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

Biswarup Paul[*] [†]

University and INFN Cagliari,
Cittadella Universitaria di Monserrato, 09042, Monserrato (CA), Italy
E-mail: biswarup.paul@cern.ch

Charmonium production is a probe sensitive to deconfinement in nucleus–nucleus collisions. The production of J/ψ via regeneration within the QGP or at the phase boundary has been identified as an important ingredient for the description of the observed centrality and p_{T} dependence of the J/ψ nuclear modification factor at the LHC. ψ(2S) production relative to J/ψ is one possible discriminator between the two different regeneration scenarios. At RHIC and LHC, there is so far no significant observation of the ψ(2S) in central nucleus-nucleus collisions at low transverse momentum, where regeneration is expected to be the dominant production mechanism. The combined Run 2 data set of ALICE allows one to extract a significant ψ(2S) signal in such a kinematic region at forward rapidity in the dimuon decay channel. In this contribution, we present for the first time results on the ψ(2S)-to-J/ψ (double) ratio and the ψ(2S) nuclear modification factor in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, calculated with respect to a new pp reference with an improved precision compared to an earlier publication. Results are compared with model calculations.

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[*]Speaker.
[†]on behalf of the ALICE Collaboration

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1. Introduction

At the extreme temperatures and energy densities produced in ultrarelativistic collisions of heavy nuclei, hadronic matter undergoes a transition into a state of deconfined quarks and gluons known as quark-gluon plasma (QGP). Charmonium (a bound state consisting of a charm quark and the corresponding anti-quark) is expected to be dissociated in a QGP by color screening [1, 2] or dissociation [3], and hence it is used as one of the most prominent probes to investigate the properties of the QGP. Differences in charmonium binding energies lead to a sequential melting of the charmonium states with increasing temperature of the QGP. Because of the larger size (by a factor 2) and weaker binding energy (by more than a factor 10) of the ψ(2S) state compared to J/ψ, ψ(2S) is expected to be strongly suppressed with respect to the J/ψ. At LHC energies, due to the large increase of the $c\overline{c}$ production cross-section with the collision energy, there is a possibility of charmonium production via recombination of uncorrelated c and $\overline{c}$ quarks either within the QGP [4] or at the phase boundary [5, 6]. Thus, the observation of charmonium production in nucleus-nucleus collisions via recombination also constitutes an evidence for QGP formation. ψ(2S) production relative to J/ψ represents one possible discriminator between the two different regeneration scenarios. Indeed, the ψ(2S)-to-J/ψ cross-section ratio is predicted to be very sensitive to the details of the recombination mechanism. Experimentally, this ratio is interesting as most of the systematic uncertainties cancel out, with the remaining systematic uncertainties being only due to the signal extraction and 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. As the two mechanisms at play, i.e. suppression and regeneration, act in opposite directions, the comparison of the yields of different charmonium states can provide insights into the evolution of the relative contributions of the two processes. Charmonium production measurements in pp collisions at the same centre-of-mass energy [7] provide a baseline for the measurement of the charmonium nuclear modification factor in Pb–Pb collisions.

2. ALICE detector and data samples

The ALICE detector has excellent capabilities for reconstructing charmonia at forward rapidity through its dimuon decay channel. A detailed description of the ALICE detector and its performance can be found in Refs. [8, 9]. Muons are identified and tracked in the Muon Spectrometer, which covers the pseudorapidity range $-4 < \eta < -2.5$. The pixel layers of the Inner Tracking System, placed in the central barrel, allow for vertex determination, while forward VZERO scintillators are used for triggering and beam-gas background rejection purposes. The latter are also used to determine the centrality in Pb–Pb collisions. The Pb–Pb data samples at $\sqrt{s_{\rm NN}} = 5.02$ TeV used for the results presented in these proceedings, were collected in 2015 and 2018 and correspond to an integrated luminosity $L_{\rm int} \sim 750\ \mu{\rm b}^{-1}$. The data sample employed for reference measurements in pp at $\sqrt{s_{\rm NN}} = 5.02$ TeV was collected in 2017 and corresponds to an integrated luminosity $L_{\rm int} \sim 1230\ {\rm nb}^{-1}$.

