Overview of quarkonium production with ALICE

QCD22 Montpellier

4-7 July 2022

Victor Feuillard, Heidelberg University, for the ALICE Collaboration

Introduction – Quarkonia in AA collisions

- Quark-gluon plasma (QGP) is a state of matter predicted by QCD where quarks and gluons are deconfined ➔ produced in relativistic heavy-ion collisions

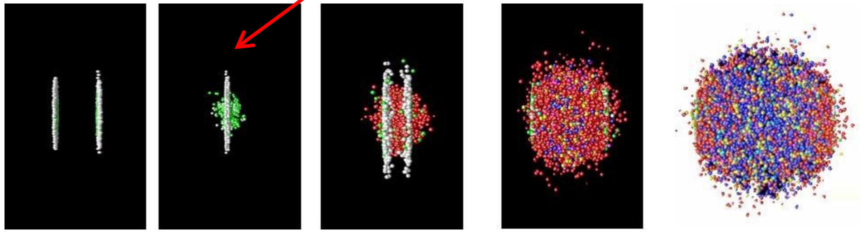
- Heavy quarks are produced at the beginning of the collision
➔experience the entire medium evolution

- Theory predicts that quarkonia, bound states of a $c\bar{c}$ pair or a $b\bar{b}$ pair, are dissociated in a QGP because of the color screening and dissociation
(*Matsui & Satz*, ***Phys. Lett. B 178 (1986) 416***)
(*Rothkopf*, ***Phys. Rep. 858 (2020) 1-117***)

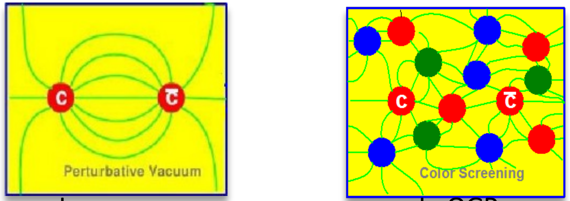
- If there are enough quark-antiquark pairs, quarkonium states can be formed, either at the freeze-out or inside the QGP
➔quarkonium regeneration
(*Braun-Munzinger & Stachel*, ***Phys. Lett. B 490 (2000) 196***, Statistical Hadronization Model)
(*Thews, Schroedter & Rafelski*, ***Phys. Rev. C 63, 054905***, Transport Model)

- Different quarkonium properties (binding energies, Debye radius, …) might lead to different behaviors in the QGP

b and c quark production



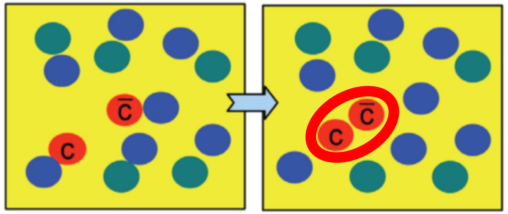
Suppression



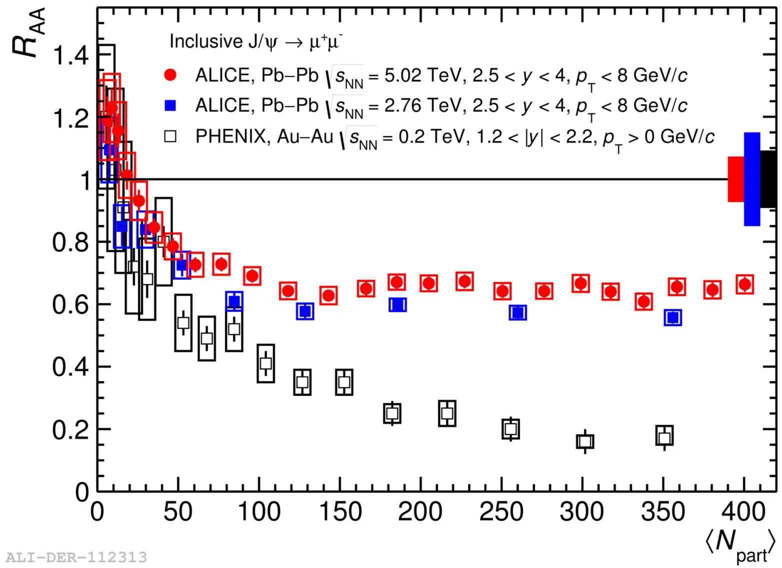
In vacuum

In QGP

Recombination



Introduction – Quarkonia in AA collisions



PLB766 (2017) 212 **(ALICE),** *Phys. Rev. C 84 (2011) 054912* **(PHENIX)**

- The effect of the medium is quantified using the nuclear modification factor:

$$R_{AA} = \frac{dN_{AA}/dy}{\langle N_{coll} \rangle \times dN_{pp}/dy}$$

- $R_{AA} \neq 1$ → nuclear effects at play
- ALICE and PHENIX observed a clear J/ψ suppression at forward rapidity
- Smaller suppression for central events in ALICE despite a collision energy more than 10 times higher

  ➔First clear sign of charmonium regeneration

- Quarkonium polarization in AA (as compared to the one in pp) can also probe regeneration
- In addition, quarkonium polarization (vs Event Plane) can probe initial stages of HI collisions: impact of strong magnetic field in QGP and large vorticity

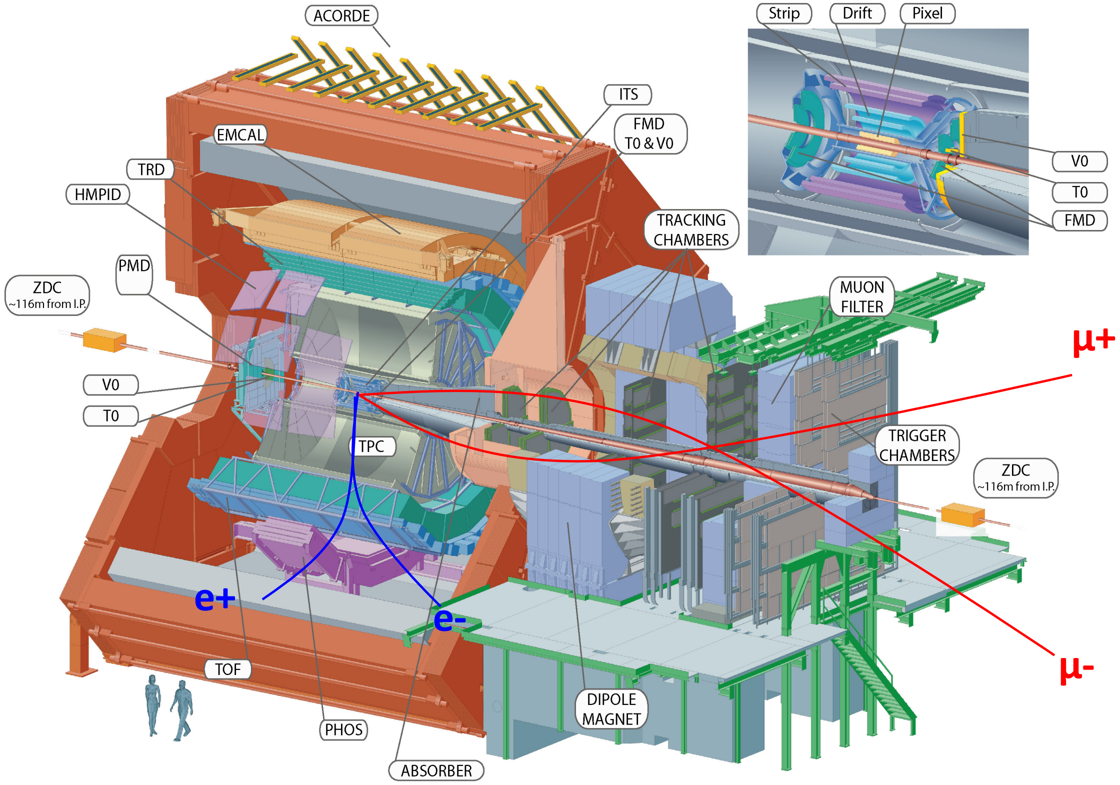
Introduction – Quarkonia in small systems

- Measurements in pp collisions :
  - Provide a reference for the measurement in p–Pb and Pb–Pb collisions
  - Study of quarkonium production mechanisms: both perturbative (i.e. $q\bar{q}$ formation) and non-perturbative (formation of the quarkonium state) QCD processes involved
    ➔Measurements of quarkonium production in pp allows to refine QCD based models

