Quarkonium results in heavy-ion collisions

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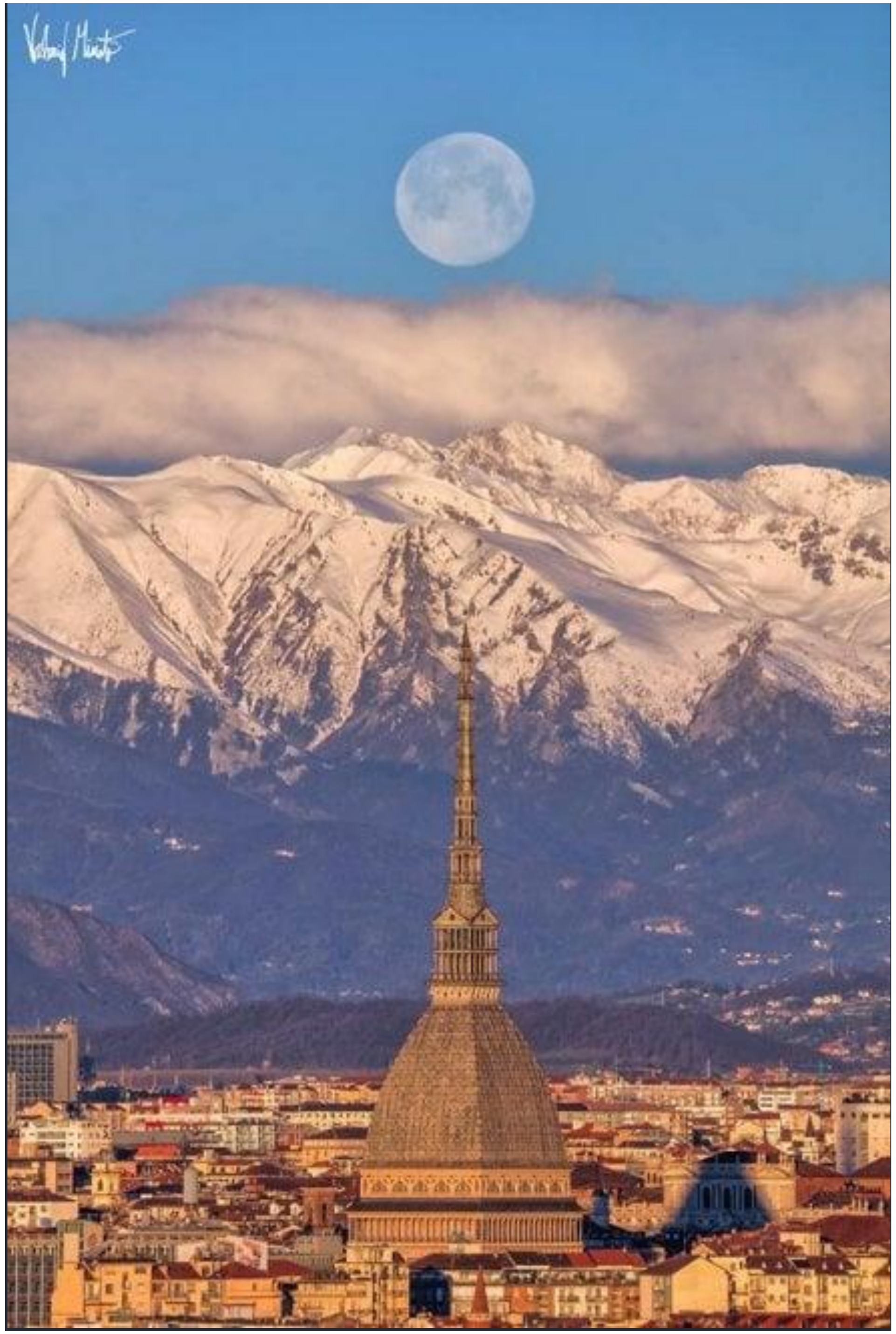
DIS 2019
TORINO
8-12 April

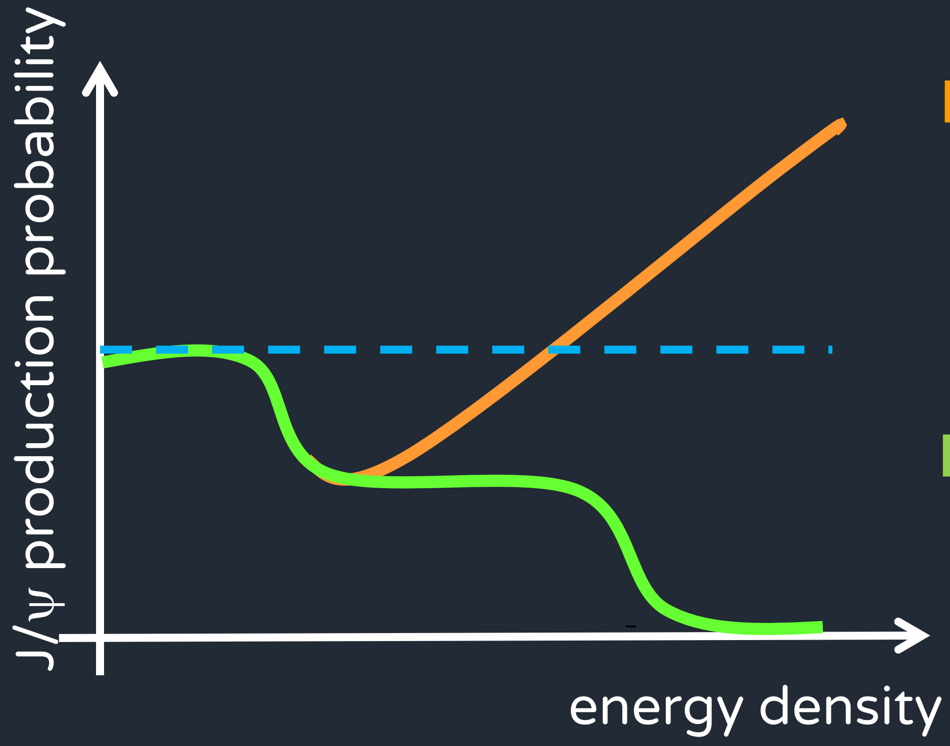


AA: hot matter effects

the original idea:

suppression of quarkonium production via color screening in the Quark Gluon Plasma

(T.Matsui,H.Satz, PLB178 (1986) 416)



Recombination

$q\bar{q}$ abundance increases with collision energy

Central AA coll	$N_{c\bar{c}}$ per event	$N_{b\bar{b}}$ per event
RHIC, 200GeV	~10	-
LHC, 5.02 TeV	~115	~3

→ (re)combination at hadronization or during QGP enhances charmonium production

→ small contribution for bottomonium (also at LHC)

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

Sequential melting

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

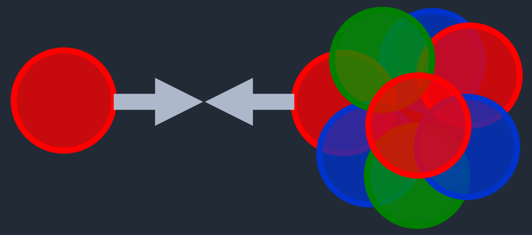
Digal,Petrecki,Satz PRD 64(2001) 0940150

pA: cold matter effects

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

  - nuclear parton shadowing/gluon saturation
  - energy loss
  - $c\bar{c}$ break-up in nuclear matter

- pA collisions address:



  - role of the various CNM contributions, whose importance depends on kinematic and energy of the collisions
  - size of CNM effects, fundamental to interpret quarkonium AA results
  - presence of possible hot matter effects

quarkonium at RHIC and LHC

- Heavy-ions program usually includes:

pp
vacuum reference + pp physics

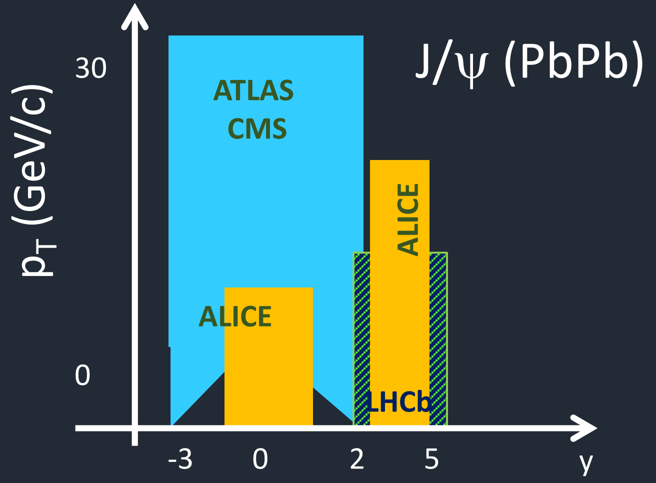
pA
cold/(hot?) nuclear matter effects

AA
hot matter effects

RHIC:
various collision systems are explored, scanning in energy

Exp.	System	$\sqrt{s_{NN}}$ (TeV)
PHENIX STAR	AuAu, CuCu, CuAu, UU	0.039 – 0.2
	p-A, d-Au, p-Al, ^{3}He-Al	0.2
	pp	0.2-0.5

LHC:
results are complementary, due to different kinematic coverages



Exp.	System	$\sqrt{s_{NN}}$ (TeV)
ALICE ATLAS CMS LHCb (*)	PbPb, XeXe	2.76, 5.02, 5.44
	pPb	5.02, 8.16
	pp	2.76, 5, 7, 8, 13

(*) only recently joined the study of AA collisions

quarkonium at RHIC and LHC

- Heavy-ions program usually includes:

pp
vacuum reference + pp physics

pA
cold/(hot?) nuclear matter effects

AA
hot matter effects

In this talk, focus on:

- results on **charmonium** (J/ψ and ψ(2S)) and **bottomonium** (ϒ(1S), ϒ(2S), ϒ(3S)) states
- most recent **pA** and **AA** results

main observables: R_{AA} and v_2

Nuclear modification factor R_{AA}

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

Medium effects quantified comparing AA quarkonium yield with pp cross section, scaled by a geometrical factor ($\propto N_{coll}$)

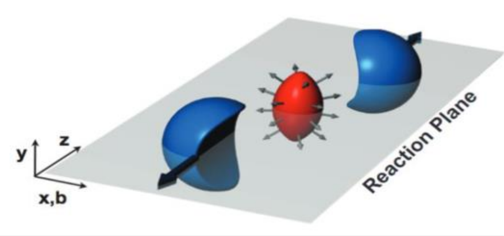
➡ $R_{AA} \neq 1$

→ presence of hot/cold matter effects

Elliptic flow v_2

Multiple interactions in the medium convert initial geometric anisotropy into particle momenta anisotropy

→ elliptic flow v_2 is the 2nd coeff. of the Fourier expansion of the azimuthal distribution of the produced particles



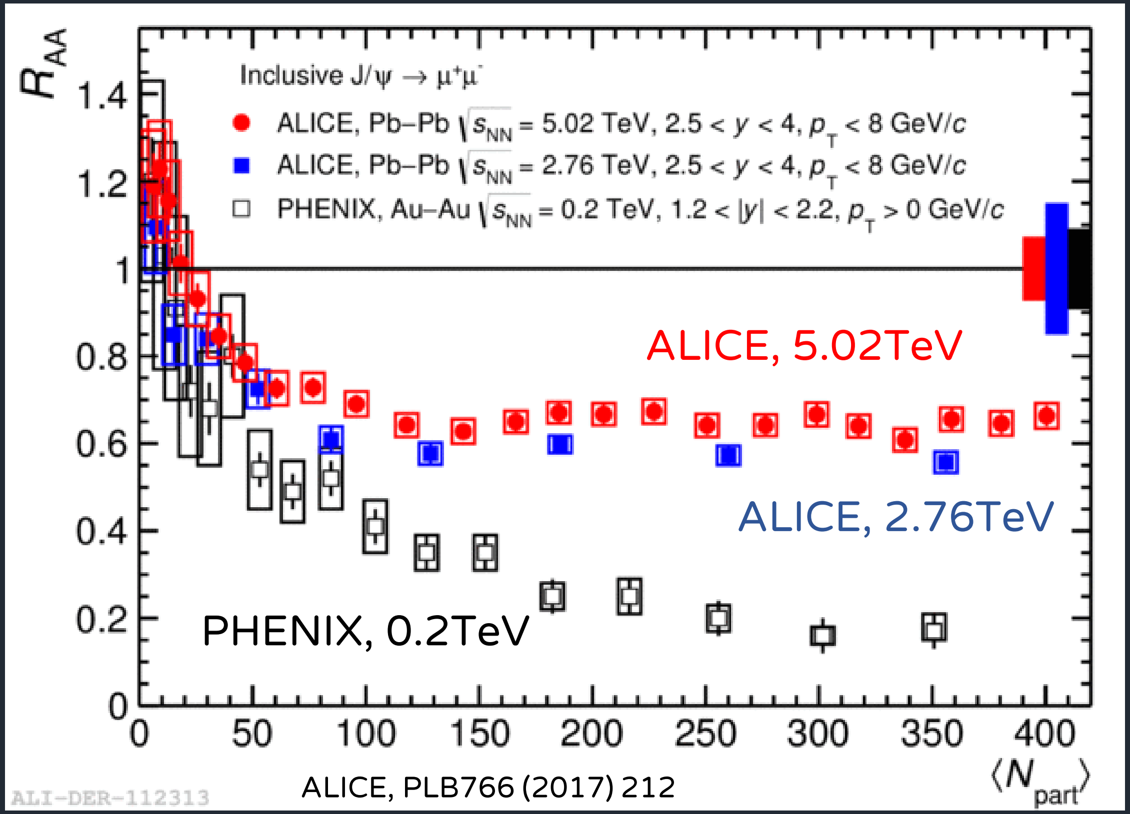
$$\frac{dN}{d(\varphi-\Psi_{EP})} = A(1+2\, v_2 \cos 2(\varphi-\Psi_{EP})+\ldots)$$

➡ J/ψ produced through (re)generation should inherit the charm-quark flow in QGP → $v_2 > 0$

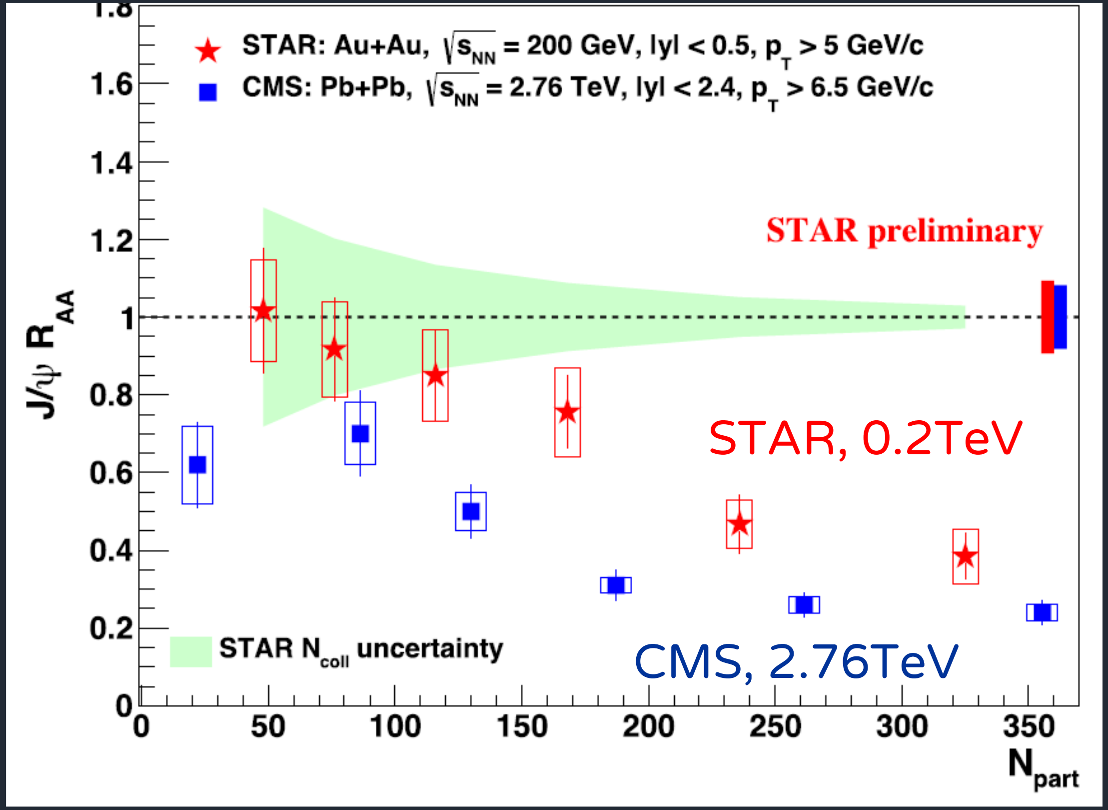
Charmonium

AA: J/ψ R_{AA} vs centrality

Low p_T J/ψ



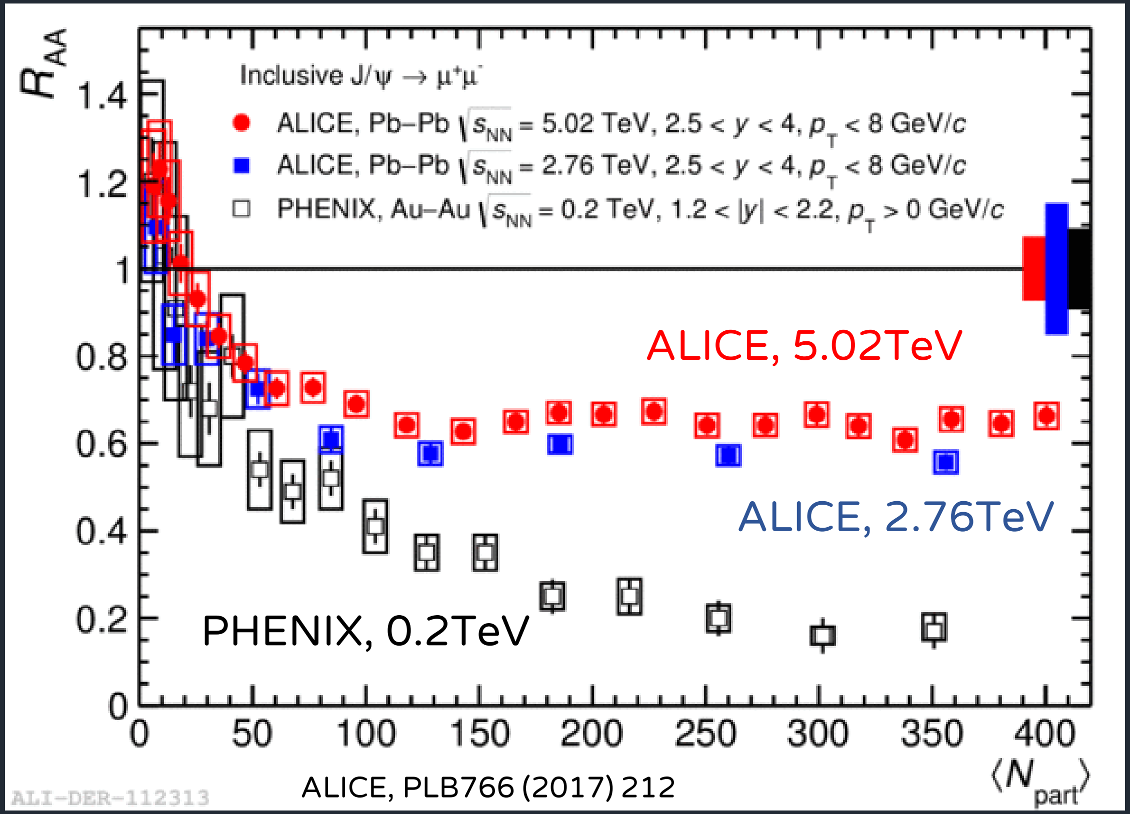
High p_T J/ψ



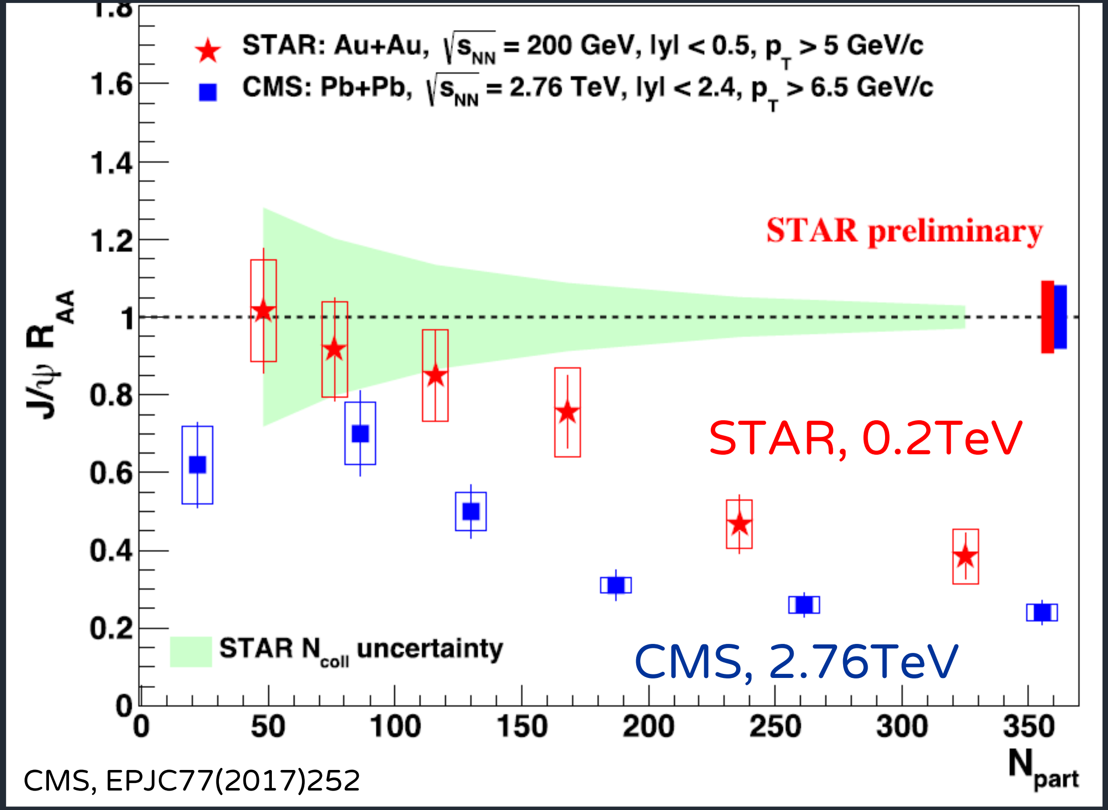
- stronger suppression at RHIC in central events, in spite of the larger LHC energy densities
- suppression increases towards central events and it's stronger at LHC energies

