XII Quark Confinement and the Hadron Spectrum
August 30th 2016

From pA to AA: an experimental overview on quarkonium at LHC

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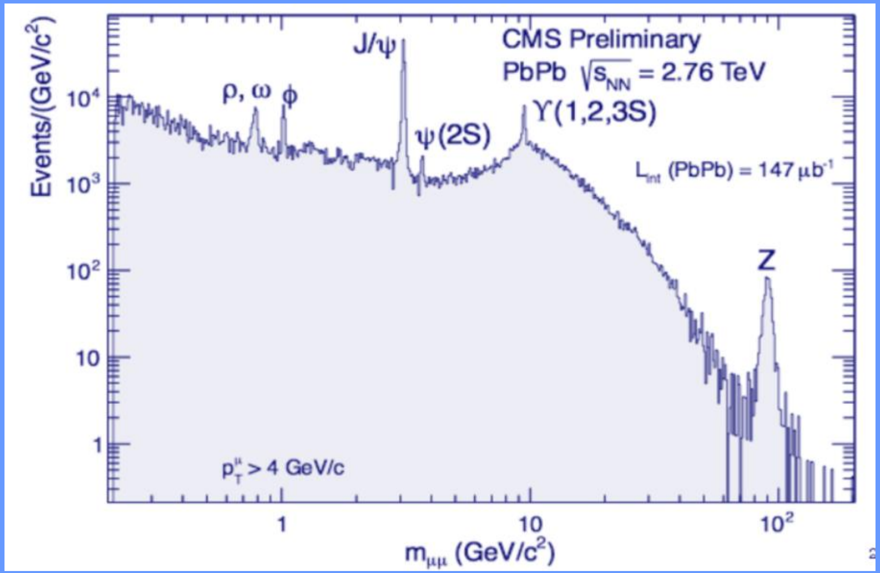
Outlook:

Selection on results on

- Charmonium: J/ψ and ψ(2S)
- Bottomonium: ϒ(1S), ϒ(2S), ϒ(3S)

in pPb and PbPb collisions at LHC energies



AA: hot matter effects

the original idea

quarkonium production suppressed via color screening in the QGP

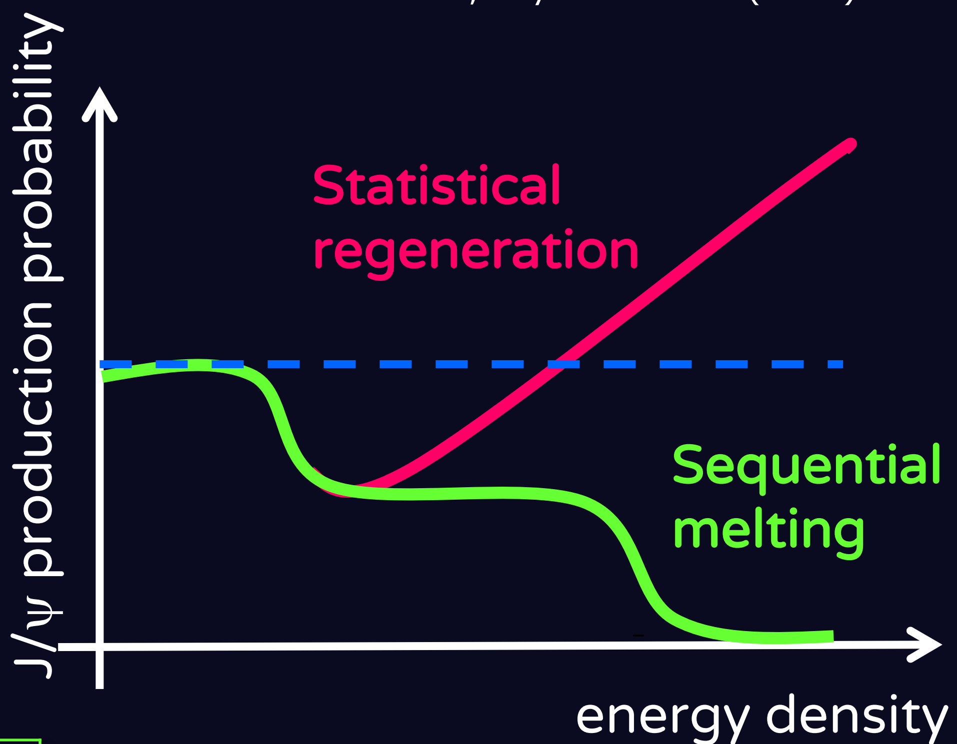
T.Matsui and H.Satz, Phys.Lett.B178 (1986) 416

sequential melting

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

(re)combination

enhanced quarkonium production through (re)combination during QGP phase or at hadronization



Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76TeV	LHC 5.02TeV
N_{ccbar}/event	~0.2	~10	~85	~115

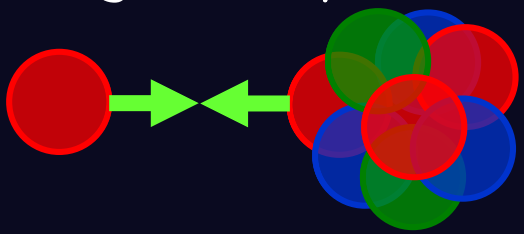
P. Braun-Muzinger,J. Stachel, PLB 490(2000) 196
R. Thews et al, Phys.Rev.C63:054905(2001)

pA: CNM effects

Cold nuclear matter effects: might affect quarkonium production on top of hot matter mechanisms

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

} investigated in p-A collisions



➡ the assessment of the size of these effects is fundamental to interpret quarkonium A-A results

Nuclear modification factor

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

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

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

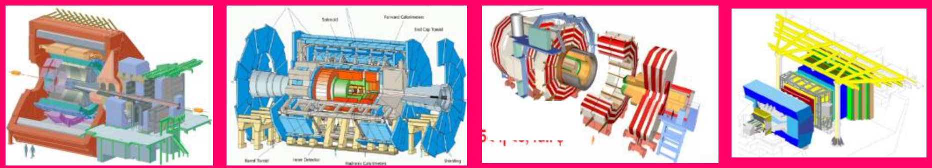
Quarkonium at LHC

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

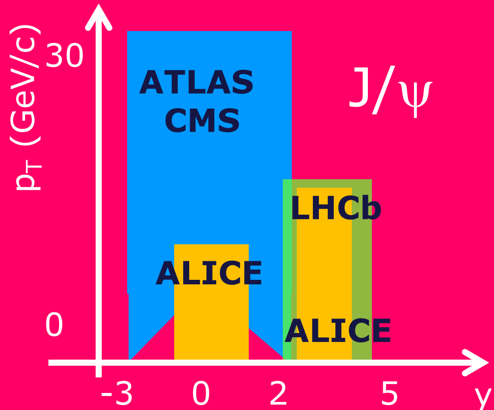
Quarkonium at LHC

Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760	2010-2013

All LHC experiments investigate quarkonium production



complementary results due to different kinematic coverages



Quarkonium at LHC

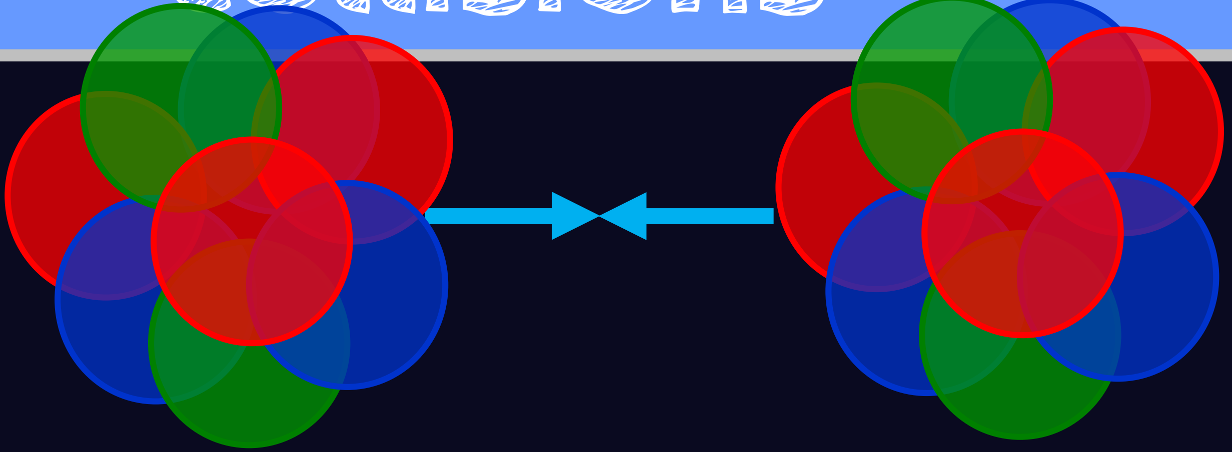
Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	Data taking
LHC	ALICE ATLAS CMS LHCb	Pb-Pb	2760 5020	2010-2012 2015
		p-Pb	5020	2013
		pp	2760 5020 7000 8000 13000	2010-2016

- pp, pA and AA systems have been studied
- top LHC energies now reached!

LHC Run-1

LHC Run-2

Quarkonium in AA collisions

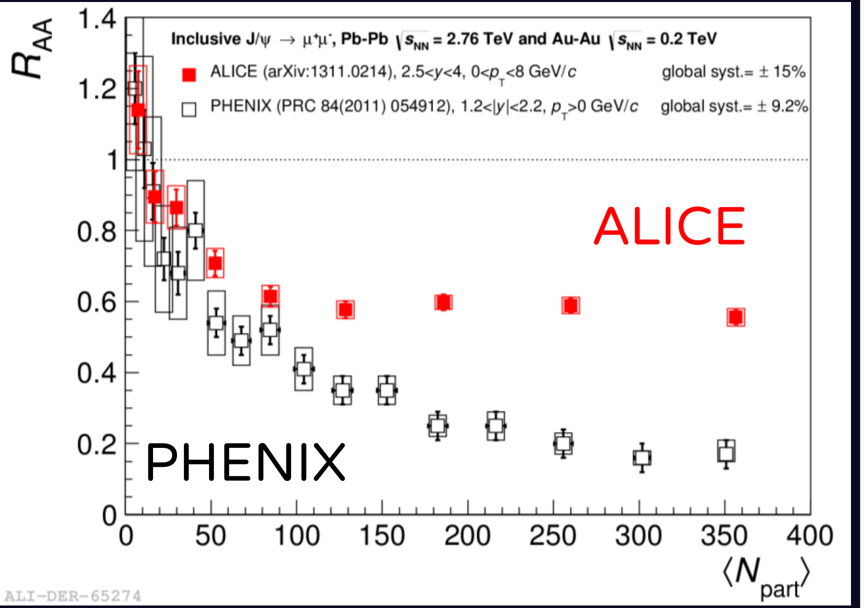


Run-1 J/ψ: where we stand?

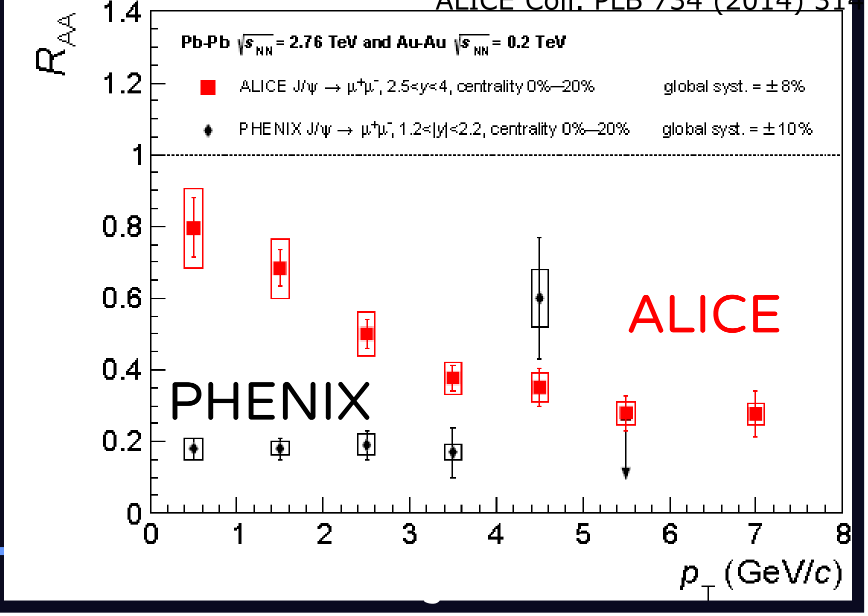
➡ Evidence of recombination for low p_T J/ψ

Observation corroborated by the comparison of LHC results with

1) lower energy experiments



ALICE Coll. PLB 734 (2014) 314



➡ J/ψ suppression vs centrality is stronger in PHENIX than in ALICE, in spite of the LHC larger energy densities

➡ weaker suppression at low p_T observed by ALICE

Run-1 J/ψ: where we stand?

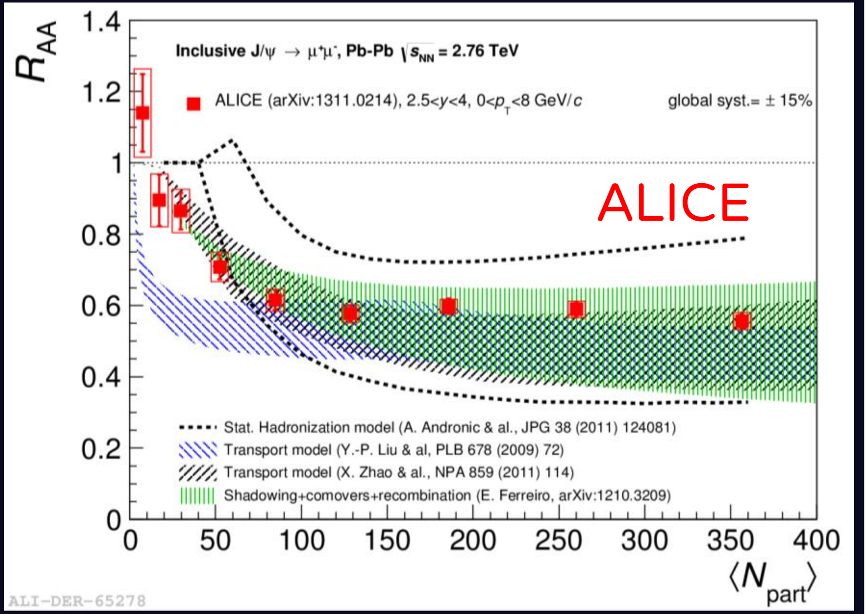
Evidence of recombination for low p_T J/ψ

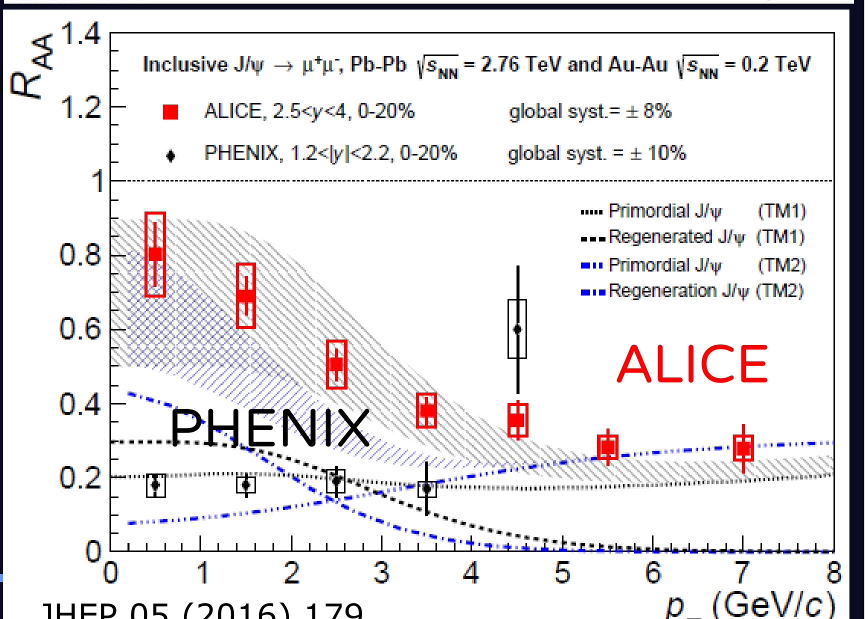
Observation corroborated by the comparison of LHC results with

