Recent charmonium measurements in Pb-Pb collisions with ALICE

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(On behalf of the ALICE Collaboration)

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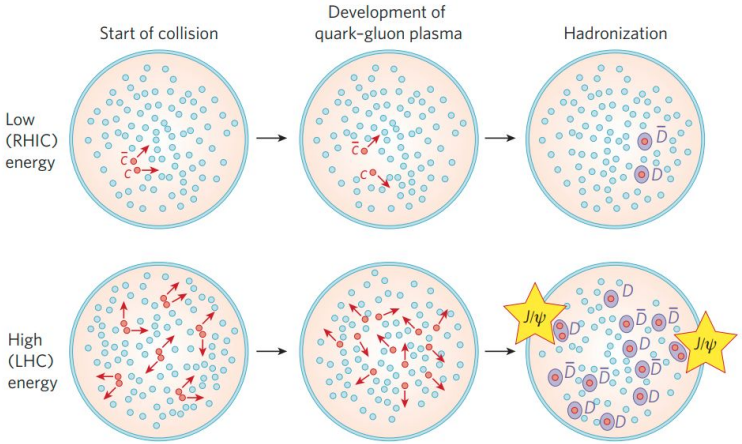
Charmonium production in Pb-Pb collisions

- **Excellent probe** of the **deconfined** medium, quark-gluon plasma (QGP), produced in high energy nuclear collisions
  - **Dissociation** of charmonium states in the hot nuclear medium
  - **Recombination** of charm and anti-charm quarks

A Rothkopf, *Phys.Rept.* 858 1-117 ,
T Matsui & H Satz *Phys.Lett.B 178 (1986) 416-422*

P Braun-Munzinger and J Stachel *Phys.Lett. B490 (2000) 196-202*,
R Thews *et al* *Phys.Rev.C* 63:054905

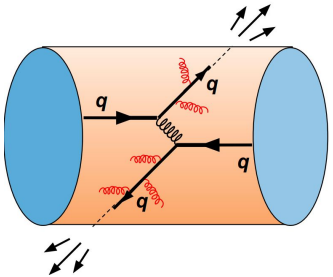


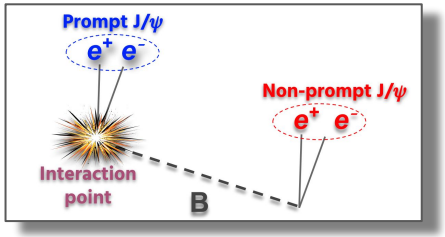
P Braun-Munzinger and J Stachel, *Nature volume 448, (2007)*

Non-prompt J/ψ: sensitive to the interaction of b quarks within the medium

Parton's mass dependent energy loss within the medium

⇒ transport properties of the QGP





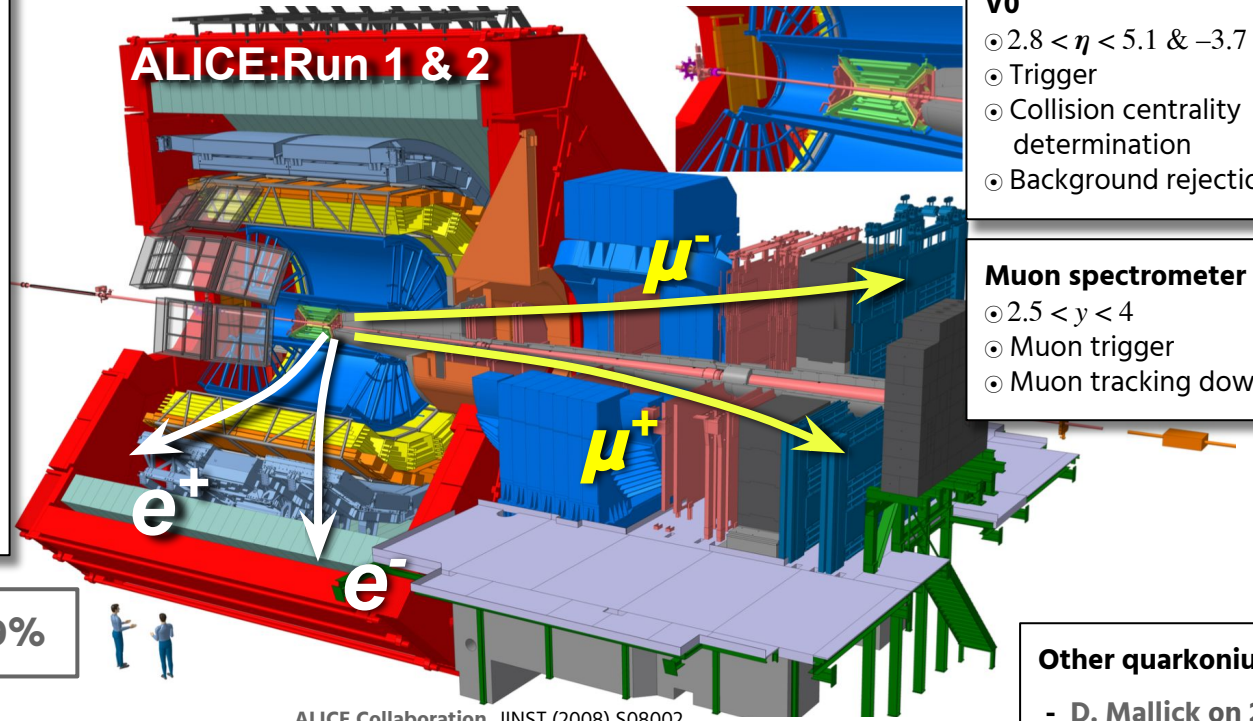
Charmonium reconstruction in ALICE

Central barrel detectors

1) ITS
- $|\eta| < 0.9$
- Tracking
- Primary and secondary B vertex reconstruction

2) TPC
- $|\eta| < 0.9$
- Tracking
- Particle identification

Excellent tracking and PID capabilities down to very low momentum



V0
- $2.8 < \eta < 5.1$ & $-3.7 < \eta < -1.7$
- Trigger
- Collision centrality determination
- Background rejection

Muon spectrometer
- $2.5 < y < 4$
- Muon trigger
- Muon tracking down to very low p_T

