Charmonium production in Pb-Pb collisions measured by ALICE at the LHC

Hard Probes 2016

Victor Feuillard, CEA Saclay, for the ALICE Collaboration

Outline

I. Introduction
   I. Physics motivation
   II. The ALICE detector

II. Previous results in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

III. New Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV results
   I. Inclusive J/ψ R_{AA}
   II. Comparison with models

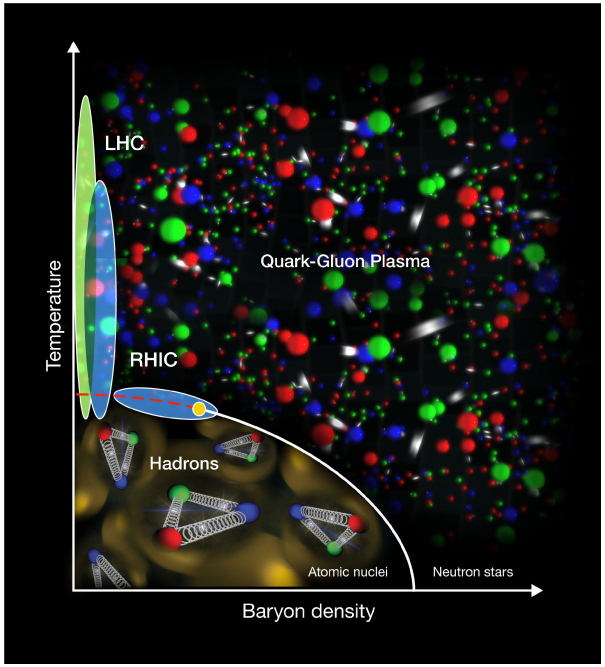
IV. Conclusion

Introduction

- Quark-Gluon Plasma (QGP) is a state of matter predicted by QCD where quark and gluons are deconfined

- Transition temperature :
  $T_C \approx 155$ MeV (Phys. Rev. D 85 (2012) 054503)

- It is the state of matter at the early stages of the universe ($\tau \approx 1\mu s$)

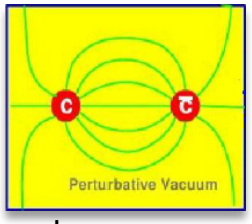


- It is possible to recreate the QGP by doing relativistic heavy-ion collisions, but only during a short period of time ($\approx$10 fm/*c* at LHC) and a very small volume ($\approx 10^4$ fm^3 at LHC)
  (Phys.Lett. B696 (2011) 328-337)

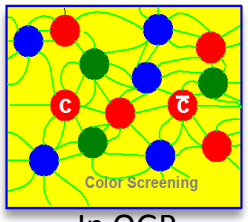
Introduction – Charmonia

- Charmonia (J/ψ, ψ(2S)) are bound states of a c-cbar pair

- Theory predicts that charmonia are dissociated in a QGP because of the colour screening
(Phys. Lett. B 178 (1986) 416)

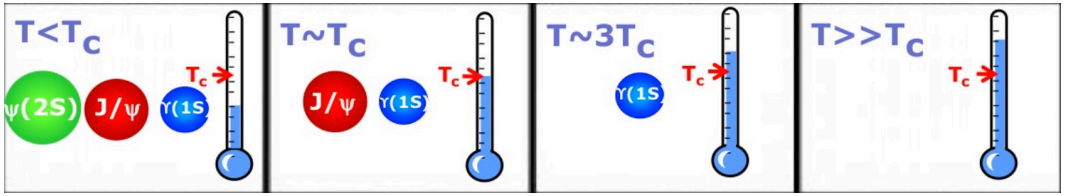


In vacuum

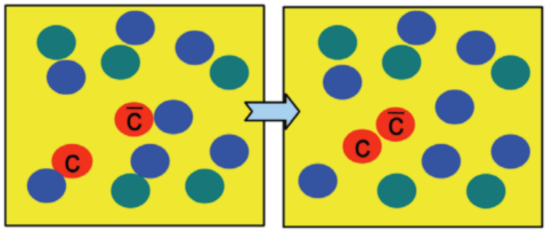


In QGP

- Difference between binding energies leads to a sequential melting of charmonia as function of temperature

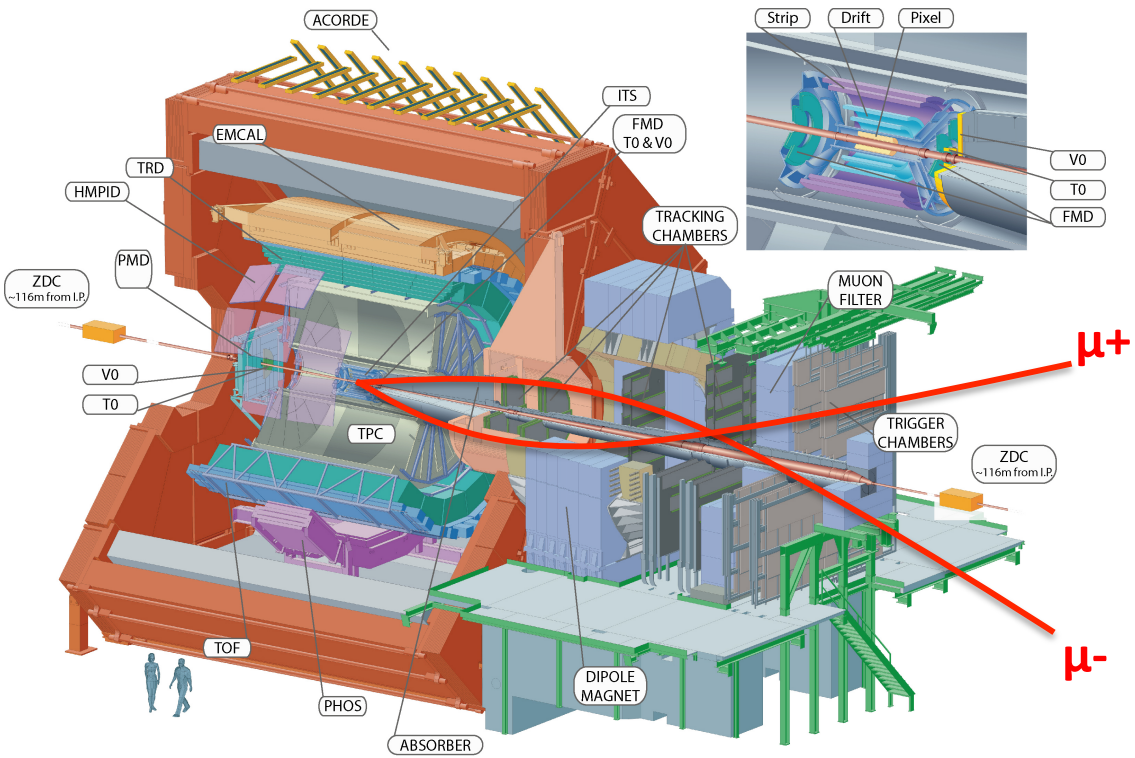


- If there are enough charm-anticharm pairs, and if thermalized in QGP:
➔quarkonia regeneration
(Phys. Lett. B 490 (2000) 196)



Introduction - ALICE

- ALICE : 41 countries, 159 institutes, 1665 members



- Muon Arm : $J/\psi \rightarrow \mu^+\mu^-$
- Acceptance : $2.5<y<4.0$
- Down to $p_T = 0$

- 5 stations of tracking chambers
- 2 stations of trigger chambers
- Dipole Magnet
- Absorbers

With the Muon spectrometer, we only measure inclusive J/ψ (prompt and non-prompt J/ψ)

