Quarkonia physics with ALICE at the LHC

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Motivation

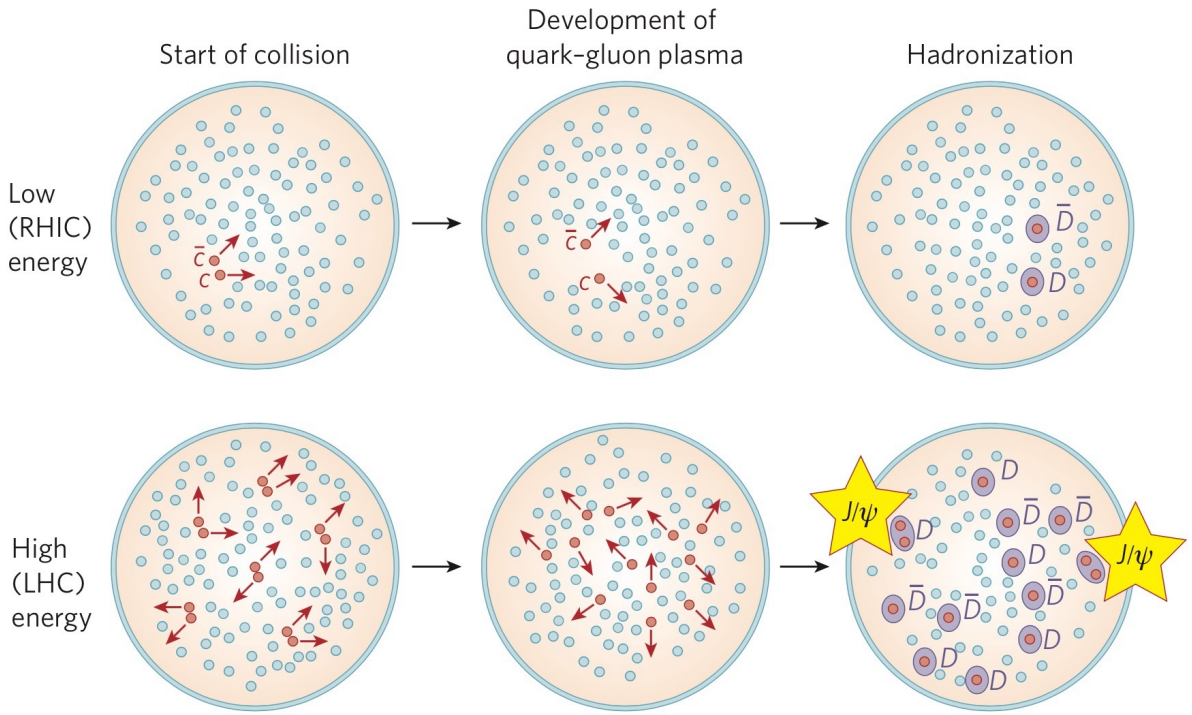
- **pp collisions:**
  - Study the quarkonium production mechanisms
  - Provide reference for p-Pb and Pb-Pb collisions

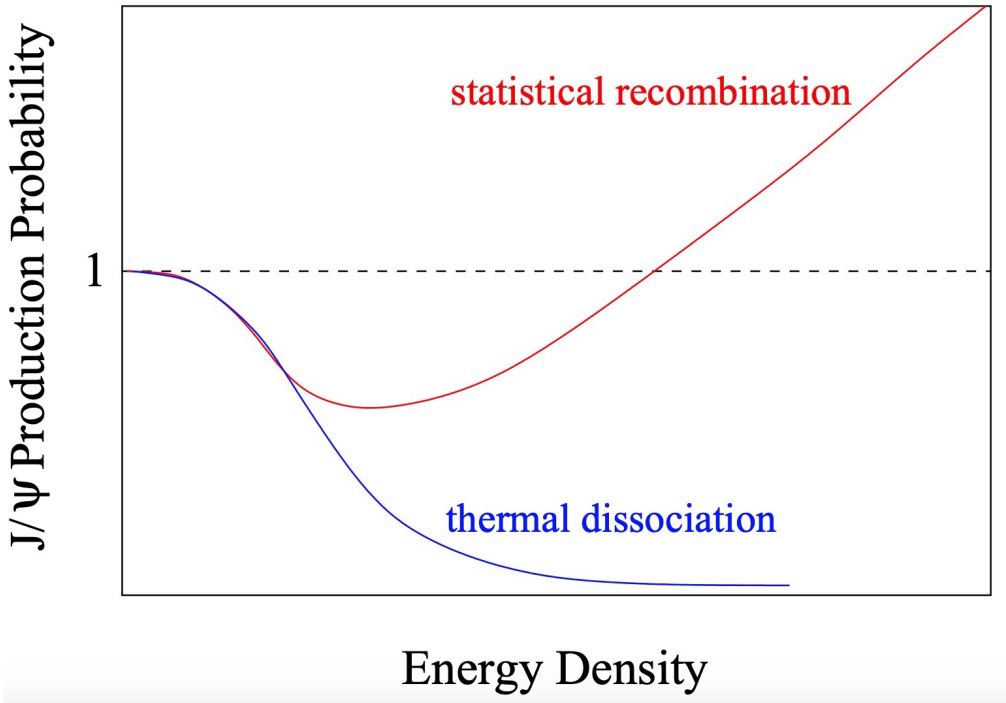
- **p-Pb collisions:**
  - Investigate the cold nuclear matter

- **Pb-Pb collisions:**
  - Quarkonium dissociation and (re-)generation in the medium
  - Measurement of the non-prompt J/ψ can study the mass dependence of parton energy loss
  - Probe the short-living ***B*** and the ***L*** of the rotating medium

Quarkonium production in AA collisions

P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302





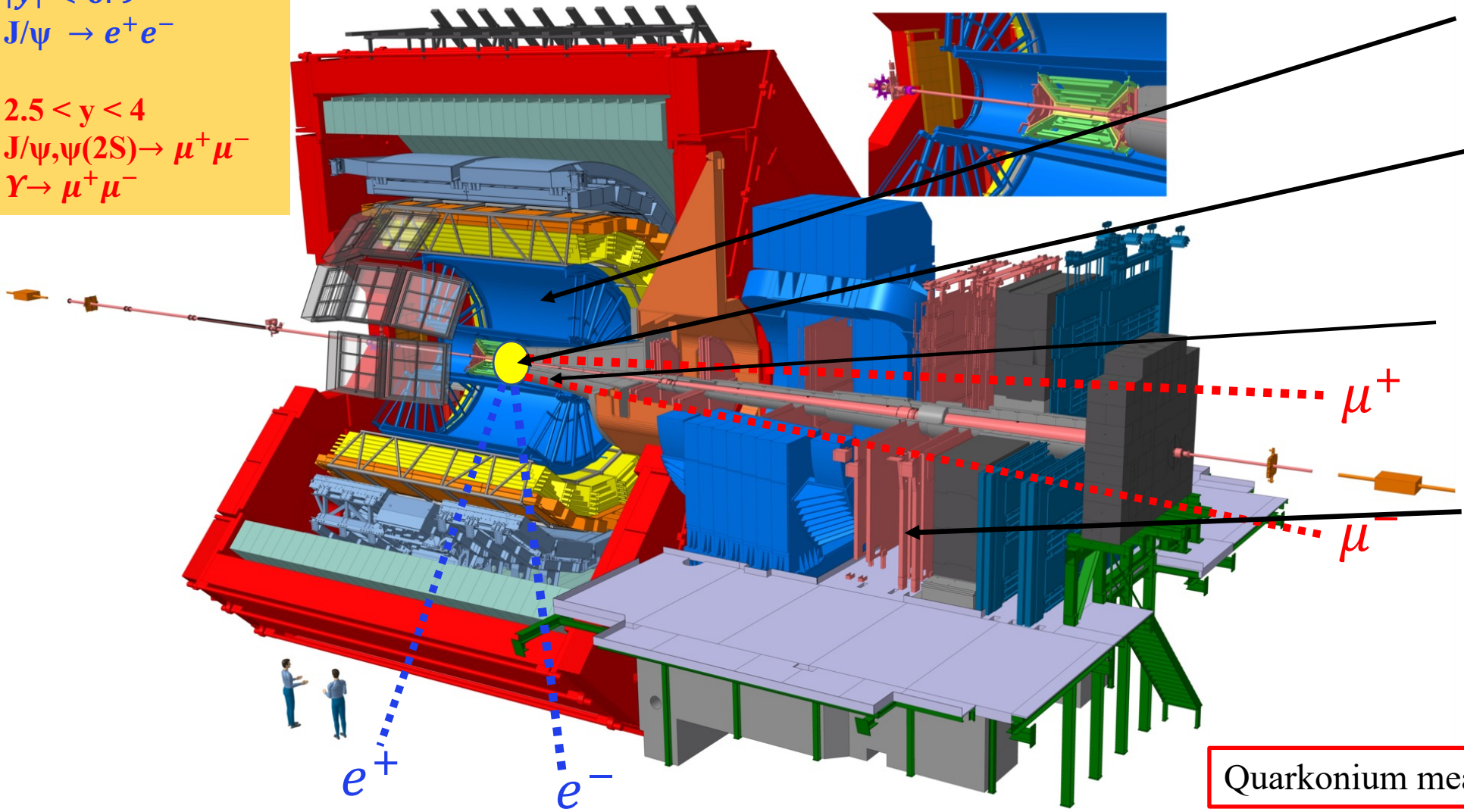
P. Braun Muzinger, J.Stachel, PLB 490 (2000) 196
R. Thews et al, Phys.Rev.C 63:054905 (2001)
Kluberg, Satz, arXiv:0901.3831

- Charm quark (c and $\bar{c}$) production cross section in LHC is larger compared to RHIC energies
- The J/ψ (re-)generation contribution is significantly higher than RHIC

Quarkonium measurements with the ALICE detector

$|y| < 0.9$
$J/\psi \rightarrow e^+e^-$

$2.5 < y < 4$
$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$
$\Upsilon \rightarrow \mu^+\mu^-$



Time Projection Chamber
Tracking, particle identification

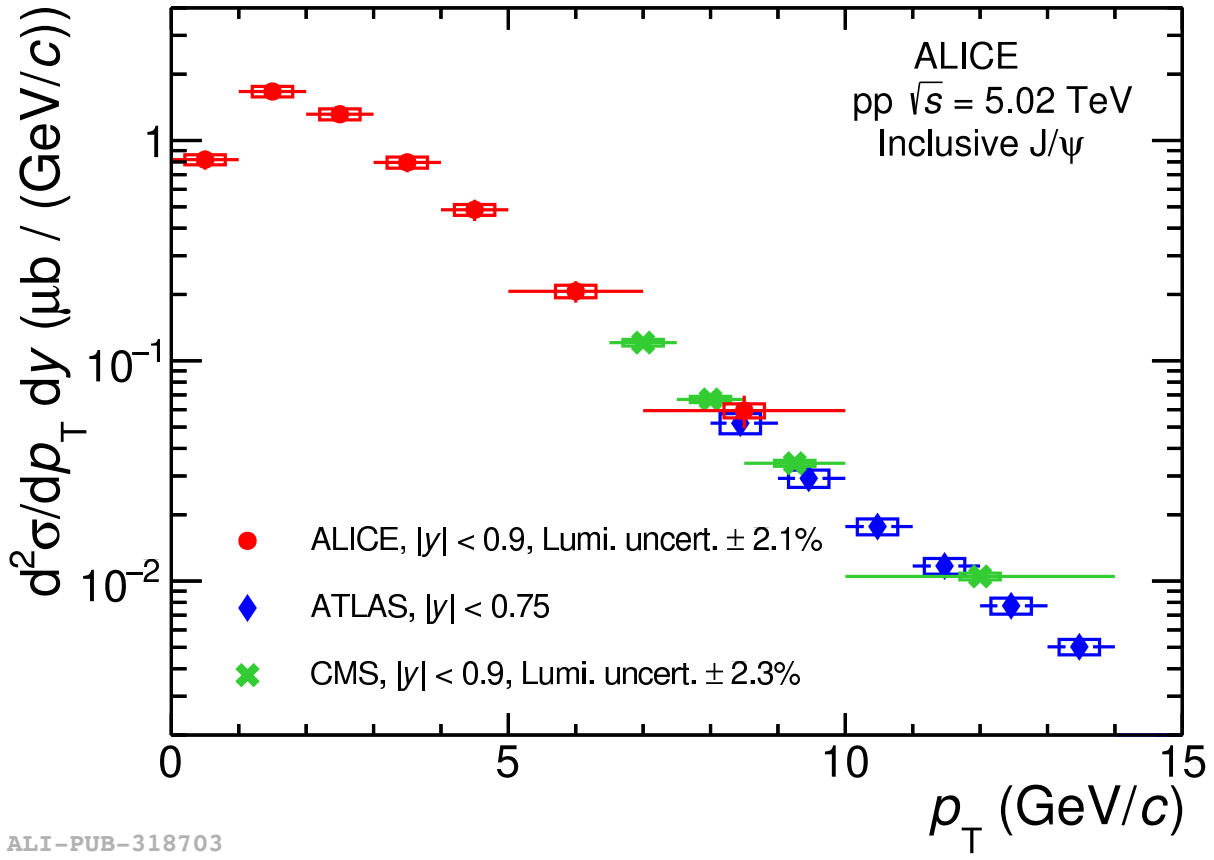
Inner Tracking System
Tracking, vertex reconstruction, Event Plane determination