1) lower energy experiments
2) **theoretical models**

models including (re)combination of J/ψ in QGP or in the hadronic phase provide a reasonable description of ALICE results

still rather large theory uncertainties: models will benefit from a precise measurement of σ_{cc} and CNM effects





JHEP 05 (2016) 179

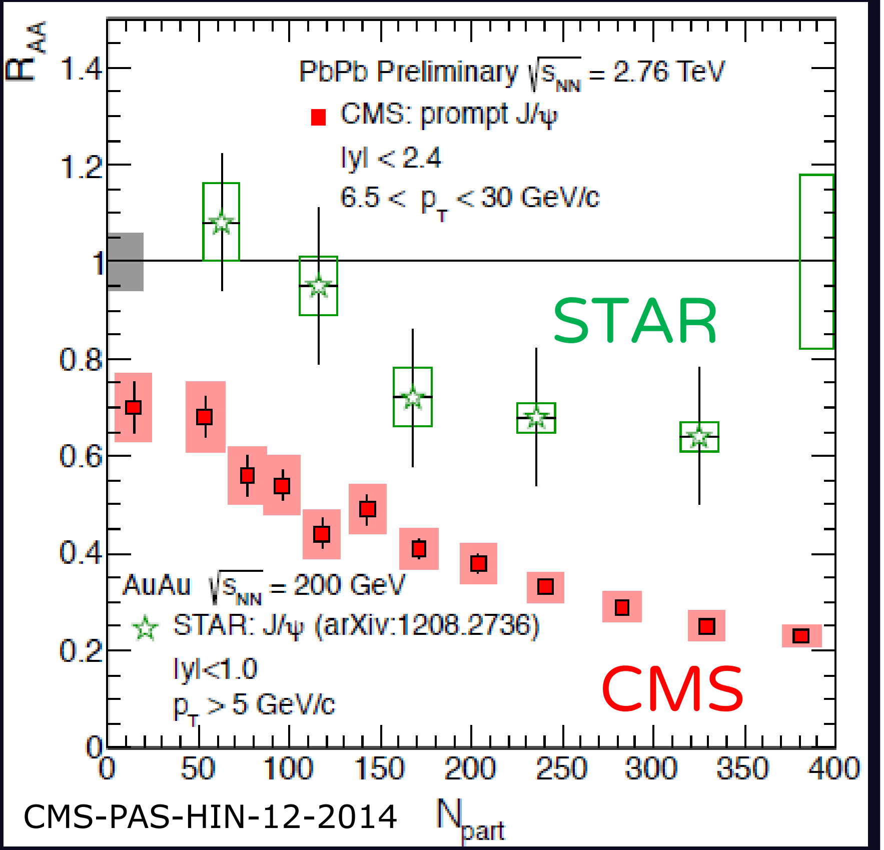
Run-1 J/ψ: where we stand?

Evidence of recombination for low p_T J/ψ

Observation corroborated by the comparison of LHC results with

1) lower energy experiments
2) theoretical models
3) **high p_T J/ψ results**

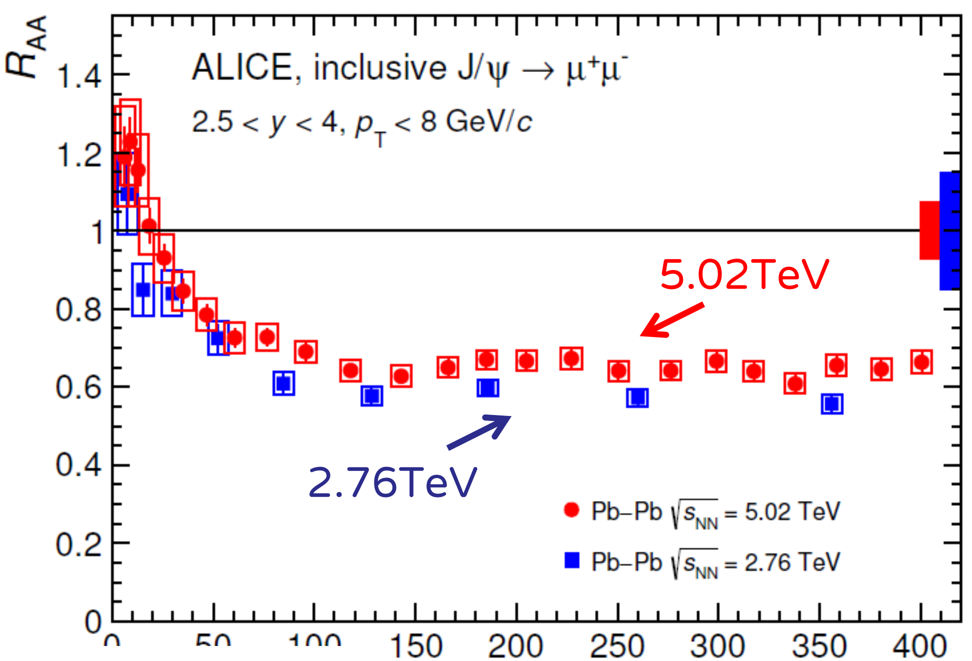
- suppression stronger at higher √s, as expected from QGP dissociation
- opposite J/ψ behavior compared to low-p_T results
- negligible re(combination) effects expected at high p_T



J/ψ results from Run-2

Pb-Pb collisions @ $\sqrt{s_{NN}}$=5.02TeV

High statistics Run-2 allows the R_{AA} evaluation in narrow centrality bins



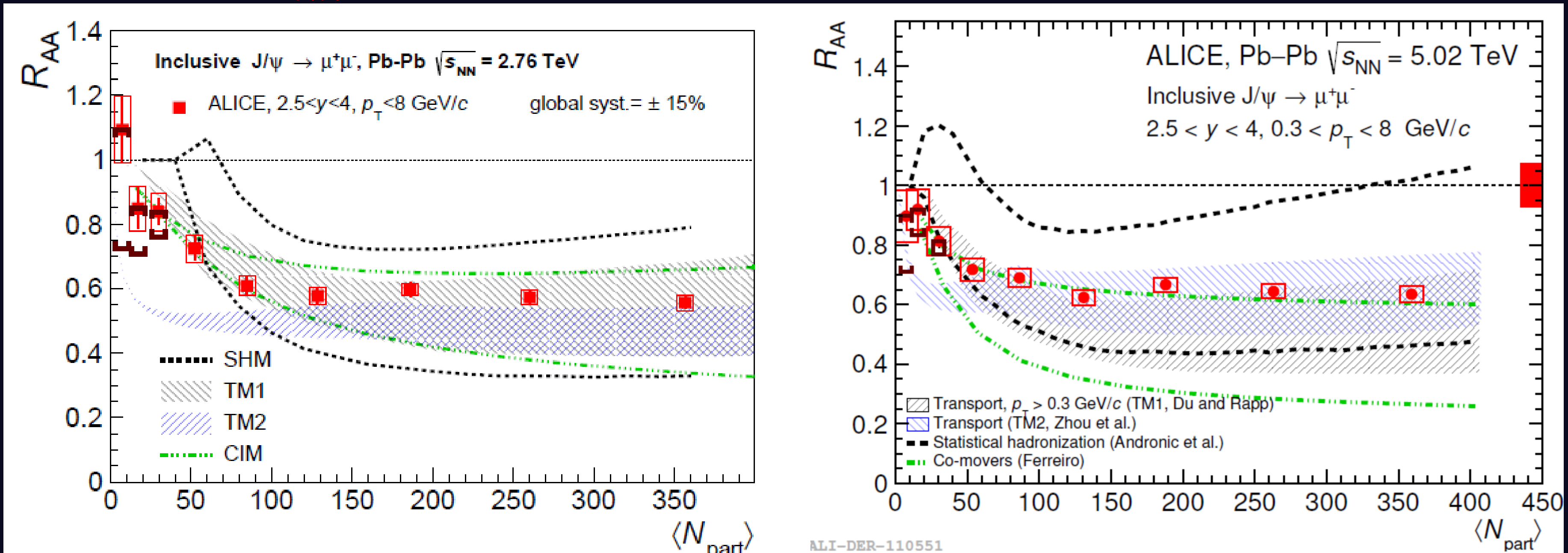
arXiv:1606.08197

- Similar centrality dependence at the two energies, with an increasing suppression up to N_{part}~100, followed by a plateau

- R_{AA} @ 5.02TeV is ~15% higher than the one at 2.76TeV, even if within uncertainties

J/ψ theory models

$\sqrt{s_{NN}}$=2.76TeV $\sqrt{s_{NN}}$=5.02TeV



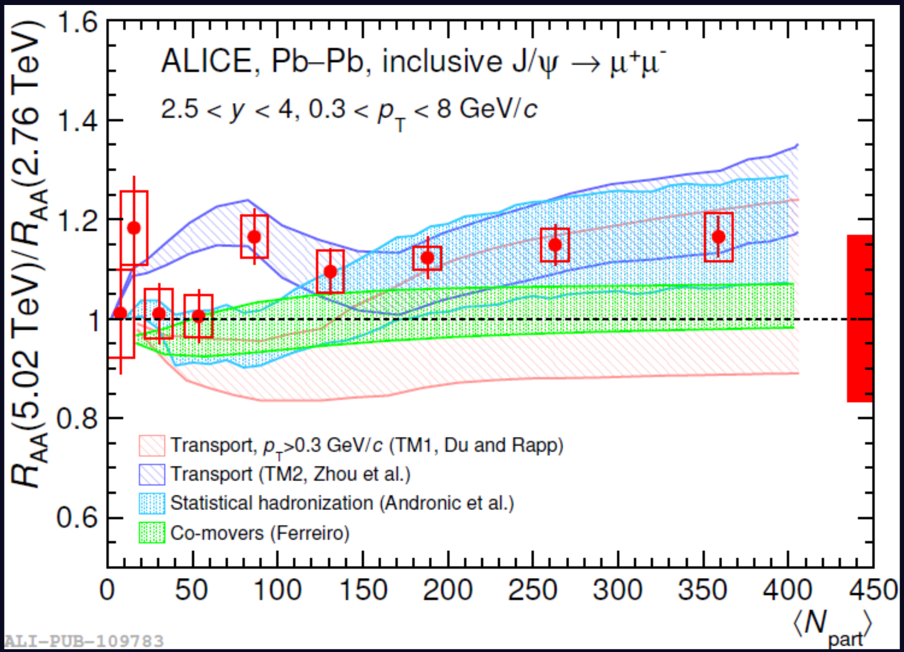
Brackets represents the possible range of variation of the hadronic J/ψ

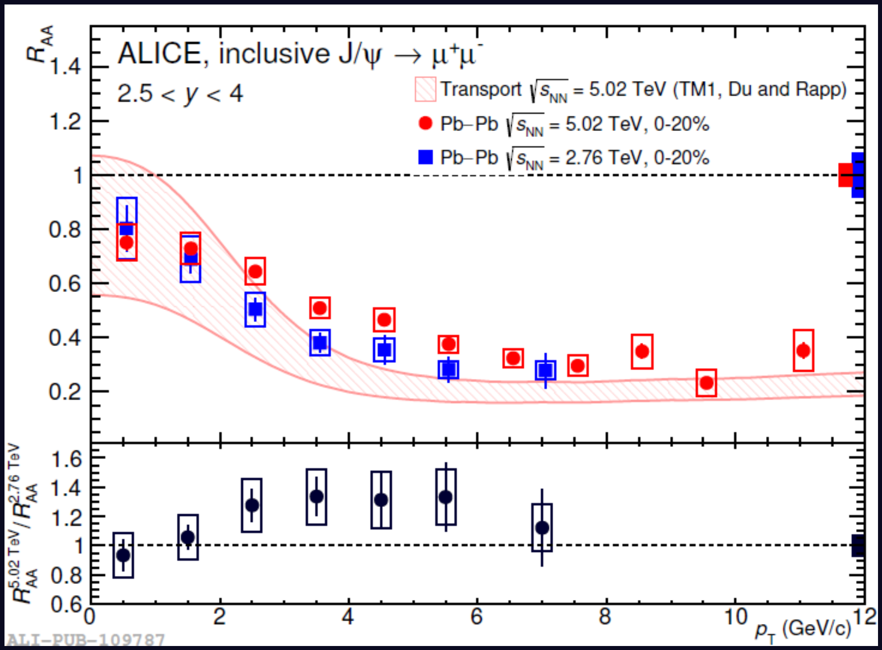
Comparison of same theory models at the two energies:

TM1, TM2 (Du et al, Zhou et al): rate equation of suppression/regeneration in QGP
SHM (Andronic et al): J/ψ produced by stat. hadronization at phase boundary
CIM (Ferreiro): suppression by the comoving partonic medium and regeneration

- Data are compatible with theory models at both energies
- Still large uncertainties mainly due to the choice of σ_{cc}

Run-2 J/ψ results



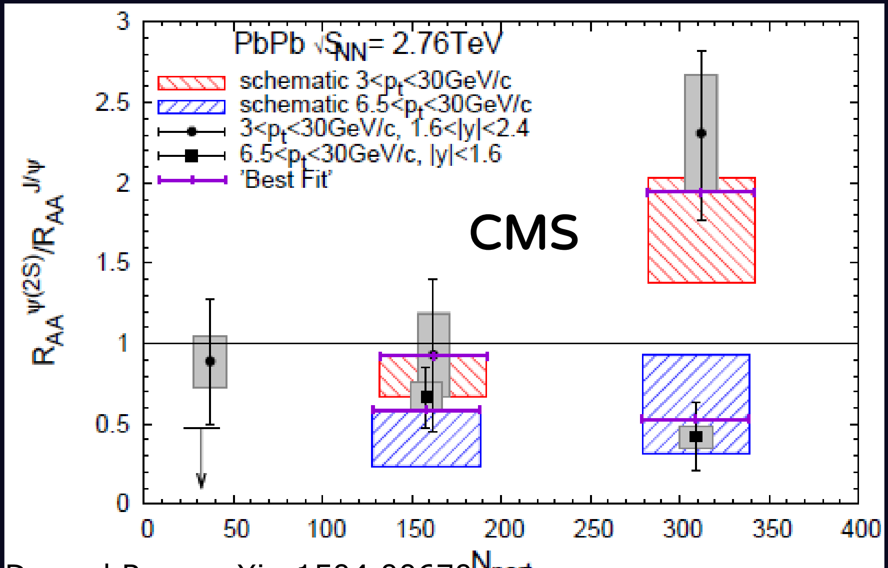


- Theoretical and experimental uncertainties reduced in the R_{AA} double ratio
- Centrality dependence of the R_{AA} ratio is rather flat
- R_{AA} increases with p_T, at both energies, as expected in a regeneration scenario
- Hint for an increase of R_{AA}, at 5.02TeV, in $2<p_T<6$ GeV/c

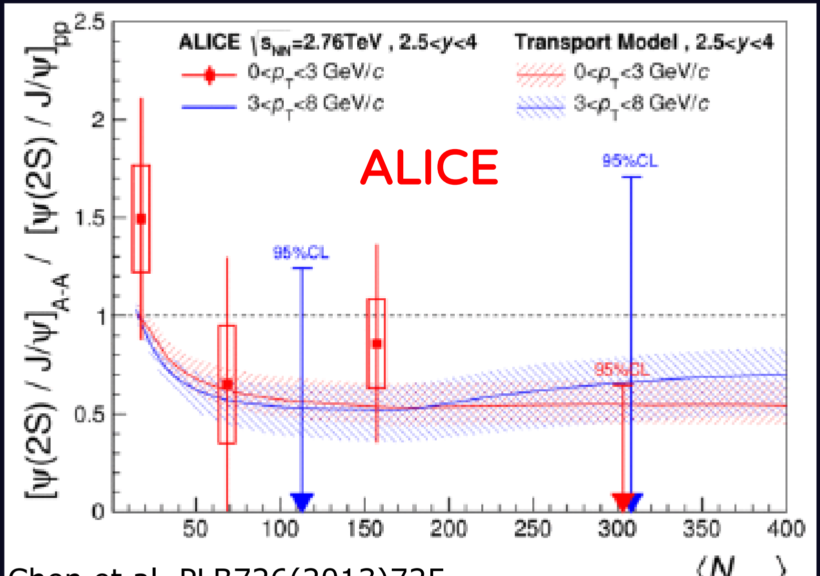
Also $\sqrt{s_{NN}}$=5.02TeV results support a picture where a combination of J/ψ suppression and (re)combination occurs in the QGP