- Measurements in p–Pb collisions:
  - Investigate cold nuclear matter (CNM) effects (shadowing, coherent parton energy loss,…)
    ➔Help the interpretation of the measurements in Pb–Pb collisions

- High multiplicity pp/p–Pb collisions:
  - Multiparton interactions may occur and affect heavy flavor production
  - Study of collective effects

Introduction – The ALICE detector



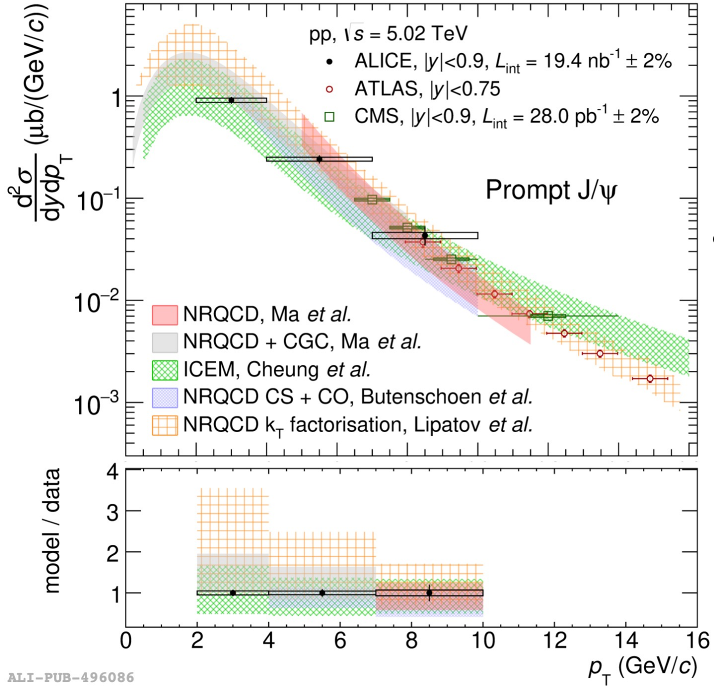
- Muon Arm :
  - J/ψ, $\psi(2S)$, $\Upsilon(nS) \rightarrow \mu^+\mu^-$
  - Acceptance: $2.5 < y < 4.0$
  - Inclusive quarkonia down to $p_T = 0$

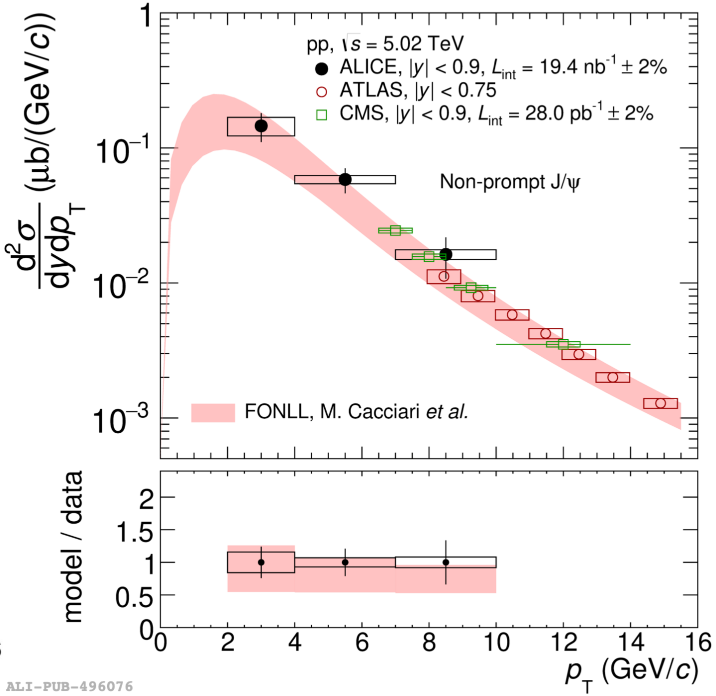
- Central Barrel:
  - $J/\psi \rightarrow e^+e^-$
  - Acceptance: $|y| < 0.9$
  - Inclusive quarkonia down to $p_T = 0$
  - Separation of prompt and non-prompt J/ψ down to very low p_T

Prompt and non-prompt J/ψ in pp collisions

midrapidity

JHEP 03 (2022) 190





At 5 TeV :

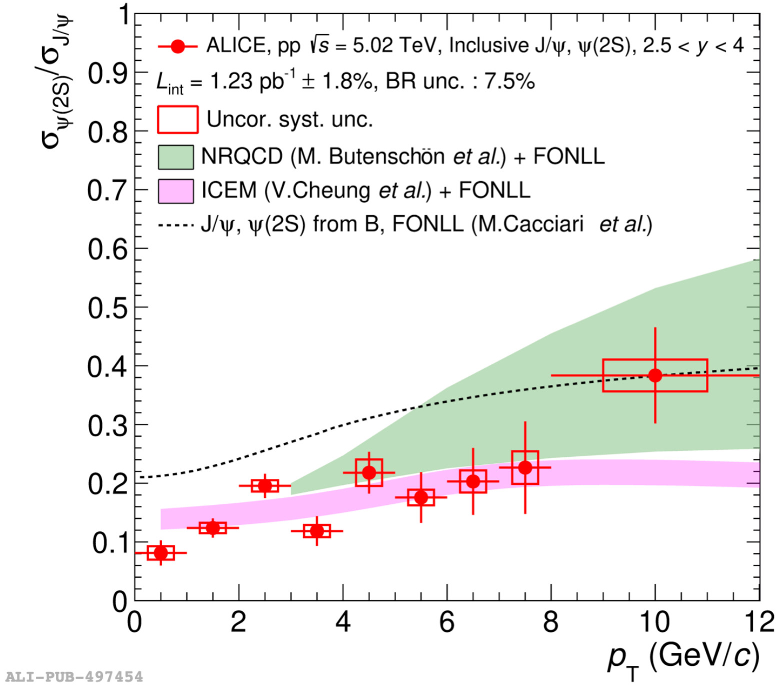
- Both cross-sections are in good agreement with ATLAS and CMS measurements in the common p_T range
- Prompt J/ψ cross-section described by NRQCD and ICEM models within uncertainties
- Non-prompt J/ψ cross-section described by FONLL calculations
- Uncertainties on model calculations do not allow to discriminate among models for prompt J/ψ

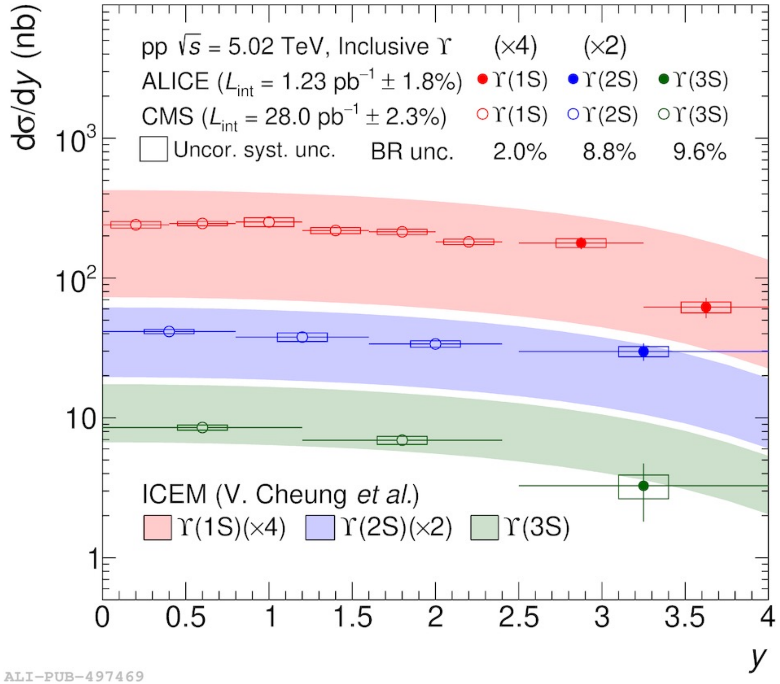
__NRQCD CS+CO :__ Butenschoen et al, Phys. Rev. Lett. 106 (2011) 022003
__NRQCD :__ Ma et al, Phys. Rev. Lett. 106 (2011) 042002
__NRQCD k_T factorization :__ Lipatov et al, Phys. Rev. D 100 no. 11, (2019) 114021
__NRQCD + CGC :__ Ma et al, Phys. Rev. Lett. 113 no. 19, (2014) 192301
__ICEM :__ Cheung et al, Phys. Rev. D 98 no. 11, (2018) 114029
__FONLL :__ Cacciari et al, JHEP 10 (2012) 137