AA: J/ψ R_{AA} vs centrality

Low p_T J/ψ

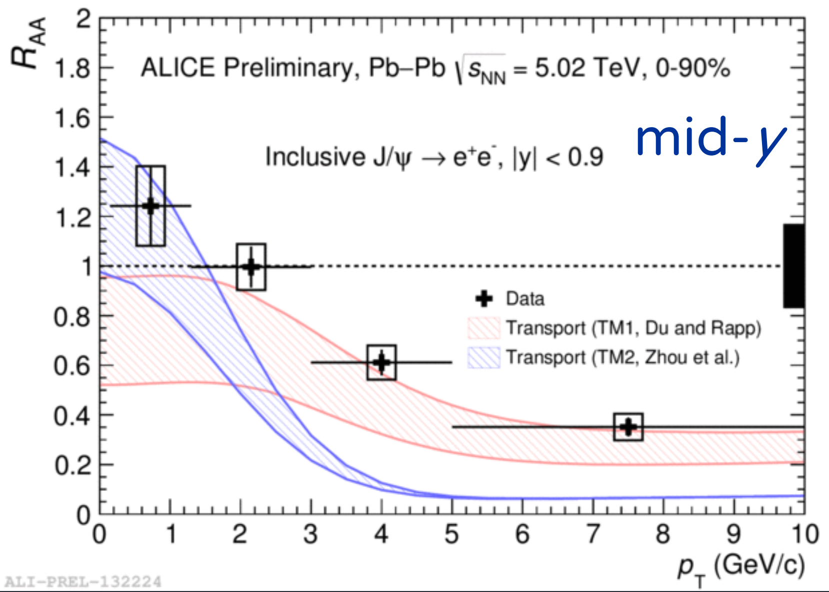


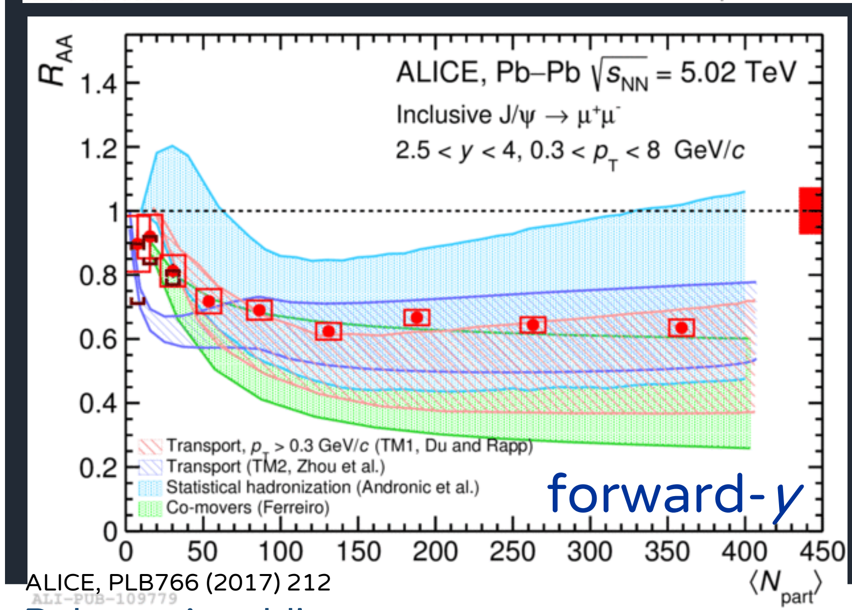
High p_T J/ψ



suppression + regeneration mechanisms, with regeneration at play in the low p_T region, at high energy

AA low p_T: comparison to theory





ALICE, PLB766 (2017) 212

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

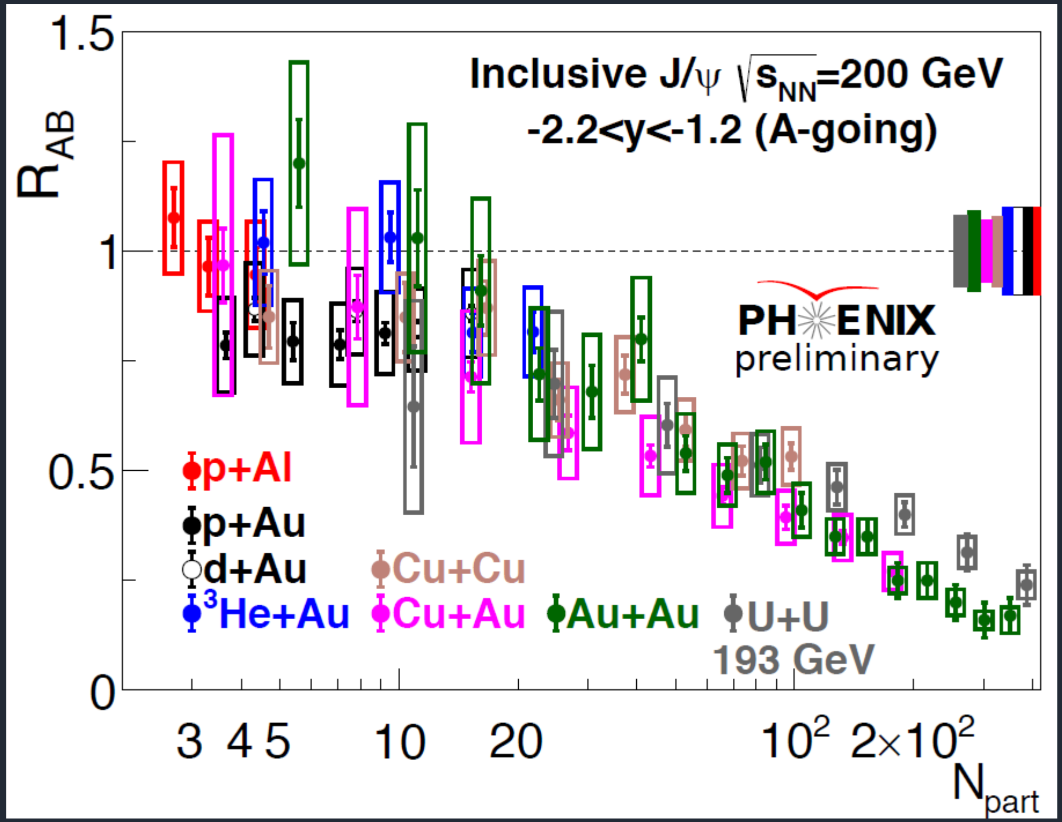
All models fairly describe the data

↓

but large uncertainties associated to charm cross section and shadowing (data precision better than the theory one)

AA: J/ψ R_{AA} in various systems

- Further constraints to the models may also come from comparison of different systems



RHIC: many different AA collisions investigated

- smooth suppression pattern from pA to AA
- R_{AA}<1 already in pA → CNM effects

precise pA measurements needed to quantitatively interpret AA results

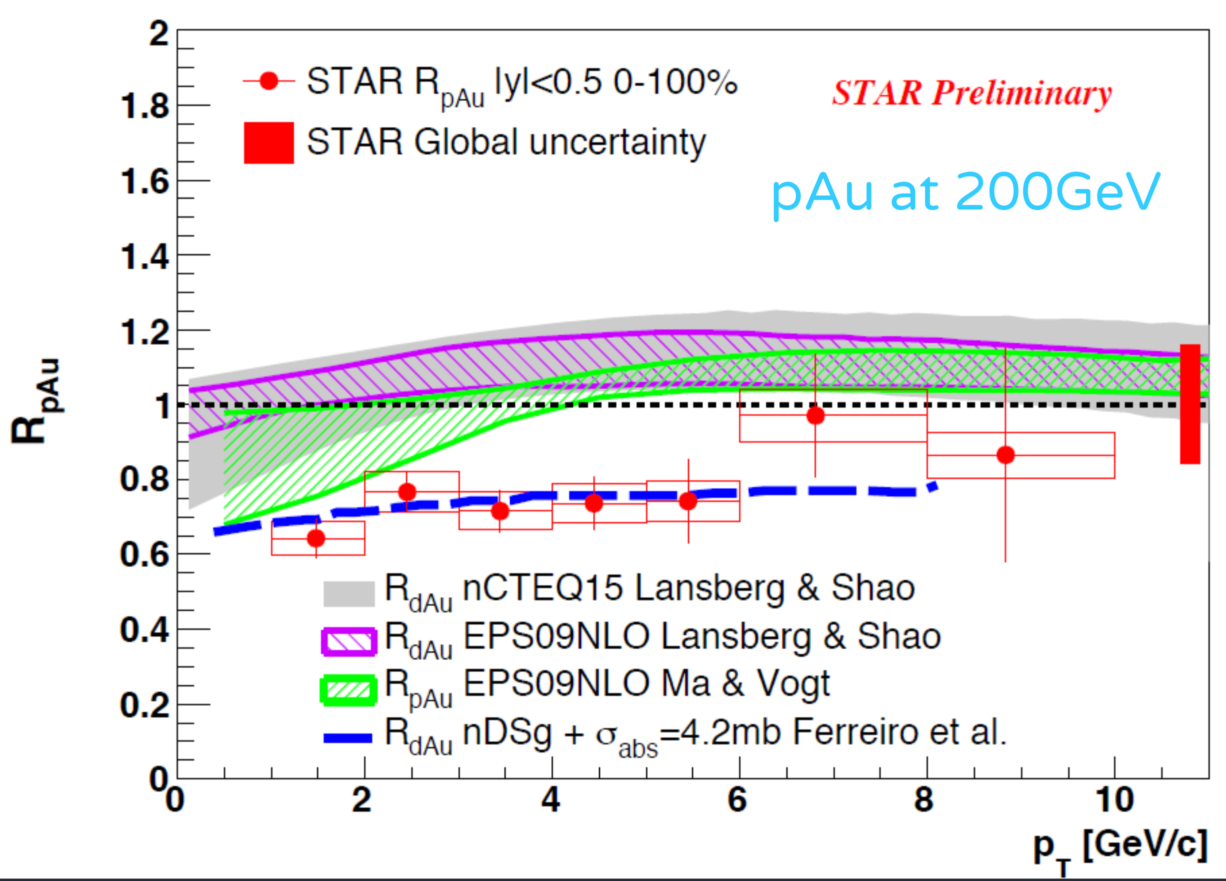
J/ψ in dA / pA

RHIC:

J/ψ R_{pA} shows a slightly increasing trend towards high p_T

shadowing models predict R_{pA} slightly higher than unity

data allow the inclusion of an additional contribution on top of shadowing, as the $c\bar{c}$ break up in medium



J/ψ in pA

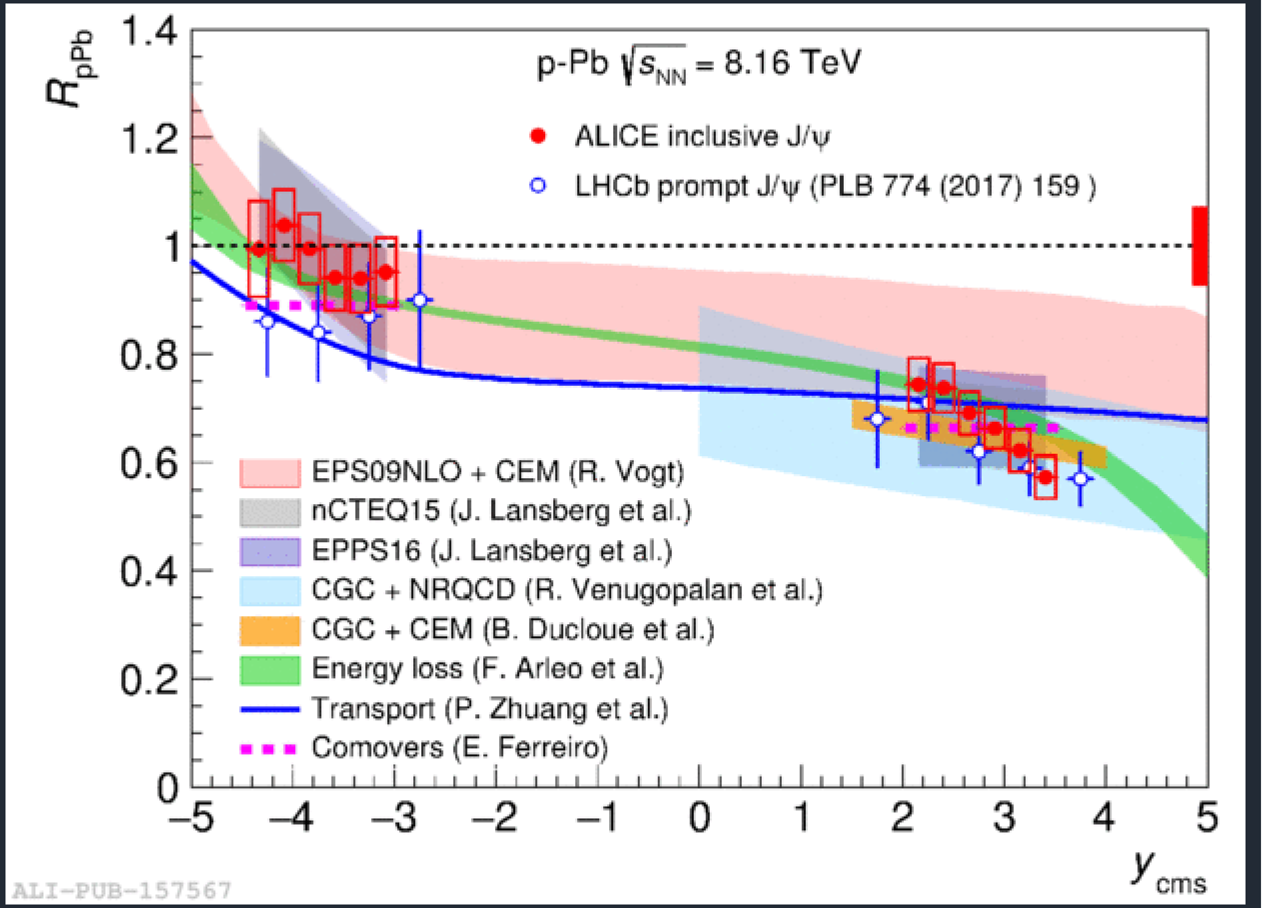
ALICE, JHEP07 (2018) 160
LHCb, PLB 774 (2017) 159

LHC:

CNM effects affect J/ψ production mainly at forward-y and low p_T

good agreement between data and models based on shadowing, CGC, energy loss

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



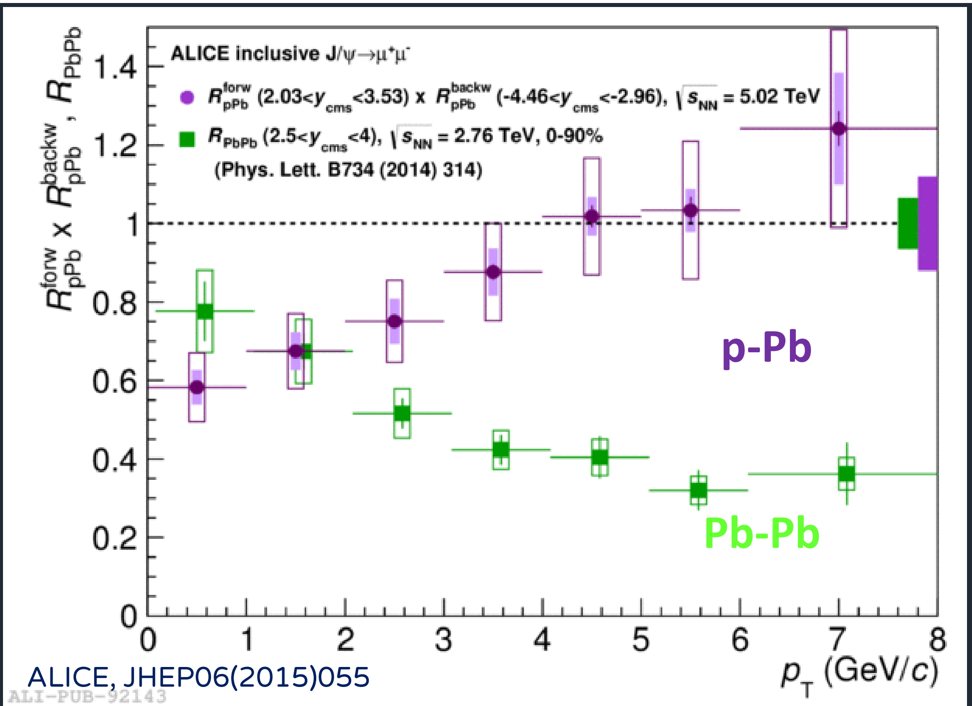
p-going direction: 2.3 10^{-5}<x<1.5 10^{-4}
Pb-going direction: 1.5 10^{-2}<x<10^{-1}

