Charmonium production in pA and AA collisions

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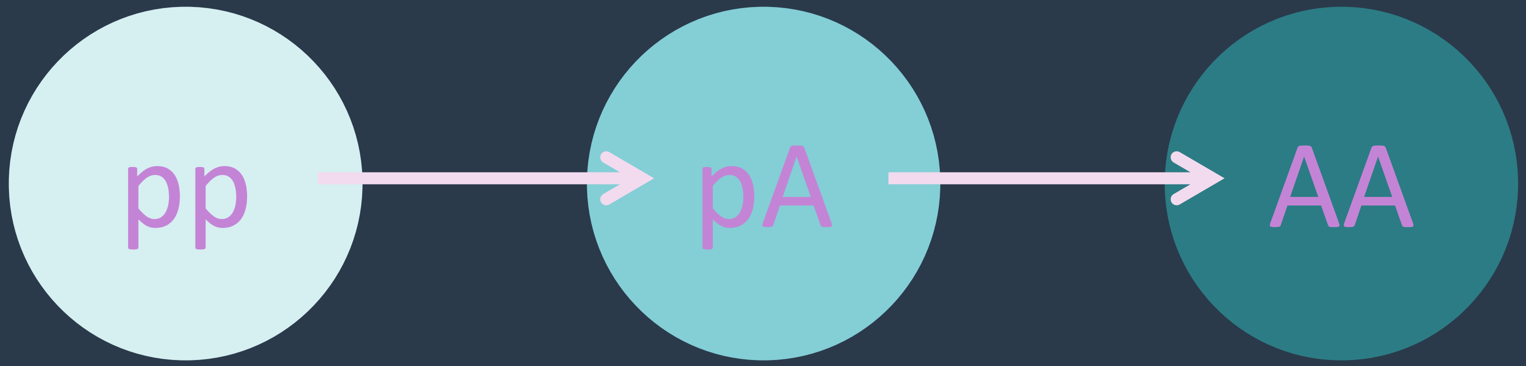
QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES
ECT*, 17 November 2021

Overview

- ✓ wrap-up of the most recent charmonium results
- ✓ at the eve of Run 3, precise results from the LHC experiments are available, in all systems and over a broad kinematic range



Observables

Nuclear modification factor R_{AA}

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

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{pp}}$$

hot/cold matter effects

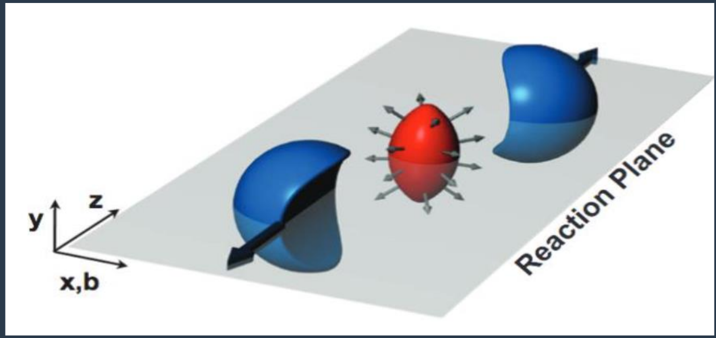
→$R_{AA} \neq 1$

Azimuthal anisotropy v_2

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

→ elliptic flow (v_2): 2nd coeff. of the Fourier expansion of the azimuthal distributions of the produced particles, wrt the event plane

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



Where are we?

A-A	RHIC	LHC (mid-y)	LHC (fw-y)
J/ψ R_{AA}	✓ (green)	✓ (green)	✓ (green)
ψ(2S) R_{AA}	✓ (red)	✓ (yellow)	✓ (yellow)
J/ψ v_2	✓ (yellow)	✓ (green)	✓ (green)
ψ(2S) v_2	✓ (red)	✓ (red)	✓ (red)
J/ψ polarization	✓ (red)	✓ (red)	✓ (green)

R_{AA}:
high precision reached for ground states, but statistics still limited for excited states

v_2:
precise J/ψ results at LHC

new observables/particles:
polarization, J/ψ in jets, exotic states

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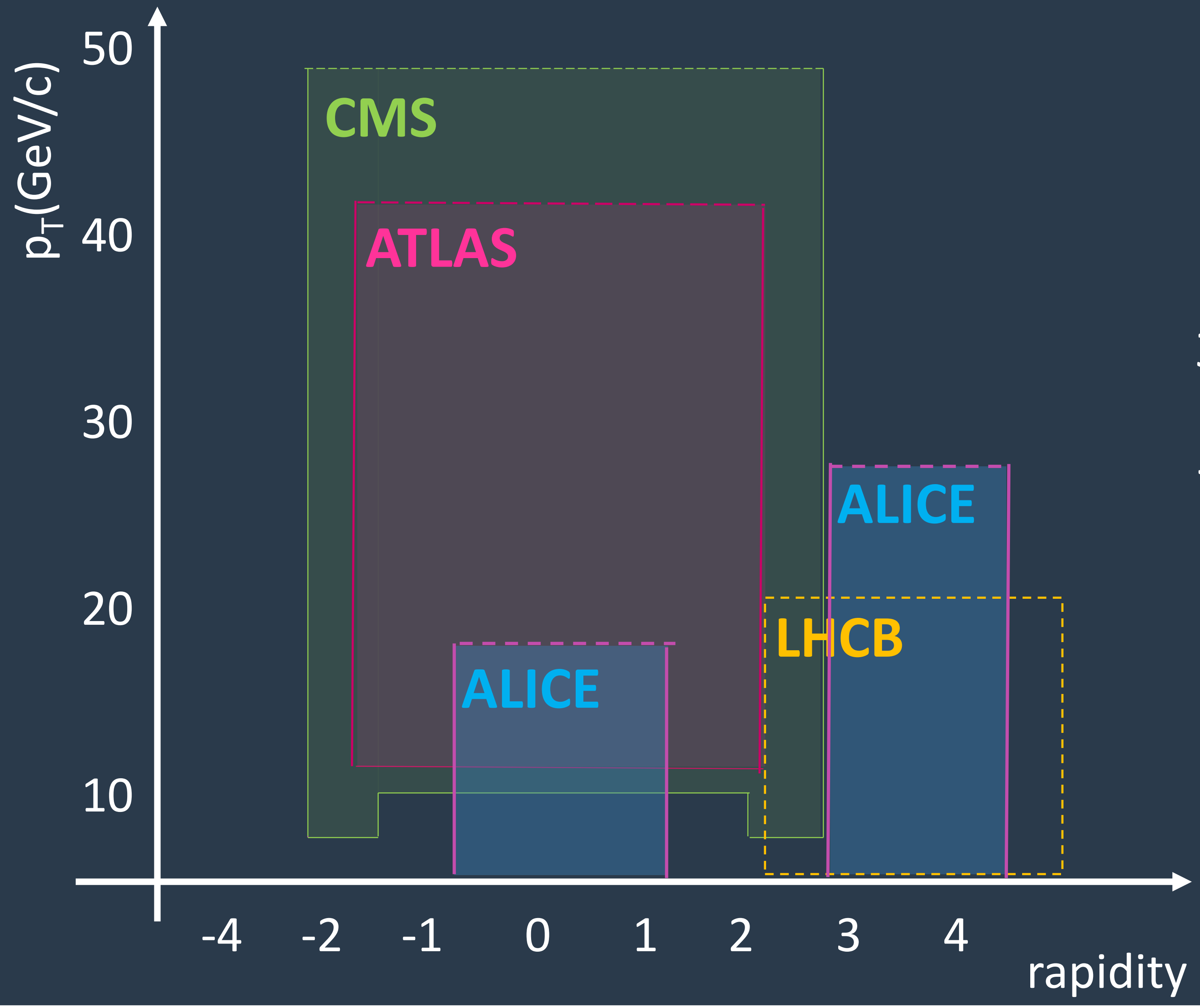
ψ(2S) R_{pA}	✓ (green)	✓ (green)	✓ (green)
J/ψ v_2	✓ (red)	✓ (green)	✓ (green)
J/ψ polarization	✓ (red)	✓ (red)	✓ (red)

R_{AA}:
available J/ψ, ψ(2S) results, over a broad kinematic range, at RHIC and LHC

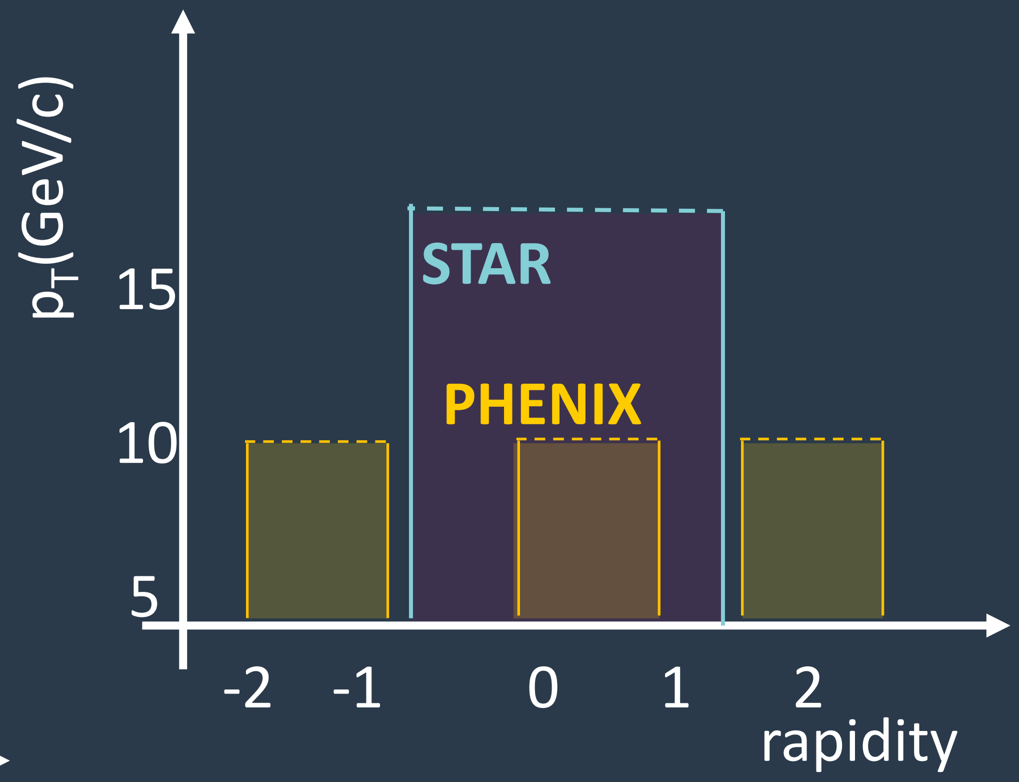
v_2:
results only available for J/ψ at LHC

Kinematic coverage

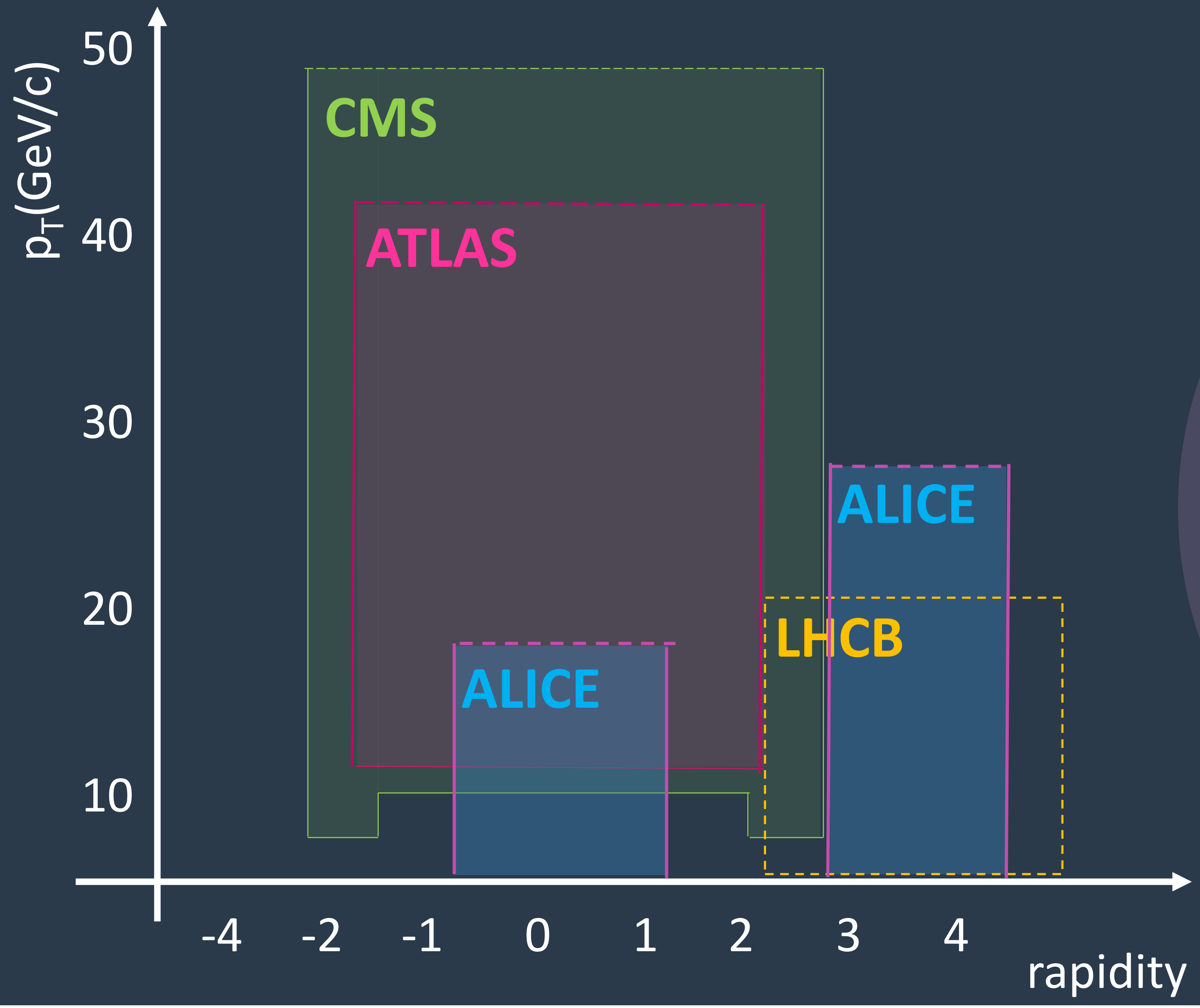


AA (pA for LHCb)

(p_T reach based on the most recent measurements)



