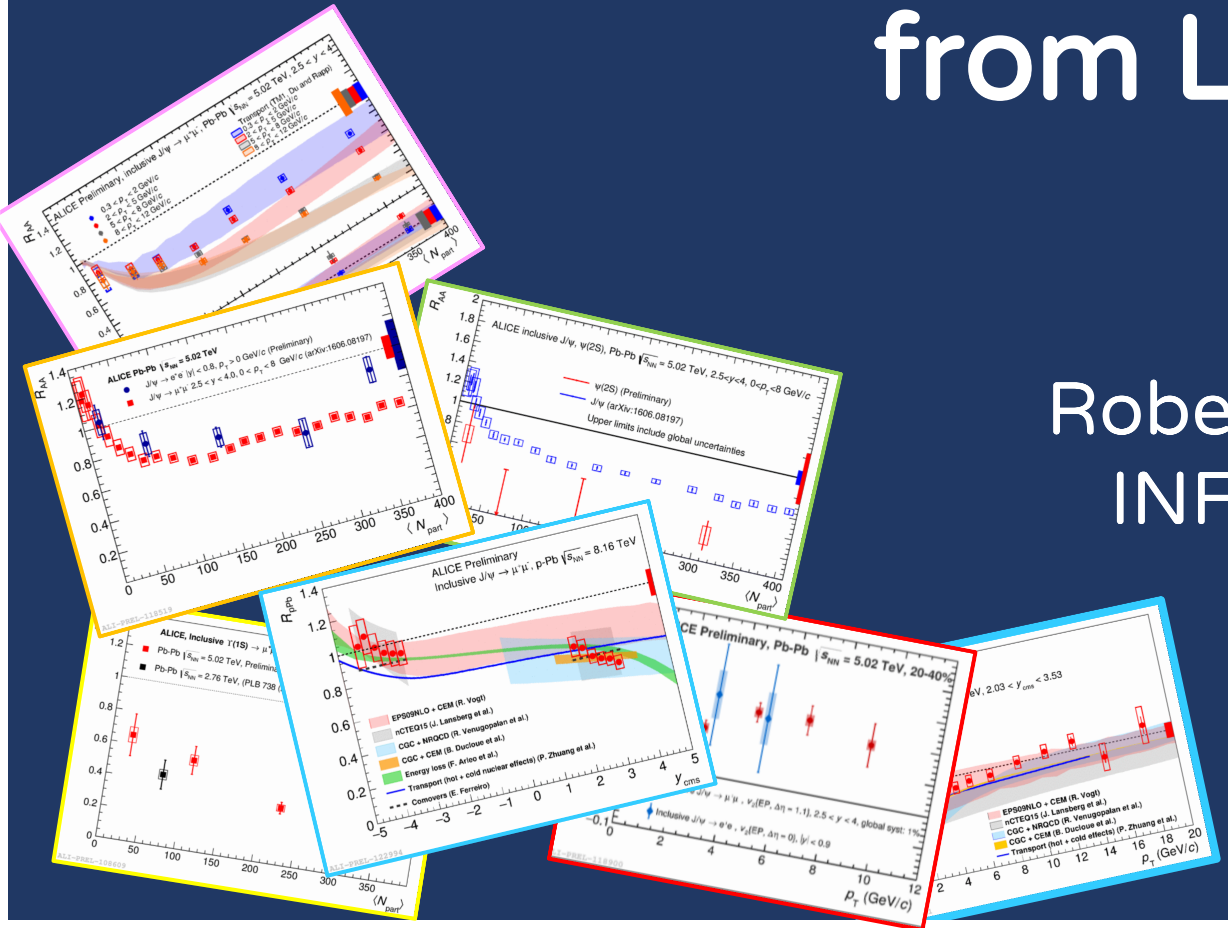
Quarkonium in ALICE: results on p-Pb and Pb-Pb collisions from LHC Run2



Roberta Arnaldi

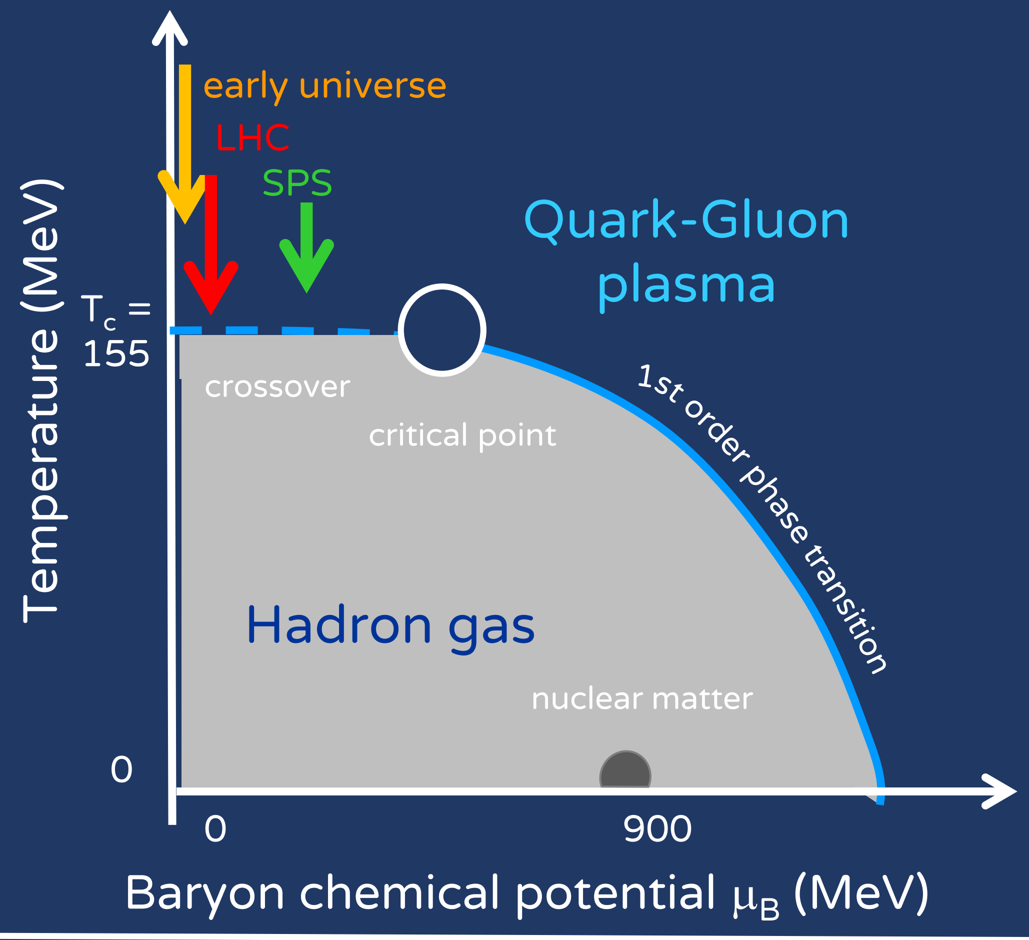
INFN Torino

CERN PH seminar, May 2nd 2017

ALICE

A look into the Quark-Gluon Plasma

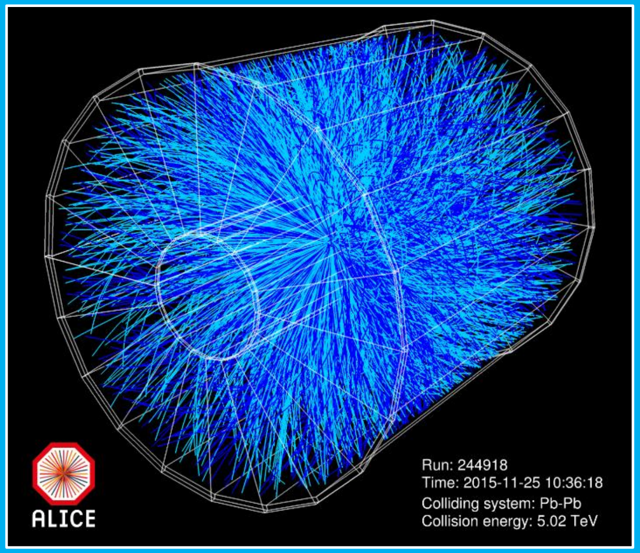
Investigate the production and properties of the Quark-Gluon Plasma, the state of matter where quarks and gluons are deconfined



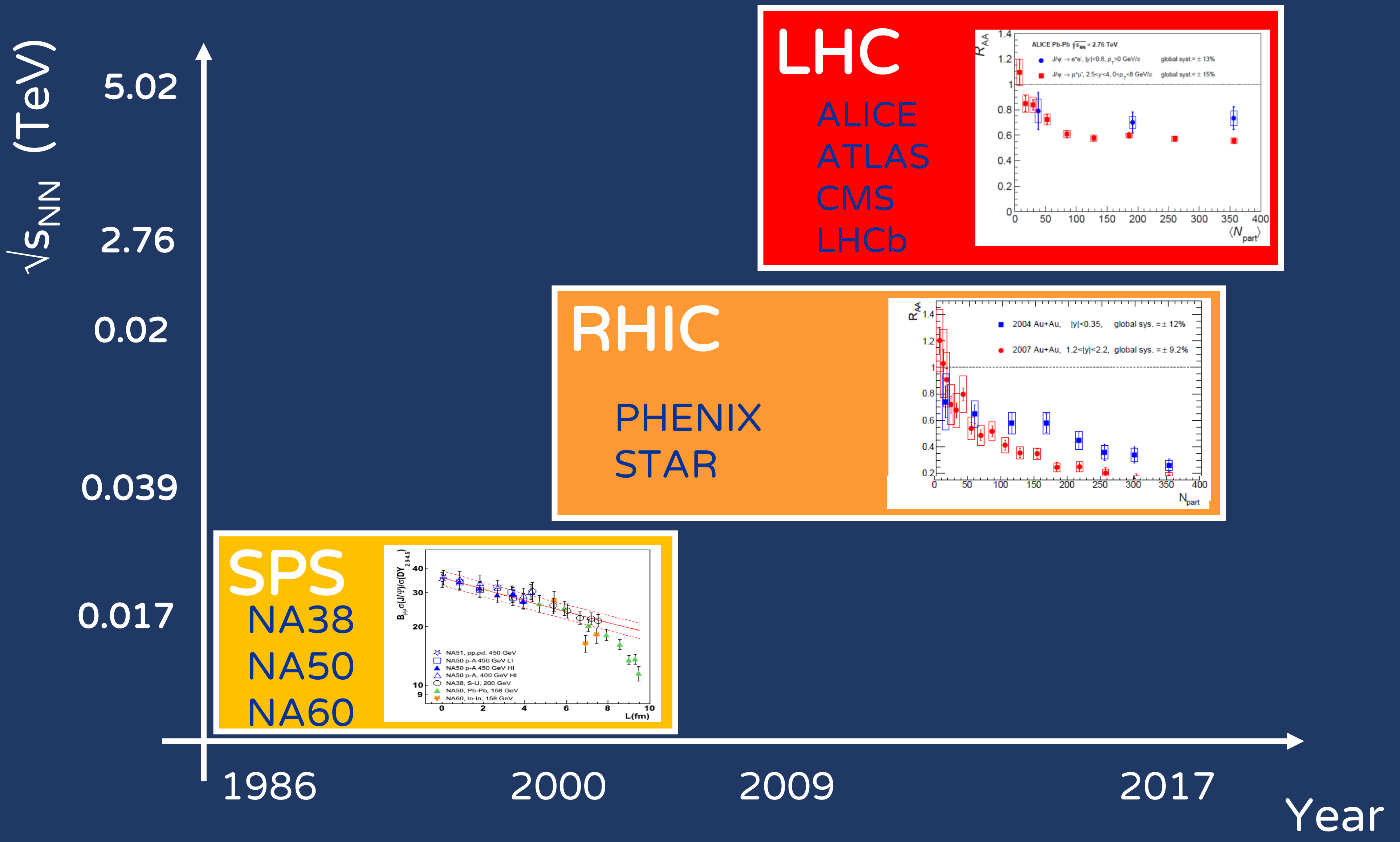
QGP is formed in the phase diagram region corresponding to high temperature and low μ_B

At LHC the QGP is formed in heavy ion collisions

Quarkonia as a probe of the QGP formation



Quarkonium studies in HI collisions

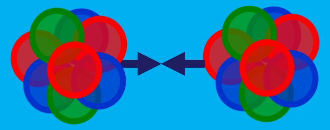


Outline

- Focus on (a selection of) new quarkonium results obtained by ALICE in the LHC Run 2:

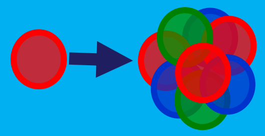
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- J/ψ nuclear modification factor (R_{AA}) and azimuthal anisotropy (v_2) at forward and mid-rapidity
- ψ(2S) R_{AA} at forward-y
- bottomonium R_{AA} at forward-y



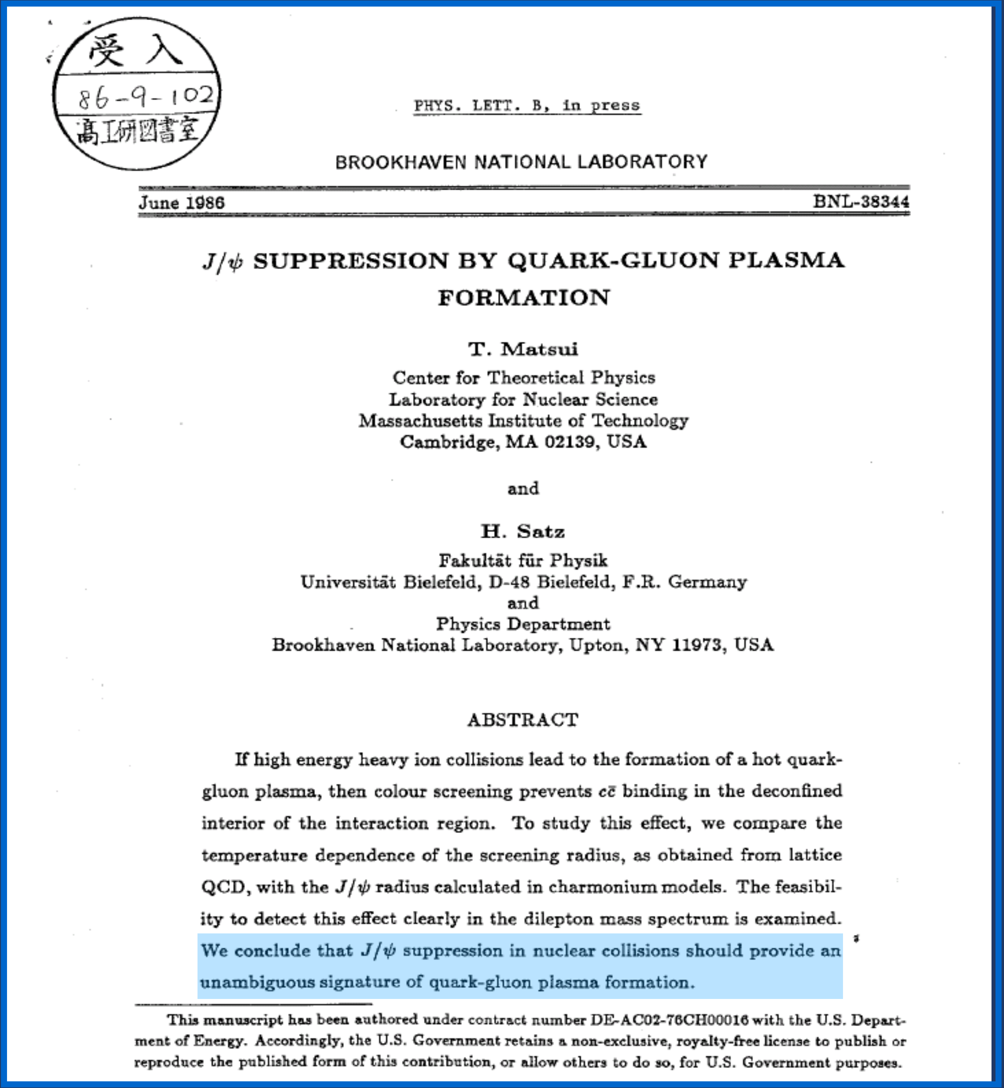
p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

J/ψ nuclear modification factor at forward-y



- Results will be compared with theoretical models, with measurements from other experiments and with Run 1 results

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

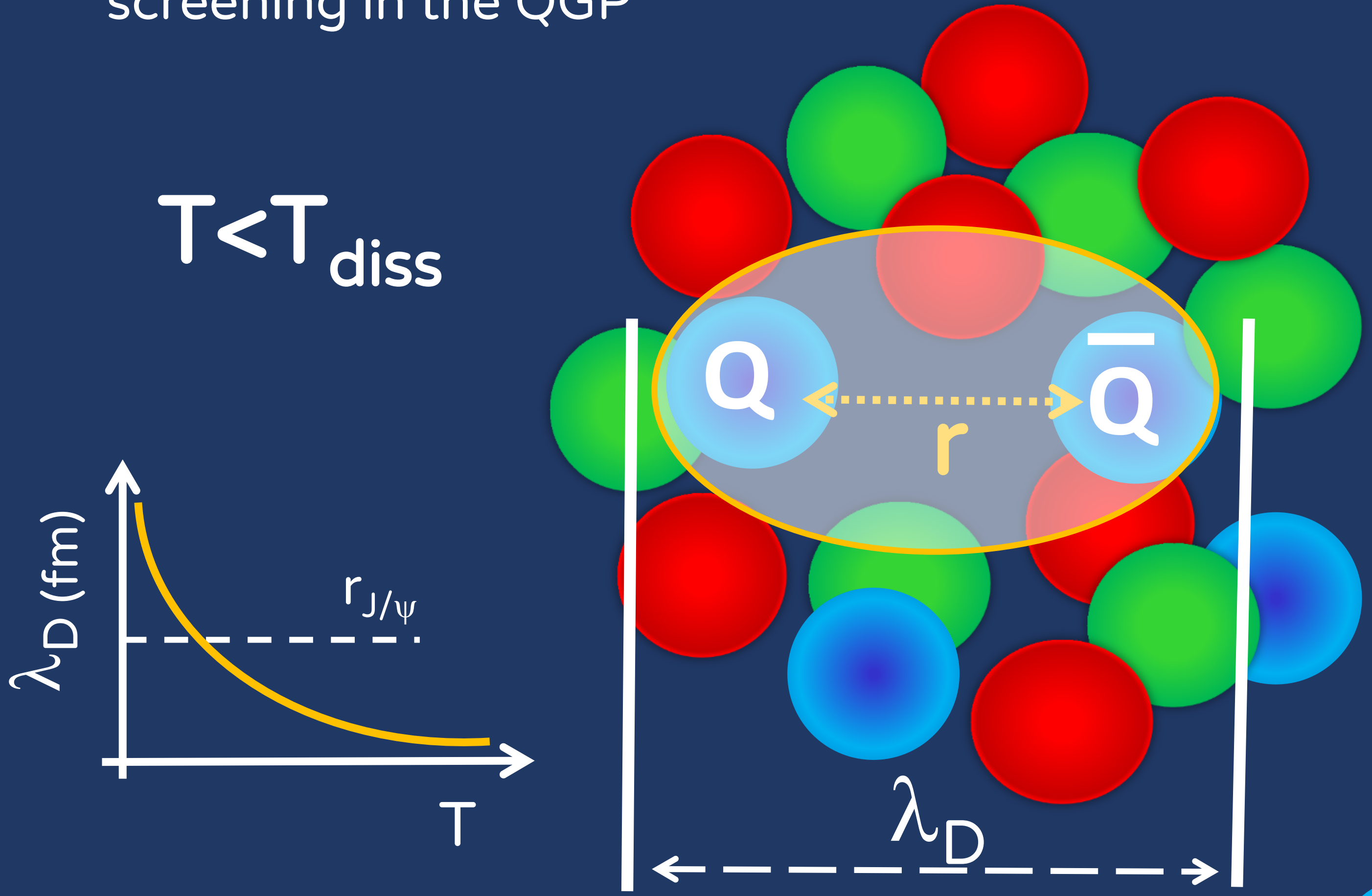
ABSTRACT

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.

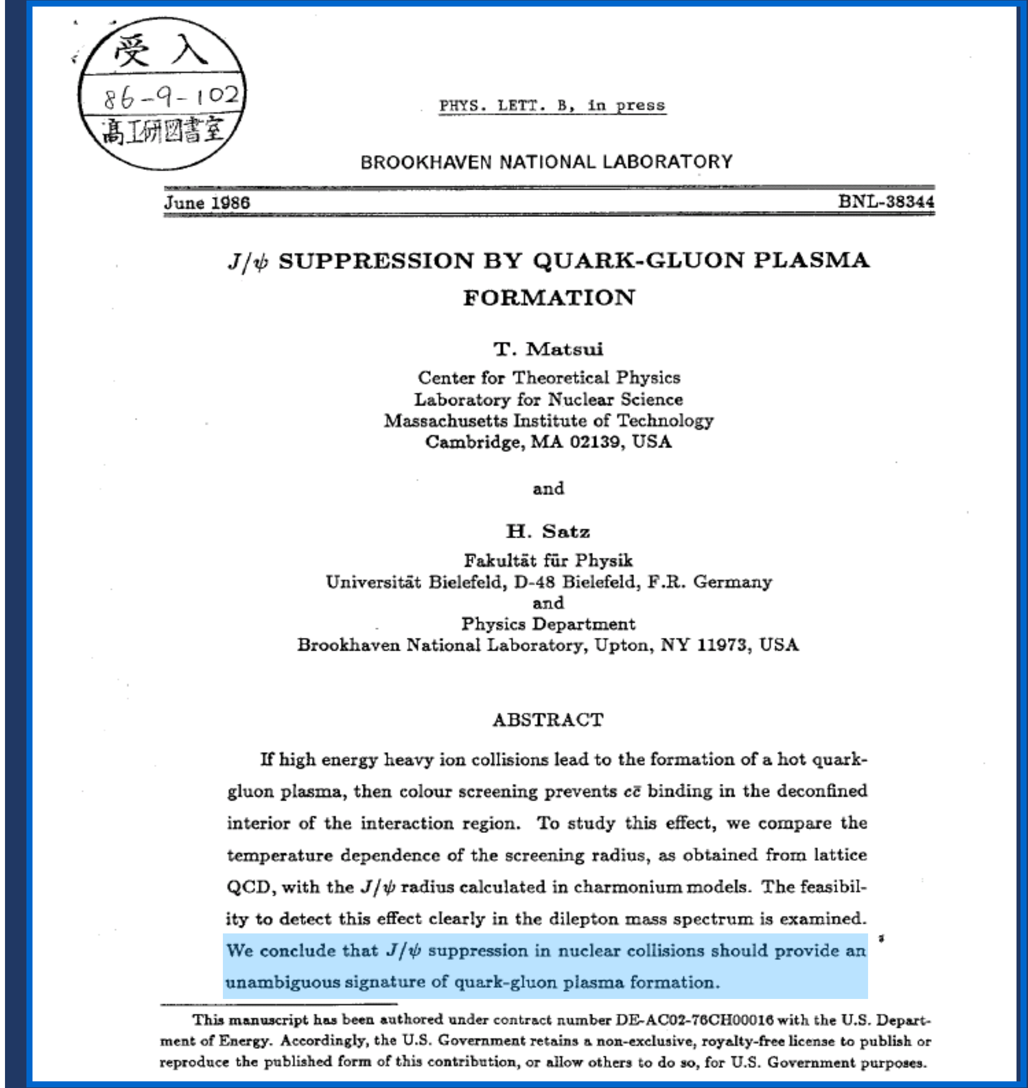
This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

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

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



Quarkonium suppression



受入
86-9-102
高エ研図書室

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

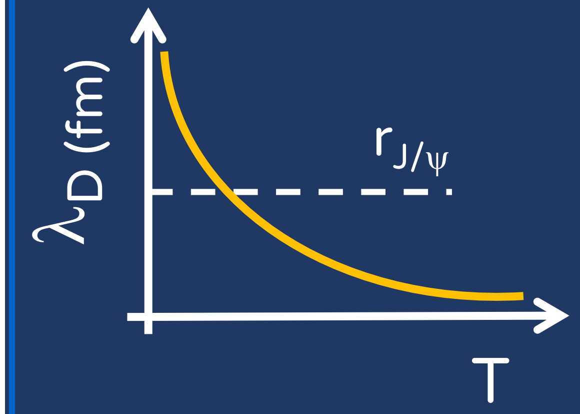
If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice 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.

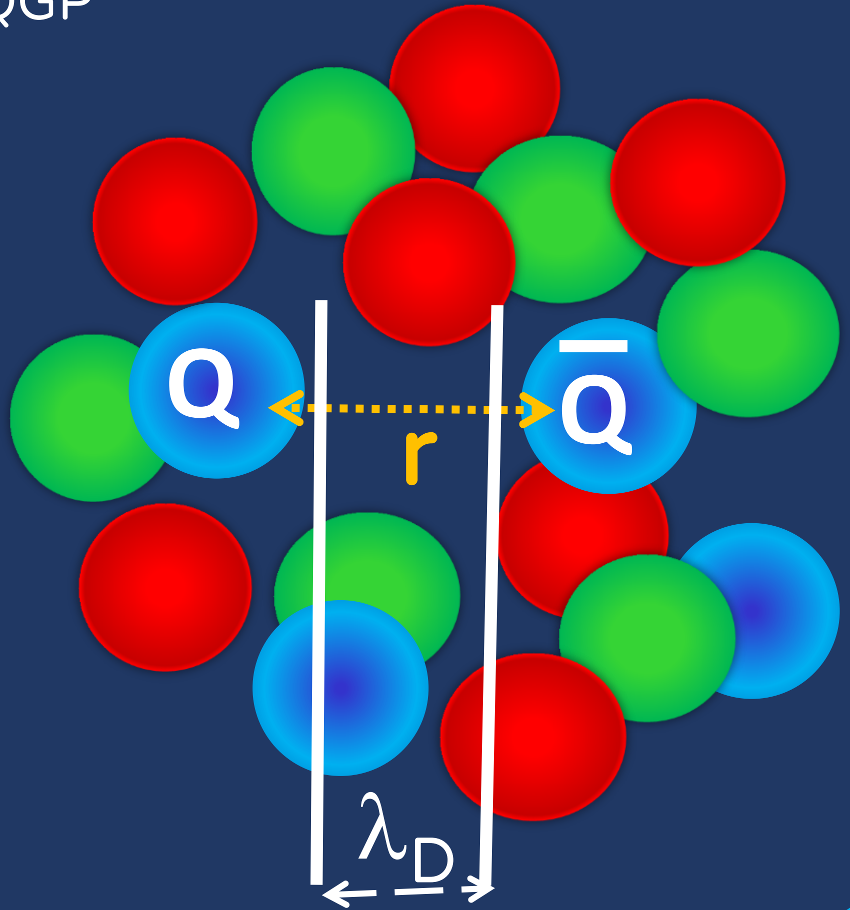
This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

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

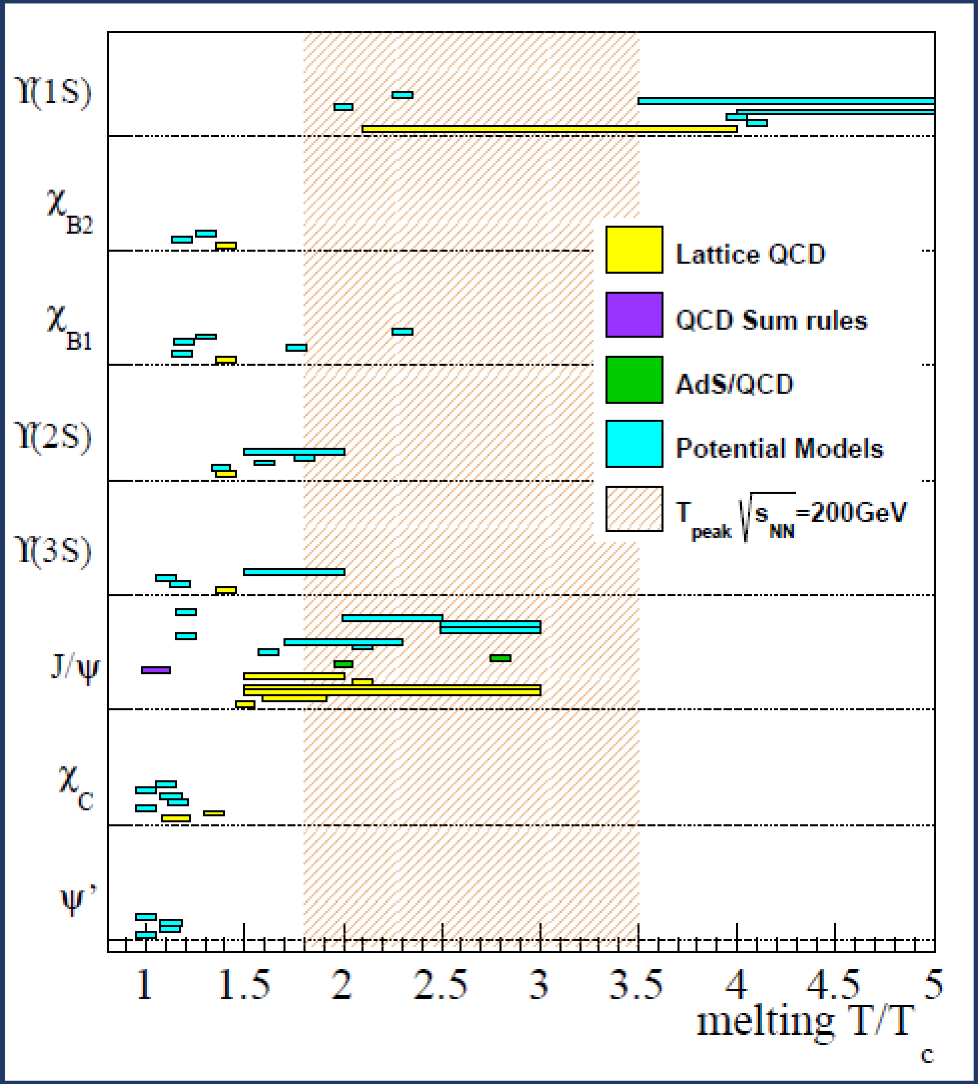
the original idea:
quarkonium production suppressed via color screening in the QGP

$T>T_{diss}$





Quarkonium suppression



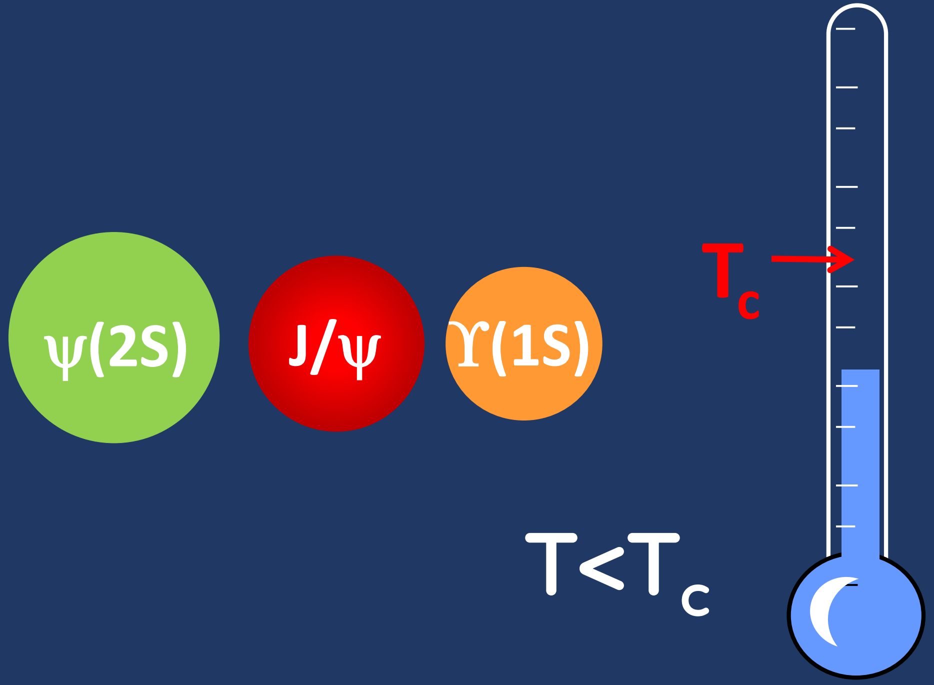
PHENIX, Phys.Rev C91, 024913

the original idea:

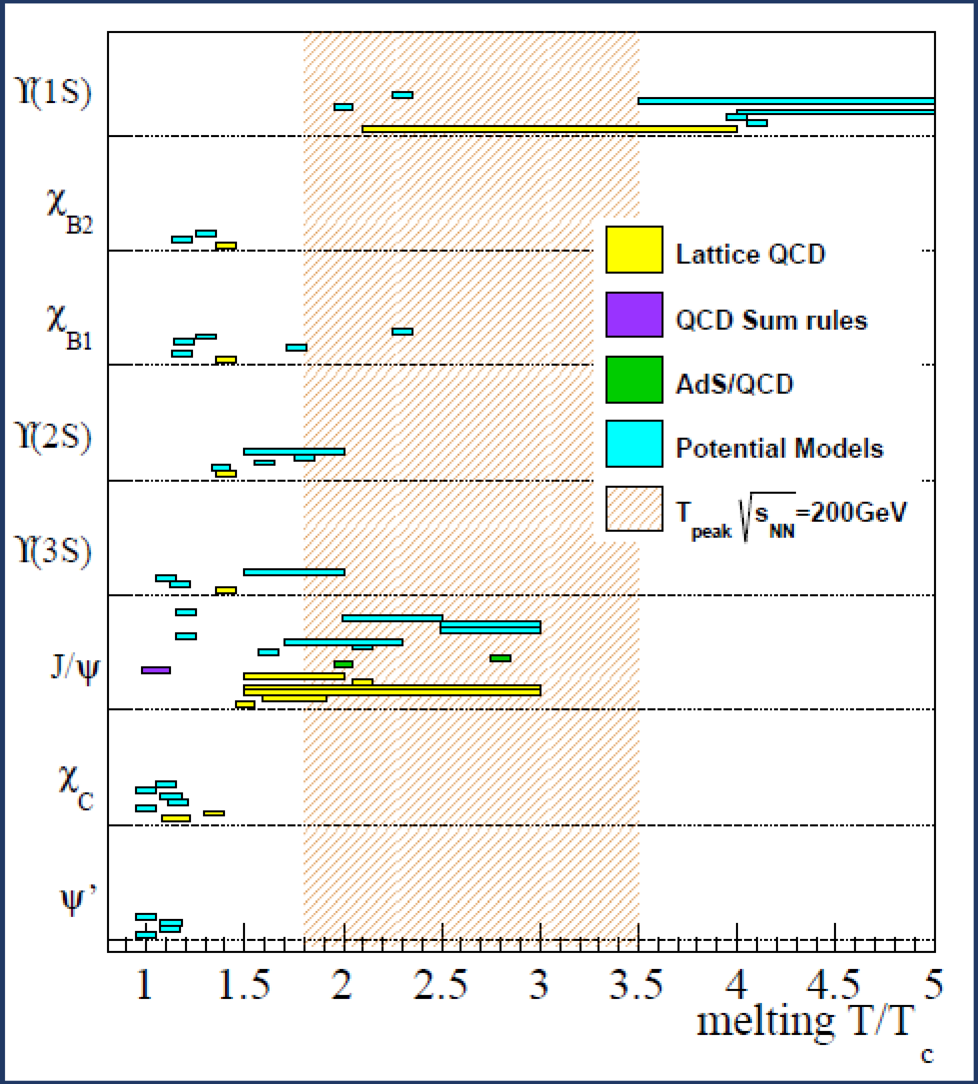
quarkonium production suppressed via color screening in the QGP

sequential melting:

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

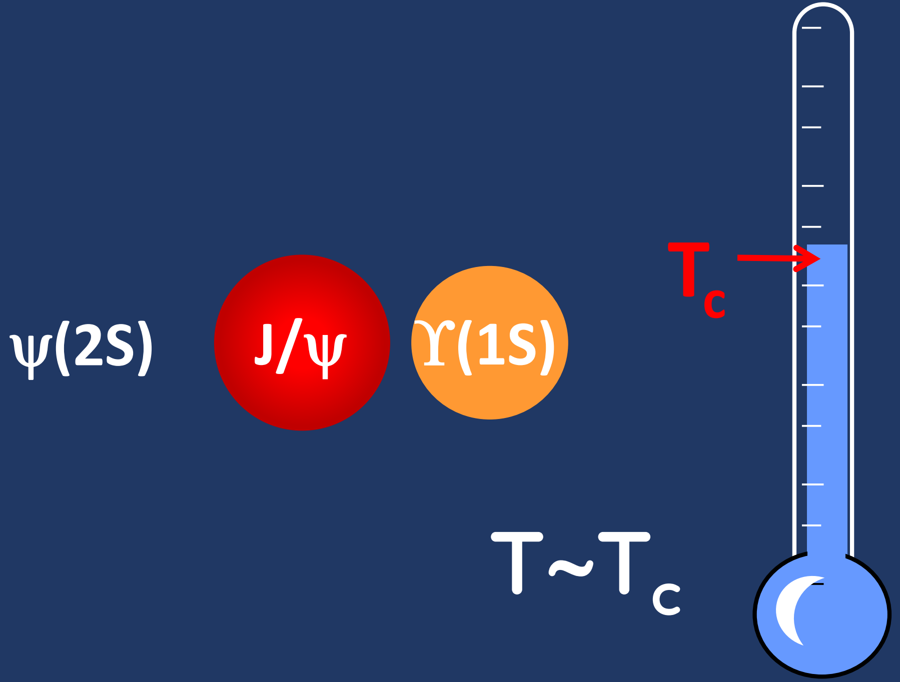


Quarkonium suppression

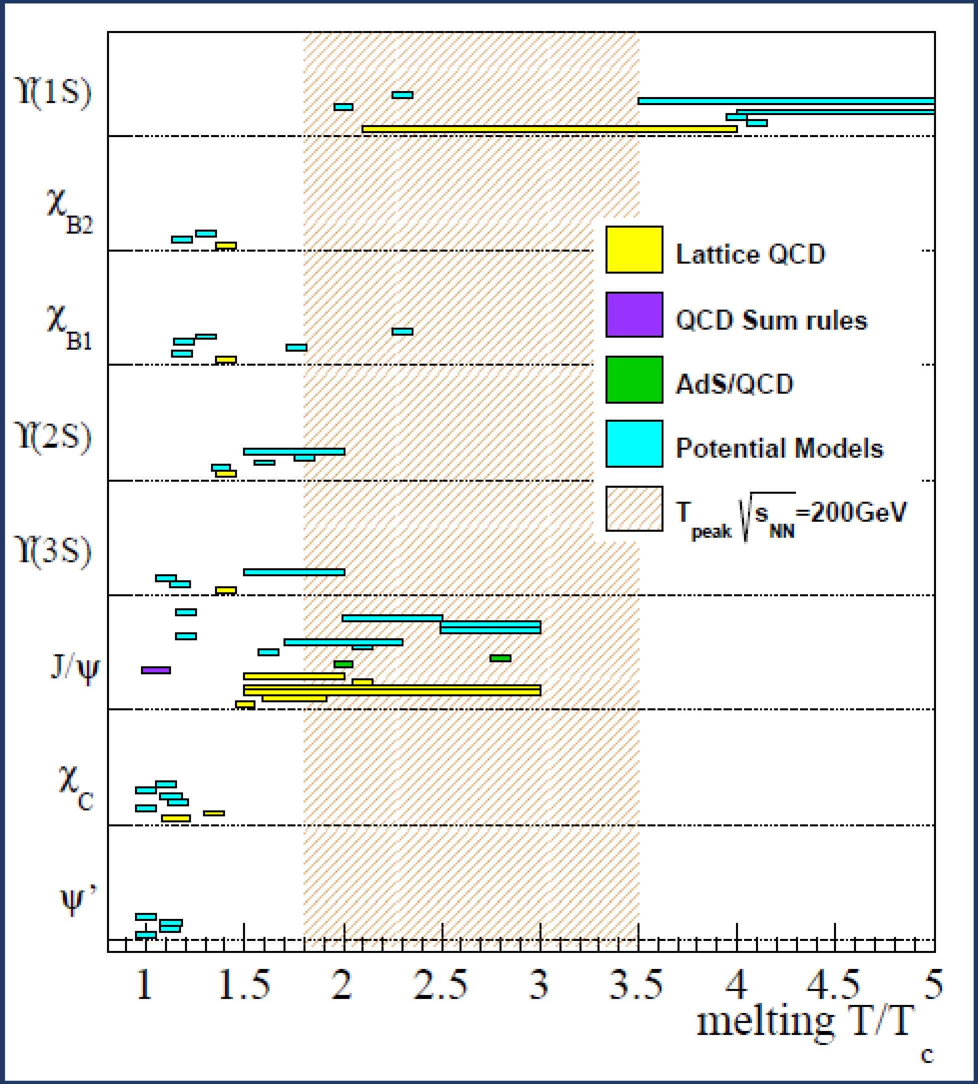


PHENIX, Phys.Rev C91, 024913

- **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



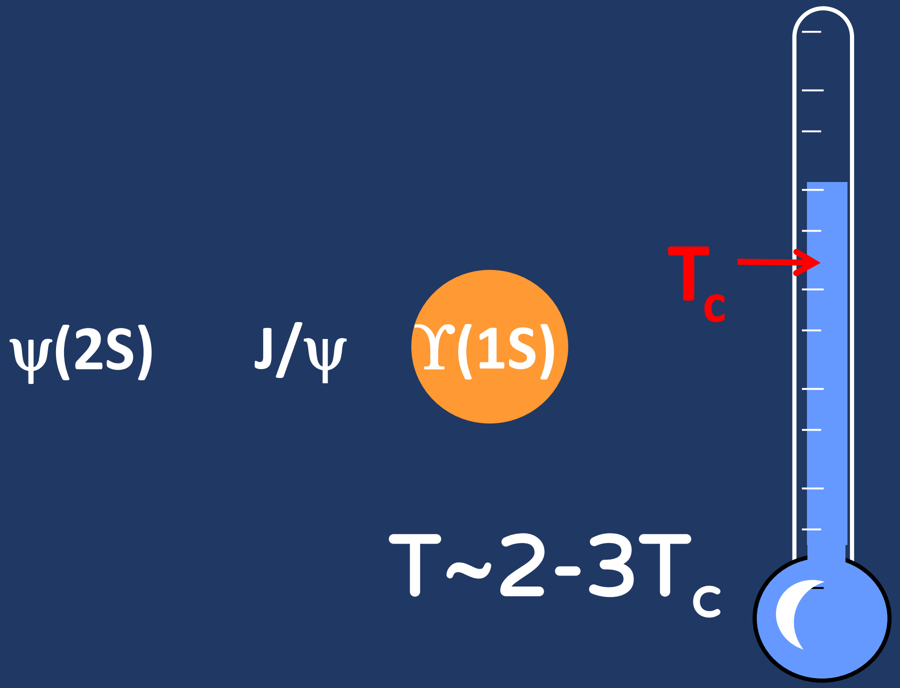
Quarkonium suppression



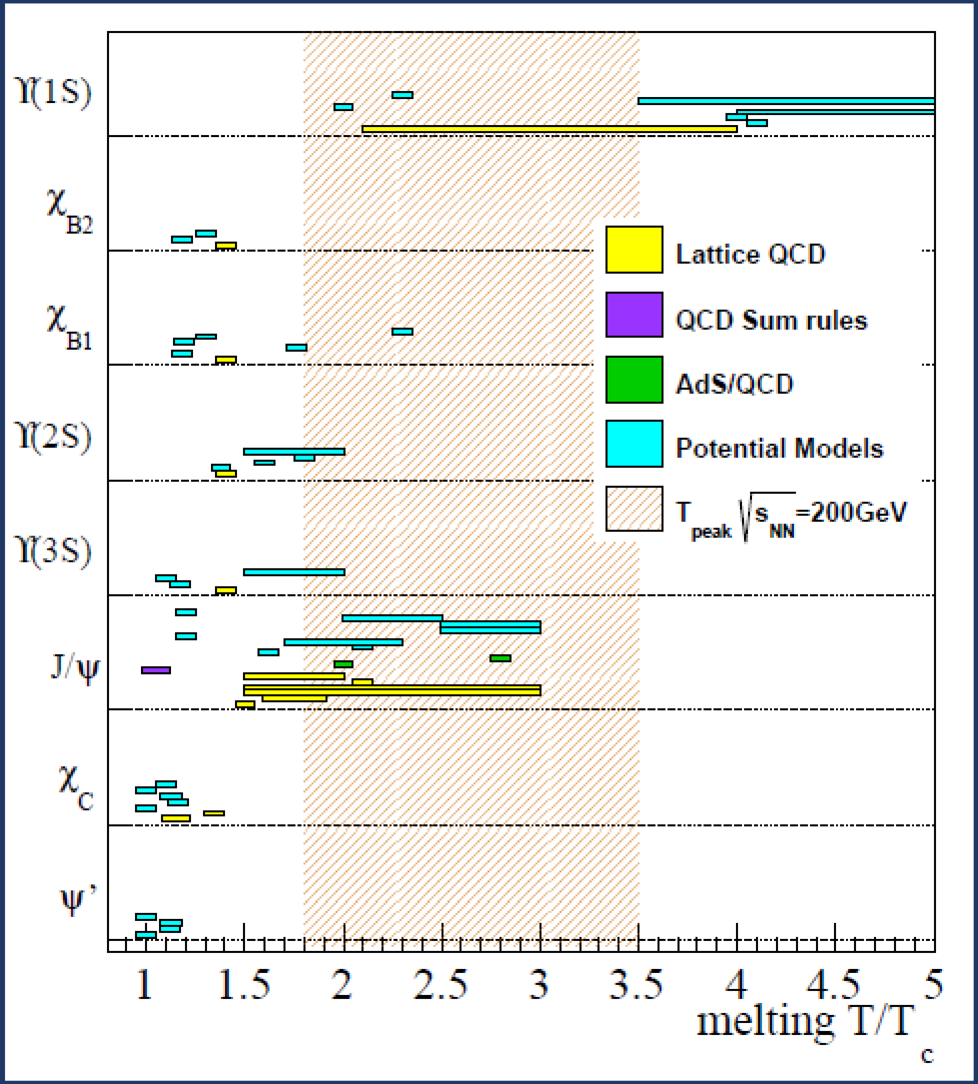
PHENIX, Phys.Rev C91, 024913

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



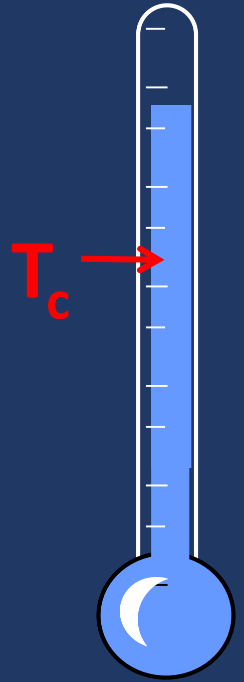
Quarkonium suppression



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

ψ(2S) J/ψ ϒ(1S)



$T>>T_c$

…and quarkonium recombination

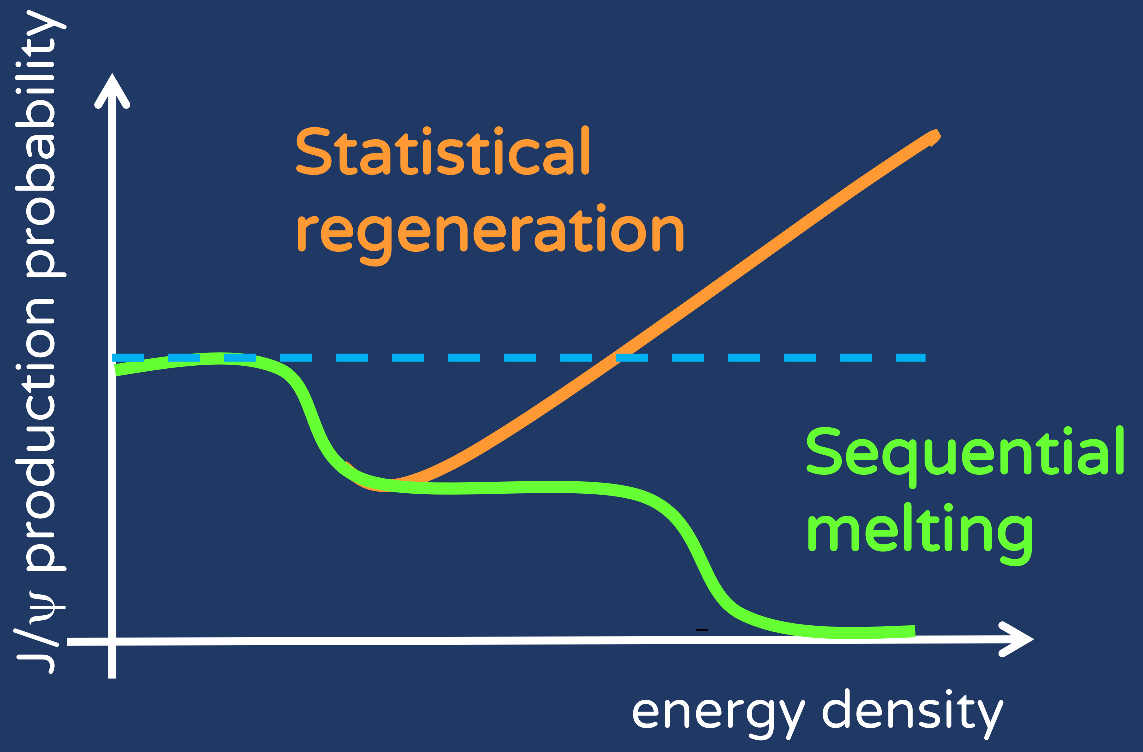
(Re)combination

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)

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

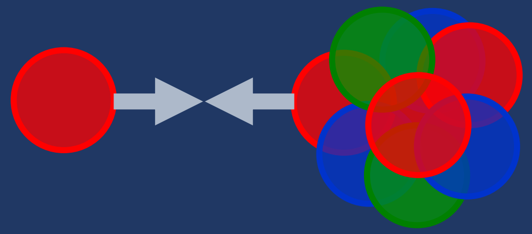
→ on the experimental side:

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

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

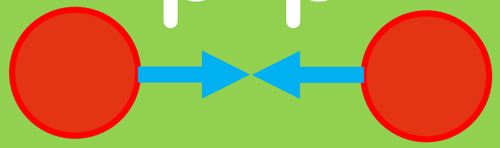
- CNM are investigated in p-A collisions, addressing:



- 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

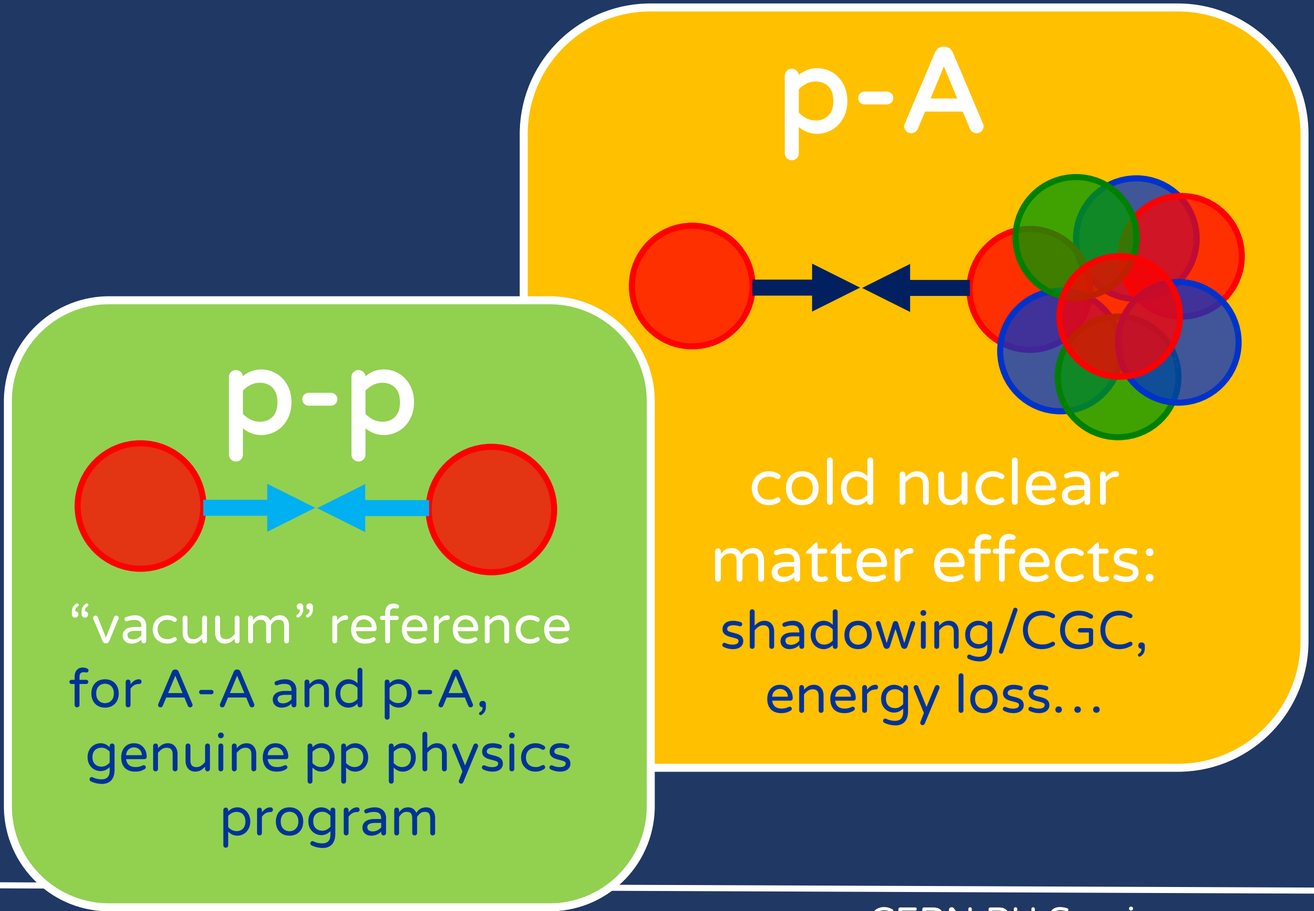
Summarizing quarkonium in pp, pA, AA

p-p



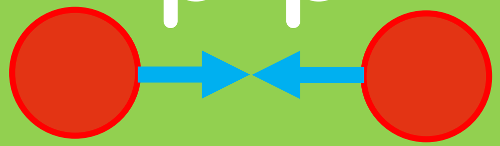
"vacuum" reference for A-A and p-A, genuine pp physics program

Summarizing quarkonium in pp, pA, AA



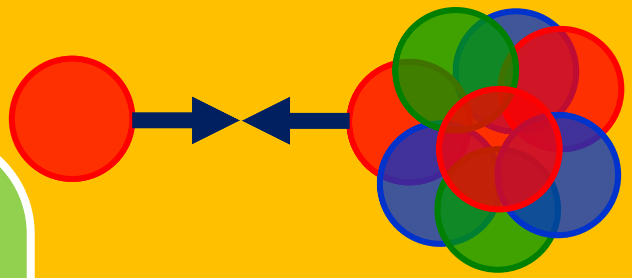
Summarizing quarkonium in pp, pA, AA

p-p



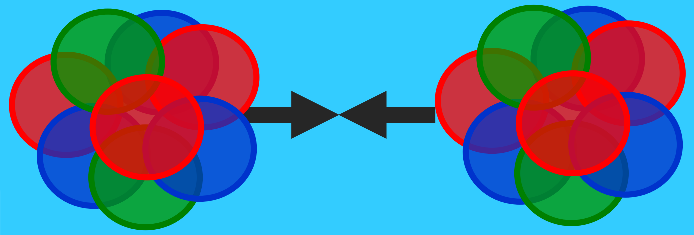
"vacuum" reference for A-A and p-A, genuine pp physics program

p-A



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

A-A



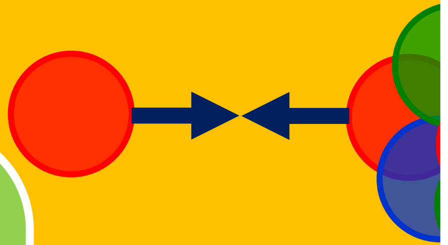
hot matter effects:
regeneration vs suppression

Summarizing quarkonium in pp, pA, AA

p-p

"vacuum" reference for A-A and p-A, genuine pp physics program

p-A

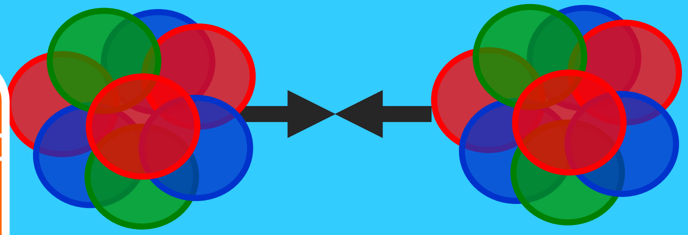


cold nucle
matter effe
shadowing/CG
energy loss…

warm-hot matter effects?

hadronic resonance gas (comovers), partonic matter

A-A



hot matter effects:
regeneration vs suppression

LHC data taking

Run 1 (2009 – 2013)

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV	L =26 μb^{-1} (MB) L =69 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L =51 μb^{-1} (MB) L_{pPb} = 5nb^{-1} (dimuon) L_{Pbp} = 5.8 nb^{-1}(dimuon)
pp, $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV	

Run 2 (2015 – 2016)

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L = 19 μb^{-1} (MB) L= 225 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ =5.02 TeV	L = 0.4 nb^{-1} (MB)
p-Pb, $\sqrt{s_{NN}}$ =8.16 TeV	L_{pPb} = 8.7 nb^{-1} (dimuon) L_{Pbp} = 12.9 nb^{-1} (dimuon)
pp, $\sqrt{s}$ = 5.02, 13 TeV	

Run 1 → Run 2

- Increase in energy
- Increase in luminosity

LHC data taking

Run 1 (2009 – 2013)

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV	L =26 μb^{-1} (MB) L =69 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L =51 μb^{-1} (MB) L_{pPb} = 5nb^{-1} (dimuon) L_{Pbp} = 5.8 nb^{-1}(dimuon)
pp, $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV	

Run 2 (2015 – 2016)

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L = 19 μb^{-1} (MB) L= 225 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ =5.02 TeV	L = 0.4 nb^{-1} (MB)
p-Pb, $\sqrt{s_{NN}}$ =8.16 TeV	L_{pPb} = 8.7 nb^{-1} (dimuon) L_{Pbp} = 12.9 nb^{-1} (dimuon)
pp, $\sqrt{s}$ = 5.02, 13 TeV	

Run 1 → Run 2

- Increase in energy
- Increase in luminosity

LHC data taking

Run 1 (2009 – 2013)

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV	L =26 μb^{-1} (MB) L =69 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L =51 μb^{-1} (MB) L_{pPb} = 5nb^{-1} (dimuon) L_{Pbp} = 5.8 nb^{-1}(dimuon)
pp, $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV	

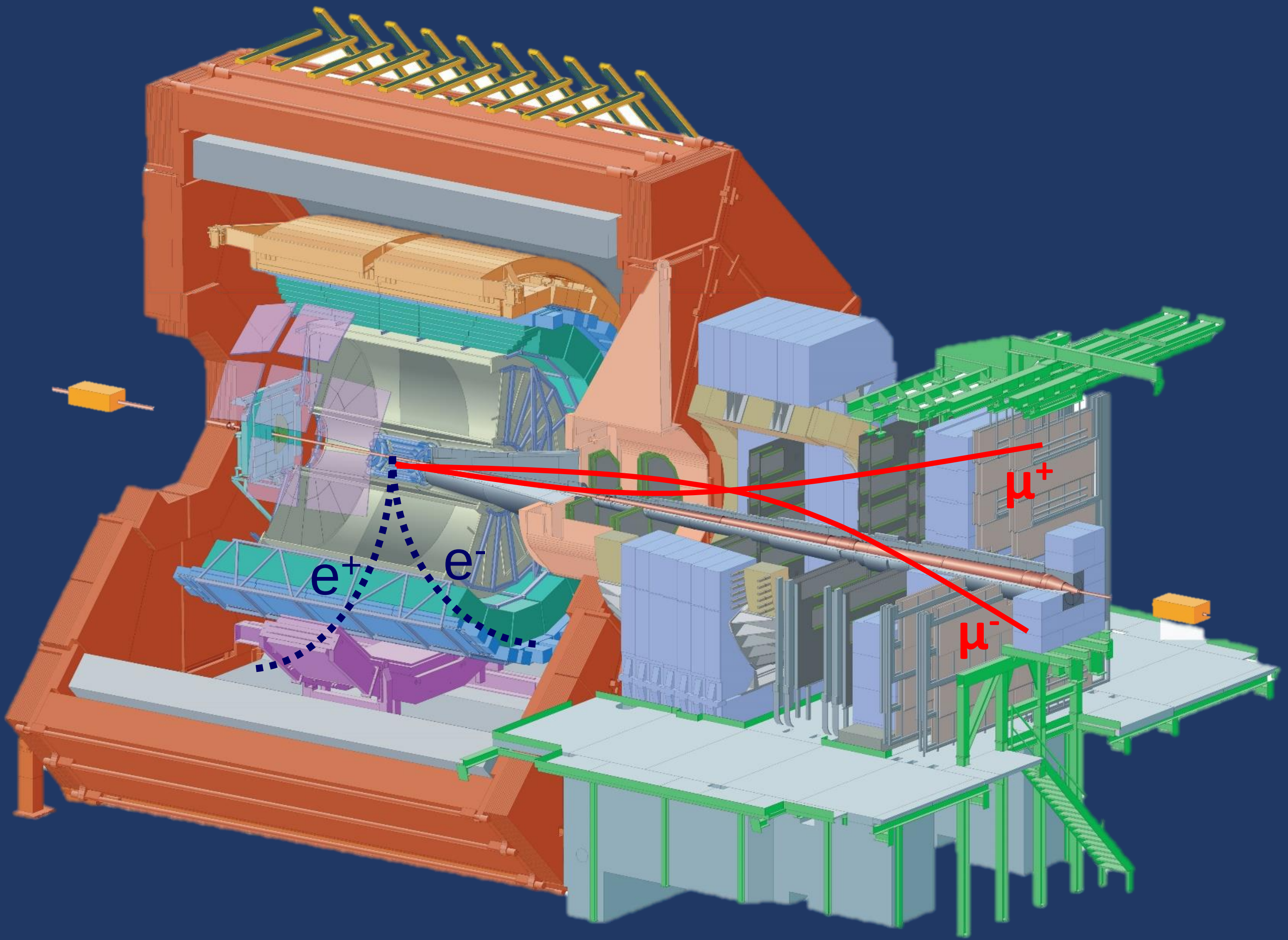
Run 2 (2015 – 2016)

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV	L = 19 μb^{-1} (MB) L= 225 μb^{-1} (dimuon)
p-Pb, $\sqrt{s_{NN}}$ =5.02 TeV	L = 0.4 nb^{-1} (MB)
p-Pb, $\sqrt{s_{NN}}$ =8.16 TeV	L_{pPb} = 8.7 nb^{-1} (dimuon) L_{Pbp} = 12.9 nb^{-1} (dimuon)
pp, $\sqrt{s}$ = 5.02, 13 TeV	

Run 1 → Run 2

- Increase in energy
- Increase in luminosity

Quarkonia in ALICE



Central Barrel $J/\psi \rightarrow e^+e^-$

$|y_{LAB}|<0.9$

Electrons tracked using ITS and TPC
Particle id: ITS, TPC, TOF, TRD

Forward muon arm $J/\psi \rightarrow \mu^+\mu^-$

$2.5<y_{LAB}<4$

Muons identified and tracked in the muon spectrometer

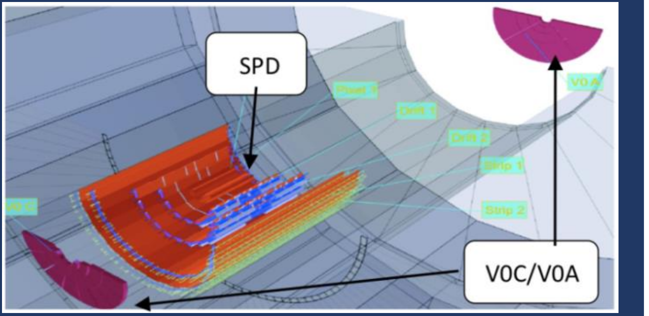
- Acceptance coverage in both y regions down to zero p_T
- ALICE measures inclusive J/ψ at mid and forward-y and prompt J/ψ at mid-y

Event and track selection

Event and track selection details are specific to the various analyses, but general features are:

Event selection:

- Rejection of beam gas and EM interactions (V0 and ZDC)
- SPD for vertex determination



Trigger:

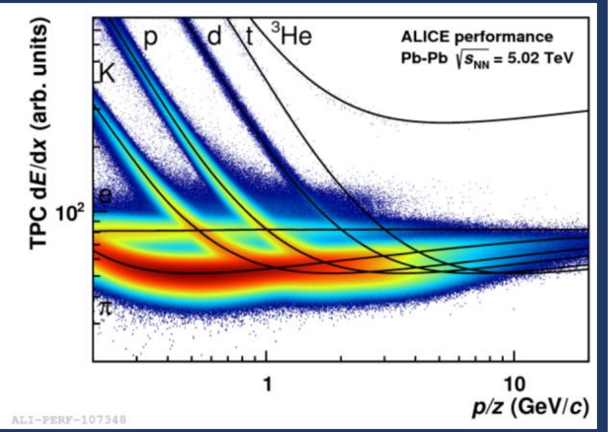
- Electron analysis: MB trigger
- Muon analysis: dimuon trigger

Centrality of the collisions:

- V0 and ZDC

Electron track selection:

- $|\eta_e|<0.8$, $p_T>1$GeV/c
- Rejection of tracks from photon conversion



Muon track selection:

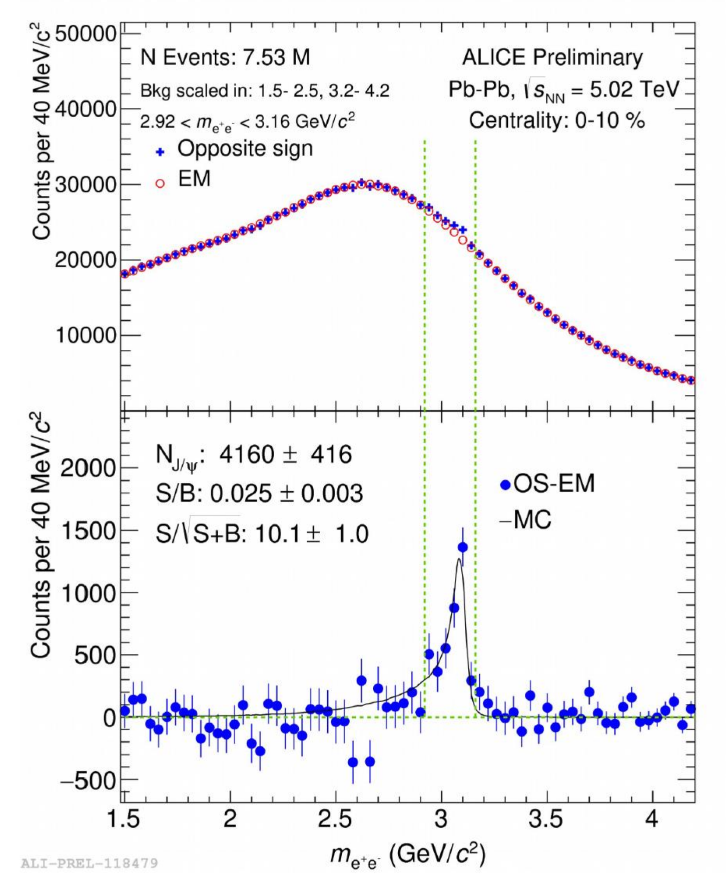
- Muon tracking-trigger matching
- $-4<\eta_\mu<-2.5$, $2.5<y^{\mu\mu}_{LAB}<4$
- $17.6<R_{abs}<89$ cm (R_{abs}= track radial position at the absorber end)

J/ψ reconstruction at mid-y

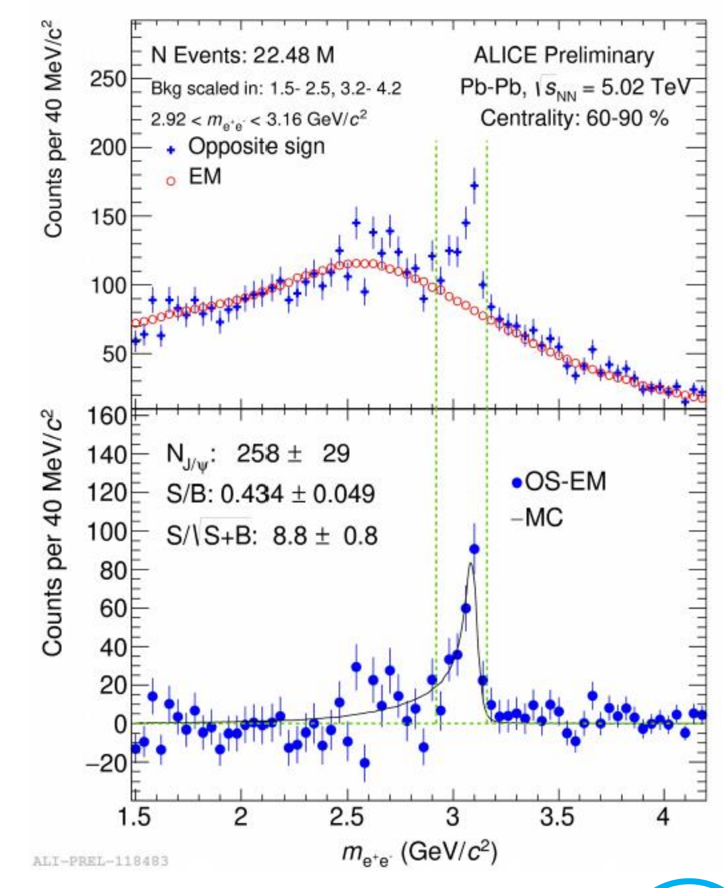
- J/ψ yields extracted with a counting technique
- Combinatorial background subtracted via event mixing [ME background normalized in $1.5<m_{e+e-}<2.5$ GeV/c^2 and $3.25<m_{e+e-}<4.2$ GeV/c^2]

PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV

0-10%



60-90%

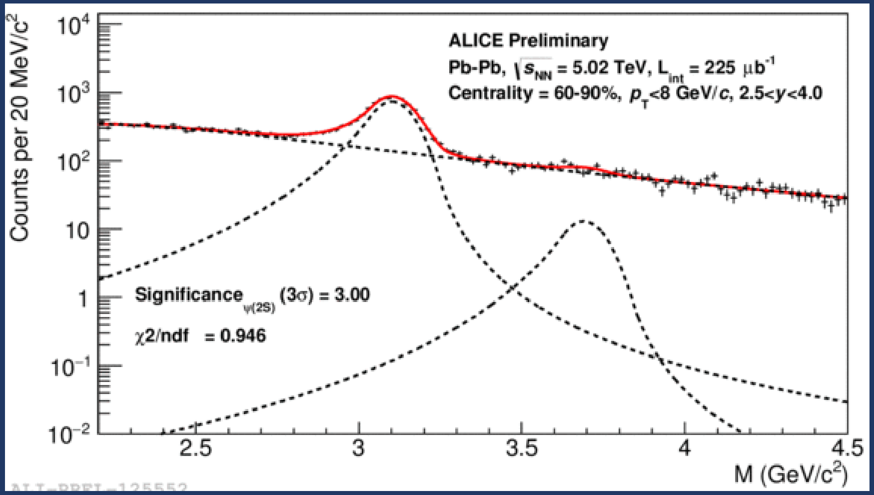


Quarkonium reconstruction at forward-y

- Yields extracted fitting the dimuon invariant mass spectrum with signal + background shapes
- In Pb-Pb, background computed also via mixed-events

PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV

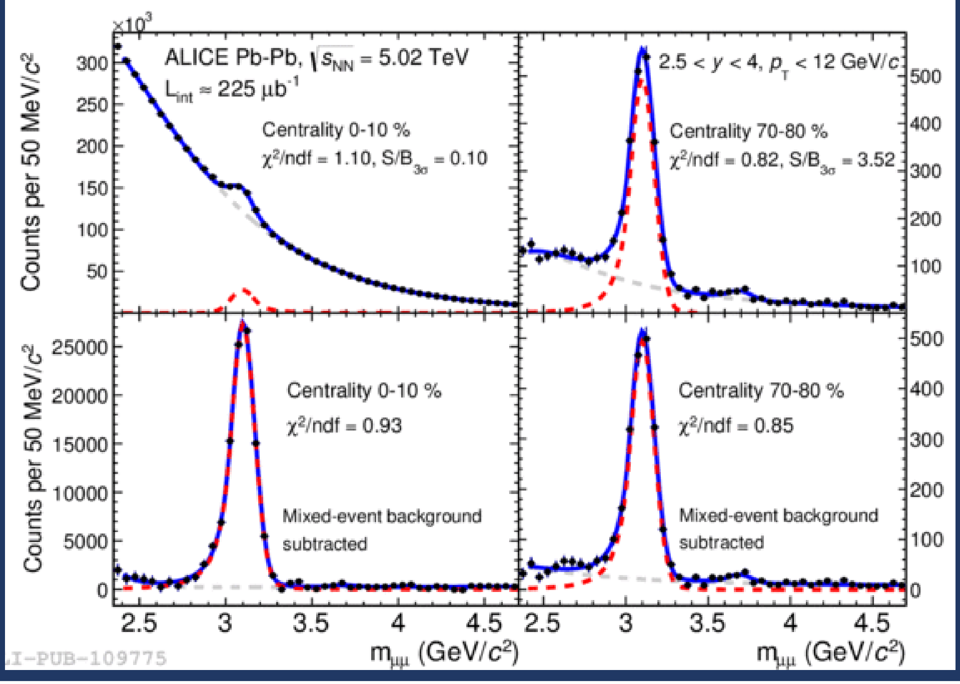
ψ(2S)



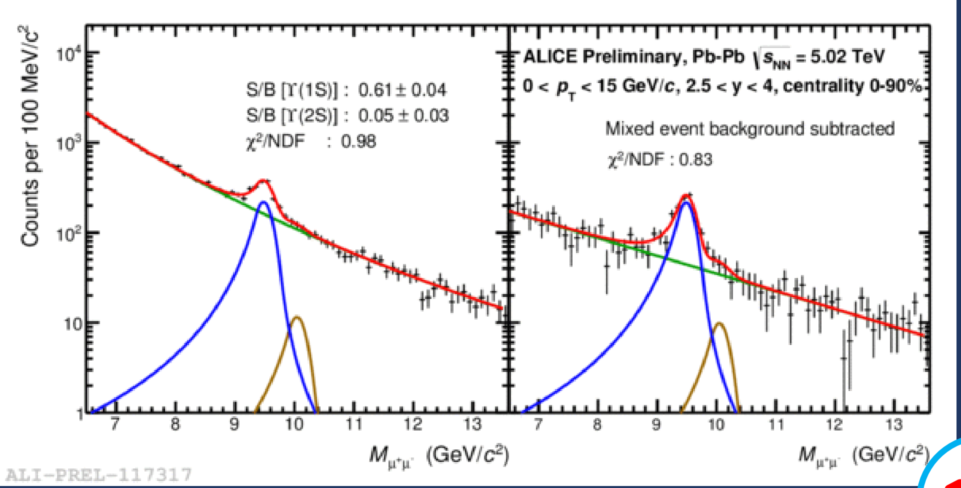
J/ψ

0-10%

70-80%



Υ



Main observables: R_{AA} and v_2

Nuclear modification factor R_{AA}

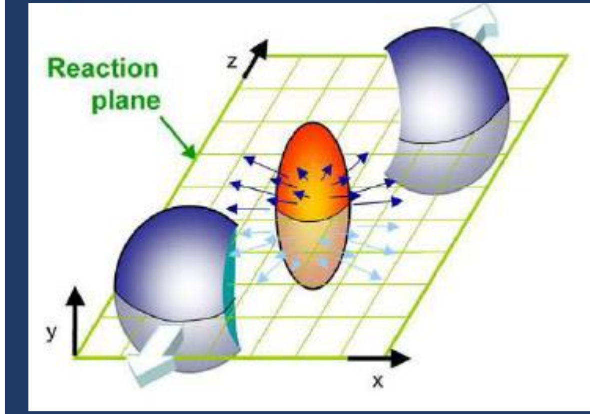
$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA}\rangle \sigma_{pp}^{J/\psi}}$$

Medium effects quantified comparing the AA 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 → $R_{AA} \neq 1$

Elliptic flow v_2

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



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

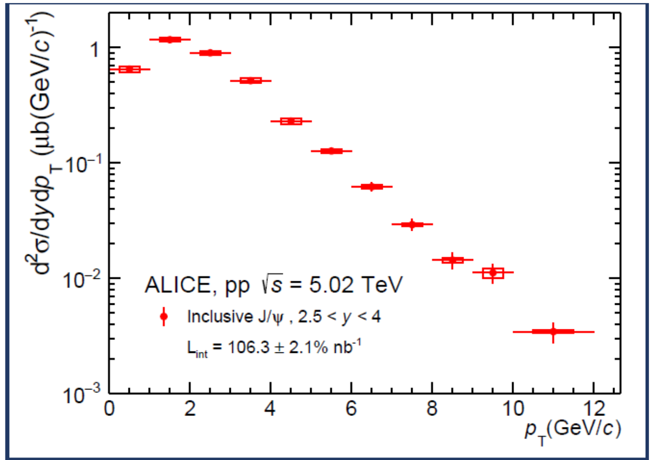
J/ψ produced through (re)generation should inherit the charm-quark elliptic flow in QGP

→ $v_2 > 0$

Towards the R_{AA}: pp reference

$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA}\rangle \sigma_{pp}^{J/\psi}}$ ➡ $\sigma_{pp}^{J/\psi}$ has to be evaluated in pp collisions at the same AA energy ➡ measured cross sections or values obtained from an interpolation are used

J/ψ,ψ(2S) fw-y in Pb-Pb



σ_{pp} measured in pp collisions at $\sqrt{s}$= 5.02 TeV

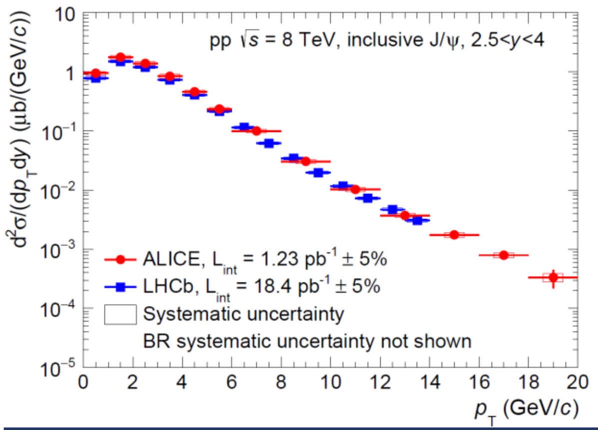
ALICE, PLB 766 (2017) 212
ALICE, arXiv:1702.00557

J/ψ at mid-y in Pb-Pb

$\sigma_{pp}^{J/\psi}$ obtained from an interpolation of mid-y results in pp collisions at $\sqrt{s}$ = 0.2, 1.96, 2.76 and 7 TeV

PHENIX, PRL 98 (2007) 232301
CDF: PRD 71, 032001 (2005)
ALICE, PLB 718, 295 (2012)
ALICE, PLB 718, 692 (2012)

J/ψ at fw-y in p-Pb



based on $\sigma_{pp}^{J/\psi}$ from pp collisions at $\sqrt{s}$ = 8 TeV

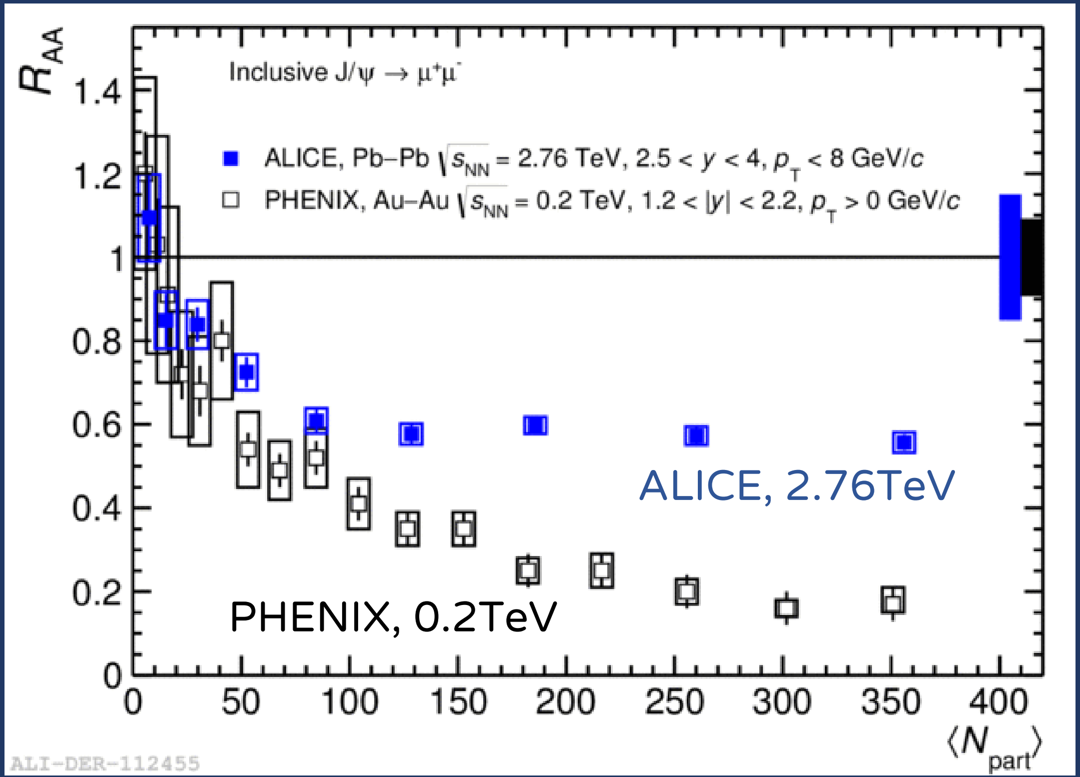
CERN-ALICE-PUBLIC-2017-001
ALICE, EPJC 76 (2016) 184
LHCb, JHEP 1306 (2013) 064

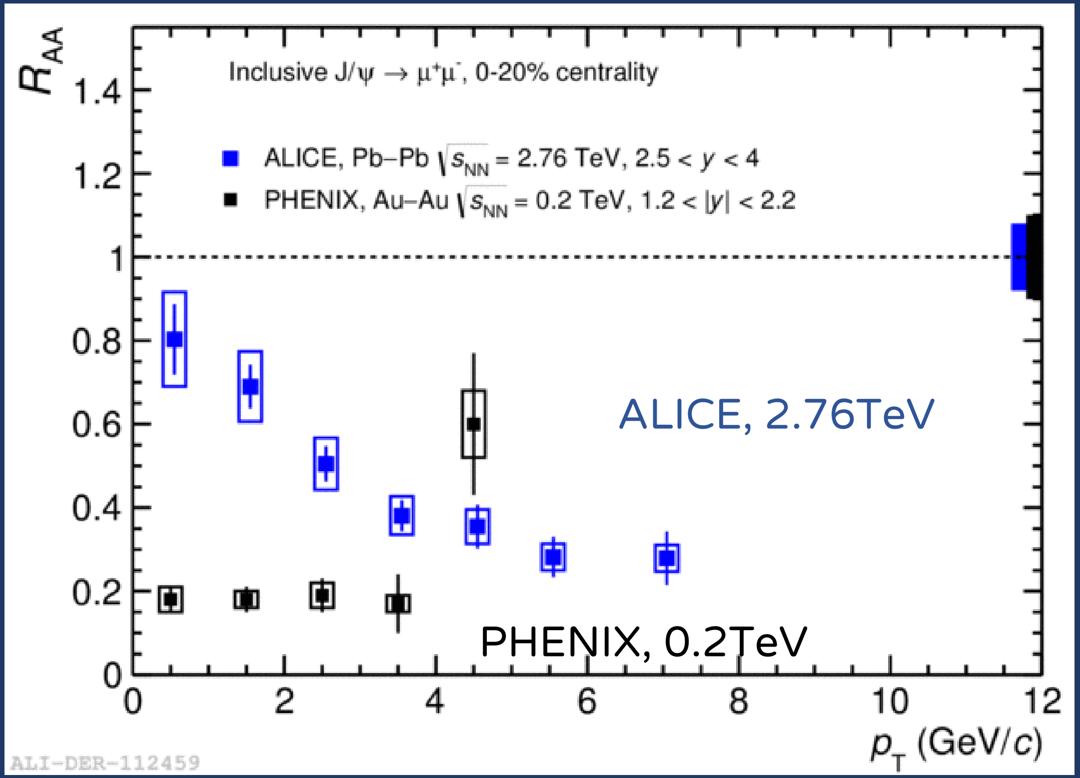
ϒ at fw-y in Pb-Pb

σ_{pp} based on an energy interpolation of results at $\sqrt{s}$ = 2.76, 7 and 8 TeV

ALICE-PUBLIC-2014-002

J/ψ R_{AA} at forward-*y*: Run 1

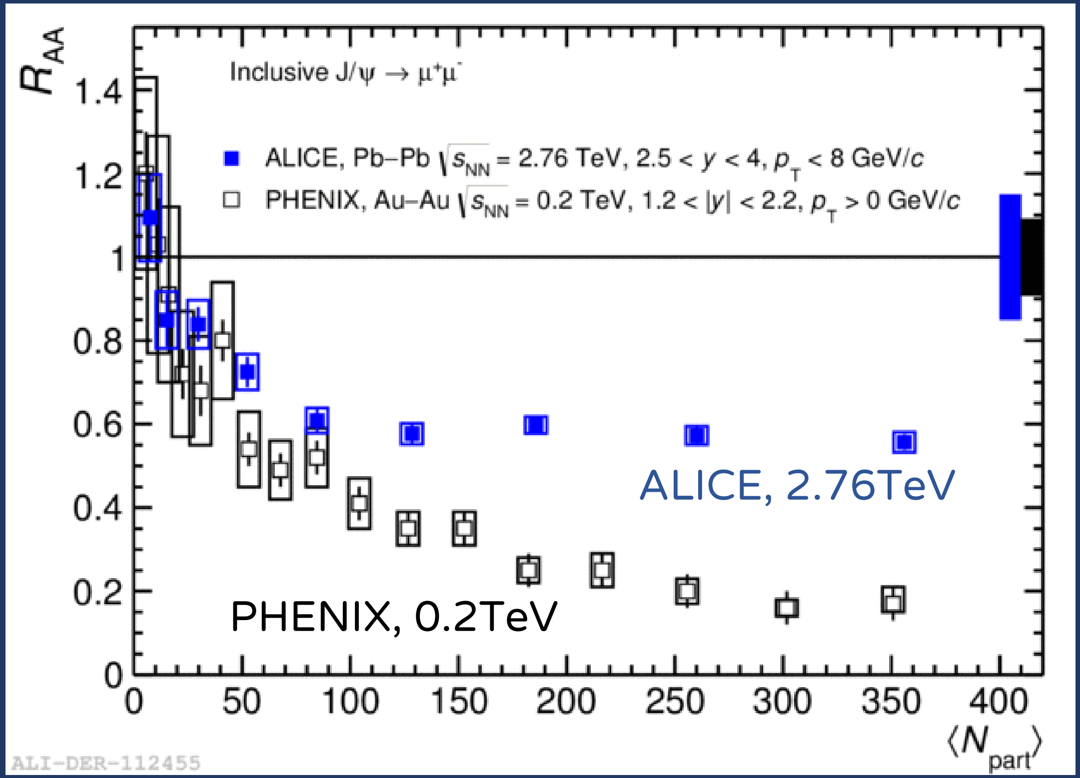


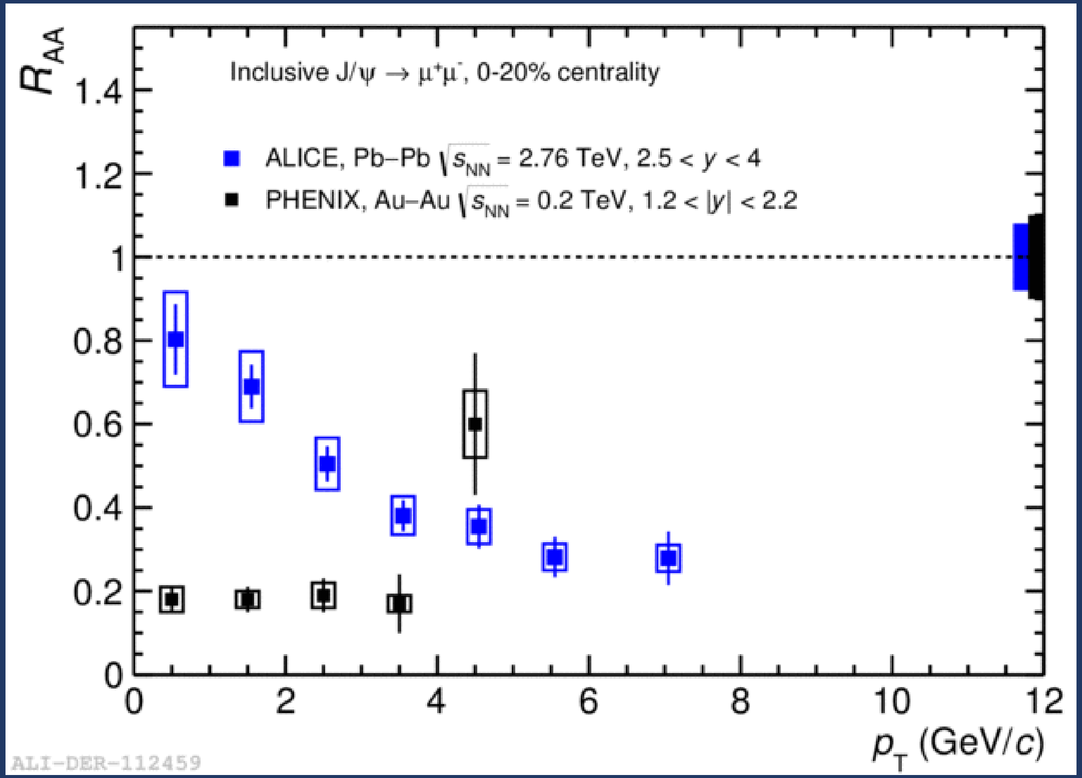


JHEP 05 (2016) 179
PLB 734 (2014) 314
PRL 109 (2012) 072301

- Clear J/ψ suppression with almost no centrality dependence for N_{part}>100
- Stronger J/ψ suppression vs centrality at RHIC than in ALICE, in spite of the LHC larger energy densities
- Very different p_T dependence observed by PHENIX and ALICE, with a weaker low p_T suppression measured by ALICE

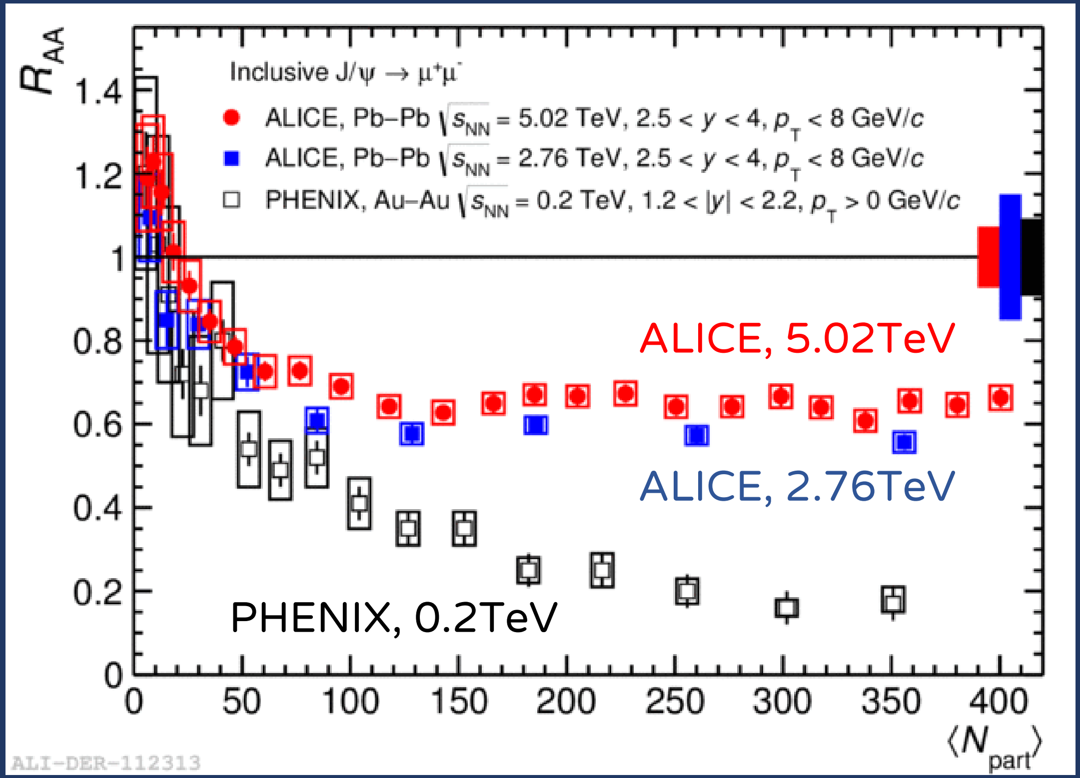
J/ψ R_{AA} at forward-y: Run 1

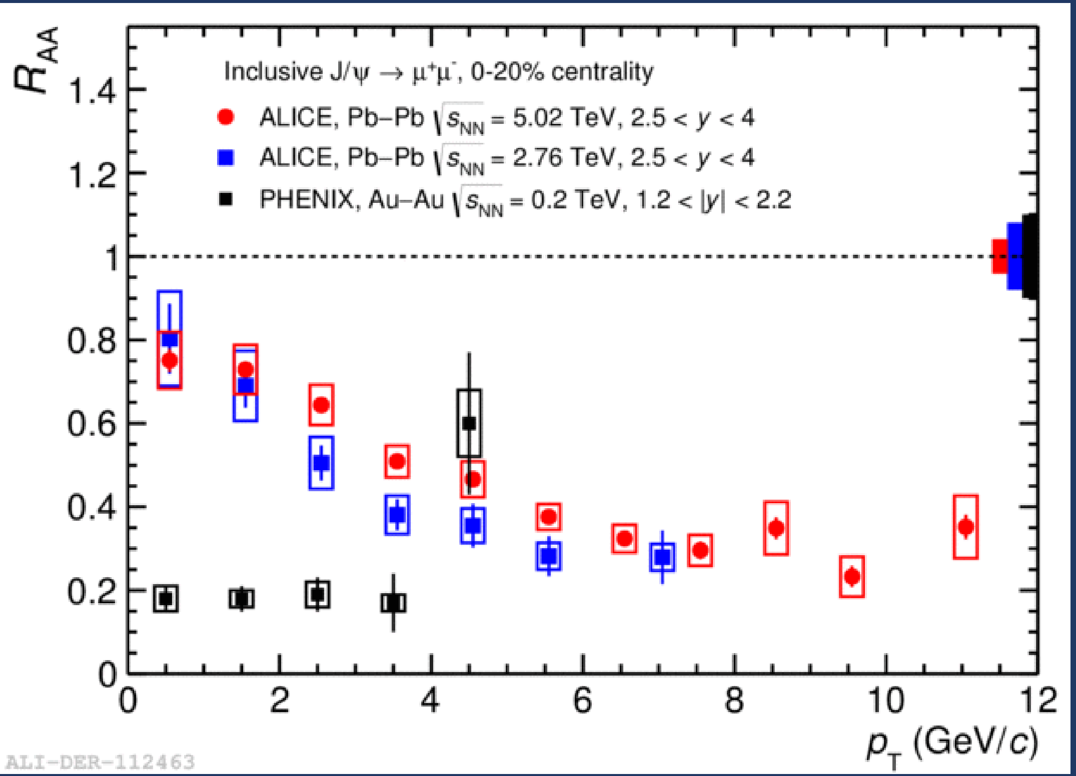




➡ Comparison with lower energy results emphasizes the role of recombination for low p_T J/ψ at the LHC

J/ψ R_{AA} at forward-*y*: Run 2



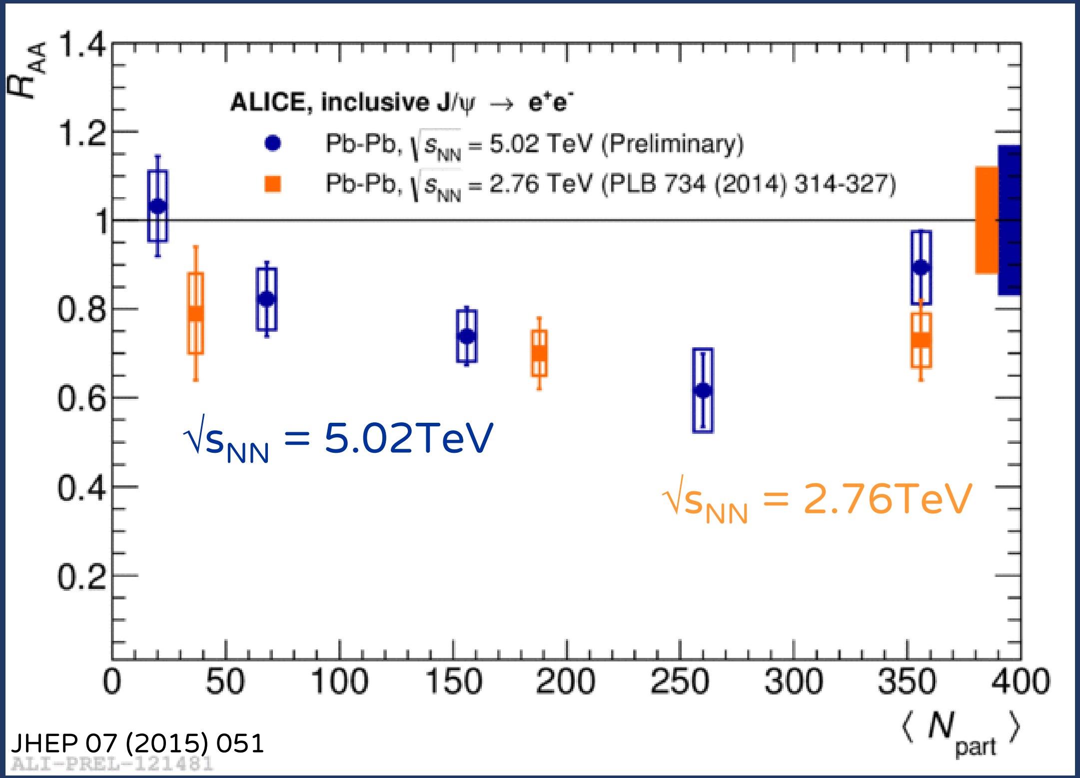


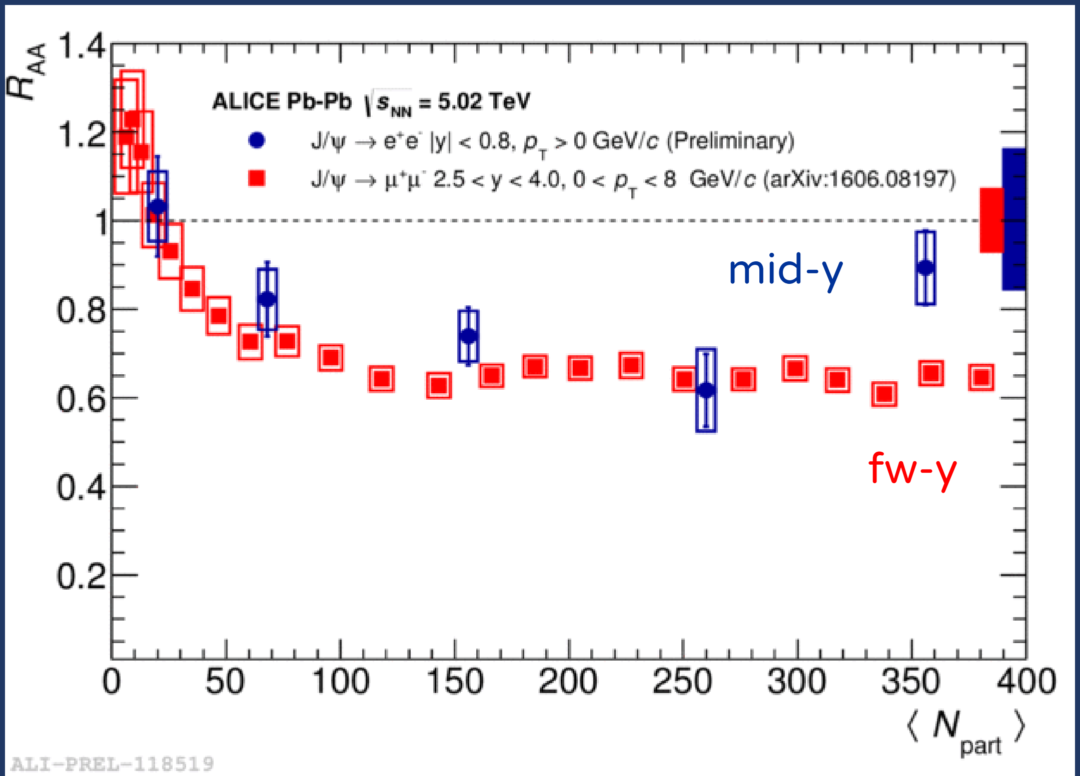
PLB766 (2017) 212

➡ 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

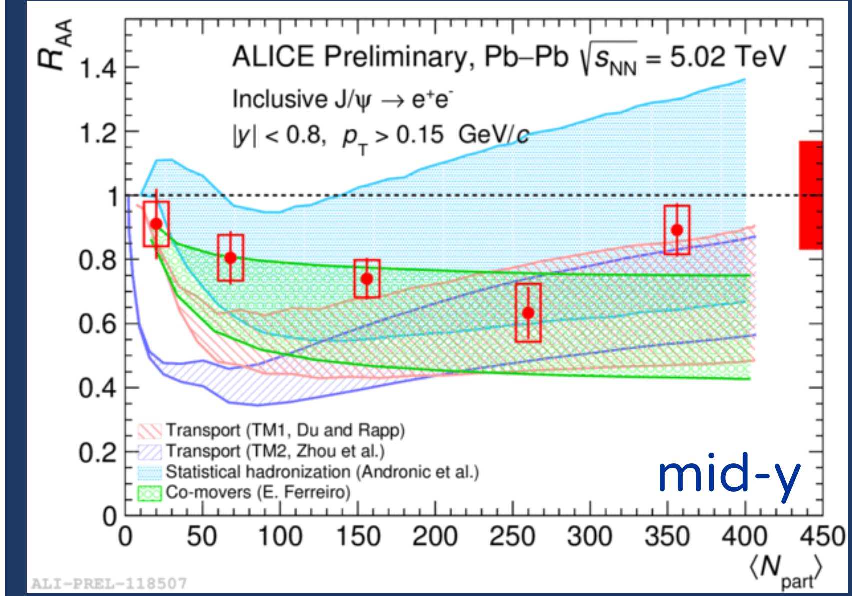
J/ψ R_{AA} at mid-*y*: Run 2

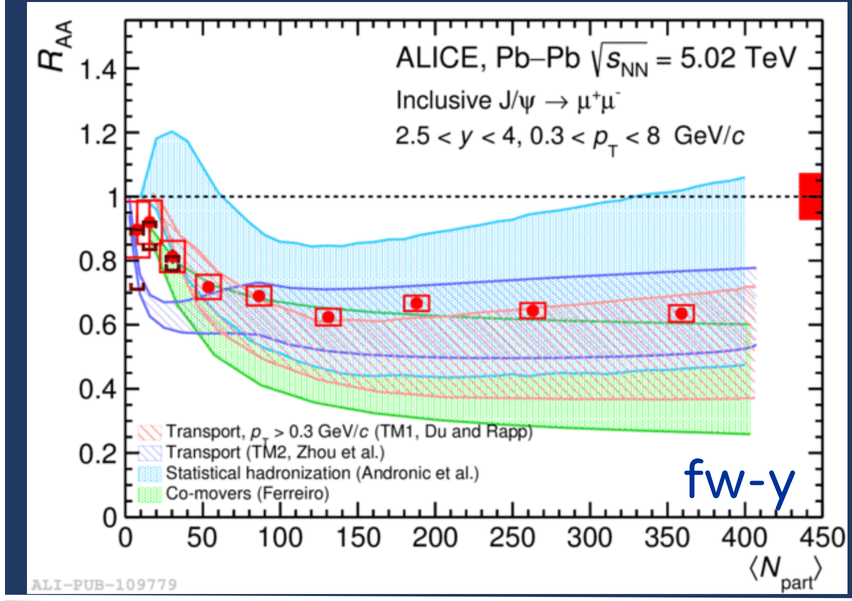




- No significant $\sqrt{s}$-dependence also at mid-rapidity, confirming observation at forward-*y*
- Small R_{AA} increase in most central collisions, wrt forward-*y*, as expected in a (re)generation scenario (but fluctuations cannot be yet excluded)

