The measurements of J/ψ production in Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with ALICE

Pengzhong Lu (for the ALICE Collaboration)

University of Science and Technology of China
GSI Helmholtzzentrum für Schwerionenforschung GmbH

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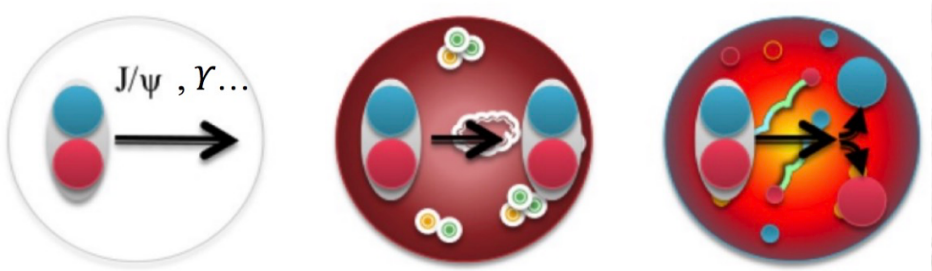
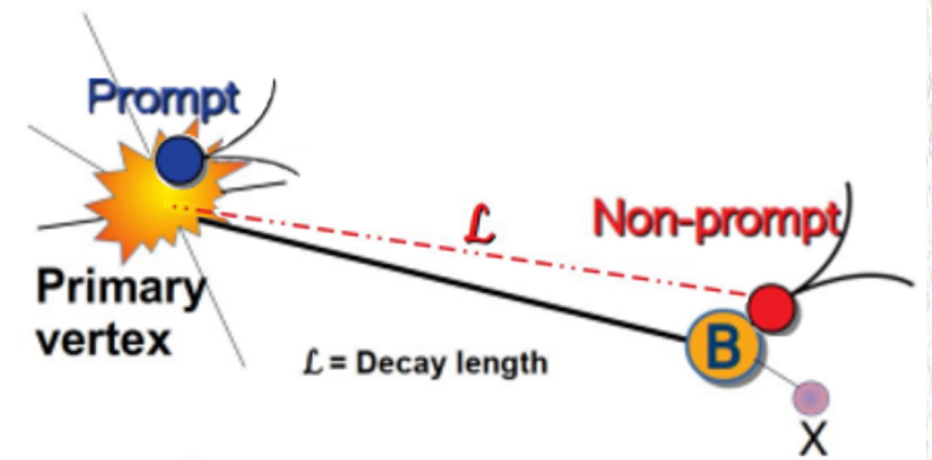
J/ψ -- excellent probe of the medium

❀ Probe of the QGP:

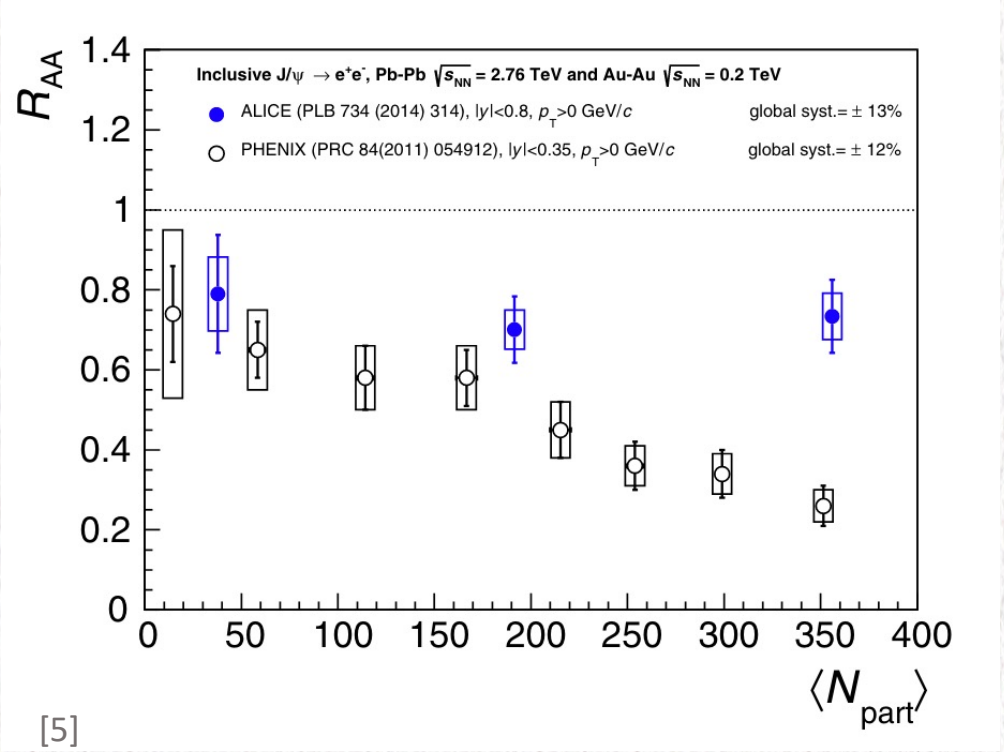
- ✓ Bound state of $c\bar{c}$
- ✓ Charm quarks produced early in the collisions and go through the whole evolution of the QGP
- ✓ Prompt and non-prompt J/ψ reflect medium effects on charm and beauty quarks respectively





J/ψ -- excellent probe of the medium

- Probe of the QGP:
  - ✓ Prompt J/ψ is sensitive to:
    - color screening [1] and dynamic dissociation [2] (suppression)
    - regeneration [3][4], which compete with suppression



[5]

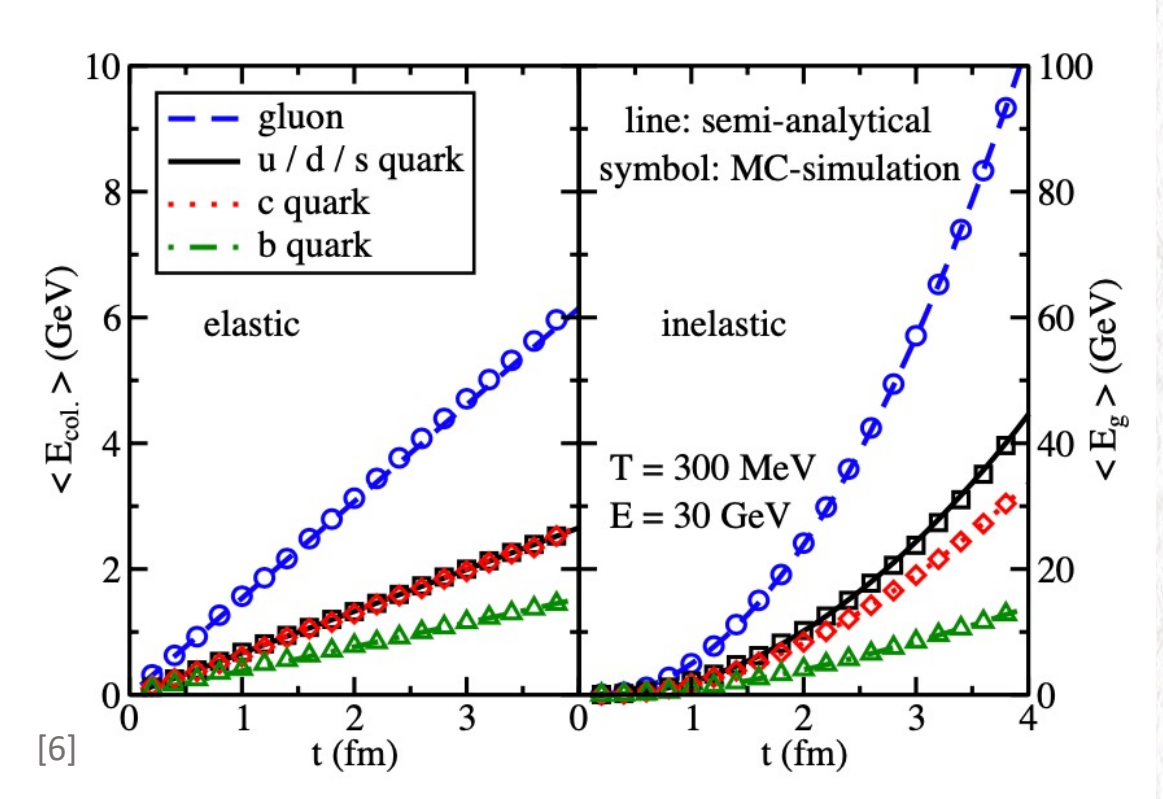
$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2 \sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

[1] T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416–422
[2] Y. Liu, N. Xu, P. Zhuang, Phys. Lett. 724, 73–76 (2013)
[3] Braun-Munzinger, P., Stachel, J., Nature 448, 302–309 (2007)
[4] Du, X. & Rapp, R., Nuclear Physics A 943, 147–158 (2015)
[5] Andronic, A. et al., Eur. Phys. J. C 76, 107 (2016)

