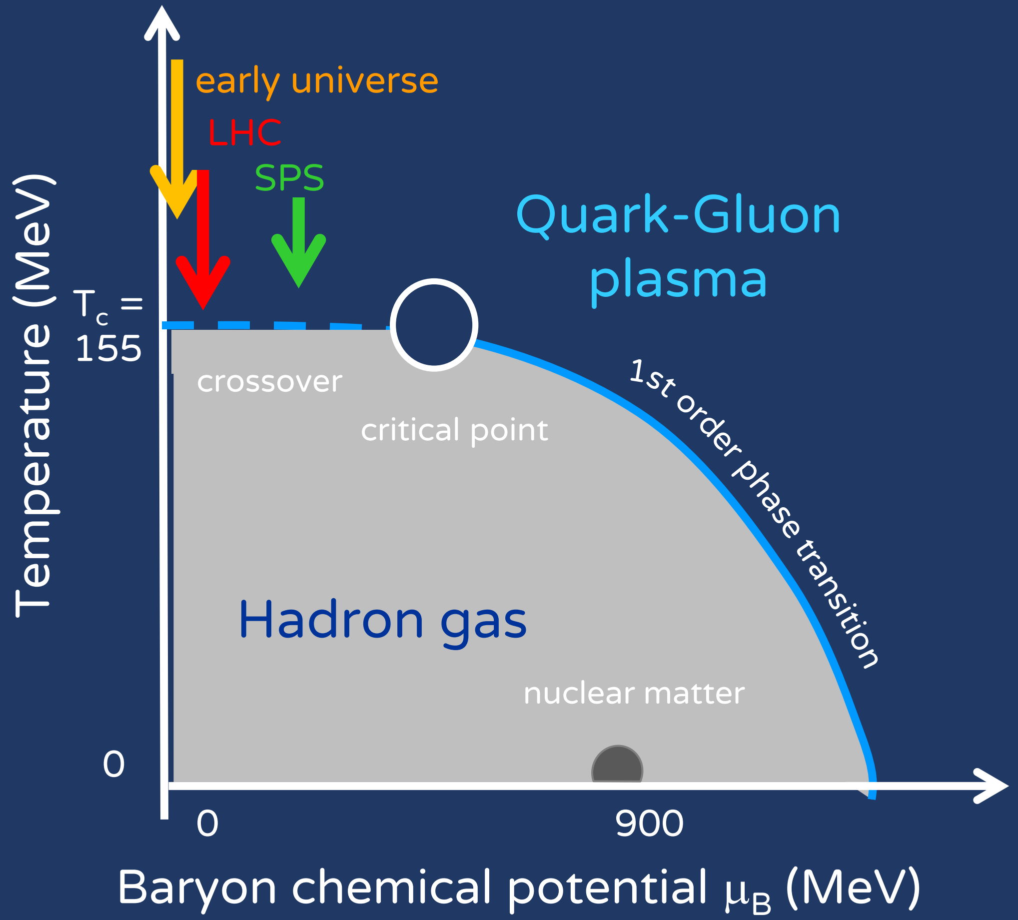
Quarkonium production in heavy-ion collisions

Roberta Arnaldi
INFN Torino

A look into the Quark-Gluon Plasma

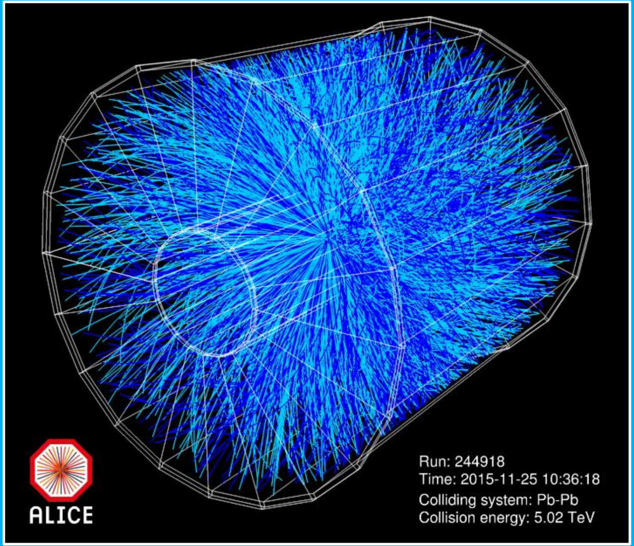
Investigate the production and properties of the Quark-Gluon Plasma, the state of matter where quarks and gluons are deconfined



QGP is formed in the phase diagram region corresponding to high temperature and low μ_B

At LHC the QGP is formed in heavy ion collisions

Quarkonia as a probe of the QGP formation



Quarkonium studies in HI collisions

$\sqrt{s_{NN}}$ (TeV)

5.02

2.76

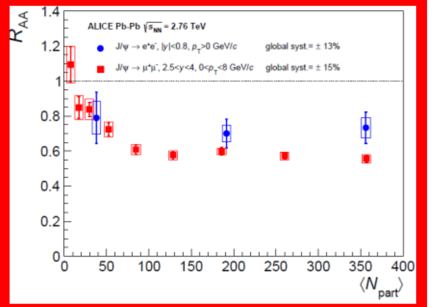
0.02

0.039

0.017

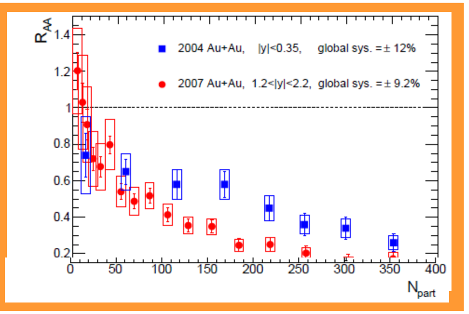
LHC

ALICE
ATLAS
CMS
LHCb



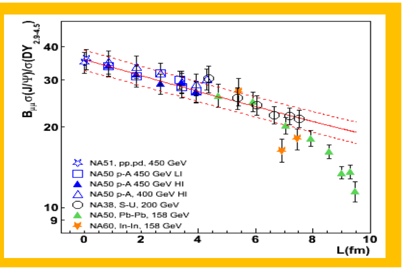
RHIC

PHENIX
STAR



SPS

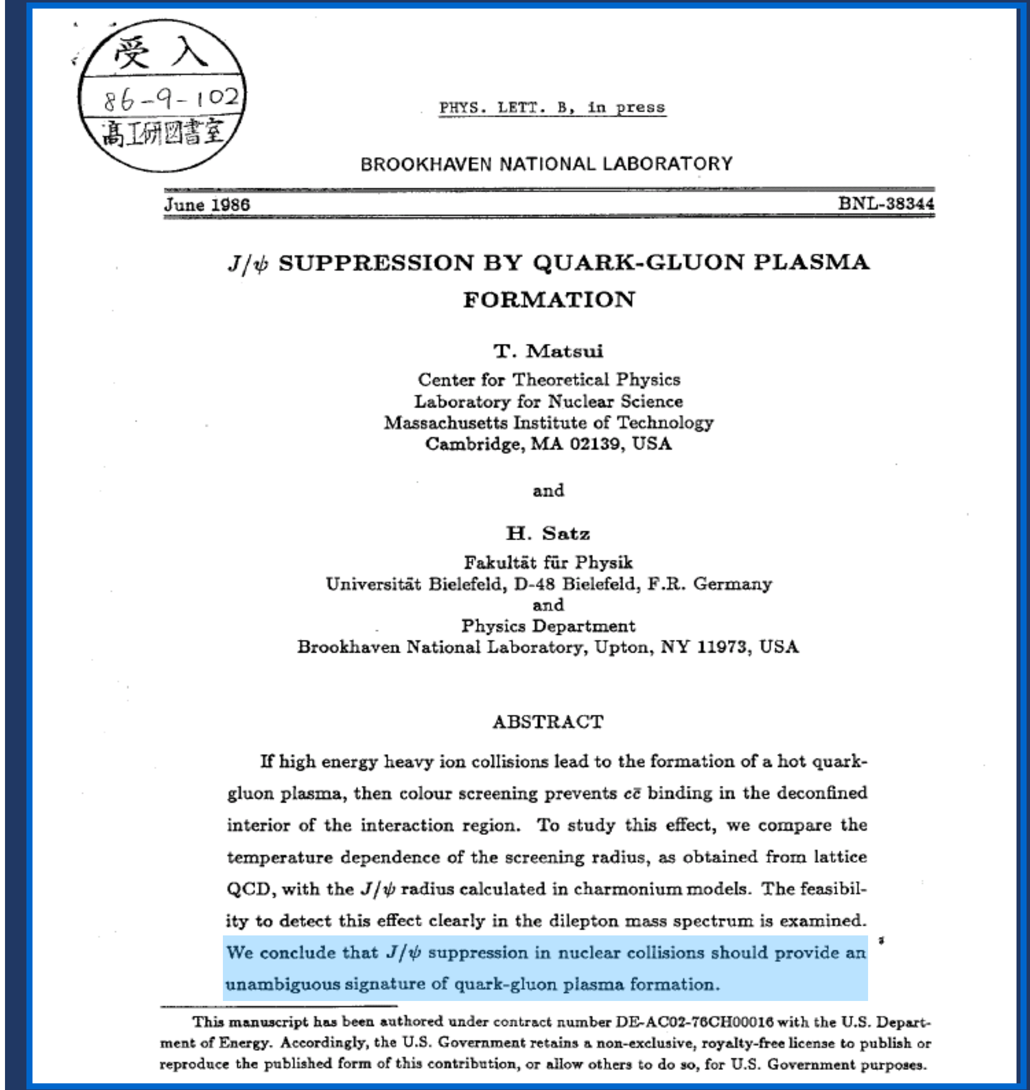
NA38
NA50
NA60



1986
2000
2009
2017

Year

Quarkonium suppression



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui
Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

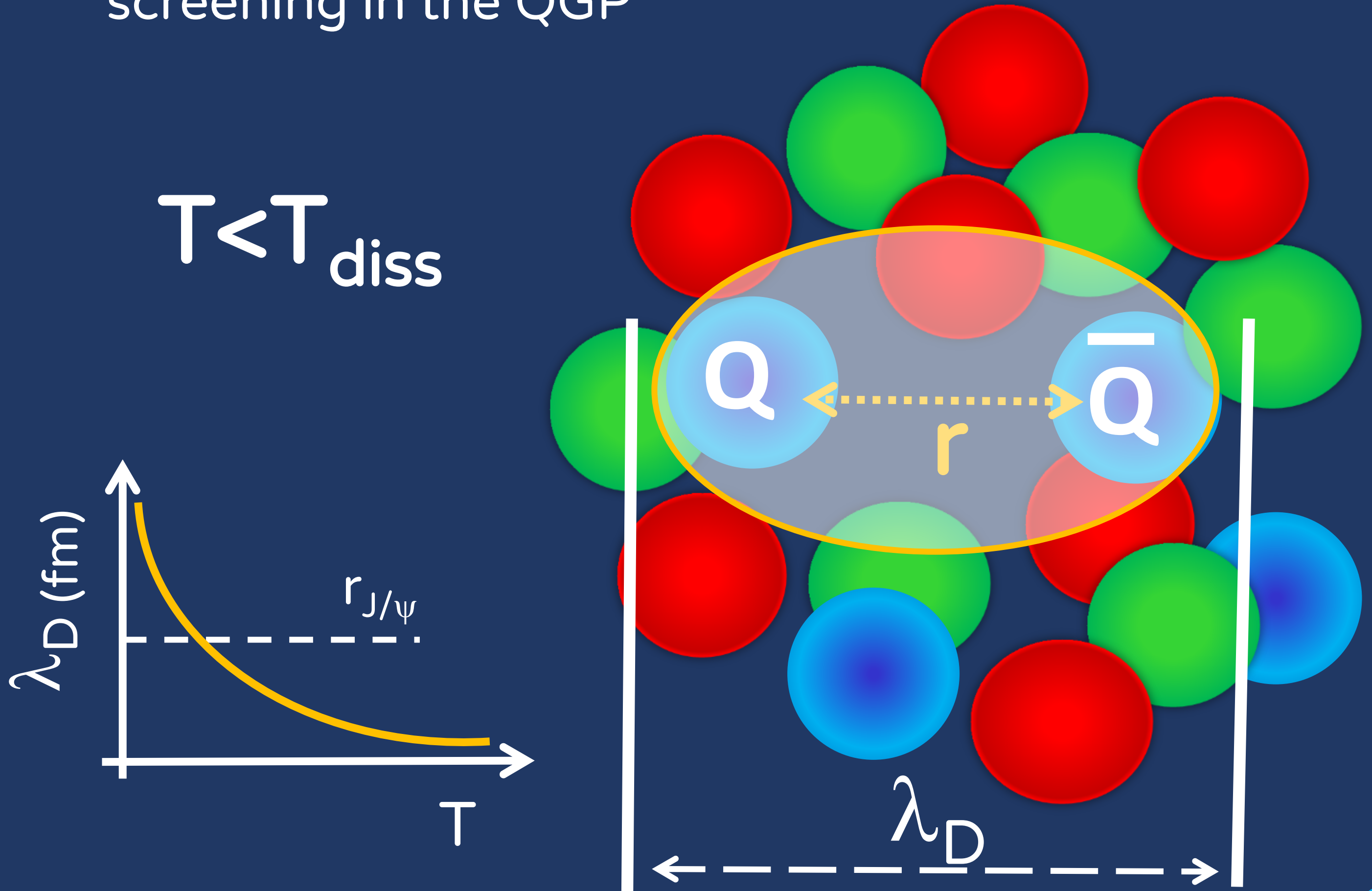
ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

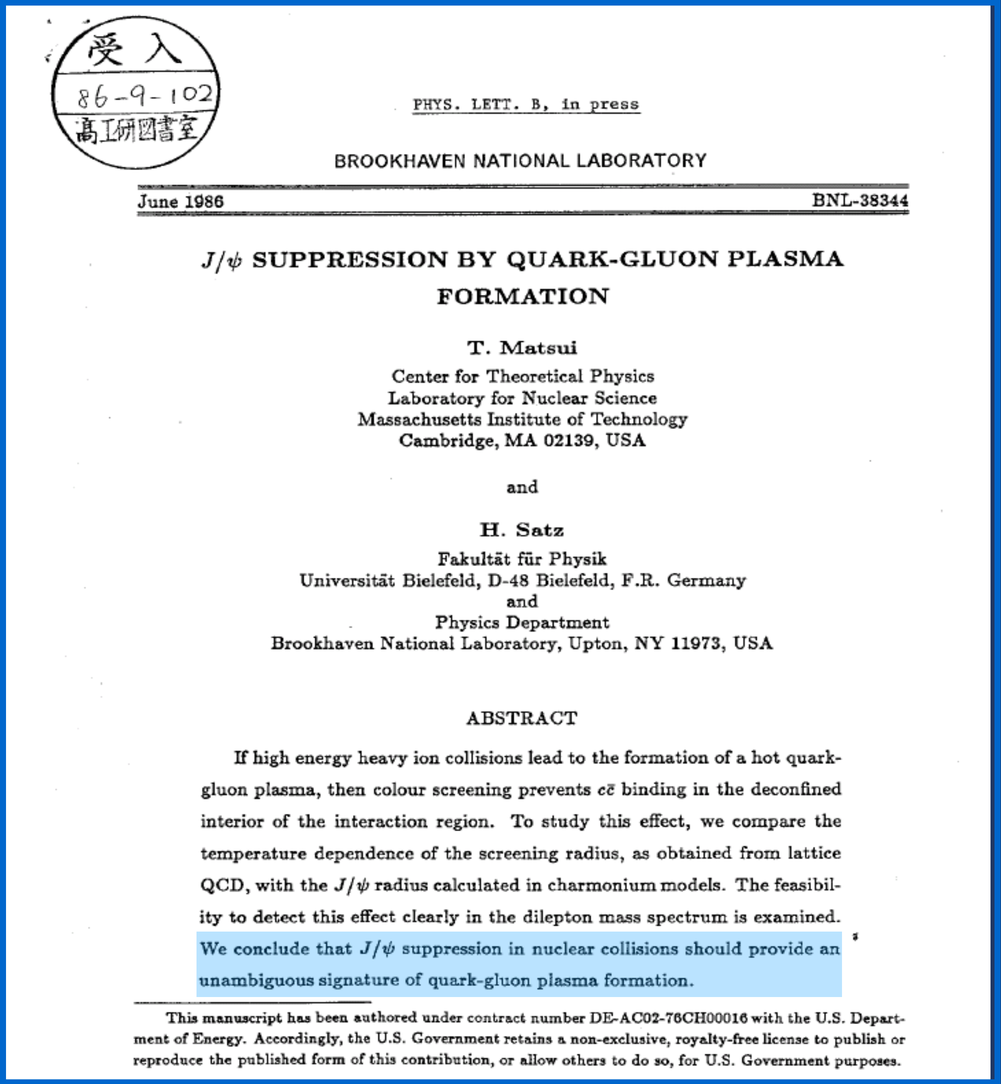
This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

T.Matsui and H.Satz, Phys.Lett.B178 (1986) 416

the original idea:
quarkonium production suppressed via color screening in the QGP



Quarkonium suppression



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui
Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

H. Satz
Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
and
Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

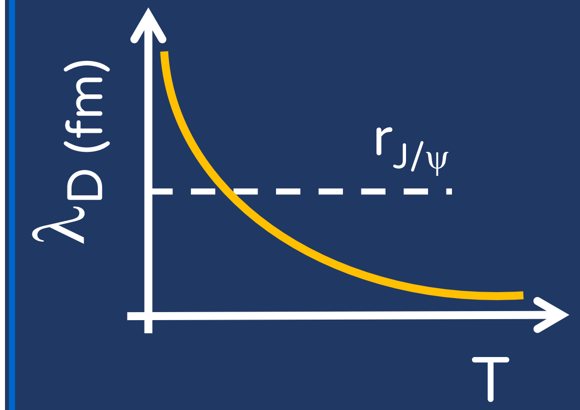
If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

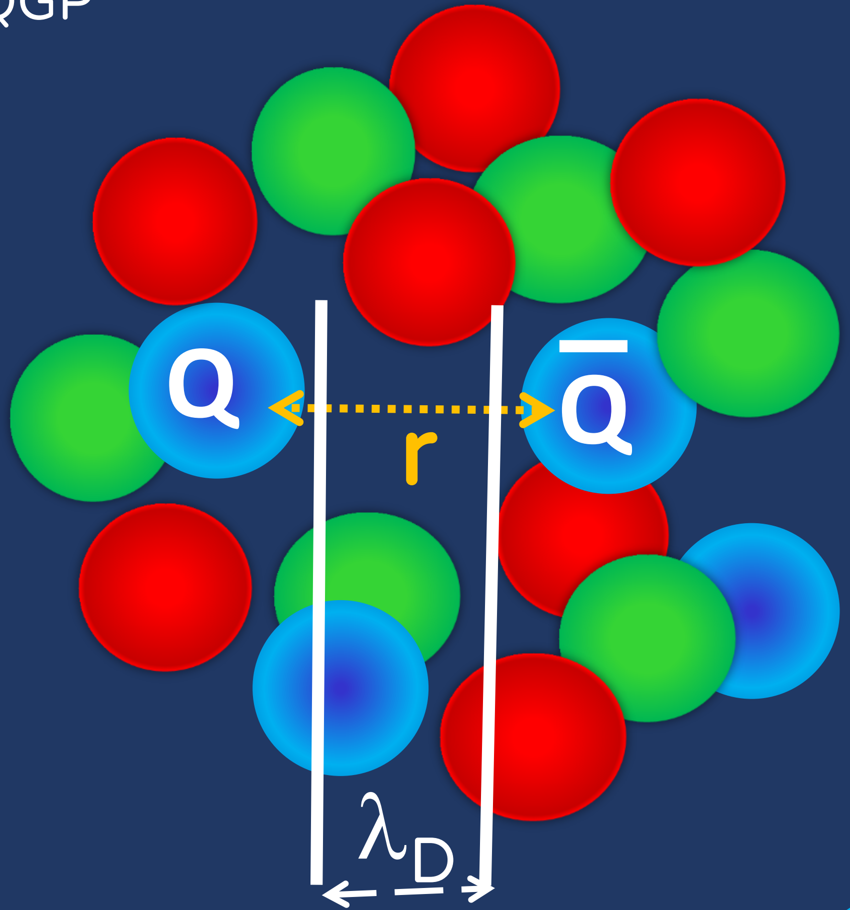
This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

T.Matsui and H.Satz, Phys.Lett.B178 (1986) 416

the original idea:
quarkonium production suppressed via color screening in the QGP

$T>T_{diss}$





Quarkonium suppression

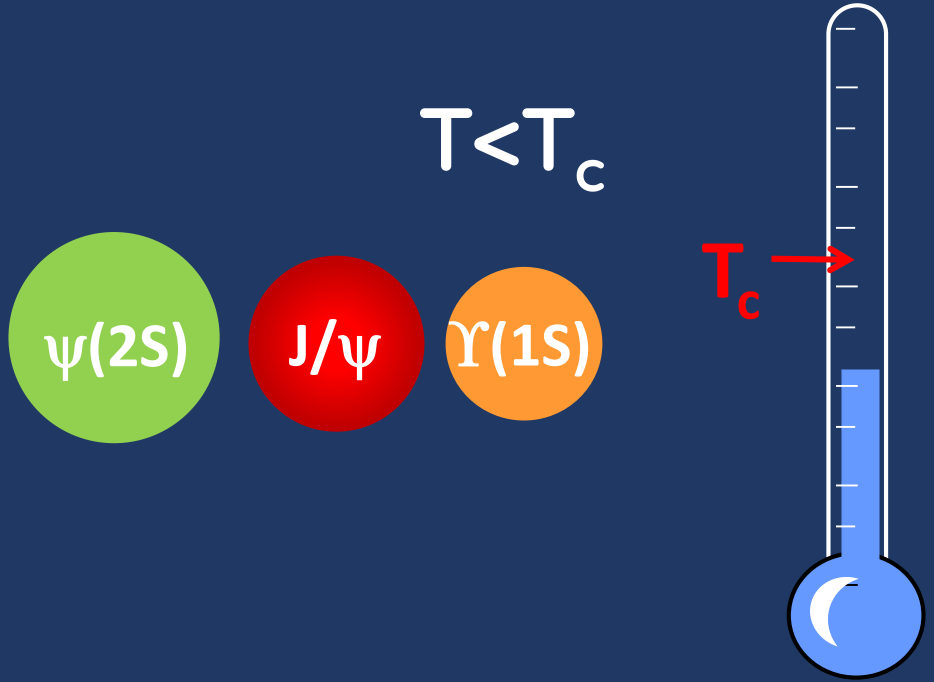
state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.51	3.69
ΔE (GeV)	0.64	0.22	0.05
r_o(fm)	0.50	0.72	0.90

state	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

(Digal,Petrecki,Satz PRD 64(2001) 0940150)

the original idea:
quarkonium production suppressed via color screening in the QGP

sequential melting:
differences in the quarkonium binding energies lead to a sequential melting with increasing temperature



Quarkonium suppression

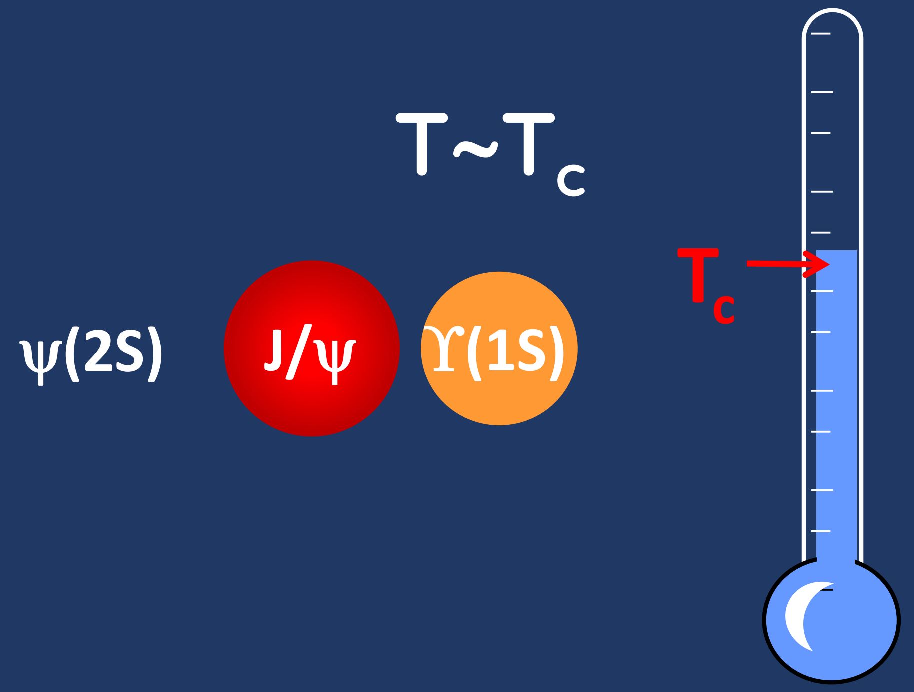
state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.51	3.69
ΔE (GeV)	0.64	0.22	0.05
r_o(fm)	0.50	0.72	0.90

state	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

(Digal,Petrecki,Satz PRD 64(2001) 0940150)

the original idea:
quarkonium production suppressed via color screening in the QGP

sequential melting:
differences in the quarkonium binding energies lead to a sequential melting with increasing temperature



