ψ(2S) production and nuclear modification factor in nucleus-nucleus collisions with ALICE

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Charmonium suppression in QGP

- At high energy density ($\gg 1 \text{ GeV/fm}^3$): phase transition of nuclear matter $\rightarrow$ quark-gluon plasma (QGP)
- In deconfined medium, quarkonia show suppression due to the Debye screening and dissociation
- Excited states (less bound) are more easily dissociated $\rightarrow$ sequential suppression (quarkonia as QGP thermometer)
Charmonium regeneration in QGP or at phase boundary

- At LHC: enhancement of charmonia states ($c\bar{c}$) via recombination due to large charm quark densities.
Charmonium observables in Pb–Pb collisions

- **Nuclear modification factor** $R_{AA}$: Ratio of the quarkonium yield in AA ($Y_{AA}$) with respect to the pp one ($Y_{pp}$), scaled by the average number of binary collisions $<N_{coll}>$ (from Glauber model)

$$R_{AA} = \frac{Y_{AA}^{\psi(2S)}}{<N_{coll}> \cdot Y_{pp}^{\psi(2S)}}$$

- **Ratio of $\psi(2S)$-to-$J/\psi$:**

  **Single Ratio**

  $$= \frac{BR \sigma_{\psi(2S)}}{BR \sigma_{J/\psi}}$$

  **Double Ratio**

  $$= \frac{\sigma_{\psi(2S)/J/\psi}_{PbPb}}{\sigma_{\psi(2S)/J/\psi}_{pp}}$$
$\psi(2S)$ measurements at the LHC energies

- Stronger suppression of the $\psi(2S)$ with respect to J/$\psi$ by a factor $\sim 2$ at high-$p_T$
- Strong suppression observed at high-$p_T$ by ATLAS and CMS

For complete characterization of $\psi(2S)$ production an extension to low-$p_T$ is needed where recombination mechanism is at play.
Motivation for $\psi(2S)$ measurement in Pb–Pb collisions

- $\psi(2S)$-to-J/$\psi$ ratio measurements weakly dependent on charm production cross section employed as input to the models in Pb–Pb collisions

**Important constraints on models**

- Hint for stronger suppression of $\psi(2S)$ compared to J/$\psi$ observed in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, but large uncertainties prevent a strong conclusion.

- Significantly higher statistics (by a factor of ~11) available using full Run 2 Pb–Pb data at $\sqrt{s_{NN}} = 5.02$ TeV!

ALICE upgrade projection
A Large Ion Collider Experiment

Central barrel:
\[ J/\psi \rightarrow e^+e^- \ (|y| < 0.9) \]
Electrons reconstructed using ITS and TPC
Particle identification: TPC dE/dx

Forward muon spectrometer:
\[ J/\psi, \psi(2S) \rightarrow \mu^+\mu^- \ (2.5 < y < 4.0) \]
Reconstruction of muon tracks; triggering of events with muon candidates

V0
(V0A: 2.8 < \eta < 5.1 & V0C: -3.7 < \eta < -1.7)
Trigger, background rejection and centrality measurements in AA collisions

Acceptance coverage in both y regions is down to zero \( p_T \)

For ALICE quarkonium results in Pb–Pb, see talks from
X. Bai on Tues. 14th June, 9 am
L. Massacrier on Tues. 14 June, 2.40 pm
Inclusive $J/\psi \ R_{AA}$

**Theoretical models, in agreement with data**

- Both centrality and $p_T$ dependencies (at low-$p_T$) are qualitatively well described
- Rapidity dependence is also described by recombination models
- Not possible to disentangle between the two different (re)generation scenarios using $J/\psi$
ψ(2S) signal extraction in Pb–Pb

- ψ(2S) signal extracted by using event mixing subtraction technique
- Significant signal observed in most central collisions and down to zero $p_T$, thanks to the usage of full Run 2 statistics
- Reference measurement is obtained from the study of ψ(2S) cross sections in pp collisions at $\sqrt{s} = 5.02$ TeV [arXiv: 2109.15240]
**ψ(2S) pp reference measurements**