BR ($J/\psi \rightarrow \ell^+\ell^-$) ~ 5.9%

ALICE Collaboration, JINST (2008) S08002

- Inclusive quarkonium measurements down to p_T = 0 at mid and forward rapidity
- Prompt and non-prompt J/ψ separation at midrapidity, down to p_T = 1.5 GeV/c in Pb–Pb collisions

Other quarkonium talks by:
- D. Mallick on 21.08 at 10:00
- W. Guo on 23.08 at 17:10

J/ψ production

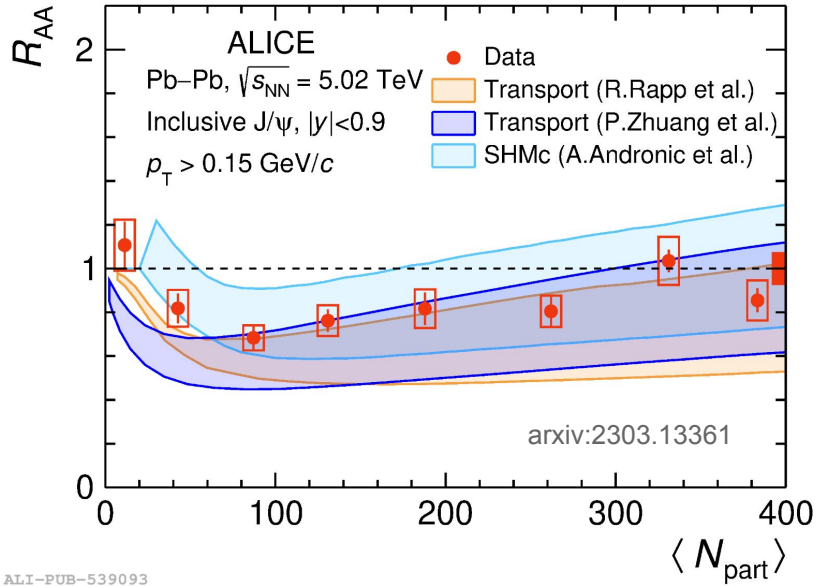
Inclusive J/ψ production

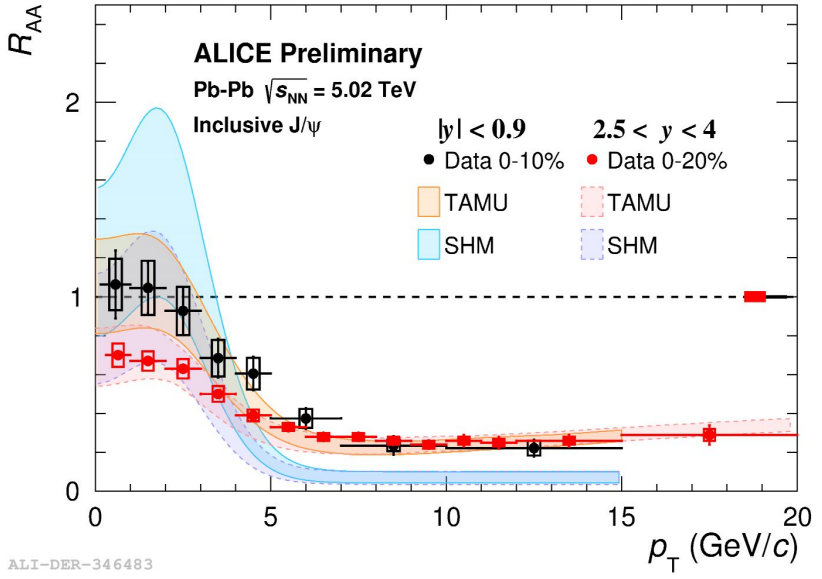
- Modifications observed for inclusive J/ψ production at mid and forward rapidity
- Production is largely suppressed at high p_T
- Indication of regeneration at low p_T especially in most central collisions
- Models including dissociation and regeneration effects
  - TAMU describes the results in all p_T and centrality ranges
  - SHMc describes the results at low p_T , overestimates suppression at high p_T

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

$R_{AA} = 1$ ⇒ Pb-Pb behaves as scaled pp
$R_{AA} \neq 1$ ⇒ modifications of the production in Pb–Pb by cold and/or hot nuclear matter

TAMU/Transport: R. Rapp et al: Nucl.Phys.A 943 (2015) 147-158
Transport: P. Zhuang et al: Phys. Rev. C **89**, 054911
SHM/SHMc: A. Andronic et al: Phys. Lett. B797 (2019) 134836





