Experimental overview of quarkonia results

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Motivation

Quarkonias are bound state of c-cbar or b-bbar quarks.
Their production starts early in heavy ion collisions, via gluon fusion
Modifications of this production with respect to pp carry information about the medium they traverse

Cold nuclear matter effects (CNM)

- Shadowing **(PRC 88(2013) 047901)**, saturation **(Nucl. Phys. 1924(2014) 47-64)**
- Energy loss (initial state/final state, or coherent) **(PRL 109(2012) 122301)**
- Nuclear absorption **(Nucl. Phys. A700(2002)539)**

In presence of a Quark Gluon Plasma (QGP)

- Color screening **(PLB 178 (1986), 416)**
- Dissociation/regeneration in the plasma **(PRC 63 (2001) 054905)**
- Recombination at phase boundary **(PLB 490 (2000) 196)**

Why study several resonances (J/ψ, ψ(2S), Upsilons) ?

Have different radius/binding energy
Same effects should be at play, but with different magnitudes

Contents

Experiments:

- SPS at CERN ($\sqrt{s_{NN}}$ ~ 20 GeV)
- PHENIX and STAR at RHIC, BNL ($\sqrt{s_{NN}}$ ~ 200 GeV)
- CMS, LHCb, ALICE at LHC, CERN ($\sqrt{s_{NN}}$ ~ few TeV)

Colliding nuclei:

- p+p collisions
- p+A, d+A collisions
- A+A, A+B collisions

Particles:

- Charmonia J/ψ, ψ(2S)
- Bottomonia Υ(1S), Υ(2S) and Υ(3S)

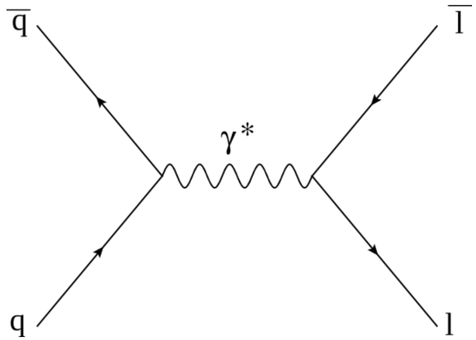
Disclaimer: all results presented here are inclusive

- for J/ψ there are contributions from higher mass excited states and b-mesons
- for Υ(1S) there are contributions from Υ(2S), Υ(3S) and χ_b decays

J/ψ

J/ψ at SPS

Drell-Yan:



L: J/ψ path length in medium

Small L: p-p collisions

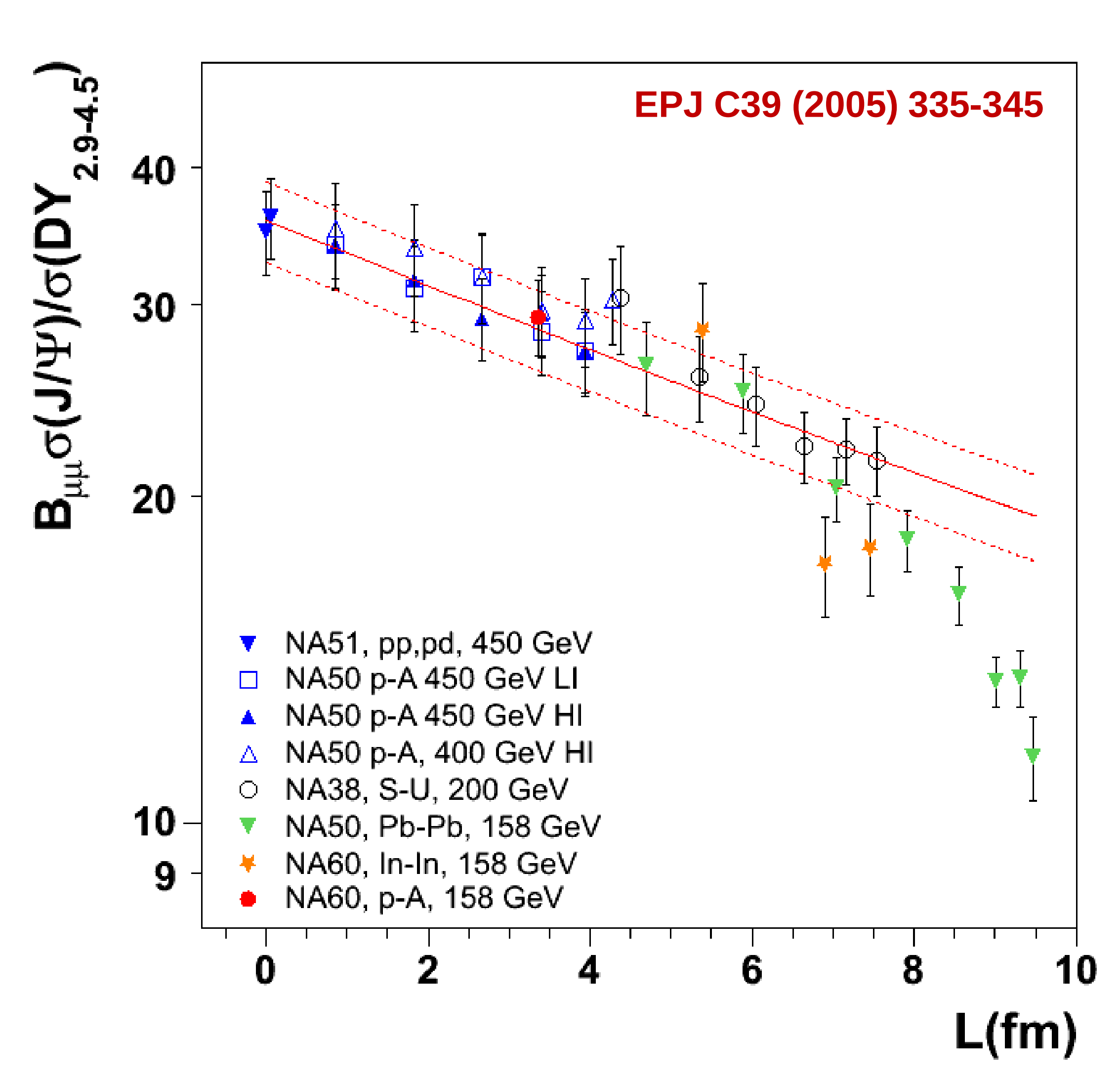
Intermediate L

Cold Nuclear Matter effect (nuclear absorption)

$$S_{pA}^{J/\Psi} = e^{-\rho L \sigma_{breakup}}$$

Large L

anomalous suppression is observed, attributed to the formation of a QGP

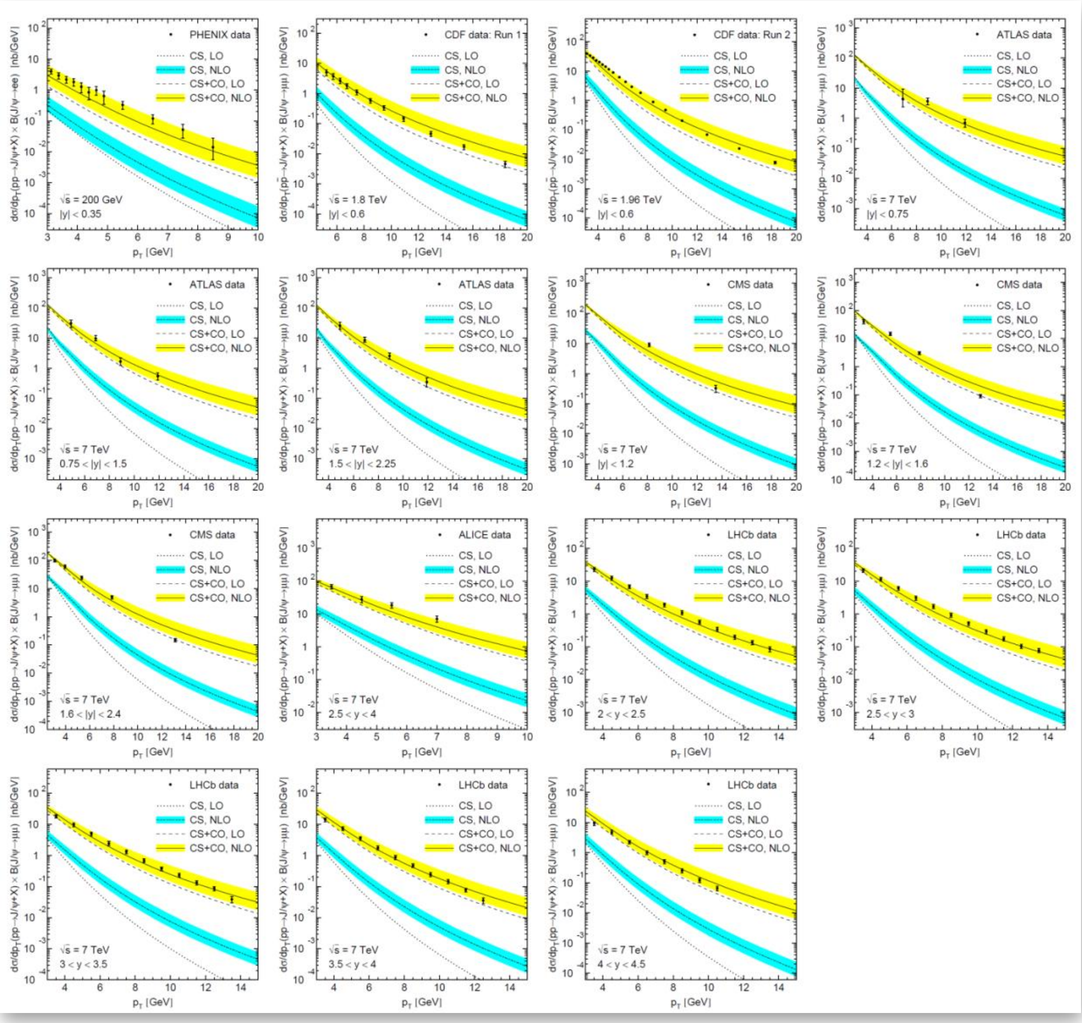


J/ψ in p+p

J/ψ data in p+p collisions

- are used to study production mechanism
- serve as a reference for heavy ion collisions

PR D84 (2011) 051501



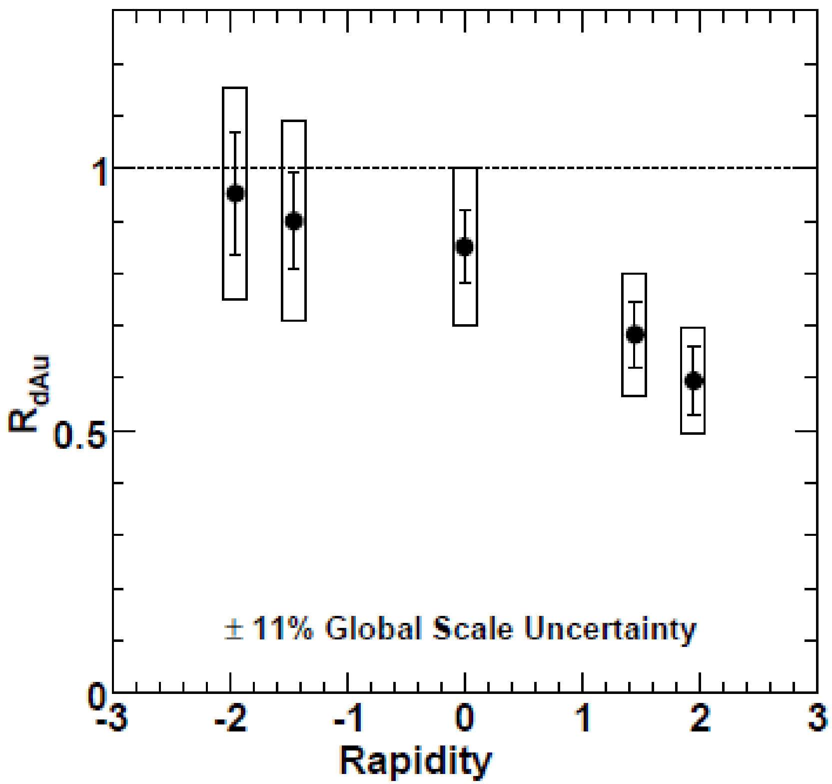
<u>Figure</u>:

Model (= fit) compared to J/ψ data vs p_T from

- RHIC
- Tevatron (ppbar)
- LHC

J/ψ cold nuclear matter effects in d+Au at RHIC

PRC 77, 024912 (2008)