- NRQCD+CGC+FONLL is able to describe cross section for $p_T > 4$ GeV/c at forward rapidity
- NRQCD+CGC provides a good description down to zero $p_T$
- Good agreement with theoretical models observed also as a function of rapidity
ψ(2S)-to-J/ψ cross section ratio shows an increasing trend with $p_T$

- No significant dependence with rapidity
- Theoretical models show an overall good agreement within uncertainties
Centrality dependence of the $\psi(2S) R_{AA}$

- $\psi(2S)$ significantly suppressed as a function of centrality, $R_{AA}$ almost flat above $N_{\text{part}} \sim 75$
- $\psi(2S)$ shows stronger suppression than the $J/\psi$
$p_T$ dependence of the $\psi(2S)$ $R_{AA}$

- $\psi(2S)$ significantly suppressed as a function of $p_T$, and shows stronger suppression than the $J/\psi$.

- 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.
$R_{AA}$ results: comparison to theoretical model

- TAMU model, which includes charmonium regeneration, reproduces $p_T$ and centrality dependence of $R_{AA}$ for both $J/\psi$ and $\psi(2S)$

**New**

ALICE Preliminary, inclusive $J/\psi$, $\psi(2S) \rightarrow \mu^+\mu^-$
Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV, $2.5 < y_{cm} < 4$

- $J/\psi$, $0.3 < p_T < 8$ GeV/c (PLB 766 (2017) 212)
- $\psi(2S)$, $0.3 < p_T < 12$ GeV/c

CMS, $|y_{cms}| < 1.6$, 0-100%

**New**

Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, $2.5 < y_{cm} < 4$, 0-90%

- $J/\psi$ (JHEP 2002 (2020) 041)
- $\psi(2S)$ (preliminary)

- TAMU
- JHEP 2002 (2020) 041

Centrality dependence of $\psi(2S)$-to-$J/\psi$

- Significant suppression of $\psi(2S)$-to-$J/\psi$ ratio in Pb–Pb with respect to pp
- No significant centrality dependence
- Hint of a larger $\psi(2S)$-to-$J/\psi$ ratio in central collisions at the LHC compared to SPS
- TAMU model well reproduces the cross section ratio at the LHC energy while SHMc tends to underestimate the data
$p_T$ dependence of $\psi(2S)$-to-$J/\psi$ in Pb–Pb collisions

- A significant suppression of $\psi(2S)$-to-$J/\psi$ ratio in Pb–Pb with respect to pp also observed as a function of $p_T$.
- The double ratio reaches $\sim 0.5$ at high-$p_T$. 

![Graph showing the dependence of $\frac{\text{BR}(\psi(2S))}{\text{BR}(J/\psi)}$ and $\frac{\sigma_{\psi(2S)}^\text{pp}}{\sigma_{\psi(2S)}^\text{Pb-Pb}}$ on $p_T$.](image)
Summary

➢ pp collisions:

✔ ψ(2S) cross section and ψ(2S)-to-J/ψ measurements carried out by ALICE at √s = 5.02 TeV.

✔ Theoretical models reproduce the ψ(2S) cross section well within uncertainties.

➢ Pb–Pb collisions:

✔ The ψ(2S) $R_{AA}$ is larger at low-$p_T$ than at high-$p_T$ as expected from the contribution of charm quark regeneration at low-$p_T$.

✔ Stronger suppression of the ψ(2S)-to-J/ψ ratio in Pb–Pb with respect to pp, no significant $p_T$ or centrality dependence observed within uncertainties.

✔ Comparison of J/ψ and ψ(2S) $R_{AA}$ with transport model shows a fair agreement within uncertainties.

✔ Transport model, that includes recombination of charm quarks in the QGP phase, reproduces the ψ(2S)-to-J/ψ ratio better than SHMc model for central events.

➢ Prospects for Run3/4

✔ Significant increase of statistical precision expected with $L_{\text{int}} \sim 10 \text{ nb}^{-1}$, thanks to continuous readout.
Thank You!