ψ(2S) in AA collisions

➡ ψ(2S) production modified in AA with a strong kinematic dependence



Du and Rapp arXiv:1504.00670



Chen et al. PLB726(2013)725

Fw-y, $3<p_T<30$GeV/c → $R_{AA}^{J/\psi} < R_{AA}^{\psi(2S)}$

- later ψ(2S) regeneration, when radial flow is stronger, might explain the rise

Mid-y $6.5<p_T<30$GeV/c → $R_{AA}^{J/\psi} > R_{AA}^{\psi(2S)}$

- stronger suppression of ψ(2S) wrt J/ψ

CMS, PRL 113(2014) 262301

Fw-y, $0<p_T<3$GeV/c → $R_{AA}^{J/\psi} > R_{AA}^{\psi(2S)}$

- ALICE trend agrees with transport models and stat. hadronization approach

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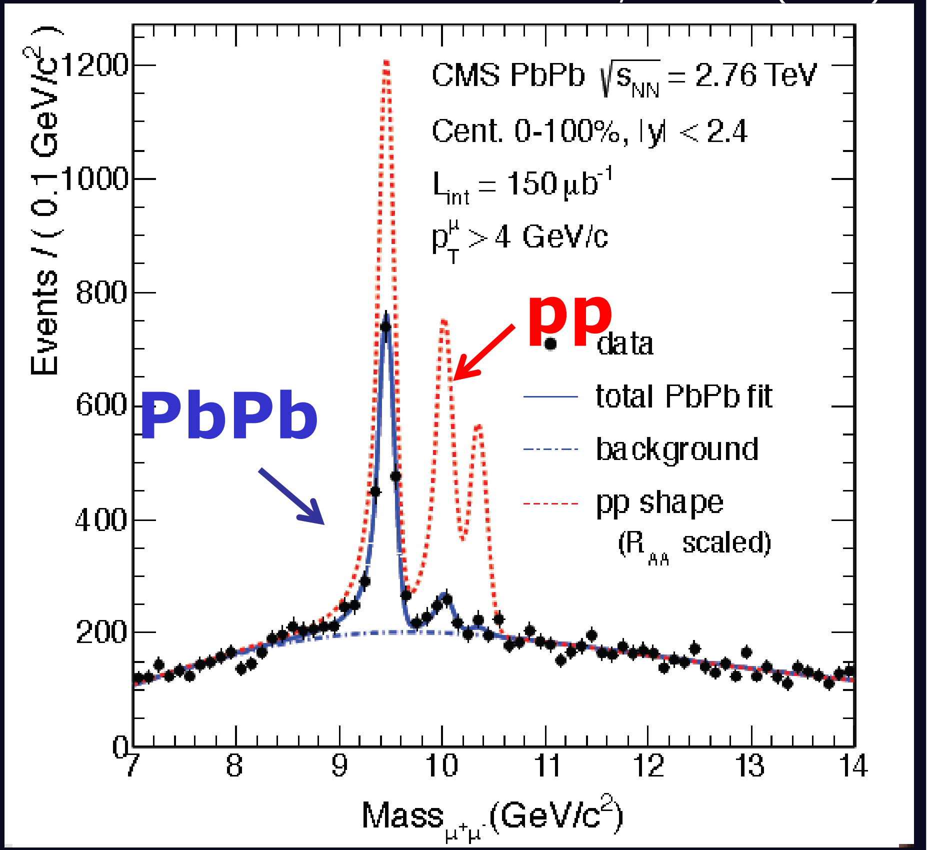
➡ Run1 data not precise enough to conclude on ψ(2S) behavior
Run2 results eagerly awaited!

Υ(ns) production in AA

PRL 109, 222301 (2012)

➡ Main features of bottomonium production wrt charmonium:

- no B hadron feed-down
- smaller gluon shadowing effects
- negligible (re)combination
- more robust theoretical predictions due to the higher b quark mass



with a drawback…smaller production cross-section

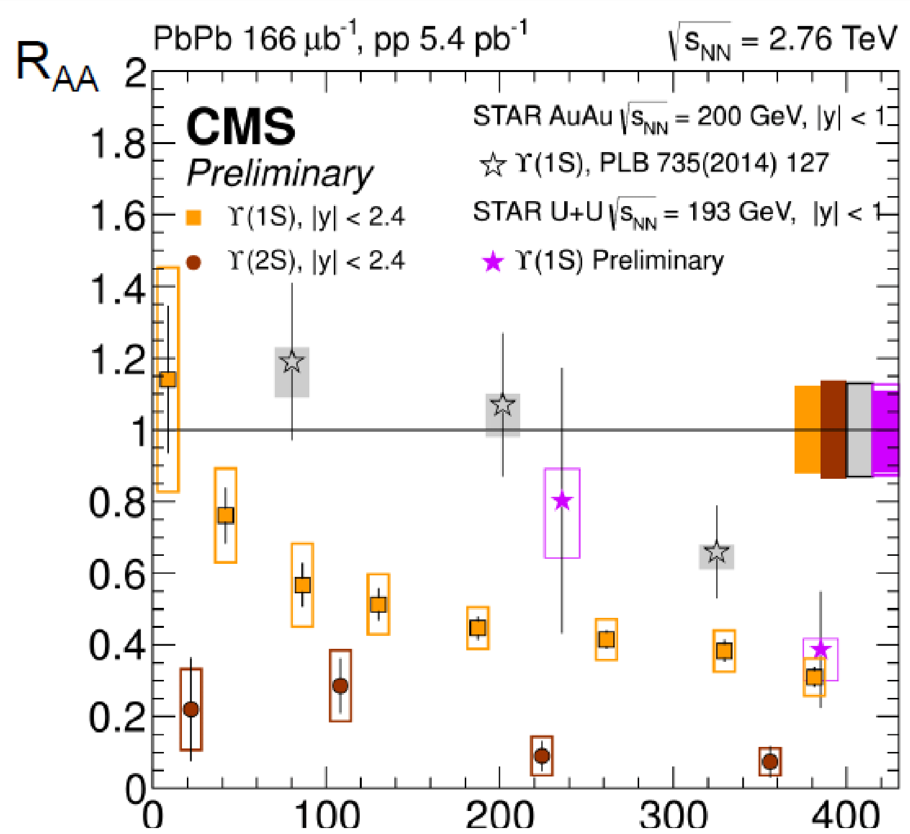
➡ Clear suppression of Υ states in PbPb with respect to pp collisions

Run-1 Υ(ns): where we stand?

Sequential suppression observed at LHC in Run 1:

$$R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$$

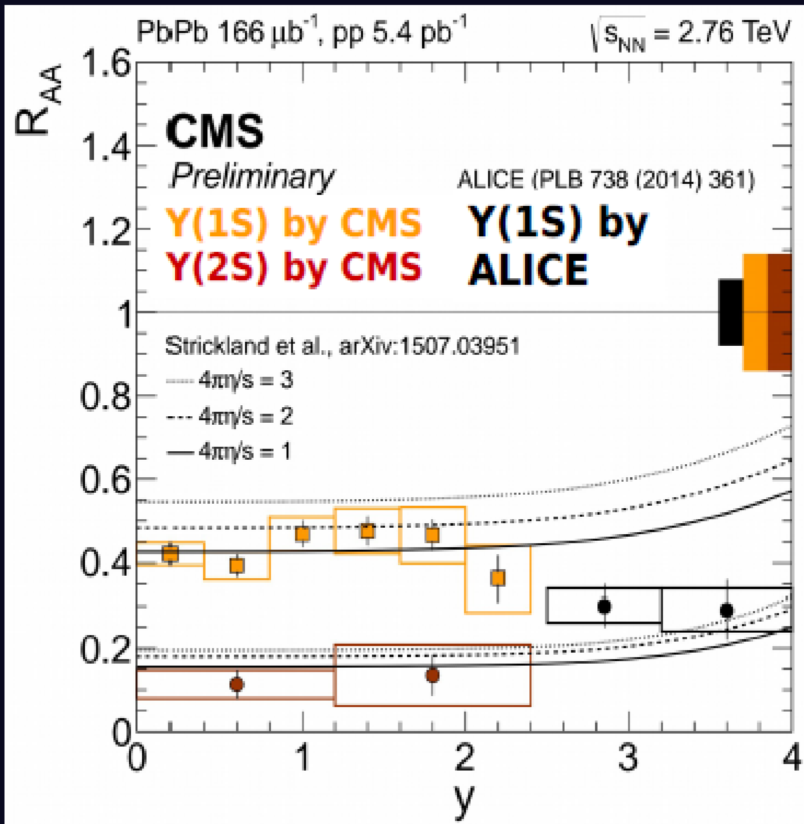
$R_{AA}(\Upsilon(1S)) = 0.43 \pm 0.03 \pm 0.07$
$R_{AA}(\Upsilon(2S)) = 0.13 \pm 0.03 \pm 0.02$
$R_{AA}(\Upsilon(3S)) < 0.14$ at 95% CL

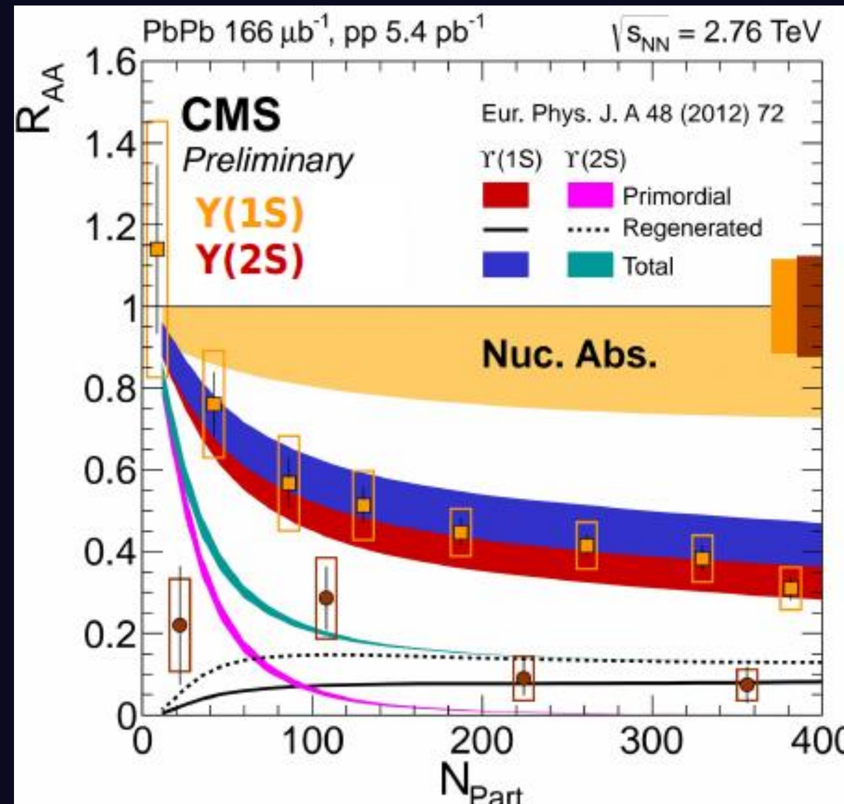


CMS, PRL109 (2012) 222301 and HIN-15-001
STAR, PLB735 (2014) 127 and preliminary U+U

- centrality dependent suppression for Υ(1S) and Υ(2S)
- at LHC Υ(1S) is already suppressed in semiperipheral collisions, while at RHIC only in the central ones
- feed-down from excited states + CNM are enough to explain the observed Υ(1S) suppression?

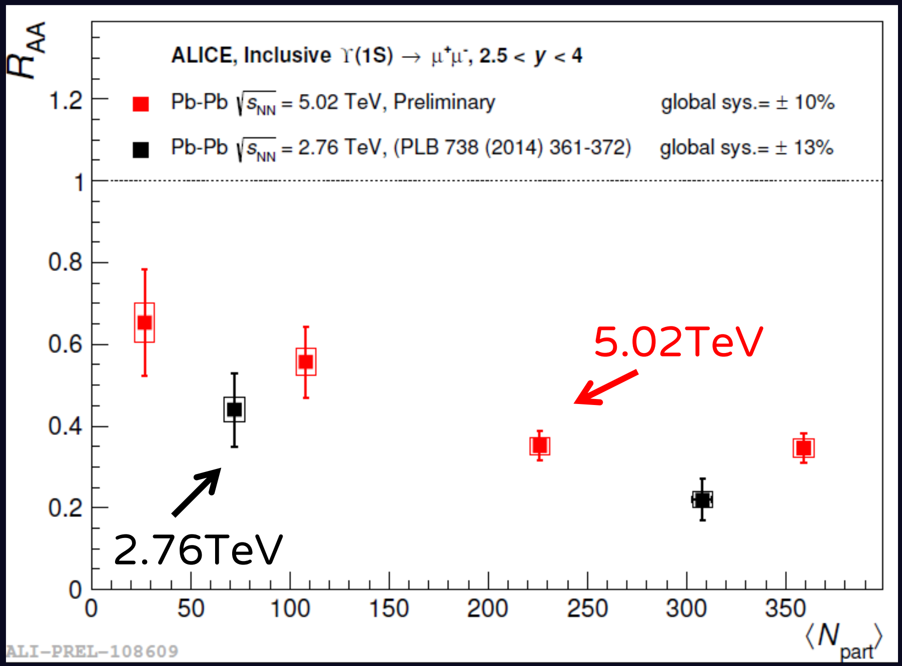
Run-1 Υ(ns) results

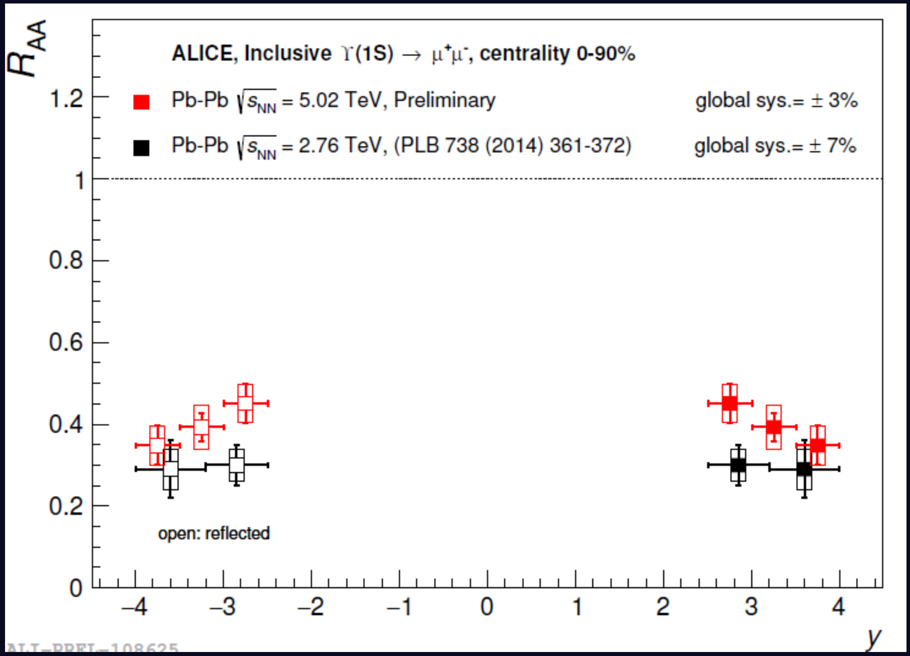




- no p_T or y dependence of the Υ(1S) and Υ(2S) suppressions
- models reproduce the p_T and centrality dependence
- rapidity description still needs tuning