Quarkonium suppression

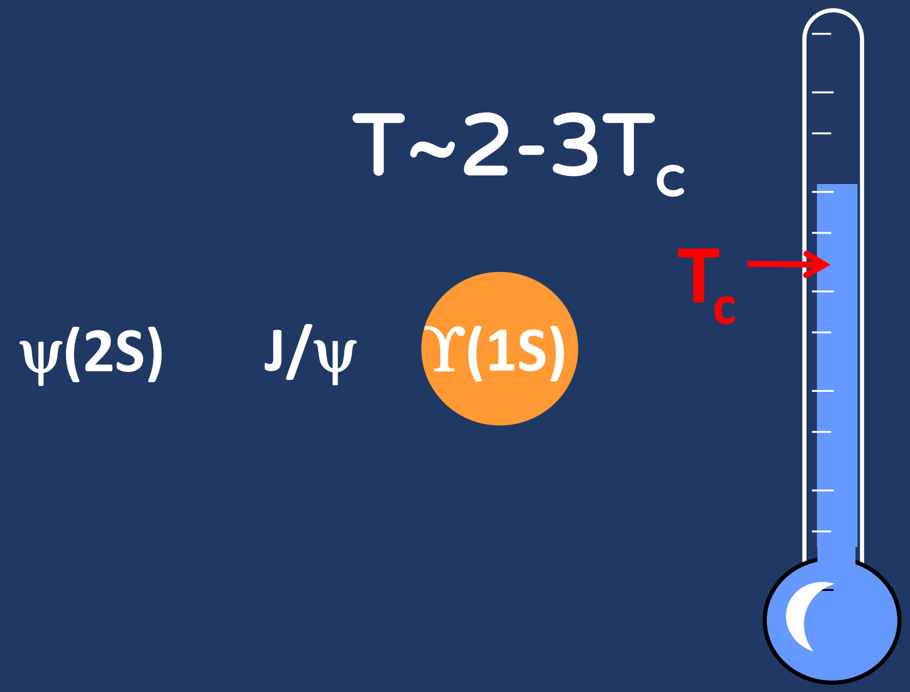
state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.51	3.69
ΔE (GeV)	0.64	0.22	0.05
r_o(fm)	0.50	0.72	0.90

state	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

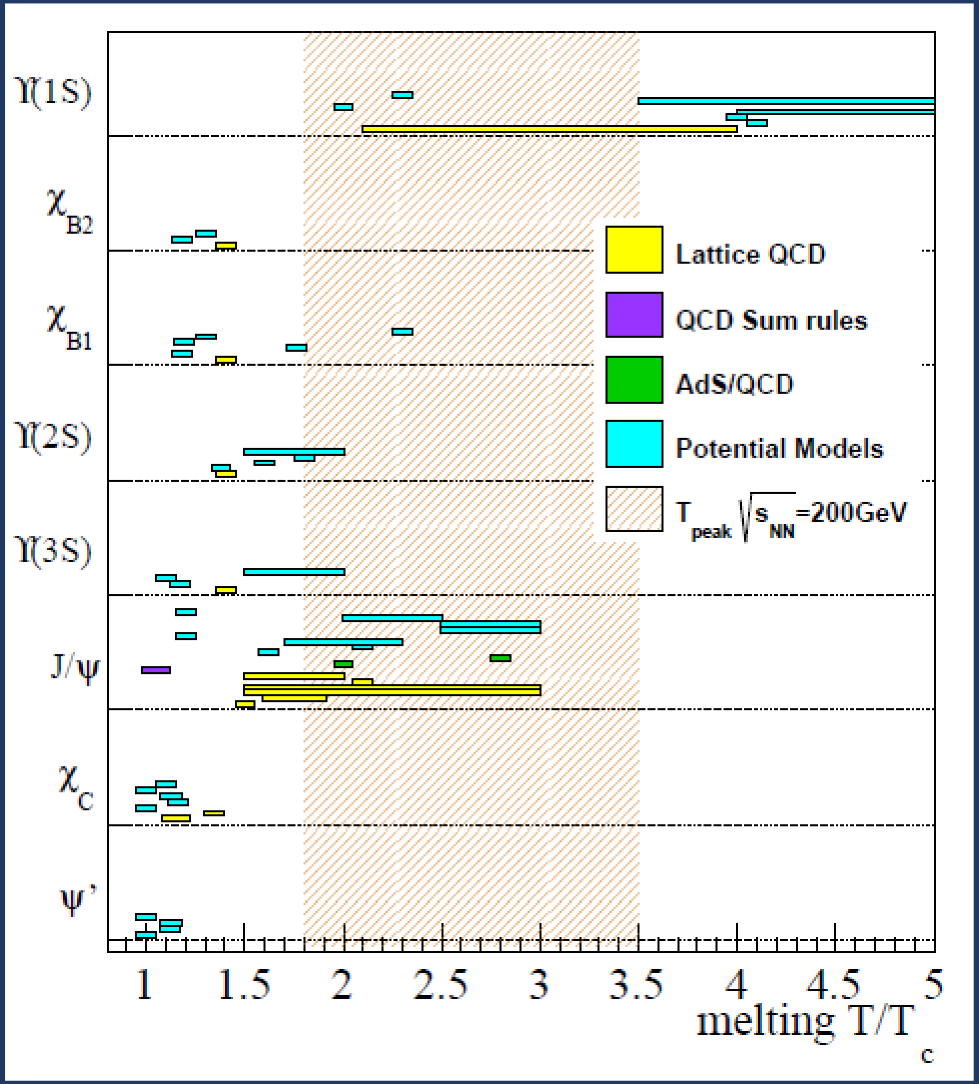
(Digal,Petrecki,Satz PRD 64(2001) 0940150)

the original idea:
quarkonium production suppressed via color screening in the QGP

sequential melting:
differences in the quarkonium binding energies lead to a sequential melting with increasing temperature



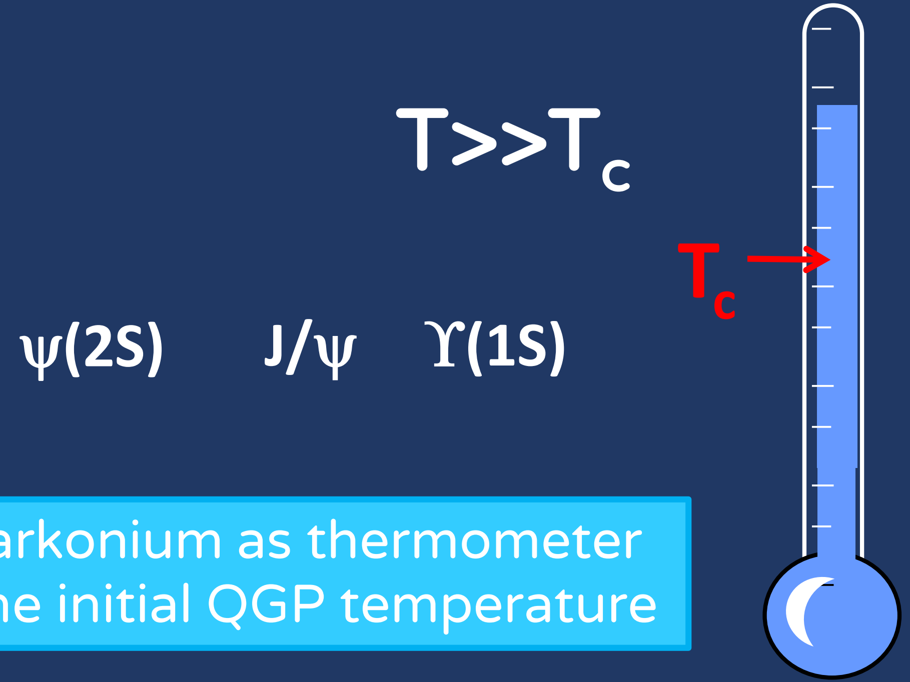
Quarkonium suppression



PHENIX, Phys.Rev C91, 024913

the original idea:
quarkonium production suppressed via color screening in the QGP

sequential melting:
differences in the quarkonium binding energies lead to a sequential melting with increasing temperature



Quarkonium as thermometer of the initial QGP temperature

...and quarkonium recombination

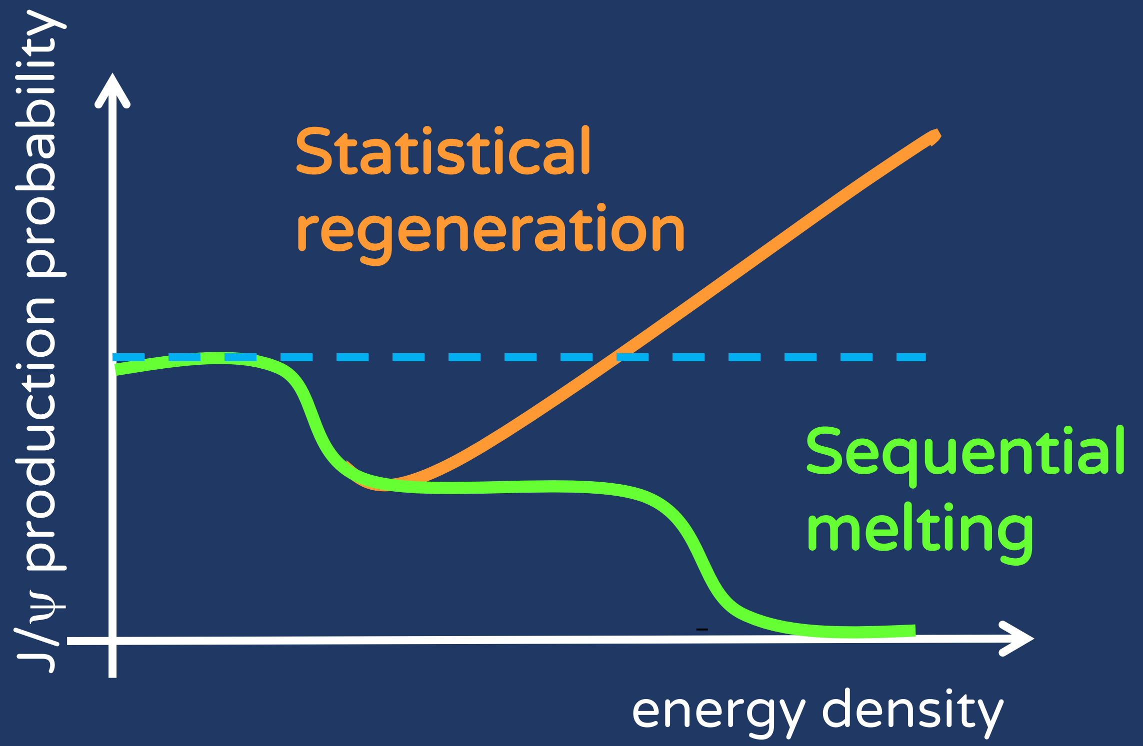
- **(Re)combination**

increasing the collision energy
the $c\bar{c}$ pair multiplicity increases

Central AA collisions	$\frac{N_{c\bar{c}}}{\text{event}}$	$\frac{N_{b\bar{b}}}{\text{event}}$
SPS, 20 GeV	~0.2	-
RHIC, 200GeV	~10	-
LHC, 2.76TeV	~85	~2
LHC, 5.02 TeV	~115	~3

- negligible recombination contribution for bottomonia, even at LHC energies

- enhanced quarkonia production via (re)combination at hadronization or during QGP phase



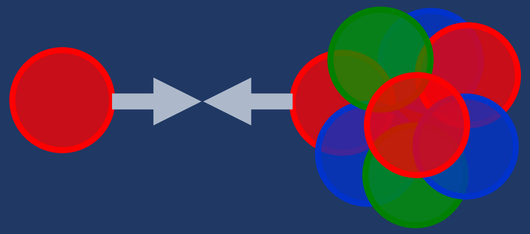
P. Braun-Muzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)

Cold nuclear matter effects

- **On top of the hot matter mechanisms, other effects, related to cold nuclear matter (CNM), might affect quarkonium production**

  - nuclear parton shadowing/color glass condensate
  - energy loss
  - $c\bar{c}$ break-up in nuclear matter

- CNM are investigated in p-A collisions, addressing:



  - Role of the various contributions, whose importance depends on kinematic and energy of the collisions
  - Size of CNM effects, fundamental to interpret quarkonium AA results

Caveat

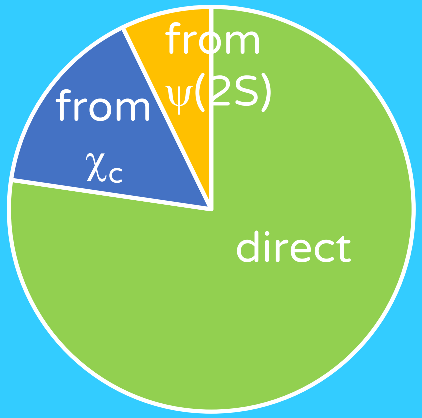
Even if the “suppression-recombination” approach looks simple, a realistic description of the involved mechanisms is rather complex:

→ on the theory side:

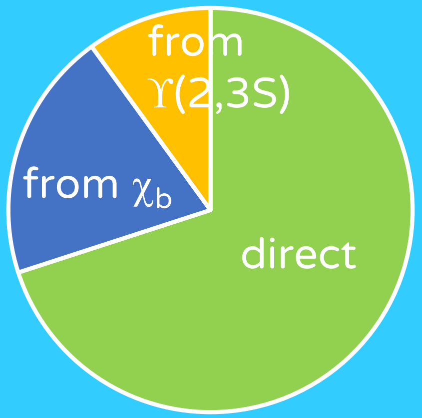
- Link between suppression and critical temperature requires precise assessment of T_D, $M_\psi(T)$, $\Gamma_\psi(T)$ from QCD calculations using EFT/LQCD spectral functions
- Short QGP thermalization time at LHC might imply in-medium formation of quarkonia rather than suppression

→ on the experimental side:

- Precise determination of open charm σ
- Assessment of quarkonium feed-down into lighter states



Low p_T J/ψ

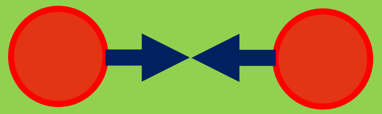


Low p_T ϒ(1S)

- Role of B feed down for charmonium

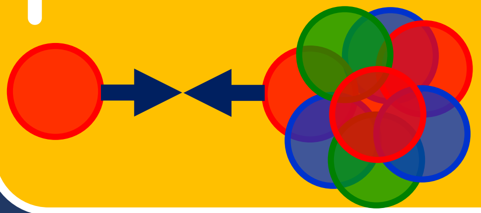
Summarizing quarkonium in pp, pA, AA

p-p



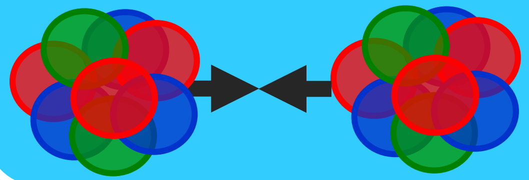
“vacuum” reference for AA, pA, genuine pp physics program

p-A



cold nuclear matter effects: shadowing/CGC, energy loss…

A-A



hot matter effects: regeneration vs suppression

Nuclear modification factor:

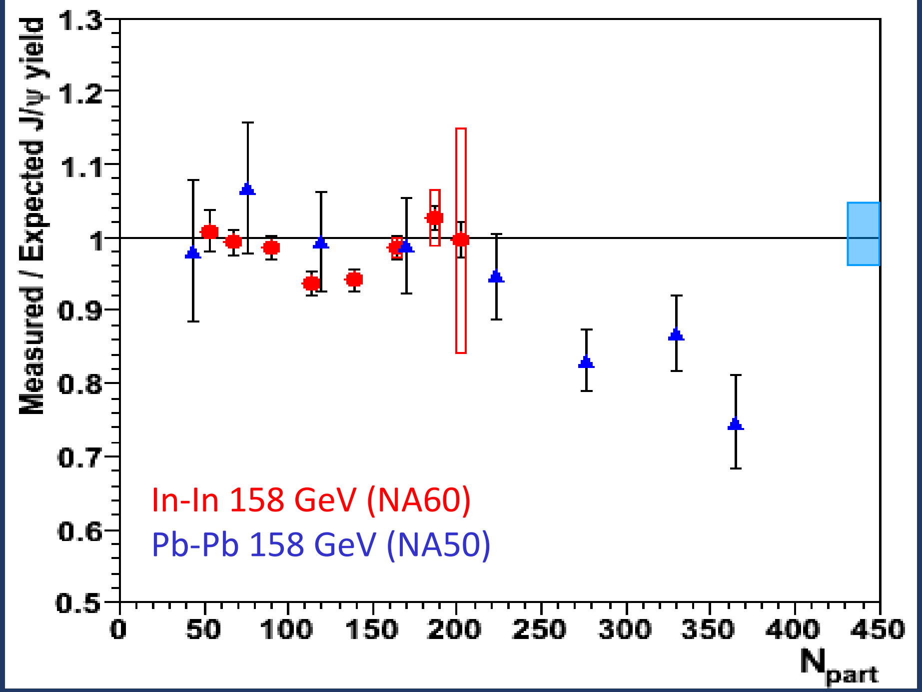
$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle \sigma_{pp}^{J/\psi}}$$

Medium effects quantified comparing AA (pA) quarkonium yield with the pp cross section, scaled by a geometrical factor (from Glauber model)

- no medium effects → $R_{AA} = 1$
- hot/cold matter effects → $R_{AA} \neq 1$

From SPS and RHIC experiments…

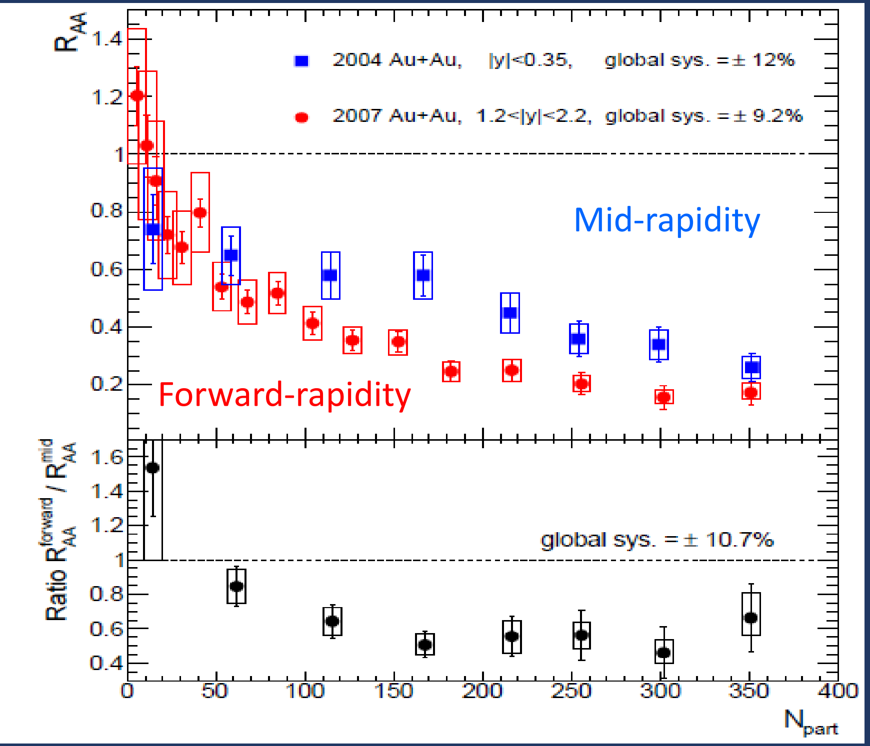
SPS (NA38, NA50, NA60) $\sqrt{s_{NN}}$ = 17 GeV



R. Arnaldi et al. (NA60 Coll.) NPA830 (2009) 345c

- first evidence of anomalous suppression (i.e. beyond CNM expectations) in Pb-Pb
~30% suppression compatible with $\psi(2S)$ and χ_c decays

RHIC (PHENIX,STAR) $\sqrt{s_{NN}}$ =39,62.4,200 GeV



RA. Adare et al(PHENIX Xoll.), PRC84 (2011) 054912

- stronger suppression at forward y
→ not expected if suppression increases with energy density, larger at mid-y

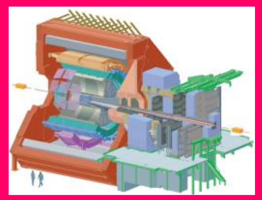
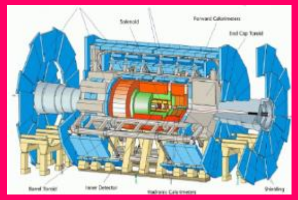
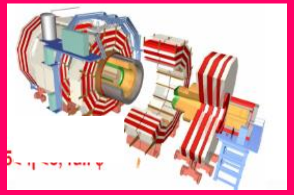
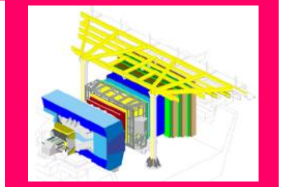
…to quarkonium at LHC

Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760 5020	2010-2012 2015
		p-Pb	5020 8160	2013 2016
		pp	2760, 7000, 5020, 8000, 13000	2010-2016

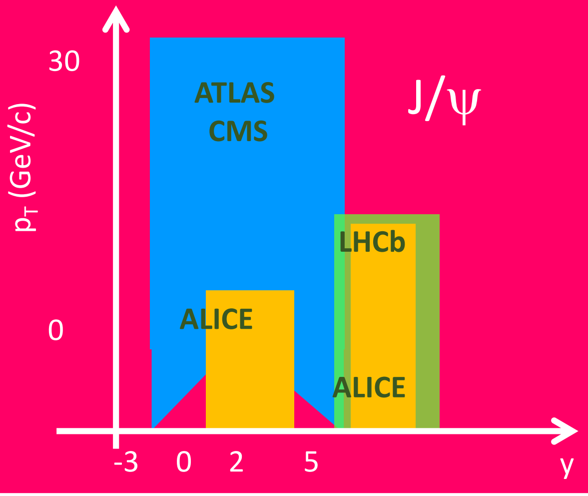
…to quarkonium at LHC

Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
LHC	ALICE ATLAS CMS LHCb	P		

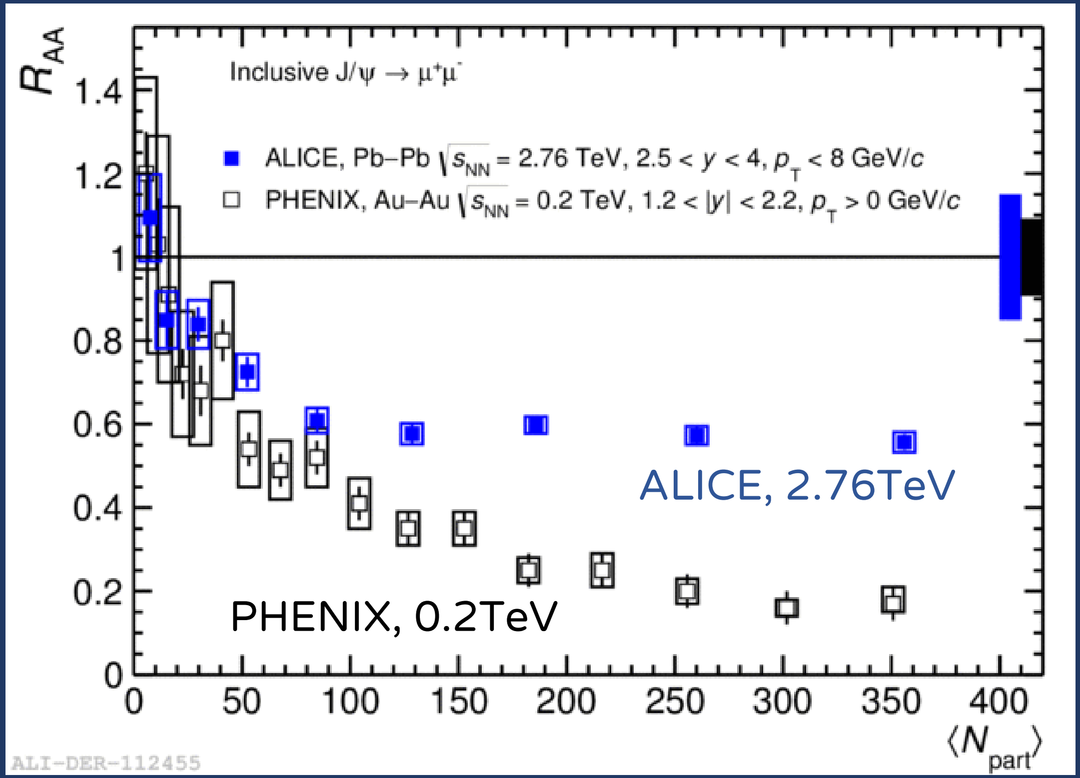
All LHC experiments investigate quarkonium production