J/ψ: pA vs AA

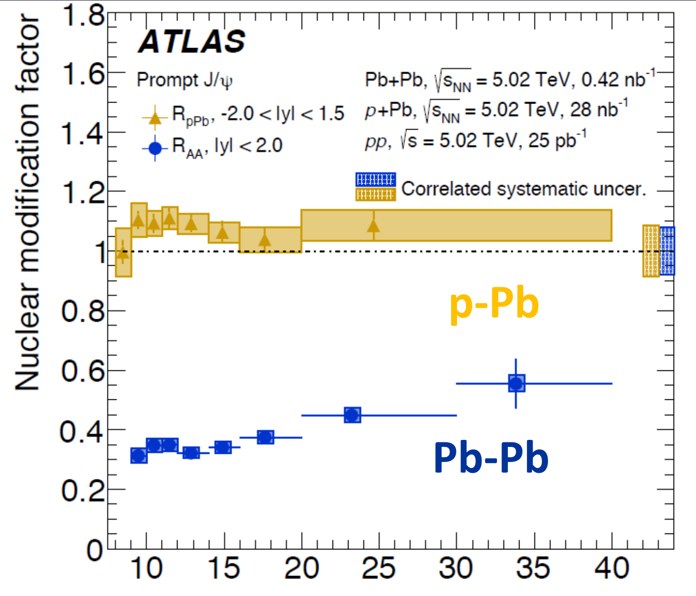
Can the suppression in AA be due to CNM effects?

assume $R_{AA} = R_{pA} \times R_{Ap}$ (as for shadowing dominance)

comparison of pA and AA results indicates that CNM effects cannot account for the observed R_{AA} at high p_T

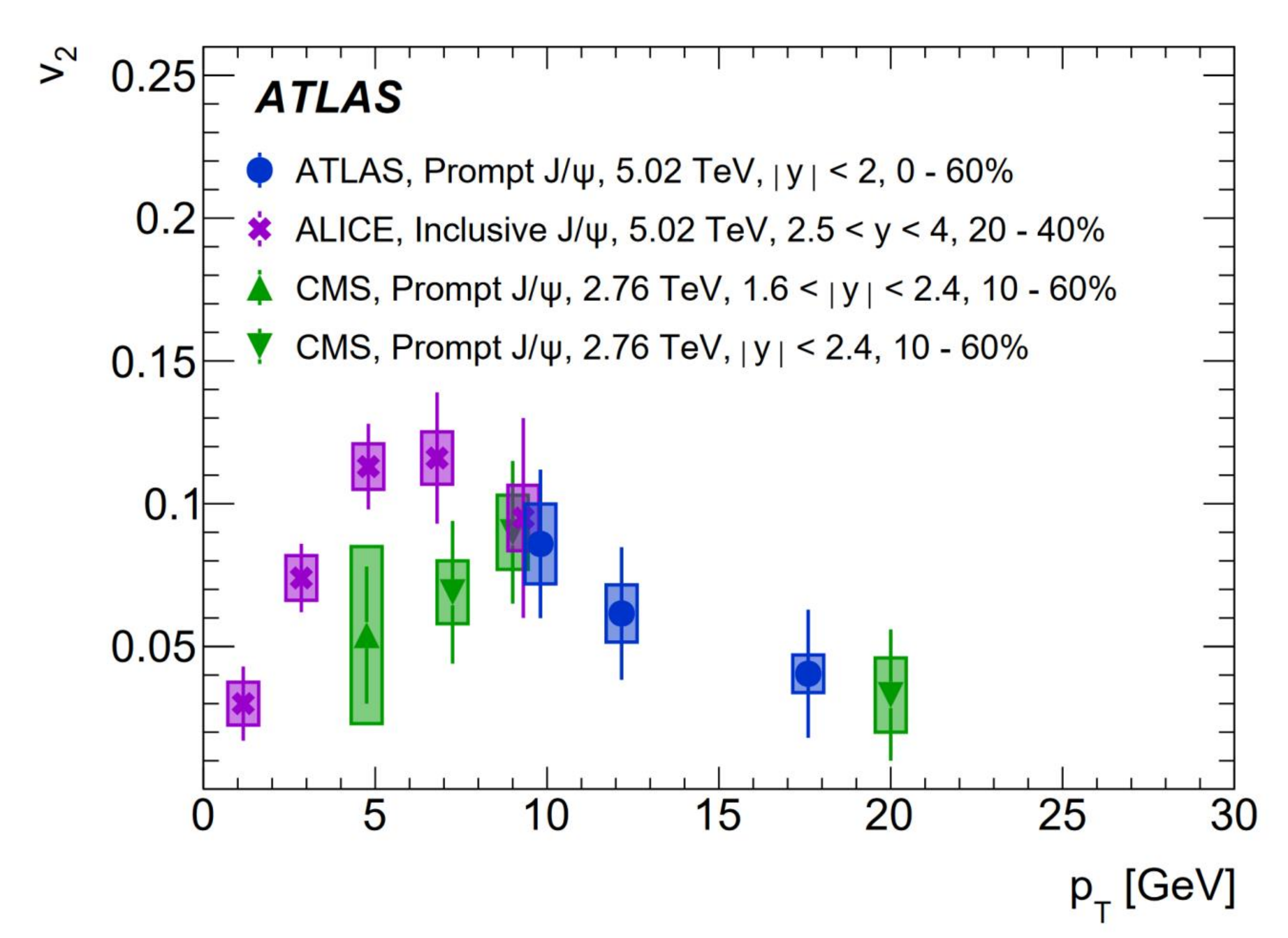


ALICE, JHEP06(2015)055



ATLAS, EPJC78(2018)762
ATLAS, EPJC78(2018)171

J/ψ elliptic flow in AA



J/ψ from recombination should inherit the thermalized charm flow

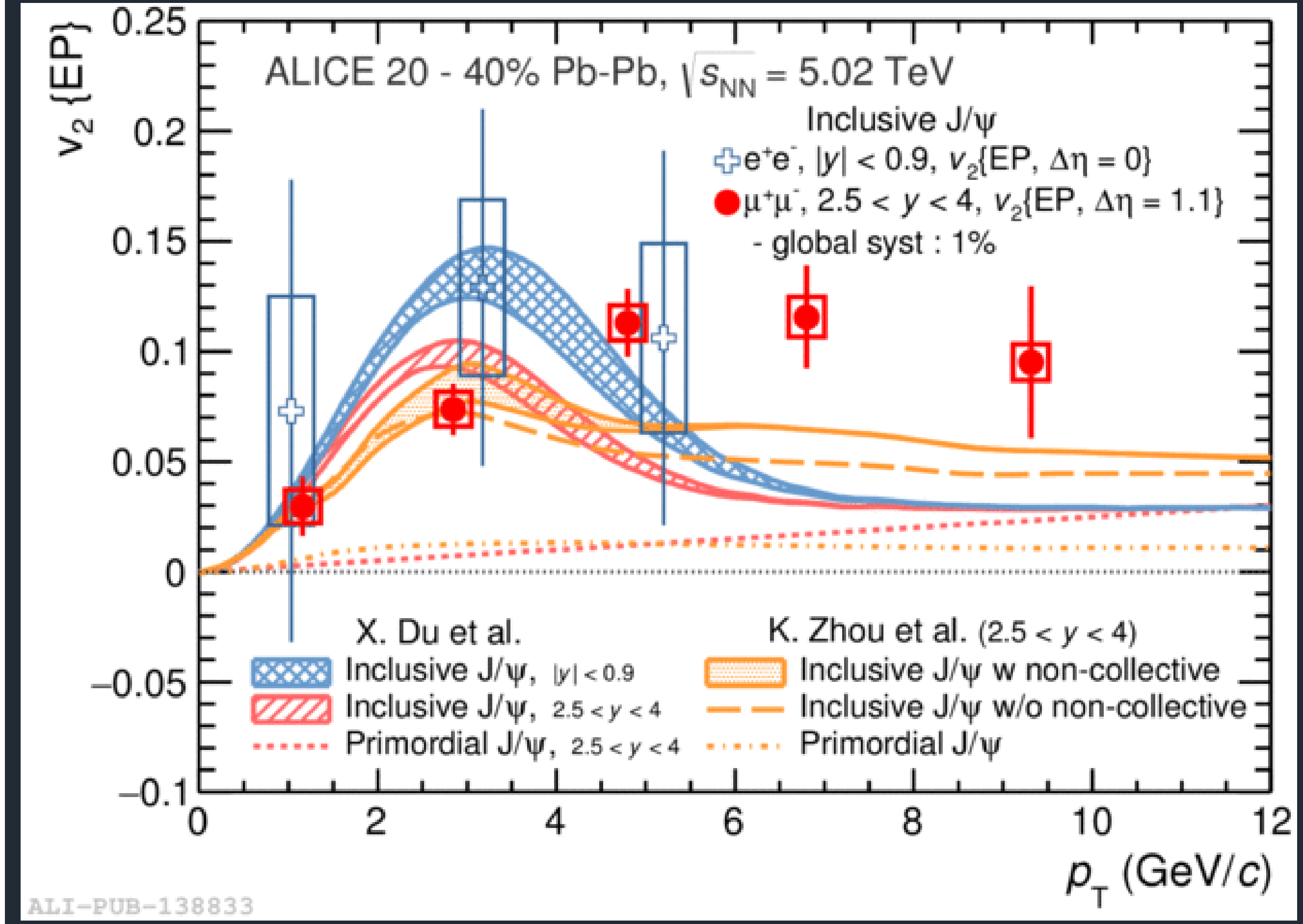
➡ J/ψ v_2 measurement over a broad p_T range

low p_T:
evidence for non-zero flow
(ALICE, 7σ effect in $4<p_T<6$ GeV/c)

high p_T:
$v_2 \neq 0$ (ATLAS and CMS)

ALICE, PRL 119 (2017) 242301, arXiv:1811.12727
ATLAS, EPJC 78 (2018) 784
CMS, EPJC 77 (2017) 252

J/ψ elliptic flow in AA



ALICE, PRL 119 (2017) 242301, arXiv:1811.12727
ATLAS, EPJC 78 (2018) 784
CMS, EPJC 77 (2017) 252

J/ψ from recombination should inherit the thermalized charm flow

- J/ψ v_2 measurement over a broad p_T range

  low p_T:
  evidence for non-zero flow (ALICE, 7σ effect in 4<p_T<6 GeV/c)

  high p_T:
  $v_2 \neq 0$ (ATLAS and CMS)

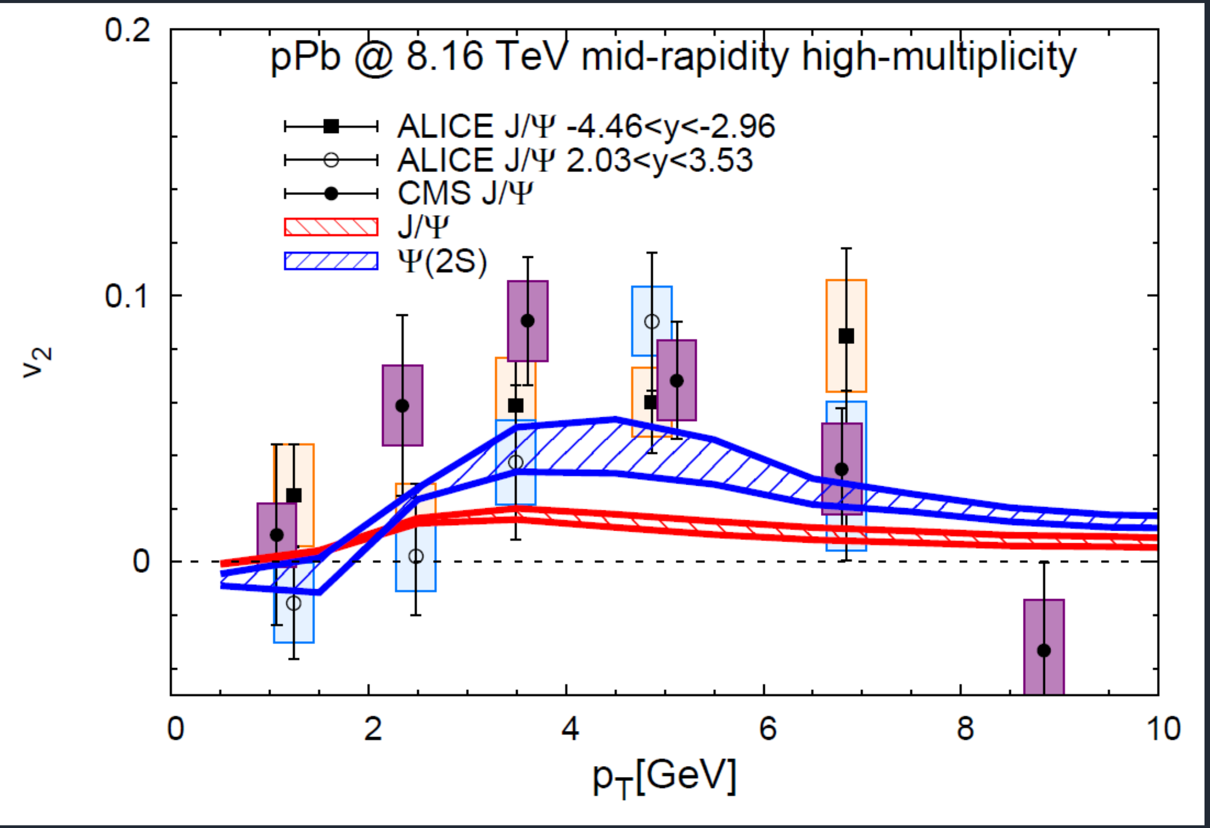
- Comparison with models:

  low p_T:
  v_2 reproduced including a strong J/ψ regeneration component

  high p_T:
  energy loss path-length dependence plays a role, but v_2 still underestimated

J/ψ elliptic flow in pA

➡ In p-Pb almost no influence from regeneration and path-length effects is expected



however, a significant non-zero v_2 is observed in high-multiplicity p-Pb

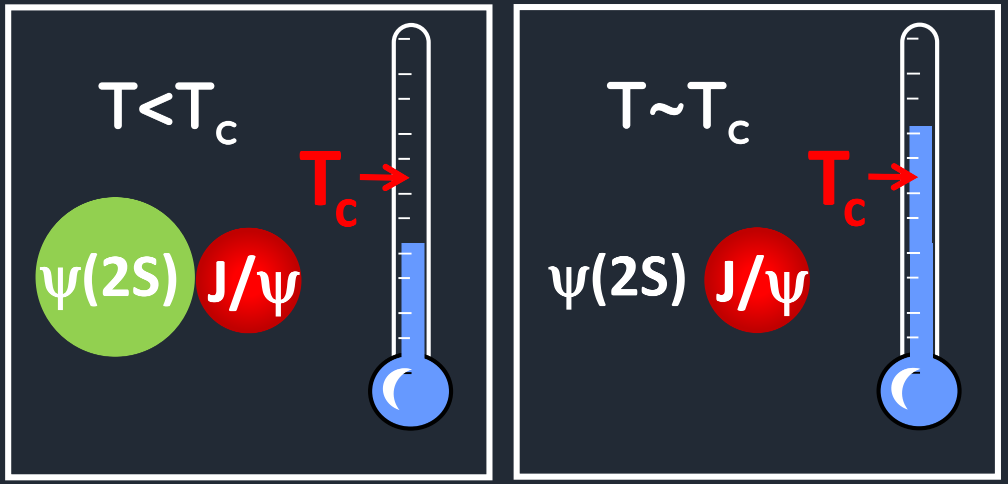
➡ At intermediate p_T, v_2 similar to the one measured in Pb-Pb
→ suggestive of a common p-Pb and Pb-Pb mechanism?

➡ Models where the v_2 originates from final-state interactions in the fireball + regeneration underestimate the data

ALICE, PLB 780 (2018) 7
CMS, PAS HIN-18-010
Rapp et al, JHEP03(2019)015

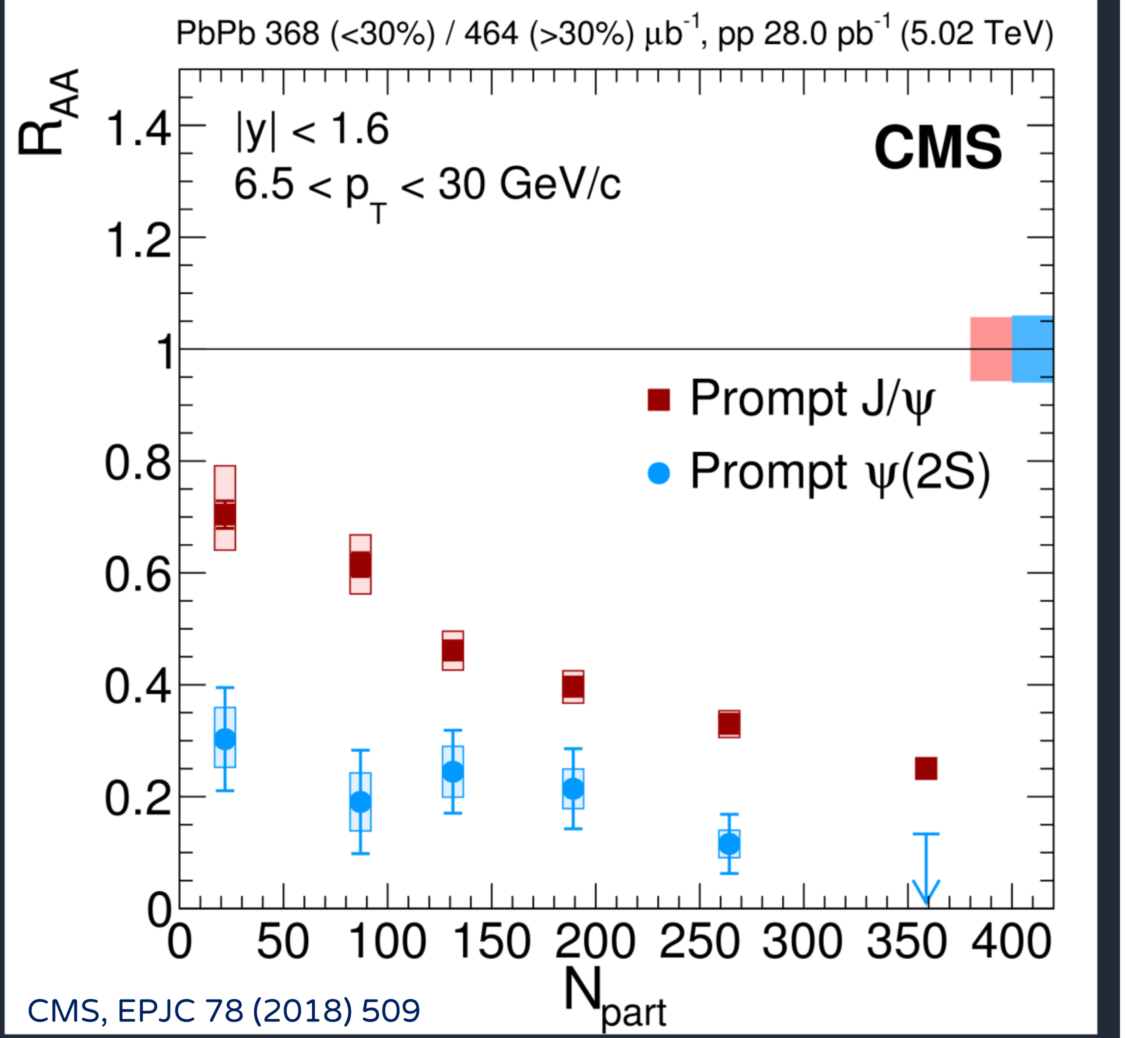
ψ(2S) in AA

- ψ(2s) is a loosely bound state (binding energy: ψ(2s)~60 MeV, J/ψ ~640MeV)