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

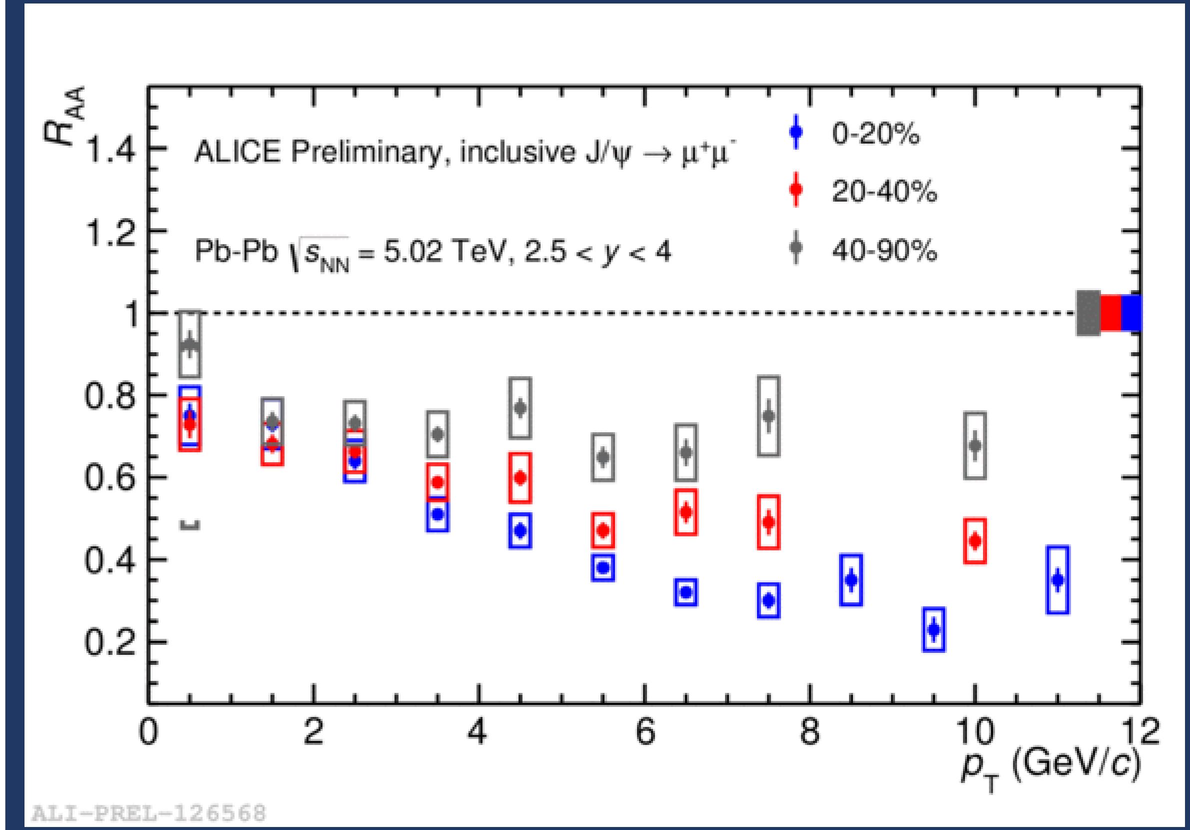
➡ All models fairly describe the data, as already in Run1

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

More differential J/ψ R_{AA}: centrality

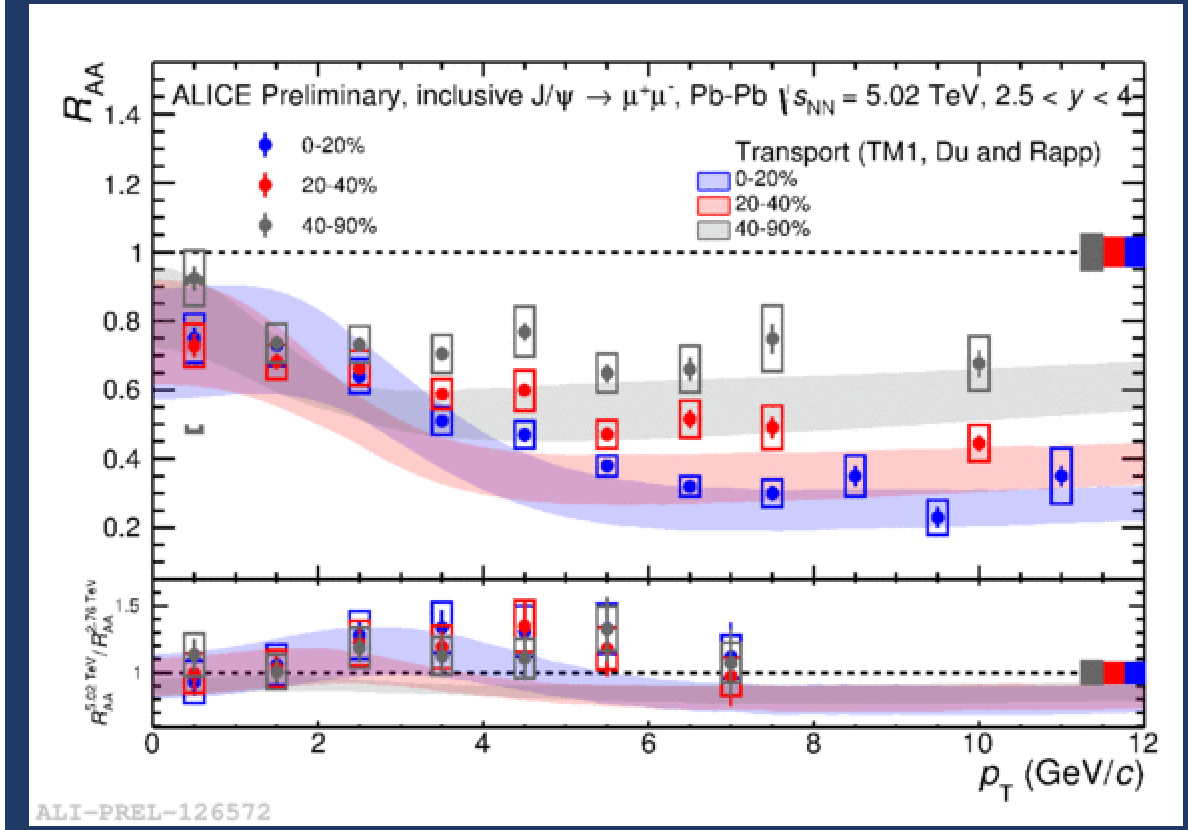
- Constraints to the theoretical models can be imposed by more differential R_{AA} studies



- Features observed in Run 1 are confirmed, but Run 2 results have
  - Smaller statistical and systematic uncertainties
  - p_T reach extended up to 12 GeV/c
- J/ψ suppression is stronger at high p_T and central collisions
- Weak p_T dependence of J/ψ suppression in semi-peripheral collisions

More differential J/ψ R_{AA}: centrality

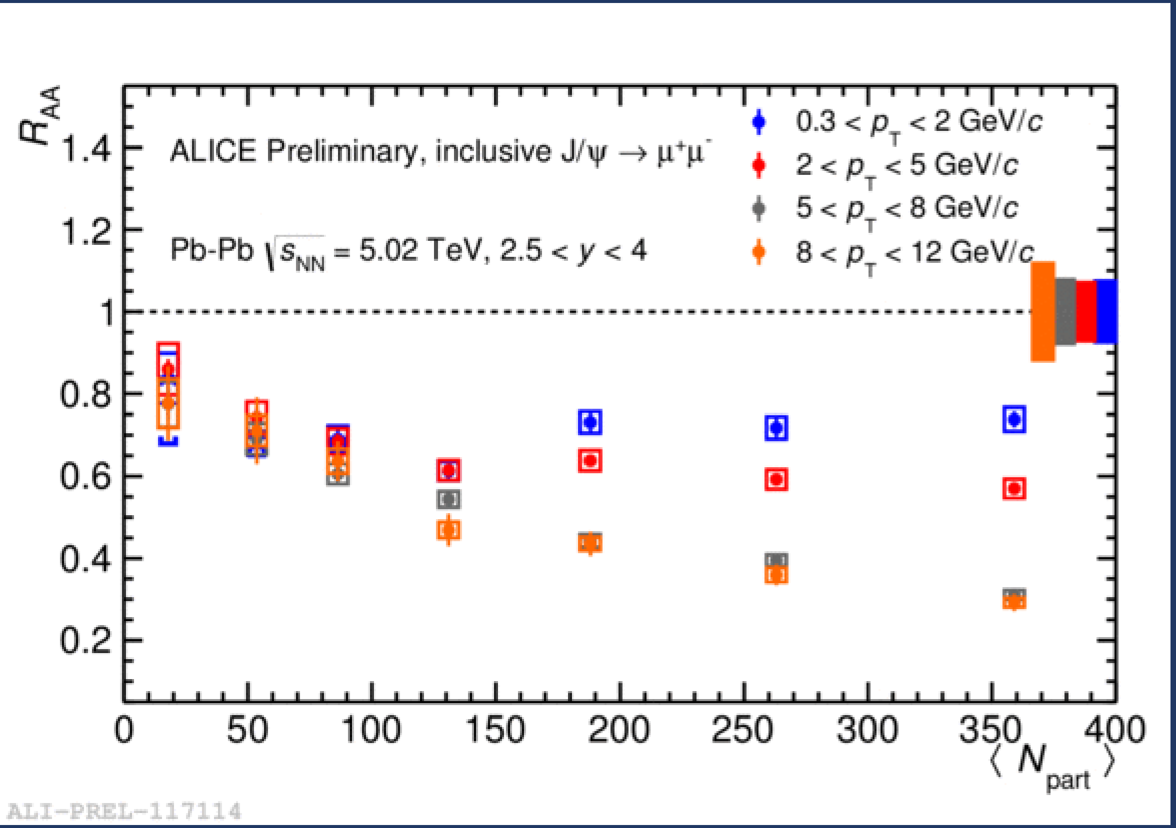
- Constraints to the theoretical models can be imposed by more differential R_{AA} studies



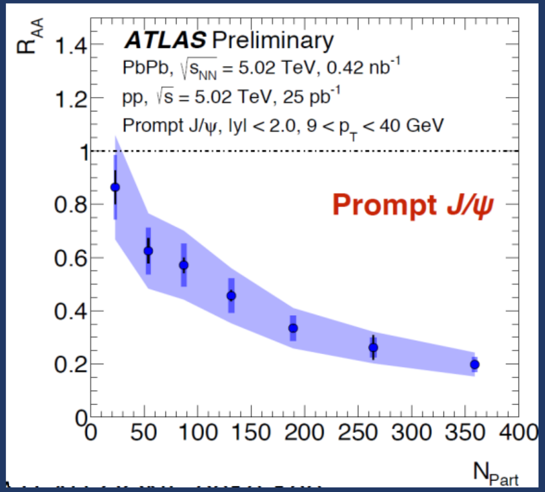
- Features observed in Run 1 are confirmed, but Run 2 results have
  - Smaller statistical and systematic uncertainties
  - p_T reach extended up to 12 GeV/c
- J/ψ suppression is stronger at high p_T and central collisions
- Feeble p_T dependence of J/ψ suppression in semi-peripheral collisions
- Transport model reproduces the trend, within the uncertainties

More differential J/ψ R_{AA}: p_T

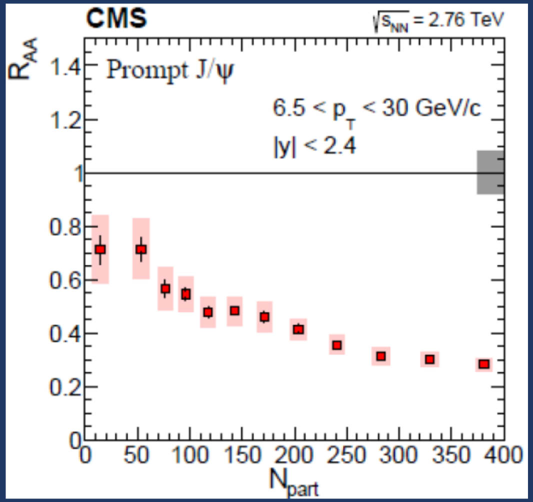
- Constraints to the theoretical models can be imposed by more differential R_{AA} studies



- no centrality dependence in 0.3<p_T<2 GeV/c
- in central collisions, smaller suppression for low-p_T J/ψ, as expected by (re)generation



ATLAS-CONF-2016-109

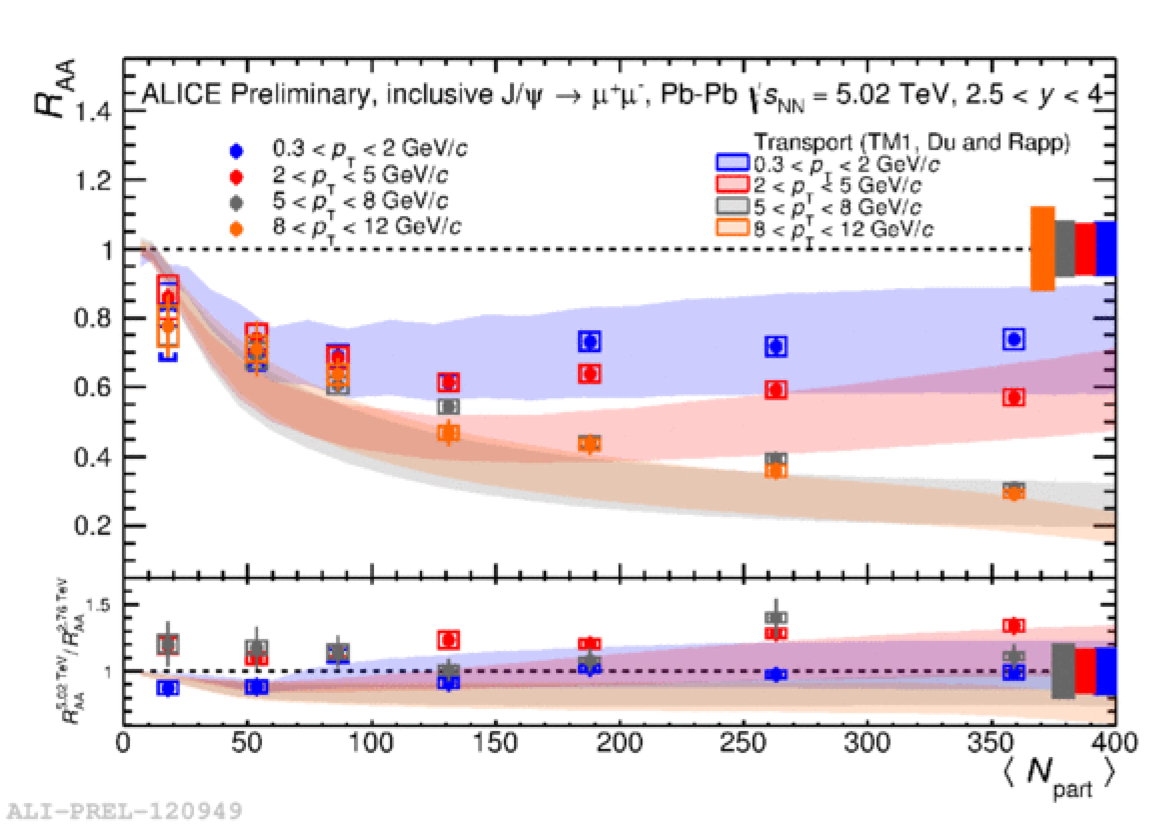


arXiv:1610.00613

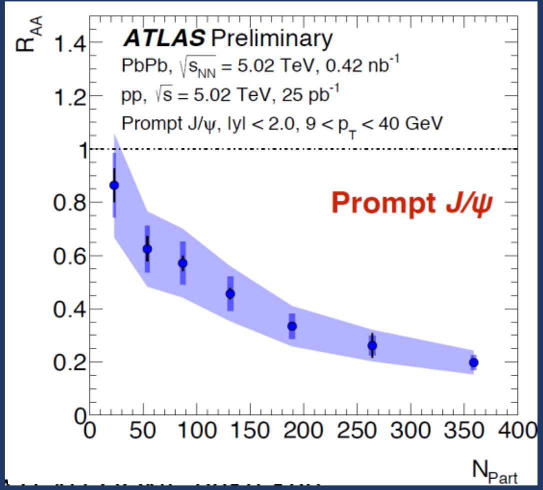
- High-p_T J/ψ : pattern qualitatively similar to the one measured by ATLAS and CMS, reaching R_{AA}~0.2

More differential J/ψ R_{AA}: p_T

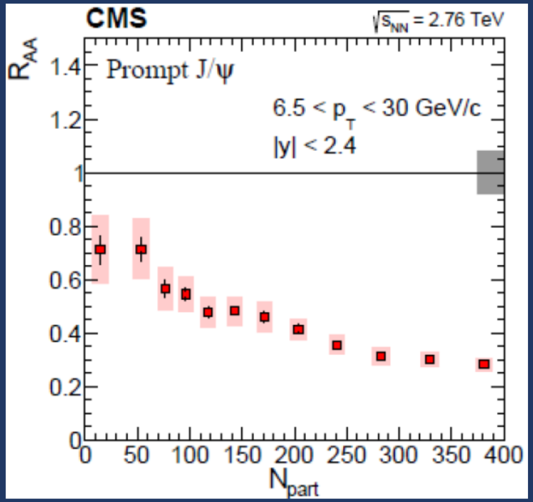
- Constraints to the theoretical models can be imposed by more differential R_{AA} studies



- no centrality dependence in $0.3<p_T<2$ GeV/c
- in central collisions, smaller suppression for low-p_T J/ψ, as expected by (re)generation



ATLAS-CONF-2016-109



arXiv:1610.00613

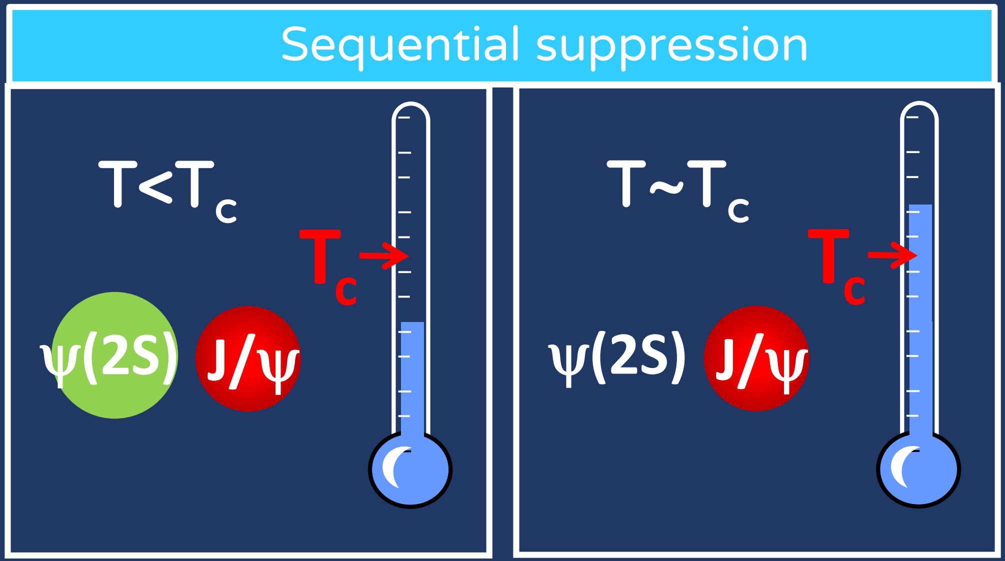
- General trend is reproduced by transport model, but some tension is visible for the intermediate p_T ($2<p_T<5$ GeV/c) R_{AA}

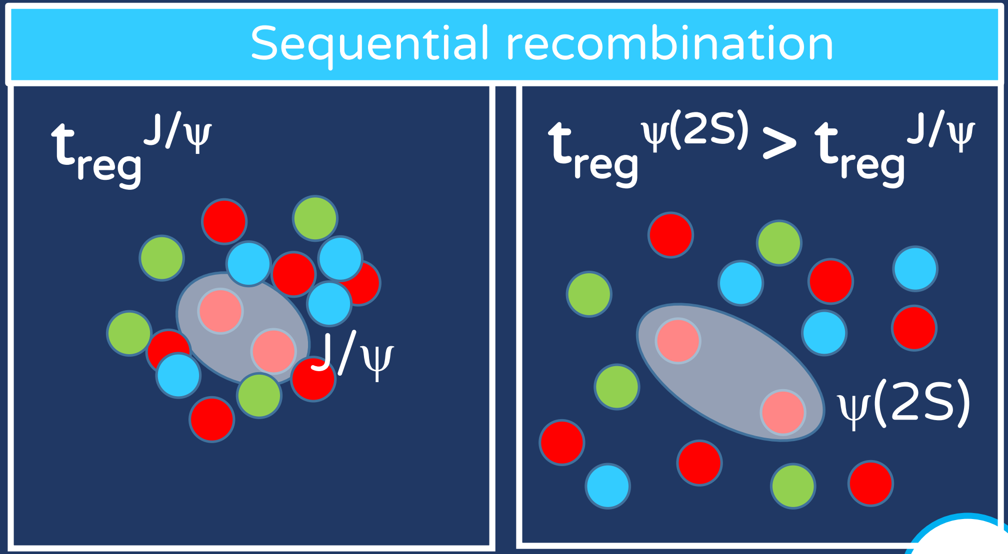
$\psi(2S)$ in AA collisions

- $\psi(2s)$ 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]

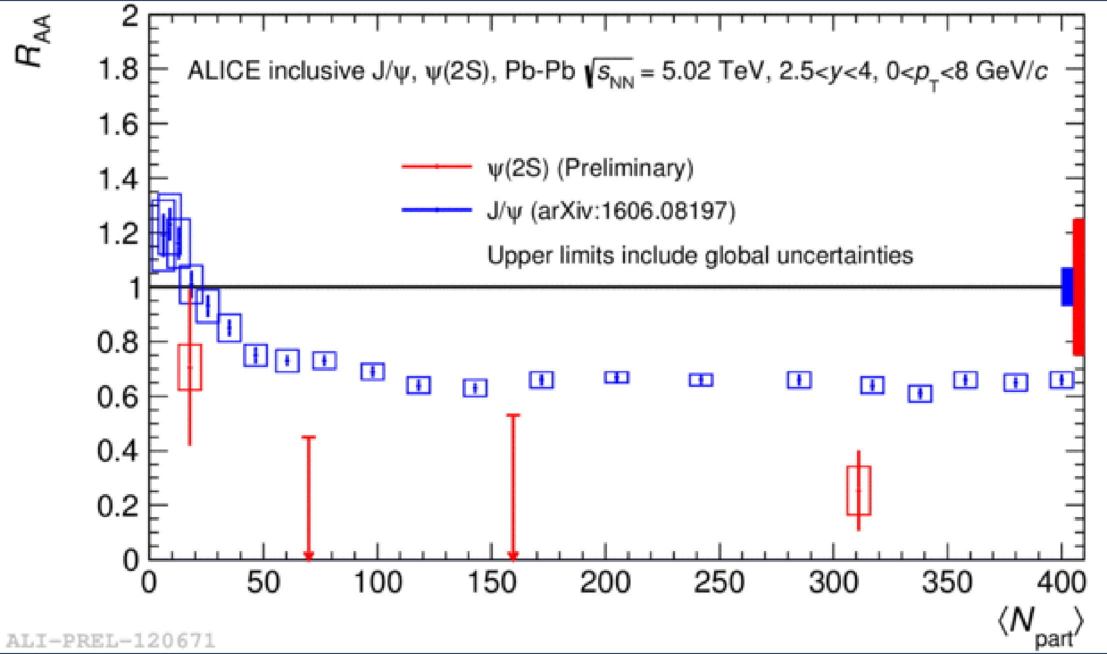




- **Ratio of charmonium states vs. centrality and vs. p_T can give insight on quarkonium behaviour**

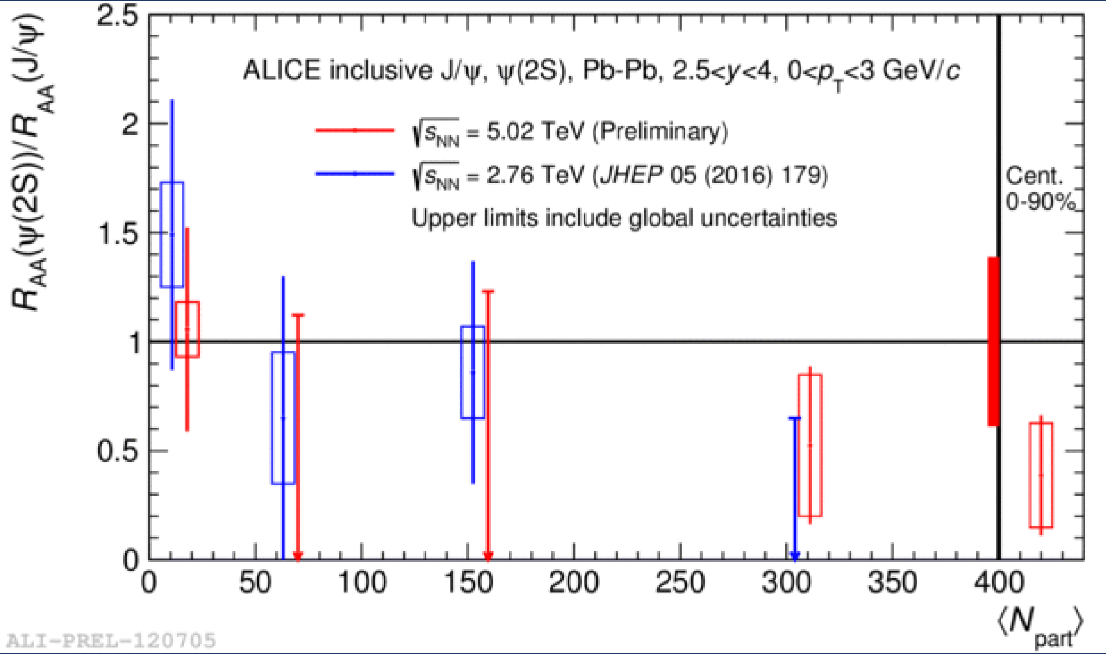
$\psi(2S)$ R_{AA}

➡ ψ(2s) shows a stronger suppression, in semi-central and central collisions, than the J/ψ one



However, the low significance limits the precision of the measurements

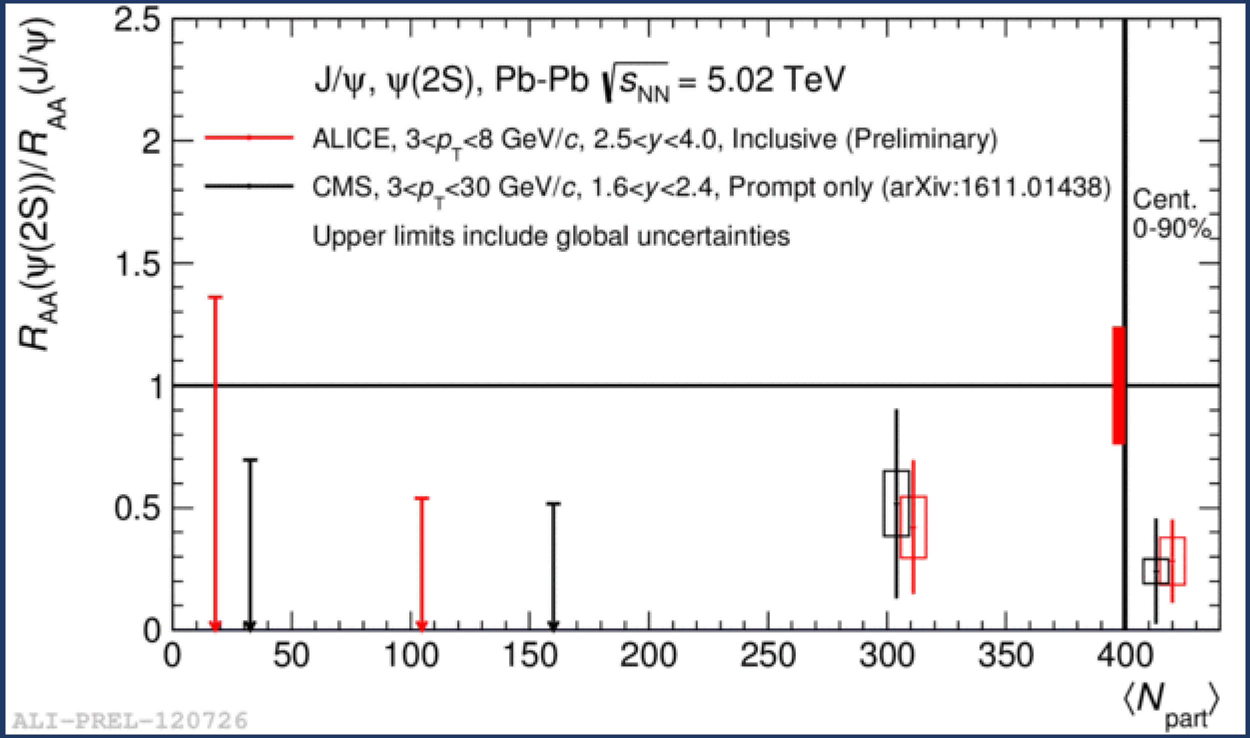
[95% CL is provided for bins with too low significance]

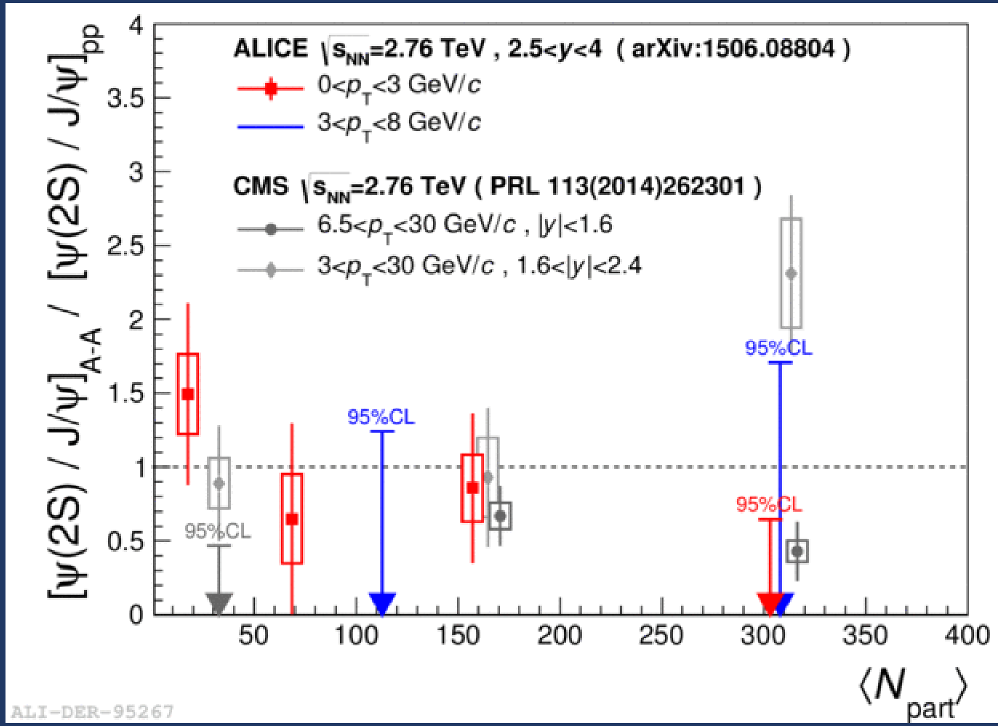


➡ Results at $\sqrt{s_{NN}}$ = 5.02 TeV are compatible with the ones at $\sqrt{s_{NN}}$ = 2.76 TeV

$\psi(2S)$ R_{AA}

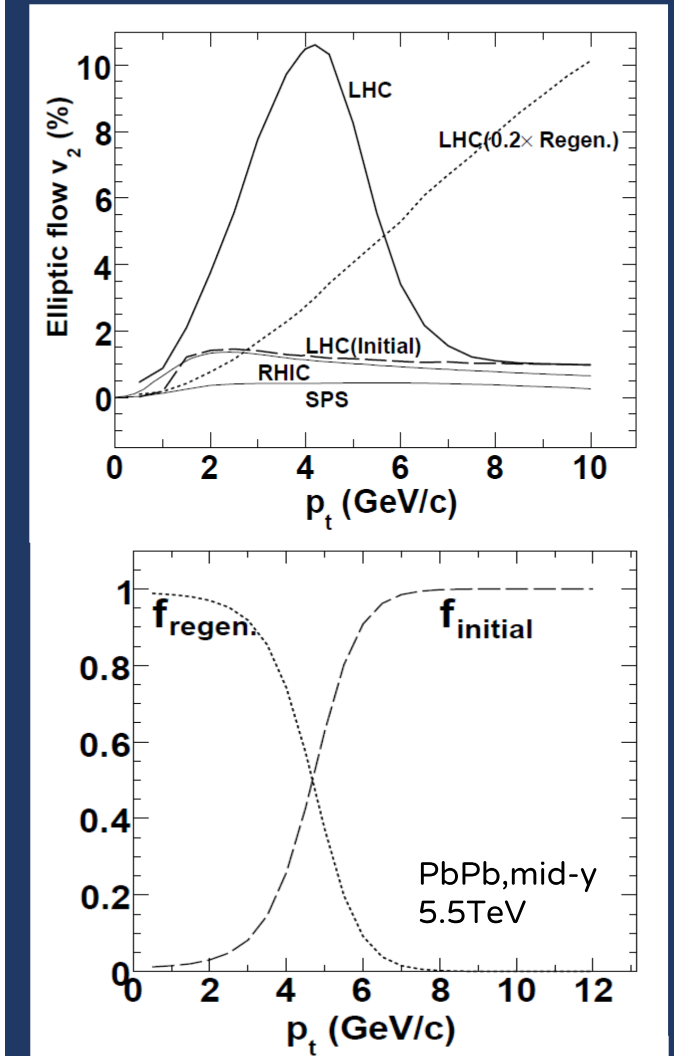
- At $\sqrt{s_{NN}} = 5.02$ TeV, results are compatible with CMS, in a similar kinematic range, while some tension exists at lower energy





- Results in different kinematic ranges are sensitive to the fraction of primordial and regenerated charmonia, to different medium temperature and flow…