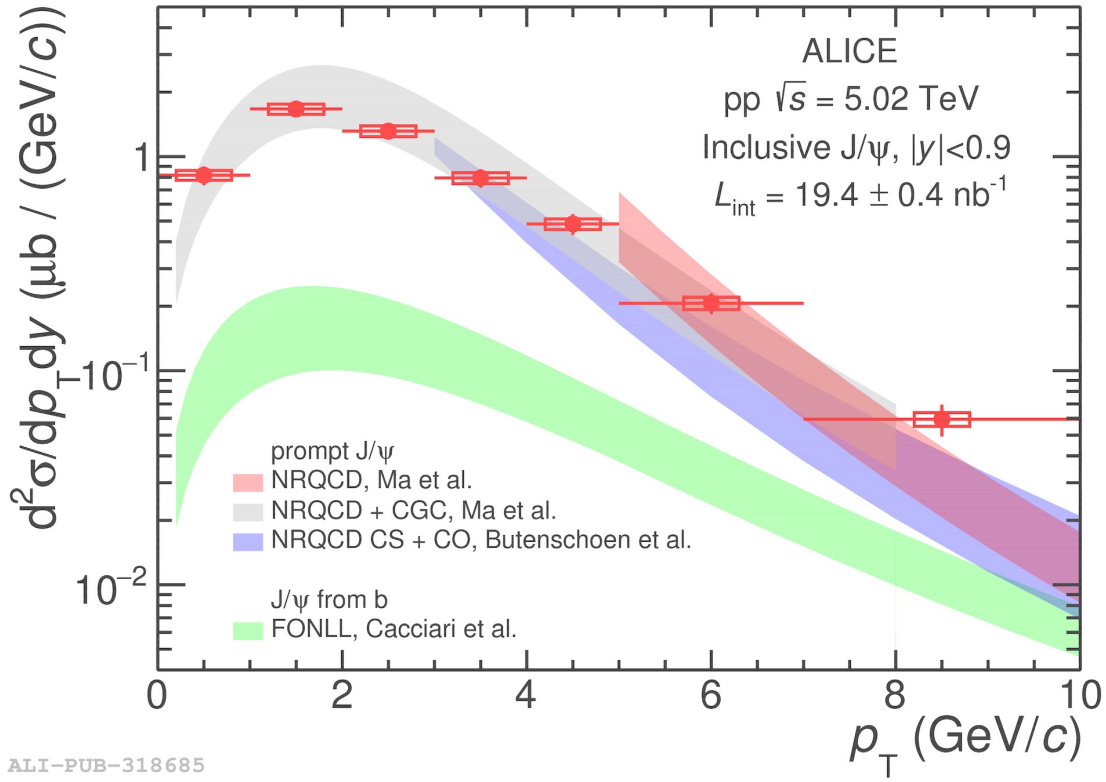
V0 Detector
Centrality determination, triggering, event plane measurement, and background rejection

Muon spectrometer
Trigger and tracking for muons

Quarkonium measurement down to $p_T = 0$

Inclusive J/ψ production at midrapidity

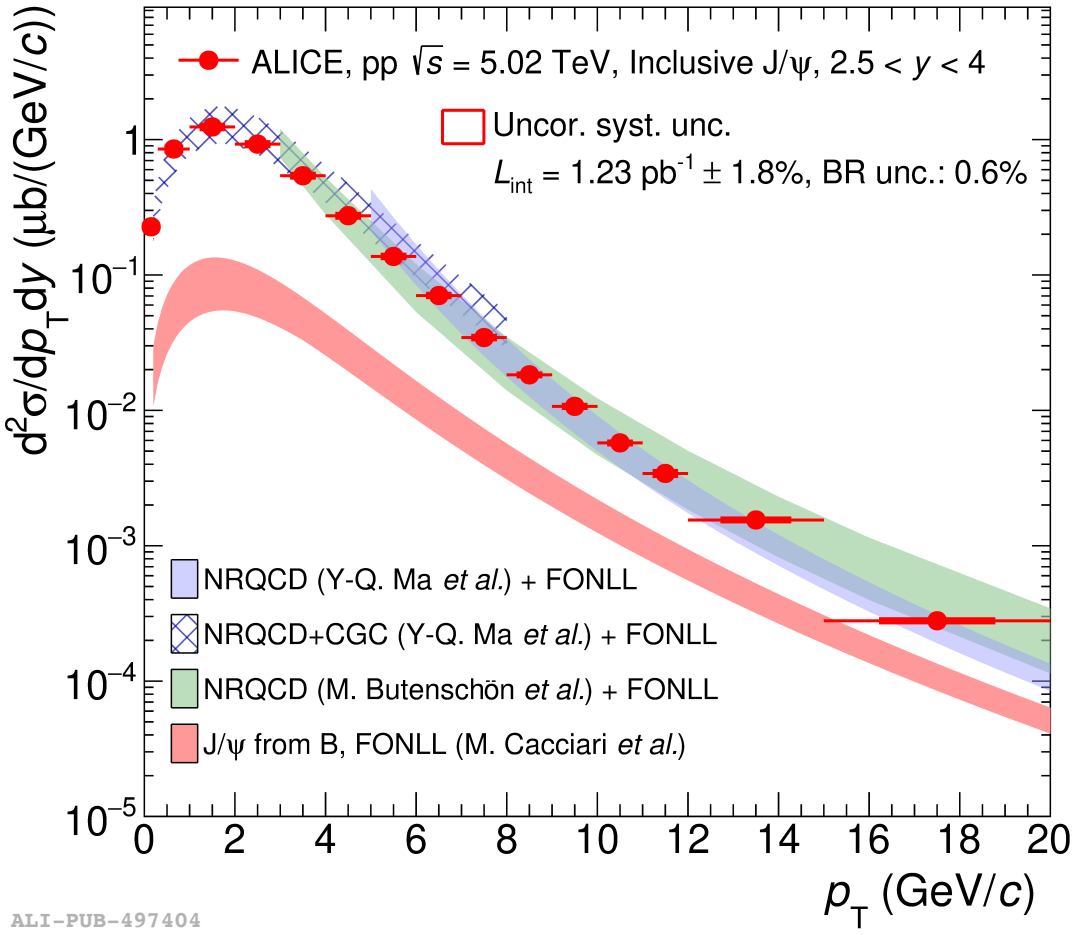


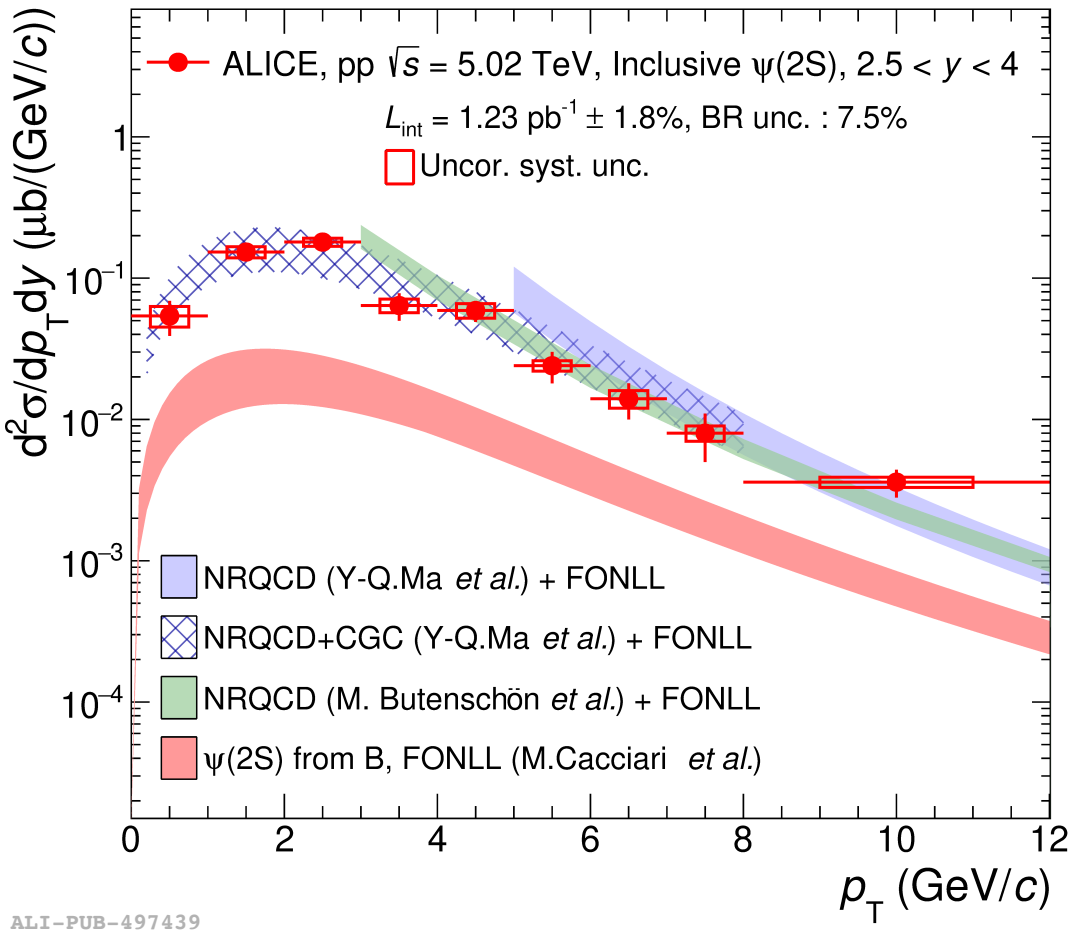


Eur. Phys. J. C 78 (2018) 171 (ATLAS)
Eur. Phys. J. C 77 (2017) 269 (CMS)
Phys. Rev. Lett. 113 (2014) 192301
JHEP10 (2019) 084 (ALICE)

- First measurement of inclusive J/ψ production at pp 5.02 TeV, p_T down to 0
- New measurement consistent with ATLAS and CMS in overlapping p_T
- NRQCD+CGC for prompt J/ψ, and FONLL for the non-prompt J/ψ calculation can describe the data

