Recent results on quarkonia in AA collisions from ALICE at the LHC

Antoine Lardeux

University of Oslo

On behalf of the ALICE collaboration

ICNFP - Crete

July 9, 2018

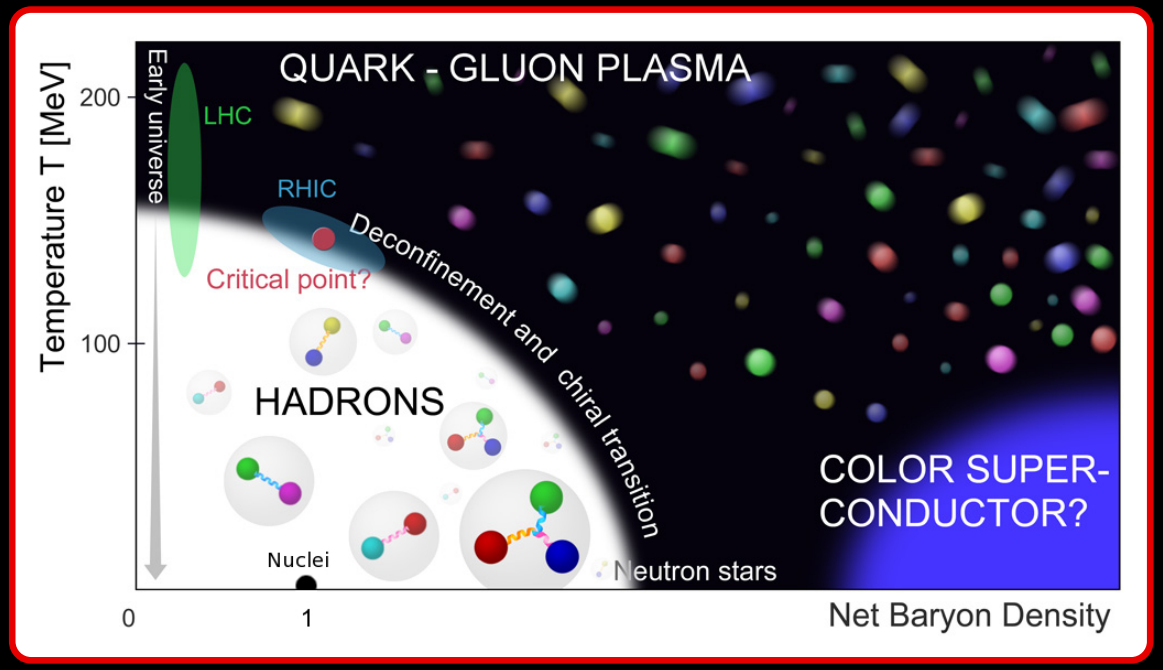
Quark Gluon Plasma

What? **Quark-gluon plasma:** state of nuclear matter for which degrees of freedom are carried by quarks and gluons, as opposed to hadrons (confinement)

Why? To study the nuclear matter properties at high pressure and temperature

How? Lattice QCD computations predict a phase transition at $T_c = 155 \pm 9$ MeV
[JHEP 09 (2010) 073, PRD 90 (2014) 094503]

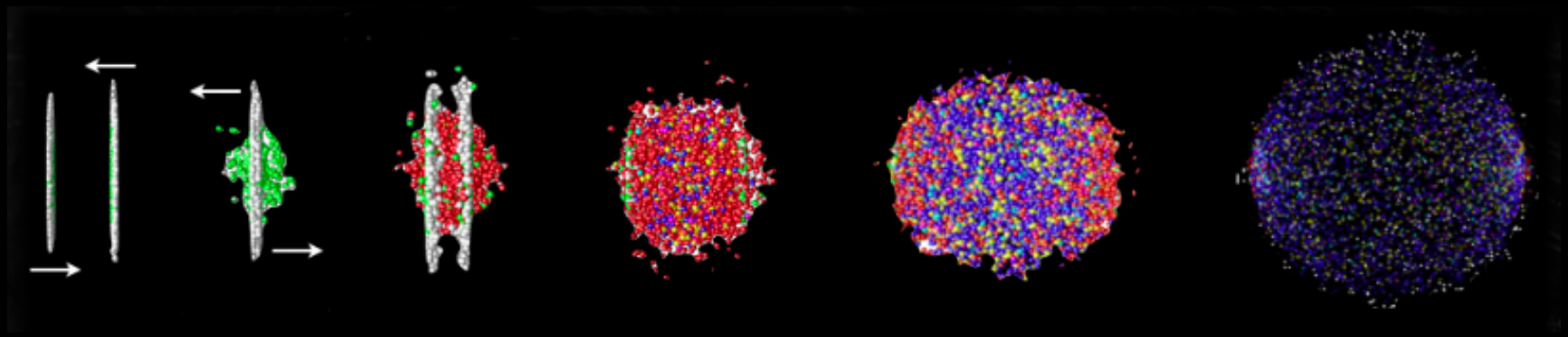
QGP should be created in heavy-ion collisions provided that energy density is large enough (> 1 GeV/fm $^3 \sim 6\times$ nuclear density)



Collision systems:

- **pp** used as reference (no QGP expected)
- **pA** Cold nuclear effects (nuclear medium)
- **A–A** Hot nuclear effects (QGP) + Cold nuclear effects

Time evolution of heavy-ion collision



Pre-equilibrium Hard process (pQCD) | **QGP?** | Hadronisation | Chemical freeze out | Kinematic freeze out

Probe? Quarkonia: meson bound states formed of a pair of heavy quark + anti-quark

Why? Heavy-quark pairs are produced in the initial hard-partonic collisions (pre-equilibrium)
$\rightarrow$ Quarkonia are sensitive to the full evolution of the system and interact with the QGP

How? By measuring the quarkonium production in pp, pA and A–A collision systems
Observables: Nuclear modification factor (R_{AA}), elliptic flow (v_2), etc

Quarkonium states are expected to provide information on deconfinement and the QGP properties

Outline

1. Quarkonium measurements with ALICE
2. pp collisions: reference production
3. pA collisions: cold nuclear matter effects
4. A–A collisions: QGP study

Outline

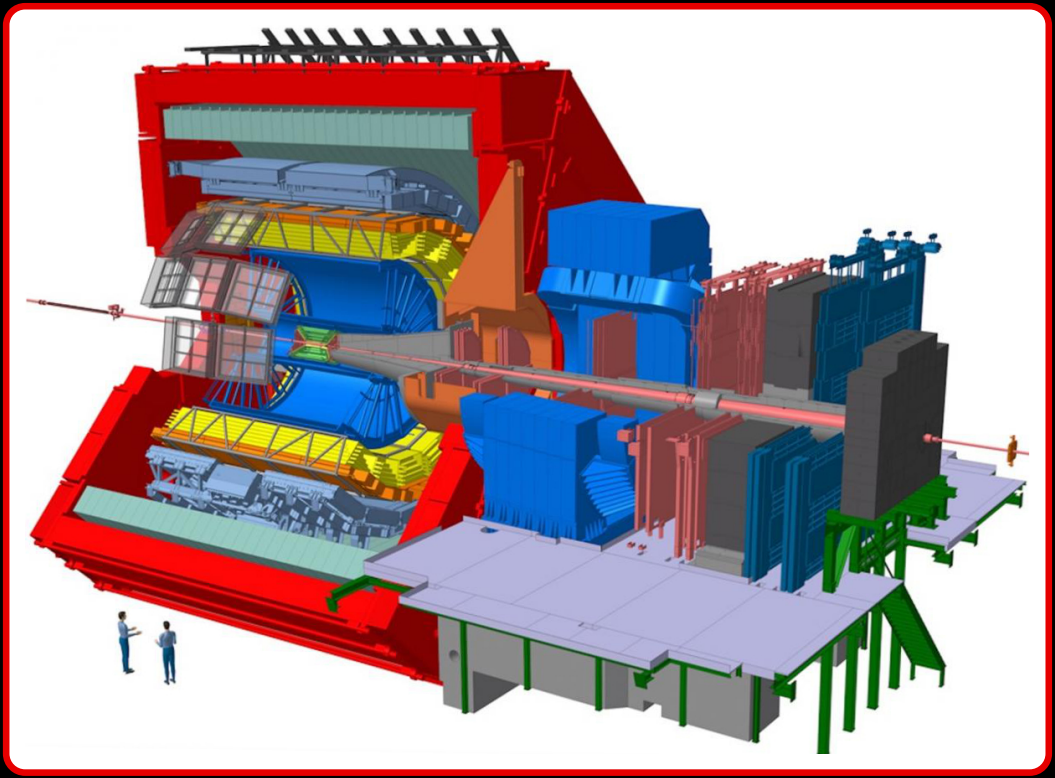
1. **Quarkonium measurements with ALICE**
2. **pp collisions: reference production**
3. **pA collisions: cold nuclear matter effects**
4. **A–A collisions: QGP study**

ALICE apparatus

Quarkonia measured down to zero p_{T} via the reconstruction of their leptonic decay products:

- **Mid-rapidity: $|y| < 0.9$**
  - dielectron decay channel
  - ITS, TPC, TOF, TRD: vertexing, tracking, PID, trigger
- **Forward-rapidity: $2.5 < y < 4$**
  - dimuon decay channel
  - Muon spectrometer: tracking, trigger

V0, T0 and ZDC provide: MB trigger, centrality, event plane, luminosity



Run-1 (2009-2013)

Pb–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 2.76$ TeV
p–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 5.02$ TeV
pp	$\sqrt{s}$	$= 0.9,\ 2.76,\ 7,\ 8$ TeV

Run-2 (since 2015)

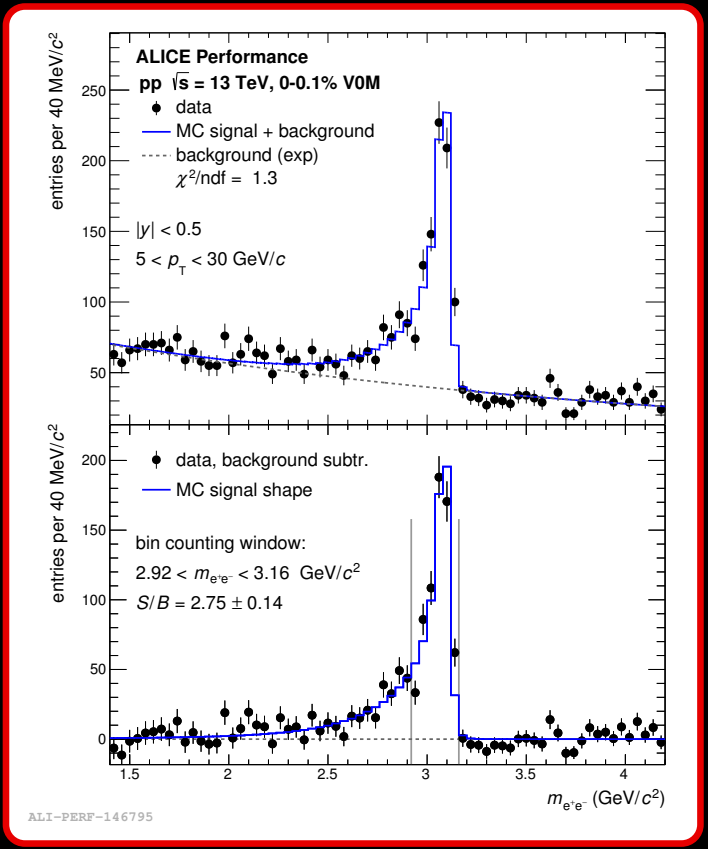
Pb–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 5.02$ TeV
p–Pb	$\sqrt{s_{\mathrm{NN}}}$	$= 5.02,\ 8.16$ TeV
pp	$\sqrt{s}$	$= 5,\ 13$ TeV

Signal extraction

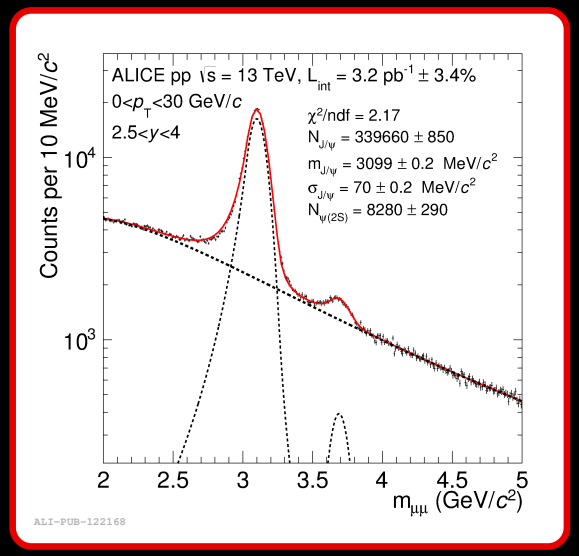
[Eur. Phys. J. C 77 (2017) 392], [Eur. Phys. J. C 74 (2014) no.8, 2974]

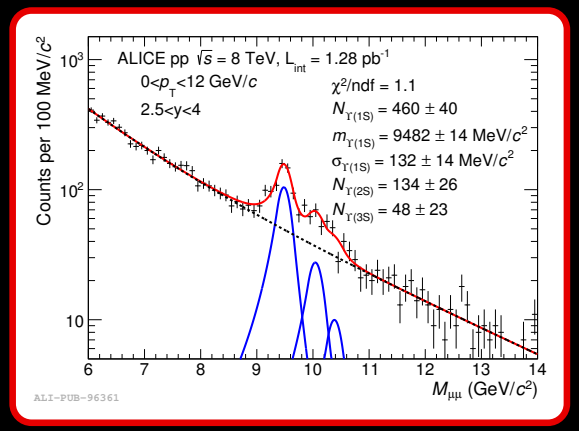
Quarkonium yields are extracted by fitting the dilepton invariant mass distribution or counting technique

$|y| < 0.9$ - dielectrons



$2.5 < y < 4$ - dimuons





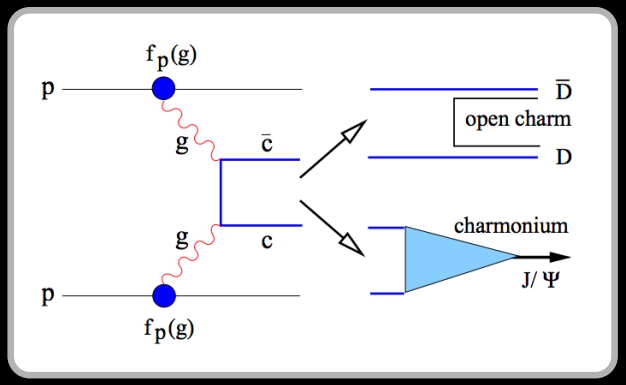
Outline

1. Quarkonium measurements with ALICE
2. pp collisions: reference production
3. pA collisions: cold nuclear matter effects
4. A–A collisions: QGP study

pp collisions: reference production (charm illustration)