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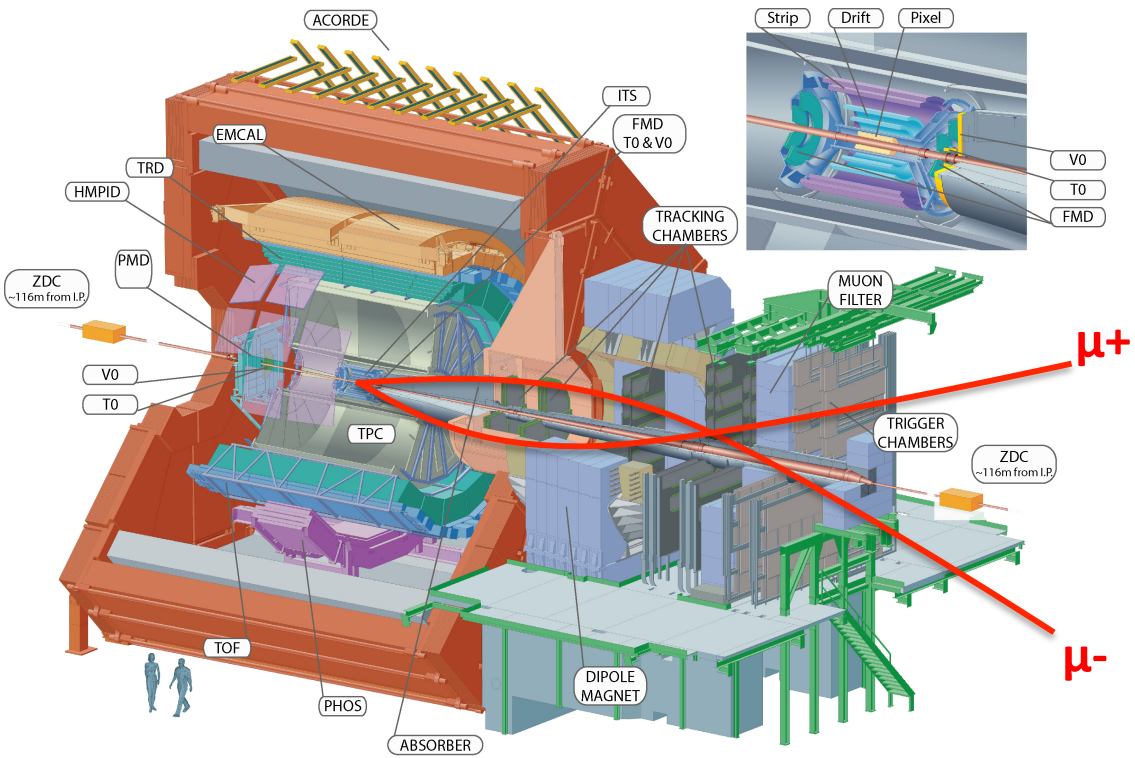

- ITS used for vertex determination
- V0 hodoscopes used as trigger (in coincidence with Muon Trigger)
- V0 and ZDC used for background rejection
- T0 Cerenkov detectors used for luminosity calculations

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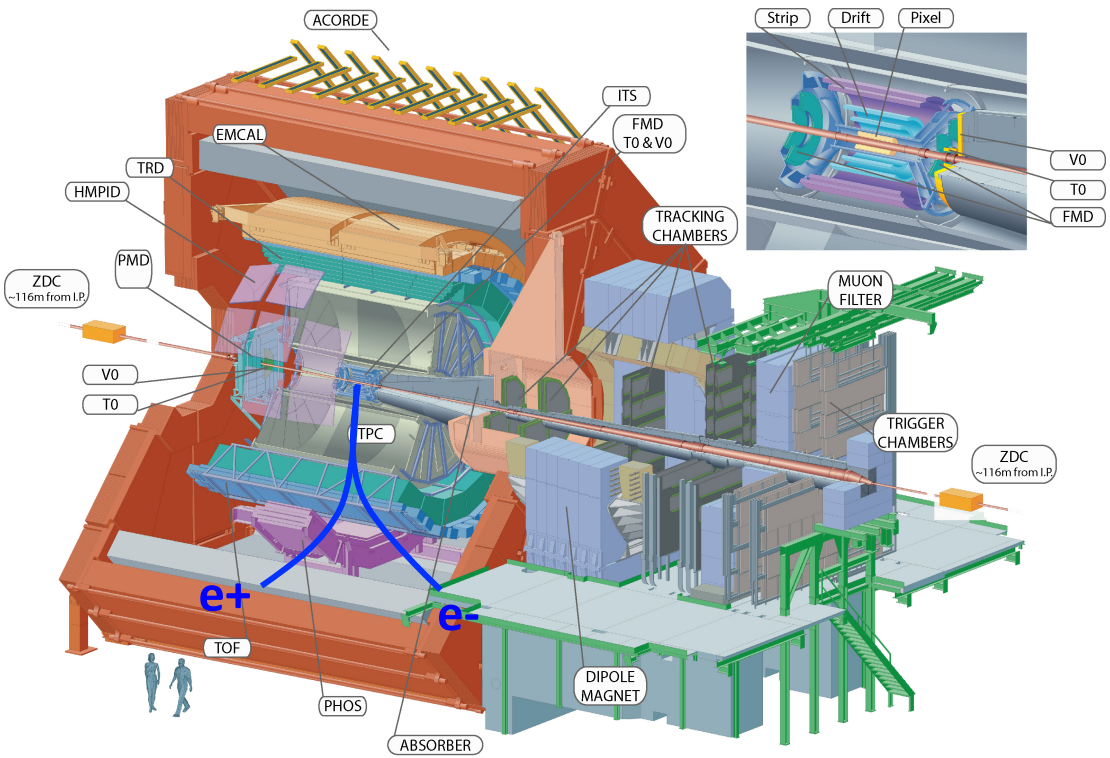


- Central Barrel: $J/\psi \rightarrow e^+e^-$
- Acceptance : $|y|<0.9$
- Down to $p_T = 0$

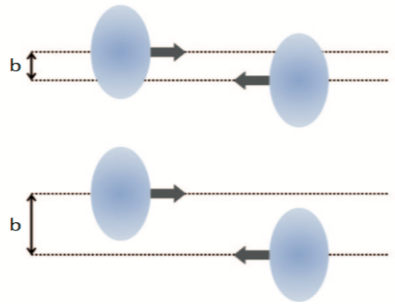
- Electrons tracked with ITS and TPC
- Particle identification with TPC and TOF

Run 1 Results - J/ψ inclusive R_{AA} at 2.76 TeV

- Nuclear modification factor :

$$R_{AA} = \frac{Y_{PbPb}}{N_{coll}.Y_{pp}}$$

- If $R_{AA} \neq 1$, then there are nuclear effects

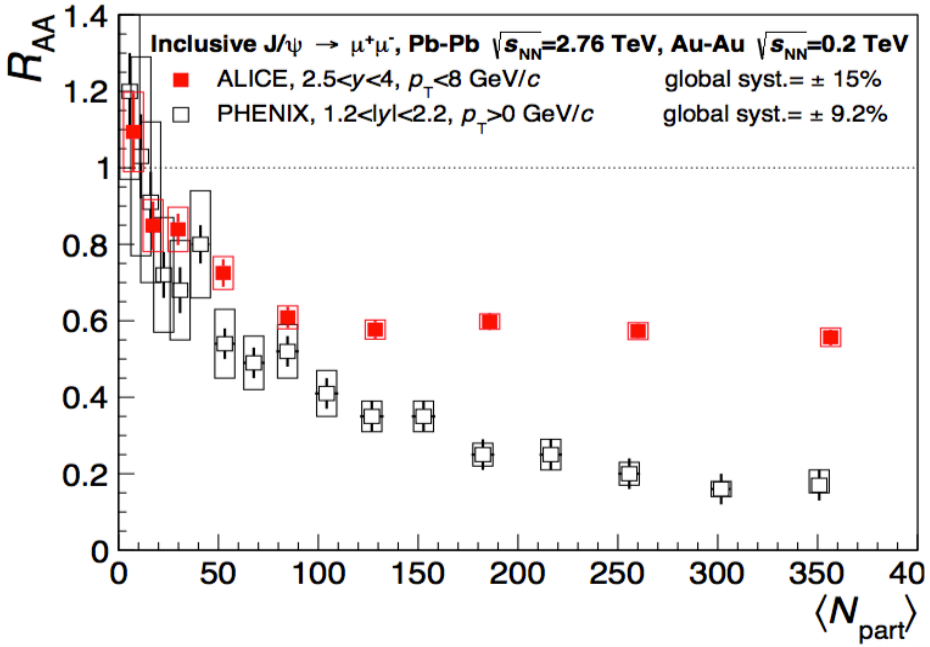


Central collision :
Small b, large N_{part}, large N_{coll}

Peripheral collision :
Large b, small N_{part}, small N_{coll}

- Centrality :
  Related to the transverse distance b between the center of the colliding nuclei
- Also expressed in terms of $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ or $\langle T_{AA} \rangle$

- Clear suppression of the J/ψ both at ALICE and PHENIX
- Smaller suppression for central events in ALICE
  ➔indication of regeneration



