

# Quarkonia: experiment

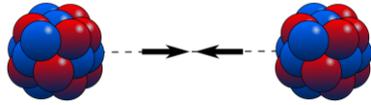
Cristiane Jahnke



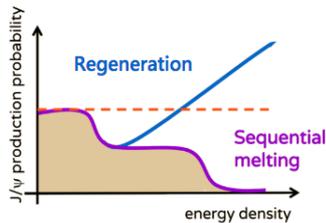
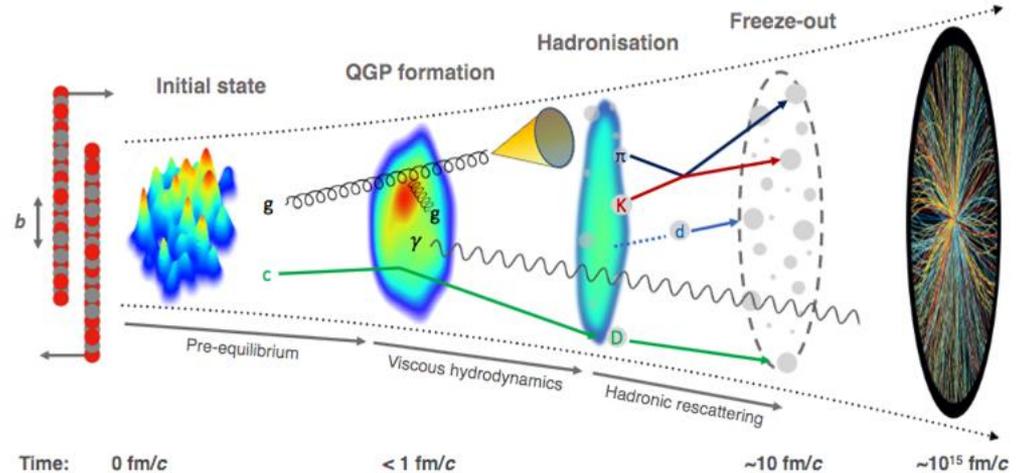
# Introduction: Why are we measuring quarkonia in A-A collisions?

Quarkonia are bound states of either a **charm-anticharm** or a **bottom-antibottom** quark pair

→ Probes of the medium formed in A-A collisions

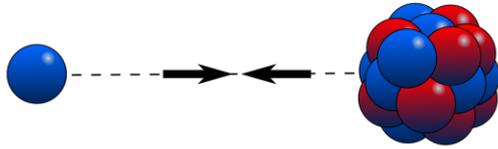


- Heavy quarks are created early in the collisions and can live longer than the QGP  
→ Experience full evolution of the medium
- Quarkonia states were initially proposed as QGP thermometer  
→ Sequential melting observed at RHIC  
→ Regeneration process observed at LHC energies



<https://arxiv.org/pdf/2211.04384>

# Introduction: Why are we measuring quarkonia in **small systems**?



**p-A, d-A**

→ Probe nuclear effects (PDF modifications, Coherent energy loss, nuclear absorption, Comover breakup)

→ Elementary collisions to understand the quarkonia production:

- Production of the heavy-quark pair can be described with pQCD calculations.
- The binding of the  $Q\bar{Q}$  is a non-perturbative process
  - treated differently in the various approaches



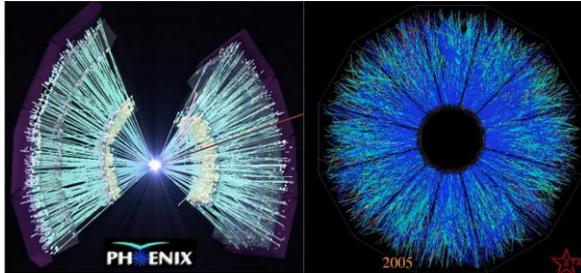
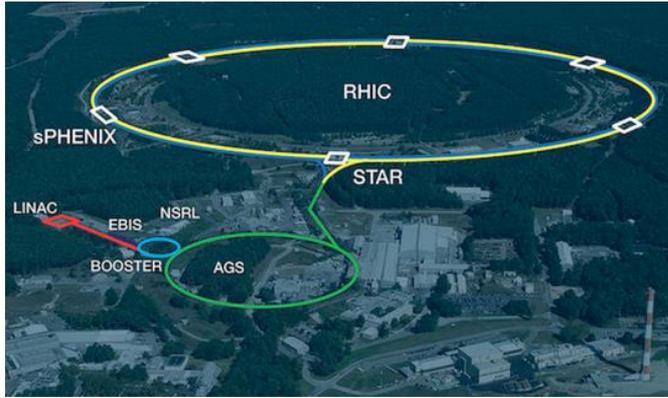
**pp, e<sup>+</sup>e<sup>-</sup>**

→ QCD tool to investigate rare decays or exotic quarkonium states

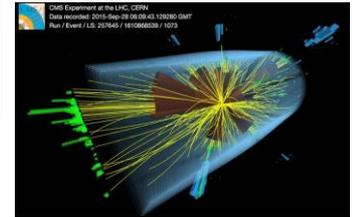
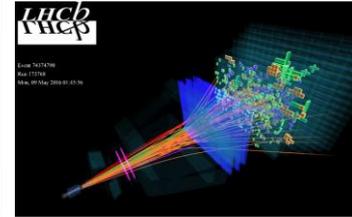
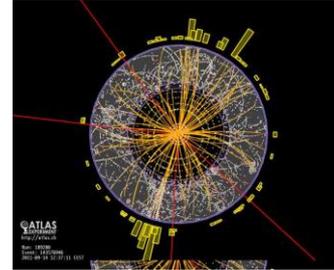
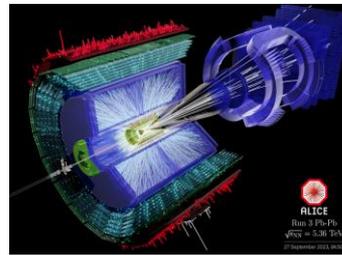
→ Baseline for A-A and p-A collisions

# Introduction: **How** are we measuring quarkonia?

## RHIC: PHENIX, STAR



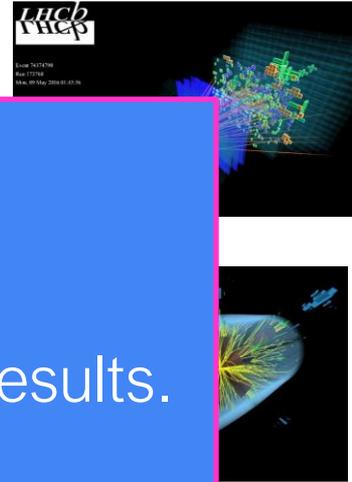
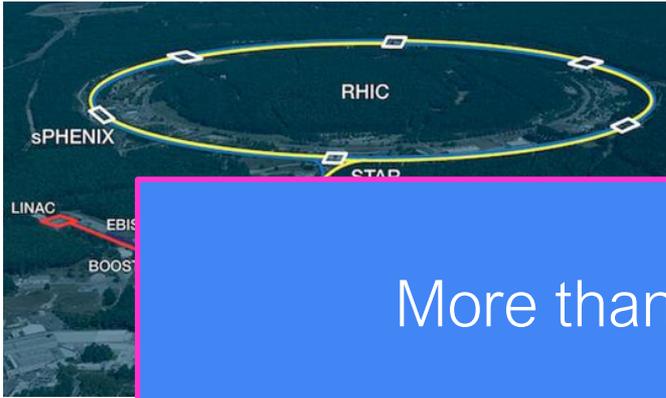
## LHC: ALICE, ATLAS, CMS, and LHCb



# Introduction: **How** are we measuring quarkonia?

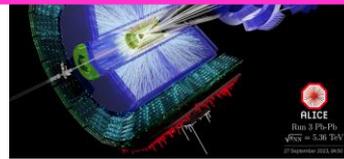
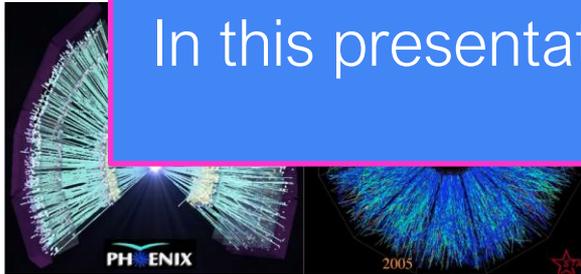
RHIC: PHENIX, STAR

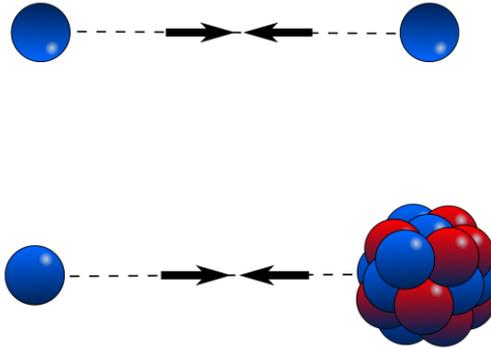
LHC: ALICE, ATLAS, CMS, and LHCb



More than 30 papers on the last 2 years!