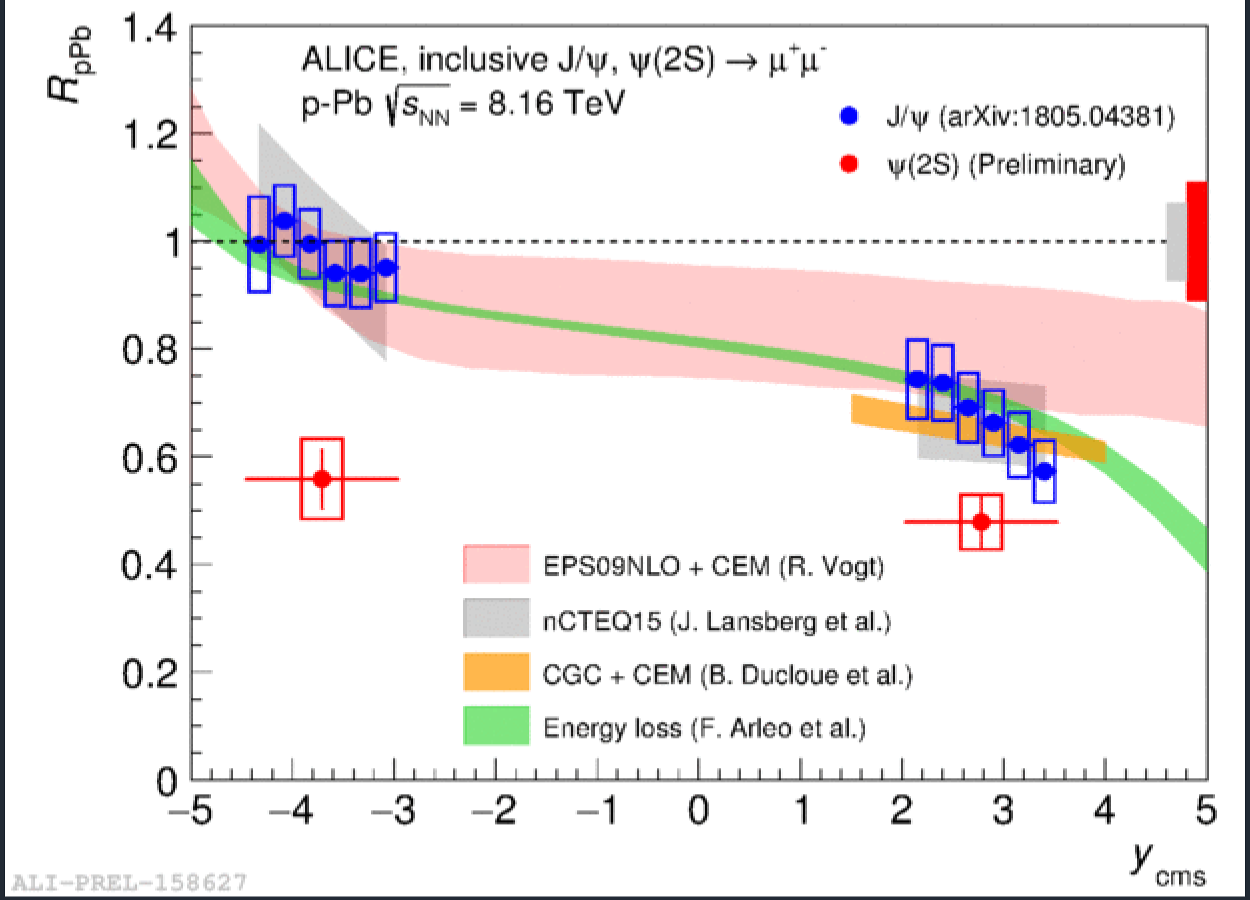


ψ(2S) suppression stronger than the J/ψ at high p_T, as expected in a sequential suppression scenario

High p_T



ψ(2S) in pA



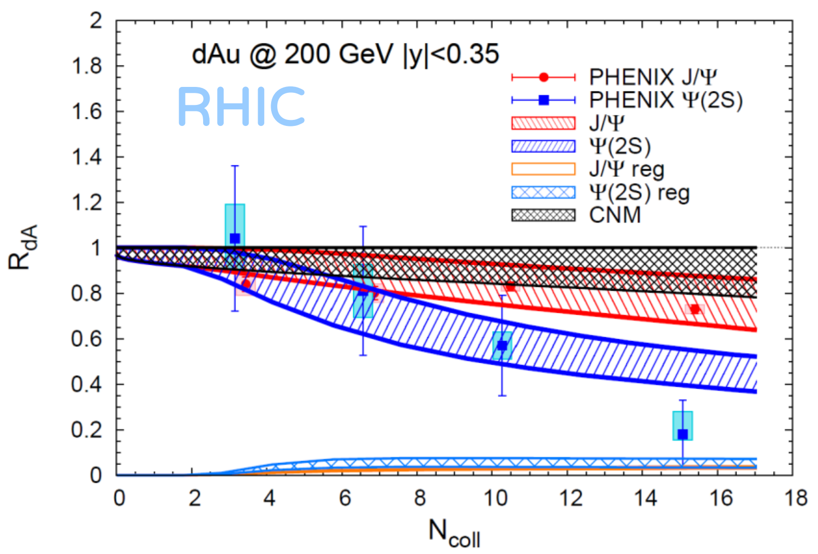
ψ(2S) suppression is stronger than the J/ψ one, in particular at backward-y and at low p_{T}, both at RHIC and LHC

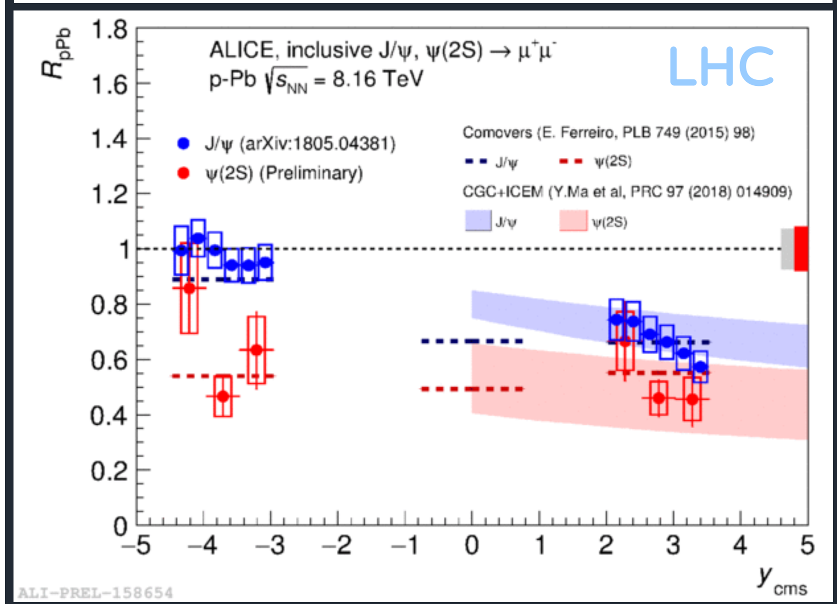
➡ different behavior for J/ψ and ψ (2S) was not expected, since at LHC (RHIC) energies

formation time > crossing time

shadowing/energy loss:
- similar for J/ψ and ψ(2S)
- not enough to describe the ψ(2S) suppression at backward-y

ψ(2S) in pA





➡ additional final state effects are needed to describe the data

- soft color exchanges between hadronizing $c\bar{c}$ and comoving partons (Ma, Venugopalan)
- "classical" comover model, with break-up σ tuned on low energy data (Ferreiro)
- regeneration and dissociation in the QGP and hadronic phase (Rapp, Zhuang)

Bottomonium

Bottomonium family

Binding Energy (MeV):

ϒ(1S):~1100 ϒ(2S):~500 ϒ(3S):~200

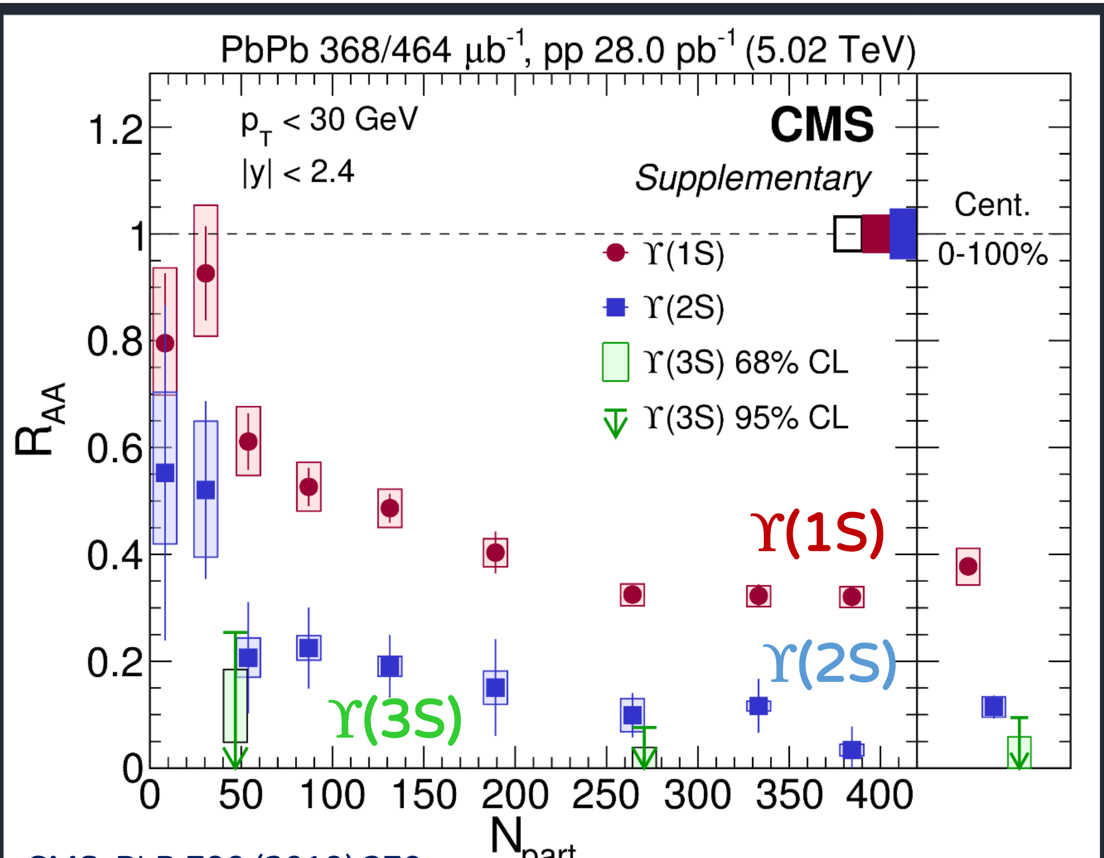
Three states with different sensitivity to the medium

⬇

Limited recombination and no B feed-down (but large feed-down from excited states)

⬇

interesting for sequential suppression studies



CMS, PLB 790 (2019) 270

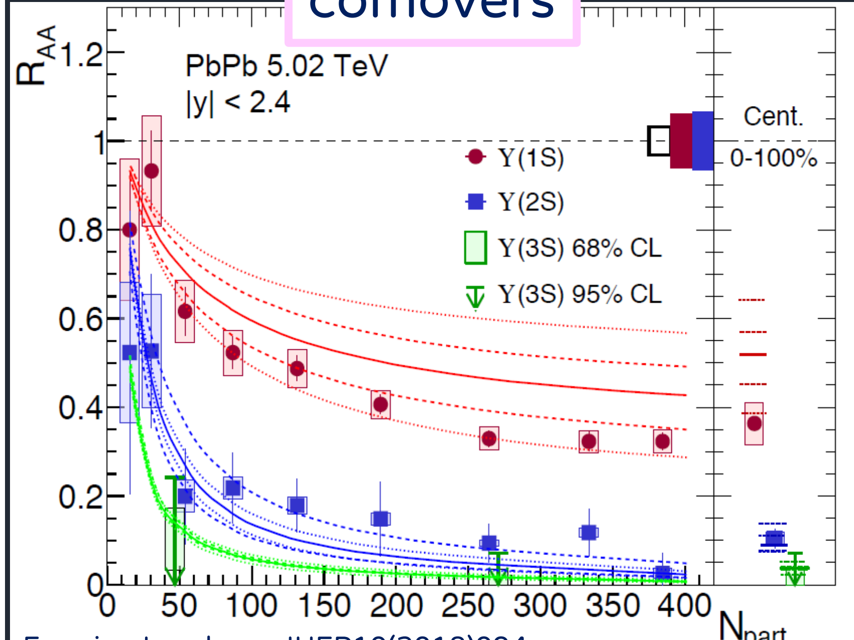
Strong suppression vs centrality for all ϒ(nS) (factor ~2 for ϒ(1S), ~9 for ϒ(2S))

➡ lower R_{AA} values for excited states compatible with sequential suppression

➡ suppression of directly produced ϒ(1S)? Feed down contribution ~ 30%

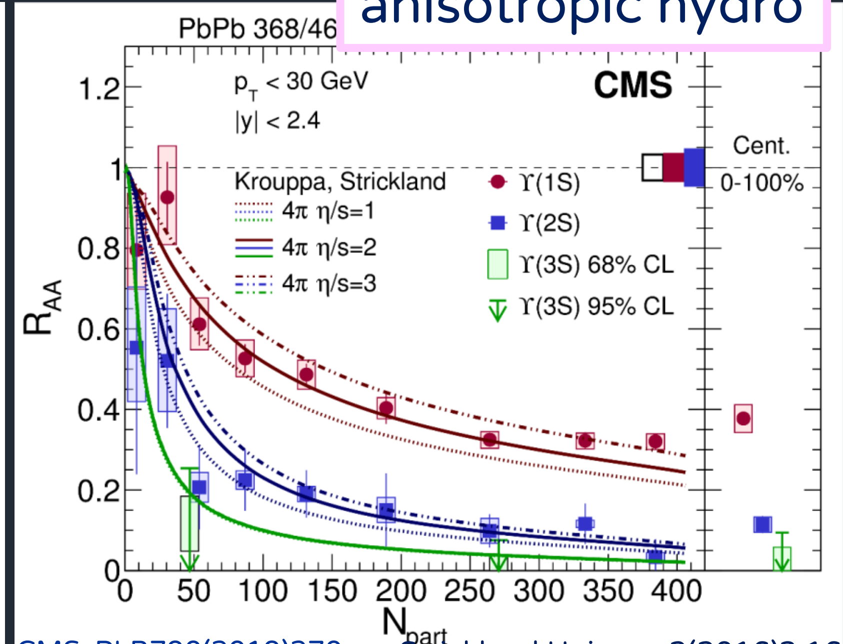
Comparison to theory

comovers



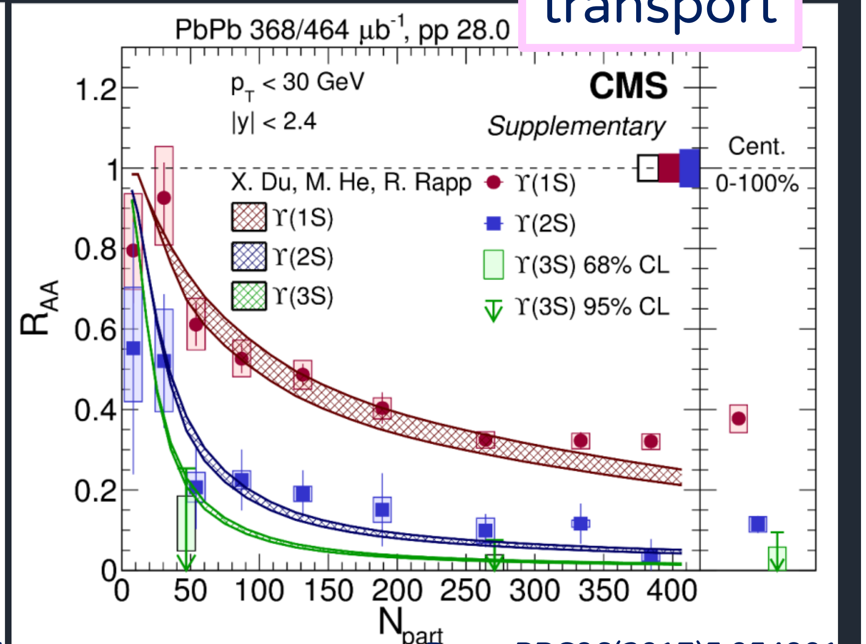
Ferreiro, Lansberg, JHEP10(2018)094

anisotropic hydro



CMS, PLB790(2019)270 Strickland,Universe2(2016)3,16

transport



Rapp, PRC96(2017)5,054901

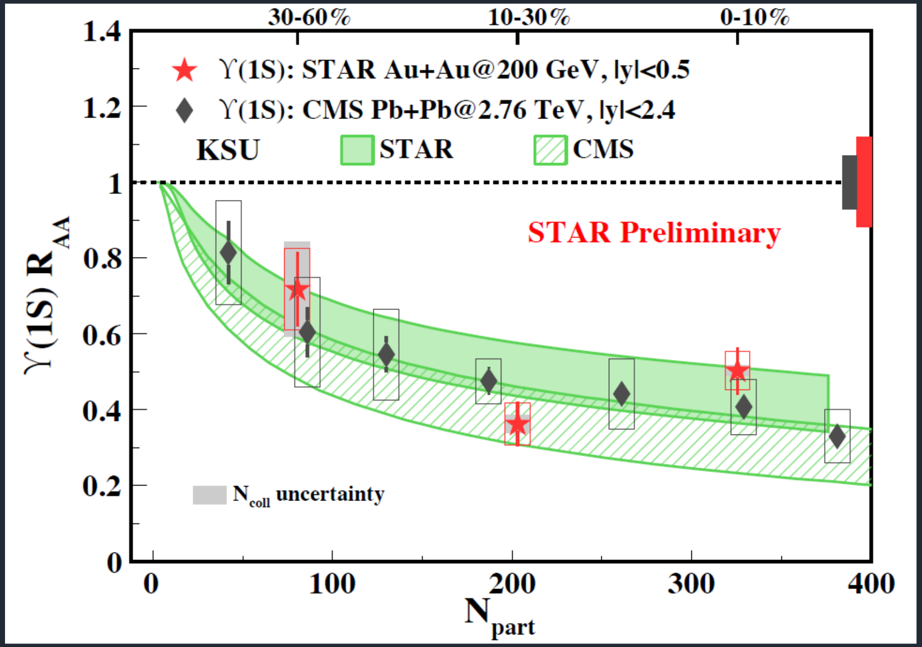
Models agree with data within uncertainties

- ➡ regeneration now included in most of the models, but contribution is small
- ➡ comparison to models might help in determining the initial QGP T

$\sqrt{s_{NN}}$ = 5.02TeV → T~630 MeV (Krouppa-Strickland) T~550-800 MeV (Du, He, Rapp)

Bottomonium at RHIC

anisotropic hydro



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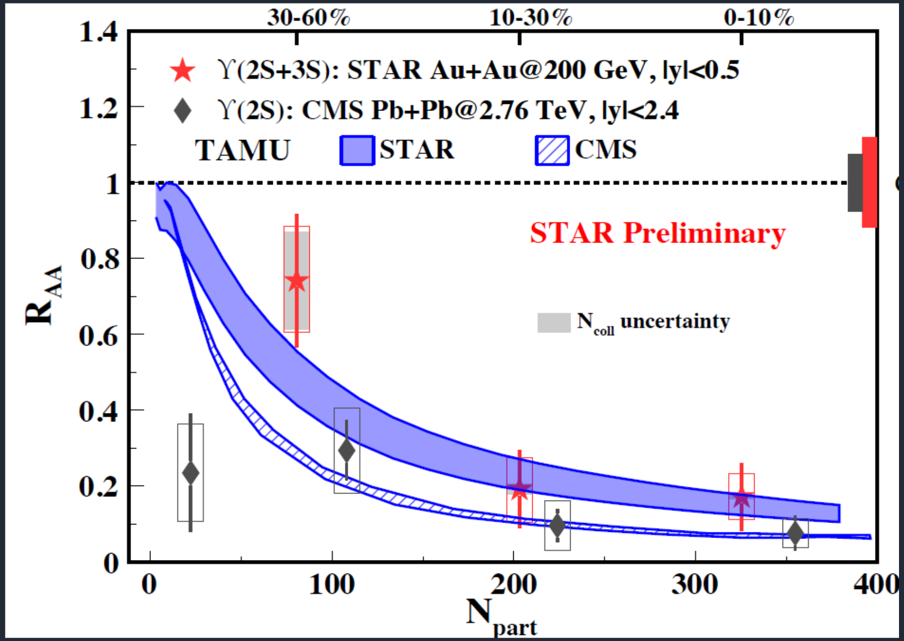


Similar Υ(1S) suppression, within uncertainties, at RHIC and LHC
→might imply weak or no suppression of direct Υ(1S) at LHC