Inclusive J/ψ and ψ(2S) production at forward rapidity

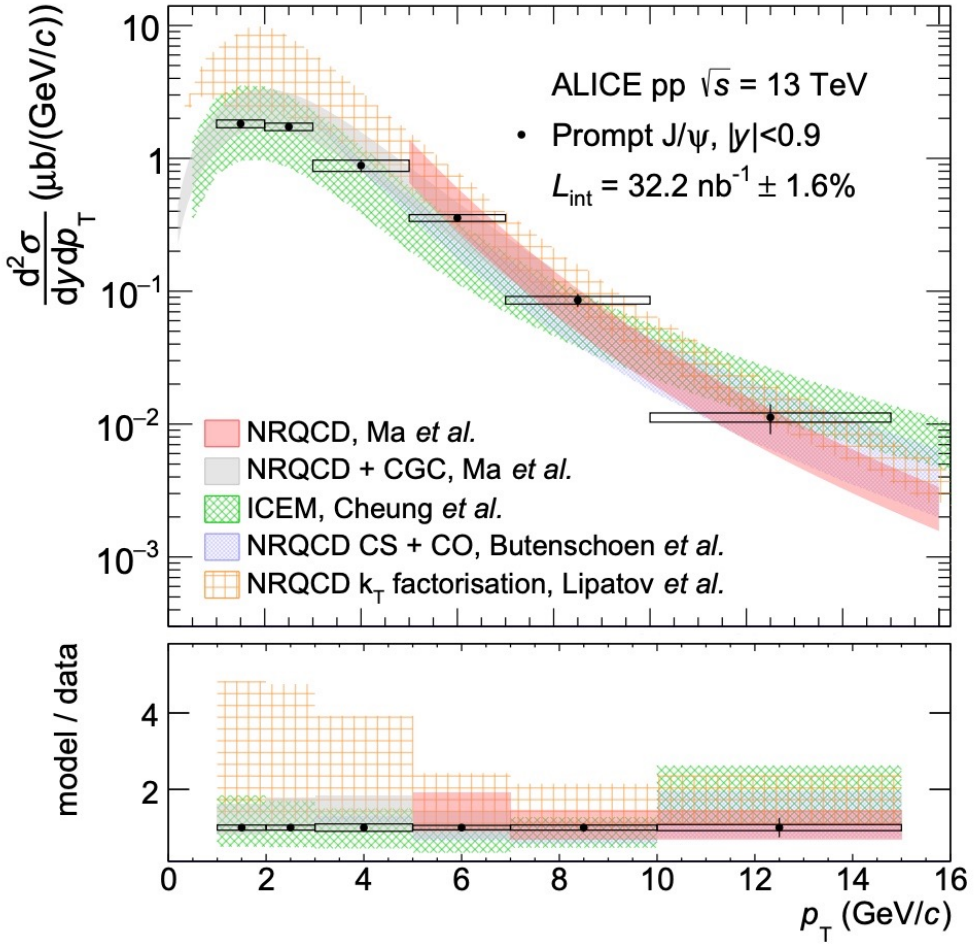


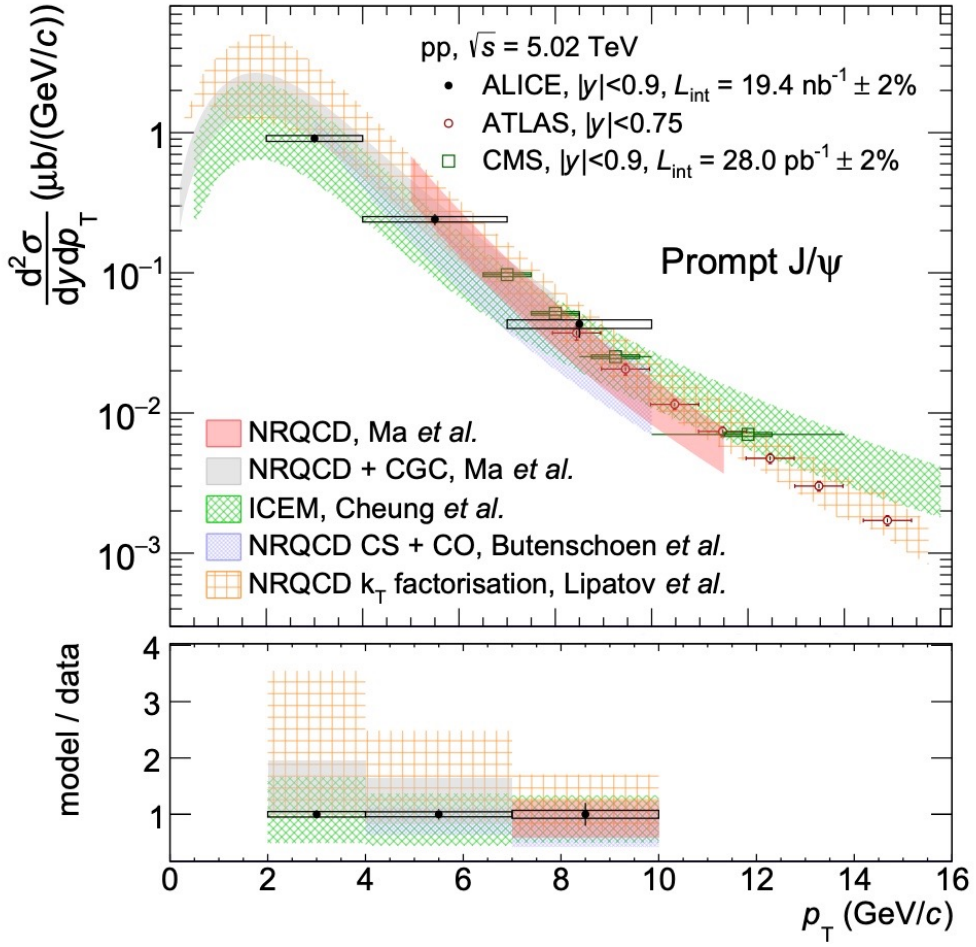


NRQCD+CGC: PRL113, 192301, (2014)
NRQCD: PRL. 106 (2011) 042002 , PRL 106 (2011) 022003
FONLL: JHEP 10 (2012) 137
ALICE,JHEP 03 (2022) 190

NRQCD+CGC (+FONLL) model provides a good description at low p_T for J/ψ and ψ(2S)

Prompt J/ψ production cross section

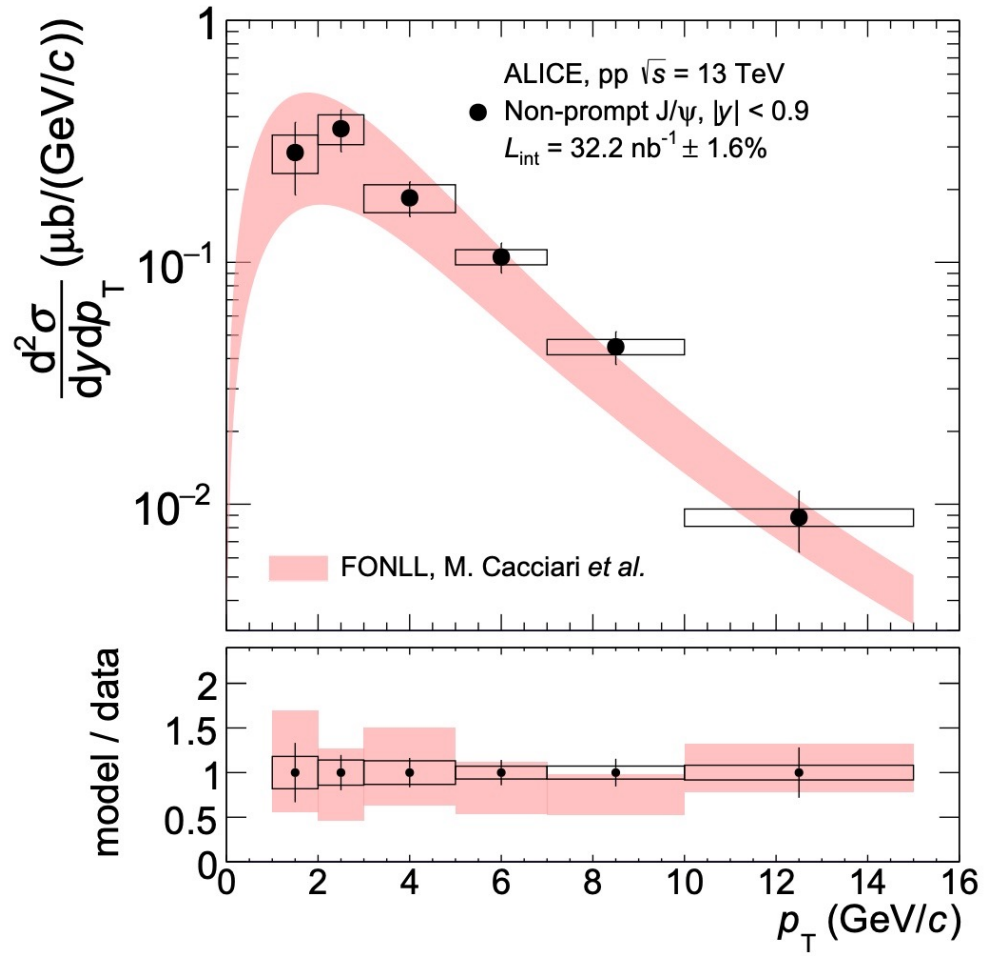


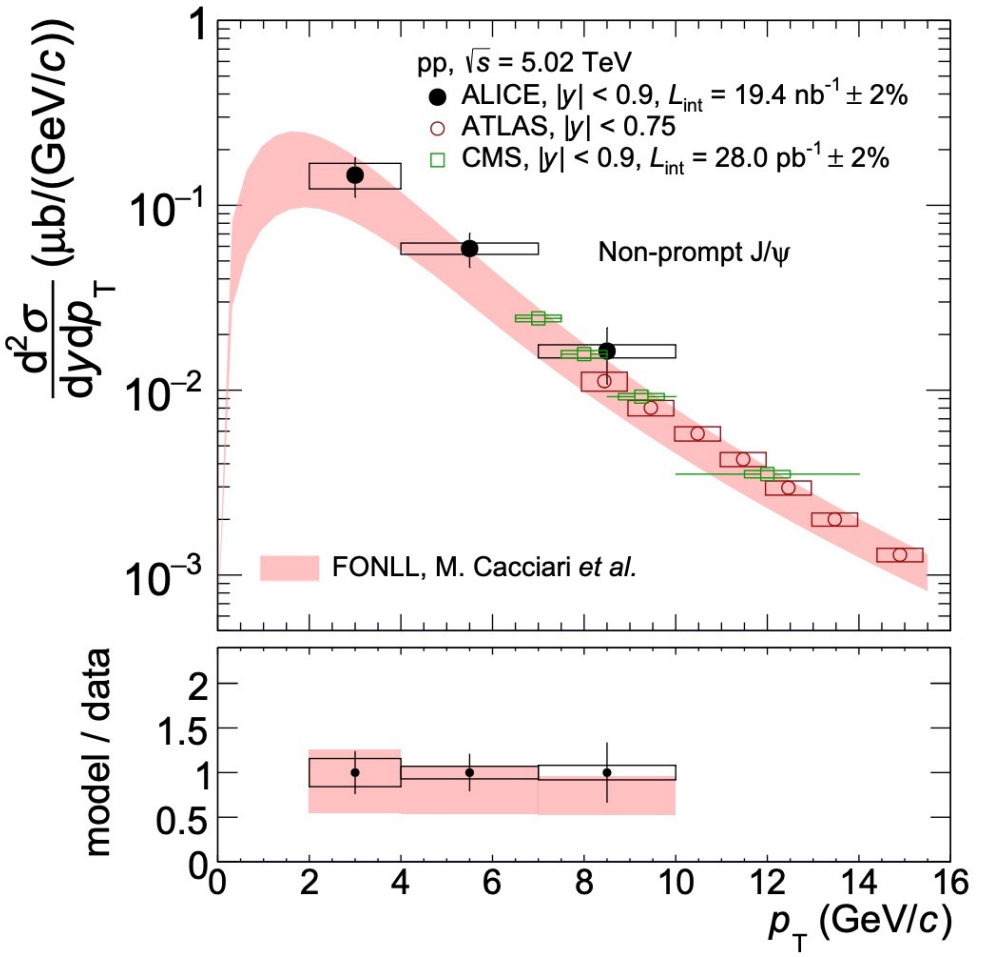


NRQCD :. Phys. Rev. L ett. 106 (2 011) 022003
ICEM, Phys. Rev. D98 n o. 11, (2 018) 114029
FNOLL ,JHEP 10 (2 012) 13 7
ALICE: arXiv:2109.15240

- Prompt J/ψ cross sections can be well described by the NRQCD+CGC and ICEM calculations
- ALICE results agree with the CMS and ATLAS measurements in the overlapping p_T