[Eur. Phys. J C76 (2016) no.3, 107]

pp collisions: small energy density $\longrightarrow$ no QGP expected $\longrightarrow$ test bench for QCD



- Heavy quarks produce in hard-scattering process (pQCD applicable)
  $\rightarrow$ gluon fusion dominant at LHC energies, sensitive to gluon PDFs
- Non-perturbative evolution into color neutral bound states
  - $\sim 90\%$ open charm
  - $\sim 10\%$ charmonia

Models for the quarkonium production mechanisms:

- Color Evaporation Model (CEM) [Phys. Rev. D 12 (1975) 2007]
- Color Singlet Model (CSM) [Phys. Lett. B 67 (1977) 217]
- Non-Relativistic QCD (NRQCD) [Phys. Rev. D 51 (1995) 1125]

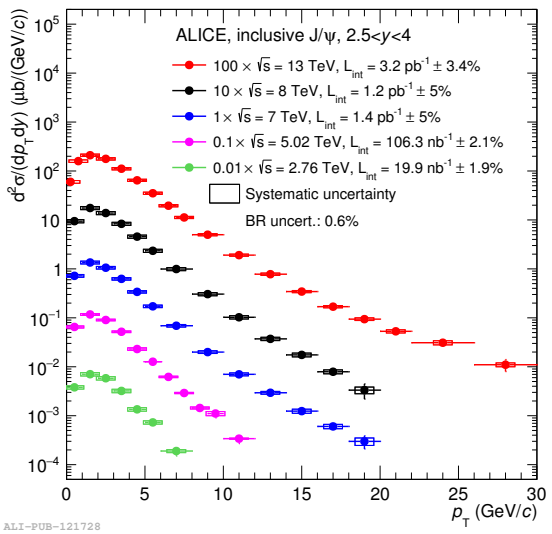
quarkonium cross sections measured in pp collisions as baseline to quantify the nuclear matter effects

Basically, the ideal reference is the total charm cross section
(nuclear medium could modify the fraction of produced $c\bar{c}$ pairs going into charmonium formation)
$\rightarrow$ Run-3: ALICE will measure the open charm component down to zero p_T

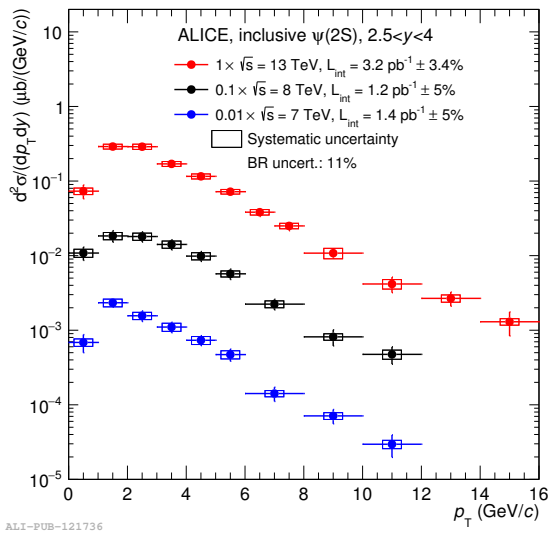
Quarkonium production cross sections

[Eur. Phys. J. C 77 (2017) 392], [Eur. Phys. J. C 76 (2016) 184]

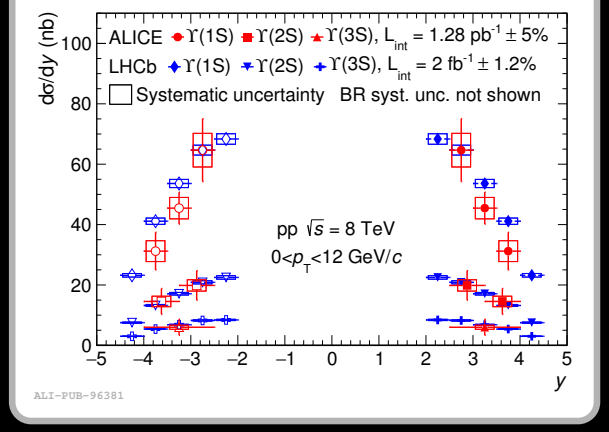
J/ψ



ψ(2S)



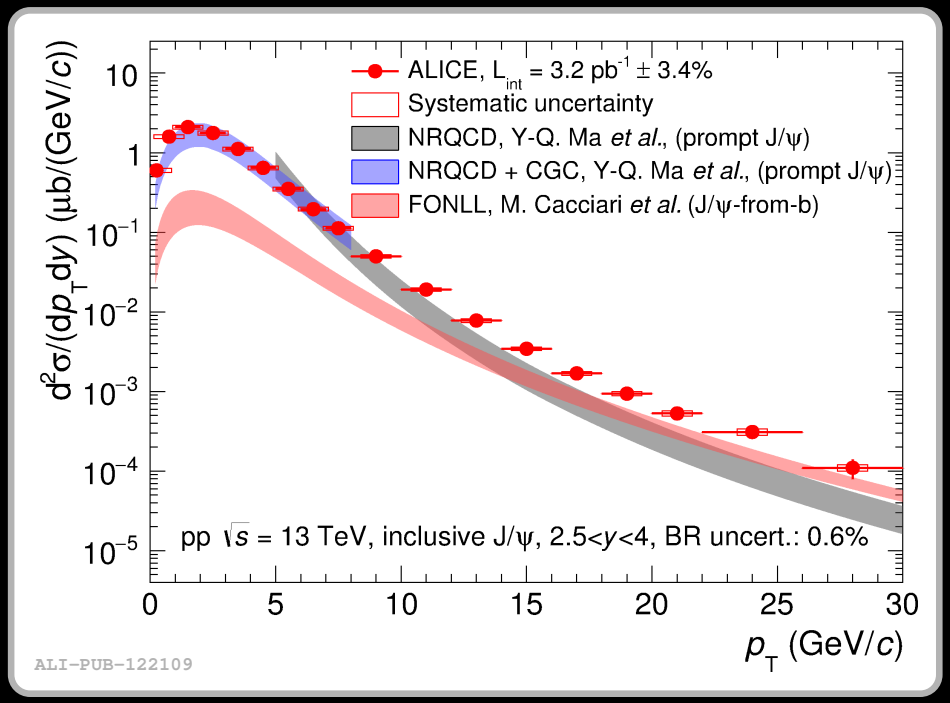
ϒ



- **J/ψ production has been measured at all available LHC energies**
- Spectra become harder with increasing energy
  $\rightarrow$ onset of the non-prompt J/ψ contribution
- Slope changes at high p_{T} and $\sqrt{s} = 13$ TeV

Model comparisons

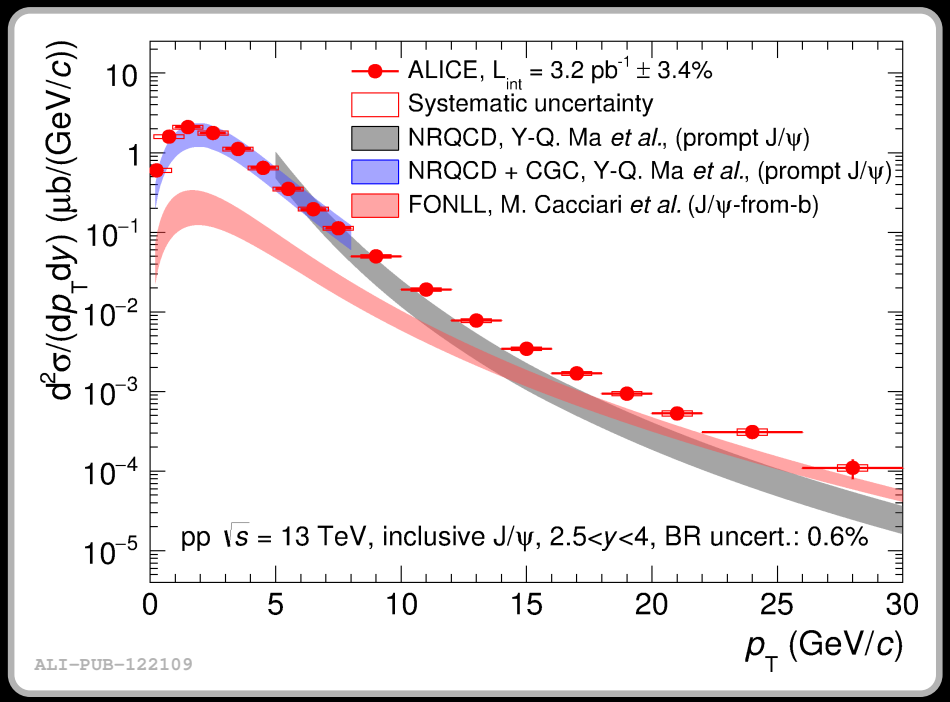
[Eur. Phys. J. C 77 (2017) 392]

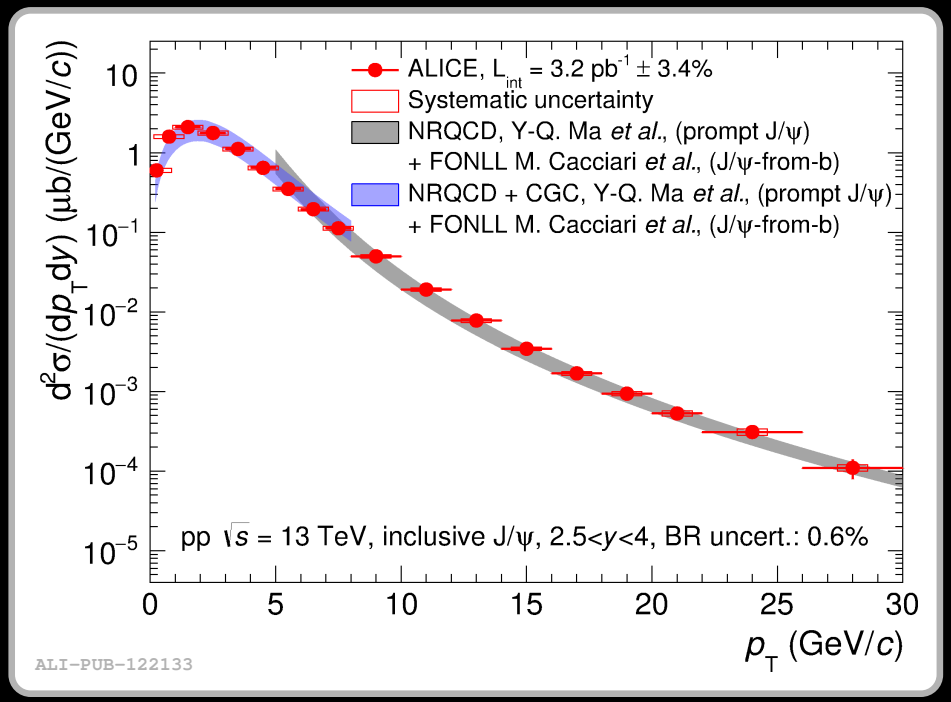


NRQCD: [PRL, 106 (2011) 042002]
NRQCD+CGC: [PRL, 113 (2014) 192301]
FONLL: [JHEP, 1210 (2012) 137]

Model comparisons

[Eur. Phys. J. C 77 (2017) 392]





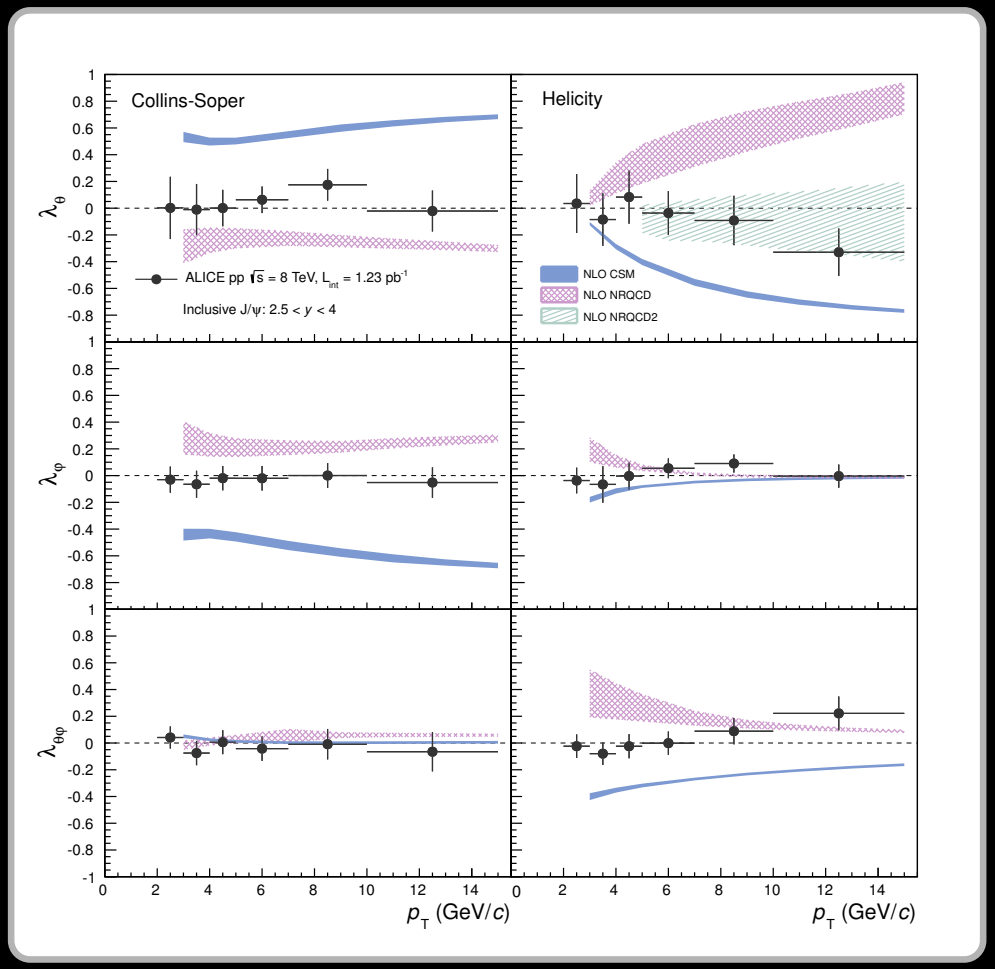
NRQCD: [PRL, 106 (2011) 042002]
NRQCD+CGC: [PRL, 113 (2014) 192301]
FONLL: [JHEP, 1210 (2012) 137]

Sum of the prompt (NRQCD) and the non-prompt (FONLL) contributions assuming fully uncorrelated uncertainties.