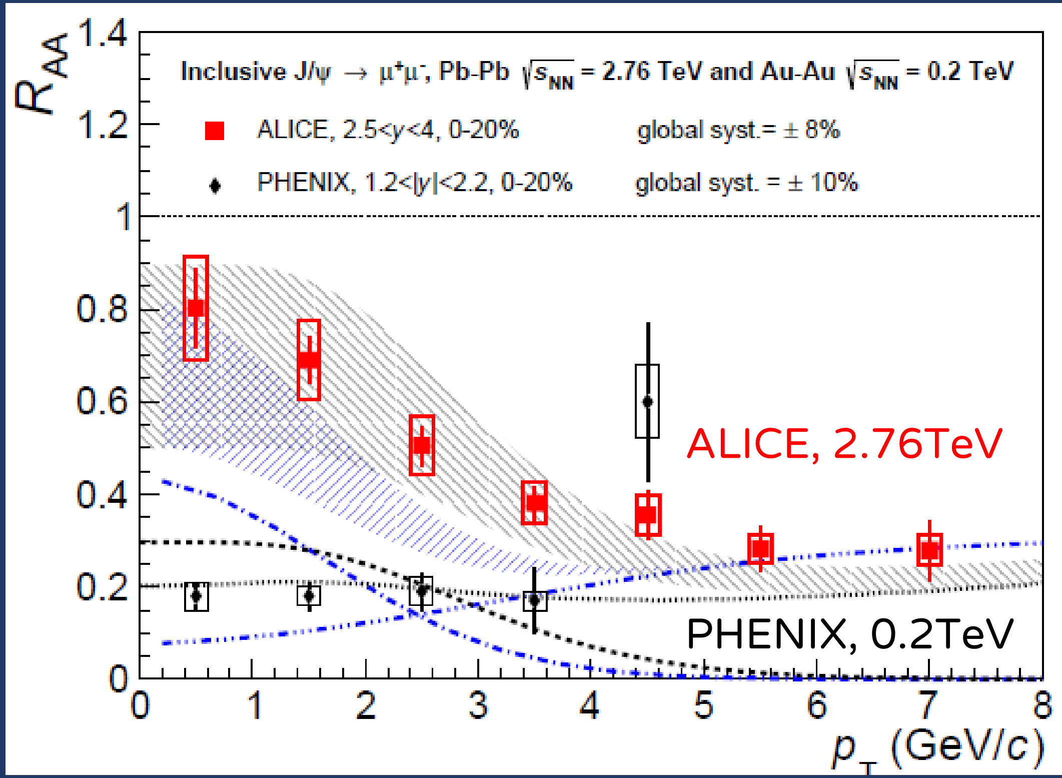





complementary results due to different kinematic coverages



J/ψ R_{AA} at low p_T





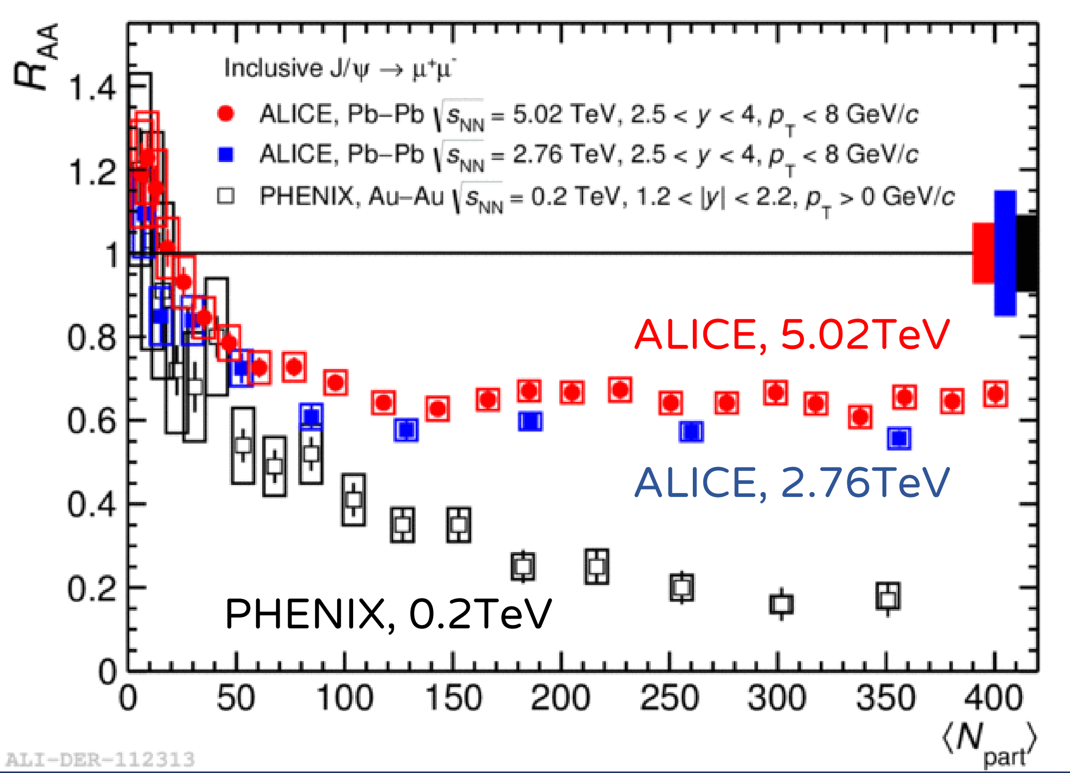
JHEP 05 (2016) 179, PLB 734 (2014) 314, PRL 109 (2012) 072301

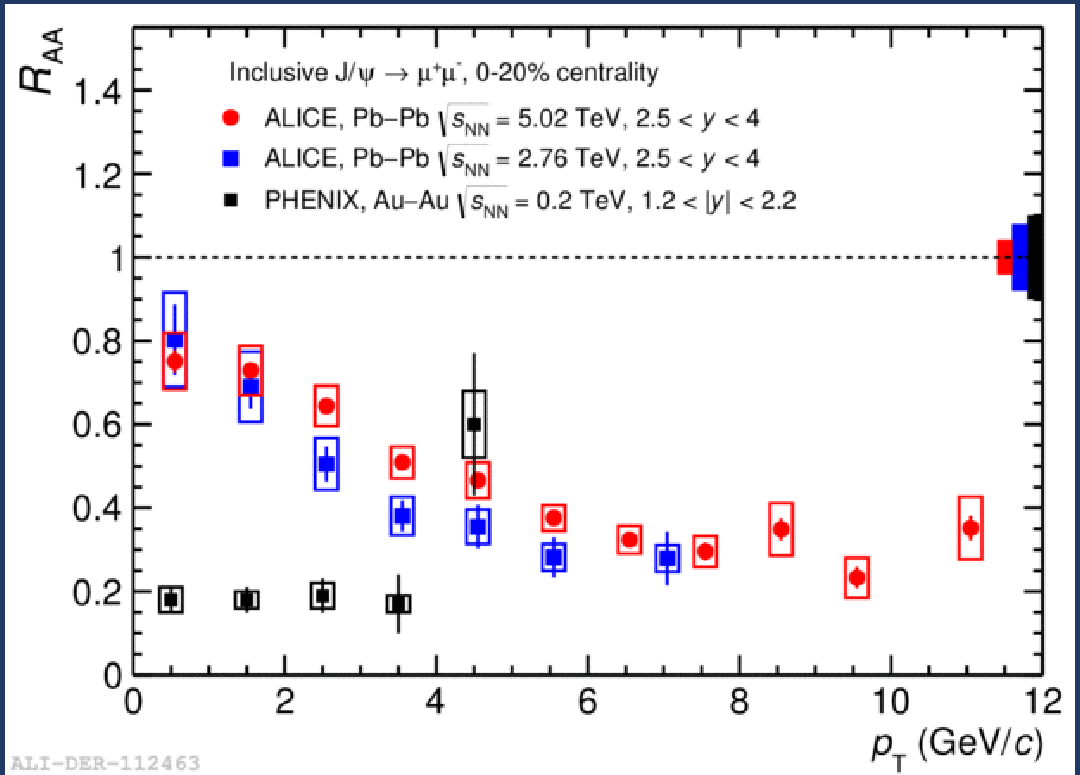
RHIC vs ALICE:

- Stronger J/ψ suppression vs centrality at RHIC, in spite of the LHC larger energy densities
- Weaker low p_T suppression measured by ALICE

➡ Comparison with lower energy results emphasizes the role of recombination for low p_T J/ψ at the LHC

J/ψ R_{AA} at low p_T: LHC Run2



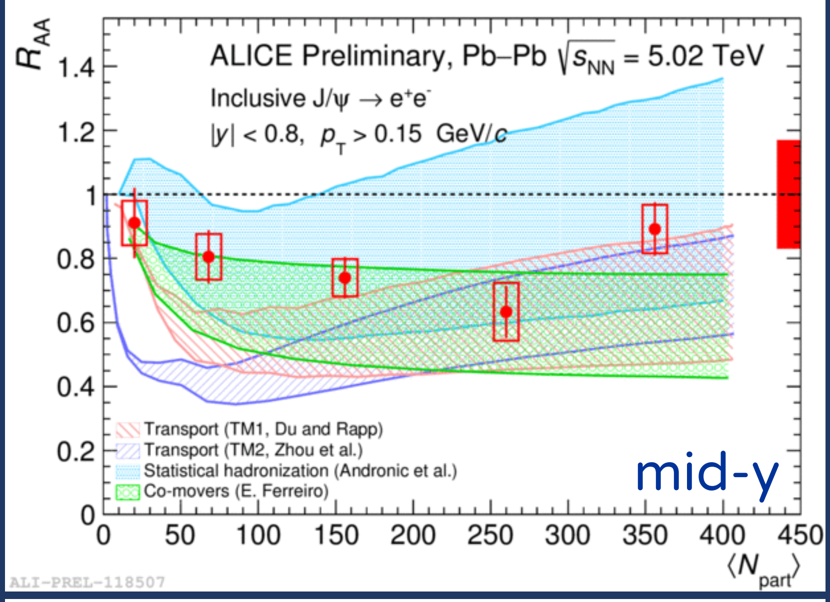


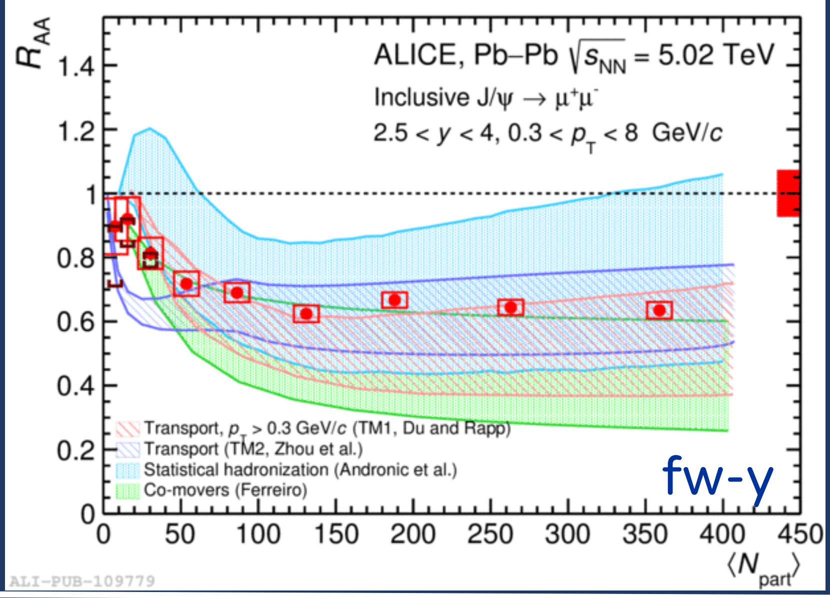
PLB766 (2017) 212

- J/ψ R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV is systematically higher by ~15% than the one at $\sqrt{s_{NN}}$ = 2.76 TeV, even if effect is within uncertainties

- J/ψ suppression in Run2 confirms Run1 observation, with an increased precision

Comparison with theoretical models





Transport models:
based on thermal rate eq. with continuous J/ψ dissociation and regeneration in QGP and hadronic phase

X. Zhao, R. Rapp NPA 859 (2011) 114, K. Zhou et al, PRC 89 (2011) 05491

Statistical hadronization:
J/ψ produced at chemical freeze-out according to their statistical weight

A. Andronic et al., NPA 904-905 (2013) 535

Comover model:
J/ψ dissociated via interactions with partons - hadrons + regeneration contribution

E. Ferreiro, PLB749 (2015) 98, PLB731 (2014) 57

➡ All models fairly describe the data, as already in Run1

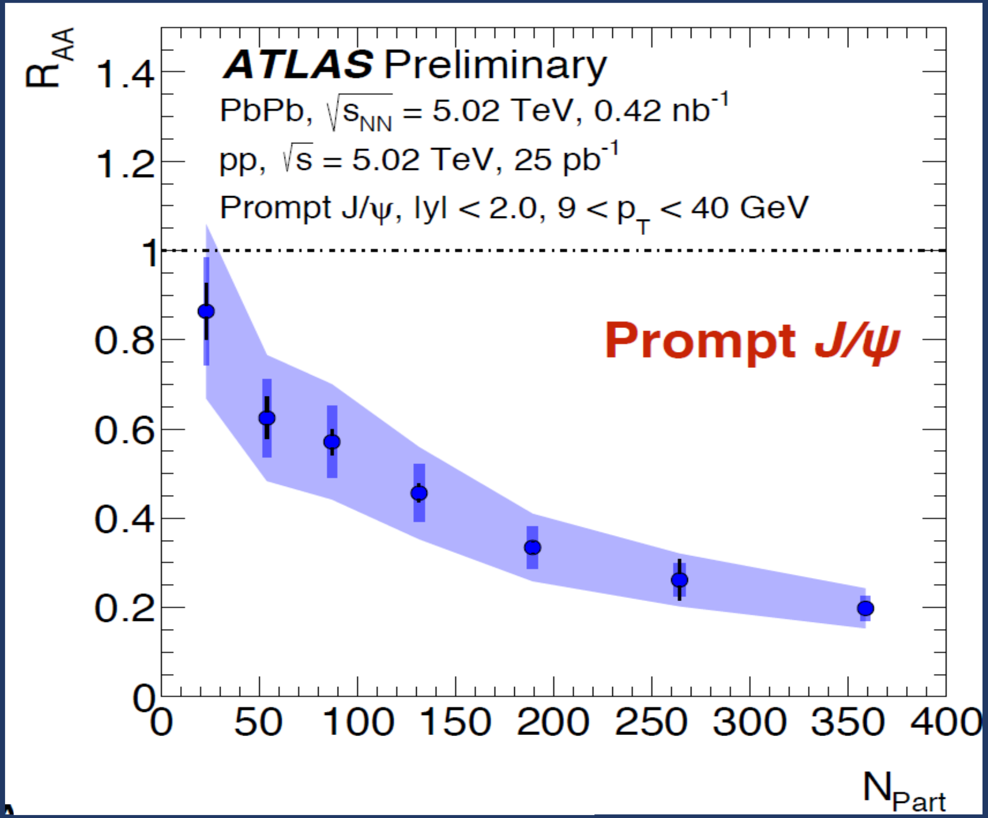
➡ but large uncertainties associated to charm cross section and shadowing

J/ψ R_{AA} at high p_T

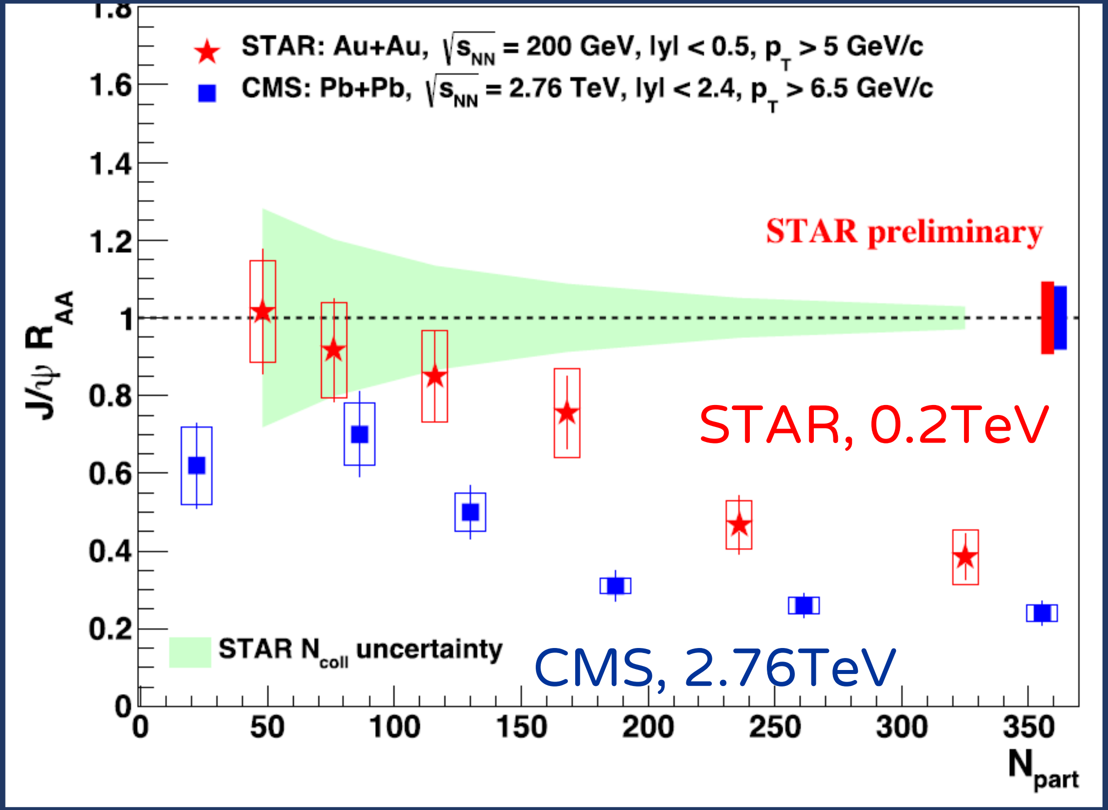
Different behavior wrt low p_T J/ψ:

- Suppression strongly increasing with centrality
- Suppression at LHC is stronger than at RHIC

→ Behaviour expected in case of weak regeneration contribution at high p_T

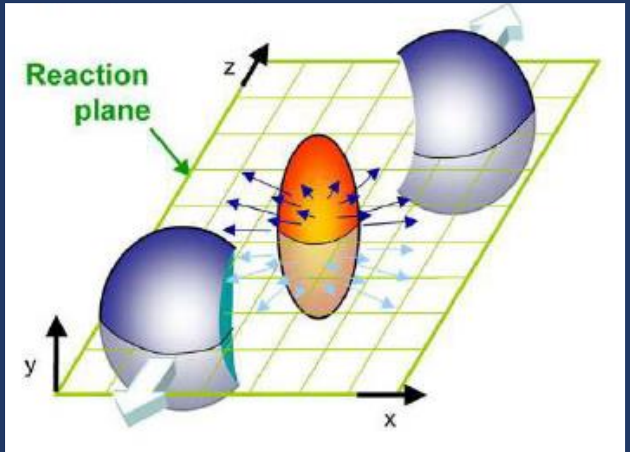


ATLAS-CONF-2016-109



J/ψ elliptic flow

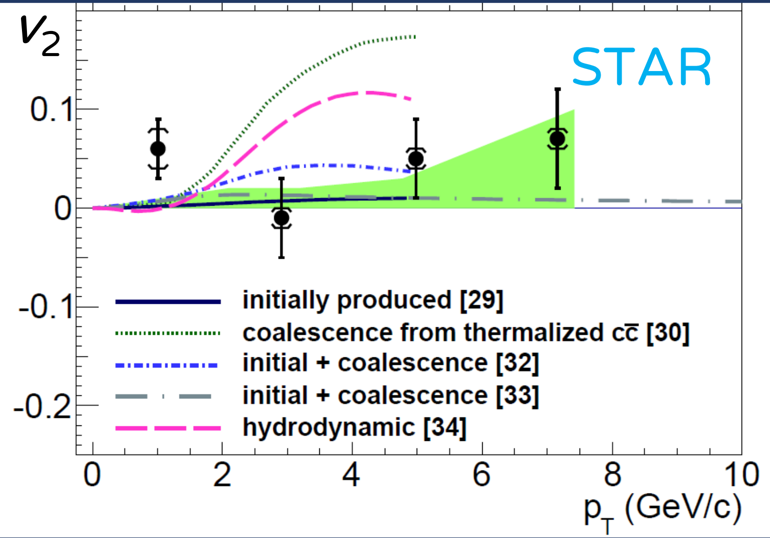
Collision dynamics is reflected in the particle azimuthal distributions
→ elliptic flow is the second coeff. of the Fourier expansion, wrt reaction plane



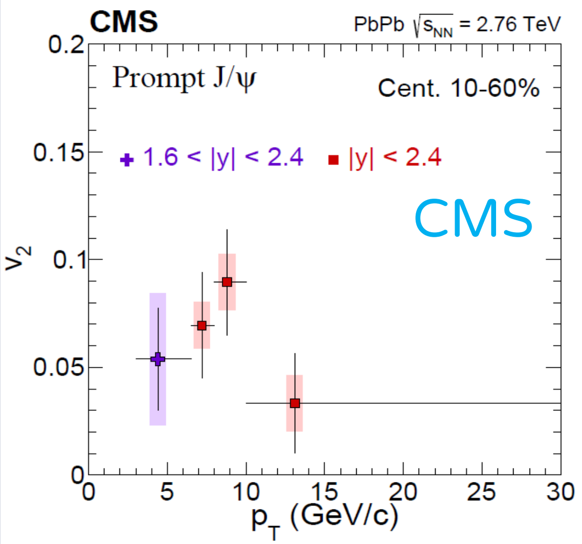
$$v_2 = \langle \cos 2(\phi_{\mu\mu} - \Psi_{EP}) \rangle$$

J/ψ from recombination should inherit the charm flow, leading to a v_2 signal

➡ Effect should be important at LHC energies, in kinematic regions where regeneration plays a role



PRL 111 052301(2013)

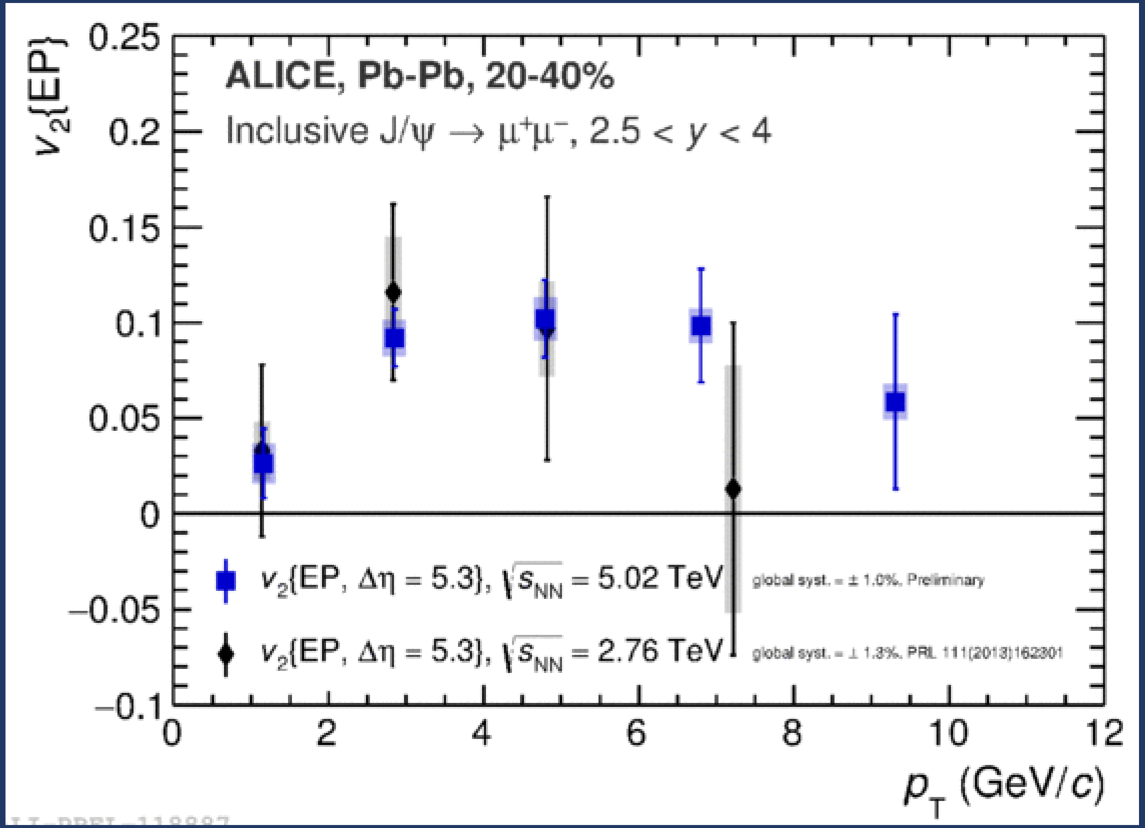


EPJC 77 (2017) 252

➡ RHIC results favour v_2~0

➡ CMS measures $v_2 \neq 0$ at high p_T, possibly due to the energy loss path-length dependence

J/ψ elliptic flow



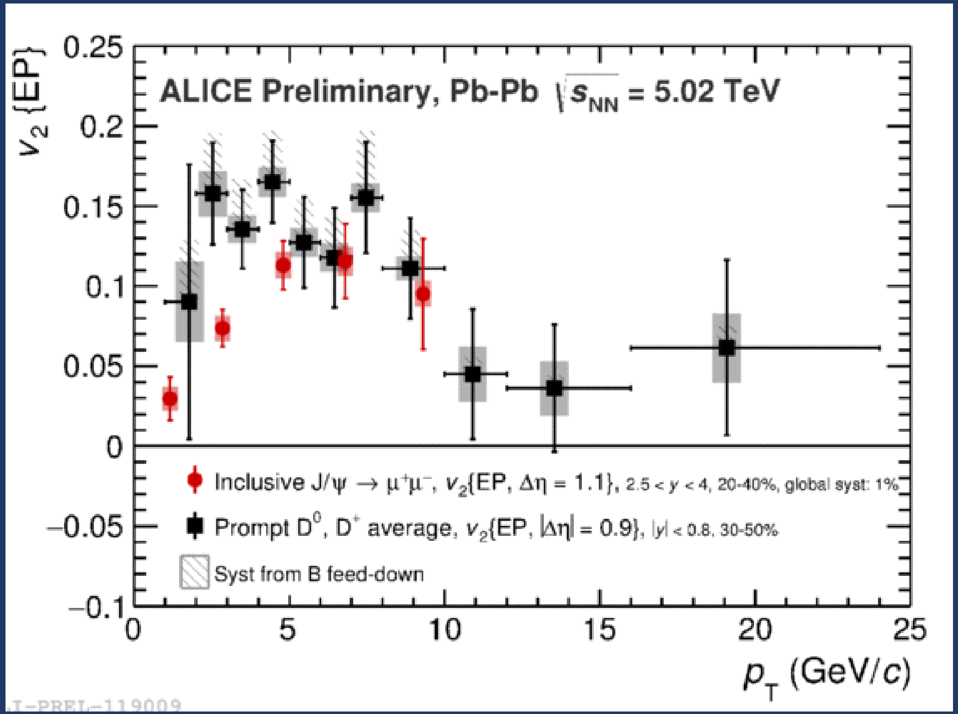
- ALICE Run 1 result gave an indication of non-zero flow → 2.7σ in $2<p_T<6$ GeV/c and 20-40% centrality
- Higher Run2 precision shows evidence for non-zero flow, with a maximum in $4<p_T<6$ GeV/c

p_T (GeV/c)	0-2	2-4	4-6	6-8	8-12
Δη=1.1	2.2σ	6.3σ	7.4σ	5.0σ	2.8σ
Δη=5.3	1.4σ	6.2σ	5.0σ	3.3σ	1.3σ

- A significant fraction of the observed J/ψ comes from charm quarks thermalized in the QGP

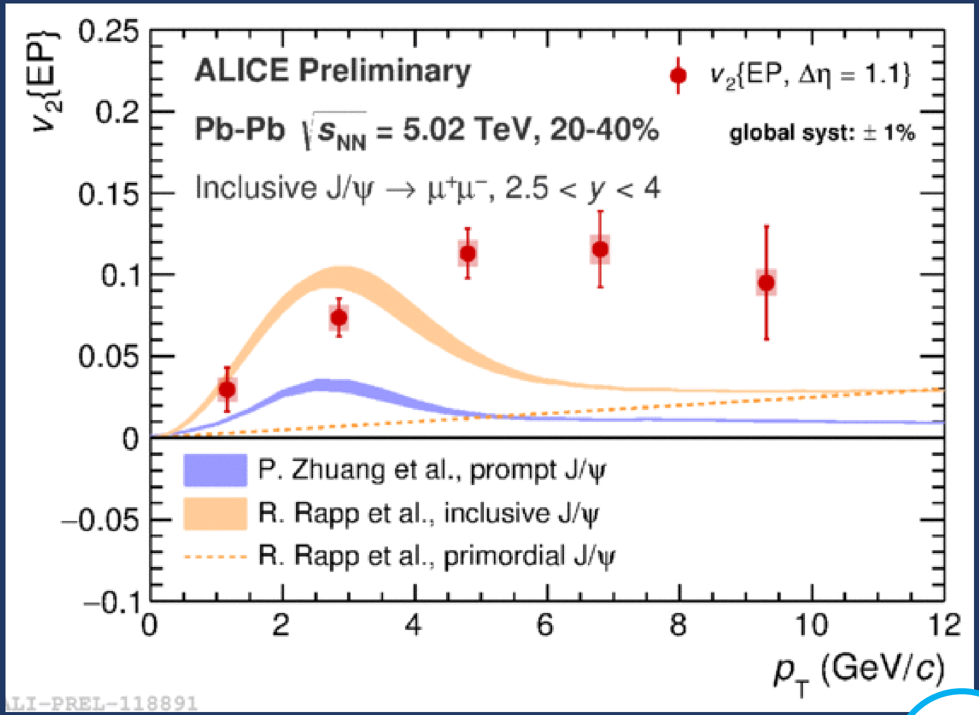
J/ψ elliptic flow

- Similar v_2 observed for open charm



- Difficulties in reproducing the v_2 shape up to high p_T with theory models

- Simultaneous description of J/ψ R_{AA} and v_2 is an interesting testing ground for theory models!