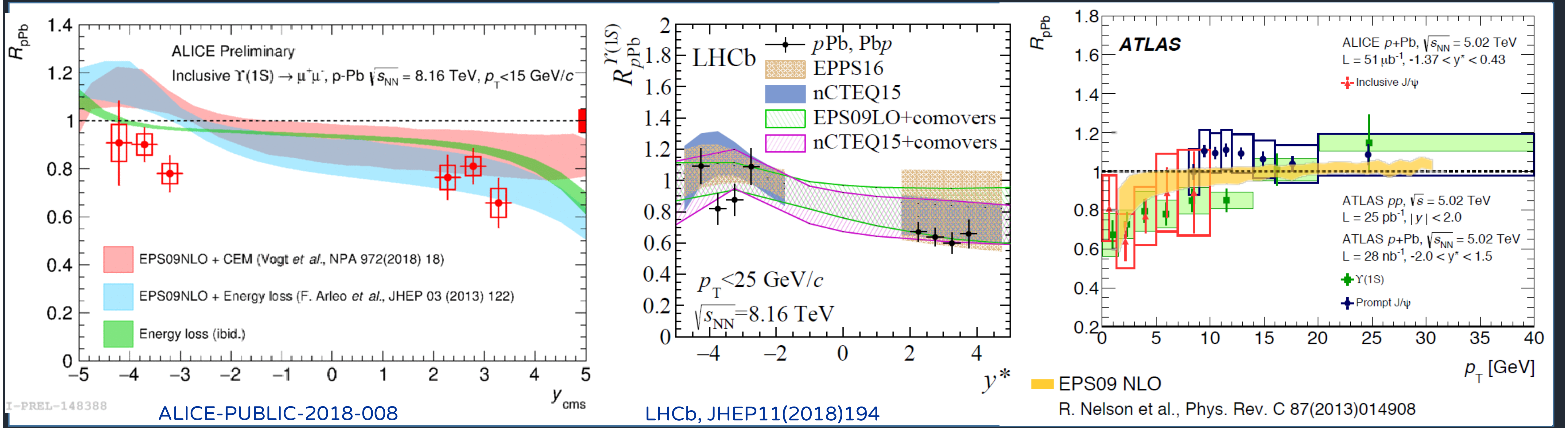
Excited states suppression stronger at LHC

➡ Models describing LHC results also describe RHIC ones

T(RHIC) ~ 440 MeV
T(LHC) ~ 630 MeV
(M. Strickland, arXiv:1807.07452)

ϒ(1S) in pA collisions

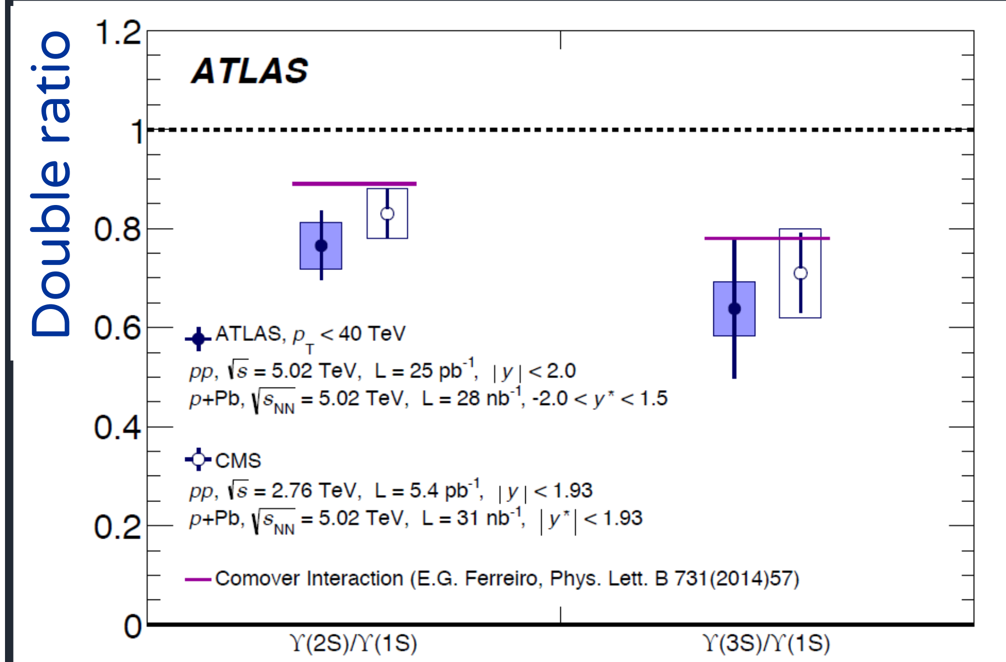
- Similar size of cold nuclear matter effects as for J/ψ



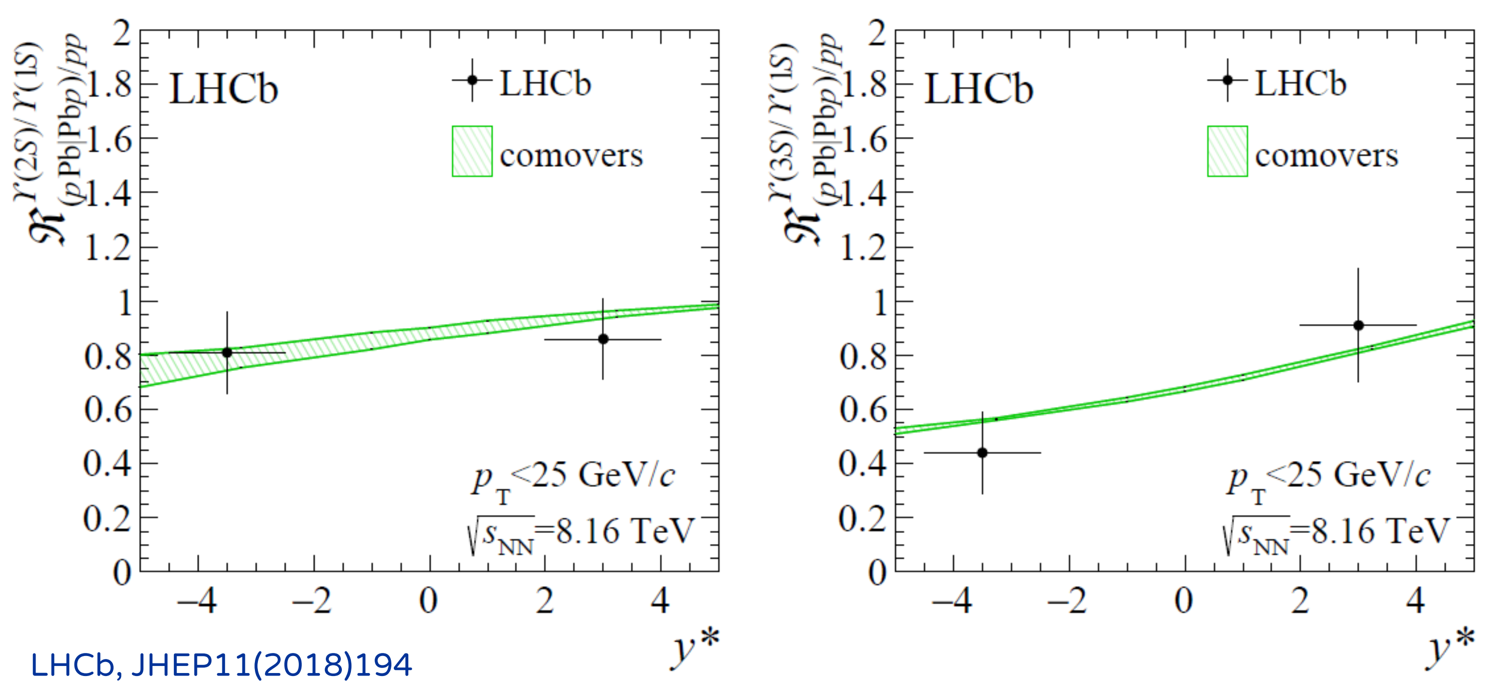
Shadowing and energy loss models fairly describe data at forward-y and mid-y, but slightly overestimate backward-y R_{pA}

Excited states in pPb

➡ Excited Υ states show a stronger suppression than Υ(1S) in pPb wrt pp



ATLAS, EPJC78(2018)171, CMS, JHEP04(2014)103



LHCb, JHEP11(2018)194

Final state effects might be needed to explain the observations, as for the charmonium case

Strong suppression for Υ(3S) wrt Υ(1S) at bck-y, consistent with comovers model

Conclusions

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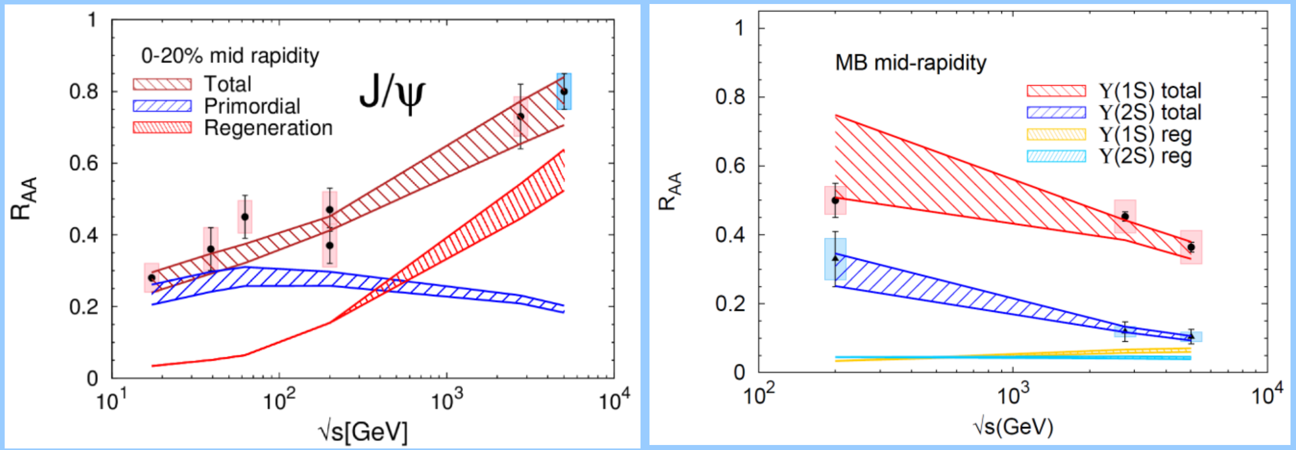
AA

- J/ψ described by interplay of suppression and recombination
- stronger suppression for $\psi(2S)$ than J/ψ
- hint for sequential suppression of bottomonium states



Rapp,NPA(2017)967,216, PRC96(2017)054901

pA

- modification of J/ψ and $\Upsilon(1S)$ yields understood in terms of “standard” CNM effects
- excited states suppression points to final state effects

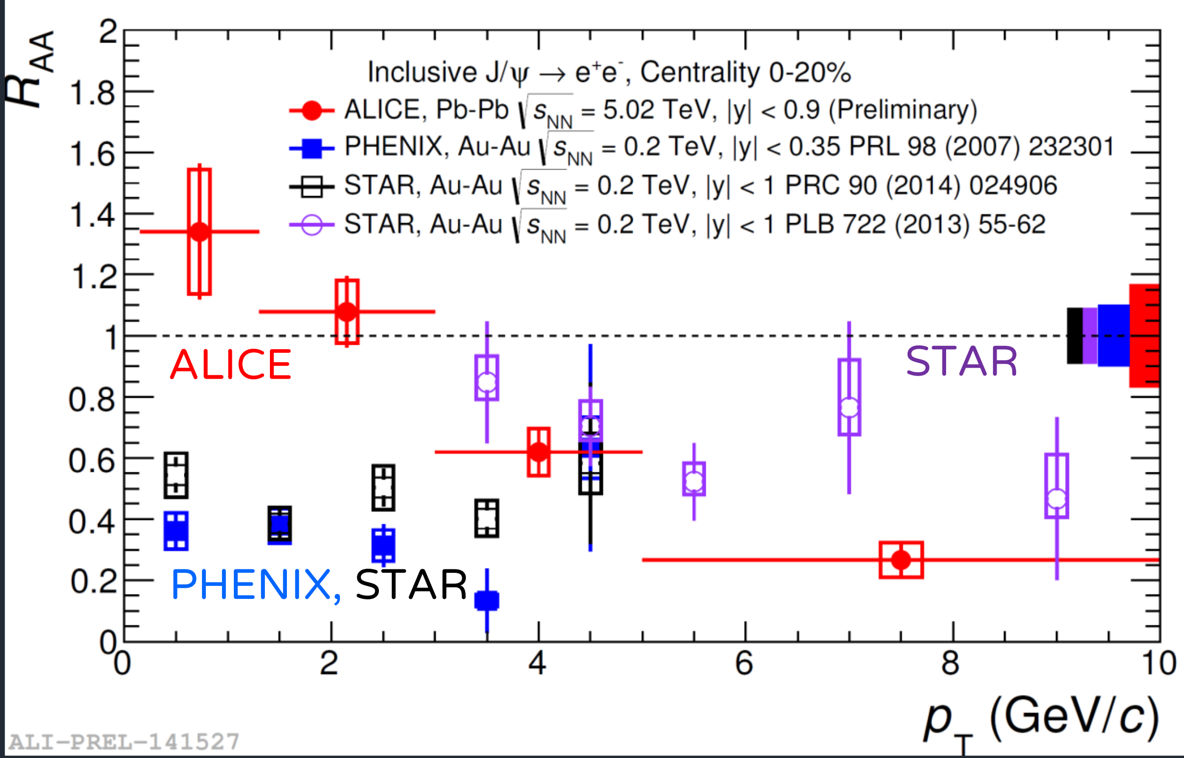
➡ High-precision results should now provide constraints to theory models in order to have a consistent picture for all quarkonium states in all systems

Thanks!

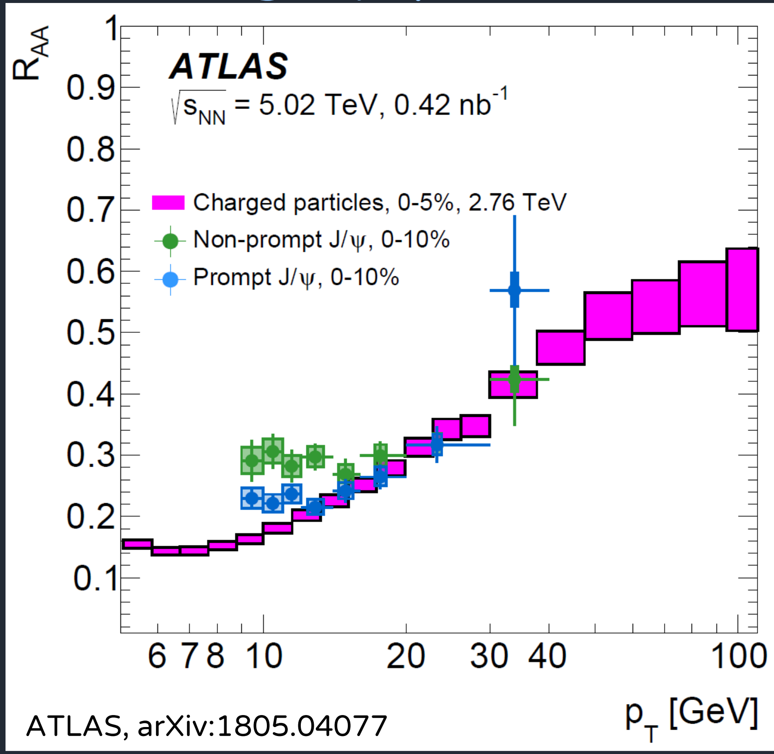
Backup Slides

AA: J/ψ R_{AA} vs p_T

Low p_T J/ψ



High p_T J/ψ



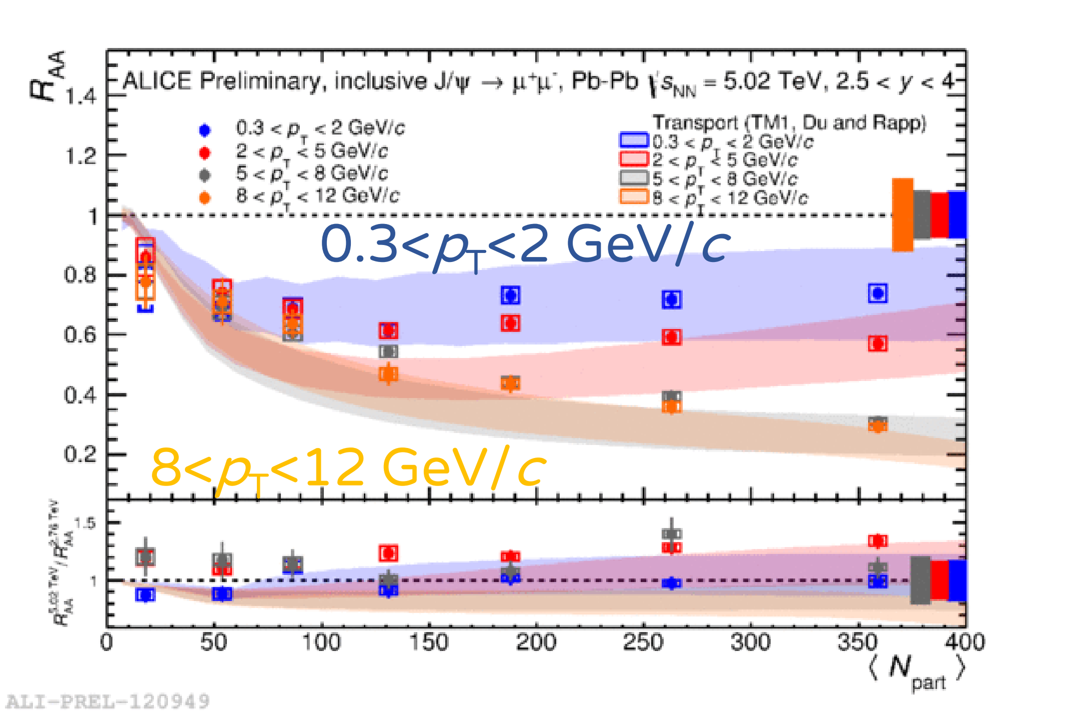
➡ different p_T dependence at RHIC and LHC

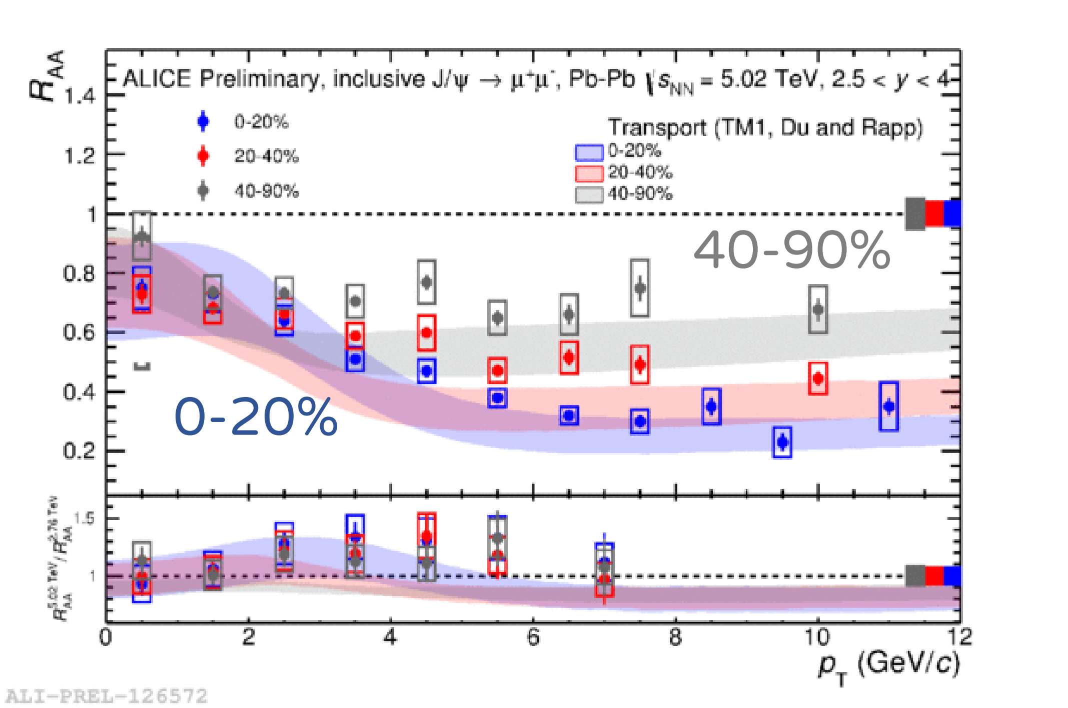
suppression + regeneration mechanisms at play

➡ hint for a high p_T rise, as for charged hadrons

weak regeneration expected, parton energy-loss at play?

