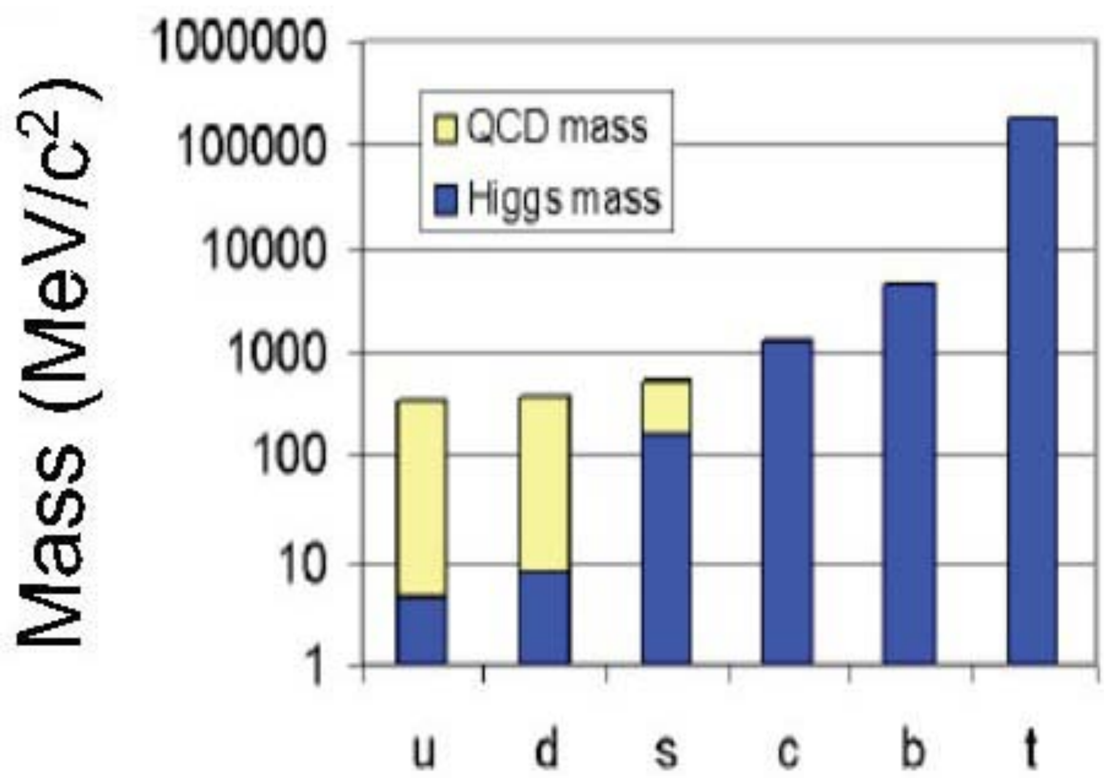
Recent results and future perspectives for quarkonia

Lijuan Ruan
(*Brookhaven National Laboratory*)

Outline:

- **Introduction**
- **The recent results**
- **The future measurements**
- **Summary**

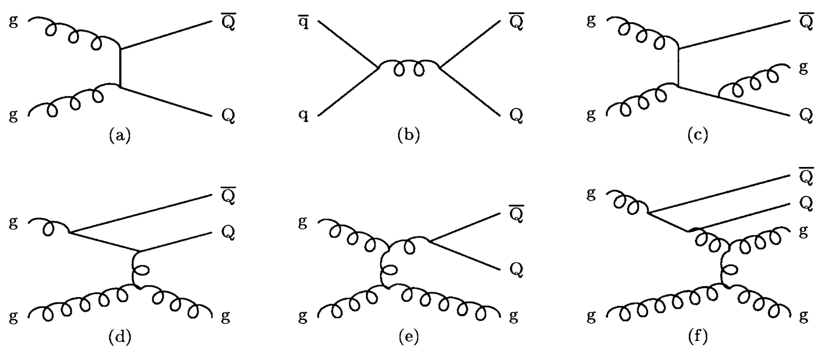
The quark mass



Heavy flavor mass, comes from the Higgs mechanism, no effect from the QCD chiral symmetry breaking.

Light flavor mass, affected by chiral symmetry breaking.

Heavy flavor and quarkonium production



$M_c \approx 1.3$ GeV
$M_b \approx 4.8$ GeV $\gg T_c, \Lambda_{QCD}, M_{uds}$

Produced at initial impact through hard process, penetrating probe.

Produced by gluon fusion, quark-antiquark annihilation, gluon emission, flavor excitation, and gluon splitting …

Charm quark into hadrons (~10% to baryon, ~1% into J/ψ, and others to mesons)

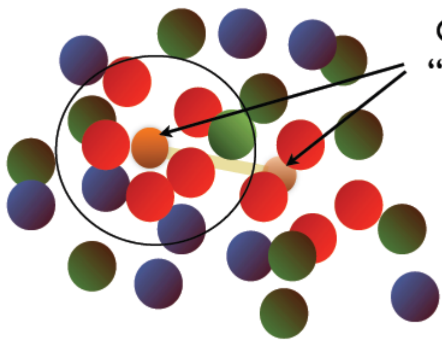
QQbar transition into quarkonium through color singlet, color octet, and color evaporation approaches.

Quarkonium as a QGP indicator

color screening

Matsui-Satz: screening the potential

Screening in a deconfined medium: effective charge of Q and $\bar{Q}$ reduced

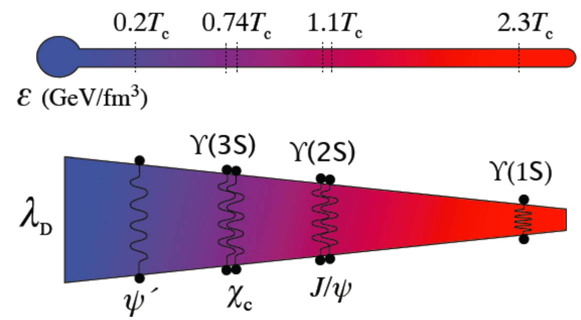


Q and $\bar{Q}$ cannot "see" each other $r_D < r_{Q\bar{Q}}$

Assume: medium effects described with a T-dependent potential

$$-\frac{\alpha_{eff}}{r} e^{-r/r_D(T)}$$

Courtesy from A. Mocsy



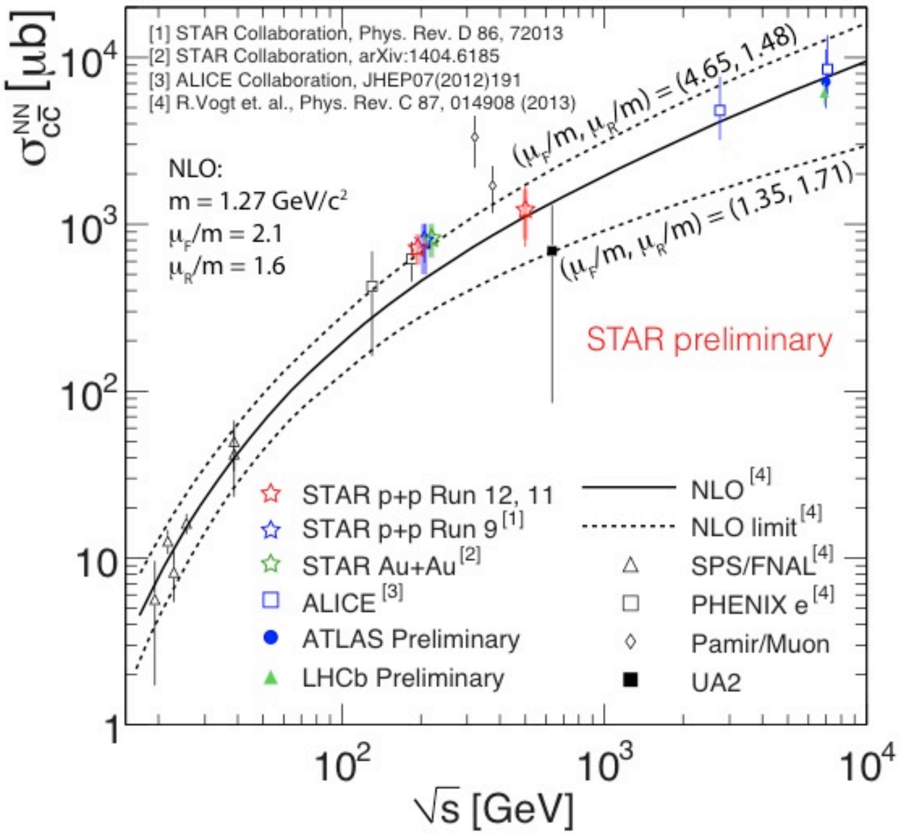
Different quarkonium states:
Heavy but small,
0.28, 0.56, 0.78 fm for ϒ(1S), ϒ(2S), ϒ(3S).
provide distance scales to probe QGP:
different dissociation temperatures.

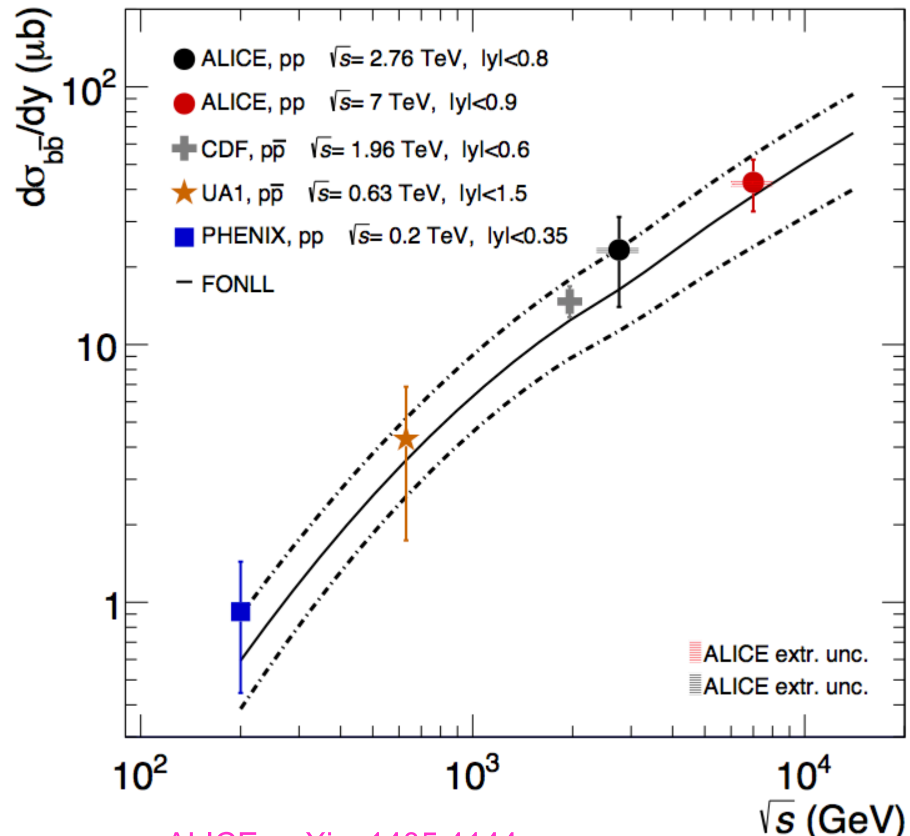
A+A collisions: **color screening, gluon dissociation, recombination**; **jet quenching, formation time; cold nuclear matter effect requires measurements:**

1) energy, collision system size, centrality, rapidity, and p_T dependences in heavy ion collisions

2) understand p+p, p+A production mechanisms

Heavy flavor total cross section





ALICE: arXiv: 1405.4144

Charm cross section follows N_{bin} scaling from p+p to Au+Au collisions

Expect to get 60 ccbar and 2 bbbar pairs in central Pb+Pb collisions at 2.76 TeV

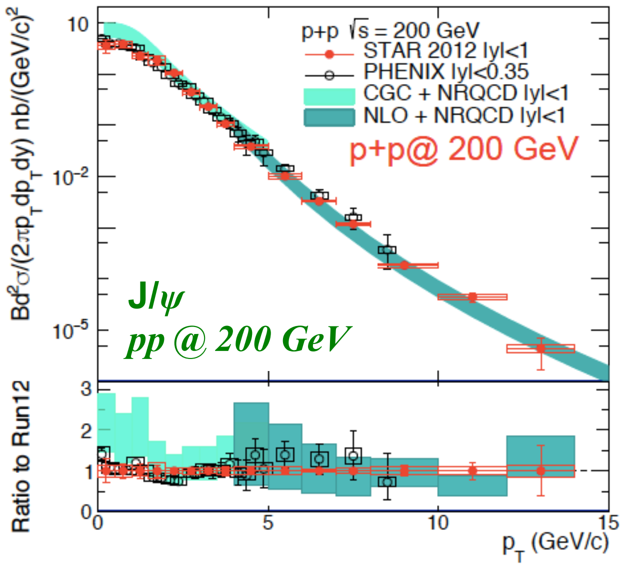
Expect to get 15 ccbar and 0.1 bbbar pairs in central Au+Au collisions at 200 GeV

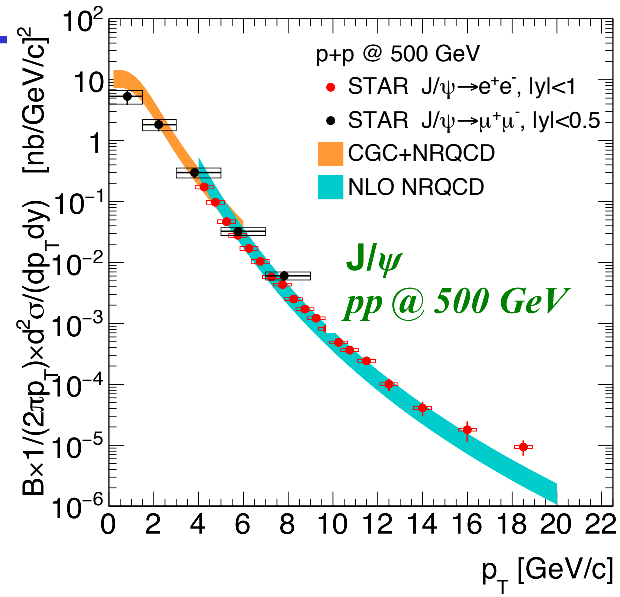
Coalescence from bbbar to ϒ is negligible at RHIC.