Charmonium cross sections well described by QCD-based models over the full p_T range

Inclusive J/ψ polarization at forward rapidity

[arXiv:1805.04374]



Polarization determined from angular distribution of muons in both Collins-Soper and Helicity frames:

$$W(cos\theta, \varphi) \propto \frac{1}{3+\lambda_\theta}\,[1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos(2\varphi) + \lambda_{\theta\varphi} \sin(2\theta) \cos\varphi]$$

No polarization of inclusive J/ψ within uncertainties

Tension between models and experimental results

NLO CSM: [PRL, 108 (2012) 172002]
NLO NRQCD: [PRL, 108 (2012) 172002]
NLO NRQCD2: [PRL, 108 (2012) 242004]

Outline

1. Quarkonium measurements with ALICE
2. pp collisions: reference production
3. pA collisions: cold nuclear matter effects
4. A–A collisions: QGP study

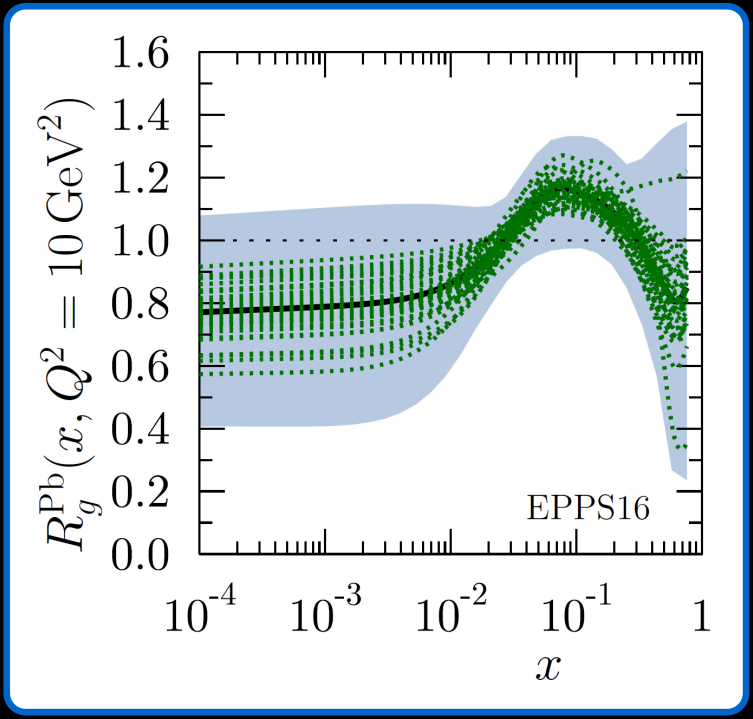
pA collisions: cold nuclear matter effects

[Eur. Phys. J C76 (2016) no.3, 107, Eur. Phys. J. C 77 (2017) no.3, 163]

pA collisions: Quantify the cold nuclear matter effects

Different mechanisms:

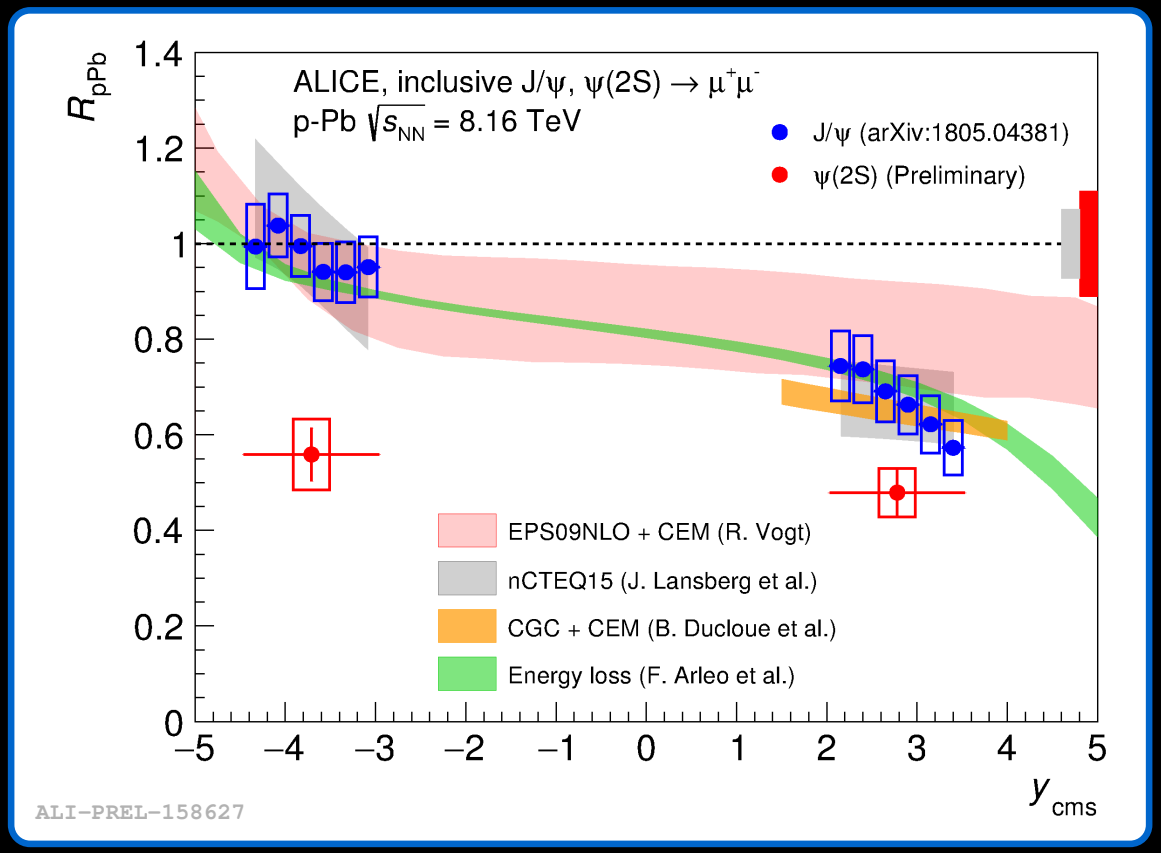
- Shadowing [Eur. Phys. J. C 77 (2017) no.3, 163]
  Saturation (CGC) [Nucl. Phys. 1924 (2014)]
- Energy loss (initial/final state, or coherent)
  [PRL 109 (2012) 122301]
- Nuclear absorption (negligible at LHC)
  [Nucl. Phys. A 700 (2002) 539]
- Comovers absorption [PLB 749 (2015) 98]



Open question: is the energy density large enough yet for QGP formation?

J/ψ and ψ(2S) R_{pPb}

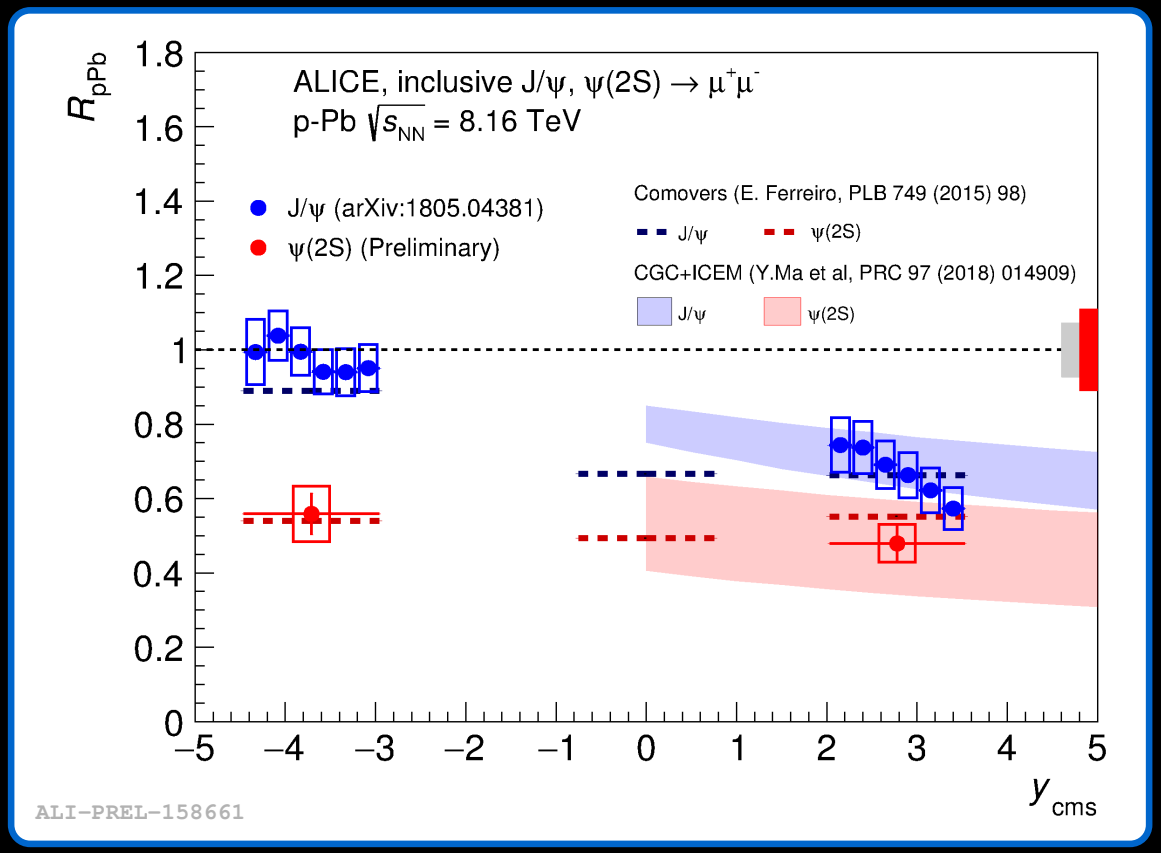
[arXiv:1805.04381]



- J/ψ suppression at forward rapidity, R_{pPb} compatible with unity at backward rapidity
- Models based on different shadowing implementations, CGC and energy loss fairly describe the J/ψ data
- Stronger ψ(2S) suppression than the J/ψ one, especially at backward rapidity
- Theoretical predictions based on shadowing and energy loss cannot describe the ψ(2S) data

J/ψ and ψ(2S) R_{pPb}

[arXiv:1805.04381]

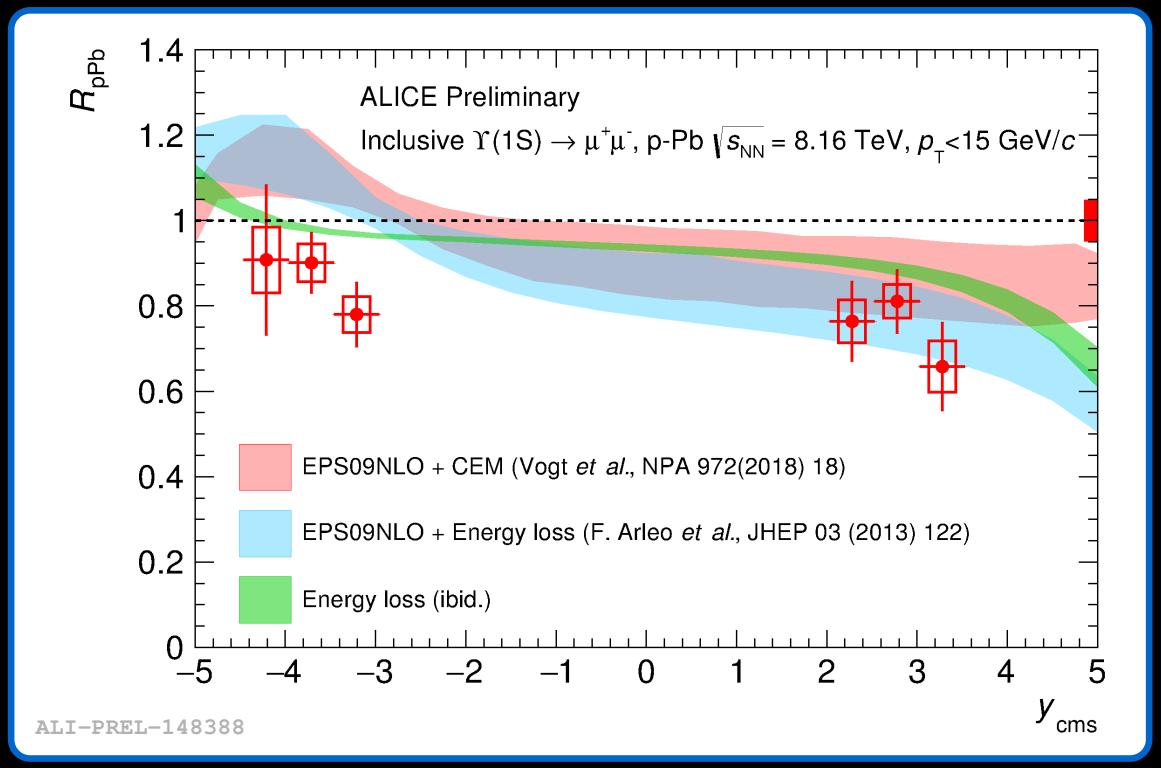


- J/ψ suppression at forward rapidity, R_{pPb} compatible with unity at backward rapidity
- Models based on different shadowing implementations, CGC and energy loss fairly describe the J/ψ data
- Stronger ψ(2S) suppression than the J/ψ one, especially at backward rapidity
- Theoretical predictions based on shadowing and energy loss cannot describe the ψ(2S) data
- Comovers model including final-state effects reproduces the data also at backward rapidity

Final-state effects needed to explain the ψ(2S) behaviour
(quarkonium formation time longer than crossing time)