Non-prompt J/ψ production cross section



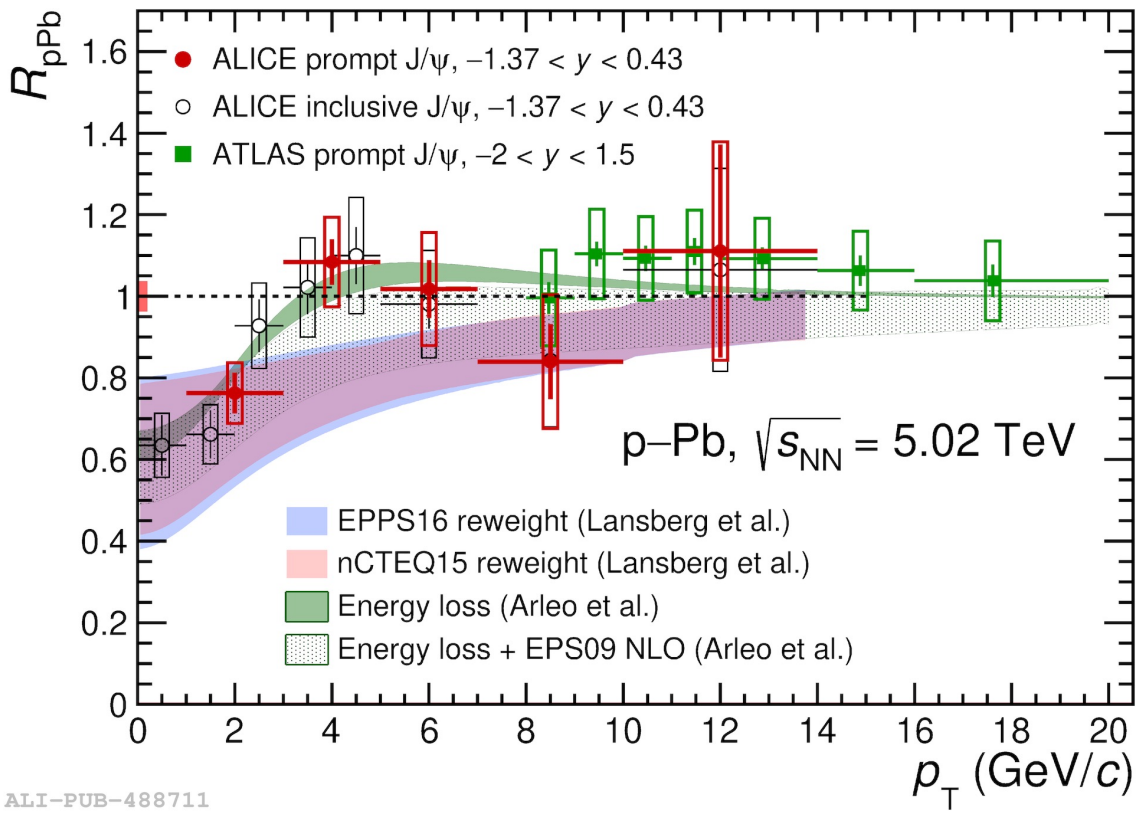


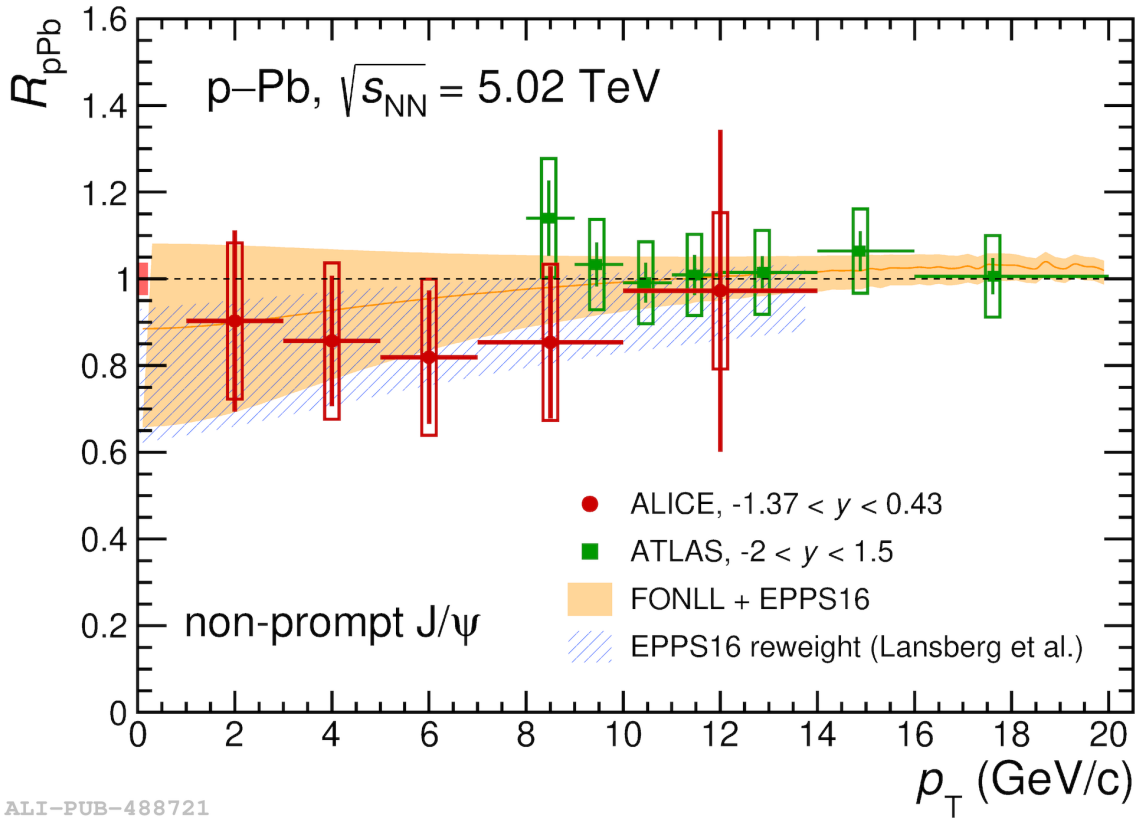
FONLL: JHEP 10 (2012) 137
ALICE,JHEP 03 (2022) 190

- Non-prompt J/ψ (decay from beauty hadrons) cross sections well described by FONLL calculations
- ALICE results agree with the CMS and ATLAS measurements in the overlapping p_T

Prompt and non-prompt J/ψ R_{pA} in p–Pb collisions

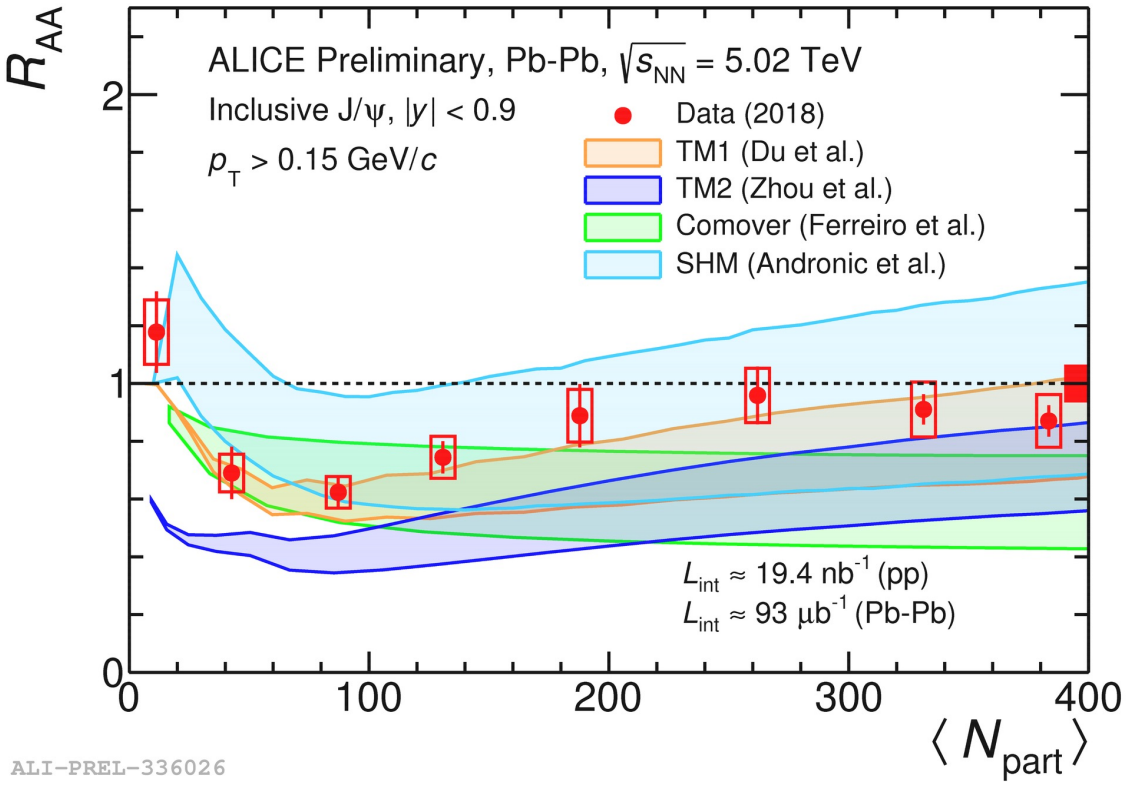
ALICE, JHEP06(2022) 011

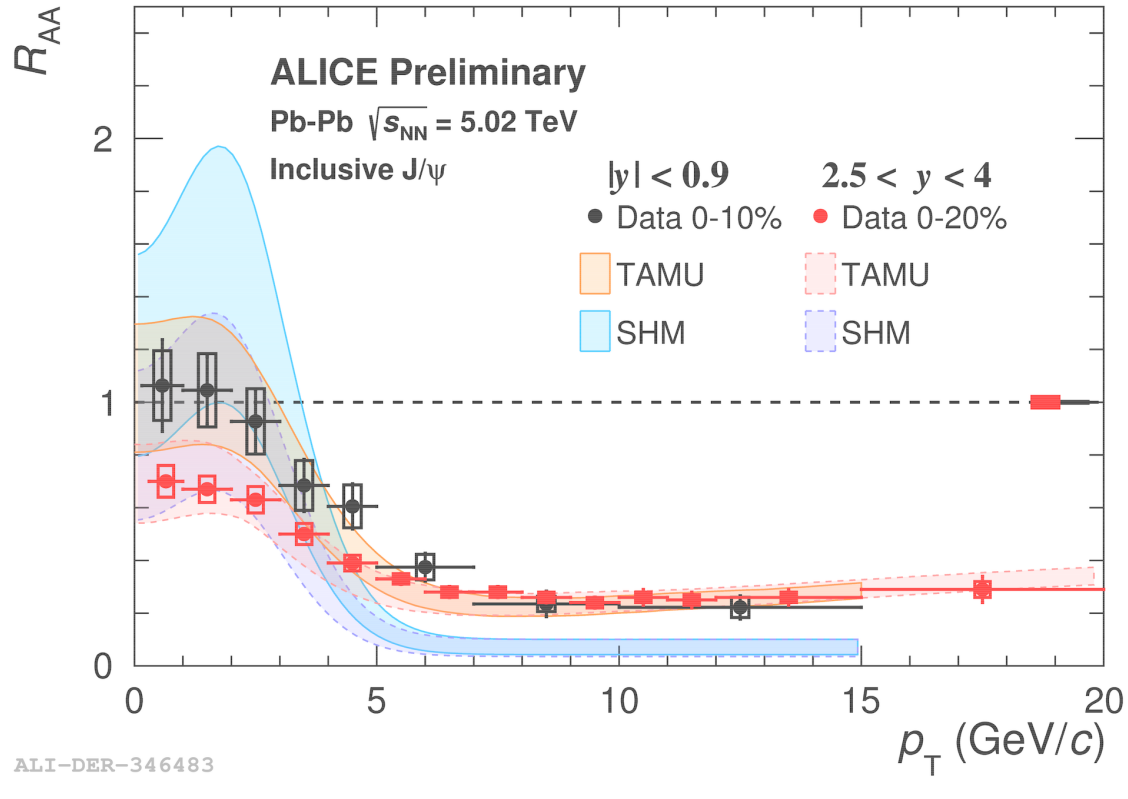




- Significant suppression for prompt J/ψ at $p_T < 3$ GeV/c, the energy loss model can describe the data
- No strong p_T dependence for non-prompt J/ψ

J/ψ R_{AA} in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

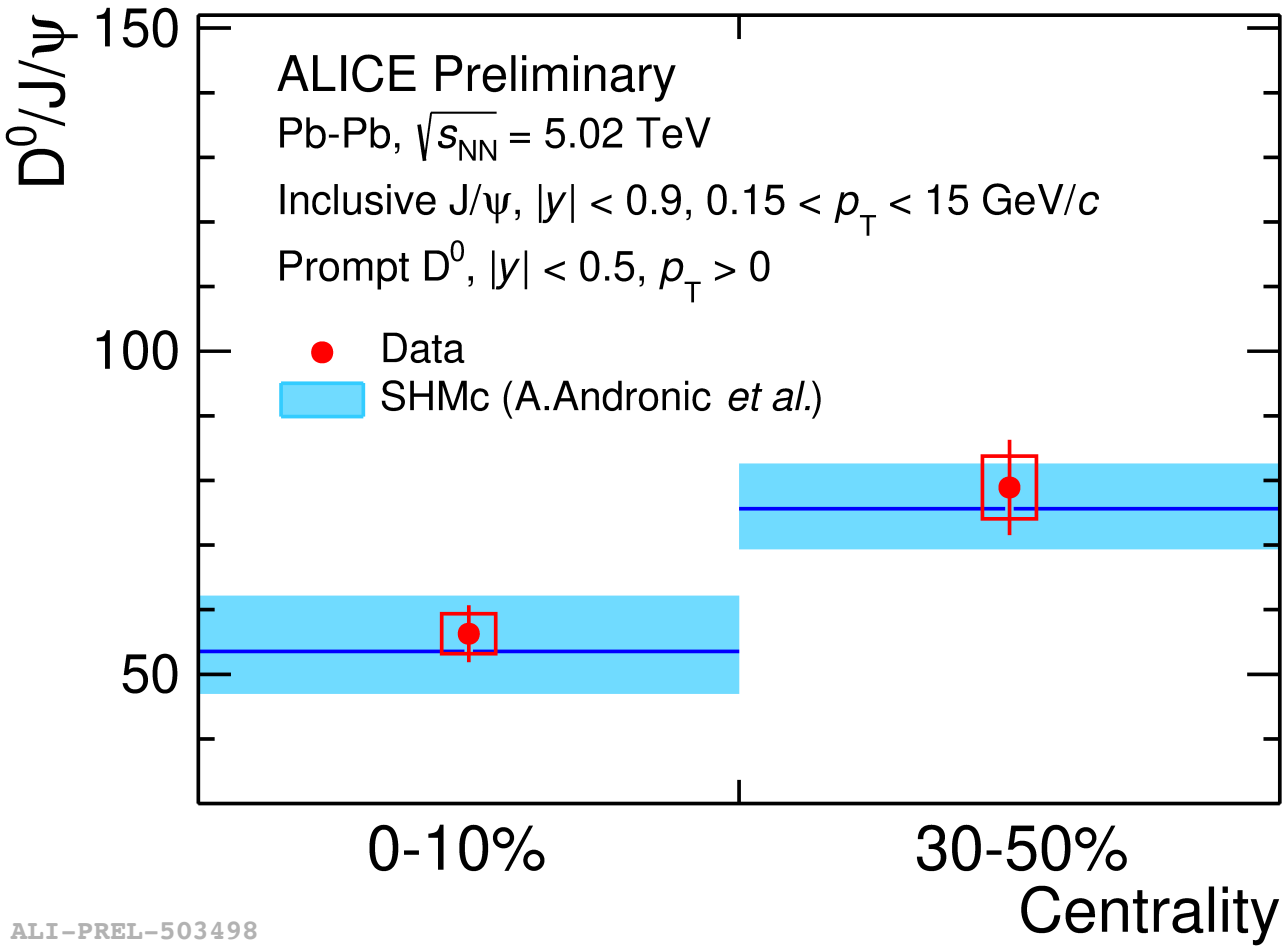




TM1: Du X. and Rapp R., NPA 943 (2015) 147-158
TM2: Zhou et al., PRC 89, 054911 (21 May 2014)
SHM: Andronic A. et al., PLB 797 (2019) 134836
Comover: Ferreiro E. et al., PLB 731 (2014) 57

- Evidence for J/ψ (re-)generation at low p_T and in central collisions, with larger contribution at at midrapidity compared to forward rapidity
- The statistical hadronization model can describe the data at low p_T, while the transport model agrees with data in the whole measured p_T ranges