To study modifications of J/ψ production in HI collisions with respect to p+p, we form the nuclear modification factor:

$$R_{AA}^{J/\Psi} = \frac{Y_{AA}^{J/\Psi}}{T_{AA}.\sigma_{pp}^{J/\Psi}}$$

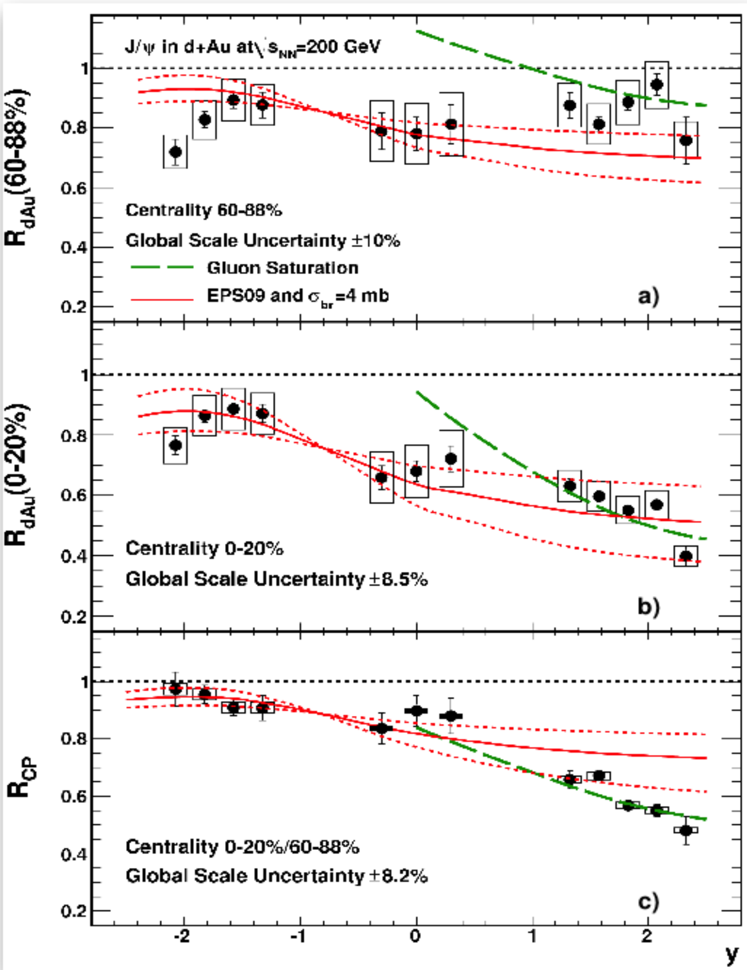
In absence of nuclear modifications (hot or cold), $R_{AA} = 1$

y<0: Au going side. Large x (gluon momentum) in Au nuclei ($x \sim 10^{-1}$)

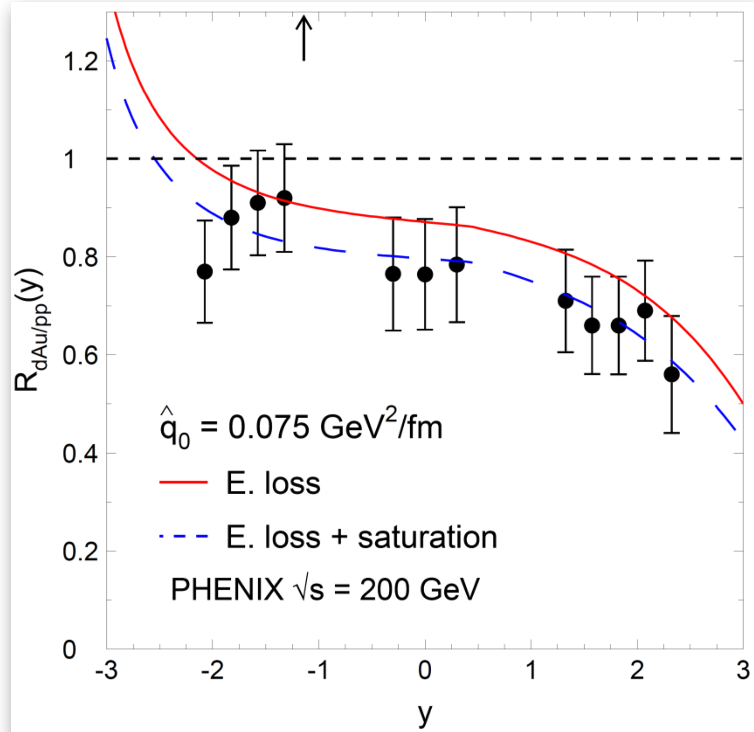
y>0: deuteron going side. Small x in Au nuclei. ($x \sim 3.10^{-3}$)

J/ψ cold nuclear matter effects in d+Au at RHIC

PRL 107 (2011) 142301



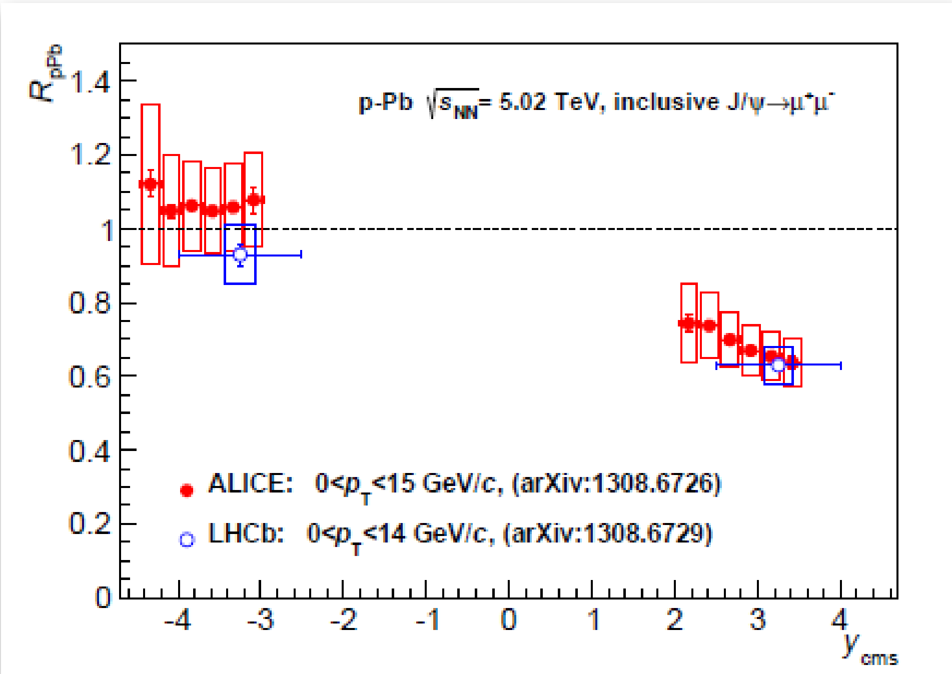
JHEP 1303 (2013) 122



Models:

- Shadowing and nuclear absorption
- Color Glass Condensate (saturation)
- Coherent Energy loss

J/ψ cold nuclear matter effects in p+Pb at LHC



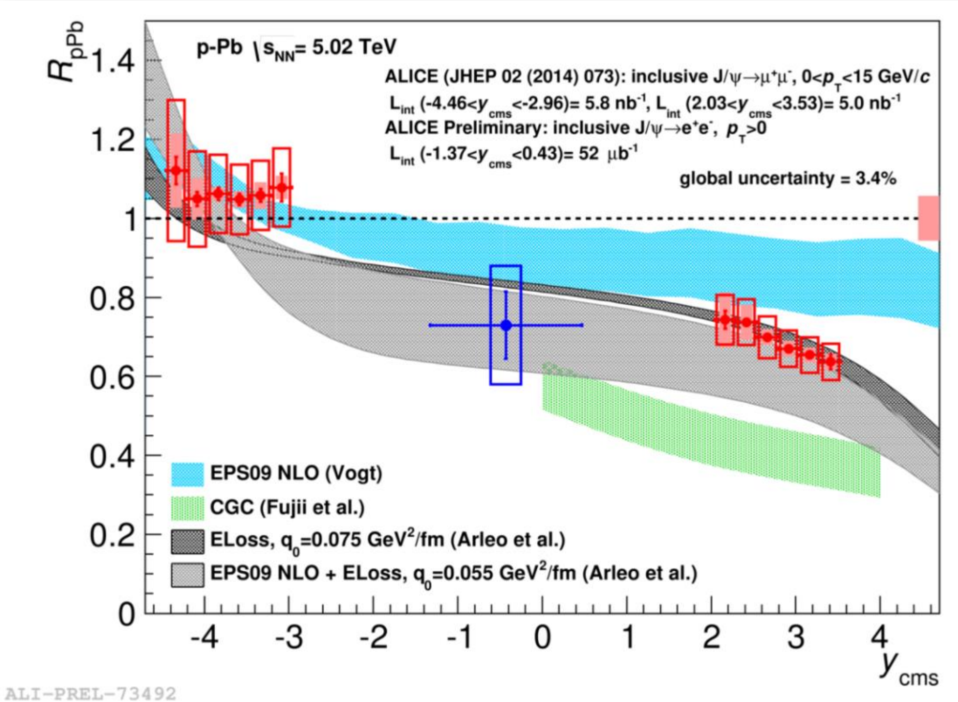
J/ψ nuclear modification factor in minimum bias p+Pb collisions as a function of rapidity

y<0: Pb going side. Large x (gluon momentum) in Pb nuclei ($10^{-2} < x < 5.10^{-2}$)

y>0: p going side. Small x in Pb nuclei ($2.10^{-5} < x < 8.10^{-5}$)

J/ψ cold nuclear matter effects in p+Pb at LHC

JHEP 02 (2014) 073



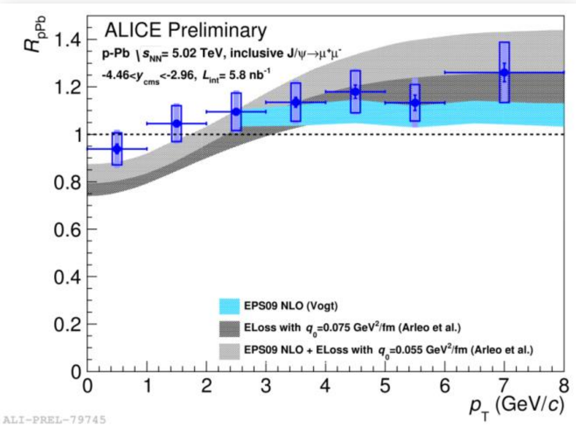
Models:

- Shadowing only
  (JMP E22 (2013) 1330007)
- Coherent energy loss (without/with shadowing)
  (JHEP 1303 (2013) 122)
- Color Glass Condensate (y>0) + CEM **(Nucl. Phys. A915 (2013) 1)**

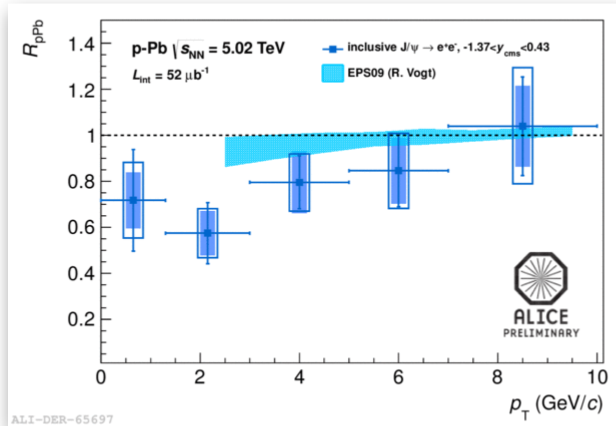
At LHC, nuclear absorption (which was needed at SPS and at RHIC) should play little to no role, because the nuclear crossing-time is too small for the charmonia to be fully formed

J/ψ cold nuclear matter effects in p+Pb at LHC

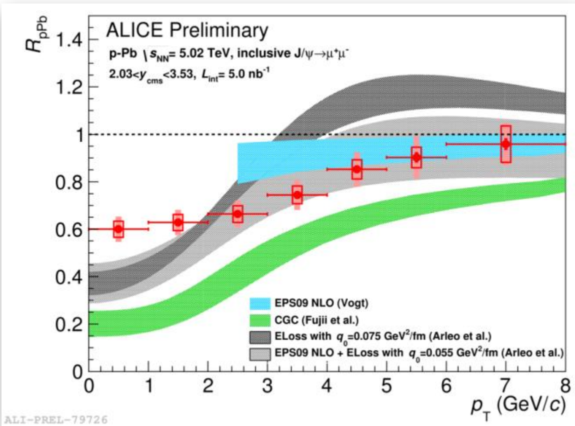
y<0 (Pb-going side)



|y|<1



y>0 (p-going side)