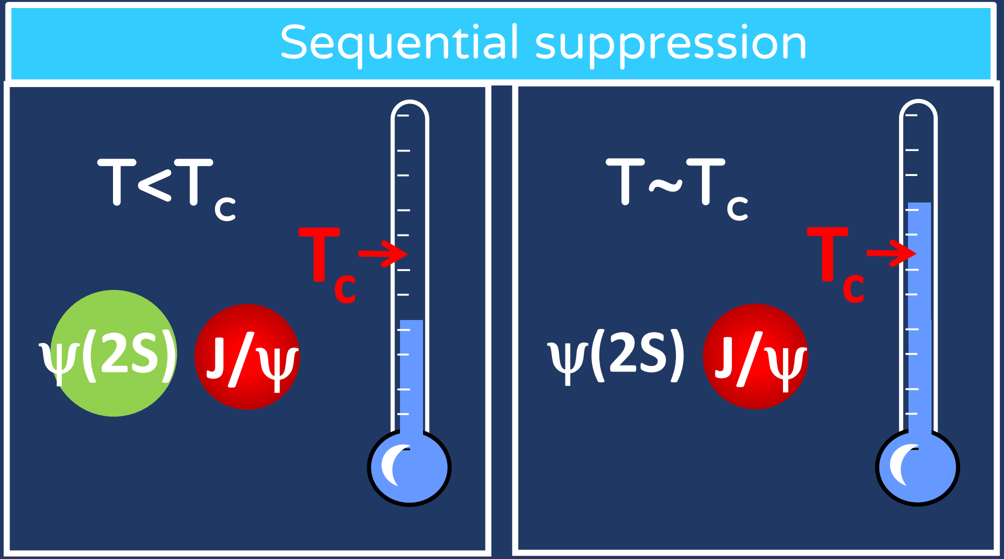
- Charm quarks strongly interact in the medium
- Comparison between J/ψ and D flow can give insights on flow properties of heavy vs light quarks

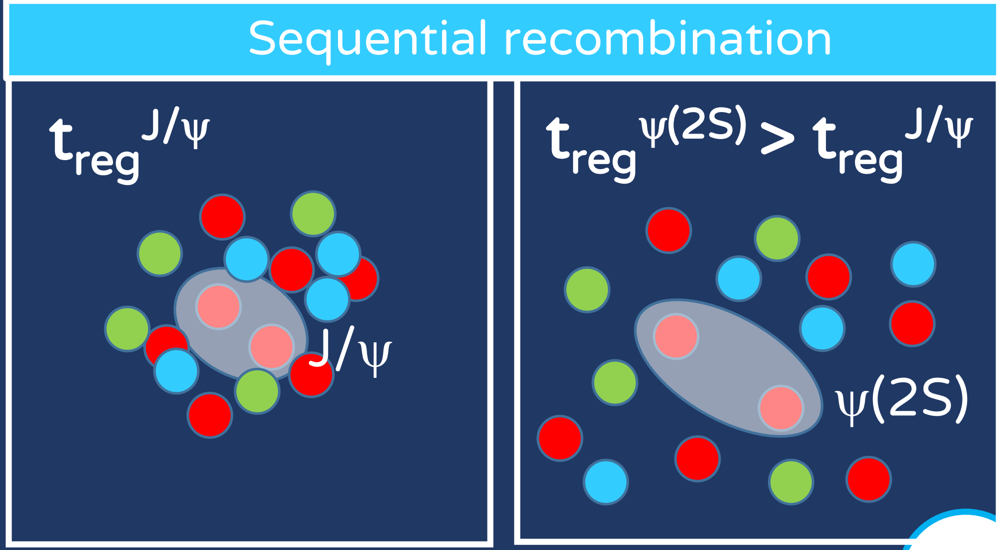
$\psi(2S)$ in AA collisions

- $\psi(2s)$ is a loosely bound state (binding energy ~60 MeV wrt to ~640 MeV for J/ψ)

- Expected to be more easily dissociated than J/ψ
  → sequential suppression scenario

- Less clear role played by recombination, taking place
  → at freeze-out, as for J/ψ in the statistical hadronization model
  → in later collision stages, when the system is more diluted (and radial flow is stronger) [sequential regeneration, Rapp, arXiv:1609.04868]

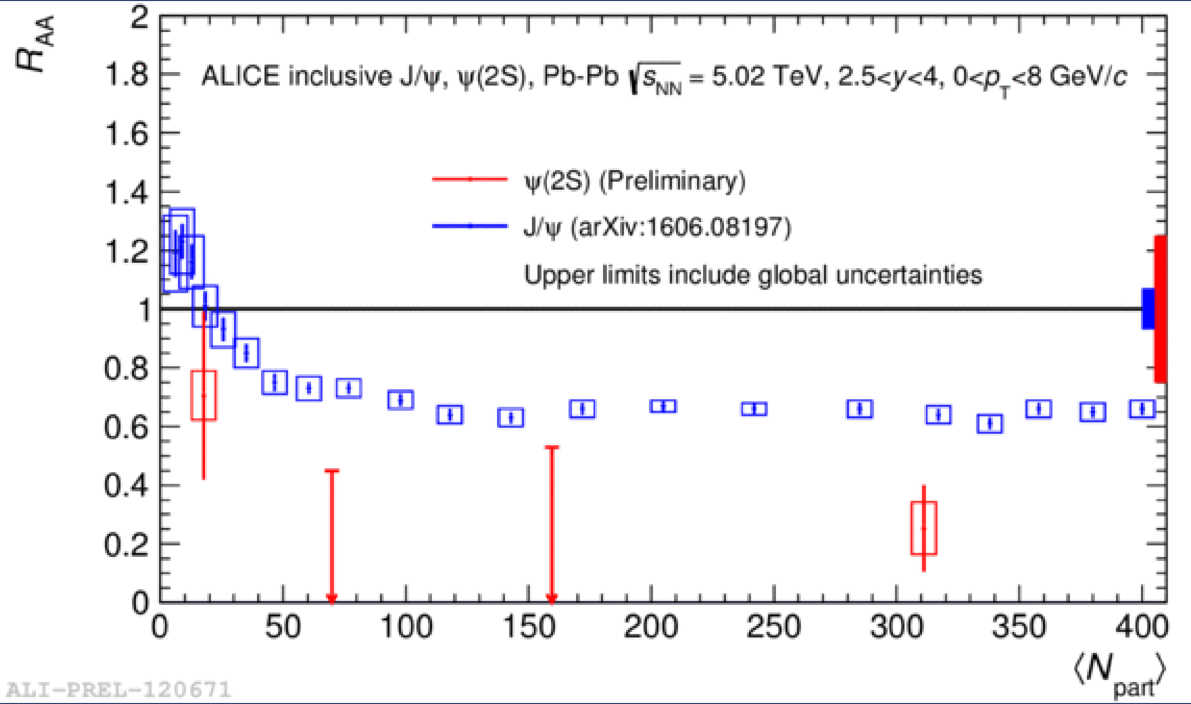


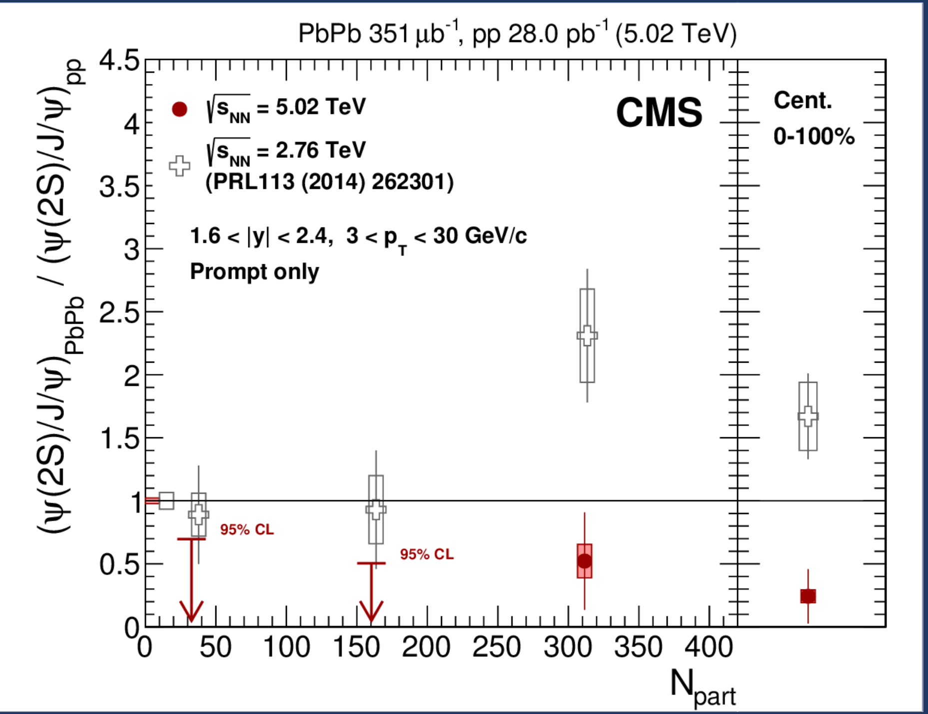


- Ratio of charmonium states vs. centrality and vs. p_T can give insight on quarkonium behaviour

ψ(2S) R_{AA}

ψ(2s) shows a stronger suppression, in semi-central and central collisions, than J/ψ
$[\psi(2S)/J/\psi]_{AA}$ / $[\psi(2S)/J/\psi]_{pp}$ <<1 → behaviour expected in a dissociation scenario





- At $\sqrt{s_{NN}}$ = 5.02 TeV, compatible results between ALICE and CMS, in similar kinematic range, while some tension exists at lower energy
- Results in different kinematic ranges are sensitive to the fraction of primordial and regenerated charmonia, to different medium temperature and flow…

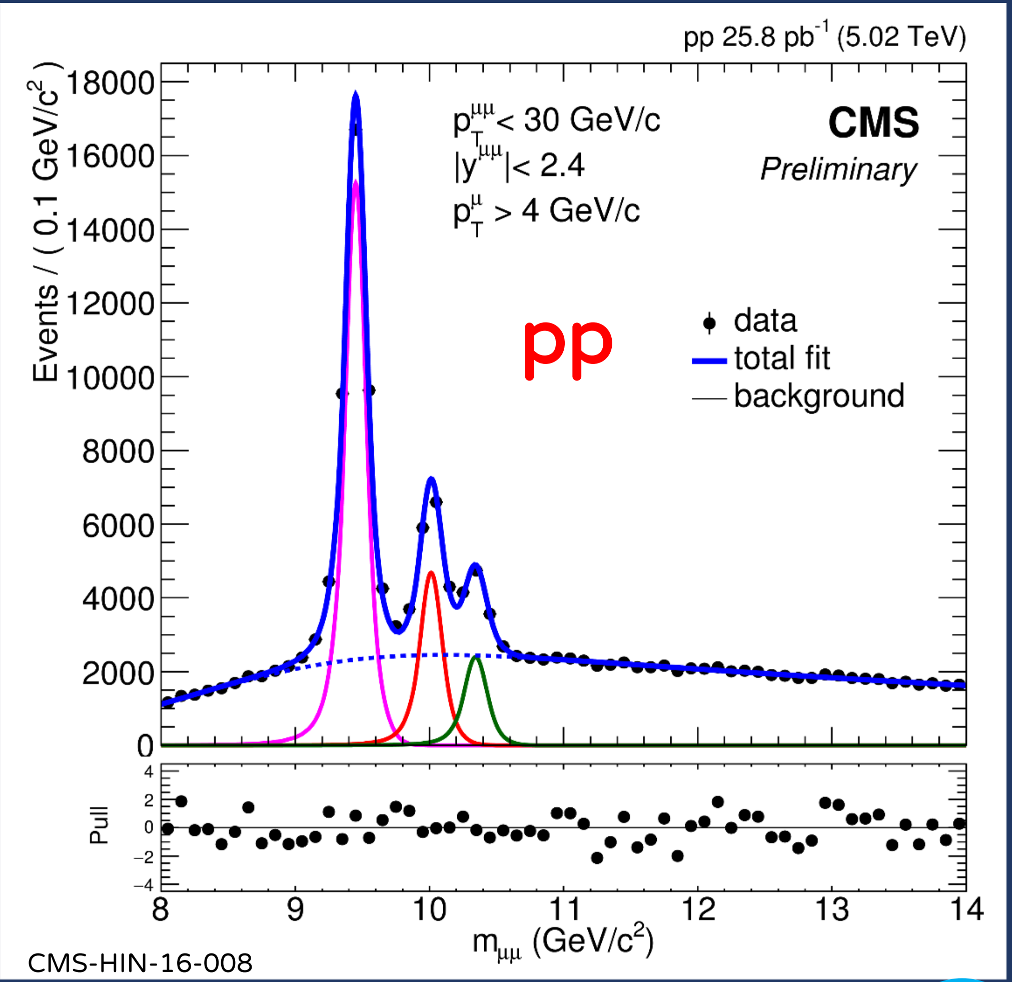
Bottomonia in AA

- Three states characterized by very different binding energies:

ϒ(1S): E_b~1100 MeV
ϒ(2S): E_b~500 MeV
ϒ(3S): E_b~200 MeV

ϒ(3S) ϒ(2S) ϒ(1S)

- Sensitive in very different ways to the medium

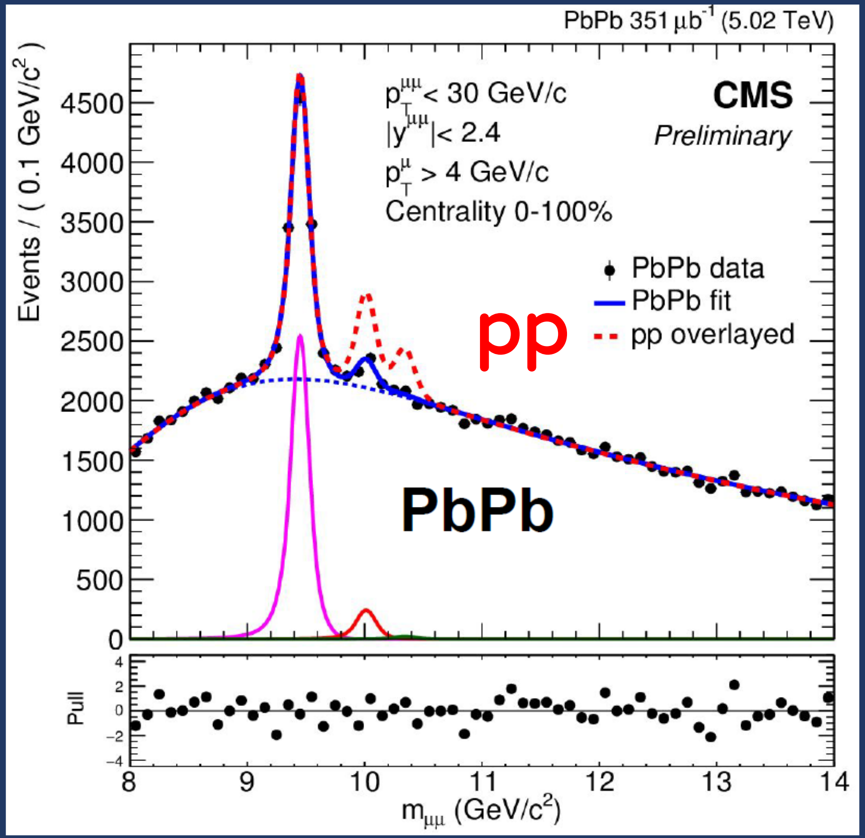


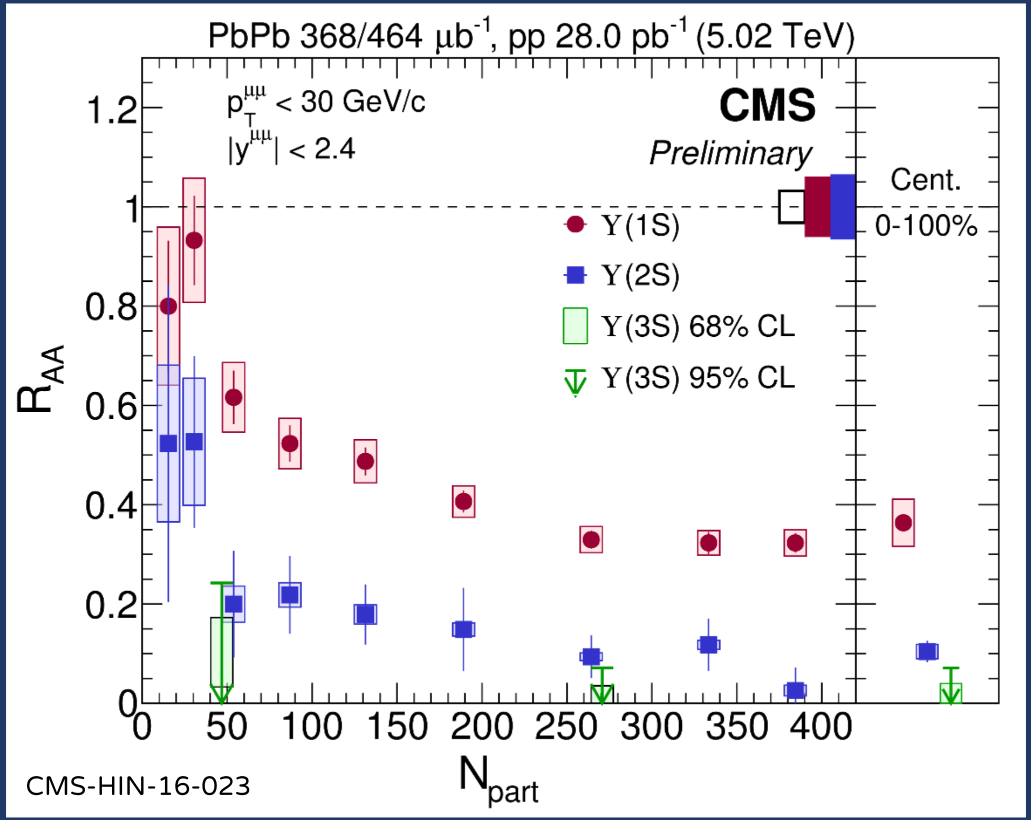
With respect to charmonium:

- Limited recombination effects → interesting for sequential suppression studies
- More robust theoretical calculations, due to higher b quark mass
- No B hadron feed-down → simpler interpretation?
- Lower production cross sections
- Non negligible feed-down from higher states

Bottomonia in AA

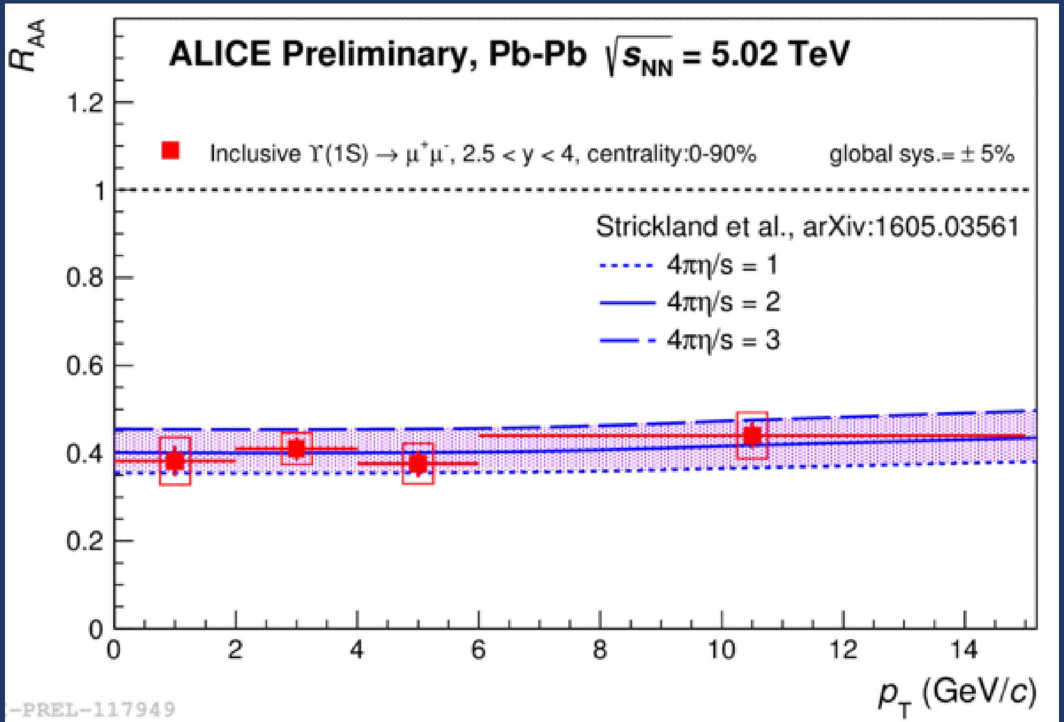
Striking suppression of Υ(2S) and Υ(3S) in PbPb!