3. Results

3.1 Inclusive charmonium cross sections in pp collisions at $\sqrt{s} = 5.02$ TeV

The inclusive ψ(2S) production cross section in pp collisions at $\sqrt{s}$ = 5.02 TeV and forward rapidity is shown in the left panel of Fig. 1 as a function of $p_{\rm T}$. An improvement of a factor ~ 3 for the statistical uncertainty is obtained for the most recent data set compared to the previous publication [10]. Thanks to the large statistics, precise measurements of the $p_{\rm T}$ and y dependence of the inclusive ψ(2S) cross section for $2.5 < y < 4$ in pp collisions at $\sqrt{s}$ = 5.02 TeV are obtained [7]. The result is also compared with theoretical models. The non-prompt ψ(2S) contribution, originating from the weak decays of beauty hadrons, predicted by FONLL [11] is also shown in Fig. 1 and it is summed to all theoretical predictions for prompt ψ(2S) production. The NRQCD calculation from Butenschön et al. [12] agrees with the experimental data for $4 < p_{\rm T} < 12$ GeV/c, and the NRQCD calculation from Ma et al. [13] describes well the data except for the interval $5 < p_{\rm T} < 6$ GeV/c, where it overpredicts them. The NRQCD+CGC [14] model provides a good description of the ψ(2S) cross section as a function of $p_{\rm T}$.

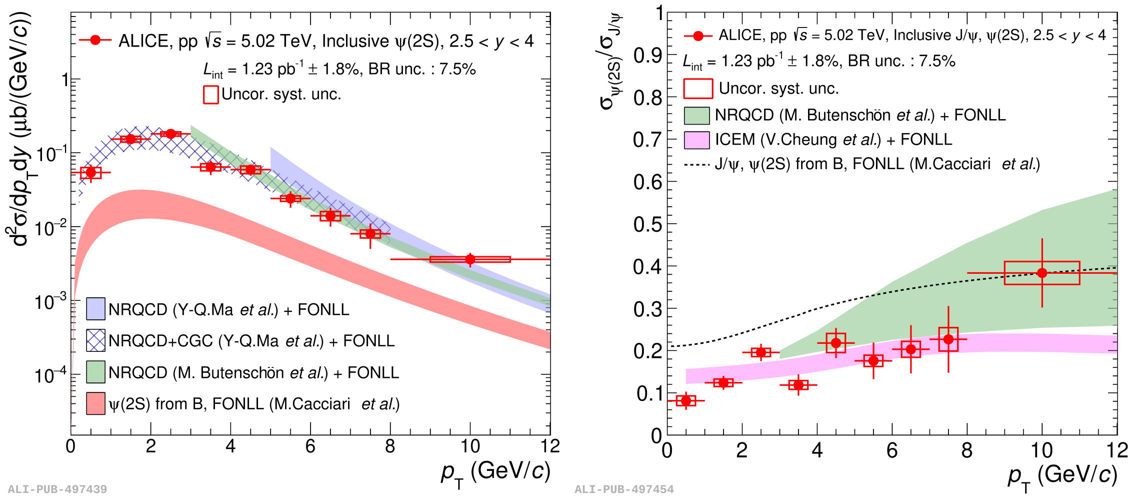

Figure 1: The left panel shows the $p_{\rm T}$ dependence of the inclusive ψ(2S) production cross section in pp collisions at $\sqrt{s}$ = 5.02 TeV. The results are compared with theory predictions based on NRQCD [12, 13, 14] models. The non-prompt ψ(2S) contribution from FONLL calculations [11] are also shown separately. The right panel shows the inclusive ψ(2S)-to-J/ψ cross section ratio as a function of $p_{\rm T}$ compared with theoretical calculations [11, 12, 15].

The $p_{\rm T}$ dependence of the ψ(2S)-to-J/ψ cross section ratio at $\sqrt{s} = 5.02$ TeV is shown in the right panel of Fig. 1. The boxes represent the uncorrelated systematic uncertainties due to the ($p_{\rm T}$, y) shapes of the ψ(2S) signal used as input to the MC and the signal extraction. The branching-ratio uncertainties, fully correlated versus $p_{\rm T}$, is reported in the legend of Fig. 1. All the other systematic uncertainties are correlated over the two resonances and cancel out in the ratio. Cross section ratio results are compared to different theoretical model calculations, with the non-prompt contributions from FONLL [11] added to all of them to describe the inclusive charmonium ratio. The NRQCD calculations from Butenschön et al. [12] describe the $p_{\rm T}$ dependence of the cross section ratio within the large model uncertainties. A good description of the trend of the

ψ(2S)-to-J/ψ cross section ratio as a function of p_T is provided by the ICEM model [15]. This inclusive ψ(2S) production cross section and ψ(2S)-to-J/ψ cross section ratio in pp collisions at $\sqrt{s} = 5.02$ TeV have been used as a baseline to calculate the ψ(2S) R_{AA} and ψ(2S)-to-J/ψ (double) ratio in Pb–Pb collisions at the same energy, and discussed in the next section.