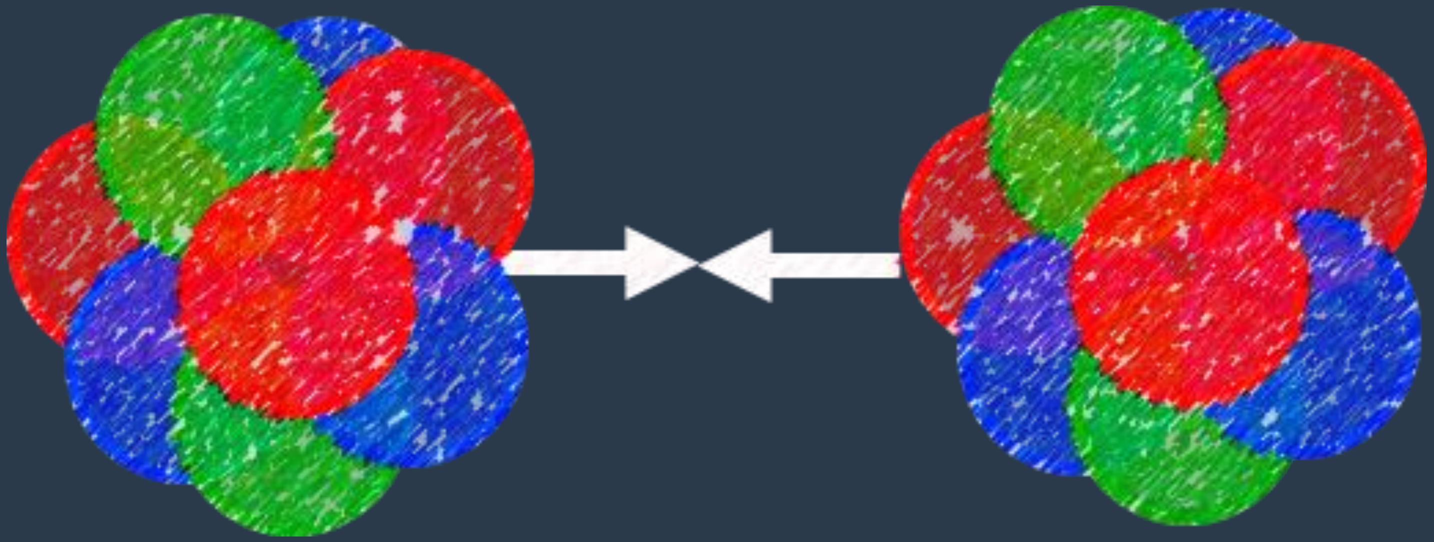
Kinematic coverage



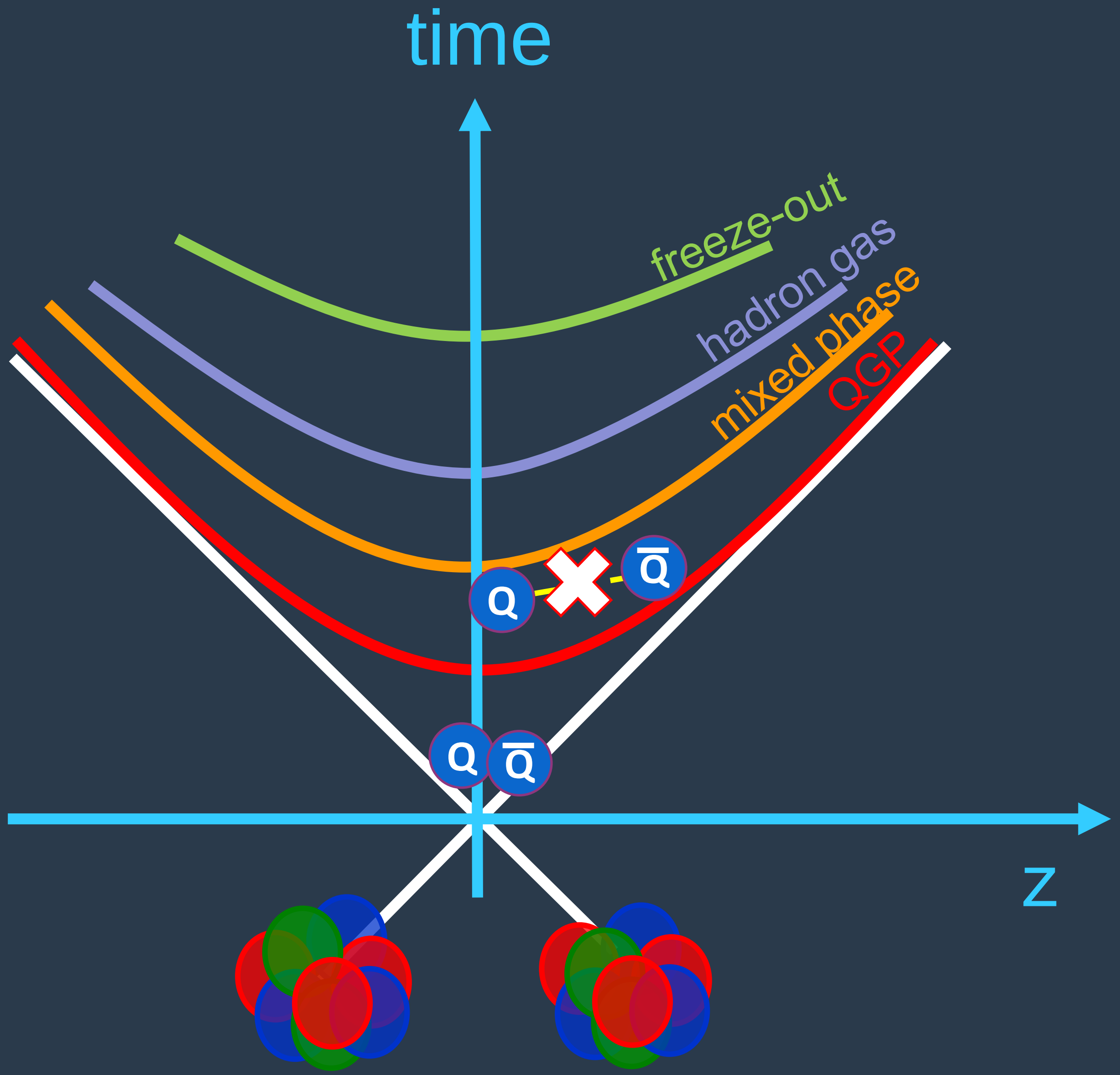
CAVEAT

- ✓ CMS, ATLAS and LHCb results are for prompt J/ψ, ψ(2S)
- ✓ ALICE results are mainly for inclusive J/ψ (fraction of J/ψ from B is ~10% for p_T < 5GeV/c and 30% for p_T ~ 10GeV/c)

A–A collisions



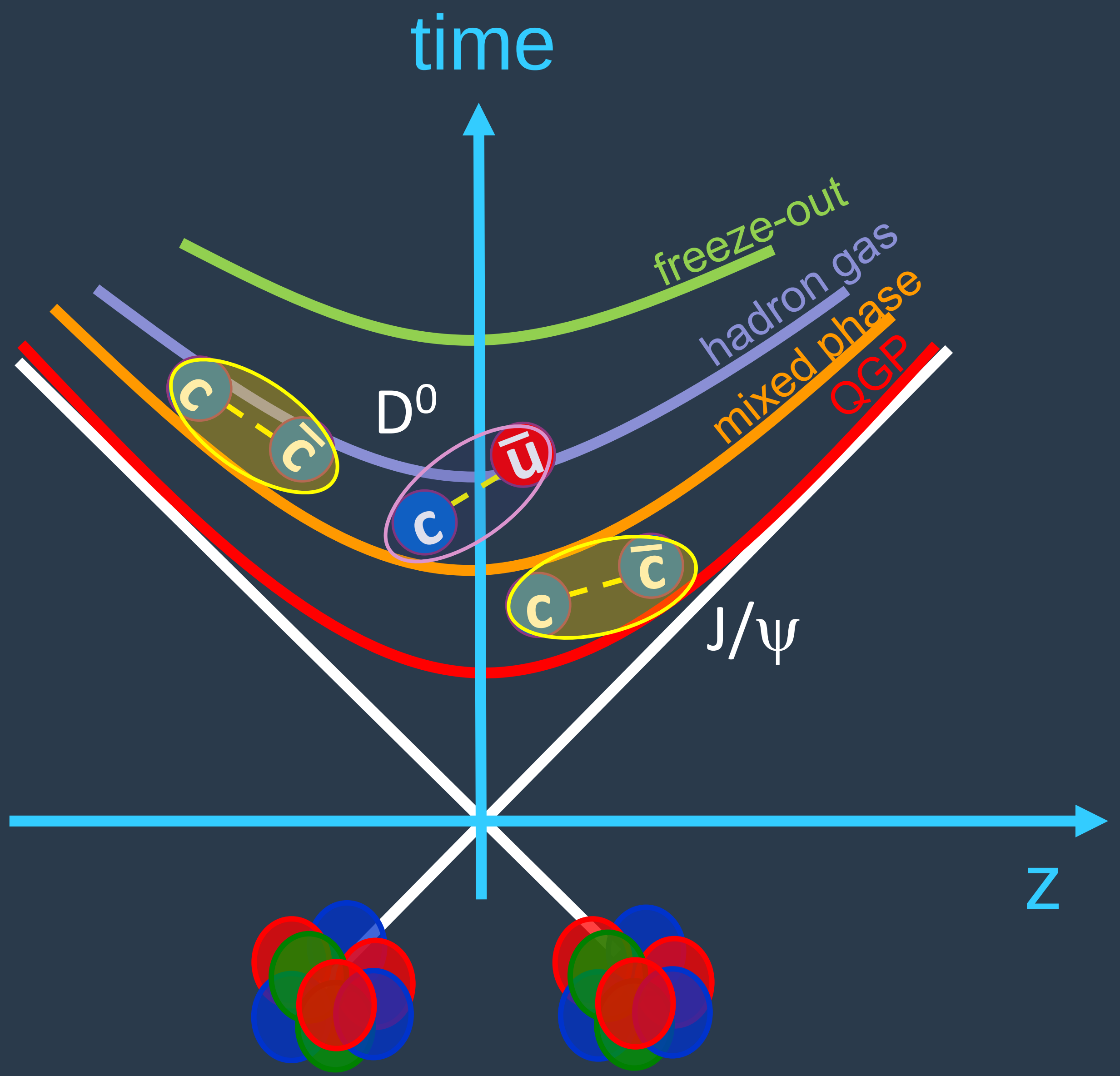
Hot matter effects



Heavy quarks produced in the early stages of the collisions

the original idea:
quarkonium production suppressed sequentially via color screening in QGP (T.Matsui,H.Satz, PLB178 (1986) 416)

Hot matter effects



Heavy quarks produced in the early stages of the collisions

the original idea:
quarkonium production suppressed sequentially via color screening in QGP (T.Matsui,H.Satz, PLB178 (1986) 416)

(re)combination:
charmonium production enhanced at hadronization or in QGP

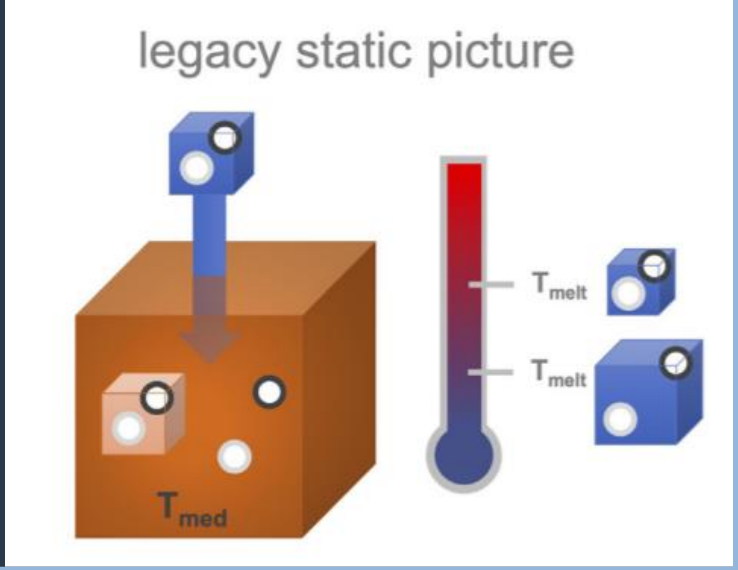
Central AA coll	$N_{c\bar{c}}$ per ev.
RHIC, 200GeV	~10
LHC, 5.02 TeV	~115

P. Braun-Munzinger, J.Stachel, PLB490(2000)196
R.Thews et al, PRC63:054905(2001)

Quarkonium as a probe

This intuitive suppression picture assumes static in-medium states

→ quarkonium as a thermometer of the system

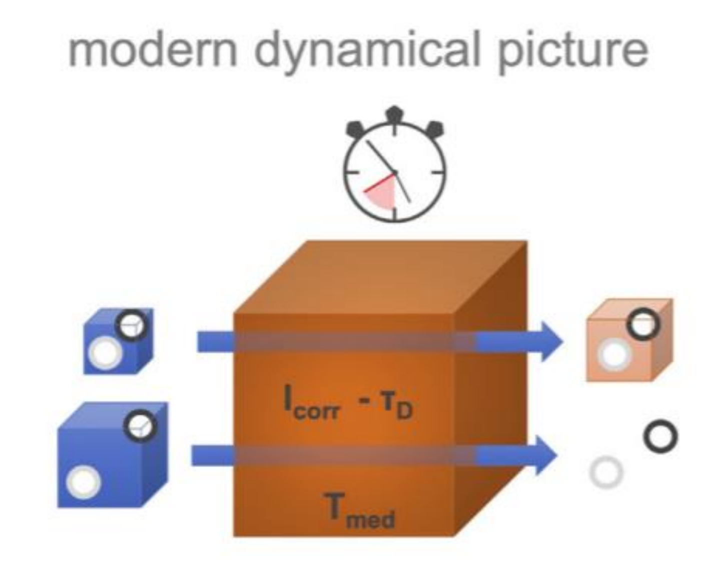


Recent theory developments introduce a dynamical approach

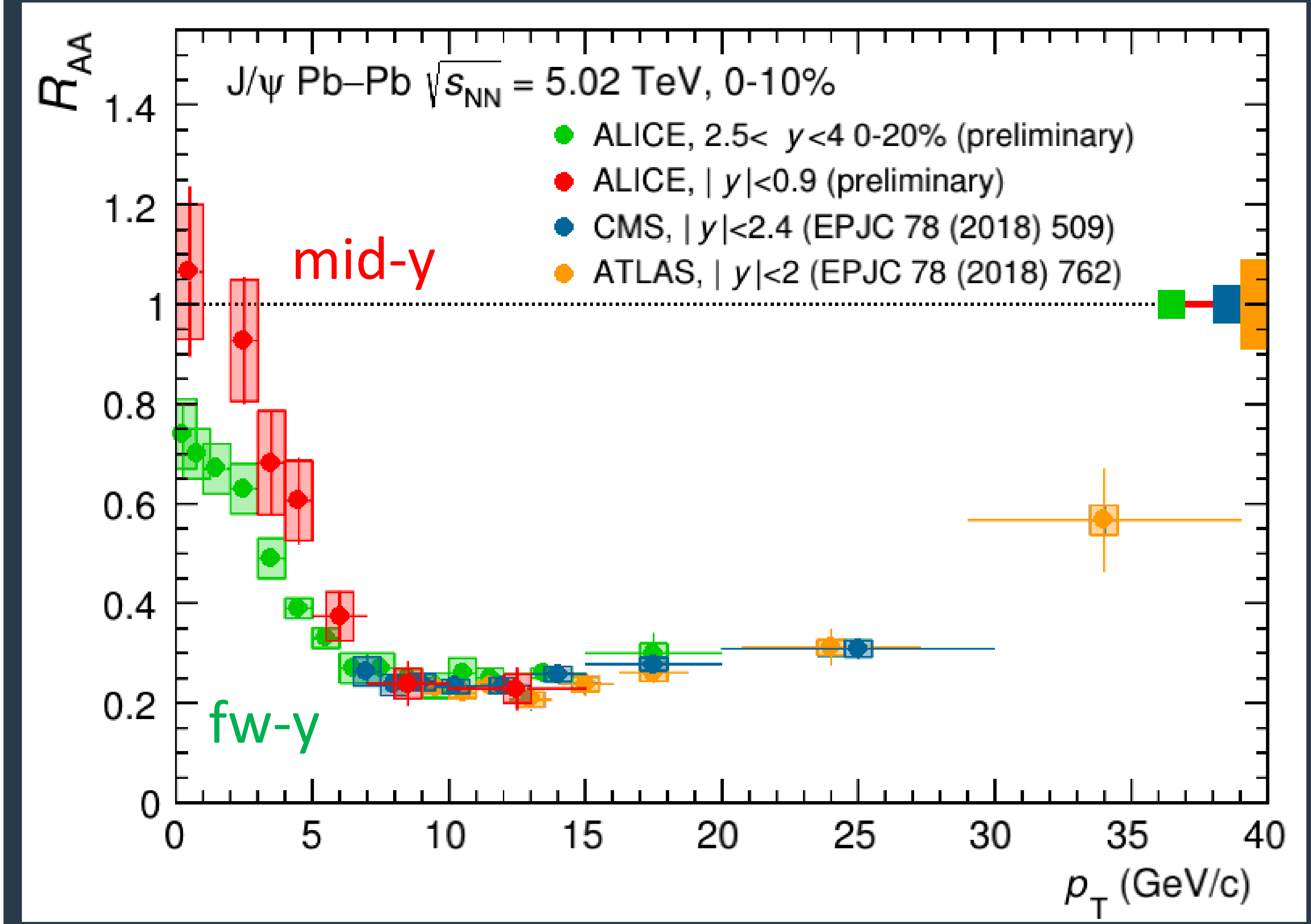
→ quarkonium survival depends on how strongly it interferes with the medium and on the time spent in the medium

