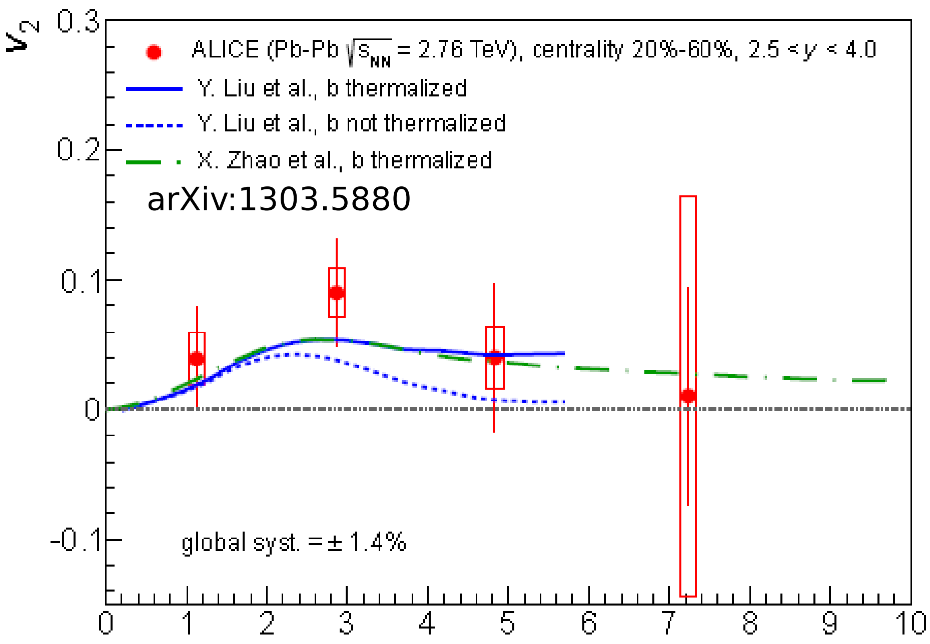
ALICE PRL105 (2010) 252302

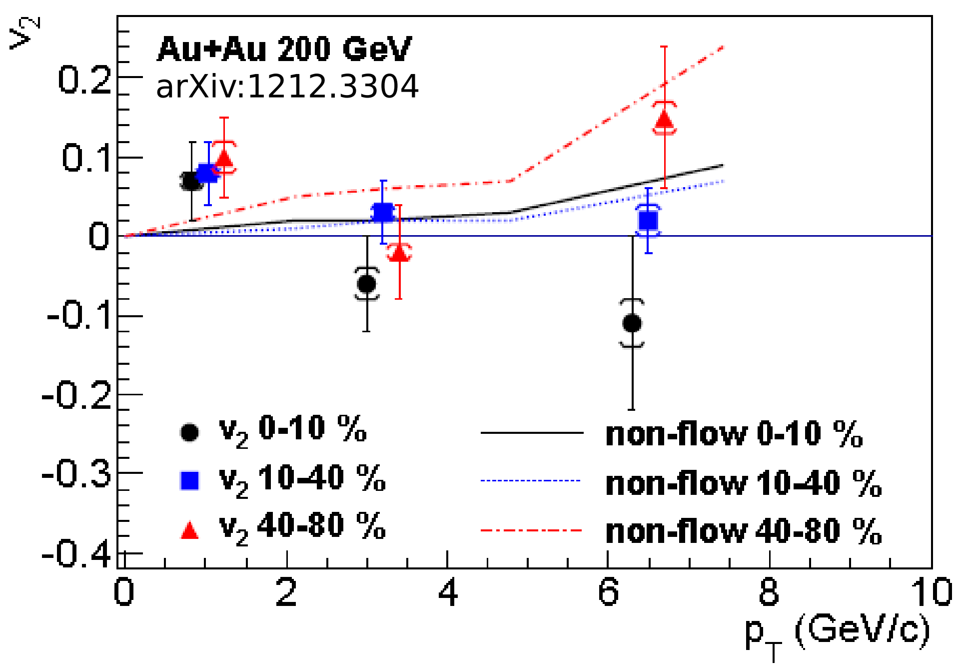


- Initial spatial anisotropy is converted into momentum-space anisotropy
- Strong elliptic flow observed for light particles
- Is J/ψ inheriting any of the fireball collective flow via (re)combination?

Elliptic flow

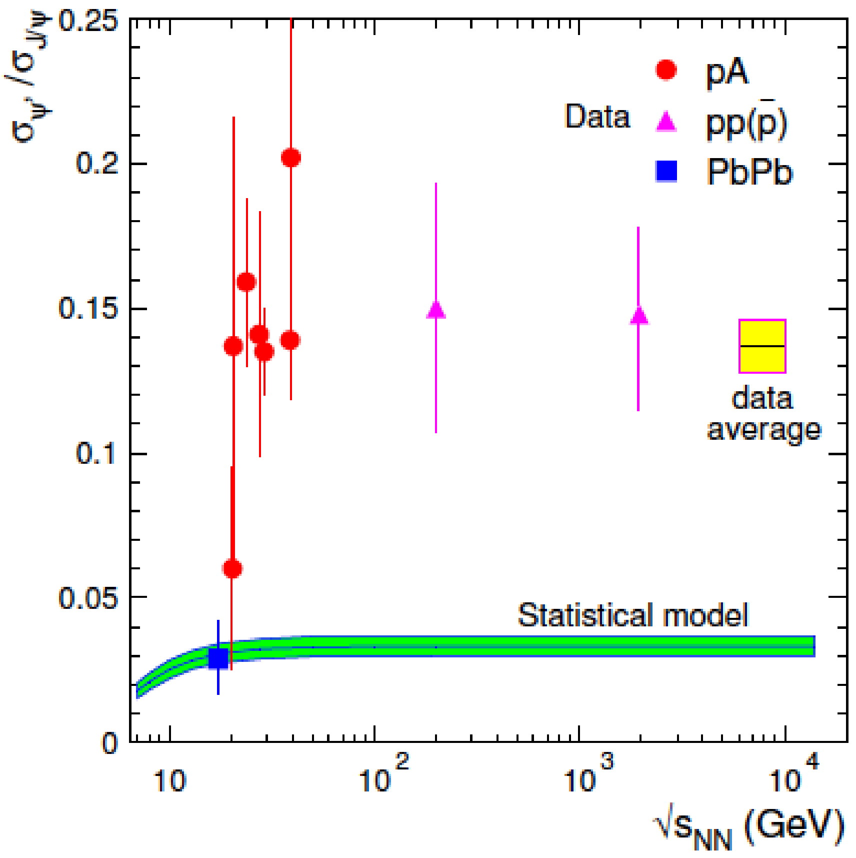


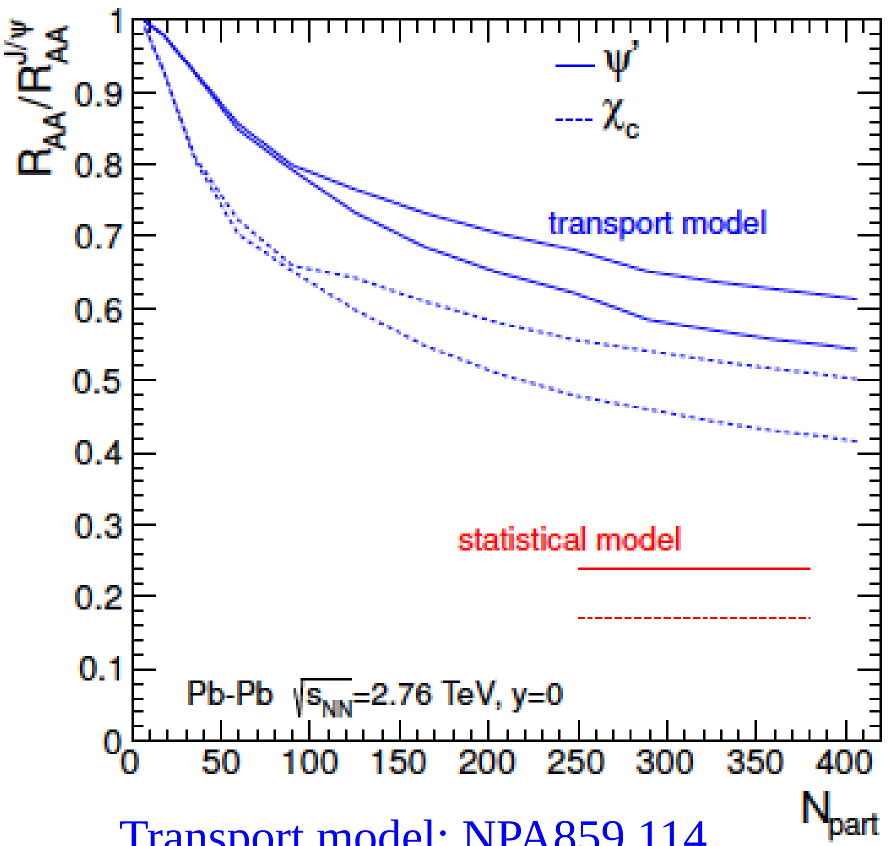




- Measurements at RHIC compatible with no flow
- LHC data hints towards a non-zero flow in semi-central collisions

ψ'