BROOKHAVEN NATIONAL LABORATORY

Charmonium cross-section in pp

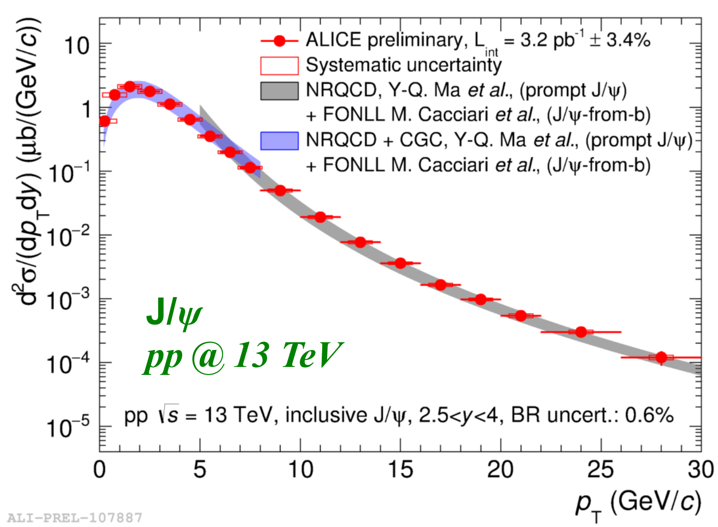
STAR

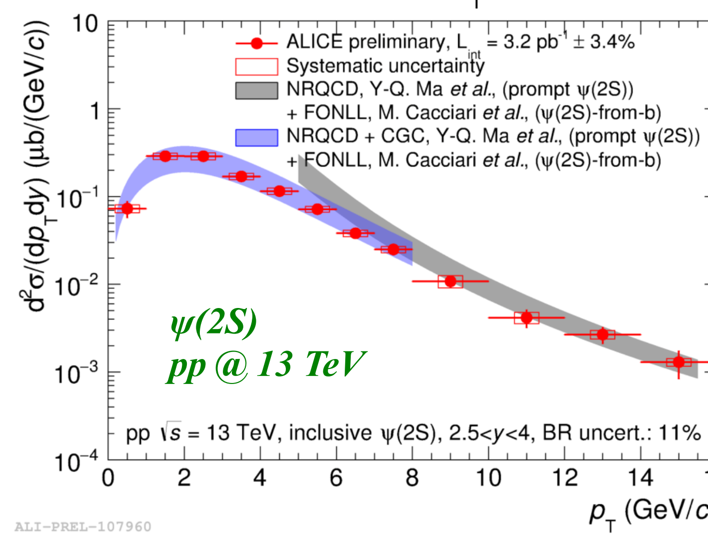




Theory:
PRL 106 (2011) 042002
PRL 113 (2014) 192301
JHEP 1210 (2012) 137

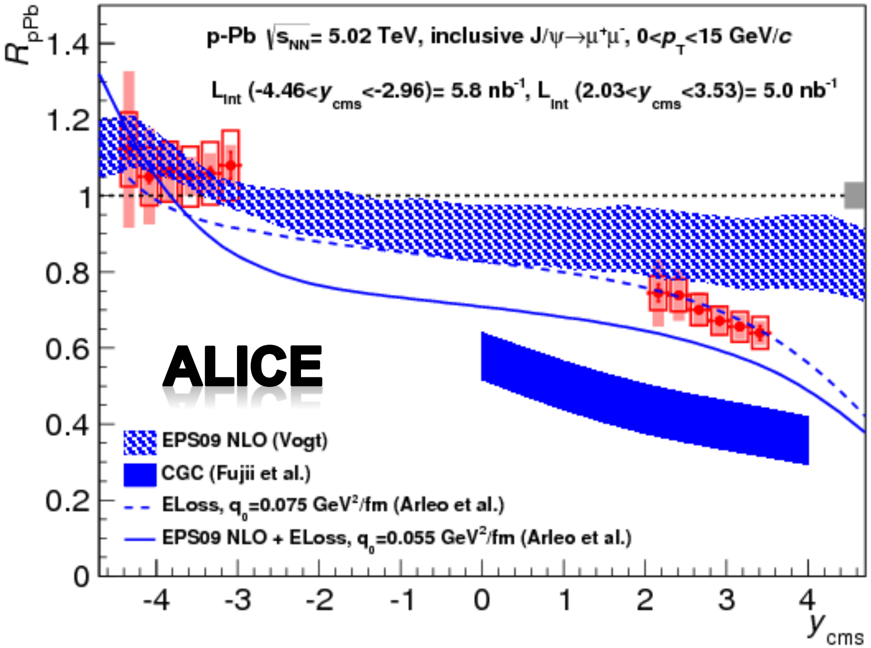
ALICE



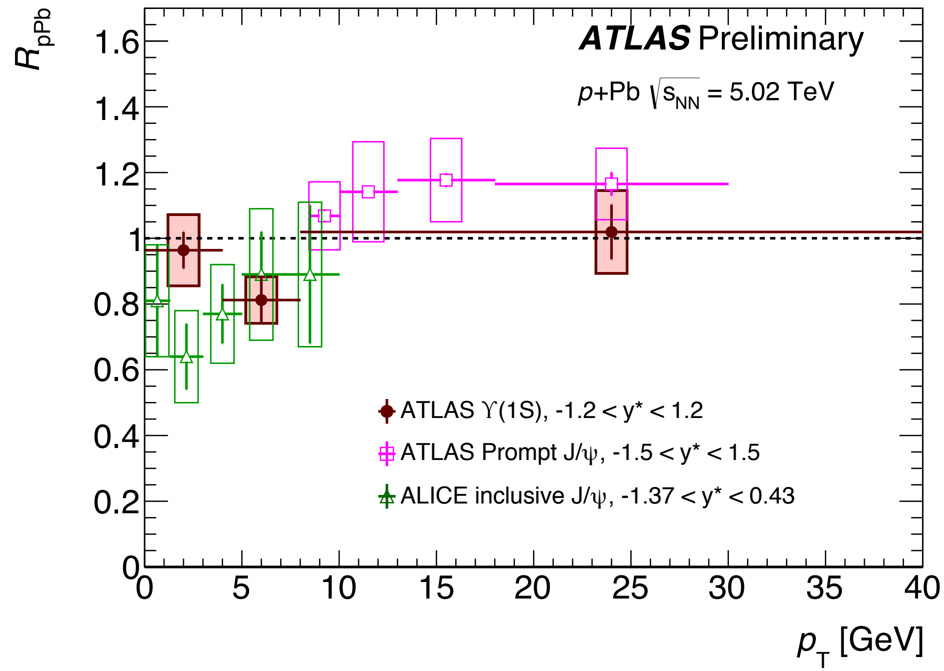


- Good understanding of charmonium cross section for $\sqrt{s}$ = 0.2 – 13 TeV

Quarkonium production in pA

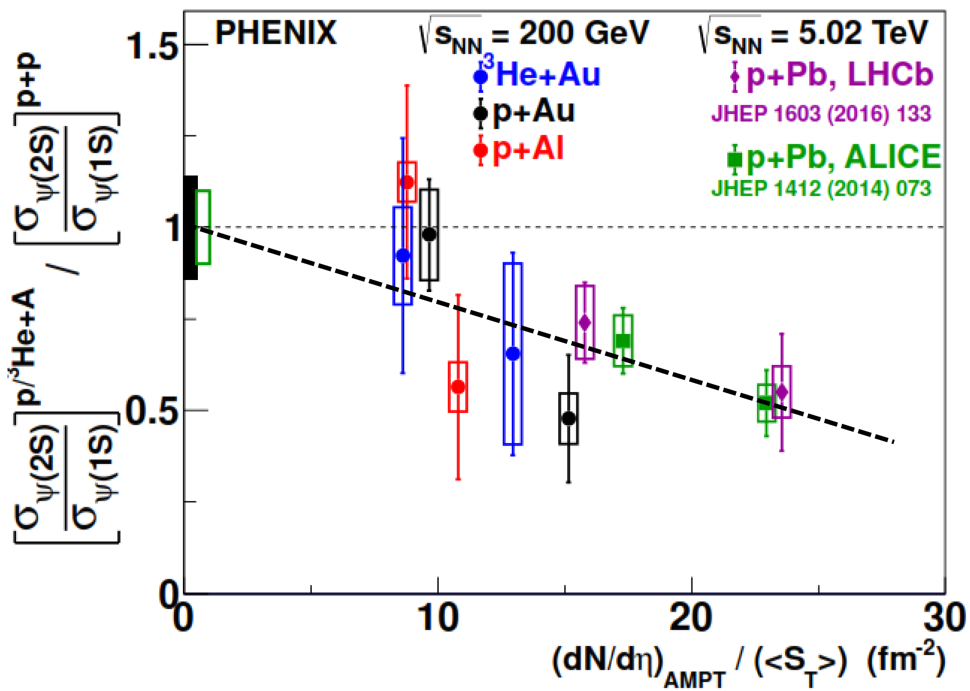


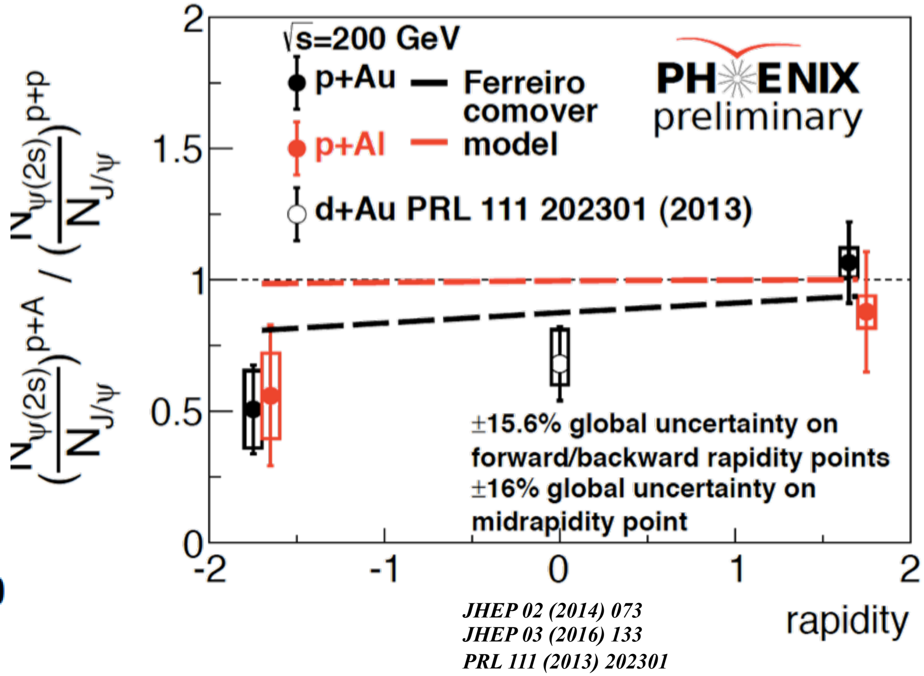
JHEP 02 (2014) 073



- J/ψ: strong suppression at forward rapidity. Backward rapidity is consistent with unity.
- Similar feature for Υ.
- At high p_T, no suppression at mid-rapidity.

$R_{p(d)A}[\psi(2S)]$ versus $R_{p(d)A}(J/\psi)$





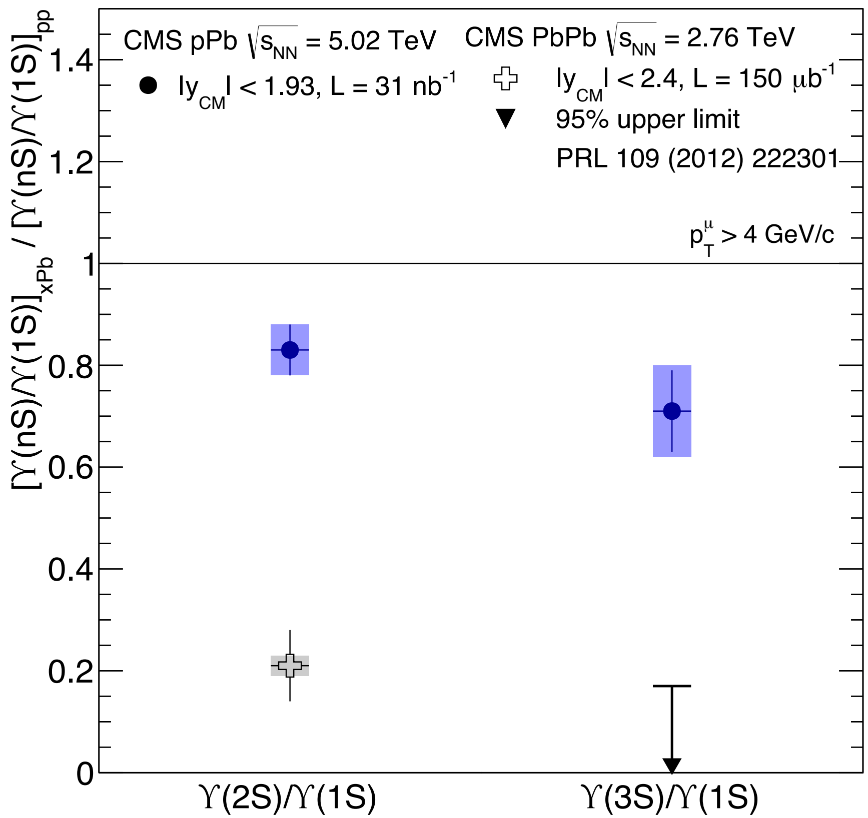
RHIC: $R_{p(d)A}[\psi(2S)] < R_{p(d)A}(J/\psi)$ on the A going direction and at midrapidity

LHC: $R_{pA}[\psi(2S)] < R_{pA}(J/\psi)$ on the A and p going direction and at mid rapidity

Consistent with co-mover suppression picture.