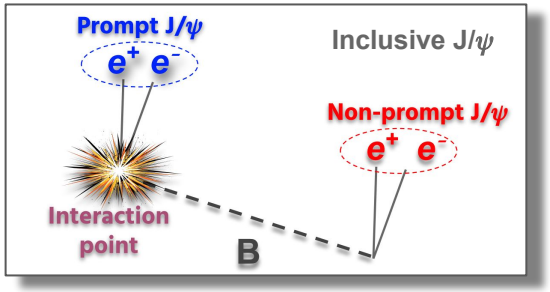
ALI-PUB-539093
ALI-DER-346483

(Non-) prompt J/ψ production

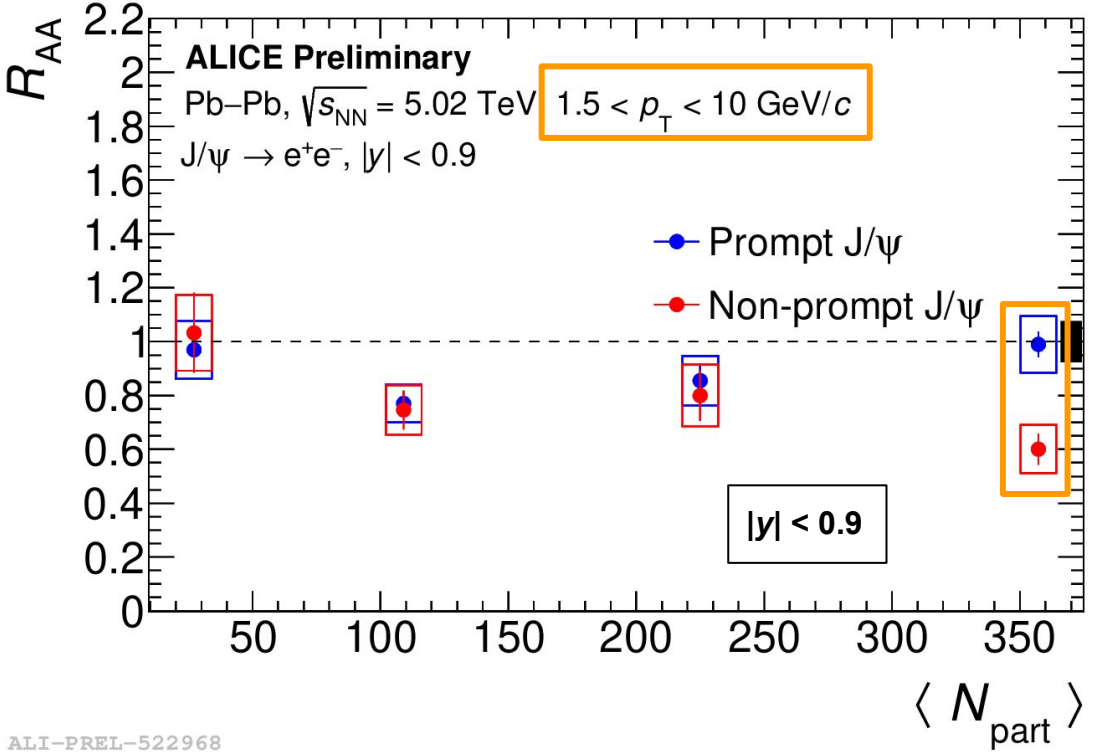
- In peripheral and semi-central collisions, similar modifications for prompt and non-prompt J/ψ production

- In the most central collisions, prompt J/ψ production significantly less suppressed in comparison to non-prompt J/ψ

  - Indication of large contribution from regeneration for prompt J/ψ

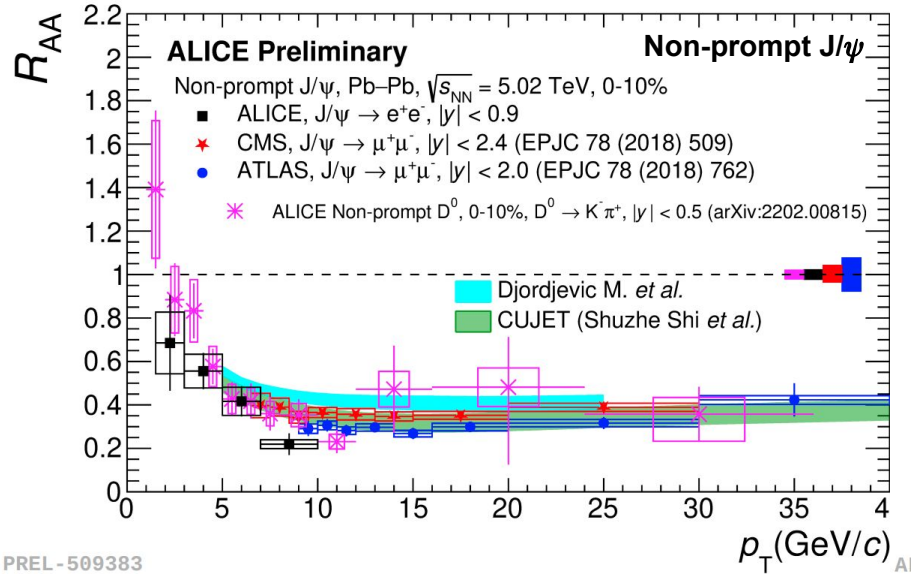


Paper will appear in arXiv soon



(Non-) prompt J/ψ production

- Prompt & non-prompt J/ψ R_{AA} in agreement with ATLAS and CMS measurements in the overlapping p_T ranges
- Similar R_{AA} values for non-prompt J/ψ and non-prompt D^0
- Non-prompt J/ψ R_{AA} consistent with models implementing collisional + radiative energy loss for $p_T > 5$ GeV/c
- Prompt J/ψ R_{AA} described by models including quarkonium dissociation (regeneration at the phase boundary) at high (low) p_T



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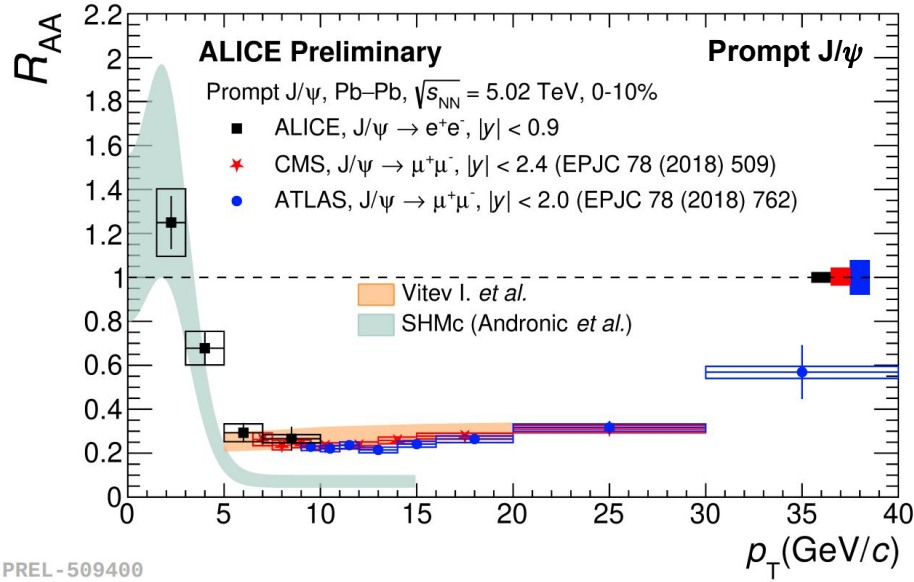


ALI-PREL-509400

CUJET, Shi S et al: Chin.Phys.C 43 (2019) 4, Chin.Phys.C 42 (2018) 10,
Djordjevic M. et al: arXiv:2110.01544

Vitev et al: arXiv:1906.04186,arXiv:1709.02372
SHMc, Andronic et al: JHEP07 (2021) 035