3.2 Charmonium suppression in Pb–Pb collisions

The ψ(2S)-to-J/ψ cross section ratio (not corrected for the branching ratios of the dimuon decay) measured by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16] and forward rapidity is shown in left panel of Fig. 2 as function of centrality, expressed in terms of average number of participant nucleons $\langle N_{part} \rangle$. The ψ(2S)-to-J/ψ double ratio is shown in the corresponding bottom panel indicating a ψ(2S) suppression effect by about 50% in Pb–Pb with respect to pp collisions. A flat centrality dependence is observed within uncertainties for the (double) ratio. The centrality dependence of both the ratios are compared with NA50 results in Pb–Pb collisions for $0 < y_{Lab} < 1$ at $\sqrt{s_{NN}} = 17.3$ GeV [17]. Results from NA50 exhibit a stronger centrality dependence compared to ALICE measurements, reaching smaller values in central collisions. TAMU model [18] reproduces the centrality dependence of the ψ(2S)-to-J/ψ ratio, while SHMc [19, 20] tends to underestimate the result in central Pb–Pb collisions.

In the right panel of Fig. 2, the p_T dependence of the ψ(2S)-to-J/ψ ratio in Pb–Pb collisions [16] is compared with the corresponding ratio in pp collisions at the same energy [7]. The ψ(2S)-to-J/ψ ratio increases as a function of p_T in both Pb–Pb and pp collisions. The corresponding double ratio shown in the bottom panel, indicates a significant relative suppression of ψ(2S) in Pb–Pb with respect to pp, with no strong p_T dependence and reaching a value of ~ 0.5 at high p_T.

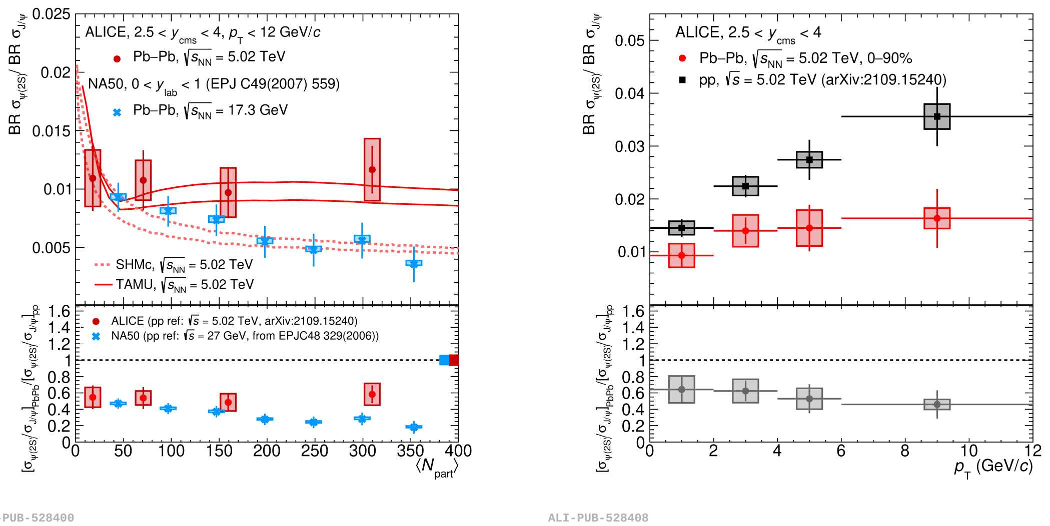

Figure 2: ψ(2S)-to-J/ψ cross section ratio measured by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16] as a function of $\langle N_{part} \rangle$ (top left) and p_T (top right). In the left panel, NA50 measurements at SPS carried out at $\sqrt{s_{NN}} = 17.3$ GeV [17] are also shown. The results, are compared with theoretical predictions from TAMU [18] and SHMc [19, 20]. Bottom panels show the ψ(2S)-to-J/ψ ratio normalized to the corresponding pp value (double ratio).

Figure 3 shows the nuclear modification factor[1] R_{AA} of J/ψ and ψ(2S) measured by the ALICE Collaboration [16] as a function of $\langle N_{part}\rangle$ (left panel) and p_T (right panel). The results show that ψ(2S) is strongly suppressed with respect to J/ψ both as a function of p_T and centrality. A flat centrality dependence of the ψ(2S) R_{AA} is observed and it is consistent with a value of about 0.4. The TAMU model [18] reproduces the centrality dependence of the R_{AA} for both J/ψ and ψ(2S), while SHMc [19, 20] reproduces the J/ψ result but tends to underestimate the ψ(2S) R_{AA} in central and semi-central collisions.

