UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

FSP ALICE
Erforschung von Universum und Materie

ALICE

Present and future prospect of ALICE Physics analysis on Dileptons and Quarkonia

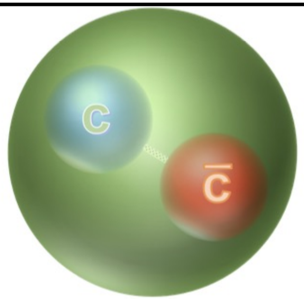
ALICE-STAR India Collaboration Meeting

Wednesday November 22nd 2023

Victor FEUILLARD

Introduction – Quarkonia

- Quarkonia are made of of charm and bottom quarks



- Because of the large mass of the quarks (m_c, m_b >> Λ_{QCD}), they can only be produced in hard scatterings
  → can be described with perturbative QCD calculations
- However, the binding of the quarks involves long distances and soft momentum scales
  → described with non-perturbative QCD
- In medium QGP medium, heavy quarks experience the whole evolution of the system
- There are many quarkonium states characterized by different masses & binding energies
  → ideal to confront models

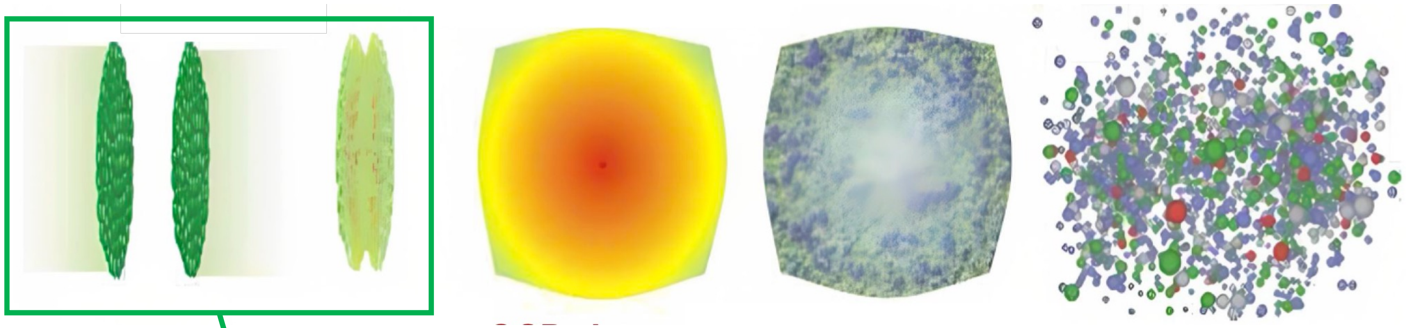
Introduction – What can we measure and learn?

Initial phase

QGP phase

Hadronisation

Hadronic phase



Initial State effects :

- Saturation
- Modification of PDFs
- …

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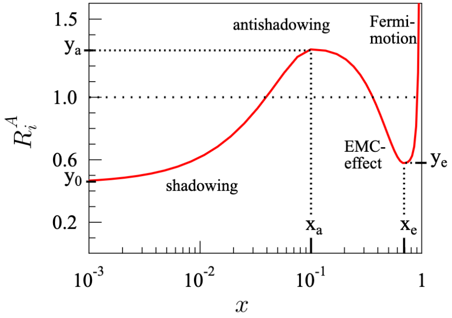
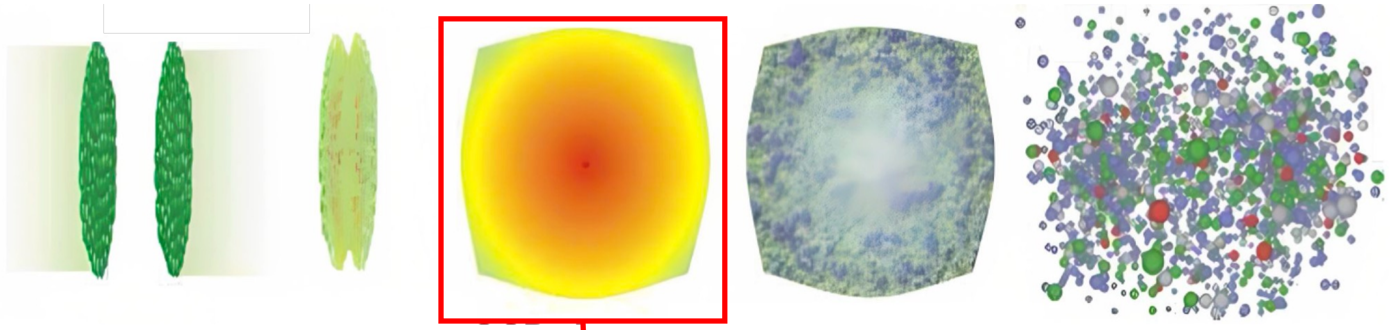


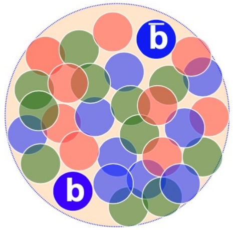
Introduction – What can we measure and learn?

Initial phase | QGP phase | Hadronisation | Hadronic phase



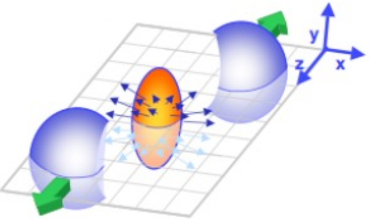
In medium effects :

- Suppression: Color Screening of heavy quarks in the medium

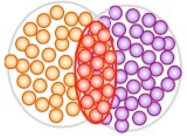


$$R_{\mathrm{AA}} = \frac{Y_{\mathrm{AA}}}{N_{\mathrm{coll}} \cdot Y_{\mathrm{pp}}}$$

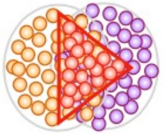
- Collectivity: $\frac{\mathrm{d}^3N}{\mathrm{d}^3p}_{\mathrm{AA}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\left[1+\sum_{n=1}^{\infty}2v_n\cos\left(n(\phi-\Psi_R)\right)\right]$



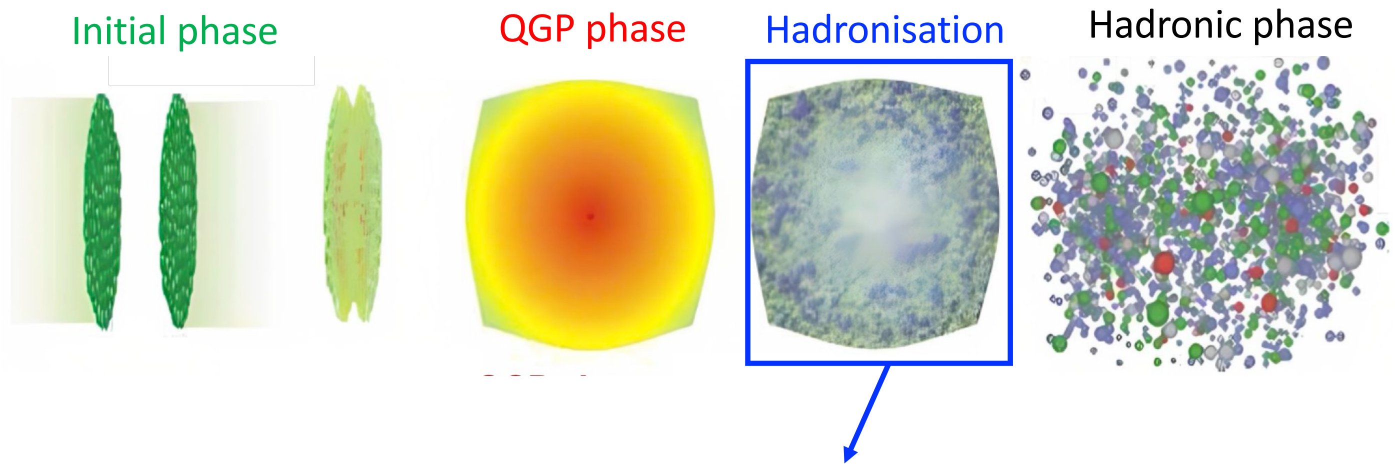
Elliptic flow v_2 : initial anisotropy and reintteractions



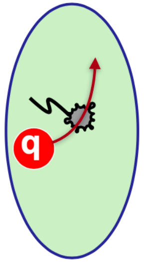
Triangular flow v_3:fulctuations of the initial state



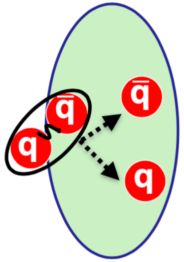
Introduction – What can we measure and learn?



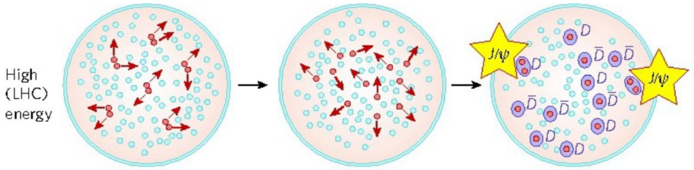
- Coherent energy loss



- Nuclear absorption



- Statistical hadronization : charm quarks distributed to hadrons according to thermal weights

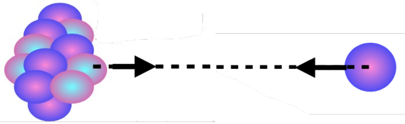


Introduction – Different collision systems

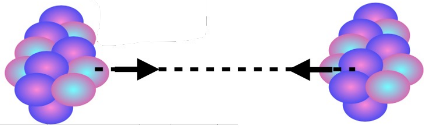
- Measurements in different collision size allow to investigate several properties

- Proton-proton collisions :
  - Measurement of fragmentation fractions
  - Test of pQCD models regarding hadron formation

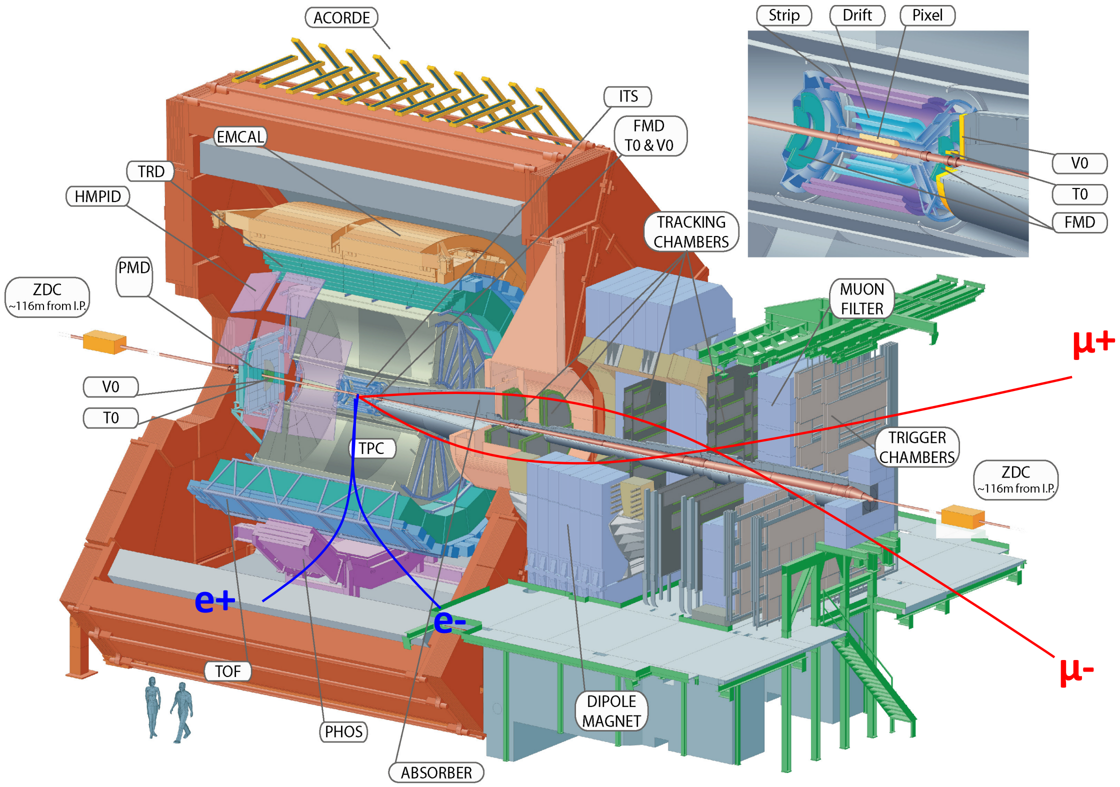
- Proton-Nucleus collisions :
  - Initial state effects
  - Interplay between soft and hard process



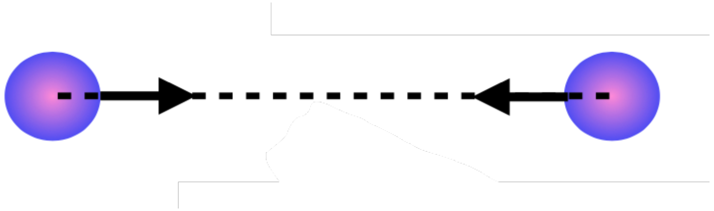
- Nucleus-Nucleus collisions
  - Properties of the Quark-Gluon Plasma
  - Final state effects



Introduction – The ALICE detector



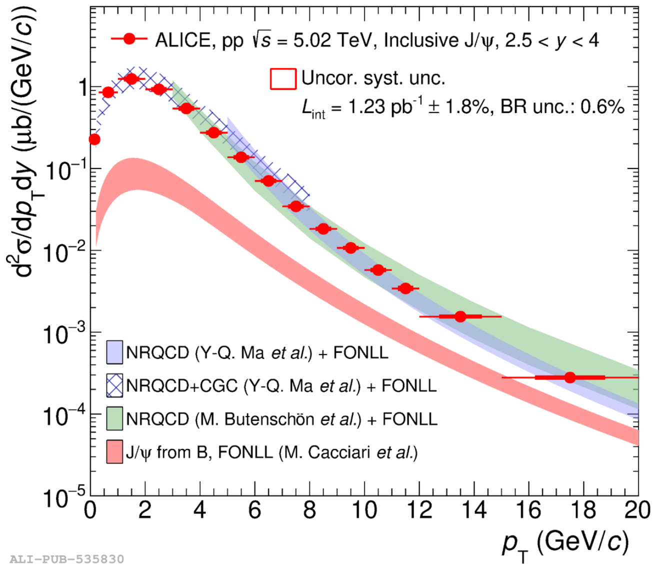
- Muon Arm :
  - J/ψ, ψ(2S), ϒ(nS) → $\mu^+\mu^-$
  - Acceptance: 2.5 < y < 4.0
  - Inclusive quarkonia down to $p_T = 0$
- Central Barrel:
  - J/ψ → e^+e^-
  - Acceptance: $|y| < 0.9$
  - Inclusive quarkonia down to $p_T = 0$
  - Separation of prompt and non-prompt J/ψ down to very low p_T