J/ψ polarization

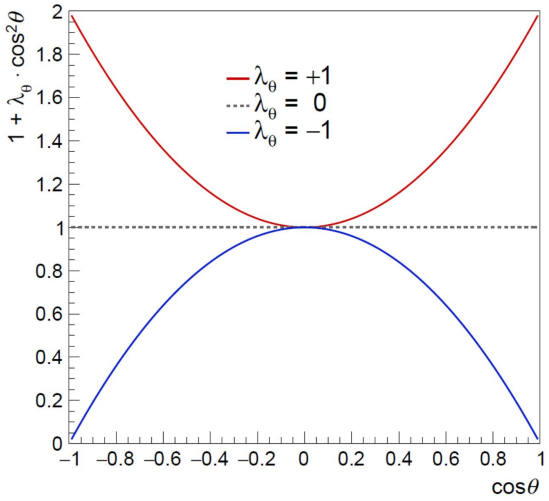
Polarization in Pb-Pb collisions

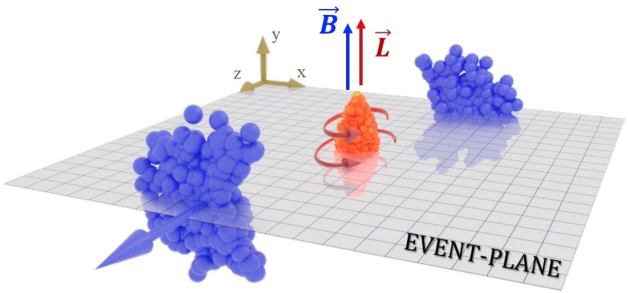
- Particle's spin alignment with respect to a given direction
- Angular distribution of dileptons:

$$W(\cos\theta, \phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$$

$(\lambda_\theta \ \lambda_\phi \ \lambda_{\theta\phi})$

- $(0, 0, 0)$ ⇒ No polarization
- $(-1, 0, 0)$ ⇒ Longitudinal polarization
- $(+1, 0, 0)$ ⇒ Transverse polarization



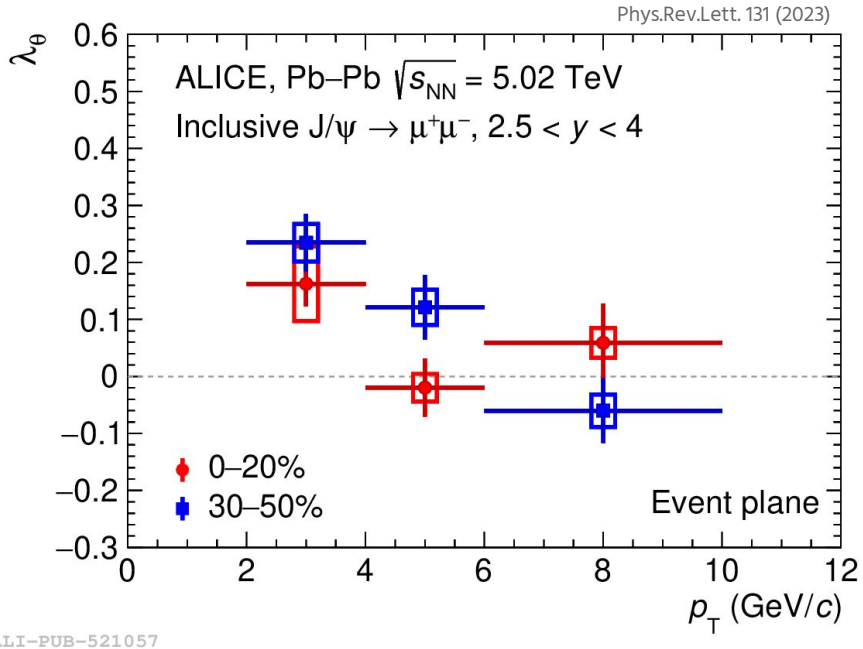


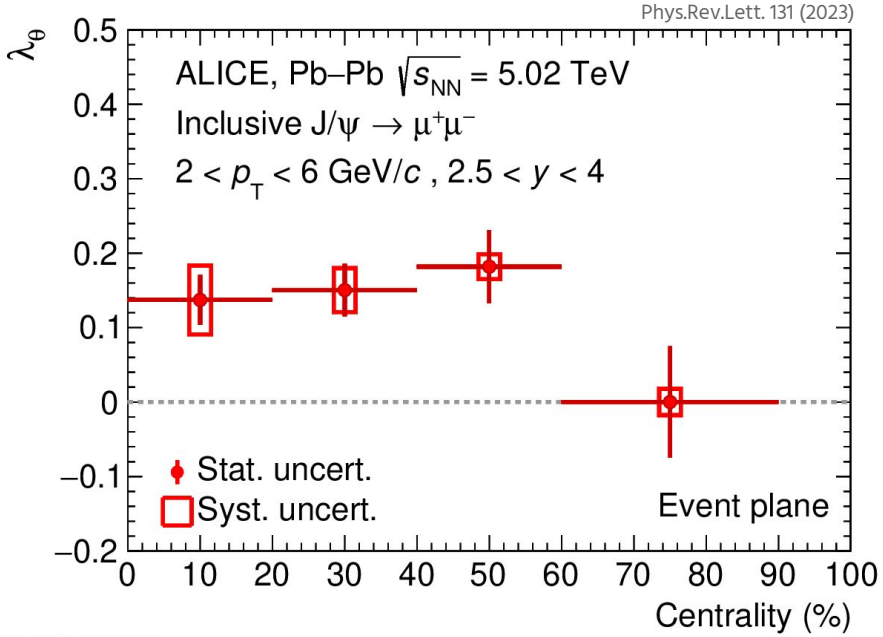
- Large magnetic field (**B**) and/or angular momentum (**L**) F. Becattini et al, Phys. Rev. C 77, 024906 , D. Kharzeev et al, Nuclear Physics A, 803
  - can affect J/ψ spin alignment w.r.t. to a polarization axis orthogonal to the **event plane**
  - Significant spin alignment observed for light vector mesons (**K*** and ϕ), ALICE, Phys. Rev. Lett. 125, 012301

Inclusive J/ψ polarization

First polarization measurement with respect to event plane

- Significant polarization (3.9σ) at low p_T in 30-50% centrality interval
- Significant polarization (3.5σ) observed in 40-60%
- Similar to **K*** and **ϕ:** maximum polarization in semicentral collisions at low p_T ALICE, Phys. Rev. Lett. 125, 012301