PLB 734 (2014) 314-327

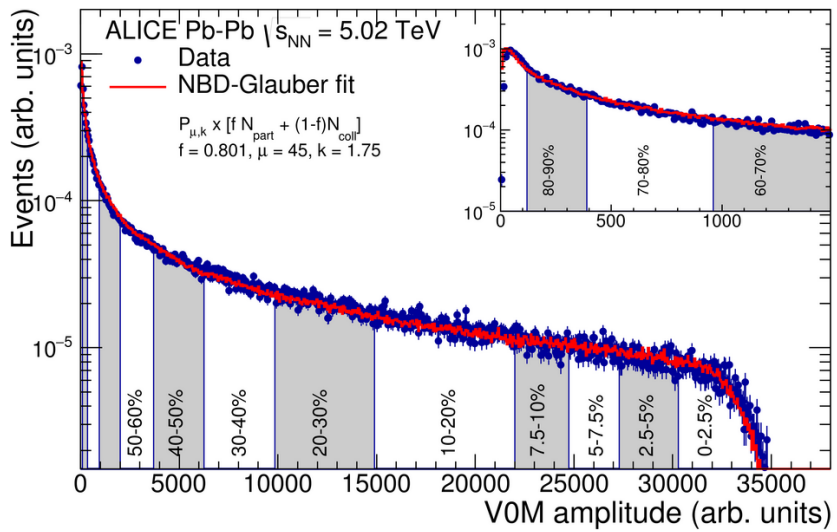
periph. ⟷ central

$\sqrt{s_{NN}}$ = 5.02 TEV RESULTS : MEASUREMENT OF R_{AA}

Event and Track Selection

- Results from Run 2, december 2015
- Integrated Luminosity ≈ 225 μb^{-1}
- Muon pair selection :
  - Pseudo rapidity on each muon $-4.0<\eta<-2.5$
  - Radial transverse position at the end of the absorber $17.6<R_{abs}<89.5$cm
  - Rapidity of the dimuon $2.5<y<4.0$
  - Muons of opposite sign
  - Matching tracks between tracking chambers and trigger
- Event selection
  - Beam gas and electromagnetic interactions rejected using V0 and ZDC
  - SPD used for vertex determination
- Centrality estimated on a Glauber model fit of the V0 amplitude (PRL. 116 (2016) 222302)

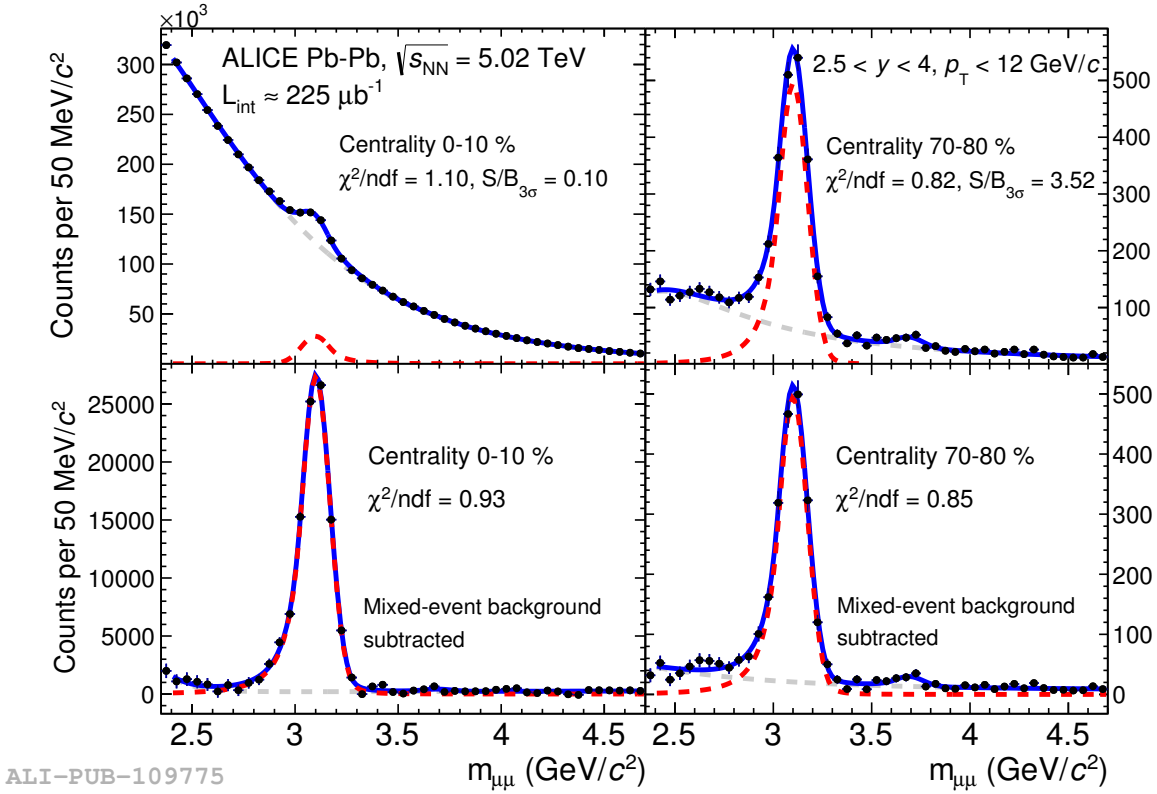
ALICE, ALICE-PUBLIC-2015-008



Signal extraction

- J/ψ yield extracted by fitting the opposite sign dimuon invariant mass spectrum

- The signal is extracted using :
  - 2 signal functions
  - 2 methods of dealing with the background : empirical fit or mixed-event background substraction
  - Several fit ranges



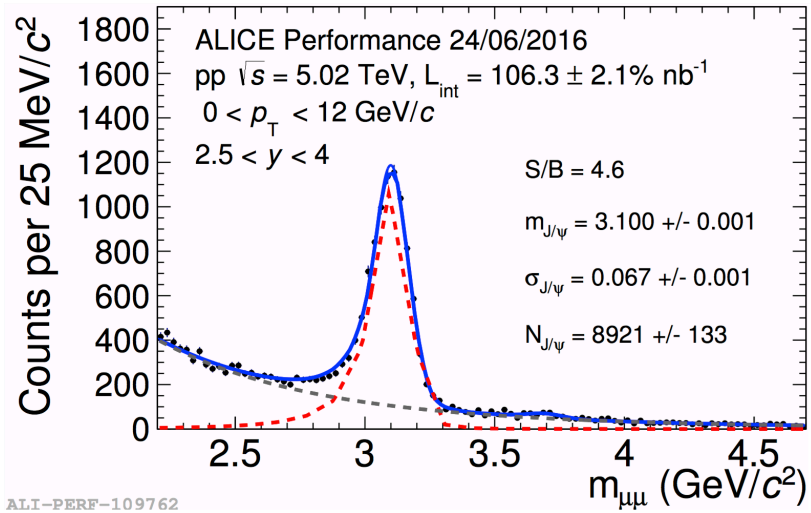
arXiv:1606.08197

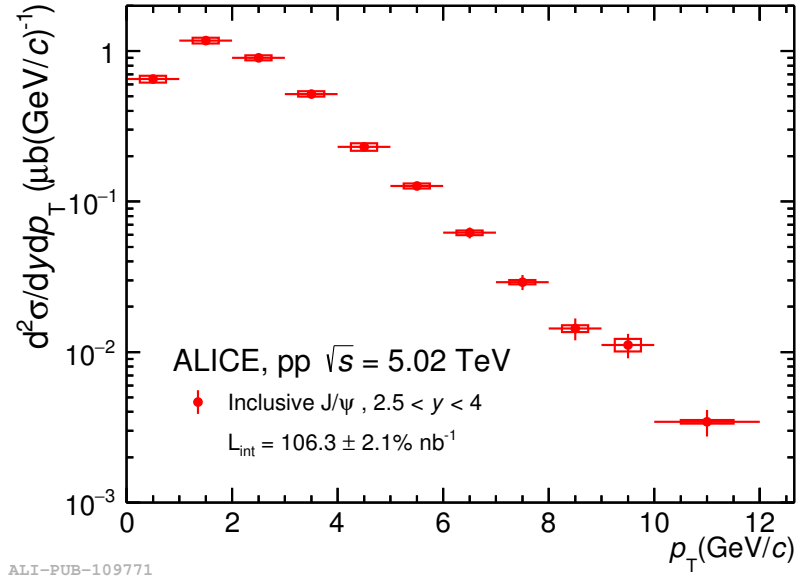
- $N_{J/\psi} \approx 277000$ (7 times larger than in Run 1)

pp cross section at √s = 5.02 TeV

$$\sigma^{pp}_{J/\Psi} = \frac{N_{J/\Psi}}{A.\varepsilon \times L \times BR_{J/\Psi \to \mu^+\mu^-}}$$