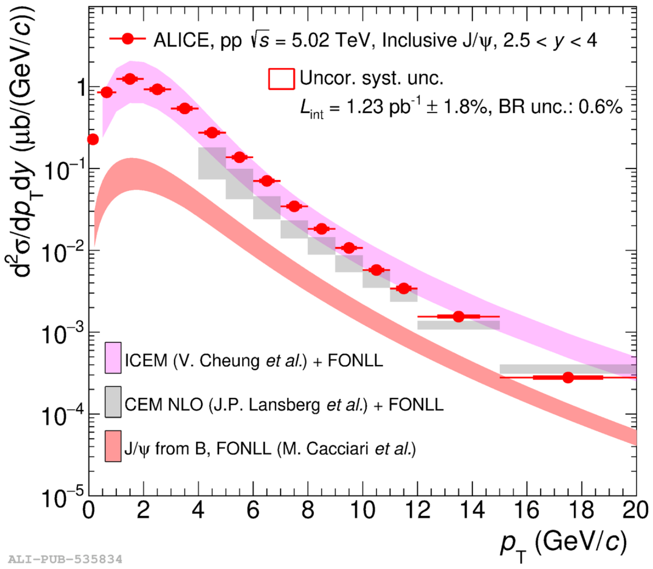


Results in pp collisions

Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

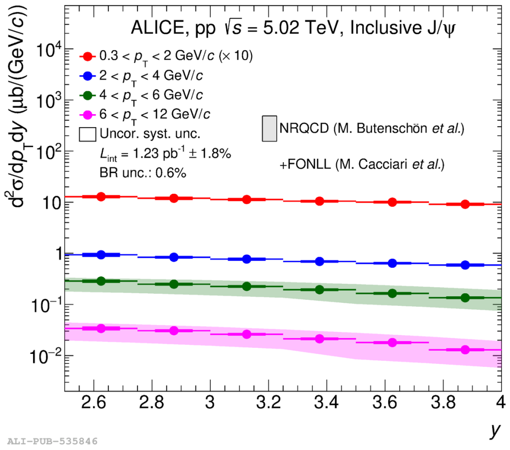




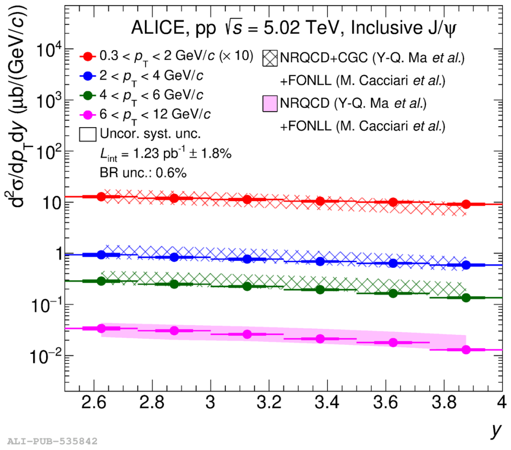
- J/Ψ cross sections described by NRQCD and ICEM
- The calculations of the non-prompt contribution are estimated using FONLL
- CEM NLO calculation underestimates the cross sections for $4 < p_T < 10$ GeV/c and reproduces the data at higher p_T

Quarkonium cross sections at forward rapidity

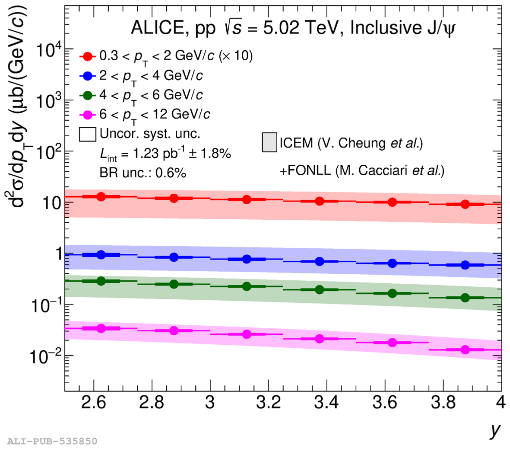
- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)



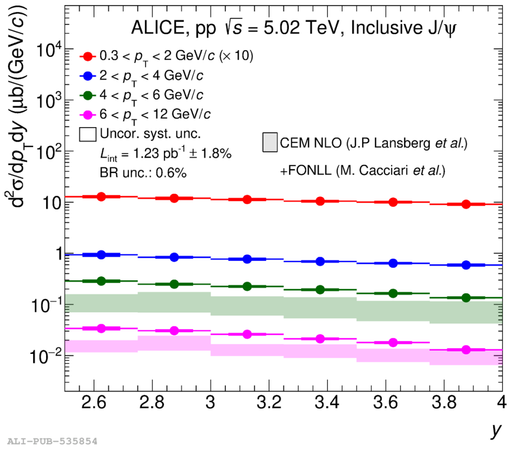
NRQCD (M. Butenschon et al.)



NRQCD+CGC (Y-Qa Ma et al), NRQCD (Y-Qa Ma et al),



ICEM (V. Cheung et al)

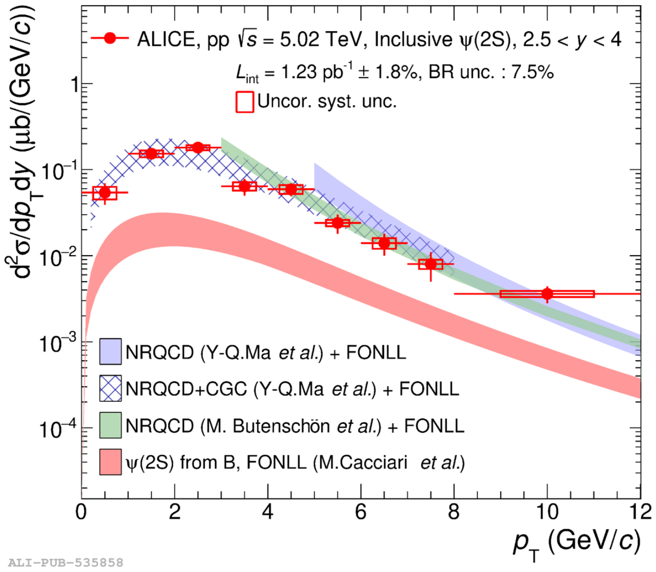


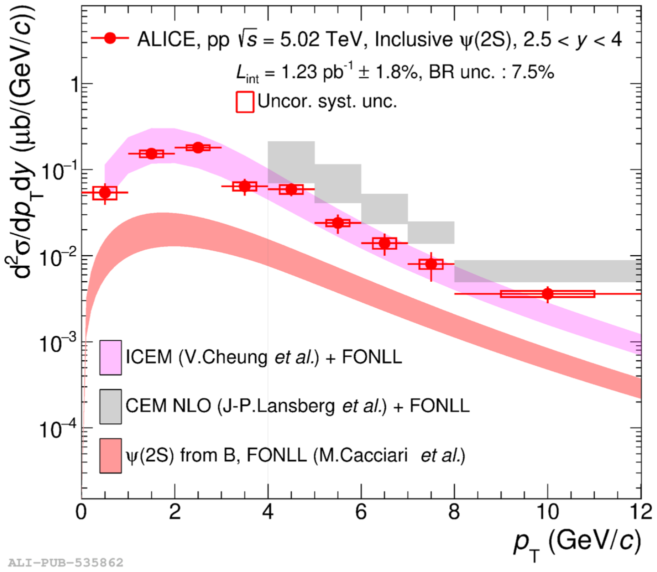
CEM NLO (J. P. Lansberg et al)

- Rapidity dependence of the J/Ψ cross section in several p_T bins compared with models
- NRQCD and ICEM described the data well within uncertainties
- CEM NLO calculation underestimates the cross sections

Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)





- Ψ(2S) cross sections described by NRQCD and ICEM
  - Except for 5 < p_T < 6 GeV/c (NRCDQ Y-Qa Ma et al) and 3 < p_T < 4 GeV/c (NRQCD M. Butenschon et al.)
  - The calculations of the non-prompt contribution are estimated using FONLL
- CEM NLO calculation overestimates the data

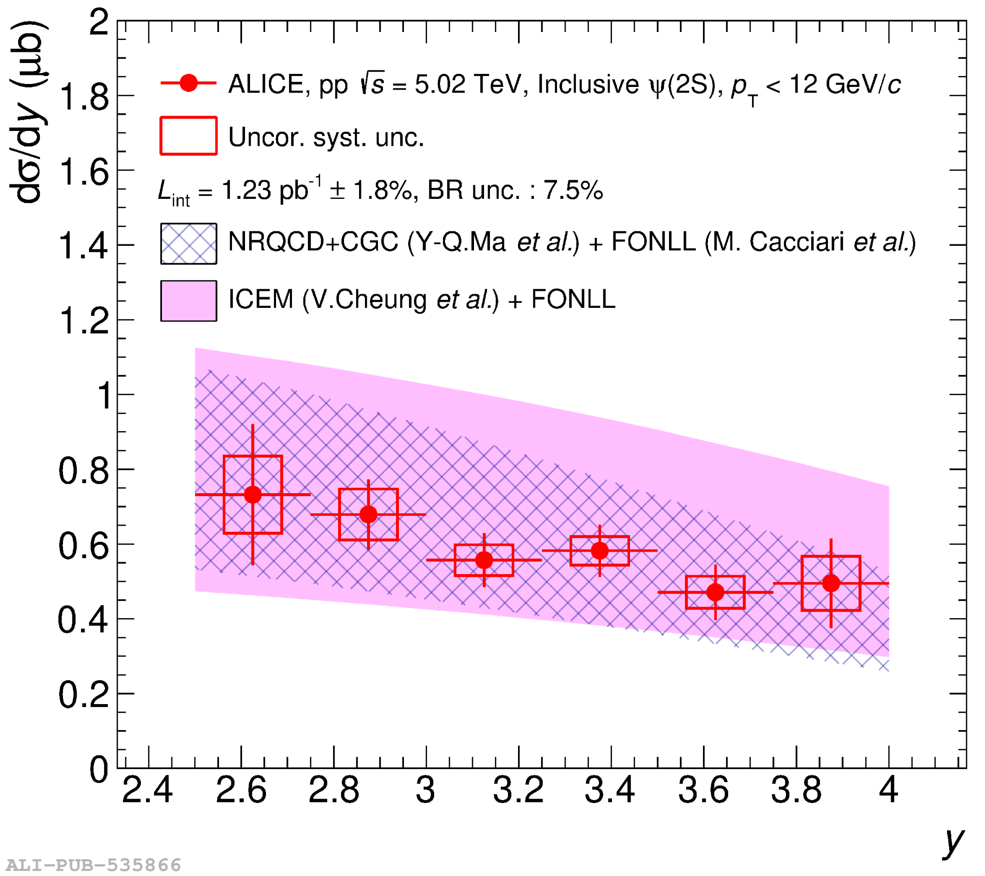
Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

- Rapidity dependence of the Ψ(2S) cross section

- The NRQCD+CGC and ICEM models provide a good description of the ψ(2S) cross section as a function of y, albeit with large uncertainties.

- The calculations of the non-prompt contribution are estimated using FONLL



Quarkonium cross sections at forward rapidity

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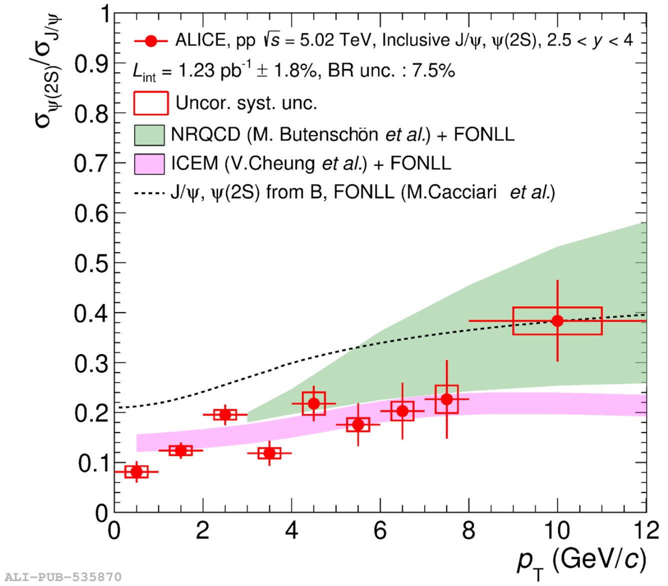
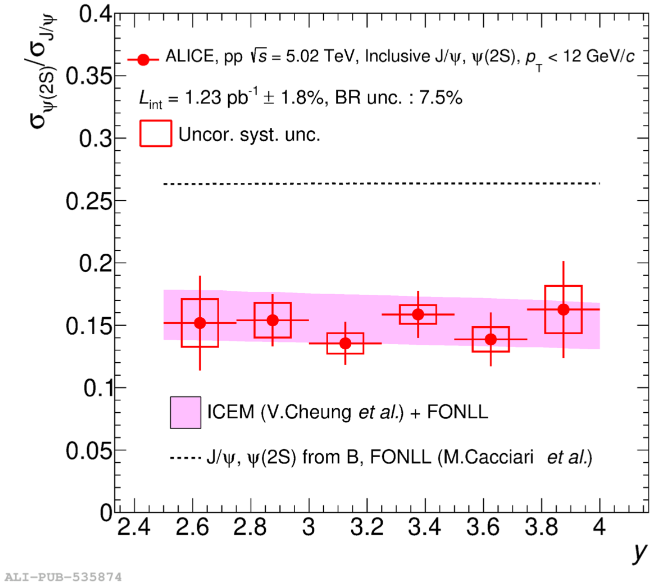
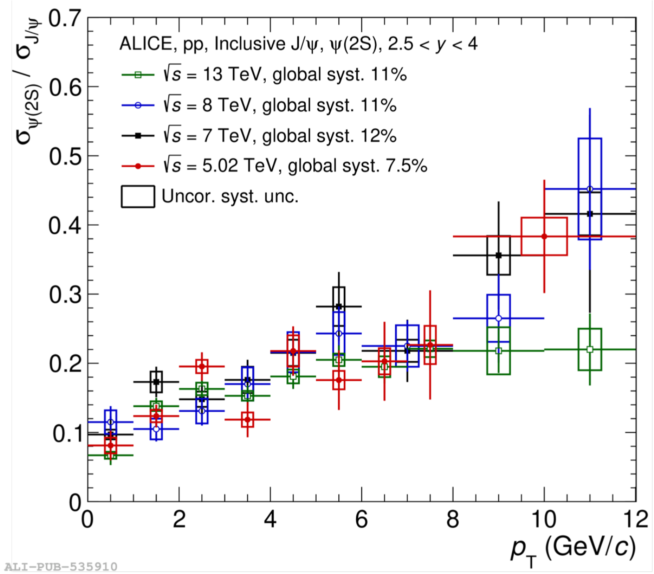


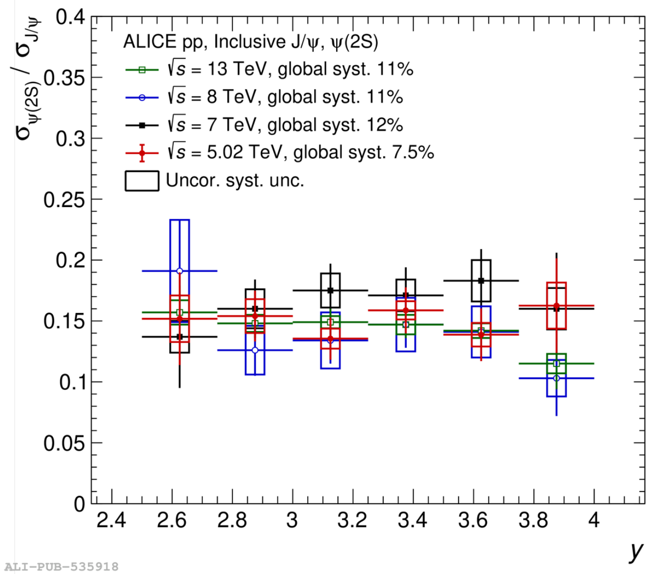


- ψ(2S) over J/ψ cross section ratio
- p_T dependence described by NRQCD (M. Butenschon *et al.*) and ICEM (V. Cheung *et al*).
- Rapidity dependence described with ICEM (V. Cheung *et al*).

Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

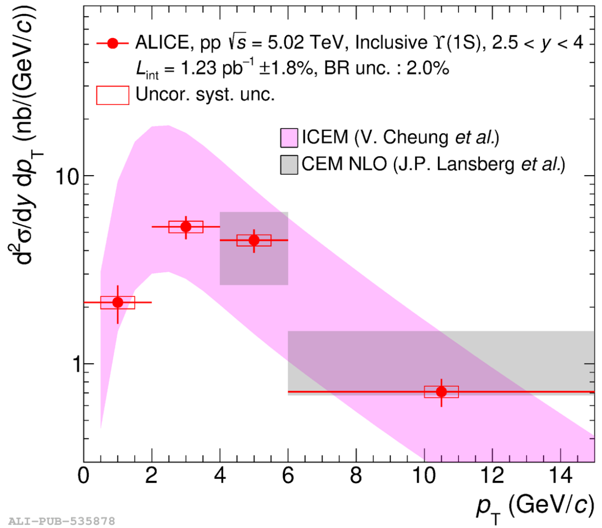


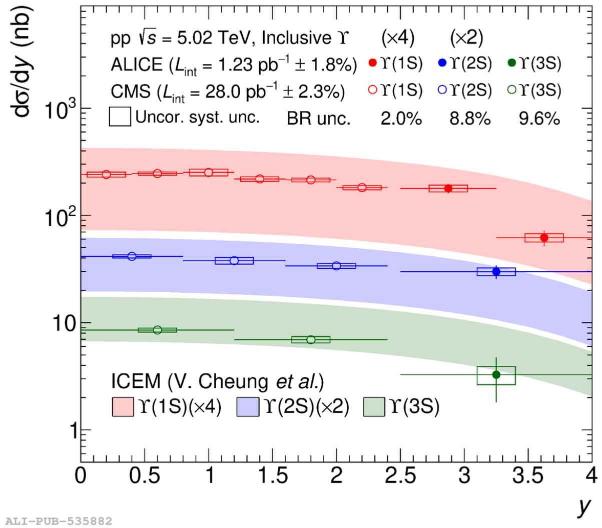


- Inclusive ψ(2S)-to-J/ψ cross section ratio as a function of p_T and rapidity y, in pp collisions at several collision energies
- The p_T-differential ψ(2S)-to-J/ψ ratio increases with increasing p_T and does not exhibit any energy dependence within the current uncertainties.
- A flat y dependence is observed for all energies

Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)





- Transverse momentum dependence of the Υ(1S) cross section (left) and rapidity dependence of the Υ(1S), Υ(2S), and Υ(3S) (right) measured by ALICE (closed points) and CMS (open points)
- p_T dependence is described by ICEM (V. Cheung *et al)*, CEM NLO (J. P. Lansberg *et al*) y dependence is described by ICEM (V. Cheung *et al*), but models have large uncertainties

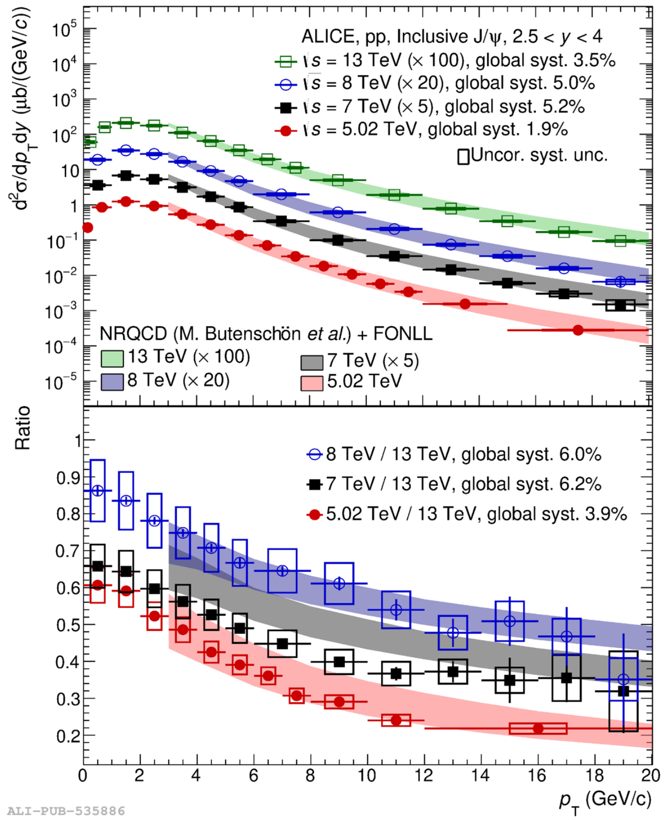
Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

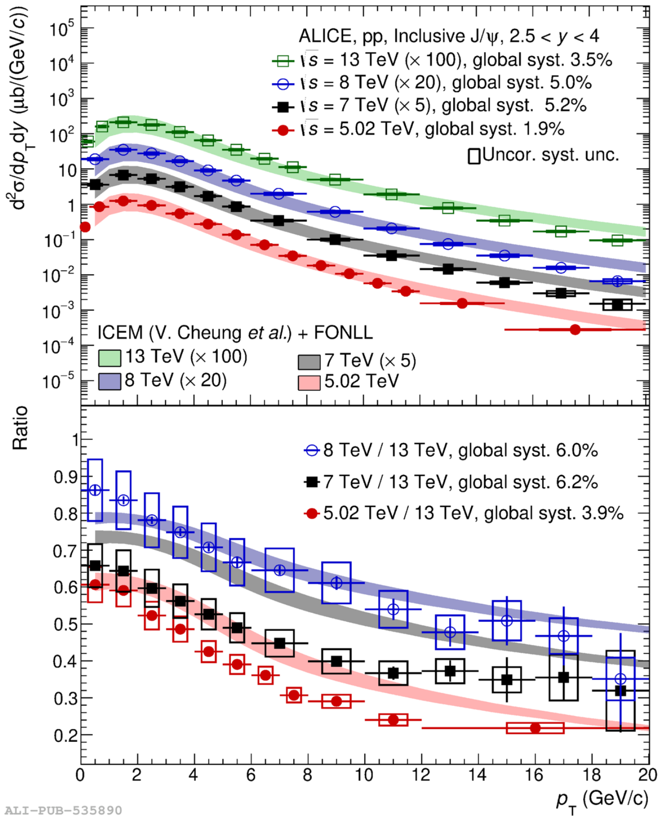
- Precise J/Ψ p_T differential measurements in a wide energy range (5.02 < √s < 13 TeV)

- Cross sections generally well described by models among energies

- BUT models are challenged by ratios



NRQCD (M. Butenschon et al.)



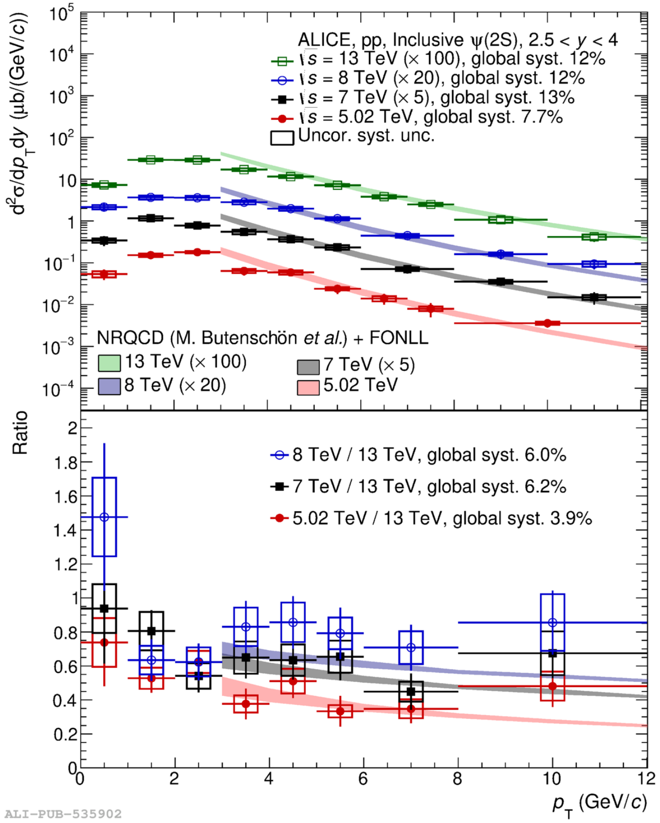
ICEM (V. Cheung et al)

Quarkonium cross sections at forward rapidity

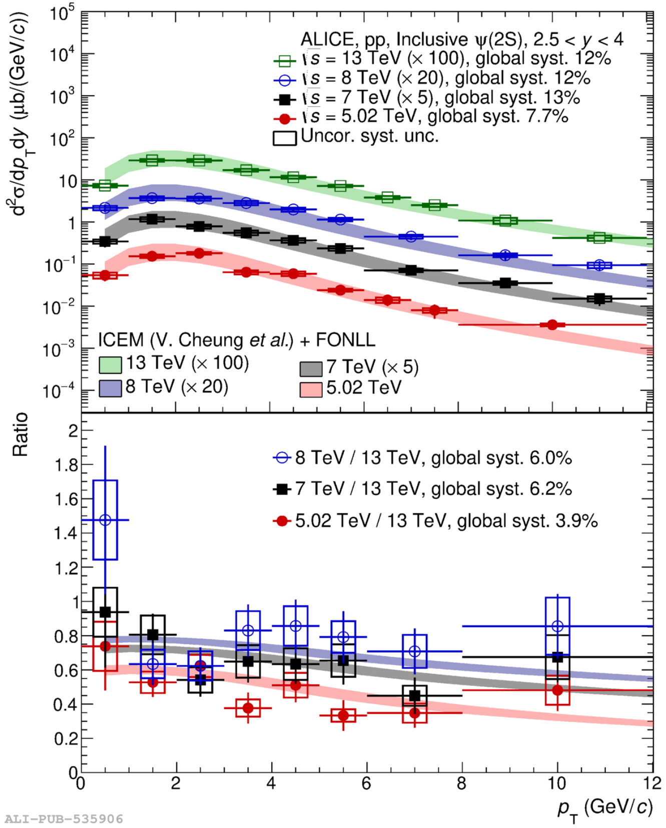
ALICE

- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

- Precise Ψ(2S) p_T differential measurements in a wide energy range (5.02 < √*s* < 13 TeV)
- The cross section described by NRQCD (M. Butenschon et al.) and ICEM (V. Cheung et al.)
- Contrary to the J/ψ case, the ratios exhibit a flat p_T dependence for $3 \leq p_T < 12$ GeV/c, indicating that no significant hardening of the p_T spectrum is seen between 13 TeV and lower energy measurements (within current uncertainties).



NRQCD (M. Butenschon et al.)



ICEM (V. Cheung et al)

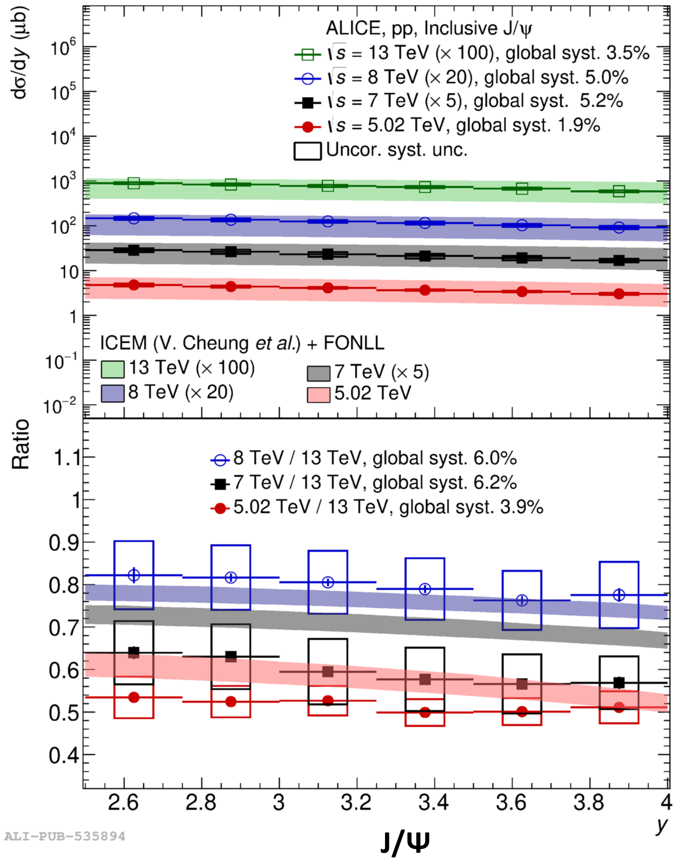
Quarkonium cross sections at forward rapidity

- Measurement of J/Ψ, Ψ(2S), Y(1S), Y(2S) and Y(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

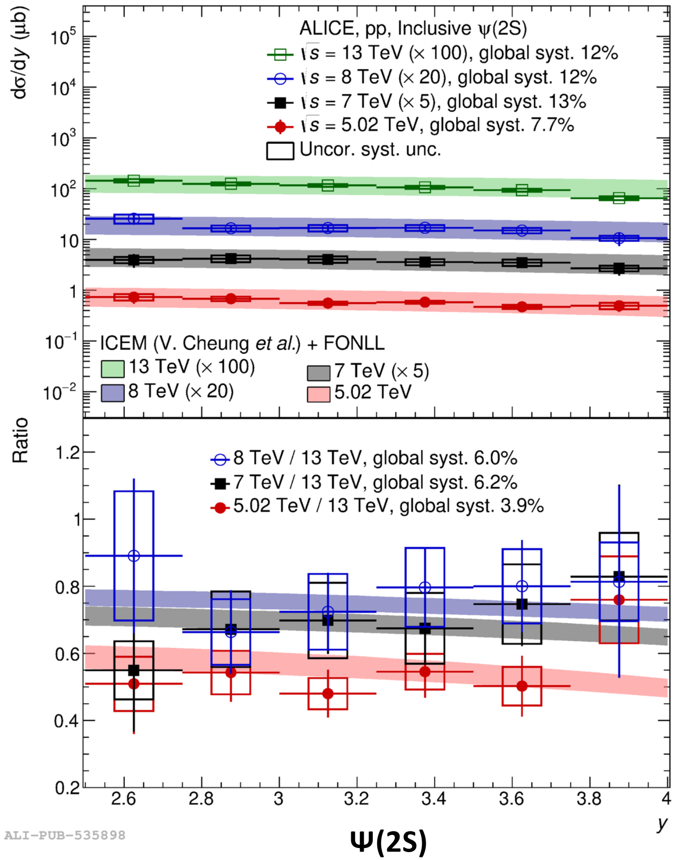
- y differential J/Ψ and Ψ(2S) measurements in a wide energy range (5.02 < √*s* < 13 TeV)

- The ICEM model (V. Cheung *et al.*) is able to reproduce the cross sections at all energies, as well as the decreasing trend with increasing y.