Inclusive quarkonia in pp collisions

arXiv:2109.15240

forward rapidity

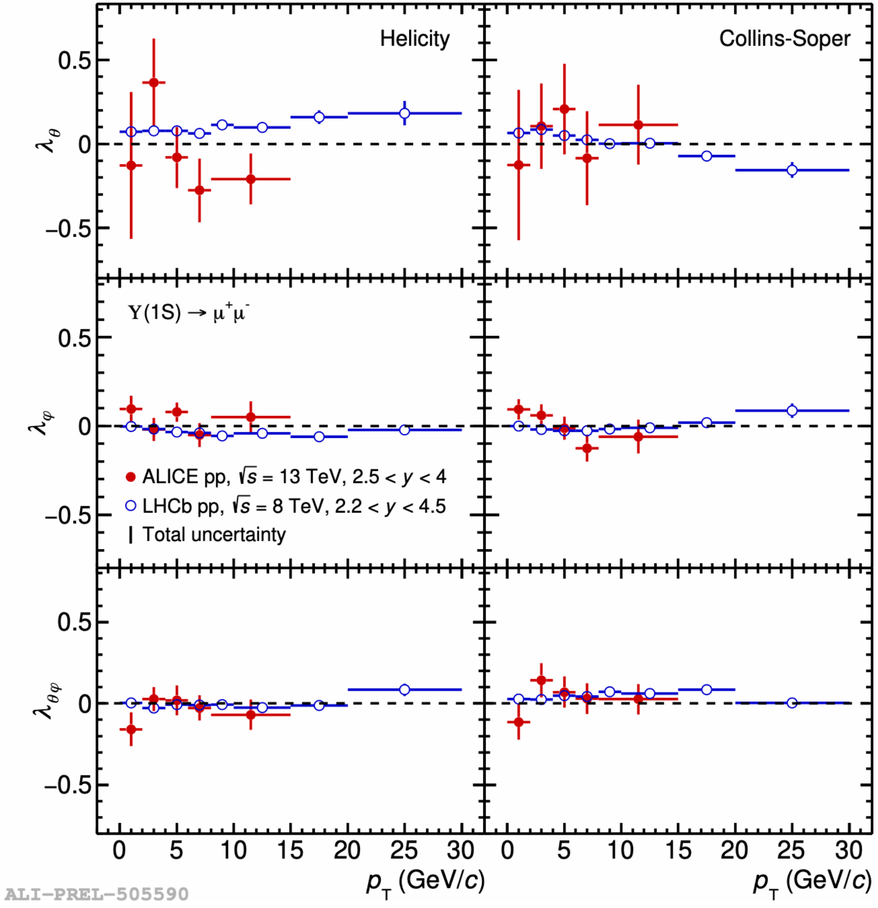




- ψ(2S)-to-J/ψ cross-section ratio described by NRQCD and ICEM models within uncertainties
- **ϒ**(nS) cross-sections as a function of rapidity show a drop-off from a plateau at forward rapidity, as predicted by ICEM model

Υ polarization in pp collisions

forward rapidity



- Polarization, i.e. the alignment of the particle spin with respect to a chosen axis, is studied via the polar angle distribution of the dilepton decay products of the charmonium:
  $$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta + \lambda_\phi\, sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right)$$
- First ALICE measurement of Υ(1S) polarization in pp collisions
- No polarization observed within uncertainties
- Results compatible with LHCb measurements
  (JHEP 12 (2017) 110)

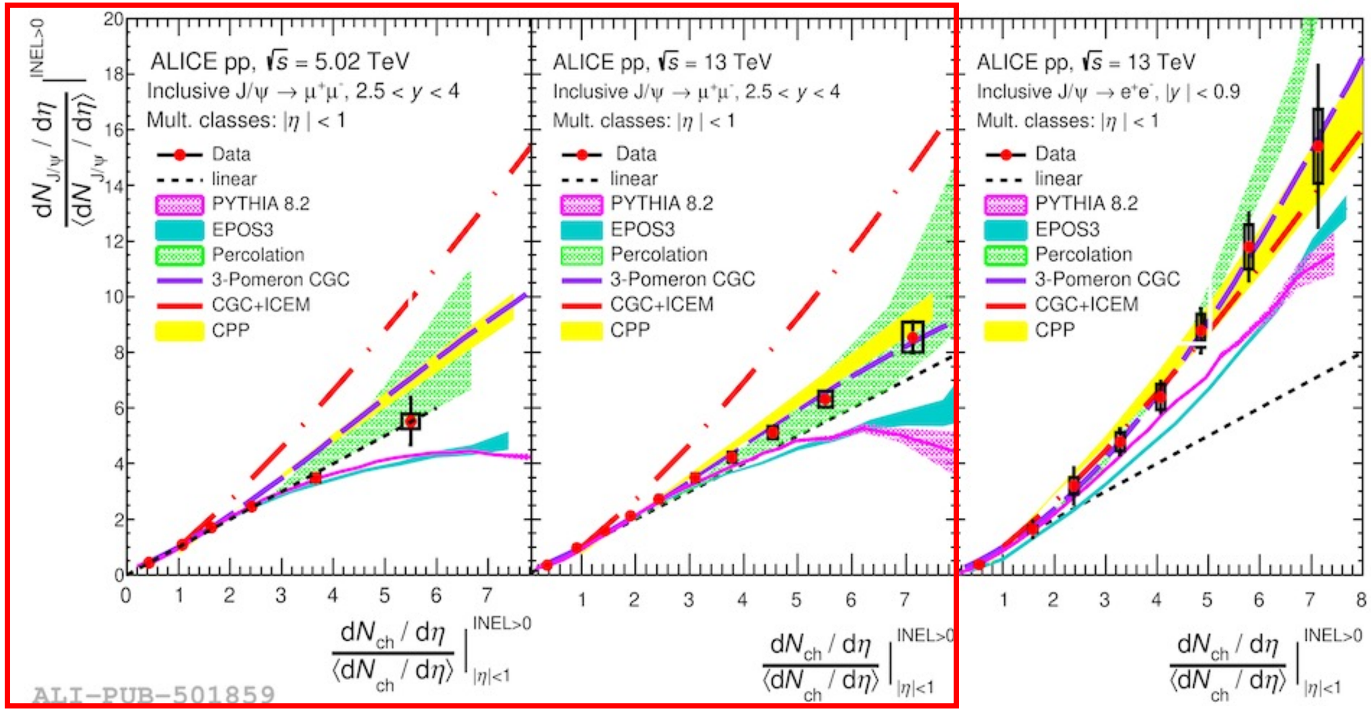
J/ψ as a function of multiplicity in pp collisions

JHEP 06 (2022) 015

- Correlations between the J/ψ yield and the charged particle multiplicity are useful to constrain the interplay between hard and soft particle production mechanisms in pp collisions

- The normalized J/ψ yield at forward rapidity approximatively grows linearly as a function of the event multiplicity, independently of the collision energy