- Data collected during 4 days before the Pb-Pb collisions
- Total luminosity of 106 nb^{-1}
- **Integrated cross section (p_T < 12 GeV/c) : 5.61 ± 0.08 (stat) ± 0.28 (syst) µb**





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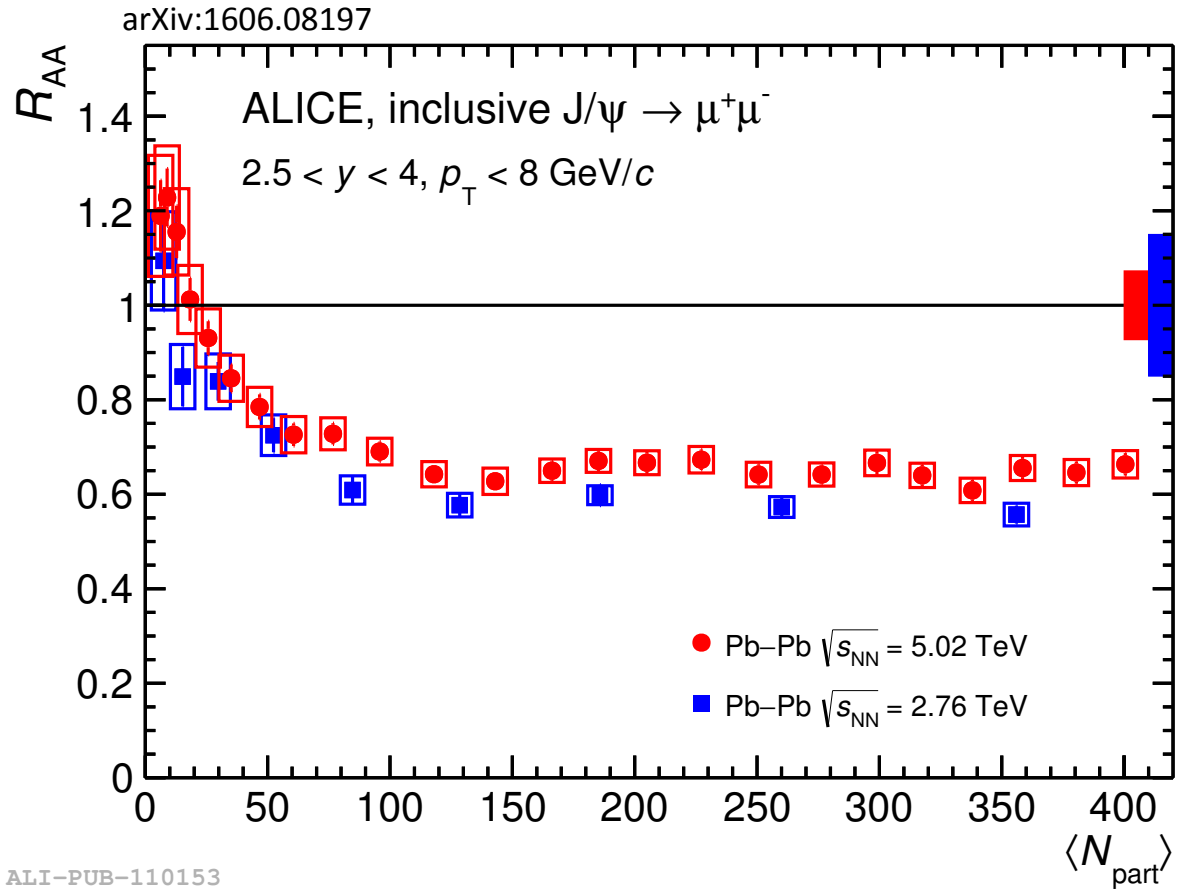
Other contributions to R_{AA}

$$R_{AA} = \frac{N_{J/\Psi}}{BR_{J/\Psi\to\mu^+\mu^-}.N_{MB}.A\varepsilon\ .\langle T_{AA}\rangle\ .\sigma^{pp}_{J/\Psi}}$$

- $A\varepsilon$: Acceptance-efficiency, correcting the number of extracted particles by the acceptance and efficiency of the detector, calculated with Monte-Carlo simulations using the embedding technique
- $BR_{J/\Psi\to\mu^+\mu^-}$: Branching ratio
- N_{MB}: Number of equivalent minimum bias events
- $\langle T_{AA}\rangle$: Nuclear overlap function, calculated using a Glauber model

➔Each one of these elements is a source of systematic uncertainty.
The total amount of systematic uncertainty is about 8% for the R_{AA}

R_{AA} vs Centrality



- Higher statistics with respect to Run 1 allows finer bins
- Clear J/ψ suppression with almost no centrality dependence for N_{part}>100
- If R_{AA}(non-prompt) = 0, then R_{AA} (prompt) would be 10% higher
- If R_{AA} (non-prompt) = 1, then R_{AA} (prompt) would be 5% to 1% lower

At $\sqrt{s_{NN}}$ = 5.02TeV, $R_{AA}^{0\text{-}90\%}(0<p_T<8\ \text{GeV}/c)$ = 0.66 ± 0.01(stat.) ± 0.05 (syst.)

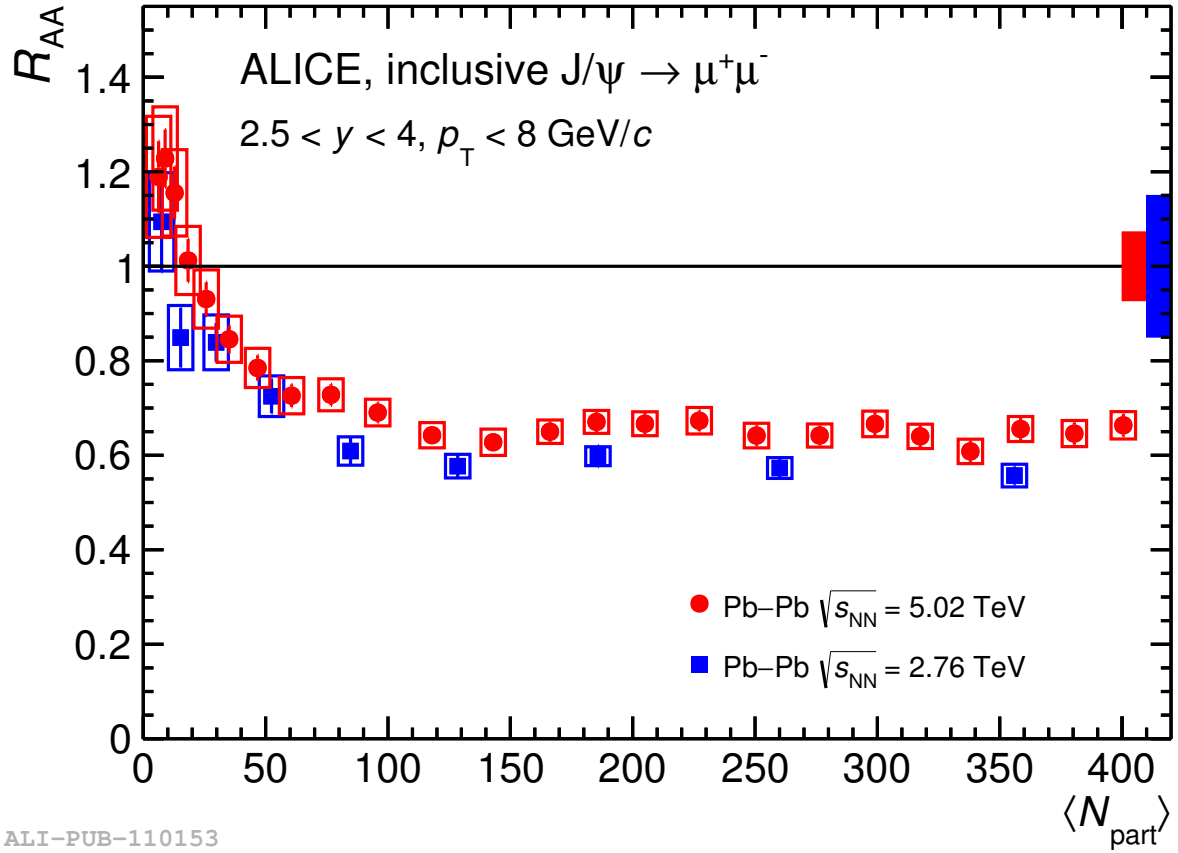
At $\sqrt{s_{NN}}$ = 2.76TeV, $R_{AA}^{0\text{-}90\%}(0<p_T<8\ \text{GeV}/c)$ = 0.58 ± 0.01(stat.) ± 0.09 (syst.)