→ medium as a "sieve" that filters quarkonia, over time, depending on the strength of their binding

A. Rothkopf, Physics Reports 858 (2020)



J/ψ R_{AA} vs p_T



Very broad p_T range (up to 40 Gev/c) now accessible

Strong R_{AA} p_T dependence

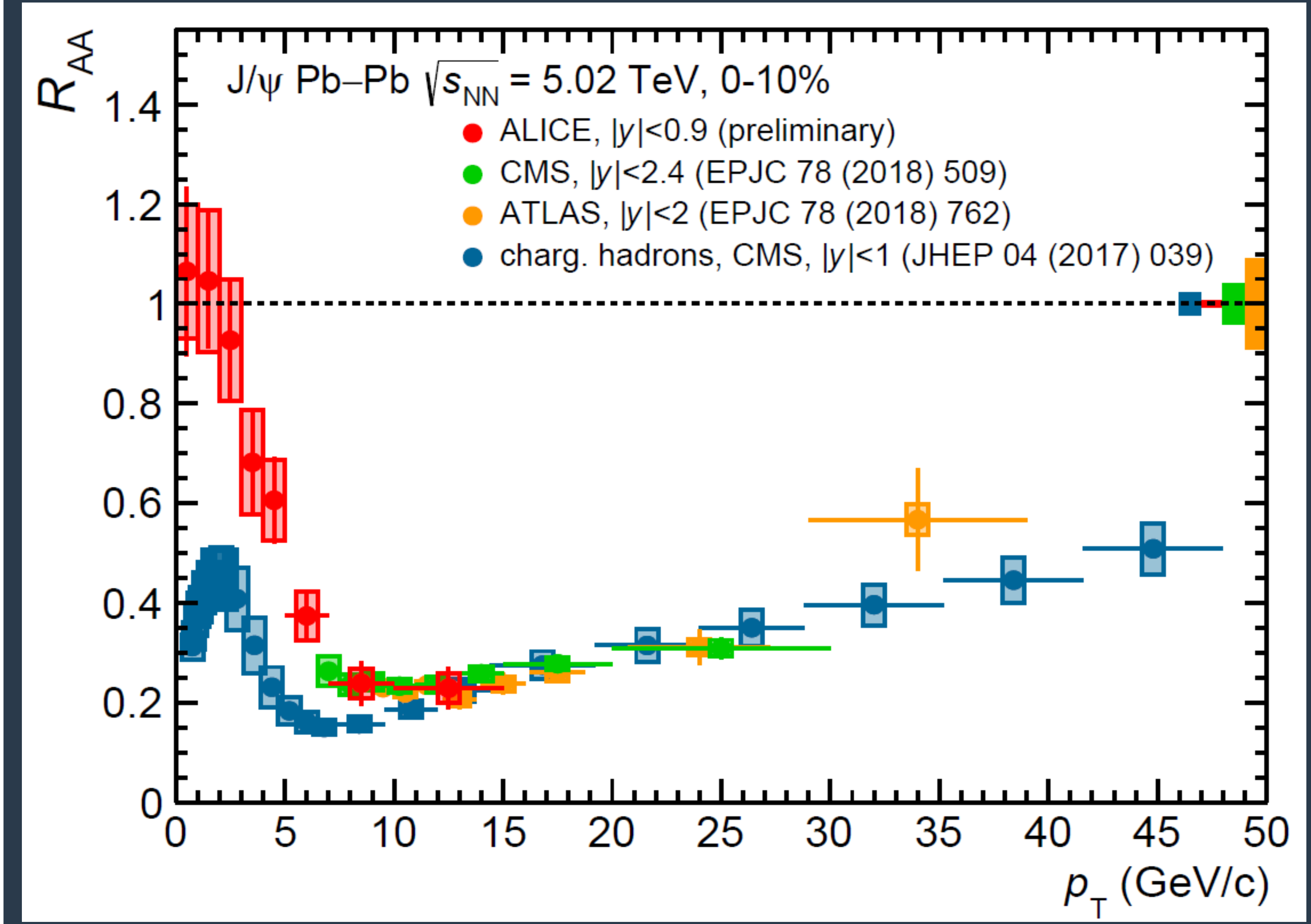
low p_T

- strong rapidity dependence

high p_T

- common behavior, independent on rapidity
- very good compatibility of results from different experiments

J/ψ R_{AA} vs p_T



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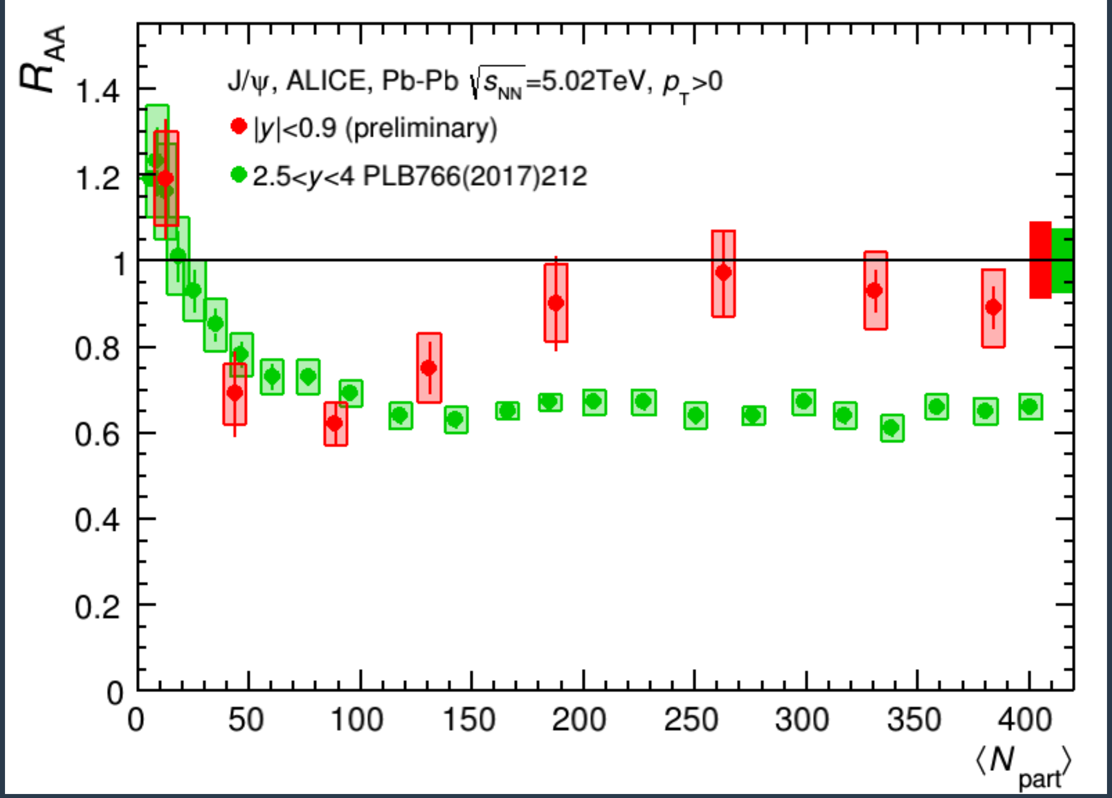
very high p_T

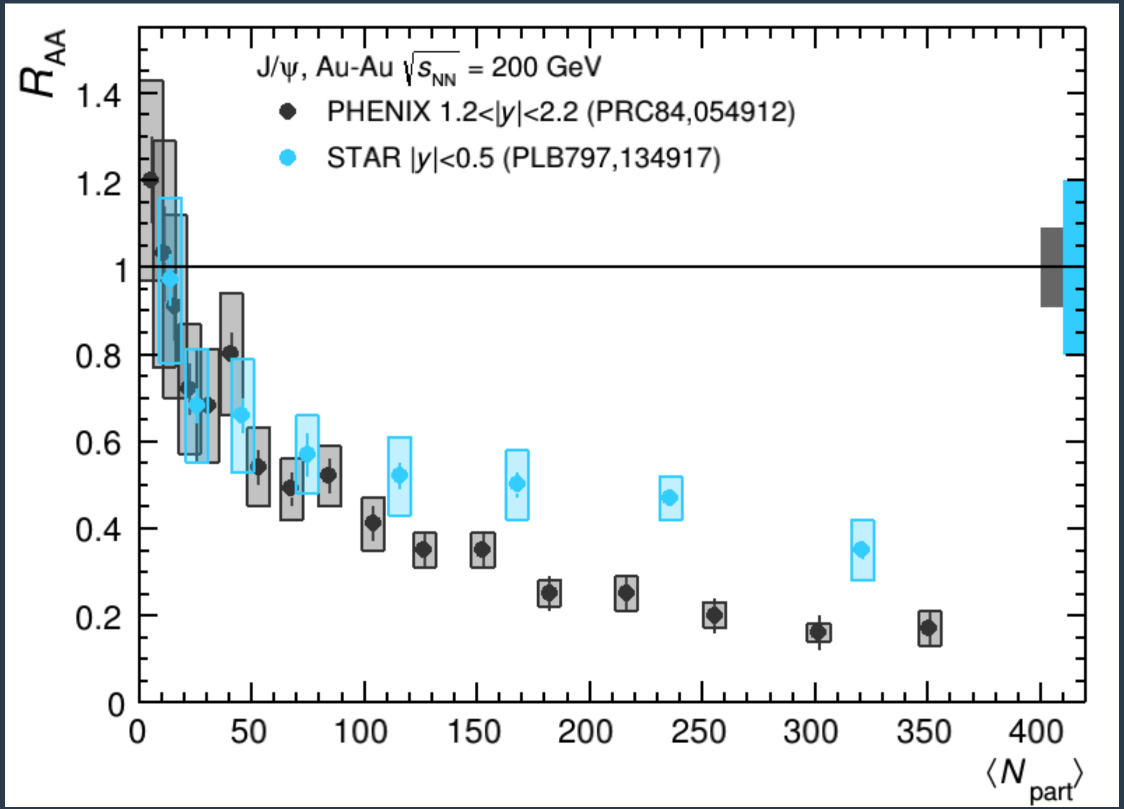
- R_{AA} rise due to partonic energy loss mechanisms observed for hadrons?

Low p_T J/ψ: mid vs fw-y

LHC



RHIC



mid-y

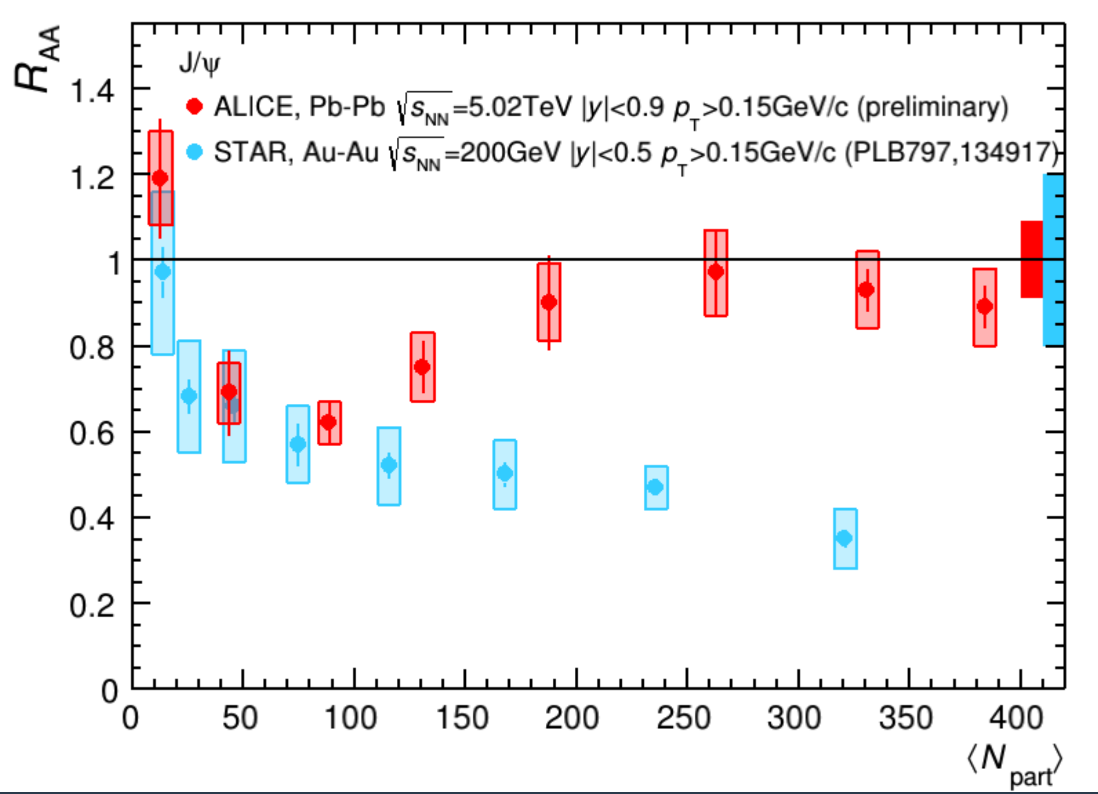
fw-y

Higher R_{AA} at mid-rapidity wrt forward-y, in central events

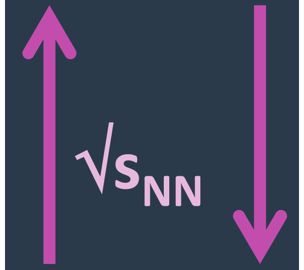
Similar y-dependence already observed at lower energies