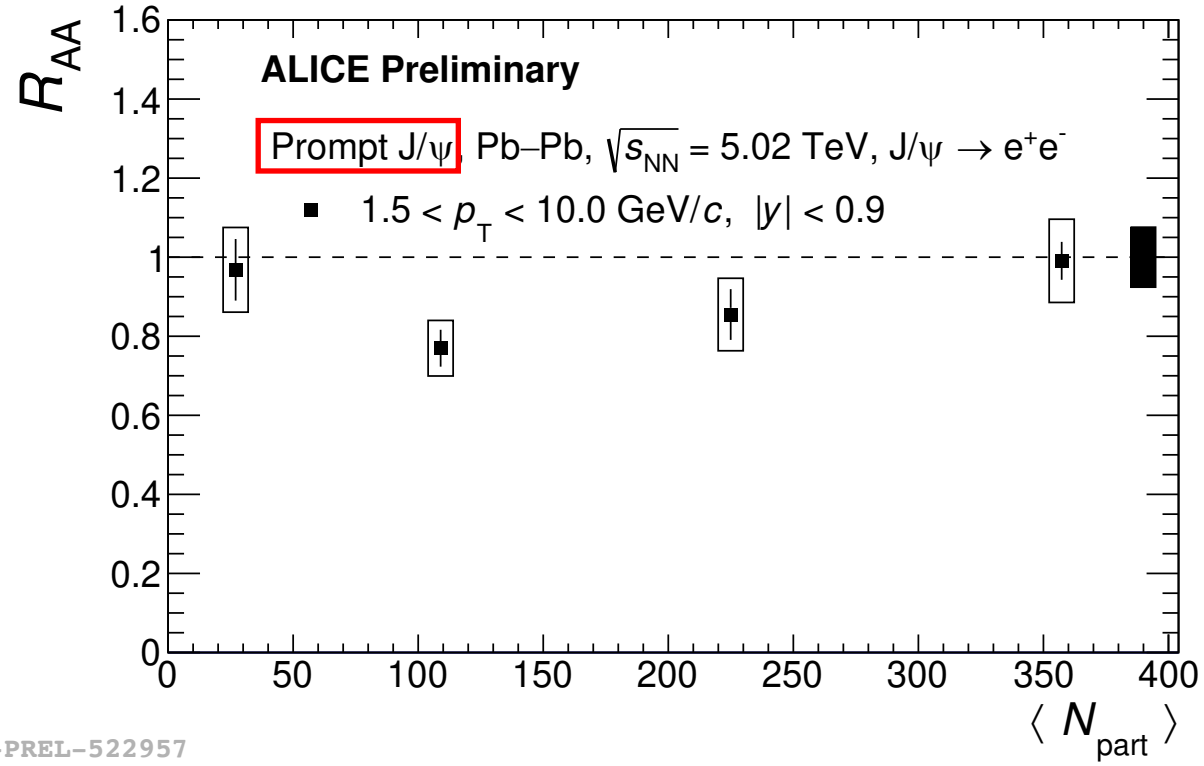
D^0-to-J/ψ ratio in Pb–Pb collisions



A. Andronic et al., JHEP07 (2021) 035

- Sensitive to hadronization mechanisms for open and hidden charm hadrons
- The centrality dependent trend of the D^0 to J/ψ ratio can be explained by the increase of charm fugacity towards most central collisions according to SHMc prediction

Centrality dependence of prompt and non-prompt J/ψ R_{AA}



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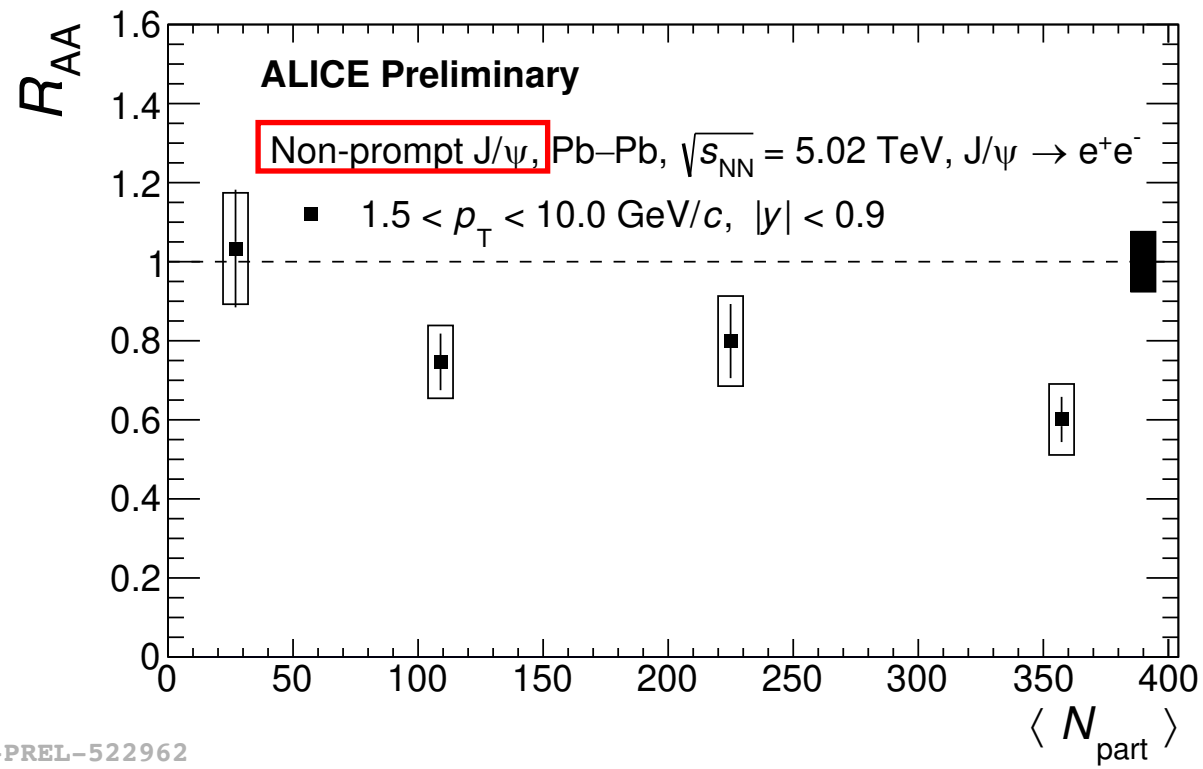
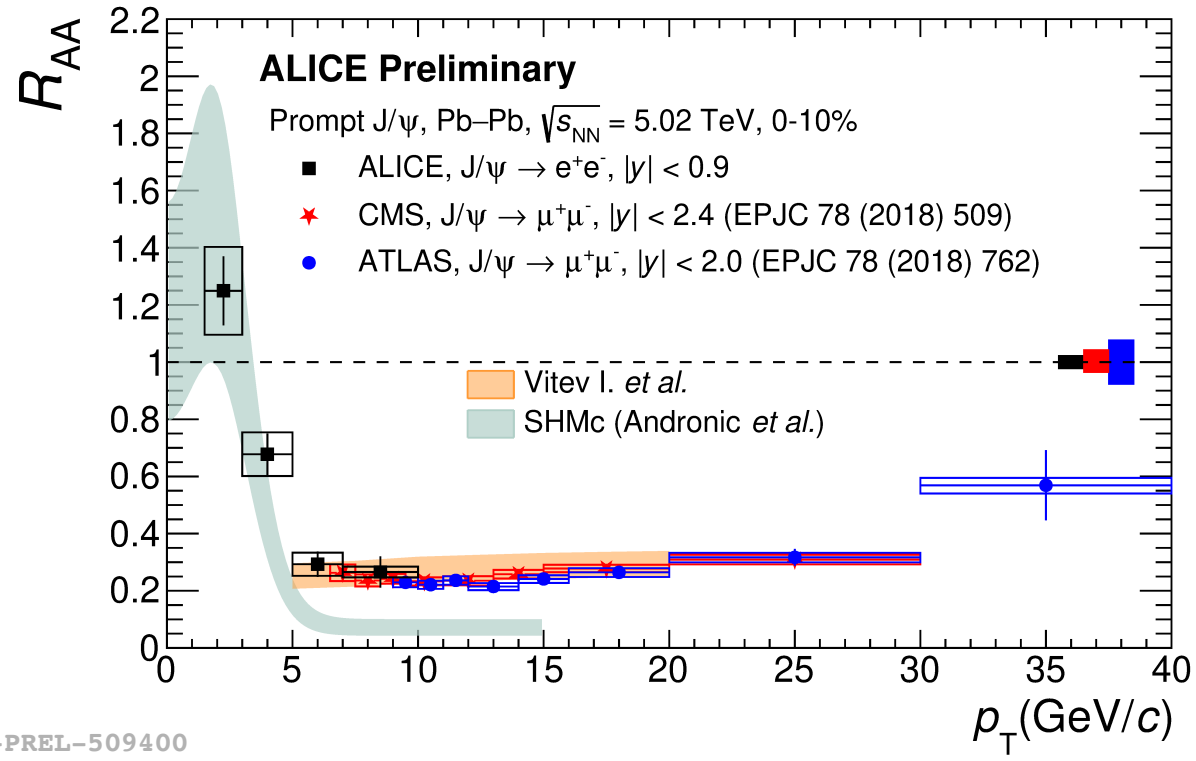


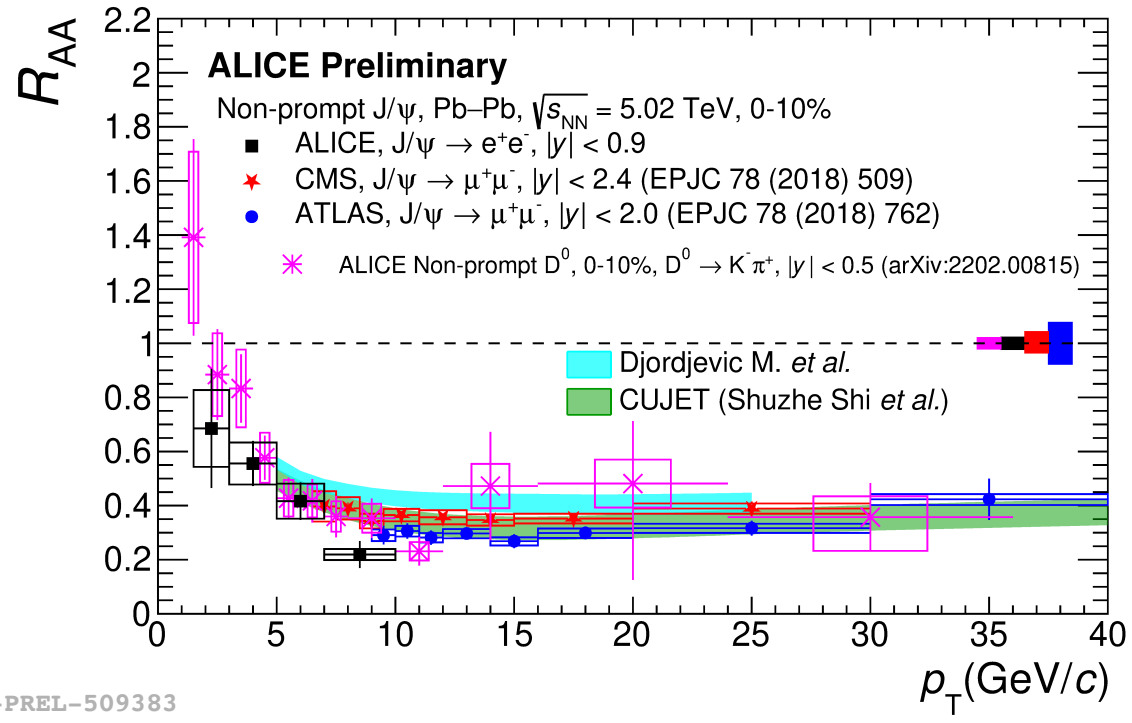
ALI-PREL-522962

- Prompt J/ψ R_{AA} increases towards more central collisions, points to an increasing contribution from (re-)generation
- Non-prompt J/ψ is more suppressed in central collisions, expected from heavy quark energy loss in the medium