The ϒ(2S,3S) case

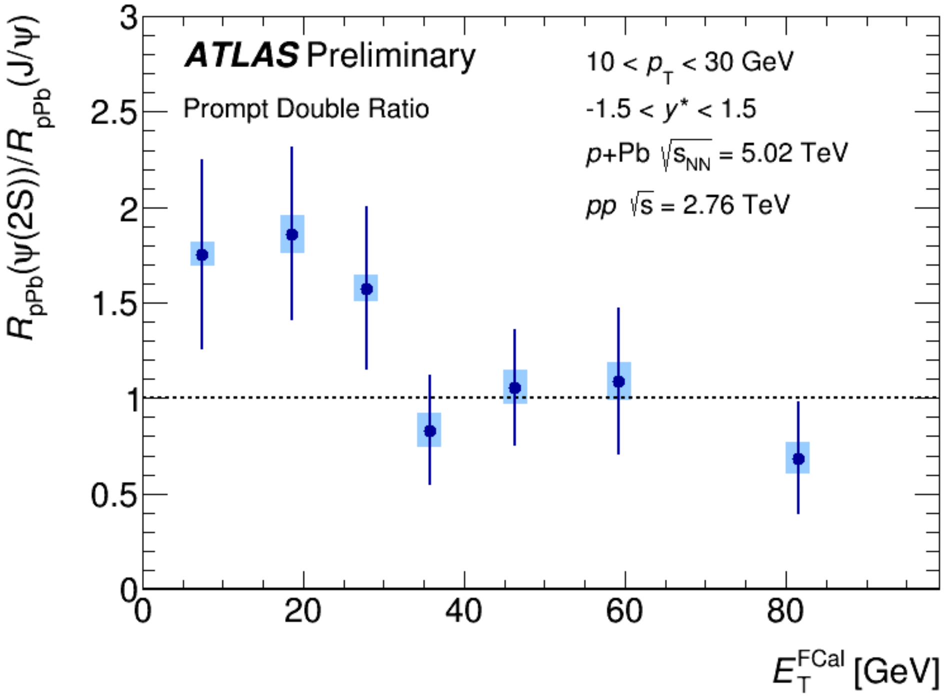
JHEP 04 (2014) 103



ϒ(2S,3S) more suppressed than ϒ(1S) in pA collisions at mid-rapidity.

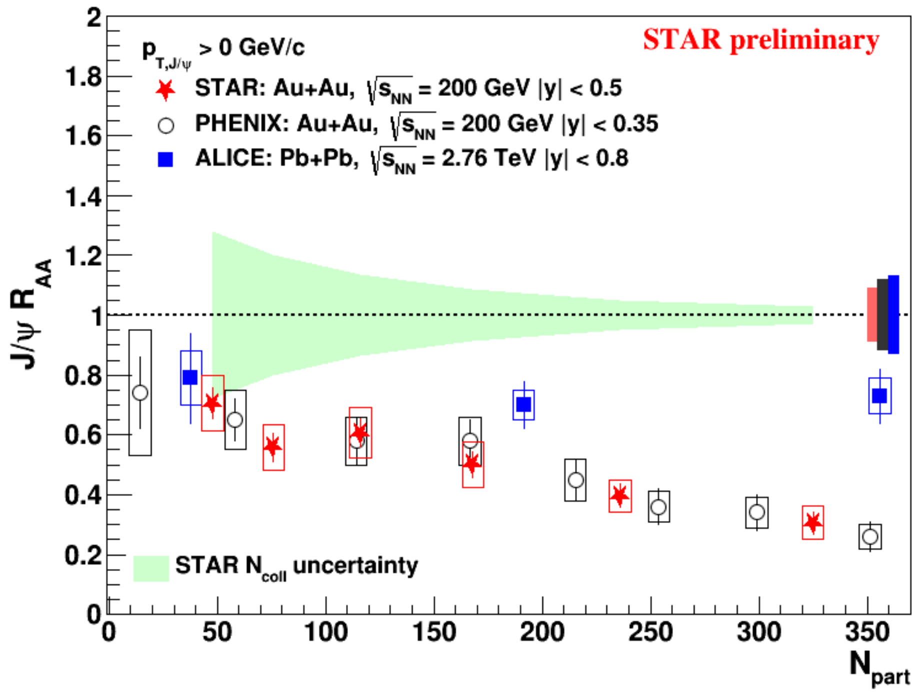
High-p_T ψ(2S) in pPb

ATLAS-CONF-2015-023

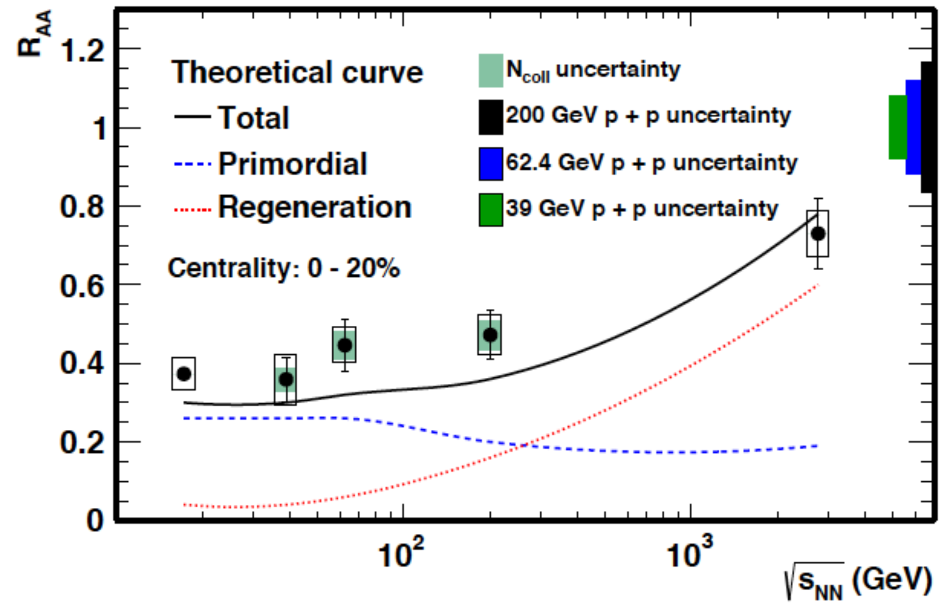


- Similar suppression in central collisions
- Hints of less suppression in peripheral collisions

J/ψ suppression pattern in A+A



STAR Collaboration, SQM2016



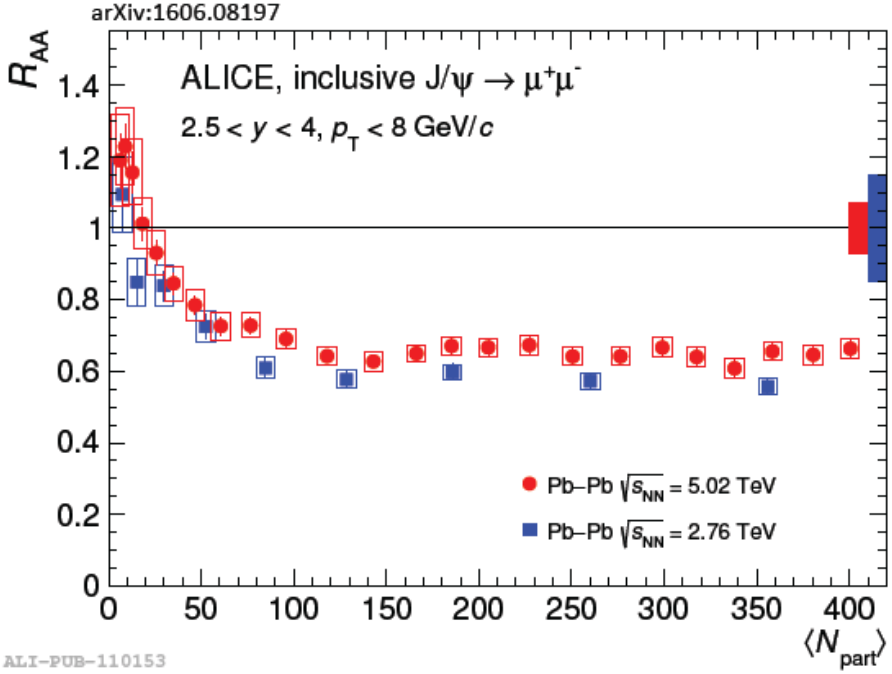
STAR Collaboration, 1607.07517

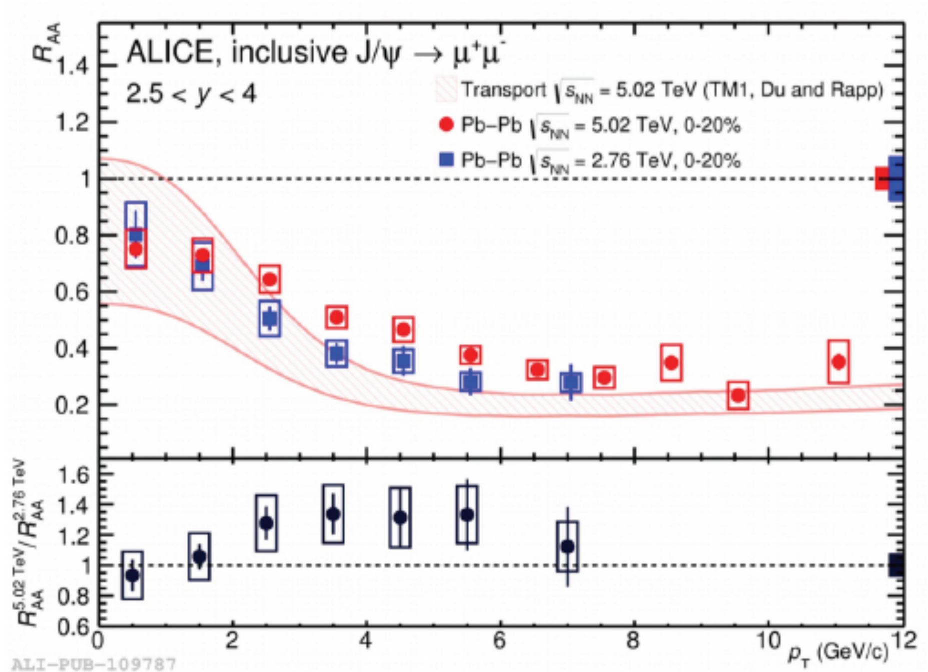
J/ψ through its dileptonic decay: indicator of deconfinement

consistent with more significant contribution from ccbar recombination at LHC energies

Interplay between color screening and recombination: describe the J/ψ suppression pattern and its energy dependence.

J/ψ in PbPb at 5 TeV

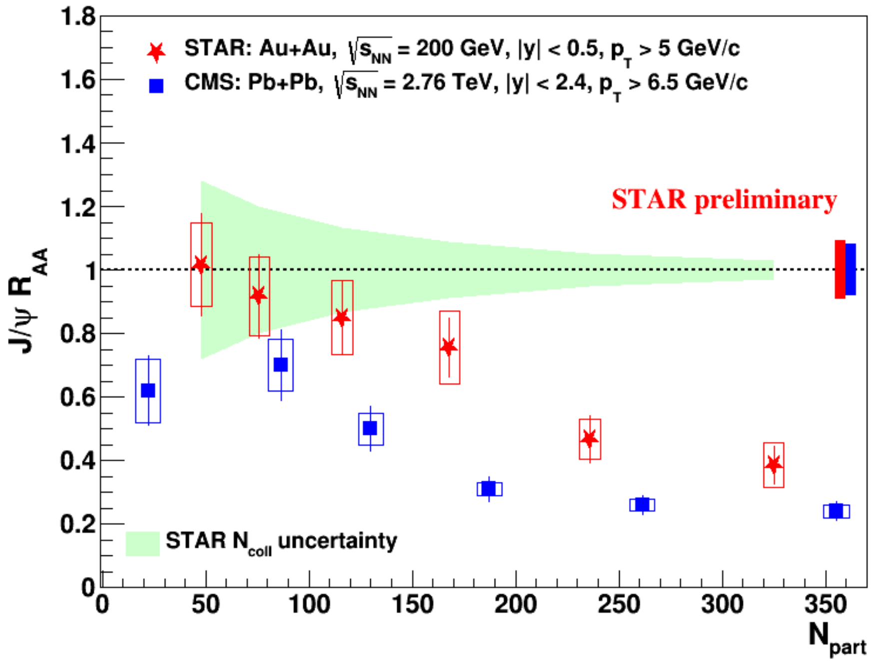


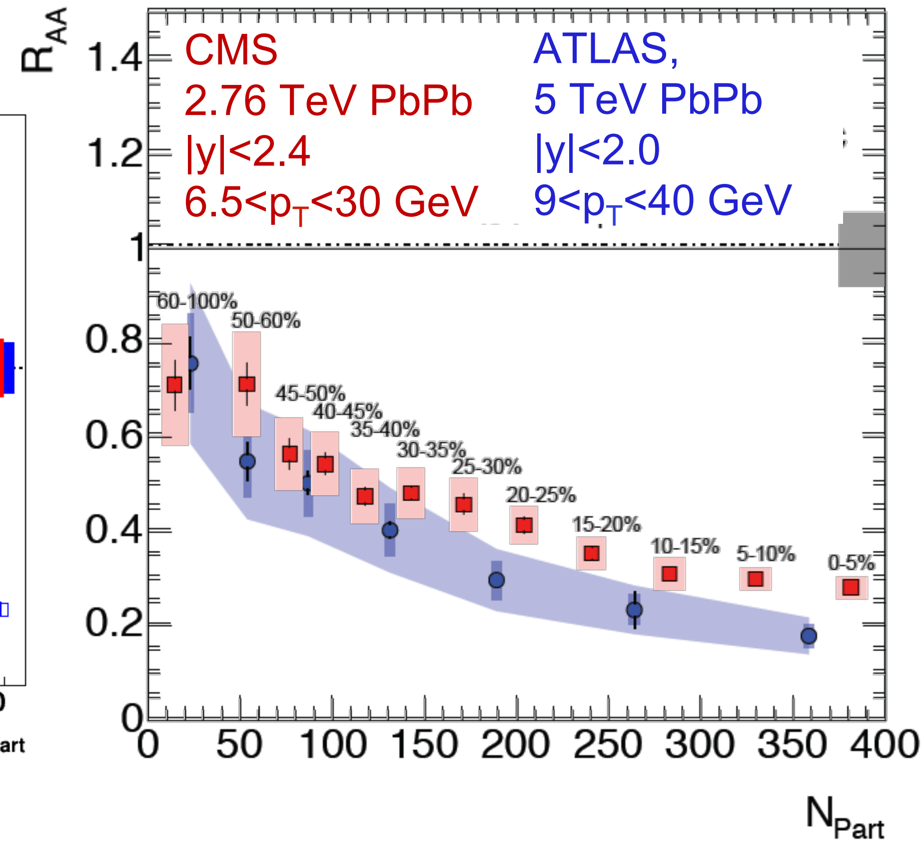


J/ψ at forward rapidity:

- Less suppression at 5 TeV than 2.76 TeV, hint of more recombination at 5 TeV.
- need further improve 2.76 TeV pp reference.