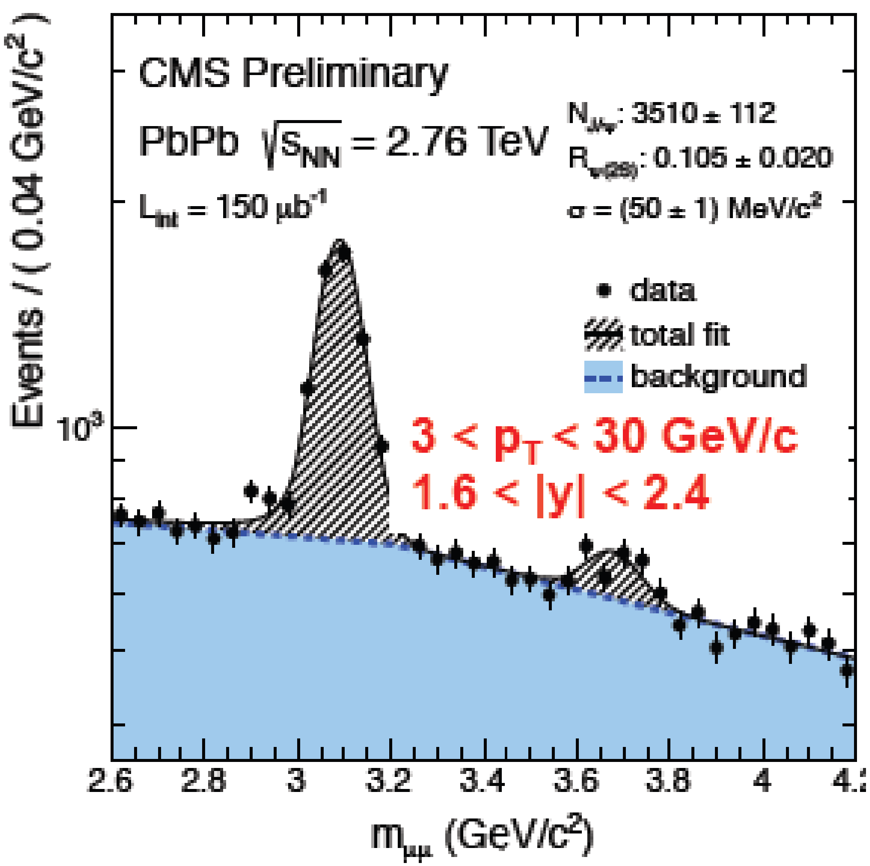


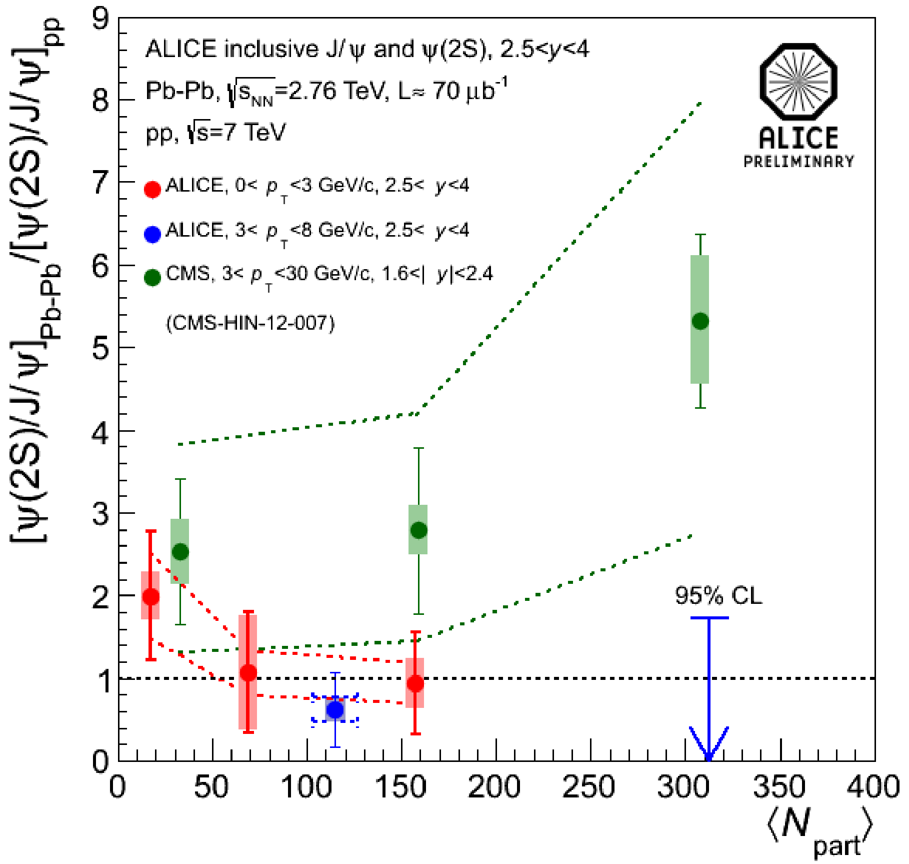


Transport model: NPA859 114
Statistical model: PLB490 196

- ψ(2S) has a much smaller binding energy
- Very important measurement since:
  - Ratio of R_{AA}'s for different charmonia are less dependent on the charm cross section
  - Transport and statistical hadronization models can be disentangled

ψ'

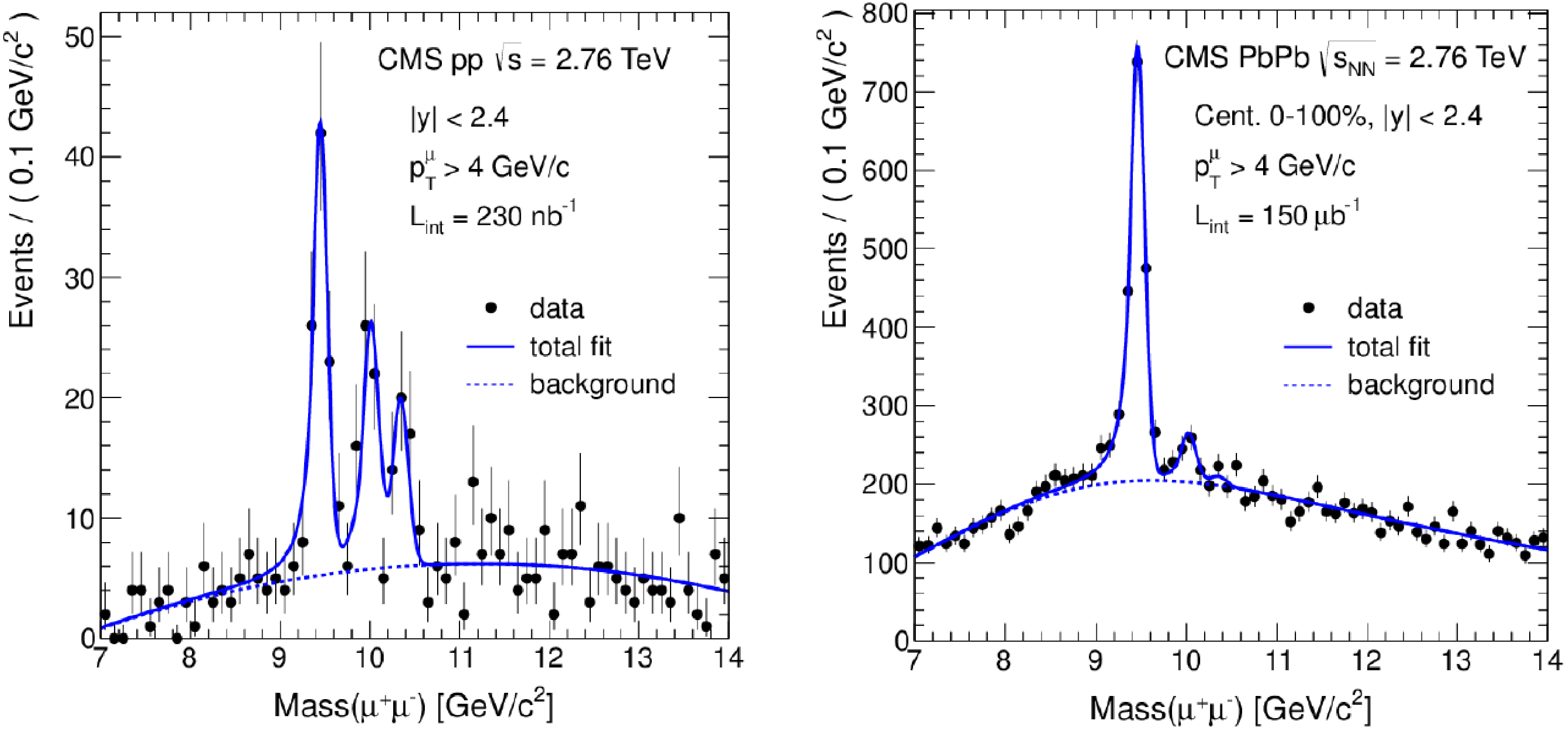




- Results available from both ALICE and CMS, but in different kinematical ranges
- Large statistical and systematic uncertainties prevent a firm conclusion
- ALICE data seems to exclude a large ψ(2S) enhancement in central collisions

Bottomonia

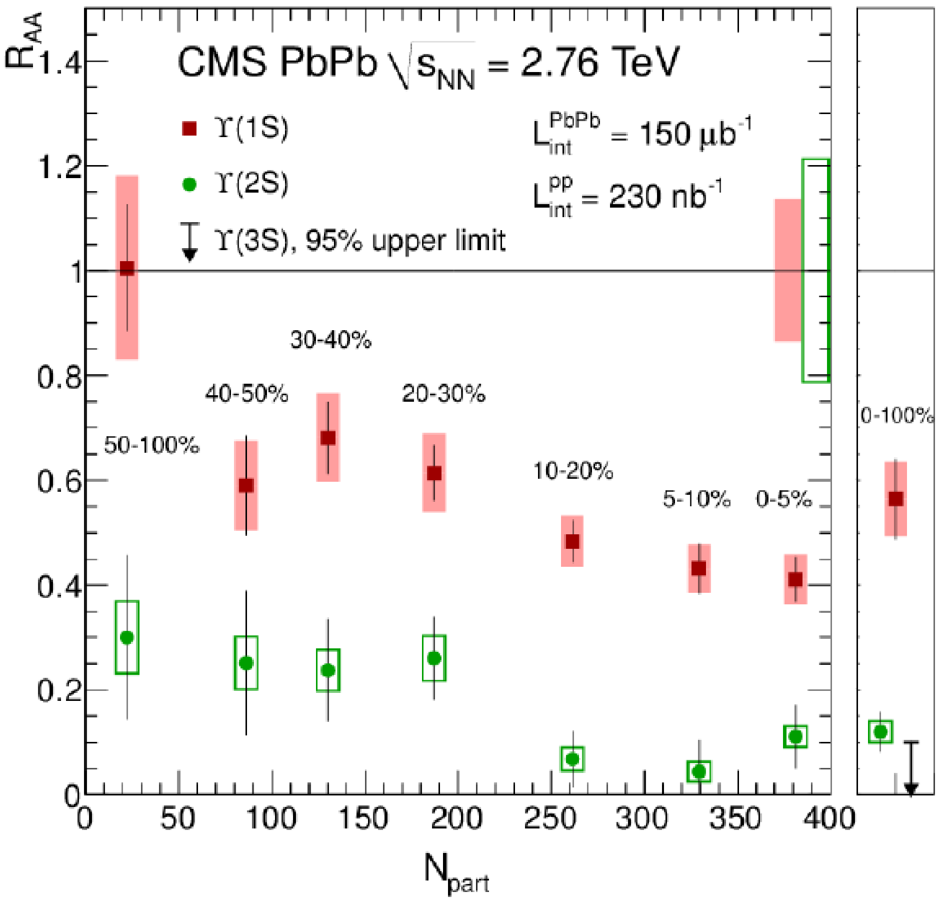
PRL109 (2012) 222301

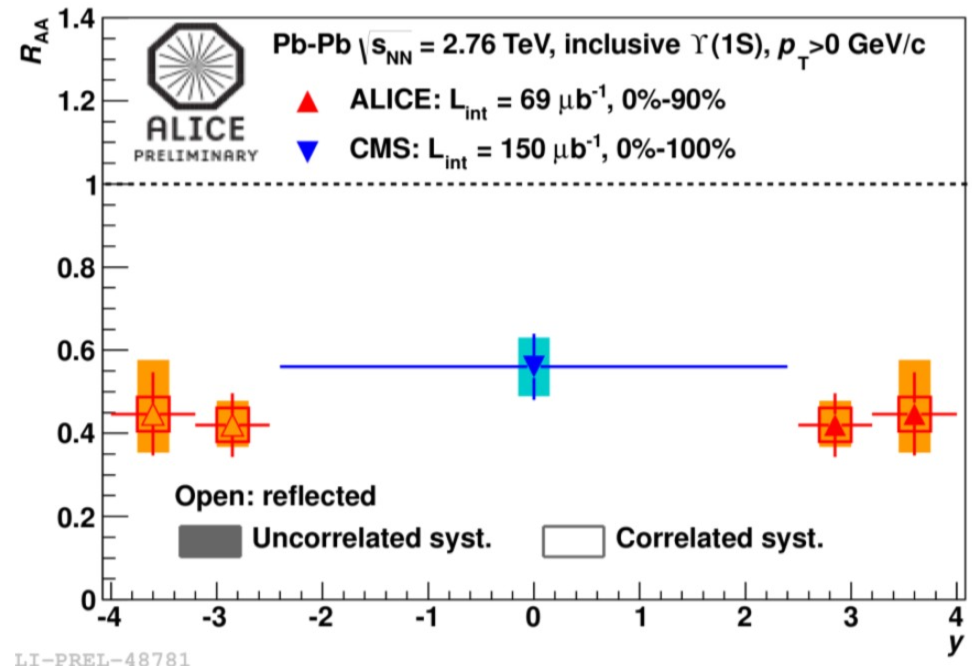


- Suppression of Υ(2S) and Υ(3S) states w.r.t. Υ(1S) in Pb-Pb already visible from the invariant mass spectra.