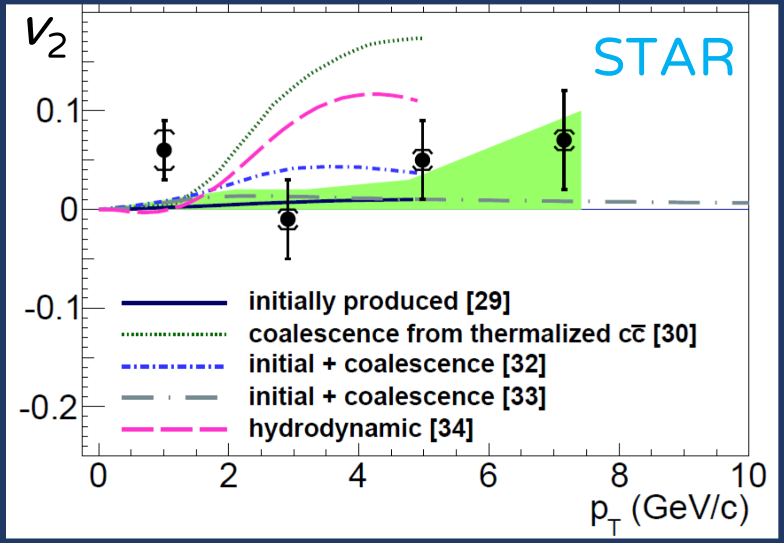
J/ψ elliptic flow



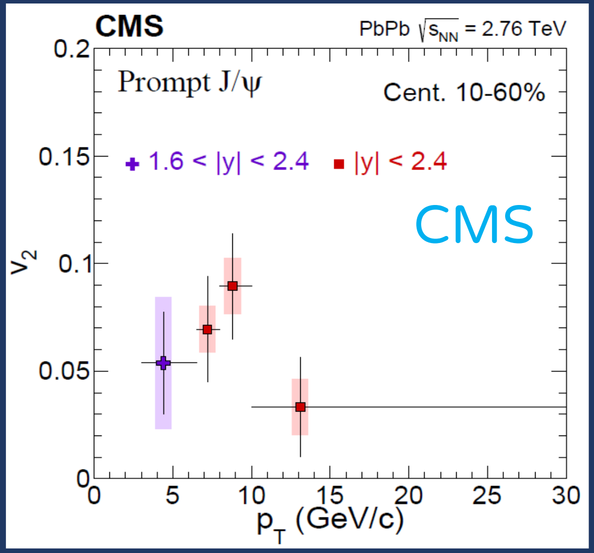
N. Xu et al, NPA834(2010) 317c

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

➡ Effect expected to 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

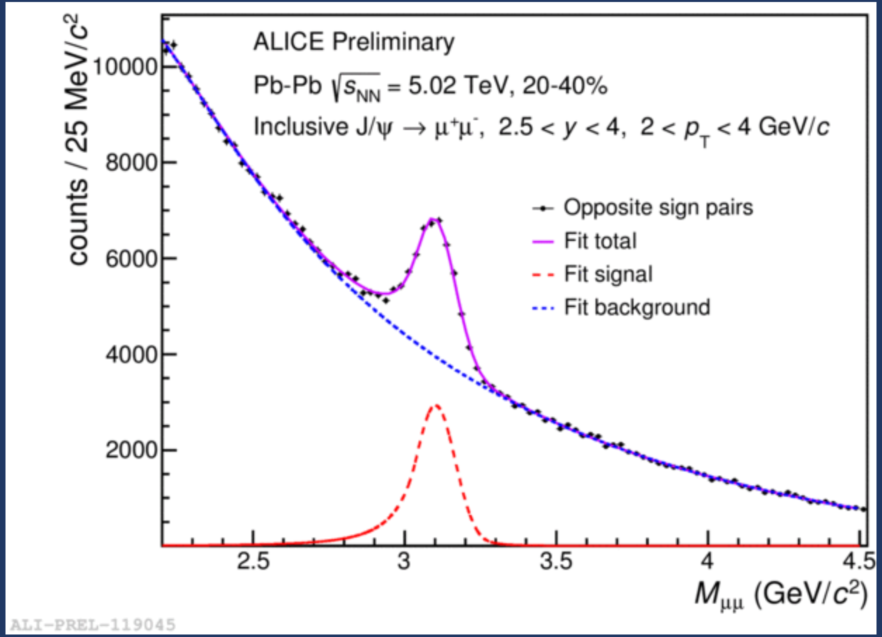
J/ψ elliptic flow: analysis technique

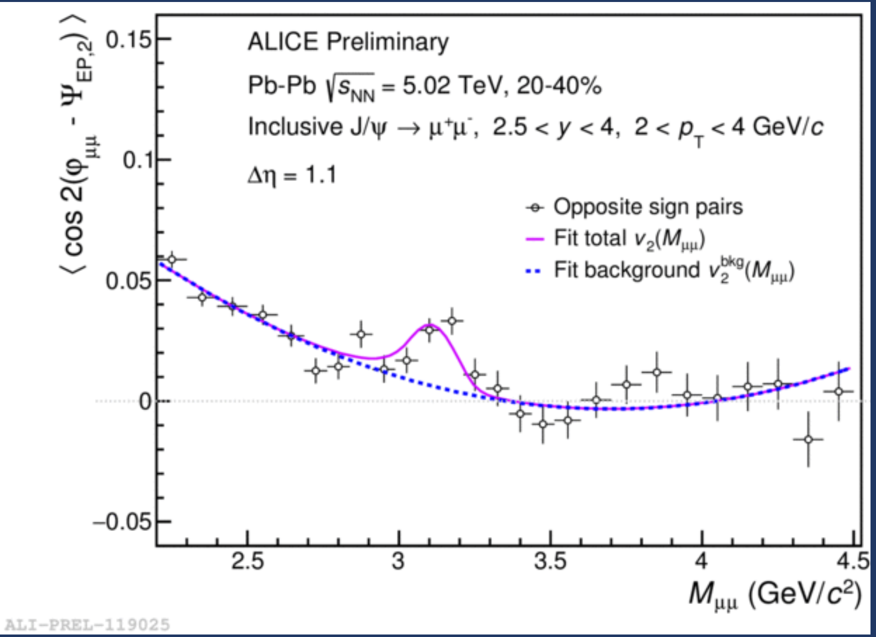
- J/ψ $v_2 = \langle\cos 2(\phi_{\mu\mu}-\Psi_{EP})\rangle$ is computed using the Event Plane from
  - SPD ($\Delta\eta$=1.1) at fw-y
  - TPC ($\Delta\eta$=0) at mid-y
- $v_2^{J/\psi}$ is obtained modeling $\langle\cos 2(\phi_{\mu\mu}-\Psi_{EP})\rangle$ vs inv. mass as

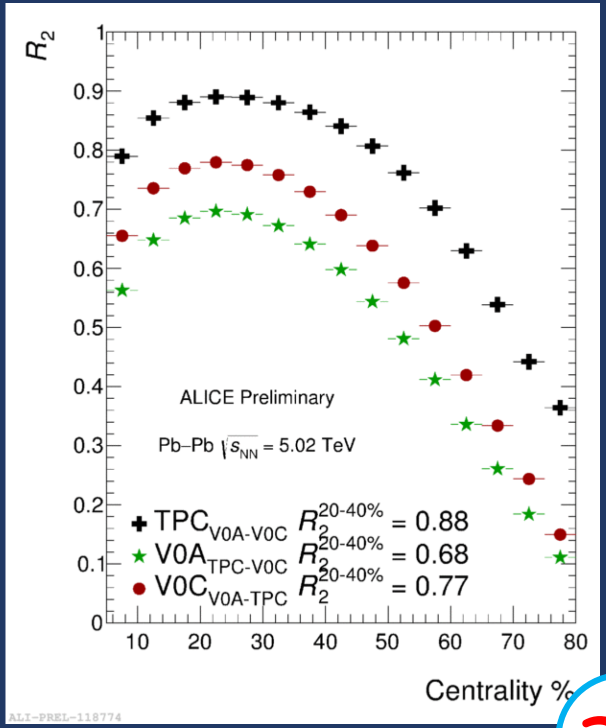
$$v_2(m_{\mu\mu}) = v_2^{J/\psi}\alpha(m_{\mu\mu}) + v_2^{bck}(1-\alpha(m_{\mu\mu}))$$

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

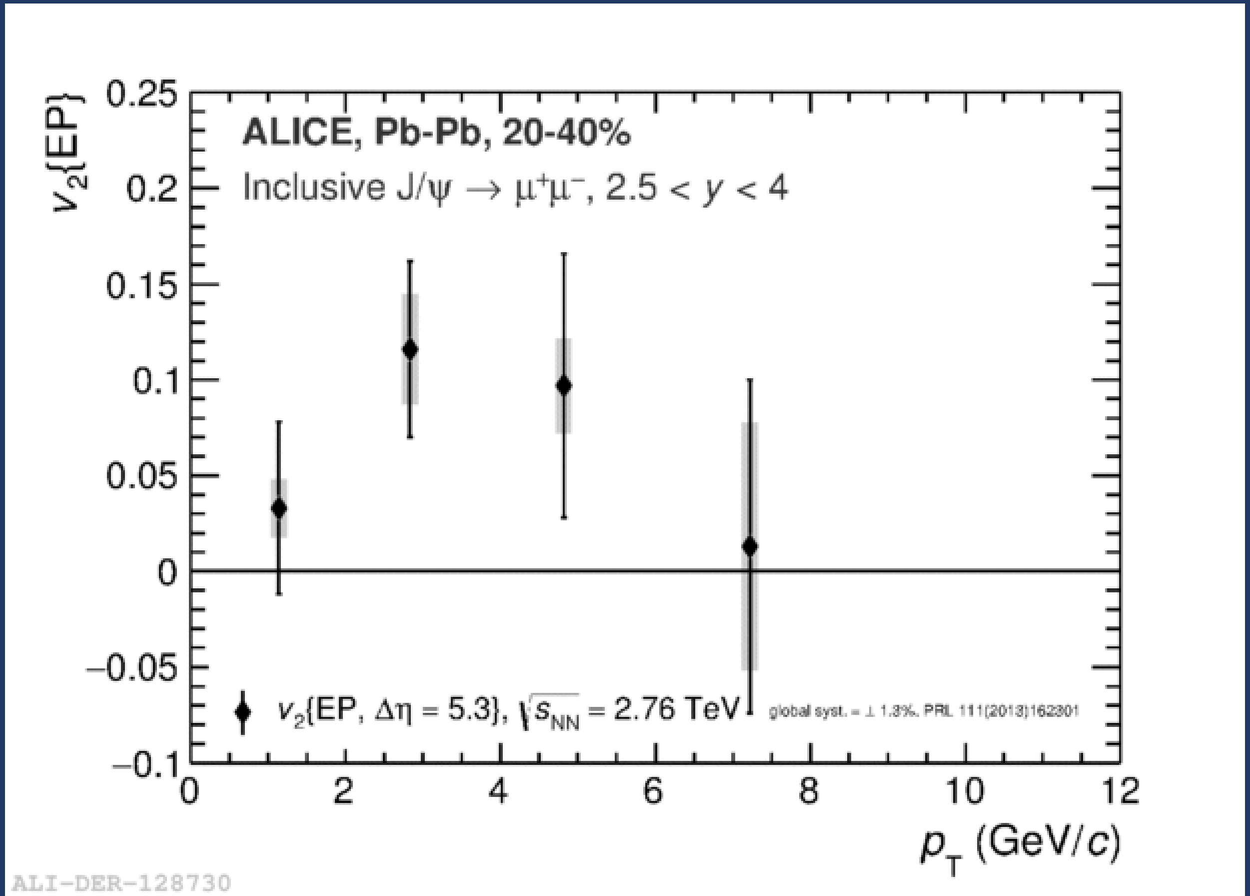
- $v_2 = v_2^{obs}/\sigma_{EP}$





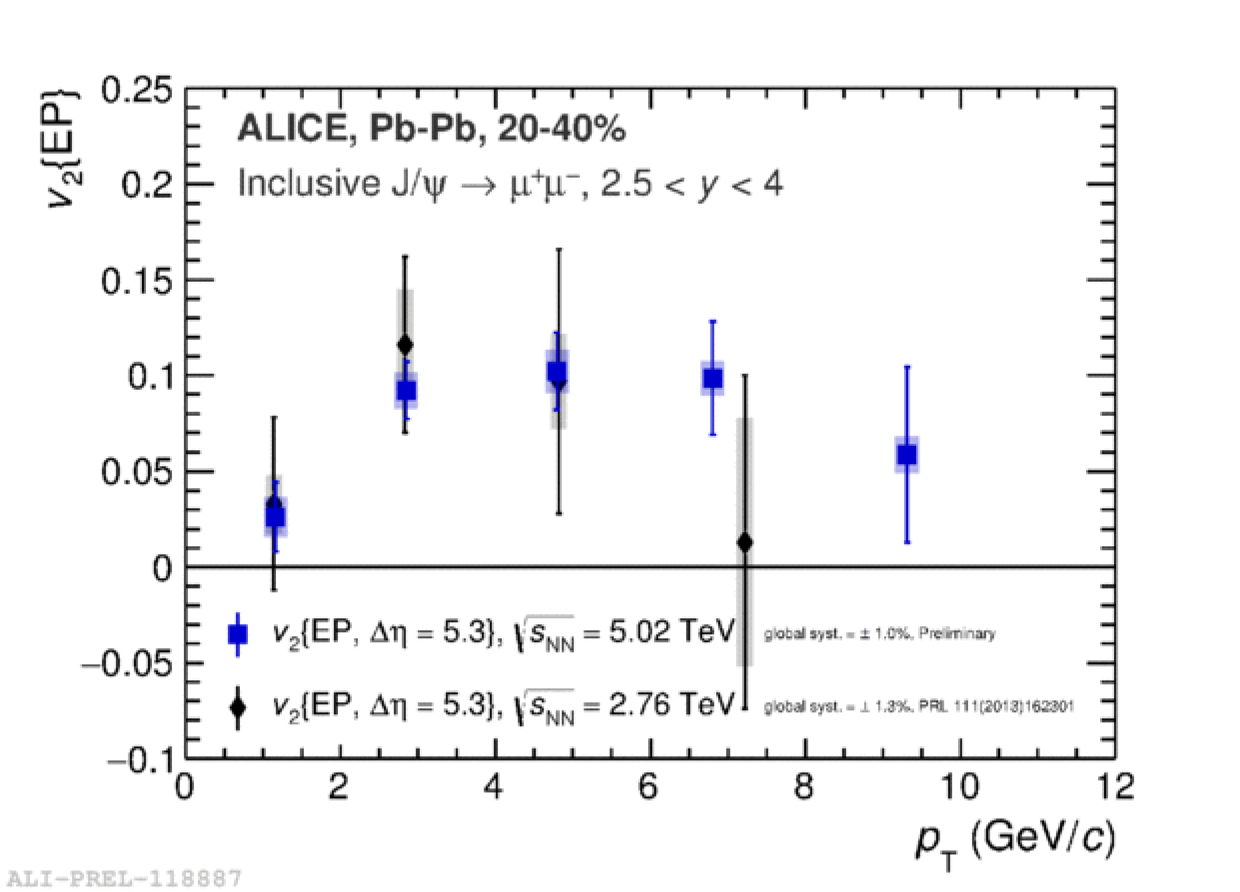


J/ψ elliptic flow: Run 1



- ALICE Run 1 result gave an indication of non-zero flow
  → 2.7σ in $2<p_T<6$ GeV/c and 20-40% centrality

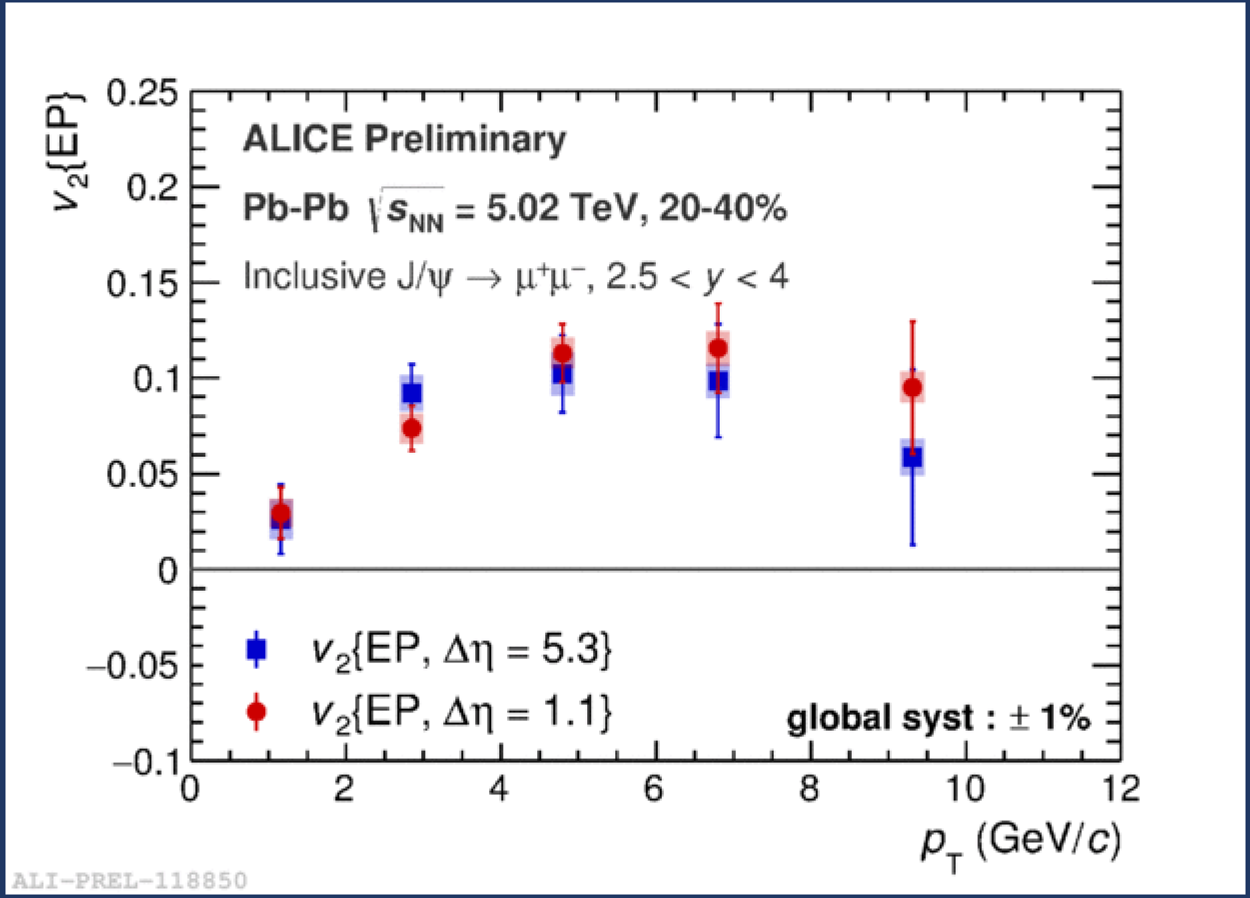
J/ψ elliptic flow: Run 2



- ALICE Run 1 result gave an indication of non-zero flow
  → 2.7σ in $2<p_T<6$ GeV/c and 20-40% centrality
- Agreement within uncertainties between Run 1 and Run 2 results
- 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

J/ψ elliptic flow: Run 2

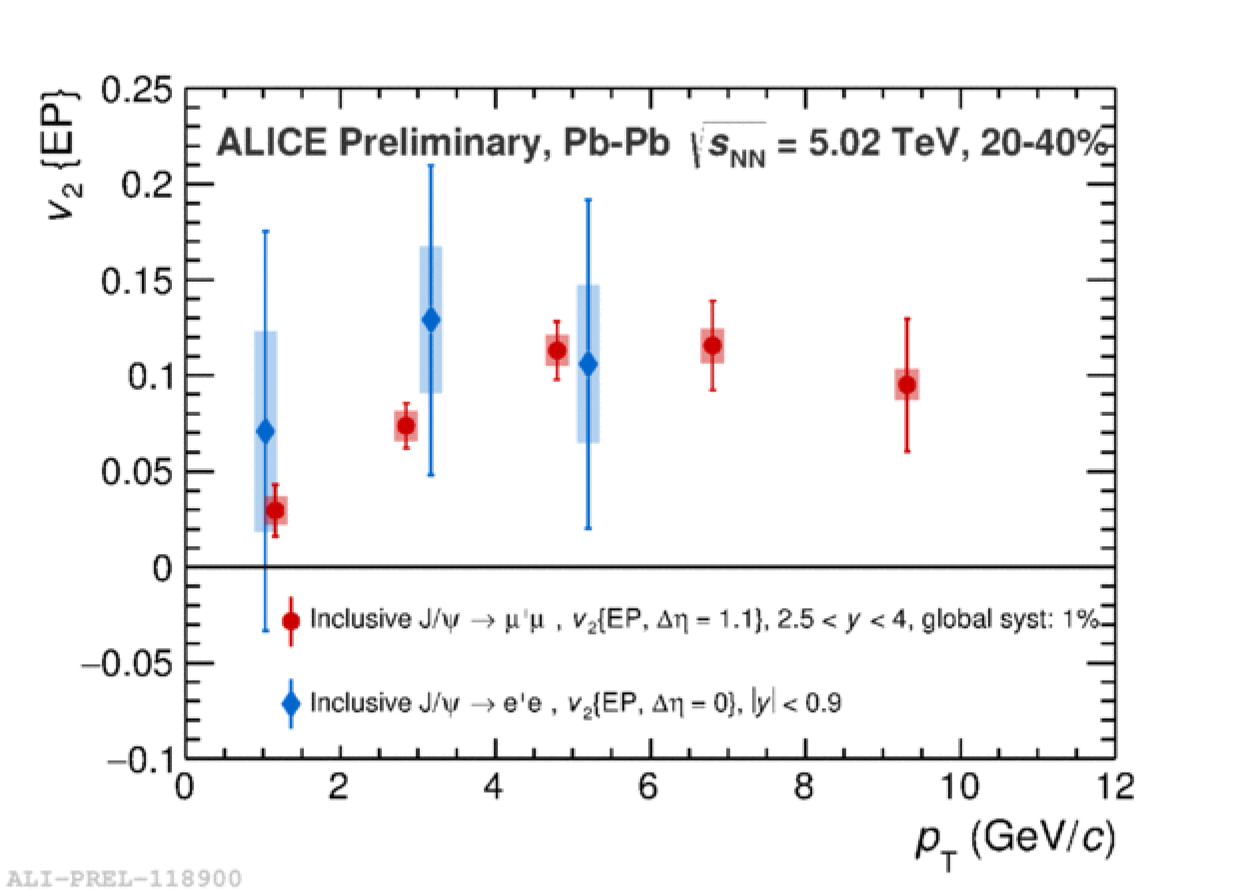


- ALICE Run 1 result gave an indication of non-zero flow
  → 2.7σ in $2<p_T<6$ GeV/c and 20-40% centrality
- Agreement within uncertainties between Run 1 and Run 2 results
- Higher Run2 precision shows evidence for non-zero flow, with a maximum in $4<p_T<6$ GeV/c

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

- Stable result, independently on the detector used for the EP determination

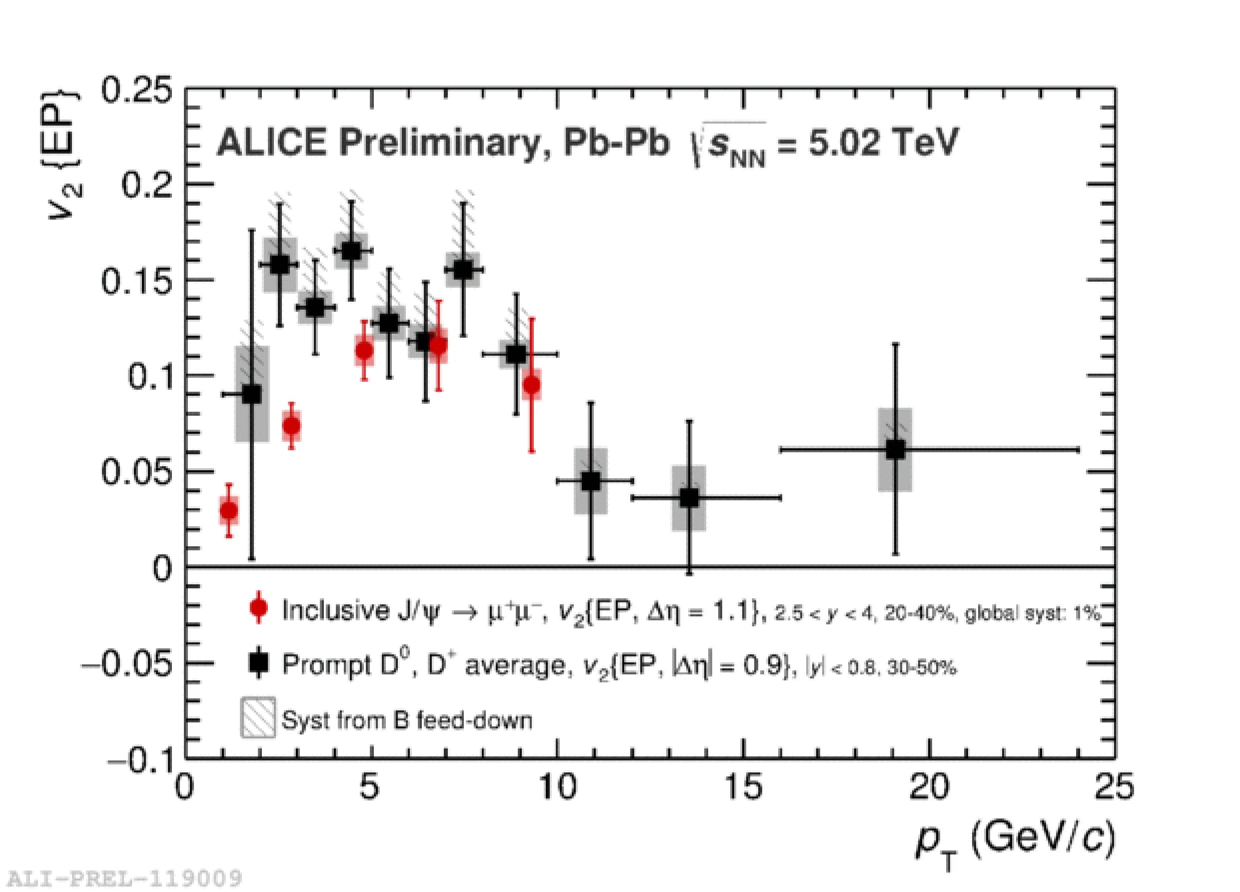
J/ψ elliptic flow: mid and forward-y



- First ALICE measurement of J/ψ v_2 at mid-y shows agreement with forward-y result, within uncertainties

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

J/ψ elliptic flow: comparison with open charm

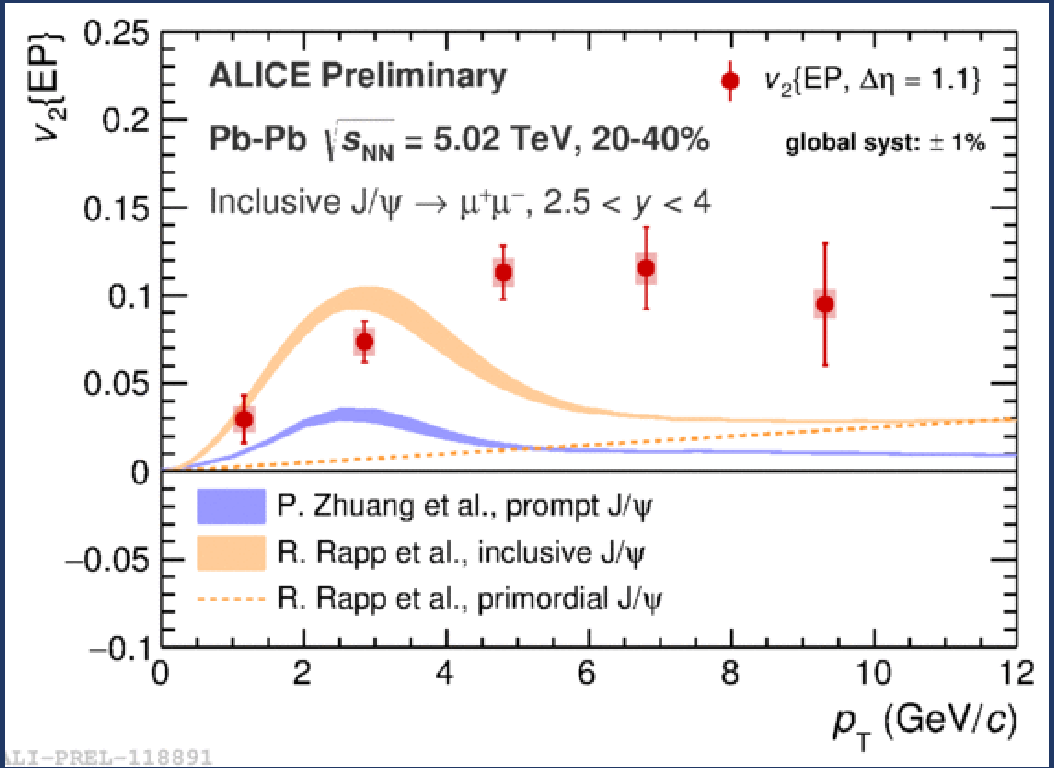


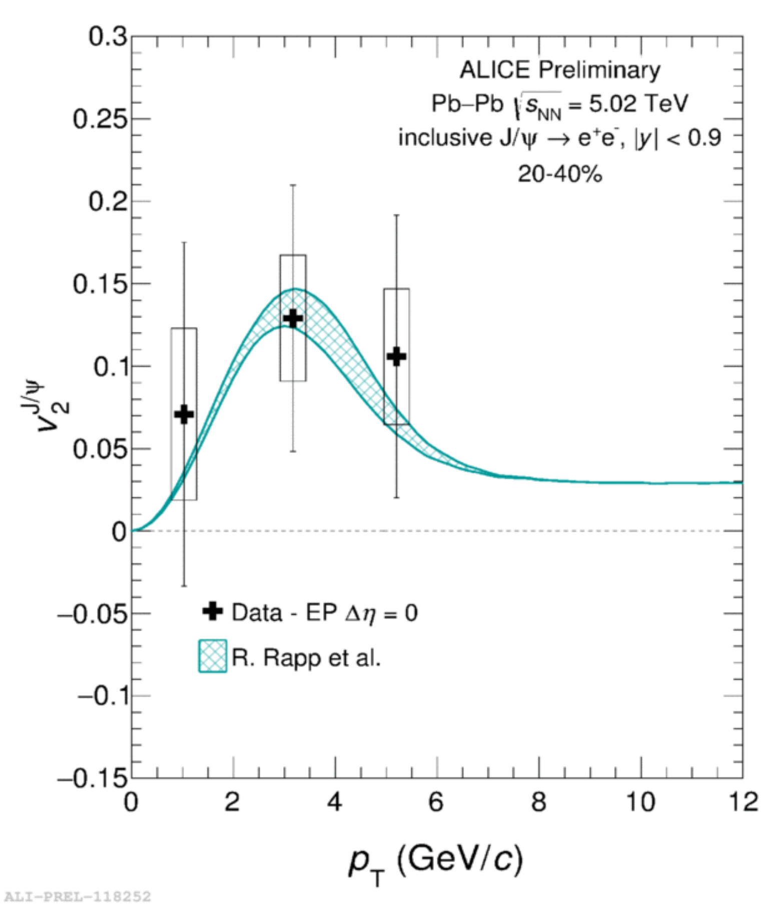
- Similar v_2 is observed in the open charm sector

  [even if in a different kinematic range:
  J/ψ: 2.5 < y < 4, centrality= 20-40%
  D: |y|< 0.8, centrality= 30-50%]

- Charm quarks strongly interact in the medium
- Comparison between J/ψ and D flow can provide information on flow properties of heavy quarks with respect to light ones

J/ψ elliptic flow: theory comparison





- J/ψ v_2 is compared to transport model calculations
- Difficulties in reproducing the pattern up to high p_T

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

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

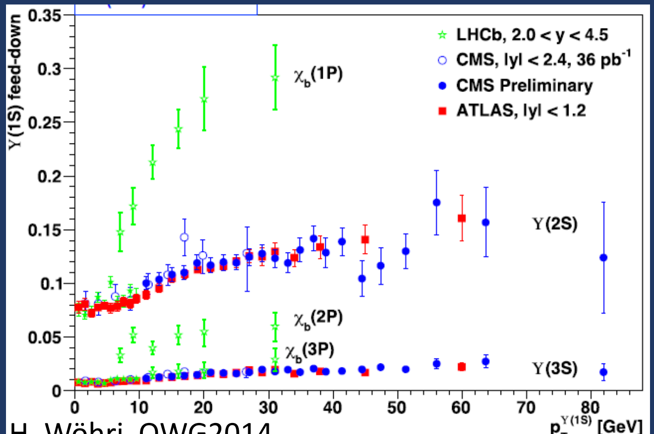
Υ(3S) Υ(2S) Υ(1S) → Sensitive in very different ways to the medium

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

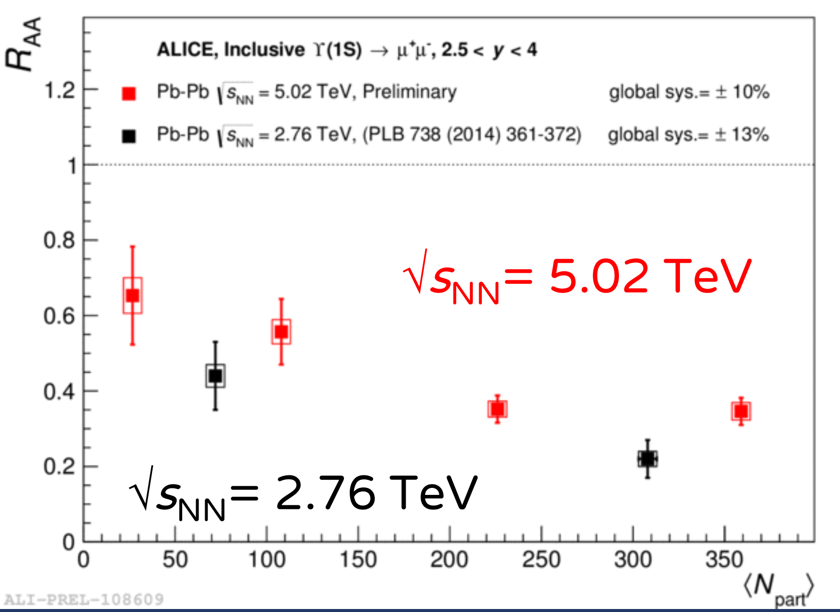
- Lower production cross sections
- Non negligible feed-down contributions from higher states