J/ψ: RHIC vs LHC

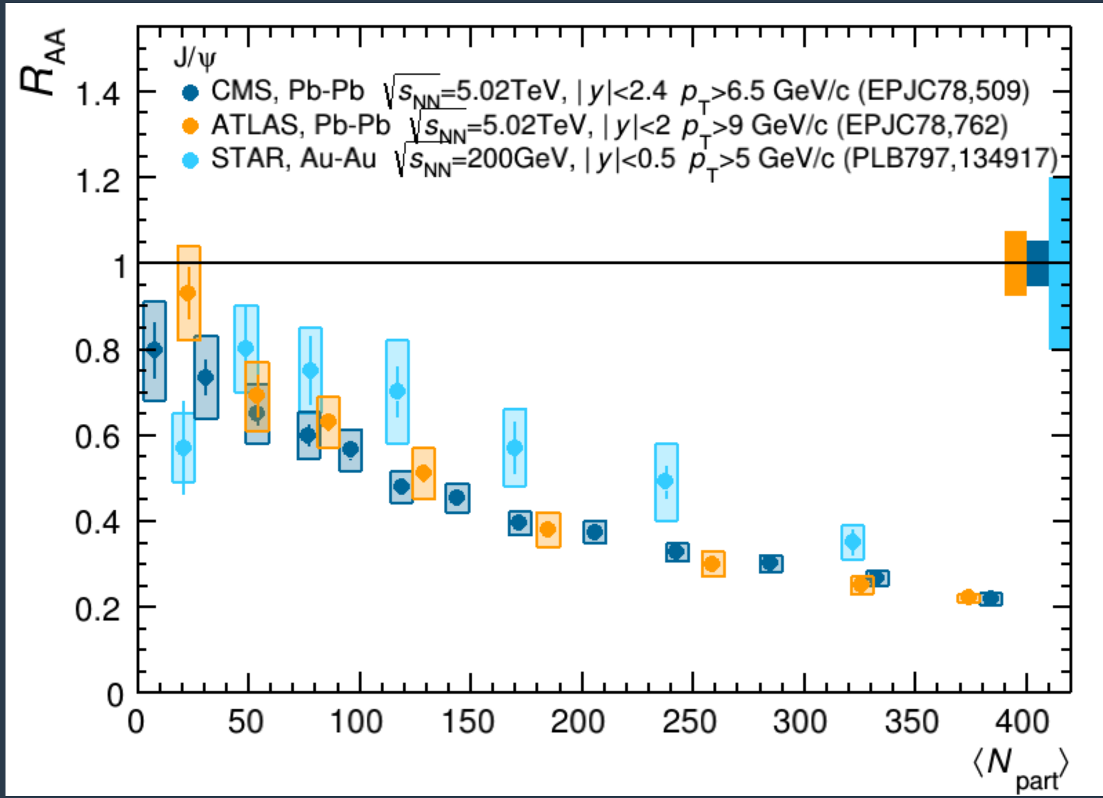
Low p_T J/ψ



Significant difference in central collisions

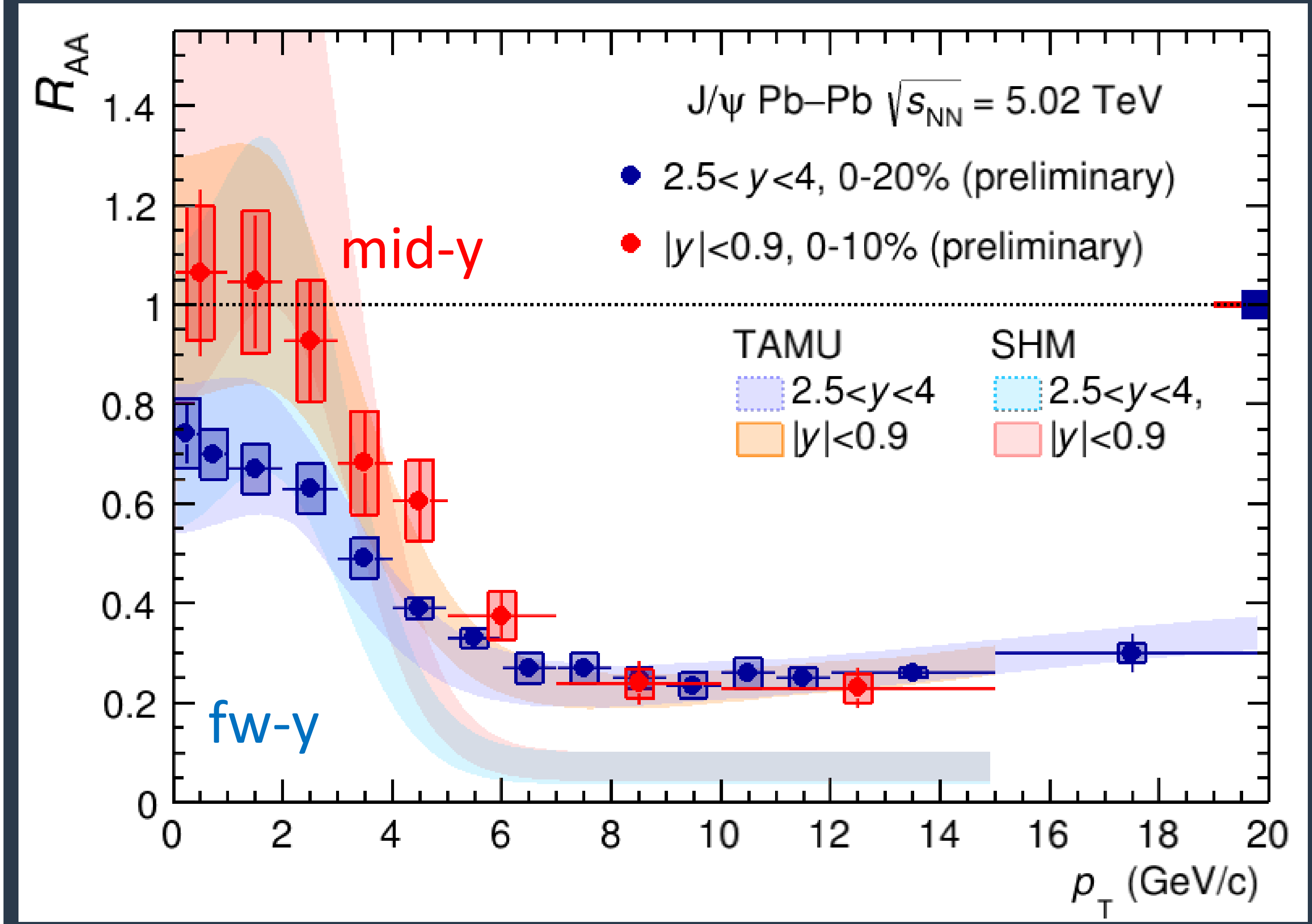


High p_T J/ψ



R_{AA} at the two $\sqrt{s_{NN}}$ are closer, with slightly higher values at RHIC

Comparison to theory

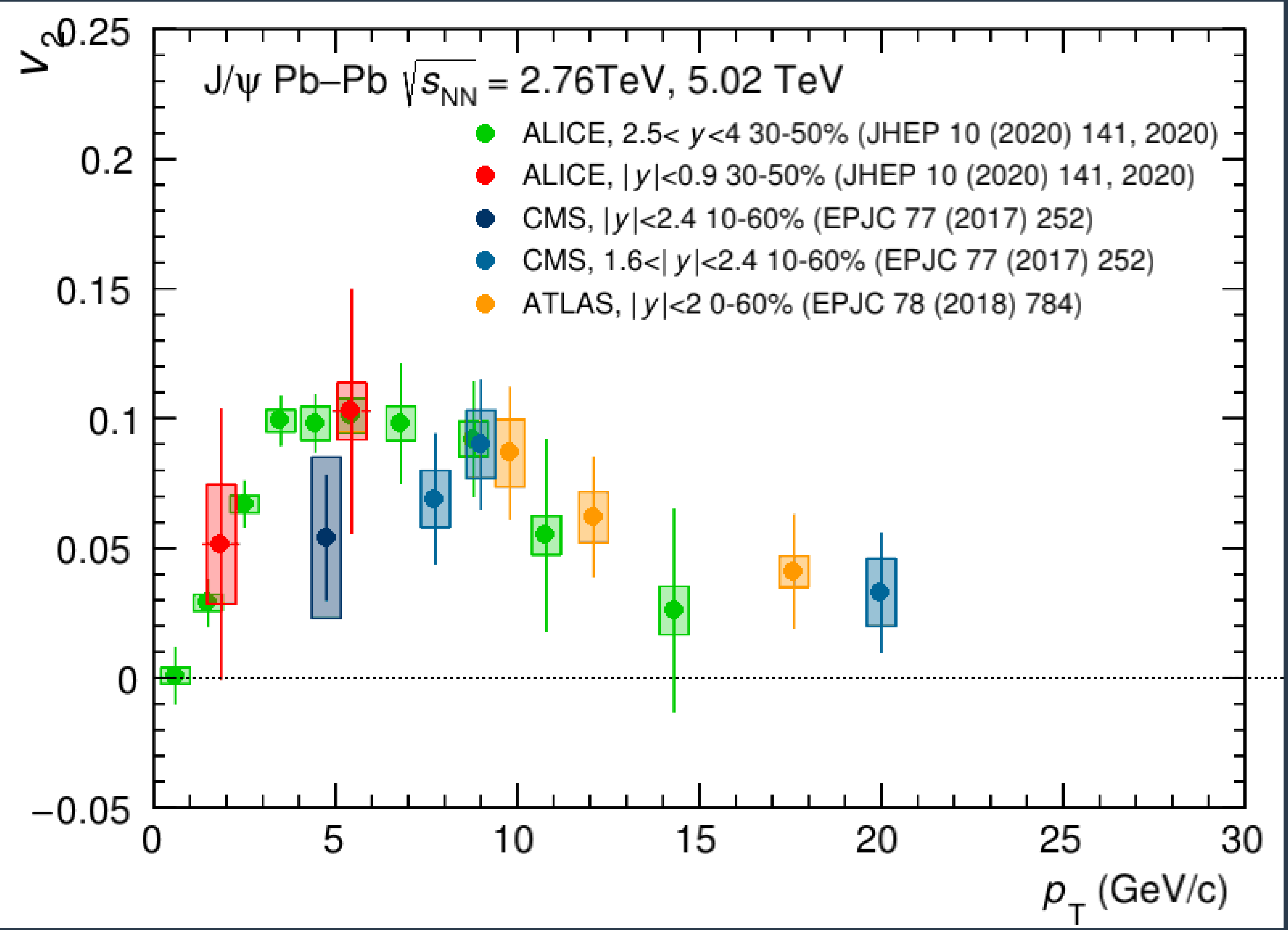


p_T dependence and difference between mid and forward-y results described by theory models, within uncertainties

suppression+regeneration mechanisms describe the data → regeneration dominates at low p_T

Precise measurement of total charm cross section needed

J/ψ v_2



v_2 provides complementary information on J/ψ production

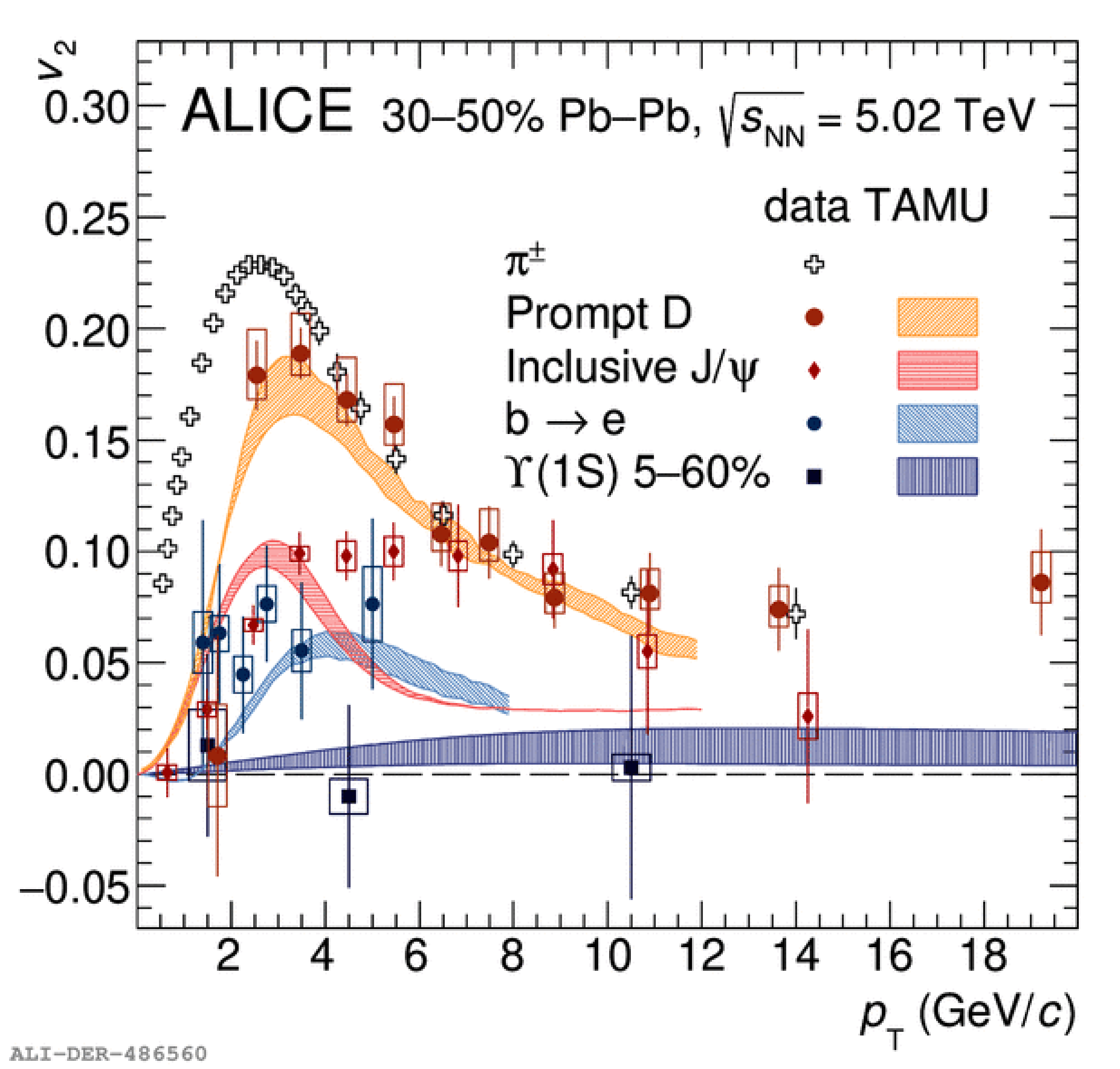
→ J/ψ from recombination should inherit thermalized charm flow

J/ψ v_2 measured up to p_T= 30 GeV/c

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)

J/ψ v_2



Clear ordering:

low p_T:

$v_2(h) > v_2(D) > v_2(J/\psi) \sim v_2(b) > v_2(\Upsilon)$

high p_T:

$v_2(h) \sim v_2(D) \sim v_2(J/\psi)$

Comparison to theory:

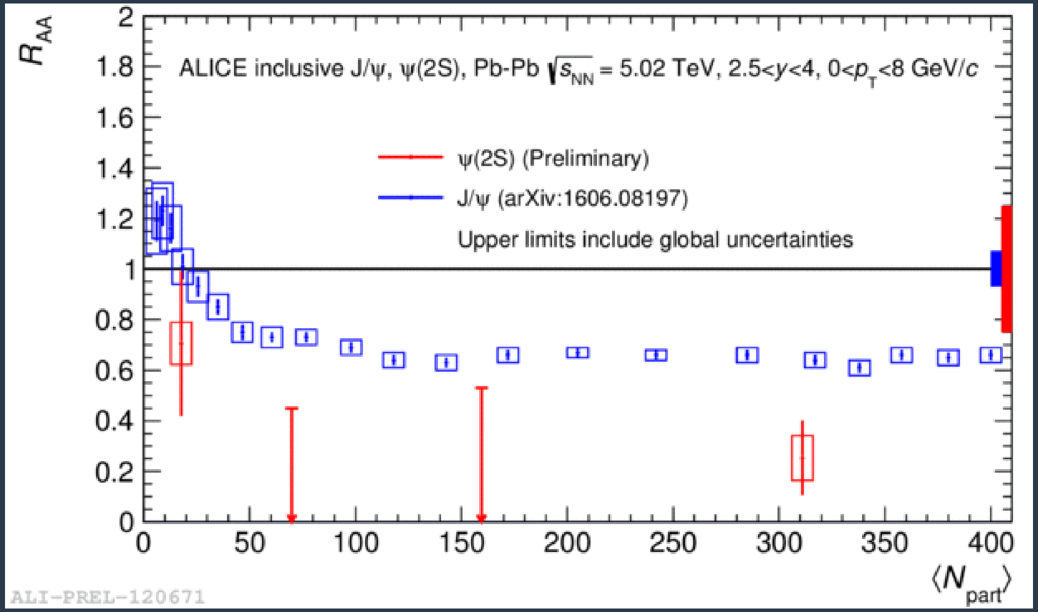
low p_T:
size of v_2 reproduced by models including a large J/ψ regeneration component

high p_T:
path-length effects play a role, but v_2 still underestimated

ψ(2S)

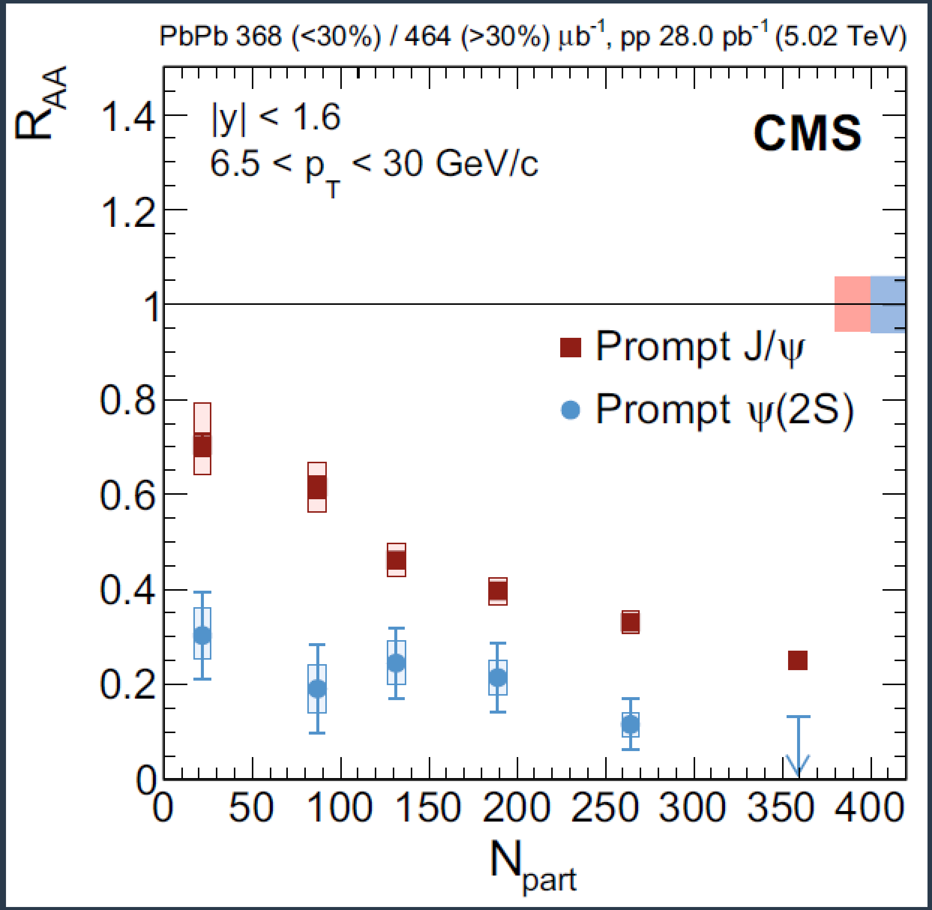
ψ(2S) loosely bound state, binding energy:
ψ(2S)~60 MeV, J/ψ ~640 MeV