In this presentation, I have selected part of these results.



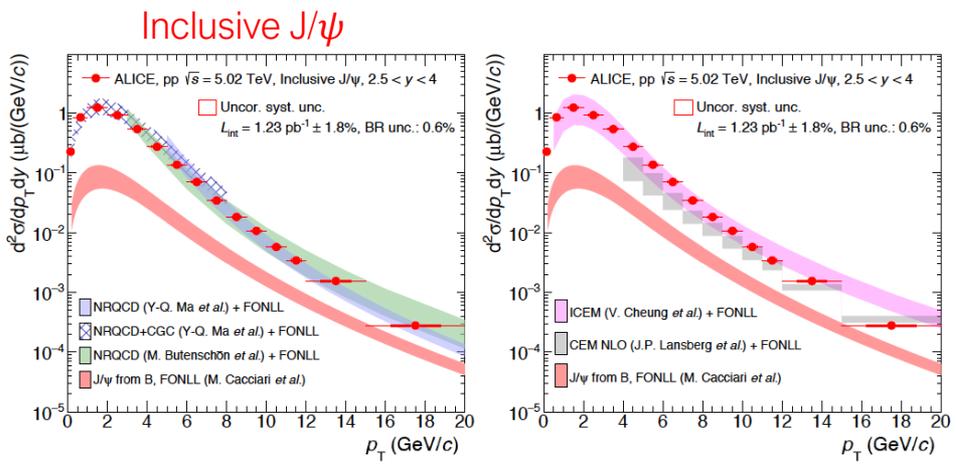


# J/ψ and ψ(2S) production in pp

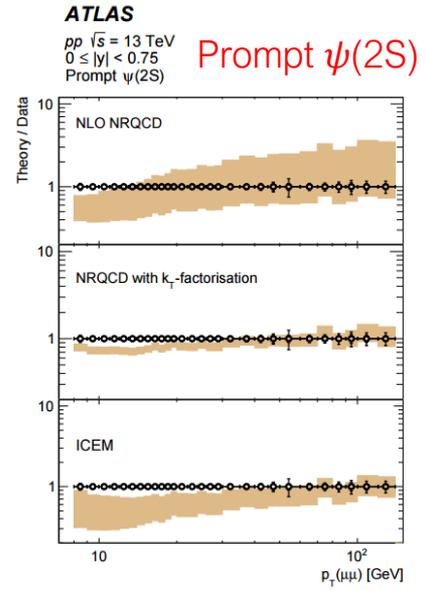
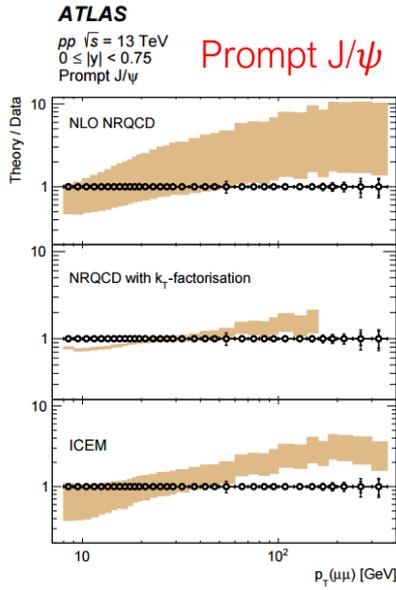


Cross section measurements to probe quarkonia production

- Good description of J/ψ cross sections at low and intermediate p<sub>T</sub> by NRQCD and ICEM
- Prompt J/ψ and ψ(2S) cross sections are described over a wide range of p<sub>T</sub> by NRQCD and ICEM



Eur. Phys. J. C 83 (2023) 61



Eur. Phys. J. C 84 (2024) 169



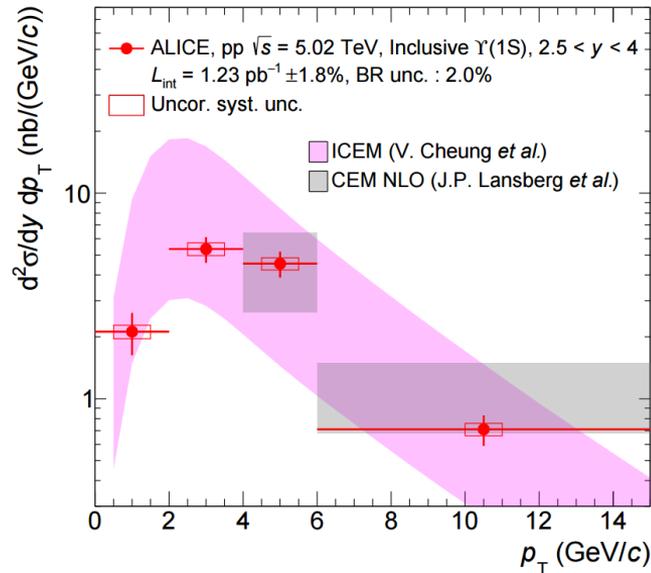
# $\Upsilon(1S)$ production in pp



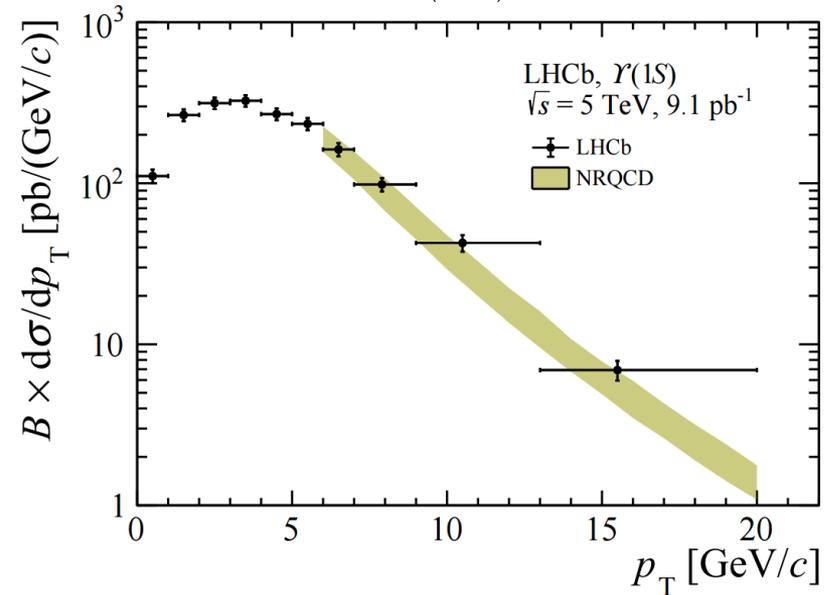
JHEP 07 (2023) 069

Cross section measurements to probe quarkonia production

→ Good description of  $\Upsilon(1S)$  cross section over  $p_T$  by **ICEM** and **NRQCD**

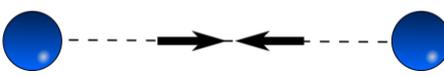


Eur. Phys. J. C 83 (2023) 61



→ Complementary results by the different experiments: provides important input for tuning of theoretical models.