Little p_T dependence at negative rapidity, consistent with unity

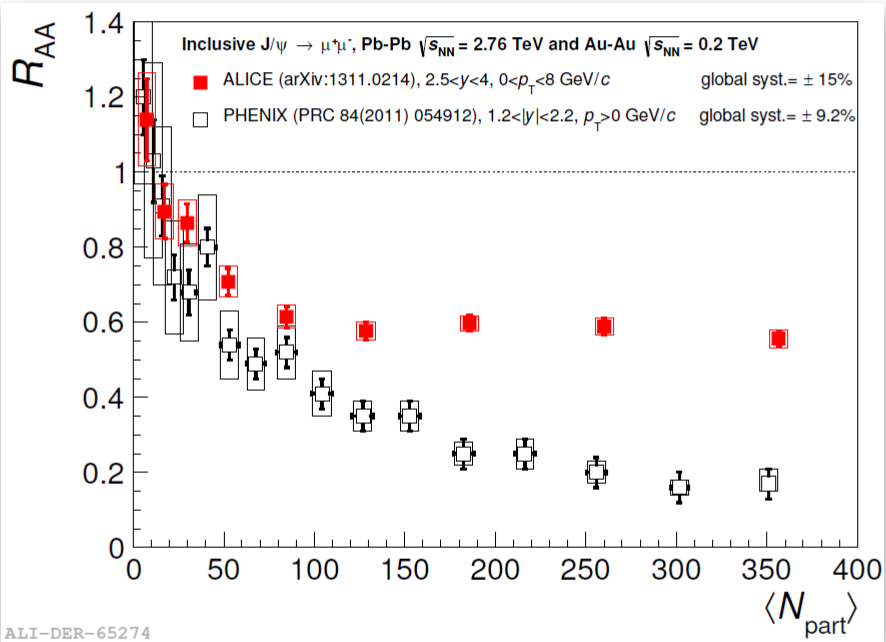
Suppression at positive rapidity (low x) and low p_T

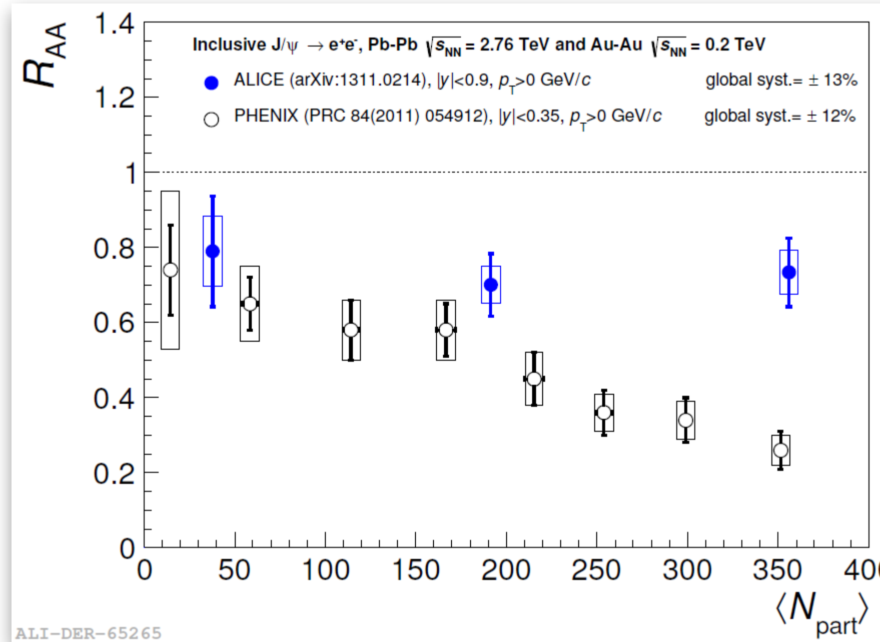
Models are the same as before:

- Shadowing only (p_T>2.5 GeV/c) **(JMP E22 (2013) 1330007)**
- Coherent energy loss (without/with shadowing) **(JHEP 1303 (2013) 122)**
- Color Glass Condensate (y>0) + CEM **(Nucl. Phys. A915 (2013) 1)**

J/ψ suppression in A+A at RHIC and LHC

PLB 743 (2014) 314-327





J/ψ R_{AA} vs centrality at forward- (left) and mid- (right) rapidity

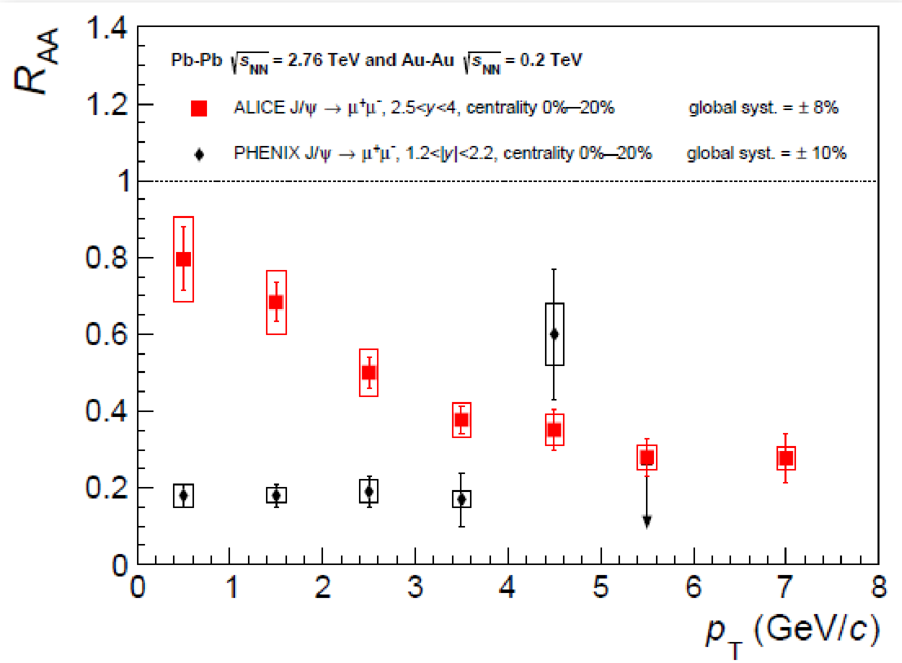
N_{Part}: number of nucleons participating to one AA collision at given centrality

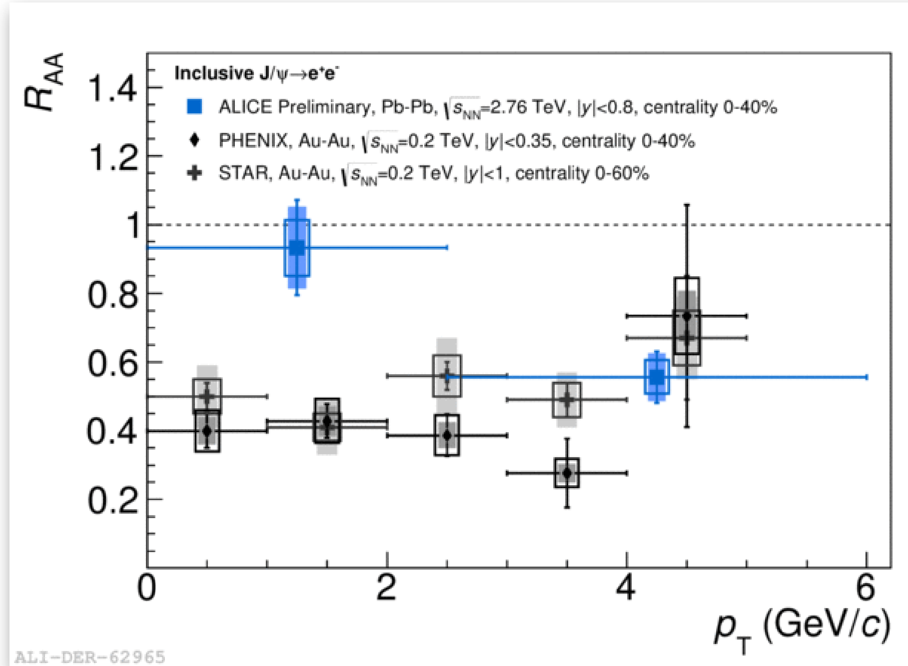
Significant suppression observed at RHIC (Au+Au @ $\sqrt{s_{NN}}$ = 0.2 TeV) and LHC (Pb+Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV) for central collisions

Suppression is stronger at RHIC than at LHC

J/ψ suppression in A+A at RHIC and LHC

PLB 743 (2014) 314-327





J/ψ RAA vs p_T for central collisions at forward- (left) and mid- (right) rapidity

At RHIC: no significant p_T dependence is observed

At LHC: R_{AA} increases at low p_T, unlike in p+A collisions and unlike at RHIC

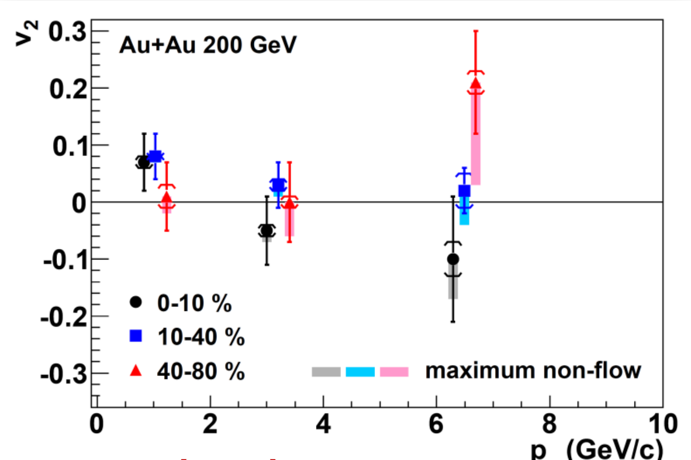
Both the centrality and p_T dependence are consistent with a large suppression of primordial J/ψ in the QGP and, at LHC, the presence of a significant fraction of low p_T J/ψ from recombination.

J/ψ elliptic flow

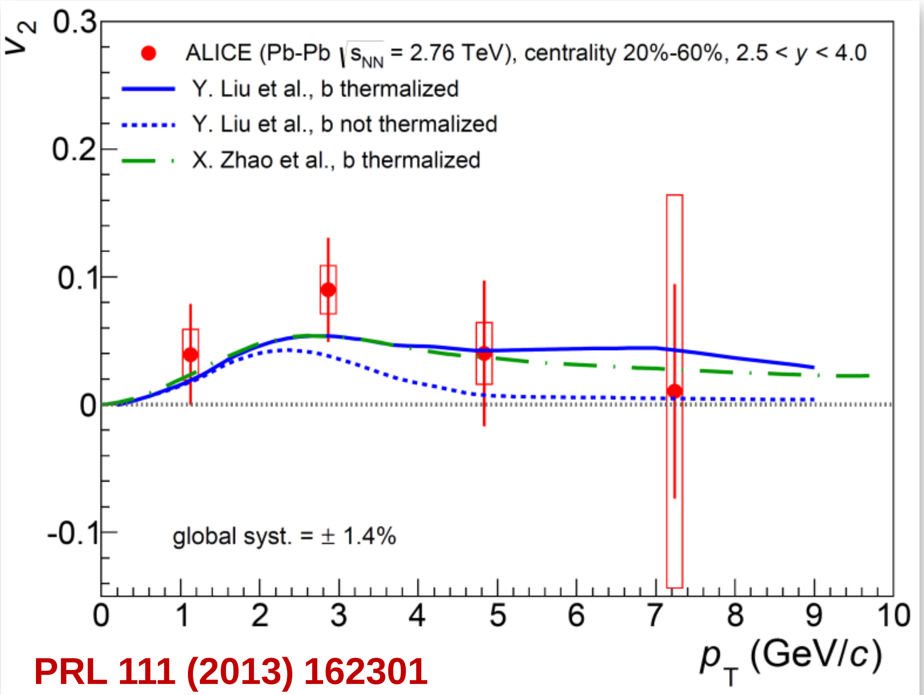
Elliptic flow parameter (v_2) characterizes azimuthal anisotropy of J/ψ production wrt reaction plane in semi-central collision

A non-zero v_2 is considered a consequence from collective behavior in the QGP

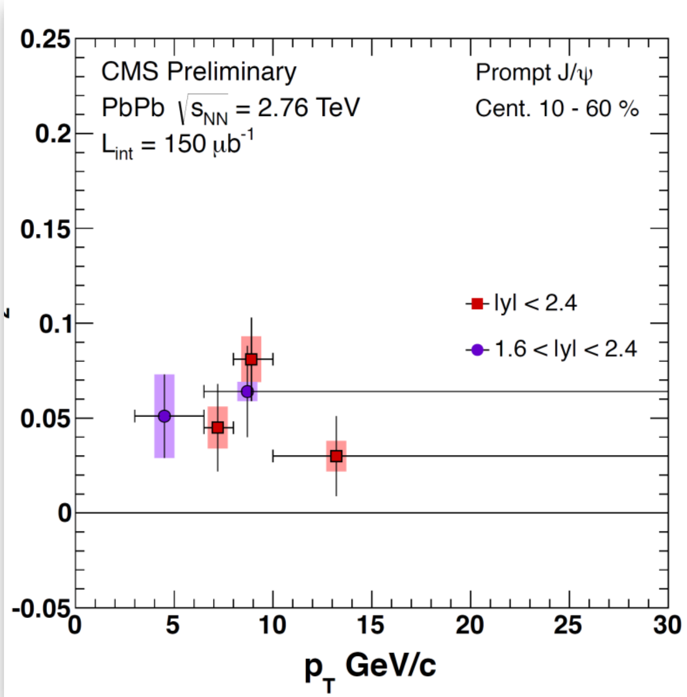
At low p_T, it is a possible signature for recombination