Multi-differential J/ψ R_{AA}





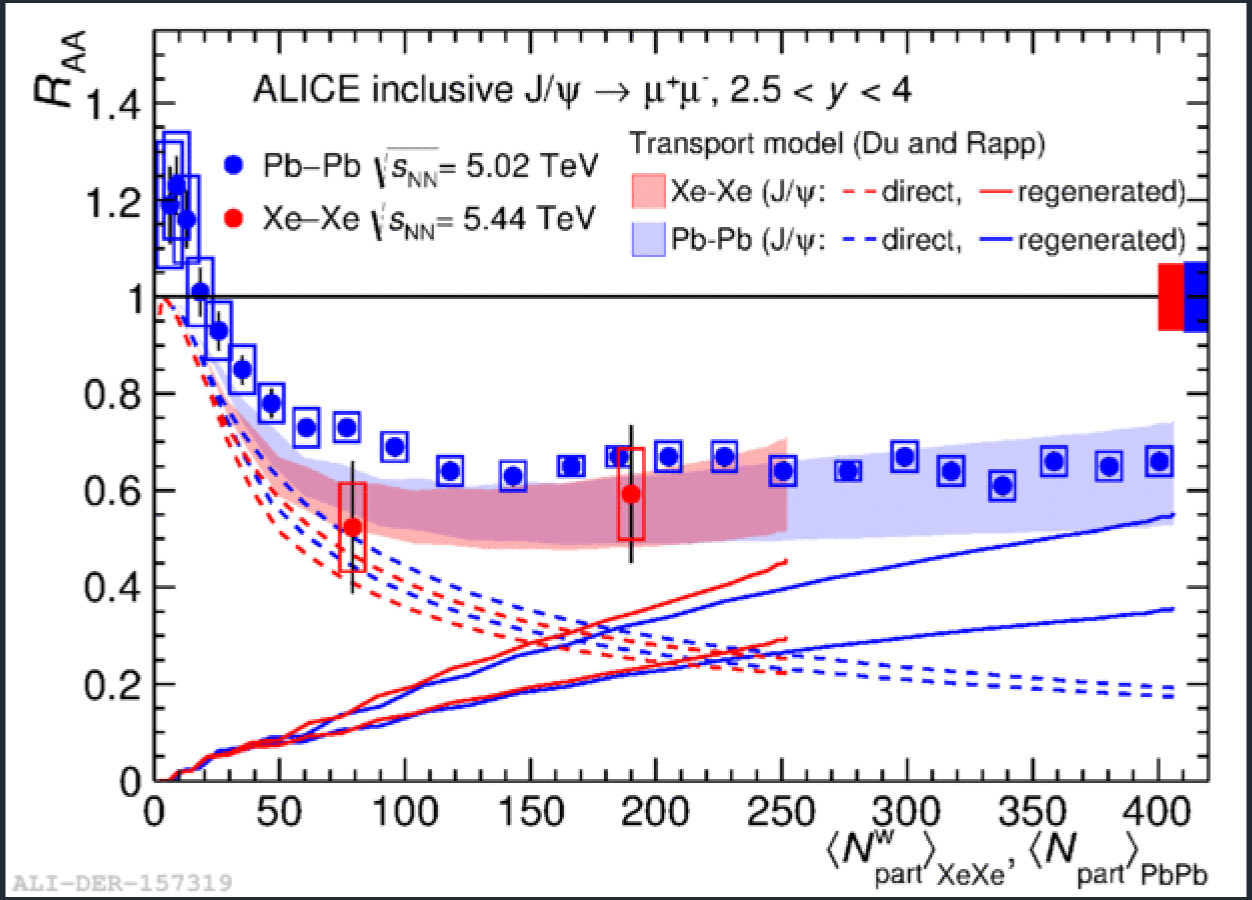
Zhao et al., NPA 859 (2011) 114

- R_{AA} vs p_T for different centrality bins (and vice-versa) at $\sqrt{s_{NN}}$=5.02 TeV

Striking features observed in ALICE results
→ no R_{AA} centrality dependence in 0.3<p_T<2 GeV/c
→ ~70% suppression for central events at p_T~10 GeV/c (as for CMS and ATLAS)

J/ψ R_{AA} in Xe-Xe collisions

- Further constraints to the models may also come from comparison of different systems

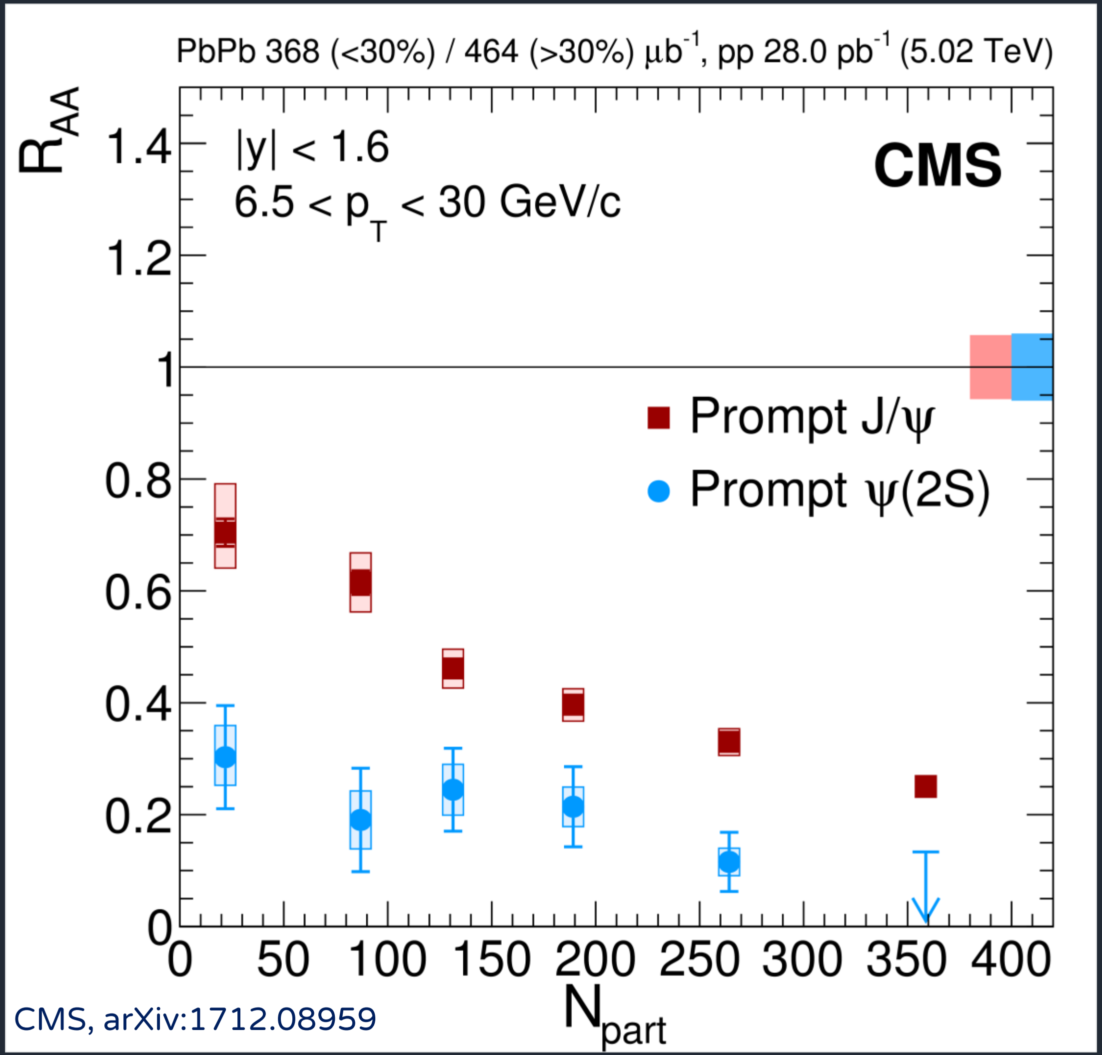


ALICE, arXiv:1805.04383

- **LHC:** few hours XeXe run in 2017
  - Similar R_{AA} in Xe-Xe and Pb-Pb (A_{Xe} = 129, A_{Pb} = 208)
  - In TAMU transport model, for a given N_{part}
    - central collisions: the higher N_{coll} and $\sqrt{s_{NN}}$ lead to a slightly larger regeneration in XeXe
    - peripheral/semi-central collisions: the larger nuclear overlap in XeXe induces a stronger suppression
- Unfortunately, not all systems at RHIC and LHC have yet enough precision to allow detailed comparisons

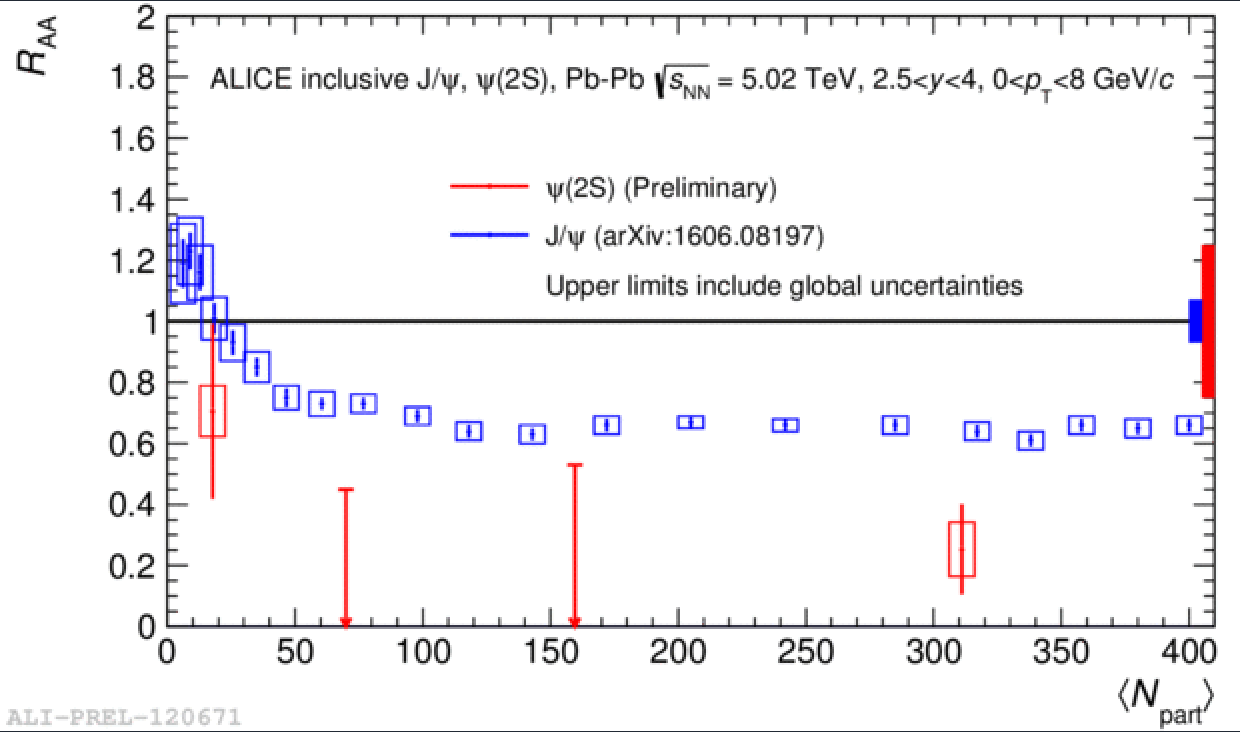
ψ(2S) in PbPb

High p_T



➡ Stronger ψ(2S) suppression wrt J/ψ over all centralities, both at high and low p_T

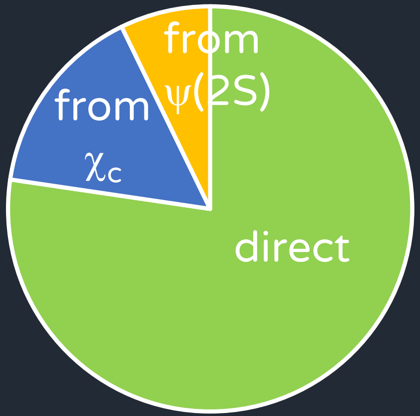
Low p_T



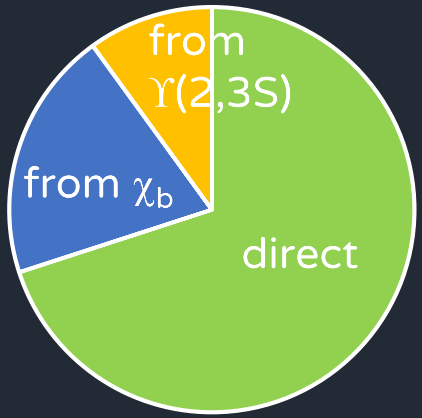
Quarkonium sequential melting

state	J/ψ	χ_c	ψ(2S)	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass(GeV)	3.10	3.51	3.69	9.46	10.0	10.36
ΔE (GeV)	0.64	0.22	0.05	1.10	0.54	0.20
r_o(fm)	0.50	0.72	0.90	0.28	0.56	0.78

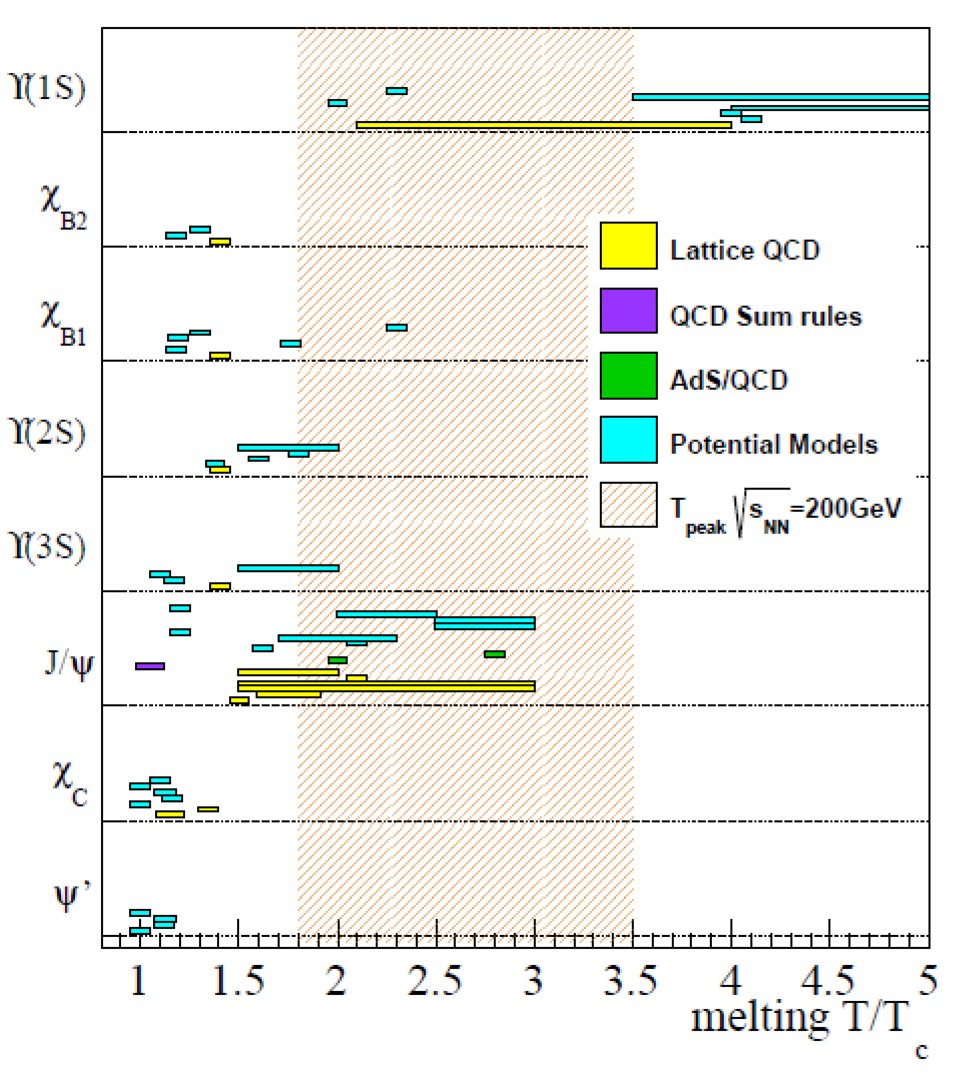
(Digal,Petrecki,Satz PRD 64(2001) 0940150)



Low p_T J/ψ

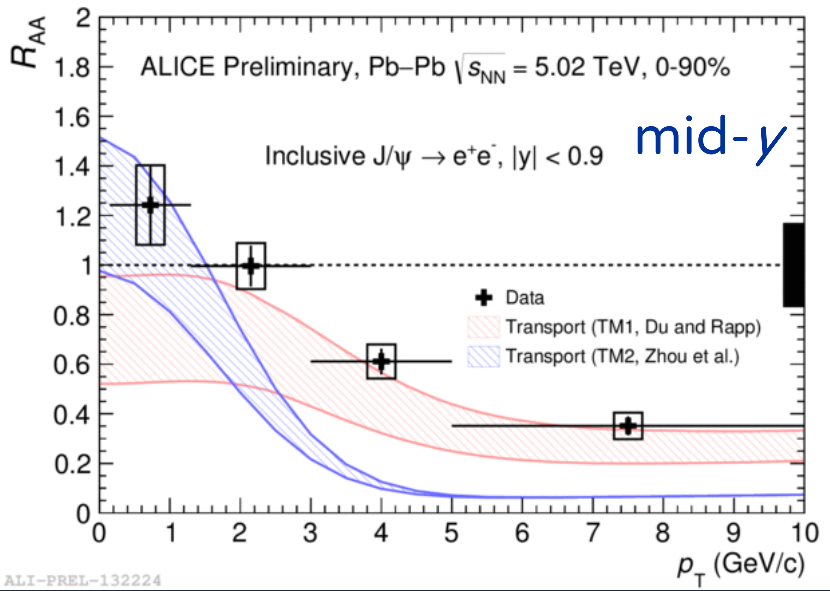


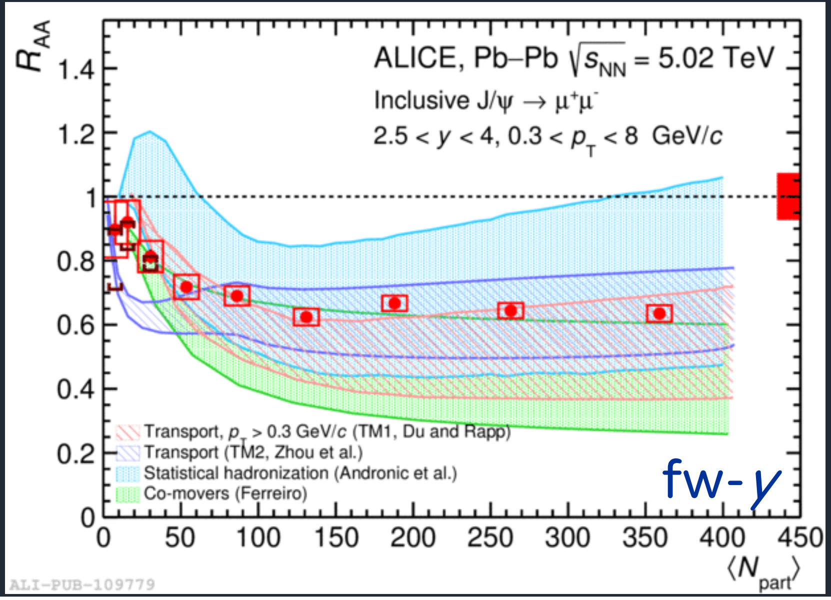
Low p_T ϒ(1S)