# Cross section ratio in pp

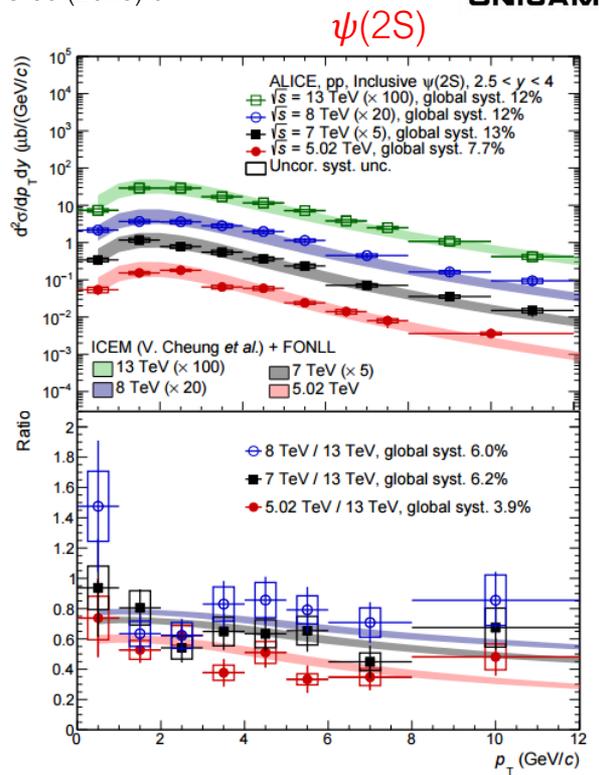
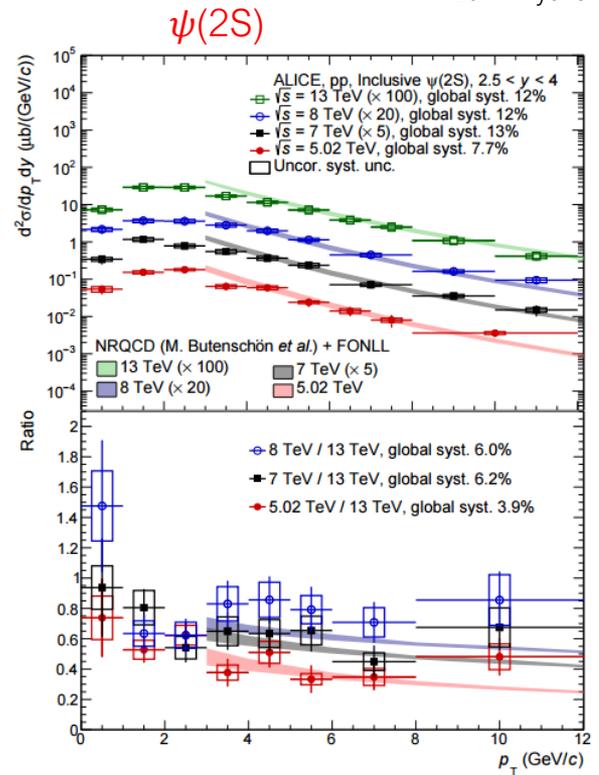


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Ratios of spectra among energies can be used to further constrain model calculations:

- Partial cancellation of several theoretical uncertainties, like renormalization scale and factorization scale
- Precise quarkonium production measurements at several c.m.s energies



HP2024  
NAGASAKI

# $\psi(2S)/J/\psi$ ratio in pp

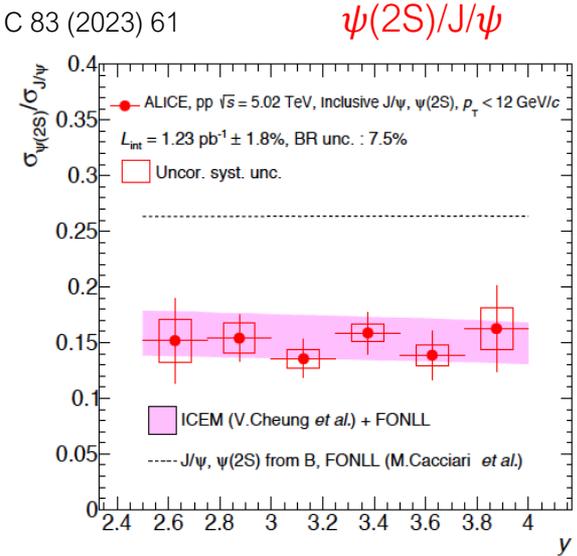
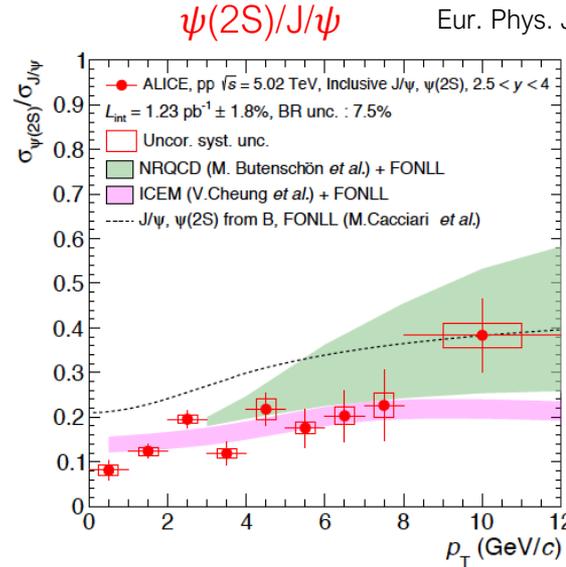


Excited to ground state ratio is used to investigate final effects

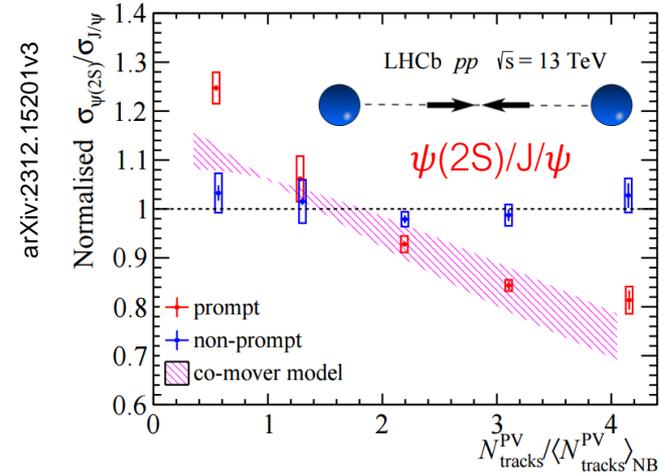
→ **theoretical uncertainty** is considered as correlated among the two states and **partially cancel in the ratio calculation**

The **NRQCD** calculations describe well the  $p_T$  dependence of the cross section ratio within the large model uncertainties.

The **ICEM** can describe the  $p_T$  and  $y$  dependence of the  $\psi(2S)/J/\psi$  cross section ratio



# Multiplicity dependence of $\psi(2S)/J/\psi$



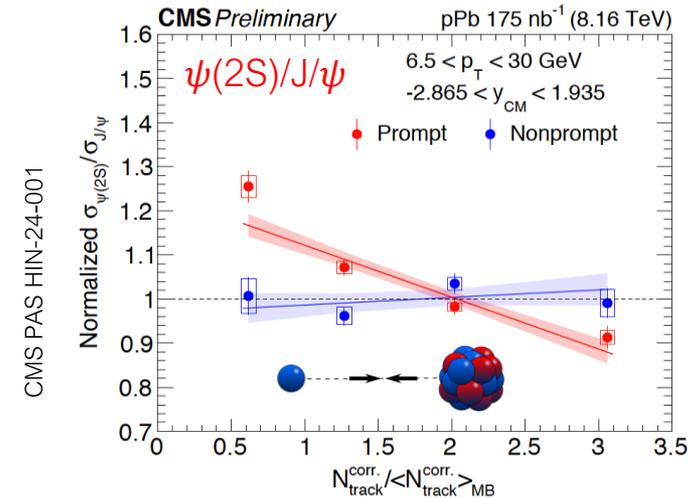
Excited to ground state ratio is used to investigate final effects