J/ψ -- excellent probe of the medium

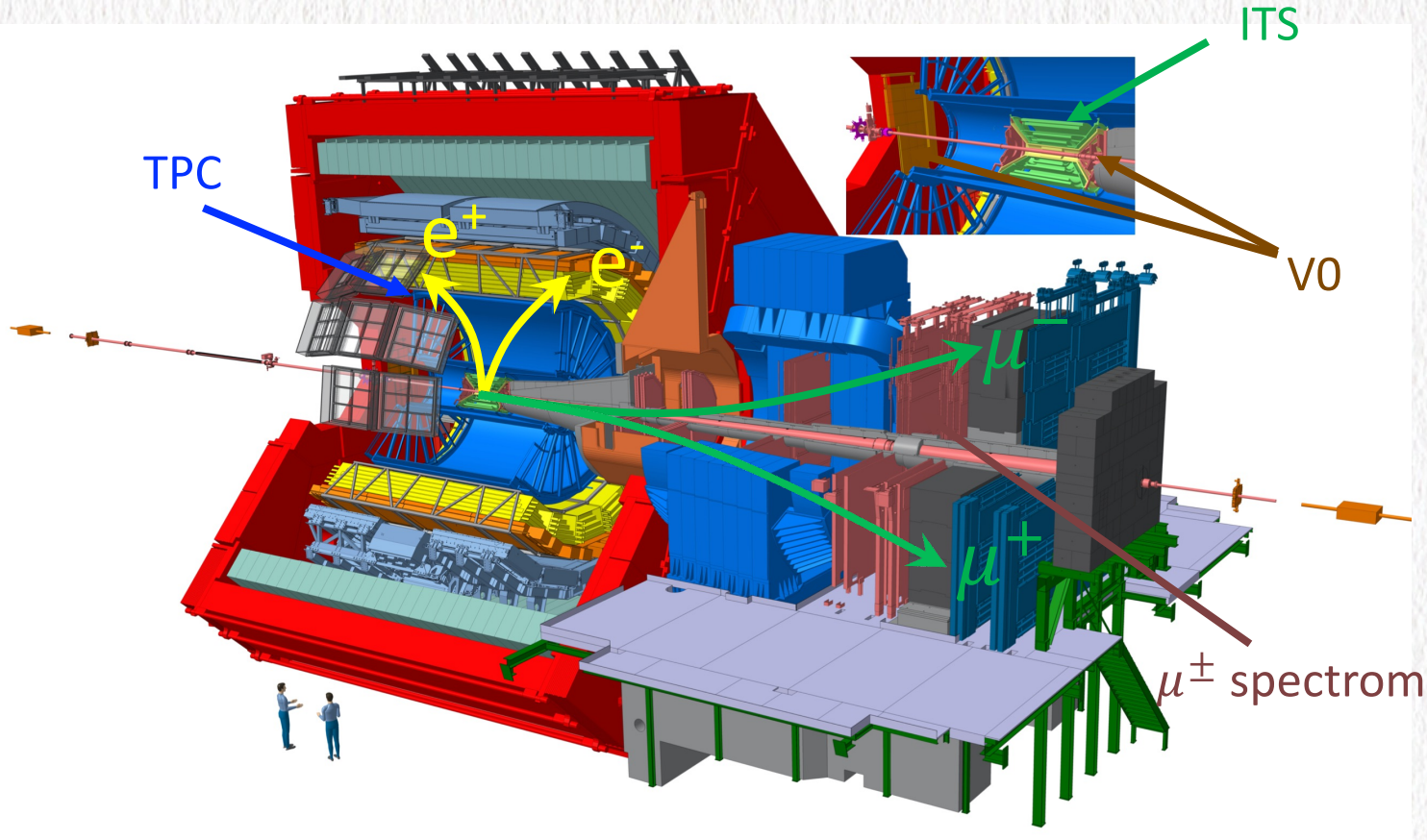
❀ Probe of the QGP:

- ✓ Prompt J/ψ is sensitive to:
  - ❉ color screening and dynamic dissociation
  - ❉ regeneration, compete with suppression
  - ❉ reflects charm quark energy loss
- ✓ Non-prompt J/ψ:
  - ❉ reflects beauty quark energy loss
  - ❉ mass dependent parton energy loss [6] in the QGP



[6] Cao, S., Luo, T., Qin, G.-Y. & Wang, X.-N., Physics Letters B **777**, 255–259 (2018)

ALICE Detector (Run 2)



- ☐ **T**ime **P**rojection **C**hamber
  - ✓ Tracking, Particle identification
- ☐ **I**nner **T**racking **S**ystem
  - ✓ Tracking, Vertex reconstruction
- ☐ **V0** Detector
  - ✓ Centrality determination
  - ✓ Trigger
  - ✓ Background rejection
- ☐ **$\mu^\pm$ spectrometer**
  - ✓ Trigger
  - ✓ $\mu^\pm$ Tracking

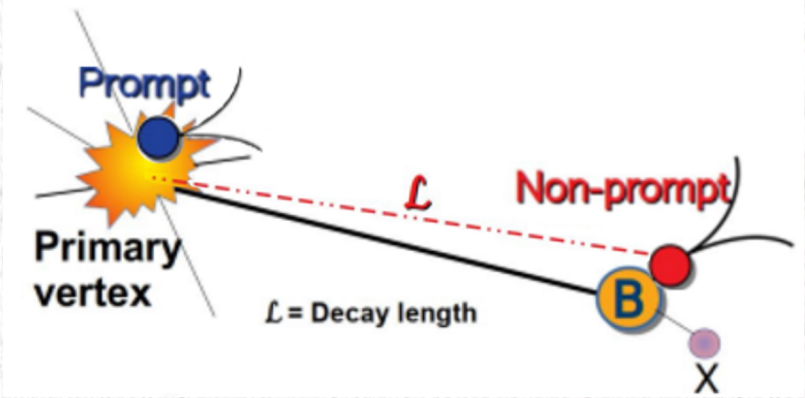
- ❀ $|y| < 0.9$, J/$\psi \rightarrow e^+e^-$
- ❀ $2.5 < y < 4.0$, J/$\psi \rightarrow \mu^+\mu^-$

- ❀ Inclusive J/ψ can be measured down to zero p_T both at mid- and forward rapidity
- ❀ Separate prompt and non-prompt components at midrapidity

Separation of prompt and non-prompt J/ψ at midrapidity

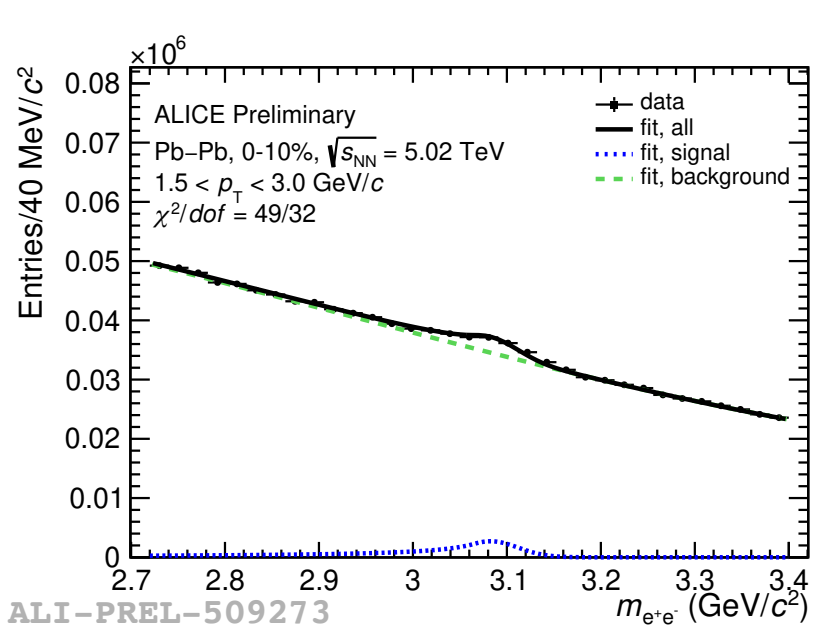
2D maximization likelihood fitting method:

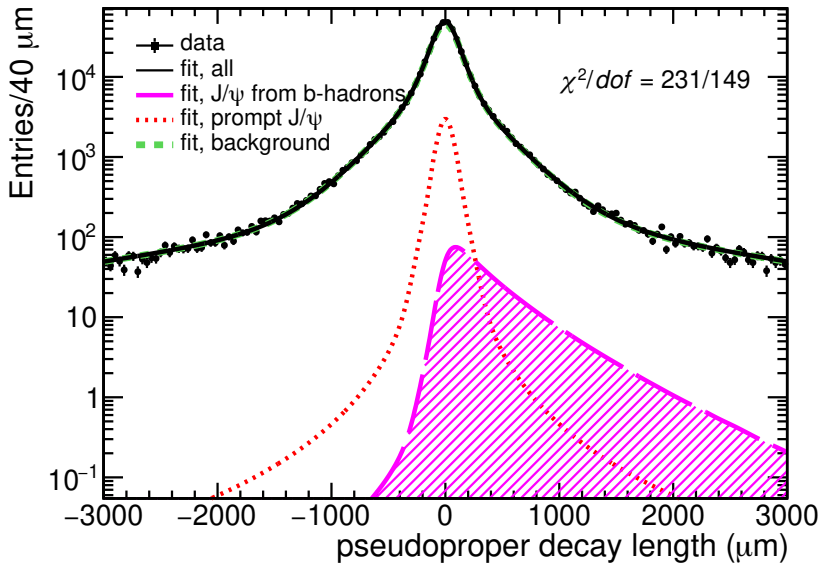
$m_{e^+e^-}$ and pseudo-proper decay length (x)