- The ICEM calculation successfully describes the 8-to-13 TeV ratio for J/Ψ over the entire y range, but overestimates the others



J/Ψ



Ψ(2S)

Quarkonium cross sections at forward rapidity

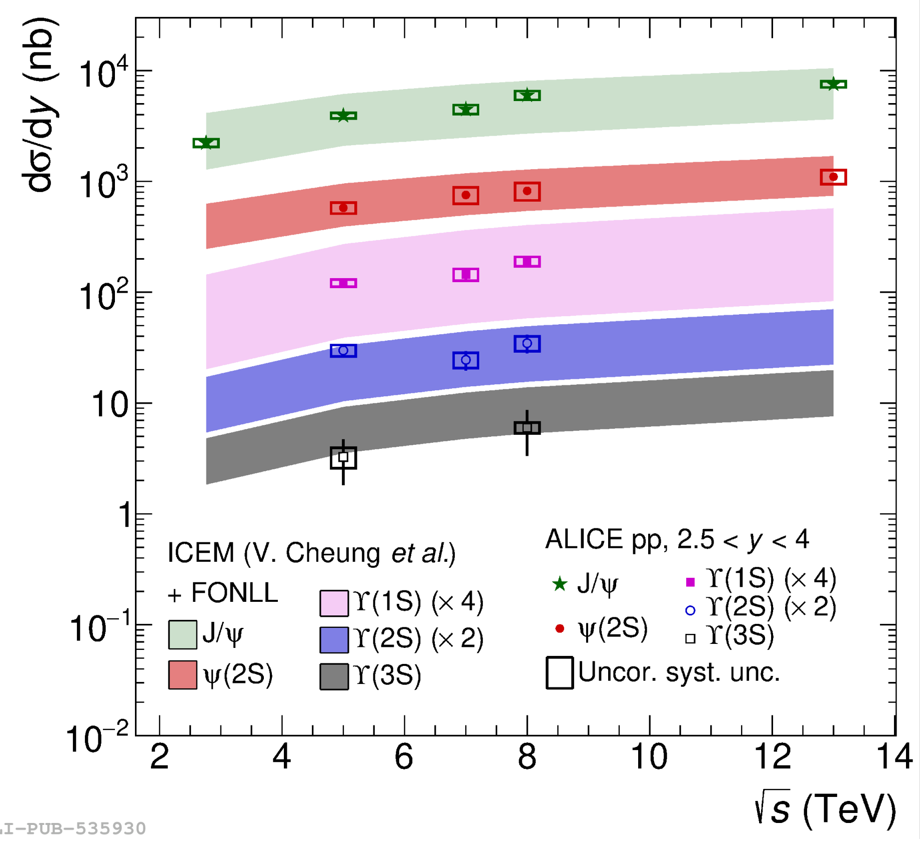
- Measurement of J/Ψ, Ψ(2S), Υ(1S), Υ(2S) and Υ(3S) in pp@5TeV (paper: Eur. Phys. J. C. 83 (2023) 61)

- J/ψ, ψ(2S), Υ(1S), Υ(2S), and Υ(3S) pT-integrated cross section per unit of rapidity as a function of the collision energy in pp collisions

- An increase of the cross section is observed with increasing √s for all the states

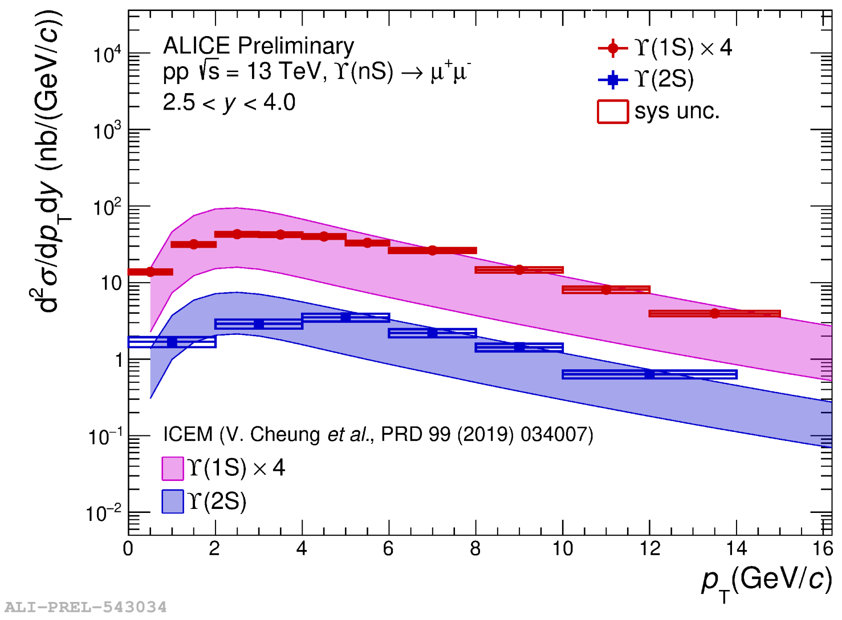
- Results described by ICEM model (V. Cheung et al.)
  → Υ(3S) results lie on the lower edge of the theoretical calculation band

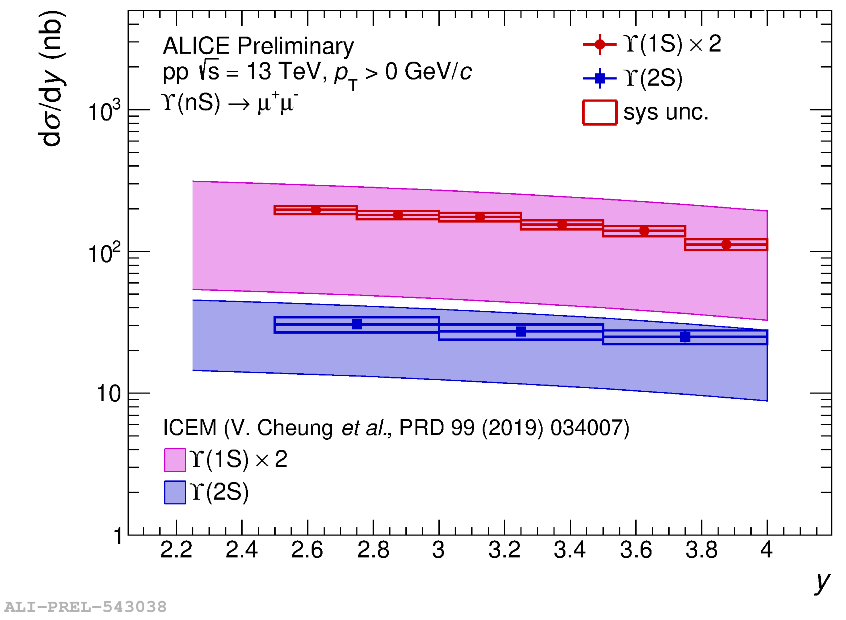
- Model uncertainties are large



Quarkonium cross sections at forward rapidity

- New preliminary reuslt : cross-section analysis of Υ(1S) and Υ(2S) in pp@13TeV



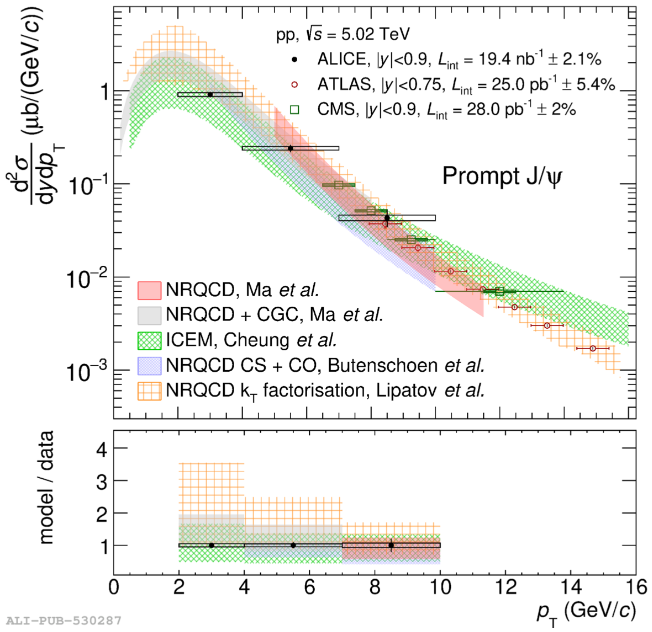


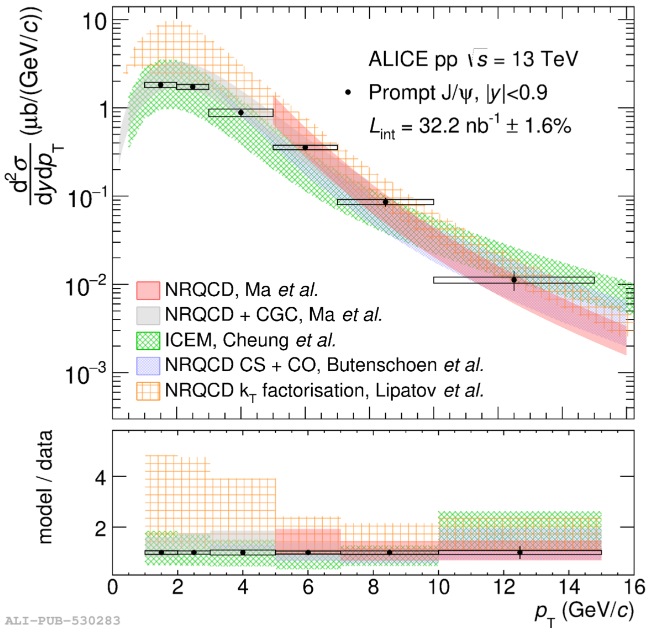
- p_T and y dependence of Υ(1S) and Υ(2S) in pp@13TeV
- Results described by ICEM model (V. Cheung *et al.*) with large uncertainties

Quarkonium cross sections at mid-rapidity

- Measurement of prompt and non-prompt J/Ψ in pp@5TeV & 13 TeV (paper: JHEP 03 (2022) 190)

5 TeV





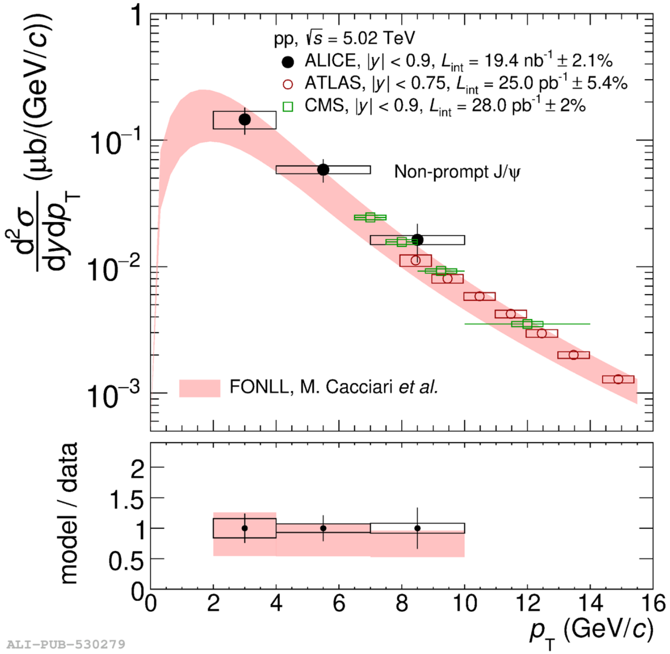
13 TeV

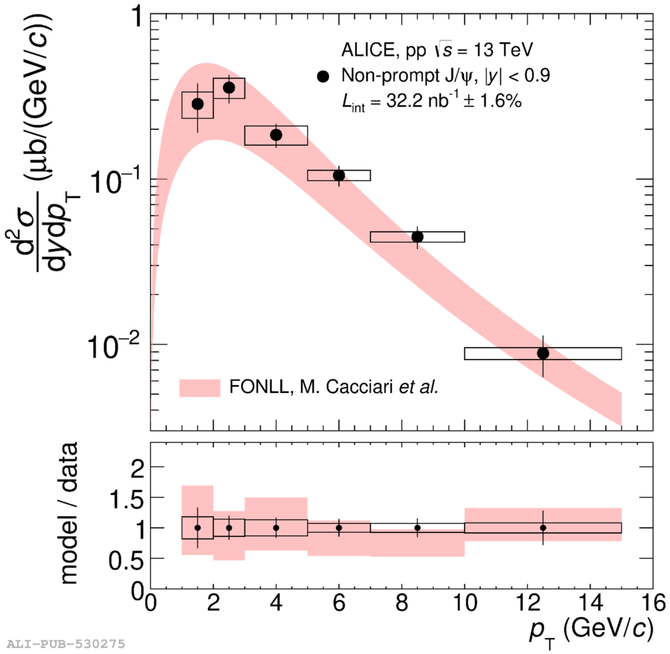
- Prompt J/Ψ cross section compared to several model calculations using NRQCD and ICEM
- The large uncertainties of the model calculations, which arise from the charm quark mass, as well as factorisation and renormalisation scales, do not allow to discriminate among different models.

Quarkonium cross sections at mid-rapidity

- Measurement of prompt and non-prompt J/Ψ in pp@5TeV & 13 TeV (paper: JHEP 03 (2022) 190)

5 TeV



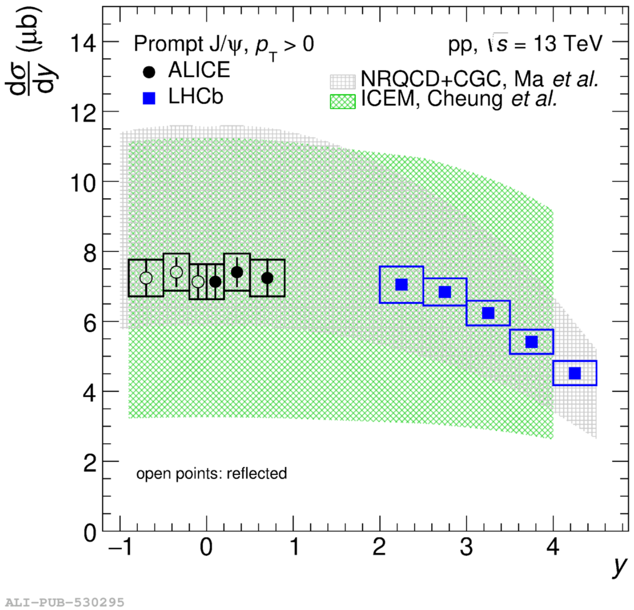


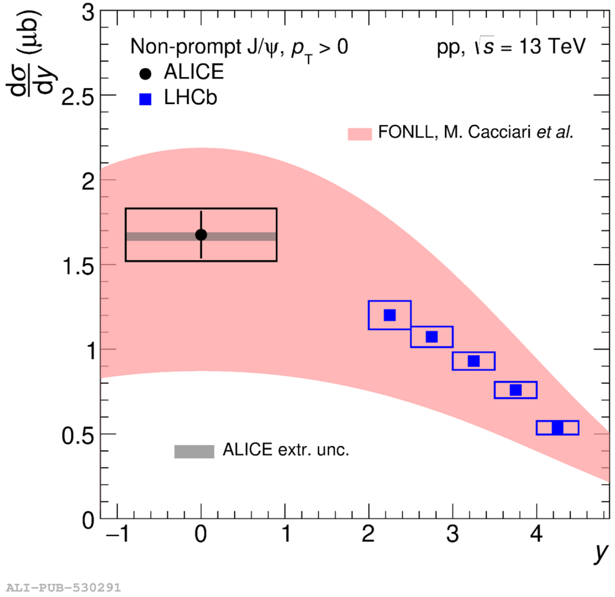
13 TeV

- Non-prompt J/Ψ cross section well described by FONLL
- Both prompt and non-prompt are in good agreement with ATLAS and CMS measurements in pp@5TeV in the common p_T range

Quarkonium cross sections at mid-rapidity

- Measurement of prompt and non-prompt J/Ψ in pp@5TeV & 13 TeV (paper: JHEP 03 (2022) 190)