New J/ψ→μμ measurement at forward rapidity



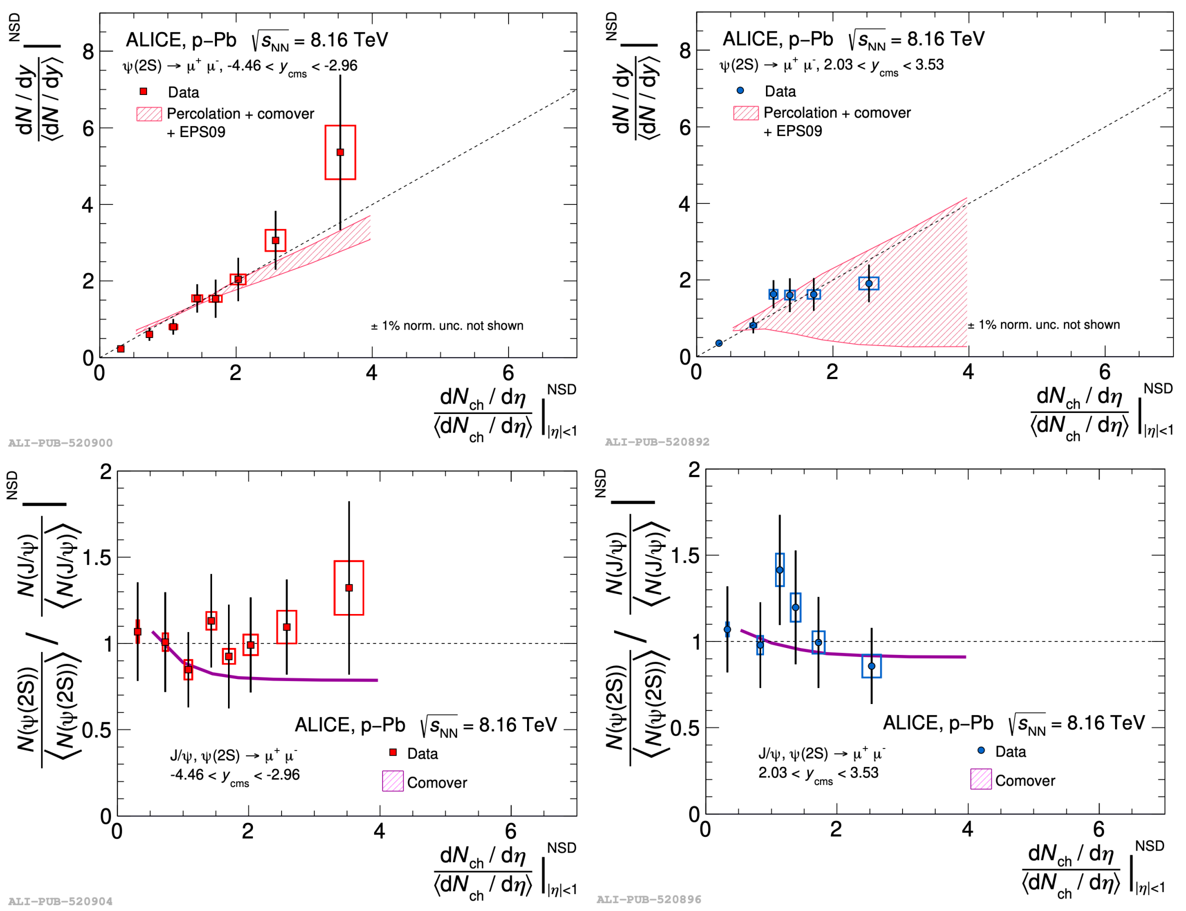
CPP : *Kopeliovich et al, Phys. Rev. D 101 no. 5, (2020) 054023*
CGC with ICEM : *Ma et al, Phys. Rev. D 98 no. 7, (2018) 074025*
3-Pomeron CGC : *Levin et al, Eur. Phys. J. C 80 no. 6, (2020) 560*
Percolation : *Ferreiro et al, Phys. Rev. C 86 (2012) 034903*
EPOS3 : *Werner et al, Phys. Rev. C 89 no. 6, (2014) 064903*
PYTHIA 8.2 : *Sjöstrand et al, Comput. Phys. Commun. 191 (2015) 159–177*

- Models including either initial state effects or both initial and final state effects can describe qualitatively the data trend and the different behaviour at forward and midrapidity

ψ(2S) as a function of charged particle multiplicity in p–Pb collisions

forward and backward rapidity

Pb-going, $-4.46<y_{CMS}<-2.96$ **p-going, $2.03<y_{CMS}<3.53$**



arXiv:2204.10253v1

- The self-normalized ψ(2S) yield increases with an approximately linear trend, with the slope close to unity
- The results can be described by models within uncertainties (those on the models are due to EPS09 nPDFs uncertainties)

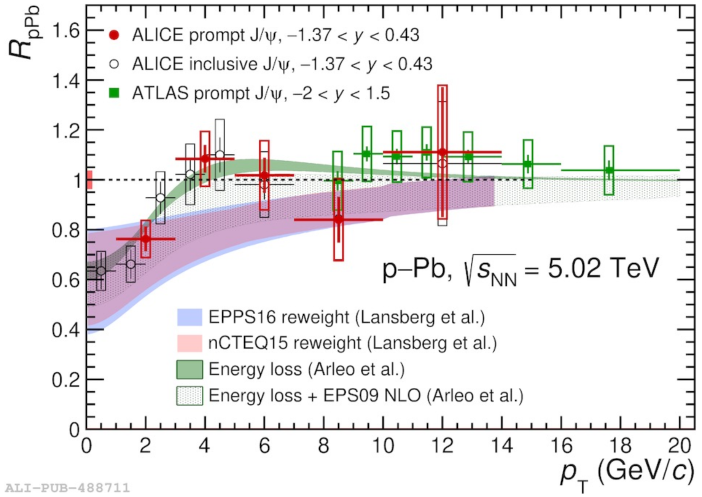
- The normalized ψ(2S)-to-J/ψ ratio is compatible with unity as a function of charged particle multiplicity
  ➔Similar multiplicity dependence for ψ(2S) and J/ψ states
- Data is compatible with comover model predictions within uncertainties
  (*Ferreiro, Phys. Lett. B 749 (2015) 98–103*)

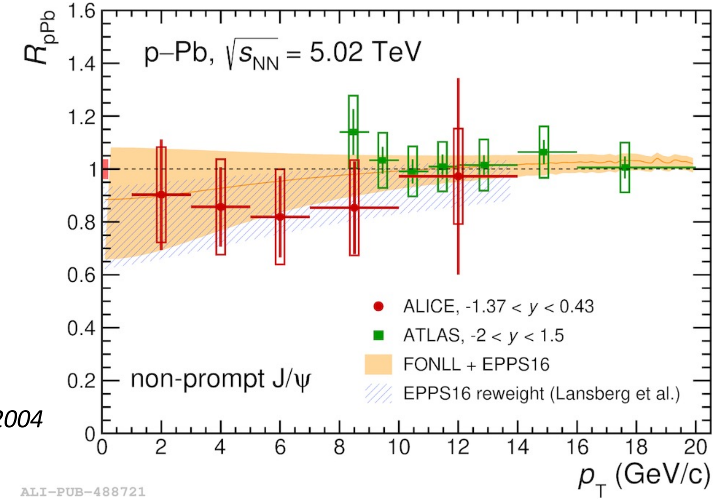
J/ψ R_{pPb} at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

midrapidity

JHEP 06 (2022) 011

- $R_{\mathrm{pPb}} = \dfrac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}y}$
- Similar R_{pPb} for prompt and inclusive J/ψ, with a clear suppression for $p_{\mathrm{T}} < 3$ GeV/c
- Results for non-prompt J/ψ indicate a smaller suppression compared to prompt J/ψ, as well as no p_{T} dependence within uncertainties
- ALICE data is compatible with ATLAS for $p_{\mathrm{T}} > 8$ GeV/c
  (*Eur. Phys. J. C78 no. 3, (2018) 171*)
- Theoretical calculations, including various combinations of cold nuclear matter effects, reproduce the data within uncertainties





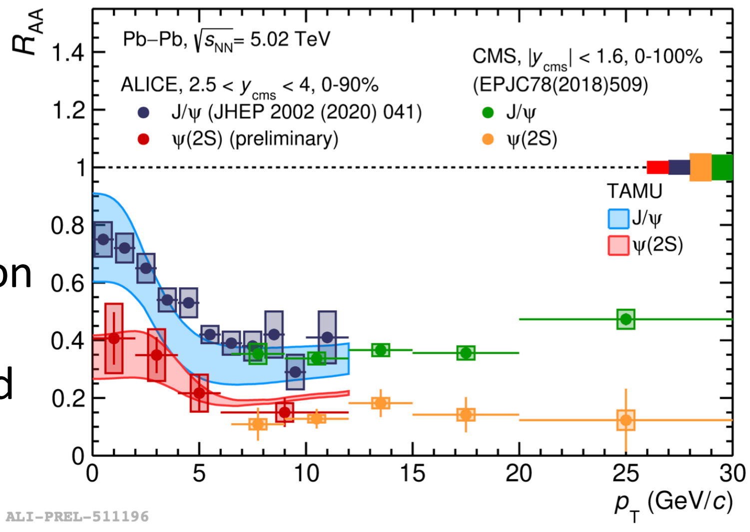
Energy Loss : *Arleo et al, J. High Energ. Phys. 05 (2013) 155*
EPPS16 & nCTEQ15 reweight : *Lansberg et al, Phys. Rev. Lett. 121 no. 5, (2018) 052004*
EPP16+ FONLL : *Eskola et al, Eur. Phys. J. C 77 no. 3, (2017) 163*