Υ R_{pPb}

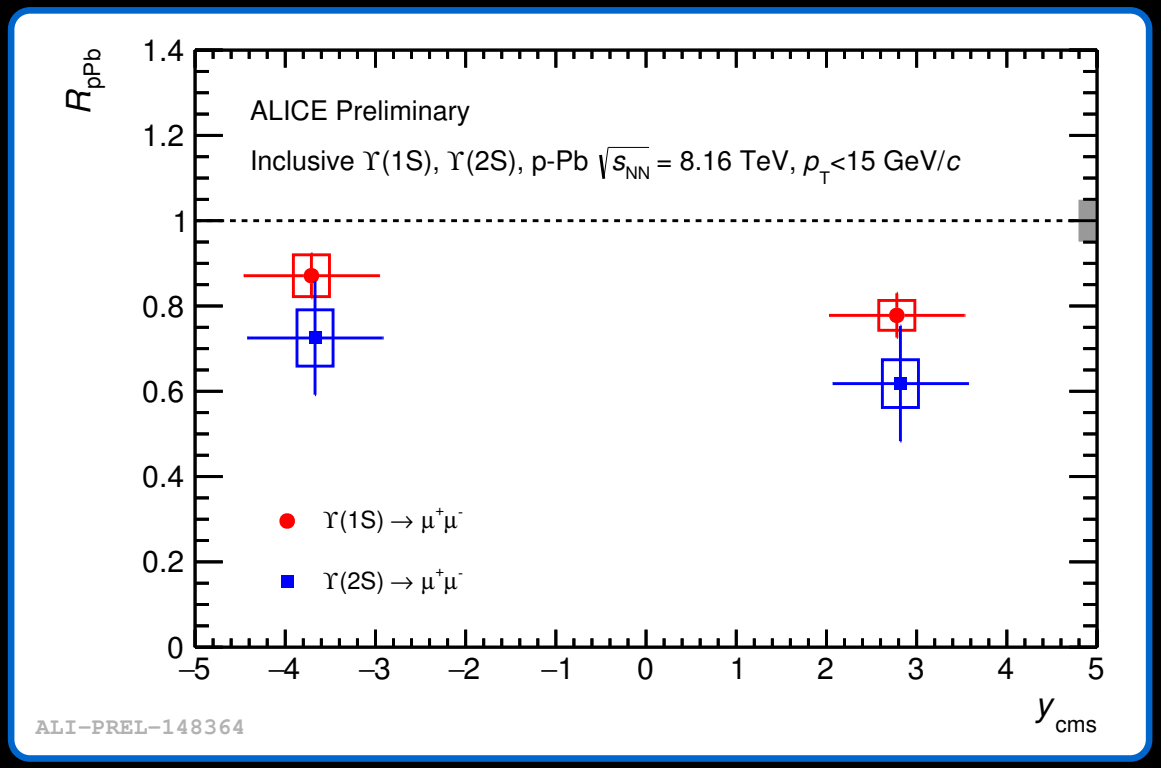
[ALICE-PUBLIC-2018-008]



- Similar Υ(1S) suppression at forward and backward rapidity
- Models based on shadowing and/or energy loss reproduce the forward rapidity data but slightly overestimate the backward rapidity data

Υ R_{pPb}

[ALICE-PUBLIC-2018-008]



- Similar Υ(1S) suppression at forward and backward rapidity
- Models based on shadowing and/or energy loss reproduce the forward rapidity data but slightly overestimate the backward rapidity data
- Υ(2S) suppression consistent with the Υ(1S) suppresion with a hint for a stronger suppression of Υ(2S) (as observed by CMS and ATLAS at mid-y)

Similar CNM effects for Υ at backward and forward rapidity

Outline

1. Quarkonium measurements with ALICE
2. pp collisions: reference production
3. pA collisions: cold nuclear matter effects
4. A–A collisions: QGP study

AA collisions: QGP study

[Eur. Phys. J C76 (2016) no.3, 107]

Pb–Pb collisions: Quantify the hot nuclear matter effects from the QGP and extract its properties

Different mechanisms for quarkonia:

- Dissociation via an effective screening of the inter-quark force induced by the high density of color charges in the QGP
  - Different binding energy of quarkonium states $\rightarrow$ sequential suppression?
  - This could provide a measurement of the QGP temperature ...

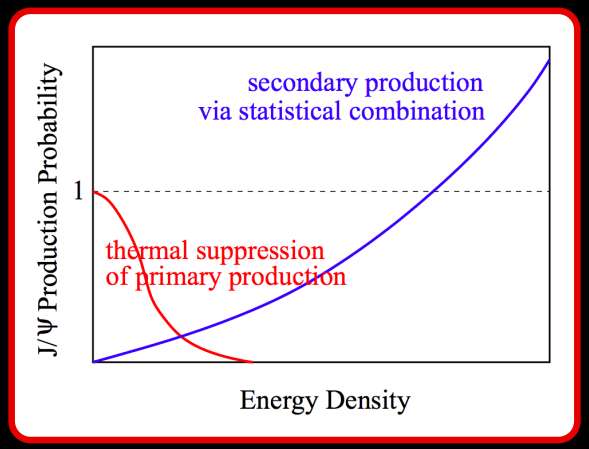
AA collisions: QGP study

[Eur. Phys. J C76 (2016) no.3, 107]

Pb–Pb collisions: Quantify the hot nuclear matter effects from the QGP and extract its properties

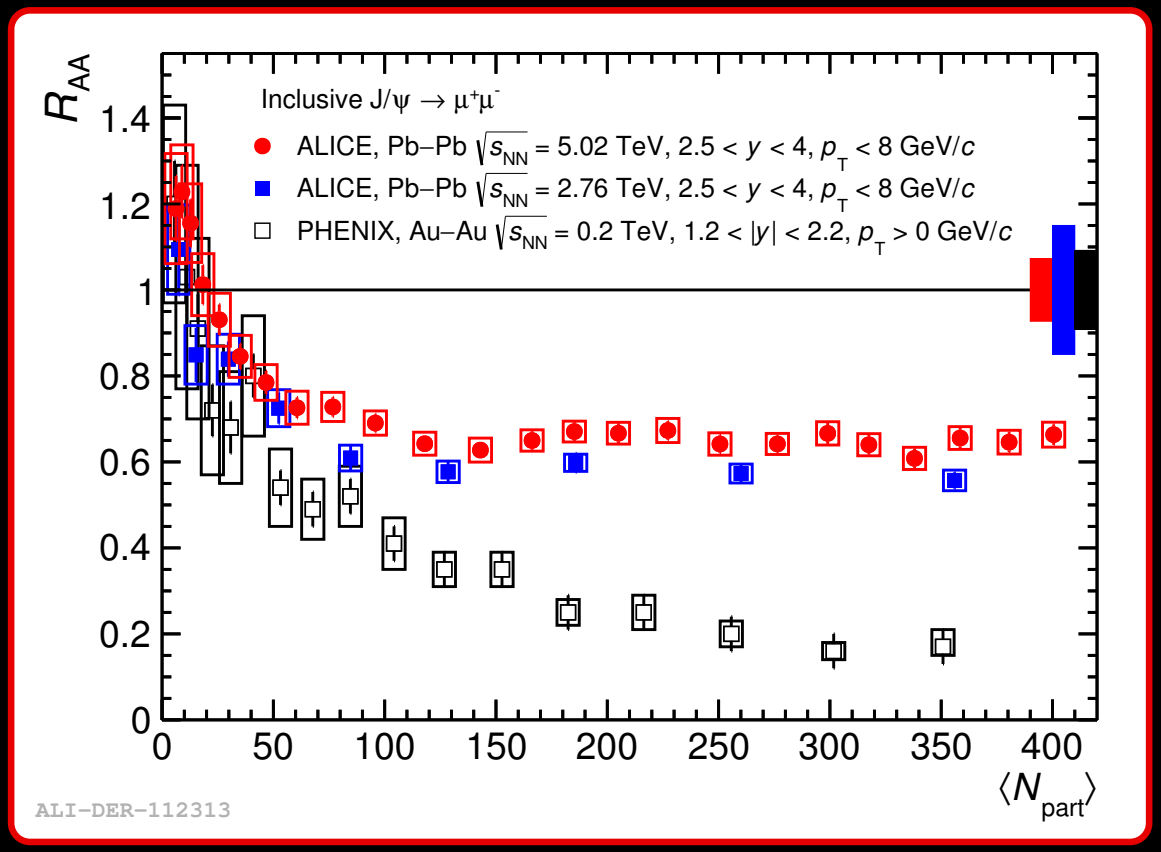
Different mechanisms for quarkonia:

- Dissociation via an effective screening of the inter-quark force induced by the high density of color charges in the QGP
  - Different binding energy of quarkonium states $\rightarrow$ sequential suppression?
  - This could provide a measurement of the QGP temperature ...
- Enhancement via the recombination of uncorrelated Q and $\bar{Q}$ quarks present in the medium
  - (Re)generation should decrease with increasing rapidity
  - (Re)generated quarkonia should be concentrated at low transverse momentum



J/ψ R_{AA} *v.s.* centrality

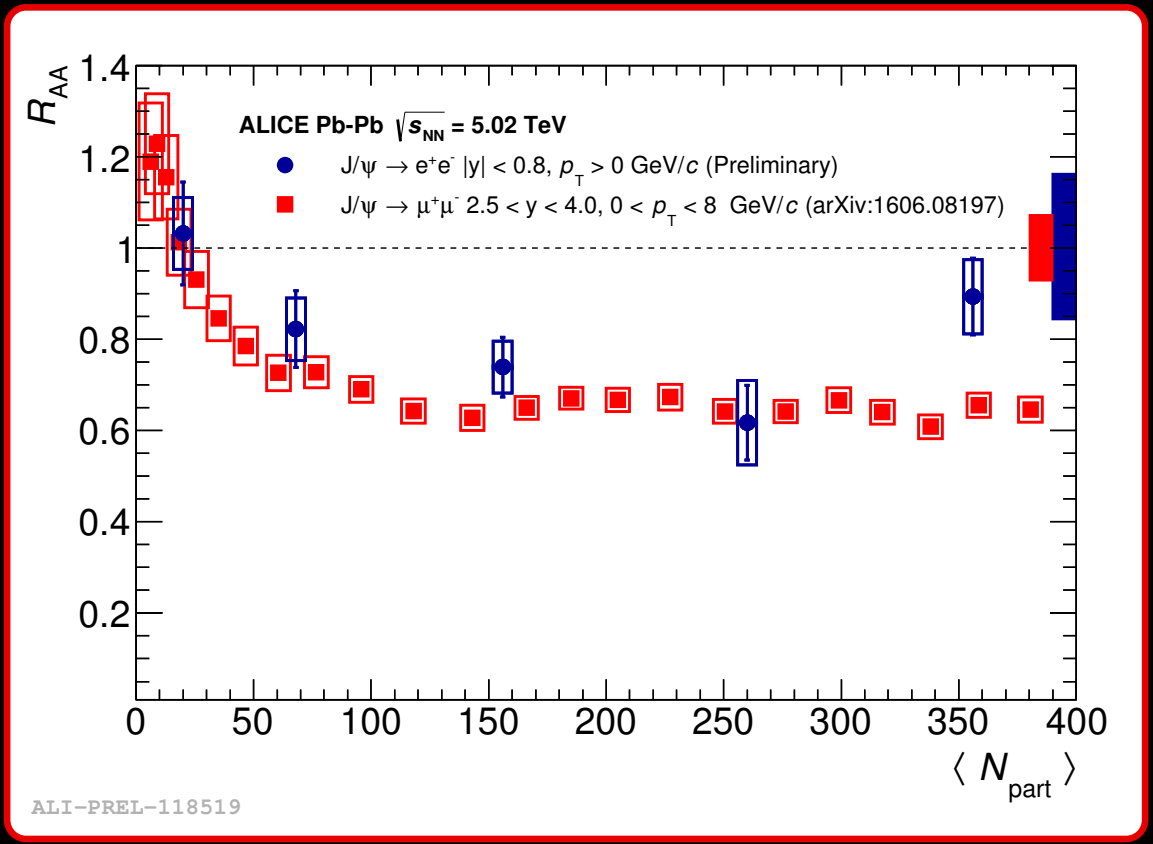
[PLB 766 (2017) 212]



- Smaller suppression at higher energy for the most central collisions

J/ψ R_{AA} *v.s.* centrality

[PLB 766 (2017) 212]

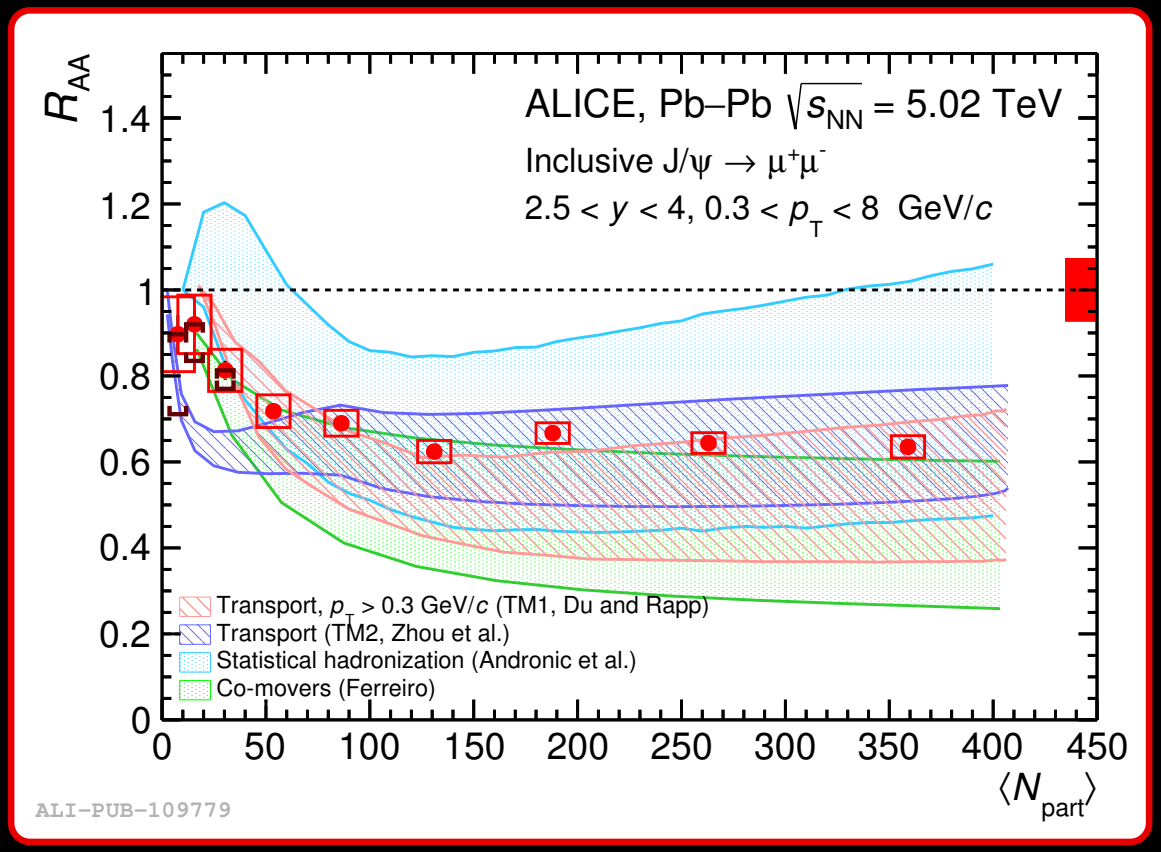


- Smaller suppression at higher energy for the most central collisions
- Indication for smaller suppression at mid-rapidity with respect to forward rapidity