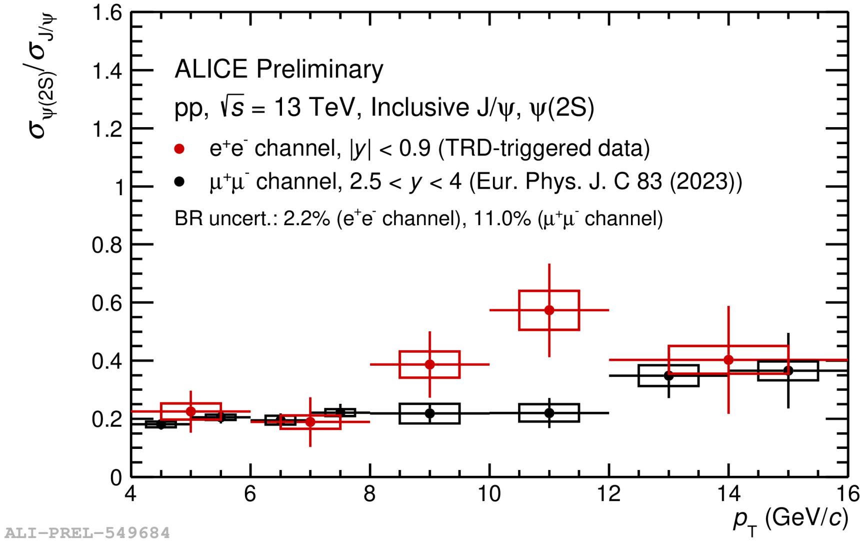


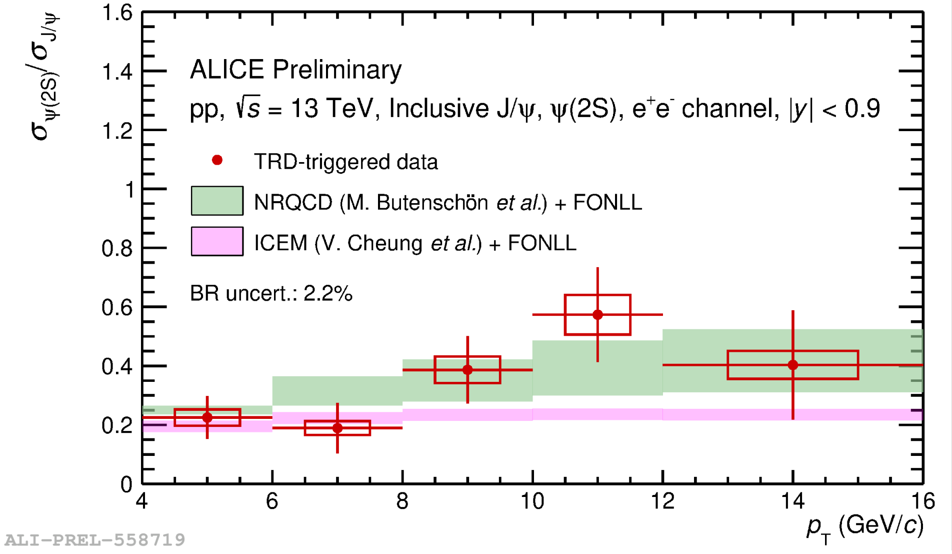


- Rapidity dependence of the prompt and non-prompt J/Ψ in pp@13 TeV
- Models describe the data, but with large uncertainties

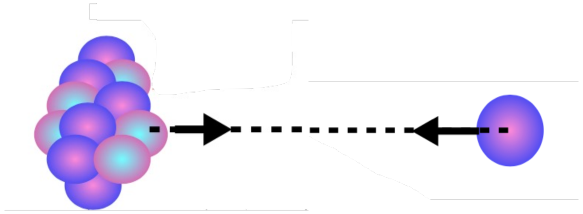
Quarkonium cross sections at mid-rapidity

- New preliminary result : ψ(2S) over J/ψ cross section ratio at mid rapidity





- Measurements in e+e- show good agreement within uncertainties with measurements in μ+μ-
- ICEM can describe the measurement at 4-8 p_T, and NRQCD shows good agreement at overall p_T region



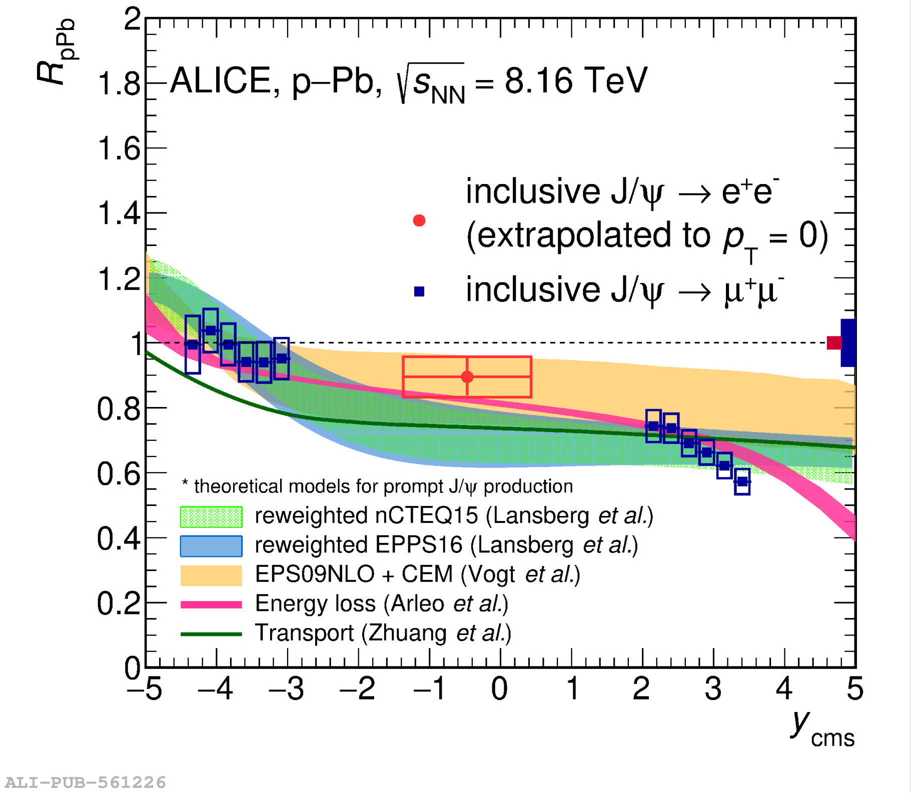
Results in p-Pb collisions

Nuclear modification factor

- Measurement of inclusive RpPb at pPb@8.16 TeV (paper: JHEP 07 (2023) 137

- Models describe the data well at forward, mid and backward rapdity, despite using different theoretical frameworks

- Uncertainties do not allow to disentagle between models

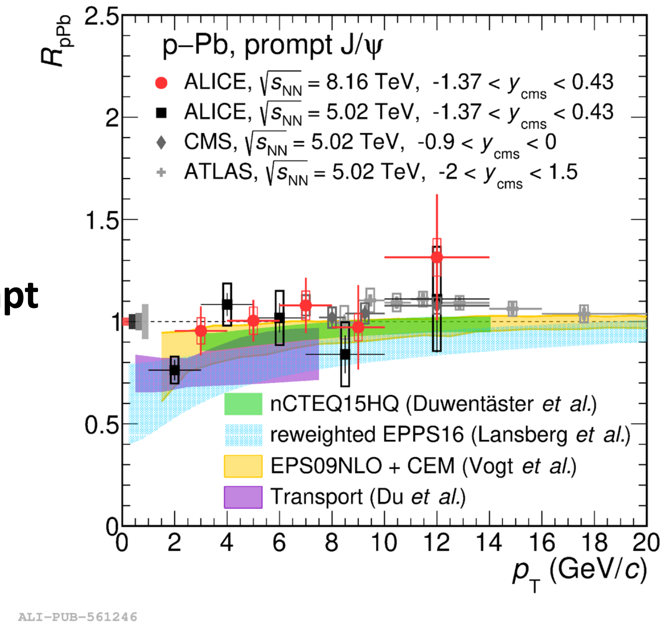


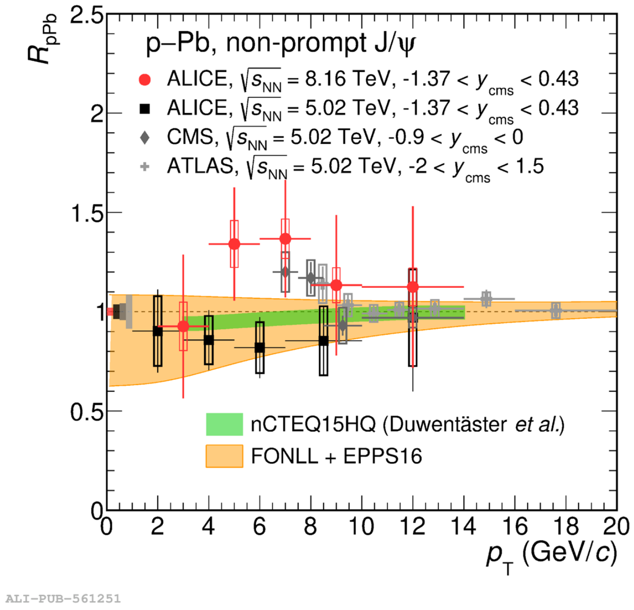
Nuclear modification factor at mid-rapidity

ALICE

- Measurement of prompt and non-prompt RpPb at pPb@8.16 TeV (paper: JHEP 07 (2023) 137)

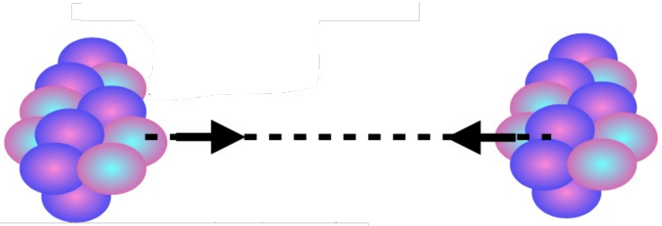
prompt





non-prompt

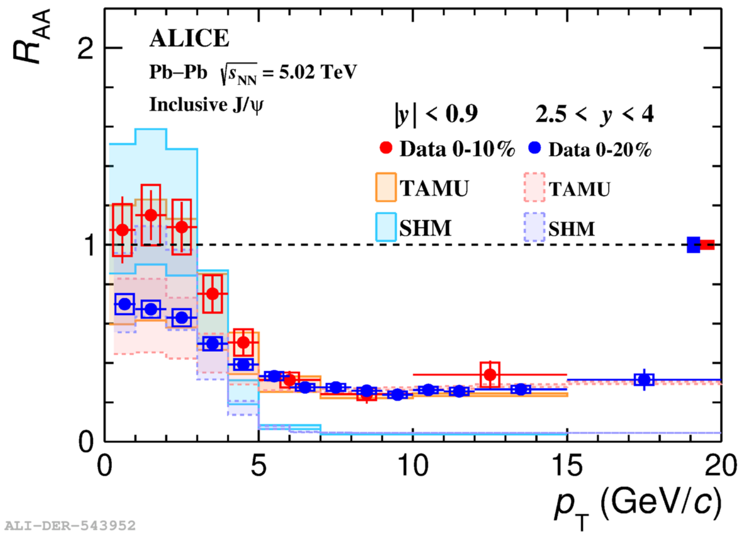
- Cold nuclear matter effects are small, even smaller than predicted by most theoretical calculations implementing nuclear shadowing.

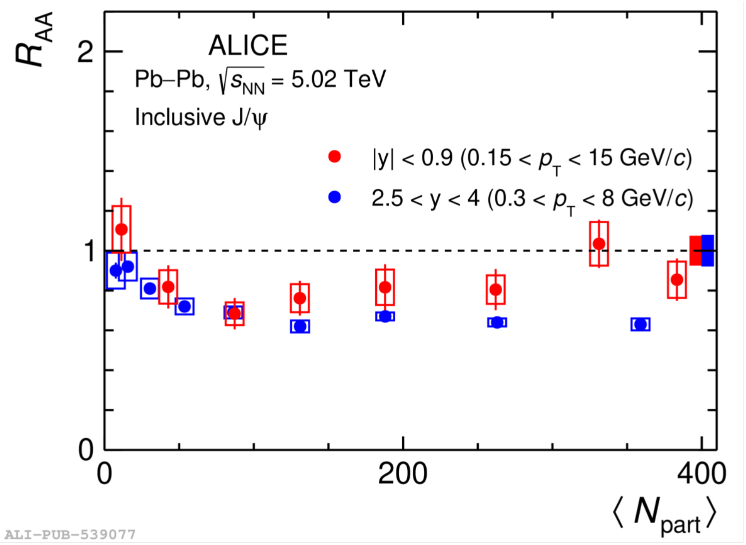


Results in Pb-Pb collisions

J/ψ Nuclear modification factor

- Inclusive J/ψ production at mid- and forward rapidity in Pb−Pb@5.02 TeV (paper: arXiv:2303.13361)

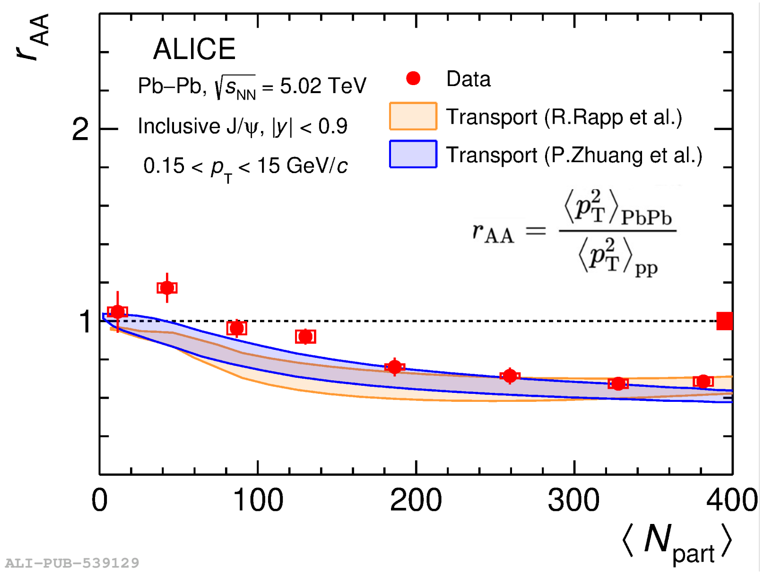


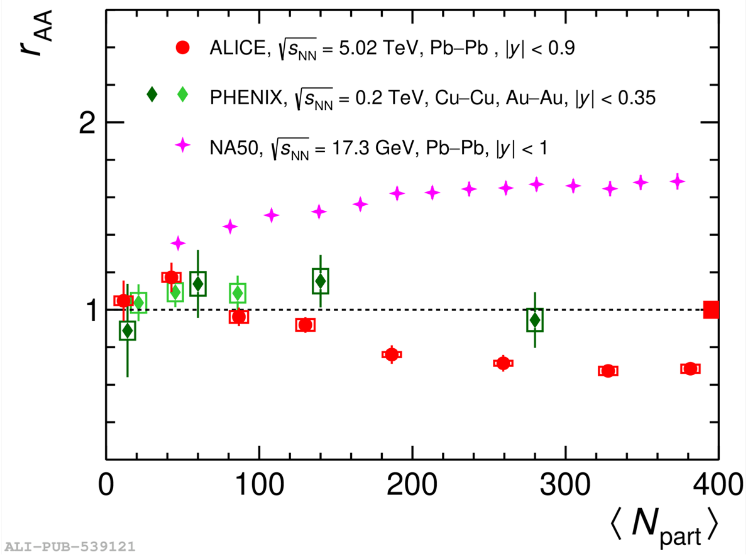


- Inclusive J/Ψ RAA as a function of p_T and multiplicity in forward and midrapidity
- Evidence for J/ψ (re-)generation at low pT and in central collisions, with a larger contribution at midrapidity compared to forward rapidity
- Transport and SHMc models describe data at low p_T, while SHMc underestimates the measurement at high p_T. The energy loss model agrees with data at high p_T

J/ψ Nuclear modification factor

- Inclusive J/ψ production at mid- and forward rapidity in Pb–Pb@5.02 TeV (paper: arXiv:2303.13361)