ALI-PUB-521057

ALI-PUB-521052

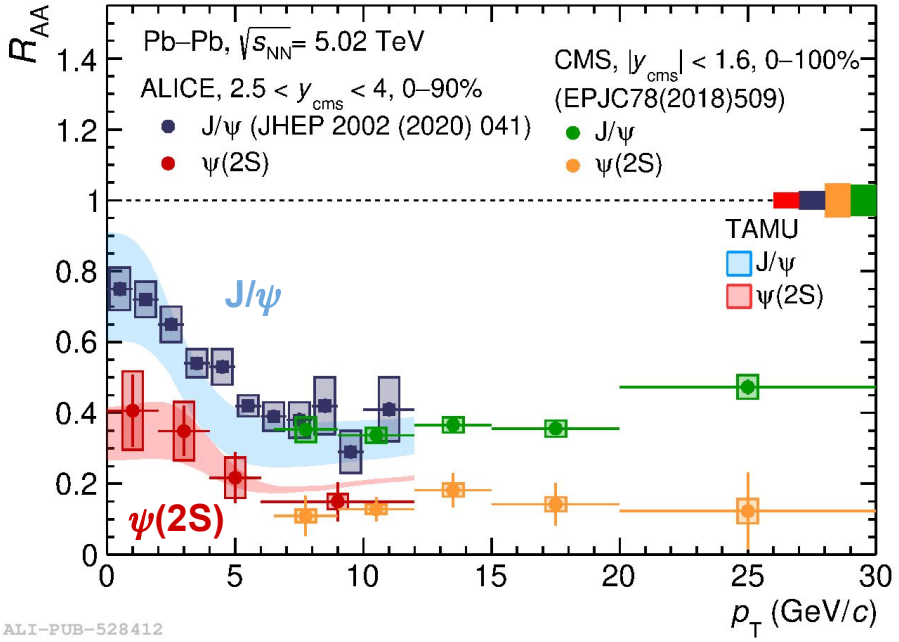
ψ(2S) production

Inclusive ψ(2S) production

- Larger suppression for ψ(2S) than J/ψ
  - Sequential suppression in medium at high p_T
- Indication of regeneration at low p_T

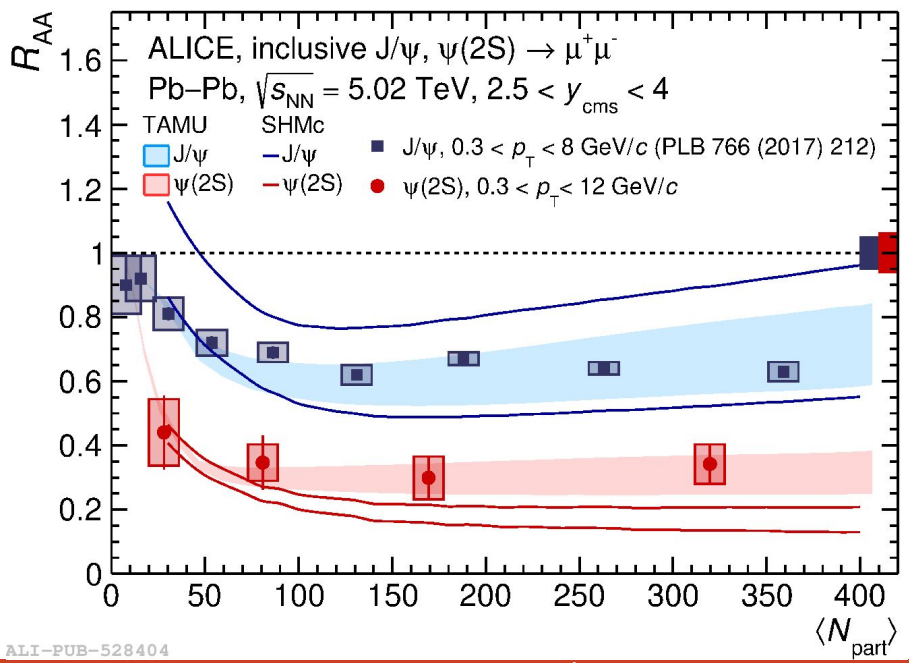
- No significant centrality dependence for ψ(2S)
- TAMU is consistent with measurements while SHMc underpredicts results in central collisions