In agreement with (re)generation scenario

J/ψ R_{AA} *v.s.* centrality

[PLB 766 (2017) 212]



- Smaller suppression at higher energy for the most central collisions
- Indication for smaller suppression at mid-rapidity with respect to forward rapidity

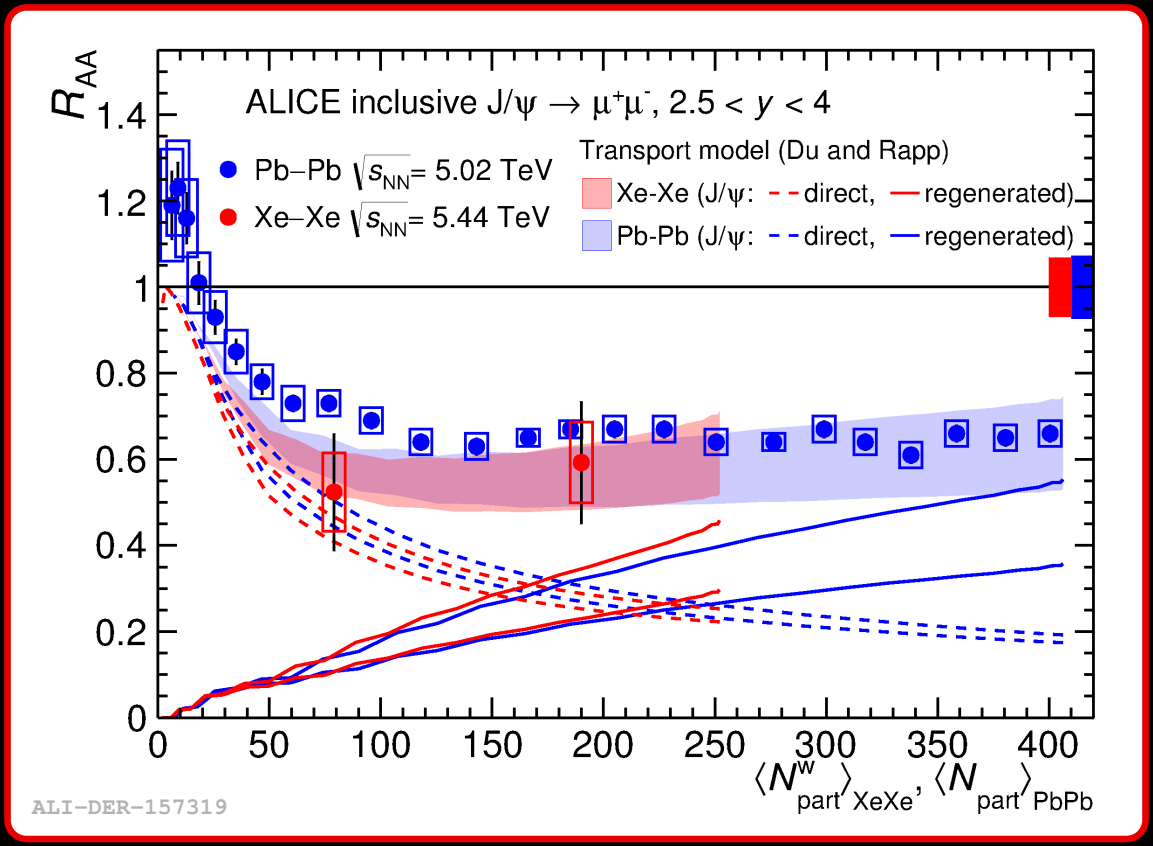
In agreement with (re)generation scenario

- All the models including a (re)generation component reproduce the data for the most central collisions,

  Large uncertainties mostly from $\sigma_{c\bar{c}}$ and CNM effects

J/ψ R_{AA} *v.s.* centrality

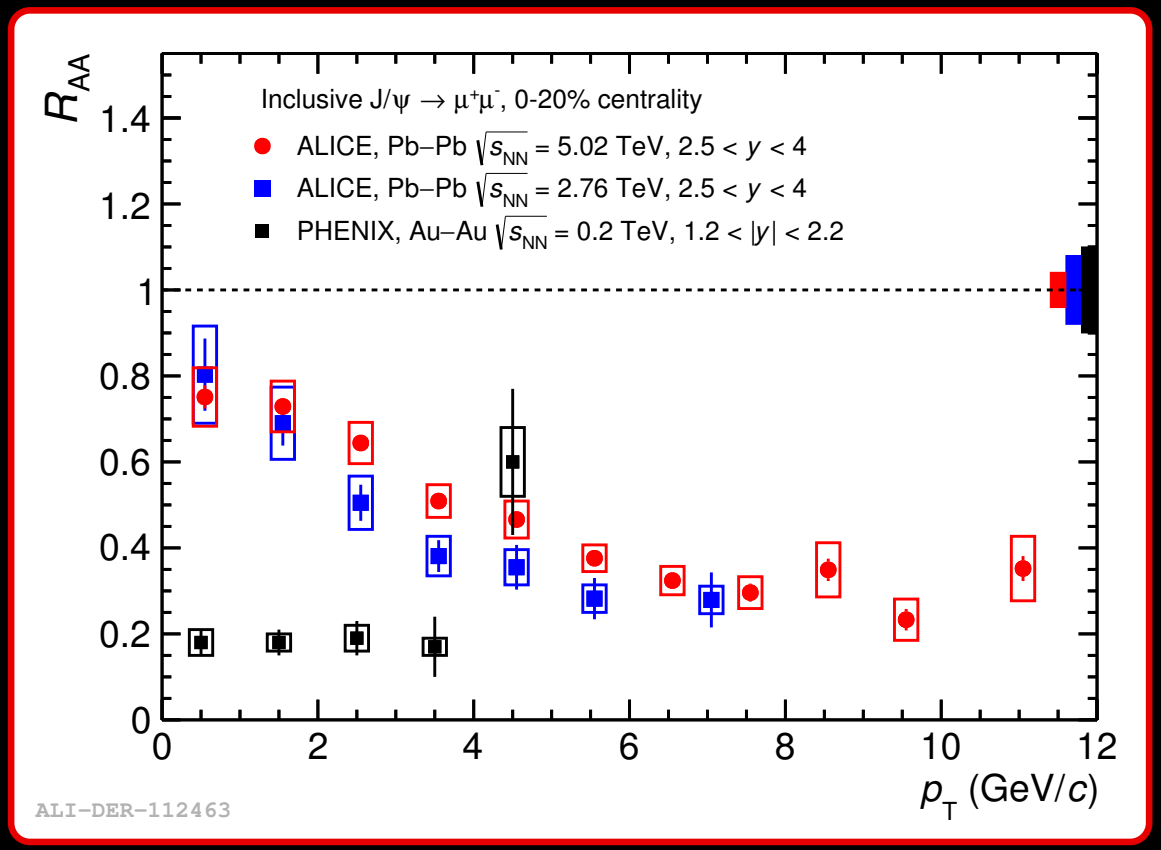
[arXiv:1805.04383]



- New collisional system at LHC: Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV ($\mathcal{L}_{\rm int} = 0.34\ \mu{\rm b}^{-1}$)
- The $R_{\rm AA}$ results of Xe–Xe and Pb–Pb agree within uncertainties
- Similar $\sqrt{s_{\rm NN}}$ and $\langle N_{\rm part}\rangle$ lead to similar relative contributions of suppression/(re)generation

J/ψ R_{AA} v.s. p_T

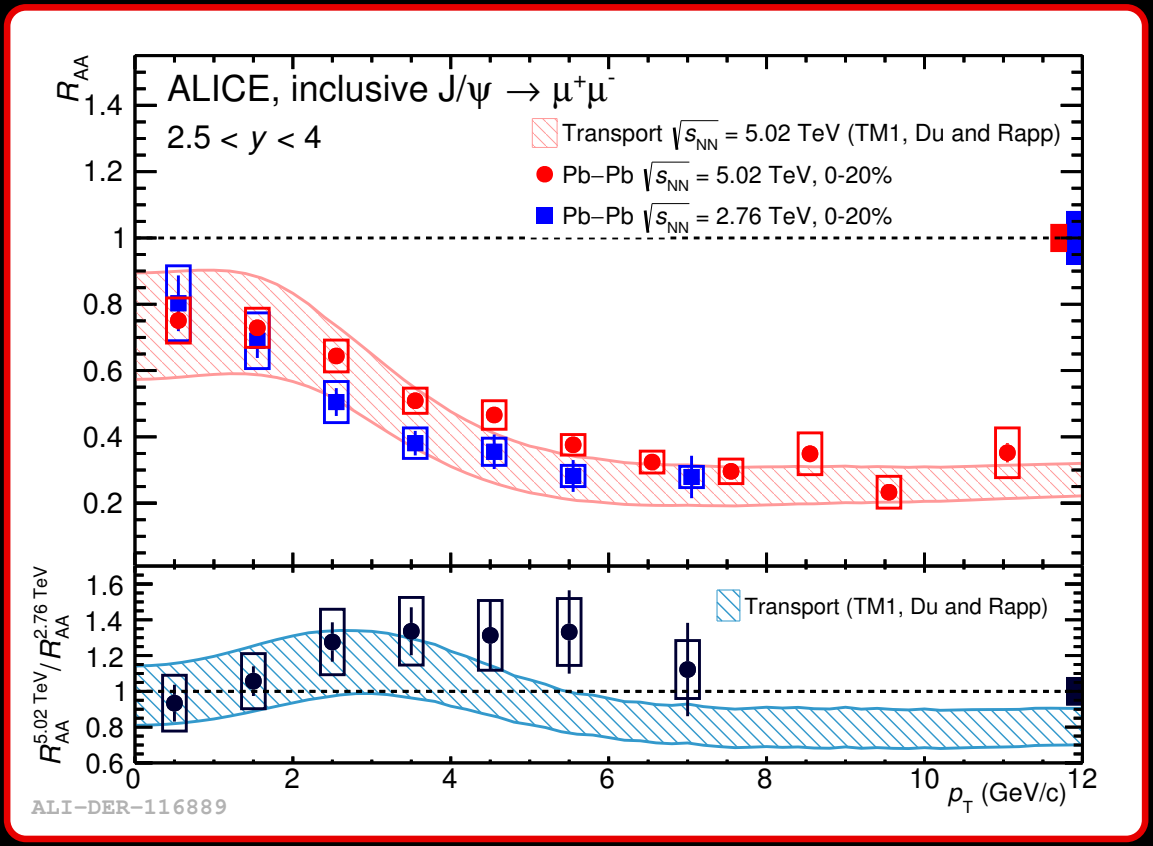
[PLB 766 (2017) 212]



- In clear contrast with the p_T dependence measured at lower energy by PHENIX

J/ψ R_{AA} v.s. p_T

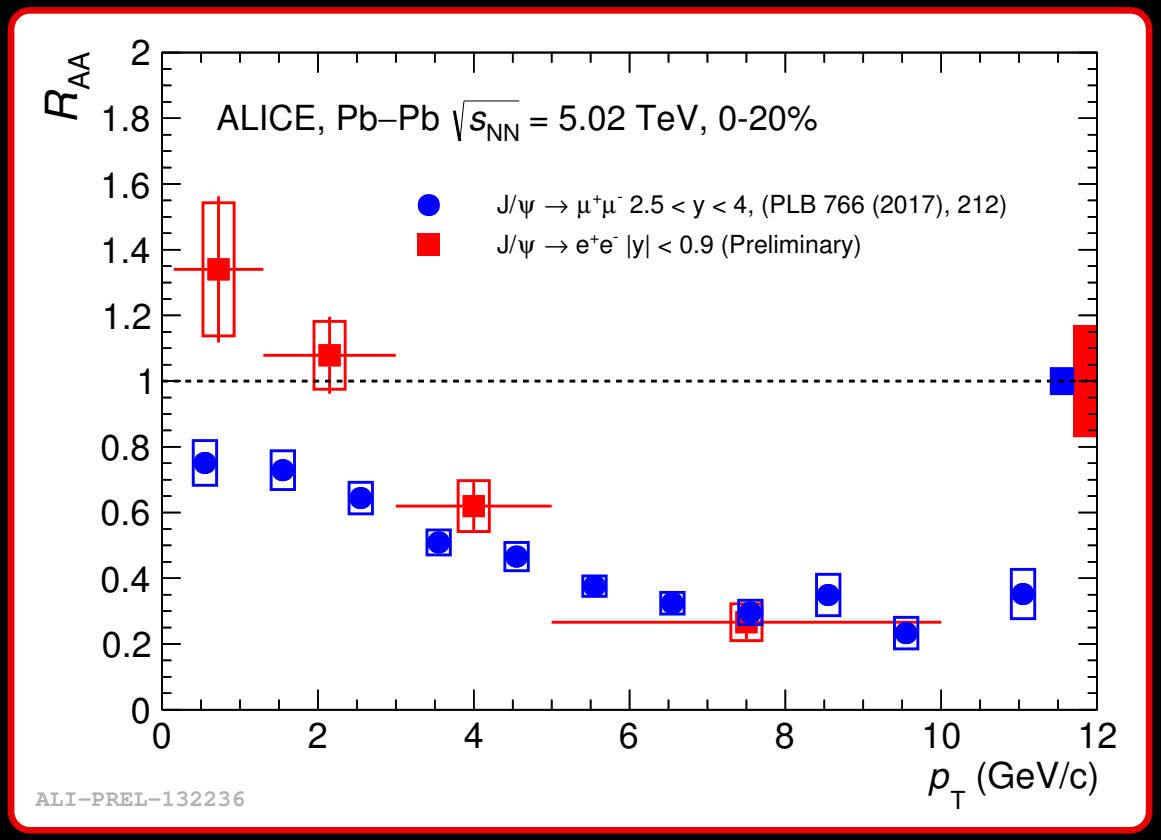
[PLB 766 (2017) 212]



- In clear contrast with the p_T dependence measured at lower energy by PHENIX
- Transport model including (re)generation componant reproduces well the data

J/ψ R_{AA} v.s. p_T

[PLB 766 (2017) 212]



- In clear contrast with the p_T dependence measured at lower energy by PHENIX
- Transport model including (re)generation componant reproduces well the data
- Higher R_{AA} at mid-rapidity than forward for the low-p_T region