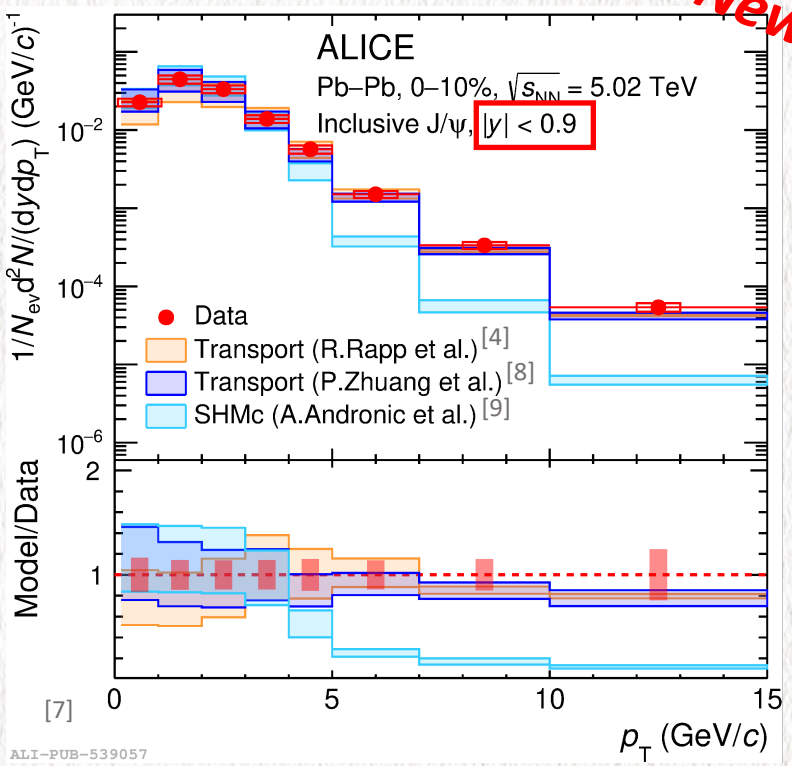
$$L_{xy} = \vec{L} \cdot \vec{p}_{\mathrm{T}}^{\,\mathrm{J}/\psi} / p_{\mathrm{T}}^{\mathrm{J}/\psi}$$

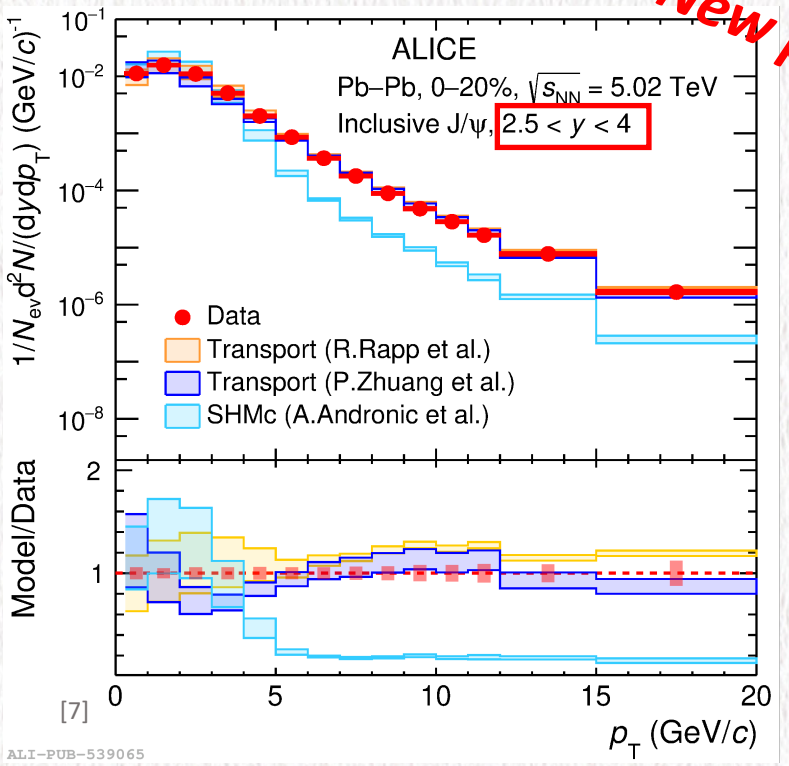
$$x = \frac{c \times L_{xy} \times m_{\mathrm{J}/\psi}}{p_{\mathrm{T}}^{\mathrm{J}/\psi}}$$