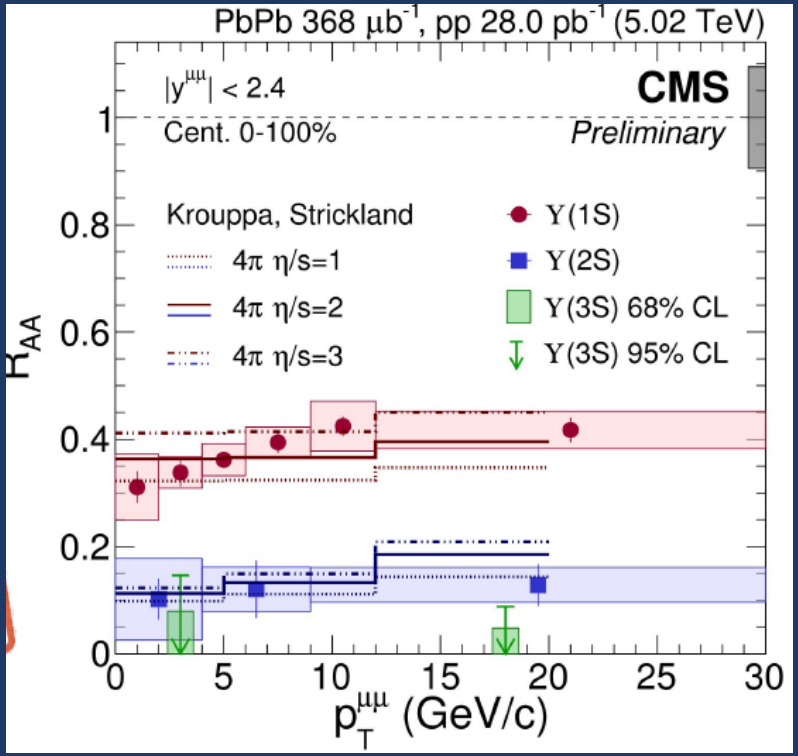




- Suppression up to a factor ~2 for Υ(1S) and ~9 for Υ(2S)
- Slightly stronger Υ(1S) suppression at 5.02 TeV wrt 2.76 TeV
- Suppression of directly produced Υ(1S) ? → feed-down contribution~30%

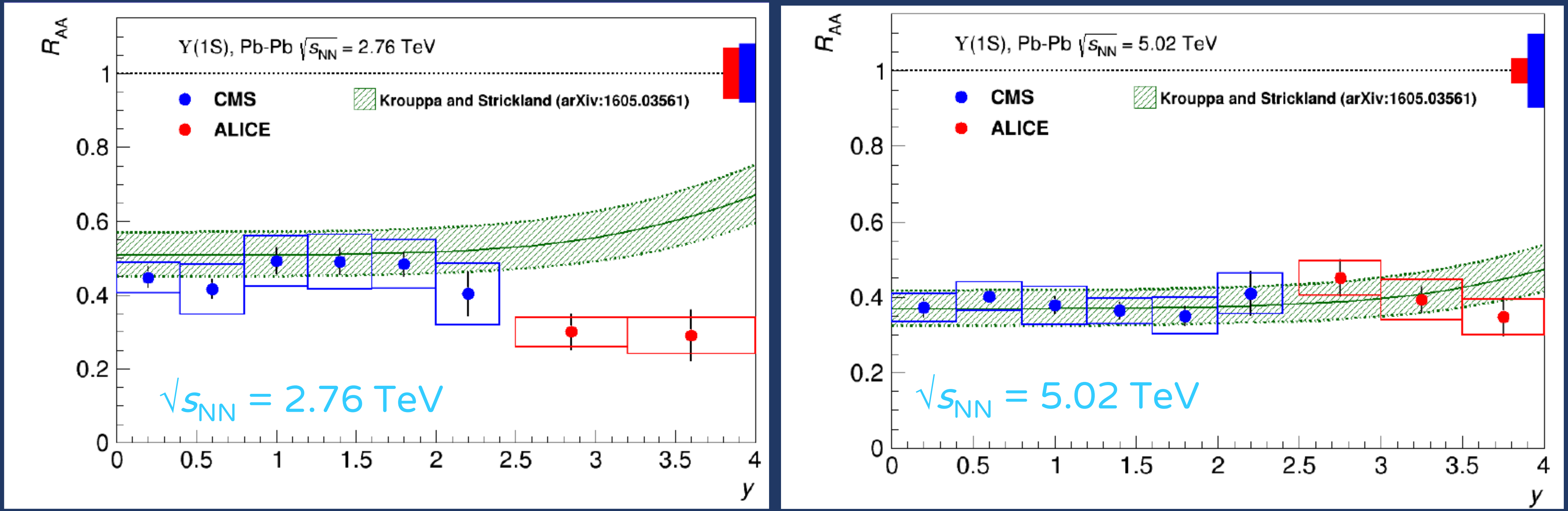
ϒ(1S) p_T dependence





- Weak p_T dependence observed from both ALICE and CMS
- Transport and anisotropic hydrodynamical models qualitatively describe the data
- No need for contribution of regenerated ϒ

Υ(1S) vs rapidity



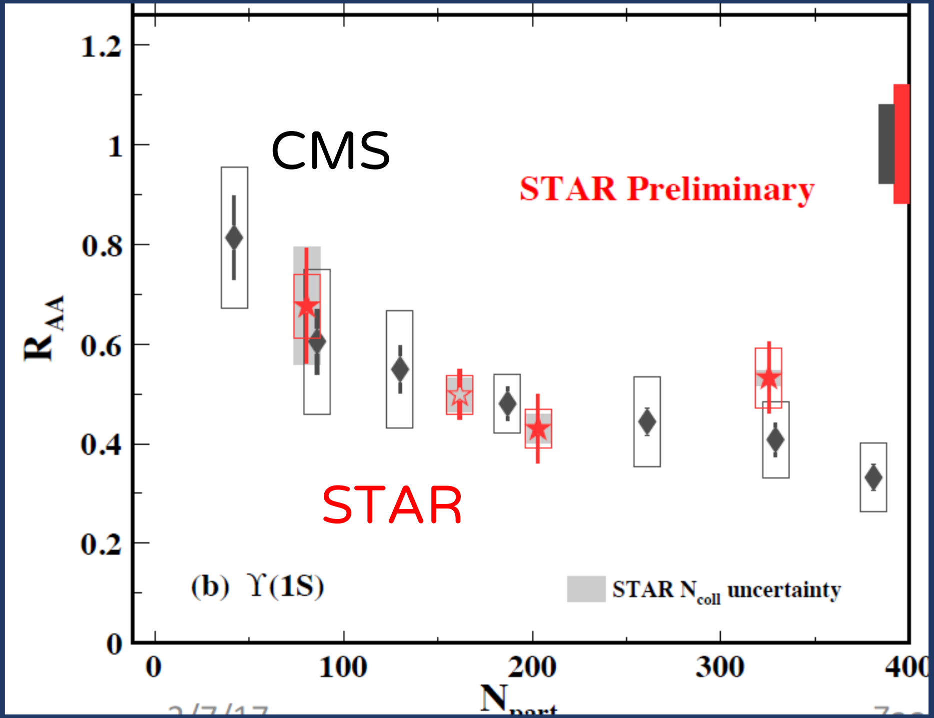
CMS-PAS-HIN16-023
CMS arXiv:1611.01510

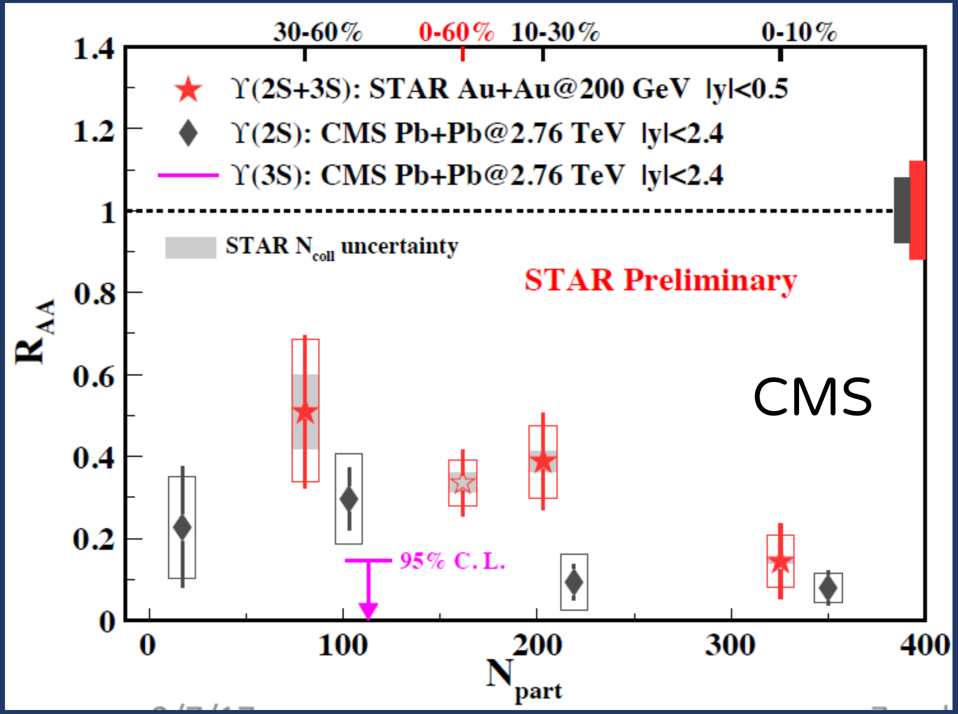
E. Scomparin, QM17

- Suppression increases with y at $\sqrt{s_{NN}}$ = 2.76TeV
- Suppression is constant at $\sqrt{s_{NN}}$ = 5.02TeV

- Some tension in the R_{AA} evolution vs y with energy, but still large uncertainties

Bottomonia at RHIC





Suppression of ϒ(1S) states also at RHIC energies

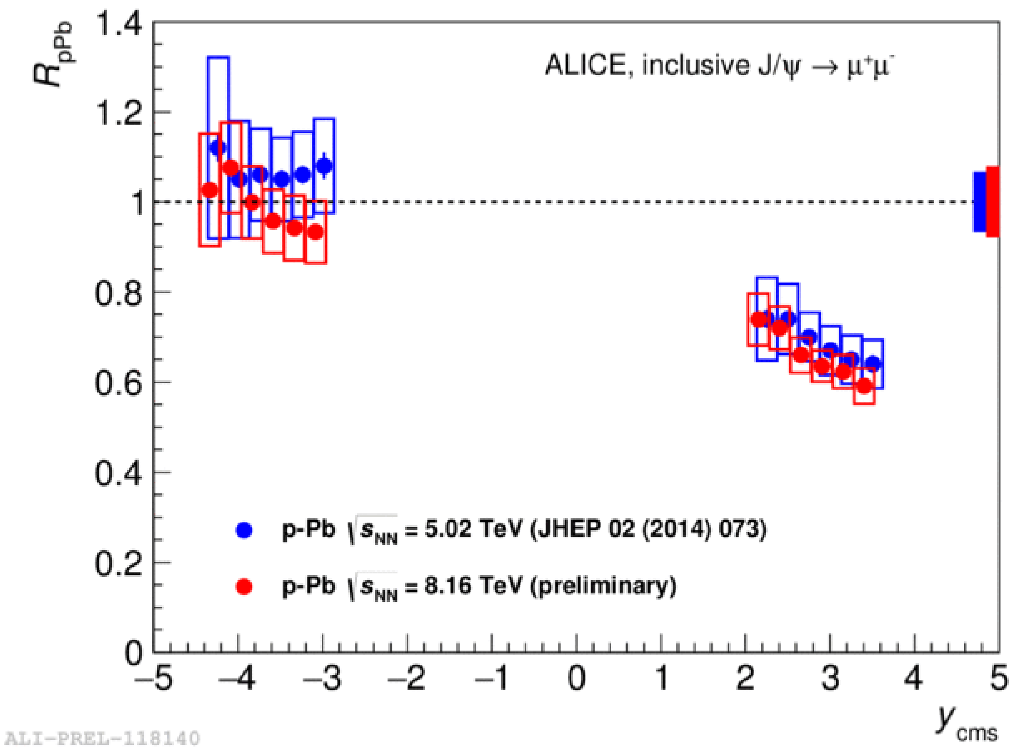
- New high-precision RHIC data suggest a similar ϒ(1S) suppression as at LHC
  → Feed down effect?

- Slightly stronger ϒ(2S+3S) suppression at LHC than at RHIC in semi-central collisions

J/ψ in p-Pb collisions

pA collisions are a tool to:

- Disentangle CNM effects, which have a different impact depending on energy regime and quarkonium kinematics
- Investigate role of CNM effects underlying AA collisions



CERN-ALICE-PUBLIC-2017-001

➡ Clear J/ψ suppression at forward-*y*, while R_{pA} is compatible with unity at backward-*y*

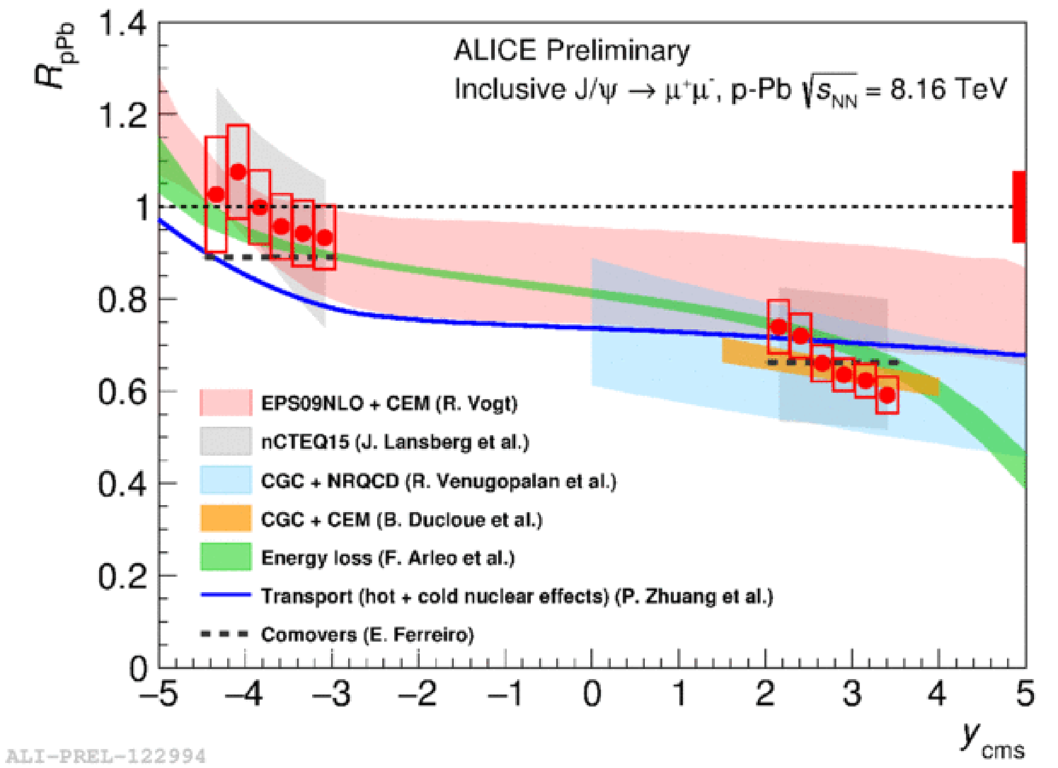
➡ R_{pA} compatible at $\sqrt{s_{NN}}$ = 5.02 and 8.16TeV, even if *x* coverage is slightly different

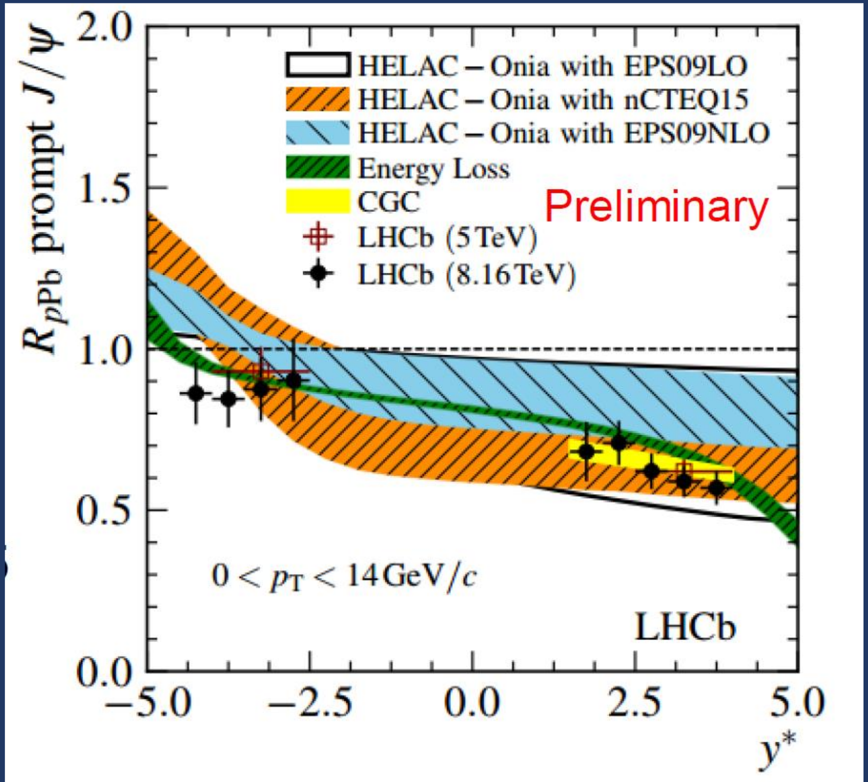
$\sqrt{s_{NN}}$ = 8.16TeV, $p_T^{J/\psi}$= 0

$1.1\ 10^{-5} < x < 5\ 10^{-5}$ (p-going)

$7.3\ 10^{-3} < x < 3.3\ 10^{-2}$ (Pb-going)

J/ψ R_{pA} vs rapidity

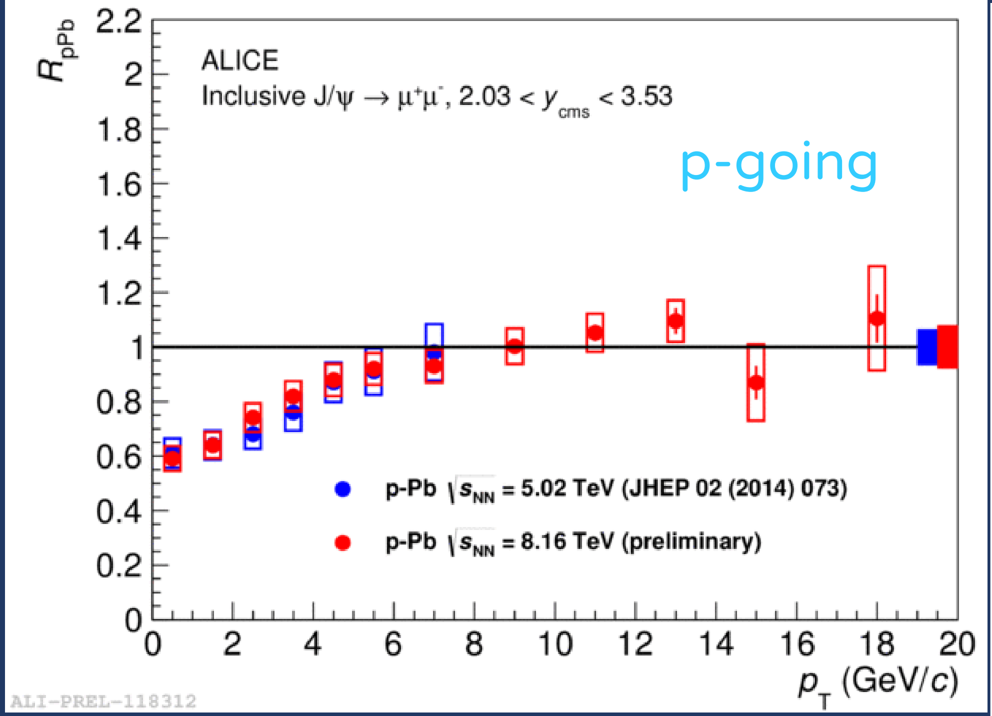


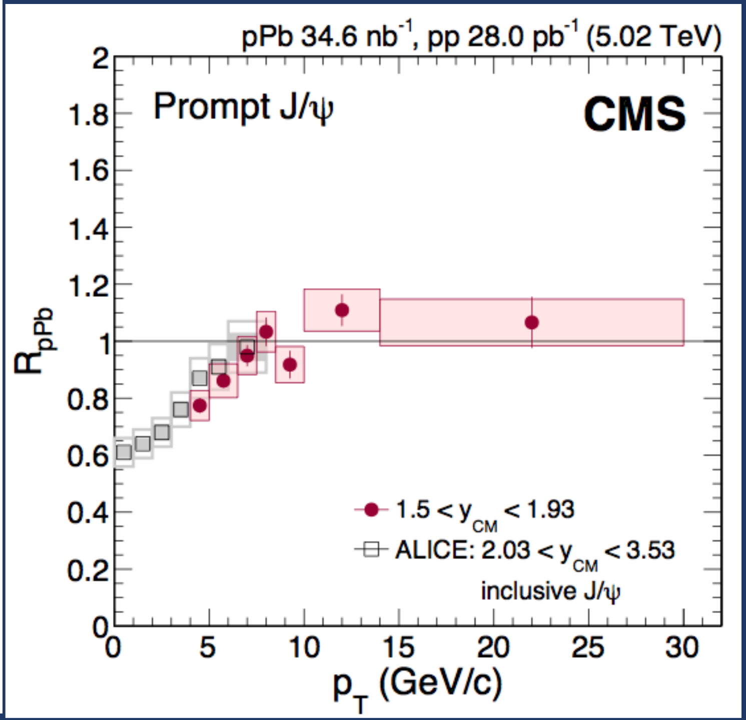


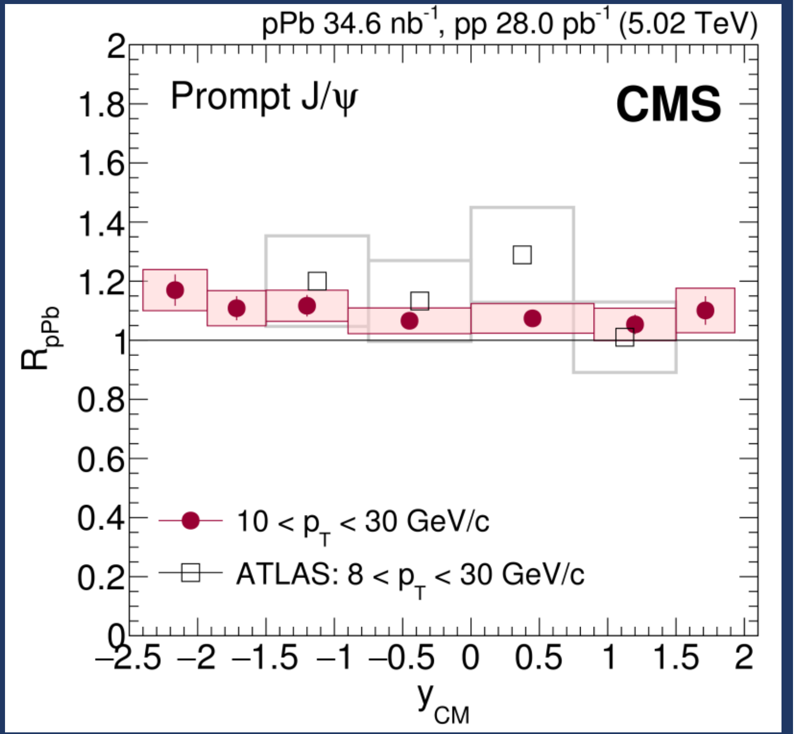
- Good agreement between ALICE and LHCb data
- Results described by models based on shadowing and/or energy loss, as at $\sqrt{s_{NN}}$ = 5.02 TeV

Size of theory uncertainties (mainly shadowing) still limits a more quantitative comparison

J/ψ production in p-Pb at $\sqrt{s_{NN}}$ = 8.16TeV







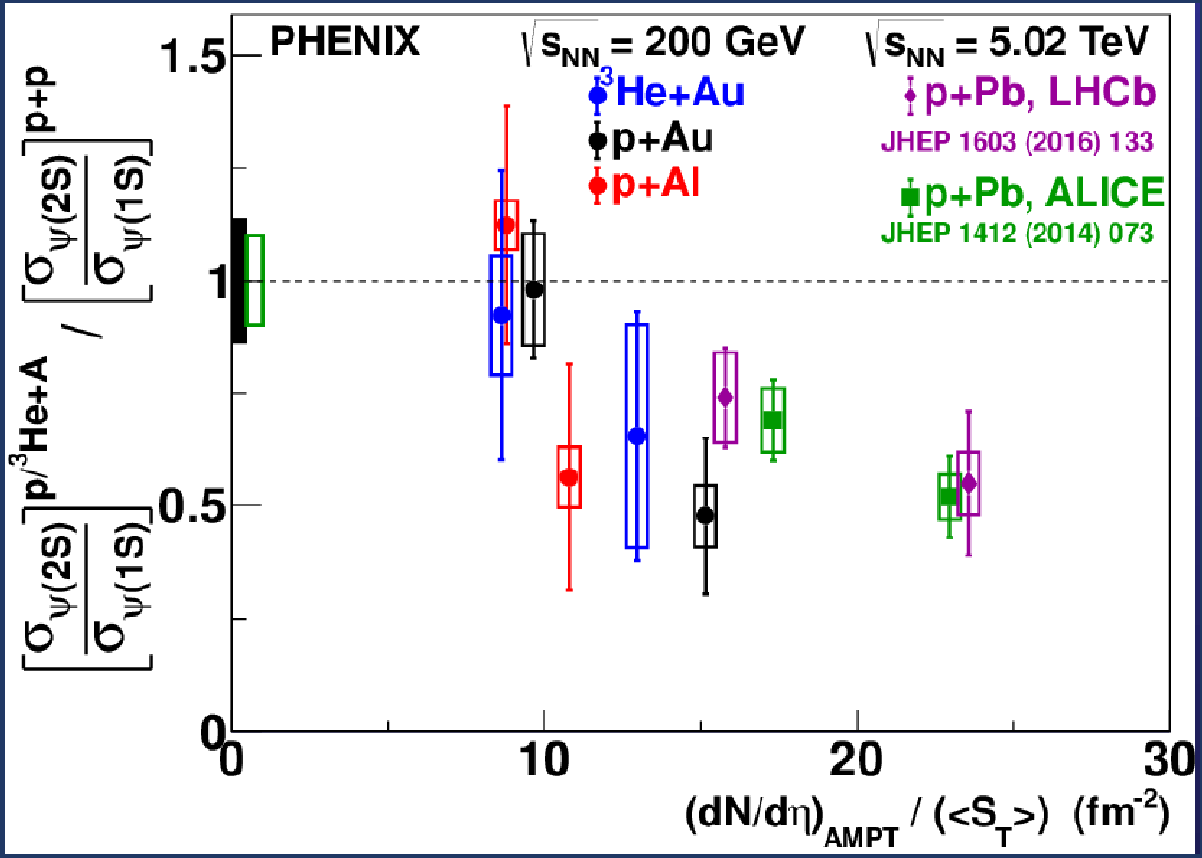
- In Run 2, the ALICE p_T coverage is extended up to 20 GeV/c
- Good agreement with CMS results

- Smaller size of CNM effects for high pT J/ψ

- The strong J/ψ suppression observed in Pb-Pb data at high p_T cannot be due to CNM effects

ψ(2S) in pA collisions

Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA



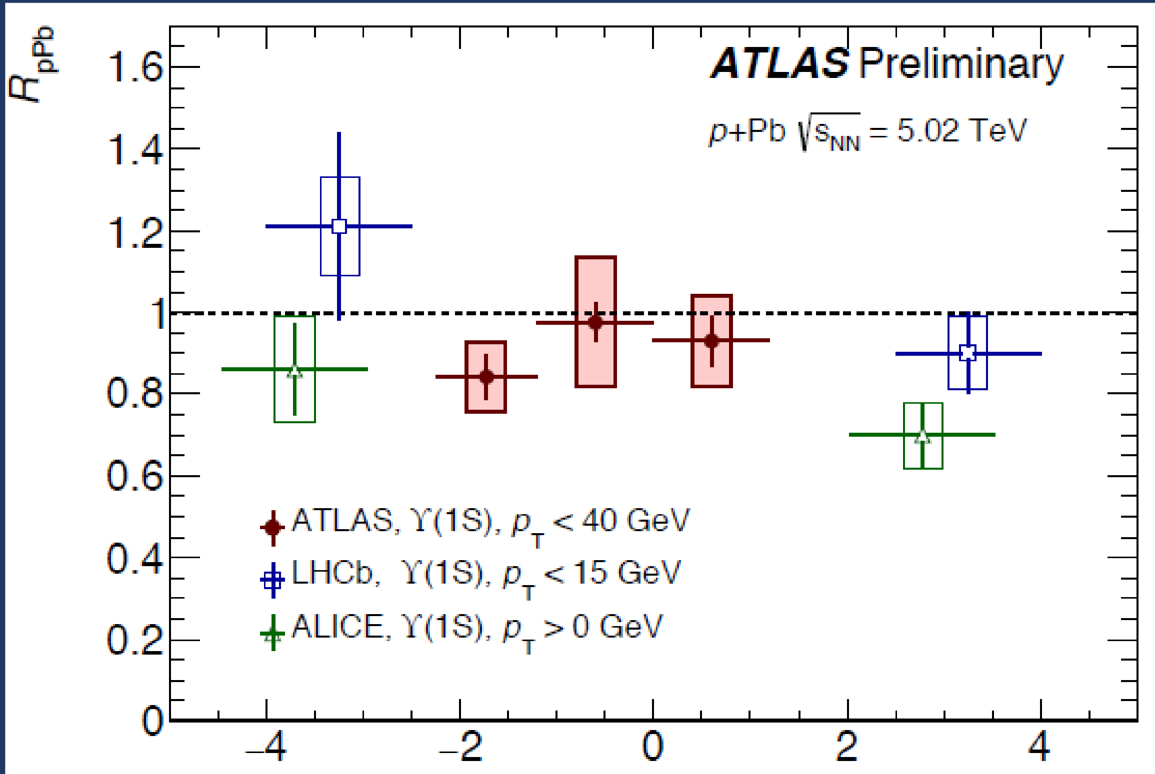
➡ ψ(2S) suppression stronger than the J/ψ one at RHIC and LHC