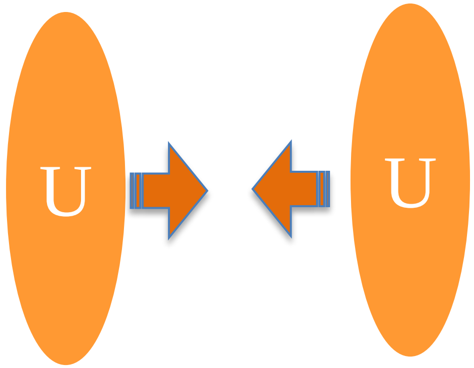
PRL 111 (2013) 052301

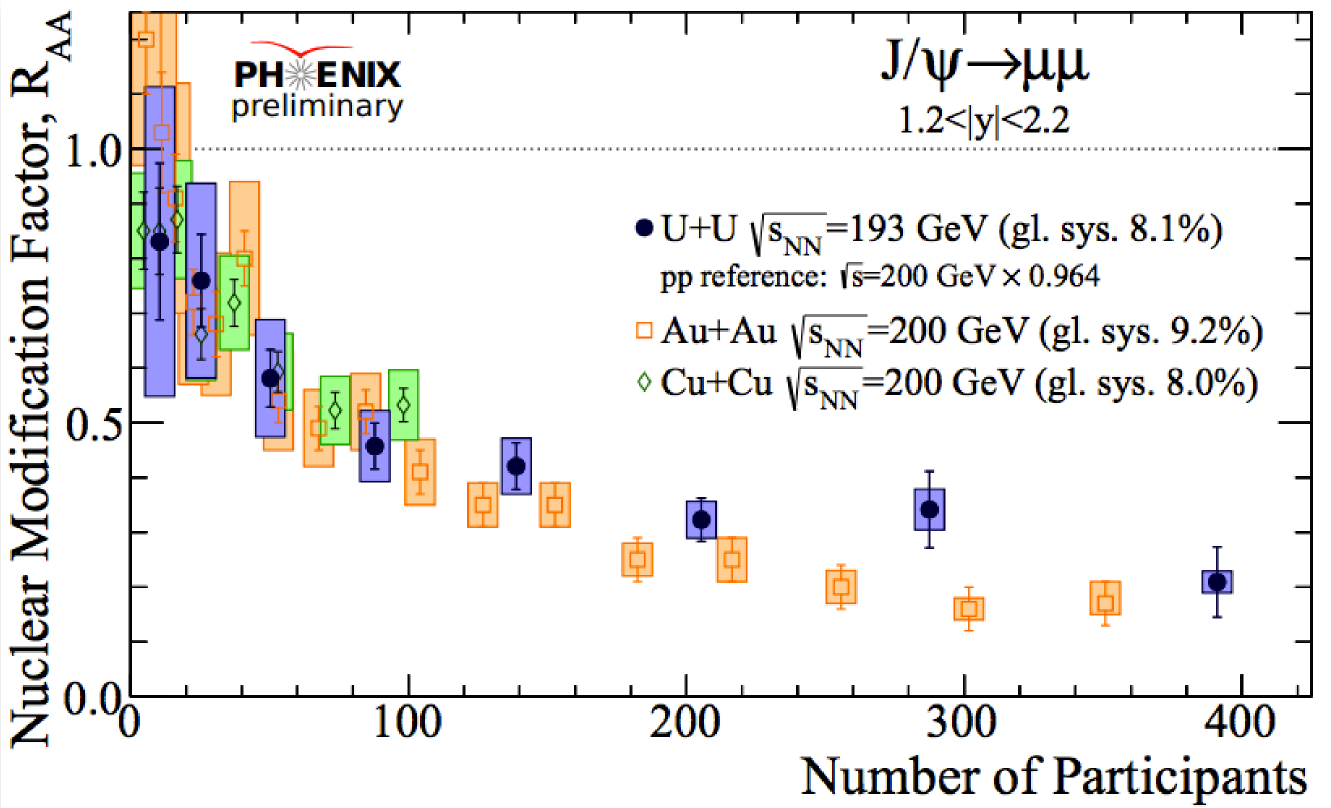


PRL 111 (2013) 162301



More collision species at RHIC: U+U



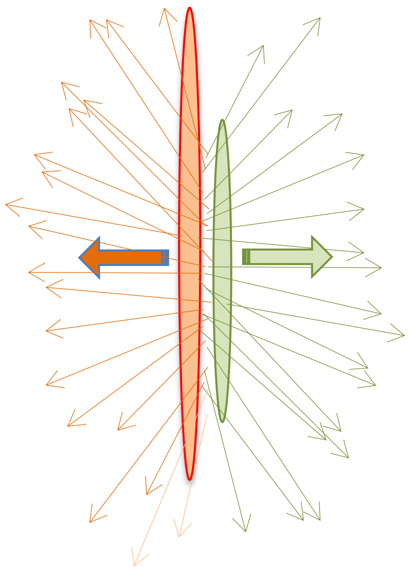


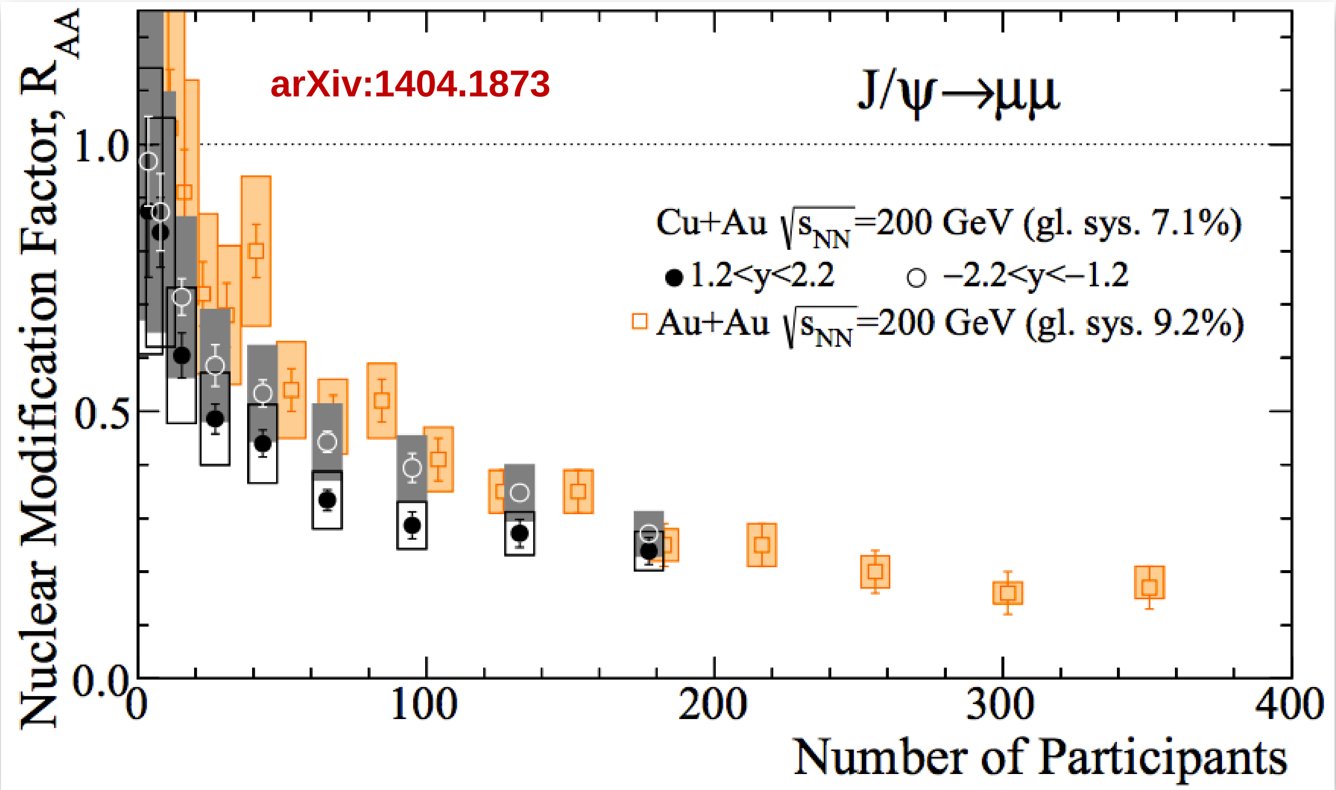
Differences from Au+Au collisions

- Maximum number of nucleons participants 15% larger than Au+Au
- larger energy density

Observed R_{AA} is consistent with the one measured in Au+Au

More collision species at RHIC: Cu+Au



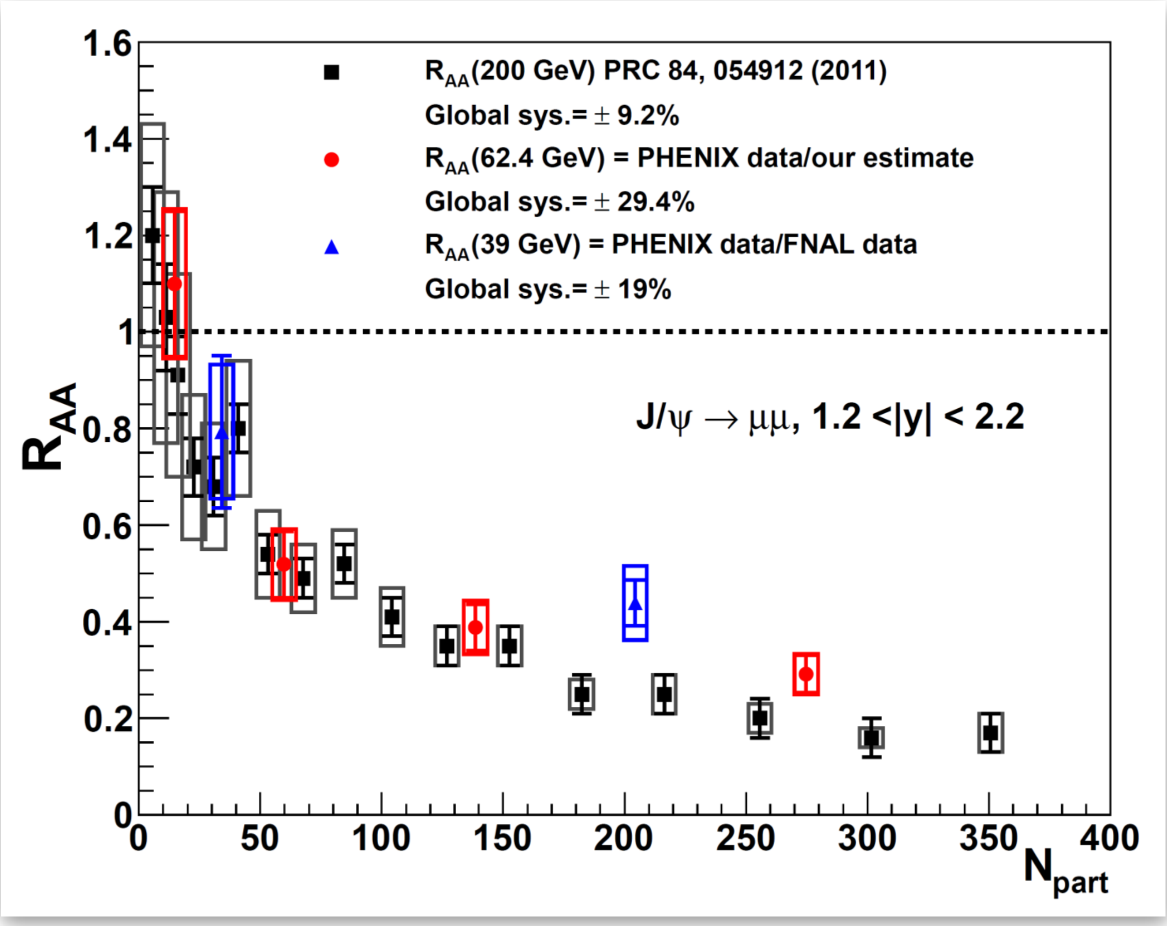


Open circles: y < 0, Au-going side

Filled circles: y > 0, Cu-going side

Beam energy scan at RHIC

PRC86 (2012) 064901



J/ψ R_{AA} vs N_{part} in Au+Au collisions @ $\sqrt{s_{NN}}$ = 200 GeV, 62.4 GeV and 39 GeV