Inclusive J/ψ -- yield

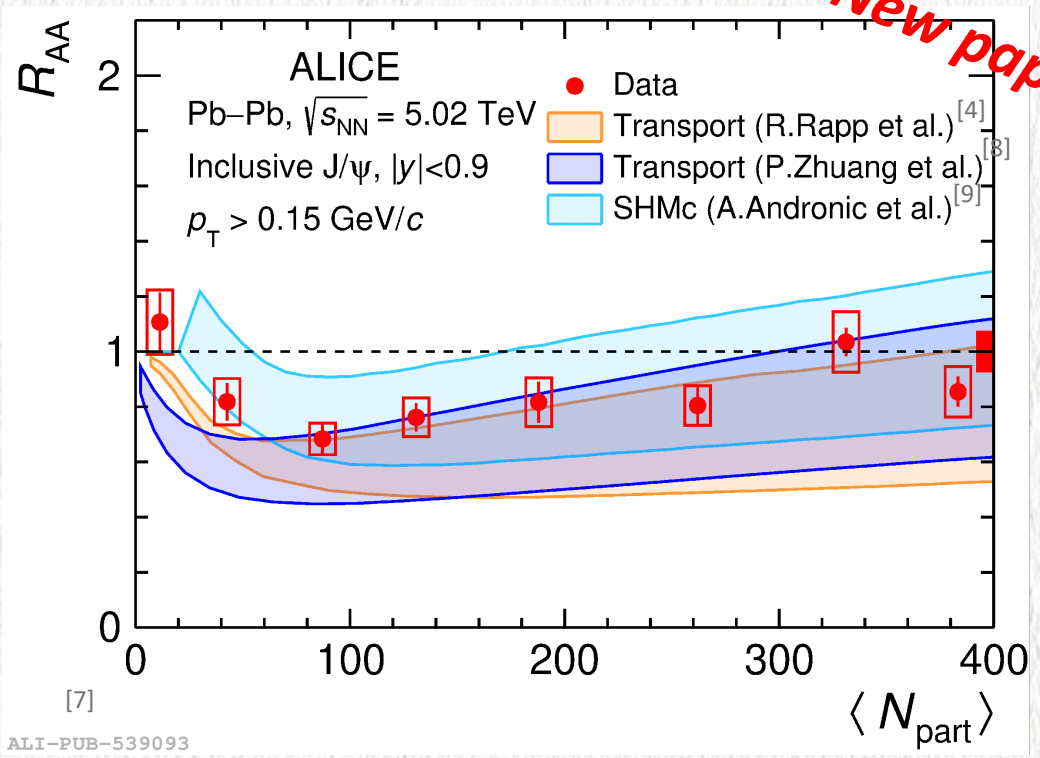


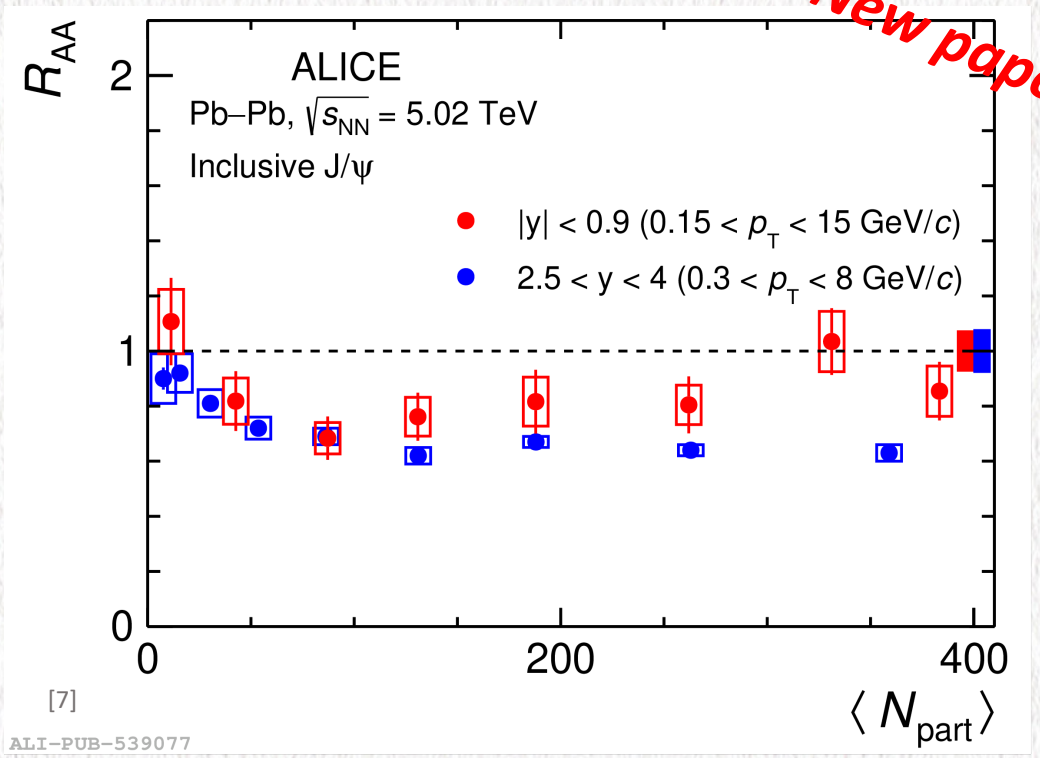


- $p_T > 0.15$ (0.3) GeV/c at central (forward) rapidity to reject J/ψ yield from photoproduction
- Model uncertainties are mainly from the total charm cross section and cold nuclear matter effects (CNM)
- Both transport models describe measurements in central collisions at mid- and forward rapidity
- SHMc agrees with data at low p_T very well, underestimates the yields at high p_T

[4] Du, X. & Rapp, R., Nuclear Physics A 943, 147–158 (2015)
[7] ALICE, arXiv:2303.13361
[8] Zhou, K., Xu, N., Xu, Z. & Zhuang, P., Phys. Rev. C 89, 054911 (2014)
[9] Andronic, A., Braun-Munzinger, P. et al, Physics Letters B 797, 134836 (2019)

Inclusive J/ψ -- R_{AA} vs. $\langle N_{part} \rangle$

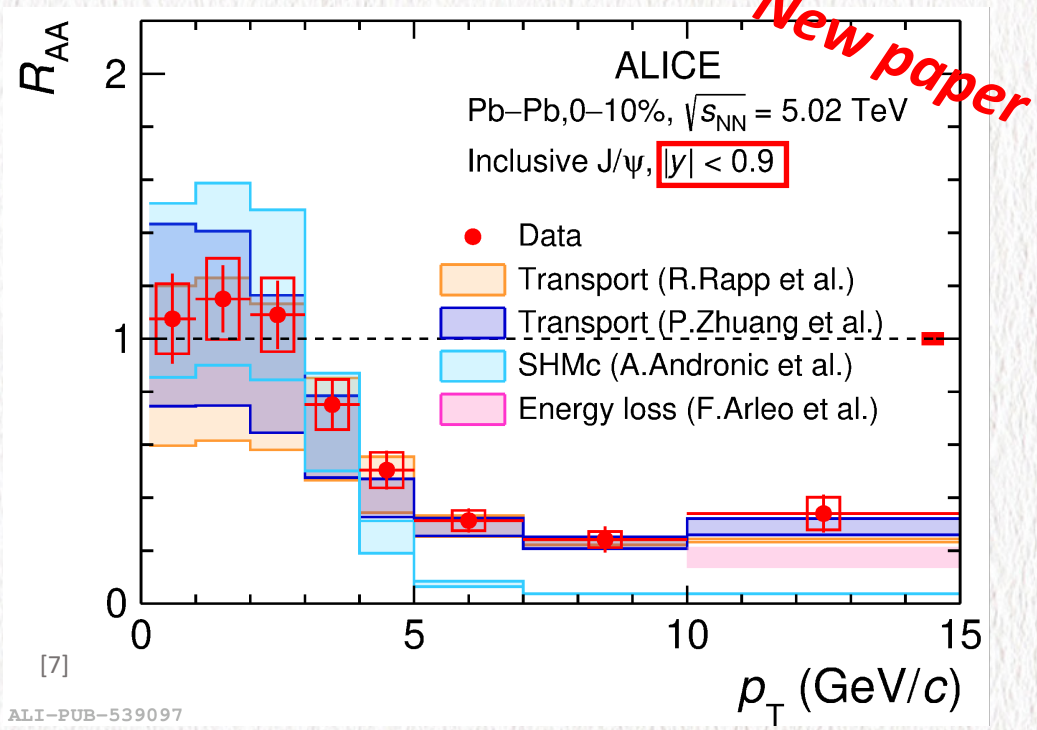


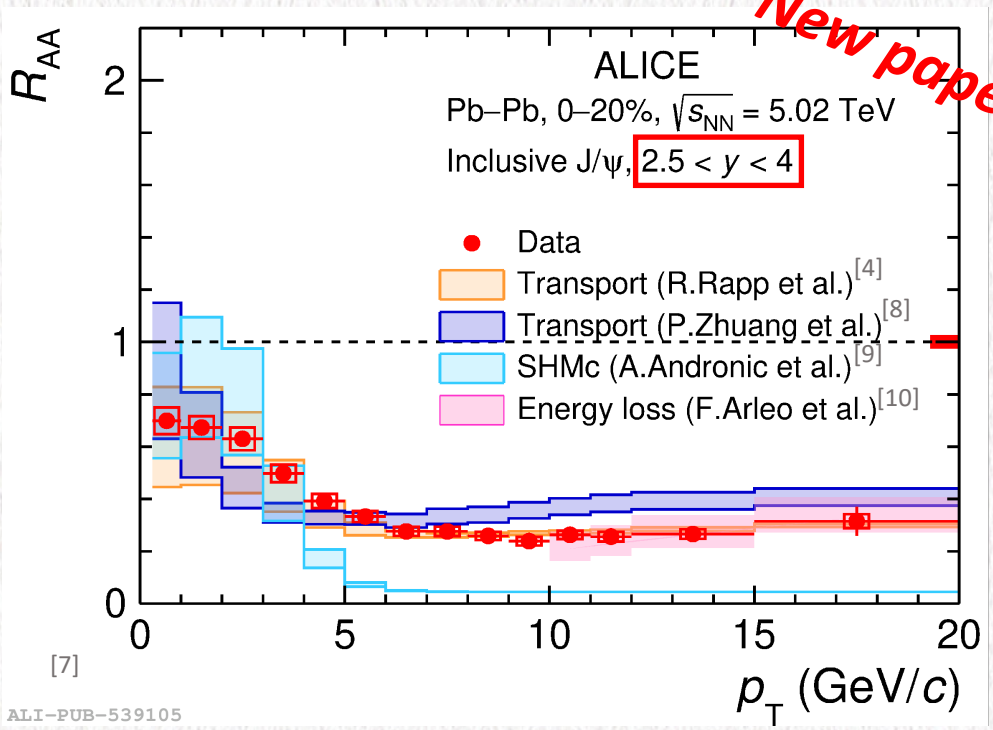


- Models that include QGP melting and regeneration are able to describe the measurements as a function of $\langle N_{part} \rangle$
- More regeneration at midrapidity due to the larger charm quark density

[4] Du, X. & Rapp, R., Nuclear Physics A 943, 147–158 (2015)
[7] ALICE, arXiv:2303.13361
[8] Zhou, K., Xu, N., Xu, Z. & Zhuang, P., Phys. Rev. C 89, 054911 (2014)
[9] Andronic, A., Braun-Munzinger, P. et al, Physics Letters B 797, 134836 (2019)