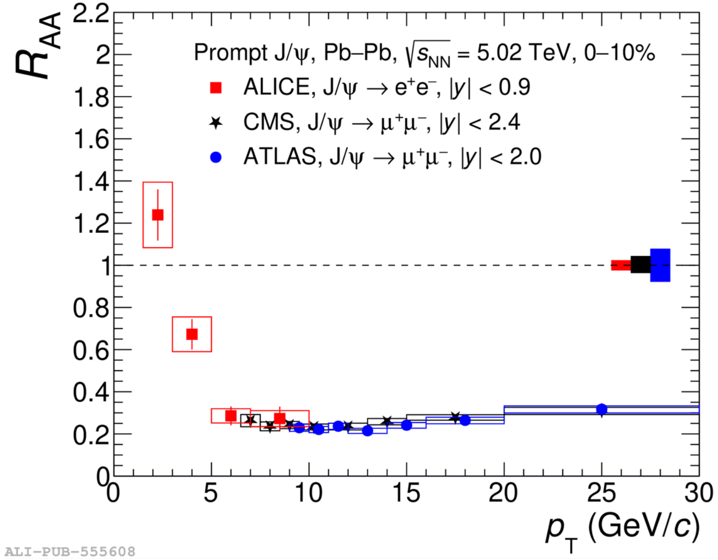


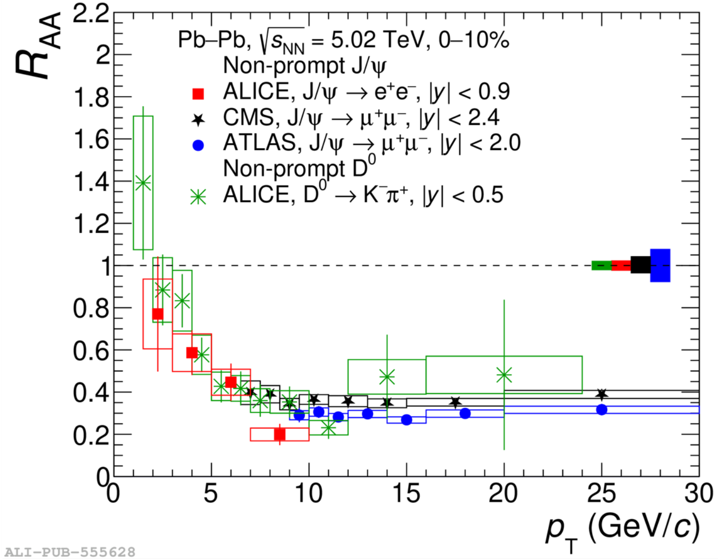
- Decreasing trend for r_{AA} from semicentral toward central collisions
- r_{AA} below unity indicates a softening of the J/ψ p_T shape in Pb–Pb collisions compared to pp collisions, the behavior is different from the lower center-of-mass energies

J/ψ Nuclear modification factor at mid rapidity

- Prompt and non-prompt J/ψ production at midrapidity in Pb–Pb@5.02 TeV (paper : arXiv:2308.16125)

prompt





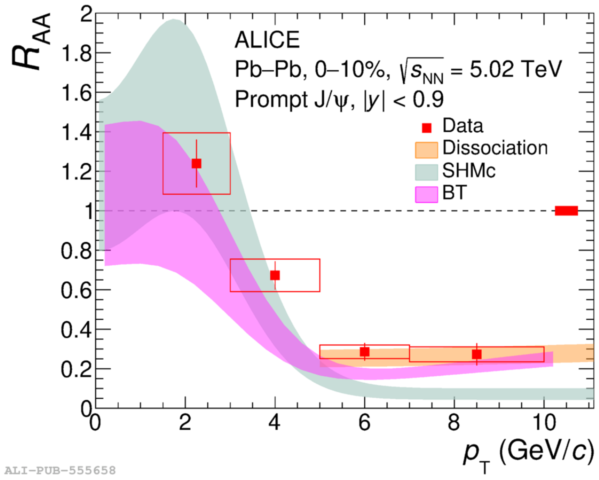
non-prompt

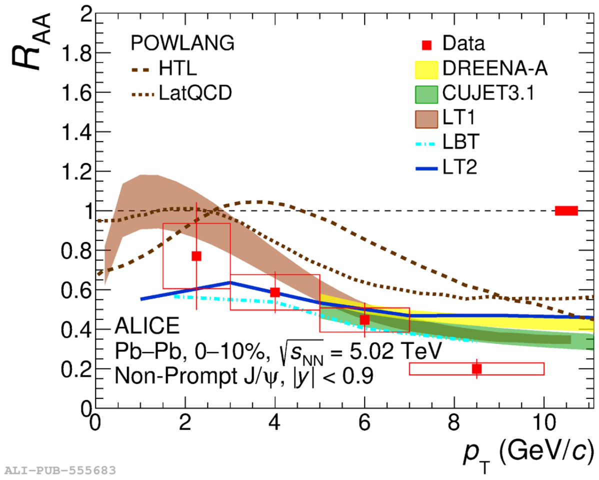
- R_{AA} extended down to p_T =1.5 GeV/*c* and compatible within uncertainties with ATLAS and CMS measurements in the common p_T range
- ALICE non-prompt J/ψ and D0 are compatible within uncertainties

J/ψ Nuclear modification factor at mid rapidity

- Prompt and non-prompt J/ψ production at midrapidity in Pb–Pb@5.02 TeV (paper : arXiv:2308.16125)

prompt



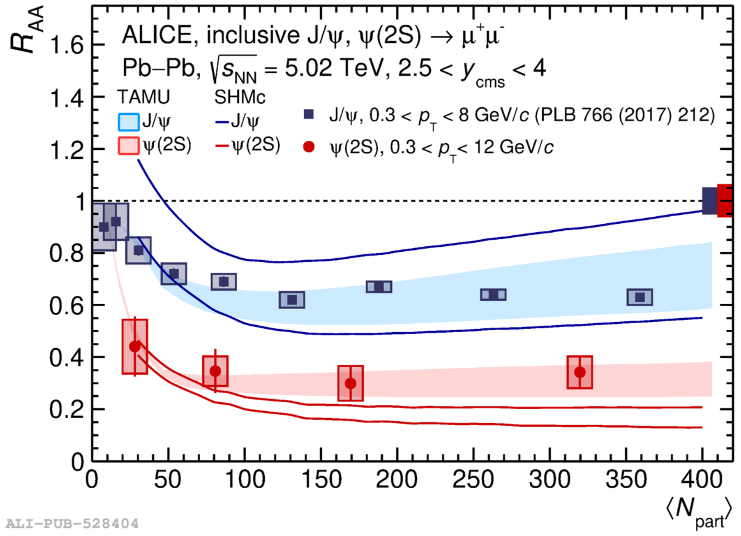


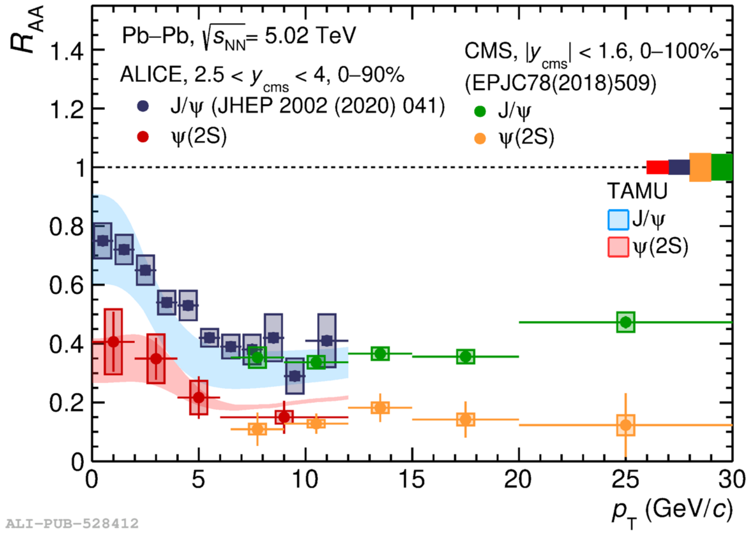
non-prompt

- The SHMc model and transport microscopic calculations that include a contribution from regeneration are compatible with the measured prompt J/ψ R_{AA} at low p_T
- Non-prompt J/ψ R_{AA} described within uncertainties by models implementing collisional and radiative energy loss contributions, but POWLANG calculations, which include only collisional contributions, overestimate the R_{AA} at intermediate and high p_T
- With current uncertainties it is not possible to disentangle between different models

ψ(2S) Nuclear modification factor

- Inclusive ψ(2S) production at forward rapidity in Pb−Pb@5.02 TeV (paper: arXiv:2303.13361)

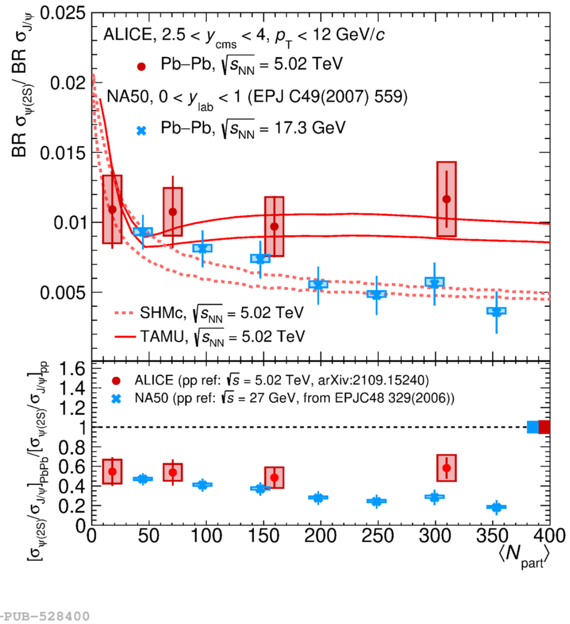


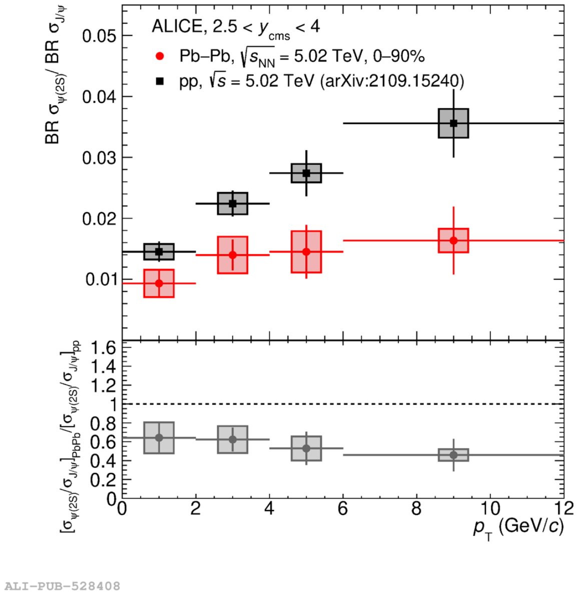


- Nuclear modification factors for ψ(2S) compared to J/ψ as a function of multiplicity (left) and as a function of p_T (right) → Stronger suppression for ψ(2S)
- TAMU model describes the measured R_{AA} for both J/ψ and ψ(2S). The SHMc model reproduces the J/ψ RAA centrality dependence, while it underestimates the ψ(2S) RAA in central and semi-central collisions

ψ(2S) Nuclear modification factor

- Inclusive ψ(2S) production at forward rapidity in Pb−Pb@5.02 TeV (paper: arXiv:2303.13361)





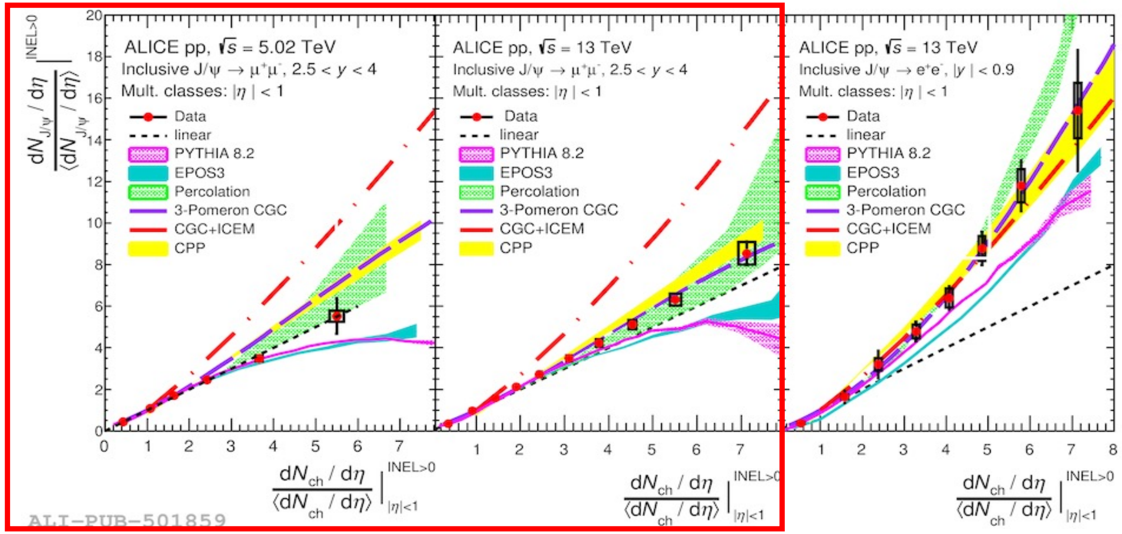
- The ψ(2S)-to-J/ψ ratio shows no significant centrality and p_{T} dependence at 5.02 TeV
- Stronger centrality dependence of the ψ(2S)-to-J/ψ ratio at lower energy
- The TAMU model describes data slightly better than SHMc in central collisions

Multiplicity analyses

Multiplicity analysis

- Multiplicity analysis: J/ψ in pp@13TeV (paper : JHEP 06 (2022) 015)

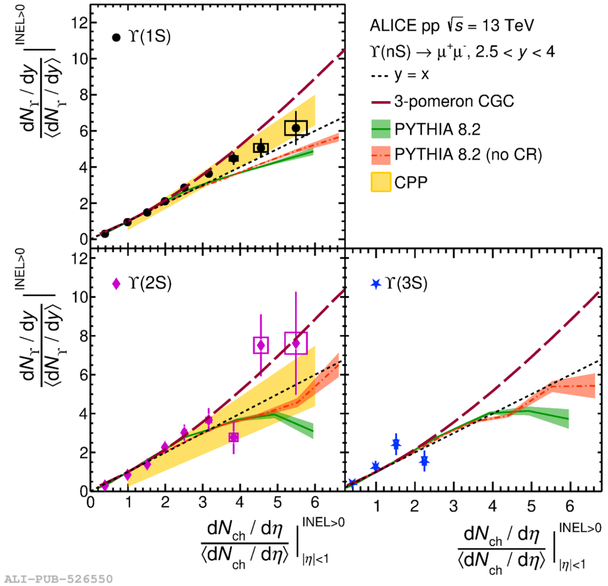
J/ψ→μμ measurement at forward rapidity

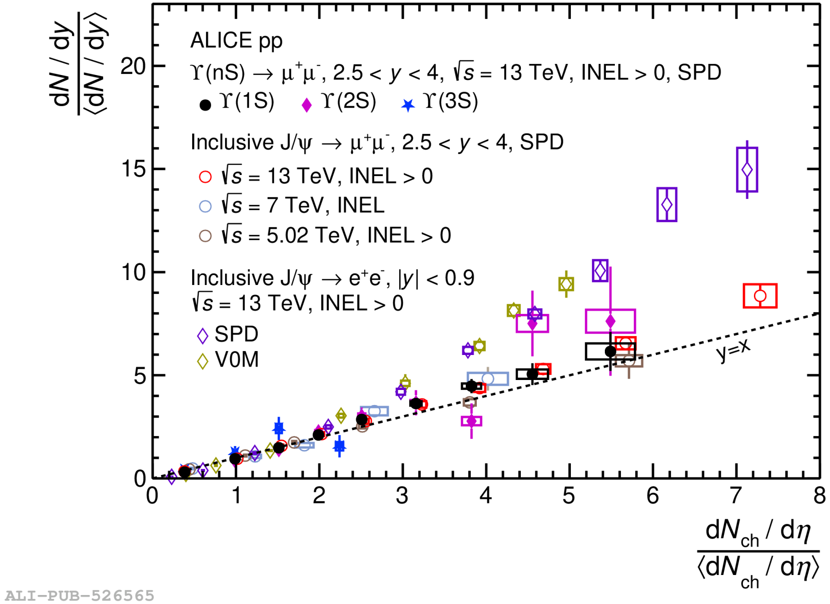


- Self-normalized J/ψ yield as a function of normalized charged-particle multiplicity
- The normalized J/ψ yield at forward rapidity approximatively grows linearly as a function of the event multiplicity, independently of the collision energy
- Models including either initial state effects or both initial and final state effects can describe qualitatively the data trend and the different behaviour at forward and midrapidity