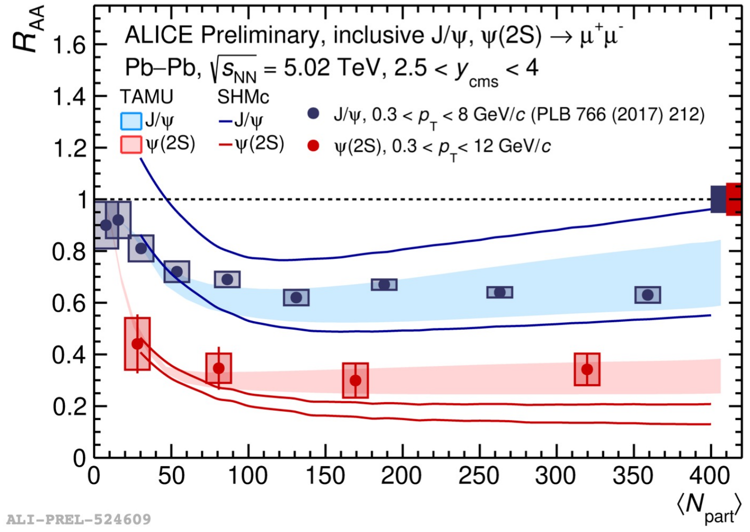
ψ(2S) in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Pb Pb

forward rapidity

- As a function of p_T, increasing trend of the J/ψ and ψ(2S) R_{AA} at low p_T → indication of recombination
- ALICE and CMS results in good agreement at high p_T in the overlapping range , in spite of the different rapidity coverage





***TAMU :** Rapp et al, Nucl. Phys. A943 (2015) 147–158*
***SHMc :** Andronic et al, Phys. Lett. B 797 (2019) 134836*

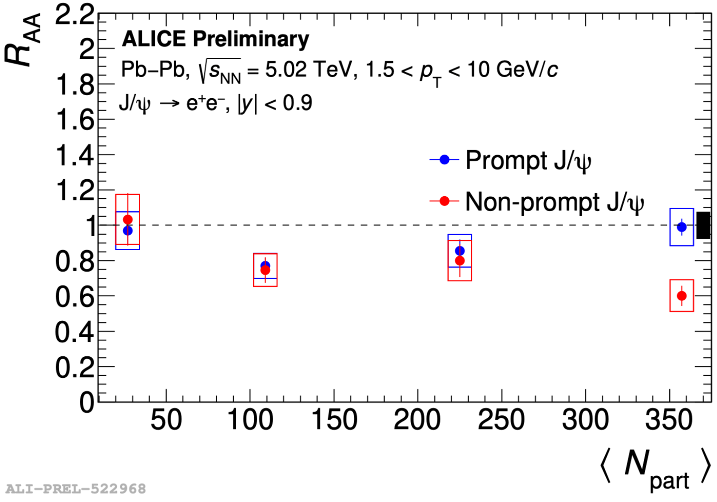
- ψ(2S) shows a stronger suppression than the J/ψ in all centralities
- ψ(2S) R_{AA} does not show any trend as a function of centrality within the current uncertainties

- Transport Model (TM) is in good agreement with results as a function of p_T and centrality
- SHMc model tends to underestimate data in central collisions
- In SHMc, charmonia are produced from deconfined charm quarks at the QCD phase boundary whereas TM includes recombination in the QGP phase

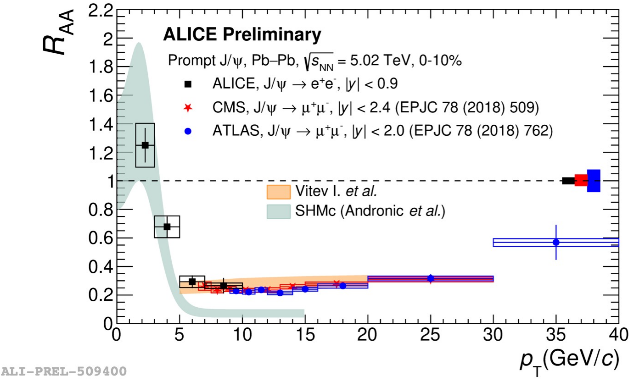
Prompt and non-prompt J/ψ in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Pb Pb

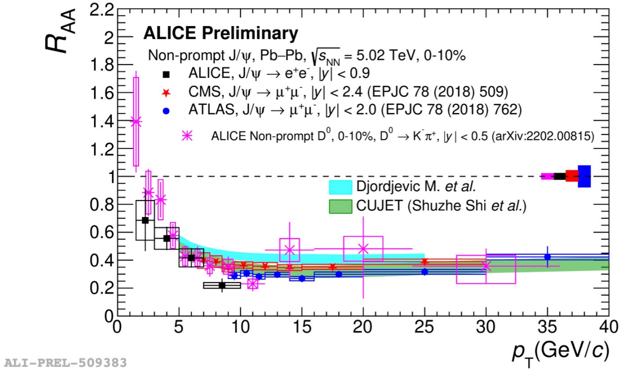
midrapidity



- Similar suppression for prompt and non-prompt J/ψ in peripheral and semi-central collisions
- Non prompt J/ψ are more suppressed than prompt J/ψ in central collisions, prompt J/ψ are less suppressed at low p_T than at higher p_T (and even enhanced at low p_T)
  ➜ indication of recombination



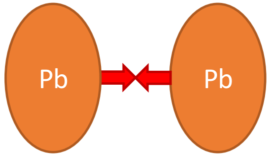
Vitev et al: *arXiv:1906.04186,arXiv:1709.02372*
SHMc: *Andronic et al, JHEP07 (2021) 035*



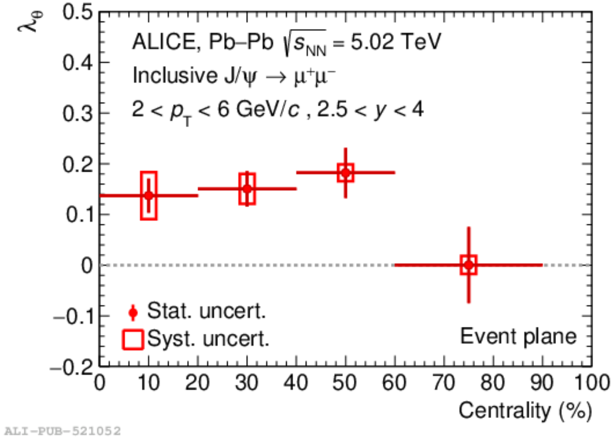
CUJET: *Shi et al, Chinese Phys. C 43 044101 (2019)*
Djordjevic et al: *arxiv:2110.01544*

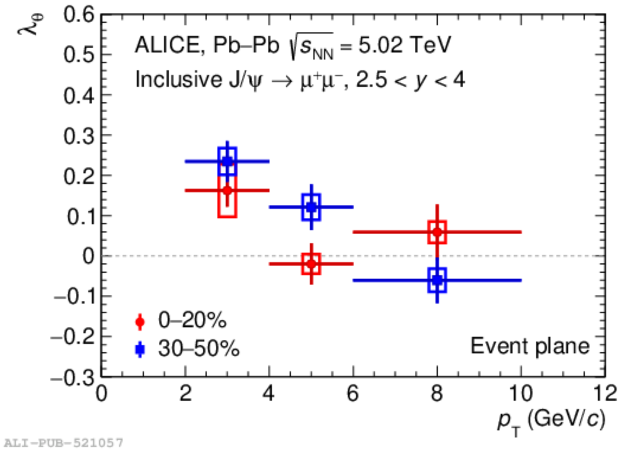
- Prompt J/ψ data is compatible with SHMc model at low p_T and with a model including quarkonium dissociation at high-p_T
- Non-prompt J/ψ data is compatible with models implementing beauty quark energy loss at high p_T
- ALICE data is compatible with ATLAS and CMS in the overlapping p_T range

J/ψ polarization in Pb–Pb as a function of Event Plane



forward rapidity





arXiv:2204.10171v1

- Polarization of quarkonia may be altered by the QGP's strong magnetic fields and large vorticity
- Polarization studied with : $W(\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$
- The direction perpendicular to the event plane of the collision used as the polarization axis
- As a function of centrality, a significant non-zero polarization is found from central collisions to the centrality interval 40–60%
- The results as a function of p_T may indicate that the deviation from zero is larger at small transverse momentum
  → indication that effects at play in the early stages of the collision contribute less to the polarization, but lack of theoretical predictions