Inclusive J/ψ -- R_{AA} vs. p_T



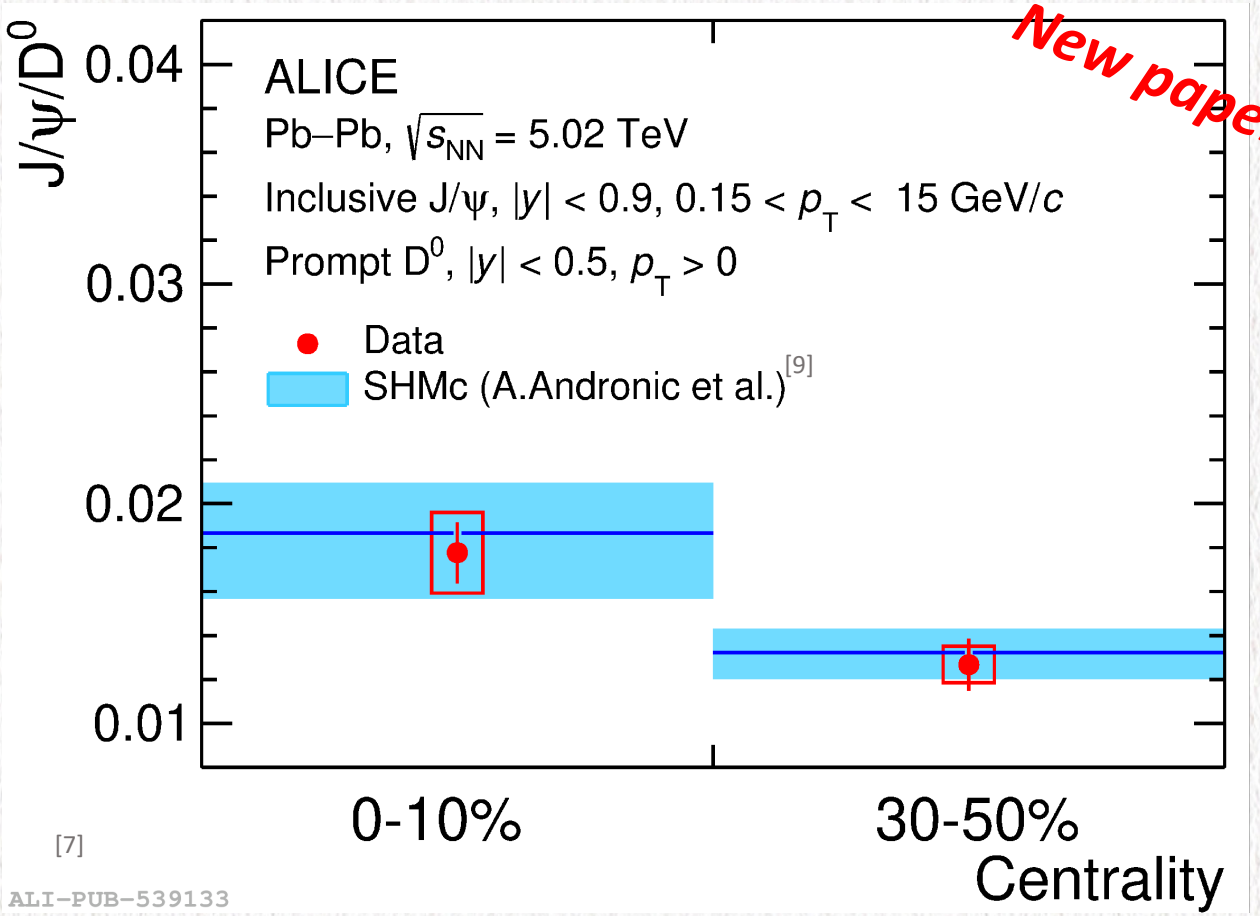


- Models can describe the measurements both at mid- and forward rapidity
- SHMc model can describe the measurements for $p_T < 5$ GeV/c
- Transport models provide good description of the data for the full p_T range
- Model from Arleo et al. (only include energy loss) can describe data for $p_T > 10$ GeV/c

[4] Du, X. & Rapp, R., Nuclear Physics A 943, 147–158 (2015)
[6] ALICE, arXiv:2303.13361
[8] Zhou, K., Xu, N., Xu, Z. & Zhuang, P., Phys. Rev. C 89, 054911 (2014)
[9] Andronic, A., Braun-Munzinger, P, et al, Physics Letters B 797, 134836 (2019)
[10] F. Arleo, Phys. Rev. Lett. 119 (2017) 062302

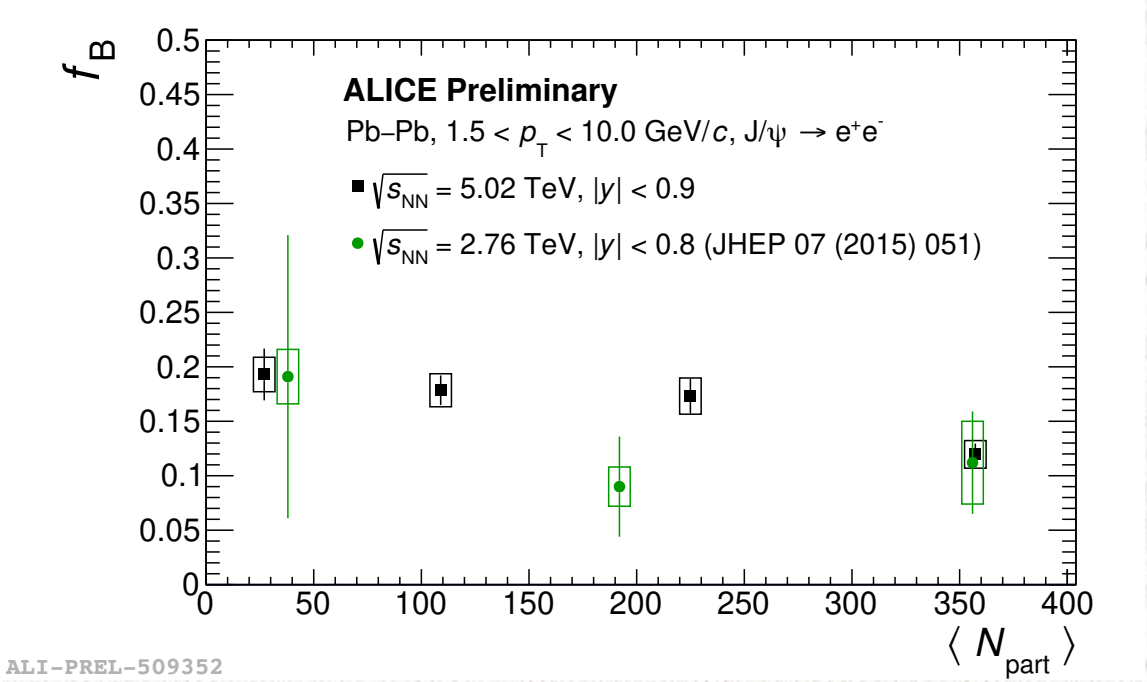
J/ψ to D^0 yield ratio at midrapidity

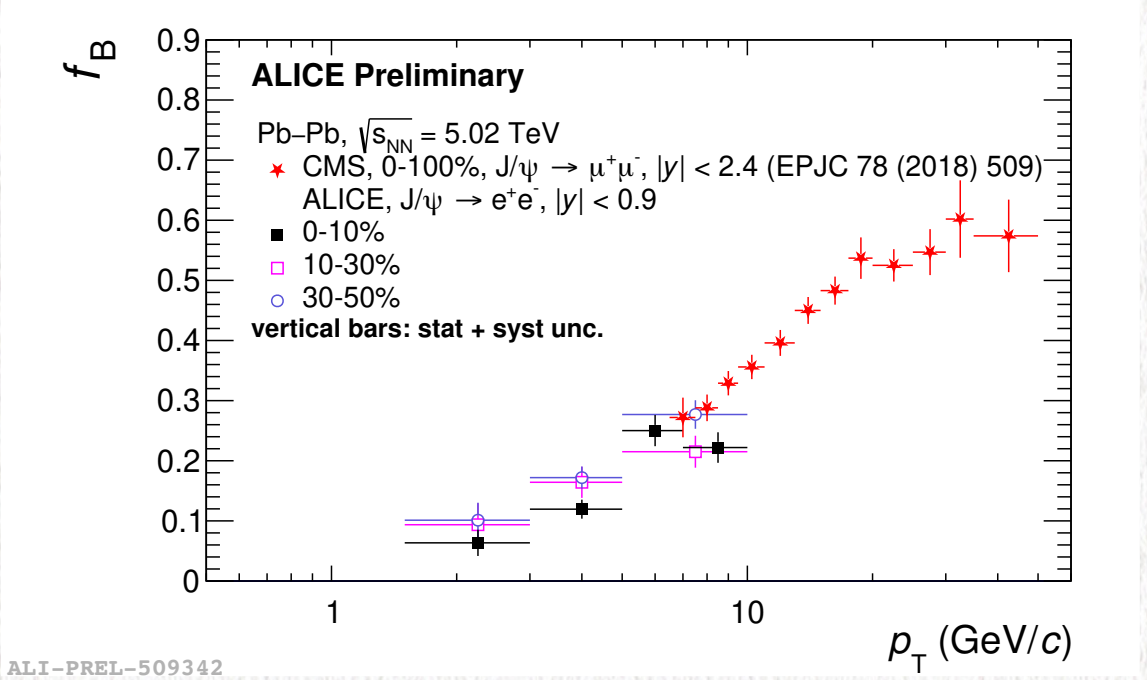
- Probe the charm hadronization mechanism
  - ✓ sensitive to the charm fugacity (g_c)
- Larger ratio in central collisions due to the larger g_c
- Common experimental (theoretical) uncertainties cancel
- Non-prompt J/ψ contributes by ~ 10-20% to the inclusive J/ψ yield, depending on the centrality