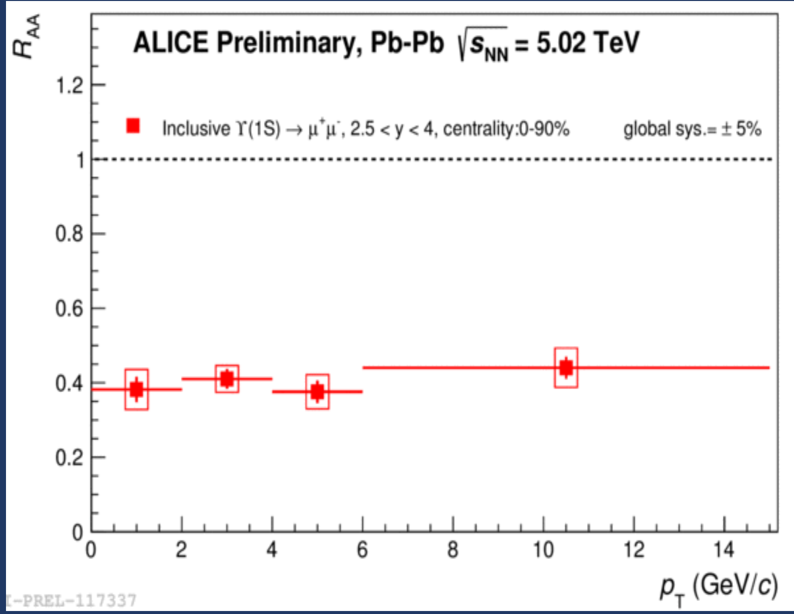


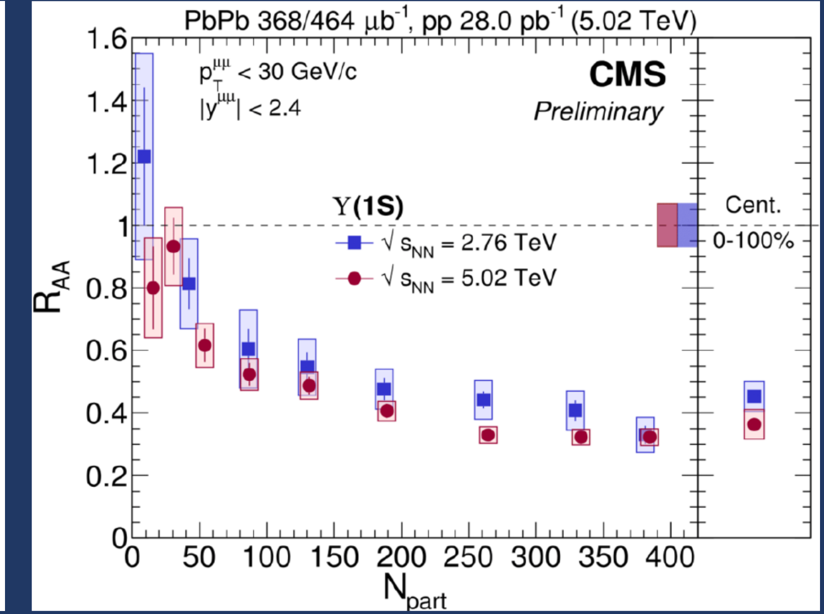
H. Wöhri, QWG2014

Bottomonia in ALICE

- Also bottomonium states accessible with higher precision in Run 2



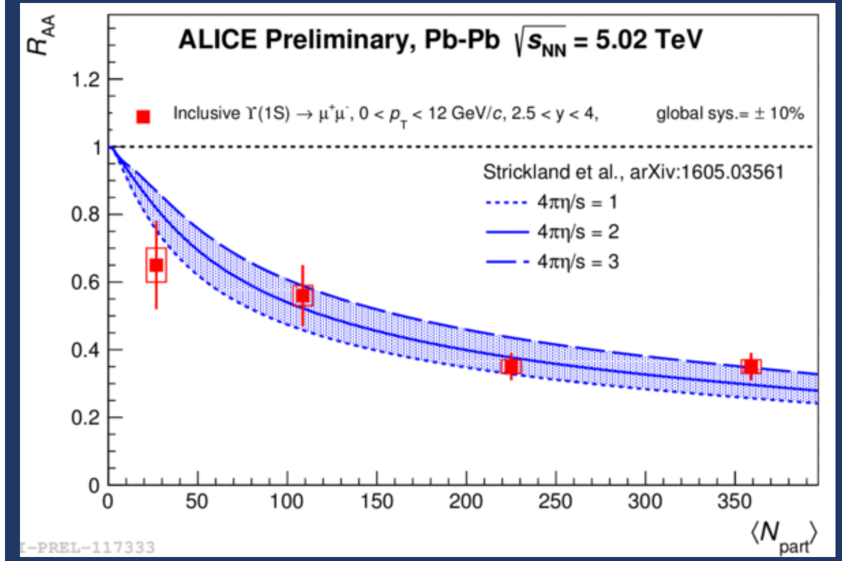


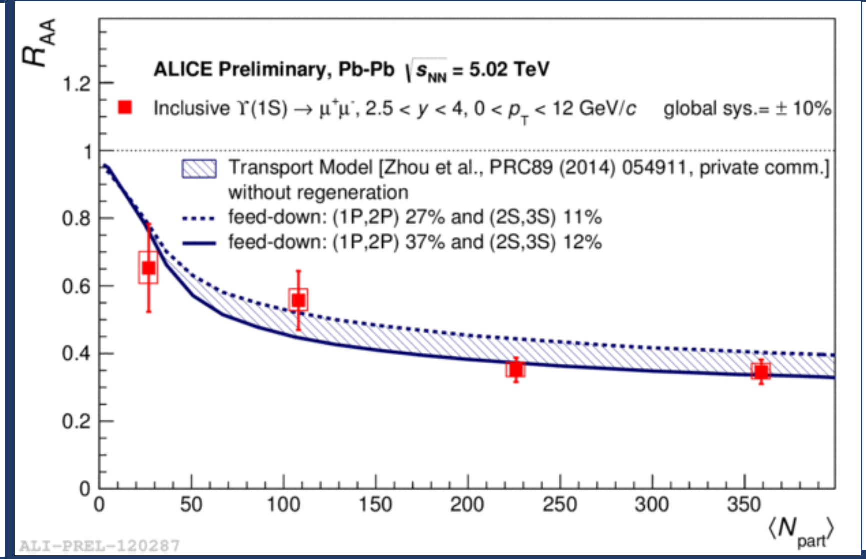


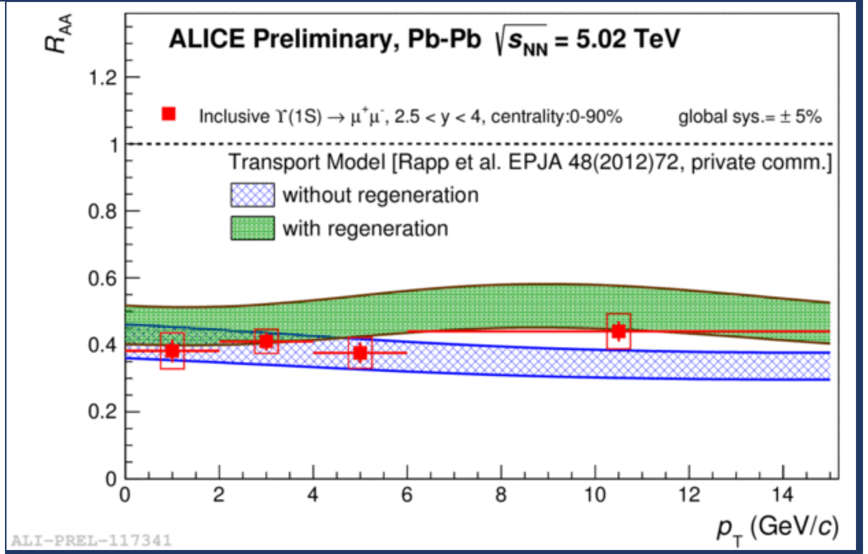
CMS-PAS-HIN-16-023

- Strong Υ(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 Υ(1S) suppression similar to the one measured by CMS
- Suppression of directly produced Υ(1S) ? → feed-down contribution~30%

Υ(1S) in ALICE: theory comparison

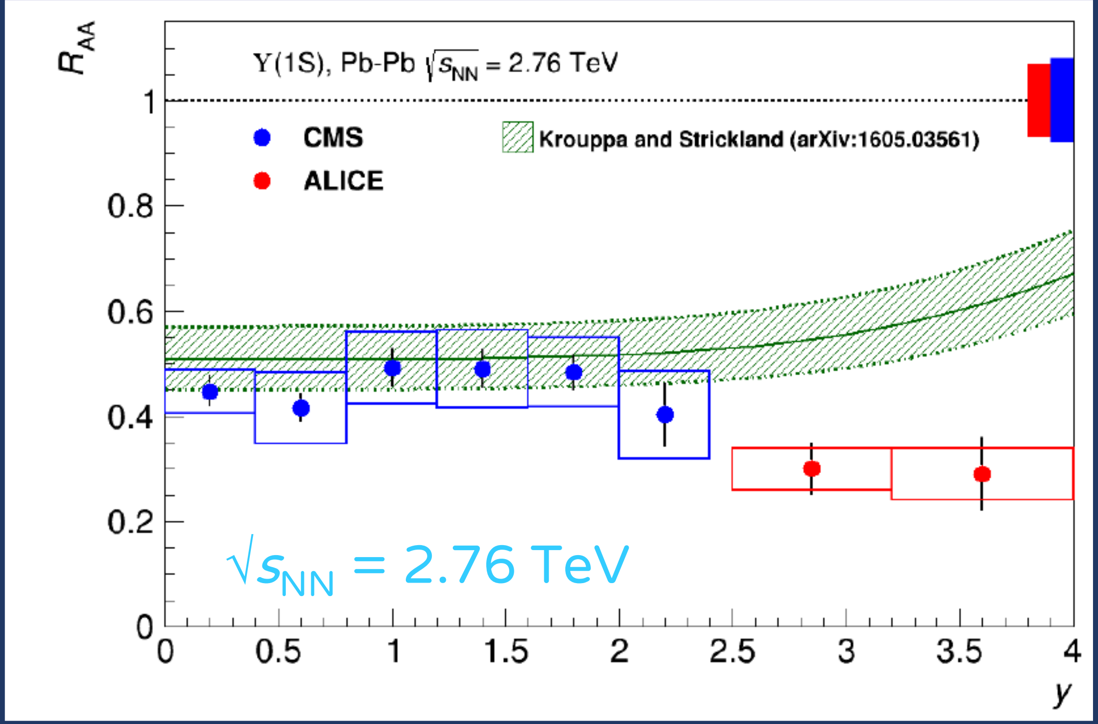


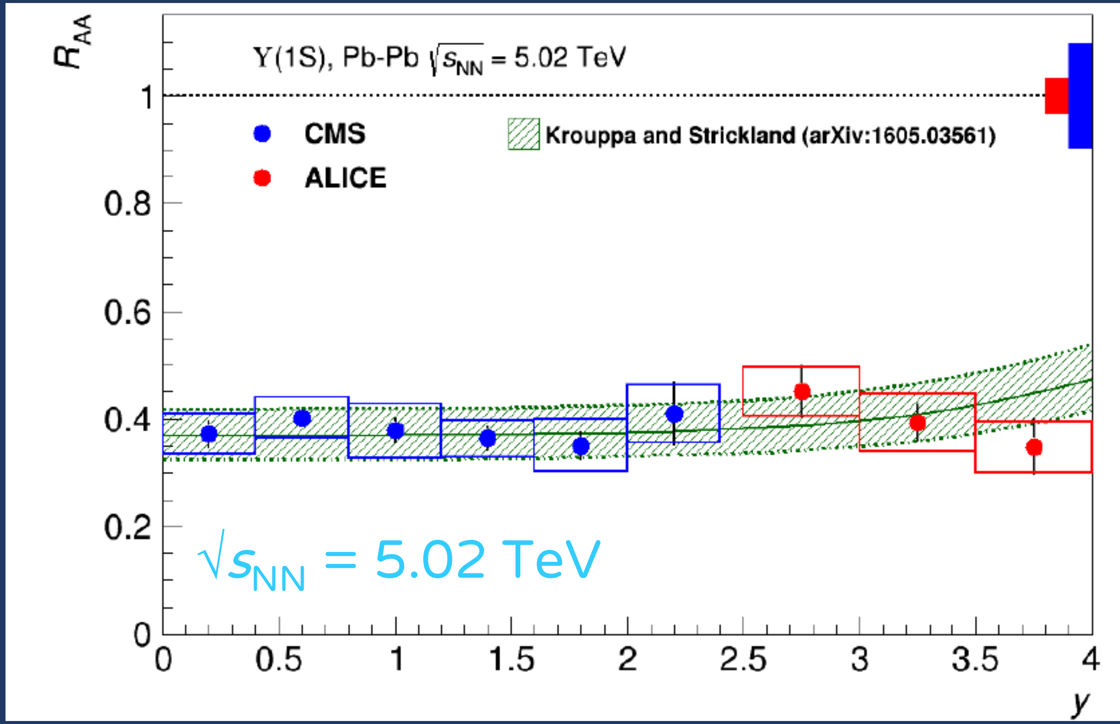




- Transport and anisotropic hydrodynamical models qualitatively describe the centrality and the p_T evolution
- No need for contribution of regenerated Υ

Υ(1S) in ALICE: theory comparison





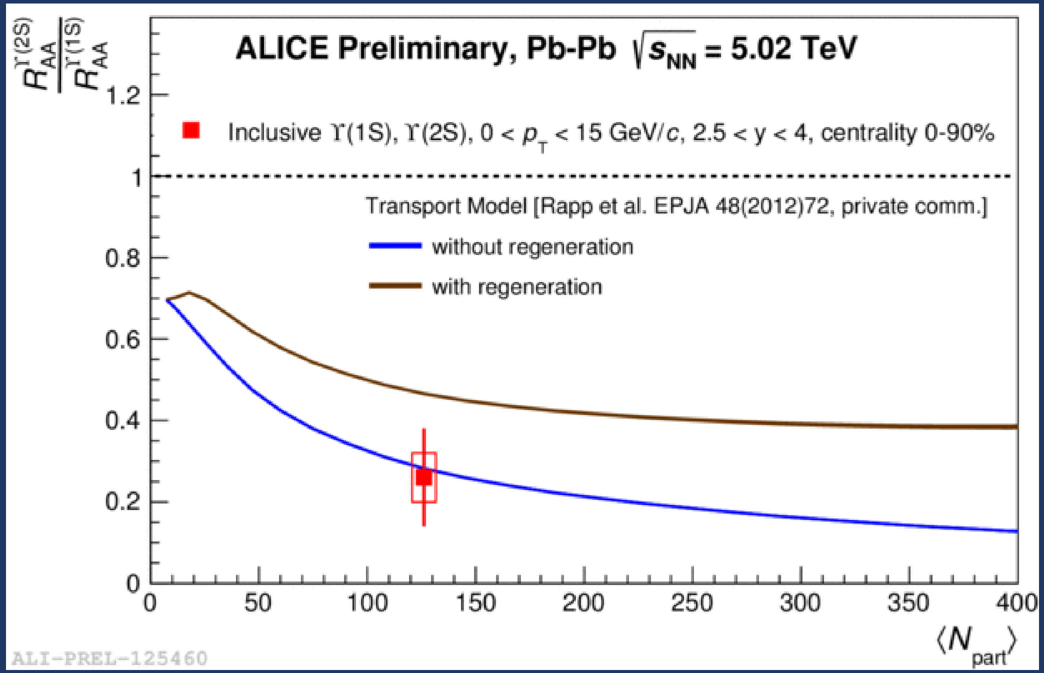
CMS-PAS-HIN16-023
CMS arXiv:1611.01510

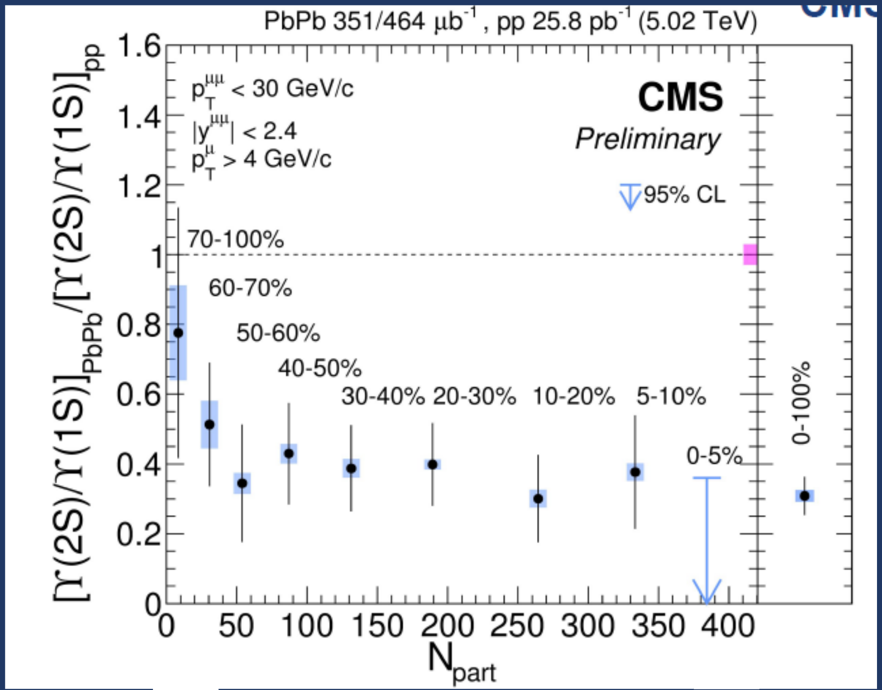
E. Scomparin, QM17

- 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

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

Quarkonia in p-Pb collisions

pA collisions are a tool to:

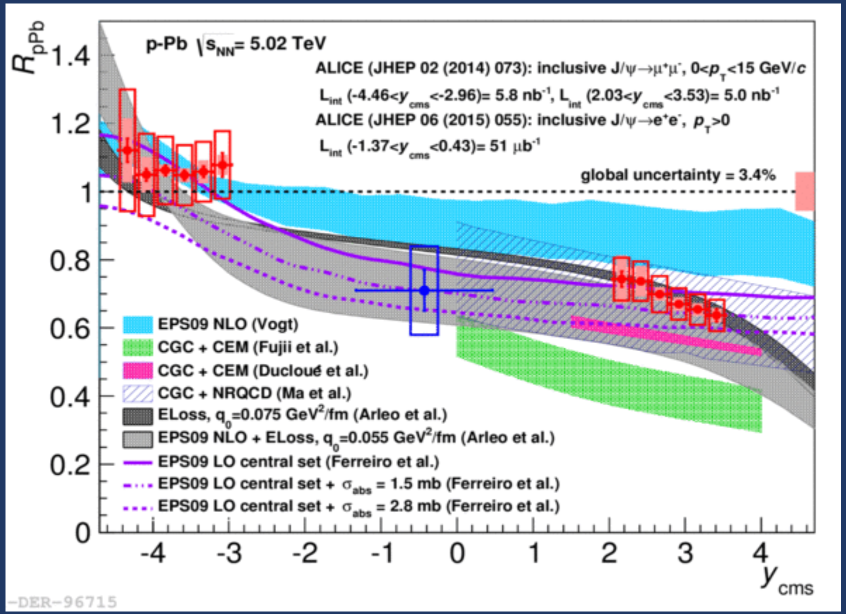
- Disentangle CNM effects, which have a different impact depending on energy regime and quarkonium kinematics
- Investigate role of CNM effects underlying AA collisions

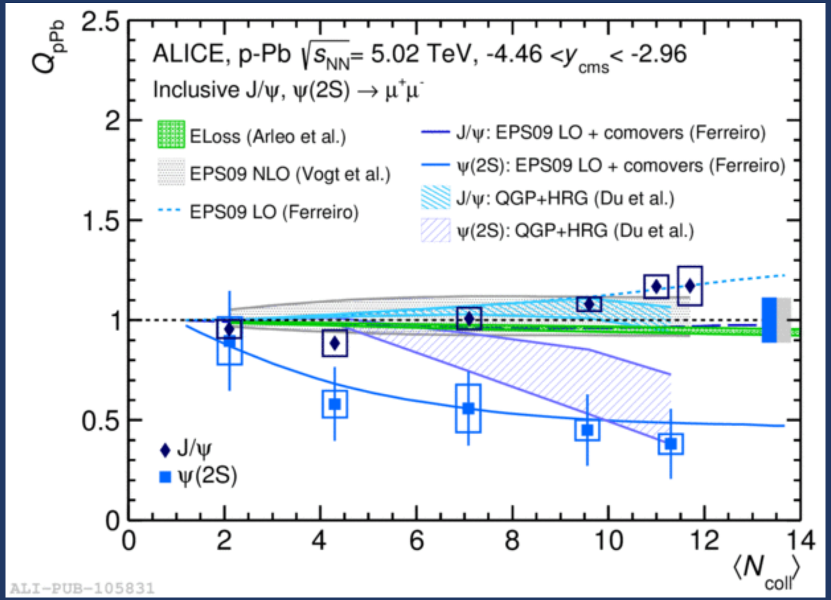
Run 1 results:

JHEP 06 (2015) 55
JHEP 12 (2014) 073
JHEP 06 (2016) 50
JHEP 11 (2015) 127
JHEP 02 (2014) 073
PLB 740 (2015) 105
arXiv:1704.00274

➡ strong CNM effects on the J/ψ, with y and p_T dependence

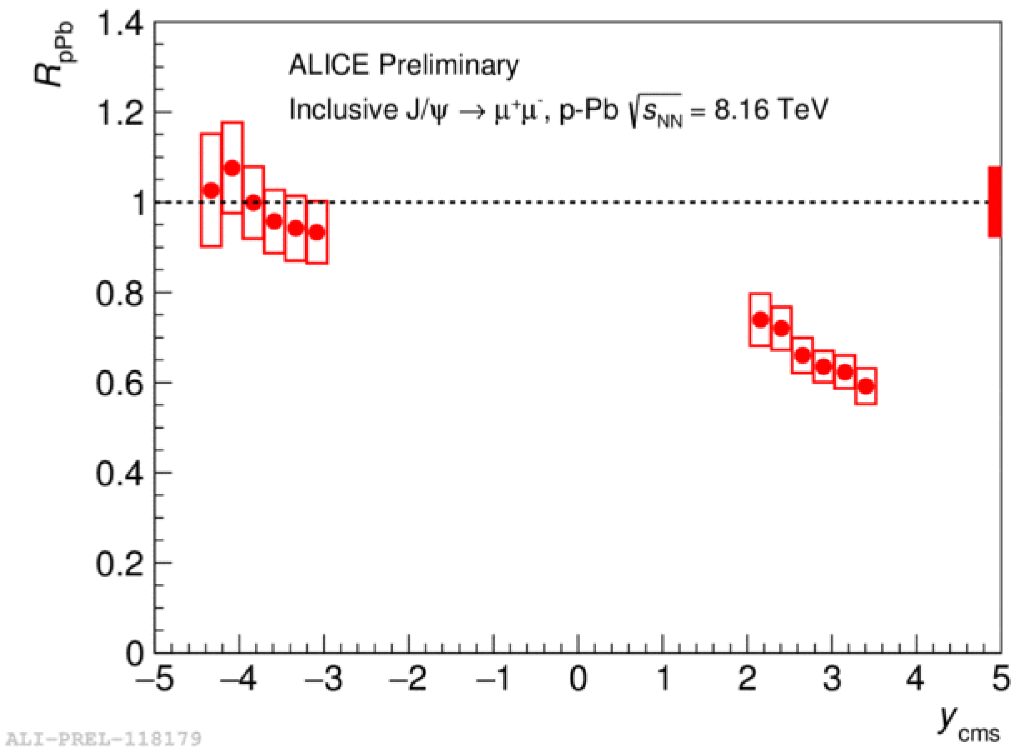
➡ stronger ψ(2S) suppression wrt J/ψ → unexpected because formation time > crossing time





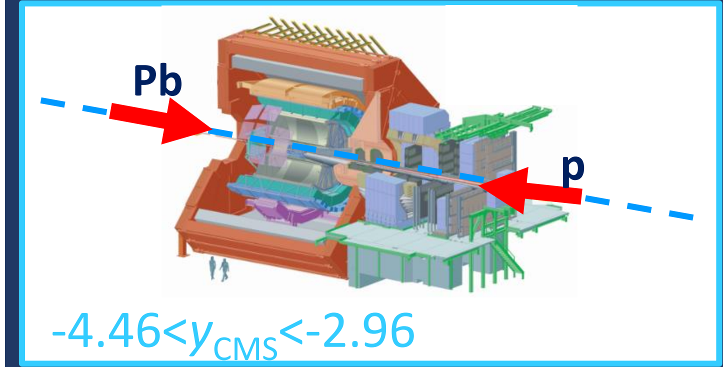
Hot medium playing a role on loosely bound ψ(2S) ?

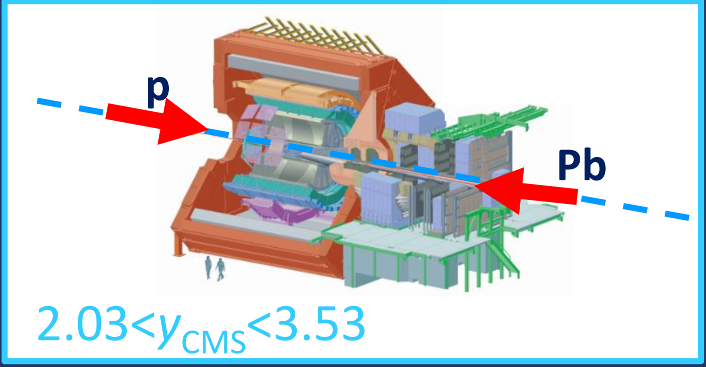
J/ψ production in p-Pb at $\sqrt{s_{NN}}$ = 8.16TeV



CERN-ALICE-PUBLIC-2017-001

- Data collected with two beam configurations: p-Pb and Pb-p in $2.5<y_{LAB}<4$

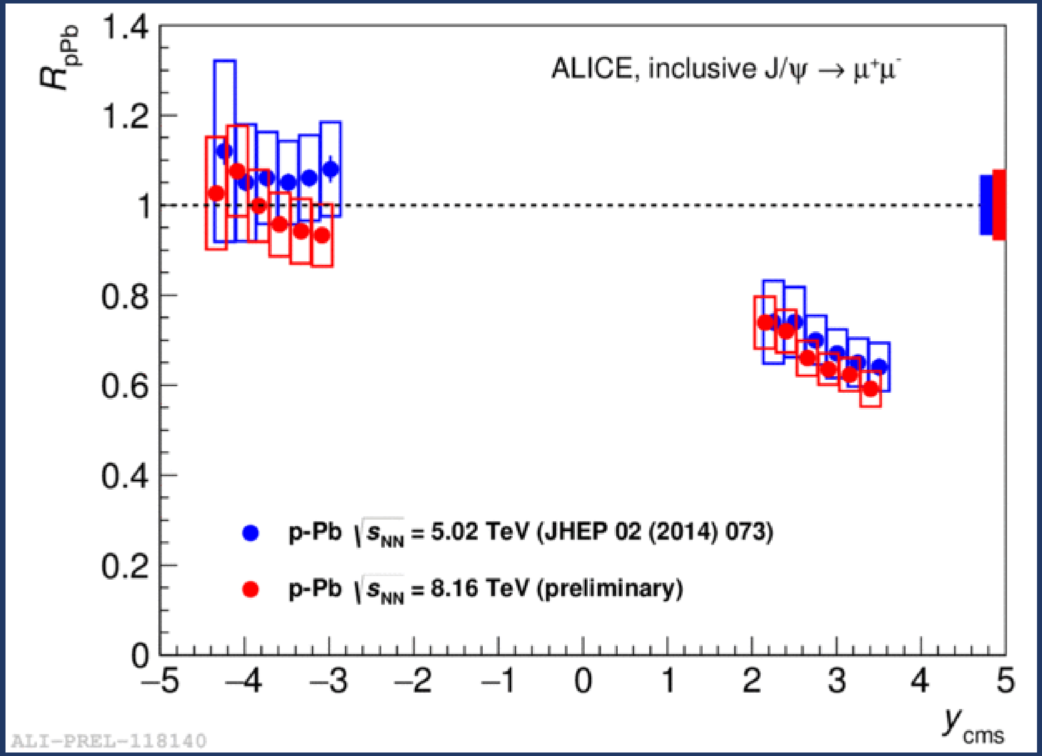




- Clear J/ψ suppression at forward-y, while R_{pA} is compatible with unity at backward-y

$\sqrt{s_{NN}}$ = 8.16 TeV, $p_T^{J/\psi}$= 0
$1.1\ 10^{-5} <x<5\ 10^{-5}$ (p-going)
$7.3\ 10^{-3}<x<3.3\ 10^{-2}$ (Pb-going)

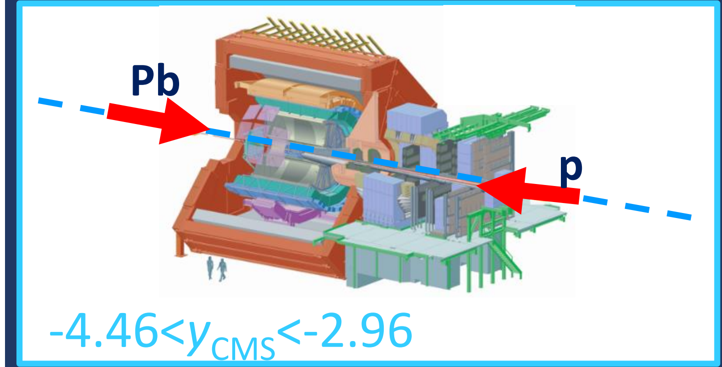
J/ψ production in p-Pb at $\sqrt{s_{NN}}$ = 8.16TeV

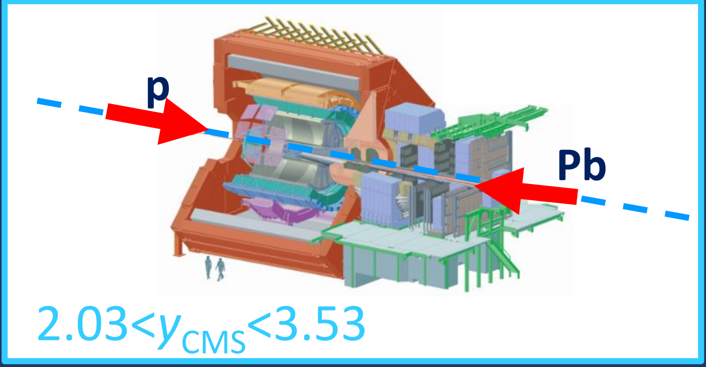


CERN-ALICE-PUBLIC-2017-001

$\sqrt{s_{NN}}$ = 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)

- Data collected with two beam configurations: p-Pb and Pb-p in 2.5<y_{LAB}<4

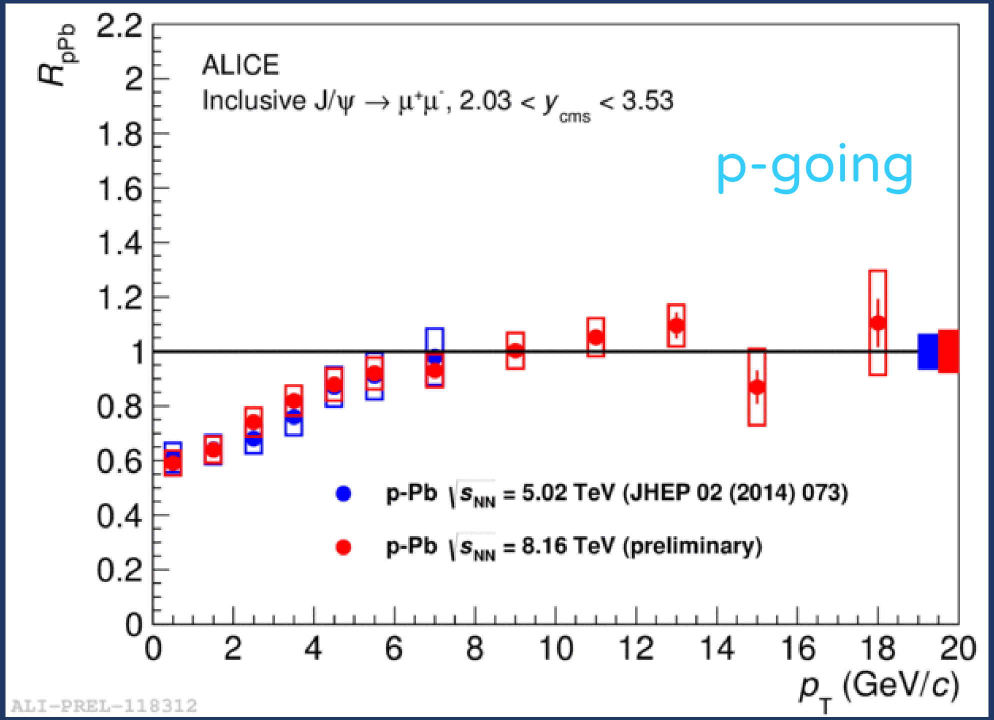


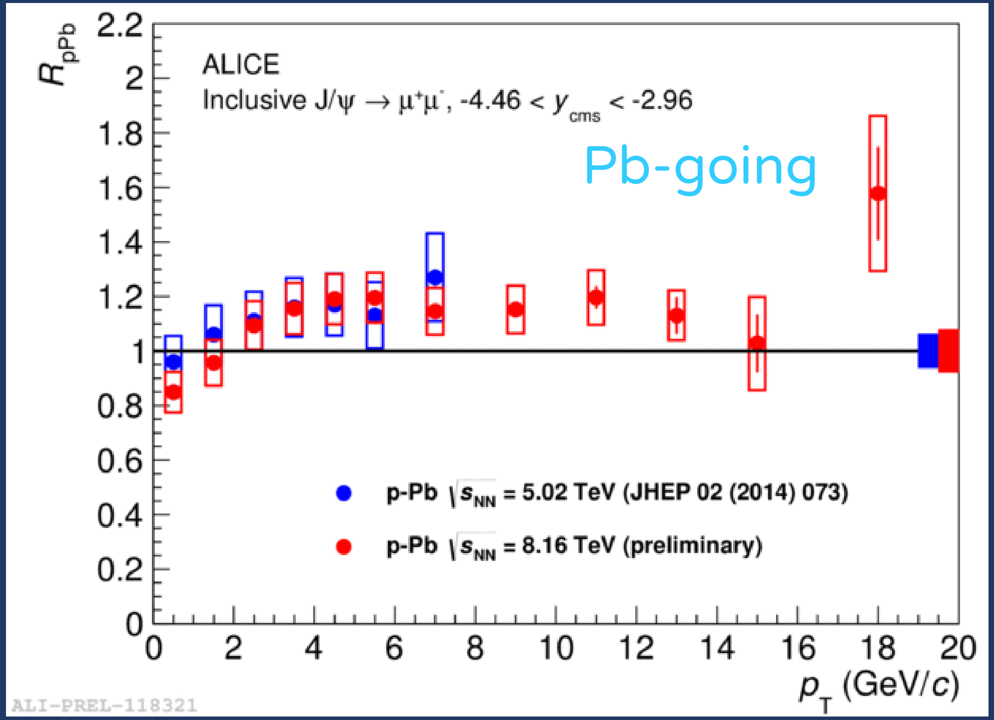


- Clear J/ψ suppression at forward-y, while R_{pA} is compatible with unity at backward-y

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

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



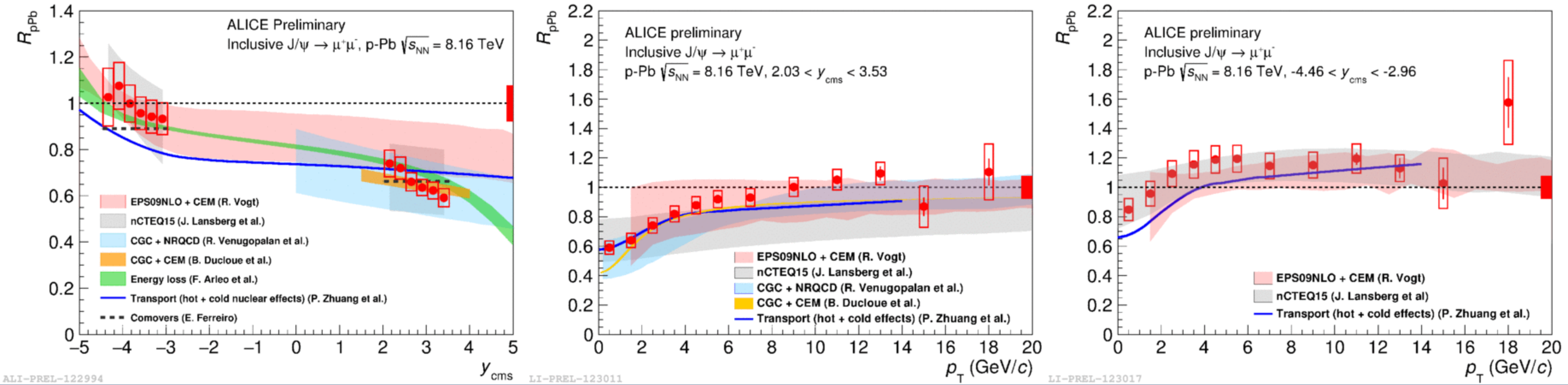


➡ In Run 2, p_T coverage extended up to 20 GeV/c

- p-going: R_{pA} increases with p_T
- Pb-going : R_{pA} rather constant

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

Comparison with theory models



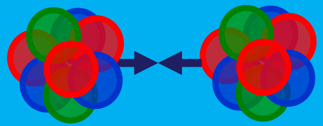
CERN-ALICE-PUBLIC-2017-001

➡ 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

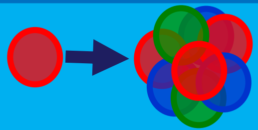
Conclusions

New high-precision Run2 results on quarkonium in p-A and A-A from ALICE

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

pA 

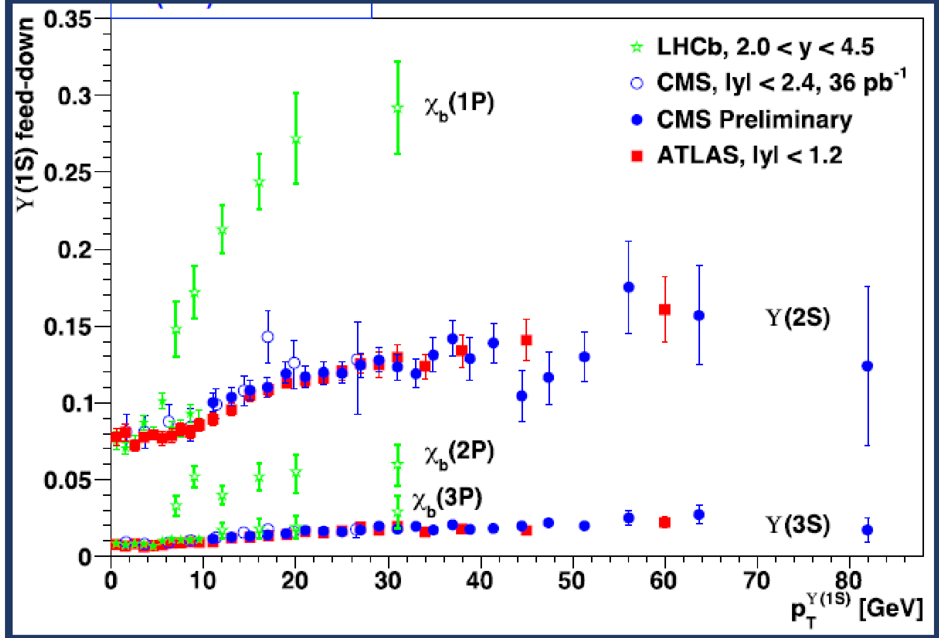
Interplay of shadowing and energy loss describes J/ψ production in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

Many new results still to come….