The **prompt normalized ratio** exhibits a decreasing trend as a function of multiplicity

Consistent with a picture of **comover** suppression effects, where a **higher density of comoving particles** corresponds to lower production rate of excited charmonium states

No significant dependence on the normalized multiplicity is observed for **non-prompt charmonia**

**Non-prompt charmonia** originate from **B hadron decays** that occur significantly **after the initial stages** of the collision evolution, they **are not expected being broken up by comoving particles**



\*probe and  $N_{\text{ch}}$  in the same rapidity interval

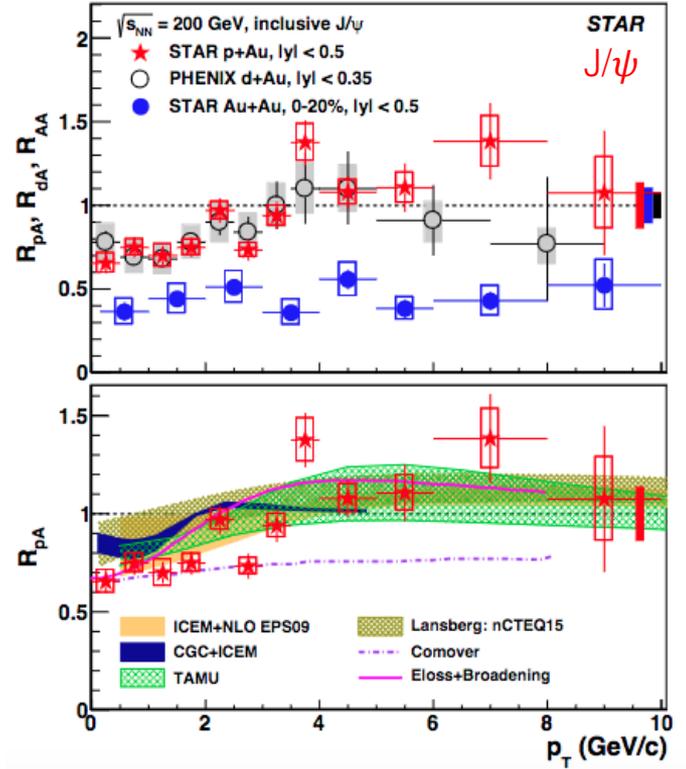
# $J/\psi$ production in p-Au and d-Au

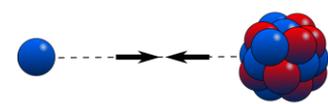


Phys. Lett. B 825 (2022) 136865

## Investigating cold nuclear matter effects on $J/\psi$ production

- A **suppression below 2 GeV/c** in p-Au and d-Au is observed. For  $p_T$  above 3 GeV/c, results compatible with unity, indicating little CNM effects in this kinematic range.
- **ICEM** and **Lansberg** calculations include only nPDF
- CGC+ICEM approach directly calculates the  $c\bar{c}$  production cross section in p+Au collisions based on the CGC formalism
- **TAMU**: considers that a **short-lived hot medium** modifies the observed  $J/\psi$  yields through both **dissociation and recombination**.
- **Comovers**: breakup of  $J/\psi$  mesons **through interactions with final state particles traveling along with  $J/\psi$**
- **Eloss+Broadening**: interactions between  $c\bar{c}$  pairs and the cold nuclear medium induce both radiative energy loss and  $p_T$ -broadening



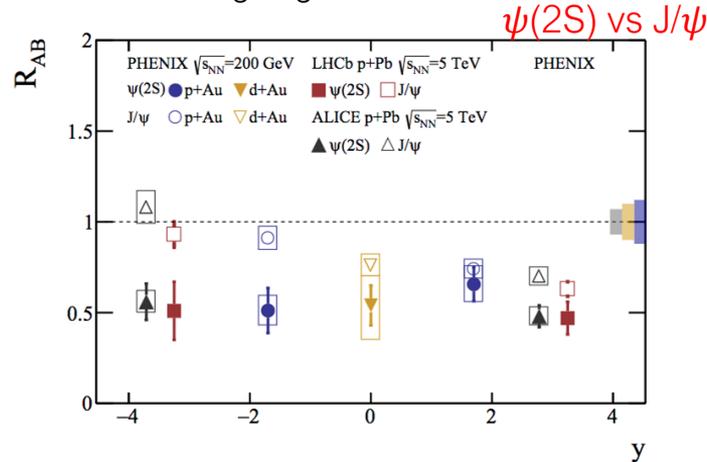


## Investigating cold nuclear matter effects on $\psi(2S)$ production

- At forward rapidity, the  $J/\psi$  and  $\psi(2S)$  suppression are similar, suggesting that initial-state effects dominate charmonium modification.
- At backward rapidity, the results show a larger suppression for  $\psi(2S)$  than for  $J/\psi$ , suggesting final-state effects in small systems for the A-going direction

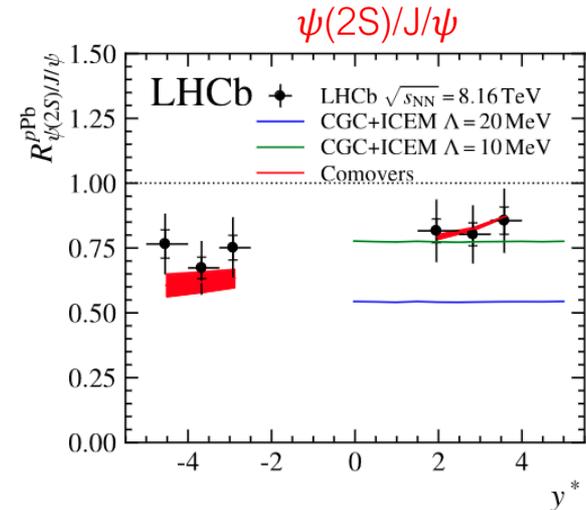
Double cross-section ratios  $\psi(2S)/J/\psi$ :

→ Suppression compatible with CGC+ICEM and comovers model



→  $\psi(2S)/J/\psi$  ratio mostly removes initial-state effects

→ Important to isolate modification due to final-state effects



JHEP 04 (2024) 111

Phys. Rev. C 105, 064912 (2022)

# Associated quarkonia production

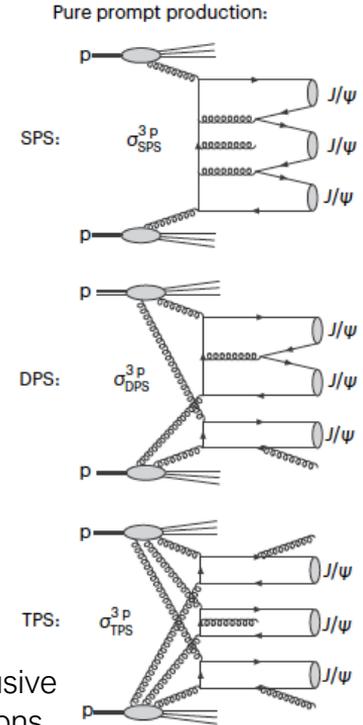
pp collisions: typically only a few partons undergo a hard scattering

CMS: [Nature Physics](#) volume 19, pages 338–350 (2023)

As the collision energy increases, the densities of gluons and sea quarks probed inside each proton grow rapidly.  
 → More than one pair of partons can undergo a hard scattering in a single pp collision  
 → leading to the simultaneous and independent production of two or more particles with high  $p_T$  and/or mass (above a few GeV).