→ unexpected because time spent by the cc pair in the nucleus (τ_c) is shorter than charmonium formation time (τ_f)

→ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

➡ QGP+hadron resonance gas or comovers models describe the stronger ψ(2S) suppression

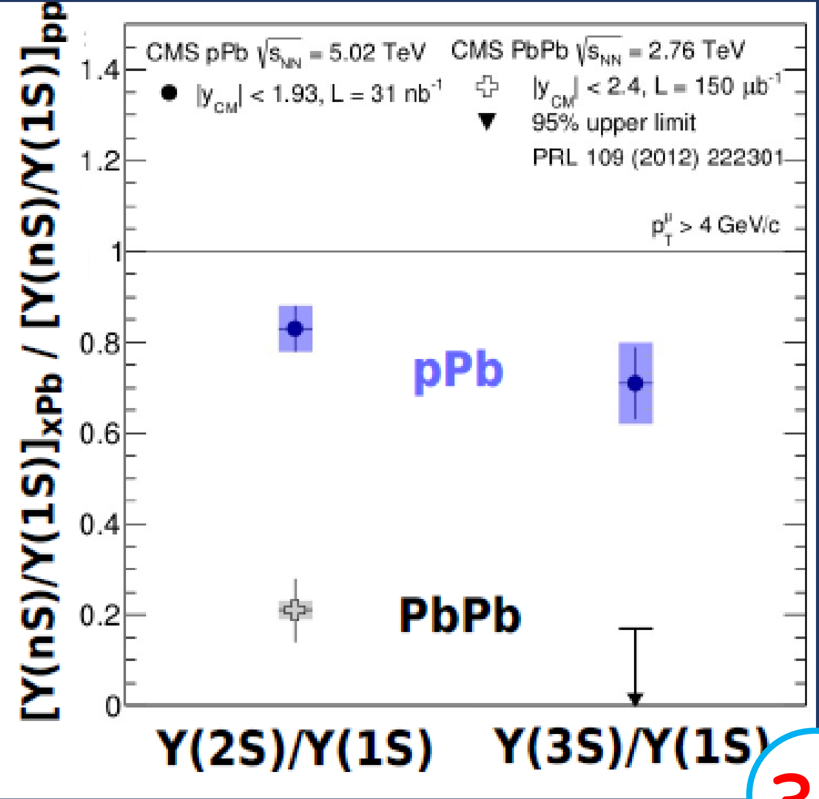
ϒ in pA collisions



ALICE, Phys. Lett. B 740 (2015) 105
ATLAS-CONF-2015-050 ,LHCb, JHEP 07(2014)094

➡ no strong rapidity dependence of ϒ(1S) R_{pA}

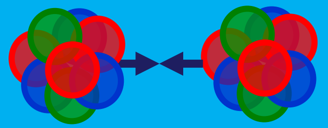
ϒ(1S) R_{pA} described by shadowing and energy loss models



➡ Stronger excited states suppression with respect to ϒ(1S)
Initial state effects similar for the three ϒ states
→ Final states effects in p-Pb?

Conclusions

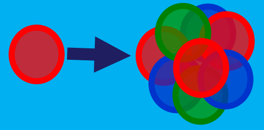
Several quarkonium states now accessible with high precision in p-A and A-A

AA 

R_{AA} results at $\sqrt{s_{NN}}$ = 5.02 TeV confirm the role of suppression and recombination mechanisms at play on the various quarkonium states

Evidence of J/ψ elliptic flow suggests charm thermalization in the medium

Υ suppression follows binding energy ordering, as expected in a melting scenario

pA 

Interplay of shadowing and energy loss describes J/ψ and Υ production in p-Pb

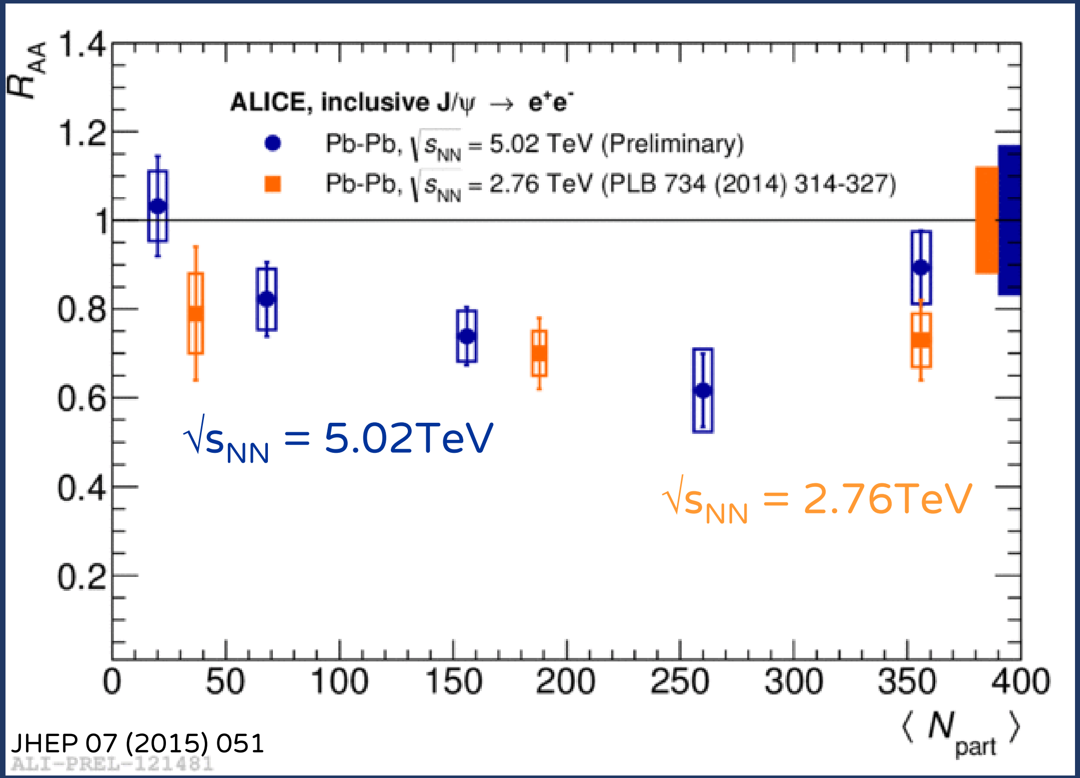
Stronger suppression observed on ψ(2S) due to QGP-like effects in pA

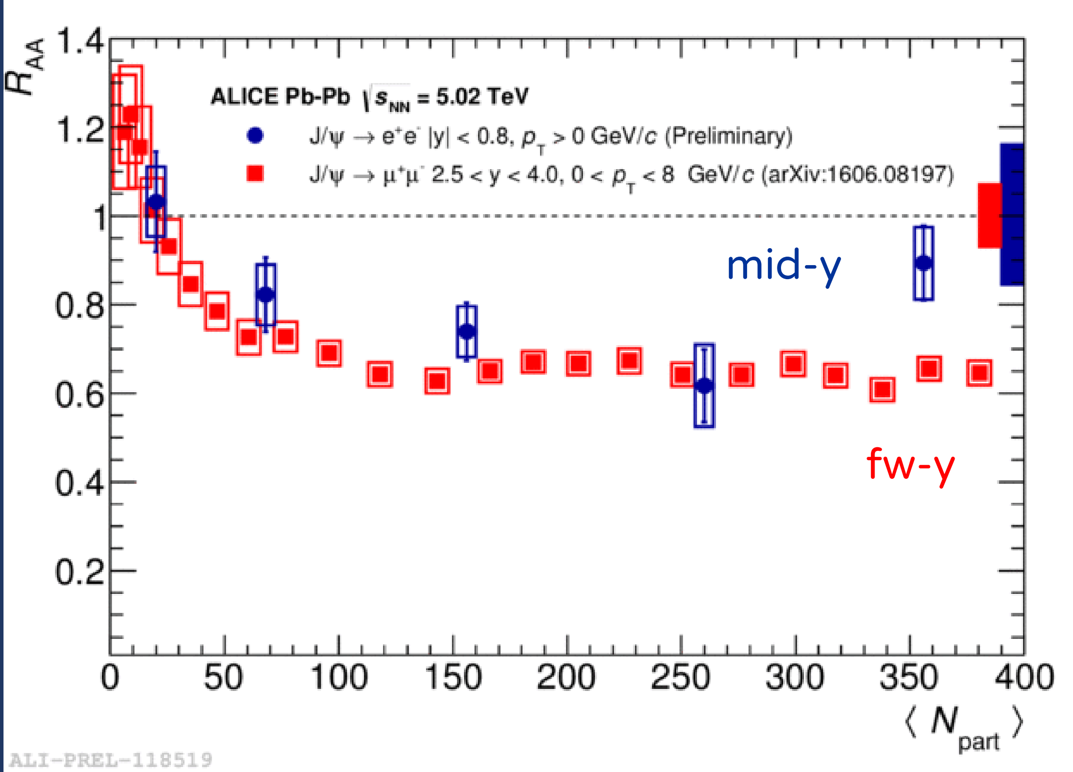
Many new results still to come….

Thanks!

Backup slides

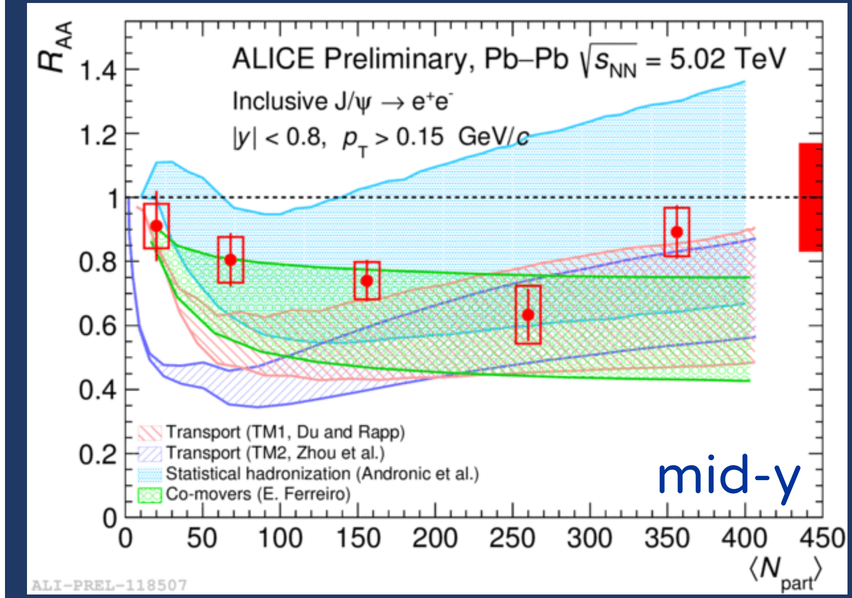
J/ψ R_{AA} at mid-y: Run 2

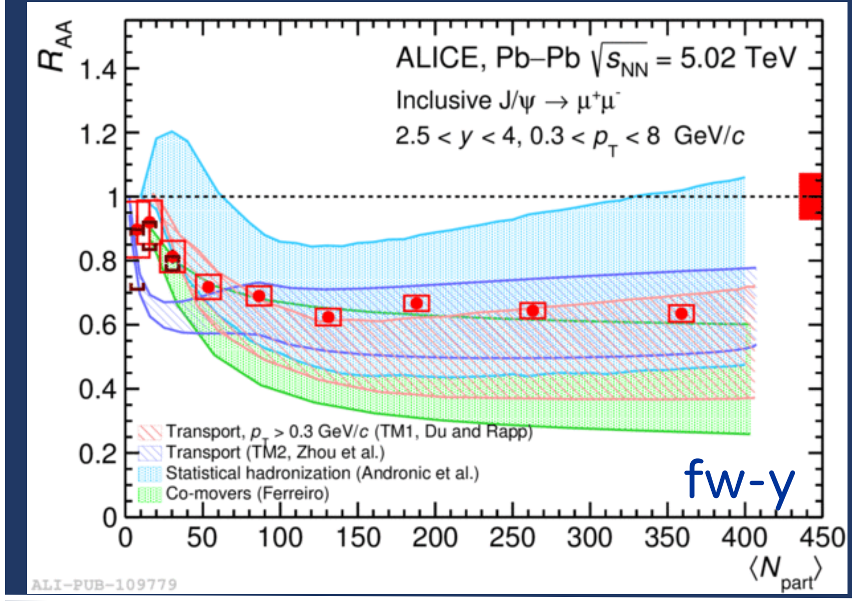




- No significant $\sqrt{s}$-dependence also at mid-rapidity, confirming observation at forward-y
- Small R_{AA} increase in most central collisions, wrt forward-y, as expected in a (re)generation scenario (but fluctuations cannot be yet excluded)

Comparison with theoretical models





Transport models: based on thermal rate eq. with continuous J/ψ dissociation and regeneration in QGP and hadronic phase

X. Zhao, R. Rapp NPA 859 (2011) 114, K. Zhou et al, PRC 89 (2011) 05491

Statistical hadronization: J/ψ produced at chemical freeze-out according to their statistical weight A. Andronic et al., NPA 904-905 (2013) 535

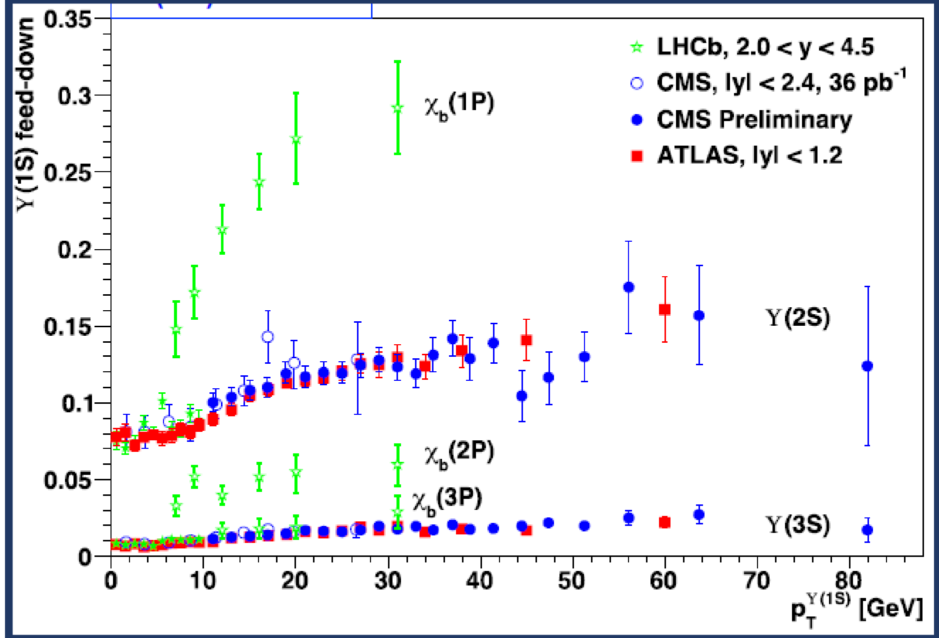
Comover model: J/ψ dissociated via interactions with partons - hadrons + regeneration contribution E. Ferreiro, PLB749 (2015) 98, PLB731 (2014) 57

➡ All models fairly describe the data, as already in Run1

Model	$d\sigma_{J/\psi}/dy$ [mb] fw-y	shadowing
Transport, TM1	0.57	EPS09
Transport, TM2	0.82	EPS09
Stat. Hadroniz.	0.32	EPS09
Comovers	0.45-0.7	Glauber-Gribov

but large uncertainties associated to charm cross section and shadowing

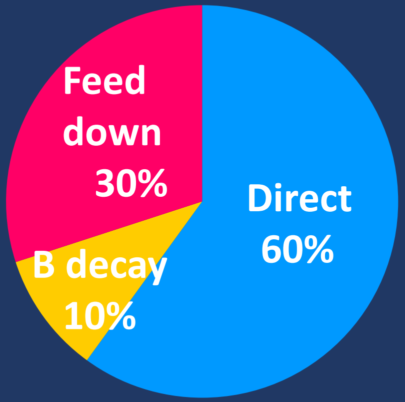
Feed down



J/ψ production

Quarkonium production can proceed:

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



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

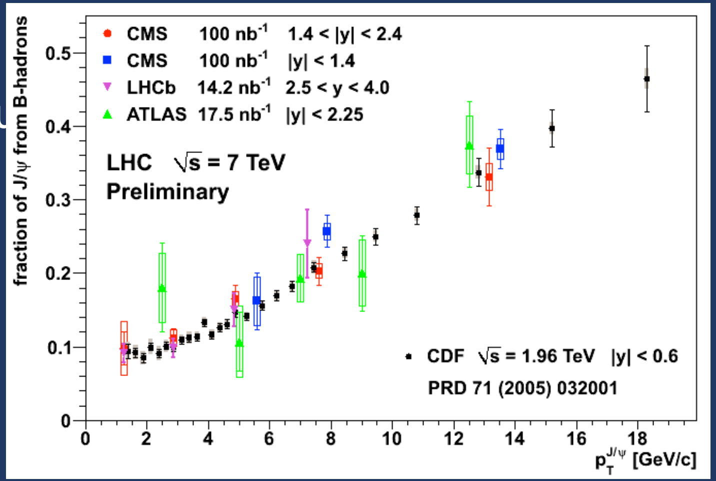
Prompt

➡ Direct production

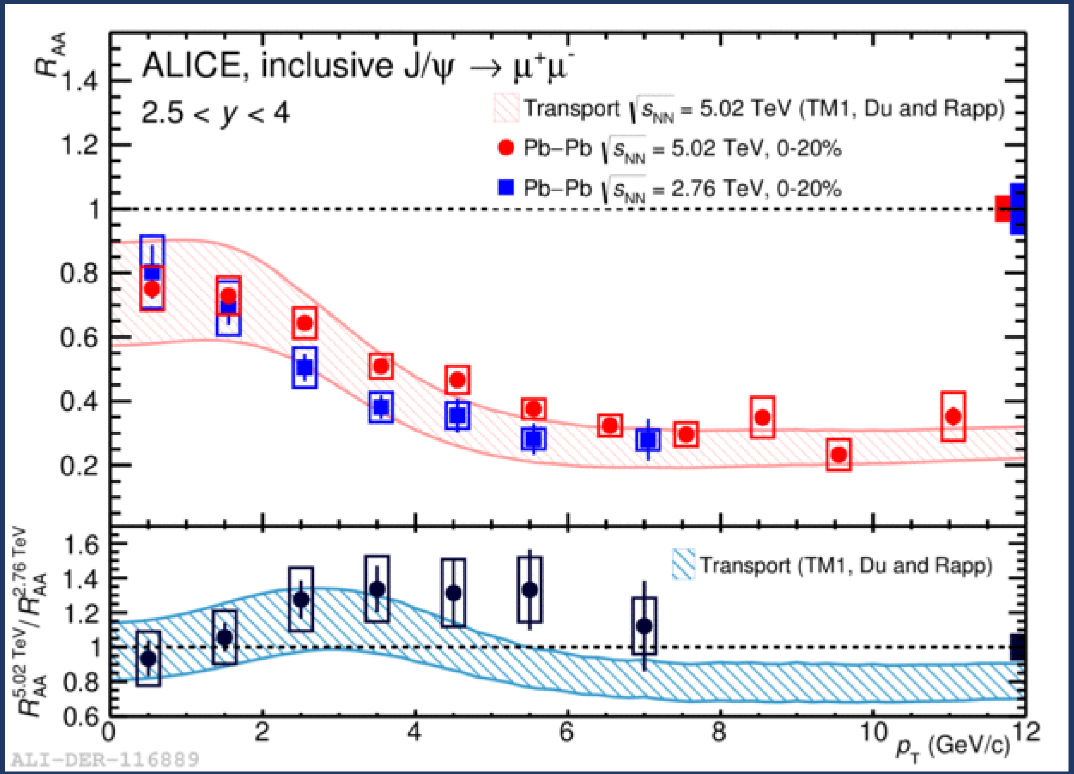
➡ Feed-down from higher charmonium states:
~ 8% from ψ(2S), ~25% from χ_c

Displaced

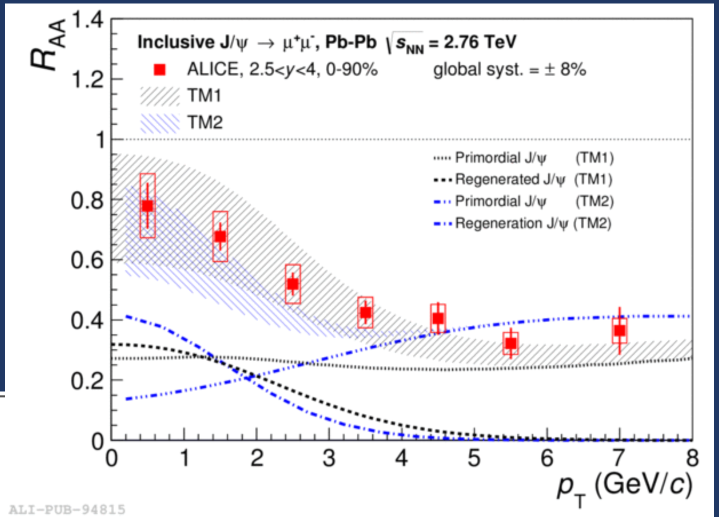
➡ B decay
contribution is p_T dependent
~10% at p_T~1.5GeV/c

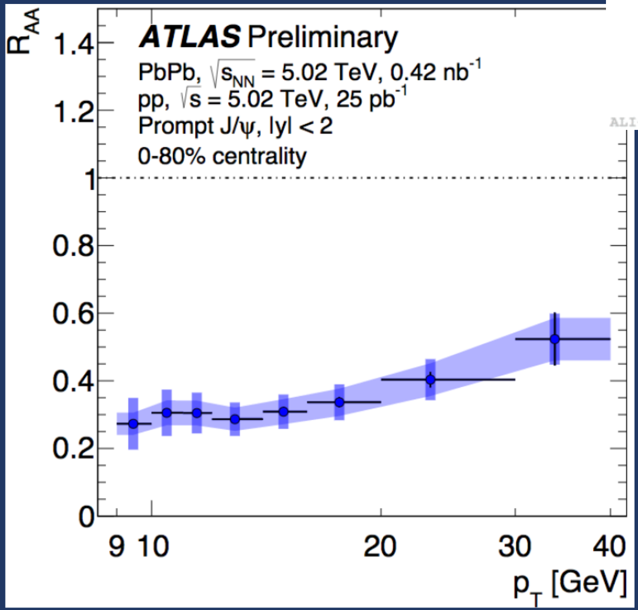


p_T dependence of R_{AA}



- J/ψ R_{AA} is higher at low p_T, where J/ψ from regeneration dominate





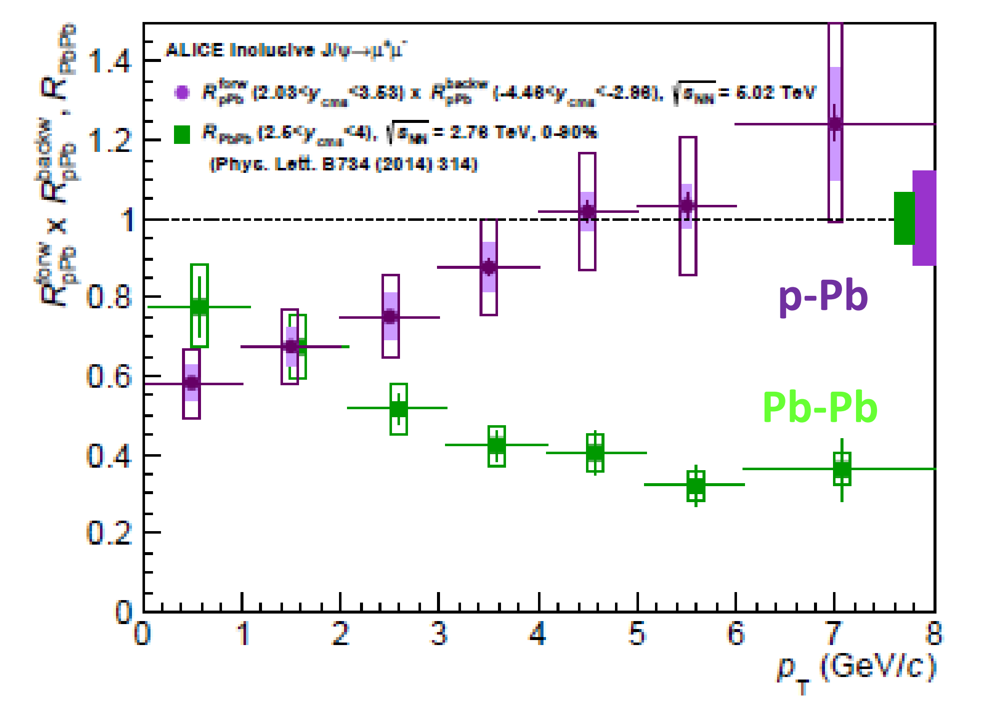
- Similar R_{AA} at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV, with a hint for an increase in the range $2<p_T<6$ GeV/c

- Very different behavior wrt R_{AA} of high-p_T J/ψ as measured by ATLAS and CMS

From pA to AA

- Once CNM effects are measured in pA, what can we learn on J/ψ production in PbPb?