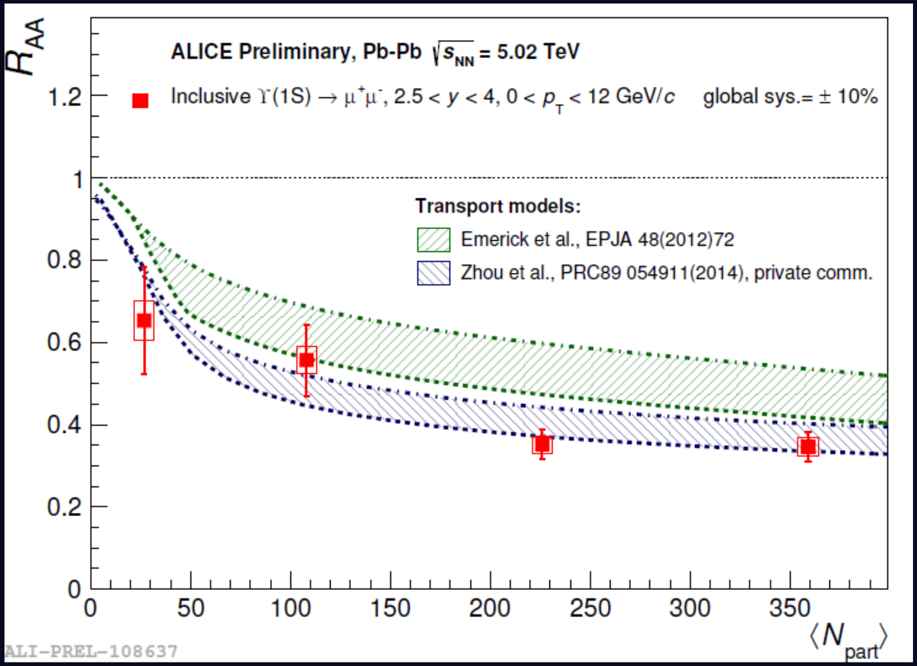
Run-2 Υ(ns) results

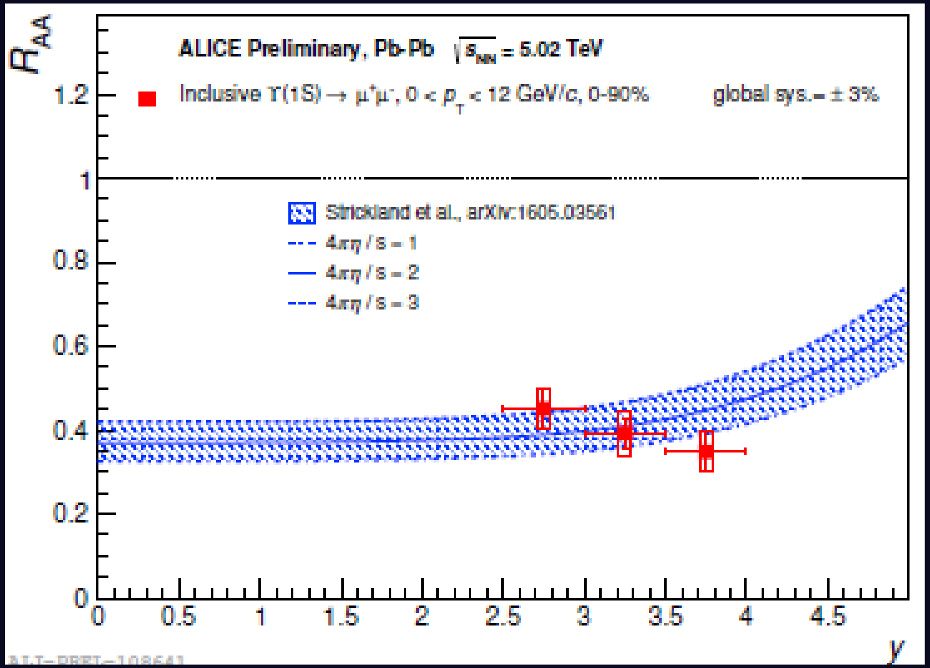




- Centrality dependent Υ(1S) R_{AA} suppression observed also at $\sqrt{s_{NN}}$=5.02TeV
- No firm conclusion on the R_{AA} energy dependence within the current uncertainties

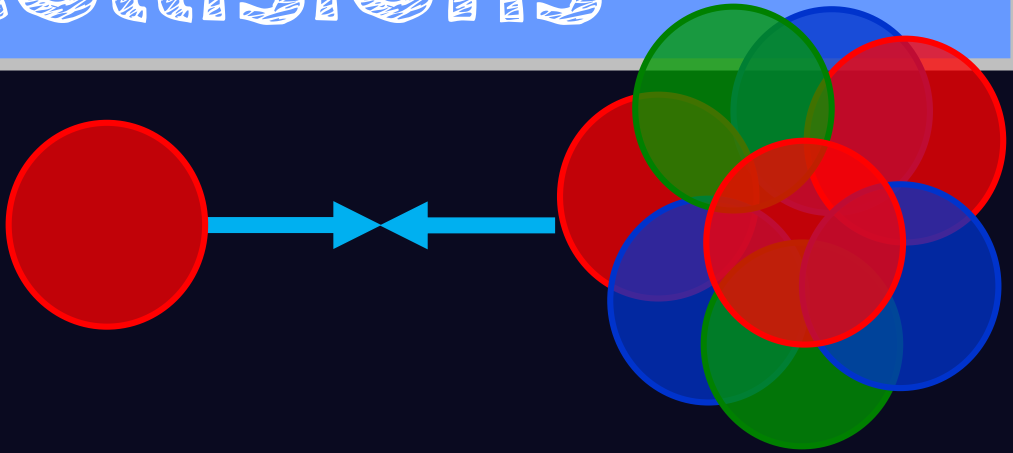
ϒ(ns) theory models



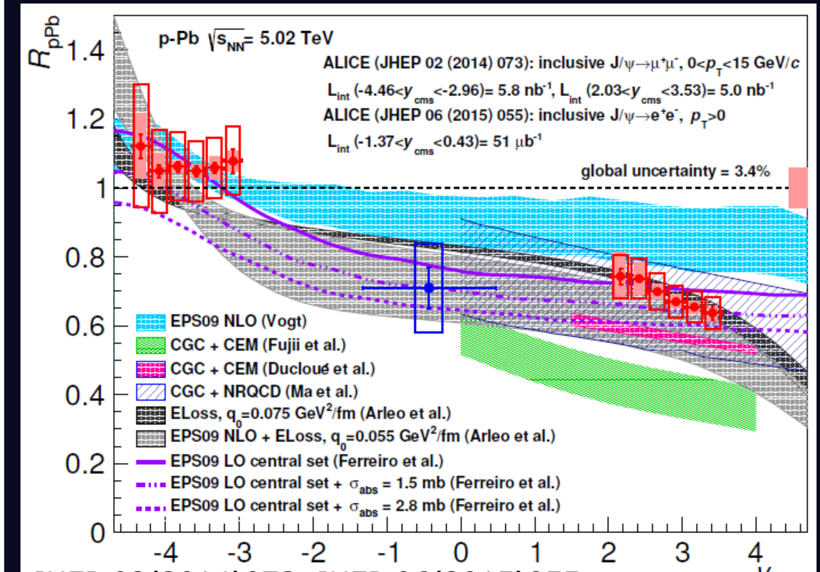


- Theory models, with (Emerick et al.) or without (Zhou et al.) regeneration component, qualitatively reproduce the data within uncertainties
- Different trend in data and theory for most forward-y?

Quarkonium in p-A collisions



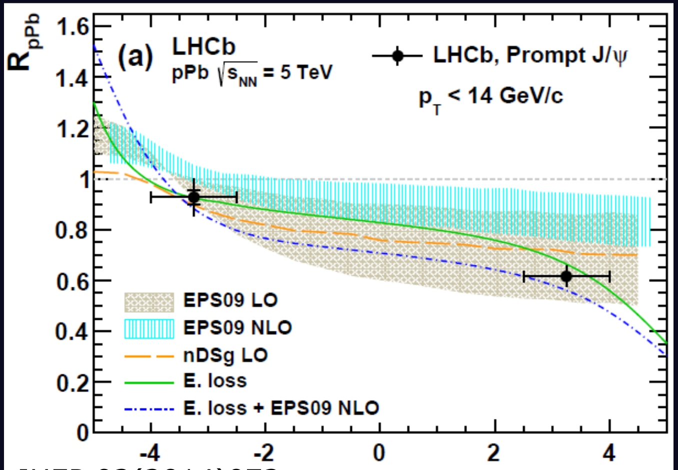
pA J/ψ results



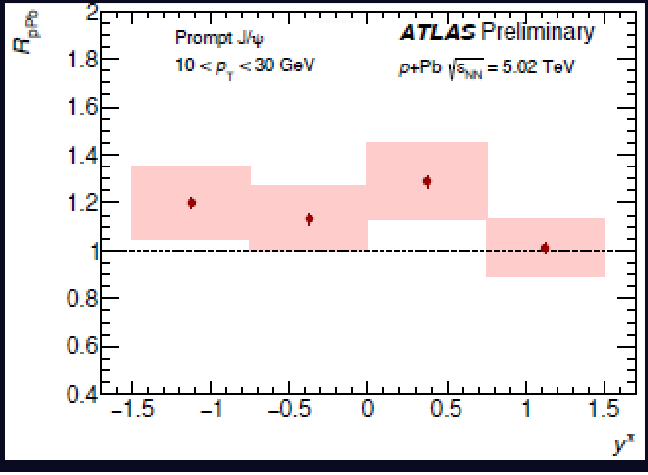
JHEP 02(2014)073, JHEP 06(2015)055

J/ψ affected by CNM effects, with a strong y and p_T dependence:
→ R_{pA} decreases towards forward y

- data consistent with shadowing and coherent parton energy loss models
- agreement with CGC depends on implementation
- good agreement between ALICE and LHCb (similar kinematic range)
- different behavior at mid-y for low and high p_T J.ψ