J/ψ R_{AA} comparison with models



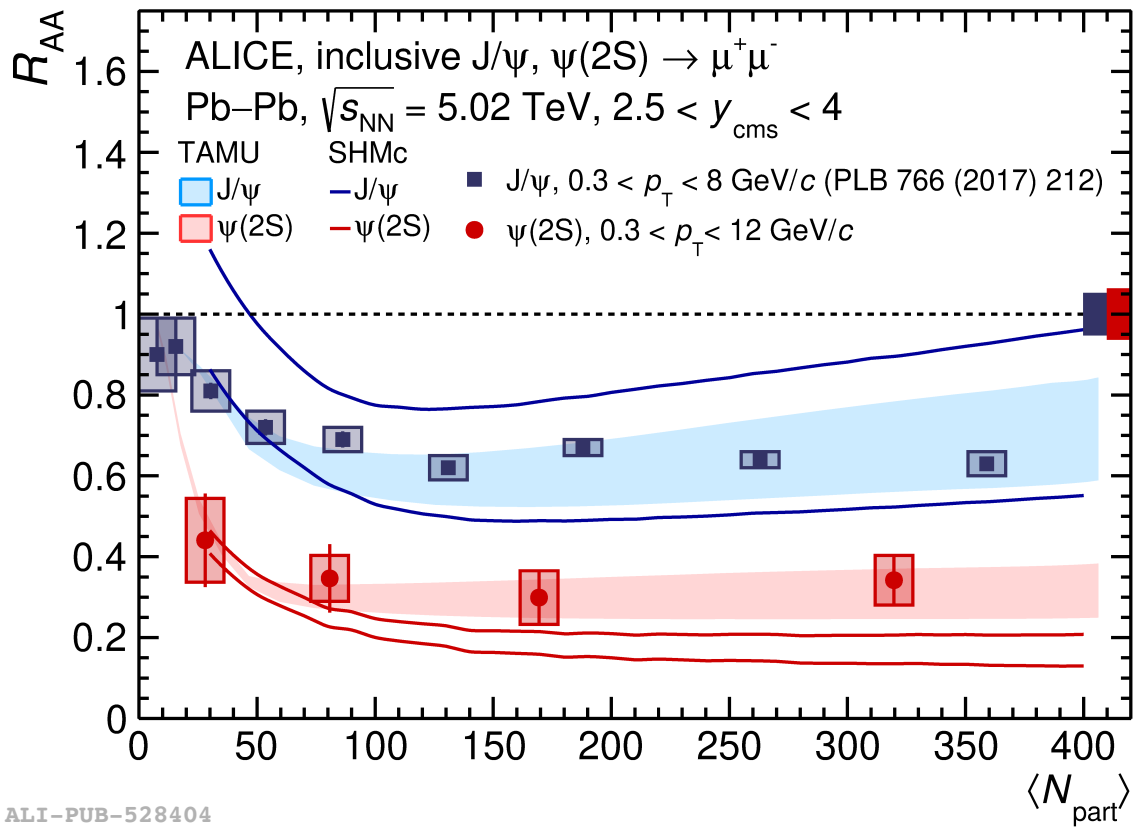
ALI-PREL-509400

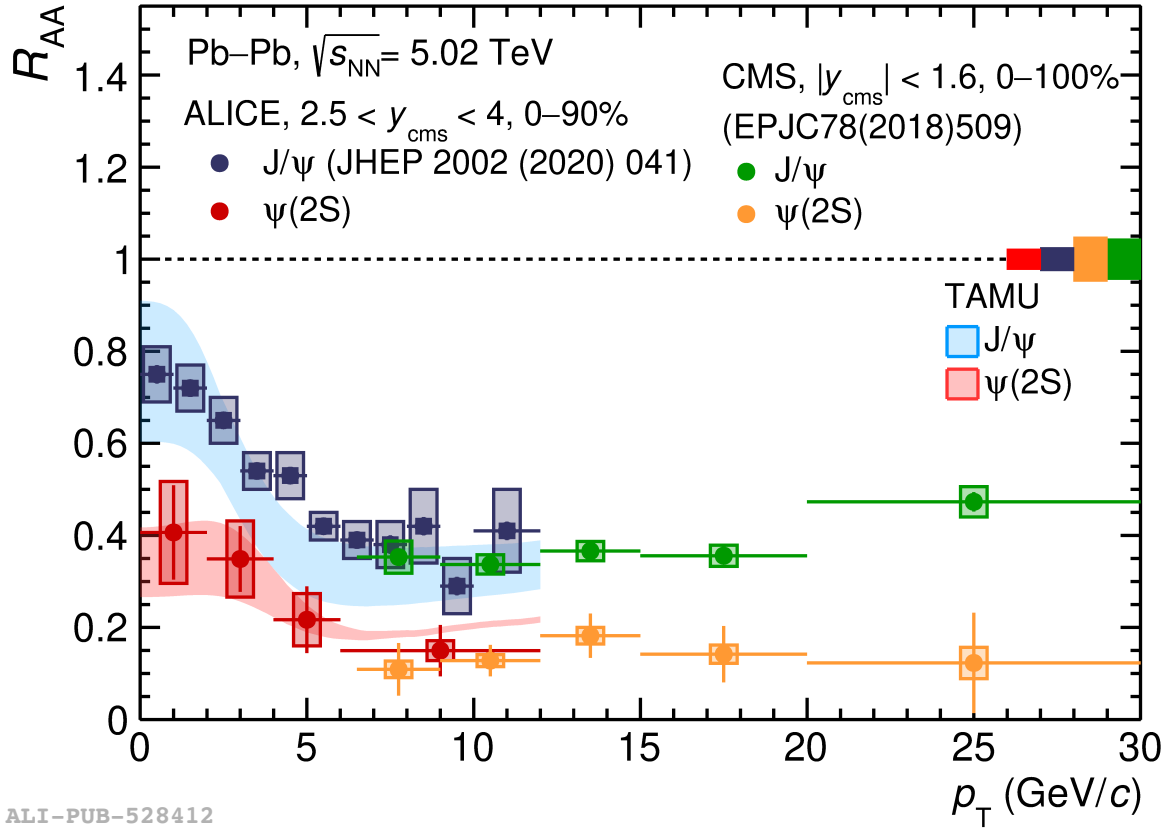


ALI-PREL-509383

- R_{AA} extended down to p_T =1.5 GeV/c and compatible within uncertainties with ATLAS and CMS measurements at high p_T
- Similar trends for non-prompt J/ψ and non-prompt D^0 R_{AA} (small difference could arise from the different decay kinematics)
- Non-prompt J/ψ R_{AA} described by models implementing collisional and radiative energy loss for p_T > 5 GeV/c
- Prompt J/ψ R_{AA} agrees with the SHMc prediction at low p_T

Centrality and p_T dependence of the ψ(2S) R_{AA}

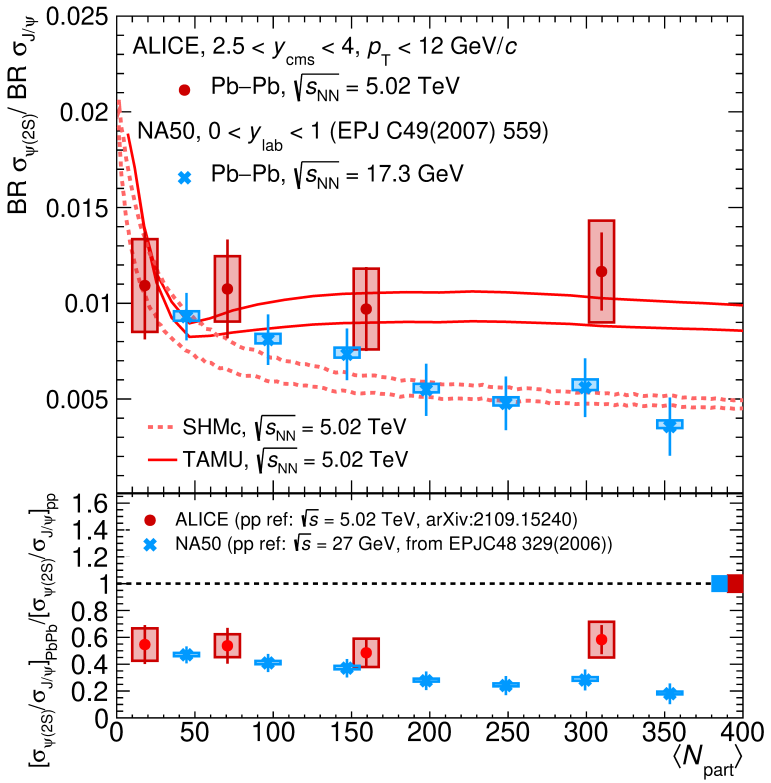




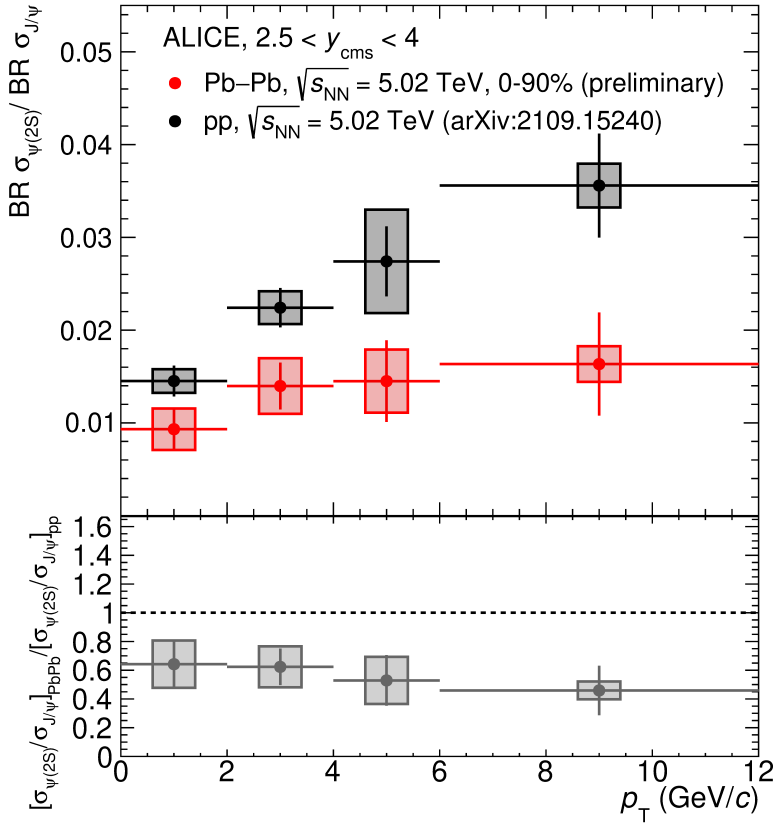
X. Du etc. NPA 943 (2015)147–158
A. Andronic etc. Nature 561no. 7723
arXiv: 2210.08893

- ψ(2S) shows stronger suppression than the J/ψ
- Stronger suppression at high-p_T and increasing trend of R_{AA} towards low-p_T for both charmonium states.
- Good agreement between CMS and ALICE data in the common p_T range, in spite of different rapidity coverages.