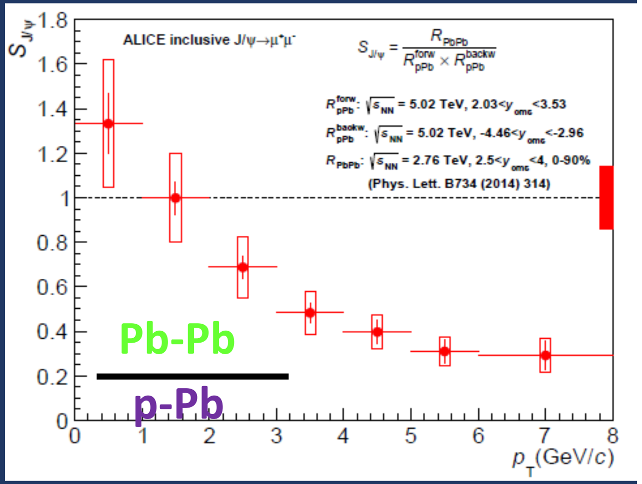
Hypothesis:
- 2→1 kinematics for J/ψ production
- CNM effects (dominated by shadowing) factorize in p-A
- CNM obtained as R_{pA} x R_{Ap} (R_{pA}^2), similar x-coverage as PbPb



- Sizeable p_T dependent suppression still visible → CNM effects not enough to explain AA data at high p_T

- we get rid of CNM effects with

AA / pA

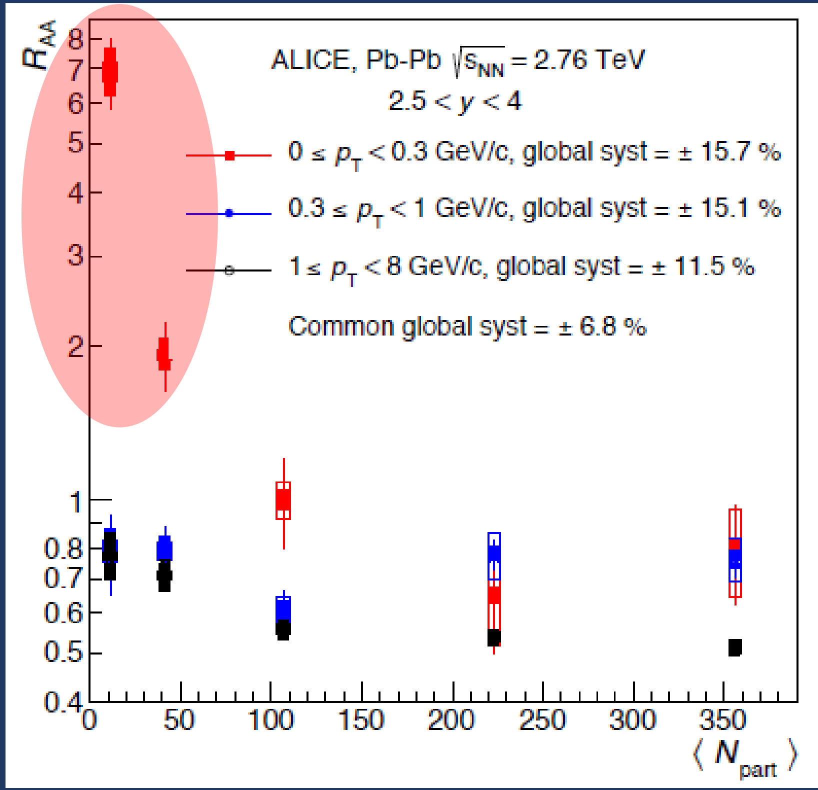


CNM effects not enough to explain PbPb data at high p_T

Evidence for hot matter effects in Pb-Pb!

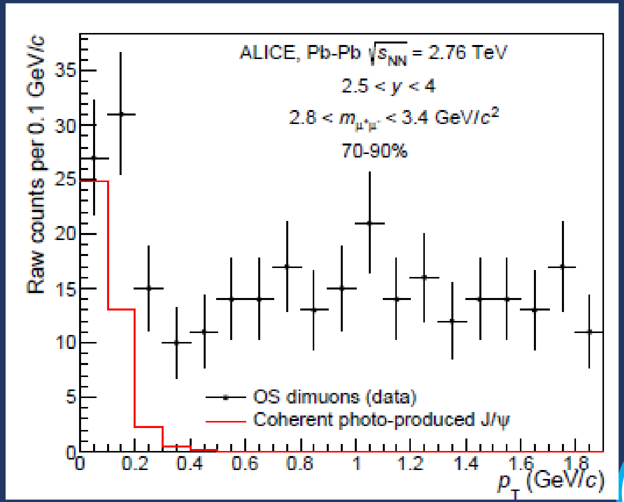
Low pT J/ψ at fw-y

- Strong R_{AA} enhancement in peripheral collisions for $0<p_T<0.3$ GeV/c



- significance of the excess is 5.4 (3.4)σ in 70-90% (50-70%)
- behaviour not predicted by transport models

- excess might be due to coherent J/ψ photoproduction in PbPb (as measured also in UPC)

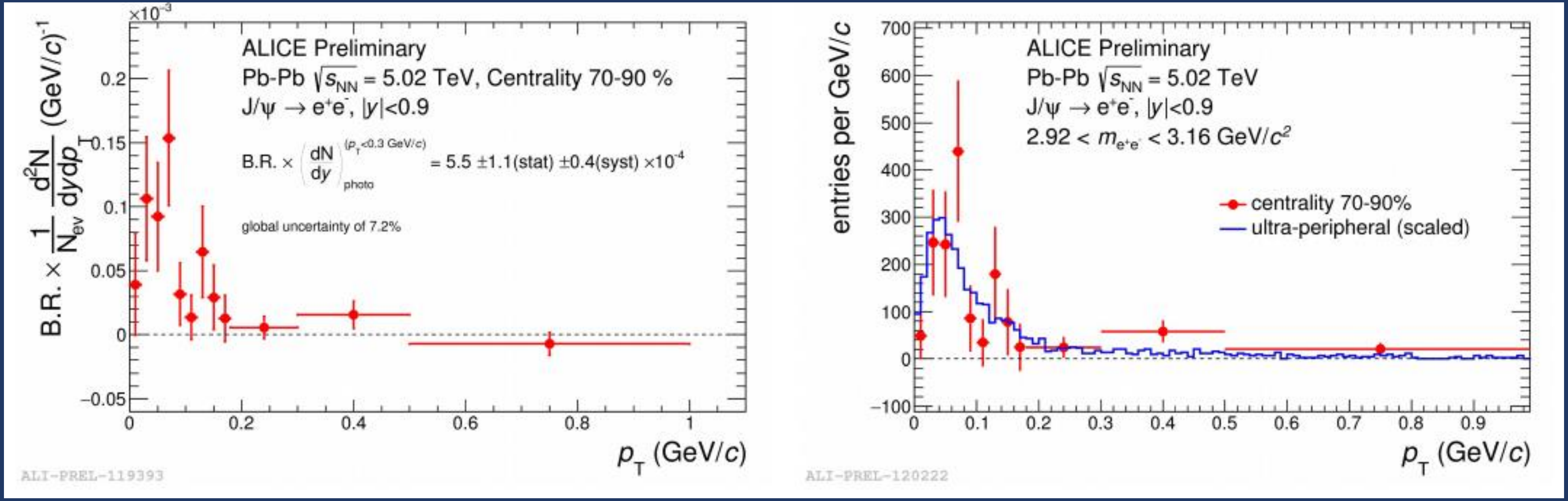


- if excess is "removed" requiring $p_T^{J/\psi}$>0.3GeV/c
→ ALICE R_{AA} lowers by 20% at maximum (in the most peripheral bin)

Low pT J/ψ at mid-y

First observation of a low pT excess at mid-y

Measurement done in 2 centrality classes: 50-70 and 70-90%

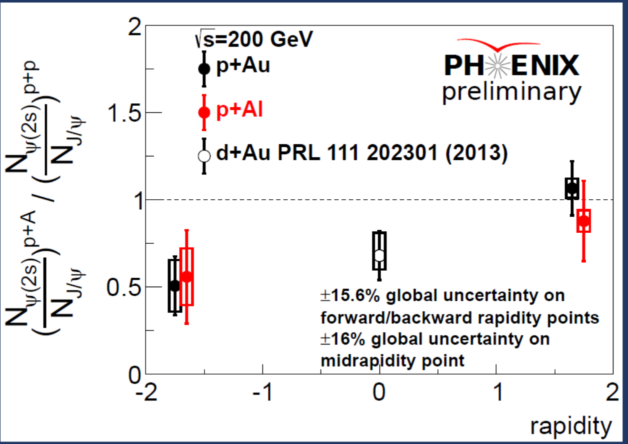


Hadronic contribution in pT<300 MeV/c subtracted

pT spectrum in agreement with UPC measurements → mostly coherent photo-production origin

$\psi(2S)$ in p-Pb at $\sqrt{s_{NN}}$ = 5.02TeV

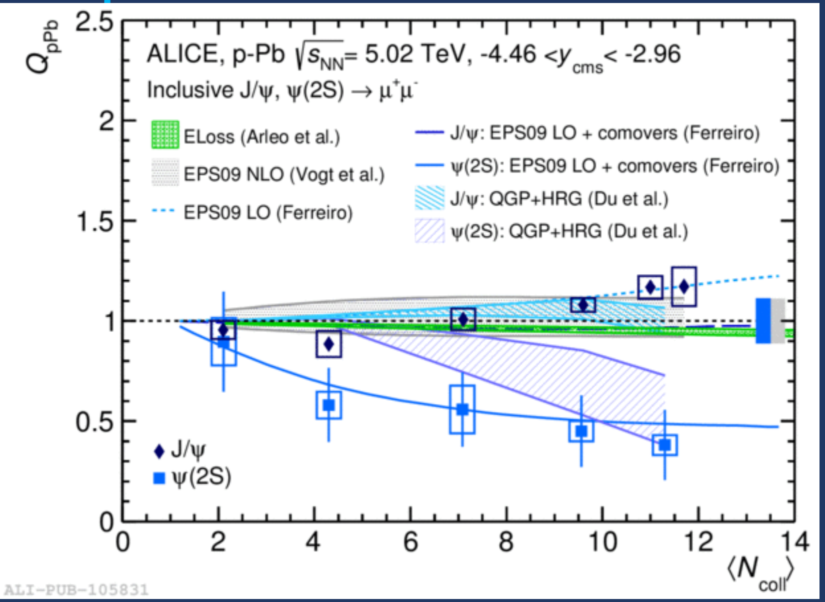
Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA

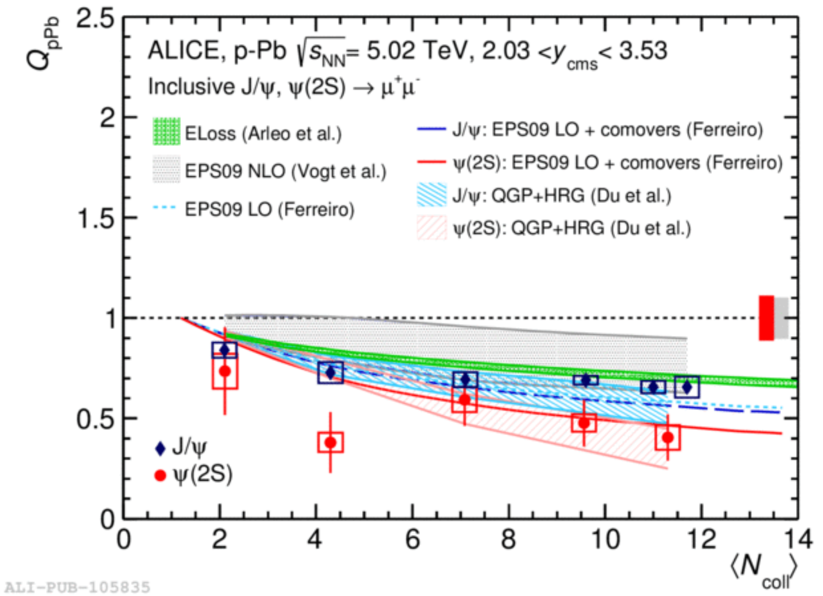


ψ(2S) suppression stronger than the J/ψ one at RHIC and LHC

→ unexpected because time spent by the cc pair in the nucleus (τ_c) is shorter than charmonium formation time (τ_f)

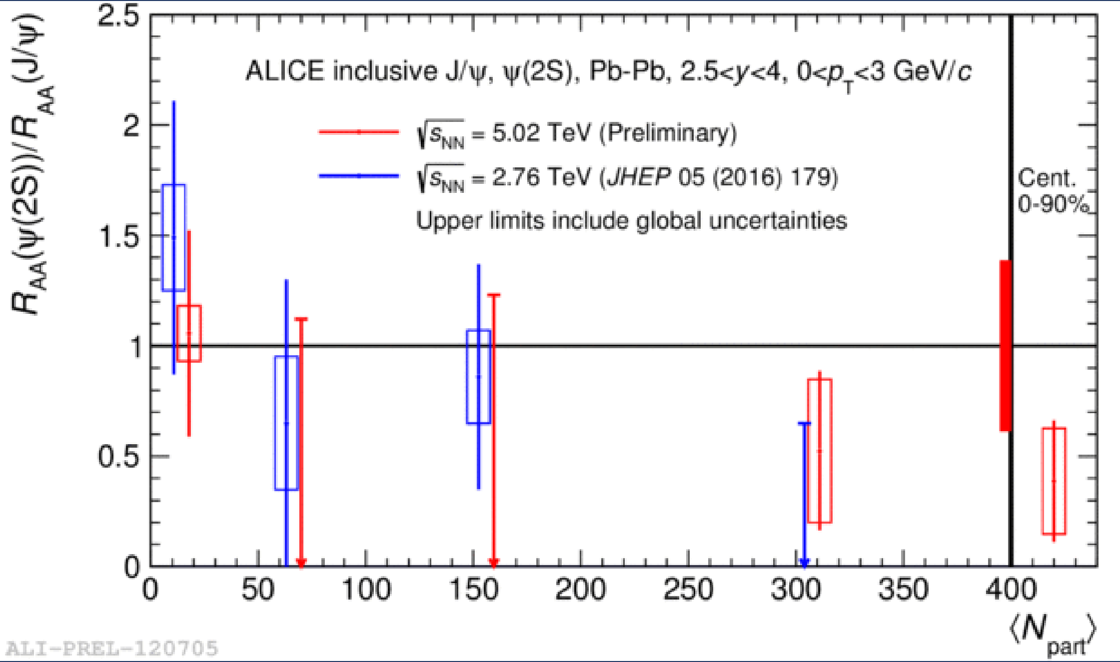
→ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

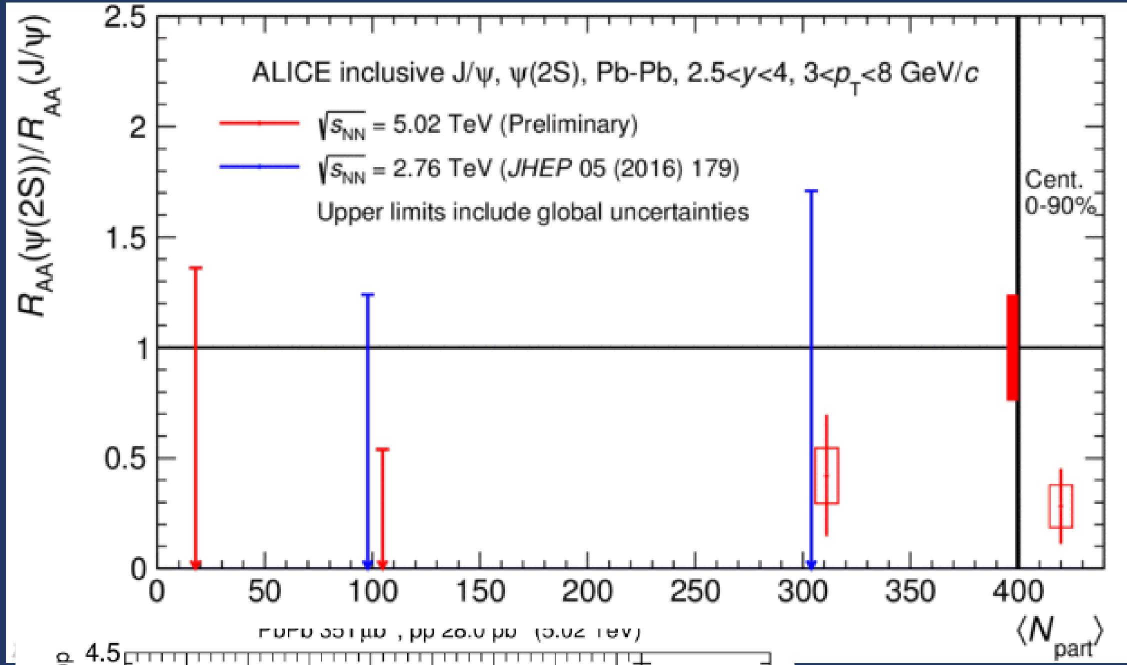


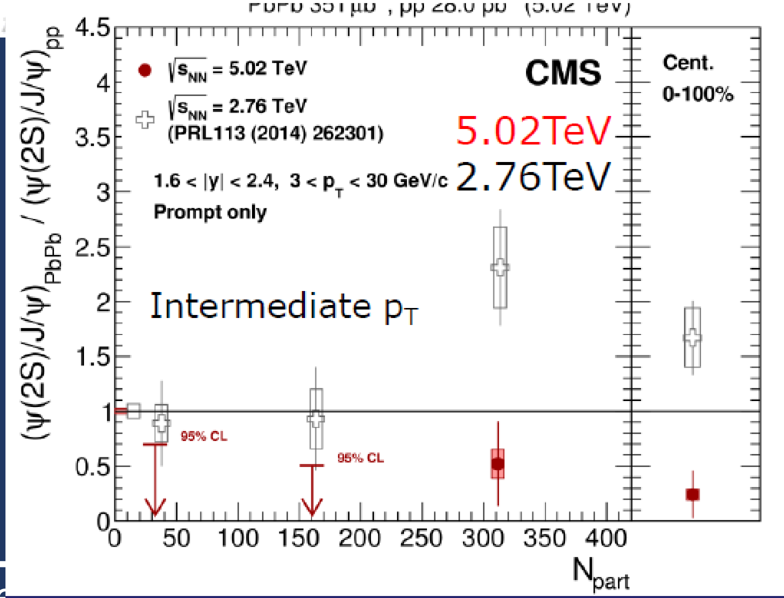


QGP+hadron resonance gas or comovers models describe the stronger ψ(2S) suppression

ψ(2S): comparison with Run 1







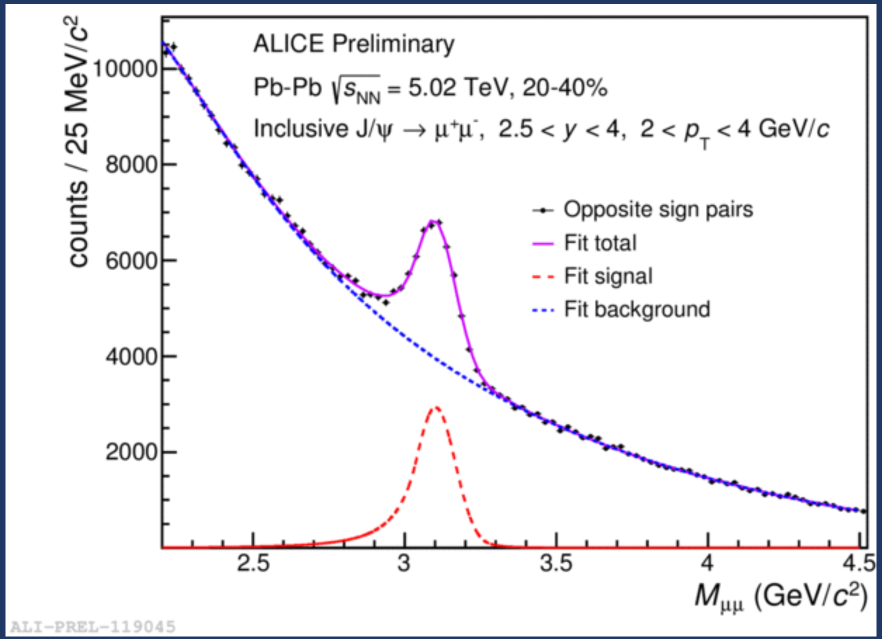
J/ψ elliptic flow: analysis technique

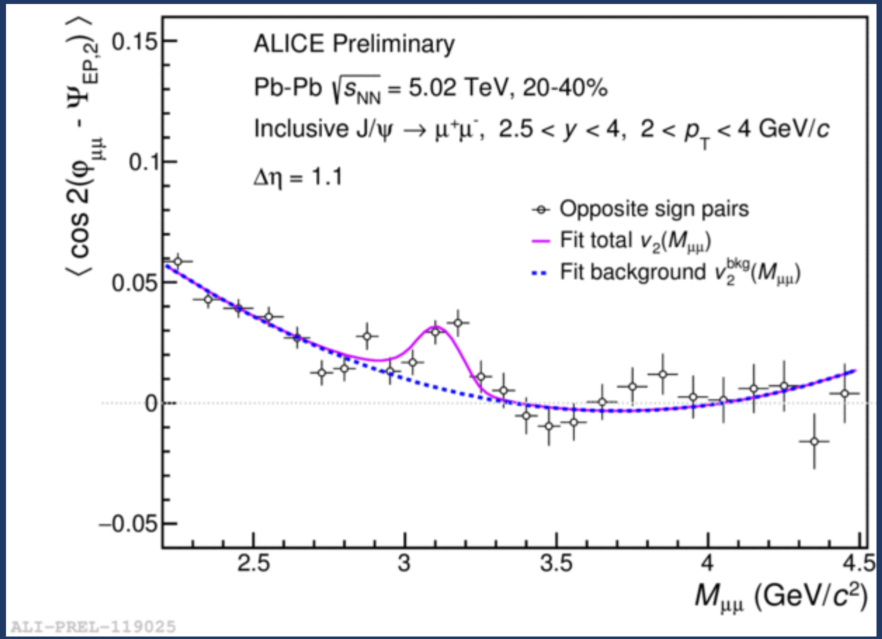
- J/ψ v_2 = $\langle\cos 2(\phi_{\mu\mu}-\Psi_{EP})\rangle$ is computed using the Event Plane from
  - SPD ($\Delta\eta$=1.1) at fw-y
  - TPC ($\Delta\eta$=0) at mid-y
- $v_2^{J/\psi}$ is obtained modeling $\langle\cos 2(\phi_{\mu\mu}-\Psi_{EP})\rangle$ vs inv. mass as

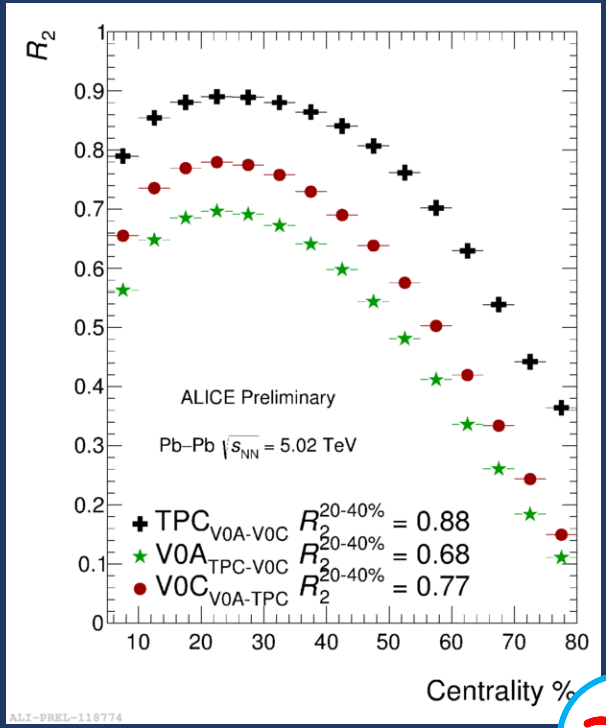
$$v_2(m_{\mu\mu}) = v_2^{J/\psi}\alpha(m_{\mu\mu}) + v_2^{bck}(1-\alpha(m_{\mu\mu}))$$

- $\alpha(m_{\mu\mu})$ is S/S+B from inv. mass fit
- v_2^{bck} background parametrized by several functions