Low p_T



ψ(2S) is strongly suppressed in central collisions, but size of uncertainties prevents a detailed comparison with J/ψ

High p_T



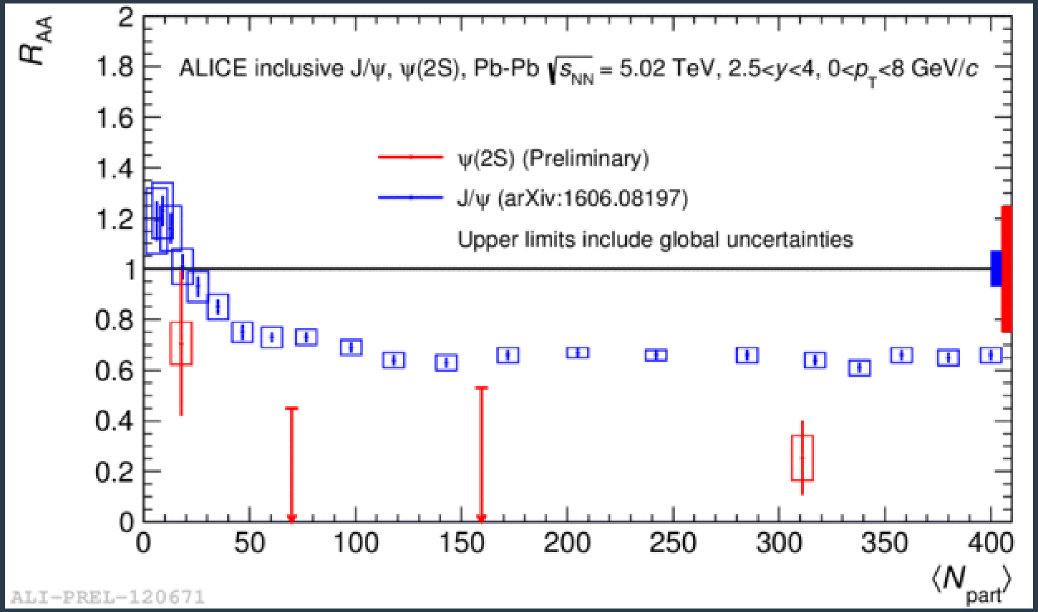
CMS, EPJC (2018) 78

Strong ψ(2S) suppression observed also at high p_T

ψ(2S)

ψ(2S) loosely bound state, binding energy:
ψ(2S)~60 MeV, J/ψ ~640 MeV

Low p_T



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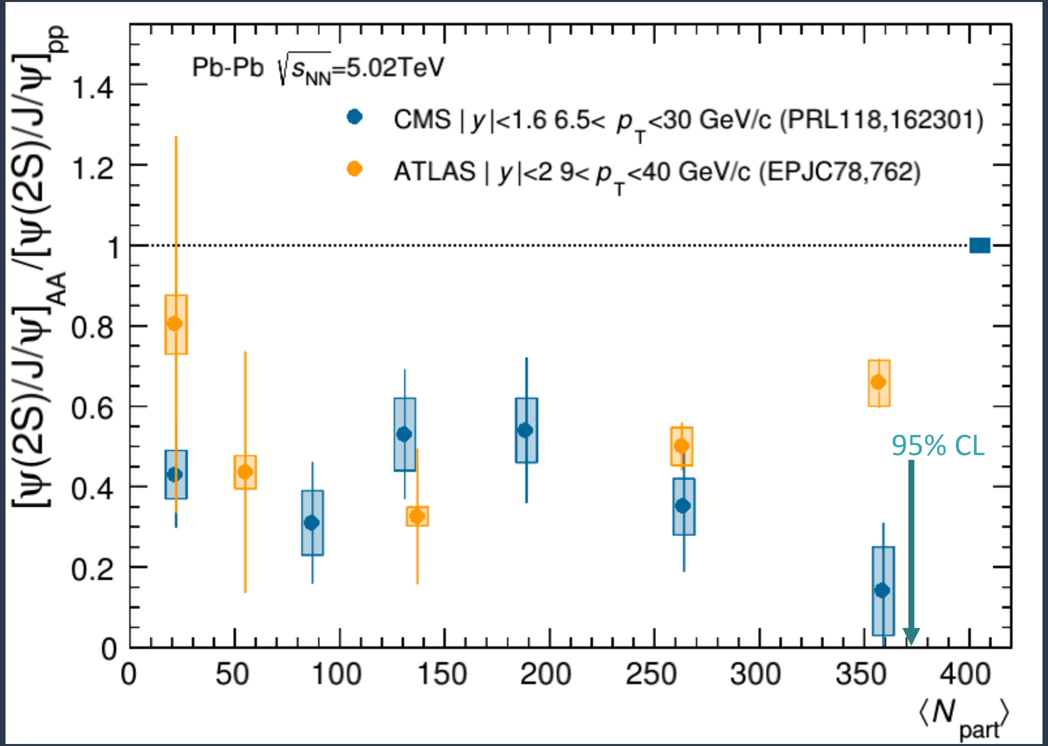
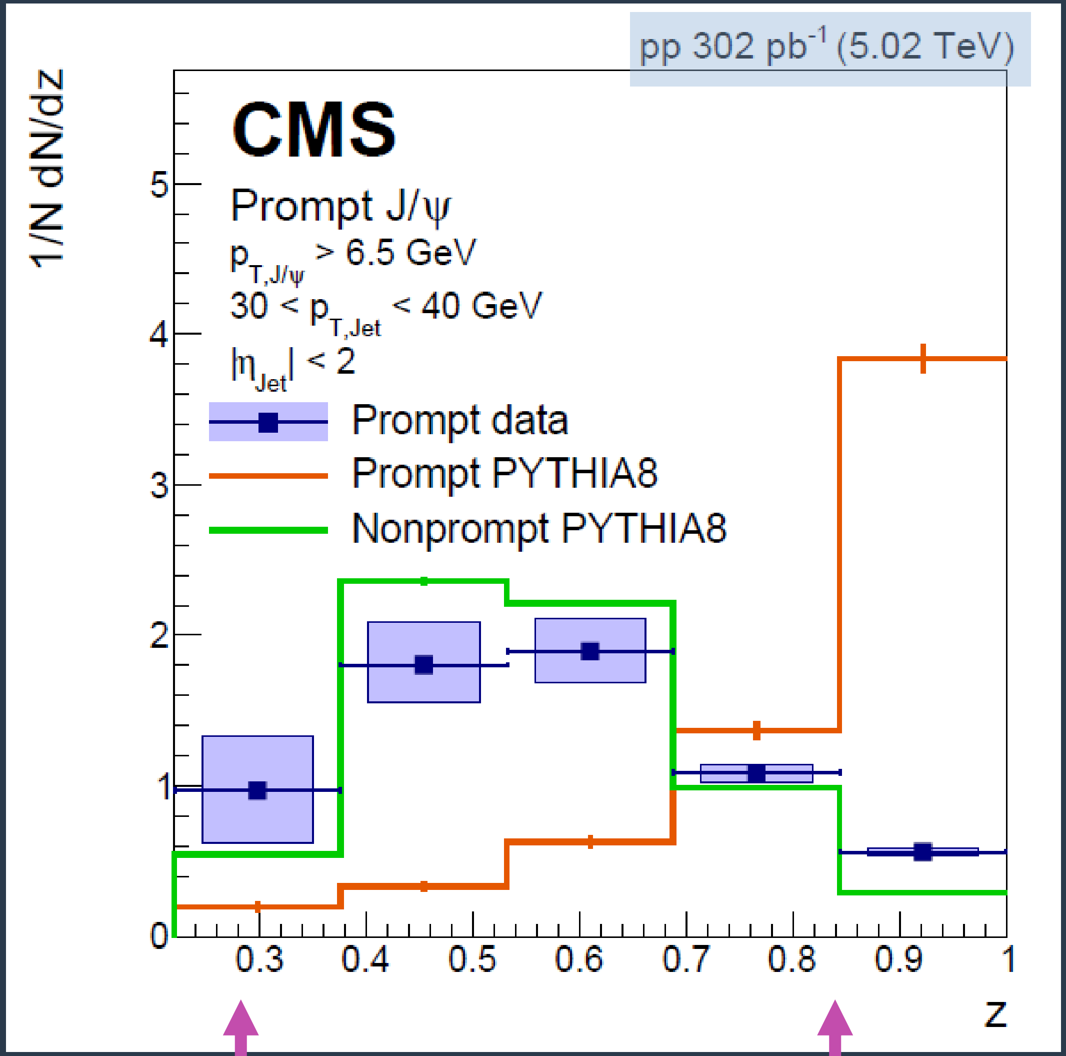
High p_T



Tension in central events between ATLAS and CMS?

J/ψ in jets



CMS, arXiv: 2106.13235

J/ψ + large jet activity

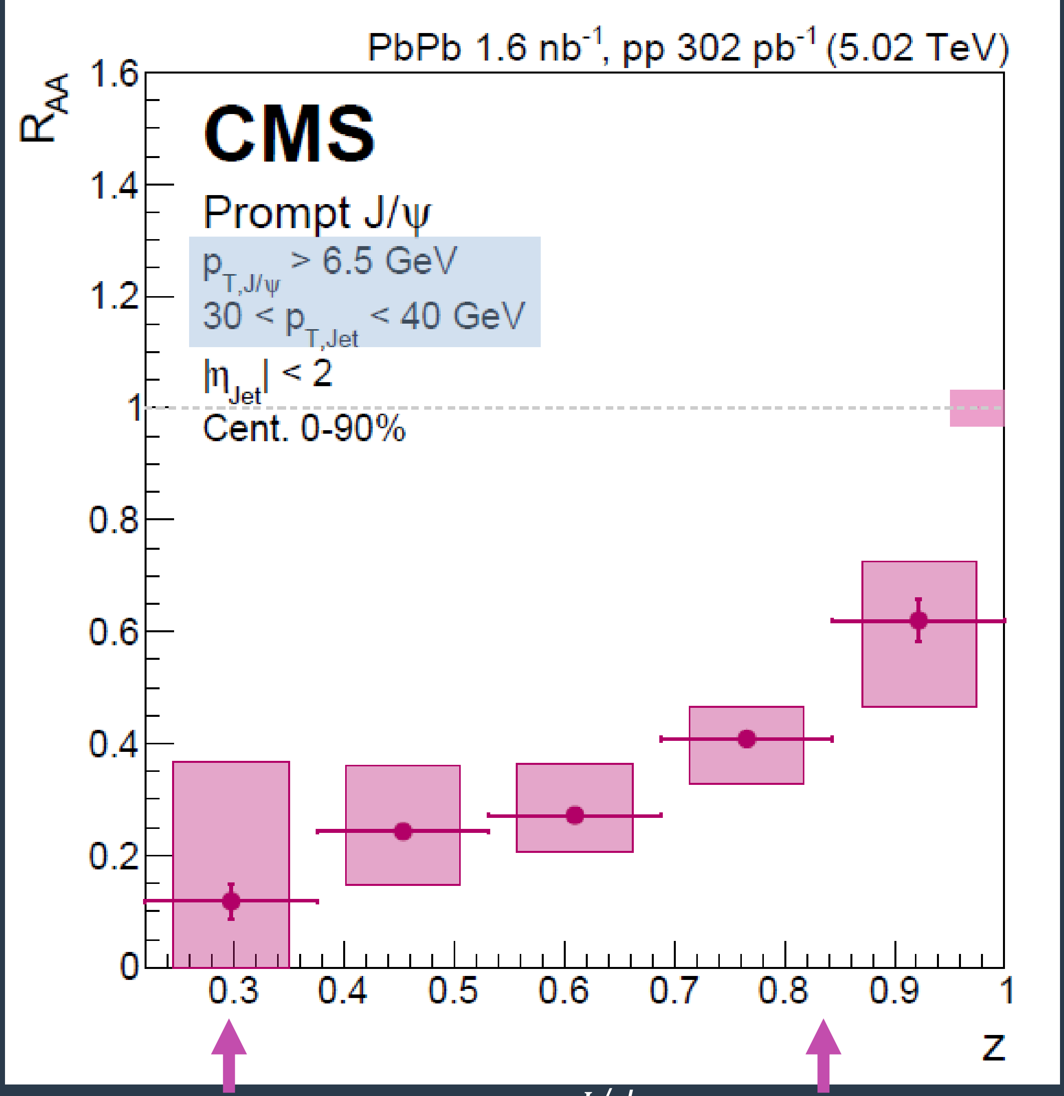
$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

J/ψ + little jet activity

J/ψ are produced less isolated than predicted by event generators (PYTHIA)

- Production in parton showers may occur later in the collision history
- it reflects the energy loss of the initial parton

J/ψ in jets



CMS, arXiv: 2106.13235

J/ψ + large jet activity

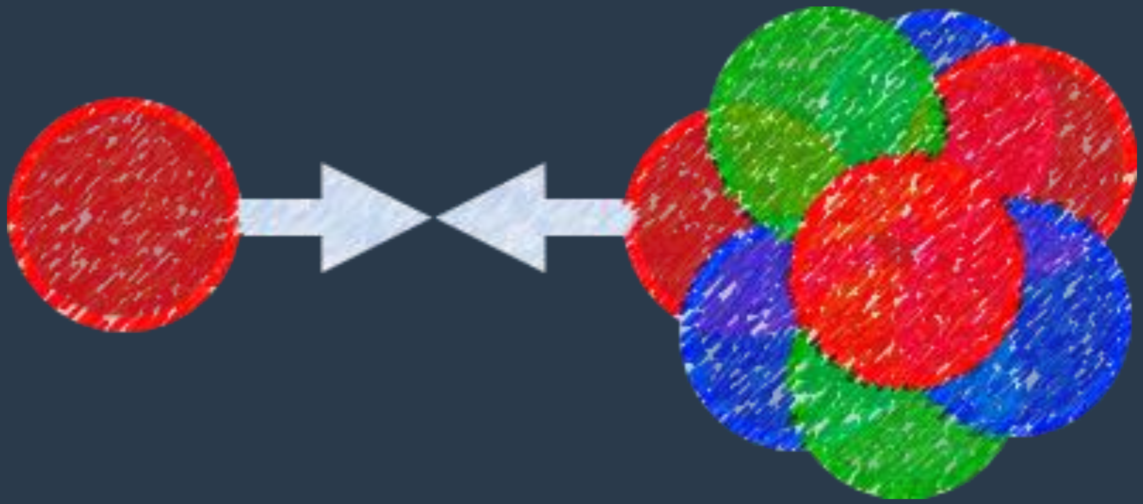
$$z = \frac{p_T^{J/\psi}}{p_T^{jet}}$$

J/ψ + little jet activity

J/ψ are produced less isolated than predicted by event generators (PYTHIA)