arXiv:2210.08893



ALI-PUB-528412

arXiv:2210.08893

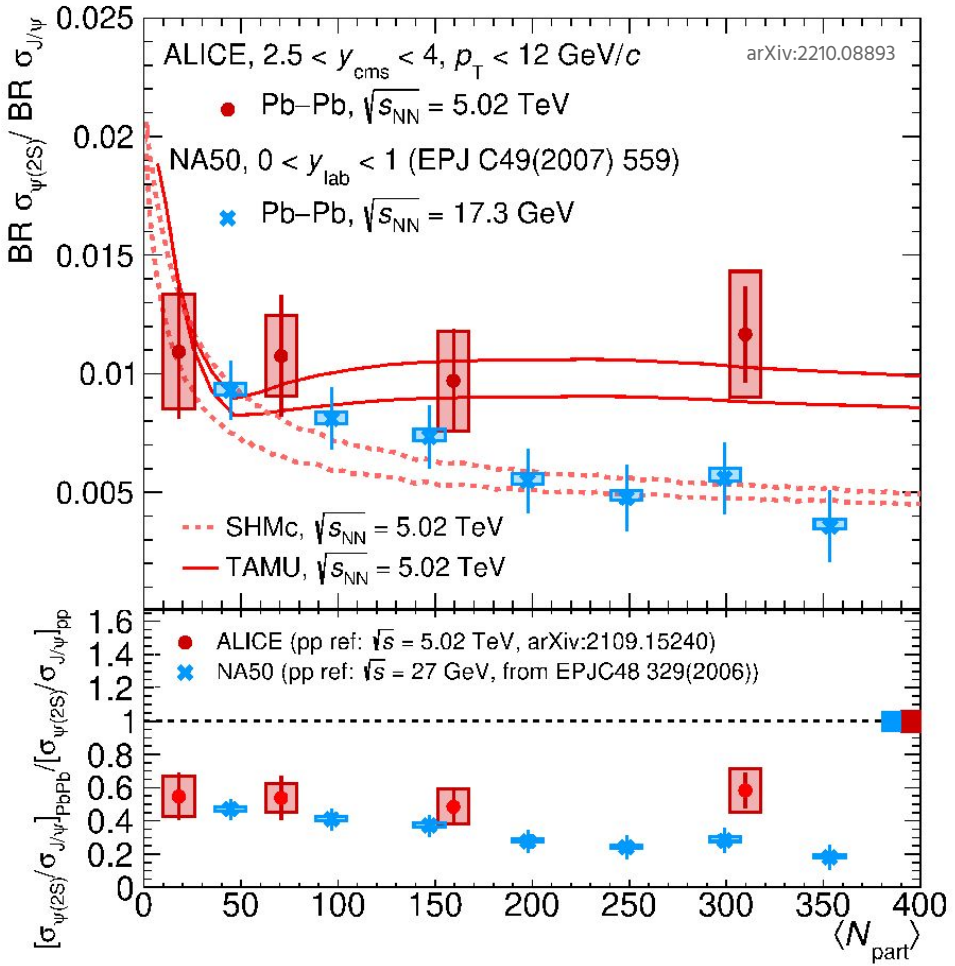


ALI-PUB-528404

Inclusive ψ(2S) production

Inclusive ψ(2S)-to-J/ψ ratio vs centrality

- Larger ratio at LHC than at SPS in central events
- No significant centrality dependence at the LHC
- TAMU describes the ratio while SHMc underestimates it in central collisions



Summary

Summary

- J/ψ production
  - Inclusive and prompt R_{AA} measurements are compatible with an interplay between dissociation and regeneration mechanism, stronger effects in central collisions
  - Non-prompt J/ψ, consistent with b-quark energy loss at high p_T

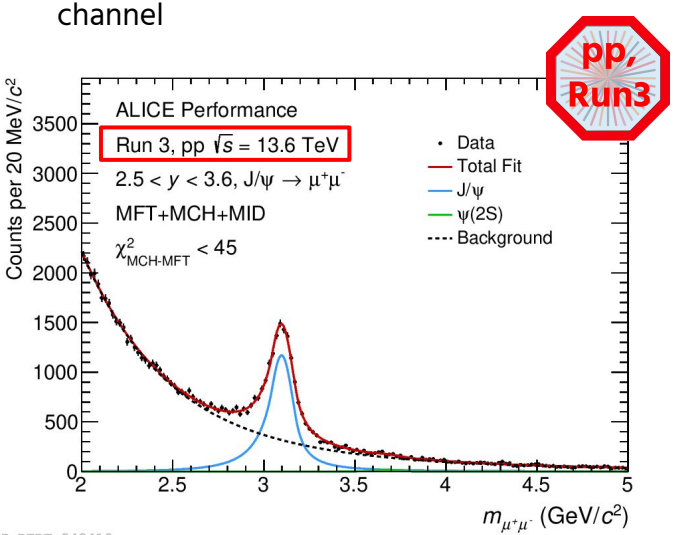
- J/ψ polarization
  - Significant polarization observed in the event plane reference frame
    - Interpretation of results requires inputs from theoretical models

- ψ(2S) production
  - ψ(2S) more suppressed than J/ψ ⇒ hints at sequential suppression
  - Indication of regeneration at low p_T also for excited charmonium states

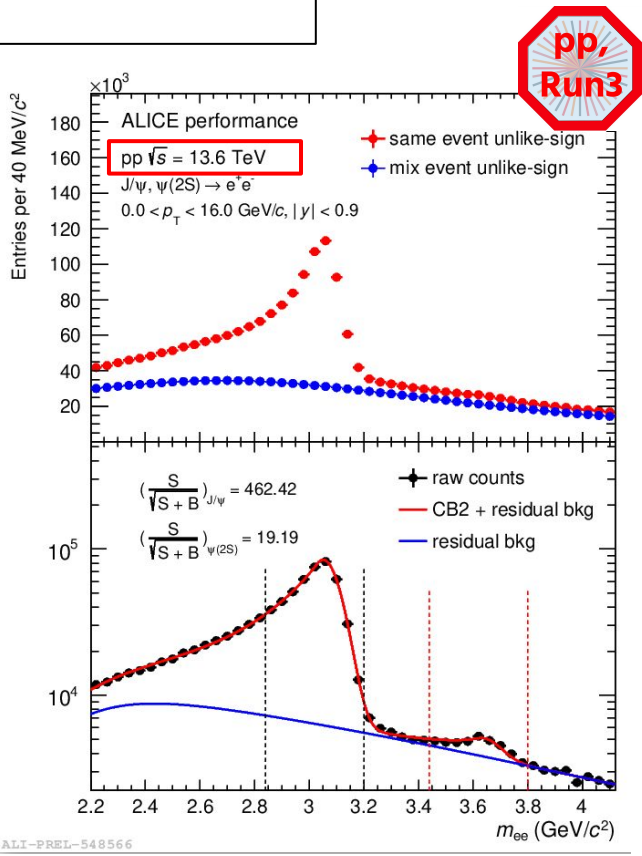
Outlook: LHC Run 3 (2022-2024)

Exciting physics program with many new quarkonium measurements… stay tuned!
Increase by **x 50** compared to Run 2 in Pb–Pb collisions

Muon Forward Tracker will enable prompt/non-prompt charmonia separation at forward rapidity (-3.6 < η < -2.5) in the dimuon decay channel



Upgraded ITS: Improved impact parameter resolution by factor of 3 (5) in transverse (longitudinal) direction, improved vertexing and tracking precision