The ratio of ψ(2S)-to-J/ψ



ALI-PUB-528400

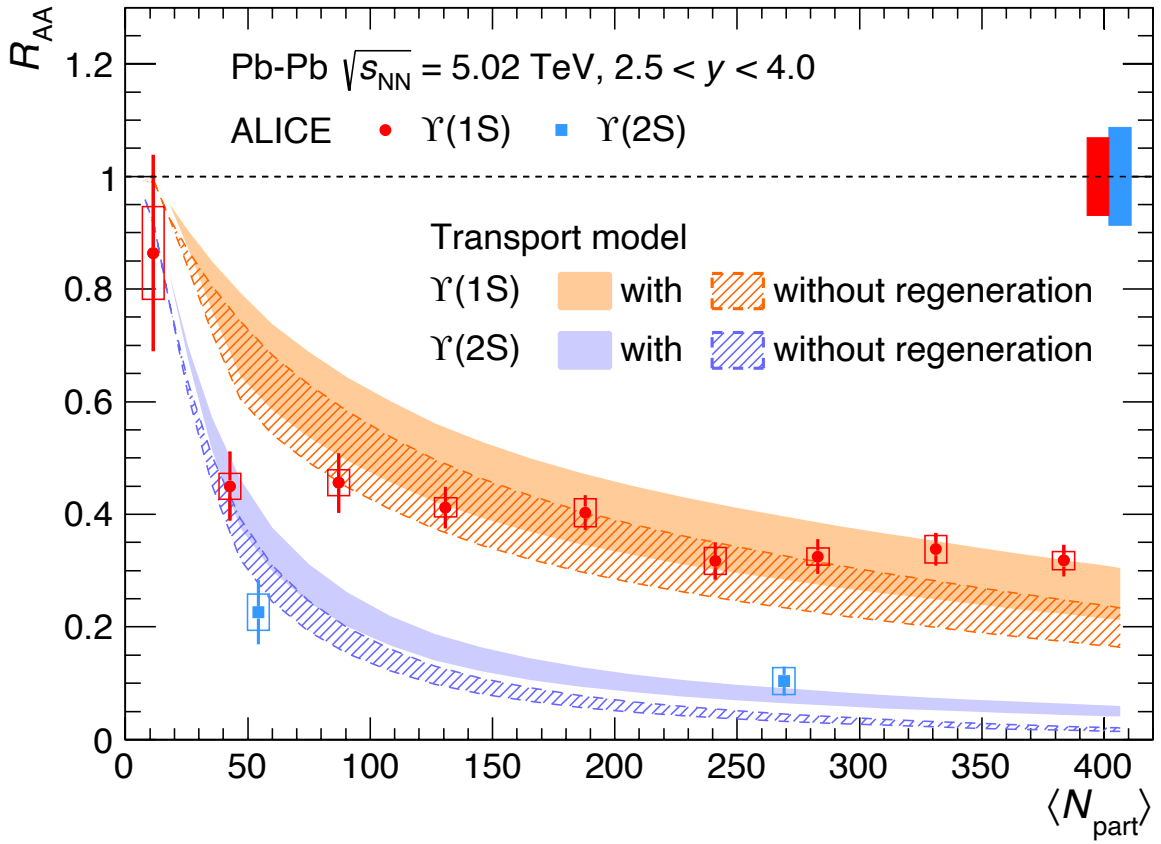


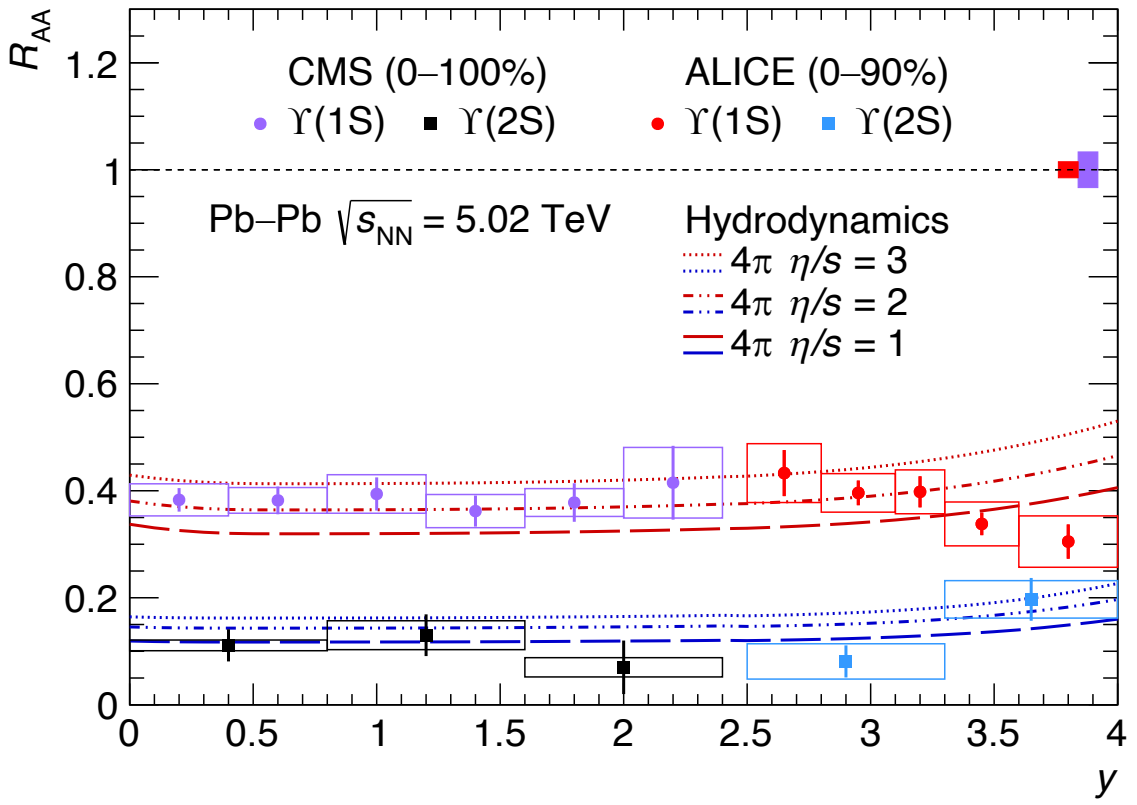
ALI-PREL-511153

X. Du etc. NPA 943 (2015)147–158
A. Andronic etc. Nature 561no. 7723
ALICE, arXiv: 2210.08893

- Significant suppression of ψ(2S)-to-J/ψ ratio in Pb–Pb with respect to pp
- No significant centrality dependence
- A significant suppression of ψ(2S)-to-J/ψ ratio in Pb–Pb with respect to pp also observed as a function of p_T

Υ(1S) and Υ(2S) R_{AA} in Pb-Pb collisions $\sqrt{s_{NN}}$ = 5.02 TeV

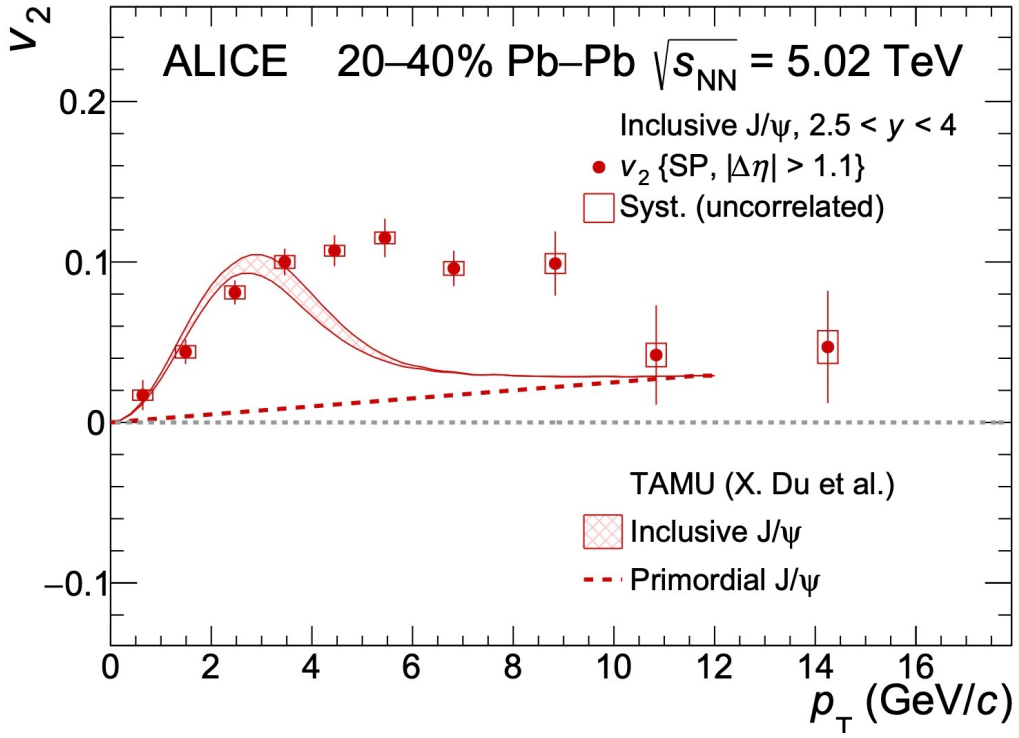


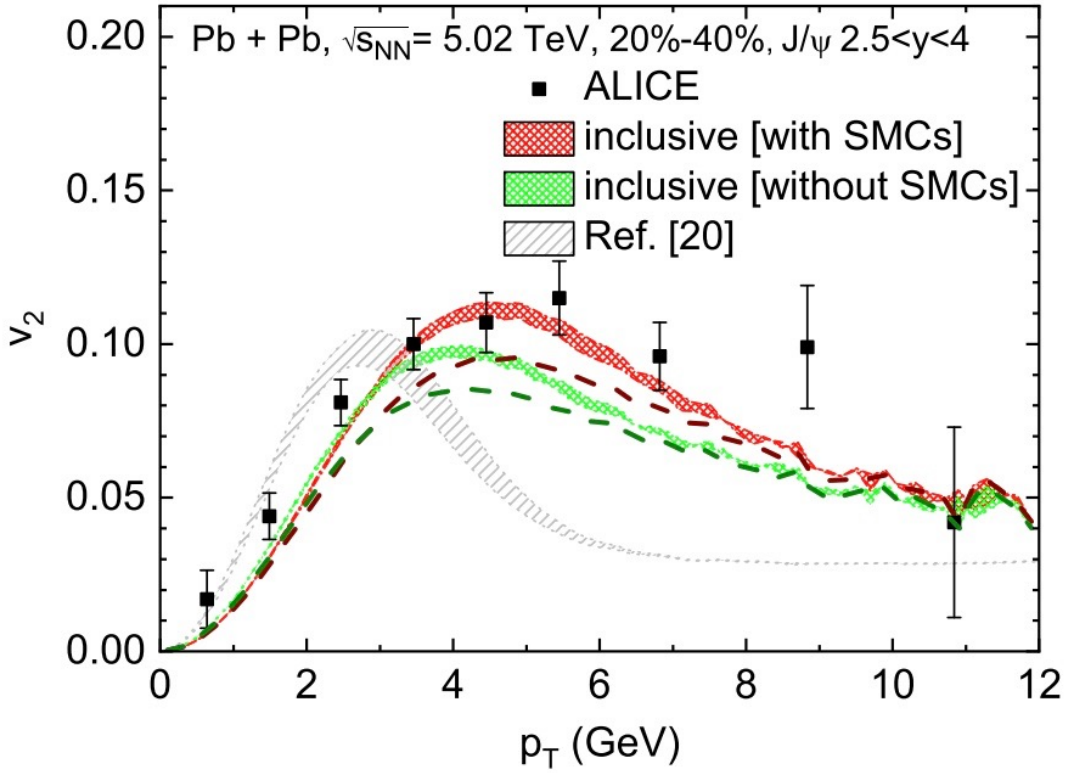


Tranport : Phys. Rev. C 96 054901
054901;JHEP 01 (2021) 046.
Hydro-dynamical:Universe 2 (2016) no.3, 16
ALICE, Phys. Lett. B 822 (2021) 136579

Slight centrality dependence for both Υ(1S) and Υ(2S) $R_{AA,}$ stronger suppression of Υ(2S) compared to Υ(1S)

Inclusive J/ψ v_2 as a function of p_T

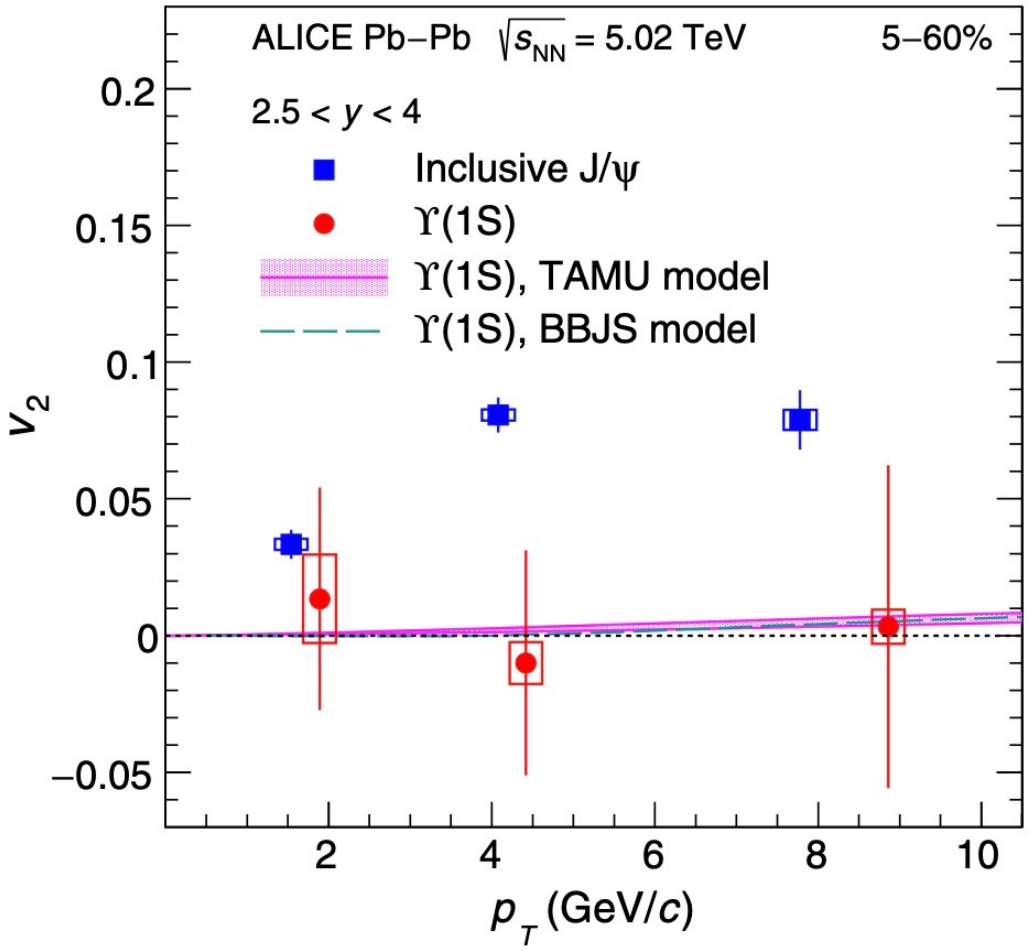


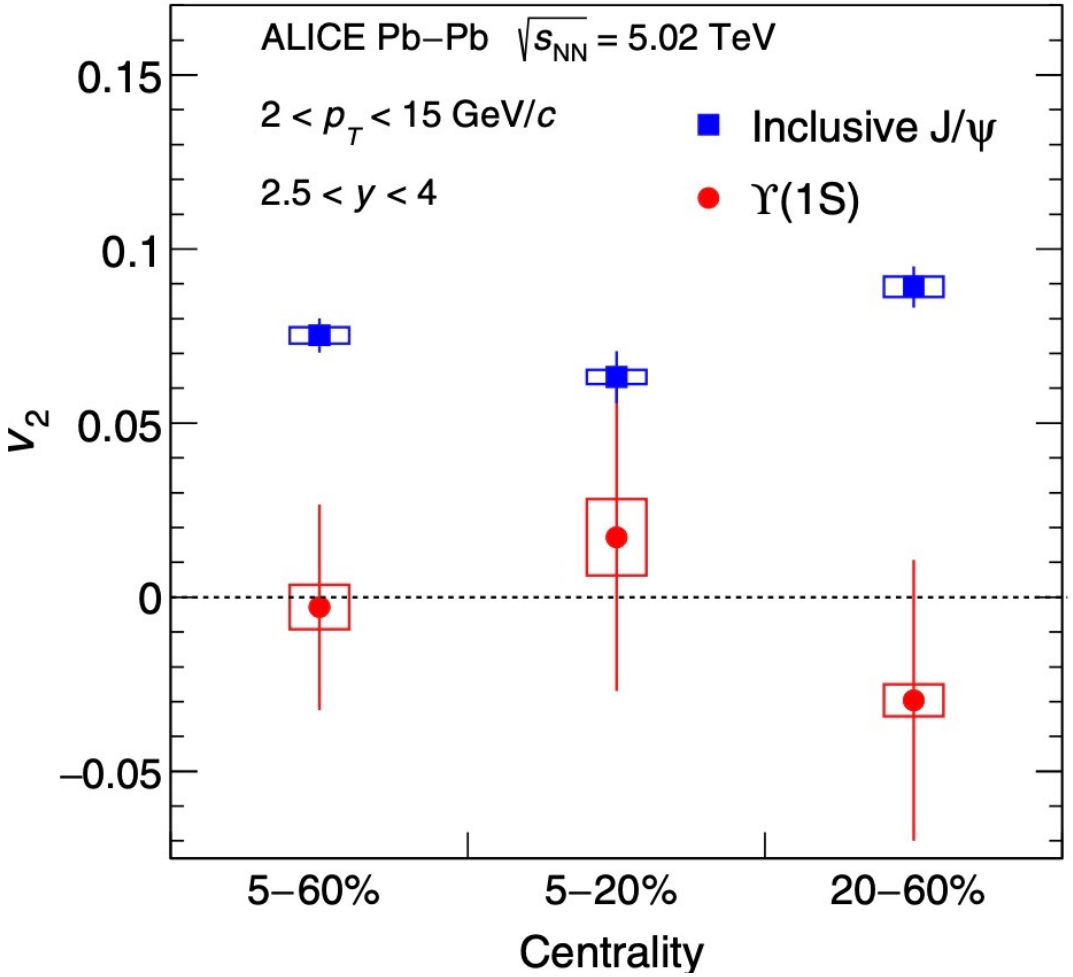


M. He et al., PRL **128**, 162301(2022)
X. Du et al., NPA 943, 147 (2015).
ALICE, JHEP 10 (2020) 141

- Observation of significant positive J/ψ v_2
- J/ψ v2 "puzzle" solved by the calculation from SMCs, the (re-)generation up to ~8 GeV/c