- Production in parton showers may occur later in the collision history
- it reflects the energy loss of the initial parton
- J/ψ produced with a large degree of surrounding jet activity are more suppressed than those produced in isolation

p–A collisions



Cold nuclear matter effects

pA collisions
to investigate

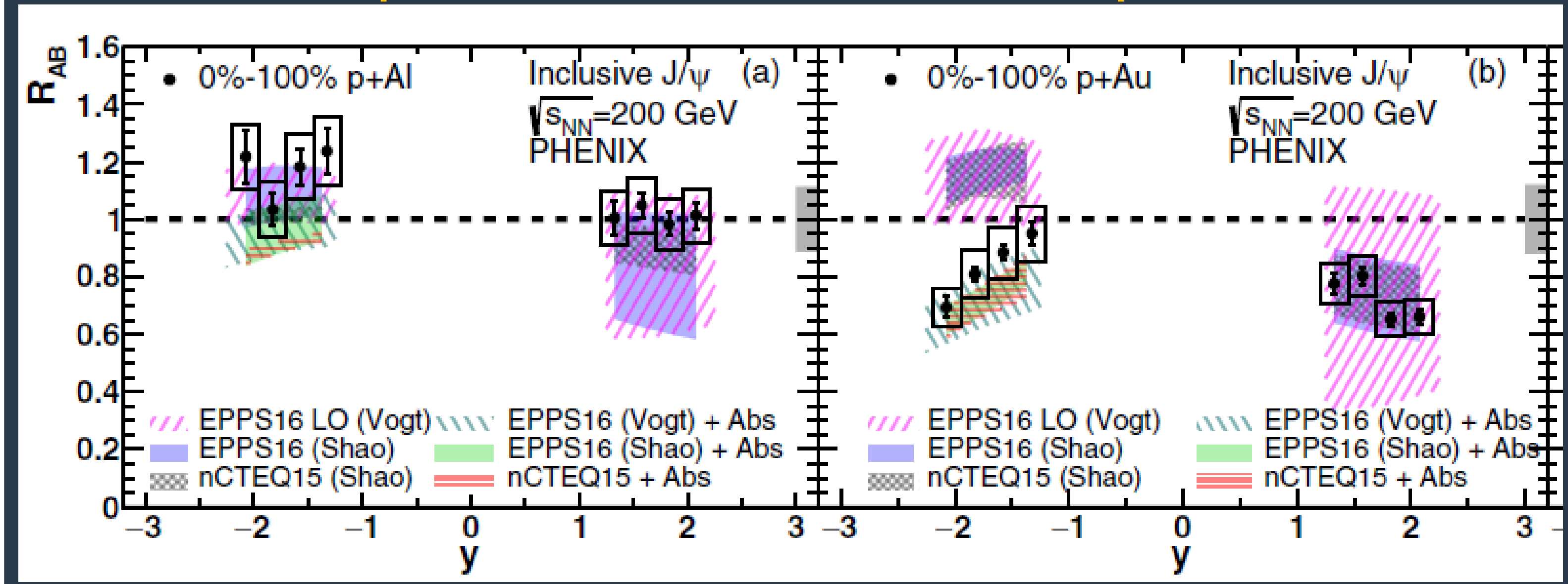
- role of the various CNM contributions, whose importance depends on kinematic and energy of the collisions
  - shadowing, coherent energy loss, break-up in nuclear matter or via hadronic/partonic comovers

- presence of possible hot matter effects

- size of CNM effects, fundamental to interpret quarkonium AA results

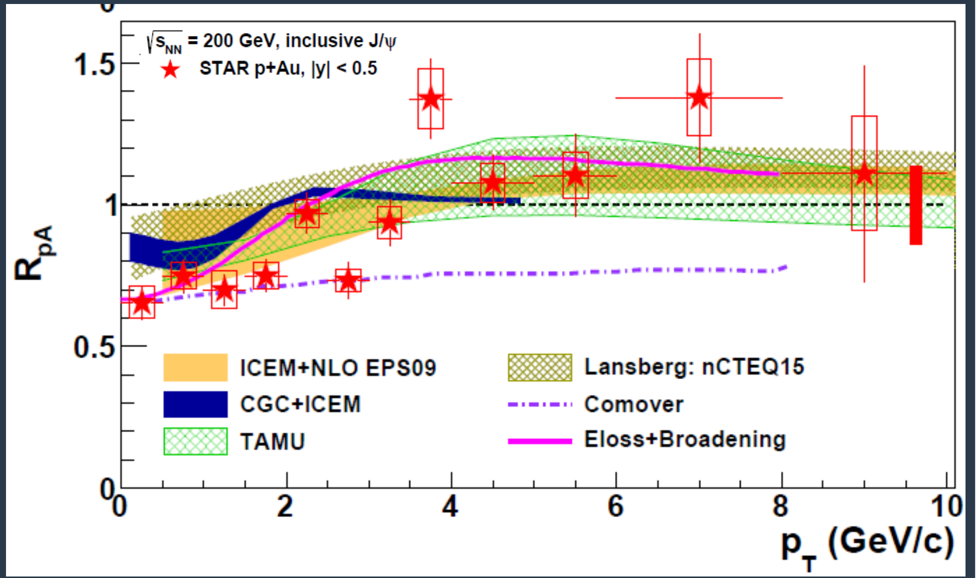
J/ψ in pA at RHIC

pAl pAu



PHENIX, PRC 102 (2020) 014902

pAu



STAR, arXiv:2110.09666

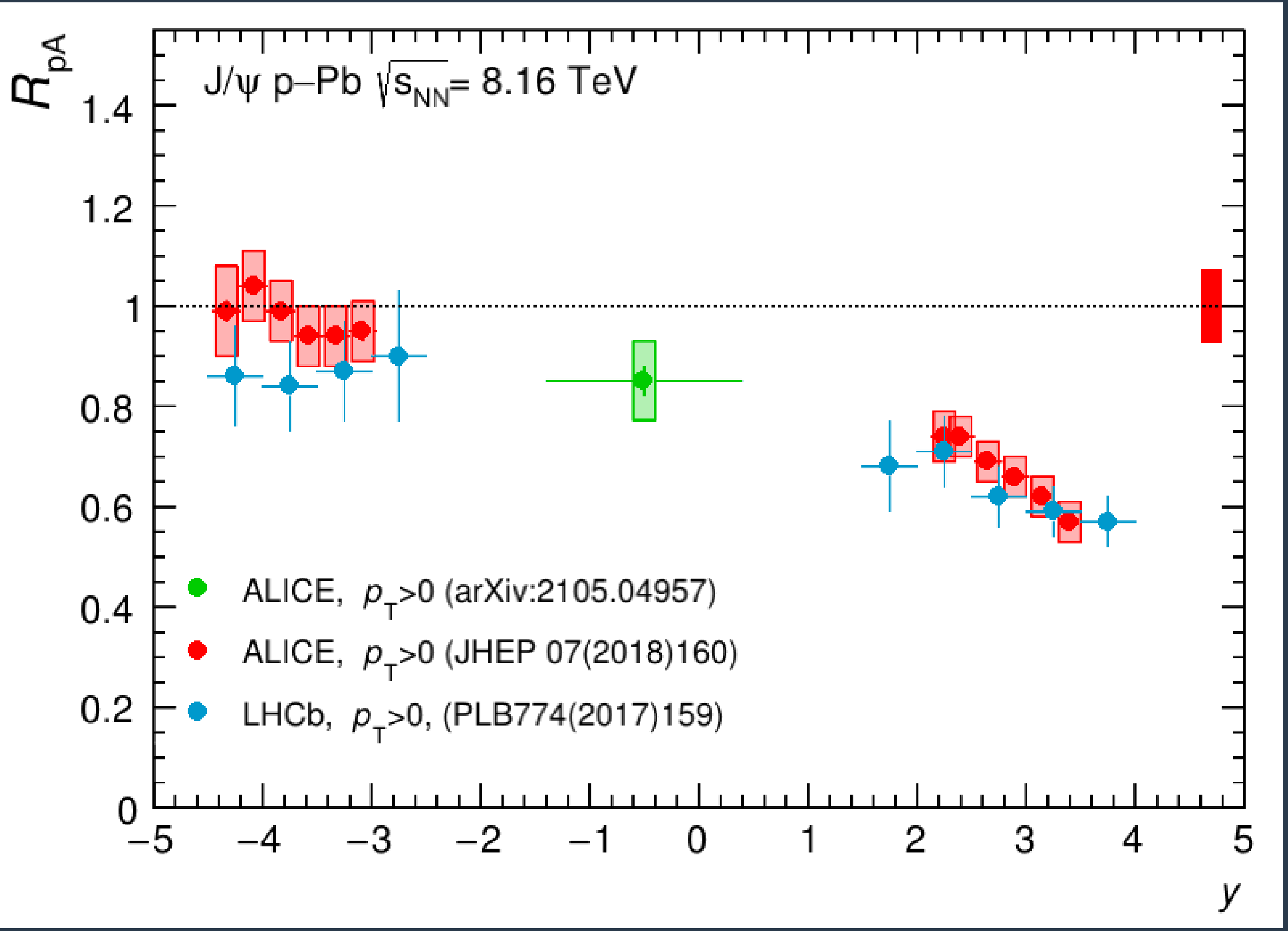
p-Al:

- no significant CNM effects

p-Au:

- Significant suppression at forward-y → consistent with shadowing
- Suppression exceeds pure shadowing effects → additional nuclear break-up contribution

J/ψ in pA at LHC



Low p_T

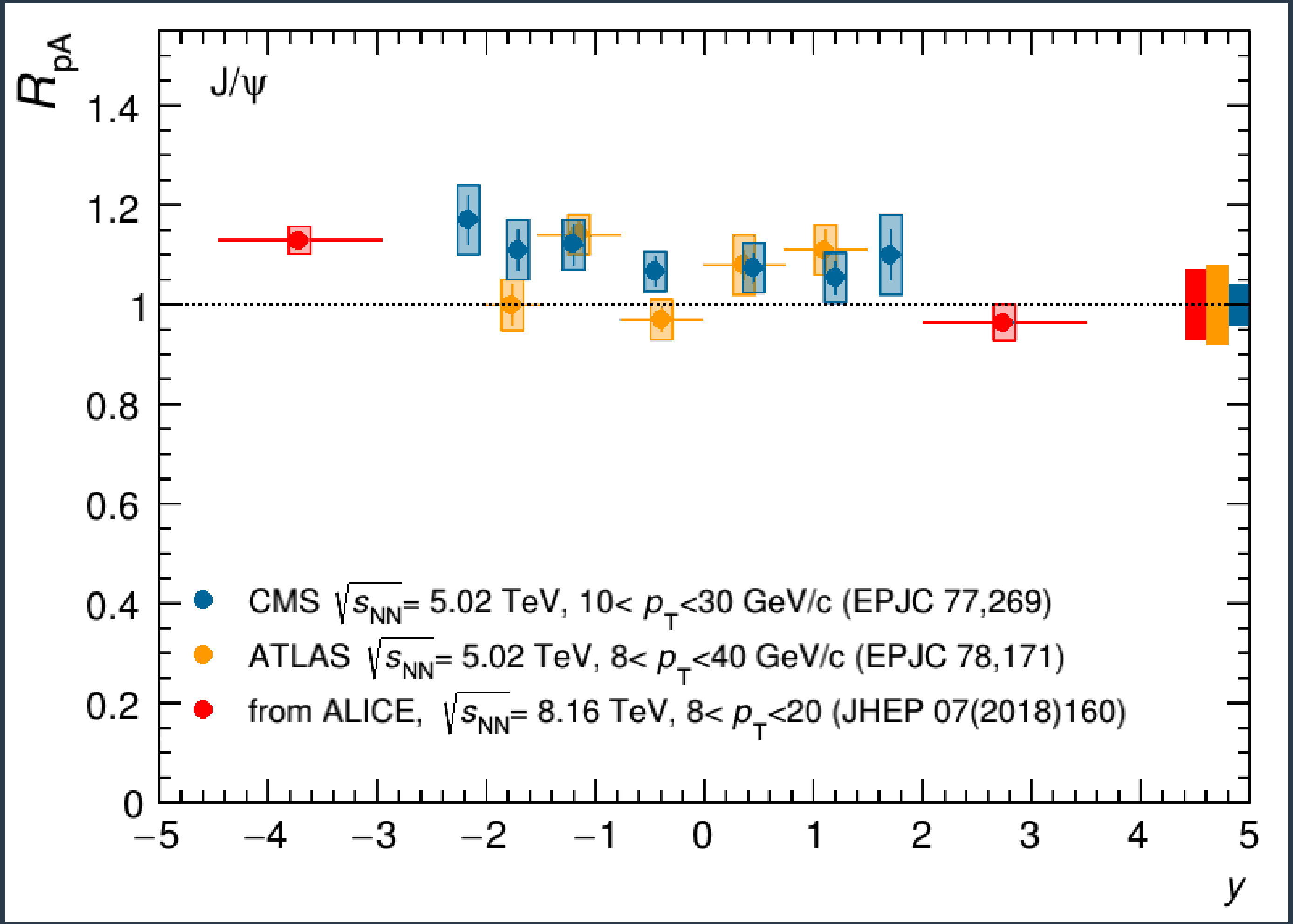
strong rapidity dependence, J/ψ production significantly suppressed at forward-y

ALICE

p-going direction: $2.3\ 10^{-5}<x<1.5\ 10^{-4}$

Pb-going direction: $1.5\ 10^{-2}<x<10^{-1}$

J/ψ in pA at LHC



Low p_T

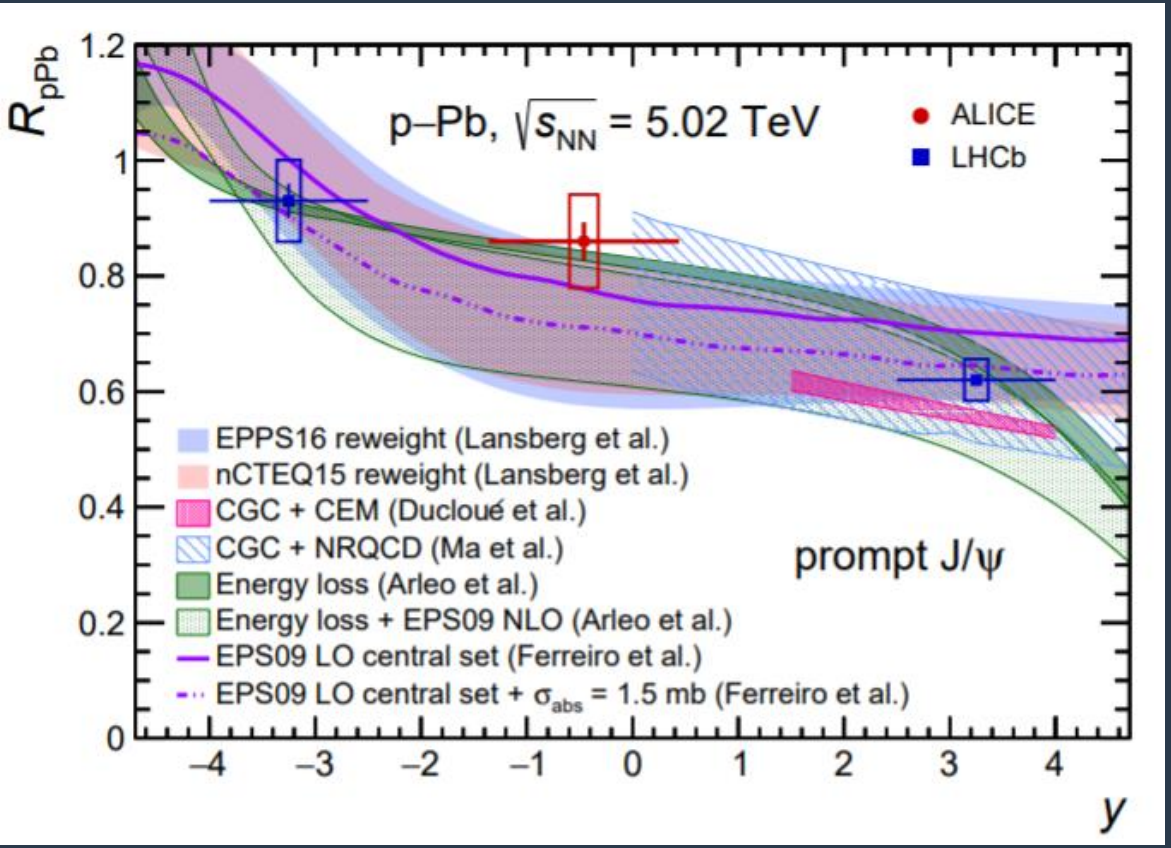
strong rapidity dependence, J/ψ production significantly suppressed at forward-y