Conclusion and outlook

- A wide variety of new quarkonium results by ALICE:
  - Quarkonium cross-sections in pp collisions is well described by models within uncertainties
  - Similar multiplicity dependence for J/ψ and ψ(2S) state in p–Pb collisions. Within the experimental uncertainties, the comover models which predicts a ψ(2S)-to-J/ψ ratio below unity at large multiplicities, is still compatible with data
  - J/ψ and ψ(2S) R_{AA} in Pb–Pb collisions show an enhancement at low-p_T, indicating recombination for prompt charmonia, compatible with model predictions
  - Significant J/ψ polarization w.r.t the event plane observed in central Pb–Pb collisions

- Prospects for Run 3 and 4 (first physics collisions of Run 3 this week) :
  - Significantly higher statistics compared to Run 1 and 2 expected (L_{int}= 10 nb^{-1} in Pb–Pb, 200 pb^{-1} in pp)
  - New MFT at forward rapidity will enable the separation of prompt and non-prompt charmonia
  - Improved tracking and vertexing capabilities at midrapidity thanks to the upgraded ITS

- Relevant improvement expected for all current quarkonium measurements and new observables will become accessible (prompt/non-prompt charmonium elliptic flow, improved precision on ψ(2S) measurement in Pb–Pb, measurement of χ_c at midrapidity, double quarkonium/HF production via correlations at mid and forward rapidities …)

THANK YOU FOR YOUR ATTENTION !

BACK-UP

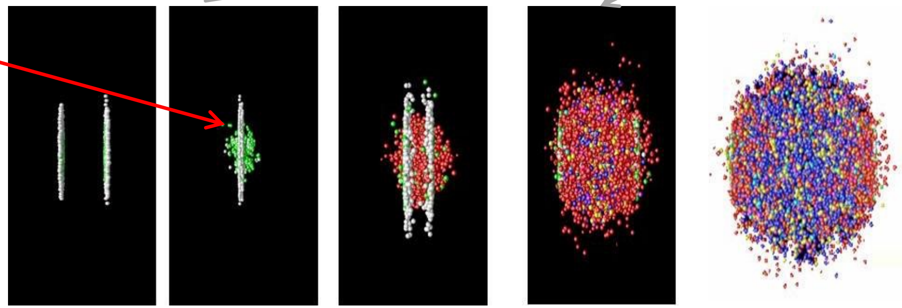
Introduction - Quarkonia

Pre-equilibrium : multiple interaction leading to an increase of the temperature

QGP Formation and rapid expansion

Temperature decrease: quarks are confined in hadrons

b and c production



Freeze-out: particles stop interacting with each other and continue to travel

- Because of their large mass, heavy quarks are produced at the beginning of the collision

- They face all the medium evolution and are affected by it
  ➔Measurement of the particle production can provide information on the QGP properties

Prompt and non-prompt J/ψ in pp collisions

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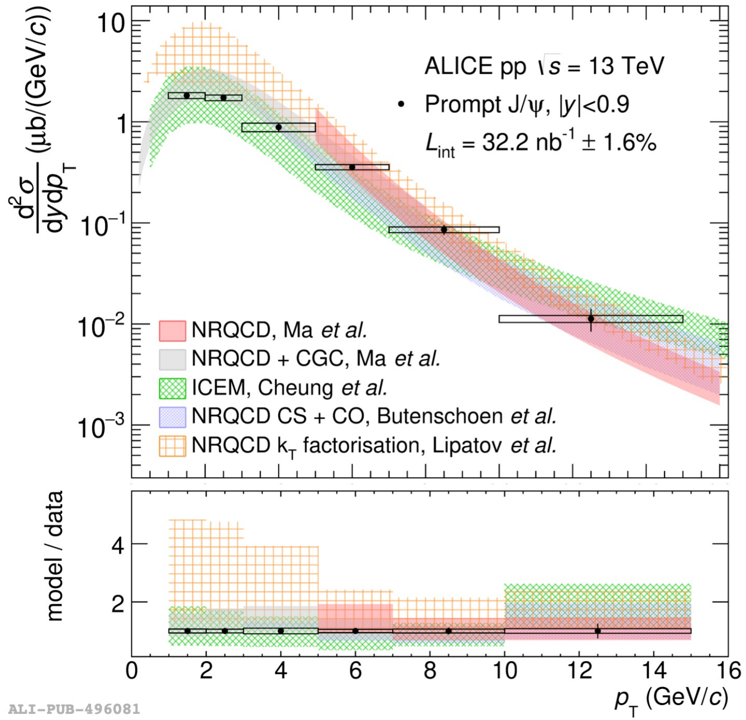

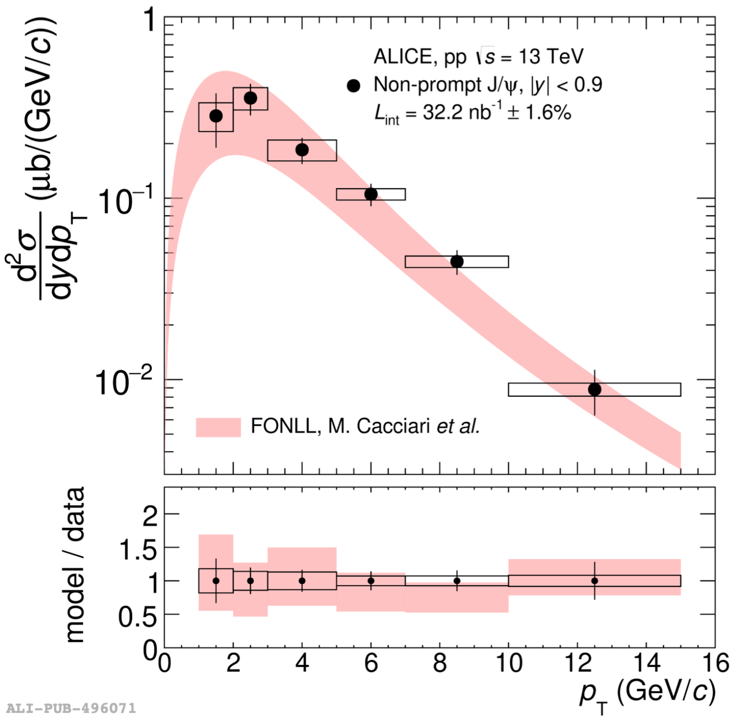

At 13 TeV :

- Prompt J/ψ cross-section described by NRQCD models within uncertainties
- Non-prompt J/ψ cross-section described by FONLL calculations

Prompt and non-prompt J/ψ in pp collisions

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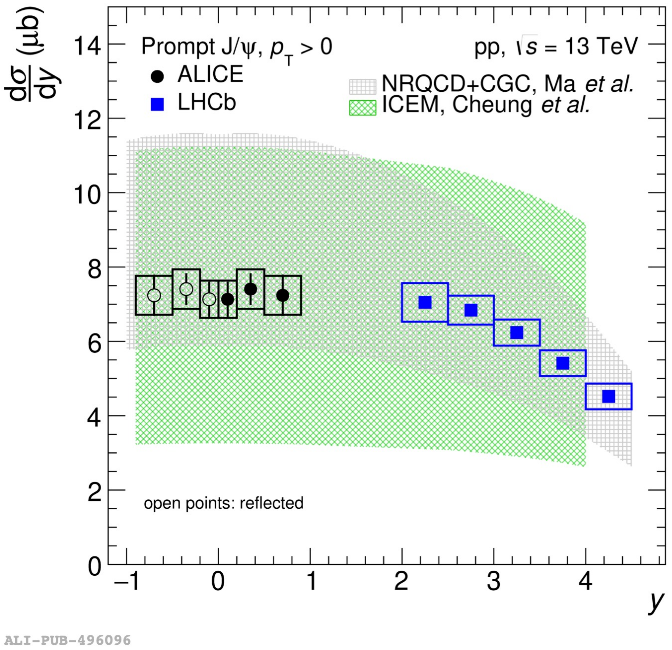
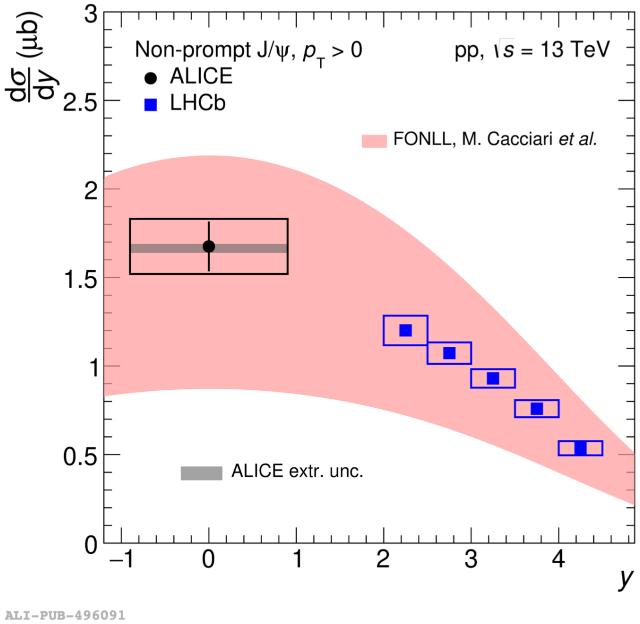