Y suppression

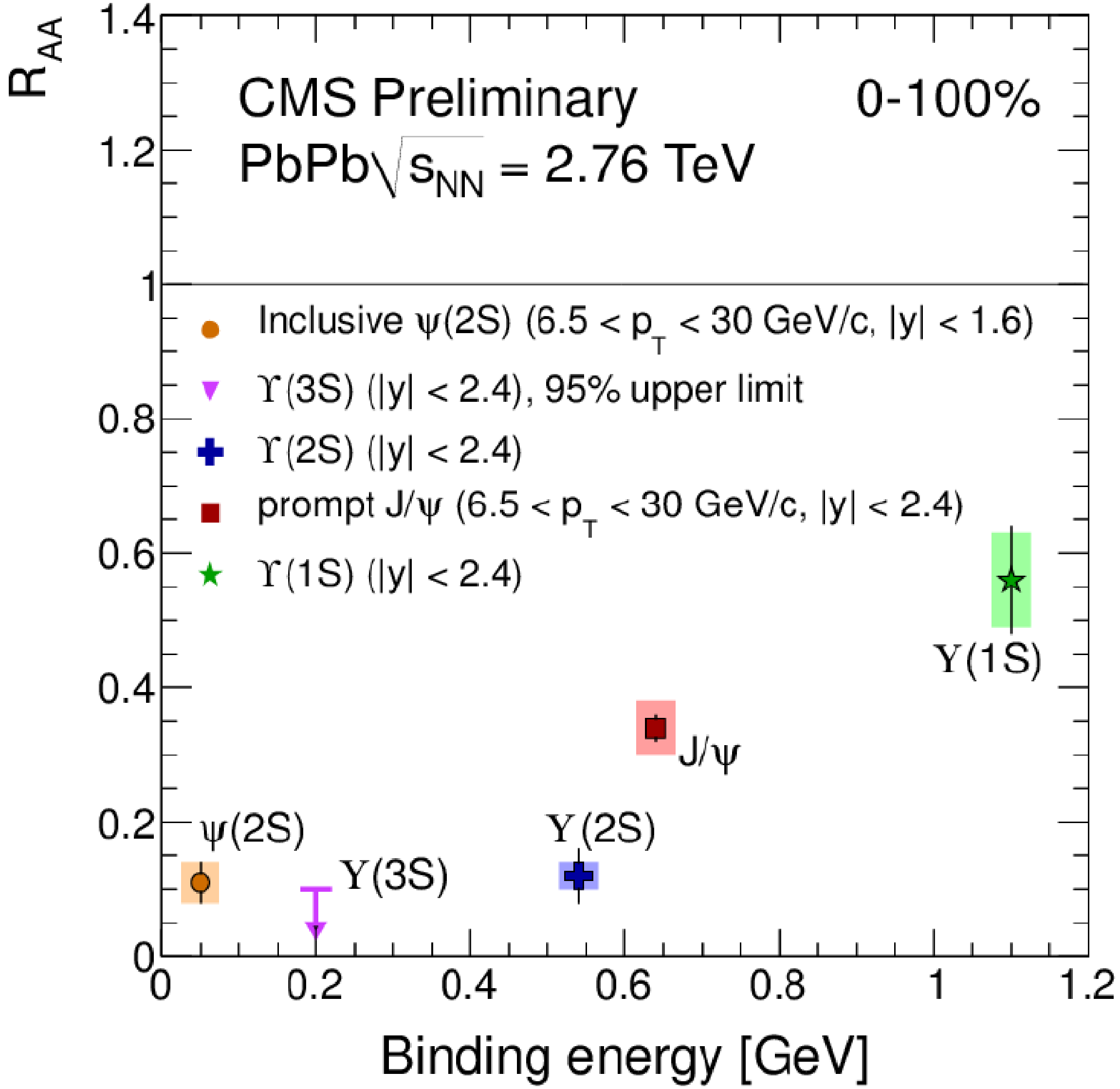
PRL109 (2012) 222301





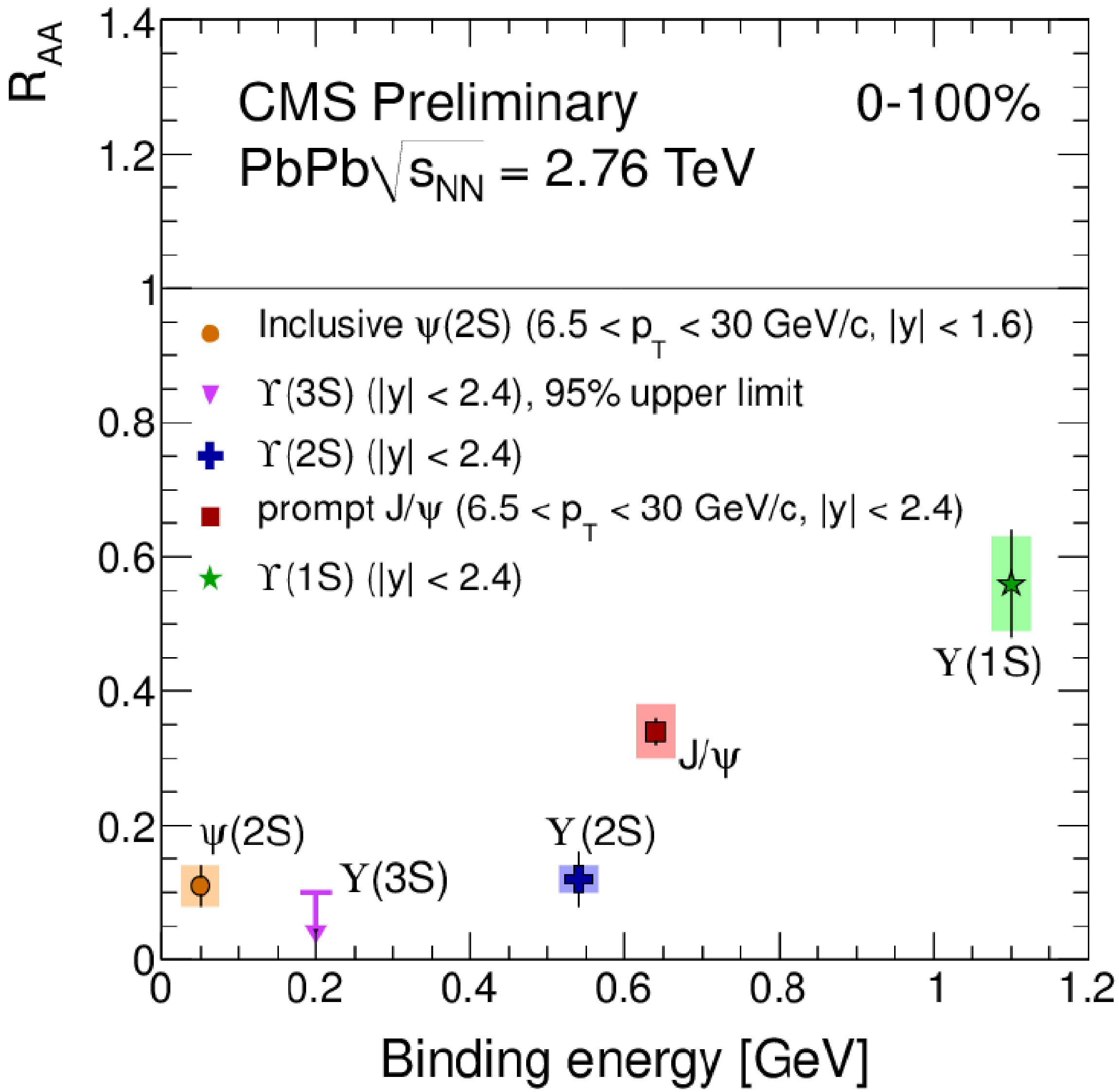
- Acceptance down to p_T=0 for both CMS and ALICE
- Strong centrality dependence for the R_{AA} of both Y(1S) and Y(2S)
  - (Re)combination should have a much smaller effect compared to charmonia
- $R_{AA}^{Y(3S)} < R_{AA}^{Y(2S)} < R_{AA}^{Y(1S)}$ → sequential suppression of Y states
- No strong rapidity dependence within uncertainties

The big picture

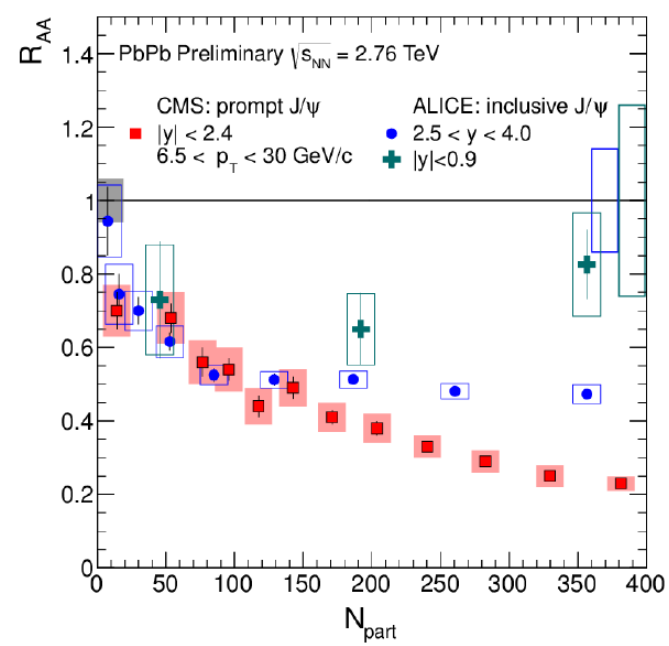


- CMS results indicate a hierarchy of quarkonia suppression which depends on the binding energy