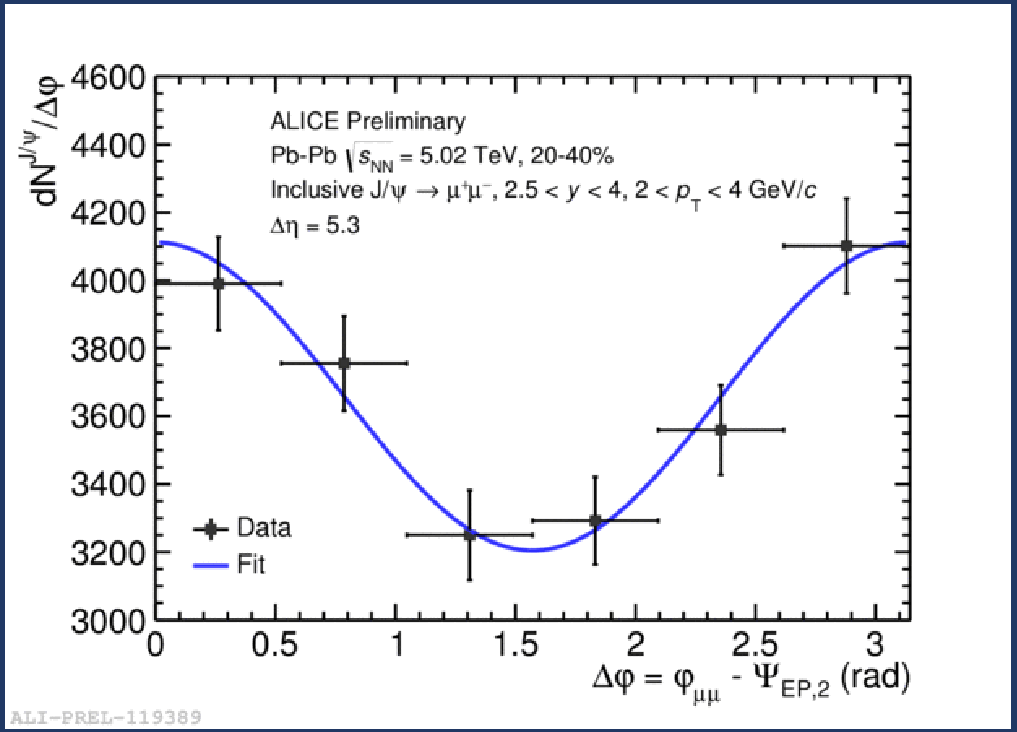
- $v_2 = v_2^{obs}/\sigma_{EP}$

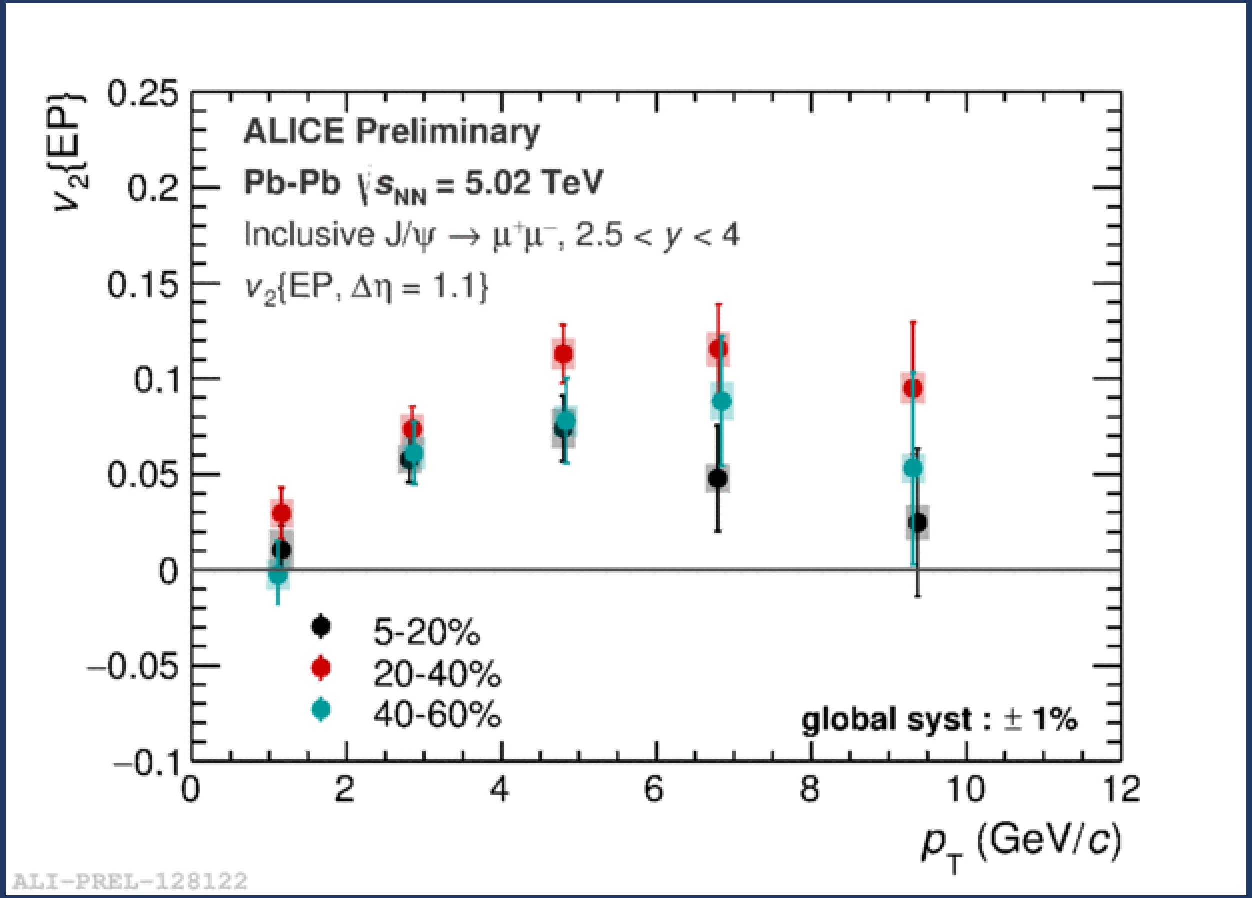


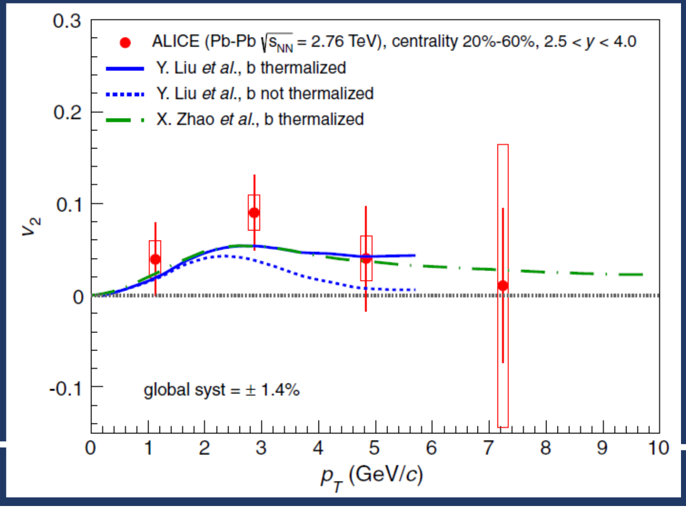




v2

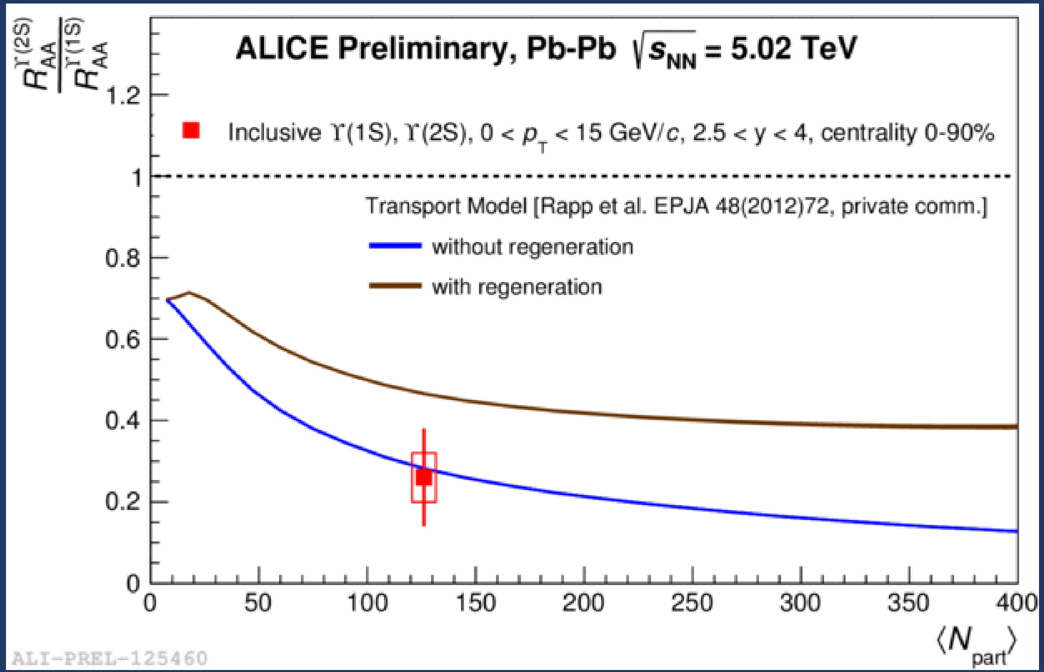


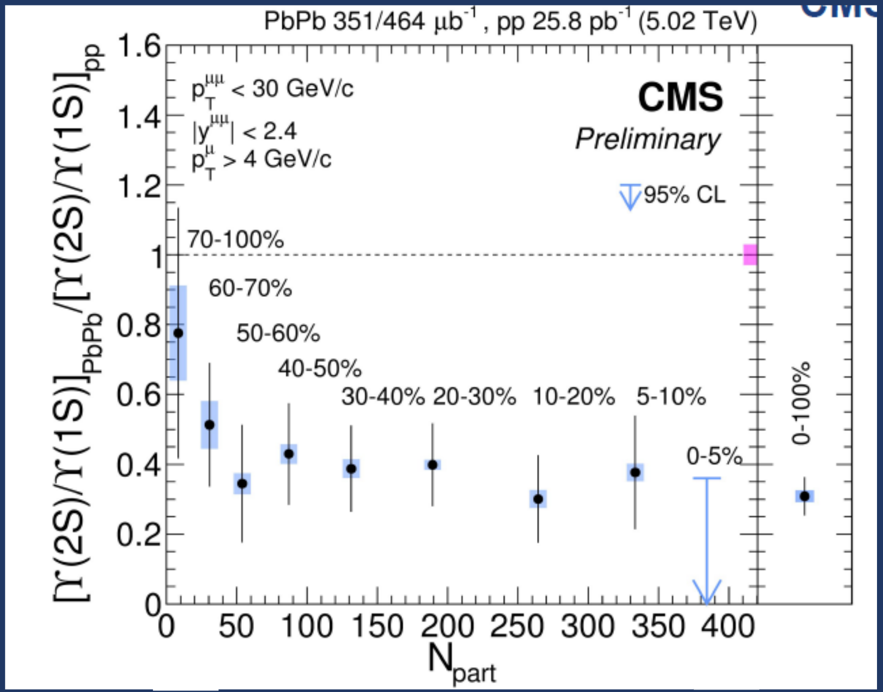




➡ Maximum effect in semi-central collisions

ϒ(2S) in ALICE





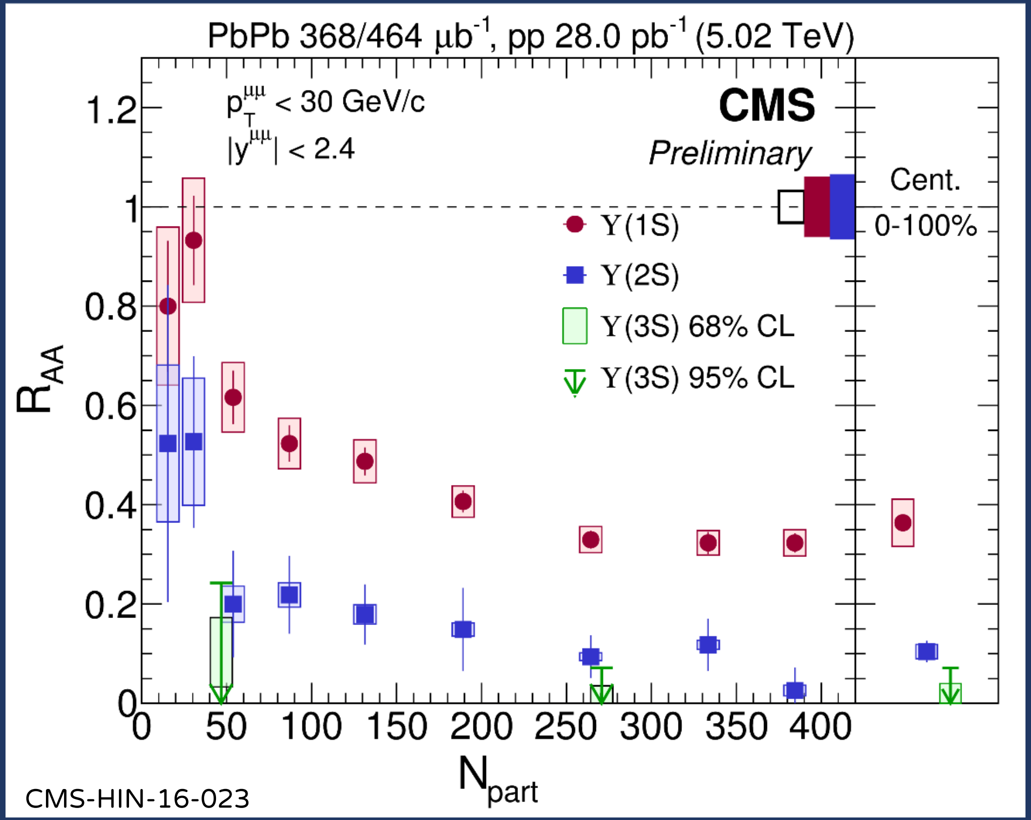
CMS-PAS-HIN 2016-008

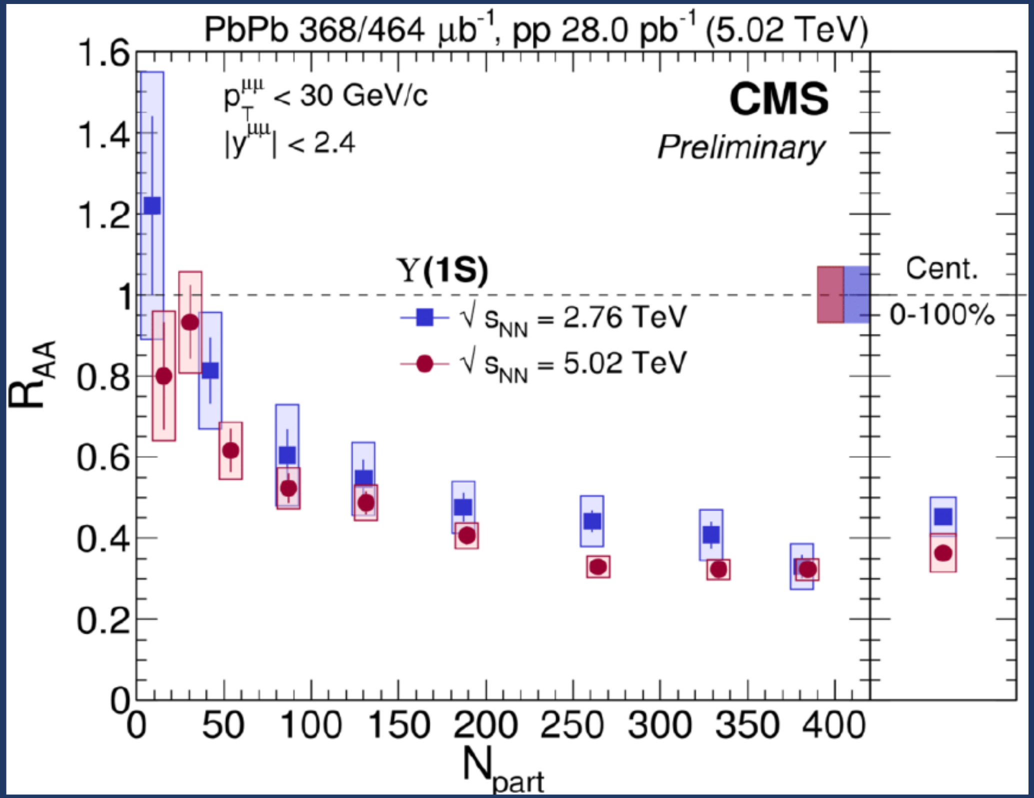
Stronger suppression has been observed for the ϒ(2S) wrt ϒ(1S)

- Theoretical models describe the R_{AA} ratio (no need for regeneration contribution)
- Result is consistent with the centrality-integrated CMS measurement

Bottomonia in AA

Striking suppression of ϒ(2S) and ϒ(3S) in PbPb!





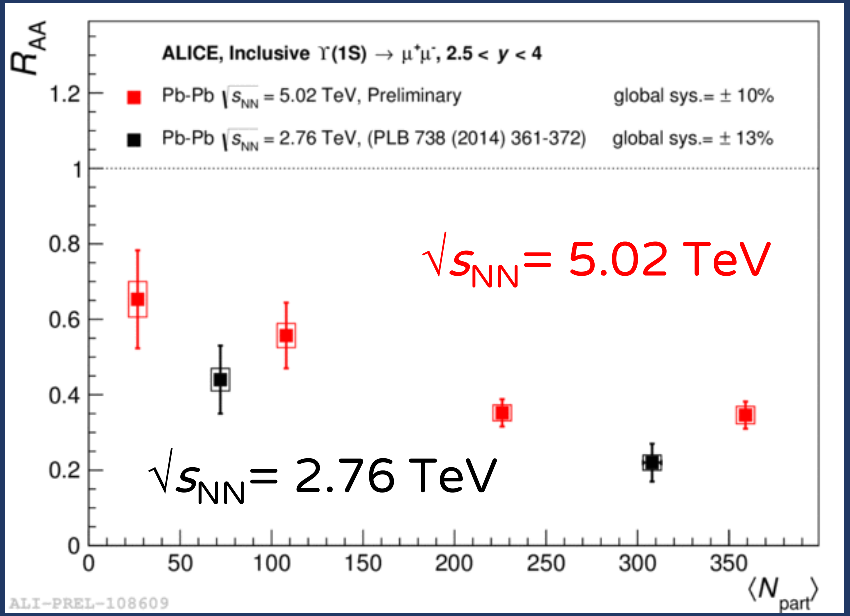
Suppression up to a factor ~2 for ϒ(1S) and ~9 for ϒ(2S)

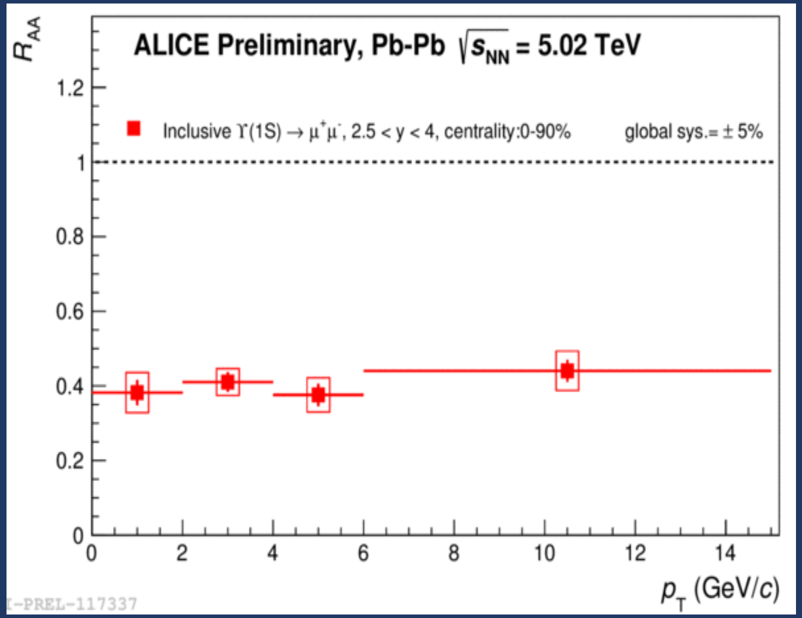
Slightly stronger ϒ(1S) suppression at 5.02 TeV wrt 2.76 TeV

Bottomonia in AA

- Also bottomonium states accessible with higher precision in Run 2

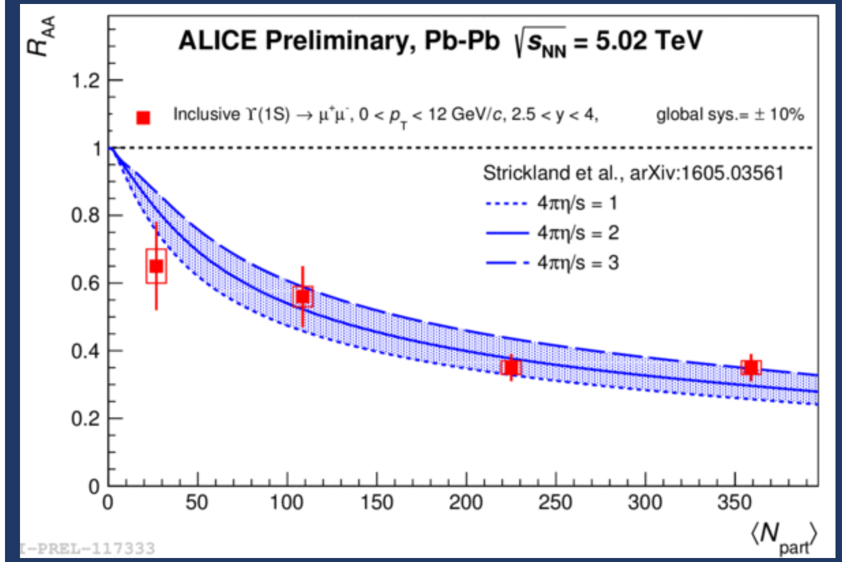
PRL 109, 222301 (2012)

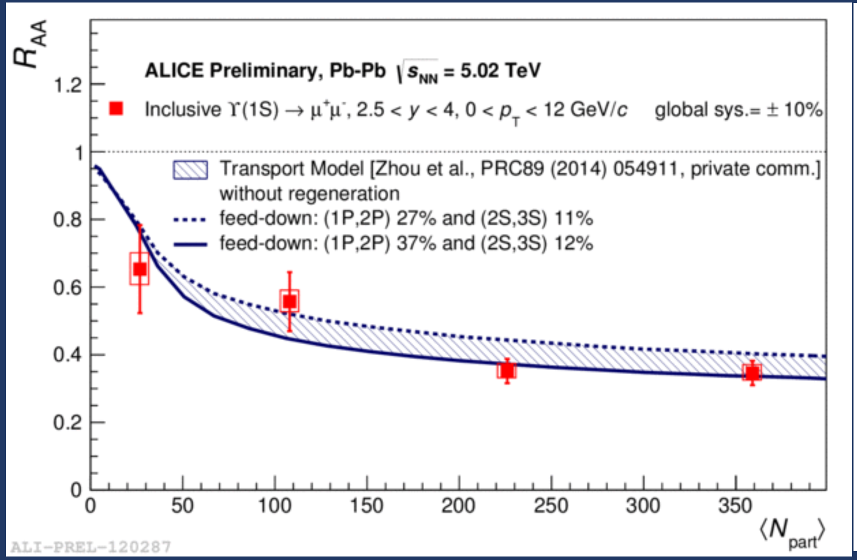


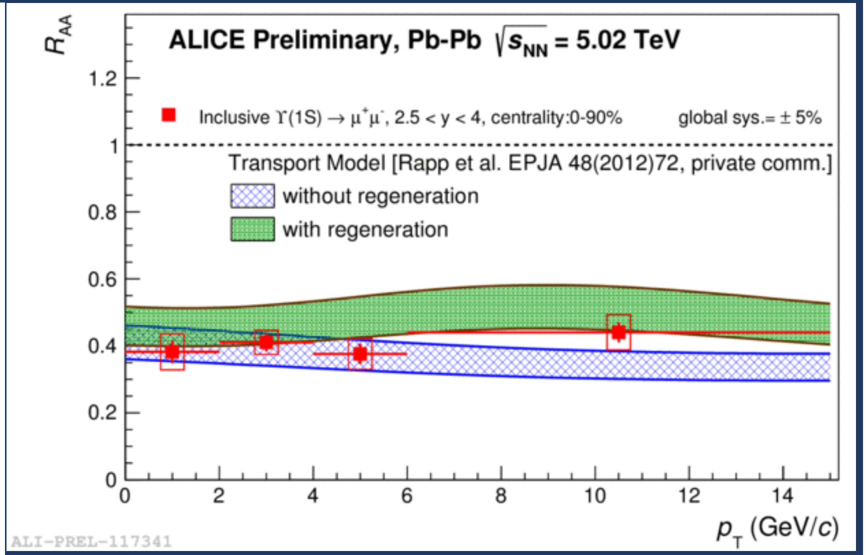


- Strong $\Upsilon(1S)$ suppression vs centrality, similar, within uncertainties, to the $\sqrt{s_{NN}}$= 2.76TeV one
- Flat behavior as a function of p_T
- Size of $\Upsilon(1S)$ suppression similar to the one measured by CMS
- Suppression of directly produced $\Upsilon(1S)$? → feed-down contribution~30%

Υ(1S) in ALICE: theory comparison

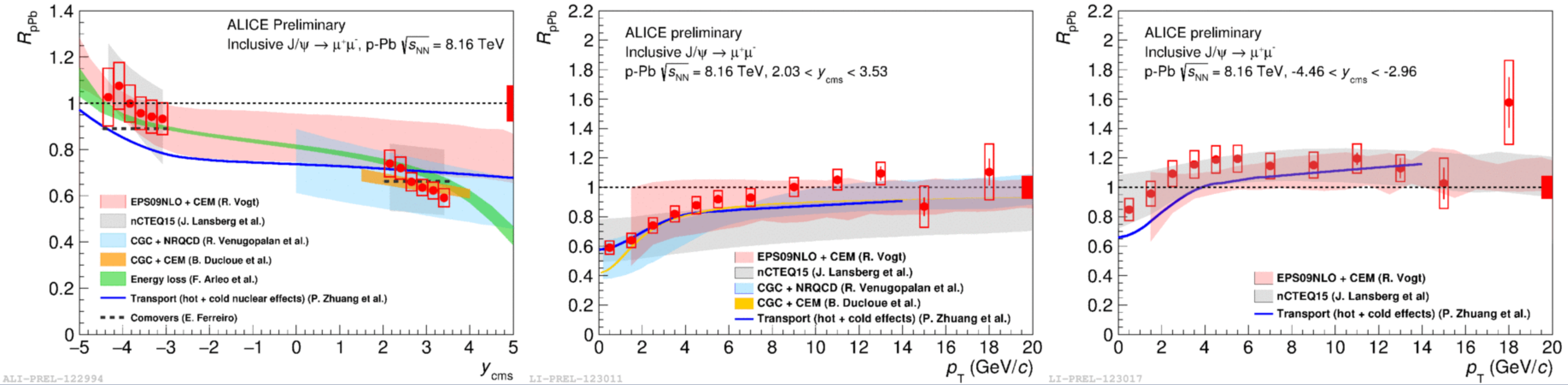






- Transport and anisotropic hydrodynamical models qualitatively describe the centrality and the p_T evolution
- No need for contribution of regenerated Υ

Comparison with theory models



CERN-ALICE-PUBLIC-2017-001

➡ Good agreement between data and models based on shadowing and/or energy loss, as at $\sqrt{s_{NN}}$ = 5.02 TeV

Size of theory uncertainties (mainly shadowing) still limits a more quantitative comparison