Little difference in the suppression pattern, within large uncertainties, and in fact suppression at 200 GeV was also similar to that seen at SPS

ψ(2S)

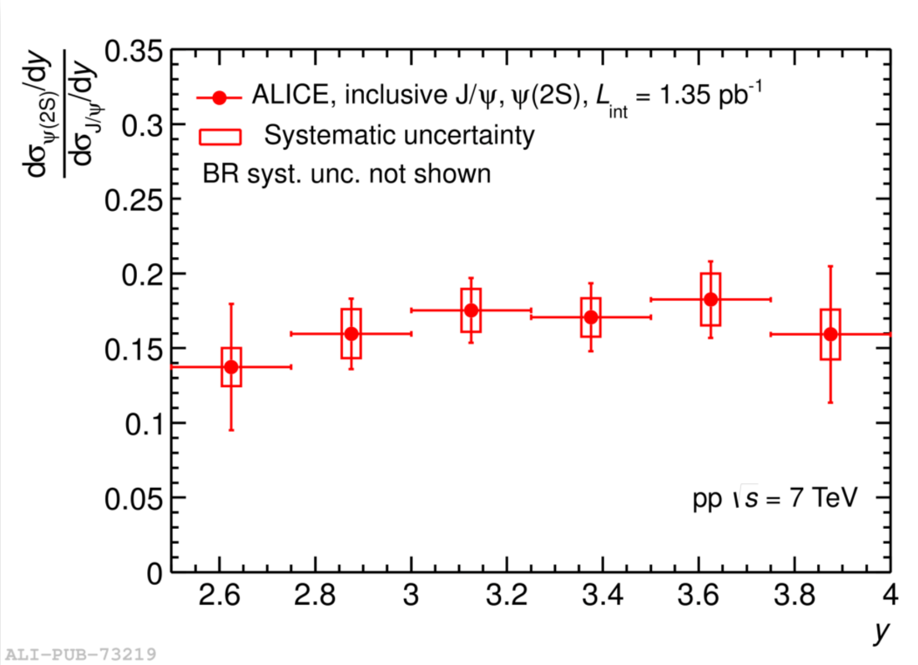
Motivation

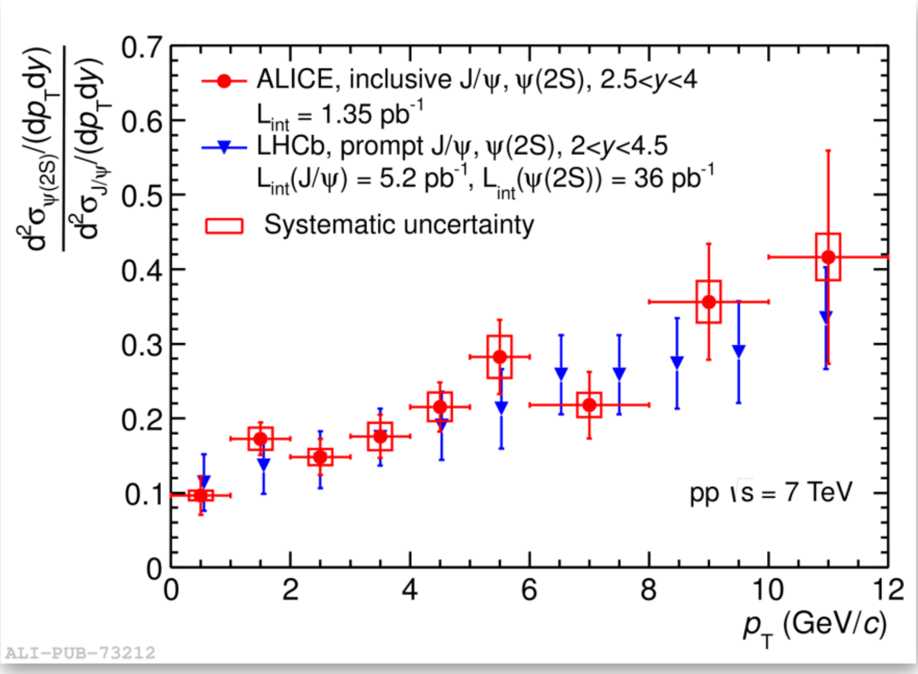
ψ(2S) has the same quark content as J/ψ and not too different mass:
→ expect similar initial state effects in cold nuclear matter

ψ(2S) binding energy is much smaller than J/ψ
→ expect larger final state effects in CNM, provided that there is enough time for such effects to develop
→ larger suppression (via color screening) in QGP

ψ(2S) in p+p collisions at LHC

EPJ C 74, 2974 (2014)



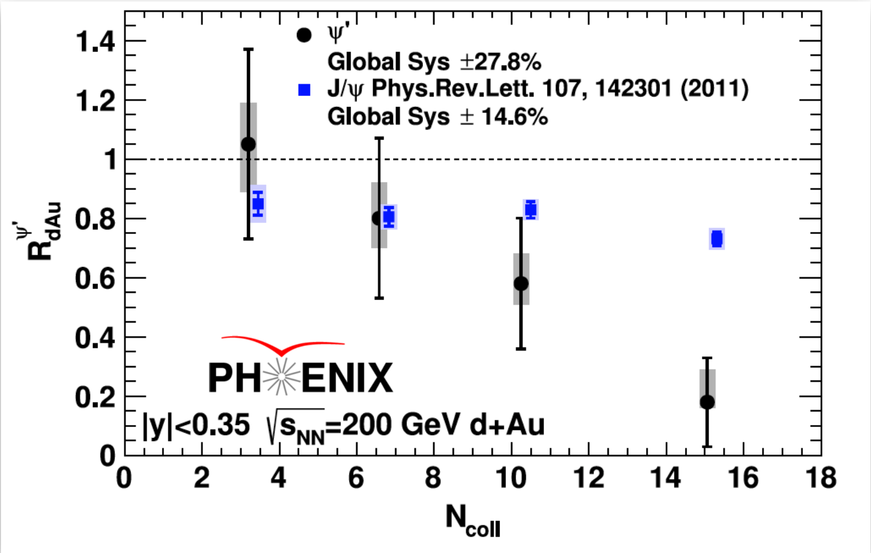


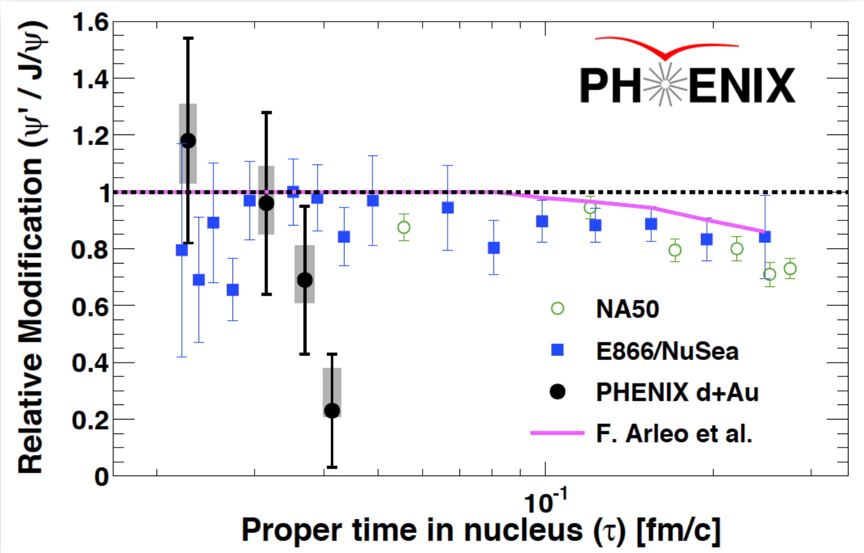
… also provides more constraints on production mechanism

Here for instance the trend observed for ψ(2S) / J/ψ ratio vs p_T is inconsistent with Color Evaporation Model, even after accounting for contributions from higher mass excited states and b-mesons

ψ(2S) in d+Au at RHIC

PRL 111 (2013) 202301





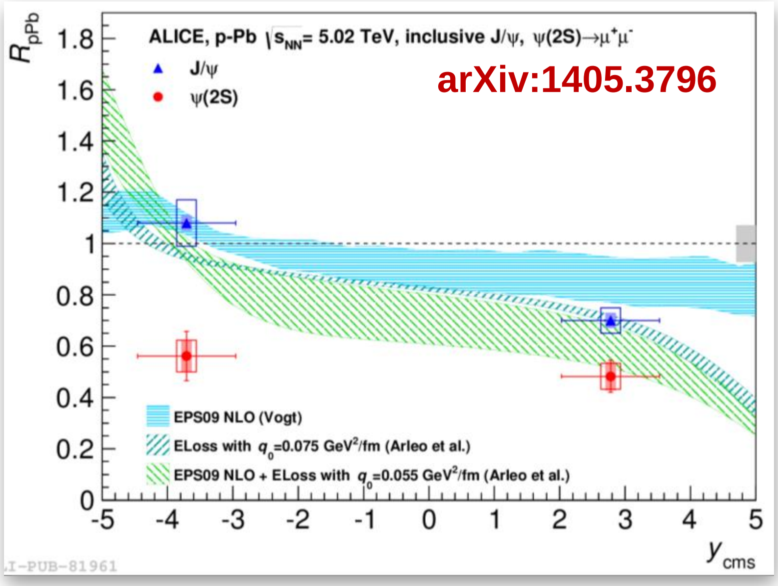
At RHIC ψ(2S) R_{dAu} is significantly smaller than J/ψ for central collisions

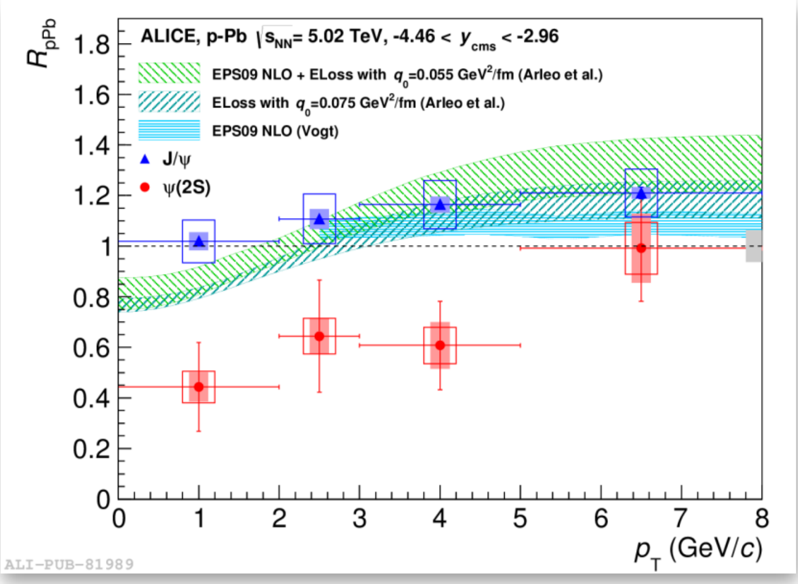
Similar (but smaller) effect already observed at lower energy. At that time explained by differences between time spent in the nucleus by both resonances.

Does not work at RHIC because

- effect is larger
- time spent in nucleus is shorter

ψ(2S) in p+Pb at LHC



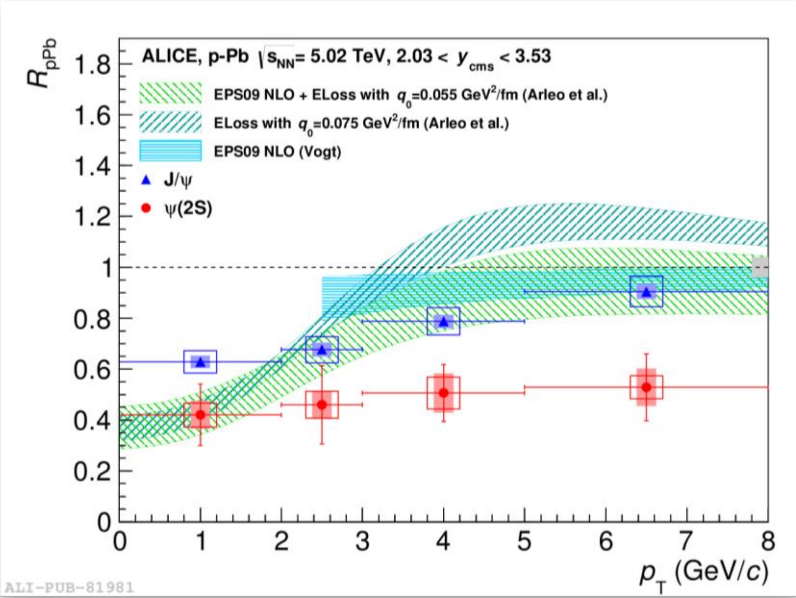


A large difference is also observed at LHC

Models have ~ identical predictions for J/ψ and ψ(2S), because no final-state effects are included, that would distinguish between the two.