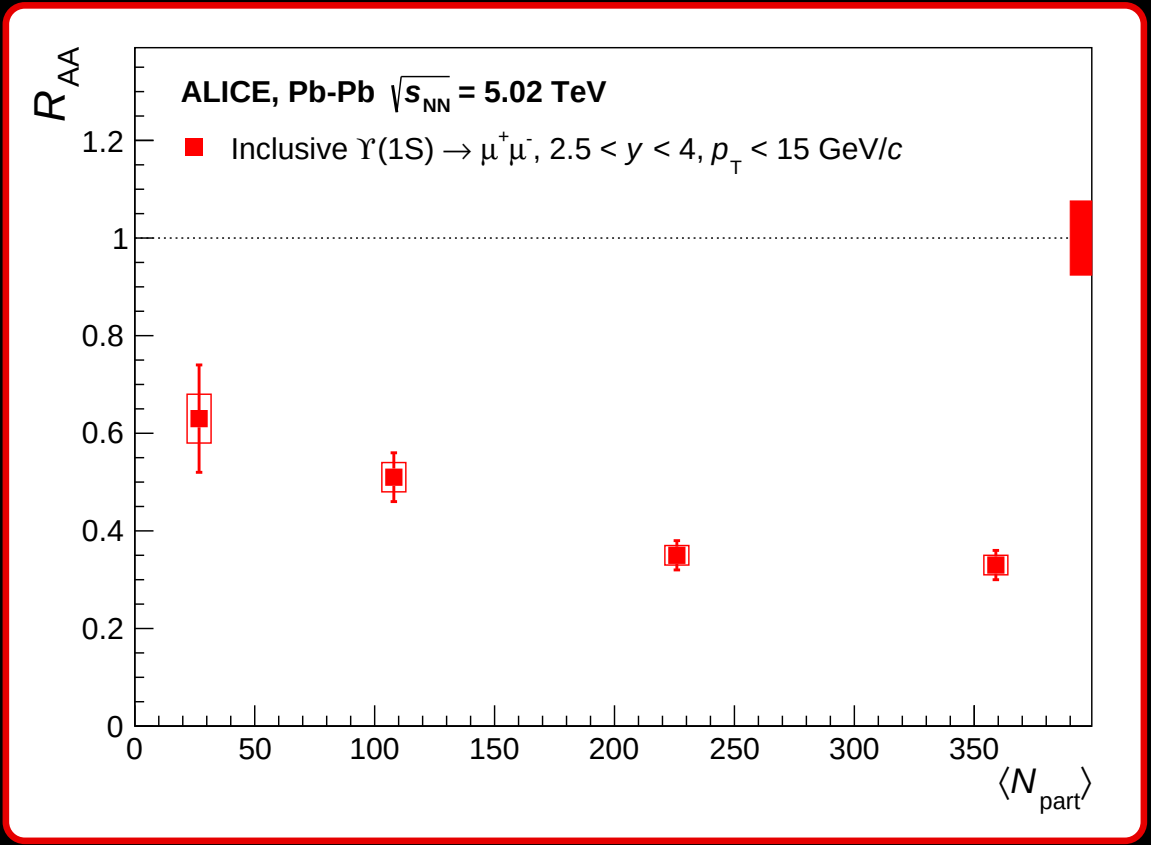
In agreement with (re)generation scenario

Υ R_{AA} *v.s.* centrality

[arXiv:1805.04387]

- Strong $\Upsilon(1S)$ suppression in most central collisions (0–10%): $0.33 \pm 0.03(\text{stat}) \pm 0.03(\text{syst})$
- Stronger $\Upsilon(2S)$ suppression (integrated centrality): $0.10 \pm 0.04(\text{stat}) \pm 0.02(\text{syst})$
- $\Upsilon(2S)$ to $\Upsilon(1S)$ R_{AA} ratio is $0.28 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$

Sequential suppression?



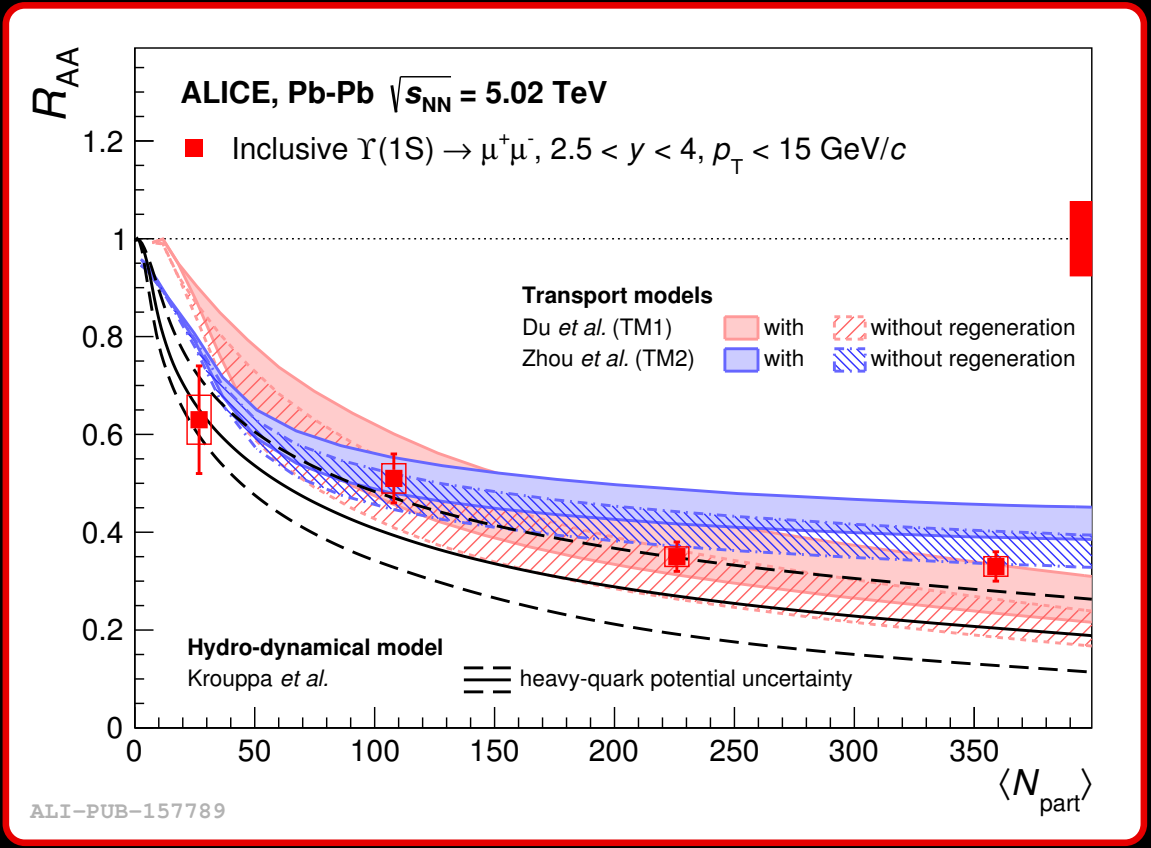
Υ R_{AA} *v.s.* centrality

[arXiv:1805.04387]

- Strong $\Upsilon(1S)$ suppression in most central collisions (0–10%): $0.33 \pm 0.03(\text{stat}) \pm 0.03(\text{syst})$
- Stronger $\Upsilon(2S)$ suppression (integrated centrality): $0.10 \pm 0.04(\text{stat}) \pm 0.02(\text{syst})$
- $\Upsilon(2S)$ to $\Upsilon(1S)$ R_{AA} ratio is $0.28 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$

Sequential suppression?

- Transport and hydro-dynamical models fairly reproduce the data

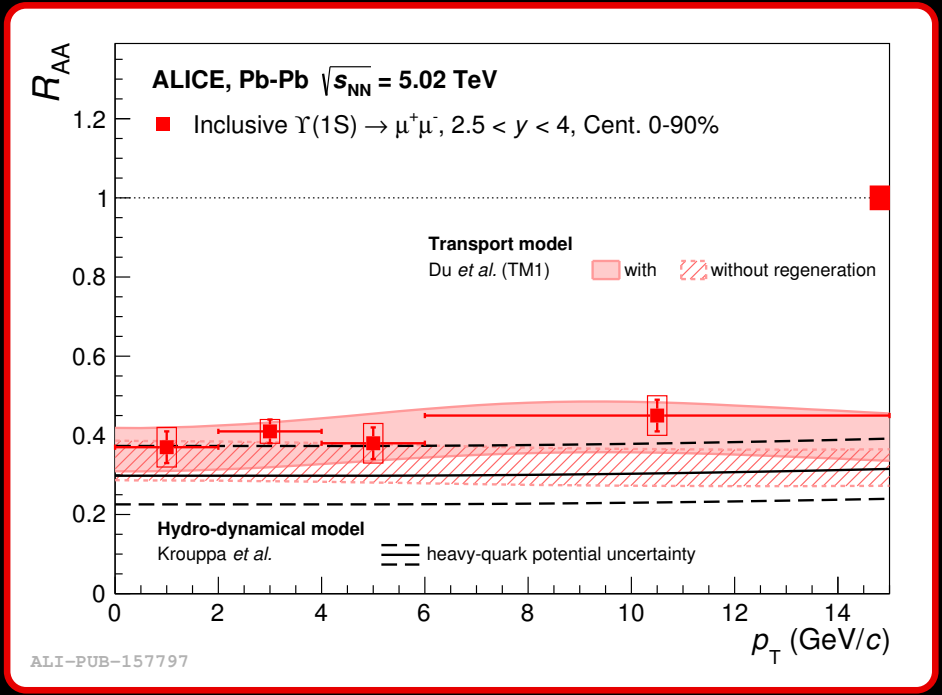


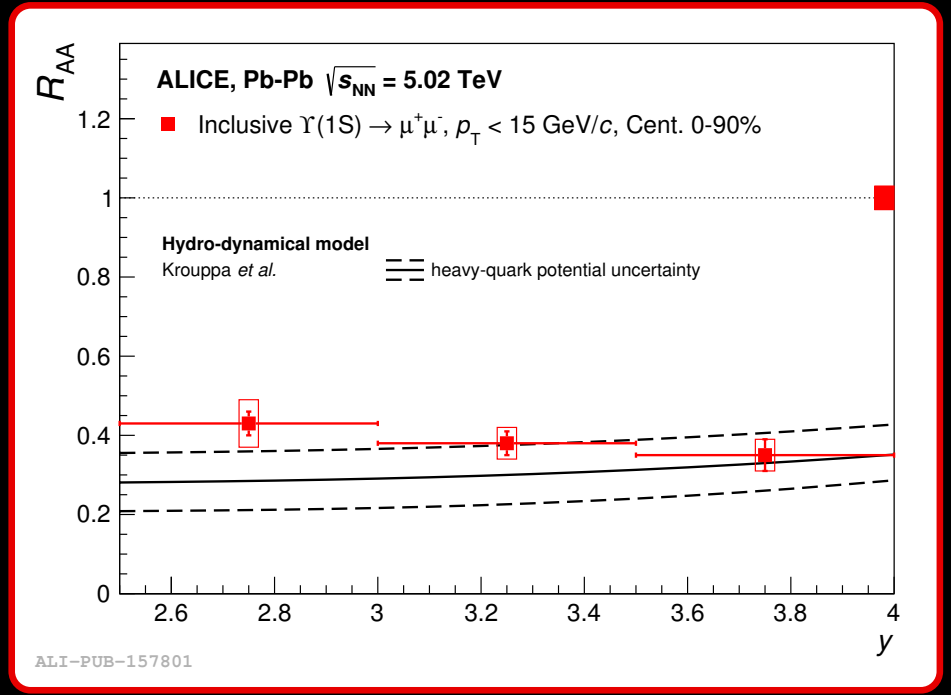
Open question: is the direct $\Upsilon(1S)$ production suppressed?

$\rightarrow$ Feed-down fraction and CNM effects not enough precisely known

Υ R_{AA} *v.s.* p_T and y

[arXiv:1805.04387]

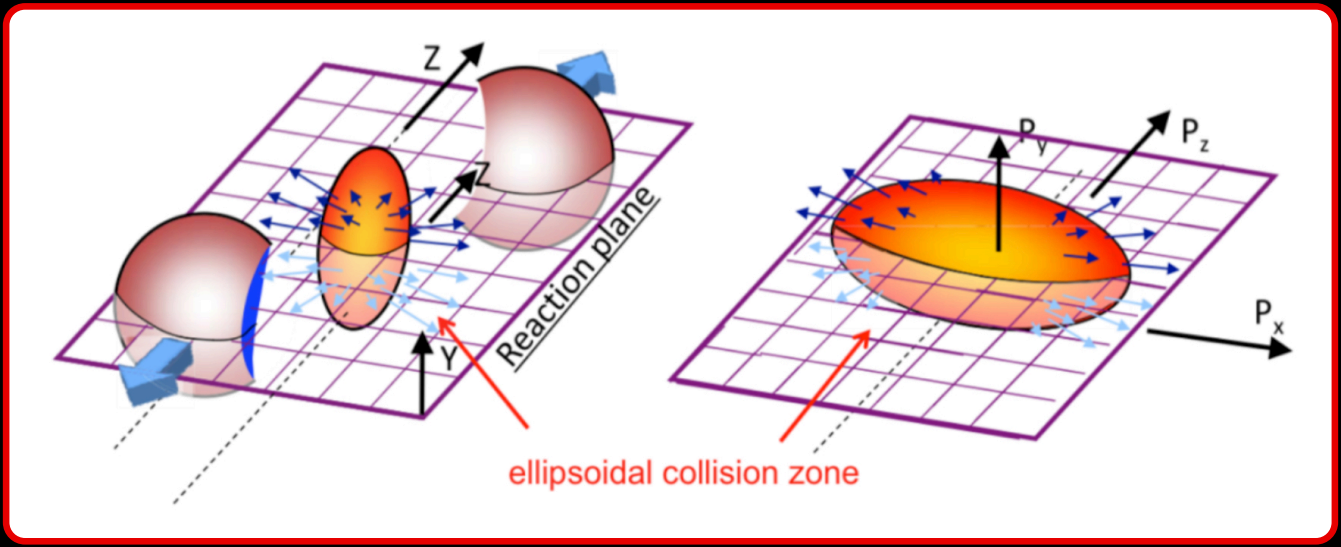




No significant p_T and rapidity dependence

J/ψ elliptic flow v_2

- Pressure gradients in a thermalized medium convert initial spatial anisotropy into momentum-space anisotropy