JHEP 02(2014)072

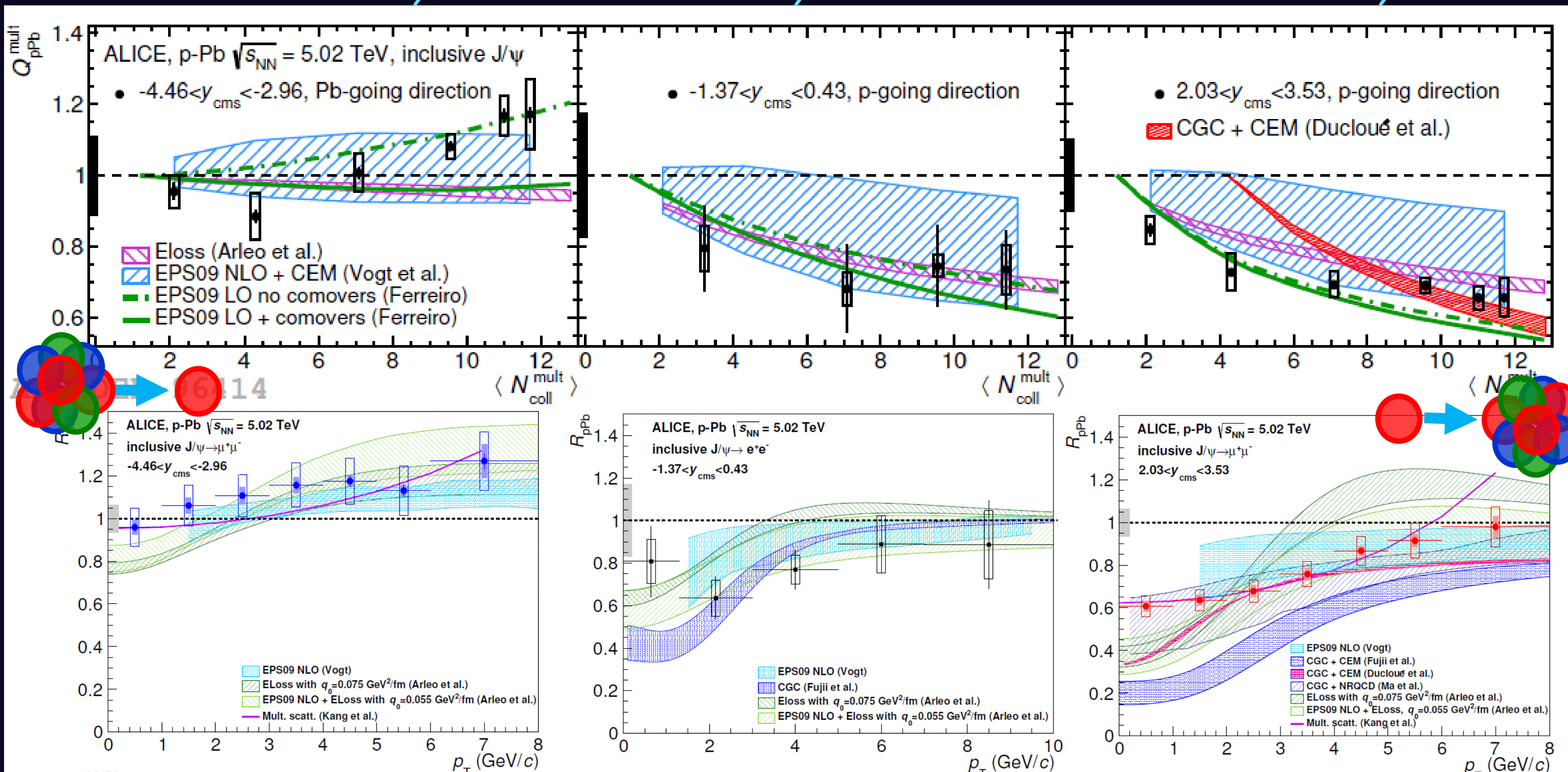


J/ψ vs pT and centrality

backward-y | mid-y | forward-y

centrality

transv. momentum



mid and fw-y: suppression increases vs centrality and is larger at low p_T

backward-y: hint for increasing Q_{pA} vs centrality, with rather flat p_T trend

➡ Shadowing and coherent energy loss models in fair agreement with data

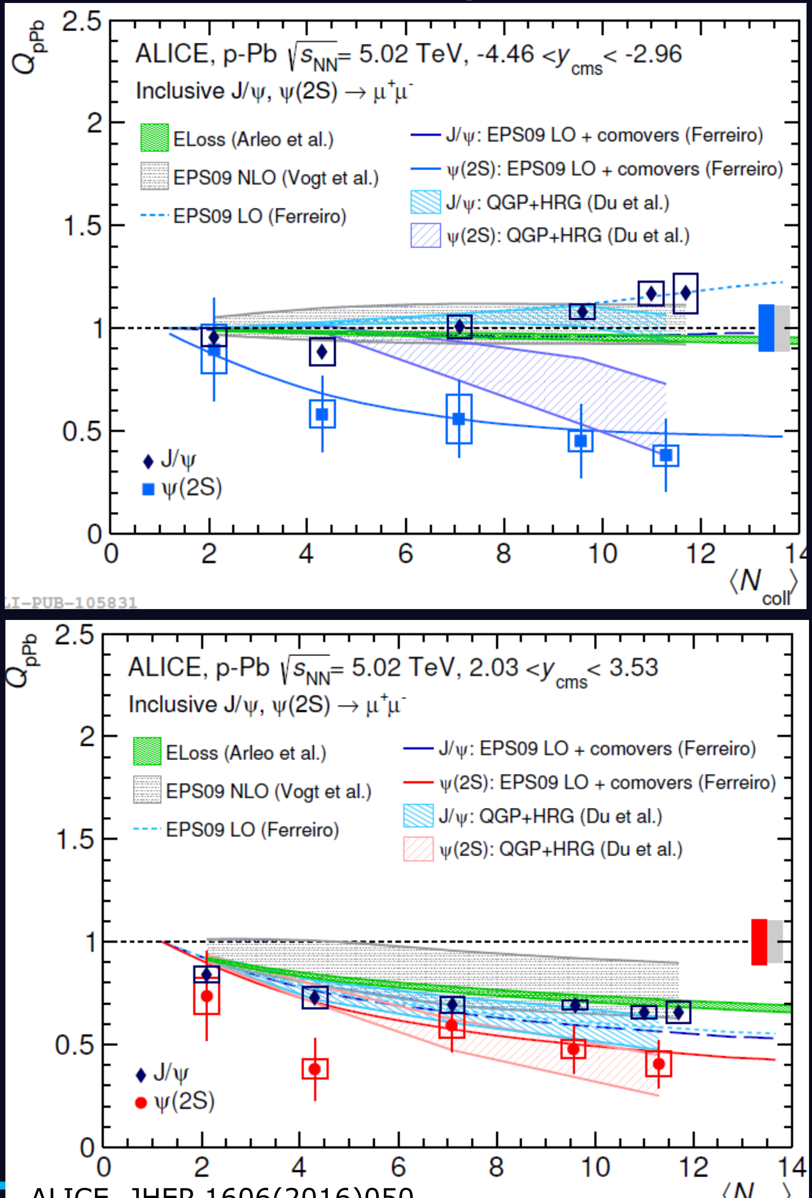
ψ(2S) production in pA

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

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

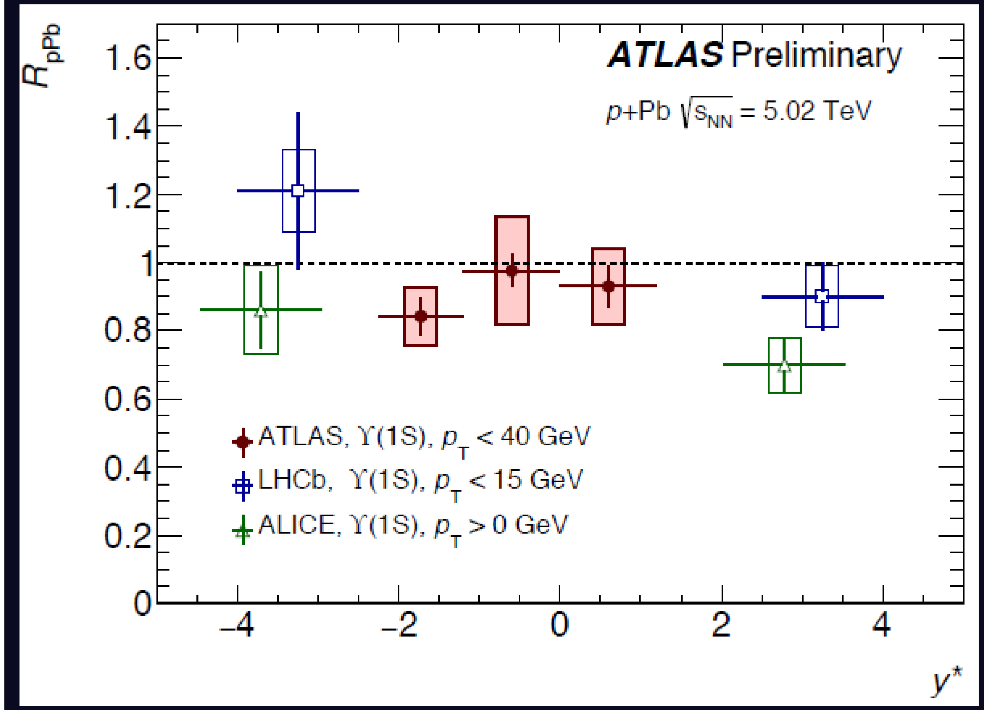
→ shadowing and energy loss, almost identical for J/ψ and ψ(2S), do not account for the different suppression

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

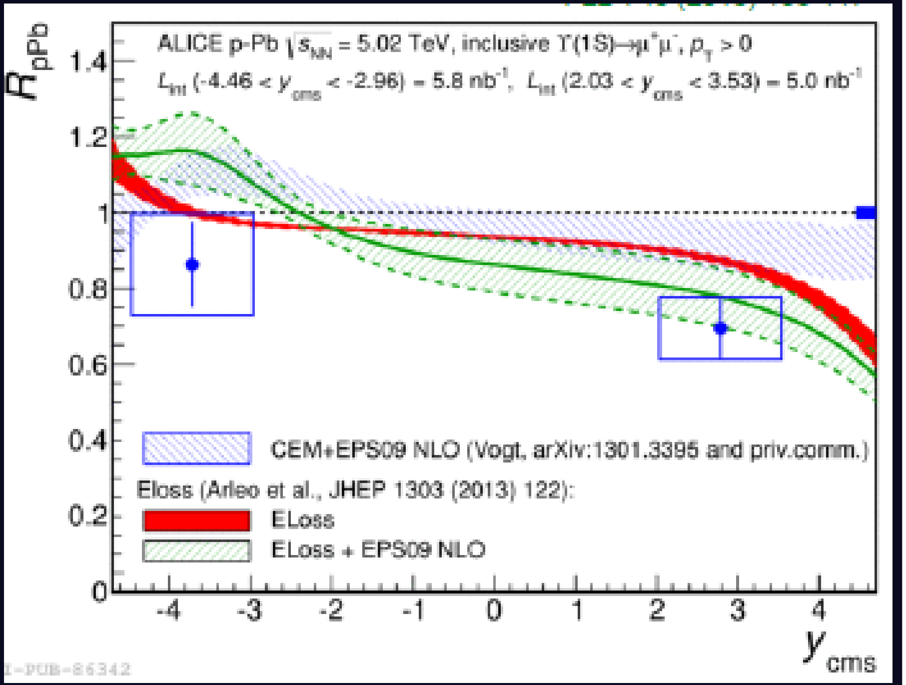


ALICE, JHEP 1606(2016)050

Υ(1s) in pA collisions



- No significant rapidity dependence of Υ(1S) R_{pA} (ALICE and LHCb agree within uncertainties)



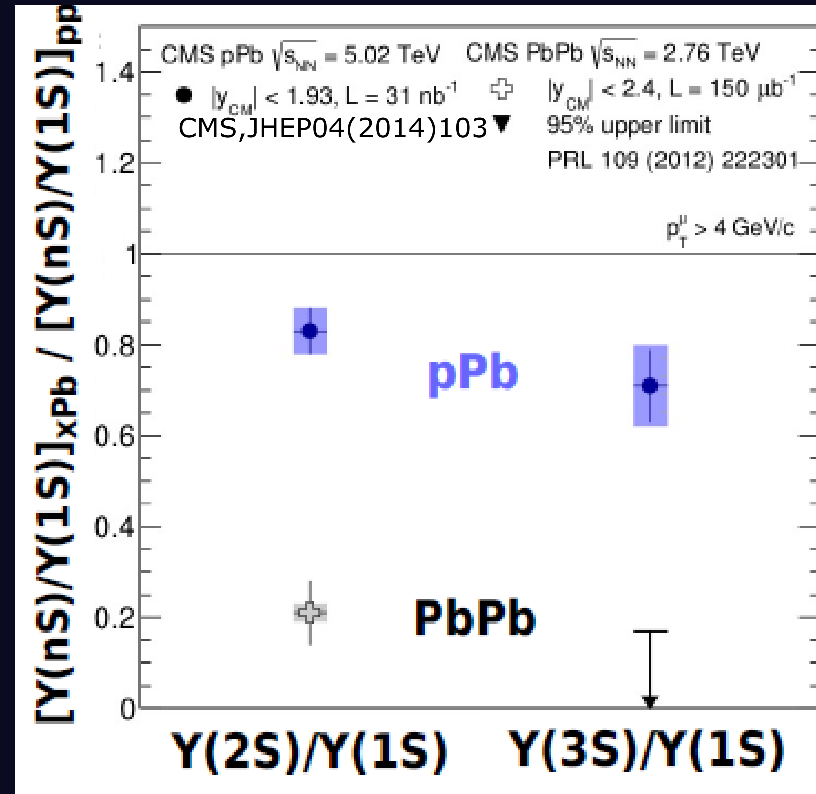
- Shadowing and energy loss models are compatible at forward-y
  At backward-y smaller anti-shadowing is suggested

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

ϒ excited states in pA

p-Pb vs pp @mid-y:
Stronger excited states suppression with respect to ϒ(1S)
Initial state effects similar for the three ϒ states
→ Final states effects in p-Pb?

p-Pb vs PbPb @mid-y :
even stronger suppression of excited states in PbPb



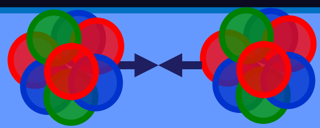
➡ ALICE (and LHCb) observes:

ϒ(2S)/ϒ(1S) (ALICE)
2.03<y<3.53: 0.27±0.08±0.04
-4.46<y<-2.96: 0.26±0.09±0.04

compatible with pp results
0.26 ± 0.08 (ALICE, pp@7TeV)

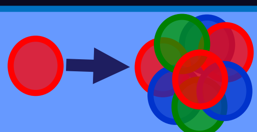
➡ Rapidity dependent final state effects at play?

Conclusions

AA 

Run1 results at $\sqrt{s}$=2.76TeV highlight the role of suppression and recombination mechanisms at play on the various quarkonium states

First Run2 results at $\sqrt{s}$=5.02TeV confirm the picture, showing a rather similar suppression level

pA 

Interplay of shadowing and energy loss describes J/ψ and Υ production

Comover-like effects seem to affect excited quarkonium states

Thanks!

Conclusions

AA

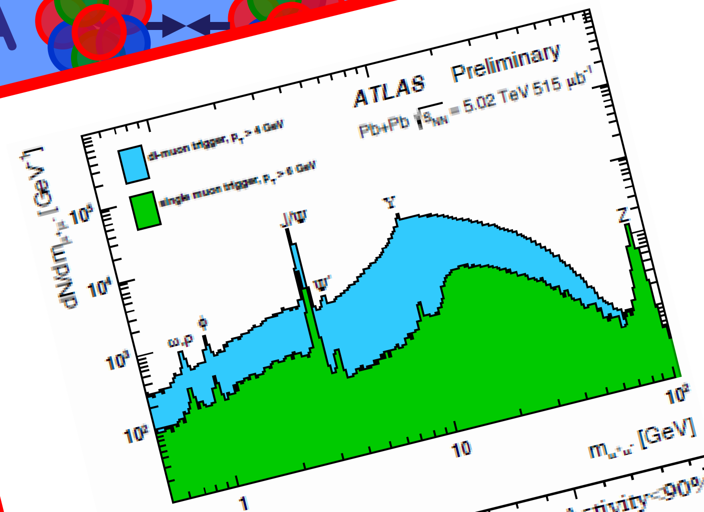
r... d ... ates

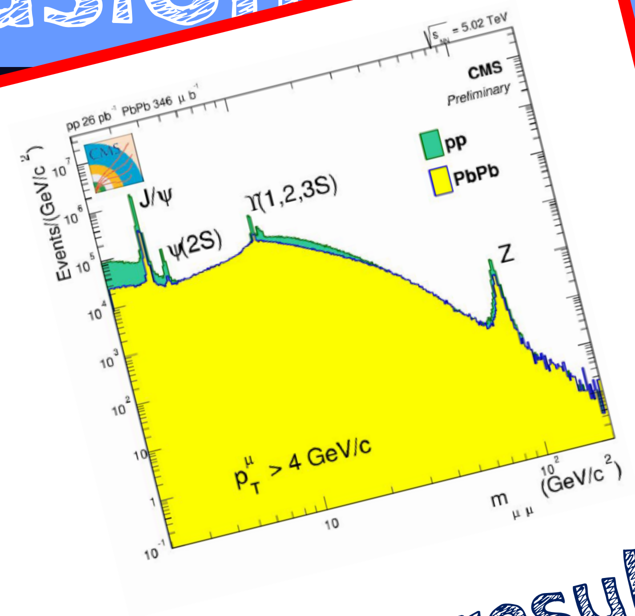
Fi... ather ... si...

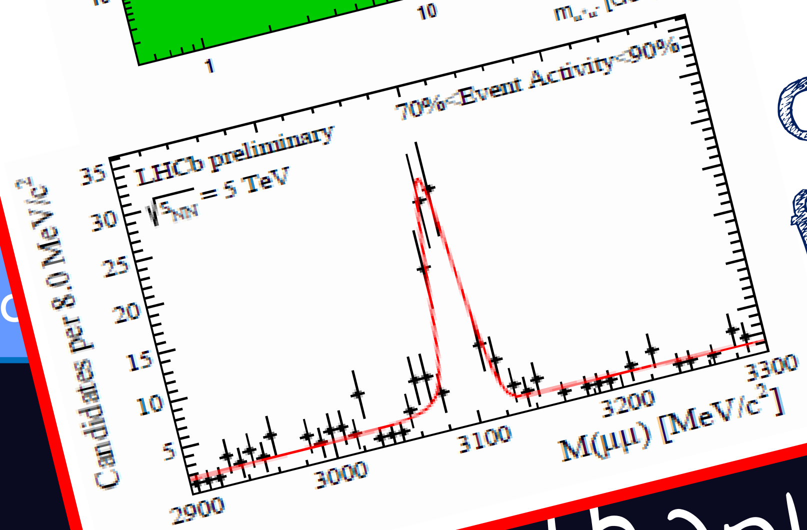
pA

Inte... prod...

Com... ates







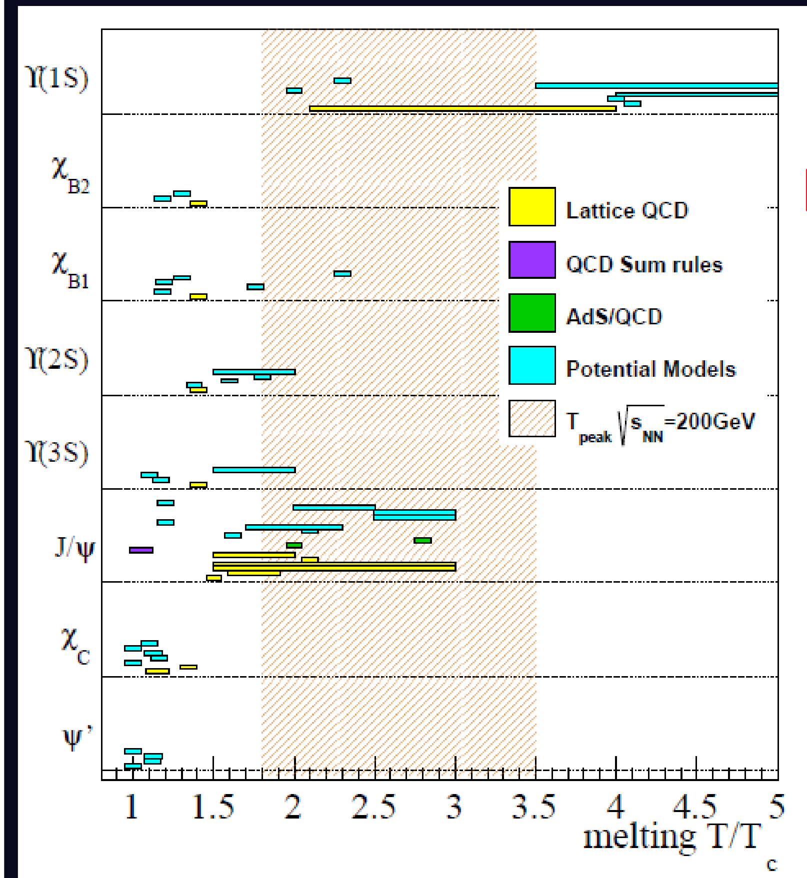
Other new results from Run2 eagerly awaited!!!

Thanks!

Backup slides

AA: from suppression...