High p_T

R_{pA} is rather flat and close to unity (or slightly higher)

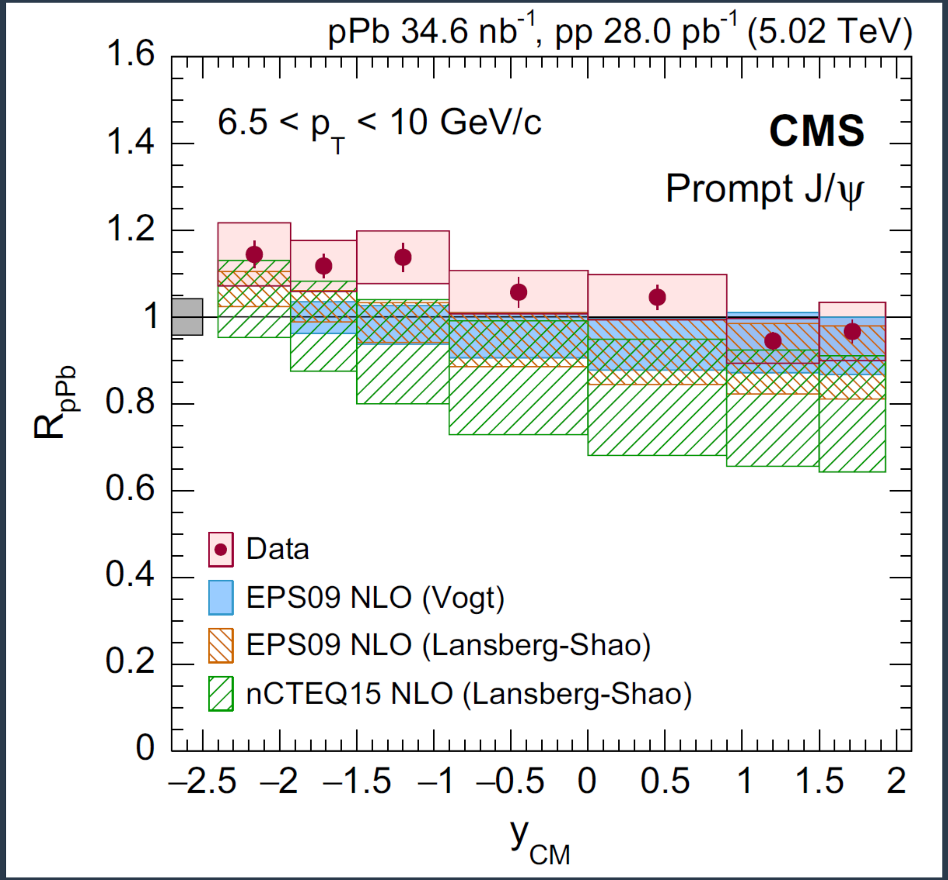
Comparison to theory

Low p_T



ALICE, arXiv:2105.04957

High p_T



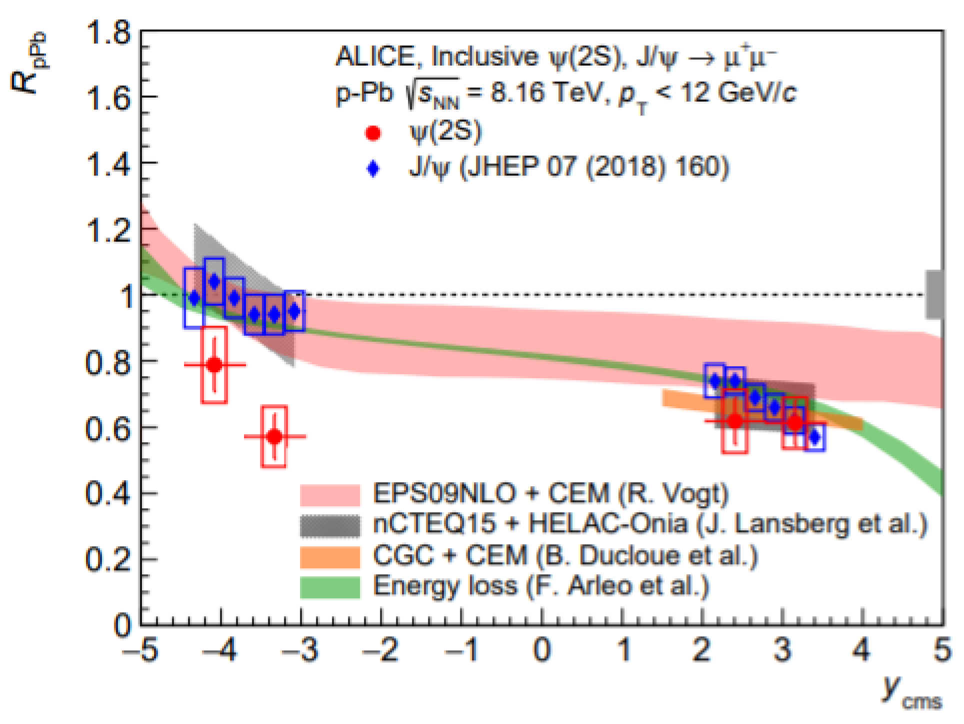
CMS, Eur. Phys. J. C (2017) 77

CNM models, based on shadowing, CGC, energy loss describe the data

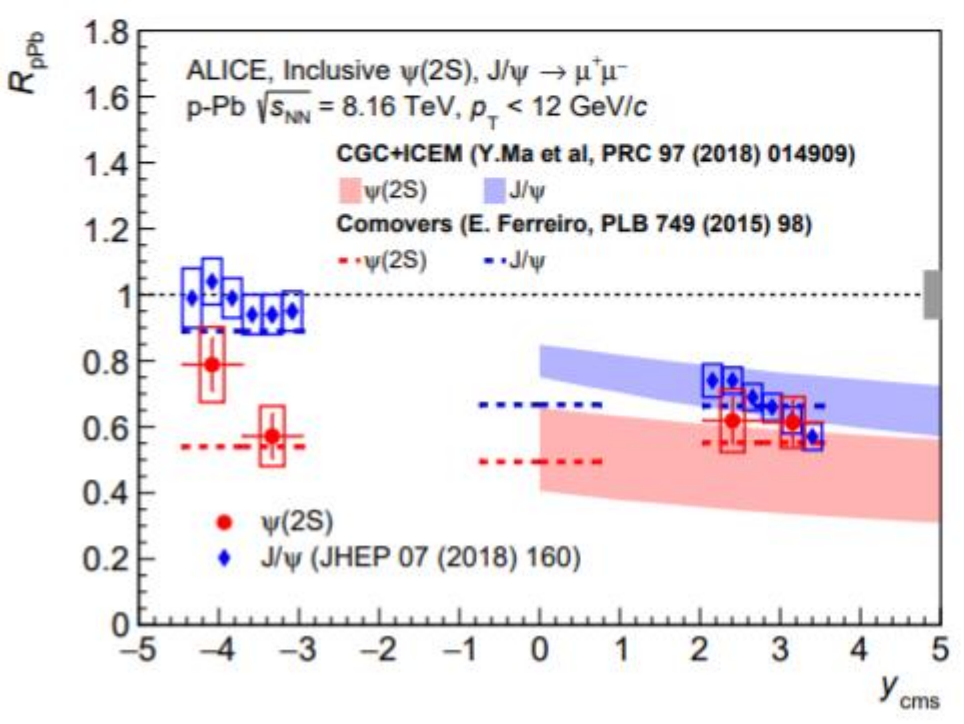
No need for additional break-up at LHC energies

ψ(2S) in pA

ψ(2S) suppression is stronger than the J/ψ one, in particular at backward-y



ALICE, JHEP07 (2020) 237



At LHC energies

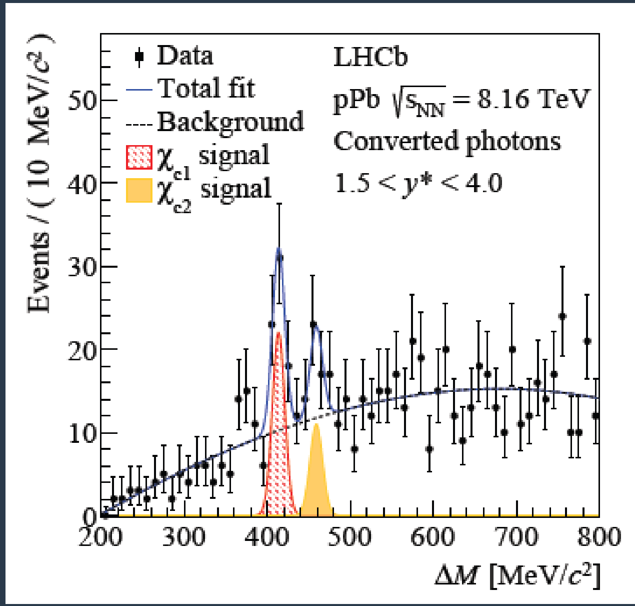
$\tau_{crossing} < \tau_{formation}$

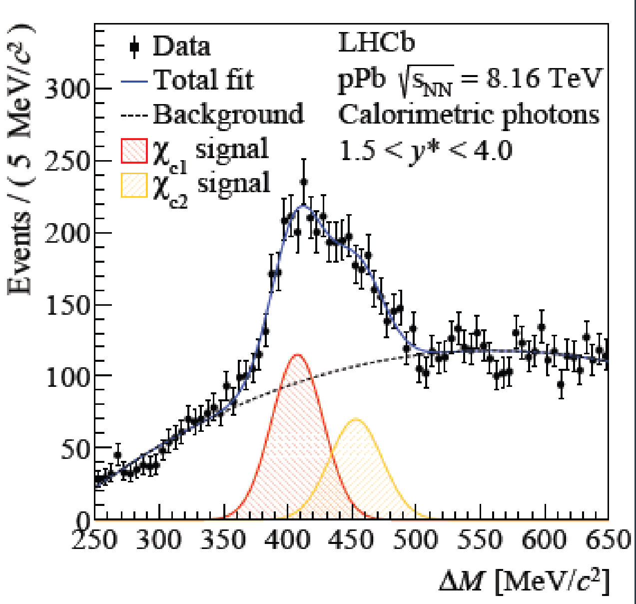
same effects were expected for the two resonances

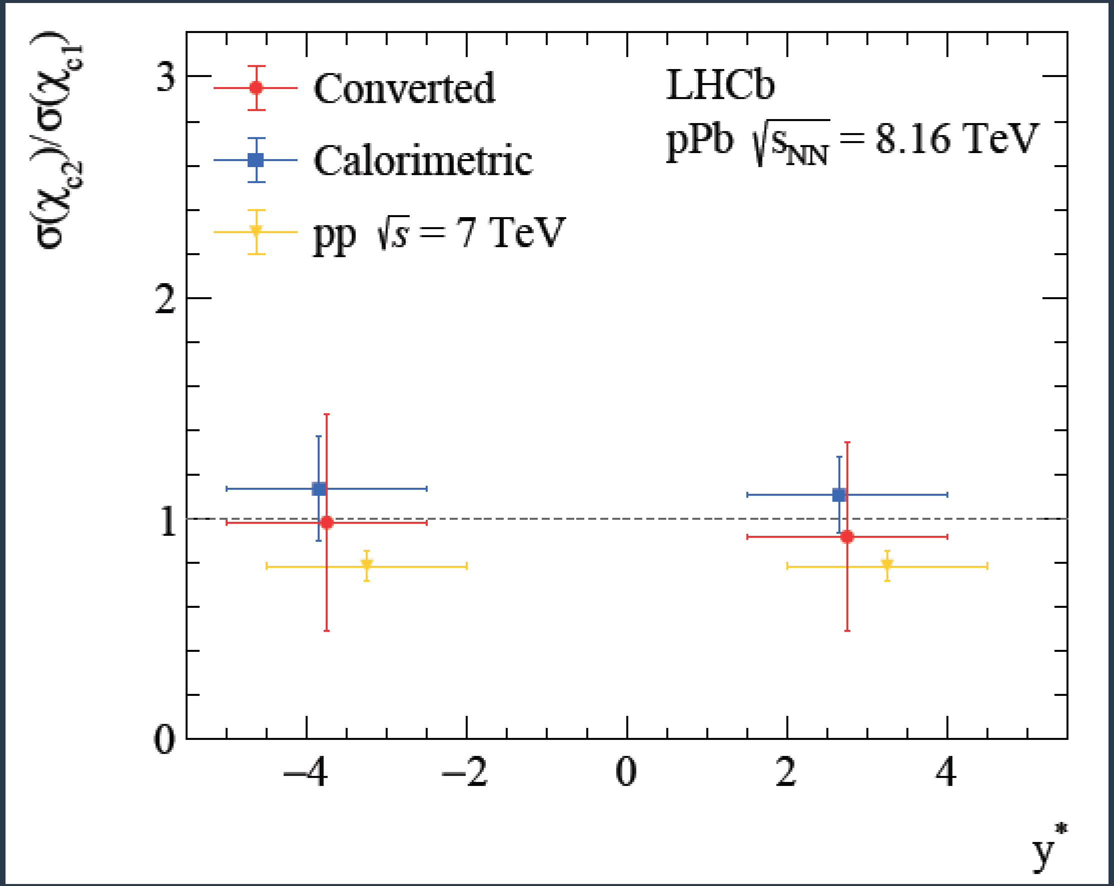
additional final state effects (interactions with hadron/partonic comovers) needed to describe the data

χ_c in pA

LHCb, arXiv:2103.07349



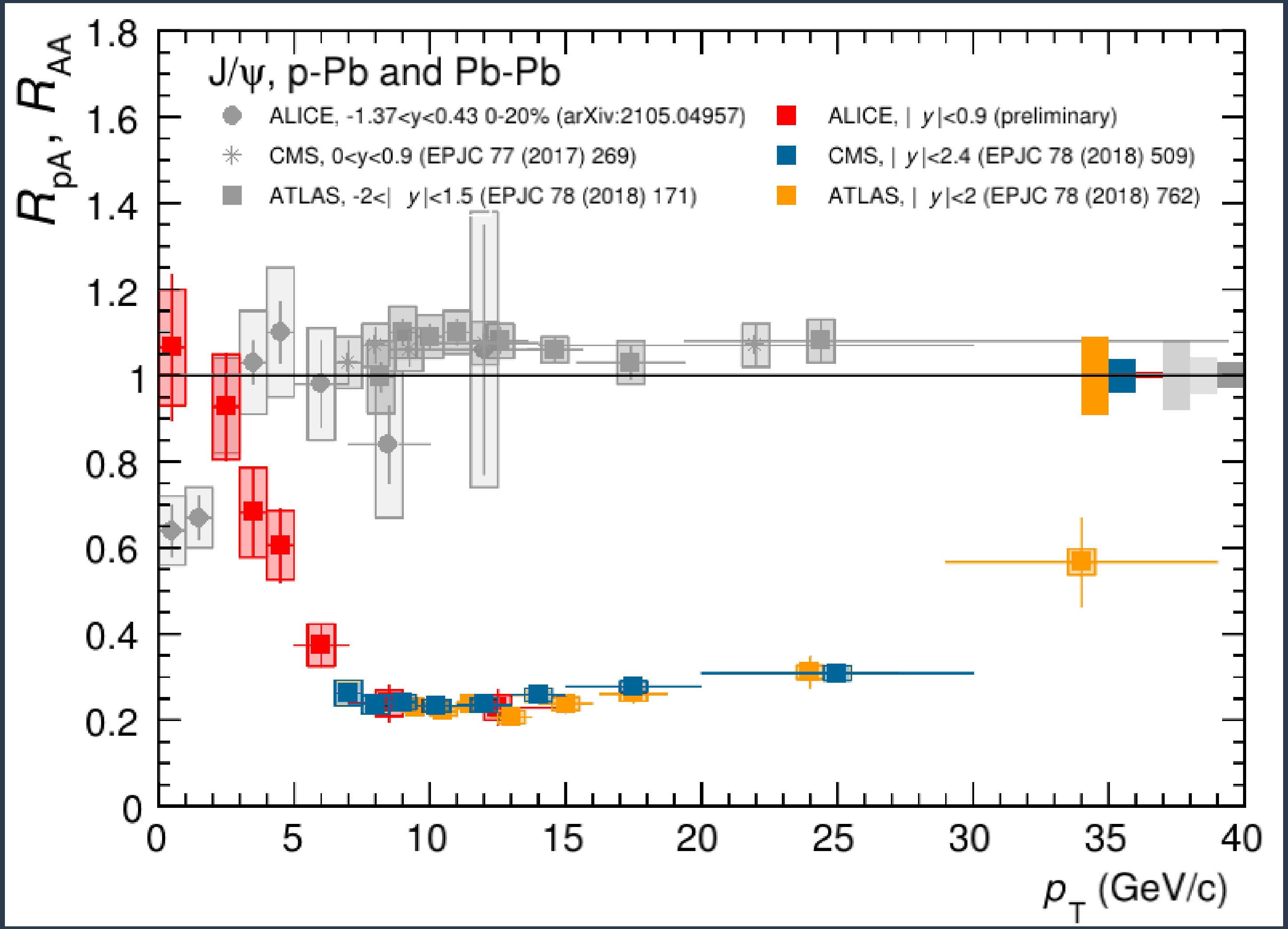




- Converted vs calorimetric photons: better resolution, but smaller reconstruction efficiency