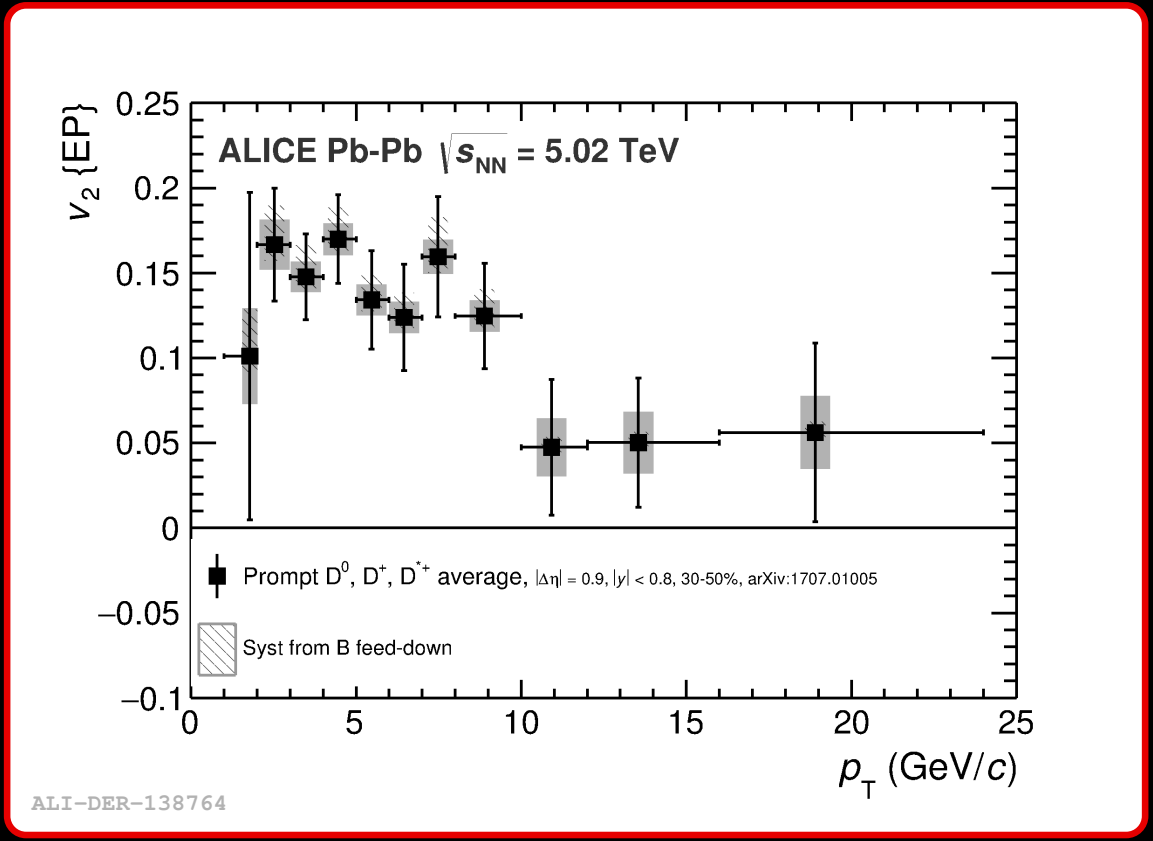


- Anisotropy is quantified by the second order coefficient v_2 of the Fourier expansion of the particle azimuthal distribution

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Phi_R))\right]$$

J/ψ elliptic flow v_2

[Phys. Rev. Lett. 120, 102301 (2018)]



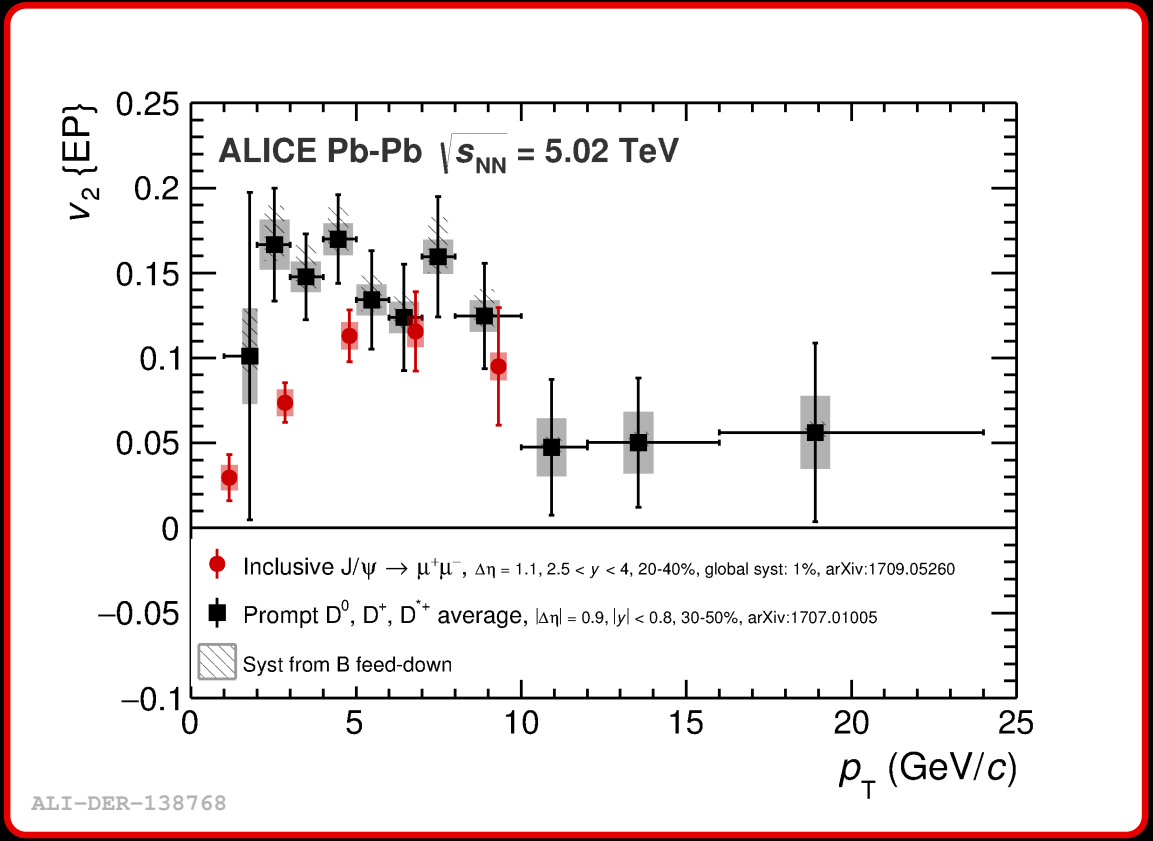
- Positive open charm D-meson v_2

  → Strong coupling of charm quark with the medium

Is the J/ψ inherit any of the fireball collective flow via (re)generation?

J/ψ elliptic flow v_2

[PRL 119 (2017) 242301]



- Positive open charm D-meson v_2

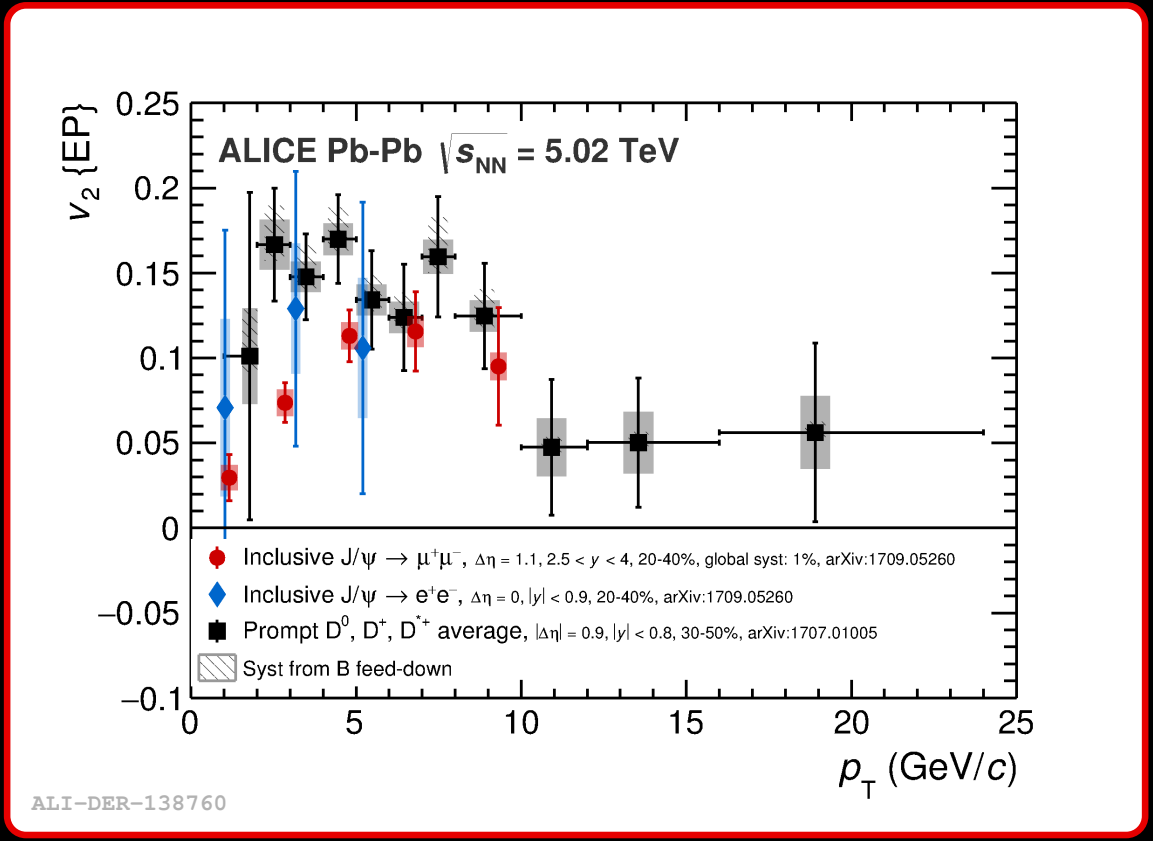
  → Strong coupling of charm quark with the medium

Is the J/ψ inherit any of the fireball collective flow via (re)generation?

- Clear J/ψ v_2 signal ($\approx 6\sigma$) observed at forward rapidity
- Similar v_2 for open and hidden charm

J/ψ elliptic flow v_2

[PRL 119 (2017) 242301]



- Positive open charm D-meson v_2

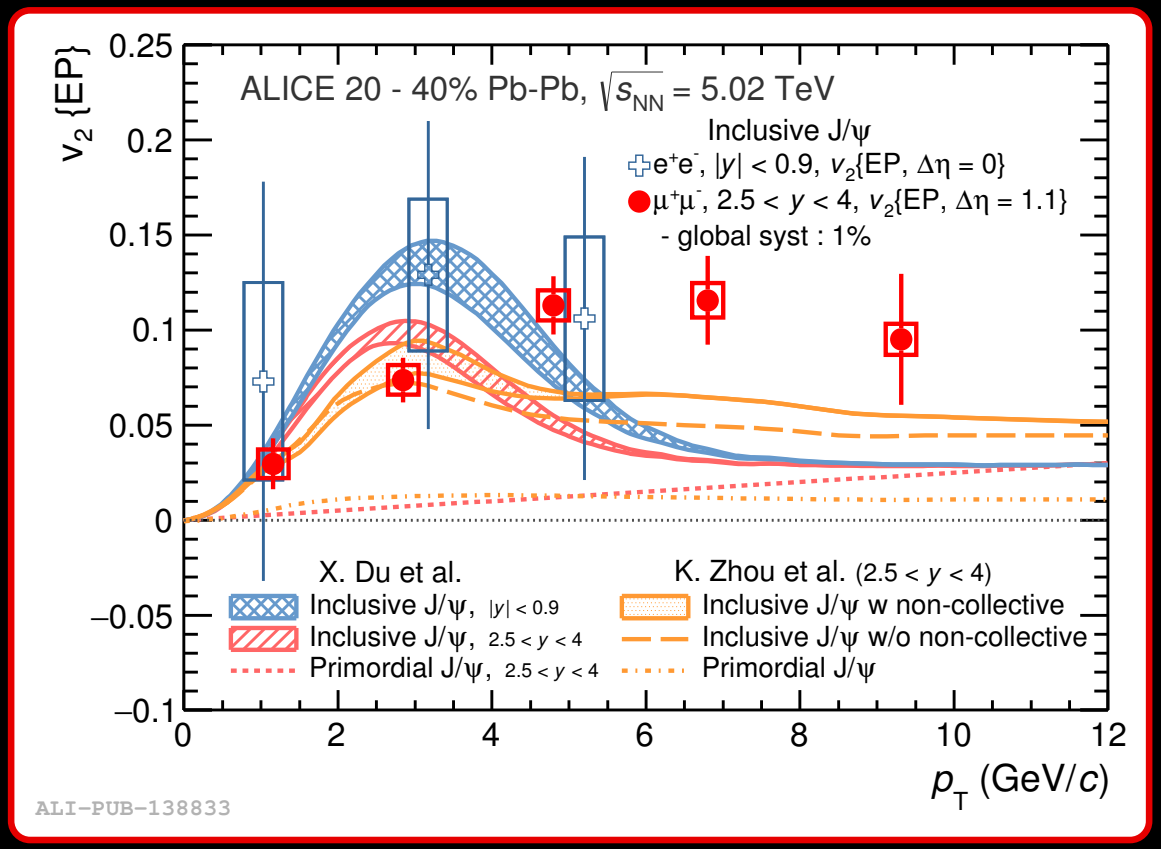
  $\rightarrow$ Strong coupling of charm quark with the medium

Is the J/ψ inherit any of the fireball collective flow via (re)generation?

- Clear J/ψ v_2 signal ($\approx 6\sigma$) observed at forward rapidity
- Similar v_2 for open and hidden charm
- Hint for larger J/ψ v_2 at mid-rapidity

J/ψ elliptic flow v_2

[PRL 119 (2017) 242301]



- Positive open charm D-meson v_2

  $\rightarrow$ Strong coupling of charm quark with the medium

Is the J/ψ inherit any of the fireball collective flow via (re)generation?