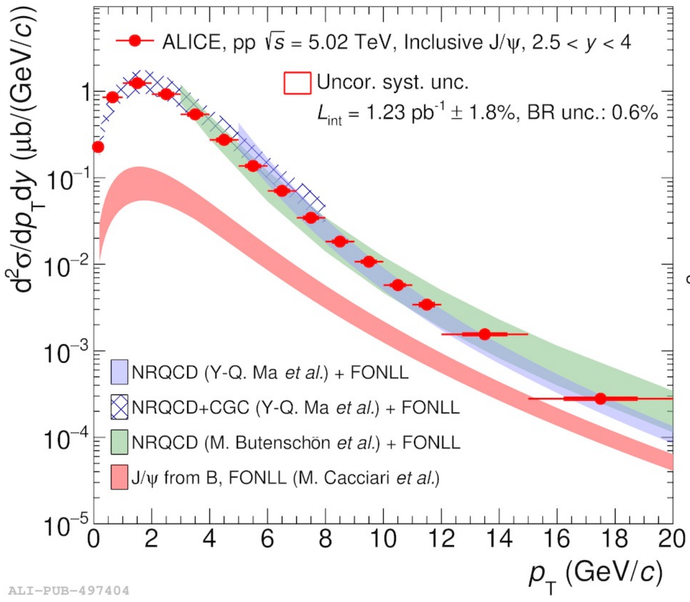
At 13 TeV :

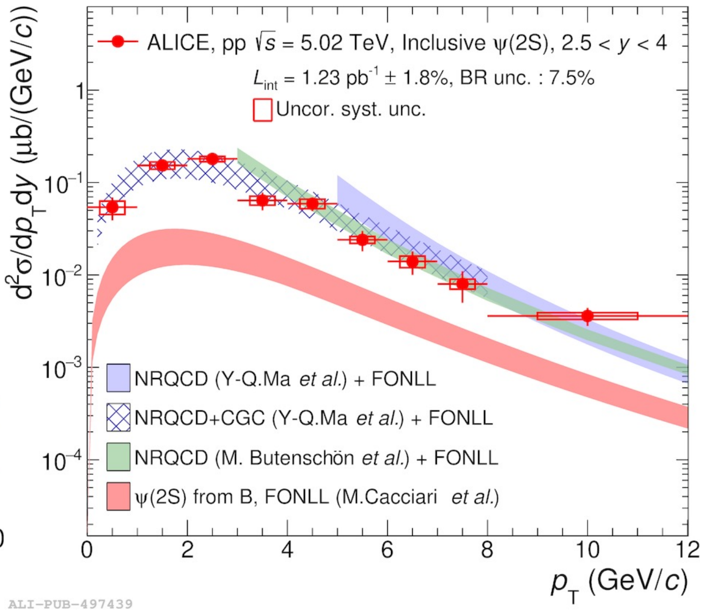
- As a function of rapidity, models are compatible within uncertainties with ALICE and LHCb measurements.
- The large uncertainties prevent from drawing firm conclusions

Inclusive Quarkonia in pp collisions

arXiv:2109.15240

- New measurement of the inclusive quarkonia in pp collisions at 5 TeV at forward rapidity





- J/ψ cross-section described by NRQCDmodels within uncertainties
- Non-prompt J/ψ cross-section described by FONLL calculations

Prompt and non-prompt J/ψ in pp collisions

p p

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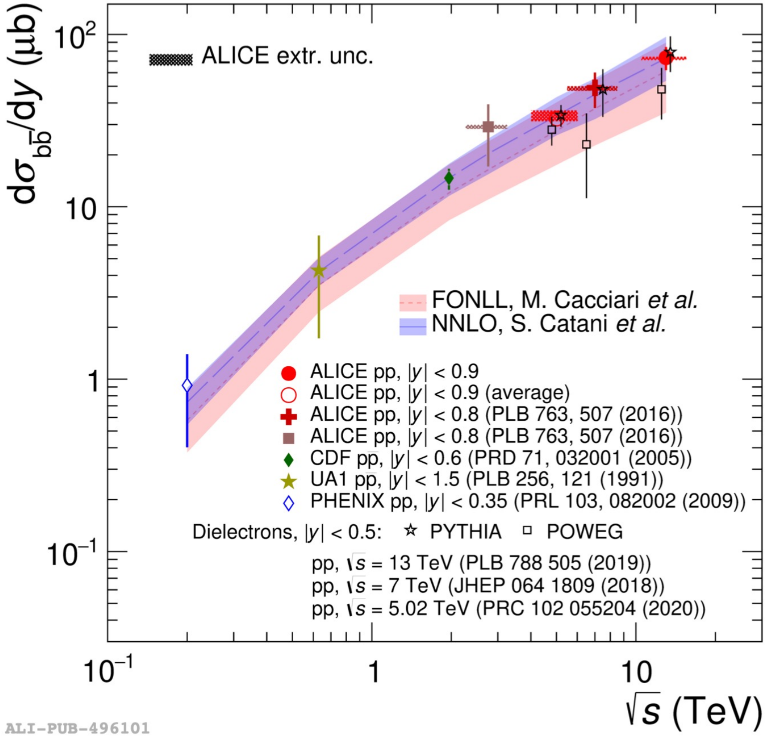
- The beauty quark production cross section at mid rapidity can be extrapolated from the non-prompt J/ψ cross-section



ALI-PUB-496101

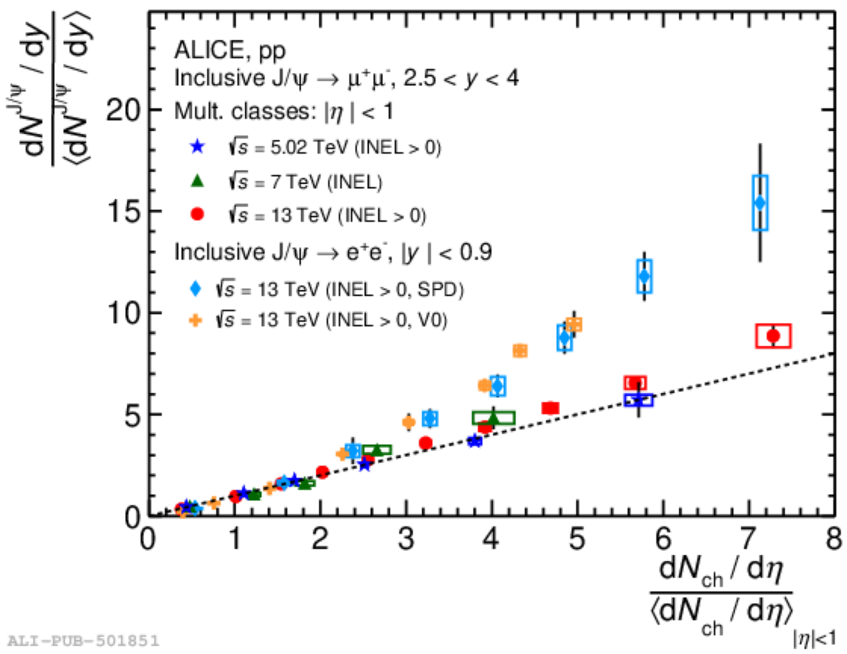
- The computed cross-section is compatible with other ALICE measurements.