J/ψ suppression pattern at high p_T

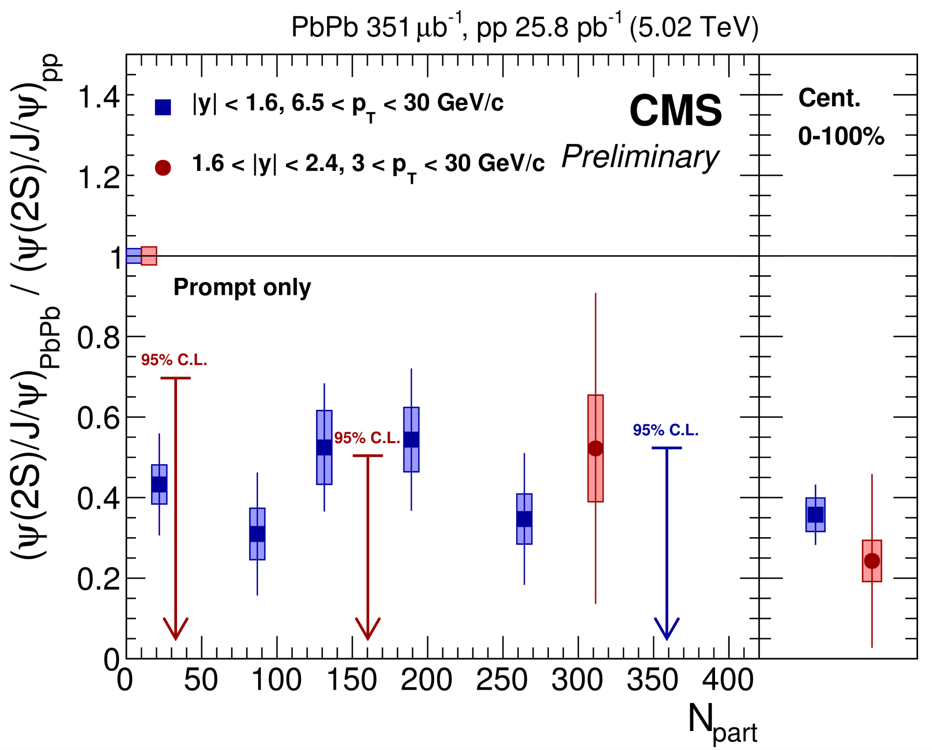


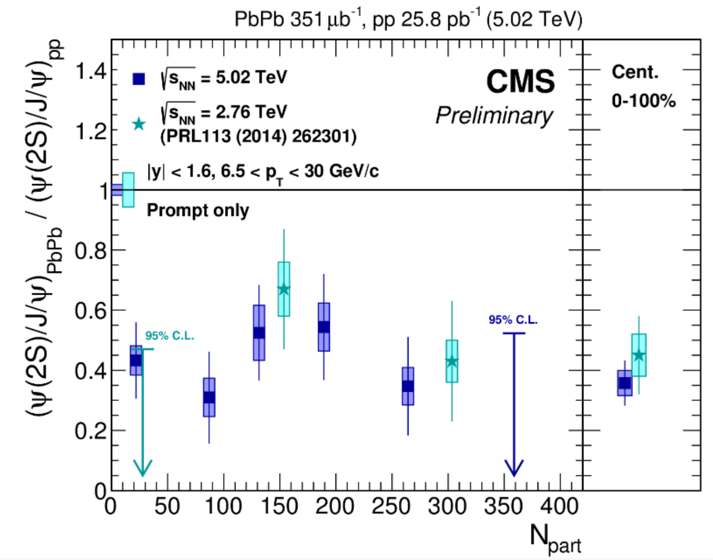


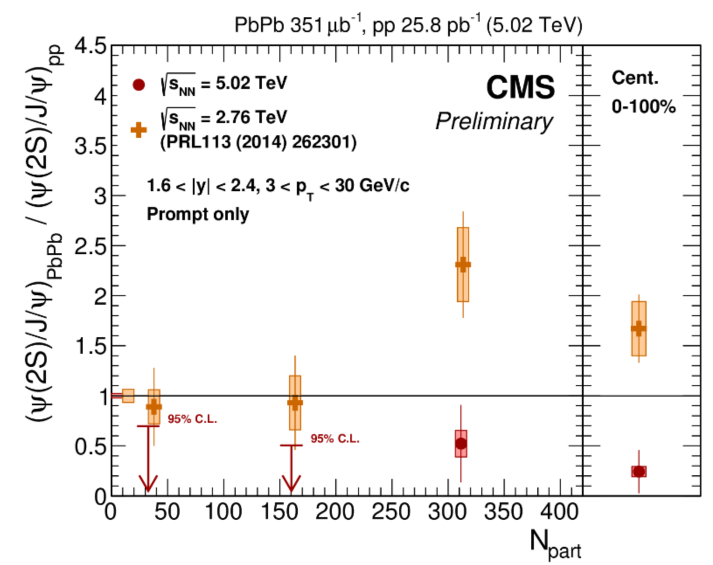
Stronger suppression for higher energies:

R_{AA}(0.2 TeV) > R_{AA}(2.76 TeV) > R_{AA}(5 TeV TeV)

ψ(2S) in PbPb at 5 and 2.76 TeV

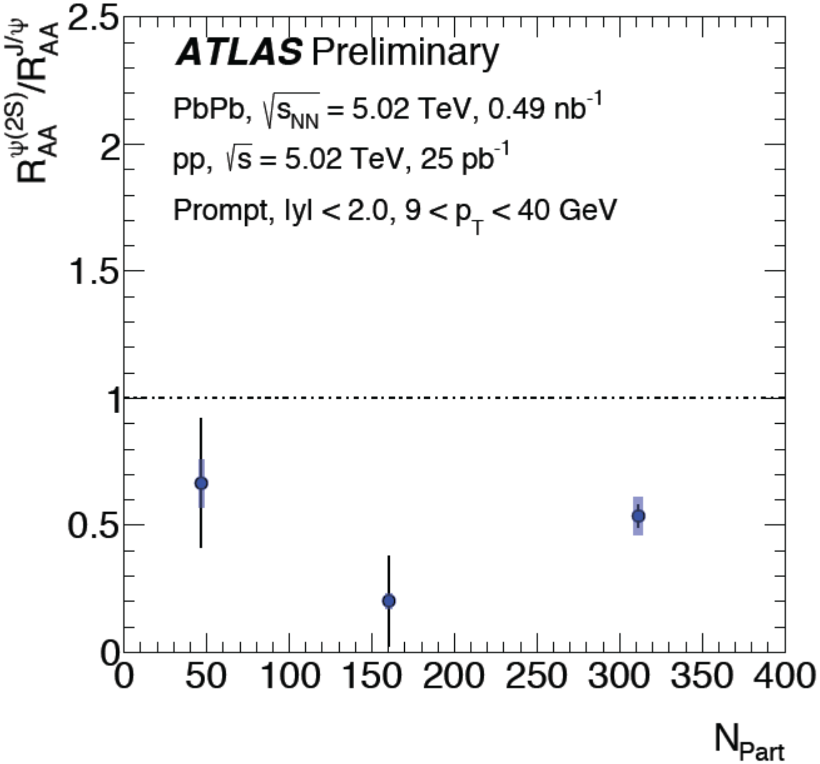






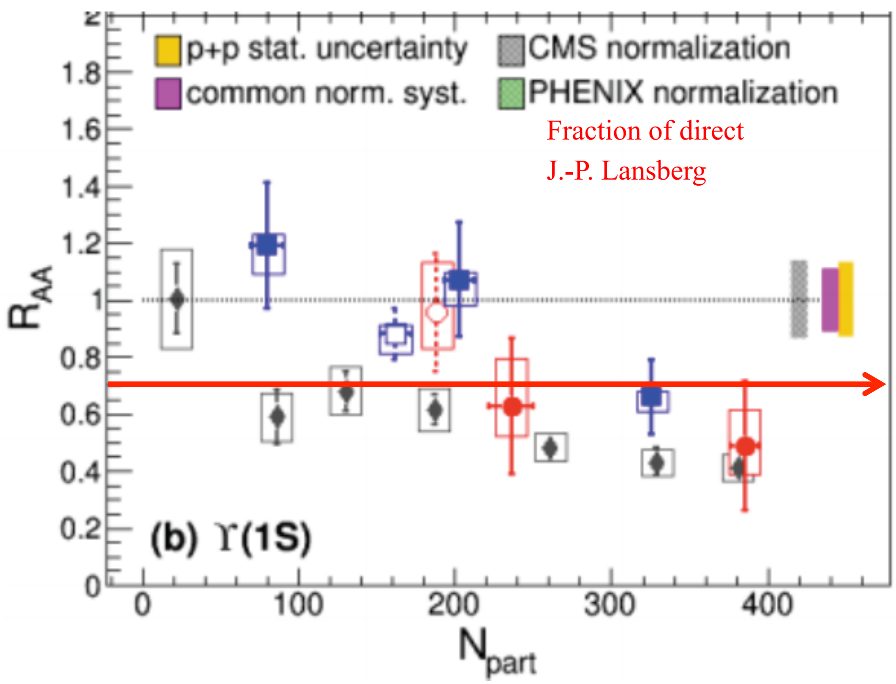
- ψ(2S) more suppressed than J/ψ,
- Relative enhancement at p_T>3GeV disappears at 5 TeV