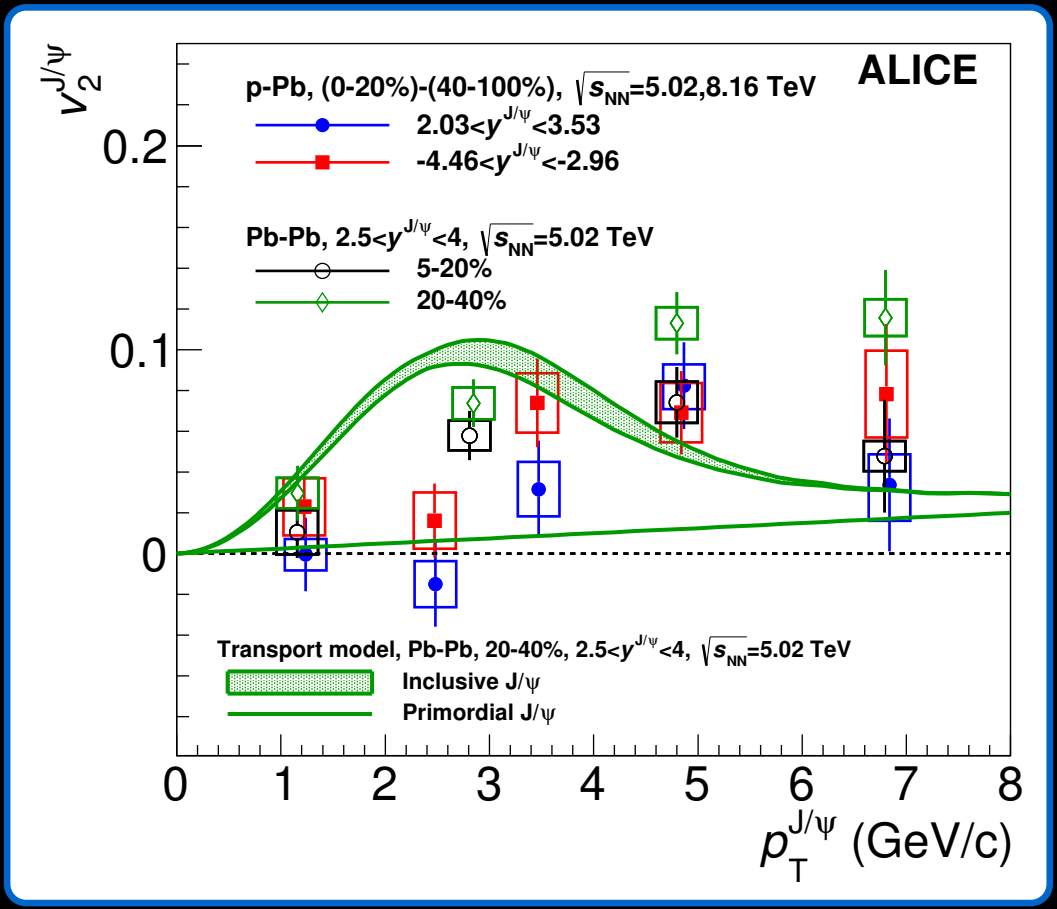
- Clear J/ψ v_2 signal ($\approx 6\sigma$) observed at forward rapidity
- Similar v_2 for open and hidden charm
- Hint for larger J/ψ v_2 at mid-rapidity

- Low-p_T: data fairly well described by transport models
- High-p_T: v_2 underestimated by the model calculations based on path-length dependent suppression in QGP ?

Further signs of charm thermalization and recombination

Back to p–Pb: J/ψ elliptic flow v_2

[PLB 780 (2018) 2]



Regeneration negligible due to low production of charm quarks

Negligible path-length dependence regarding the small system size

- Low-p_T: v_2 compatible with zero

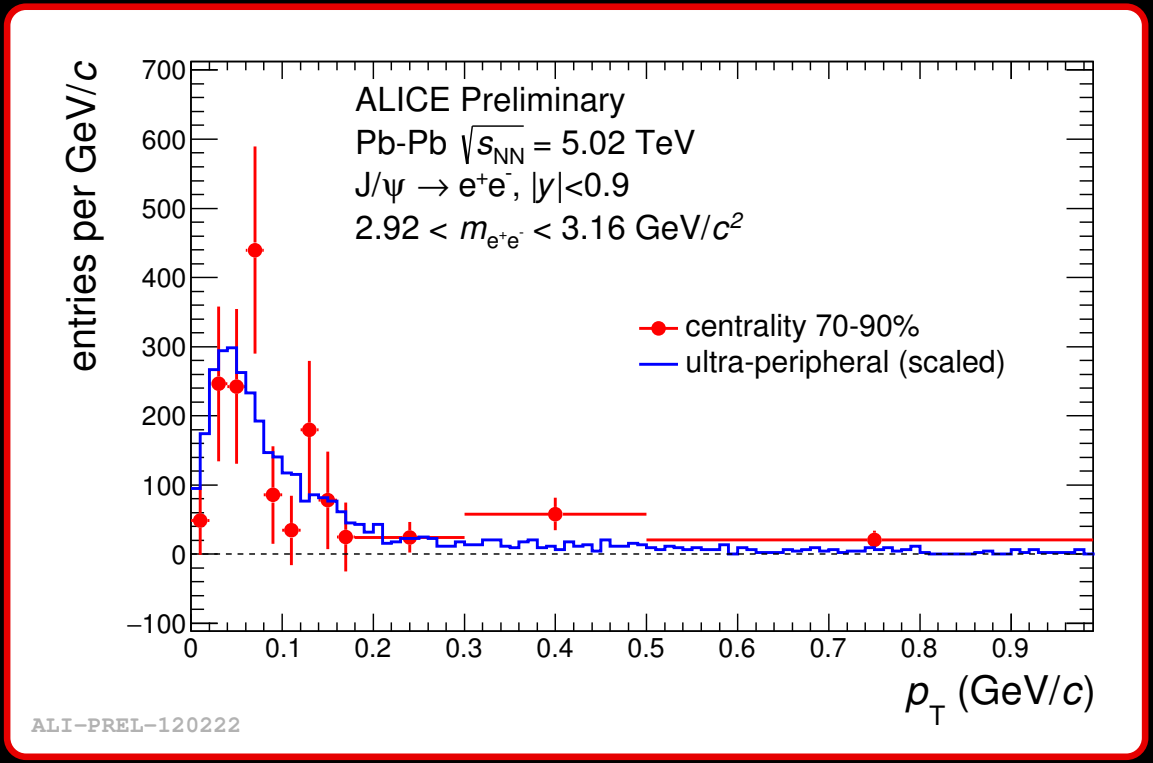
  $\rightarrow$ agree with no regeneration

- High-p_T: positive v_2

  $\rightarrow$ similar to the Pb–Pb measurement!! Not understood

Similar magnitude of v_2 in p–Pb and Pb–Pb could indicate a common mechanism

Low p_T J/ψ excess



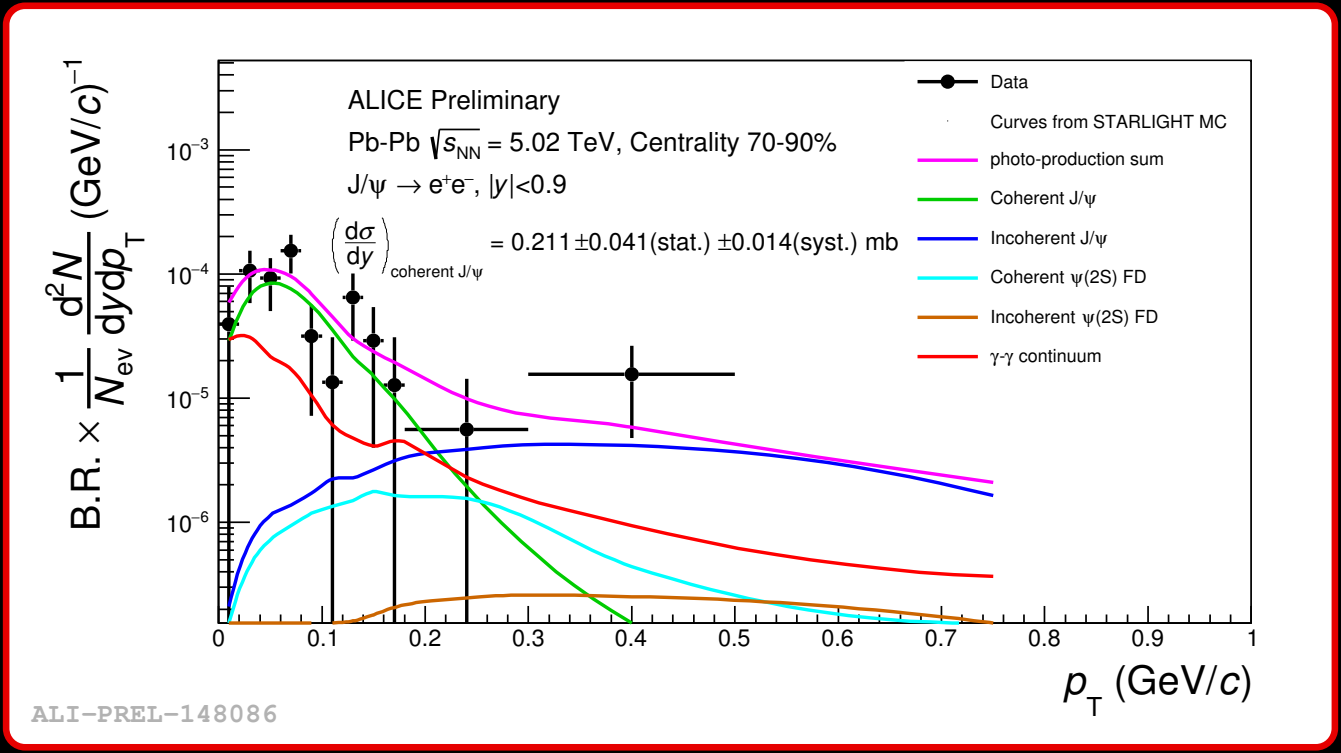
- Run-1: An excess of J/ψ has been observed at very low-p_T in peripheral collisions at forward rapidity

Interpreted as coherently photo-produced J/ψ
$\langle p_T \rangle \sim 60$ MeV/c

- Run-2: Measurement of this excess at mid-rapidity

A suppression of the coherent J/ψ photo-production in hadronic collisions could be a direct probe of the color screening mechanism (not mimicked by regenerated J/ψ)

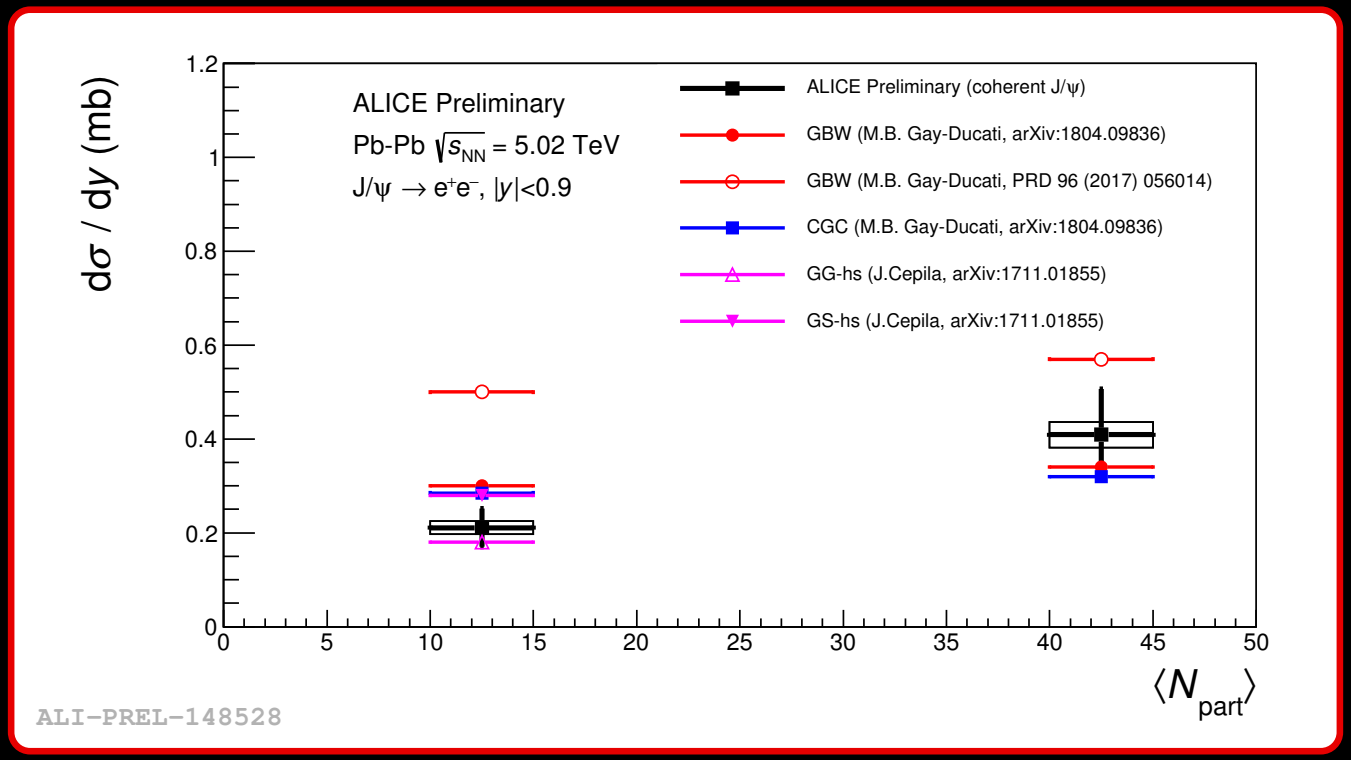
Low p_T J/ψ excess



- Corrected J/ψ yields, after subtraction of the hadronic contribution, $v.s.$ p_T for 70–90% centrality with template fits from STARLIGHT

→ **Extraction of the coherently photo-produced J/ψ cross section**

Low p_T J/ψ excess



- GBW 2017: γ flux with nuclear overlap
- GBW 2018: γ flux corrected
- CGC: color-glass condensate
- GC-hs, GS-hs: energy-dependent hot-spot models

→ All models reproduce the data except GBW2017

Measurements towards more central collisions needed to disentangle between models and underlying mechanisms

Summary

ALICE has measured quarkonium production in pp, p–Pb, Pb–Pb and Xe–Xe collisions at LHC energies.

pp Quarkonium production spectra well described with QCD-based models but underlying mechanism still not settled (polarization tensions)

p–Pb Models face difficulties in describing consistently all results
Final-state effect needed to describe the $\psi(2S)$ suppression
Positive J/ψ v_2 similar to Pb–Pb for $p_{\mathrm{T}} > 4$ GeV/c $\rightarrow$ common mechanism?

Pb–Pb **Interplay between dissociation and (re)generation mechanisms at LHC energies**
Is the direct $\Upsilon(1S)$ production suppressed? $\rightarrow$ need more precise measurements of CNM effects and feed-down fractions
Positive J/ψ v_2 $\rightarrow$ charm quark thermalization?
J/ψ excess at low-p_{T} interpreted as coherent photo-production

Perspectives:

- New Pb–Pb data taking period that year $\rightarrow$ stay tuned!
- ALICE upgrades for Run-3: continuous readout (will in particular enhance the mid-rapidity quarkonium samples), new Muon Forward Tracker detector

Thanks