Backup

Summary

- J/ψ production
  - Inclusive and Prompt R_{AA} measurements are compatible with an interplay between dissociation and regeneration mechanism, stronger effects in central collisions
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- ψ(2s) production
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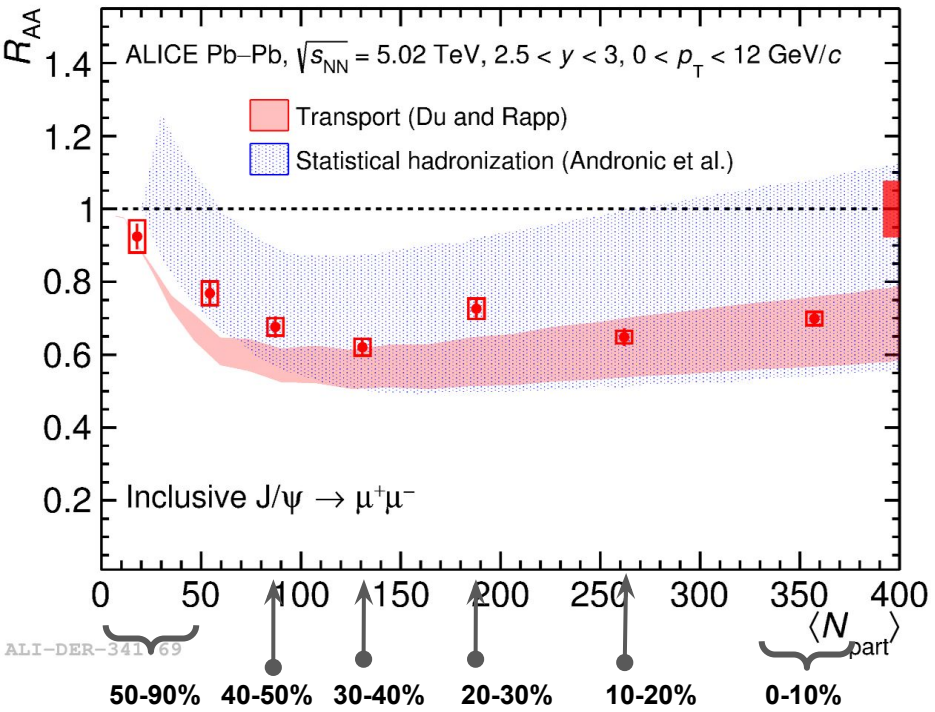
  - Hints at regeneration at low p_T also for excited charmonium states

- Outlook (?):
  - Detector Upgrade,
  - Improved Psi(2s), non-prompt J/ψ production,

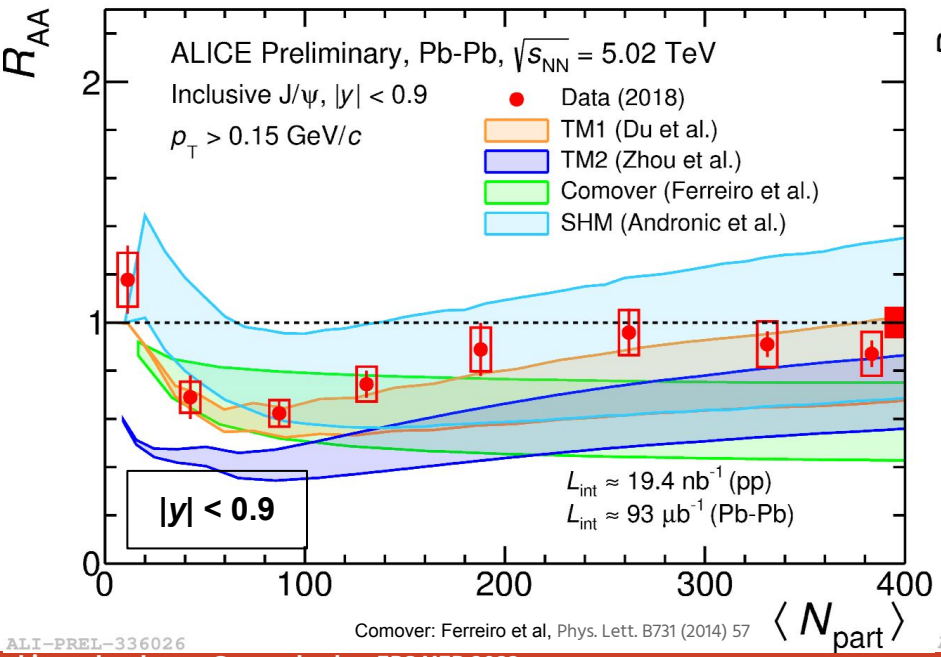
<Npart> and centrality in Pb-Pb

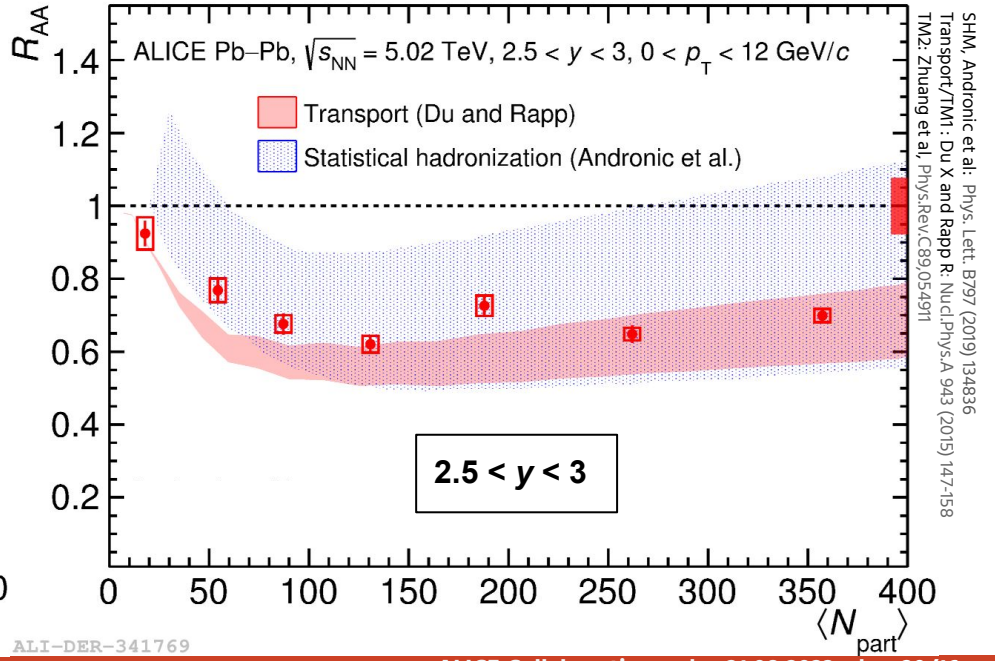
Centrality	$\langle T_{AA} \rangle (\mathrm{mb}^{-1})$	$\langle N_{\mathrm{part}} \rangle$
0-5%	26.08 ±0.18	383.40 ±0.57
0-10%	20.44 ±0.17	331.20 ±1.03
10-20%	14.4 ±0.13	262.00 ±1.15
20-30%	8.77 ±0.10	187.90 ±1.34
30-40%	5.09 ±0.08	130.80 ±1.33
40-50%	2.75 ±0.05	87.14 ±0.93
50-70%	0.98 ±0.02	42.65 ±0.63
70-90%	0.016 ±0.001	11.34 ±0.13