[7] ALICE, arXiv:2303.13361
[9] Andronic, A., Braun-Munzinger, P, et al, Physics Letters B 797, 134836 (2019)

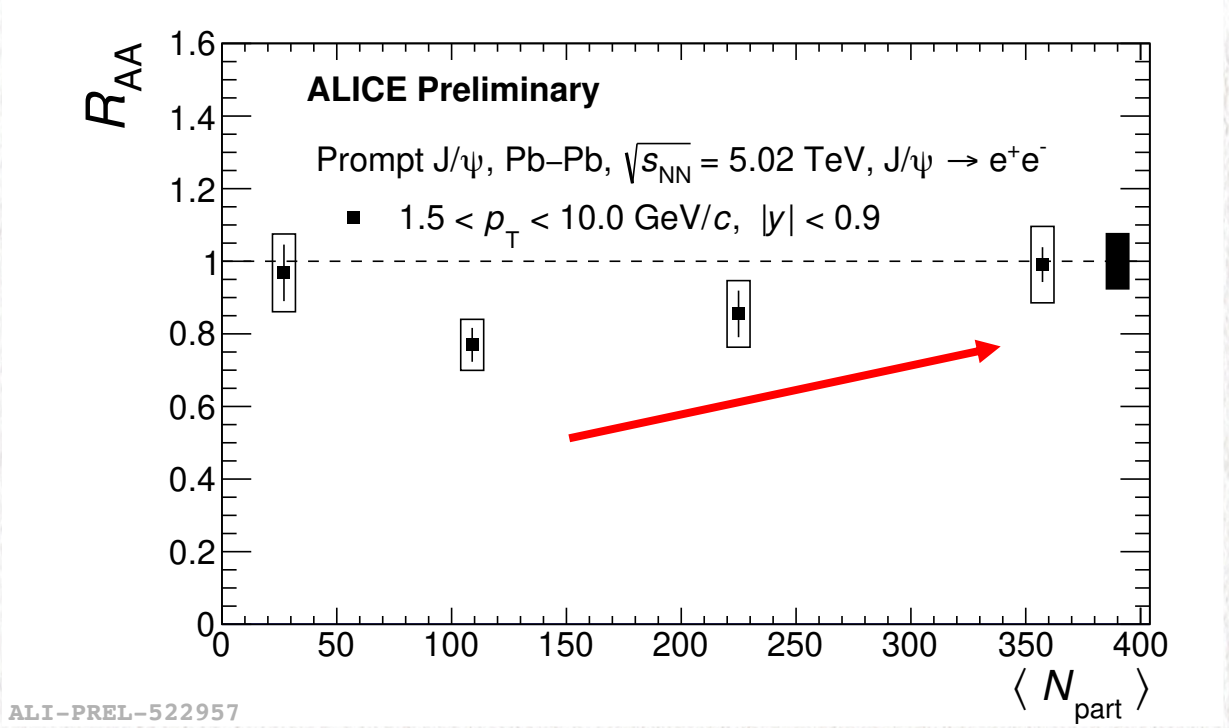
Non-prompt J/ψ yield fraction

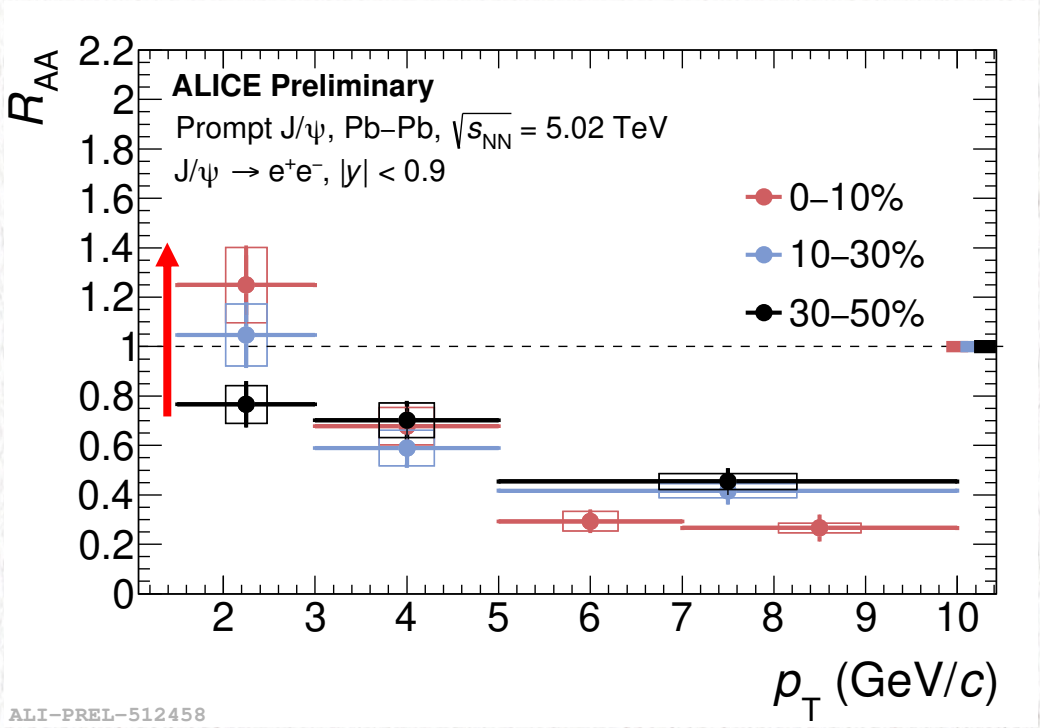




- Improved precision compared to $\sqrt{s_{NN}}$ = 2.76 TeV
- A slightly decreasing trend towards central collisions
- ALICE extends results to low p_T, and agrees with the trend observed by CMS

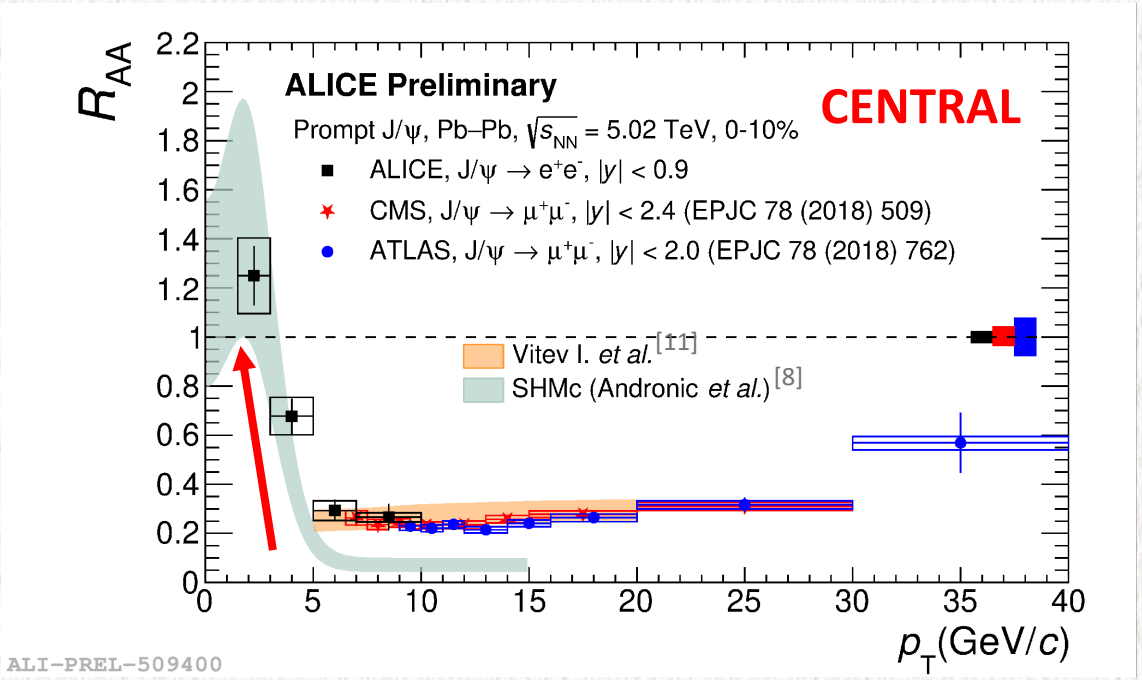
Prompt J/ψ -- R_{AA} vs. $\langle N_{part} \rangle$ and p_T

