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# Measurements of $\psi$(2S) production in Pb–Pb collisions with ALICE at the LHC

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Quantum chromodynamics predicts the existence of dense and hot nuclear matter which is described in terms of a deconfined medium of quarks and gluons, known as quark-gluon-plasma (QGP). High energy density and temperature can be reached by colliding heavy-ions at ultra-relativistic energies, enabling the study of the QGP in the laboratory. The ALICE detector at the LHC was designed to study the properties of such a deconfined medium. In the presence of a QGP, the charmonium yield would be suppressed due to color Debye screening and dissociation. Due to its larger size and weaker binding energy, the $\psi$(2S) is expected to experience a stronger suppression compared to the $J/\psi$. At the LHC, the magnitude of the $J/\psi$ suppression is smaller than that observed at lower energies at SPS and RHIC, indicating that charmonium (re)generation via the (re)combination of charm and anticharm-quarks, happening either in medium or at the phase boundary, plays an important role at LHC energies. The $\psi$(2S) production relative to $J/\psi$ represents one possible discriminator between the two different regeneration scenarios. Due to its smaller production cross section and branching ratio in the dilepton decay channel, the $\psi$(2S) measurement is more challenging as compared to the $J/\psi$ one. The combined Run 2 data sets of ALICE allows one to extract the $\psi$(2S) signal over the full centrality range, in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and at forward rapidity with the muon spectrometer.
In this contribution, we report on the $\psi$(2S) nuclear modification factor and on the $\psi$(2S)-to-$J/\psi$ single and double ratio, in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, as a function of centrality and transverse momentum. All the measurements are compared with theoretical predictions

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## 1. Introduction

Charmonia, bound states of $c\bar{c}$ pairs, are considered unique probes of the deconfined hot and dense medium made of free quarks and gluons, known as quark-gluon plasma (QGP) and created in ultra-relativistic heavy-ion collisions. In such medium, charmonium production yield is expected to be significantly suppressed with respect to the yield measured in proton-proton (pp) collisions at the same centre-of-mass energy and scaled by the number of binary nucleon-nucleon collisions, due to color screening of the $q\bar{q}$ potential [1] or dissociation [2]. The temperature required for dissociating a specific charmonium state depends on its binding energy, or equivalently on its radius. Hence, the strongly bound charmonium states, such as $J/\psi$, should melt at higher temperatures compared to more loosely bound states, namely $\psi$(2S) and $\chi_c$. This is known as sequential dissociation. As a consequence, the in-medium dissociation probability of such states should provide an estimate of the medium temperature [3], assuming that the charmonium dissociation is the main mechanism at play. At the LHC energies, a large number of $c\bar{c}$ pairs is expected to be produced in central Pb–Pb collisions, leading to the possibility to form charmonia via recombination of c and $\bar{c}$ quarks, either in medium [4] or at the phase boundary [5, 6]. This new additional source of charmonium production can counterbalance the suppression mechanism. The regeneration mechanism has been identified as an important ingredient for the description of the observed centrality, rapidity ($y$) and transverse momentum ($p_{\mathrm{T}}$) dependence of the J/$\psi$ production in Pb–Pb collisions at the LHC [7, 8]. The measurement of the single (double) ratio between the $\psi$(2S) and $J/\psi$ cross sections in Pb–Pb collisions (with respect to pp collisions), is predicted to be very sensitive to the details of the recombination mechanism. Experimentally, the single ratio is interesting as most of the systematic uncertainties cancel, with the remaining systematic uncertainties being only due to the signal extraction and some uncorrelated components related to the acceptance times efficiency evaluation. On the theory side, this ratio is also weakly dependent on the total charm production cross section employed as inputs to the models.

## 2. Experimental setup and data analysis

The ALICE collaboration has studied the $\psi$(2S) production in Pb–Pb collisions down to zero transverse momentum through its dimuon decay channel. The details of the ALICE detector are described in Ref. [9]. Muons from quarkonium decays are recontructed in the muon spectrometer, which covers pseudorapidity range $-4 < \eta < -2.5$. The two innermost layers of the inner tracking system (ITS), which consist of silicon pixel detectors, provide primary vertex reconstruction. The VZERO detectors, two scintillator arrays covering the pseudorapidity intervals $2.8 \leq \eta \leq 5.1$ and $-3.7 \leq \eta \leq -1.7$, provide the minimum-bias trigger, the collision centrality and reject the beam-induced background. Two sets of zero degree calorimeters (ZDC) are used to suppress the background from electromagnetic processes in Pb–Pb collisions.