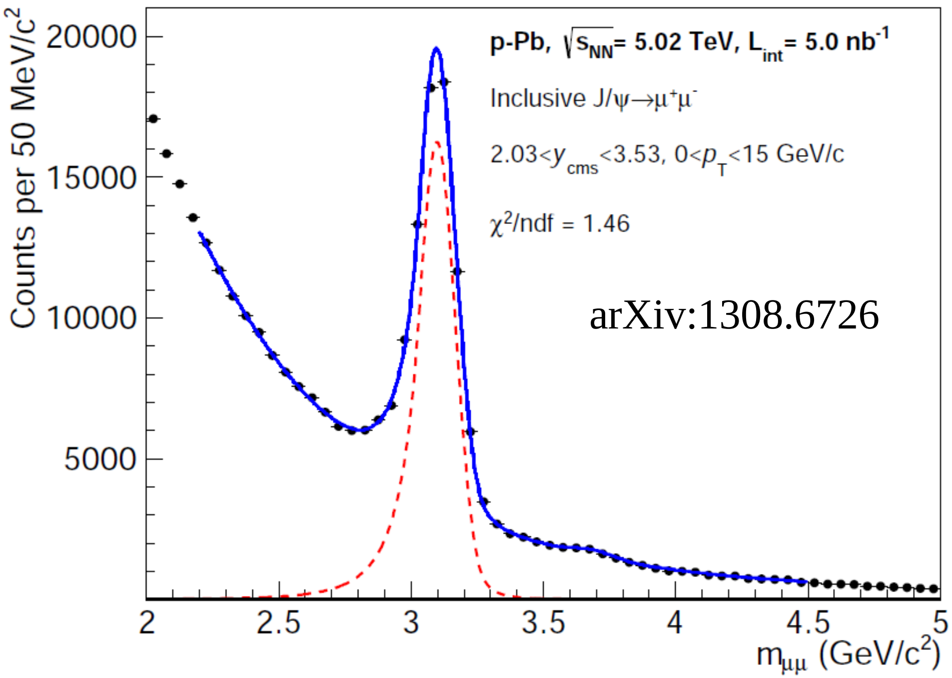
The big picture

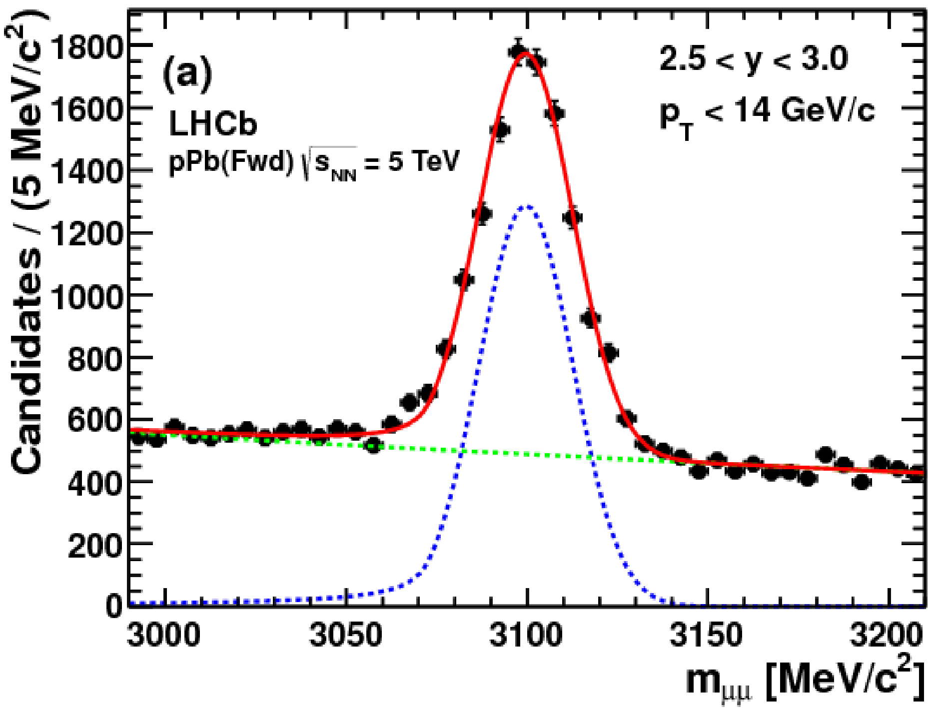


- CMS results indicate a hierarchy of quarkonia suppression which depends on the binding energy
- However, different kinematical coverage for the Y and ψ families make comparisons difficult



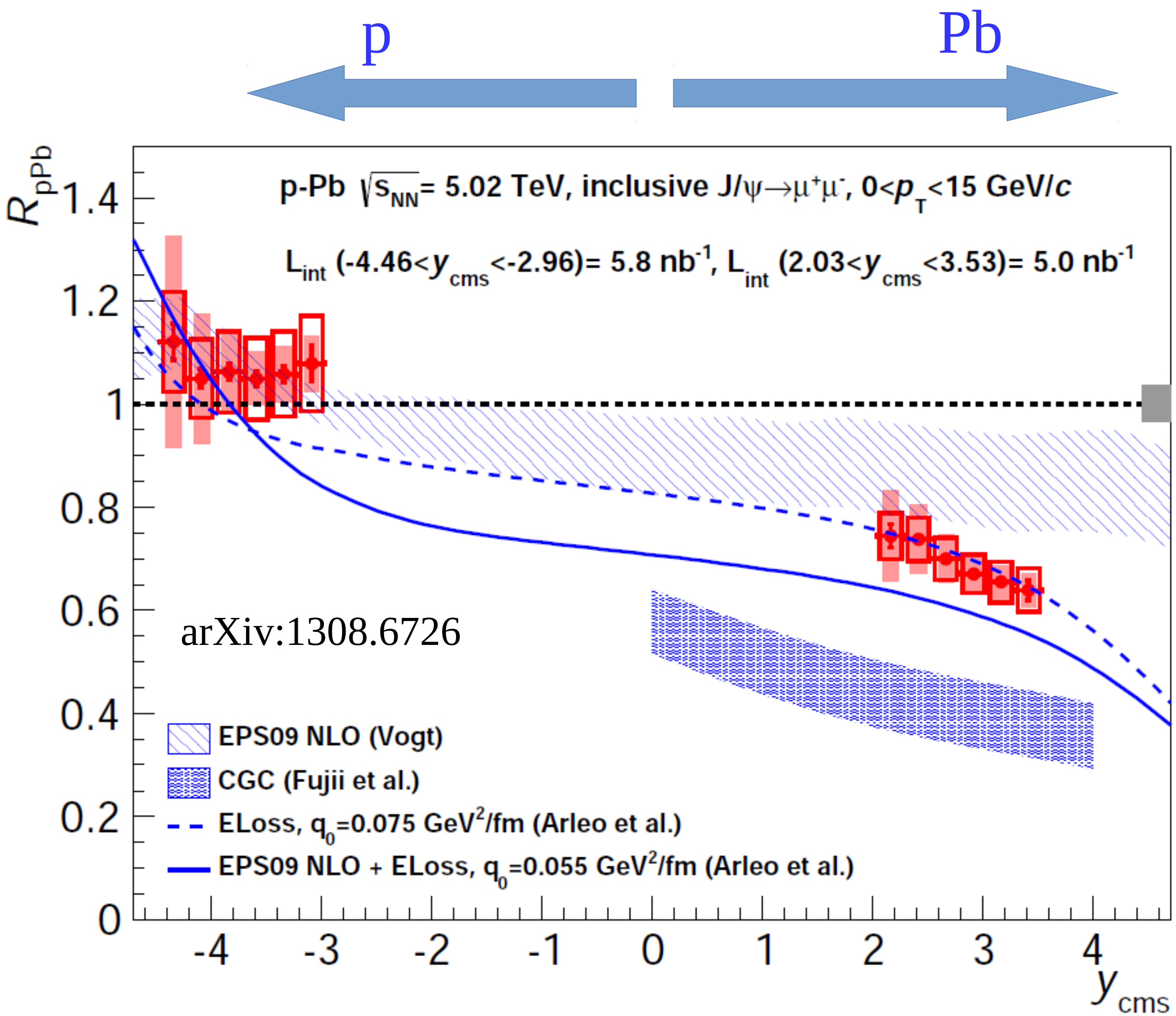
p-Pb collisions at 5.02 TeV





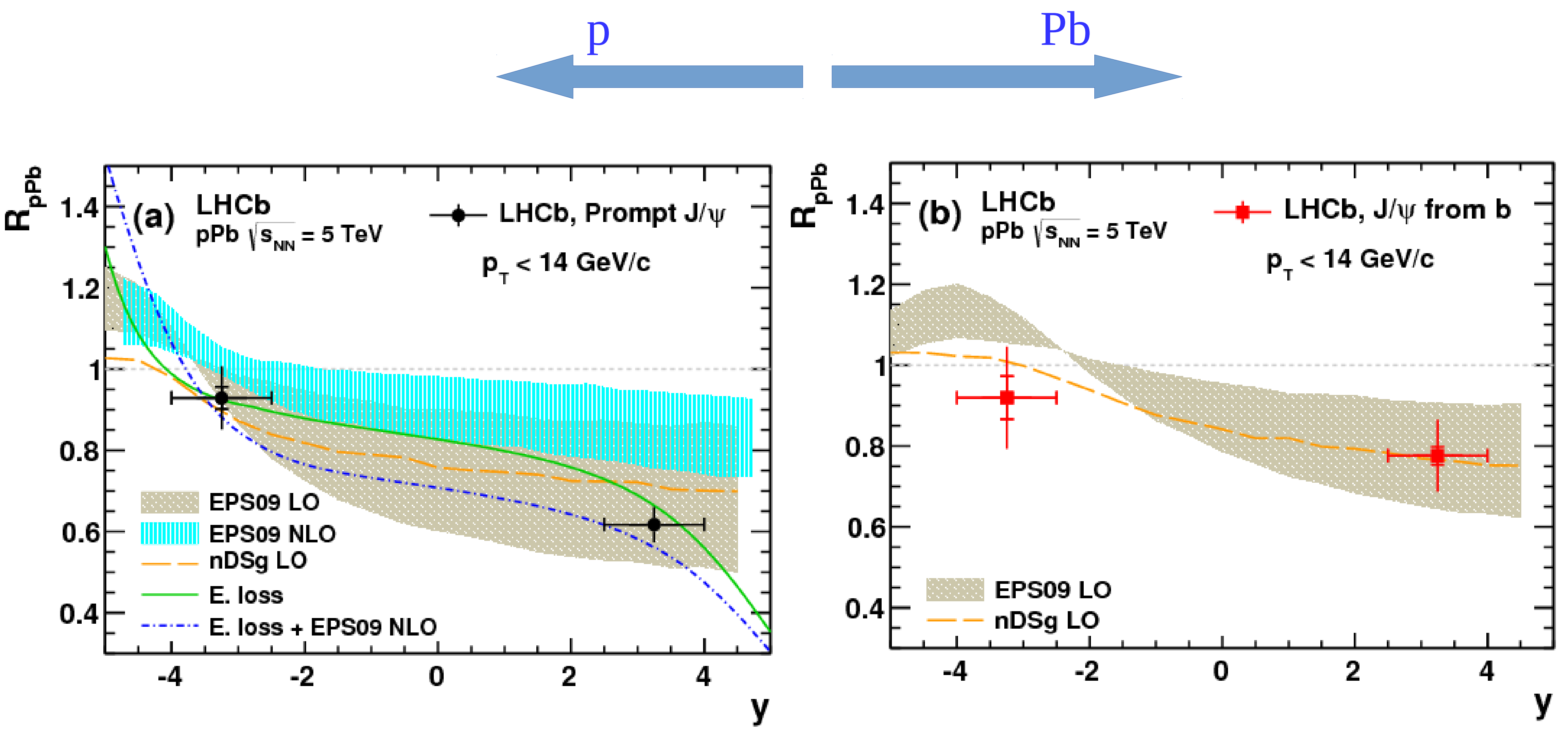
- Investigate cold nuclear matter effects:
  - Shadowing, gluon saturation, parton energy loss, etc...
- Help to understand pure QGP effects