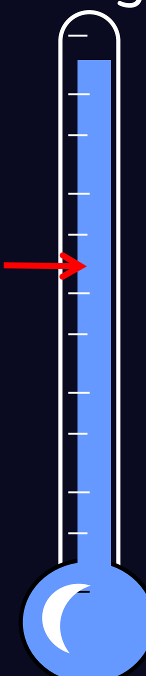
- **the original idea:**
  quarkonium production suppressed via color screening in the QGP
- **sequential melting**
  differences in the quarkonium binding energies lead to a sequential melting with increasing temperature



PHENIX, Phys.Rev C91, 024913

ψ(2S) J/ψ Υ(1S)

T_c

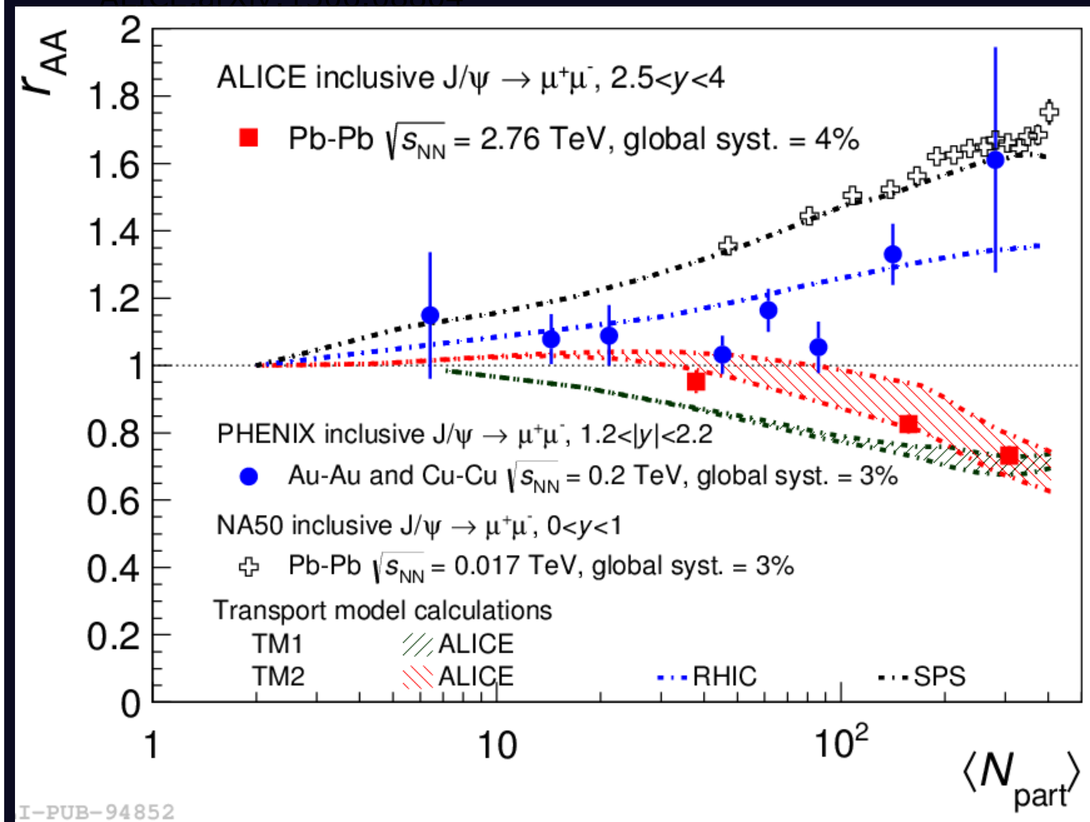


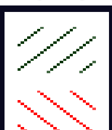
$T >> T_c$

Quarkonium as QGP thermometer

Evolution of J/ψ $\langle p_T^2 \rangle$

ALICE arXiv:1506.08804





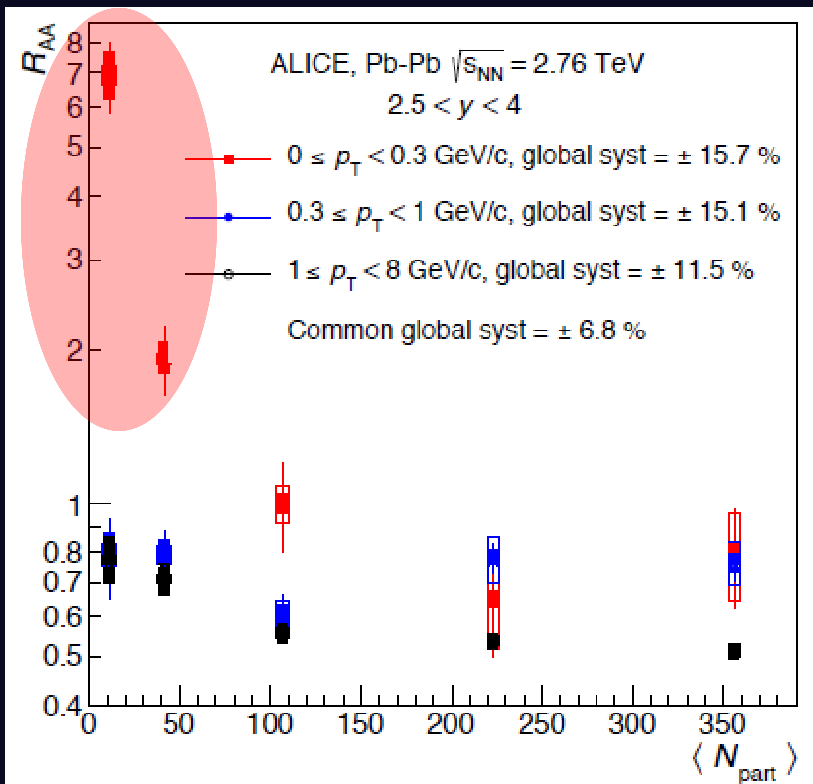
TM1: Zhao et al., Nucl.Phys.A859 (2011) 114
TM2: Zhou et al. Phys.Rev.C89 (2014)054911

$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

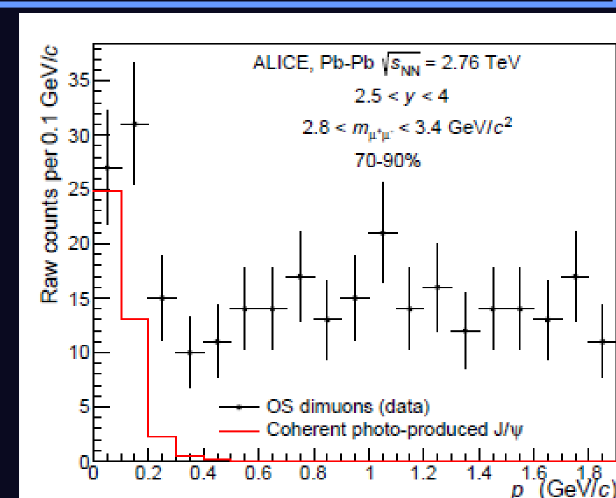
- r_{AA} centrality evolution strongly depends on √s
- decreasing r_{AA} trend, observed at LHC
  → due to (re)combination, which dominates J/ψ production at low p_T
- transport models, already describing J/ψ R_{AA}, also reproduce the r_{AA} evolution

J/ψ at very low p_T

- 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)

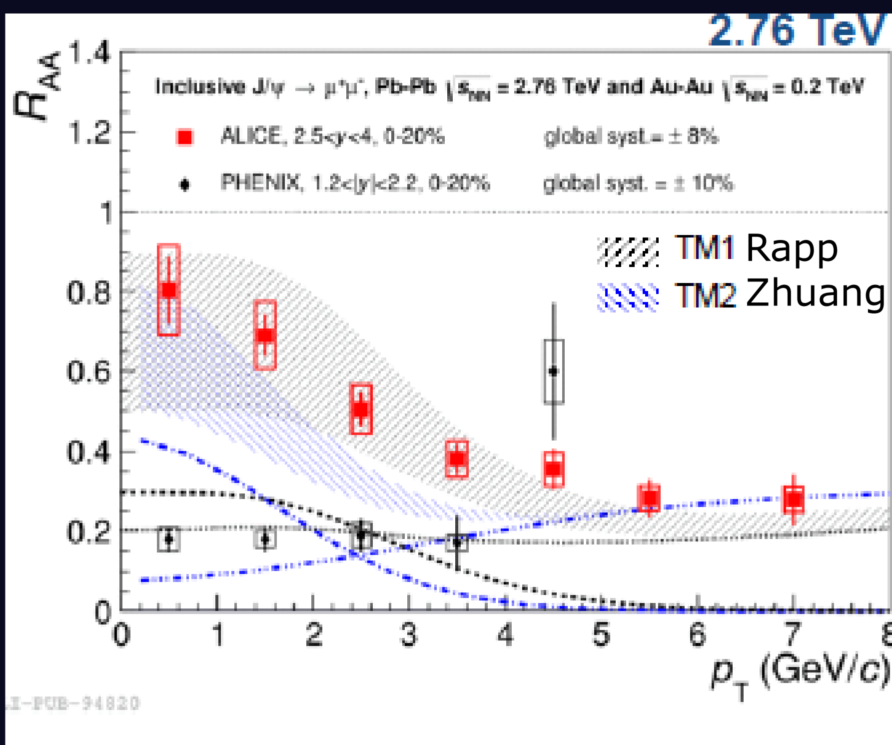


- if excess is "removed" requiring $p_T^{J/\psi}$>0.3GeV/c → ALICE R_{AA} lowers by 20% at maximum (in the most peripheral bin)

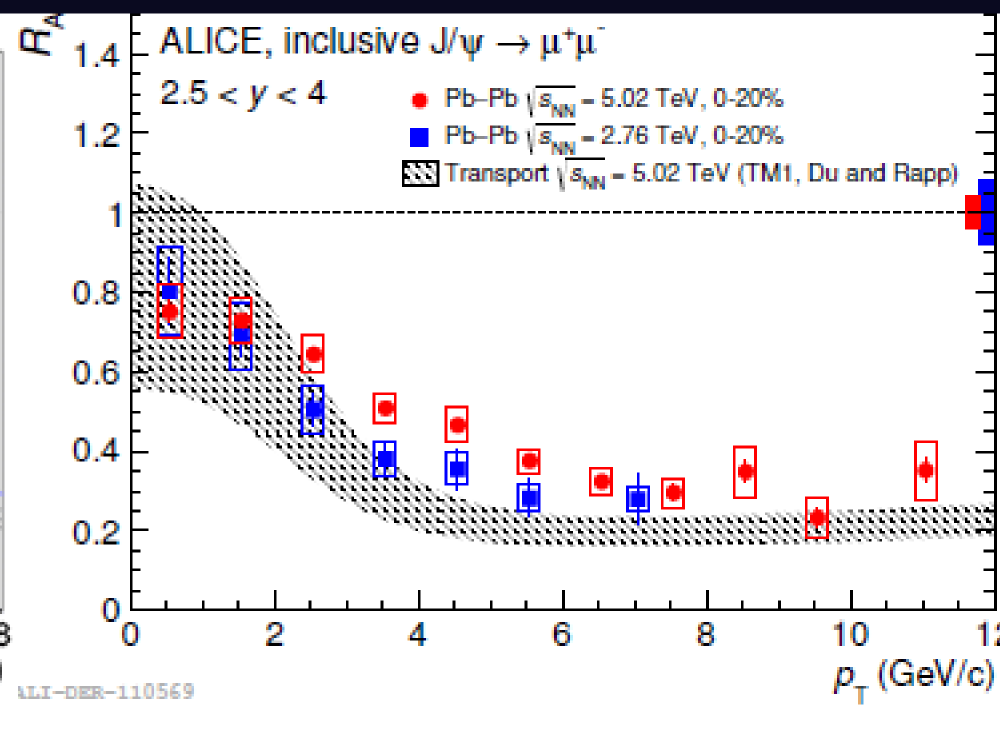
RAA vs pT

ALICE, PLB 734 (2014) 314, JHEP 07(2015)051, arXiv:1506.08804

2.76TeV

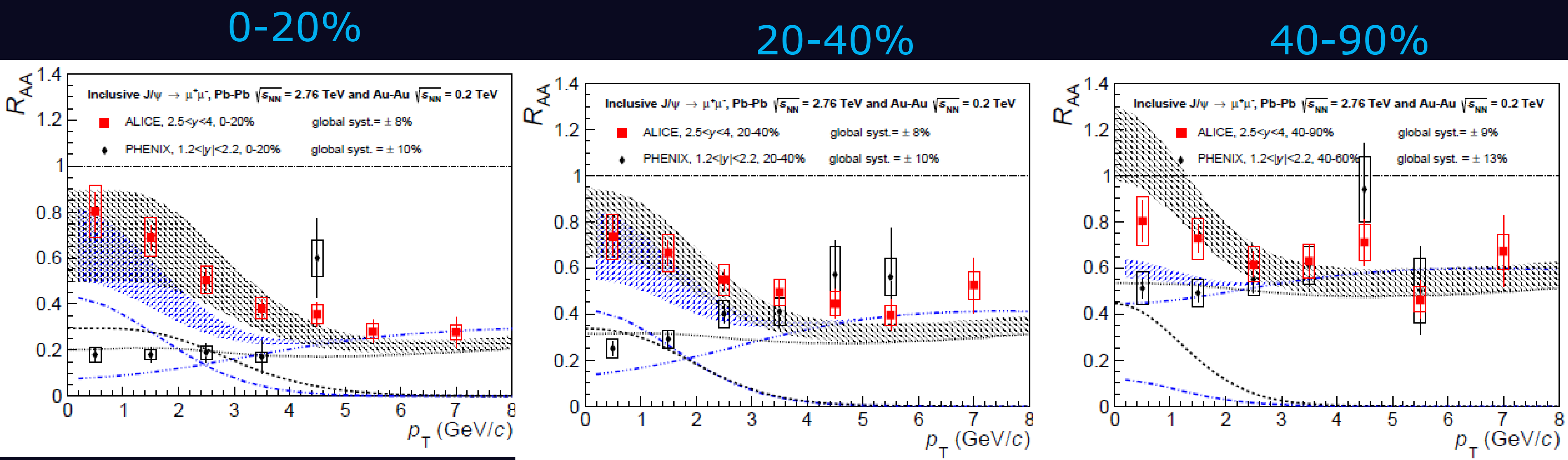


5.02TeV



Multi-differential J/ψ studies

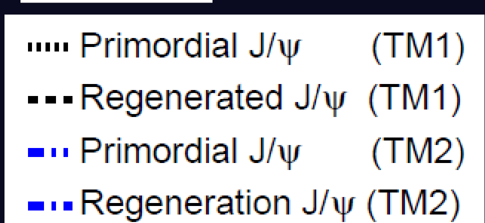
- p_T-centrality multi-differential studies allows detailed comparison with theory models



Zhao et al., Nucl.Phys.A859 (2011) 114

Zhou et al. Phys.Rev.C89 (2014)054911

ALICE, arXiv:1506.08804



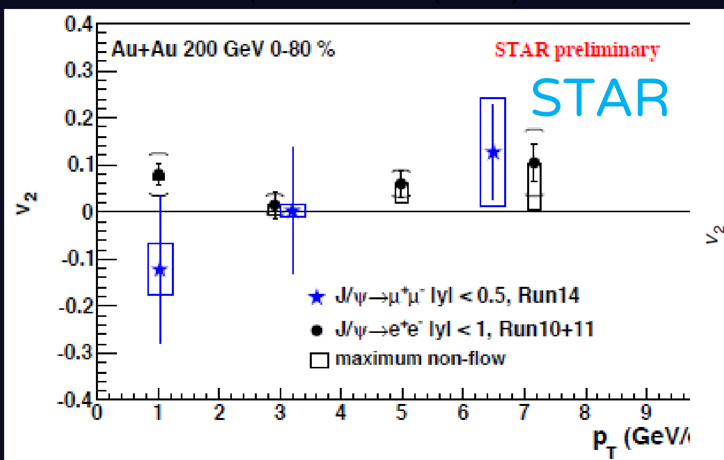
- Model provide a fair description of the data, even if with different balance of primordial/regeneration components