Multiplicity analysis

- Multiplicity analysis: Y(1S), Y(2S) and Y(3S) in pp@13TeV (paper : arXiv:2209.04241)



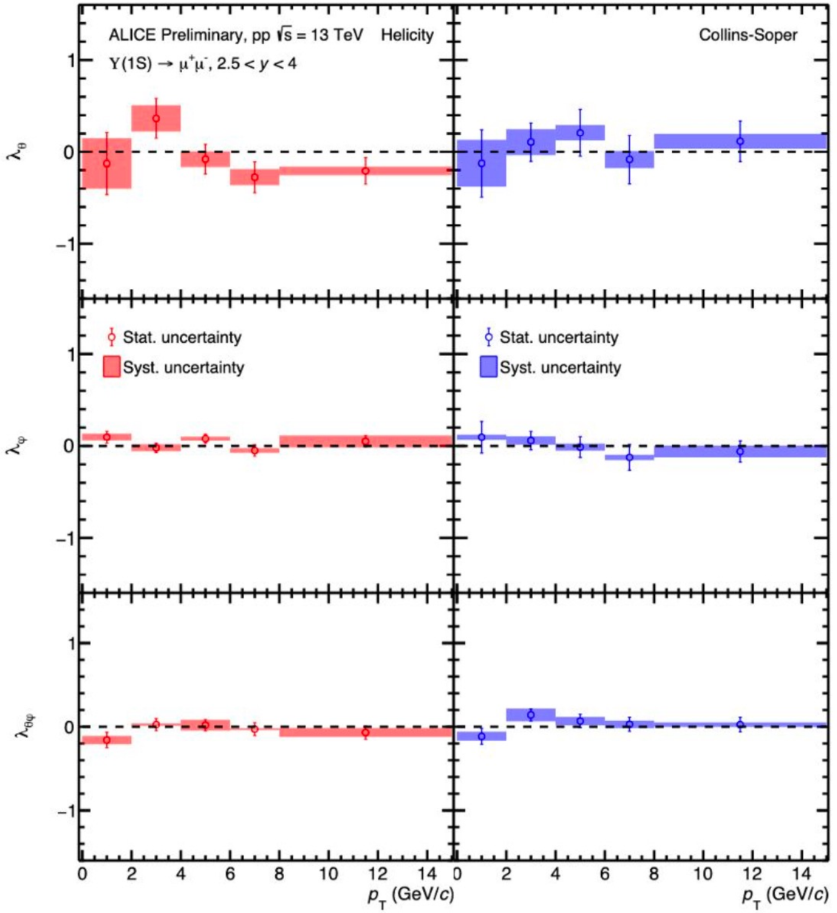


- Self-normalized yield of Y(nS) states as a function of normalized charged-particle multiplicity
- Linear increase with multiplicity for all forward quarkonium states, when multiplicity measured at midrapidity.

Polarization

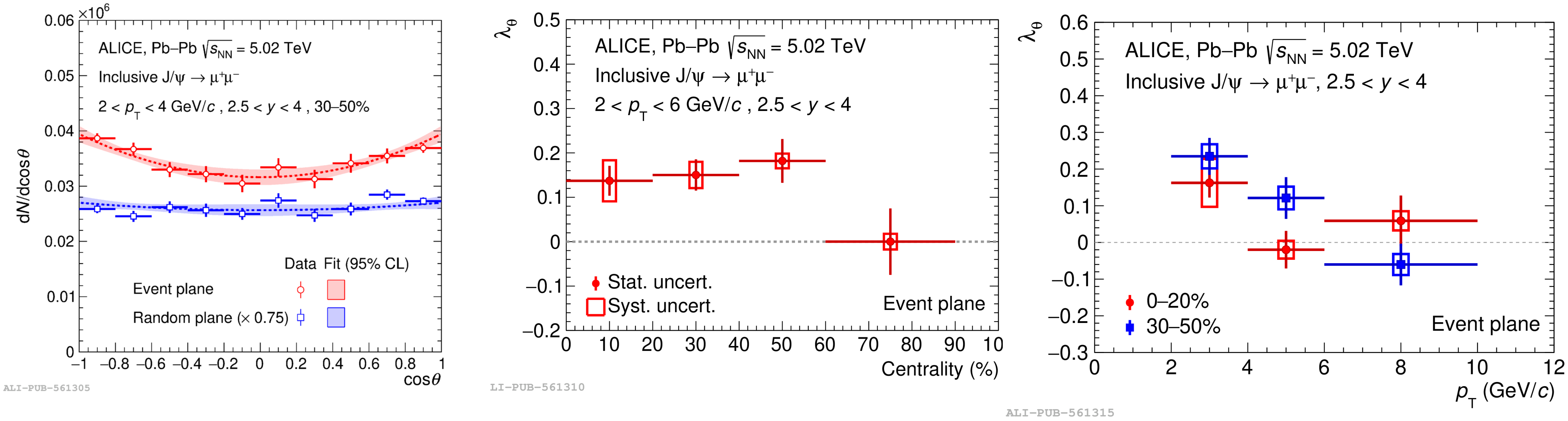
Quarkonium Polarization

- Polarization analysis: Y(1S) in pp@13TeV
- Constrain theoretical models for quarkonium production mechanisms
- $\boldsymbol{\lambda_\theta}$ compatible with zero (maximum deviation of 1.5$\boldsymbol{\sigma}$ with respect to zero in the helicity frame), all points compatible with zero in Collins-Soper frame
- $\boldsymbol{\lambda_\phi}$ and $\boldsymbol{\lambda_{\theta\phi}}$ compatible with zero within uncertainties in both frames



Quarkonium Polarization

- Polarization analysis: J/Ψ polarization in Pb-Pb using EP (paper : arXiv:2204.10171)

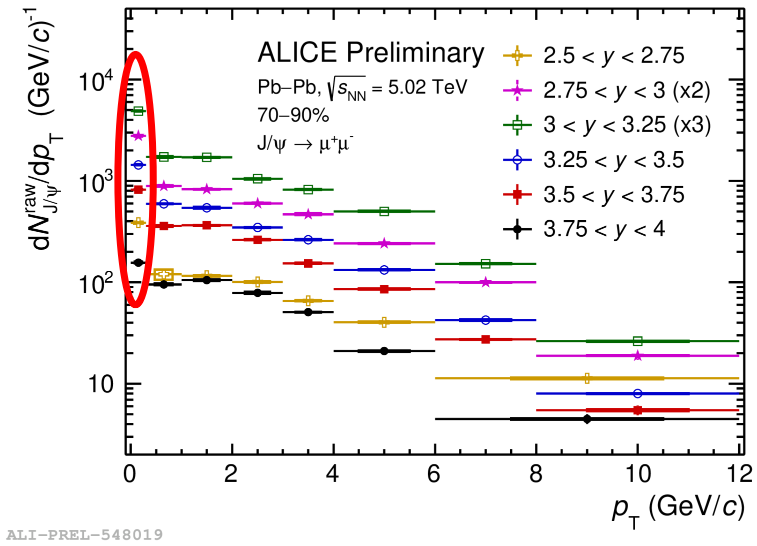


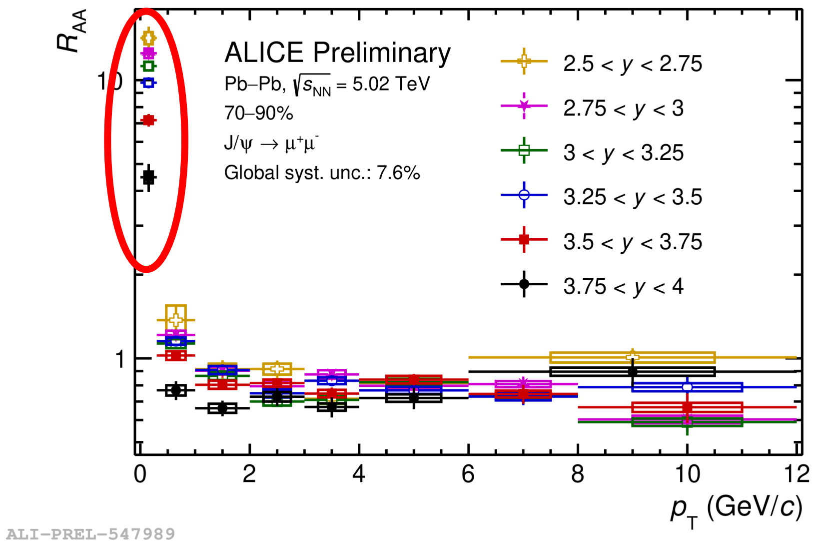
- First measurement of quarkonium polarization w.r.t the event plane via angular distribution of the decay products
- Significant polarization (~$\mathbf{3.5\sigma}$) observed in semicentral collisions (40-60%) in 2 < p_T < 6 GeV/c
- The significance of the polarization reaches ~$\mathbf{3.9\sigma}$ at low pT (2 < p_T < 4 GeV/c) in 30-50%

Photoproduction

Photoproduction

- y-differential coherent J/ψ photoproduction cross section in peripheral Pb-Pb collisions

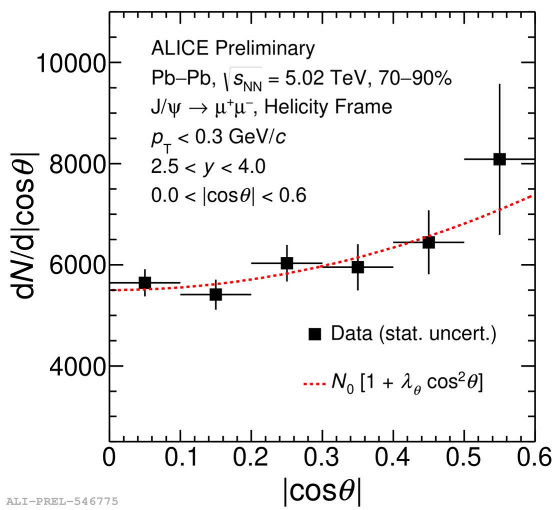


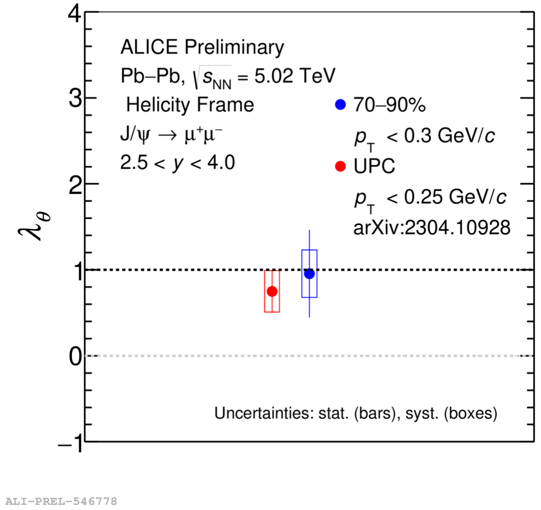


- Probe nuclear gluon distribution at low Bjorken-x
- Provide further constraints on photoproduction models in Pb-Pb collisions with nuclear overlap
- Clear excess in all y intervals, R_{AA} > 1 with clear hierarchy in rapidity

Photoproduction

- Photoproduced J/Ψ polarization in Pb-Pb@5.02 TeV



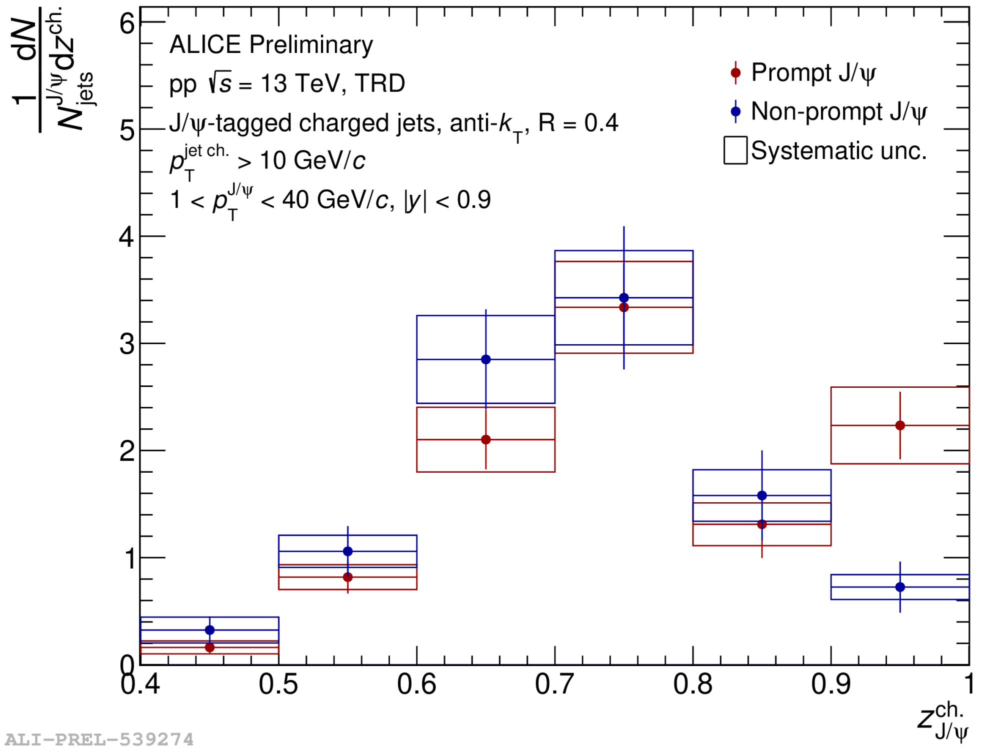


- Photoproduced Vector Meson expected to have transverse polarization due to the s-channel helicity conservation → Confirmed by UPC measurements
- Polarization measurement interesting to probe mechanism at the origin of the low p_T J/ψ excess
- Hint for transverse polarization of inclusive J/ψ for p_T < 0.3 GeV/c → in line with a dominant contribution from photoproduction process in this kinematic region

J/Ψ in jets

J/Ψ in jets

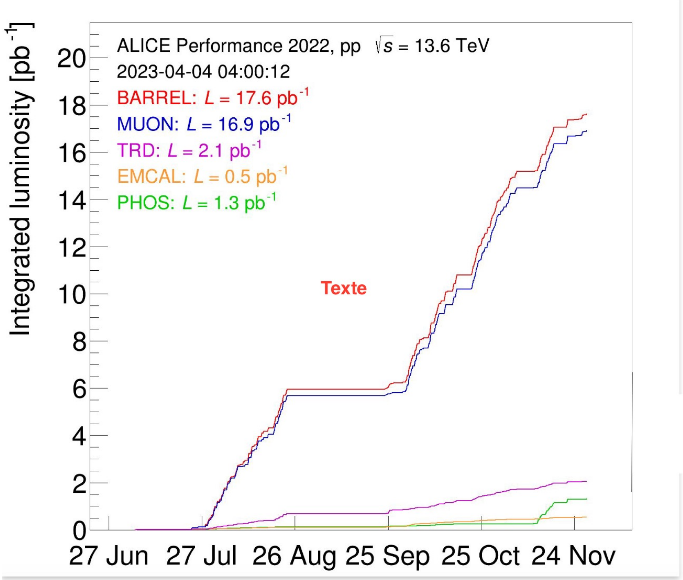
- J/Ψ in jets in pp@13 TeV
- Preliminary measurement of prompt and non-prompt J/ψ production as a function of $z_{J/\psi}$ (fraction of the jet momentum carried by the J/ψ) in charged jets for pp@13 TeV and midrapidity.
- Prompt and non-prompt J/ψ yields exhibit a similar pattern
- Except in the high-$z_{J/\psi}$ region, mainly corresponding to high-p_T isolated J/ψ in jets.