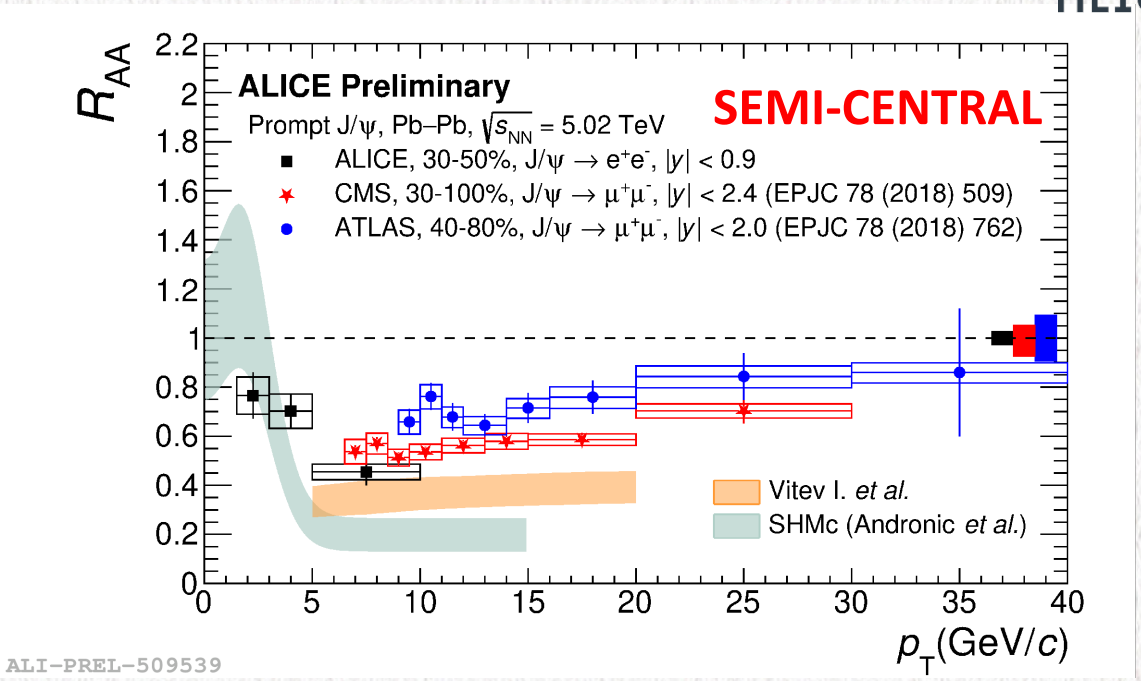




- Increasing trend for R_{AA} towards central collisions (left) and low p_T (right)
- Expected from regeneration mechanism

Prompt J/ψ -- centrality dependence of R_{AA} vs. p_T



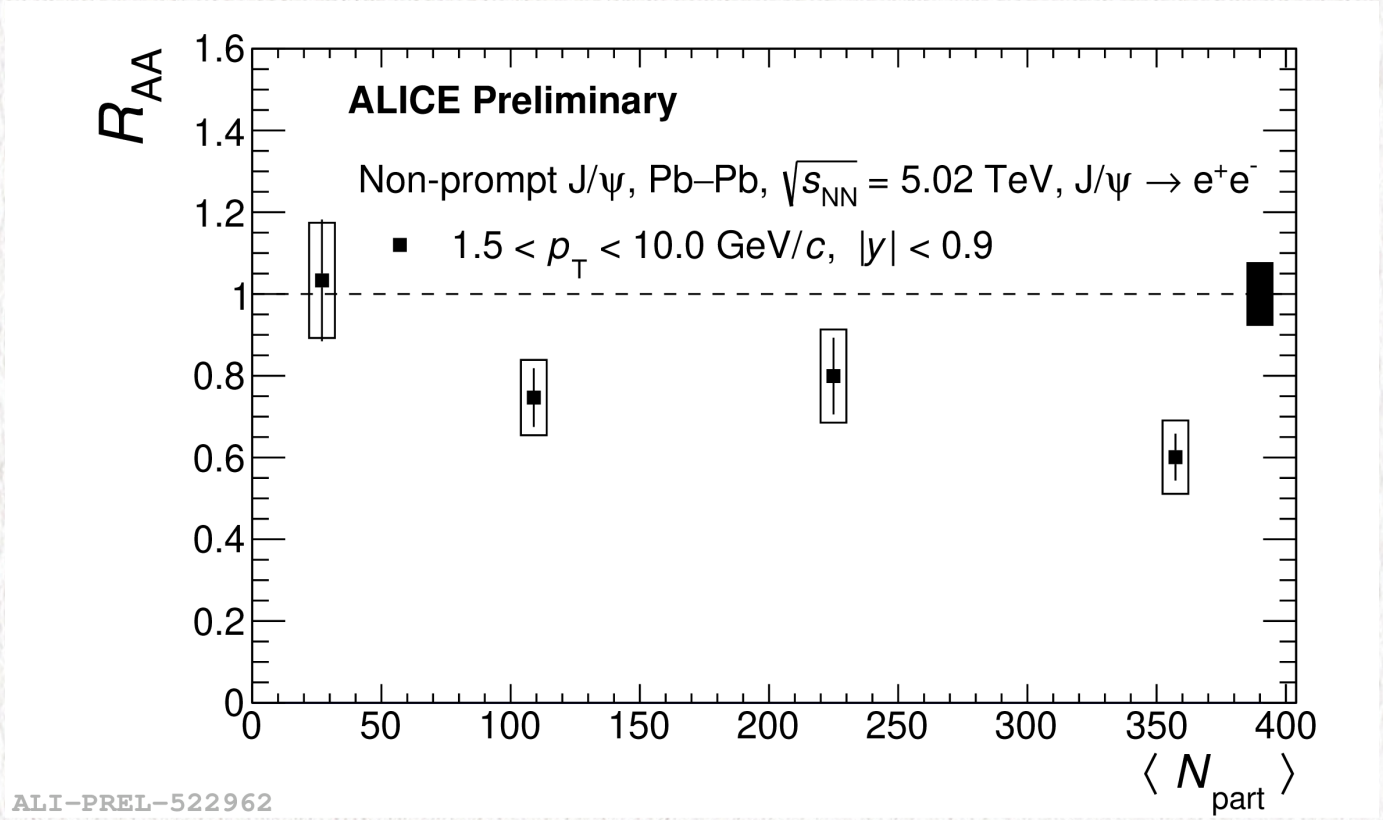


- ALICE extends measurements to very low p_T
- Increasing trend towards low p_T in central collisions
- At high p_T, compatible with ATLAS and CMS results in the overlapping range
- Good agreement with SHMc model for $p_T < 5$ GeV/c
- Compatible with the model by Vitev et al. for $p_T > 5$ GeV/c in central collisions

Models are computed for the ALICE acceptance and cuts

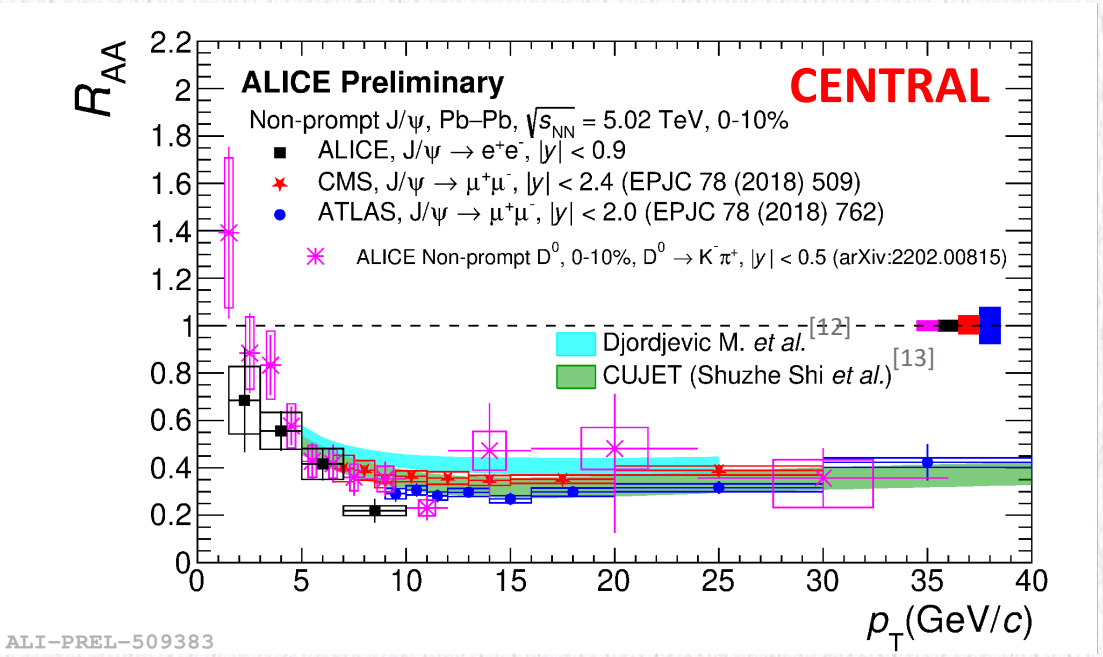
[8] Andronic, A. et al., J. High Energ. Phys. 2021, 35 (2021)
[11] Vitev I. et al. arXiv:1709.02372, arXiv:1906.04186