J/ψ suppression in p-Pb



- J/ψ suppressed in the Pb going side while slightly enhanced in the p going side
- The results can be largely explained via shadowing only but adding final state energy loss provides good predictions as well
- Gluon saturation / CGC model seem to overestimate the suppression

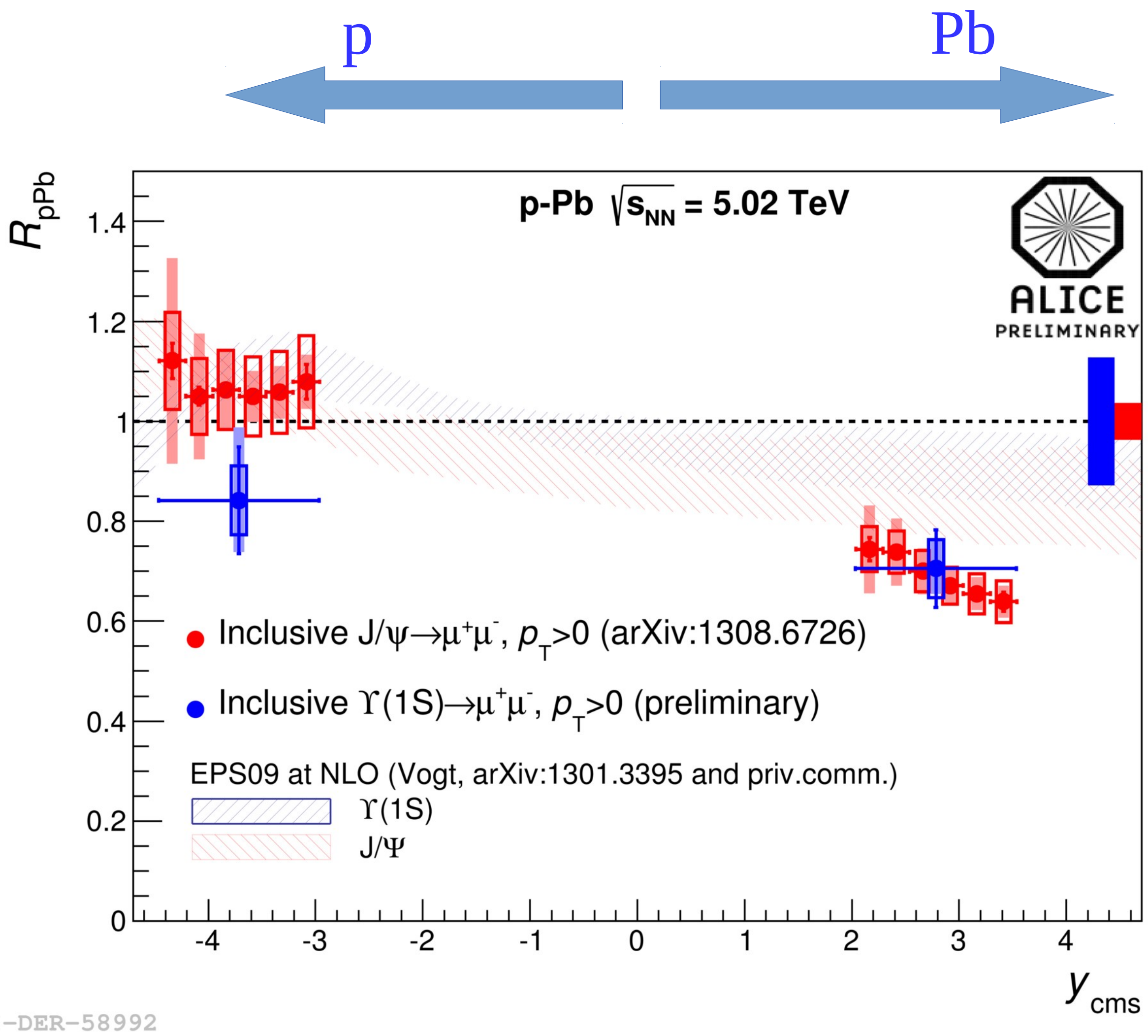
J/ψ suppression in p-Pb



LHCb joined the heavy ion program !

- J/ψ suppressed in the Pb going side while slightly enhanced in the p going side
- The results can be largely explained via shadowing only but adding final state energy loss provides good predictions as well
- Gluon saturation / CGC model seem to overestimate the suppression

Y suppression in p-Pb



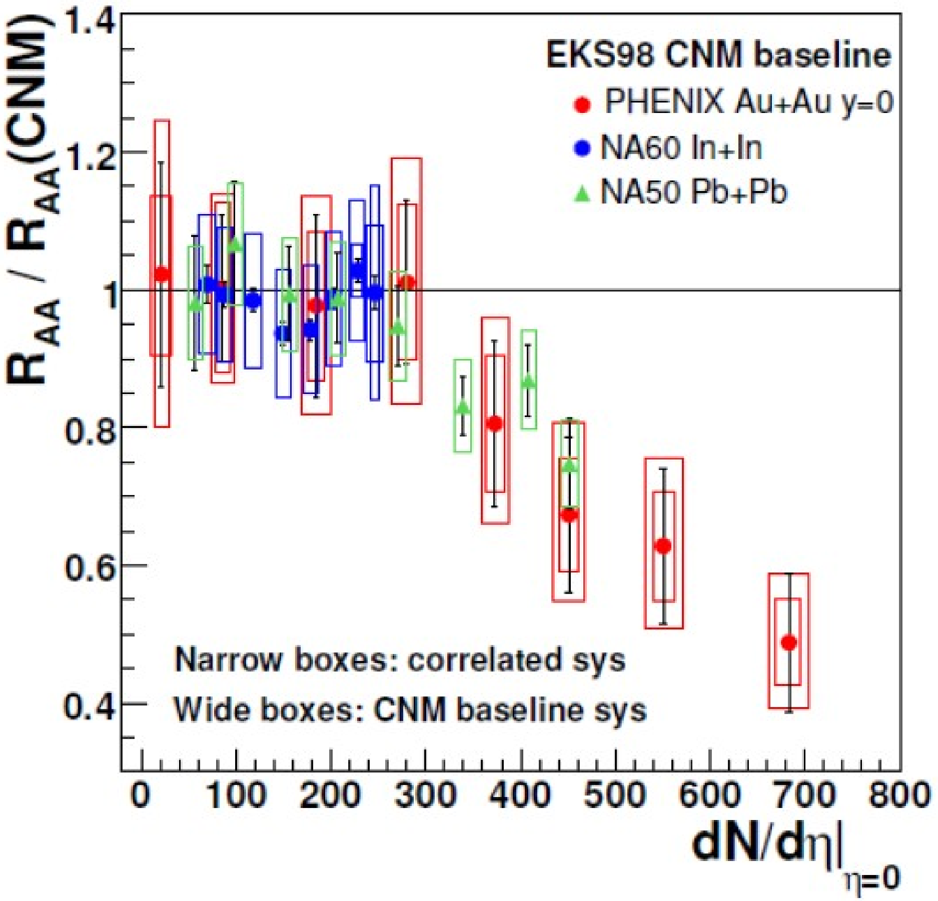
- Y(1S) shows similar suppression as J/ψ in the Pb going side
- Differences observed on the p going side but uncertainties are still rather large

Summary

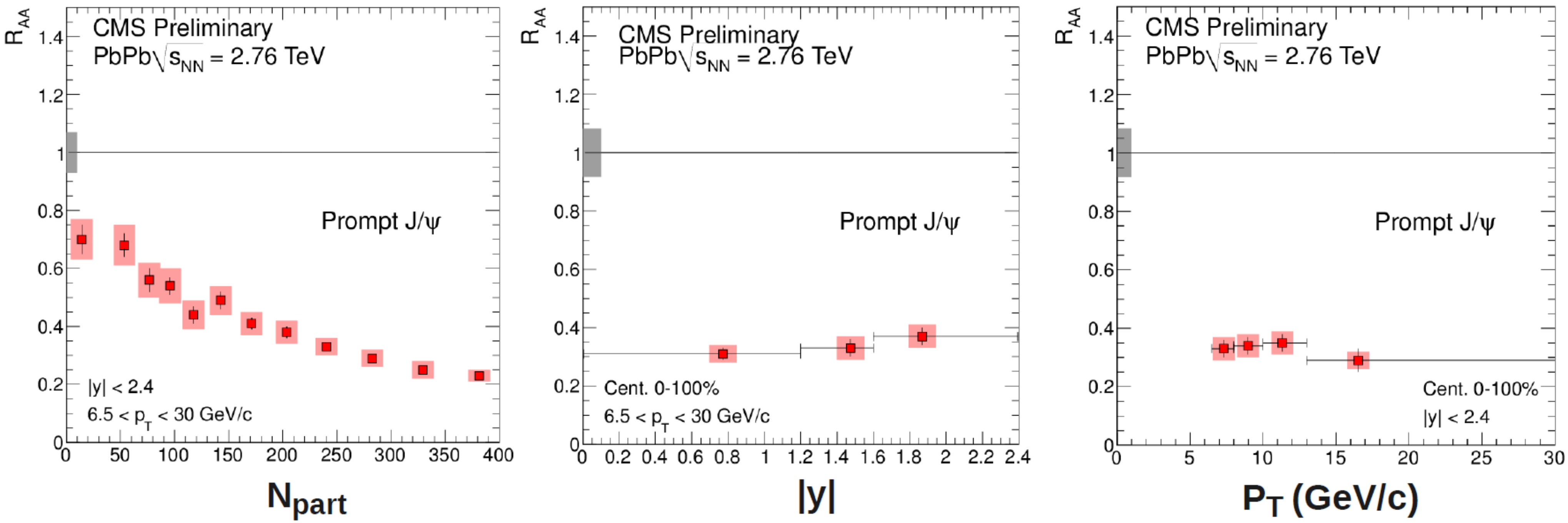
- LHC provided interesting new observations on heavy quarkonia
  - Strong support for a new charmonia production mechanism: (re)combination
  - Clear sequential suppression of bottomonia states
- We still need to
  - Understand the impact of CNM effects
  - Disentangle the suppression and enhancement effects
  - Quantify the feed-down contributions
  - Understand how all this fits into what we already know