## 3. Results

The top left panel of Fig. 1 shows the $\psi$(2S)-to-J/$\psi$ cross section ratio measured by the ALICE collaboration in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and forward rapidity, as function of centrality

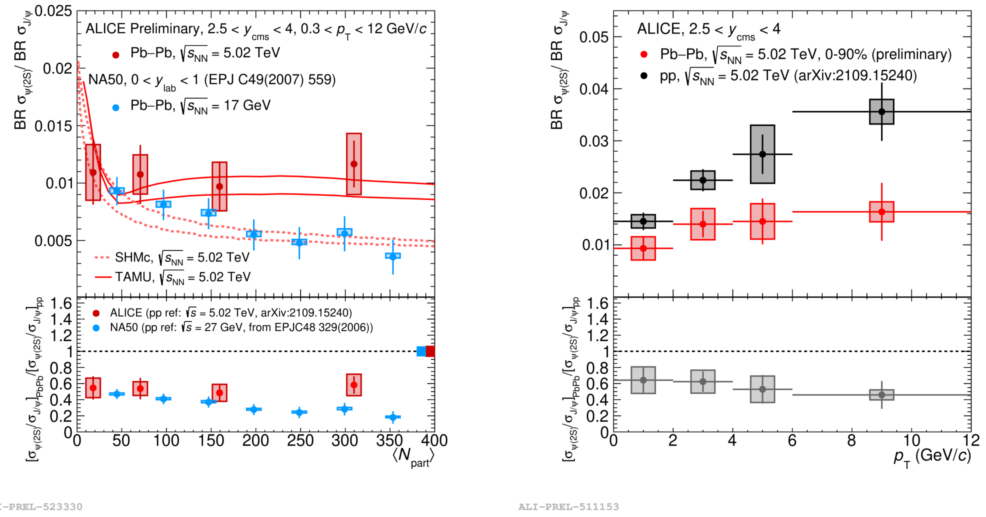

**Figure 1:** $\psi$(2S)-to-J/$\psi$ cross section ratio measured by the ALICE collaboration in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV and forward rapidity, as a function of the average number of participant nucleons ($\langle N_{\rm part}\rangle$) and $p_{\rm T}$, in the left and right panel, respectively. In the left panel, NA50 measurements at SPS carried out at $\sqrt{s_{\rm NN}}$ = 17 GeV are also shown. The results are compared with theoretical predictions from TAMU [10] and SHMc [11, 12]. Bottom panels show the $\psi$(2S)-to-$J/\psi$ ratio normalized to the corresponding pp value (double ratio).

(expressed in terms of average number of participant nucleons $\langle N_{\rm part}\rangle$). The corresponding bottom panel shows the values of the $\psi$(2S)-to-$J/\psi$ double ratio, indicating a suppression effect by about 40% in Pb–Pb with respect to pp collisions. No significant centrality dependence is observed within uncertainties. The ALICE results in the left panel are also compared with NA50 ones in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 17 GeV and $0 < y_{\rm Lab} < 1$ [13]. Both the $\psi$(2S)-to-$J/\psi$ single and double cross section ratios measured by NA50 exhibit a stronger centrality dependence and reach smaller values in central collisions. The $\psi$(2S)-to-$J/\psi$ single ratio measured by ALICE is compared with theoretical calculations based on a transport approach (TAMU) [10] and with the Statistical Hadronization Model (SHMc) [11, 12]. The TAMU [10] model is in good agreement with the $\psi$(2S)-to-$J/\psi$ cross section ratio as a function of centrality, while SHMc [11, 12] is in tension with the data in central Pb–Pb collisions.

In the top right panel of Fig. 1, the $\psi$(2S)-to-$J/\psi$ ratio as a function of $p_{\rm T}$ in Pb–Pb collisions is compared with the corresponding ratio in pp collisions. The $\psi$(2S)-to-$J/\psi$ ratio in Pb–Pb collisions is systematically larger compared to the one measured in pp. The corresponding double ratio shown in the bottom panel, indicates a significant relative suppression in Pb–Pb with respect to pp, with no strong $p_{\rm T}$ dependence and reaching a value of $\sim 0.5$ at high $p_{\rm T}$.