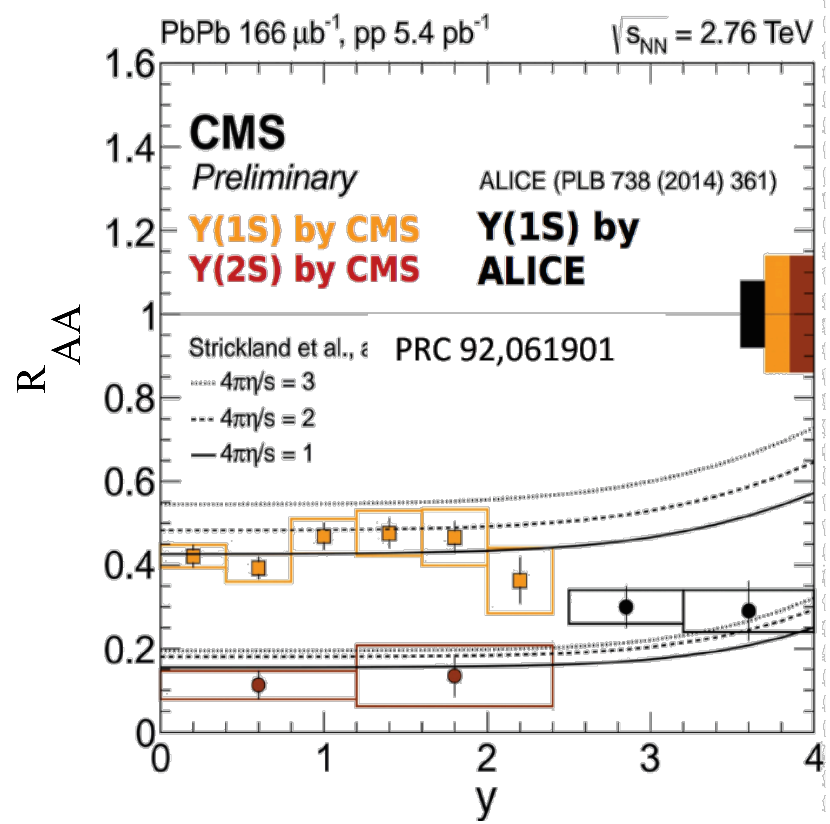
High-p_T ψ(2S) in PbPb



- Significantly stronger suppression with respect to J/ψ

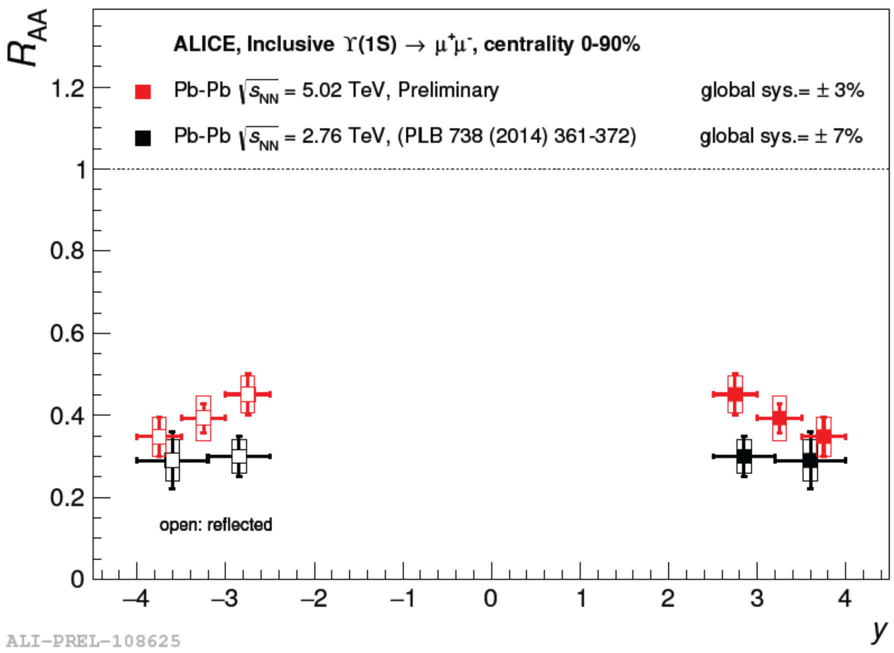
ϒ(1S) in AA

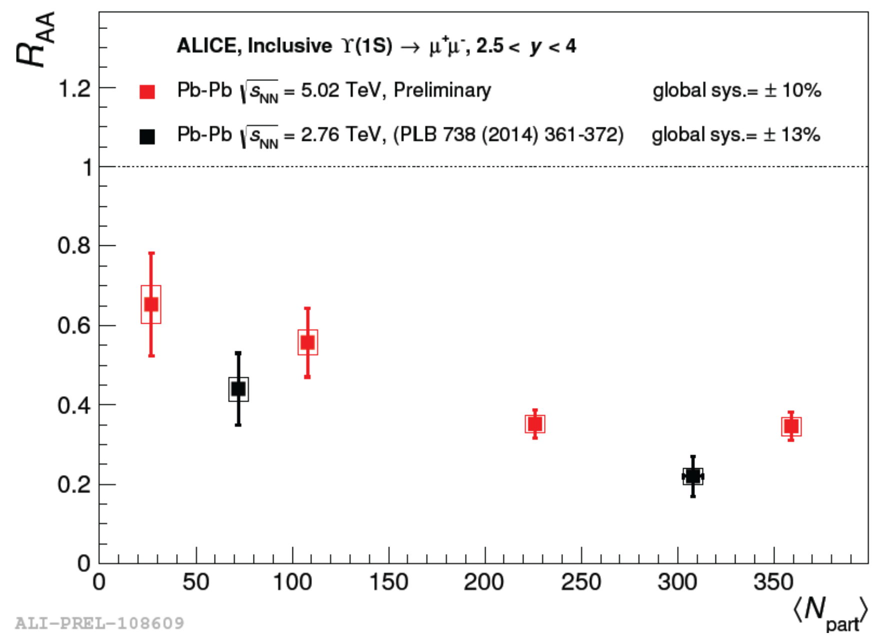




- Stronger suppression at LHC than at RHIC
- Suppression of direct ϒ(1S) in central collisions?
- More suppression at forward rapidity than mid-rapidity (Re)combination?

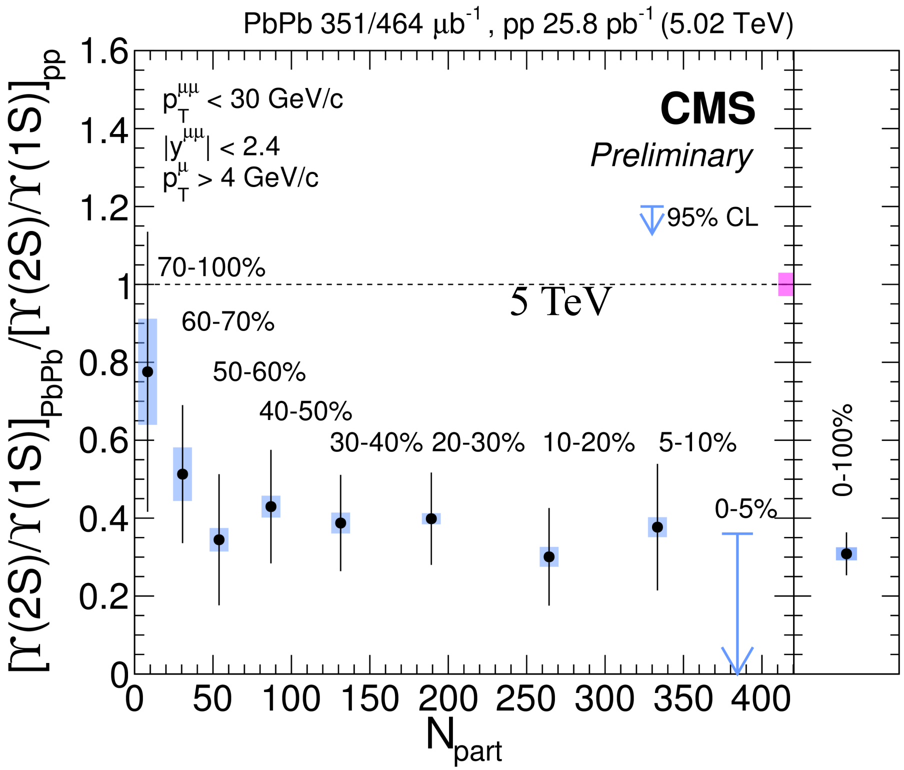
Υ(1S) in PbPb at 5 TeV

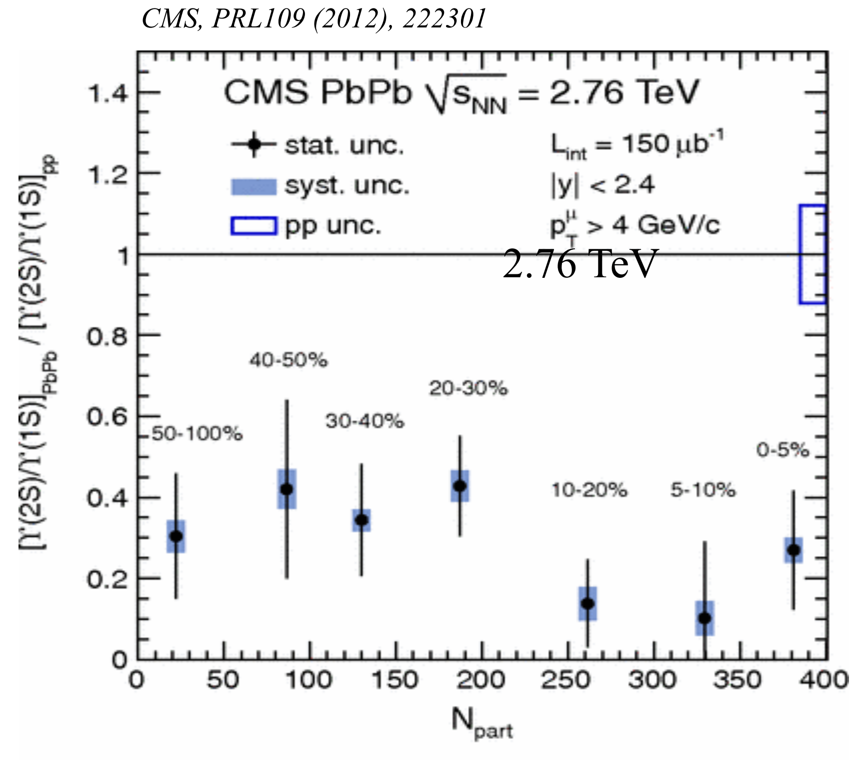




- Hints of stronger suppression in more forward rapidity
- Hints of less suppression at higher beam energy
  Ratio(0-90%) = 1.3±0.2(stat.)±0.2(syst.)

ϒ(2S) in PbPb

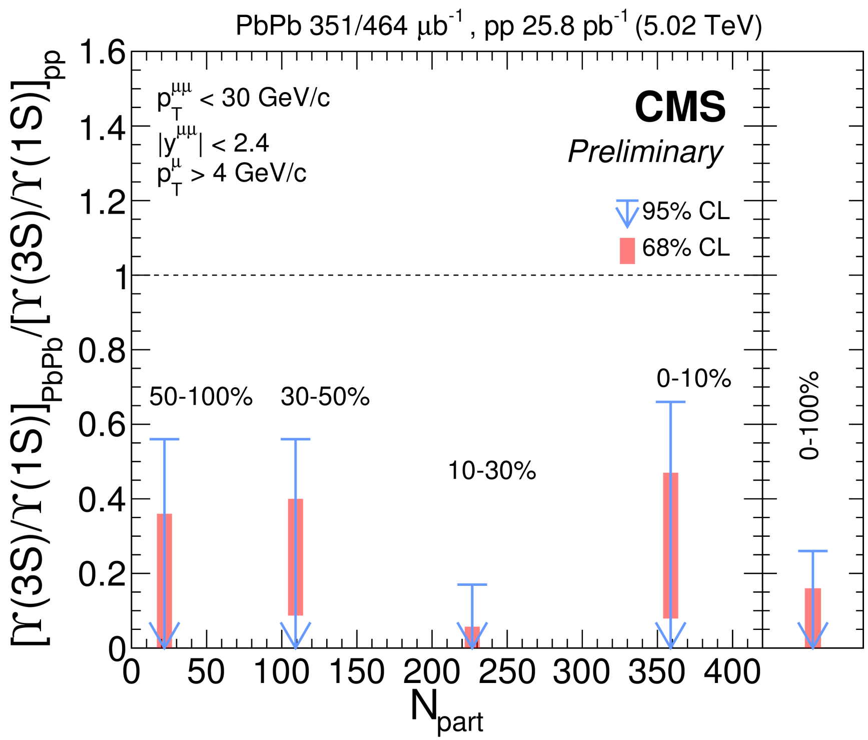




0.308±0.055(stat.)±0.017(syst.)

0.21±0.07(stat.)±0.02(syst.)

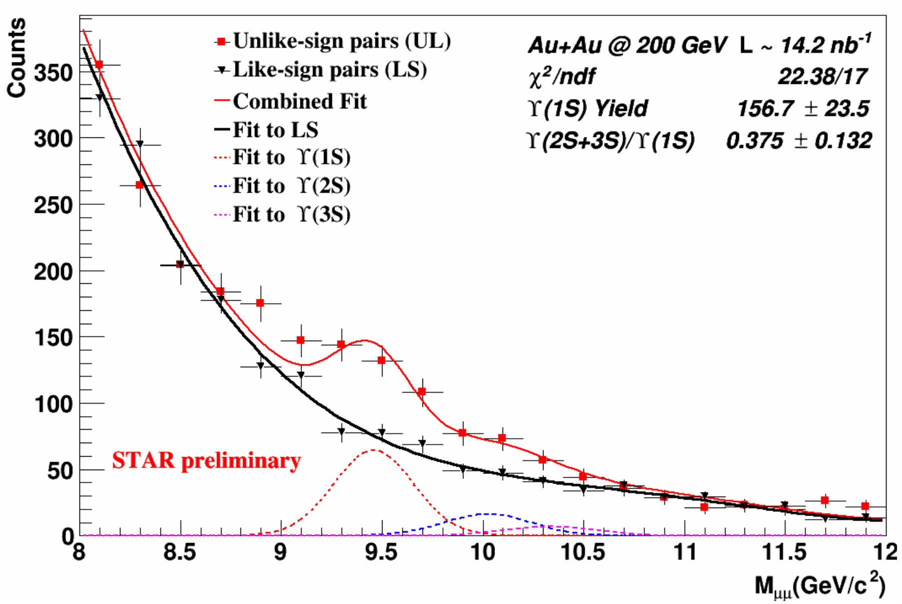
ϒ(3S) in PbPb

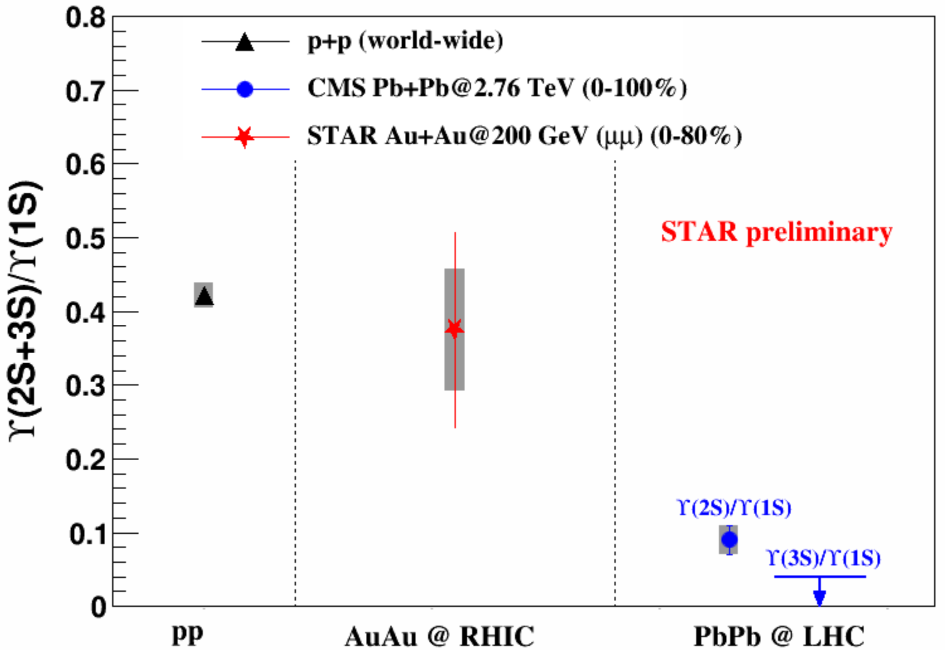


- Double Ratio < 0.26 (95% CL) at 5 TeV
- Double Ratio < 0.17 (95% CL) at 2.76 TeV

ϒ(2S+3S) in AuAu

STAR Collaboration, SQM2016





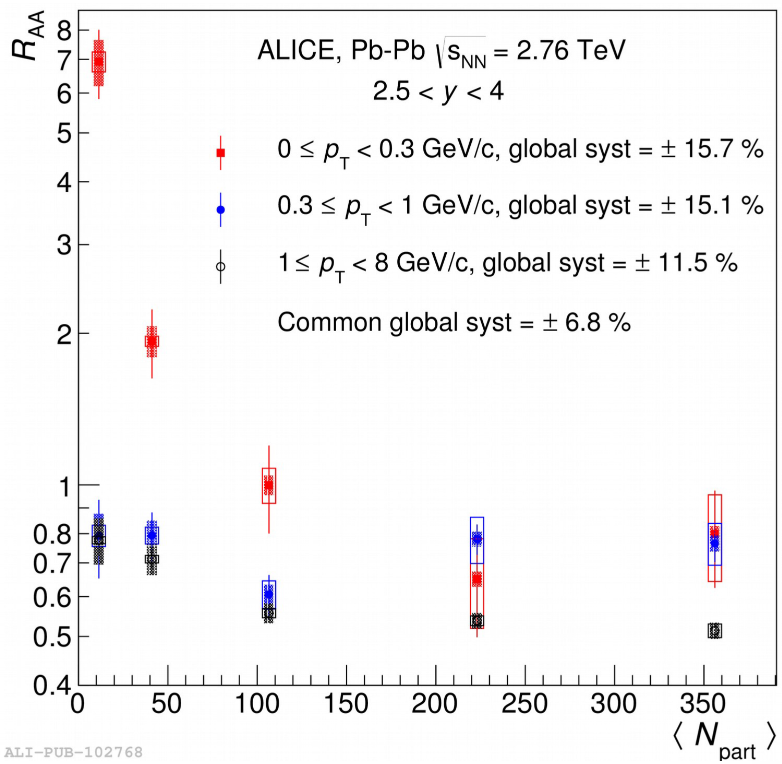
0.28, 0.56, 0.78 fm for ϒ(1S), ϒ(2S), ϒ(3S).