$R_{AA}^{0\text{-}90\%}$(5.02 TeV)/$R_{AA}^{0\text{-}90\%}$(2.76 TeV) = 1.13 ± 0.02(stat.) ± 0.18 (syst.)

Results at 2.76 TeV and 5.02 TeV are compatible within uncertainties

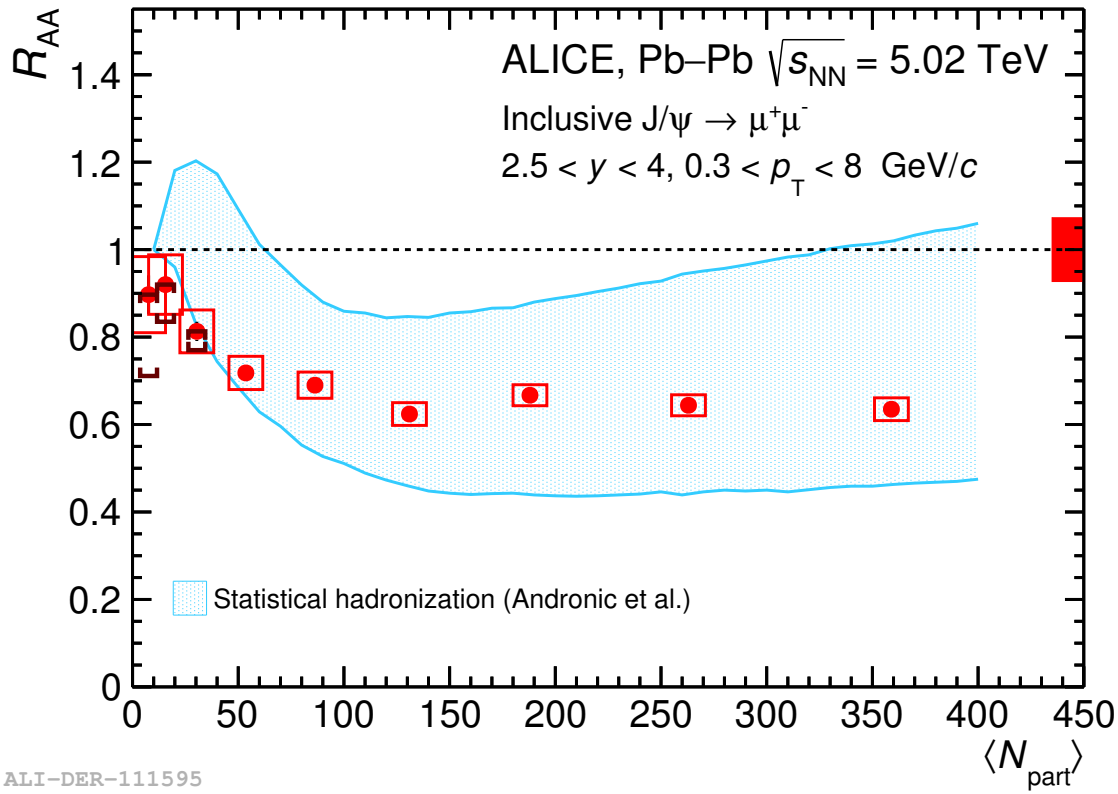
R_{AA} vs Centrality

arXiv:1606.08197



- In peripheral Pb-Pb collisions, we observed R_{AA}>1
- It is explained by an excess of J/ψ at very low p_T
- Photoproduction of J/ψ in Pb-Pb collisions with b<2R was proposed to be at the origin of this excess. (ALICE, PRL 116 (2016) 222301)
- The cut p_T > 0.3 GeV/c removes about 80% of photoproduced J/ψ -> better suited to compare with models

Comparison to Models



- **Statistical Hadronization Model (SHM) :**
  Andronic et al., Nucl. Phys. A 904-905 (2013) 535c
  - Primordial charmonia are completely suppressed in the QGP
  - Charmonium production occurs at phase boundary by the statistical hadronization of charm quarks

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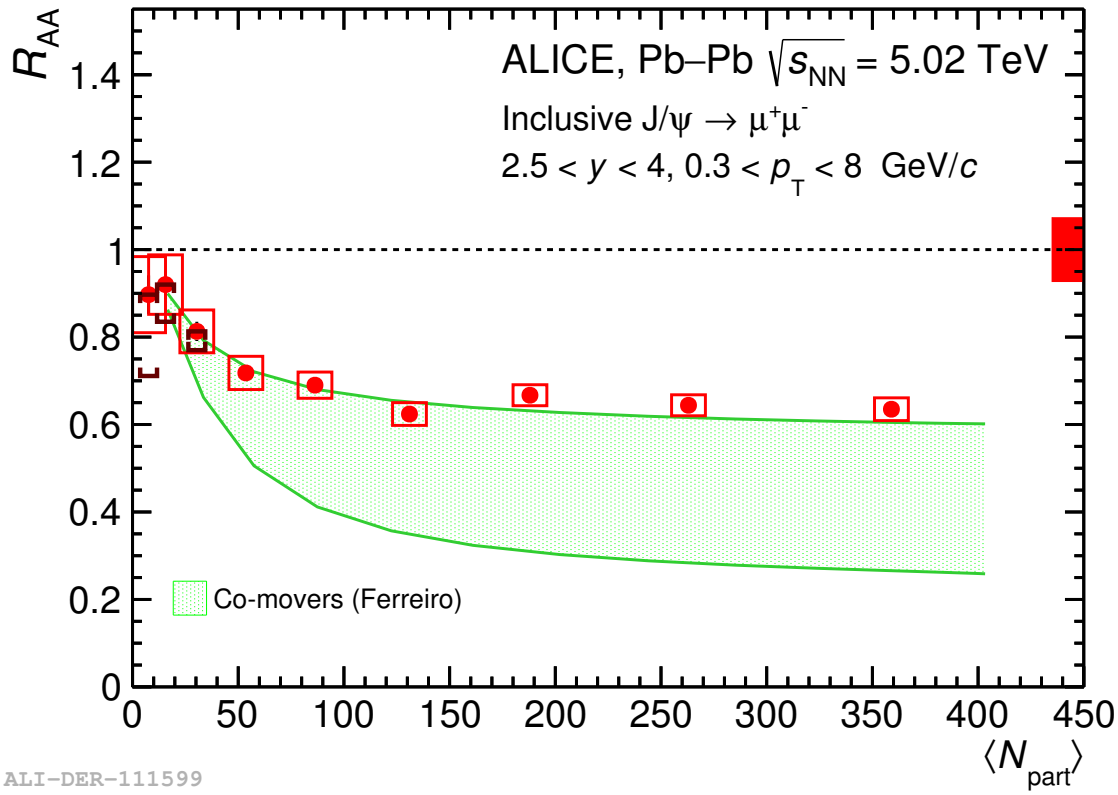

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  Ferreiro, Phys. Lett. B 731 (2014) 57
  - Dissociation occurs by interaction with a dense co-moving partonic medium
  - Regeneration is added as a gain term to the comover dissociation