Inclusive J/ψ production in Pb-Pb collisions

- Modifications observed with respect to pp, at central and forward rapidity
- R_{AA} increases from peripheral to the most central collisions at midrapidity, described by the models including J/ψ dissociation and regeneration mechanism
- R_{AA} exhibits a flat behaviour at forward rapidity





Inclusive J/ψ production

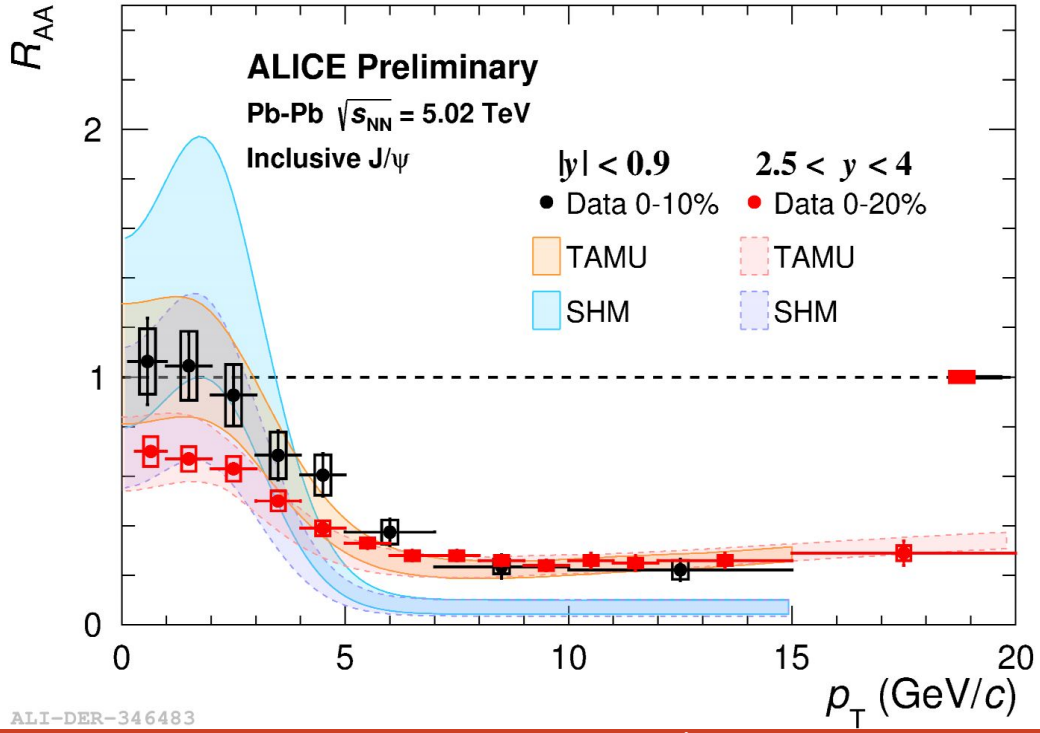
- Modifications observed for inclusive J/ψ production at mid and forward rapidity
- Suppressed production for p_T > 5 GeV/c ⇒ Dissociation and energy loss effects at play
- Lower suppression for p_T < 5 GeV/c, in particular at midrapidity compared to forward rapidity ⇒ consistent with J/ψ regeneration
- Models including J/ψ regeneration throughout the medium evolution (TAMU) or at the phase boundary (SHM), describe the R_{AA} at low p_T

SHM: Andronic et al: Phys. Lett. B797 (2019) 134836
TAMU: Du X and Rapp R: Nucl.Phys.A 943 (2015) 147-158

Nuclear Modification factor

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

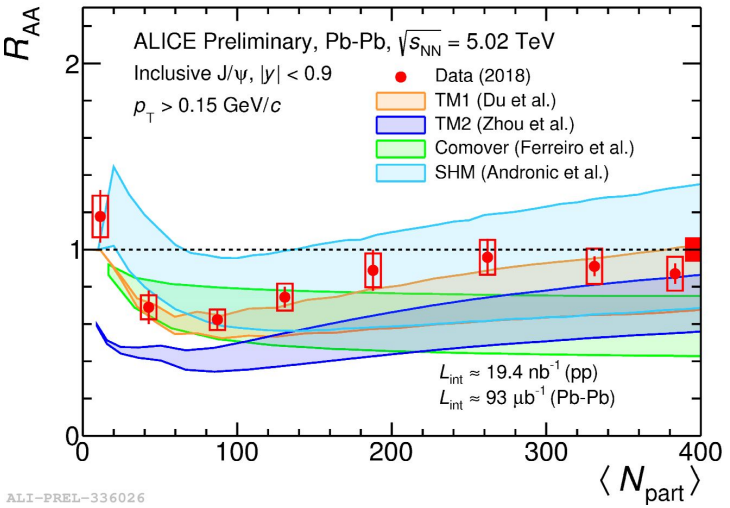
R_{AA} = 1 ⇒ Pb-Pb behaves as scaled pp
R_{AA} ≠ 1 ⇒ modifications of the production in Pb–Pb by medium



Charmonium Models in Pb-Pb

Comover model
- J/ψ suppression and dissociation via co-moving
- Partonic/hadronic interaction of J/ψ with medium
- Dissociation Π density of comovers
- Regeneration Π c quark cross section

Π = “depends on”



Transport models
- Boltzmann equation
- With dissociation and regeneration effects
- Idea hydrodynamics

TM1 (Rapp et al)
- Dissociation rate Π LQCD inspired binding energy of charmonia
- Regeneration, c quarks reach stat equilibrium after relaxation time of few fm/c

TM2 (Zhou et al)
- Dissociation rate Π $r^2_{charmonia}$
- Regenration, same cross section as dissociation, thermalized distribution of c quarks

Charmonium Models in Pb-Pb

SHM

- HQ produced via hard parton scatterings initially
- All J/ψ melt in medium
- Form bound states at the phase boundary according to thermal weights of the bound state
- Core-corona model, core - high density medium (QGP), corona - < 10% density of core, pp like conditions

At higher p_T, lack of description might be related to:

- Underestimate the survived primary J/ψ yield during QGP phase
- Hydro inspired freezeout hypersurface underestimate the radial flow of c quarks