Backup

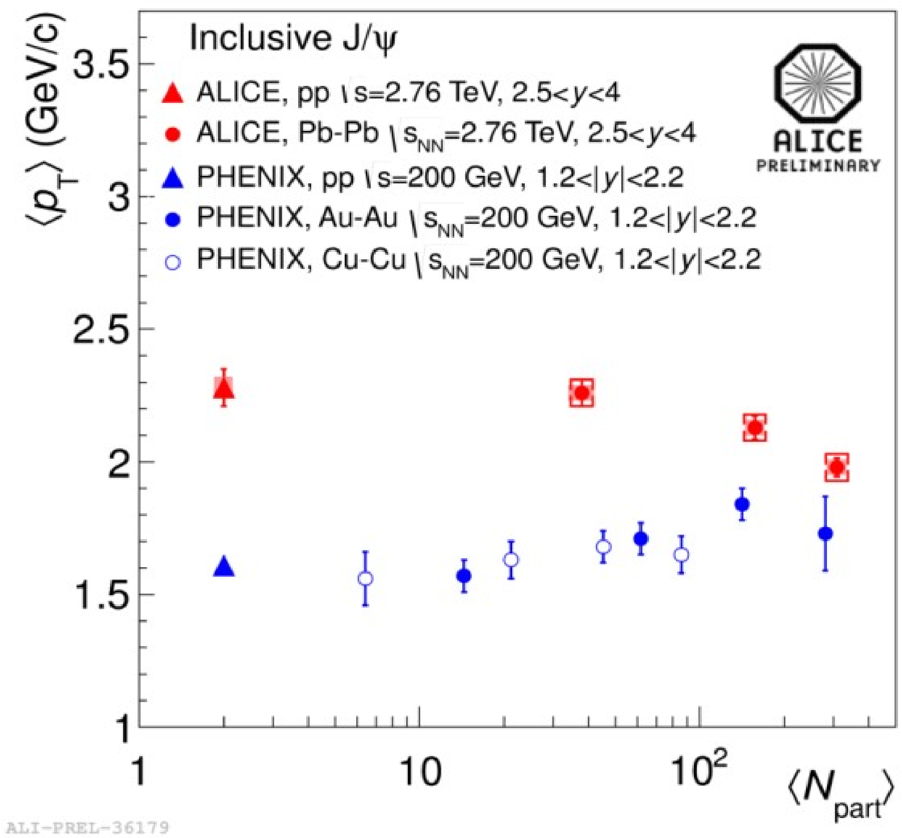
J/ψ suppression beyond CNM

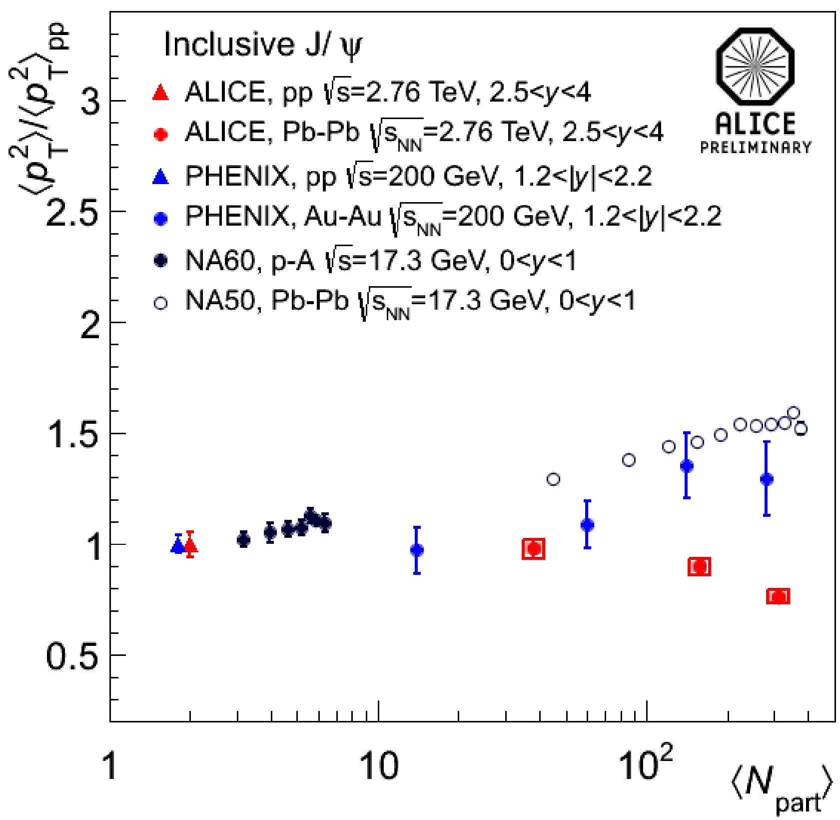


Prompt J/ψ in CMS

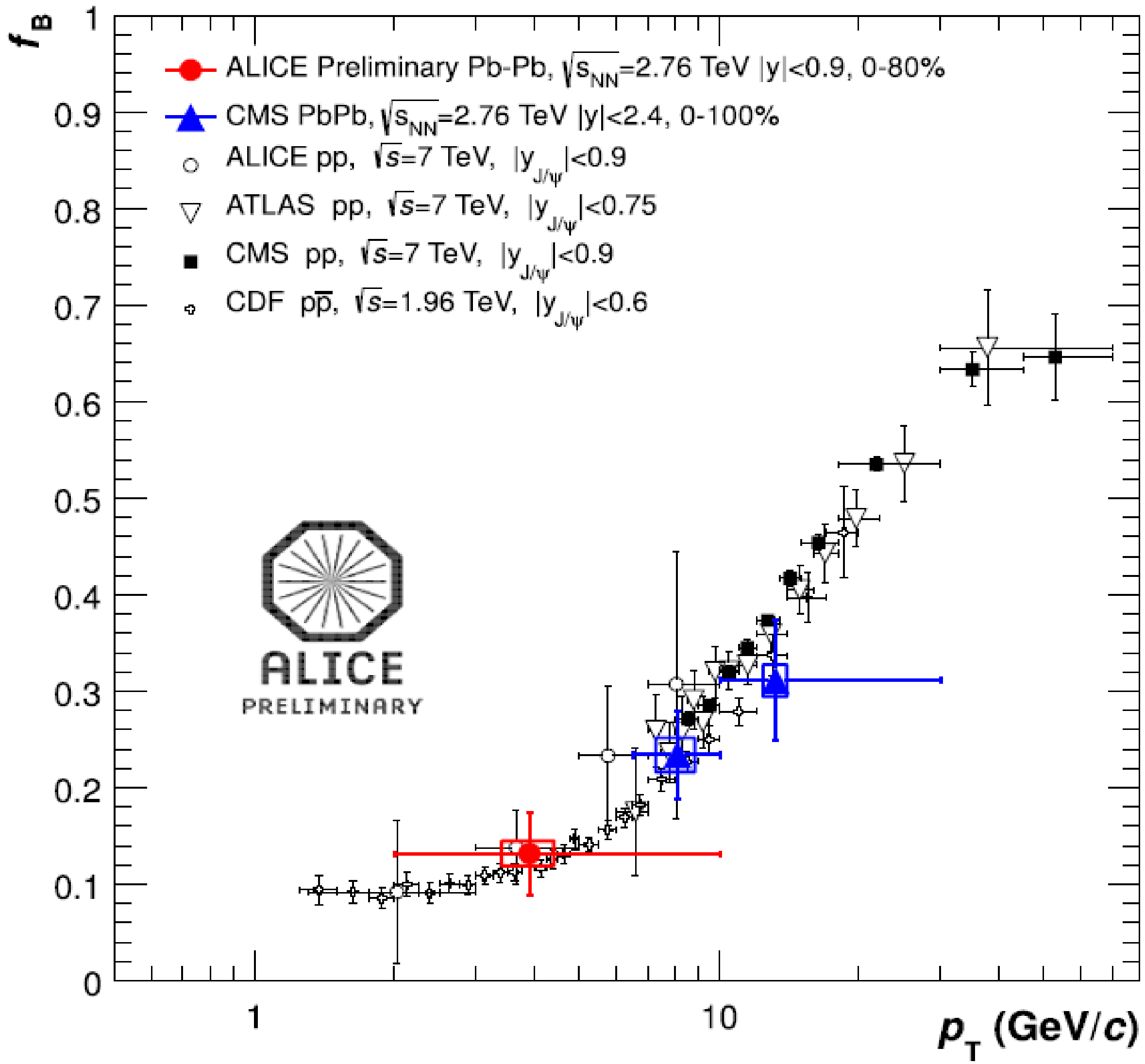


J/ψ average p_T



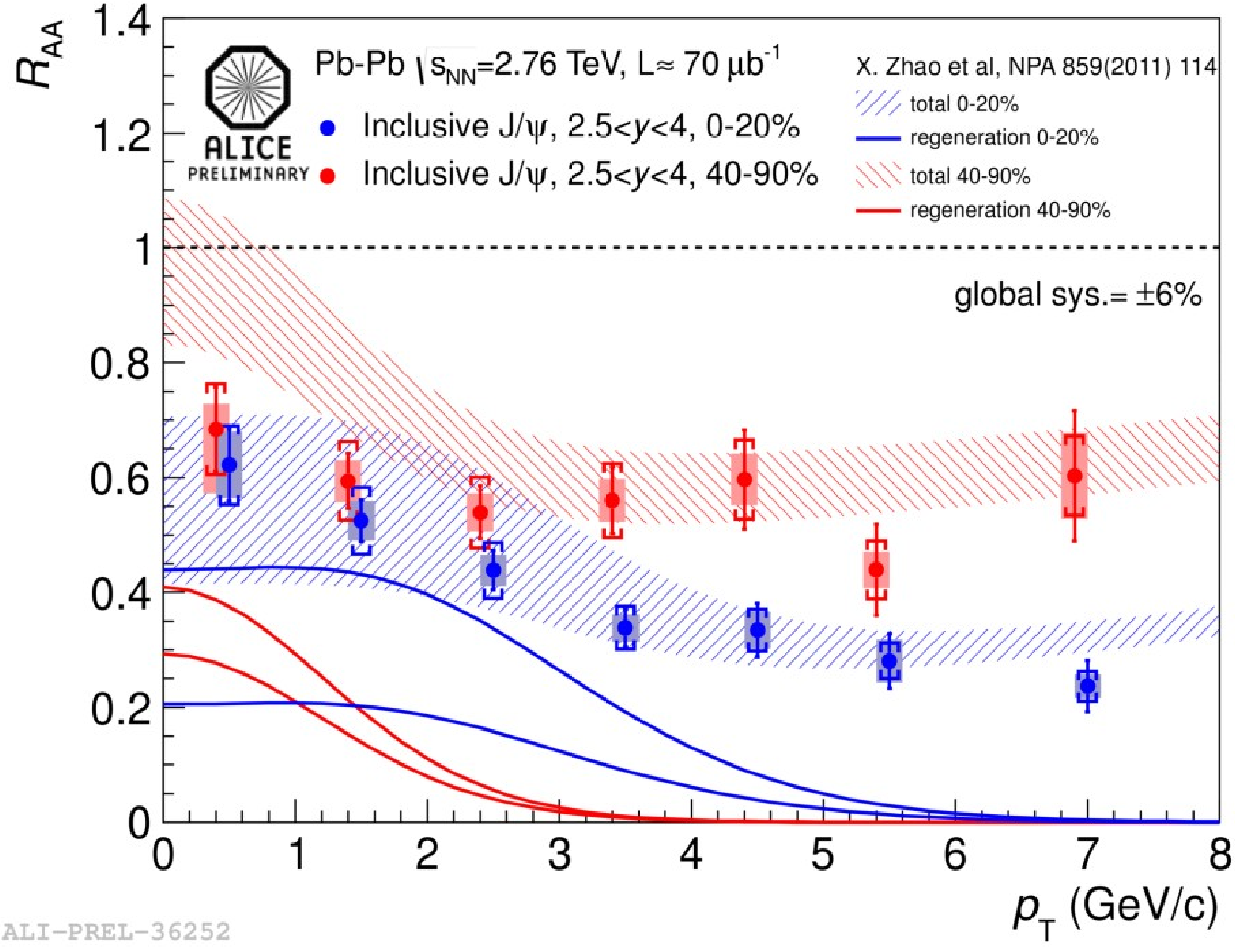


J/ψ←B (Pb-Pb)