This is in disagreement with the data.

Final state CNM effects are unexpected because charmonia formation time is larger than crossing time.



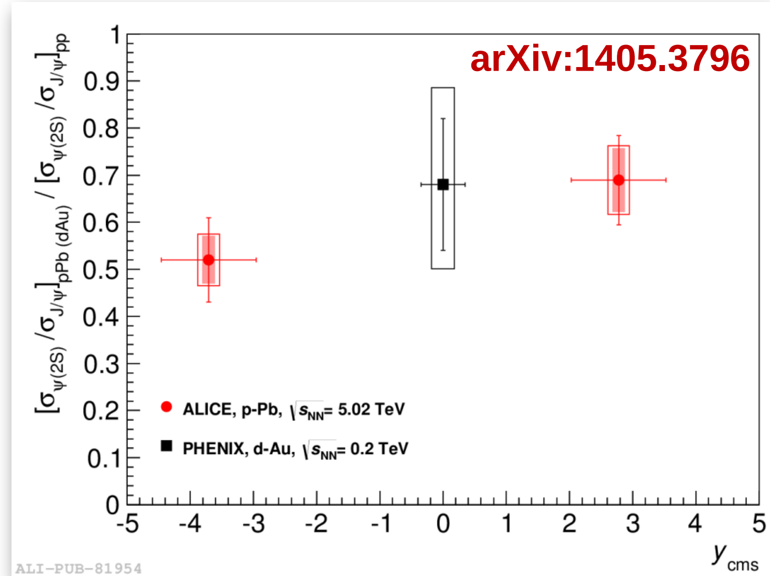
ψ(2S) / J/ψ double ratio in p+Pb at LHC

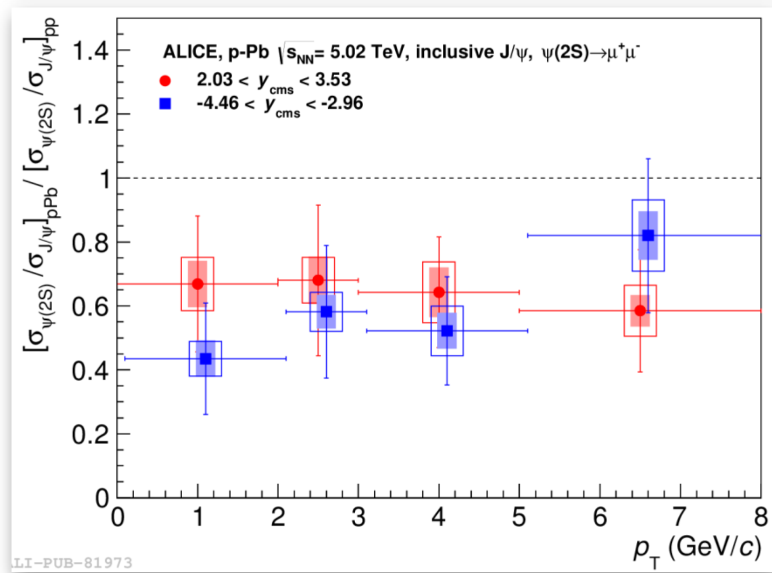
<u>Double ratio</u>: $$\frac{\sigma_{\psi(2S)} / \sigma_{J/\psi}\big|_{pPb}}{\sigma_{\psi(2S)} / \sigma_{J/\psi}\big|_{pp}} = \frac{R_{pPb}^{\psi(2S)}}{R_{pPb}^{J/\psi}}$$

Double ratio is significantly beyond unity, with no strong dependence on p_T

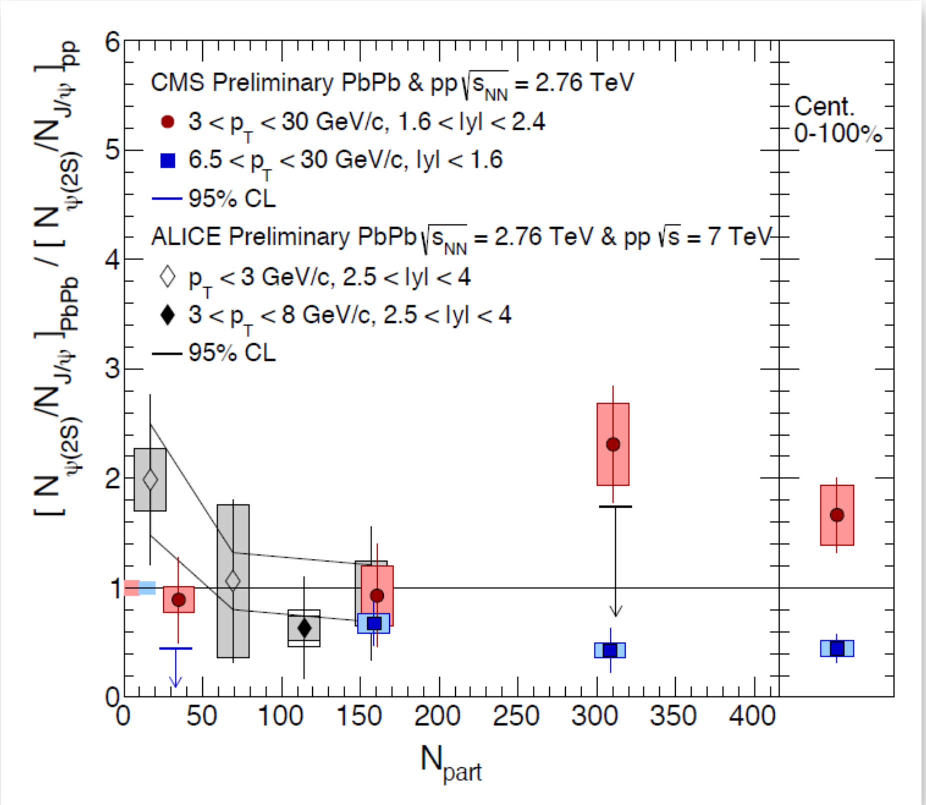
Similar effect observed at RHIC, in d-Au collisions, at mid-rapidity **(PRL 111 (2013) 202301)**

Models from previous page would predict a ratio around unity, within few percent (due to shadowing)





ψ(2S) / J/ψ double ratio in Pb+Pb at LHC



<u>Peripheral and mid-central collisions</u>: double-ratio is consistent with unity

<u>For central collisions</u>, large deviations from unity:

- high p_T: double ratio < 1 (consistent with expt. from screening/dissociation)
- intermediate p_T: double ratio > 1 (recombination ?)

Alice lacks statistics to confirm/complement these results

Upsilons

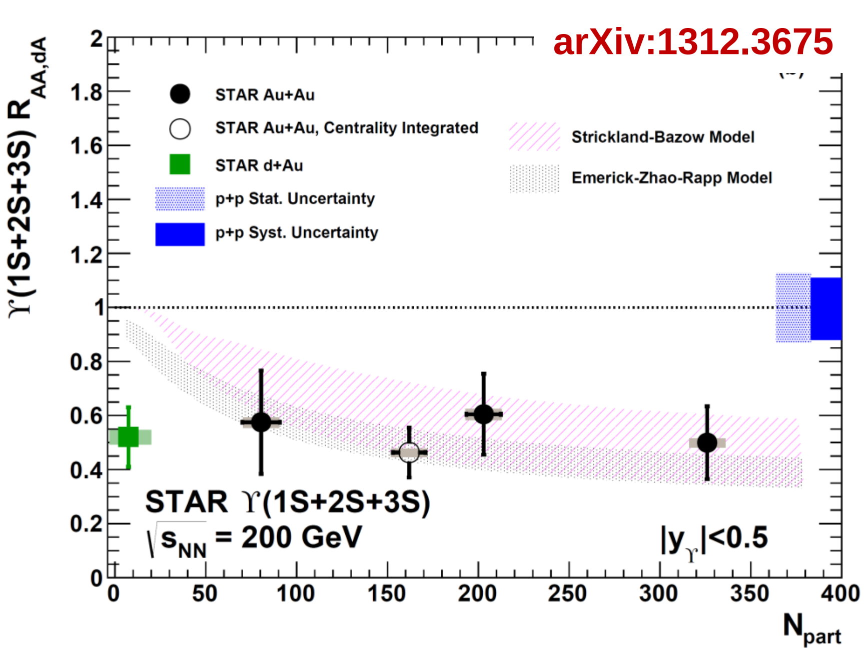
Motivation

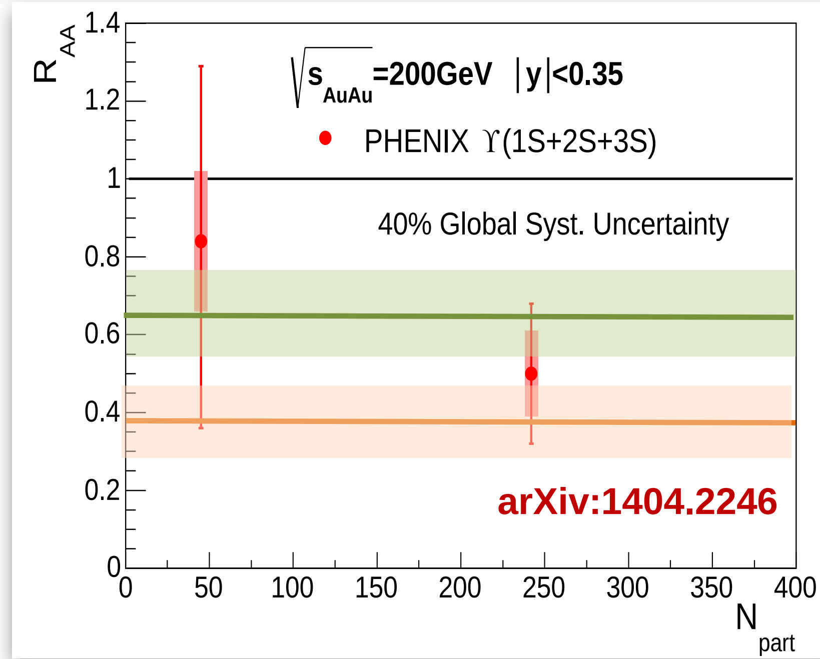
Upsilon (1S) has larger mass and binding energy
→ screening should occur at higher temperature

Upsilon (2S) has similar binding energy as J/ψ
→ similar suppression ?

b-bbar cross-section is much smaller than c-cbar
→ no significant recombination is expected, even at LHC

Upsilons at RHIC





Suppression is observed in Au+Au collisions by both STAR and PHENIX

Green band: complete suppression of Y(2S) and Y(3S)

Red band: complete suppression of Y(2S), Y(3S) and χ_b

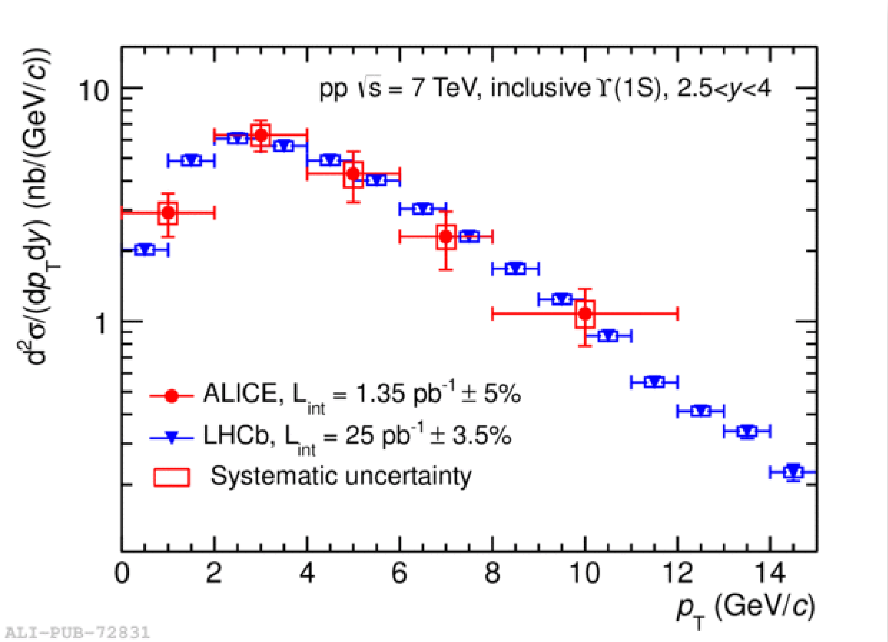
Models:

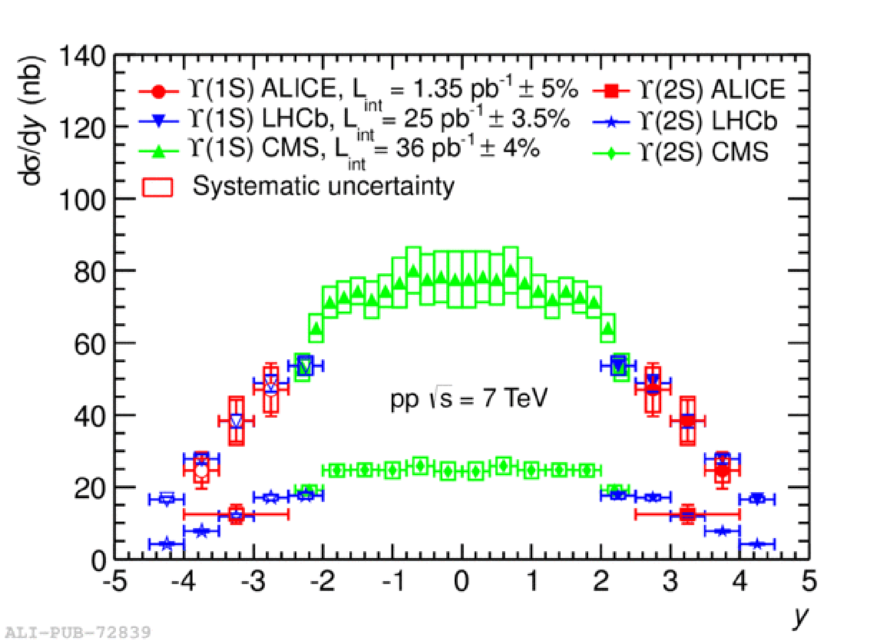
- transport model (dissociation in plasma + small recombination + effective CNM effects) **EPJ. A48, 72(2012)**
- hydro + thermal suppression **Nucl.Phys. A879, 25(2012)**

But: strong CNM effects observed by STAR (green square)

Upsilons in p+p at LHC

EPJ C 74, 2974 (2014)



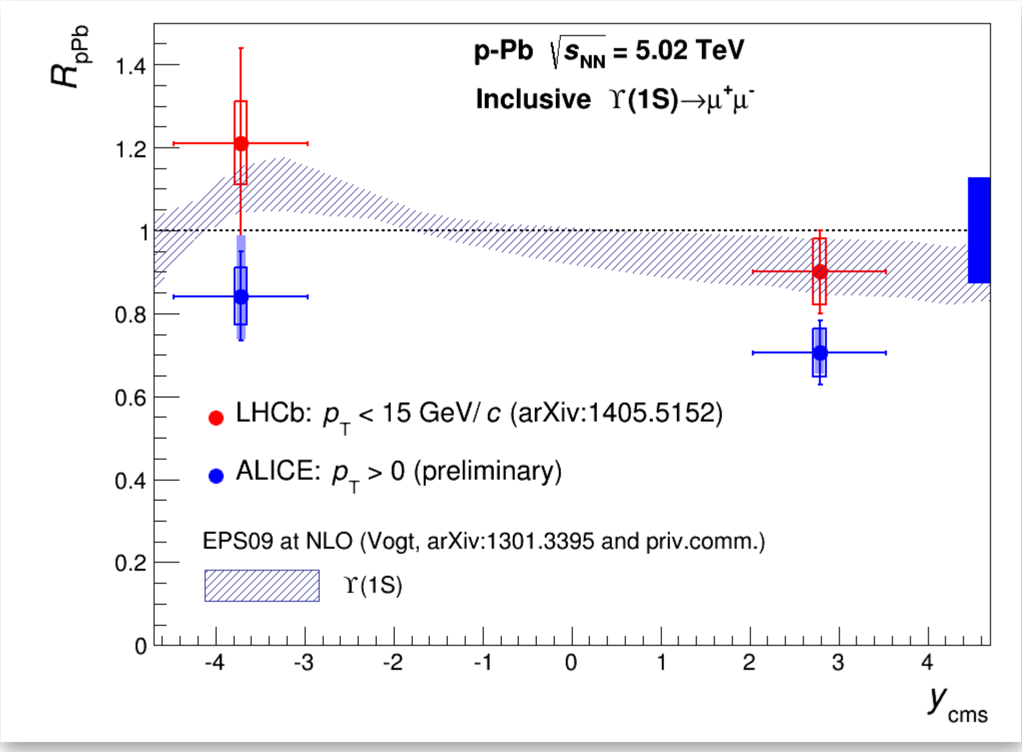


At LHC there is enough resolution to separate the three Upsilon states

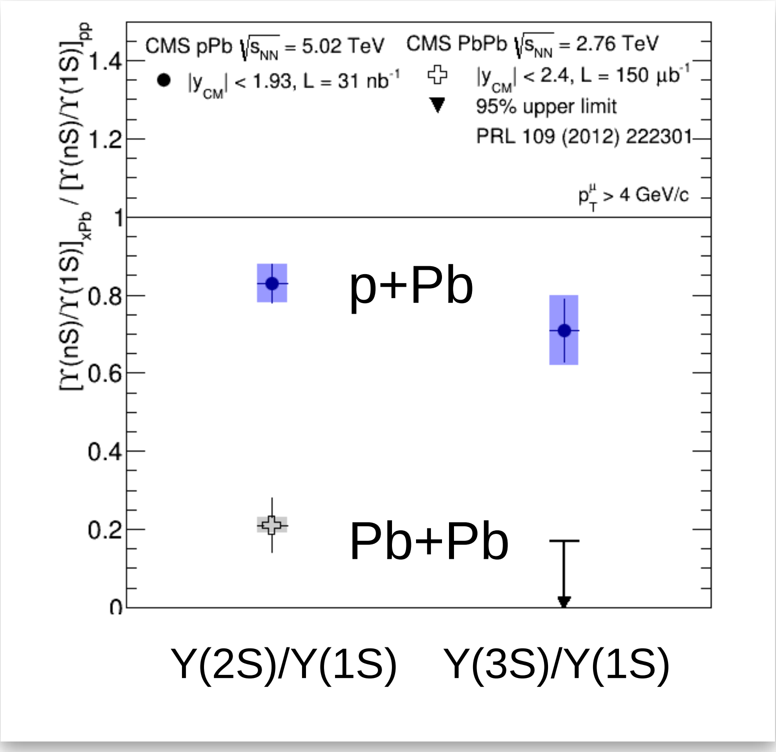
Upsilon (1S) measured in p+p @ 7 TeV by LHCb, CMS and ALICE

Excellent agreement between all three experiments

Upsilon Cold Nuclear Matter Effects at LHC



JHEP 04 (2014) 103



Left : Upsilon(1S) R_{pPb} measured by LHCb and ALICE.
Results are ~ in agreement (taking global uncertainties seriously).
Consistent with expectations from shadowing → little CNM at LHC

Right: Upsilon's double ratios in p+Pb and Pb+Pb by CMS
Significant deviations from unity in p+Pb, similar to what is seen for ψ(2S) / J/ψ

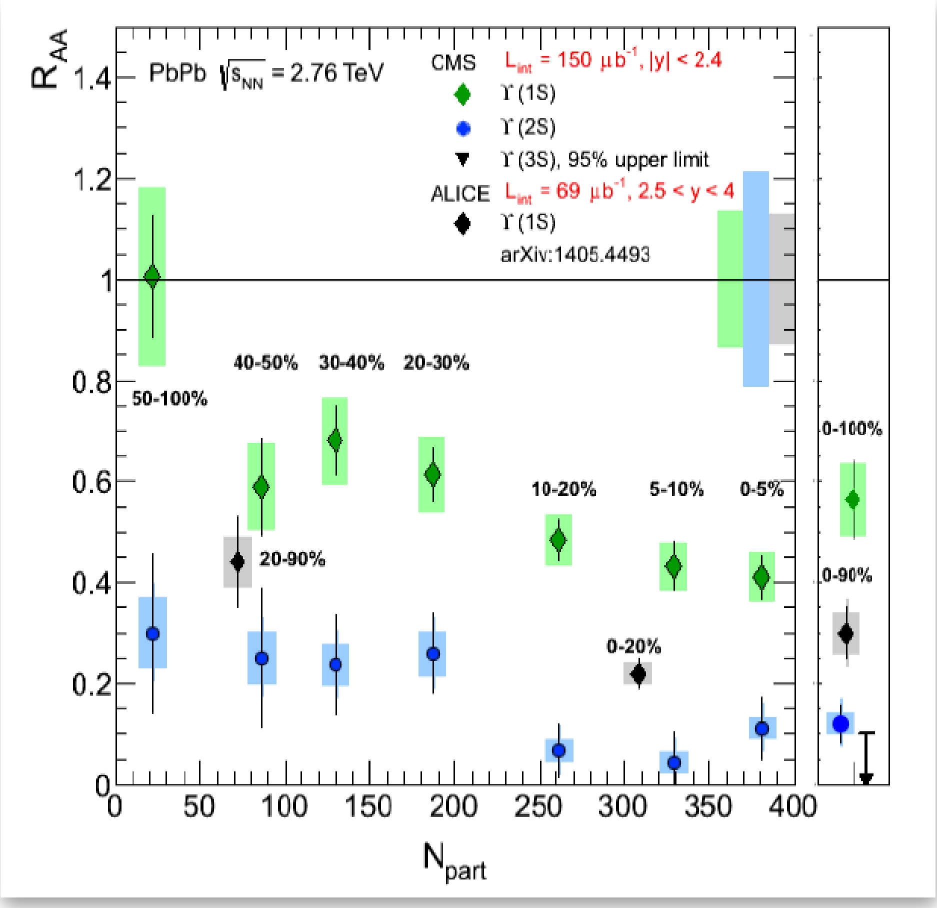
Upsilon in Pb+Pb at LHC

Suppression of Y(1S) observed at LHC (CMS) is similar to that of RHIC, consistent with suppression of higher mass excited states

First observation of Y(2S) (strong) suppression (CMS), and Y(3S) complete disappearance.

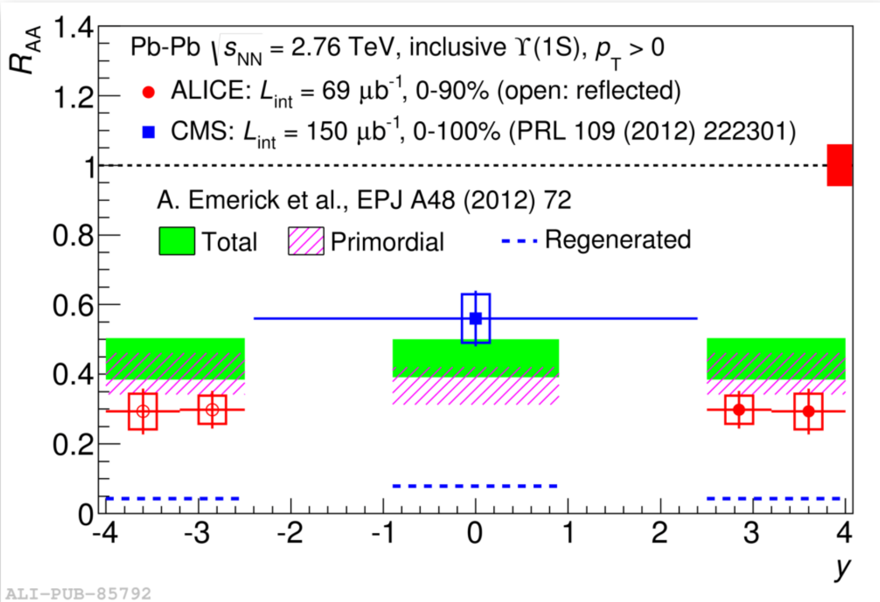
Forward rapidity Y(1S) R_{PbPb} (ALICE) is smaller than at mid-rapidity (similar to J/ψ trend observed at RHIC in Au+Au)

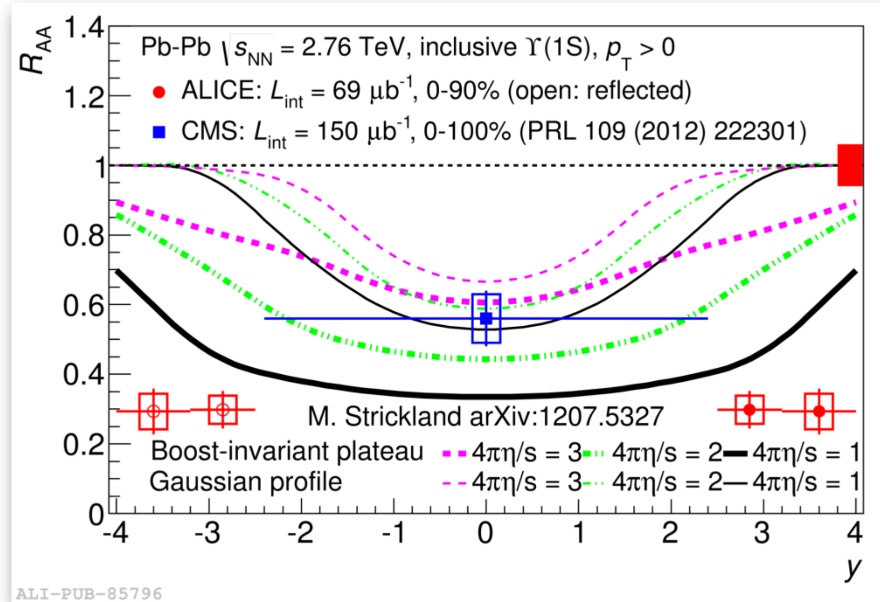
PRL 109 (2012) 222301



Upsilons in Pb+Pb at LHC

arXiv:1405.4493





Models are the same a the one shown for RHIC

As was the case for J/ψ at RHIC, they have a hard time at getting the rapidity trend right

Conclusion

J/ψ production seems at least qualitatively understood

Cold nuclear matter effects can be described with shadowing and energy loss, as well as nuclear absorption (at RHIC)

Production in HI collisions is described by a combination of

- suppression (either color screening, or in-medium dissociation)
- recombination (either in-medium or at phase boundary)

Challenge will be to discriminate between these possible scenarios

For ψ(2S), Cold Nuclear Matter Effects pose a challenge to models at both RHIC and LHC, because final state effects, that would be able to distinguish between J/ψ and ψ(2S), are expected to play a minor role.