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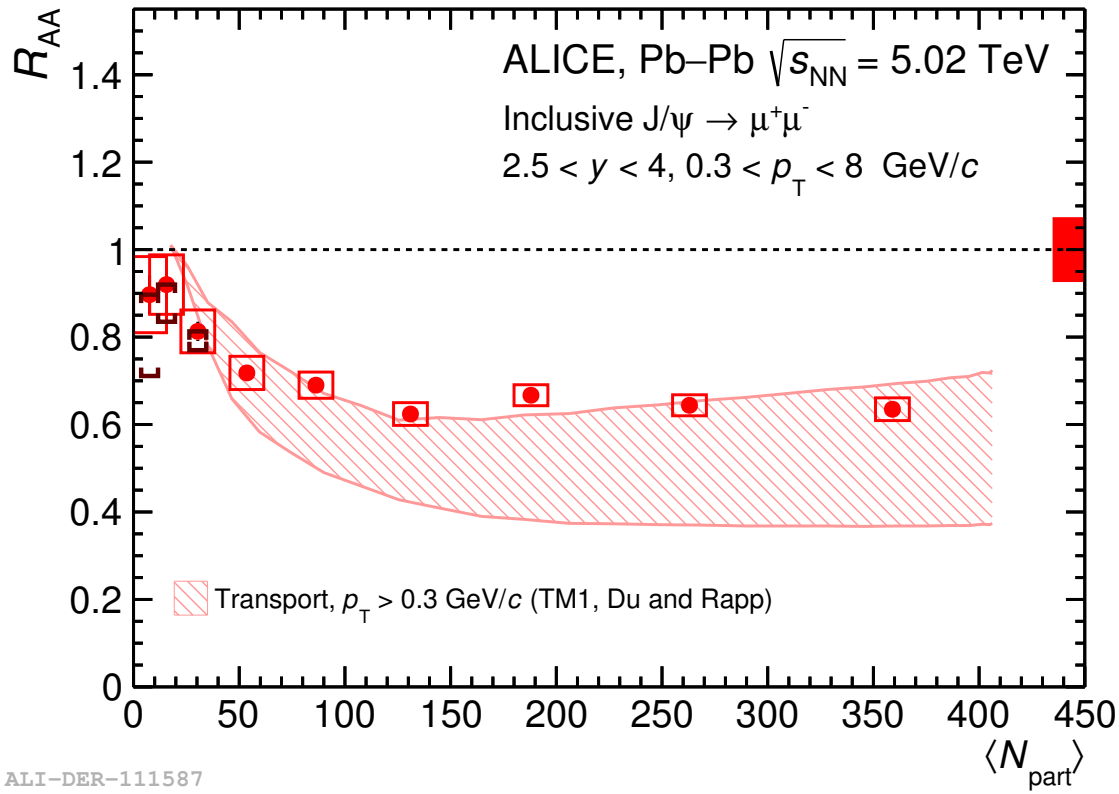

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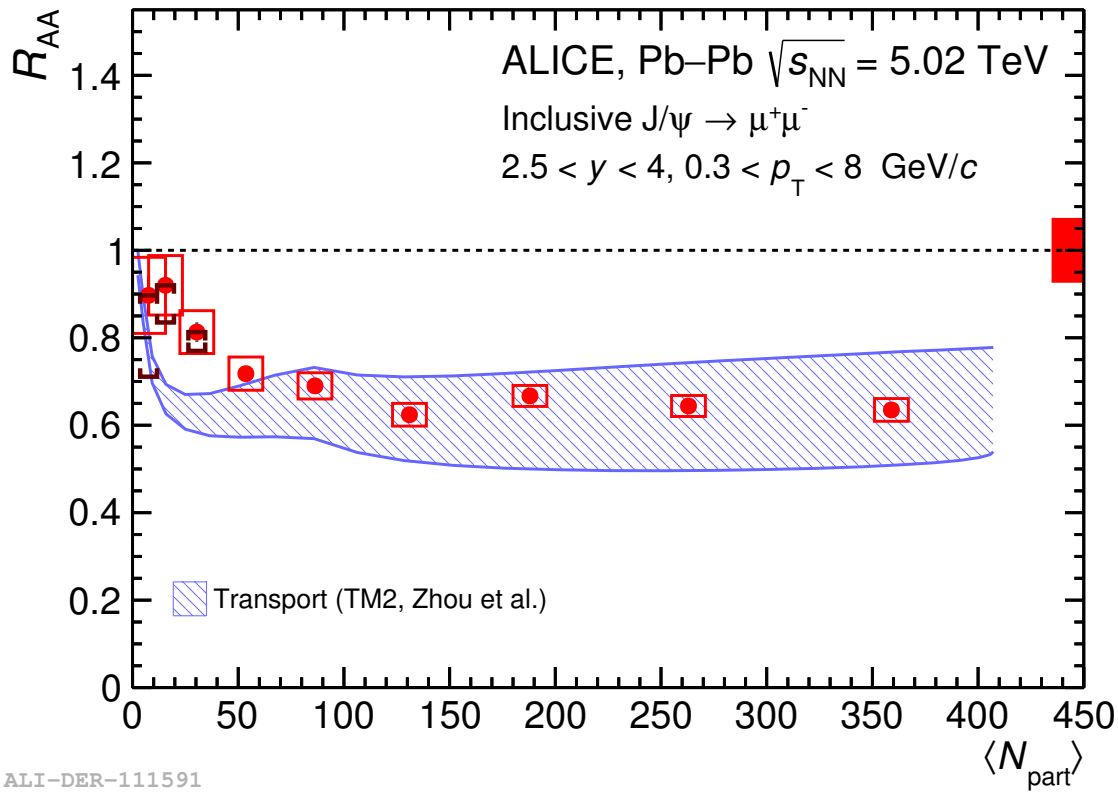
  - Continuous charmonium dissociation/ regeneration in the QGP, described by a rate equation

Comparison to Models



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  Zhou et al., Phys. Rev C 89 no.5, 459 (2014) 054911
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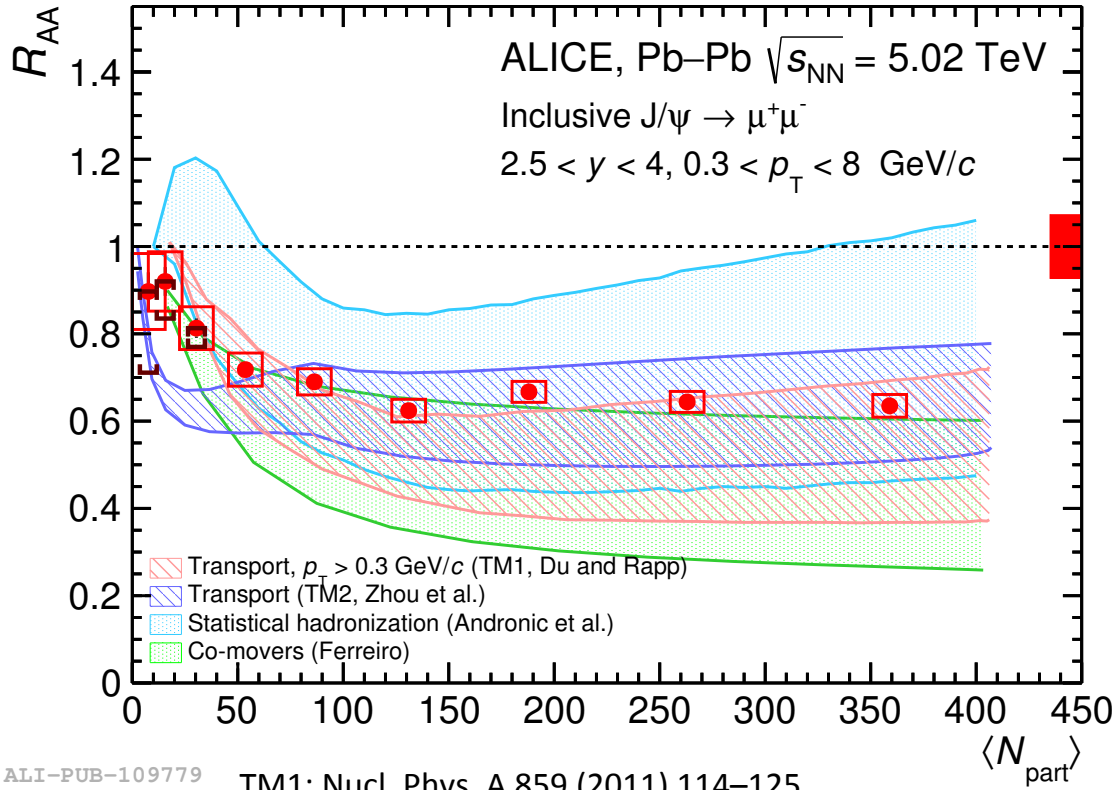
Comparison to Models