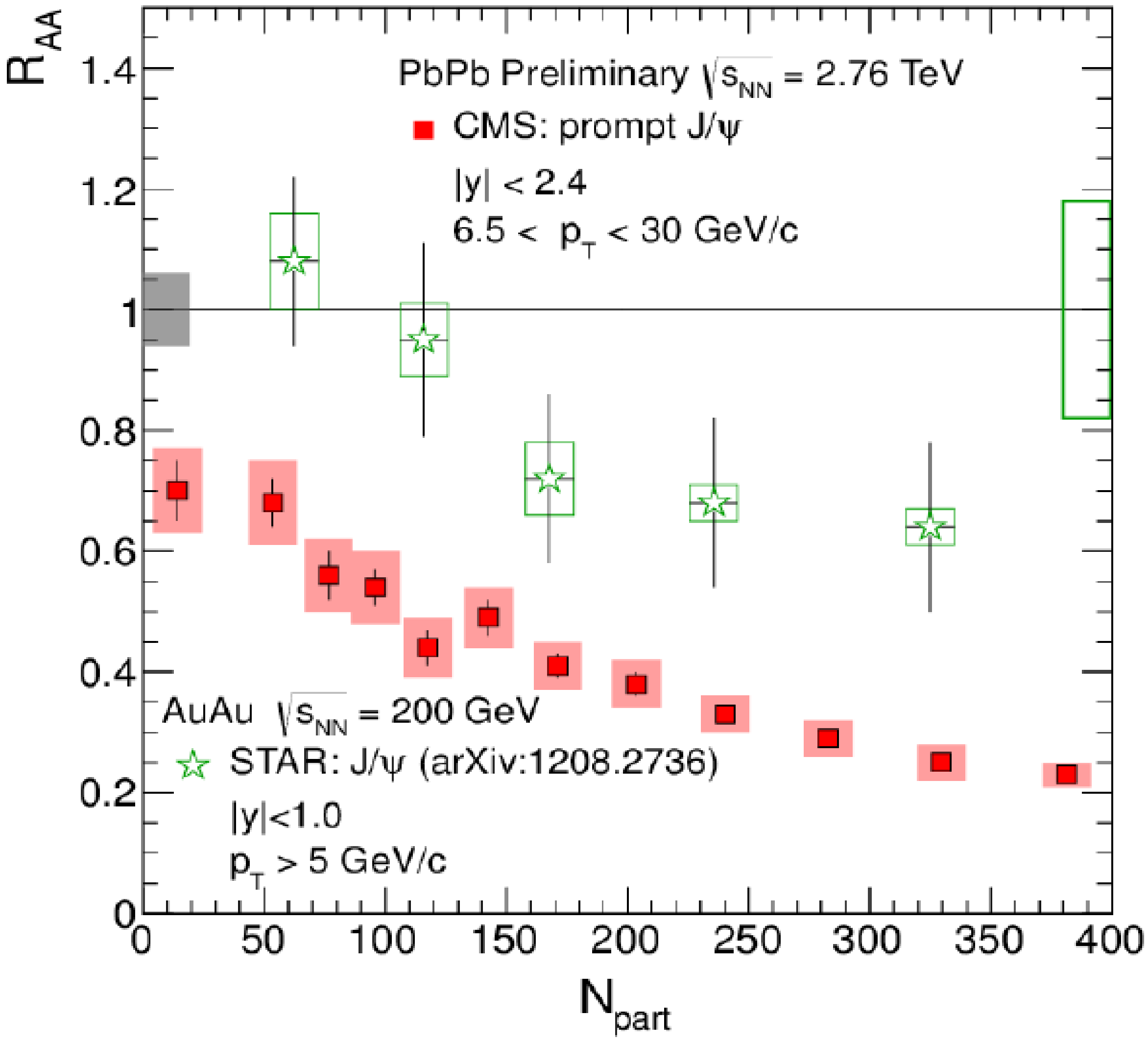
f_B
ALICE Preliminary Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV |y|<0.9, 0-80%
CMS PbPb, $\sqrt{s_{NN}}$=2.76 TeV |y|<2.4, 0-100%
ALICE pp, $\sqrt{s}$=7 TeV, $|y_{J/\psi}|$<0.9
ATLAS pp, $\sqrt{s}$=7 TeV, $|y_{J/\psi}|$<0.75
CMS pp, $\sqrt{s}$=7 TeV, $|y_{J/\psi}|$<0.9
CDF $p\bar{p}$, $\sqrt{s}$=1.96 TeV, $|y_{J/\psi}|$<0.6
ALICE
PRELIMINARY
p_T (GeV/c)

J/ψ R_{AA} vs p_T

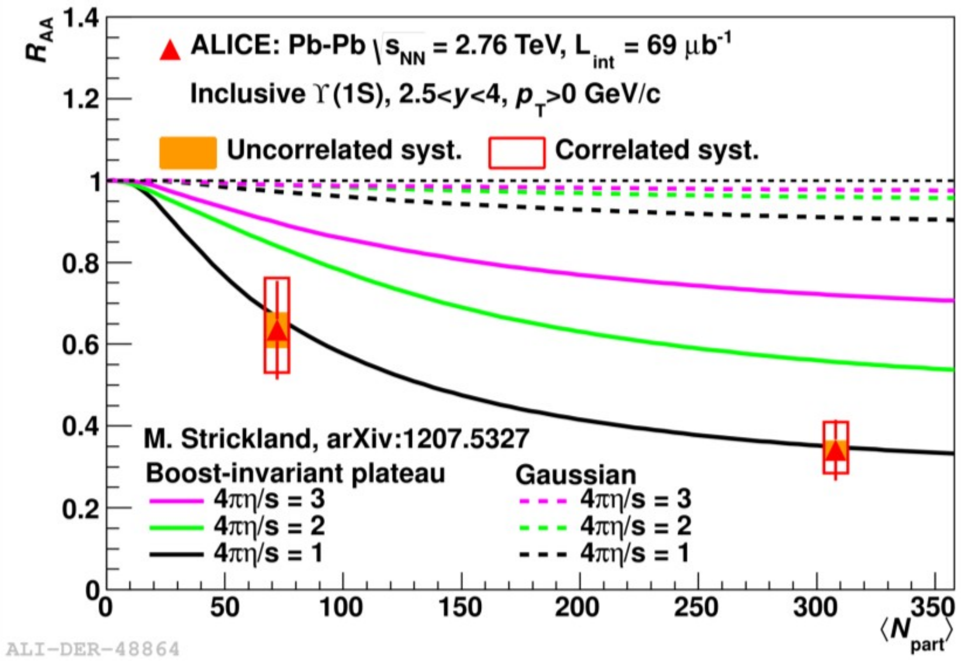


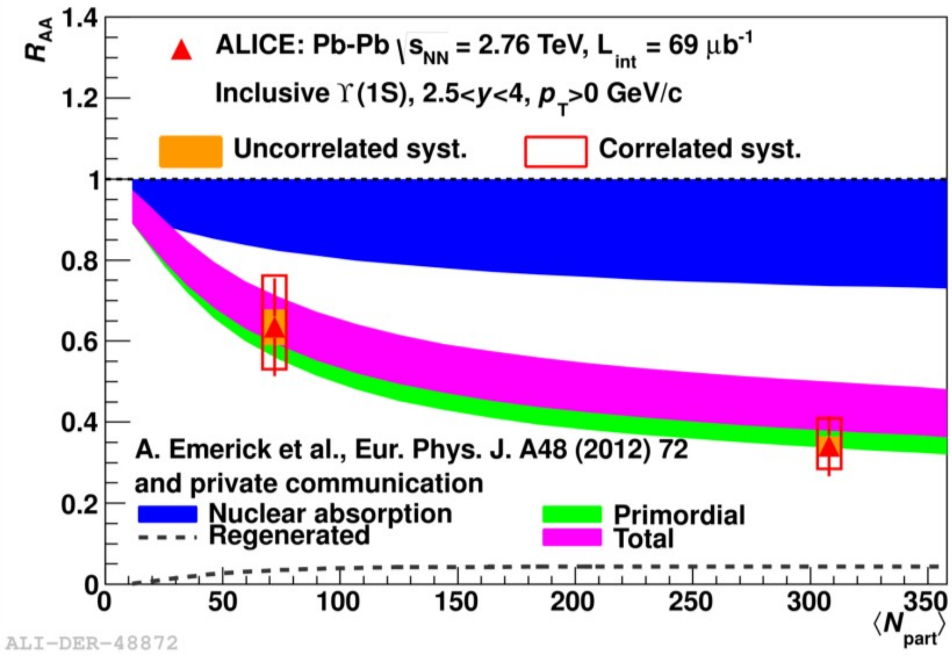
R_{AA}
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ALICE
PRELIMINARY
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV, L≈ 70 μb^{-1}
Inclusive J/ψ, 2.5<y<4, 0-20%
Inclusive J/ψ, 2.5<y<4, 40-90%
X. Zhao et al, NPA 859(2011) 114
total 0-20%
regeneration 0-20%
total 40-90%
regeneration 40-90%
global sys.= ±6%
0 1 2 3 4 5 6 7 8
p_T (GeV/c)
ALI-PREL-36252

J/ψ (CMS vs STAR)