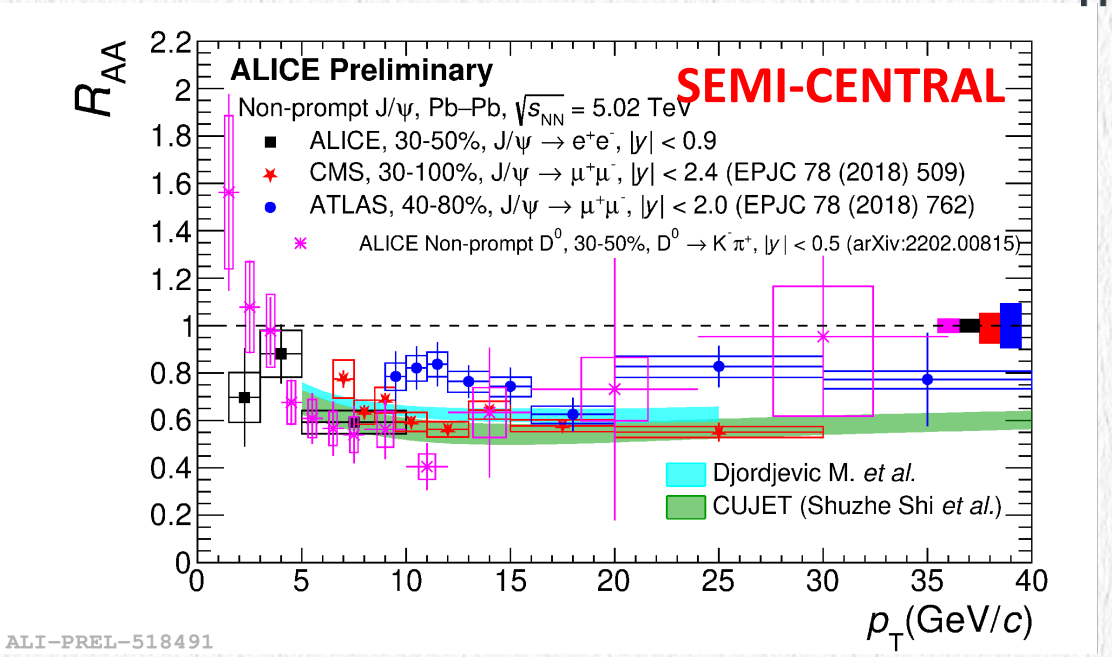
Non-prompt J/ψ -- R_{AA} vs. $\langle N_{part} \rangle$



- Indicates stronger suppression towards central collisions
- Expected from heavy quark energy loss effects in the medium

Non-prompt J/ψ -- centrality dependence of R_{AA} vs. p_T





- Similar R_{AA} trend for non-prompt D^0 and non-prompt J/ψ
  - ✓ strong suppression for p_T > 5 GeV/c, increasing trend towards low p_T
  - ✓ differences can arise due to decay kinematics
- Consistent with energy loss models including collisional and radiative contributions
- ALICE extends the J/ψ measurement to very low p_T, and is complementary to ATLAS and CMS

[12] Djordjevic M. *et al.*, Front. Phys. 10:957019 (2022)
[13] Shuzhe S. et al. Chin.Phys.C 43 (2019) 4, 044101, Chin.Phys.C 42 (2018) 10, 104104

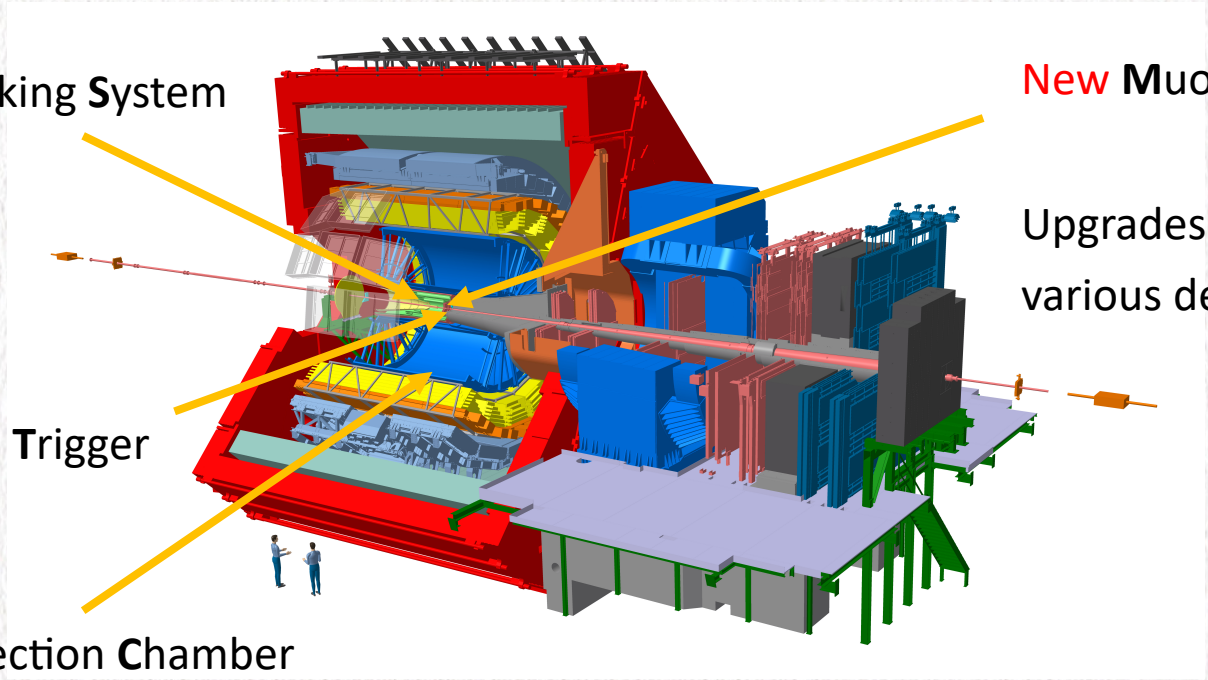
ALICE opportunities for J/ψ measurements in Run 3

Upgraded **I**nner **T**racking **S**ystem

New **M**uon **F**orward **T**racker

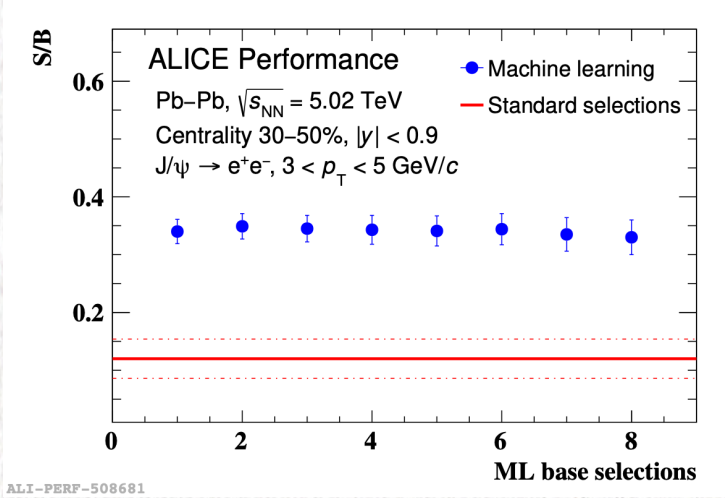
Upgrades on front-end readout of various detectors

New **F**ast **I**nteraction **T**rigger



Upgraded **T**ime **P**rojection **C**hamber

- Major detectors upgrades and new detectors
- Machine learning is under developments to analyze Run 3 data
- Opportunities for more precise or new J/ψ measurements
  - ✓ prompt and non-prompt separation at forward rapidity
  - ✓ collective flow, polarization at midrapidity…



s/b -- ML vs. SM

Summary

- ALICE extends inclusive (prompt and non-prompt) J/ψ Pb—Pb measurement down to zero (low) p_{T}
- Models which include regeneration describe inclusive J/ψ and prompt J/ψ production
  - ✓ regeneration mainly at low p_{T}, significant suppression at high p_{T}
- Prompt J/ψ suppression at high p_{T} can be reproduced by models including collisional and thermal dissociation
- Non-prompt J/ψ indicates stronger suppression towards central collisions
  - ✓ compatible above 5 GeV/c with models implementing mass dependent quark energy loss
- SHMc describes the J/ψ/D^0 yield ratio vs. centrality
- ALICE Run 3 provides excellent opportunities for more precise and new J/ψ measurements

J/ψ Results presented at Hard Probes 2023

Talks:

- J/ψ photoproduction in Pb—Pb collisions with nuclear overlap, Ionut Arsene (link)
- Multiplicity dependence of quarkonium production in small systems, Ailec Hechavarria (link)
- Quarkonium polarization in pp and Pb—Pb collisions, Andrea Ferrero (link)
- ψ(2s) production in Pb—Pb, Victor Feuillard (link)

Posters:

- J/ψ photoproduction and exclusive dimuon production in p—Pb collisions at 8.16 TeV, Minjung Kim and Michael Winn (link)
- Quarkonium production and flow in small systems, Tabea Eder (link)