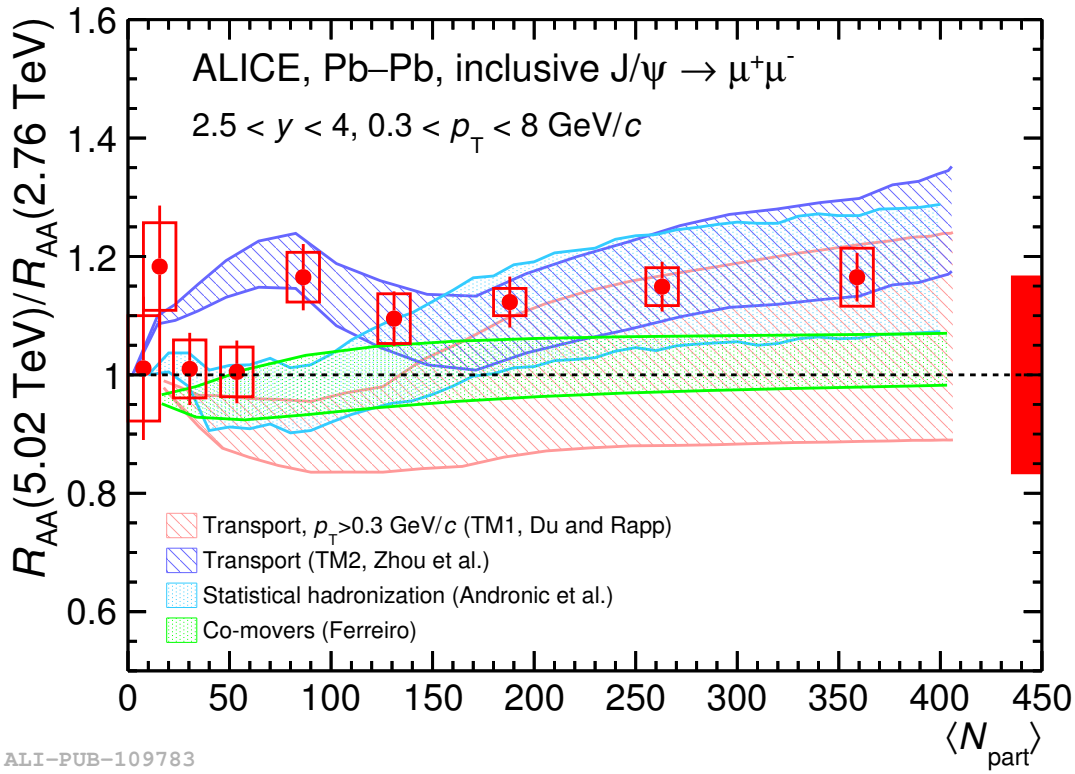


TM1: Nucl. Phys. A 859 (2011) 114–125
TM2: Phys. Rev. C 89 no. 5, 459 (2014) 054911
Stat. hadronization: Nucl. Phys. A 904-905 (2013) 535c
Co-movers: Phys. Lett. B 731 (2014) 57–63

- Large uncertainties are mainly due to the choice of $\sigma_{c\bar{c}}$ and cold nuclear matter effects
- For transport and comovers models, a better agreement is found with the upper limits
- For transport models it corresponds to an absence of nuclear shadowing
- Nuclear shadowing is a cold nuclear matter effect observed among others by ALICE in p-Pb collisions
- An absence of nuclear shadowing is an extreme assumption

- Each of the model uses a different $\sigma_{c\bar{c}}$: difficult to rule out some of the models

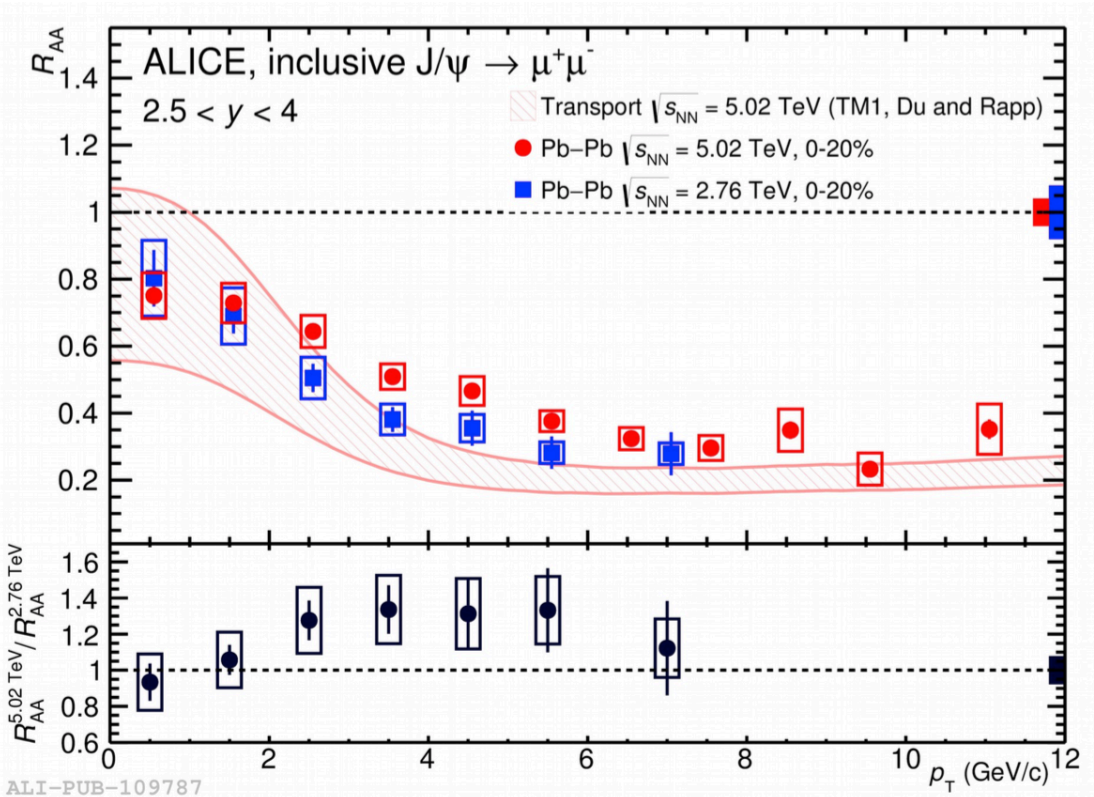
Comparison to Models



- By doing the double ratio, some of the uncertainties of the models cancel out
- The uncertainty on the T_{AA} also cancels
- The uncertainty bands in the models correspond to a 5% variation on $\sigma_{c\bar{c}}$
- When considering the non-prompt contribution, the double ratio varies within 2%

- The double ratio for central collisions (0-10%) is 1.17 ± 0.04(stat.) ± 0.20(syst.)
- **Data are compatible with the theoretical models within uncertainties.**
- **No clear centrality dependence of the ratio**.

Comparison to Models vs p_T



- R_{AA} calculation is extended to p_T = 12 GeV/c
- We observe less suppression at low p_T, as expected from models with a strong regeneration component
- Hint of an increase of the R_{AA} with respect to $\sqrt{s_{NN}}$ = 2.76 TeV is observed between 2 and 6 GeV/c

Conclusion

- The J/ψ cross section in pp collisions at $\sqrt{s}$ = 5.02 TeV has been measured both versus p_T and integrated, and the results are used as reference for the R_{AA} calculation
- The inclusive nuclear modification factor of the J/ψ in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV at forward rapidity has been measured down to $p_T = 0$
- The p_T range of the R_{AA} has been extended up to 12 GeV/c
- The centrality and p_T dependence of the R_{AA} have been studied and show :
  - An increase of the J/ψ suppression up to N_{part} = 100 followed by a plateau
  - An increase of the J/ψ suppression at high p_T with respect to low p_T
- The comparison with the 2.76 TeV results shows :
  - Results are compatible within uncertainties in the full centrality range
  - A hint of an increase with colliding energy for R_{AA} as a function of p_T for $2<p_T<6$ GeV/c
- These results are compatible within uncertainties with theoretical models and support a picture of J/ψ suppression and regeneration competing in the QGP

Perspectives

- Expected R_{AA} results for J/ψ at mid-rapidity
- Measurement of the R_{AA} for the ψ(2S) is ongoing
- Measurement of the J/ψ elliptic flow also ongoing