PHENIX, Phys.Rev C91, 024913

Low p_T: 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

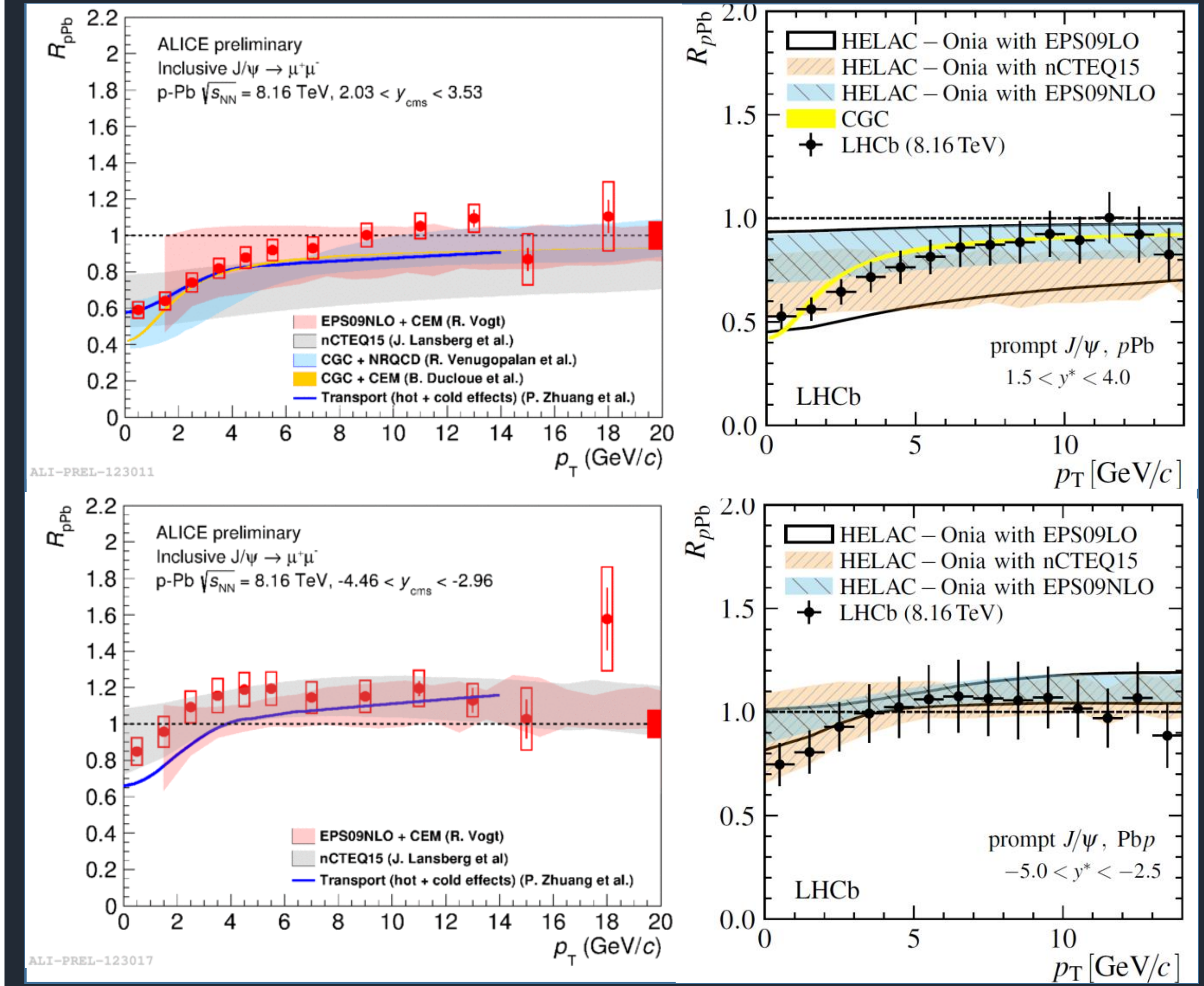
Comover model: J/ψ dissociated via interactions with partons - hadrons + regeneration contribution E. Ferreiro, PLB749 (2015) 98, PLB731 (2014) 57

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

All models fairly describe the data

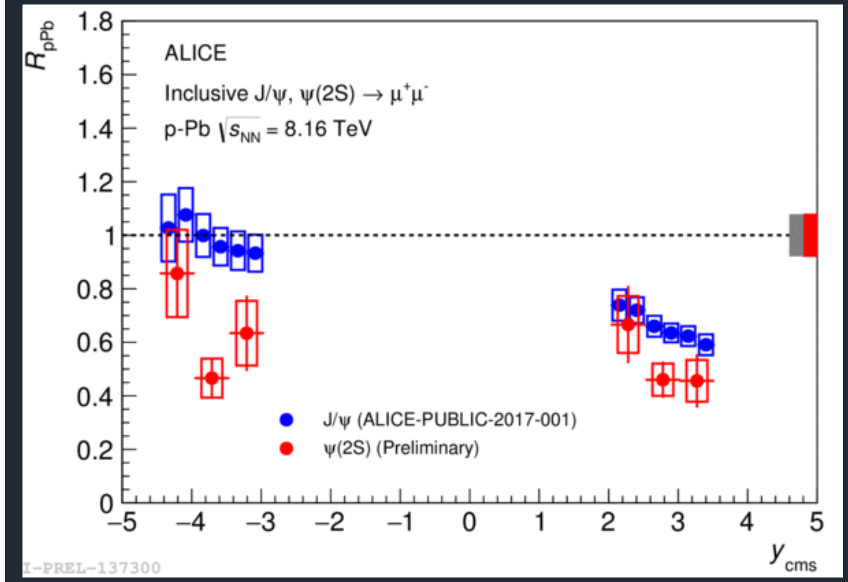
but large uncertainties associated to charm cross section and shadowing

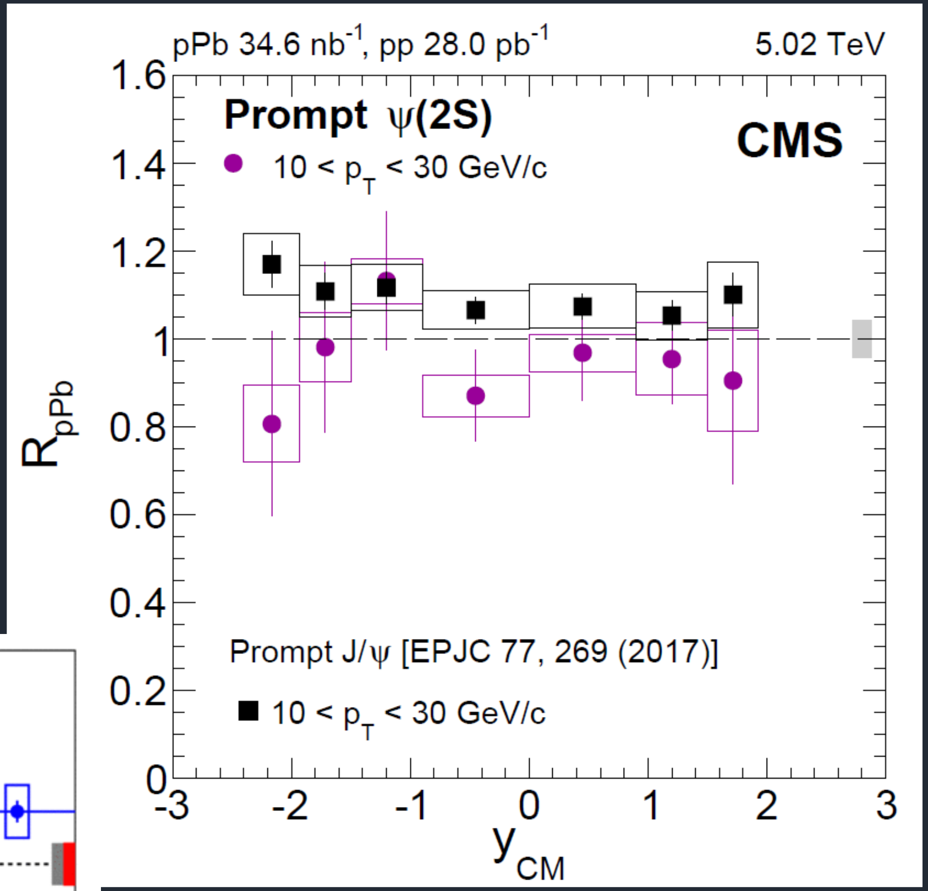
p_T dependence of J/ψ R_{pA}

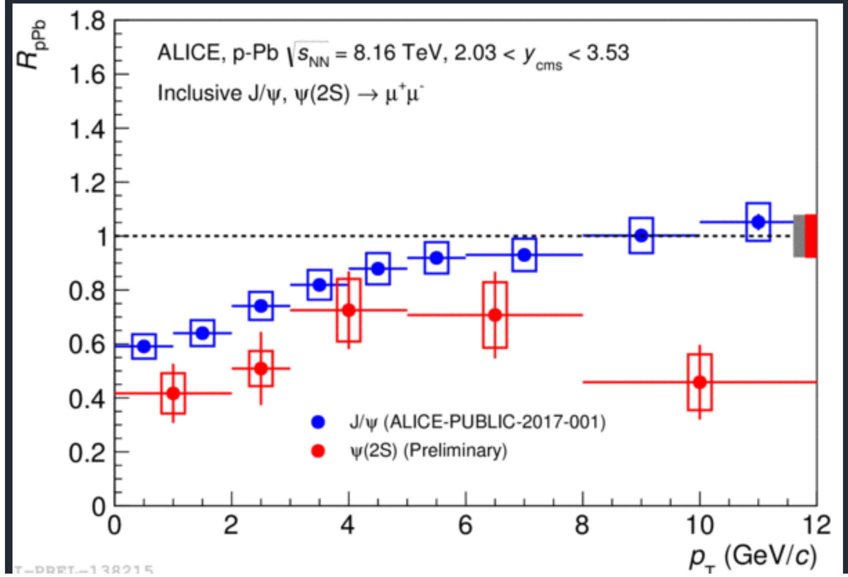


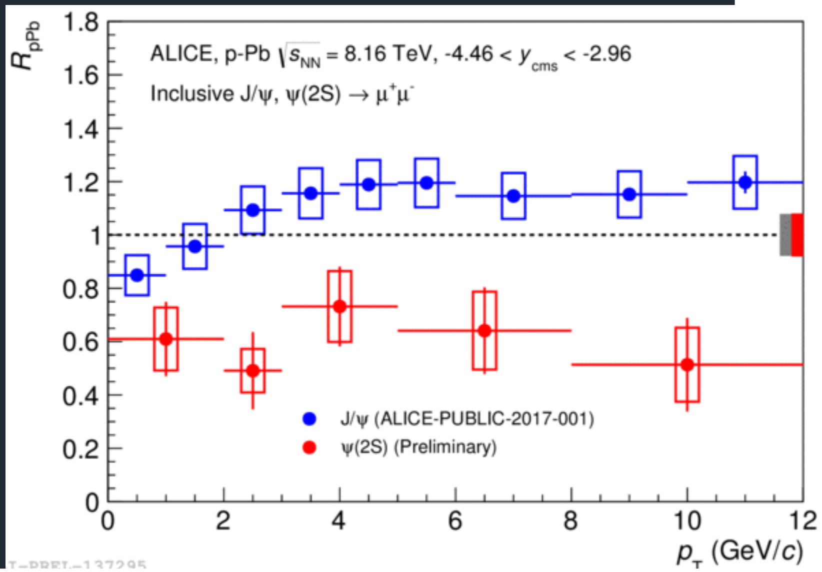
- Slightly different y coverage in ALICE and LHCb, but rather similar p_T dependences
- Shadowing and energy loss models describe R_{pA} vs p_T

J/ψ and ψ(2S) comparison in pA









Bottomonia in AA

Three states characterized by very different binding energies:

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

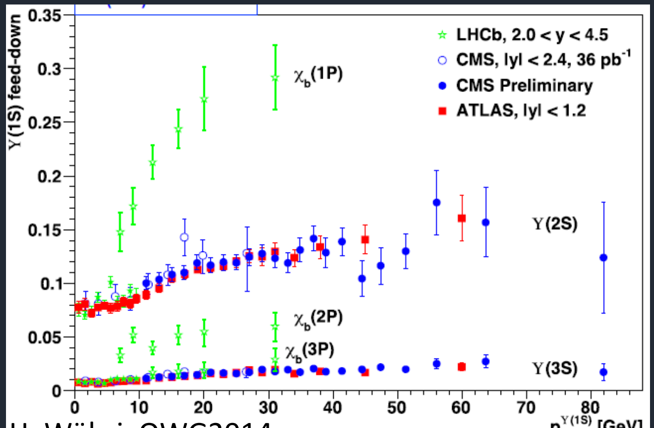
Υ(3S) Υ(2S) Υ(1S) → Sensitive in very different ways to the medium

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?

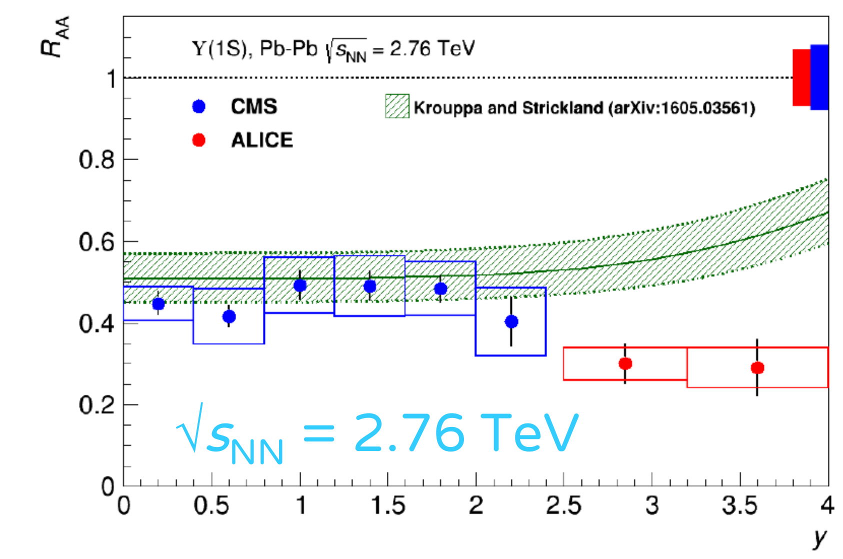
Some drawbacks

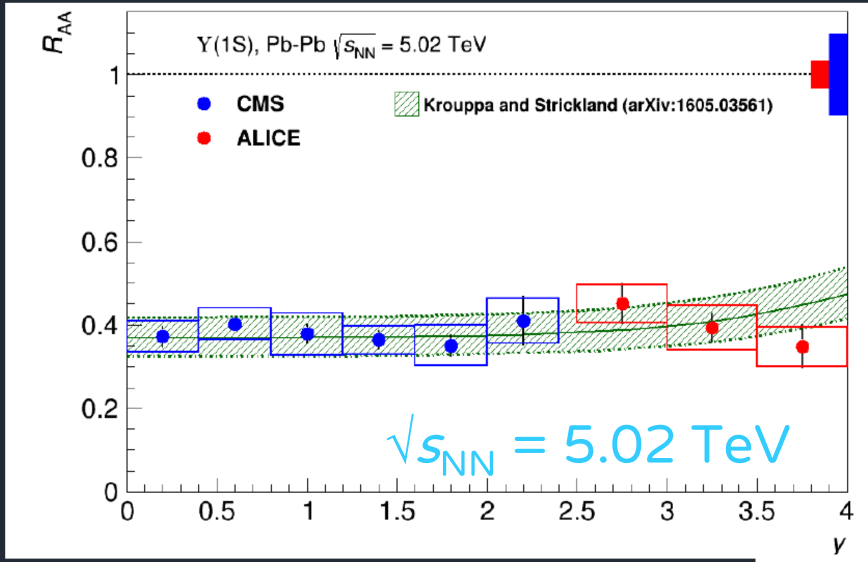
- Lower production cross sections
- Non negligible feed-down contributions from higher states