Studies of n-parton scattering (NPS) processes are important to elucidate the **inner structure of the proton and its evolution with energy**

→ **double  $J/\psi$ , triple  $J/\psi$ ,  $J/\psi$ - $\psi(2S)$ ,  $J/\psi$ -D**



Leading-order diagrams for inclusive triple- $J/\psi$  production in pp collisions

# Double and triple $J/\psi$ production

Summary of **effective cross section**  $\sigma_{\text{eff}}$

$\sigma_{\text{eff}}$   $\rightarrow$  characterizes the area occupied by the interacting partons in the transverse space

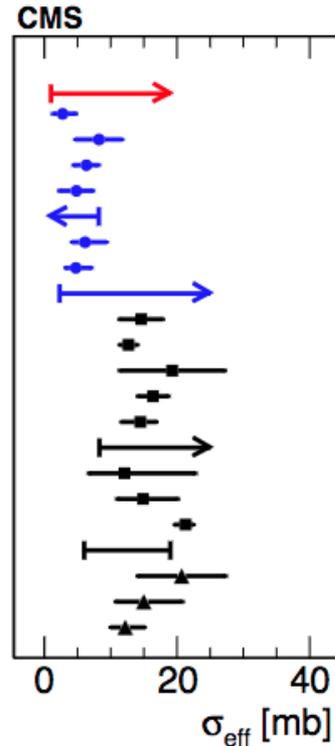
Double  $J/\psi$  production in **p-Pb**:

$\rightarrow$  large transverse parton density of the nucleus enhances DPS contribution w.r.t pp

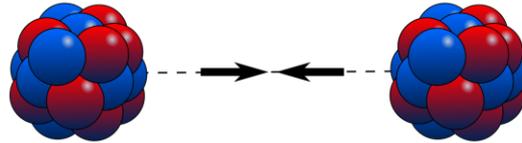
$\rightarrow$  **Triple  $J/\psi$**  production is a golden channel to study DPS and TPS, with **minimal SPS contamination**

$\rightarrow$  The effective cross sections obtained from **multi-quarkonium production favor a smaller value of  $\sigma_{\text{eff}} \approx 3\text{--}10$  mb** compared with the  **$\sigma_{\text{eff}} \approx 10\text{--}20$  mb result of the other types of multiple hard scattering processes**

arXiv:2407.03223v1



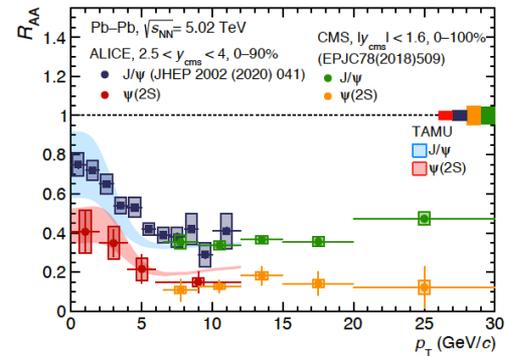
pPb $\rightarrow J/\psi+J/\psi$ , $\sqrt{s_{NN}}=8.16$ TeV, <b>CMS</b> (this work)	
pp $\rightarrow J/\psi+J/\psi+J/\psi$ , $\sqrt{s}=13$ TeV, <b>CMS</b>	Nat. Phys. <b>19</b> (2023) 338
pp $\rightarrow J/\psi+J/\psi$ , $\sqrt{s}=7$ TeV, <b>CMS*</b>	Phys. Rept. <b>889</b> (2020) 1
pp $\rightarrow J/\psi+J/\psi$ , $\sqrt{s}=8$ TeV, <b>ATLAS</b>	Eur. Phys. J. C <b>77</b> (2017) 76
pp $\rightarrow J/\psi+J/\psi$ , $\sqrt{s}=1.96$ TeV, <b>D0</b>	Phys. Rev. D <b>90</b> (2014) 111101
pp $\rightarrow J/\psi+Y$ , $\sqrt{s}=1.96$ TeV, <b>D0*</b>	Phys. Rev. Lett. <b>117</b> (2016) 062001
pp $\rightarrow W+J/\psi$ , $\sqrt{s}=7$ TeV, <b>ATLAS*</b>	Phys. Lett. B <b>781</b> (2018) 485
pp $\rightarrow Z+J/\psi$ , $\sqrt{s}=8$ TeV, <b>ATLAS*</b>	Phys. Rept. <b>889</b> (2020) 1
pp $\rightarrow Z+b \rightarrow J/\psi$ , $\sqrt{s}=8$ TeV, <b>ATLAS*</b>	Nucl. Phys. B <b>916</b> (2017) 132
pp $\rightarrow \gamma+b/c+2\text{-jet}$ , $\sqrt{s}=1.96$ TeV, <b>D0</b>	Phys. Rev. D <b>89</b> (2014) 072006
pp $\rightarrow \gamma+3\text{-jet}$ , $\sqrt{s}=1.96$ TeV, <b>D0</b>	Phys. Rev. D <b>89</b> (2014) 072006
pp $\rightarrow 2\text{-}\gamma+2\text{-jet}$ , $\sqrt{s}=1.96$ TeV, <b>D0</b>	Phys. Rev. D <b>93</b> (2016) 052008
pp $\rightarrow \gamma+3\text{-jet}$ , $\sqrt{s}=1.96$ TeV, <b>D0</b>	Phys. Rev. D <b>81</b> (2010) 052012
pp $\rightarrow \gamma+3\text{-jet}$ , $\sqrt{s}=1.8$ TeV, <b>CDF</b>	Phys. Rev. D <b>56</b> (1997) 3811
pp $\rightarrow 4\text{-jet}$ , $\sqrt{s}=640$ GeV, <b>UA2</b>	Phys. Lett. B <b>268</b> (1991) 145
pp $\rightarrow 4\text{-jet}$ , $\sqrt{s}=1.8$ TeV, <b>CDF</b>	Phys. Rev. D <b>47</b> (1993) 4857
pp $\rightarrow 4\text{-jet}$ , $\sqrt{s}=7$ TeV, <b>ATLAS</b>	JHEP <b>11</b> (2016) 110
pp $\rightarrow 4\text{-jet}$ , $\sqrt{s}=7$ TeV, <b>CMS</b>	Eur. Phys. J. C <b>76</b> (2016) 148
pp $\rightarrow 4\text{-jet}$ , $\sqrt{s}=13$ TeV, <b>CMS</b>	JHEP <b>01</b> (2022) 177
pp $\rightarrow W+2\text{-jet}$ , $\sqrt{s}=7$ TeV, <b>CMS</b>	JHEP <b>03</b> (2014) 032
pp $\rightarrow W+2\text{-jet}$ , $\sqrt{s}=7$ TeV, <b>ATLAS</b>	New J. Phys. <b>15</b> (2013) 033038
pp $\rightarrow WW$ , $\sqrt{s}=13$ TeV, <b>CMS</b>	Phys. Rev. Lett. <b>131</b> (2023) 091803



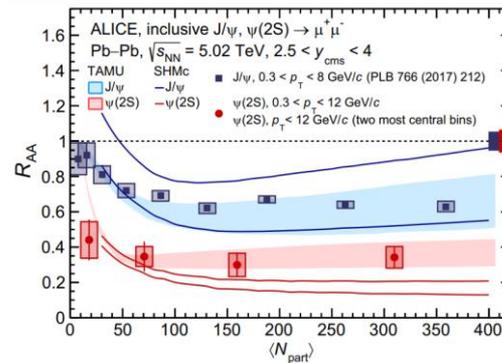
# Nuclear modification factor of $J/\psi$ and $\psi(2S)$

$J/\psi$  and  $\psi(2S)$  differ in binding energy by more than a factor of 10 ( $\sim 640$  versus  $\sim 50$  MeV, respectively) and by about a factor of 2 in size.

- sequential dissociation
- $\psi(2S)$  is suppressed by a factor of  $\sim 2$  with respect to the  $J/\psi$
- The  $\psi(2S)$   $R_{AA}$  show a hint for a decrease as a function of  $p_T$ 
  - charm quark recombination processes.