Thanks!

Backup slides

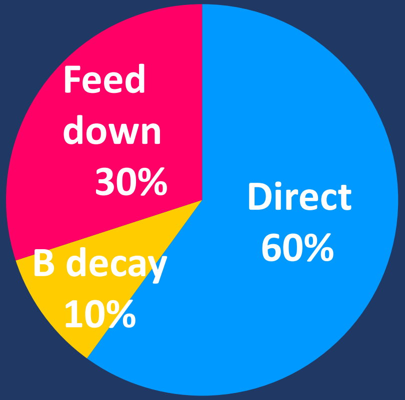
Feed down



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:

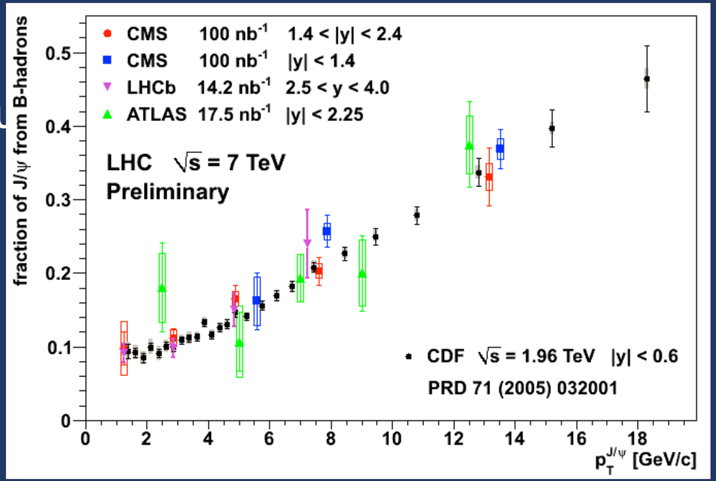
Prompt

➡ Direct production

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

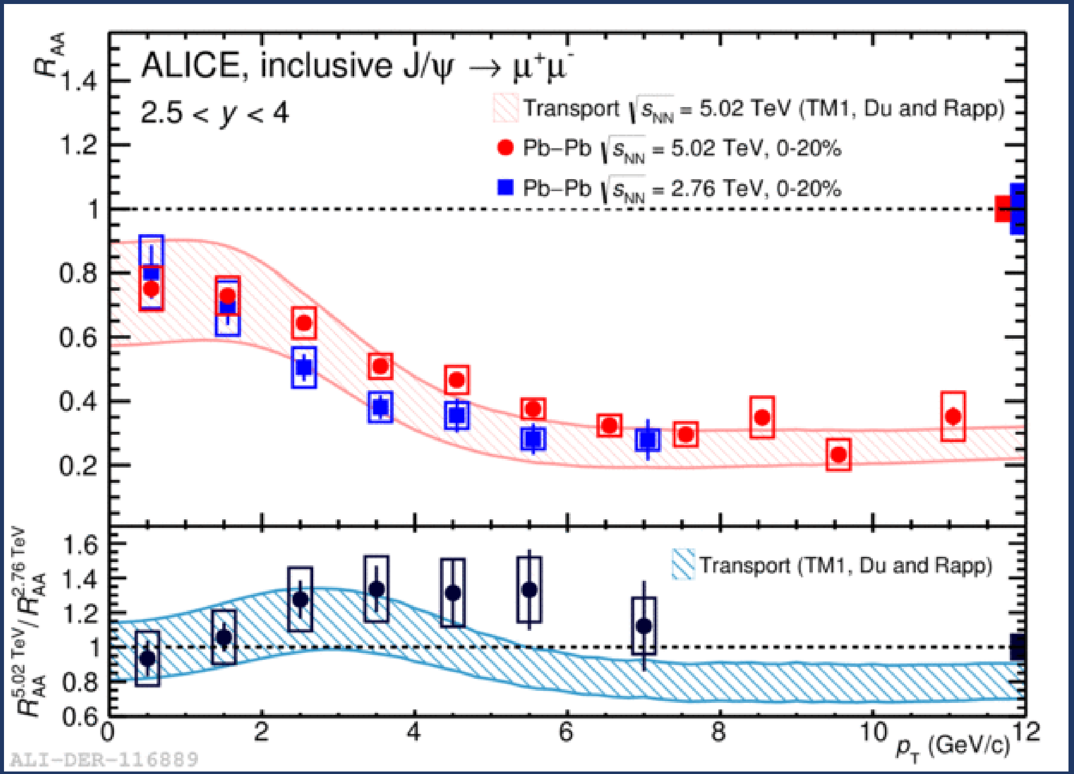
Displaced

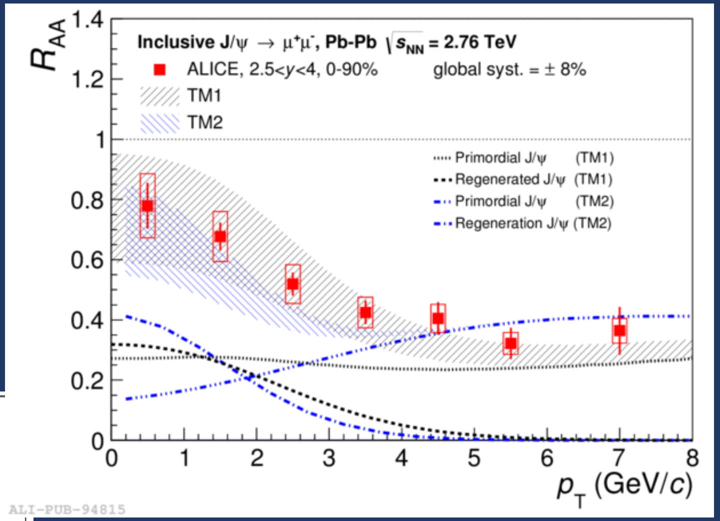
➡ B decay
contribution is p_T dependent
~10% at p_T~1.5GeV/c

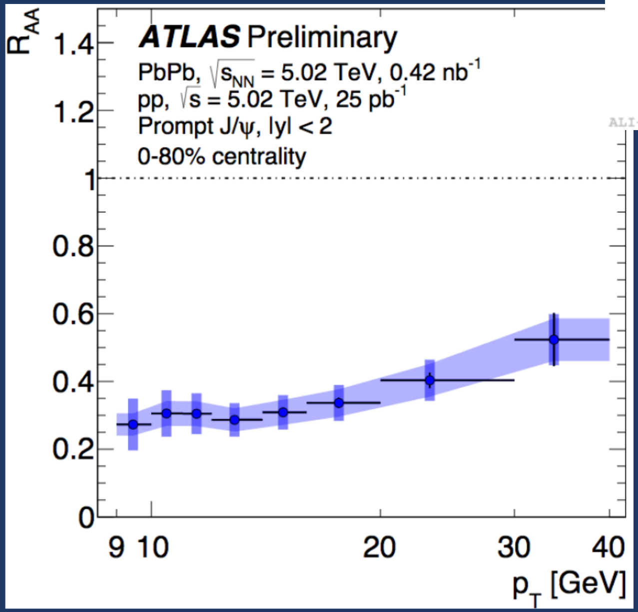


p_T dependence of R_{AA}

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





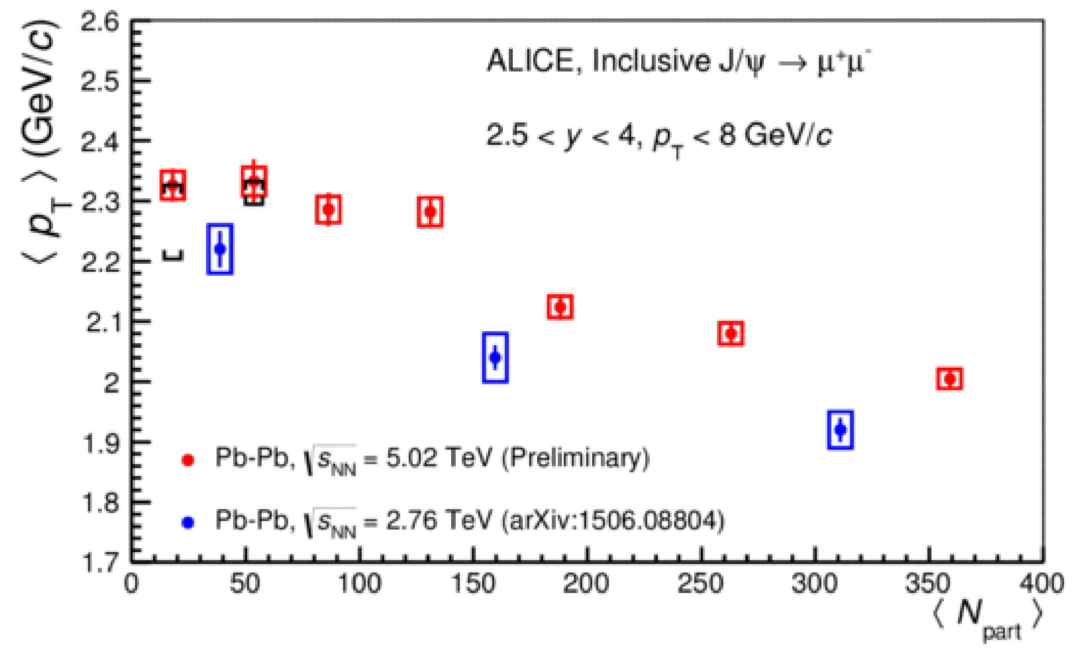


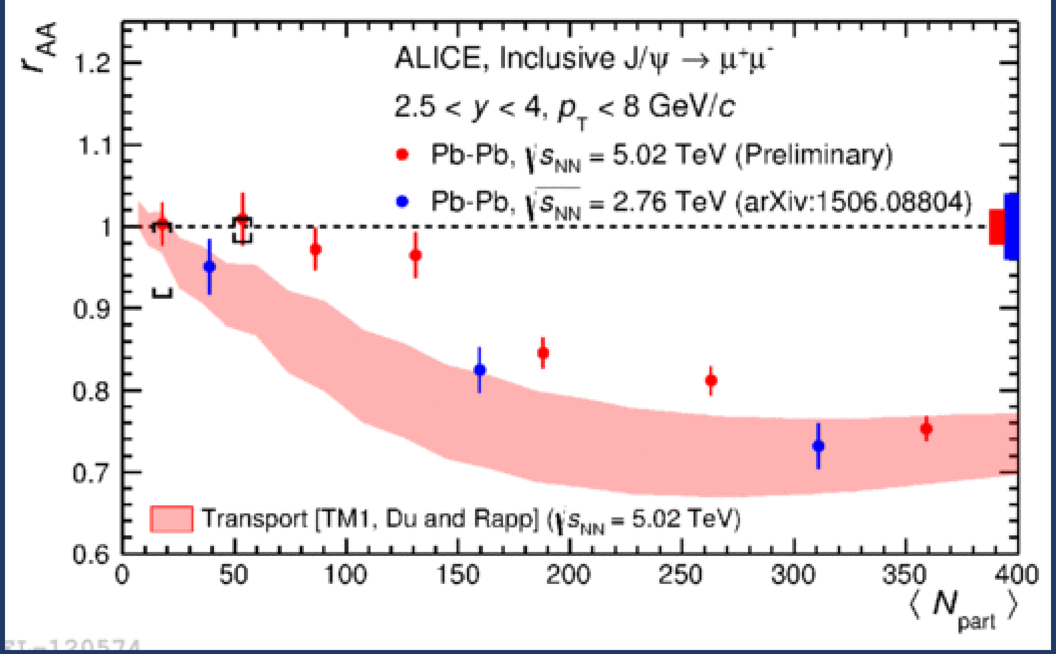
➡ Similar R_{AA} at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV, with a hint for an increase in the range $2<p_T<6$ GeV/c

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

J/ψ <p_T> and r_{AA}

- The <pT> and <pT2> evolution provide complementary information on the J/ψ





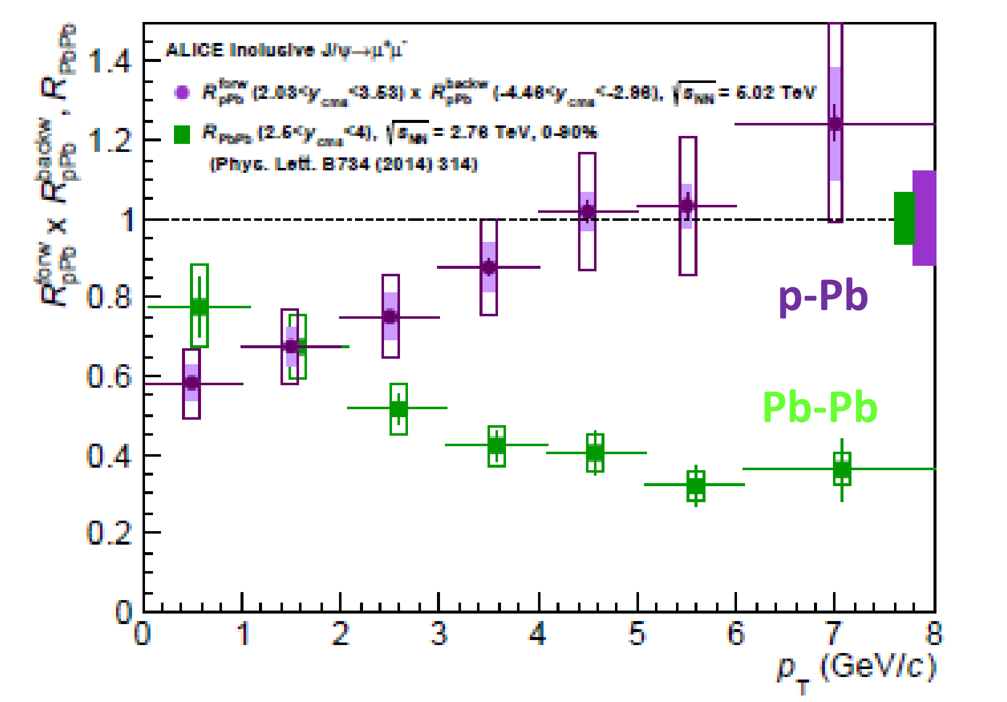
- The J/ψ <pT> is smaller in central collisions, as expected from (re)generation
- <pT> distributions are slightly harder at √sNN = 5.02 TeV
- Some tension in the transport model description of rAA

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

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

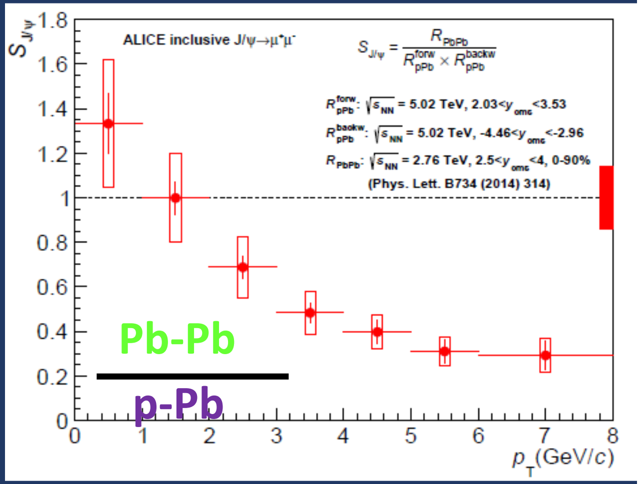


- Sizeable p_T dependent suppression still visible → CNM effects not enough to explain AA data at high p_T

- we get rid of CNM effects with

AA / pA

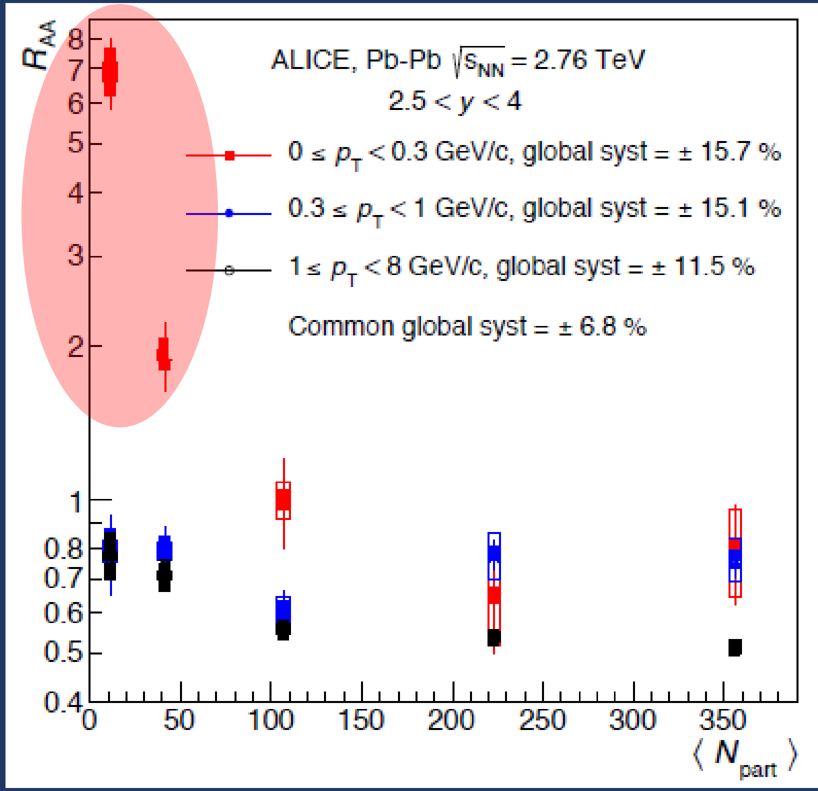
CNM effects not enough to explain PbPb data at high p_T



Evidence for hot matter effects in Pb-Pb!

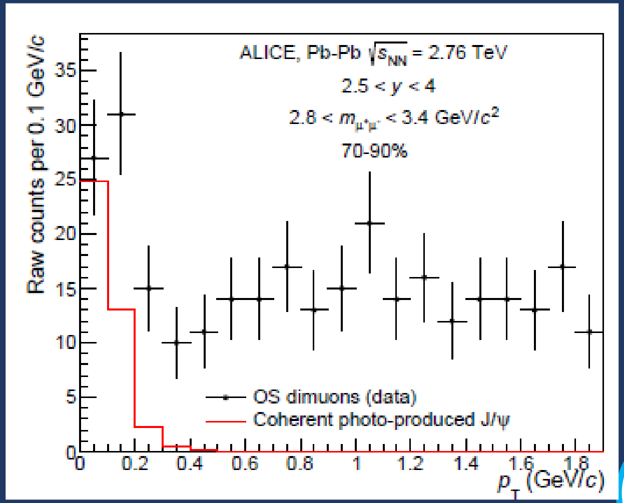
Low pT J/ψ at fw-y

- 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)

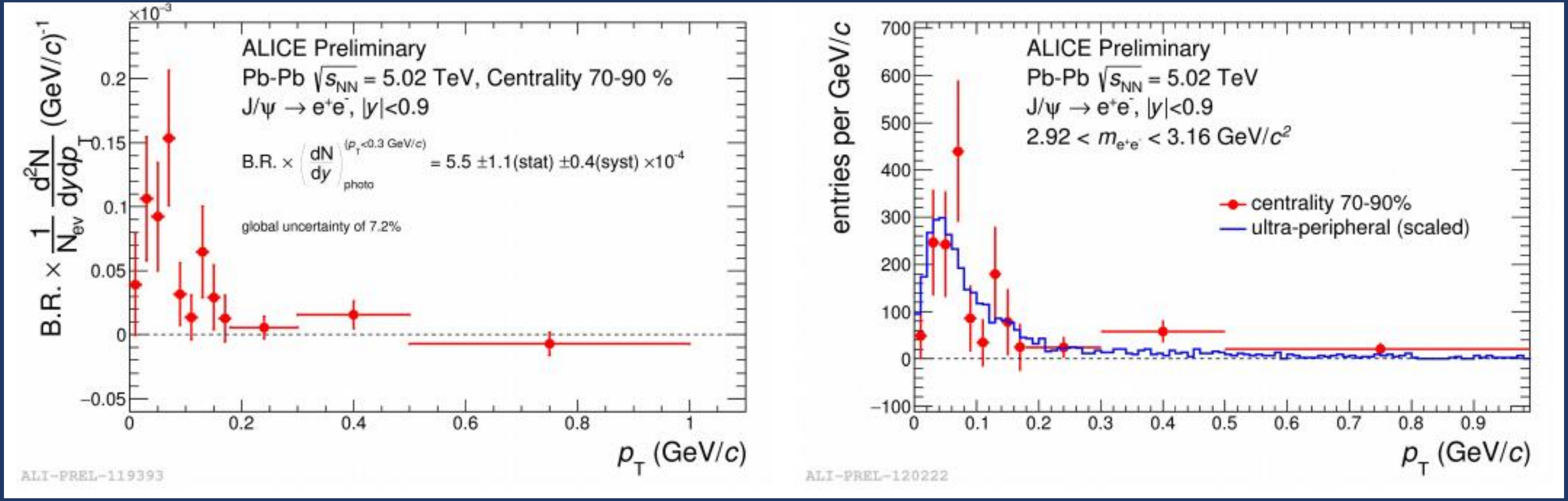


- if excess is "removed" requiring $p_T^{J/\psi}$>0.3GeV/c → ALICE R_{AA} lowers by 20% at maximum (in the most peripheral bin)

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%



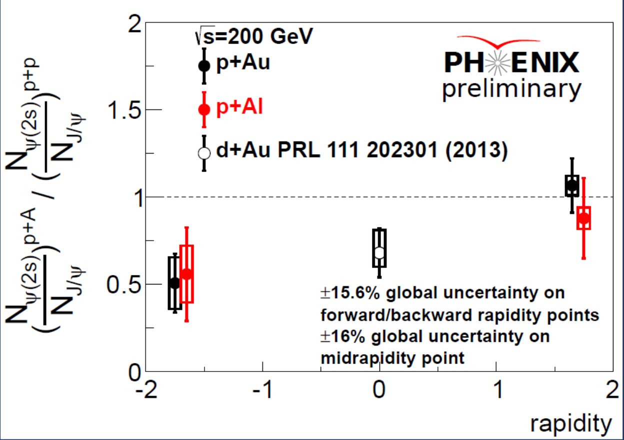
Hadronic contribution in pT<300 MeV/c subtracted

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

2

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

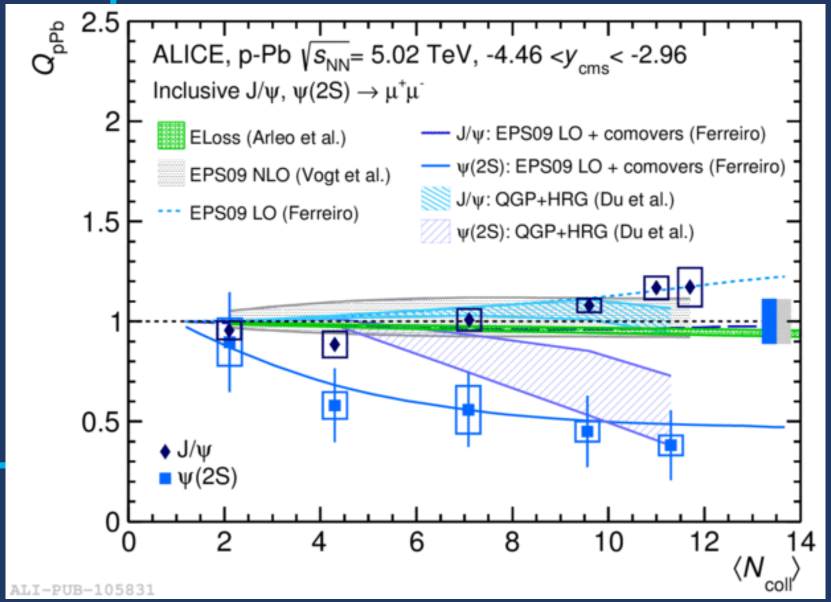
- Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA

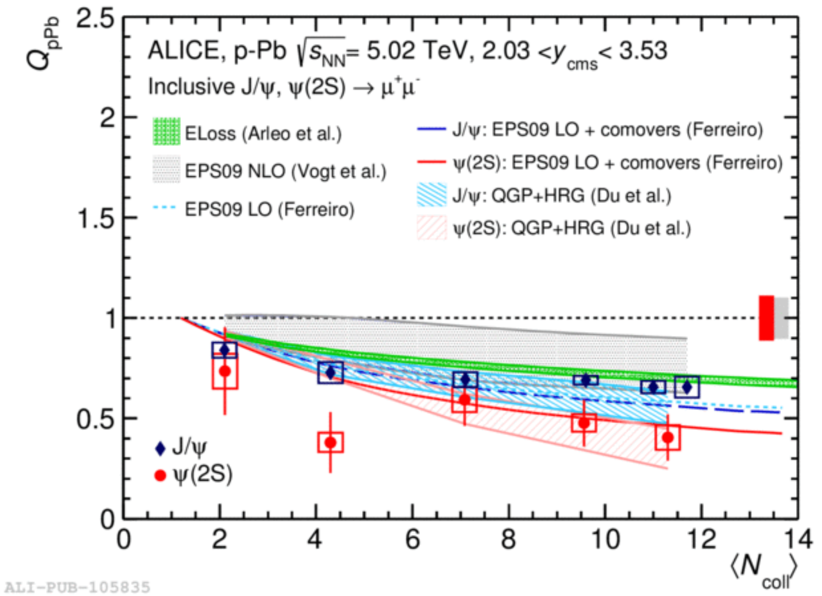


- ψ(2S) suppression stronger than the J/ψ one at RHIC and LHC

→ 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

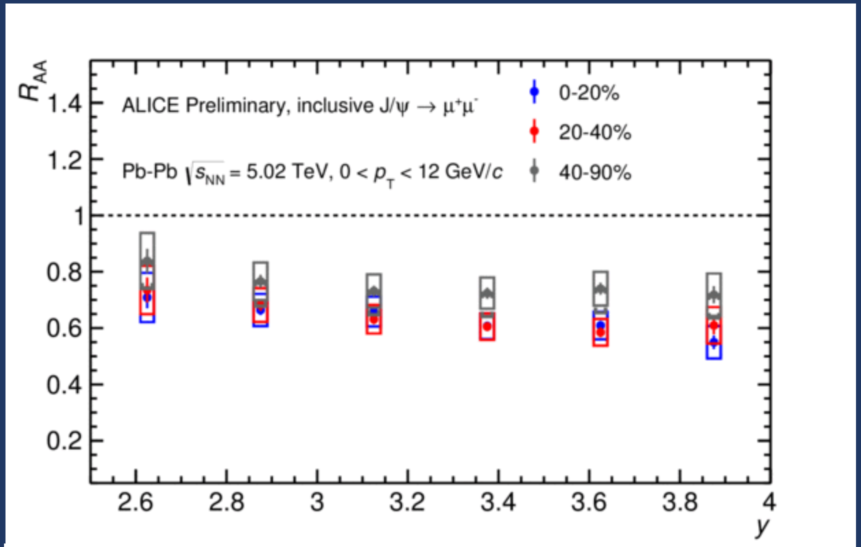


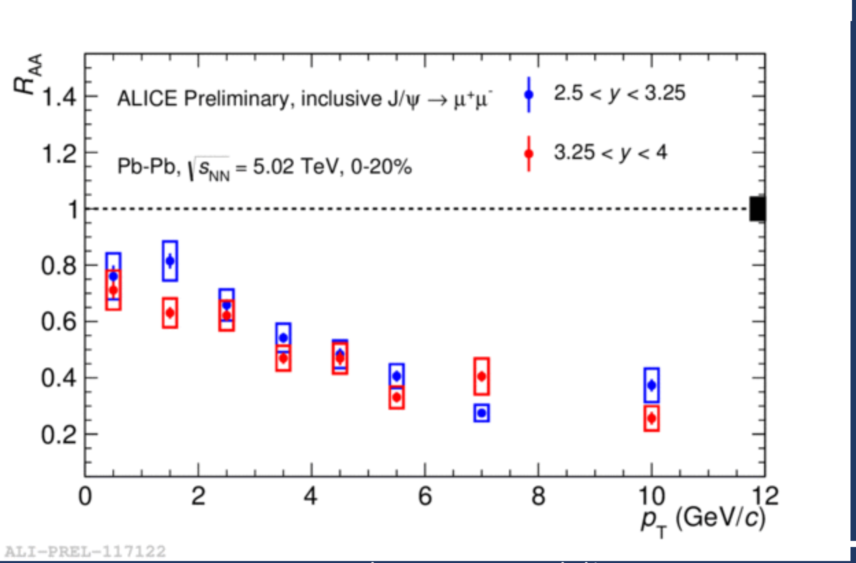


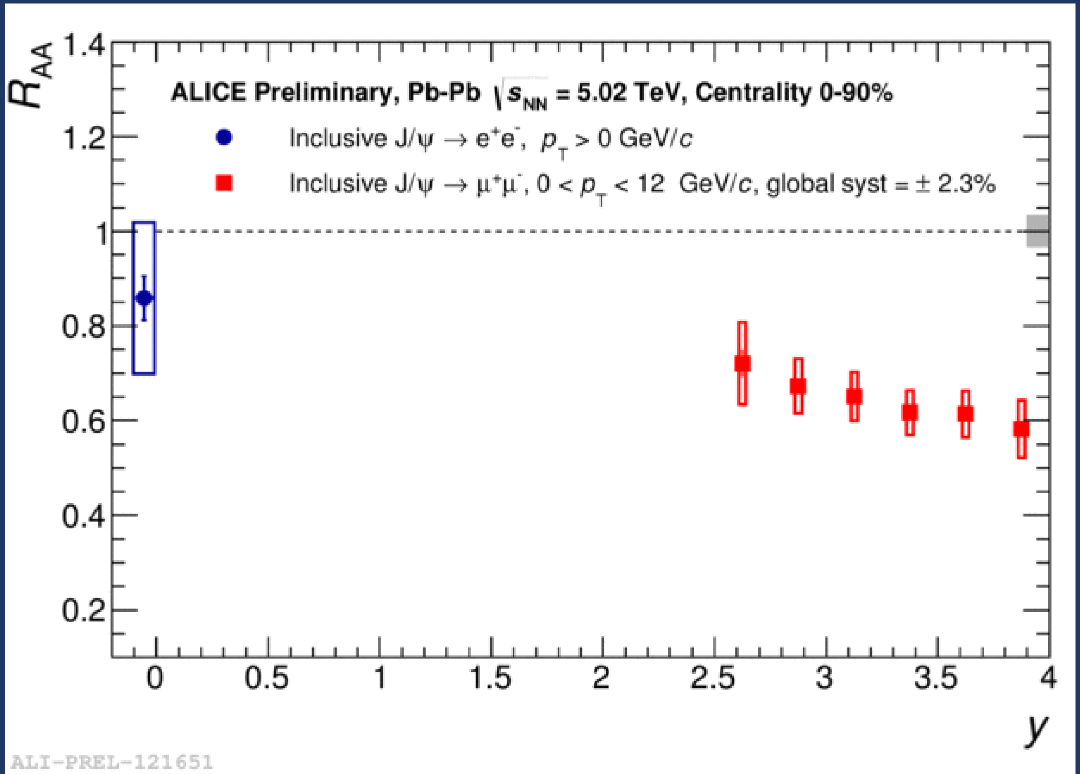
QGP+hadron resonance gas or comovers models describe the stronger ψ(2S) suppression

RAA vs y

- Constraints to the theoretical models can be imposed by more differential RAA studies