Υ(1S) v_2 in Pb-Pb collisions



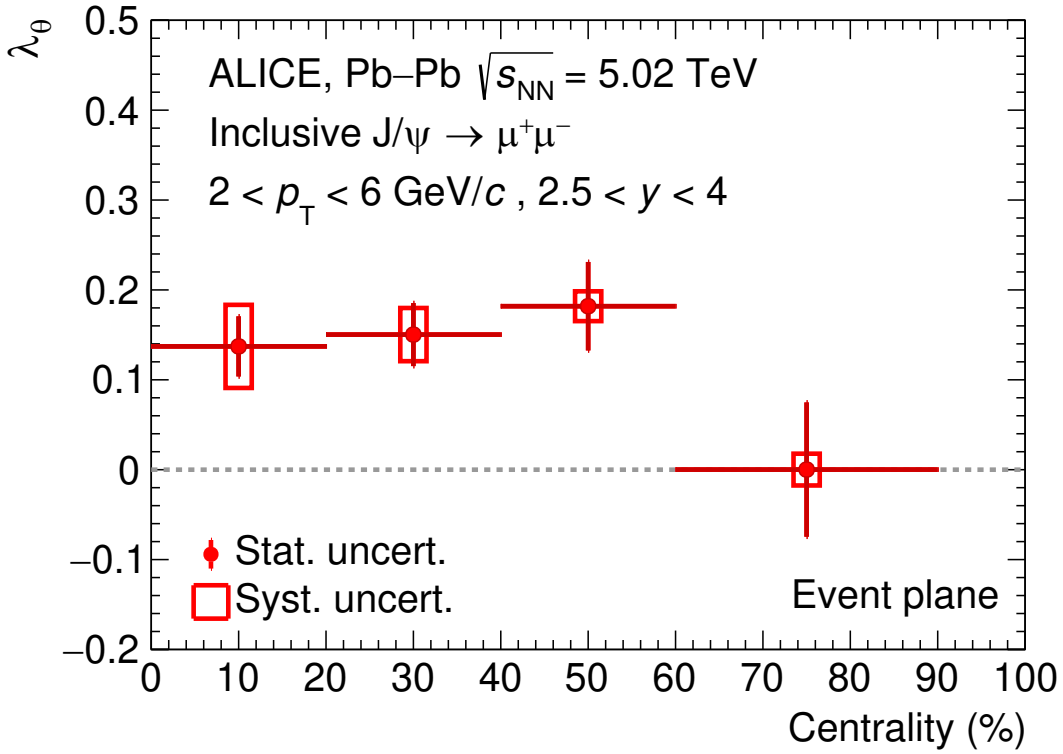


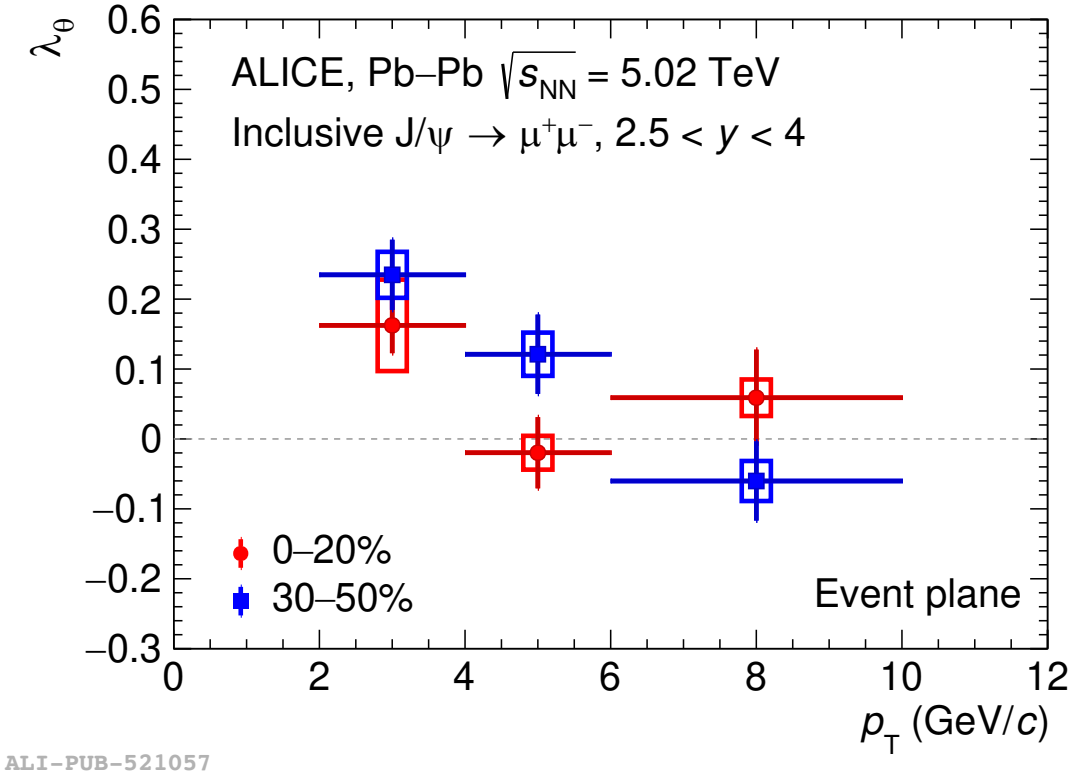
TAMU: Phys. Rev. C 96, (2017) 054901
BBJS: arXiv:1809.06235
ALICE, Phys. Rev. Lett. 123, 192301 (2019)

- First measurement of the Υ(1S) elliptic flow coefficient v_2
- v_2 consistent with zero and lower than J/ψ v_2 by 2.6σ

J/ψ polarization in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:2204.10171





- First measurement of quarkonium polarization w.r.t the event plane
- Significant polarization (~$\mathbf{3.5\sigma}$) observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The deviation reaches ~$\mathbf{3.9\sigma}$ at low p_T ($2 < p_T < 4$ GeV/c) in 30-50%
- Interpretation of results requires inputs from theoretical models

Summary

➢ Quarkonium production in pp and p-Pb collisions

- NRQCD+CGC can describe the prompt J/ψ and ψ(2S) , and FONLL agrees with the non-prompt J/ψ production
- The R_{pA} shows the significant modification at forward rapidity w.r.t backward rapidity

➢Quarkonium production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

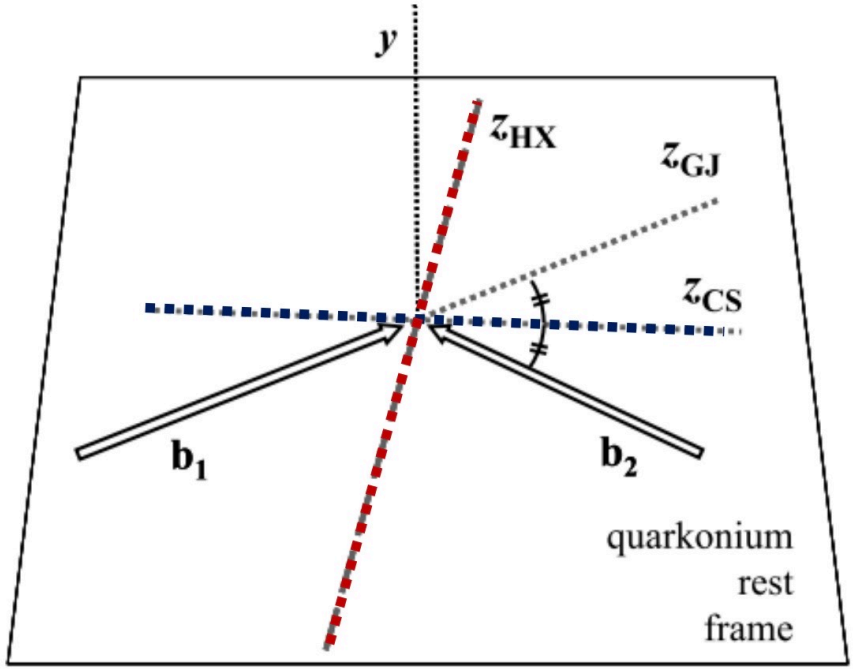
- Dominant contribution from (re-)generation for J/ψ, stronger suppression of ψ(2S) compared to J/ψ
- Significant non-zero J/ψ polarization observed w.r.t event plane
- Stronger suppression of ϒ(2S) compared to the ϒ(1S), the ϒ(1S) v_2 is consistent with zero

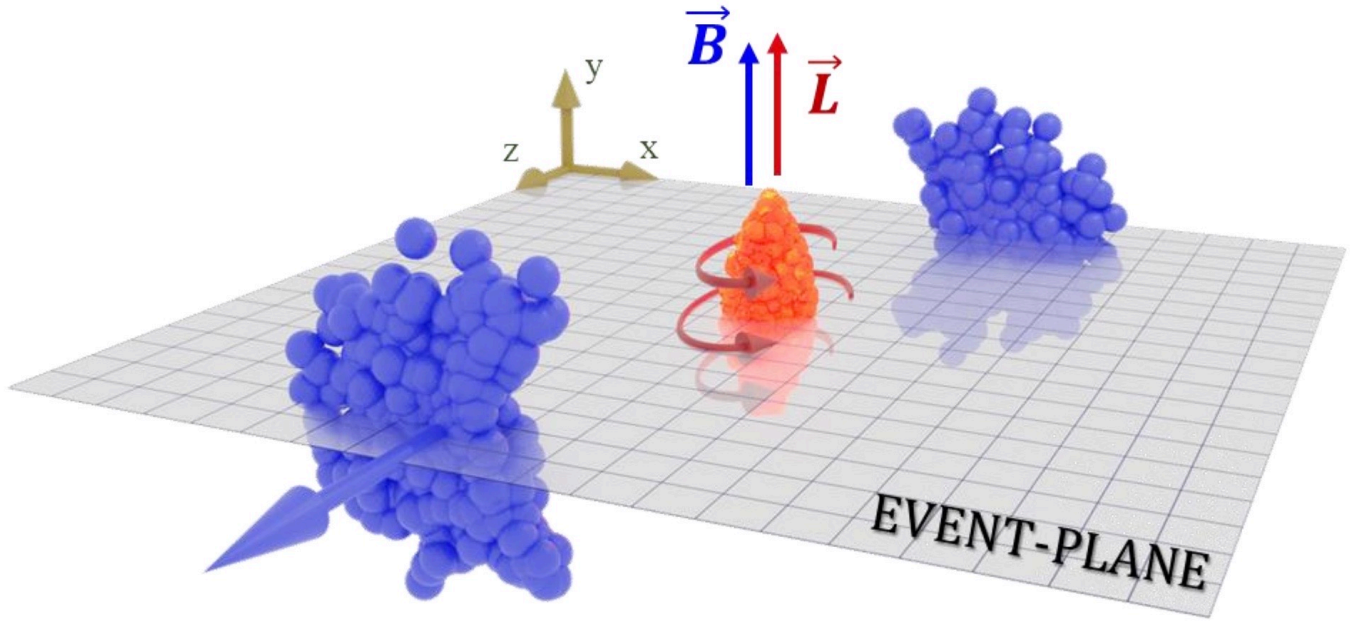
➢ Detector upgrade in Run 3

- More precise measurements can be expected from high statistics
- The newly installed MFT enables the separation between prompt and non-prompt J/ψ at forward rapidity

Thanks

Quarkonium polarization





Figures from P. Faccioli et al. EPJ C69 (2010) 657-673

- Constrains quarkonium production mechanism in pp collisions.
- Probe of the dissociation/(re-)generation in QGP
- Heavy quark pairs are produced in the earlier stage of AA collision and can experience both the short living ***B*** and the ***L*** of the rotating medium, can affect J/ψ polarization w.r.t a chosen axis (event plane)