Phys. Rev. Lett. 132 (2024) 042301



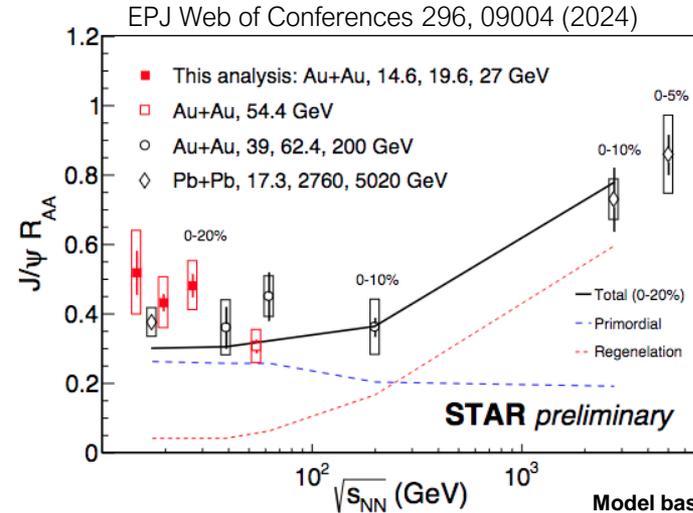
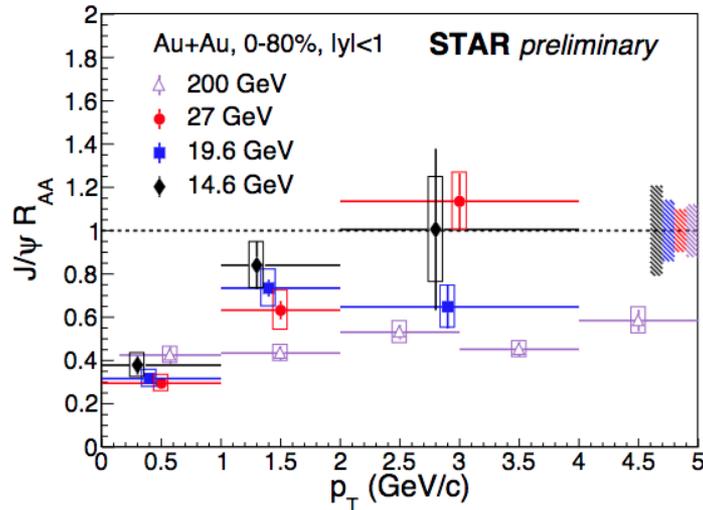
TAMU: uses an expanding fireball; lower dissociation temperature of the  $\psi(2S)$  relative to the  $J/\psi$ . This implies a sequential freezeout of those two mesons, with most of the  $\psi(2S)$  regeneration occurring later in the fireball evolution

SHMc: assumes that all charm quarks are produced during the initial hard partonic interactions and then thermalize in the QGP.

→ Model implements a hydro-inspired freeze-out hypersurface.

# Nuclear modification factor of $J/\psi$

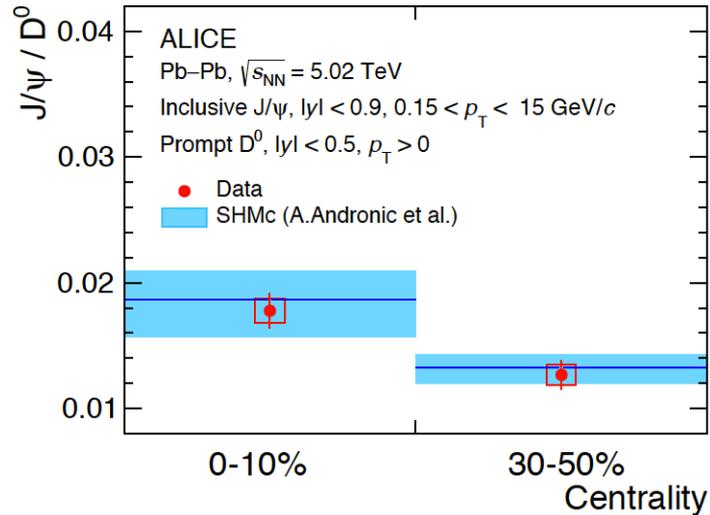
- $R_{AA}$  in different collisions energies to probe dissociation vs regeneration
- Increasing the collision energy shows a stronger suppression at RHIC energies
  - Different  $p_T$  dependence for 200 GeV (flat) versus 20 GeV (increasing with  $p_T$ )
- Going to LHC energies, the  $R_{AA}$  is less suppressed, which is compatible with the regeneration scenario
  - Model calculation including regeneration can describe the data (but underestimates the data below 20 GeV)



Model based on thermal lattice  
QCD: Phys. Rev. C 82, 064905  
(2010)

# Ratio $J/\psi$ over $D^0$

- $J/\psi/D^0$  measurement provides a tight constraint to models because some of the model parameters and most model uncertainties related to the  $c\bar{c}$  cross section cancel in the ratio



Phys. Lett. B 849 (2024) 138451

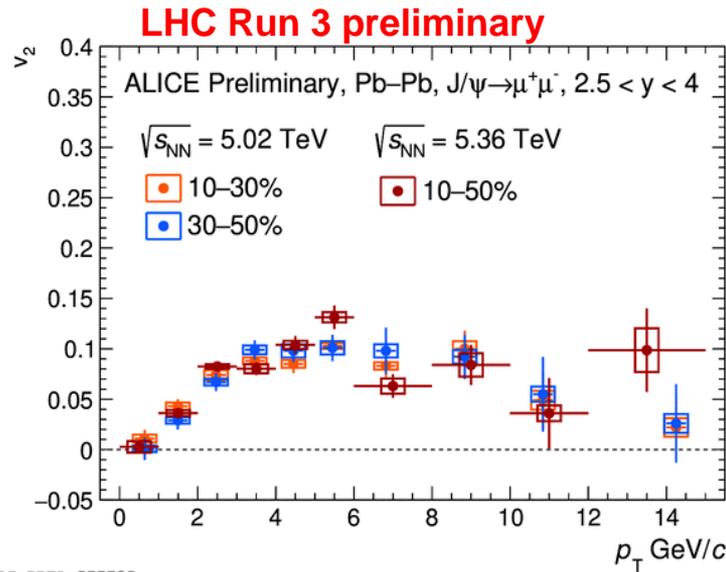
- The results suggest a higher value for this ratio in central compared to semicentral collisions.
- This is supported by the SHMc calculations, which suggests both the  $J/\psi$  and  $D^0$  are produced via the coalescence of charm quarks at the phase boundary
- The model uncertainty from the SHMc model is due to uncertainties on the charm fugacity parameter, which is fitted to the ALICE  $D^0$  data

## Azimuthal anisotropy of $J/\psi$ at LHC energies:

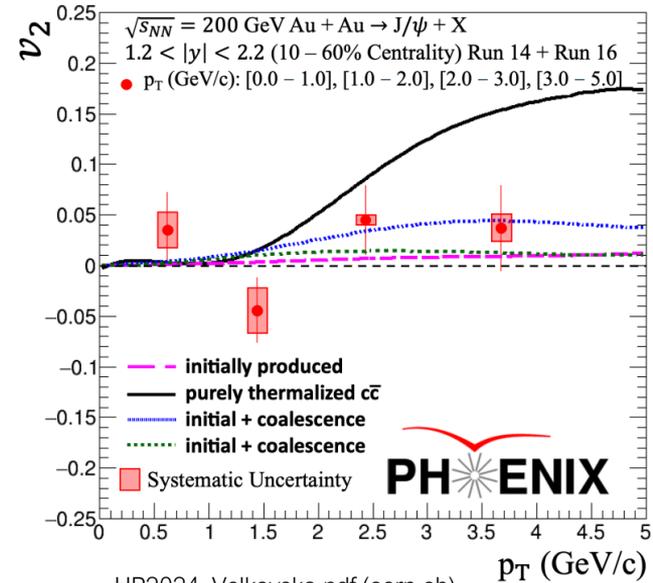
→ At low  $p_T$ , an increasing trend of flow is observed

Agrees with microscopic transport model which consider **charmonia formation from both initial hard interaction and recombination of thermalized charm quarks**

→ At high  $p_T$ , path length dependent effect are expected (for primordial  $J/\psi$ )



ALI-PREL-577735



HP2024\_Velkovska.pdf (cern.ch)