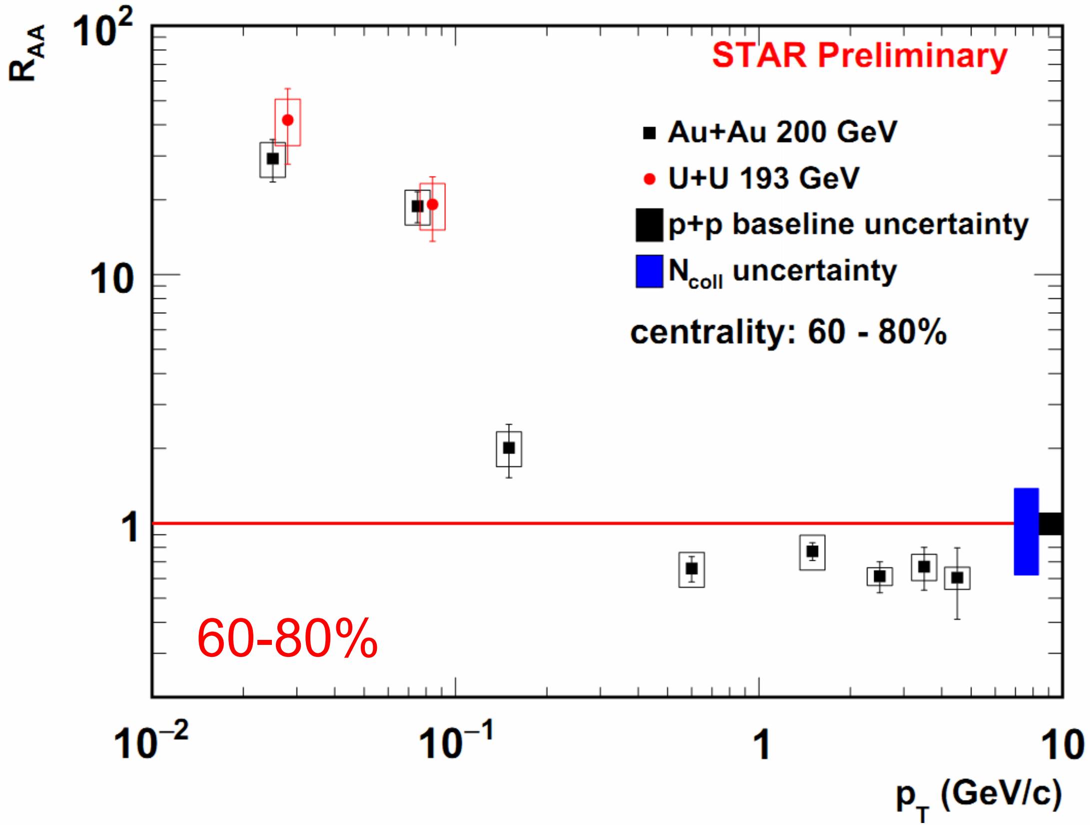
Negligible contribution from b and bbar recombination at RHIC

A better probe to study color-screening feature of QGP.

A hint of ϒ(2S+3S) less suppressed at RHIC than at LHC!

Very low pt J/ψ: largely enhanced!

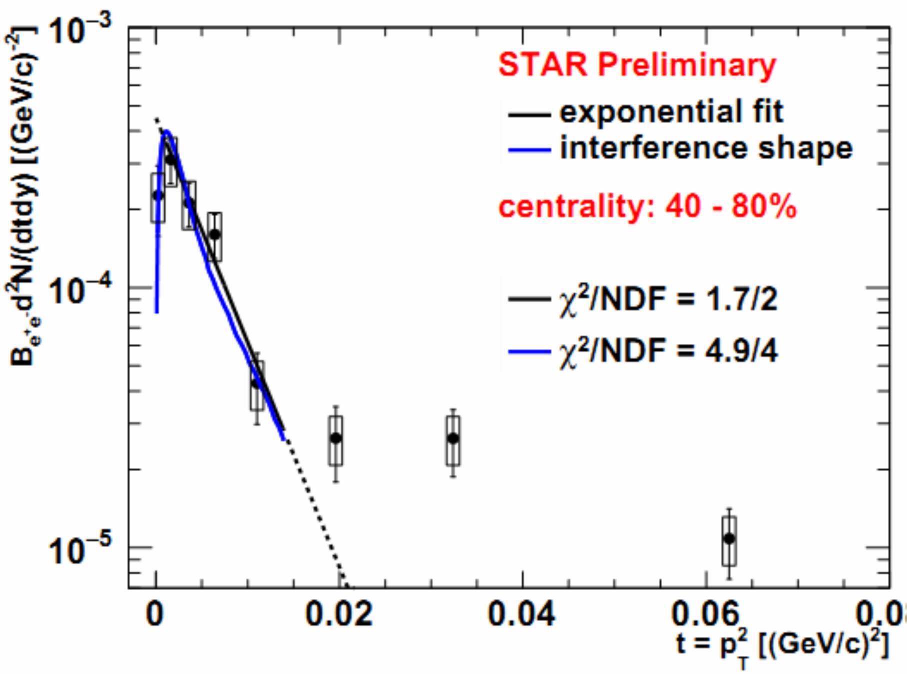


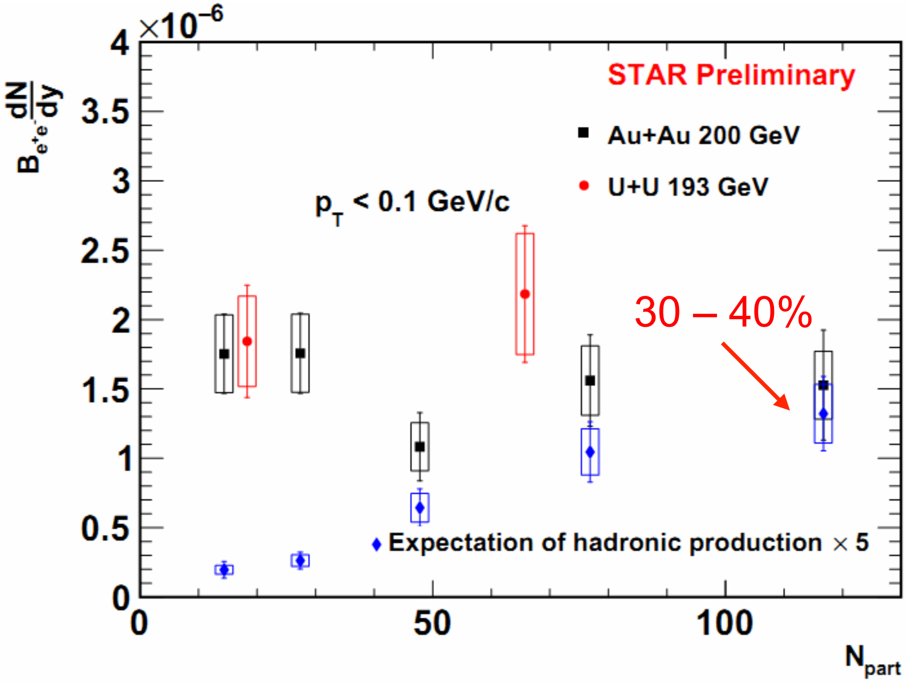


Large enhancement of J/ψ yield observed in peripheral A+A collisions!

Prominent centrality and p_T dependence.

J/ψ yield :$t=p_T^2$ and centrality dependence



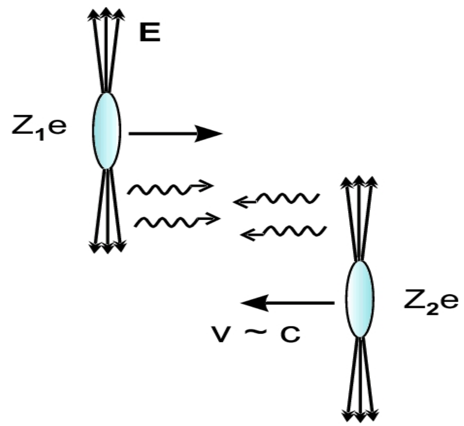


Slope parameter consistent with the size of the Au nucleus. Interference structure observed. Coherent photon-nucleus interactions?

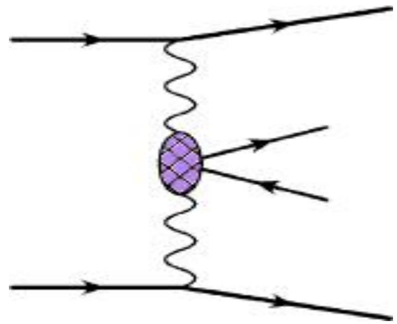
No significant centrality dependence of the excess yield! Interplay between photon flux cancellation in the overlapped area and the distance of the spectators of the two nuclei?

Simulations ongoing and need theoretical inputs!

Coherent photonuclear and two-photon processes

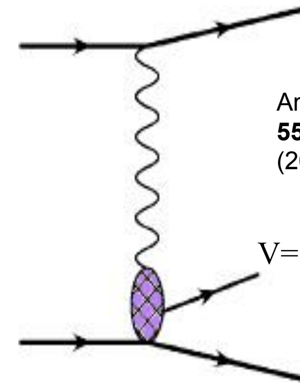


=



Two-photon

+



photonuclear

Ann. Rev. Nucl. Part. Sci. **55**:271 (2005)

Studied extensively in ultra-peripheral collisions

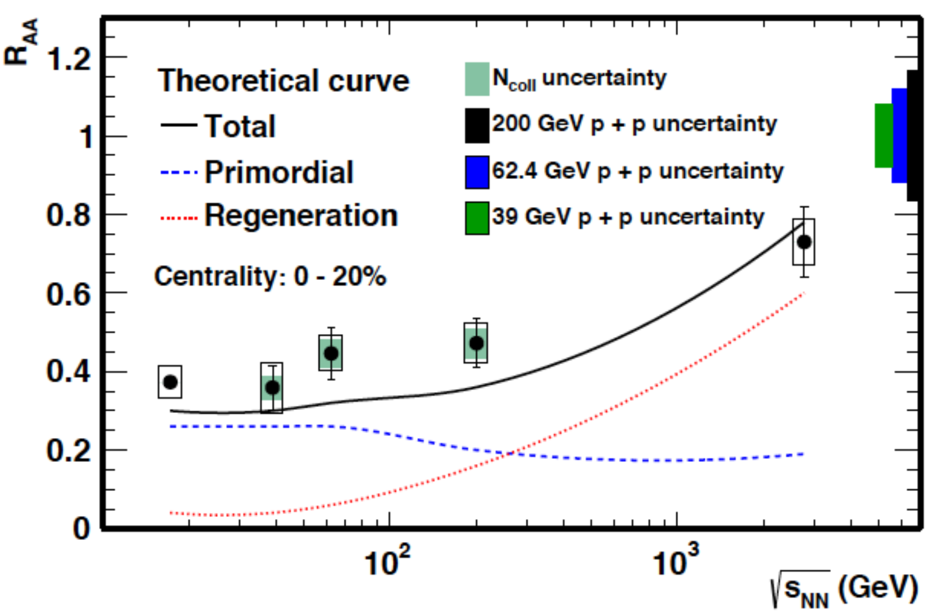
How is **the J/ψ from coherent photonuclear process affected by hot and cold QCD matter! Why do we still be able to observe** these J/ψs**?**
A new tool to study enriched multi-body dynamics on the strong QCD force!

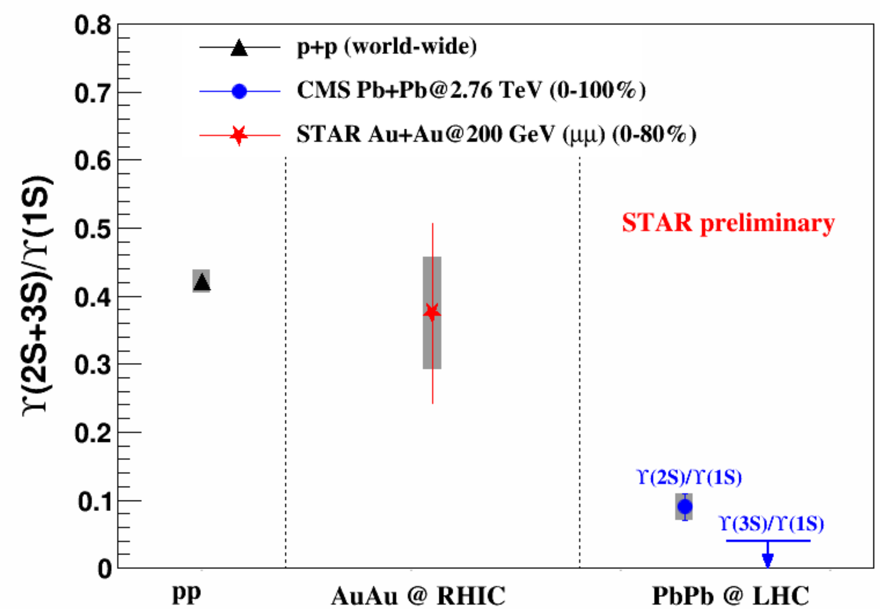
Achievements

The collision energy, centrality and p_T, rapidity dependences of J/ψ suppression pattern at RHIC and LHC can be interpreted as the interplay of two key ingredients: recombination and color screening qualitatively.