- Results are compatible with model calculations

J/ψ as a function of multiplicity in pp collisions

JHEP 06 (2022) 015

- At forward rapidity same linear close to 1 trend observed in different energies
- At forward rapidity there is no faster than linear increased as is the case at mid-rapidity

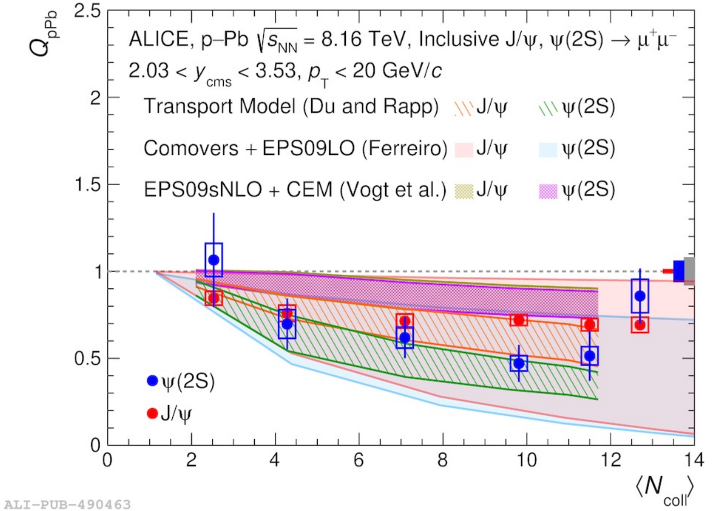


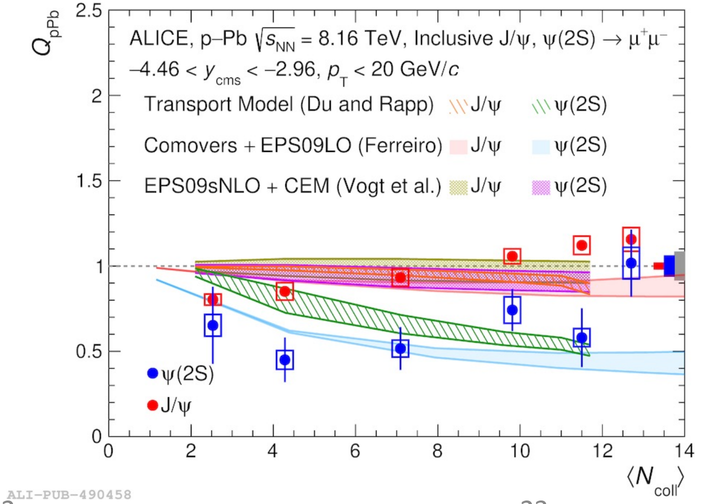
Charmonium Q_{pPb} at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

JHEP 02 (2021) 002

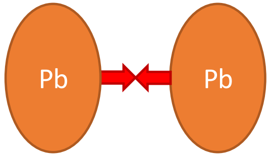
- $Q_{\mathrm{pPb}} = \frac{\mathrm{d}N_{\mathrm{PbPb}}/\mathrm{d}y}{N_{\mathrm{coll}} \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}y}$
- At forward rapidity, the Q_{pPb} is similar for the ψ(2S) and the J/ψ.
- At backward rapidity, a systematically stronger suppression of the ψ(2S) relative to the J/ψ is observed

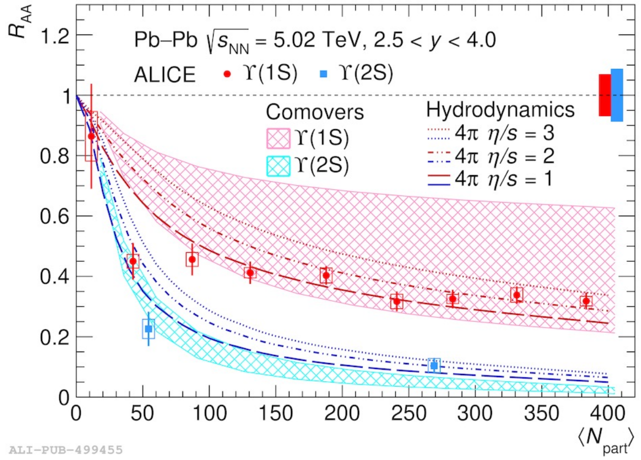
- EPS09s NLO + CEM calculations fail to describe ψ(2S) behavior
- Transport Model describes both J/ψ and ψ(2S) at forward but overestimate ψ(2S) suppression in peripheral collisions at backward rapidity
- Comovers + EPS09LO model describes well the stronger suppression of the ψ(2S) suppression at backward rapidity

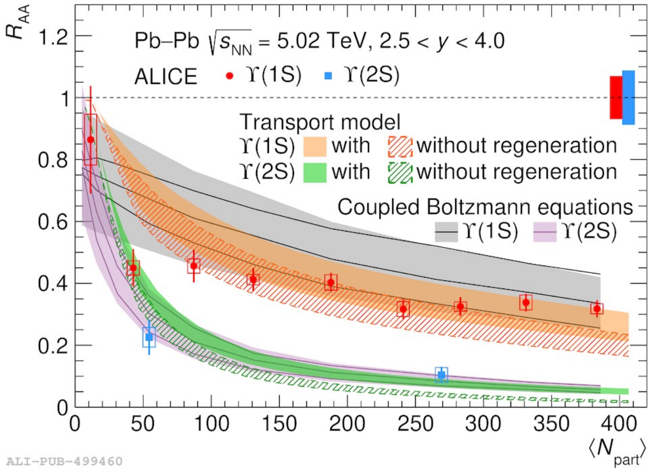




Upsilon at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



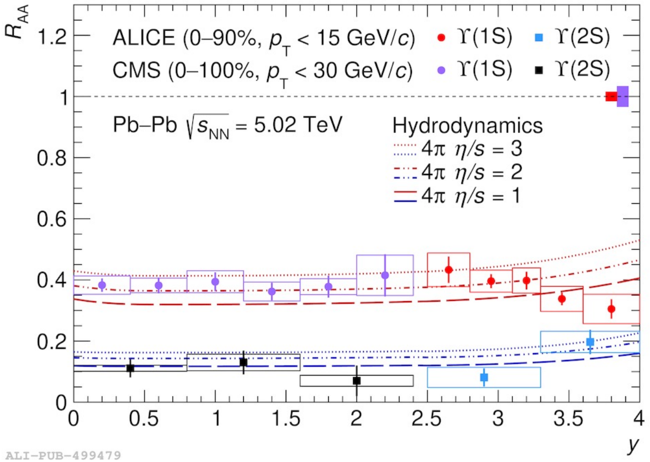


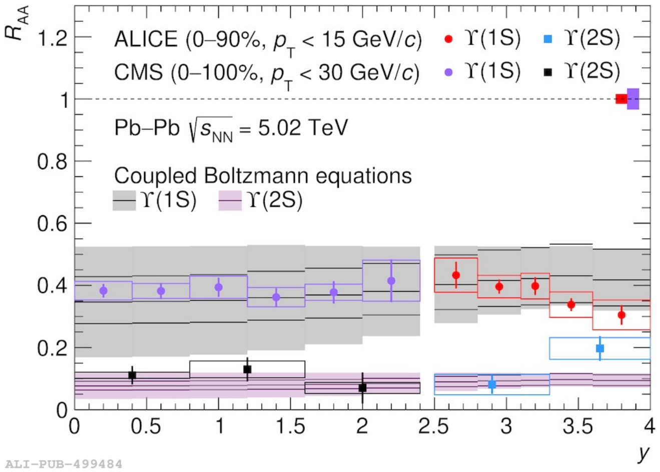


Phys. Lett. B 822 (2021) 136579

- The suppression of Υ(1S) production gets stronger towards more central collisions
- The R_{AA} of Υ(1S) is compatible with unity in the most peripheral interval and decreases to a plateau ~0.32 for $N_{\mathrm{part}} > 200$
- The R_{AA} of Υ(2S) is smaller by about a factor 2–3
- The different models reproduce the trend of the data within uncertainties.

Upsilon at $\sqrt{s_{\rm NN}} = 5.02$ TeV





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- The Υ(1S) R_{AA} as a function of rapidity combining ALICE and CMS measurements indicates a plateau between 0 < y < 3
- The decrease at forward rapidity seems not to be described by models
- The Υ(2S) R_{AA} is independent of rapidity within uncertainties