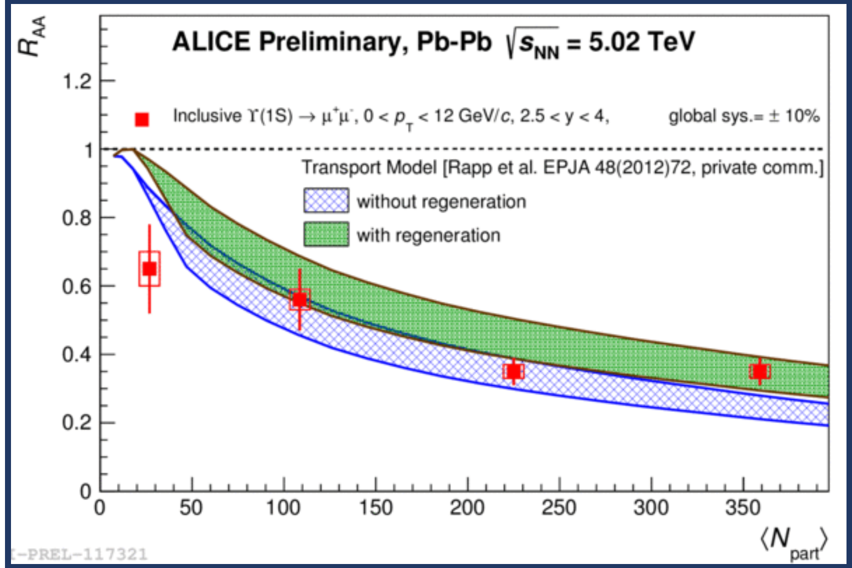


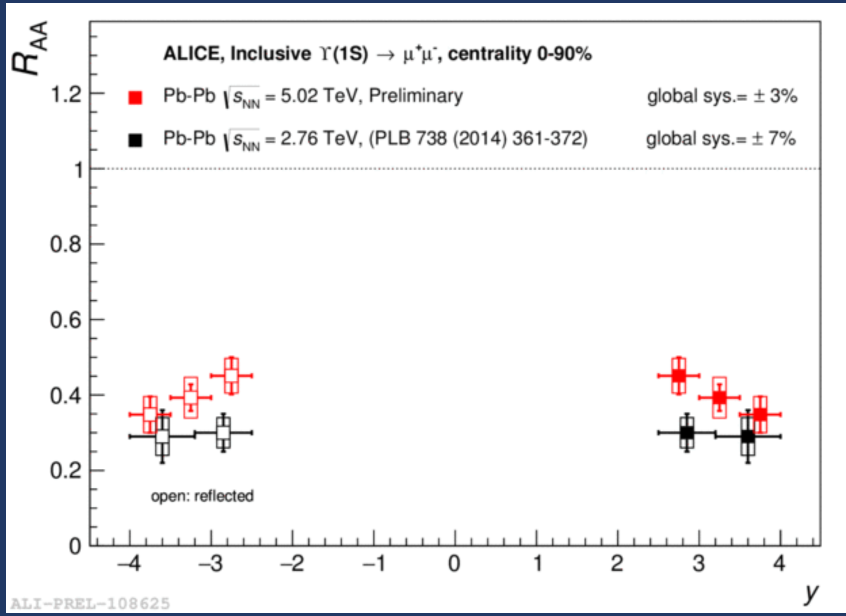


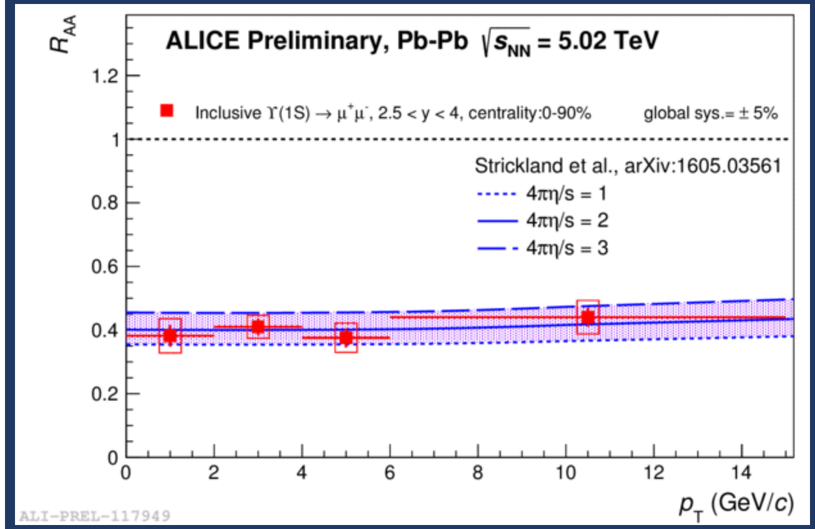
- Hint of enhanced production towards mid-*y*

Bottomonium in ALICE

Also bottomonium states accessible with higher precision in Run 2







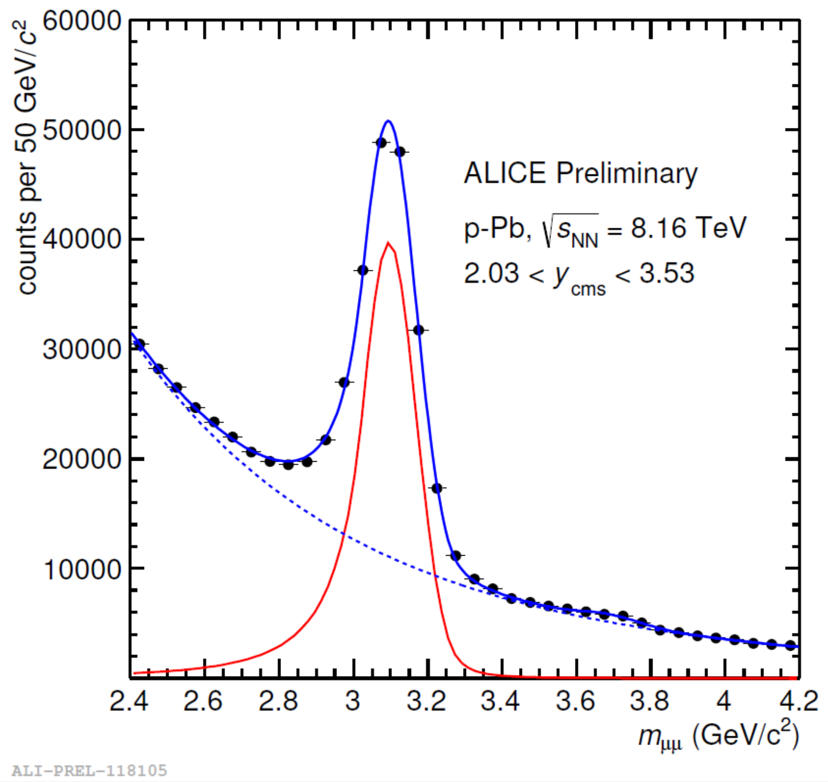
- Strong Υ(1S) suppression as a function of centrality, similar within uncertainties to the one measured at $\sqrt{s_{NN}}$ = 2.76TeV
- Hint for a decreasing trend vs y, even if within uncertainties
- Flat behavior as a function of pT
- Size of Υ(1S) suppression similar to the one measured by CMS

Quarkonium reconstruction at forward-y

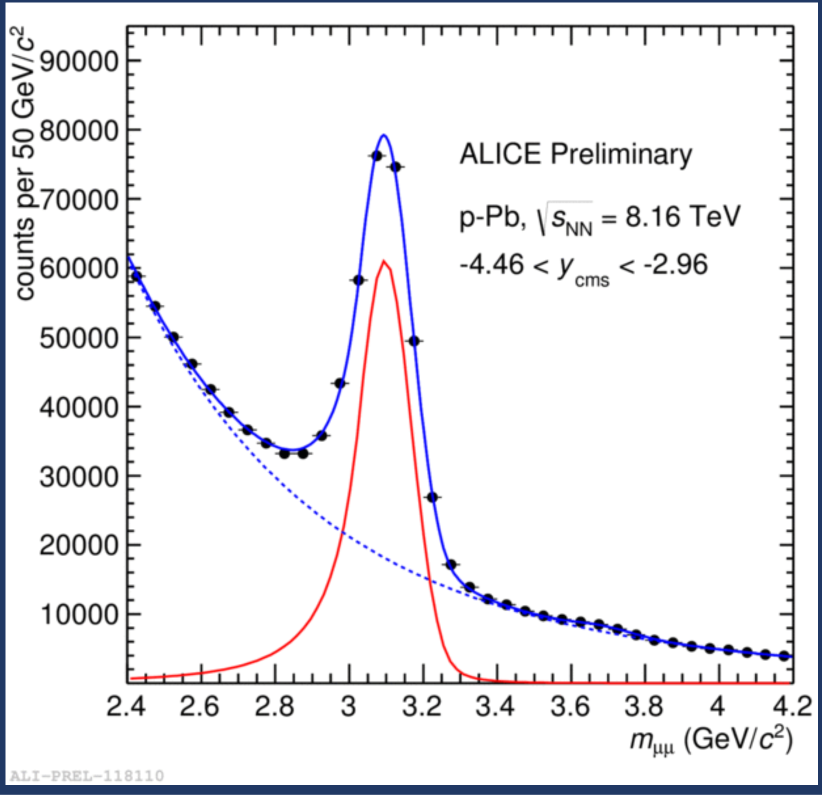
➡ Yields extracted fitting the dimuon invariant mass spectrum with signal + background shapes

p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

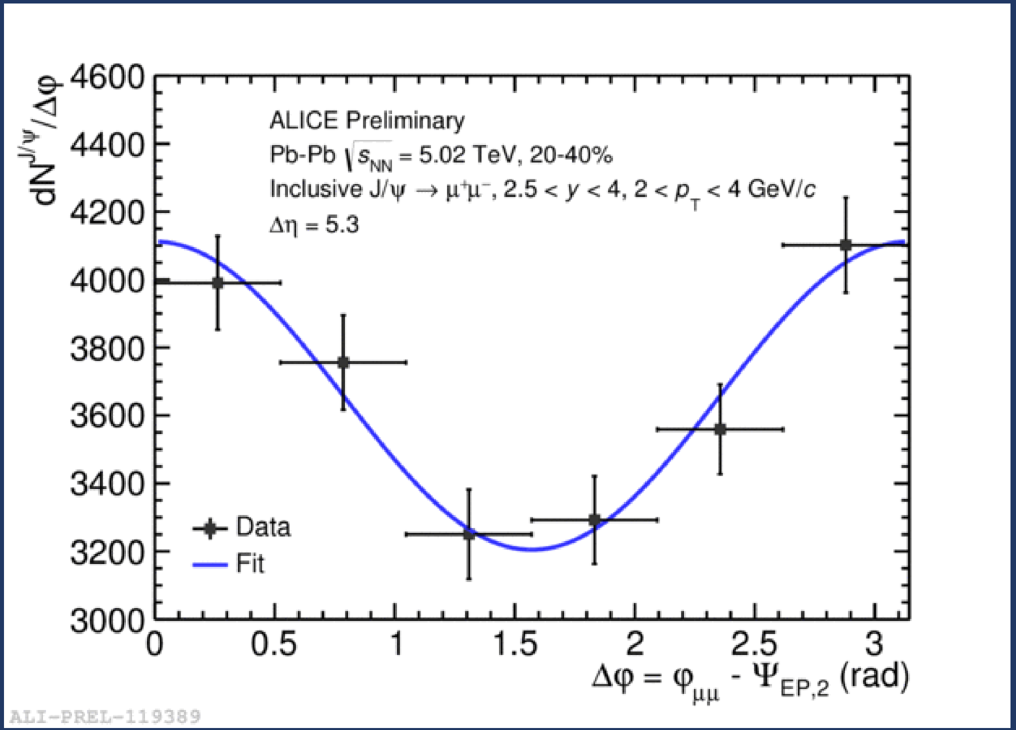
J/ψ, p-Pb

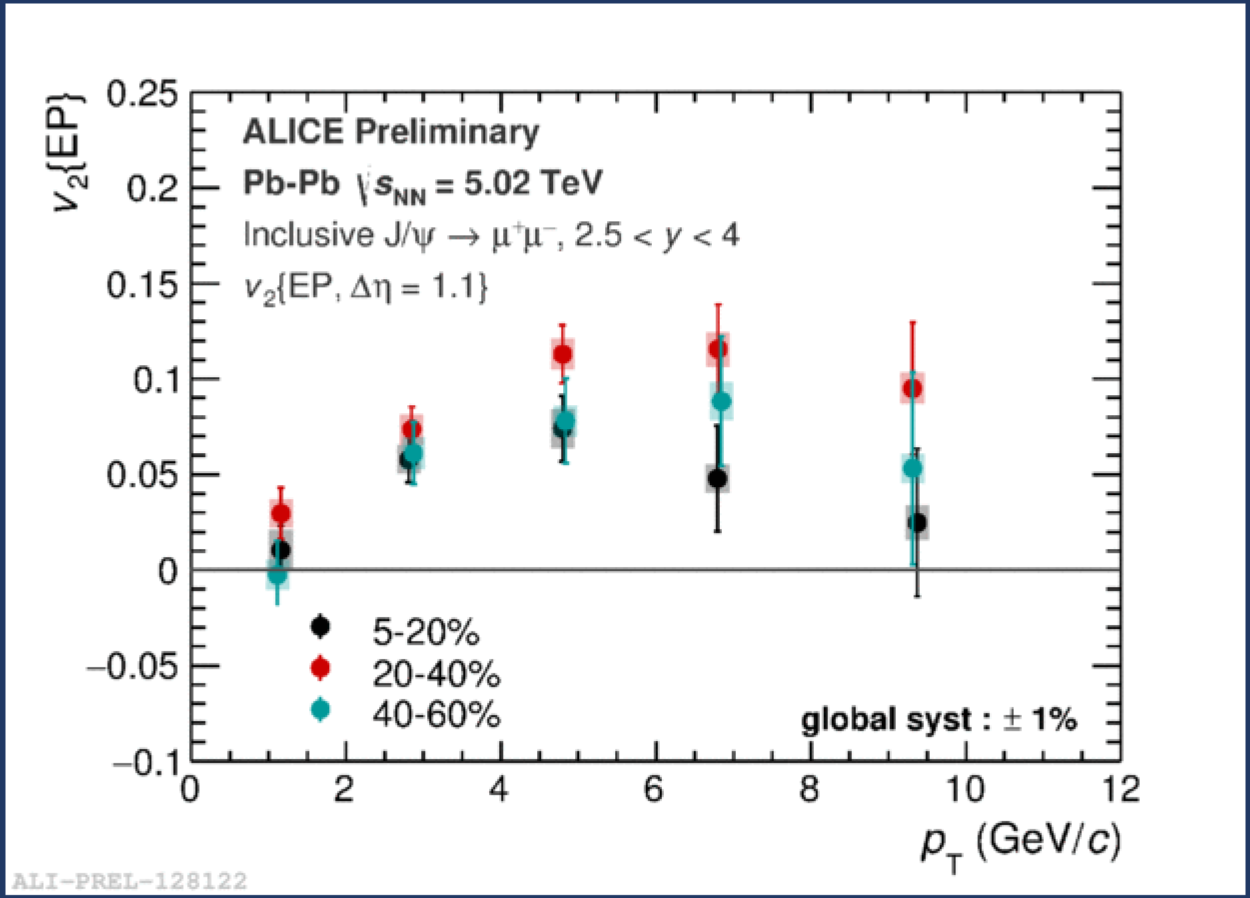


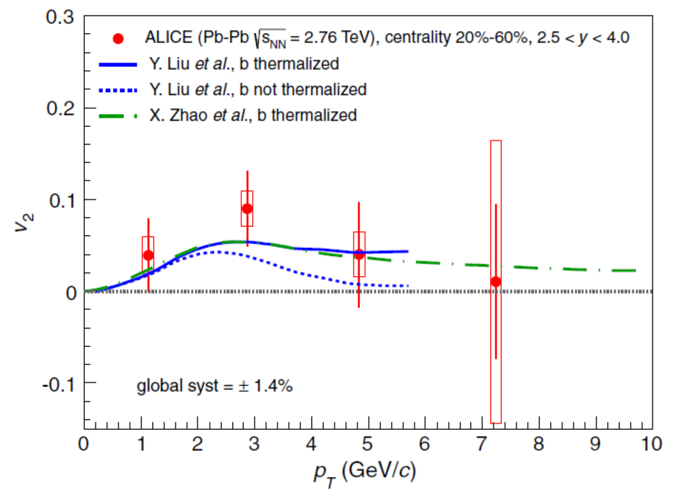
J/ψ, Pb-p



v2

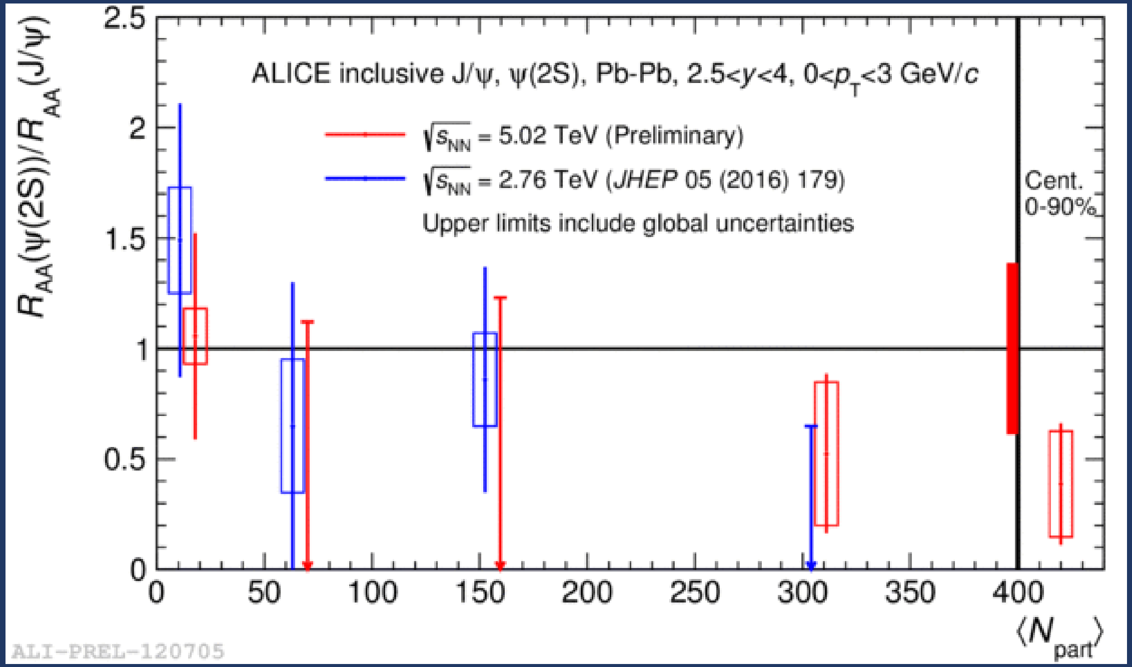


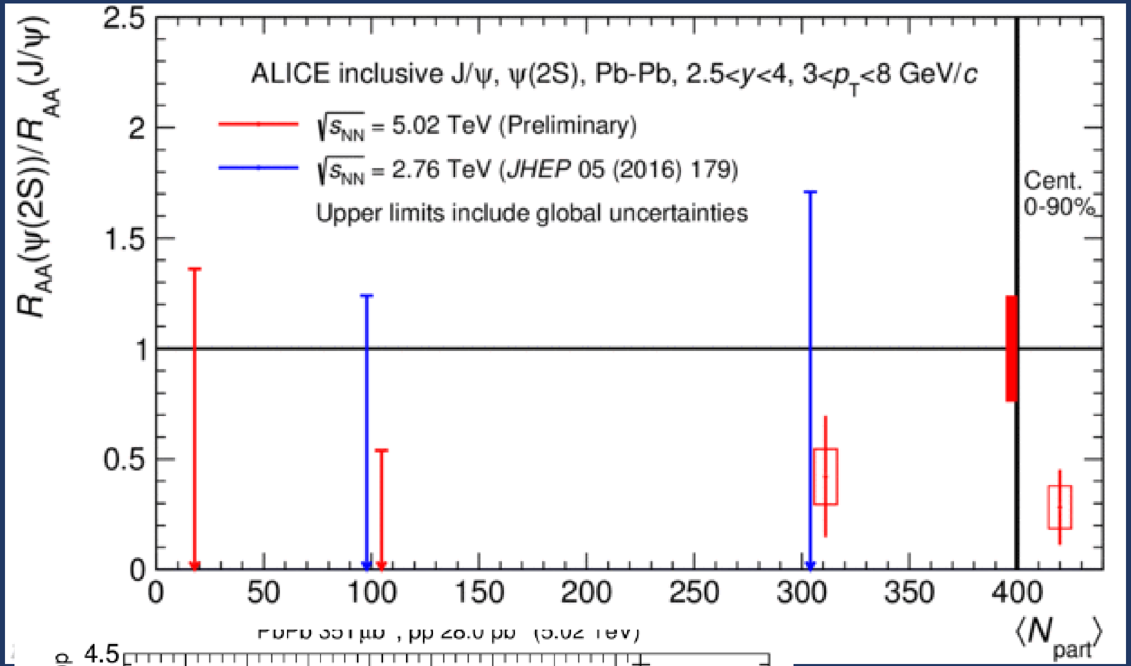


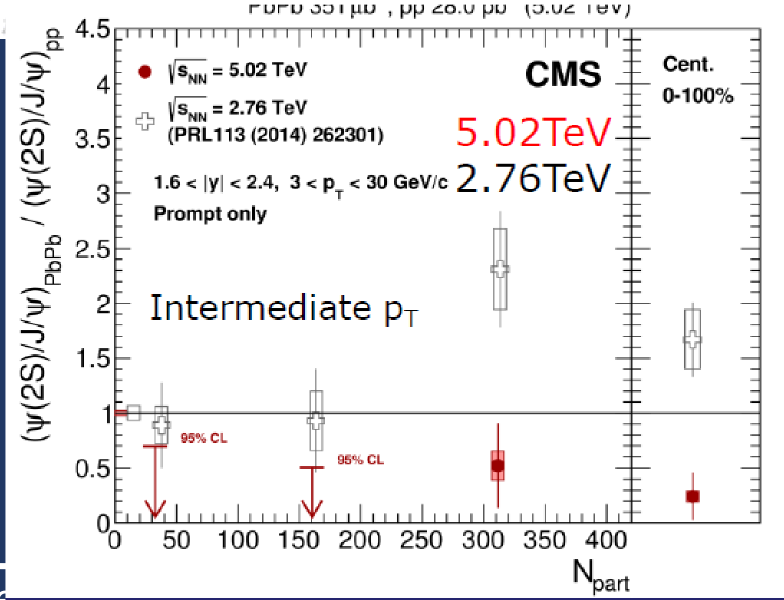


Maximum effect in semi-central collisions

ψ(2S): comparison with Run 1

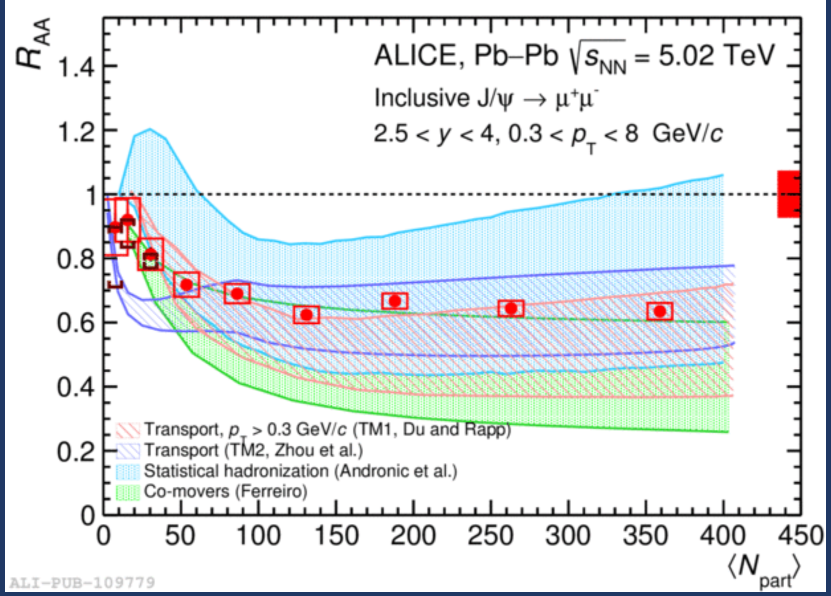


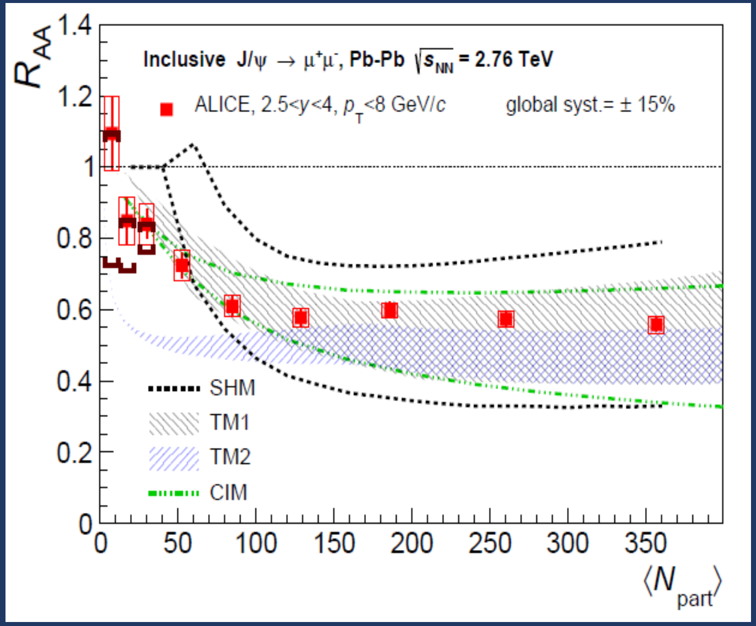




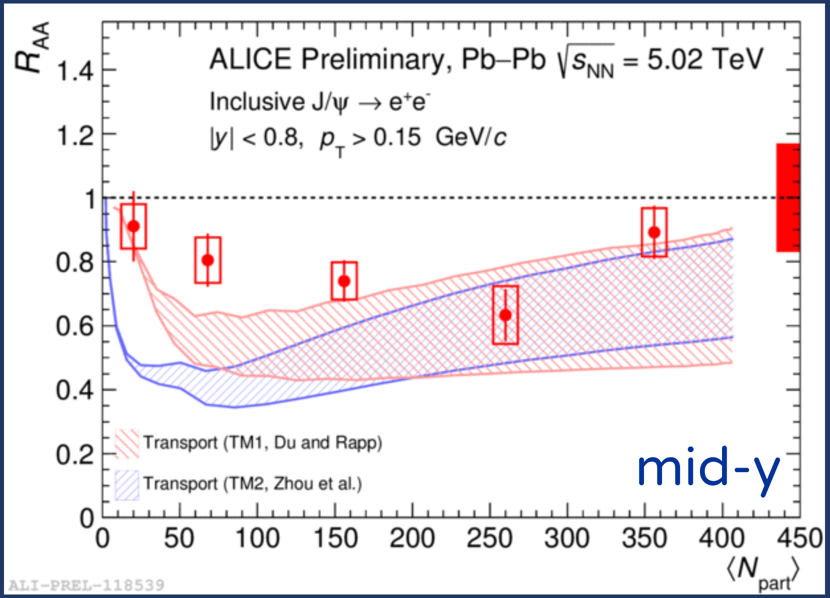
Comparison with theory models

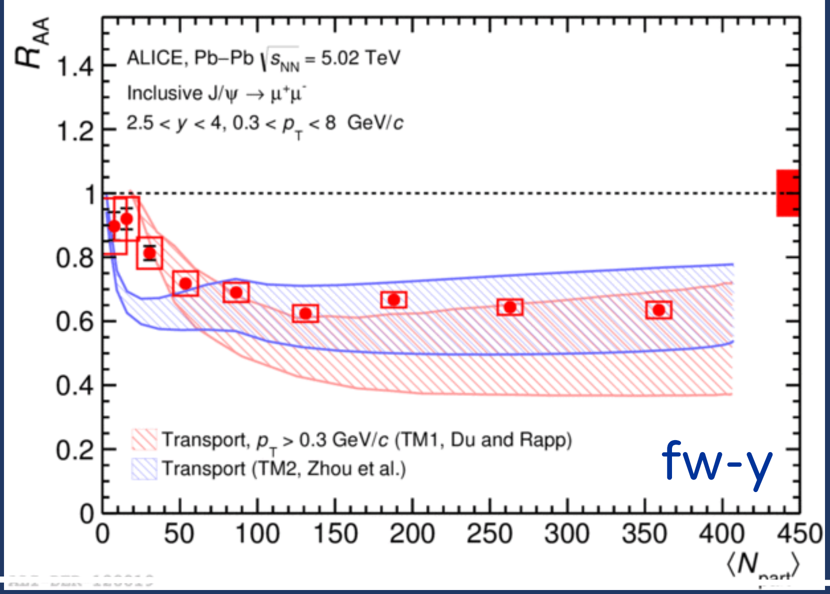
- All theory models fairly describe the data
- but still large uncertainties associated to charm cross section and shadowing





Comparison with theory models





Transport models

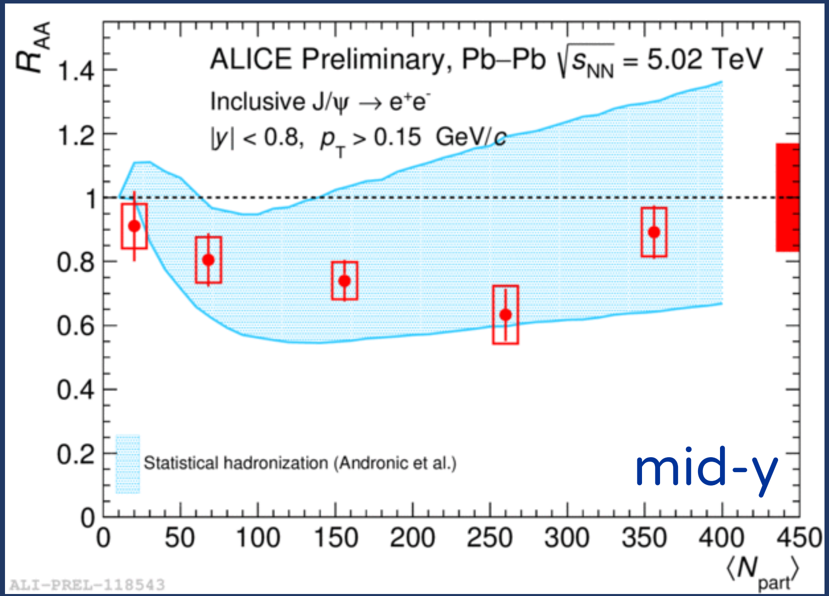
- Based on thermal rate equations including continuous dissociation and regeneration of the J/ψ in QGP and hadronic phase
- σ_{cc} consistent witn FONLL

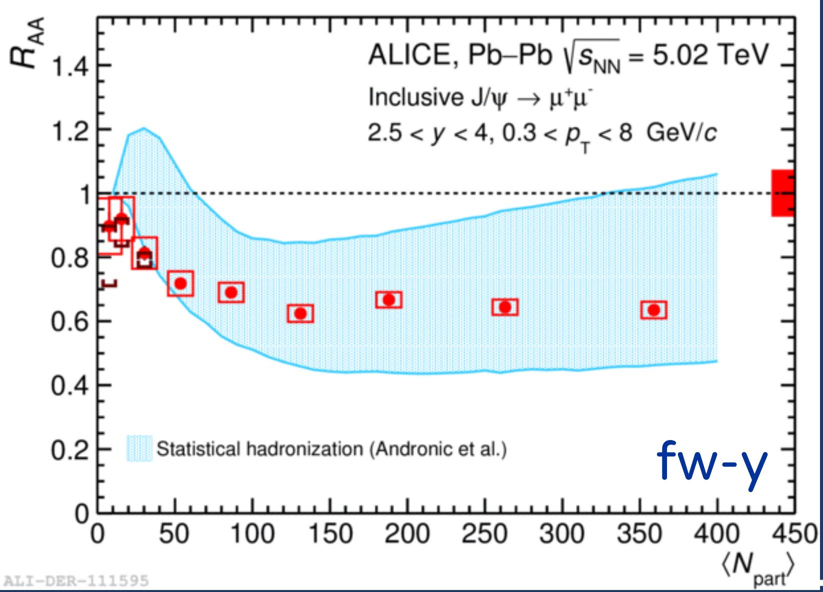
X. Zhao, R. Rapp NPA 859 (2011) 114
K. Zhou et al, PRC 89 (2011) 05491

Model	$d\sigma_{cc}/dy$ [mb] fw-y	shadowing
Transport, TM1	0.57	EPS09
Transport, TM2	0.82	EPS09

Model	σ_{cc}(mb)	Shadowing
TM1	0.72 +-0.13	EPS09 NLO
TM2	0.86+-0.085	EPS09 NLO
SHM	0.448 ± 0.169	EPS09 NLO
Co-movers	0.555±0.105	Glauber-Gribov theory

Comparison with theory models





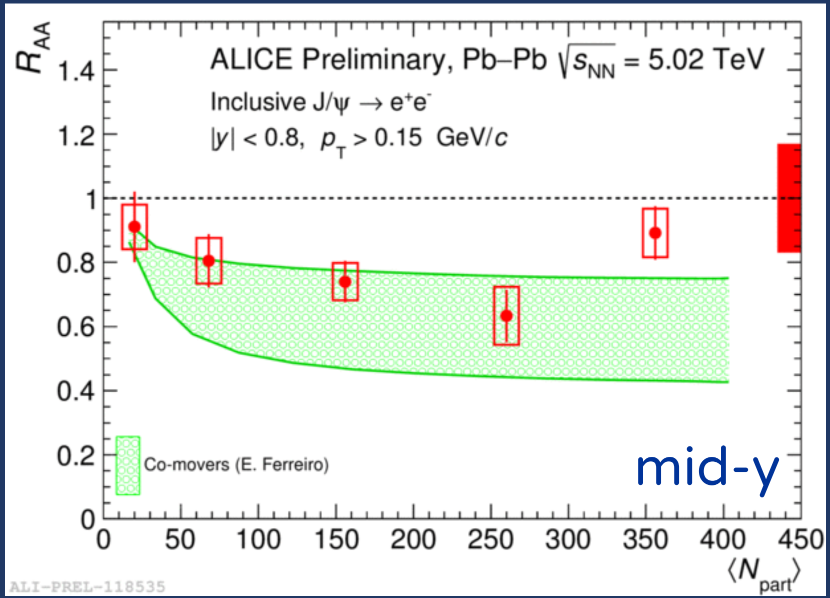
Statistical hadronization

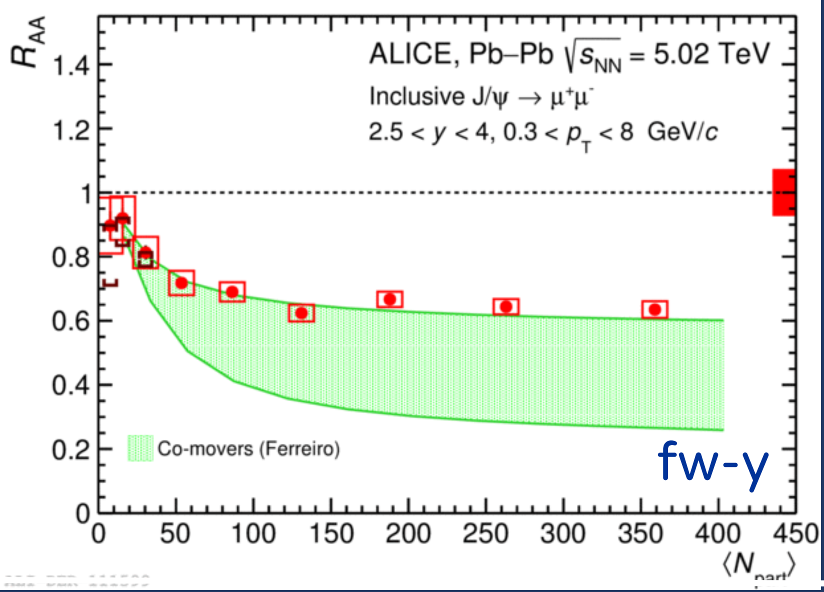
- J/ψ produced at chemical freeze-out according to their statistical weight
- σ_{cc} from LHCb pp measurement at $\sqrt{s}$ = 7 TeV + FONLL

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

Model	$d\sigma_{cc}/dy$ [mb]	shadowing
Transport, TM1	0.57	EPS09
Transport, TM2	0.82	EPS09
Stat. Hadroniz.	0.45	EPS09

Comparison with theory models





Comover model

- J/ψ are dissociated via interactions with partons/hadrons in the same *y*-range + regeneration contribution
- $\sigma_{J/\psi\text{-comovers}}$ = 0.65 mb (from lower energy results)

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

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