At LHC: Sequential melting for ϒ(1S, 2S, 3S), ψ(2S) more suppressed than J/ψ. Hint of recombination contribution to ϒ.

We are in the era to study color screening features of hot, dense medium





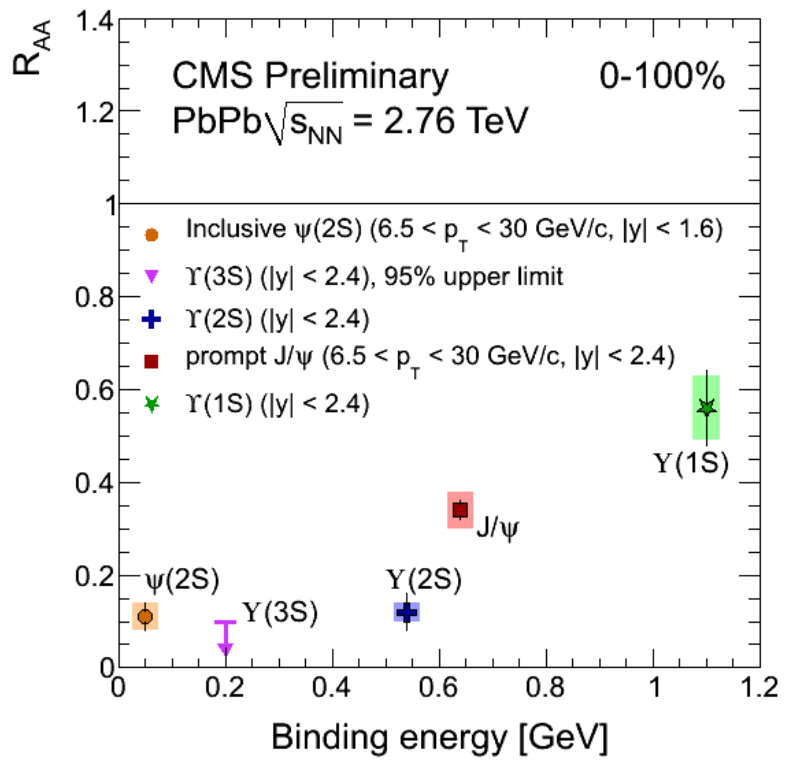
Towards the future

We are in the era to study color screening features of hot, dense medium

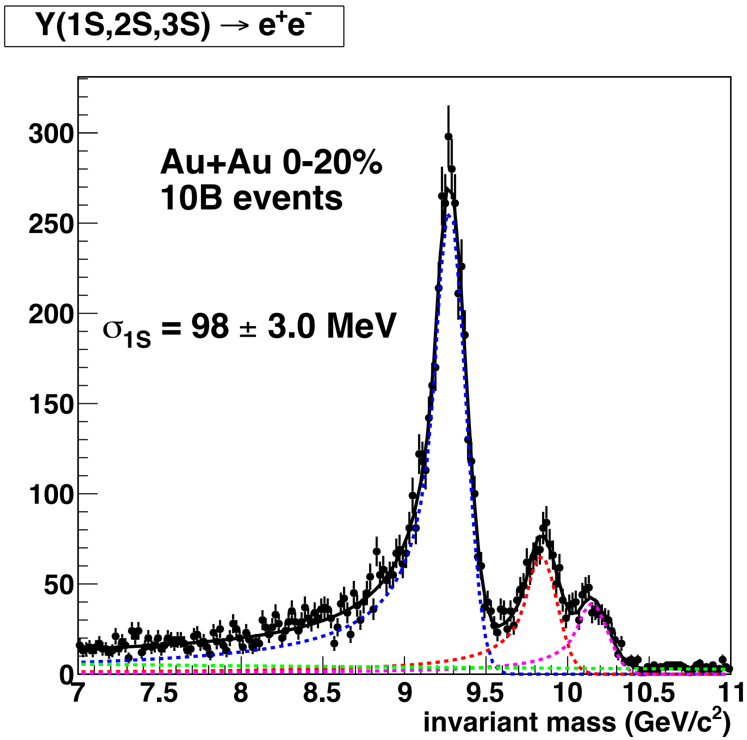
Questions:
How does the in-medium QCD force depend on temperature?

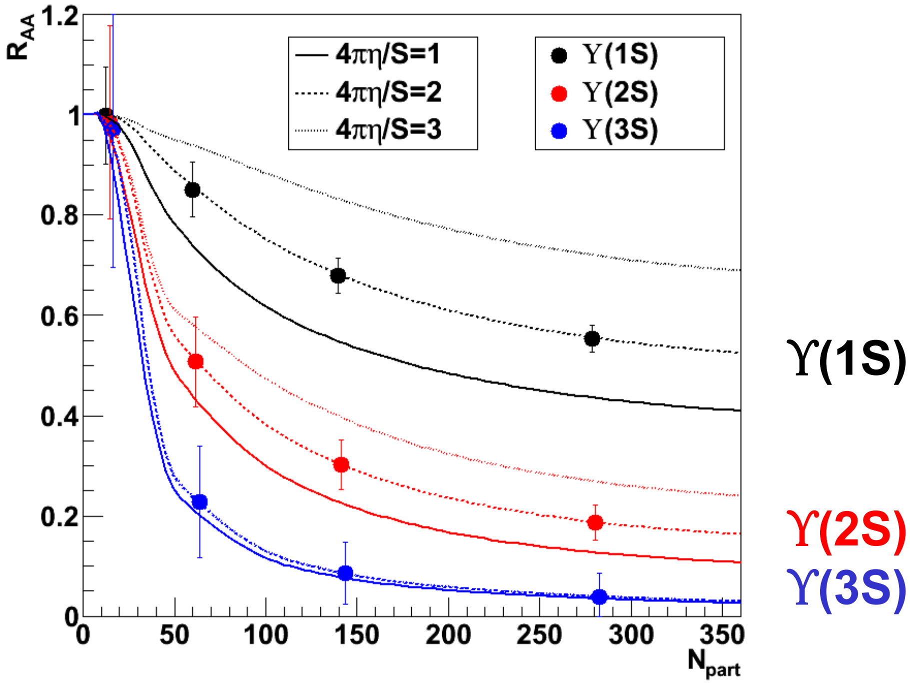
Sequential melting at RHIC?

A cleaner probe: Υ at RHIC, and charmonia at high p_T.



sPHENIX: Quarkonium measurements for 2020+





sPHENIX will provide more precise measurements.

Constrain color screening feature and initial temperature of QGP evolution.

Open questions

Turn qualitative features into quantitative understanding!

- Understand our p+p reference: CS versus CO contributions et al.
- Knowing the p+p production mechanism is crucial in order to obtain a complete picture in heavy ion collisions: for example, a colored object will lose energy when traversing the medium. Has this effect been considered in theoretical calculations?
- Dynamic modeling is critical!

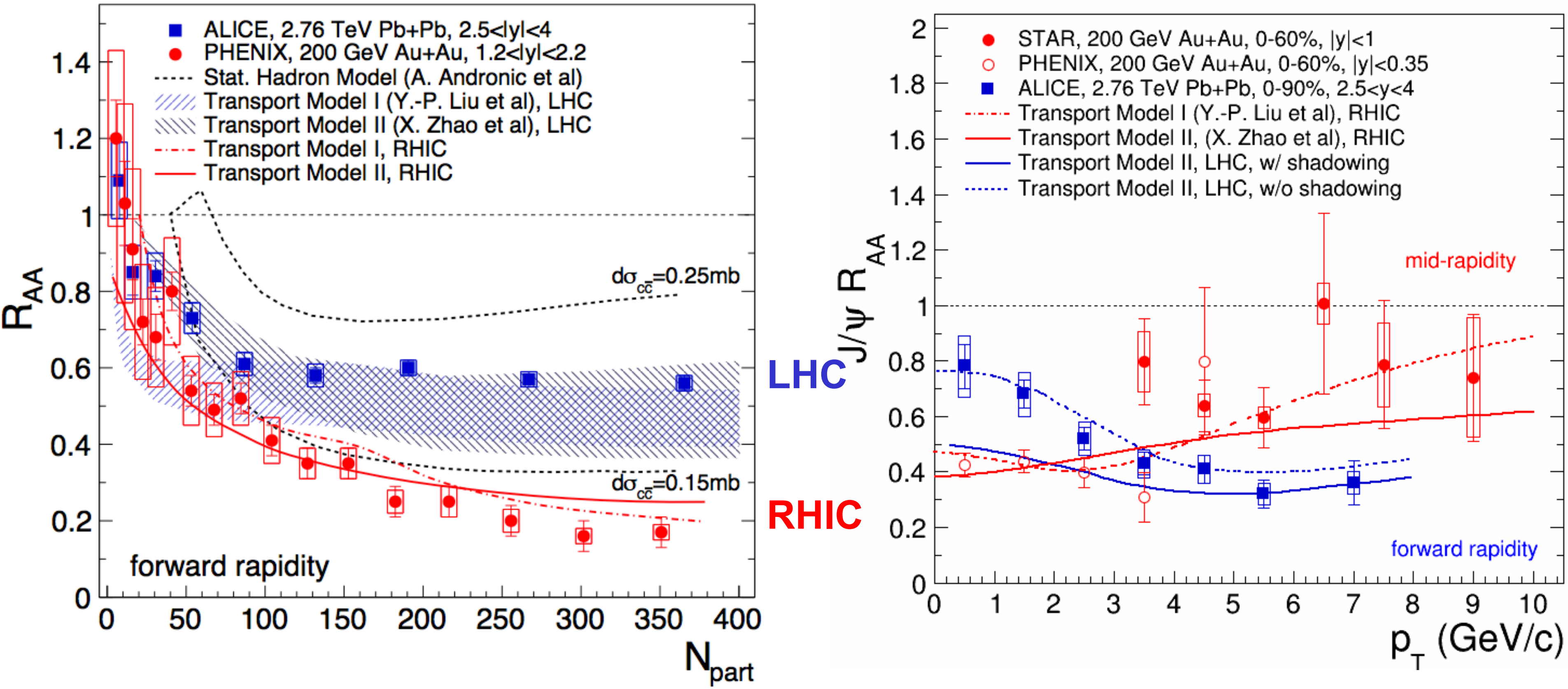
Will the coherent photo-nuclear quarkonium production be helpful to probe the in-medium QCD force?

I have not talked about:
Non-prompt quarkonia → B physics.

Study a gluon jet by tagging a quarkonium at RHIC?

Backup

J/ψ suppression pattern

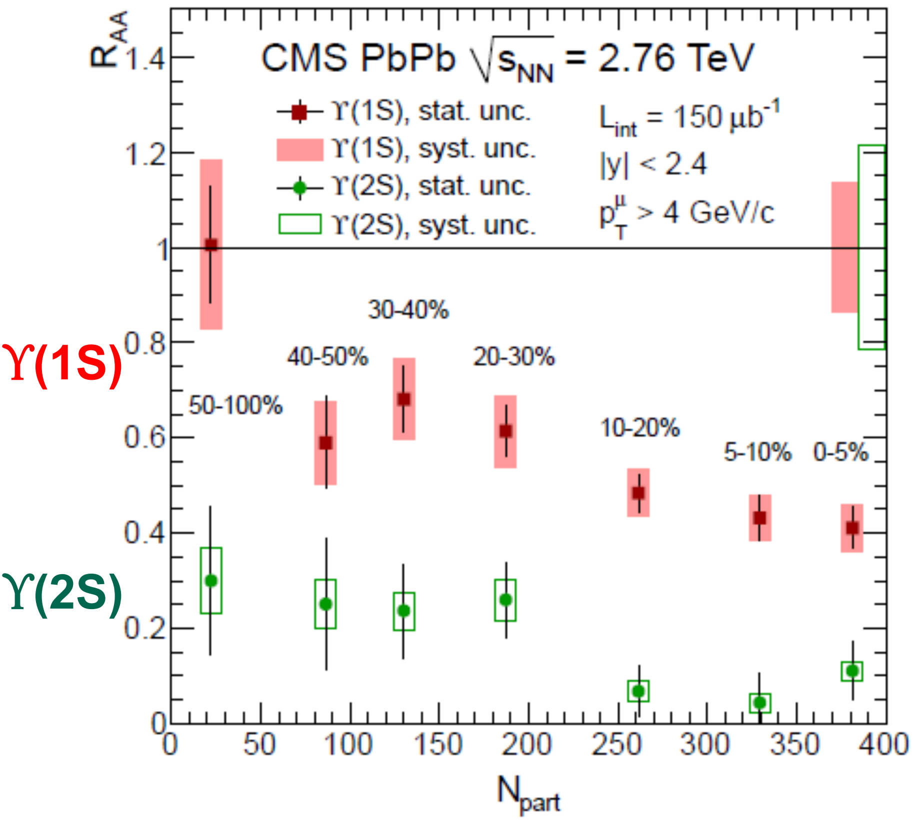


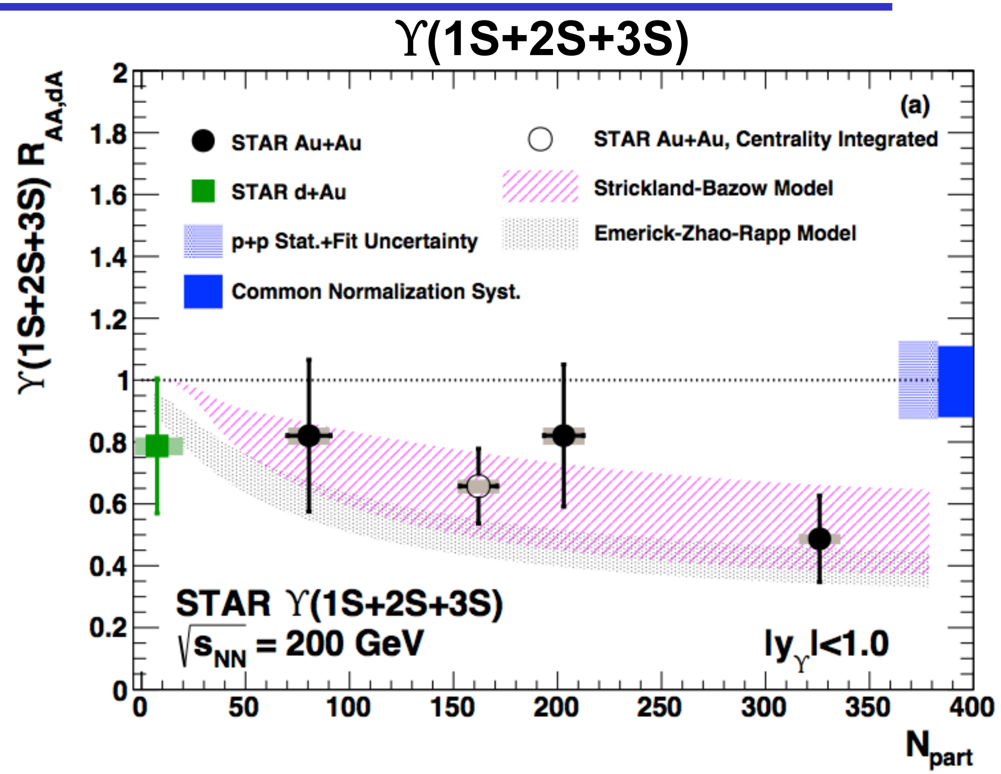
consistent with more significant contribution from ccbar recombination at LHC energies