Still rather large theory uncertainties: models will benefit from precise measurement of σ_{cc} and CNM effects

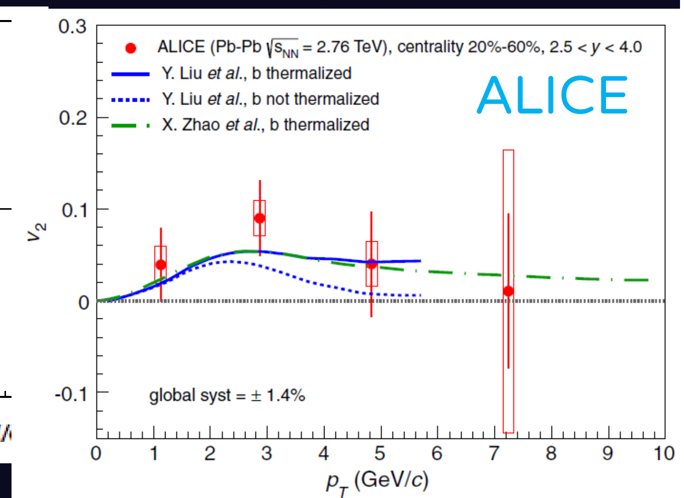
J/ψ flow

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

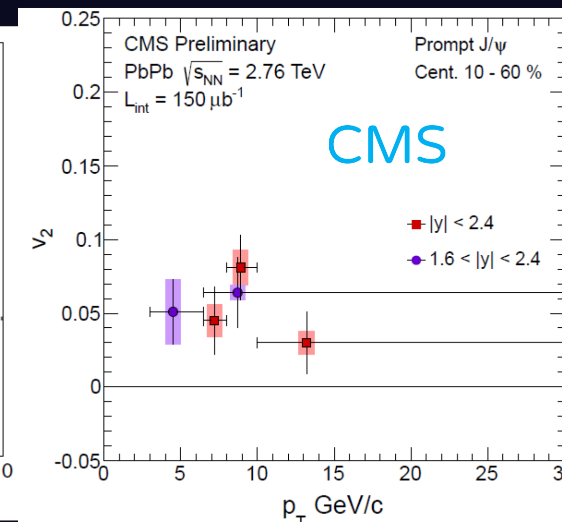
STAR, PRL 052301(2013)



ALICE, PRL 111(2013) 162301



CMS-PAS-HIN-12-001

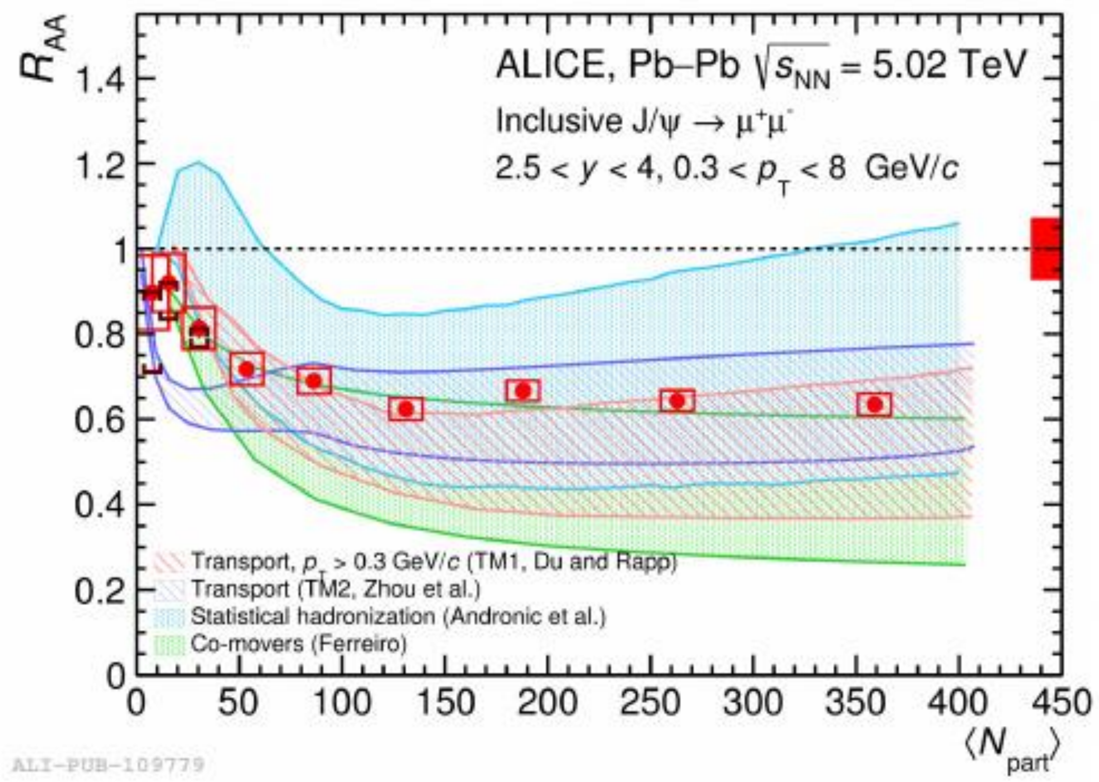


- Hint for J/ψ flow at LHC, contrary to v_2~0 observed at RHIC!

ALICE: qualitative agreement with transport models including regeneration

CMS: path-length dependence suppression effect?

LHC Run-2 J/ψ results



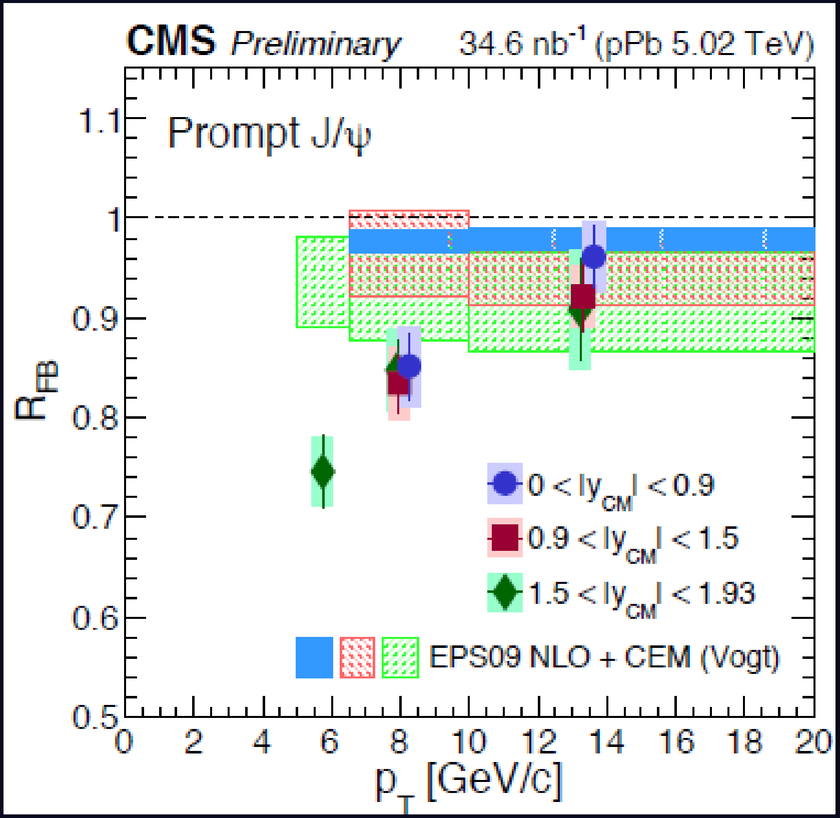
model	$\sigma_{c\bar{c}}$	N-N $\sigma_{J/\psi}$	comover $\sigma_{J/\psi}$	Shadowing
Transport(Rapp)	0.57 mb	3.14 μb	-	EPS09
Transport(Zhou)	0.82 mb	3.5 μb	-	EPS09
Stat. hadronization	0.45 mb	-	-	EPS09
Comovers	[0.45,0.7] mb	3.53 μb	0.65 mb	Glauber-Gribov theory

RFB

- Forward-to-Backward Ratio :

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y) = \frac{d^2\sigma(p_{\mathrm{T}}, y > 0)/dp_{\mathrm{T}}dy}{d^2\sigma(p_{\mathrm{T}}, y < 0)/dp_{\mathrm{T}}dy}$$

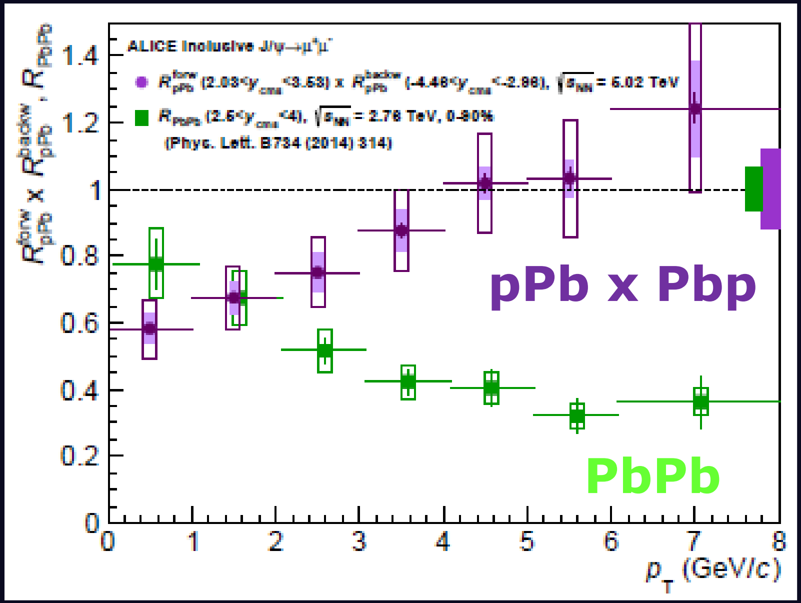
$$= \frac{\text{p-going } (x\sim10^{-4})}{\text{Pb-going } (x\sim10^{-2})}$$



From pA to AA

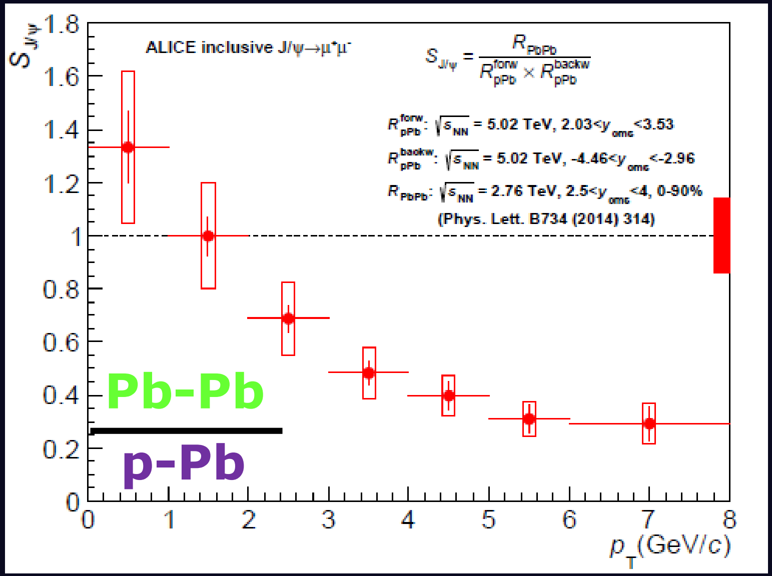
Once CNM effects are measured in pPb, what can we learn on J/ψ production in PbPb?

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}, similar x-coverage as PbPb



CNM effects not enough to explain PbPb data at high p_T

we get rid of CNM effects with AA / pA x Ap

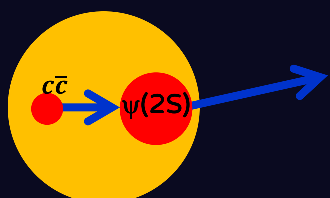


Evidence for hot matter effects in Pb-Pb!

ψ(2S) production in pA

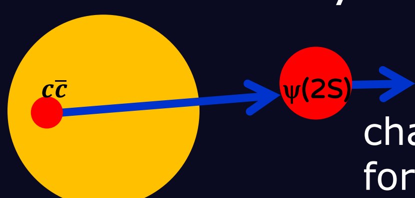
- Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA
- Low energy ψ(2S) p-A results from NA50, E866 and HERA-B:

mid-*y* ($x_F \sim 0$):
ψ(2S) suppression stronger than J/ψ one, interpreted via pair break-up
→ fully formed resonances traversing the nucleus