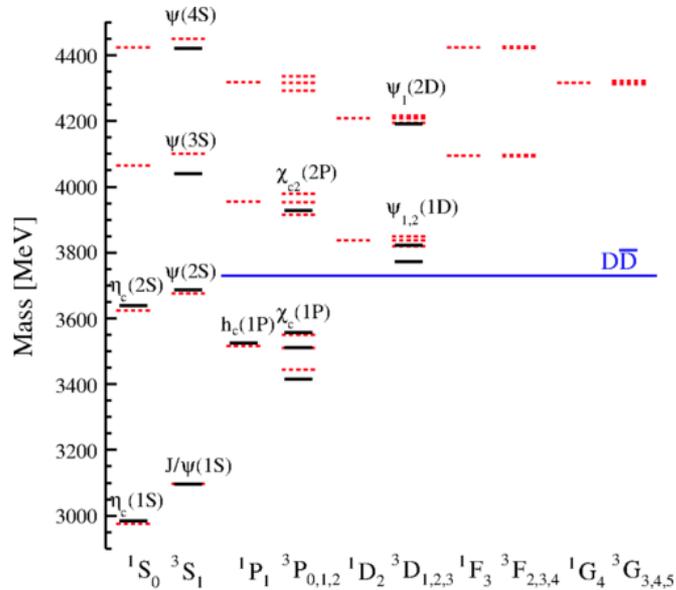
**PHENIX**

# Exotic quarkonium-like states

Experimentally established charmonium states:

**dashed red lines: calculations**

**black solid lines: experimentally observed**



Rev. Mod. Phys. 90, 015003

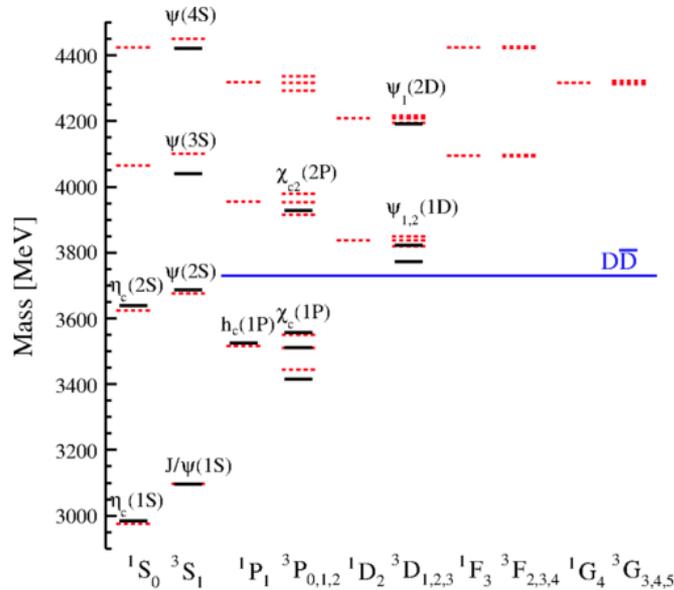
Quarkonia: recent experimental results - Cristiane Jahnke - Sep. 25<sup>th</sup>

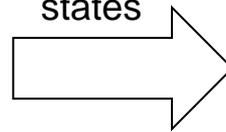
# Exotic quarkonium-like states

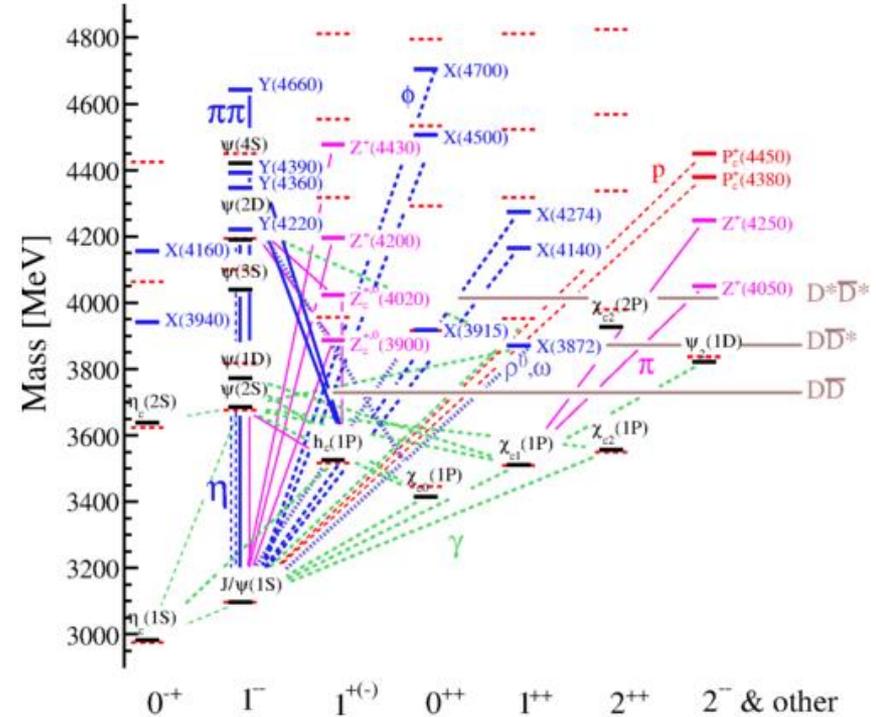
Experimentally established charmonium states:

**dashed red lines: calculations**

**black solid lines: experimentally observed**

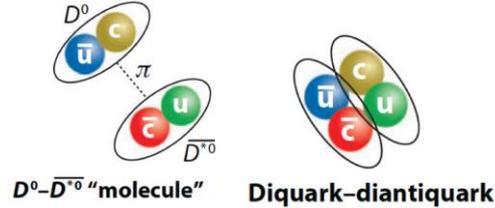


Exotic states  




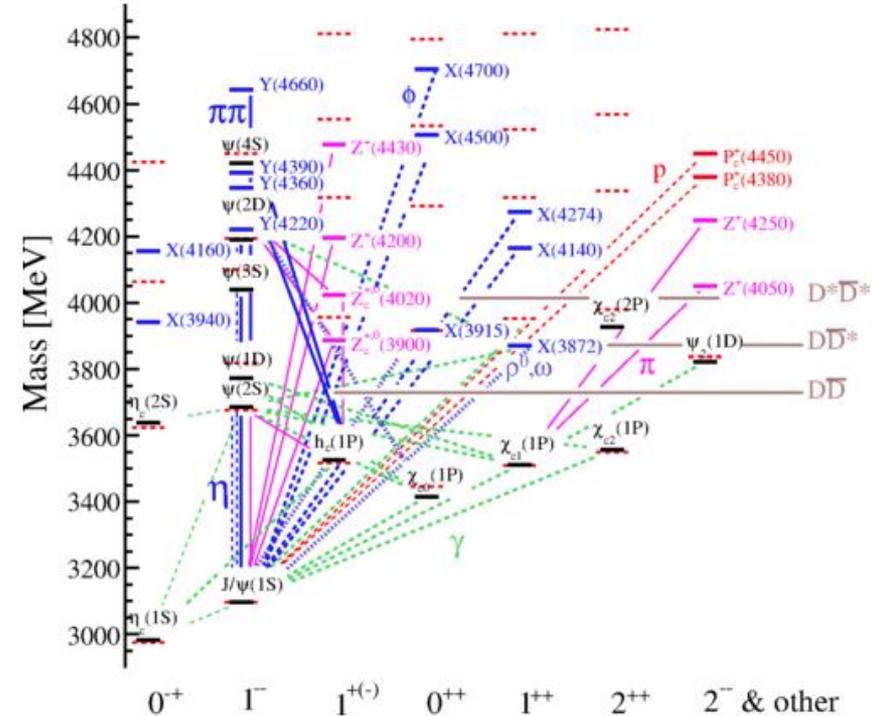
# Exotic quarkonium-like states

Example of exotic state X(3872):



<https://cms.cern/news/x-3872-exotic-charmonium-charming-puzzle>

- Different hadronic structures can affect the interaction with the medium formed.
  - In Pb-Pb collisions, the production of X(3872) may increase via coalescence or decrease due to dissociation (similar to quarkonia states).
    - Processes depend on spatial configuration.