H. Wöhri, QWG2014

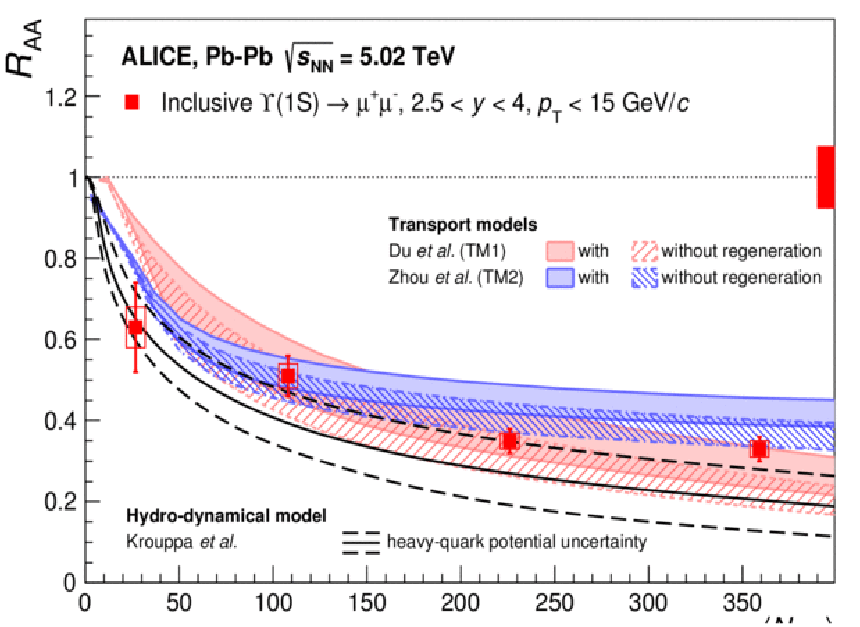
ϒ(1S) in ALICE: theory comparison





CMS-PAS-HIN16-023
CMS arXiv:1611.01510

E. Scomparin, QM17

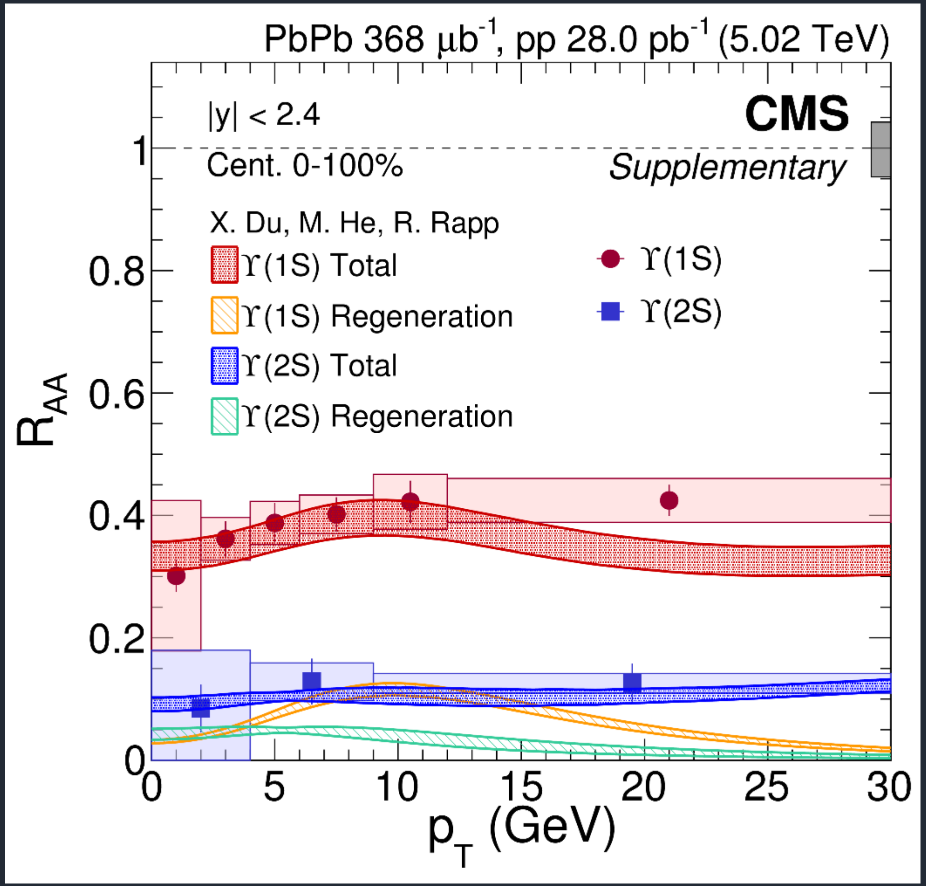


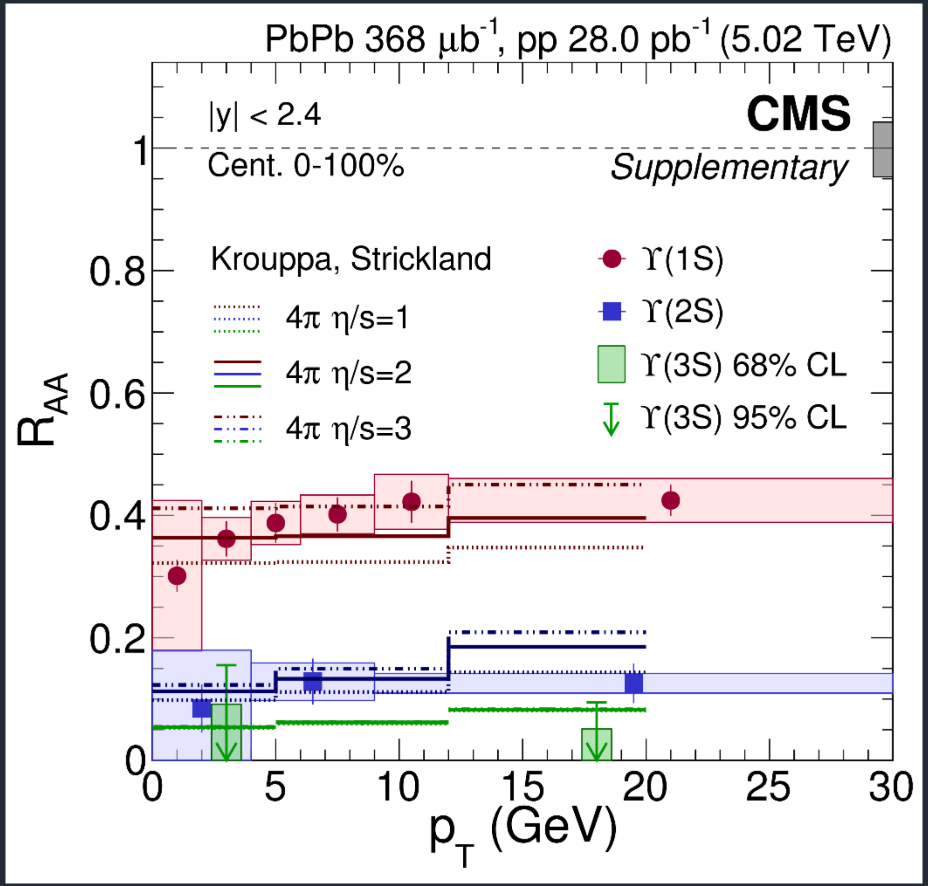
- Suppression increases with y at $\sqrt{s_{NN}}$ = 2.76TeV
- Suppression is constant at $\sqrt{s_{NN}}$ = 5.02TeV

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

Bottomonium family

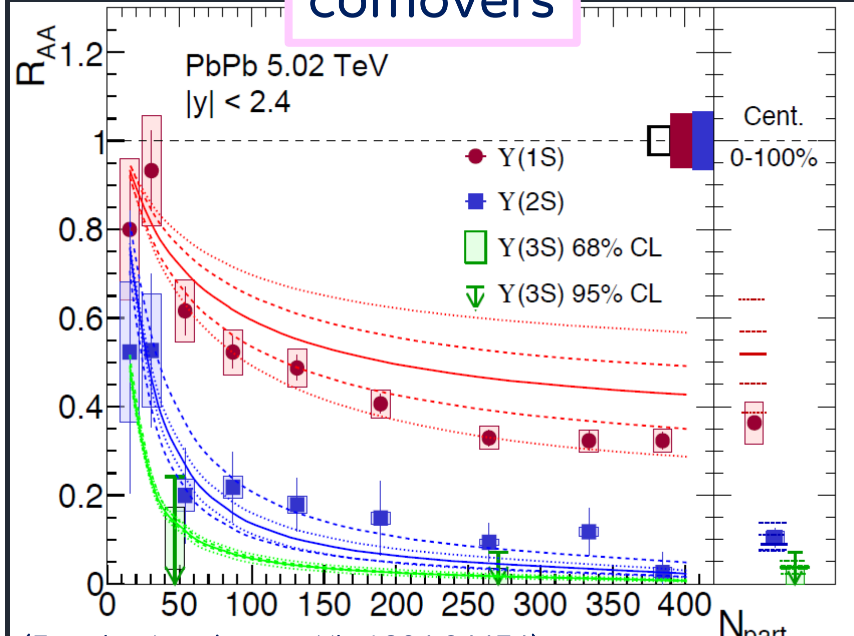
➡ No significant pT or y dependence





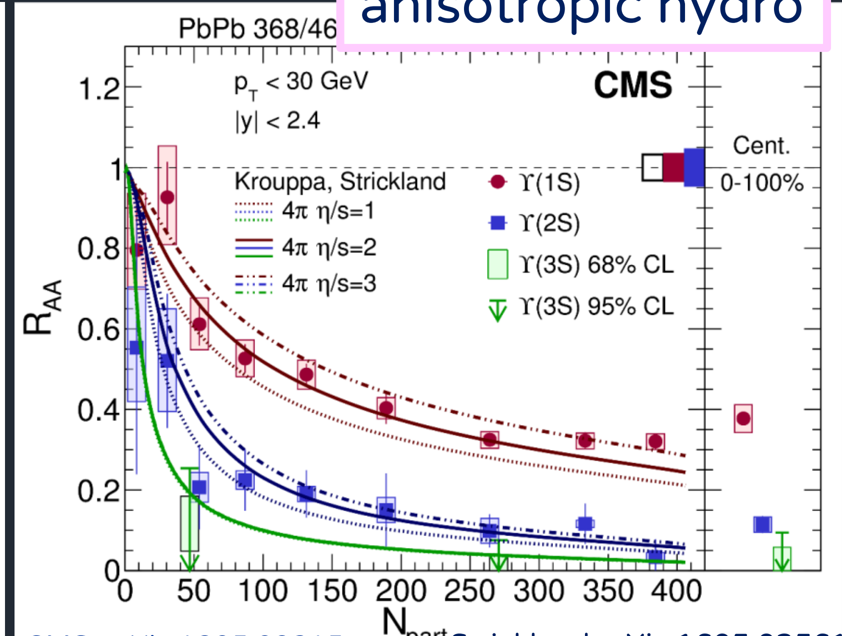
Comparison to theory

comovers



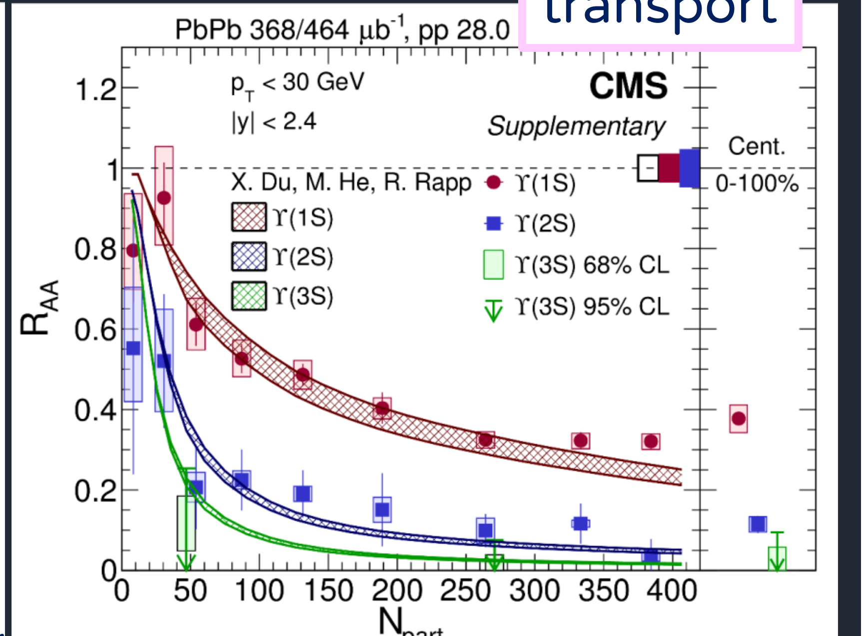
(Ferreiro, Lansberg, arXiv:1804.04474)

anisotropic hydro



CMS, arXiv:1805.09215 Strickland,arXiv:1605.03561

transport



(Rapp, arXiv:1706.08670)

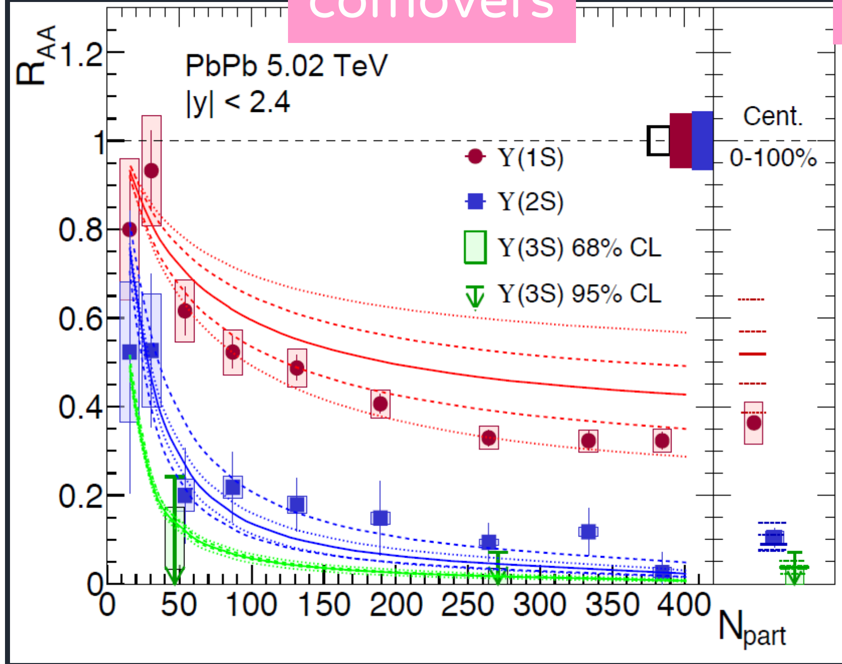
- $\sigma_{co\text{-}\Upsilon 1S}$ ~ 0.02mb, $\sigma_{co\text{-}\chi(3P)}$~ 12mb
- feed-down from higher states
- CNM effects

- Υ suppression (and regeneration)
- feed-down from higher states
- dynamical evolution with a-hydro
- no CNM effects

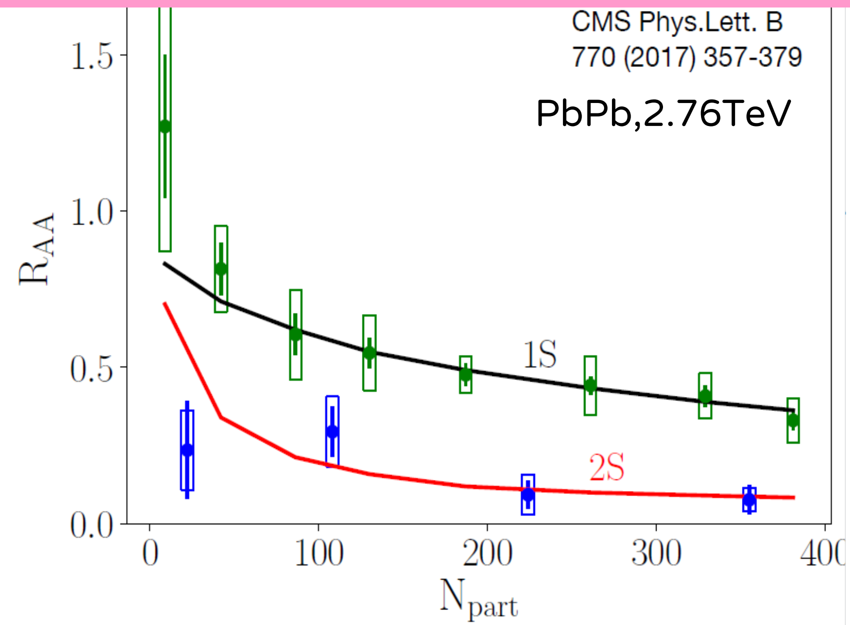
- Υ suppression and regeneration
- feed-down from higher states
- CNM effects

Comparison to theory

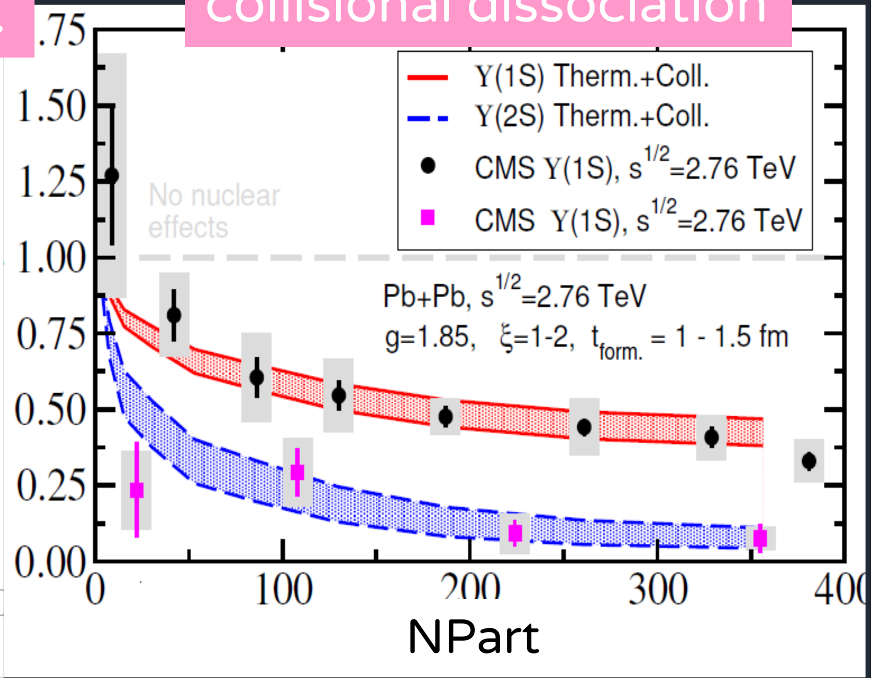
comovers



coupled Boltzmann transport eq.



collisional dissociation



Comover model:

- $\sigma_{co\text{-}\Upsilon 1S}$ ~ 0.02mb, $\sigma_{co\text{-}\chi(3P)}$~ 12mb
- feed-down from higher states
- CNM effects

(Ferreiro, Lansberg, arXiv:1804.04474)

Coupled Boltzmann transport eq:

- describe in medium heavy-q and qq dynamical evolution
- energy loss included
- feed-down from higher states
- CNM effects

(Bass et al, 1807.06199)

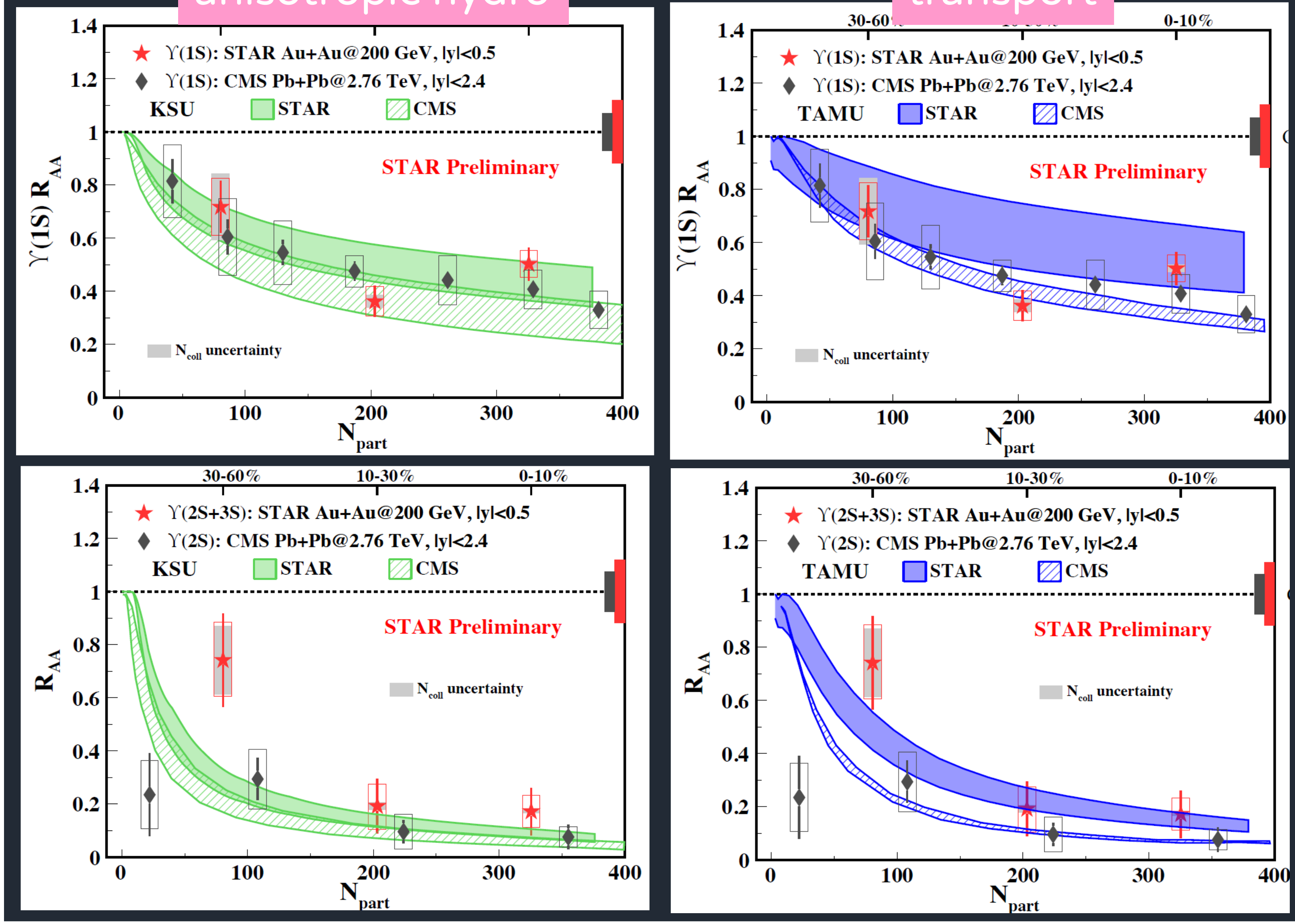
Collisional dissociation:

- collisional energy loss + thermal screening
- feed-down from higher states
- no CNM effects

(Vitev, 1807.08401)

Bottomonium at RHIC

anisotropic hydro | transport



- Similar Υ(1S) suppression, within uncertainties, at RHIC and LHC
- Excited states suppression is stronger at LHC

→ √s-dependence of feed down and CNM effects need to be precisely quantified

➡ Models describing LHC results also describe RHIC ones

T (RHIC) ~ 440 MeV
T (LHC) ~ 630 MeV
(M. Strickland, arXiv:1807.07452)