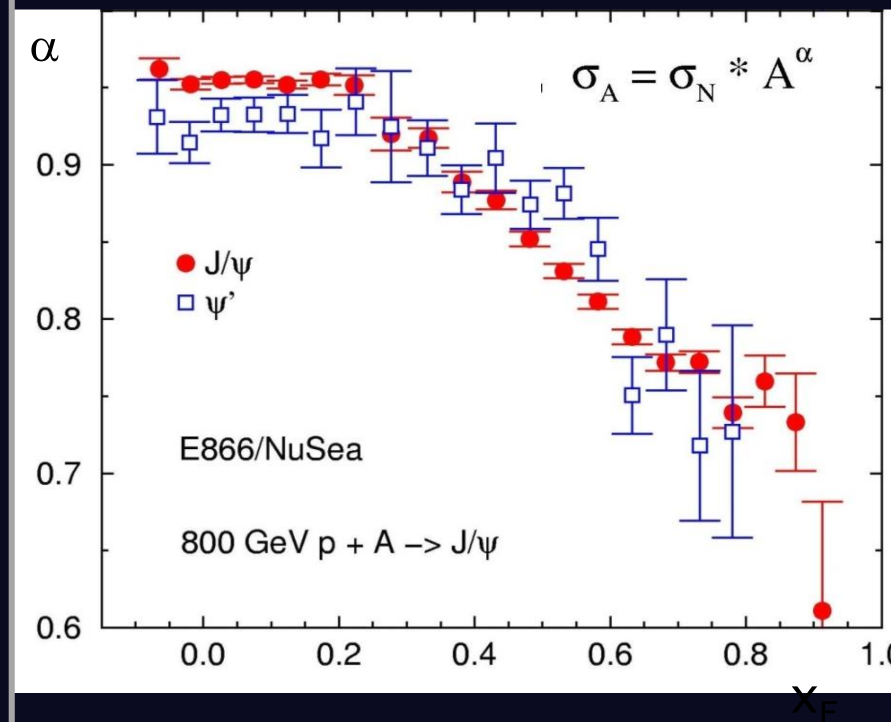
charmonium
formation time<crossing time

forward-*y* (high x_F):
suppression becomes identical
→ dominated by energy loss

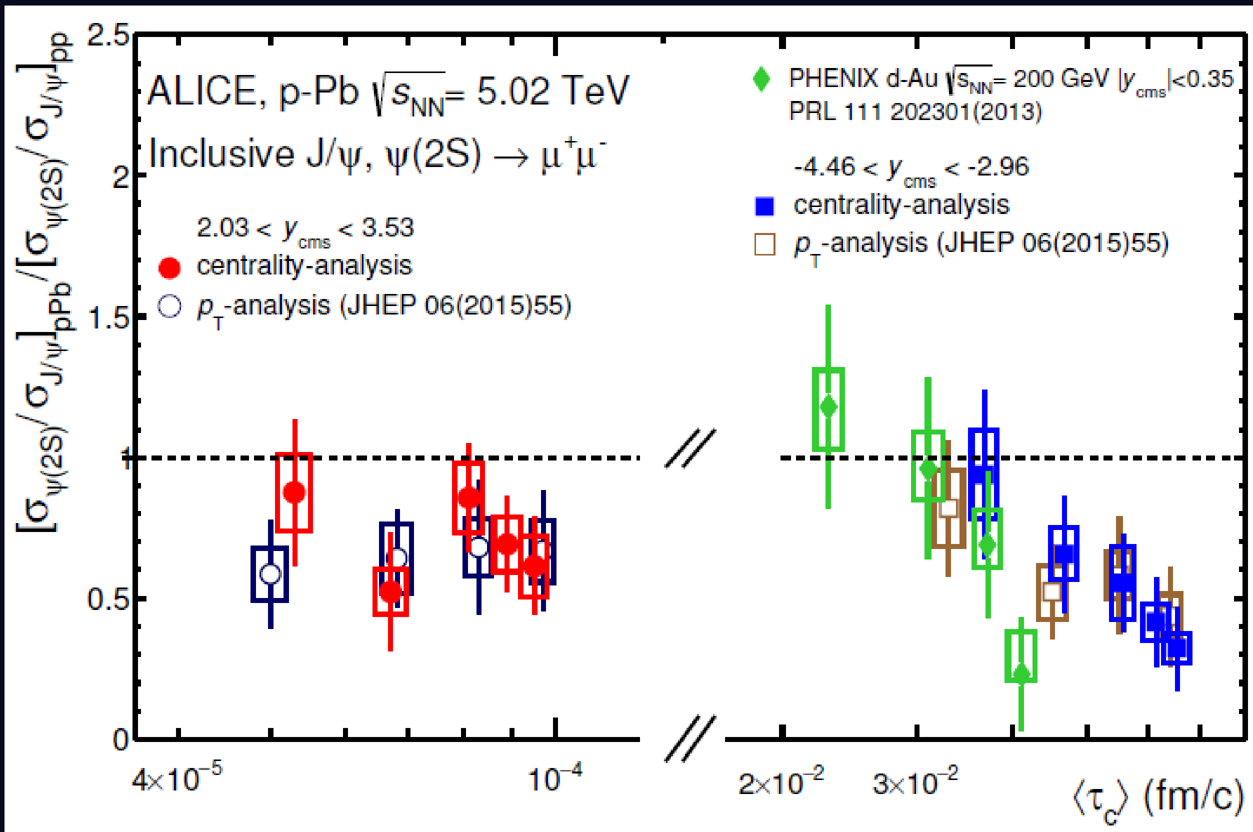


charmonium
formation time>crossing time

E866 Collab., PRL 84 (2000) 3256



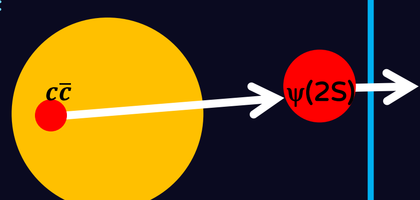
ψ(2S) versus crossing time



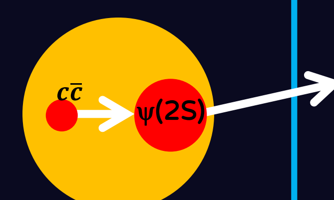
$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

D. McGlinchey, A. Frawley and R.Vogt, PRC 87,054910 (2013)

Forward-y: $\tau_c << \tau_f$
interaction with nuclear matter cannot play a role

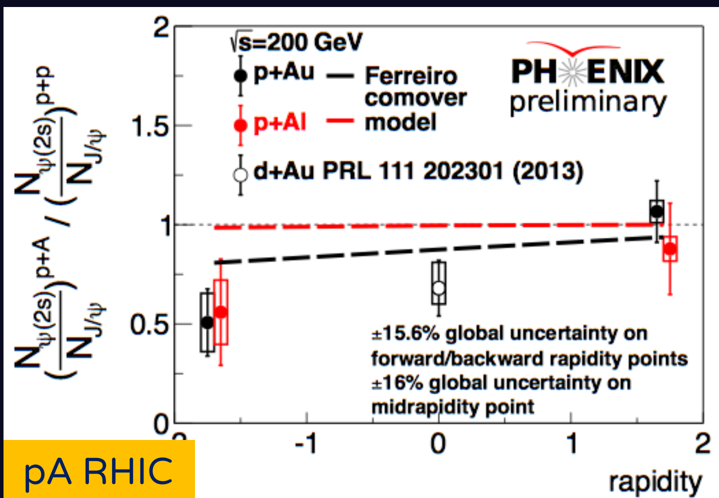


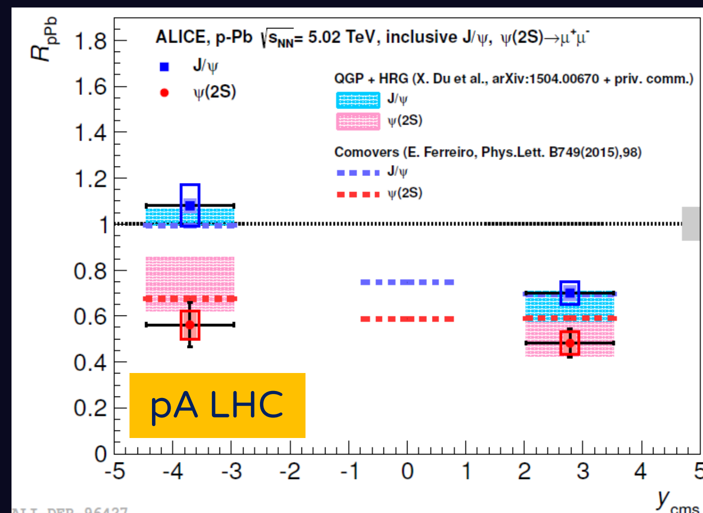
Backward-y: $\tau_c \lesssim \tau_f$
indication of effects related to break-up in the nucleus?

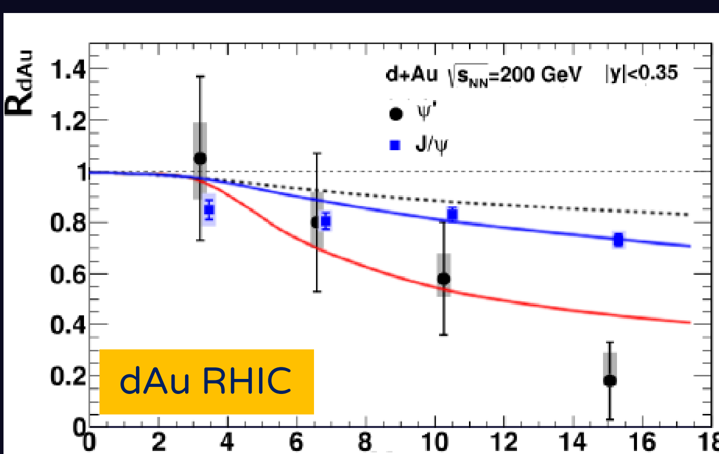


Comparison to theoretical models

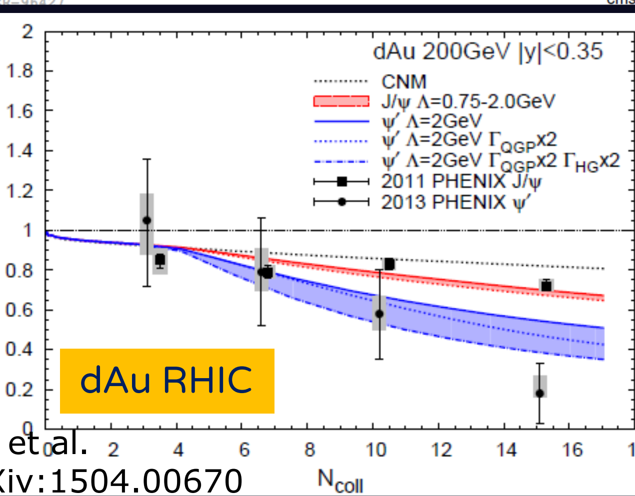
➡ QGP+hadron resonance gas (Rapp) or comovers models (Ferreiro) reasonably describe both J/ψ and ψ(2S) suppression at RHIC and LHC







Ferreiro, PLB 749(2015)98

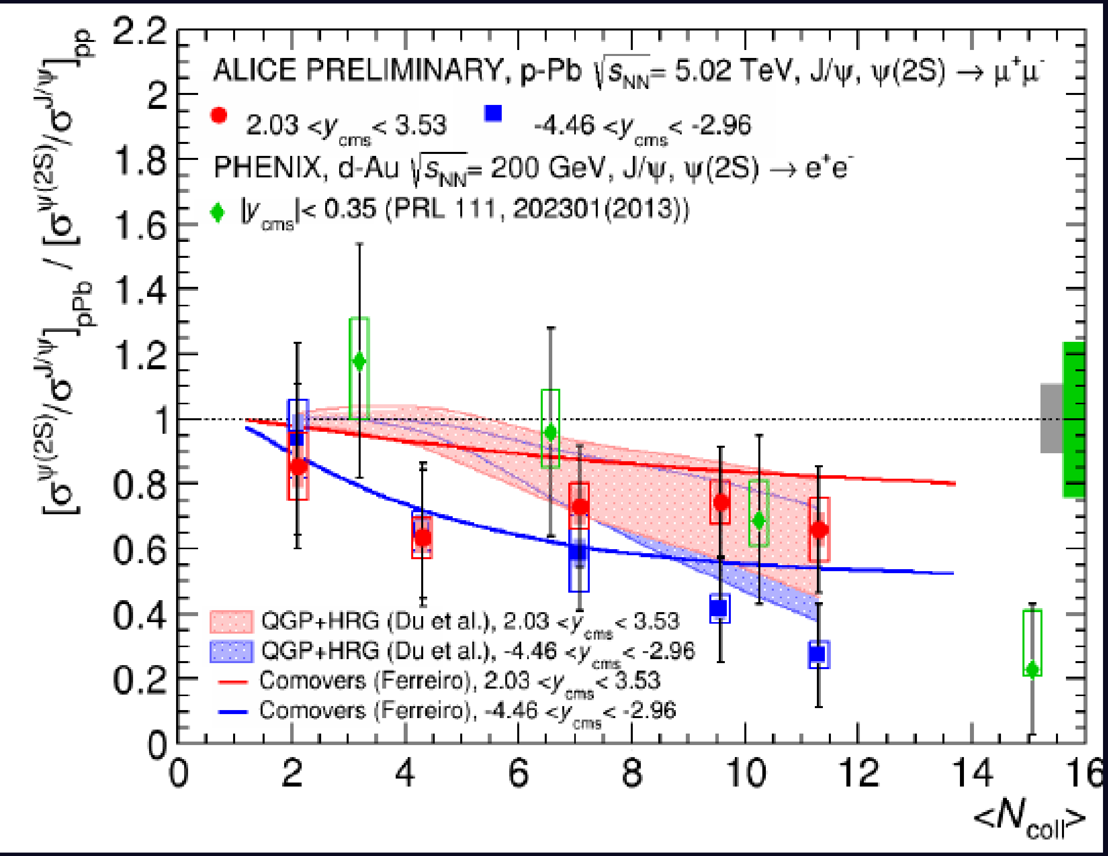


Du et al. arXiv:1504.00670

J/ψ
→ small suppression beyond CNM effects

ψ(2S)
→ strongly affected by comovers due to its larger size
→ comovers more important in the A-going direction

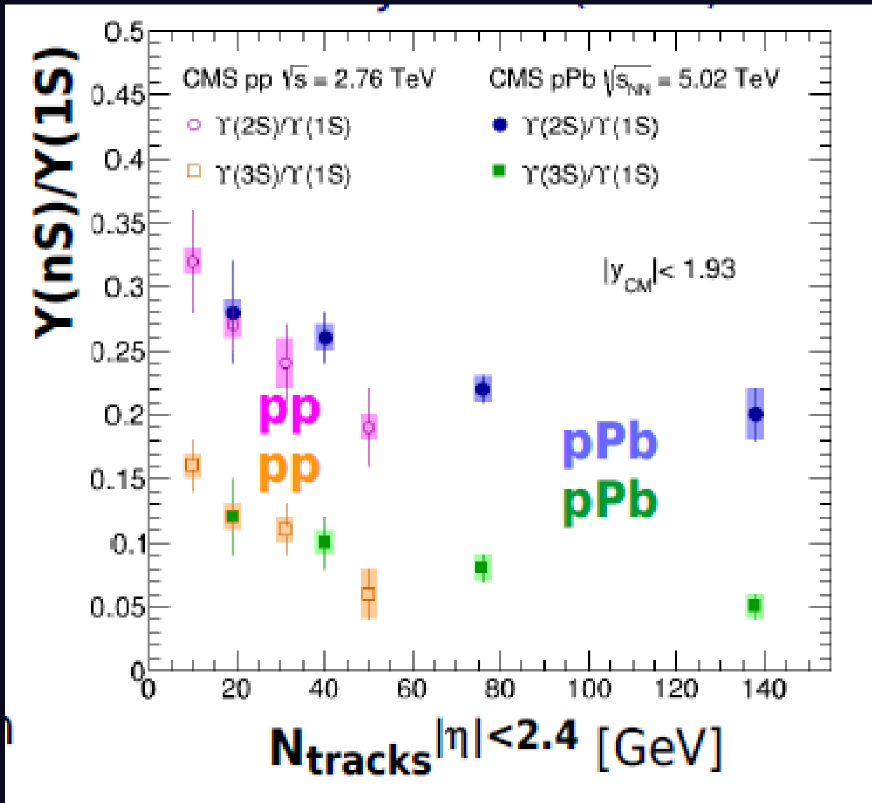
ψ(2S) / J/ψ double ratio



Similar suppression trend observed versus centrality, by both ALICE and PHENIX

➡ QGP+hadron resonance gas (Rapp) or comovers models (Ferreiro) describe the observed suppression

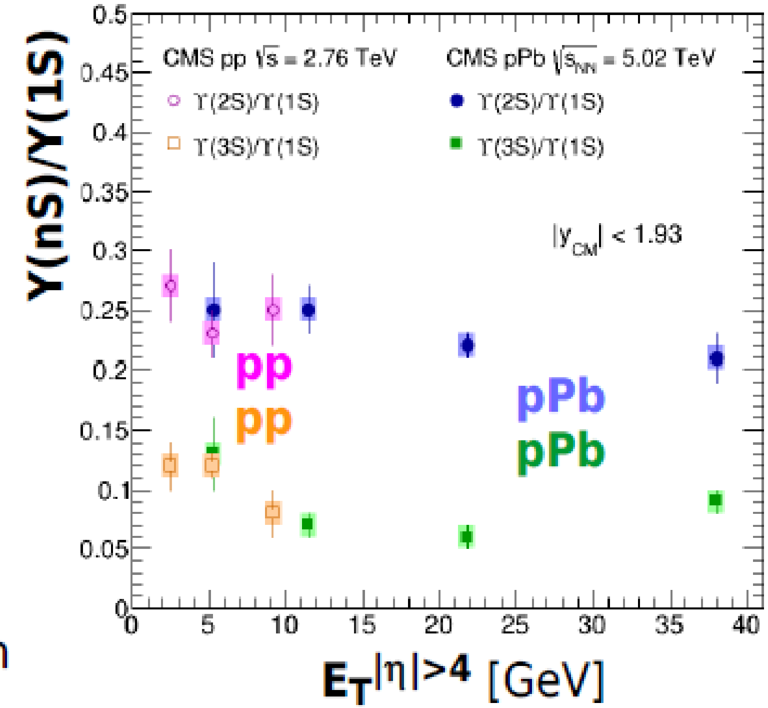
Υ vs ev. activity

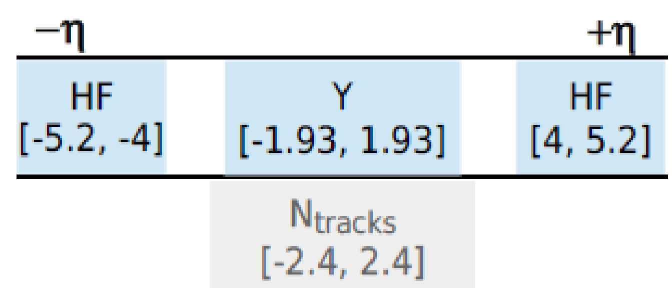


- Υ(nS)/Υ(1S) ratios fall with event-activity
  - Is the multiplicity affecting the Υ(nS)?
  - Are the Υ(nS) produced differently with multiplicity?

CMS

JHEP 04 (2014) 103





Υ compared to theory