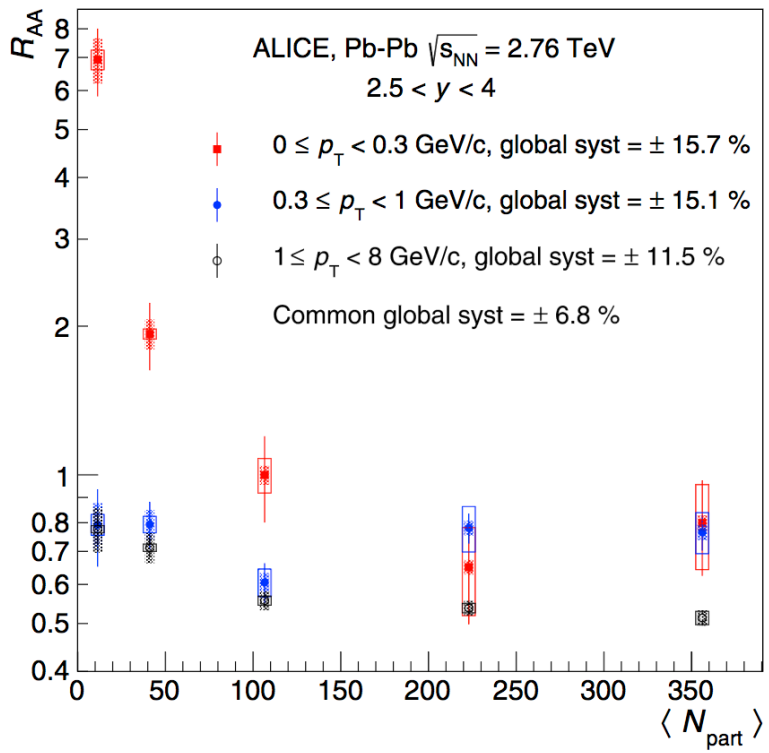
➔This should help discriminate between models

THANK YOU FOR YOUR ATTENTION!

QUESTIONS?

BACK-UP

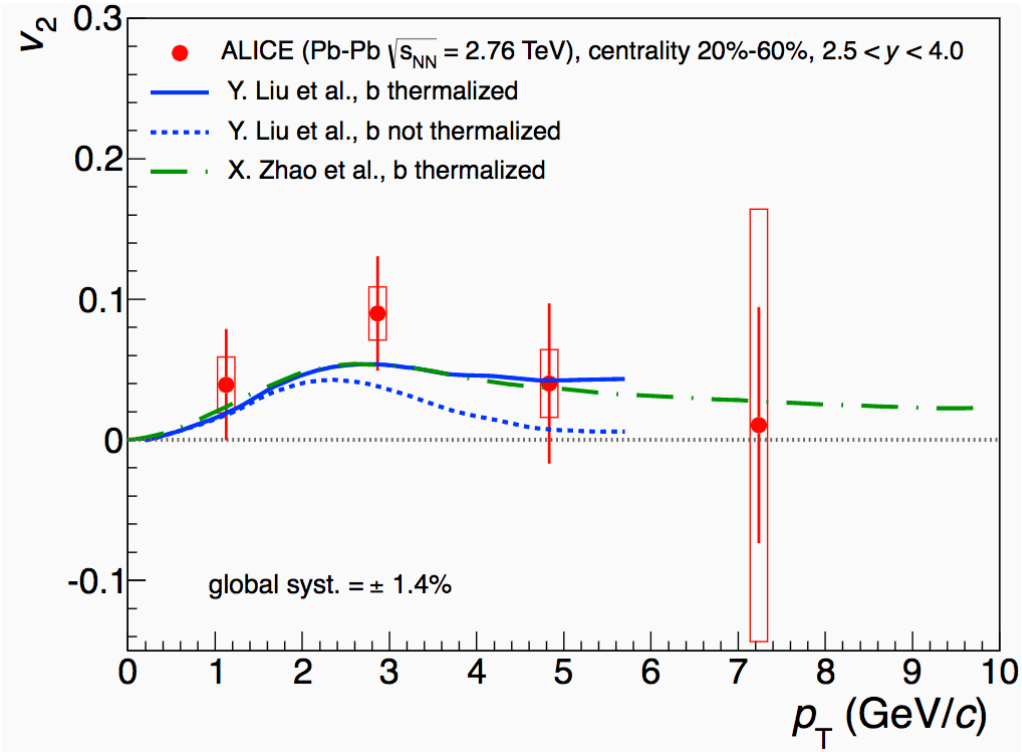
Low-p_T excess



ALICE Coll. PRL116 (2016) 222301

- Excess of J/Psi at very low pT is observed in peripheral PbPb collisions
- Photoproduction of J/ψ in Pb-Pb collisions with $b < 2R$ was proposed to be at the origin of this excess. The cut pT > 0.3 GeV/c removes ~75% of photoproduced J/ψ

Elliptic Flow



ALICE Coll. PRL111 (2013) 162301

- Hint of a J/ψ flow measured by ALICE while *v*2 compatible with zero at RHIC
- Agreement within uncertainties between data and transport model with regeneration

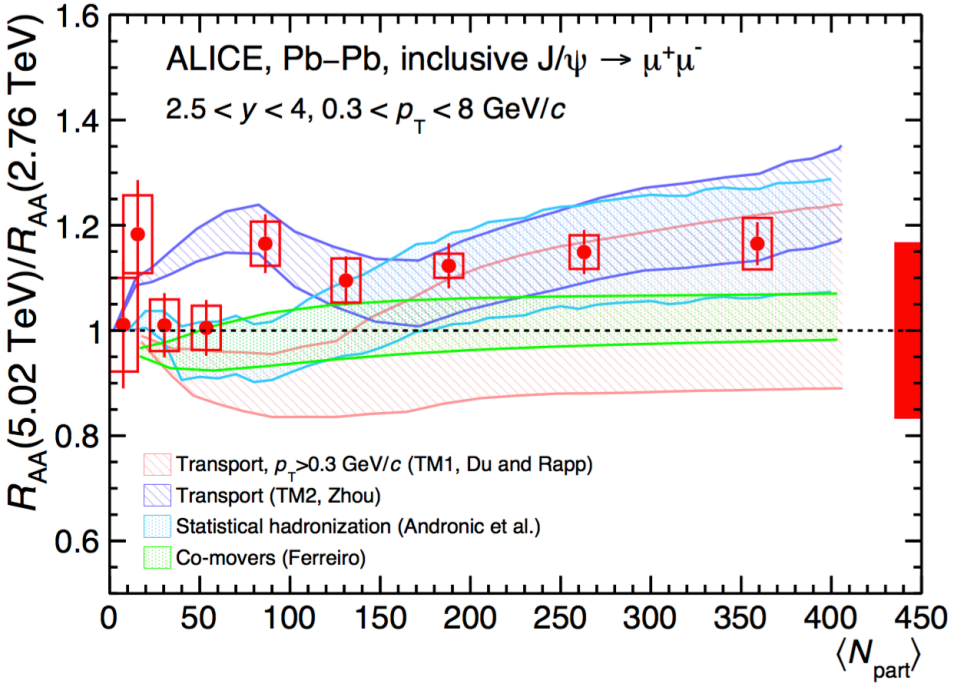
Summary of the systematic uncertainties for PbPb at 5TeV

Source	0-90% ; p_T<12 GeV/c	p_T (0-20%)	centrality
Signal extraction	1.8%	1.2% - 3.1%	1.6% - 2.8%
MC input	2.0%	2.0%	2%*
Tracking eff	3.0%	3.0%	3%*
Trigger eff	3.6%	1.5% - 4.8%	3.6%*
Matching eff	1%	1%	1%*
F_{Norm}	0.5%	0.5%*	0.5%*
T_{AA}	3.2%	3.2%*	3.1% - 7.6%
Centrality limits	0%	0.1%*	0 – 6.6%
Sigma pp	5.0%	3% - 10% + 2.1%*	5.2%*

Summary of the systematic uncertainties for pp at 5TeV

Source	$0<p_T<12$ GeV/c	p_T
Signal extraction	3%	1.5% - 9.3%
MC input	2.0%	0.7% - 1.5%
Tracking eff	1.0%	1.0%
Trigger eff	1.8%	1.5% - 1.8%
Matching eff	1%	1%
Luminosity	2.1%	2.1%*

Model parameters



Model	$\sigma_{ccbarre}$	N-N $\sigma_{J/\psi}$	Comover $\sigma_{J/\psi}$	Shadowing
TM1	0.57 mb	3.14 µb	-	EPS09
TM2	0.82 mb	3.5 µb	-	EPS09
statistical	0.45 mb	-	-	EPS09
Comovers	[0.45 ; 0.7]	3.53 µb	0.65 mb	Glauber-Gribov Theory