Upsilon (2S) and (3S) are strongly suppressed at LHC.

Upsilon (1S) suppression is the same at RHIC and LHC, consistent with higher mass excited states suppression

Rapidity dependence poses a challenge to models, not unlike the J/ψ at RHIC, back in the days

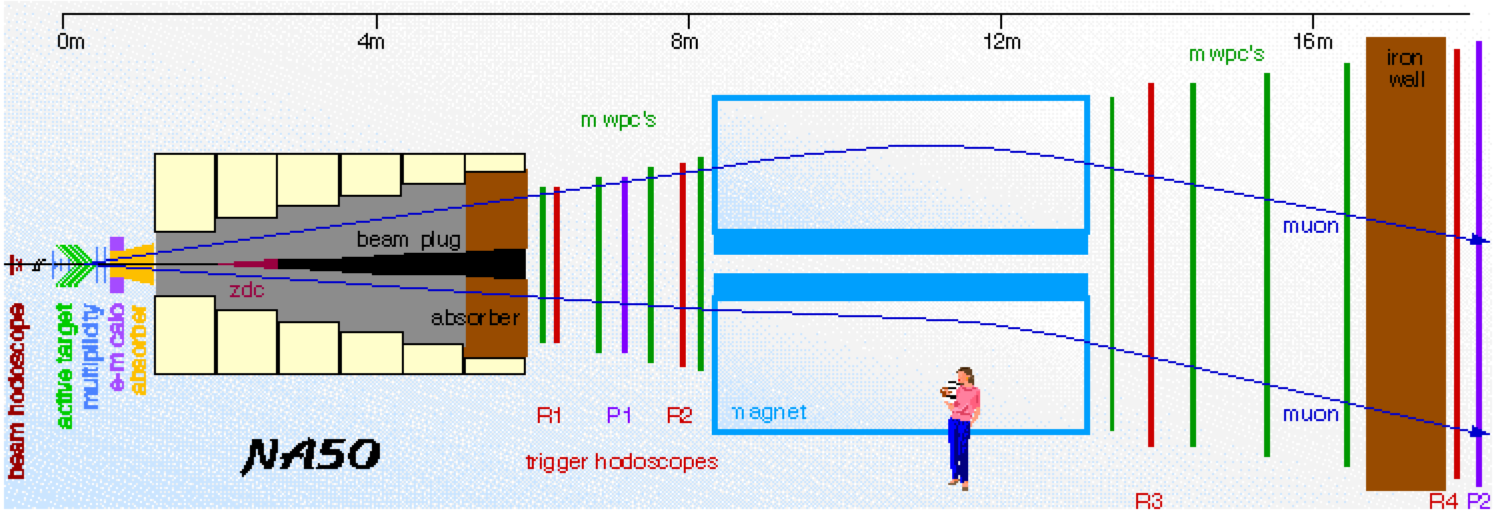
Backup

SPS experiments – NA50

Several experiments using proton and heavy ion beams from the SPS, at CERN on fixed target: NA38, NA50, NA51 and NA60

Colliding species: p+p, p+A, S+U, Pb+Pb, In+In

Colliding Energy: $\sqrt{s_{NN}} \approx 20$ GeV



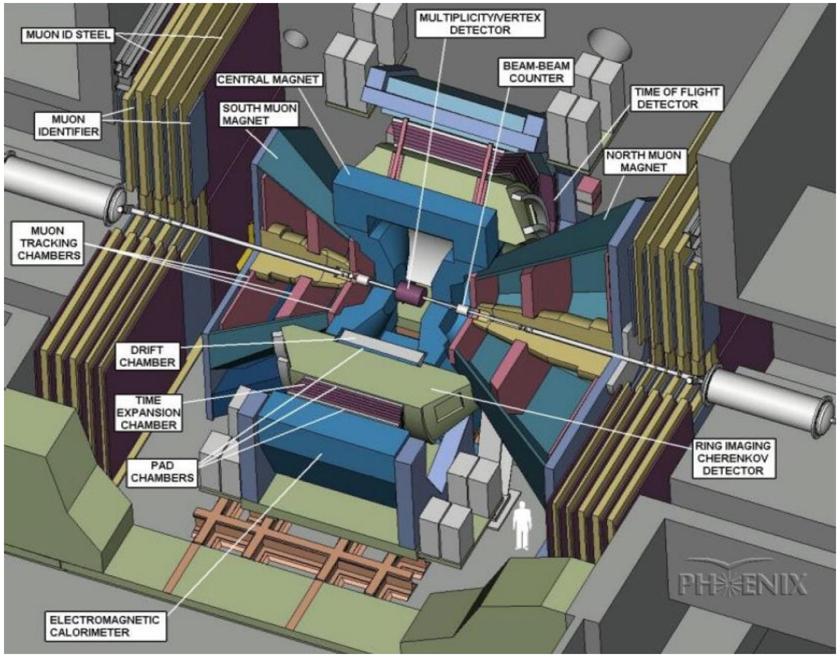
RHIC experiments (STAR and PHENIX)

Two collider experiments at RHIC (Brookhaven National Laboratory): PHENIX and STAR

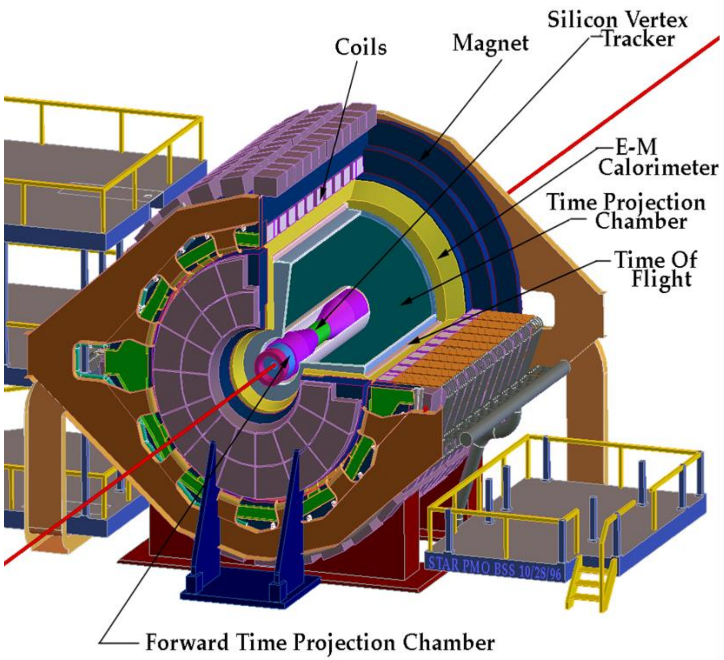
Colliding species: p+p, d+Au, Au+Au

Collision Energy: $\sqrt{s_{NN}}$ = 200 GeV (10 x SPS)

PHENIX



STAR



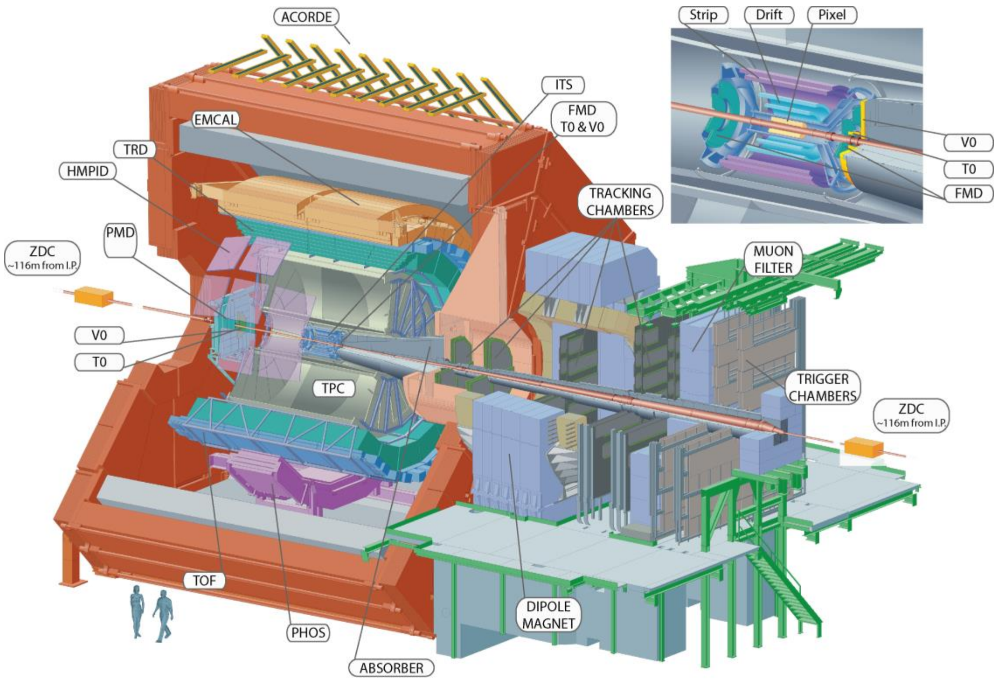
LHC Experiments (here: ALICE, CMS)

Four experiments on the LHC at CERN: ALICE, ATLAS, CMS and LHCb

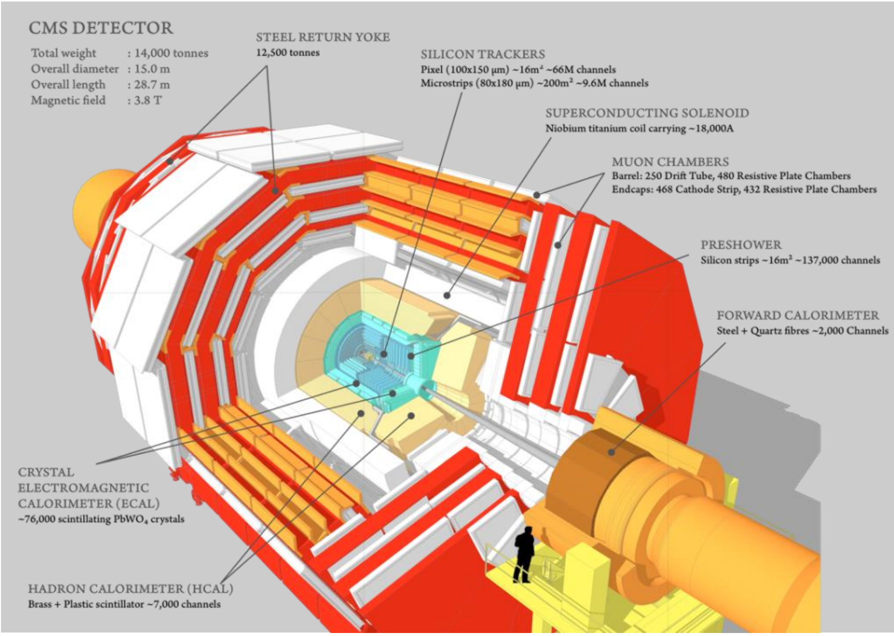
Colliding species: p+p, p+Pb (and Pb+p), Pb+Pb

Collision Energy: $\sqrt{s_{NN}}$ = 2.76 TeV (14 x RHIC)

ALICE



CMS



Upsilons at RHIC