The p_T dependence of R_{AA} shows a stronger suppression at high p_T and an increasing trend of R_{AA} towards low p_T for both charmonium states. This is the first hint for ψ(2S) regeneration. The result is in good agreement with CMS measurements in $|y| < 1.6$, $6.5 < p_T < 30$ GeV/c and centrality 0–100 % at high p_T [21]. TAMU [18] reproduces the p_T dependence of the R_{AA} for both J/ψ and ψ(2S), as it was the case for the centrality dependence.

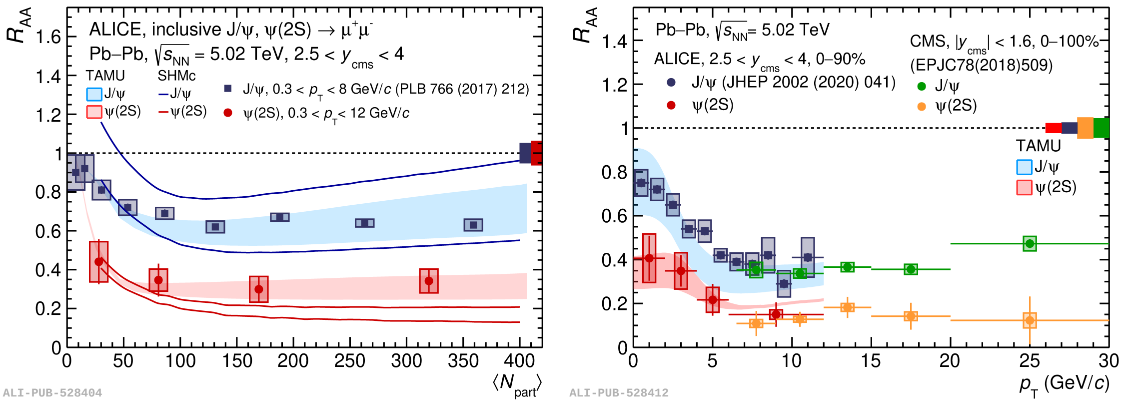

Figure 3: The R_{AA} of ψ(2S) and J/ψ as a function of $\langle N_{part}\rangle$ (left) and p_T (right), measured by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [16]. In the right panel, the ALICE data are compared with CMS results for $|y| < 1.6$, $6.5 < p_T < 30$ GeV/c and centrality 0–100 % [21]. The results are also compared with theoretical predictions from TAMU [18] (left and right panels) and SHMc [19, 20] (left panel).

4. Summary

The ψ(2S) cross section and ψ(2S)-to-J/ψ cross section ratio have been measured in pp collisions at $\sqrt{s}$ = 5.02 TeV, with significantly improved precision compared to an earlier publication. The first accurate measurement of the ψ(2S) production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV down to zero p_T has been reported by the ALICE Collaboration at forward rapidity. ψ(2S)-to-J/ψ single and double ratios, as well as the nuclear modification factor of the ψ(2S), have been measured. The ψ(2S) is more suppressed than the J/ψ as a function of p_T and centrality. From the double ratio, a relative suppression by a factor $\sim$ 2 for the ψ(2S) with respect to the J/ψ is observed, with an almost flat p_T and centrality dependence within the uncertainties. The (double) ratio measurements from NA50 show a more pronounced centrality dependence compared to ALICE results. A flat centrality dependence of the ψ(2S) R_{AA} with values around $R_{AA} \sim 0.4$ is observed. For the

[1]The nuclear modification factor represents the ratio between the quarkonium yields in Pb–Pb to those in pp at the same energy, normalised to the number of binary nucleon–nucleon collisions in Pb–Pb.

J/ψ the raising trend of the R_{AA} towards low p_{T} is significant given the data point uncertainties, while for the ψ(2S) this is more a hint of ψ(2S) regeneration as uncertainties are large. Transport model (TAMU), which includes recombination of charm quarks within the QGP phase, reproduces the ψ(2S) R_{AA} and ψ(2S)-to-J/ψ ratio better than the SHMc model for central events.

A significant increase of the statistical precision is expected in Run 3 and 4 with $L_{\mathrm{int}} \sim 10$ nb^{-1} [22]. The Muon Forward Tracker (MFT) will allow one to separate the prompt charmonium from the contribution originating from beauty hadron decays, at forward rapidity.

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