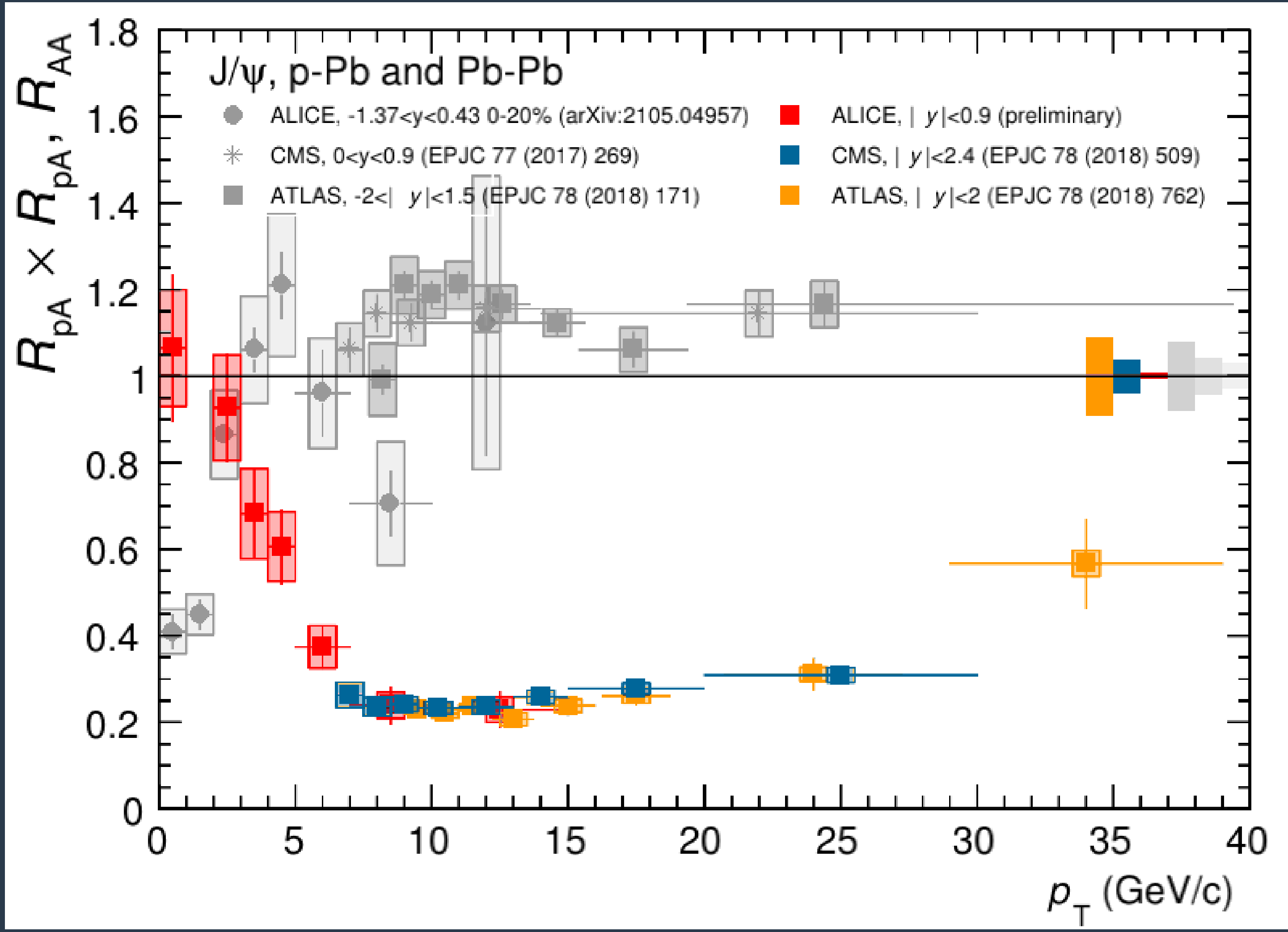
Similar cross section ratios in pp and pPb, both at forward and mid-y
Similar CNM effects on the two resonances

Compare pA and AA: J/ψ



significant difference between J/ψ R_{pA} and R_{AA} over all the p_T range

Compare pA and AA: J/ψ

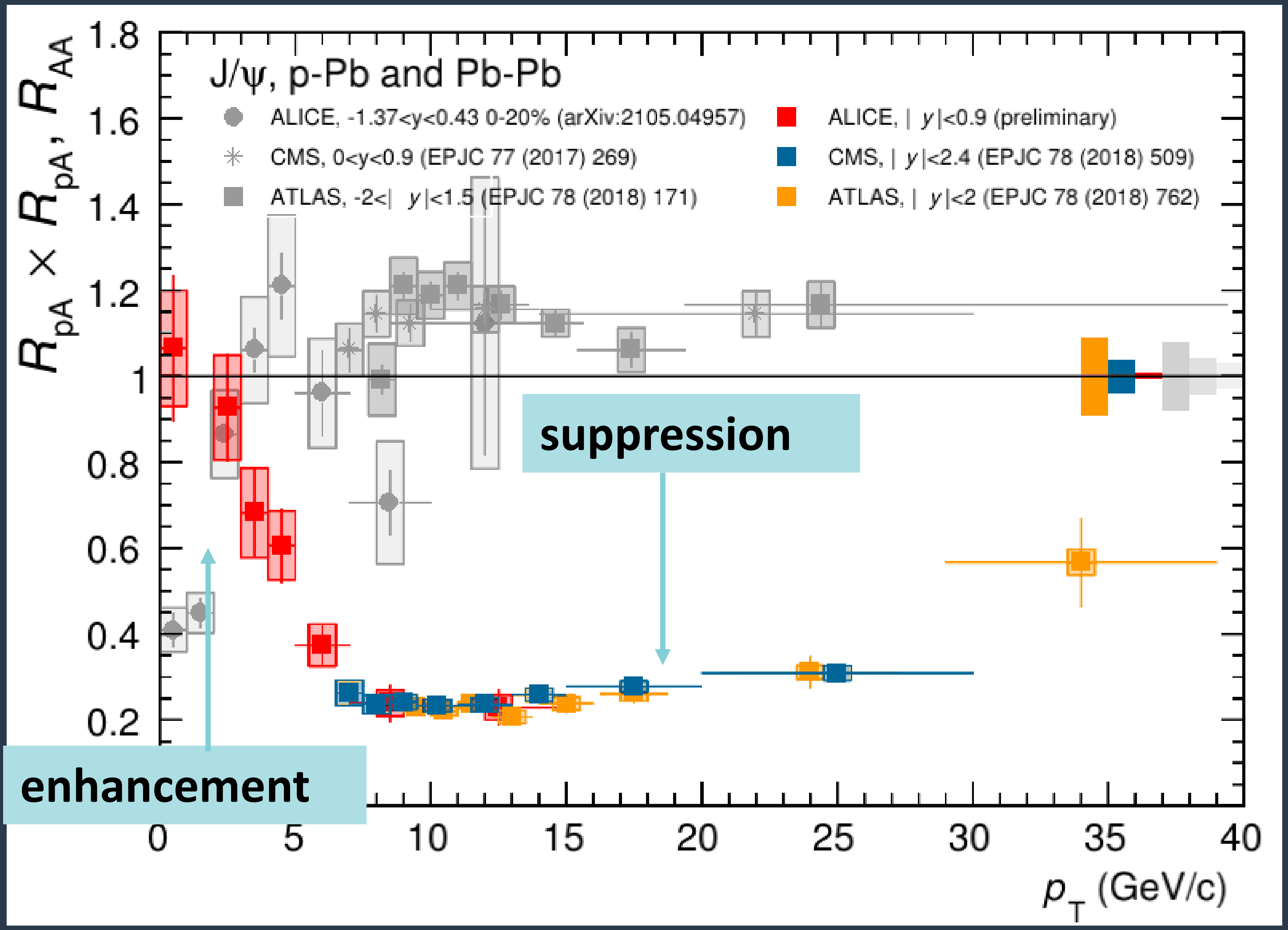


significant difference between J/ψ R_{pA} and R_{AA} over all the p_T range

Assuming shadowing as the main CNM effect at mid-y:

$$R_{AA}^{CNM} = R_{pA}^{2}$$

Compare pA and AA: J/ψ



significant difference between J/ψ R_{pA} and R_{AA} over all the p_T range

Assuming shadowing as the main CNM effect at mid-y:

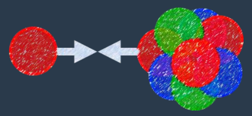
$$R_{AA}^{CNM} = R_{pA}^2$$

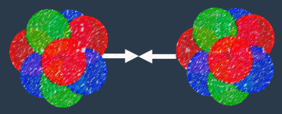
Clear R_{AA} enhancement at low p_T and suppression at high p_T

Crossing between suppression and enhancement at p_T ~ 4 GeV/c

Conclusions

A large variety of charmonium results are now available, from RHIC and LHC, in pA and AA, over a broad kinematic range





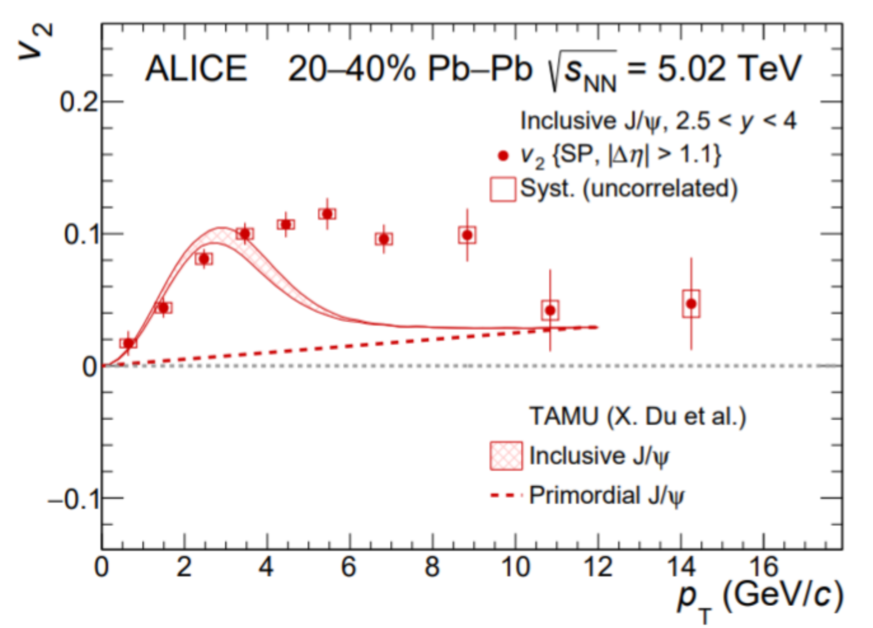
Results from all the LHC experiments show an overall good compatibility in similar kinematic ranges and point to a coherent picture

Results for J/ψ have already reached a high level of precision, still room for improvements for excited states

Thank you!

Backup

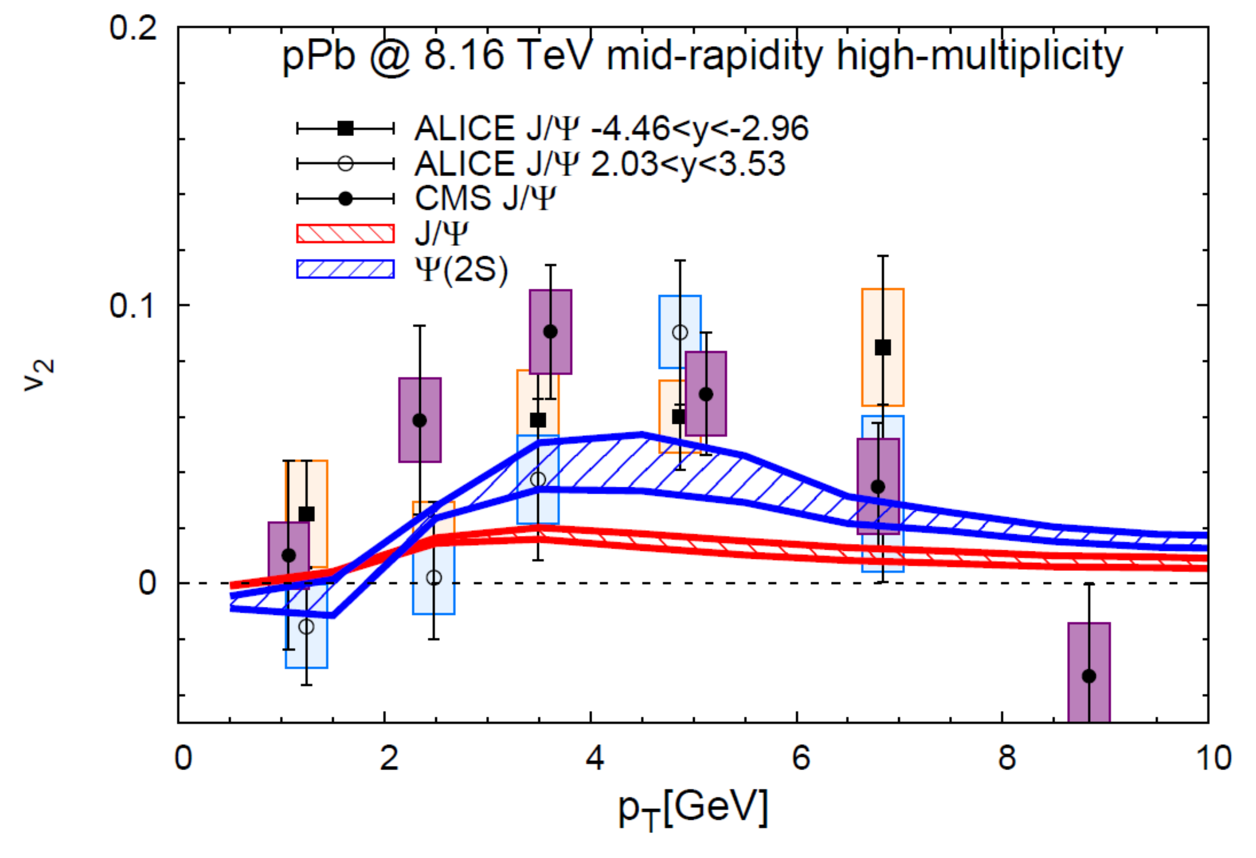
J/ψ v_2



low p_T:
Size of v_2 reproduced by models including a large J/ψ regeneration component

high p_T:
path-length effects play a role, but $\boldsymbol{v_2}$ still underestimated

J/ψ v_2 in pA



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

- size of v_2 similar to the one measured in PbPb
- however, usual v_2 interpretation for PbPb, based on regeneration or path lengths effects, doesn't work in pPb
- models where v_2 originates from final state effects in the fireball (dissociation, regeneration) underestimate the data

ALICE, PLB 780 (2018) 7
CMS, PLB791(2019)172
Rapp et al, JHEP03(2019)015