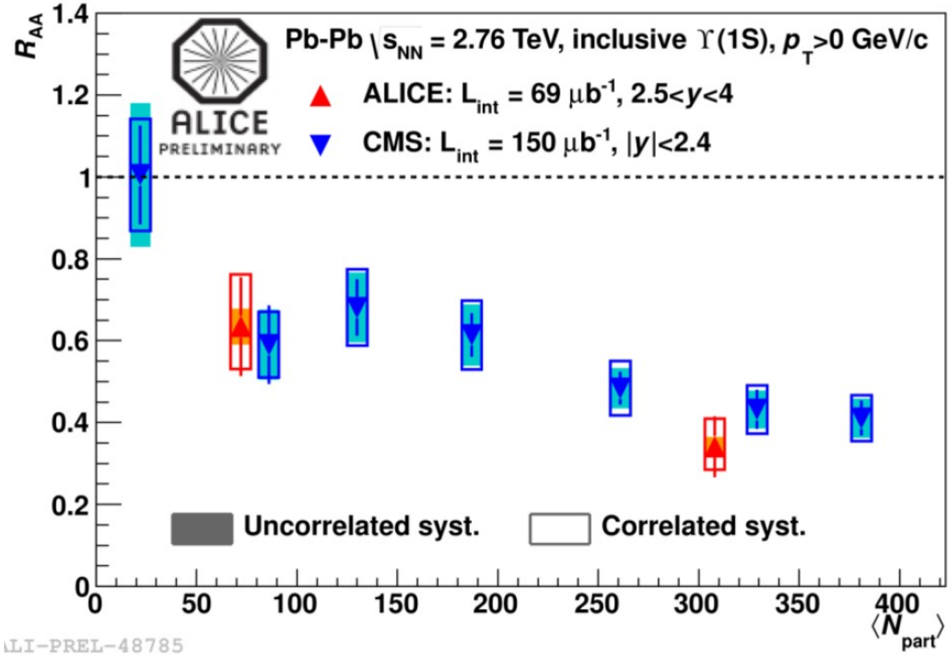


Y vs models (ALICE)

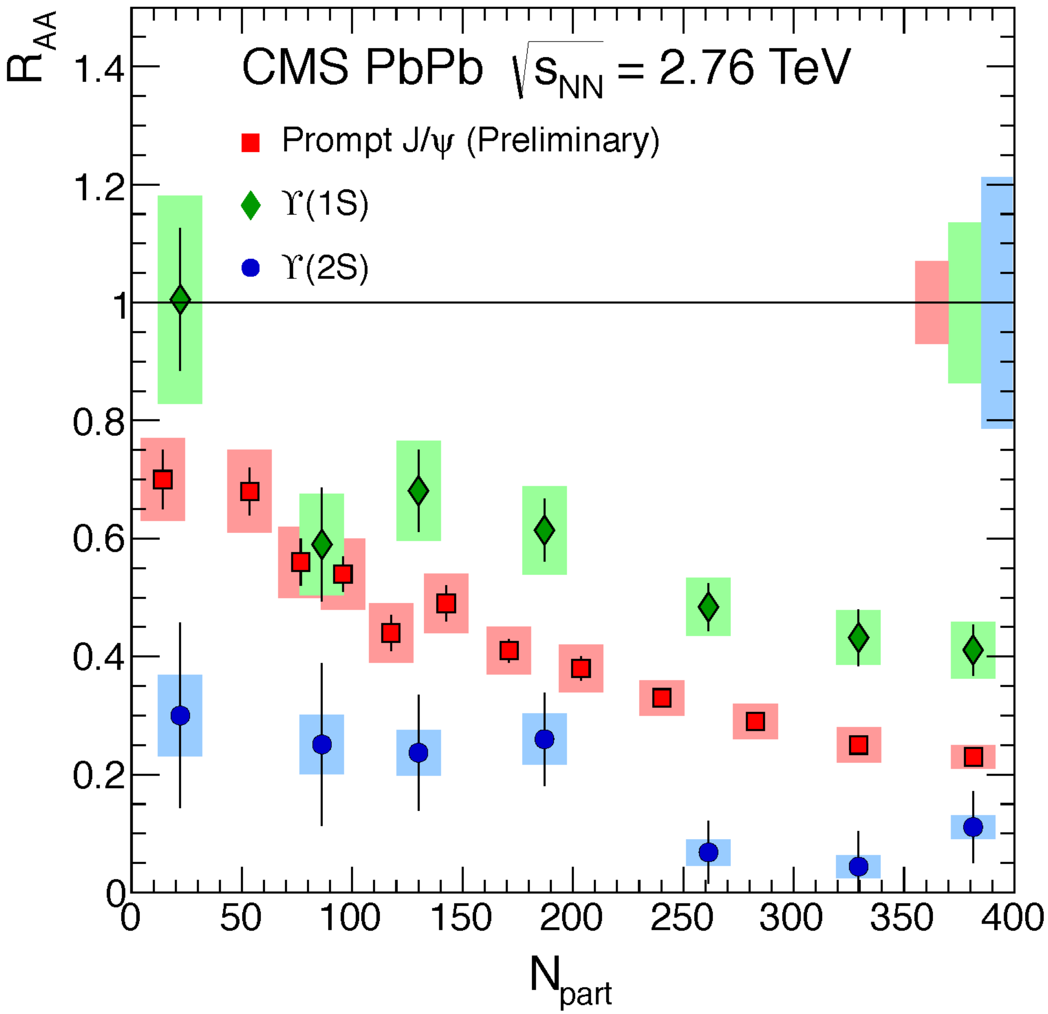




Υ (ALICE vs CMS)

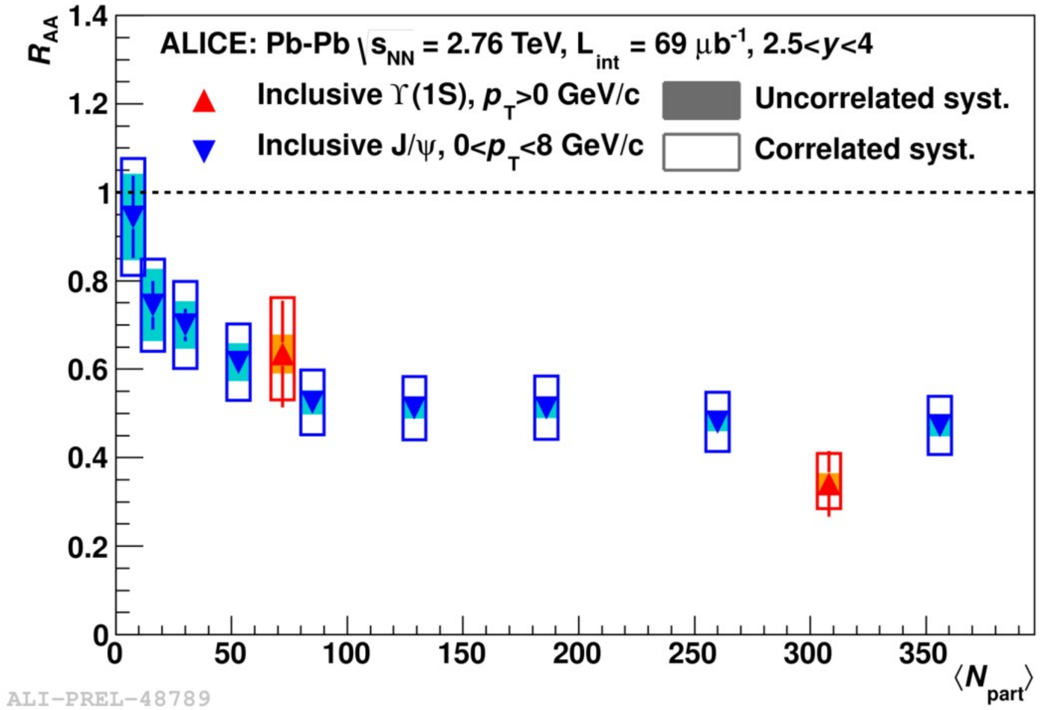


Υ vs J/ψ



- Sequential suppression:
  - $R_{AA}^{Y(2S)} < R_{AA}^{J/\psi} < R_{AA}^{Y(1S)}$?
  - Different kinematical coverage for J/ψ and Υ make interpretation difficult

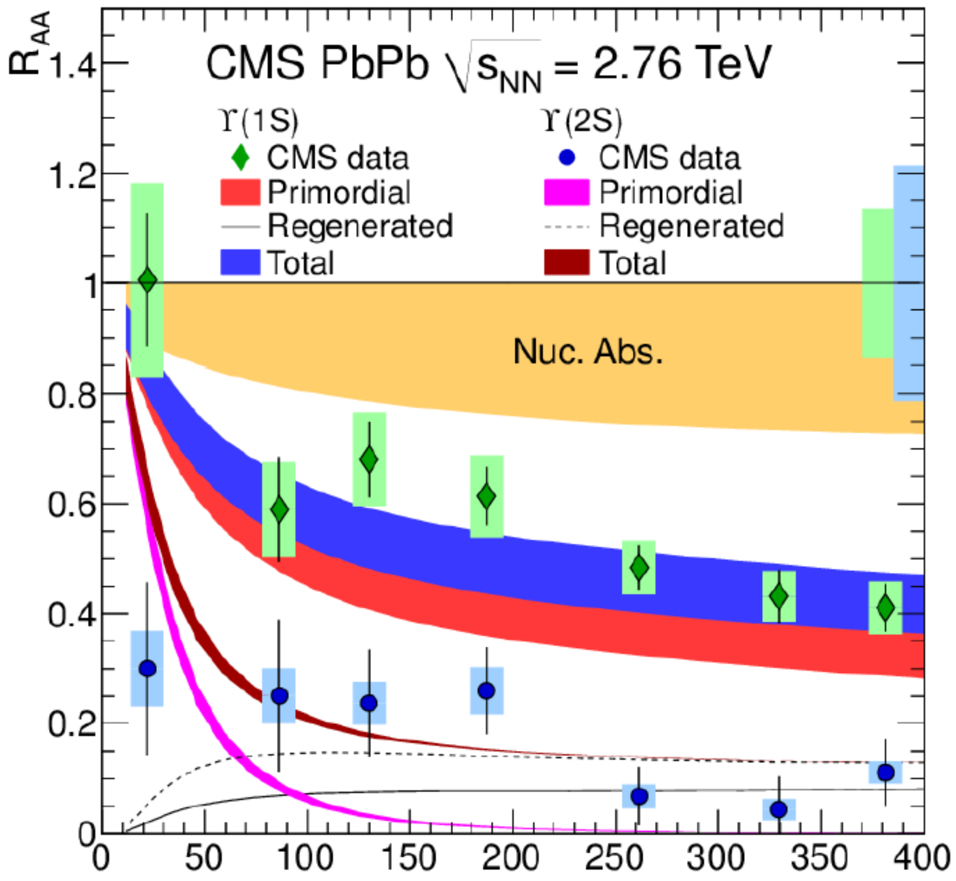
Υ vs J/ψ



- Sequential suppression:
  - $R_{AA}^{\Upsilon(2S)} < R_{AA}^{J/\psi} < R_{AA}^{\Upsilon(1S)}$?
  - Different kinematical coverage for J/ψ and Υ make interpretation difficult

- ALICE results, down to p_T=0, indicate an almost opposite behaviour
  - Charmonia from (re)combination breaks the expected hierarchy ?

Υ vs transport model



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