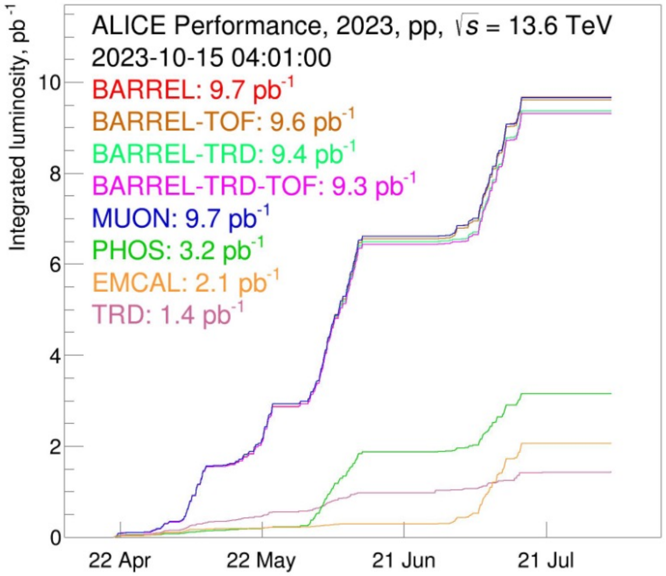


Run3 Analyses

Status of Run 3

- Run 3 started in 2022
- Upgrades installed to improve measurements

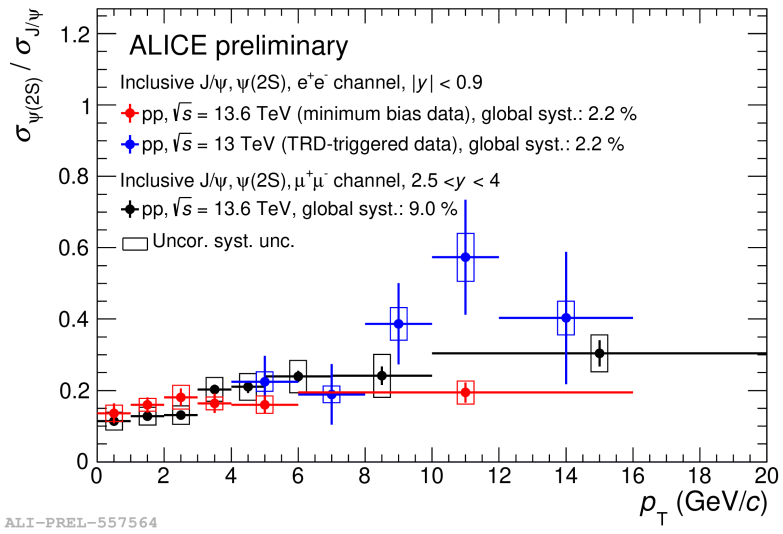


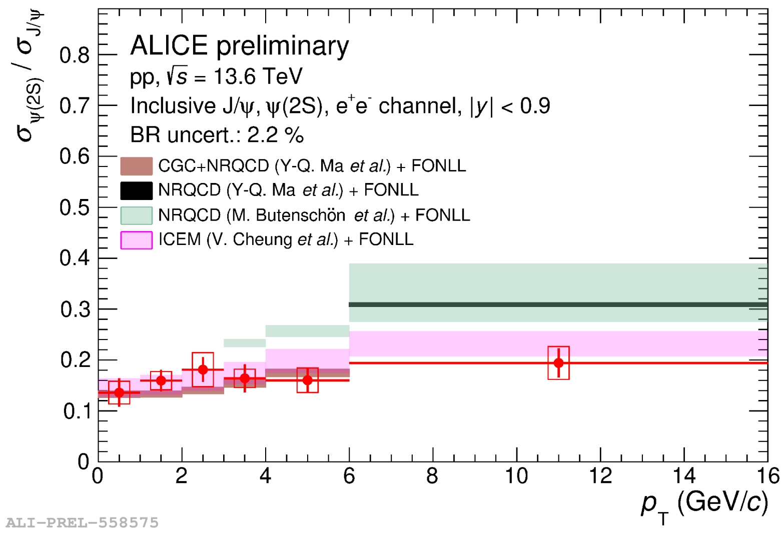


- Already (17.6+9.3)pb^{-1} collectted : more than Run1+Run2 !

Preliminary result run 3

- Ψ(2S)/J/Ψ in pp@13.6TeV (Run 3 data)

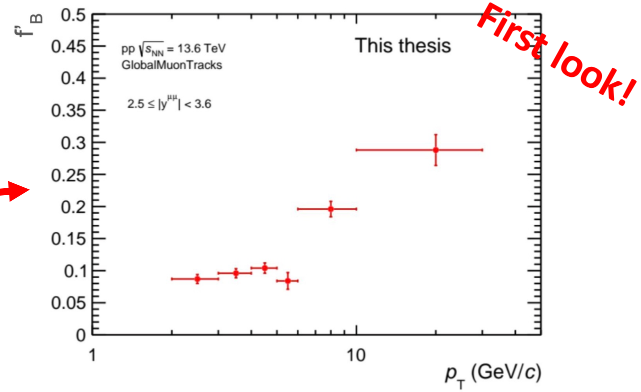


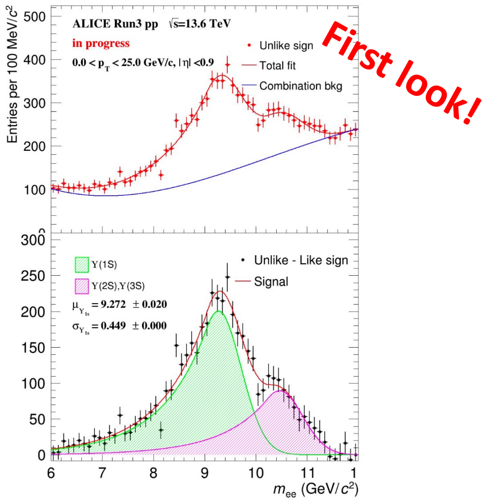


- First Run 3 analysis
- Large systematic uncertainty but demonstrates that the O2/DQ framework is ready for large scale analysis

Prospect analyses for Run 3

- Many planned analyses for Run3 :
  - J/ψ and ψ(2S) analysis in pp@13.6 TeV at mid-rapidity
  - J/ψ - D0 correlations in pp collisions at 13.6 TeV
  - Prompt and non-prompt J/ψ production in pp collisions at 13.6 TeV at forward rapidity
  - Upsilon production at midrapidity
  - J/ψ v2 in pp@13.6 TeV data at midrapidity
  - Quarkonium polarization in pp@13.6 TeV data
  - Bc in pp collisions at 13.6 TeV
  - Exclusive reconstruction of B mesons in the J/ψ + K decay channel in pp@13.6 TeV data
  - J/ψ photoproduction in Pb-Pb
  - Study of the χ(3872) and ψ(2S) in pp and Pb-Pb
  - …
- And many more to come!



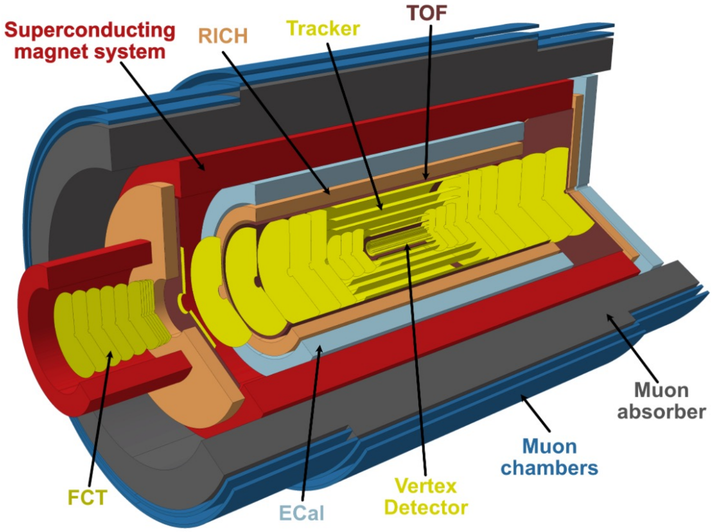


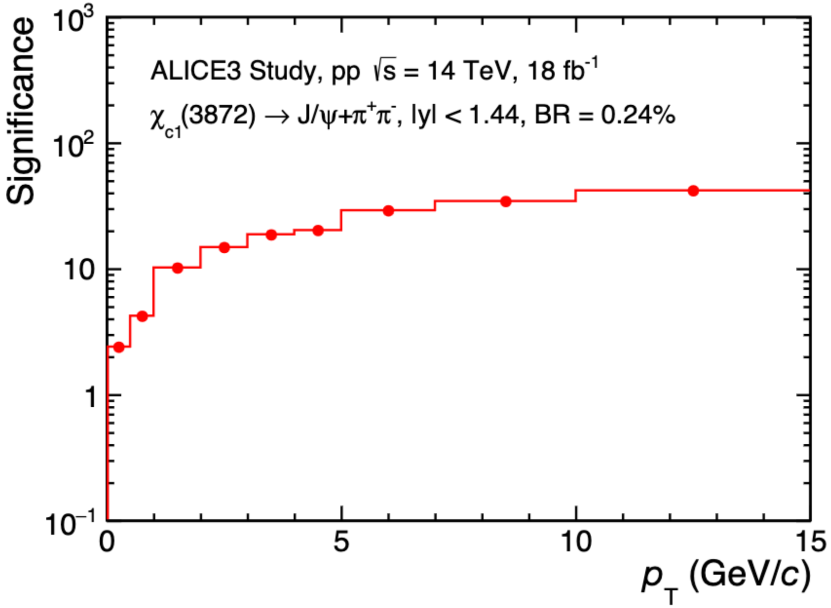
Conclusion

- We have now many precise measurements of quarkonia in pp, p-Pb and Pb-Pb collisions, allowing to confront the production models and the in medium models in a variety of ways :
  - pp collisions :
    - ➢ Results well described by models but large model uncertainties
    - ➢ Cross section ratios are challenging the models
    - ➢ Multiplicity dependence qualitatively described by models including MPI
  - Pb-Pb collisions
    - ➢ Interplay between suppression and (re-)generation
    - ➢ Sequential suppression of excited states
  - Polarization :
    - ➢ Observed small polarization vs event plane (magnetic field or vorticity effect?)
  - Quarkonia photoproduction
    - ➢ Measured in UPC and hadronic collisions
    - ➢ Hint of transverse polarization of J/ψ for pT < 0.3 GeV/c
  - And more…!
- With the increase statistics of Run3 and the new and improved ALICE detectors, we are having the first glimpse at the new measurments that will further

Conclusion

- More in the future, ALICE3 will include quarkonium physiscs and allow to measure more exotic states such as χc, χb, χc1(3872)





- Special thanks to Laure Massacrier and Cristiane Jahnke !

THANK YOU FOR YOUR ATTENTION!

BACK-UP

Model descriptions vs multiplicity

- Kopeliovich et al (CPP): higher Fock states. It assumes that hadron multiplicities larger than the mean value in pp collisions can be reached using higher Fock states in the proton, which contains an increased number of gluons. (Kopeliovich et al., PRD88 (2013) 116002)
- EPOS3: MPI and hydrodynamic expansion of the system. Uses same formalism to calculate cross sections and particle production (QCD-inspired field theory). Uses a unified treatment of soft and hard scattering: no fundamental cutoff parameter is used to define a border between soft and hard scattering. (Werner et al., Phys.Rept.350 (2001) 93)
- CGC: Model based on Color Glass Condensate (CGC) effective field theory to compute short distance charmonium cross-sections. J/ψ hadronization employing Nonrelativistic QCD (NRQCD) and an **Improved Color Evaporation model.** With increasing event activity the J/ψ production is dominated by the 3S [8] state, which is consistent with an interpretation of the dominance of hard gluon fragmentation in J/ψ hadronization. A faster than linear trend generically arises from the Bjorken-x dependent saturation scale which would suppress more the soft-particle multiplicity, produced at low-x, compared to J/ψ production which is sensitive to larger values of x.
- **3- Pomeron CGC:** Correlation arises as J/ψ production via 3-gluon fusion processes from various Pomeron configurations.
- Ferreiro et al (percolation): Saturation of soft particle production and string interactions (percolation model). It assumes that all projectiles have a finite spatial extension and collides at finite impact parameter by means of elementary parton-parton collisions.
(Ferreiro, Pajares, PRC86 (2012) 034903)
- PYTHIA8: MPI and saturation of soft particle production via color reconnection. The colour reconnection is used in the final state, in which there is a certain probability for the partons of two sub-scatterings to have their colours inter arranged in a way that reduces the total string length. (Sjostrand et al.,Comput.Phys.Commun.178(2008)852)

Model descriptions quarkonium production

- Quarkonium production can be described by various approaches that essentially differ in the treatment of the hadronization part.

- The Color Evaporation Model (CEM) considers that the quantum state of every heavy-quark pair produced with a mass above its production threshold and below twice the open heavy flavor (D or B meson) threshold production evolves into a quarkonium. In this model, the probability to obtain a given quarkonium state from the heavy-quark pair is parametrized by a constant phenomenological factor.
- The Color Singlet Model (CSM) assumes no evolution of the quantum state of the pair from its production to its hadronization. Only color-singlet heavy-quark pairs are thus considered to form quarkonium states.
- The Non-Relativistic QCD (NRQCD) considers that both color-singlet and color-octet heavy-quark pairs can evolve towards a bound state. Long Distance Matrix Elements are introduced in order to parametrize the binding probability of the various quantum states of the heavy-quark pairs. They can be constrained from existing measurements and do not depend on the specific production process under study (pp, electron–proton, etc.)
- Improved CEM: In contrast to the traditional color evaporation model, it is imposed a constraint that the invariant mass of the intermediate heavy quark-antiquark pair needs to be larger than the mass of produced quarkonium. It also introduces a momentum shift between the heavy quark-antiquark pair and the quarkonium.

Model descriptions in medium

- Transport models: includes dissociation and regeneration in QGP and hadronic phase
- Comovers: suppression via comovers interactions and includes regeneration
- SHM: charmed particles are generated at chemical freeze-out

Polarization reference frames

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

- Reference frames the polarization:
- Helicity: measured with respect to directions directly connected with the production process, i.e., the momentum direction of the J/ψ itself.
- Collins-Soper: the direction of motion of the colliding hadrons.
- Reaction plane: by measuring the polarization with respect to the estimated reaction plane of the nuclear collision

  → one rather selects a reference frame that should naturally be connected with the observation of polarization effects due to the presence of early electromagnetic fields and/or QGP vorticity.