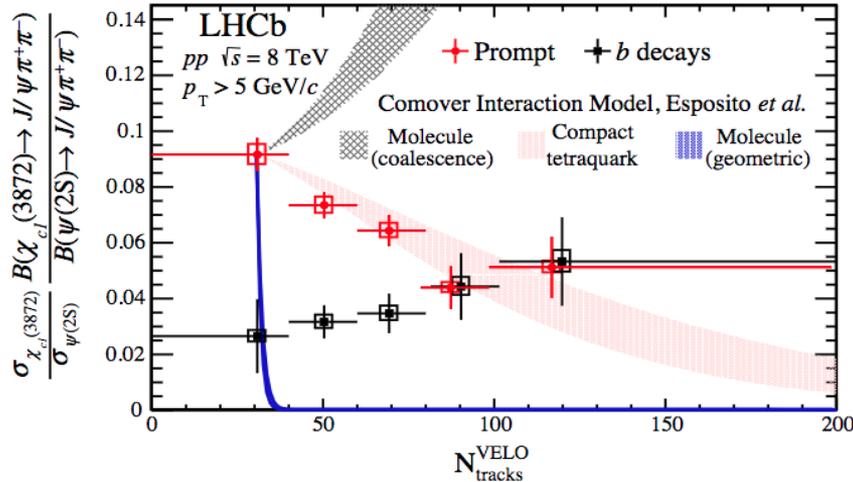
Rev. Mod. Phys. 90, 015003

# Exotic quarkonium-like states

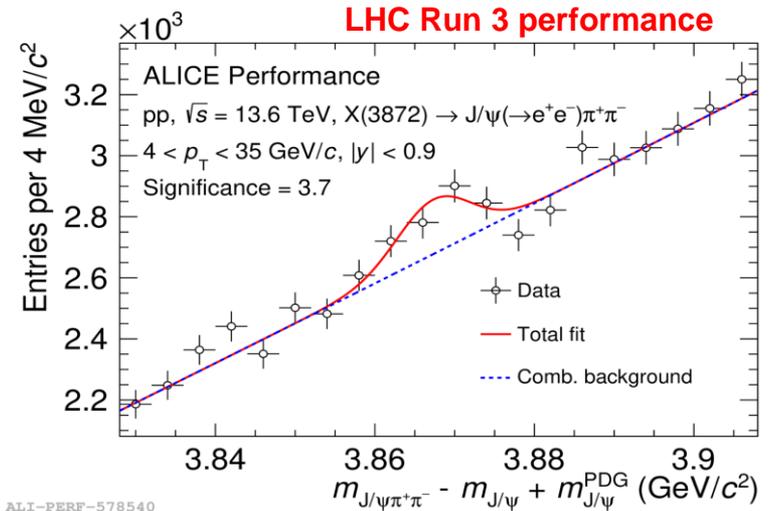
The ratio  $X(3872)/\psi(2S)$  of cross sections

→ shows a decrease in the prompt production of  $X(3872)$  hadrons relative to prompt  $\psi(2S)$  mesons as the charged particle multiplicity increases. Model comparison suggests a “compact tetraquark” state.

→ LHC Run 3 data allows ALICE to also explore the  $X(3872)$  production



Phys. Rev. Lett. 126, 092001



## Small systems:

- **pp**: Precise quarkonium cross section measurements over wide kinematic and energy ranges **thanks to complementary experiments**
  - making **ratios constrain even more** the model calculations
- **p-Au, d-Au and p-Pb**:  $\psi(2S)$  is more suppressed than  $J/\psi$  at backward rapidity, **suggesting final-state effects**.
- Prompt  $\psi(2S)/J/\psi$  exhibits **a decreasing trend as a function of multiplicity**, explained by comovers model
- **Associated** quarkonia production is used to study **Single, Double and Triple Parton Scattering**.

## Large systems:

- **Quarkonia suppression** explained by models including **dissociation and regeneration**
- **Thermalization of charm quarks** in medium at LHC

Exotic quarkonium-like states being explored by several experiments

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*Thank you!*



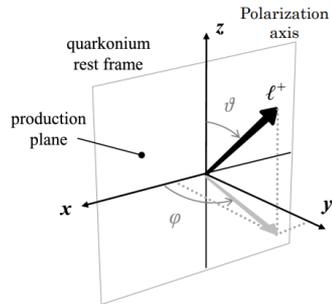
- I would like to thank the FAPESP (projeto especial 2020/04867-2) and INCT CERN-Brazil for the financial support

# $J/\psi$ and $\psi(2S)$ polarization

Averaged polarization determined by measuring the angular distributions of the muons emitted in the decay of the mesons

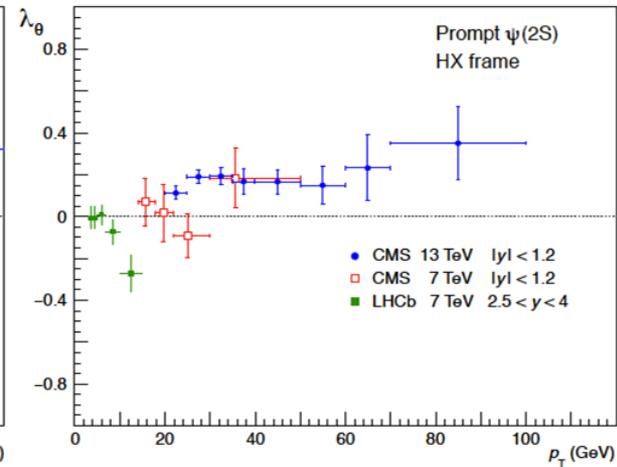
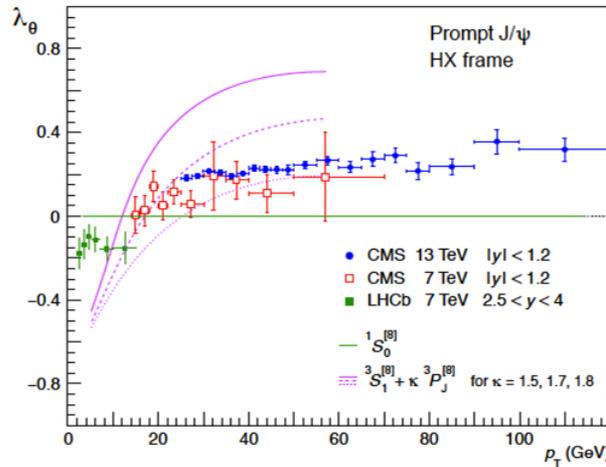
$$W(\cos \vartheta, \varphi | \vec{\lambda}) = \frac{3}{4\pi(3 + \lambda_\vartheta)} (1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi)$$

Polarization is defined as the alignment of spin along a chosen direction.



Faccioli et al. Eur. Phys. J. C (2010) 69: 657–673

Helicity (HX): direction of vector meson in the collision center of mass frame

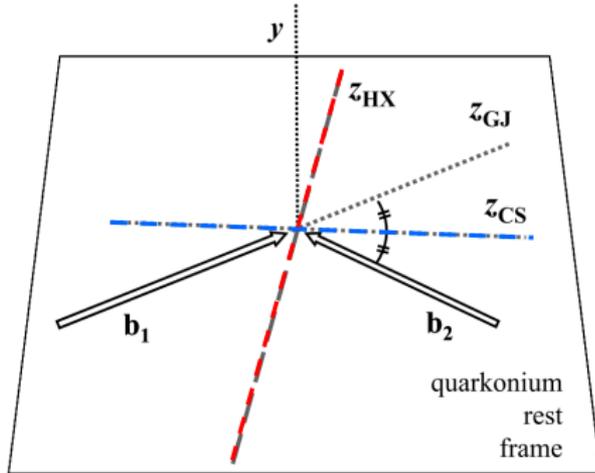


CMS paper: [2406.14409](#)

At high  $p_T$ , the polarizations tend to an asymptotic value,  $\lambda_\theta \approx +0.3$  (HX)

→ indicates a small transverse polarization

# Polarization axis



Faccioli et al, Eur. Phys. J. C (2010) 69: 657–673

- **Helicity (HX)**: direction of vector meson in the collision center of mass frame.
- **Collins-Soper (CS)**: the bisector of the angle between the beam and the opposite of the other beam, in the vector meson rest frame.

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