Interplay between color screening and recombination: describe the J/ψ suppression pattern and flow measurements

PHENIX: PRC84(2011)054912, PRL98(2007)232301
ALICE: PLB734(2014)314
STAR: PLB722(2013)55

Sequential melting for different Υ



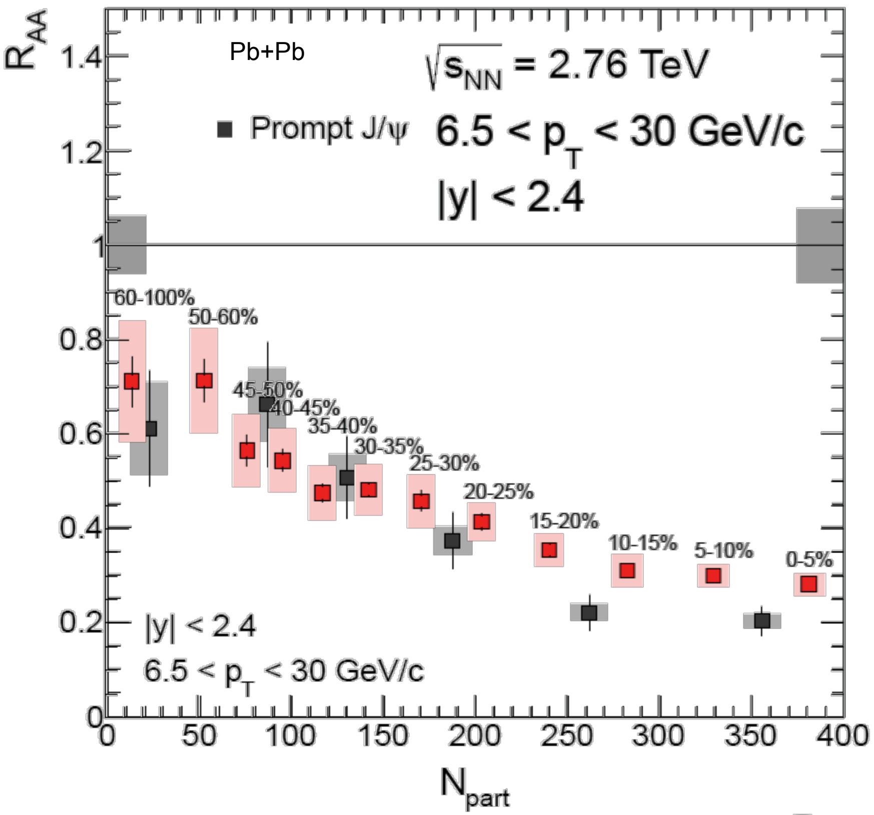


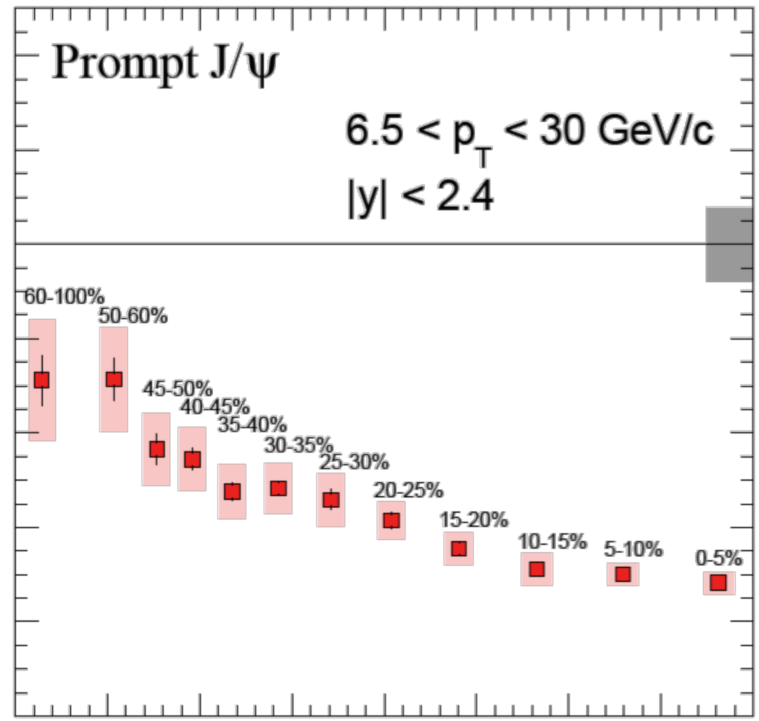
Υ(1s) suppression magnitude consistent with excited states suppression.

Υ(2S) strongly suppressed, Υ(3S) completely melted.

CMS: PRL109(2012)222301
STAR: PLB735(2014)127

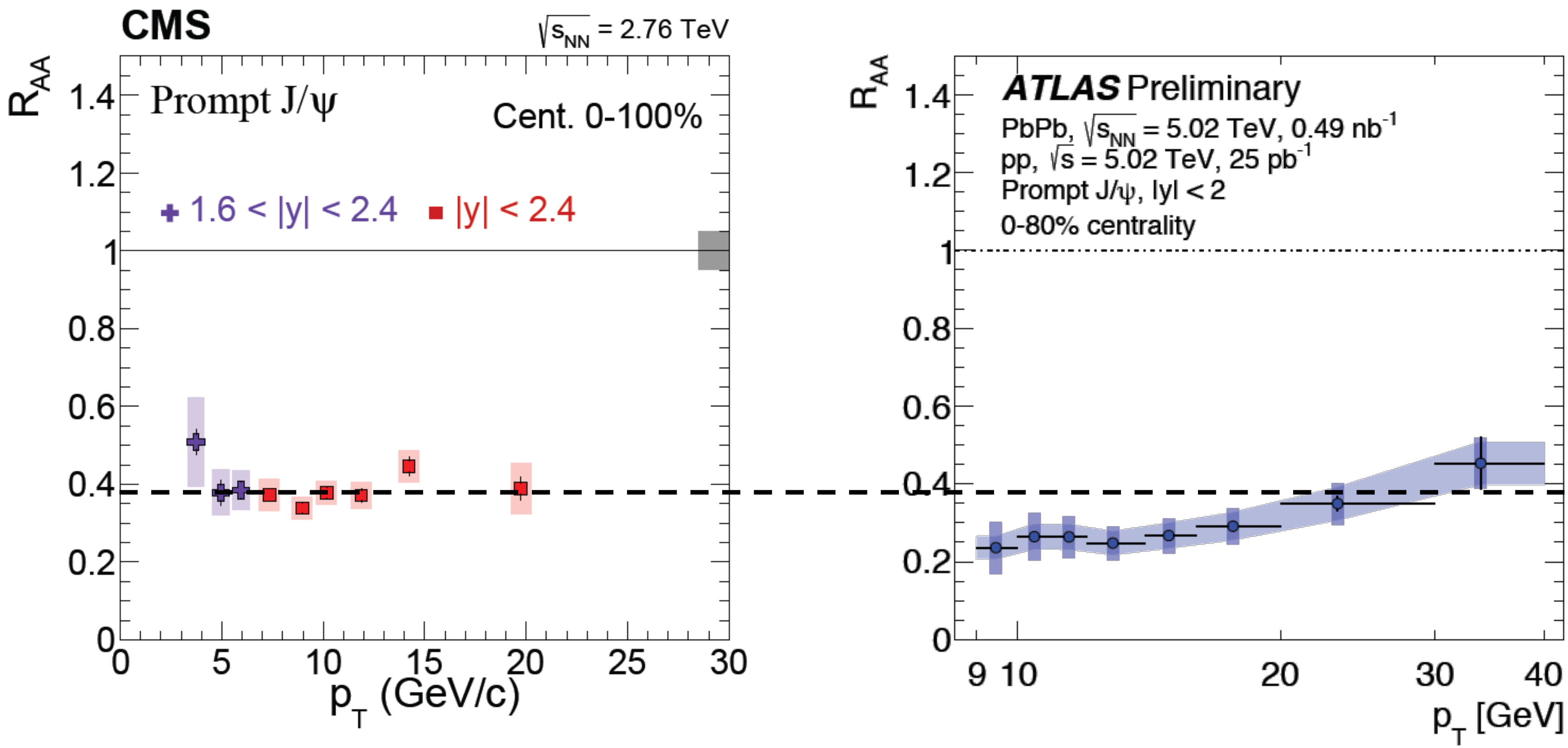
High-p_T J/ψ in PbPb at 2.76TeV





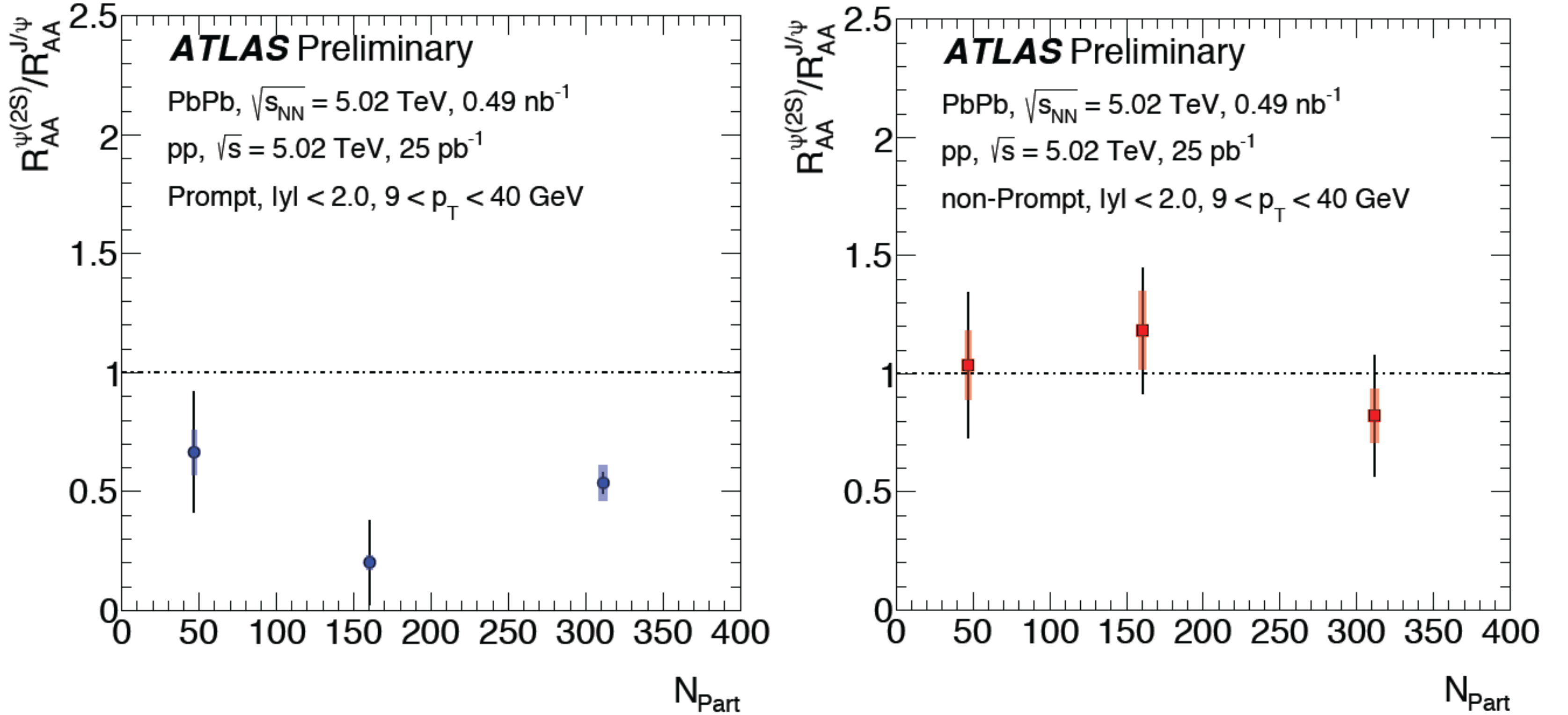
- CMS final results on J/ψ in Pb+Pb at 2.76 TeV
- Better precision with finer centrality bin

p_T dependence



- Flat at 5<p_T<~15 GeV/c and then increase with p_T
- Stronger suppression at higher beam energy

High-p_T ψ(2S) in PbPb



- Significantly stronger suppression with respect to J/ψ
- Same suppression for non-prompt