Figure 2 shows the nuclear modification factor $R_{\rm AA}$ of J/$\psi$ and $\psi$(2S) measured by the ALICE collaboration as a function of $\langle N_{\rm part}\rangle$ (left panel) and $p_{\rm T}$ (right panel). The $\psi$(2S) $R_{\rm AA}$ shows a significant suppression and no strong centrality dependence (assuming an almost constant value of about 0.4). It is significantly smaller compared to the $R_{\rm AA}$ of the $J/\psi$, both as a function of $p_{\rm T}$ and centrality. It also hints at less suppression at low-$p_{\rm T}$ with respect to higher $p_{\rm T}$, as also observed with more significance for the J/$\psi$. This could be a first indication for $\psi$(2S) production via recombination of $c\bar{c}$ pairs. The TAMU model calculation [10] reproduces both the centrality and $p_{\mathrm{T}}$ dependence of the $R_{\mathrm{AA}}$ for both charmonium states. On the other hand, the SHMc model [11, 12] reproduces the centrality dependence of the $J/\psi$ $R_{\mathrm{AA}}$, while it underestimates the $\psi$(2S) suppression in central events.

The charmonium $R_{\mathrm{AA}}$ as a function of $p_{\mathrm{T}}$ is compared with CMS measurements [14] carried out for $|y| < 1.6$, $6.5 < p_{\mathrm{T}} < 30$ GeV/$c$ and centrality 0 - 100 %. A strong suppression of the $\psi$(2S) persists up to 30 GeV/$c$, as shown by the CMS data which agree very well with those from ALICE in the common $p_{\mathrm{T}}$ range, in spite of the different rapidity coverages.

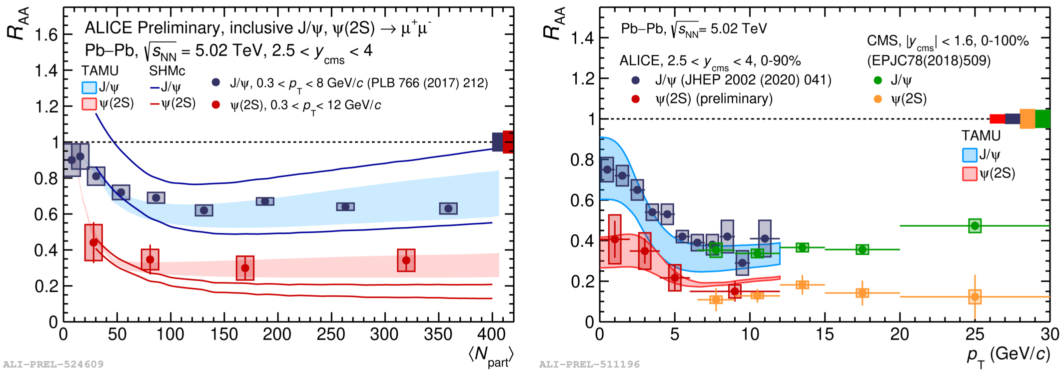


**Figure 2:** The $R_{\mathrm{AA}}$ of $\psi$(2S) and J/$\psi$ as a function of the average number of participant nucleons ($\langle N_{\mathrm{part}}\rangle$) and $p_{\mathrm{T}}$, in the left and right panel, respectively. In the right panel, the ALICE data are compared with CMS results [14] for $|y| < 1.6$, $6.5 < p_{\mathrm{T}} < 30$ GeV/$c$ and centrality 0 - 100 %. The results are also compared with theoretical predictions from TAMU [10] and SHMc [11, 12].

## 4. Summary

The first accurate measurement of the $\psi$(2S) production in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV and low-$p_{\mathrm{T}}$ has been reported by ALICE at forward rapidity. The $\psi$(2S)-to-$J/\psi$ double ratio shows a relative suppression of ~40 %. No significant $p_{\mathrm{T}}$ or centrality dependence is observed within the uncertainties. The double ratio measurements from NA50 show a more pronounced centrality dependence compared to ALICE. The $\psi$(2S) $R_{\mathrm{AA}}$ hints at a decrease as a function of $p_{\mathrm{T}}$ similar to the $J/\psi$ one and connected with charm quarks recombination processes. As a function of centrality, the value of the $\psi$(2S) $R_{\mathrm{AA}}$ is almost constant and reaches ~0.4. The $\psi$(2S) shows more suppression with respect to the $J/\psi$, both as a function of centrality and $p_{\mathrm{T}}$. The transport model, which includes recombination of charm quarks through the QGP medium and is already able to describe the $J/\psi$ data, shows a fair agreement with $\psi$(2S), as a function of $p_{\mathrm{T}}$ and centrality.

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