Recent ALICE results on quarkonium production in nuclear collisions

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Abstract. Quarkonium production has long been regarded as a potential probe of deconfinement in nucleus-nucleus collisions. Recently, the production of $J/\psi$ via regeneration within the quark-gluon plasma (QGP) or at the phase boundary has been identified as an important ingredient for the interpretation of quarkonium production results from lead-lead collisions at the Large Hadron Collider (LHC). Quarkonium polarization could also be used to investigate the properties of the hot and dense medium created at LHC energies, as well as the initial stages of the heavy-ion collision. In this contribution, the latest ALICE quarkonium results are presented and discussed. These include, among others, the nuclear modification of (prompt, non-prompt and inclusive) $J/\psi$, the $\psi(2S)$ production, and the $J/\psi$ polarization, all measured in lead-lead collisions at the LHC. The results are compared with available theoretical model calculations.

1. Introduction
The characterization of the QGP is the main goal of ultra-relativistic heavy-ion collision studies. Charmonium is one of the most prominent probes used to investigate and quantify the properties of the QGP. Charmonium states are expected to be dissociated in a QGP medium by color screening [1] or dissociation [2]. Differences in their binding energies lead to a sequential suppression [3] of the charmonium states with increasing temperature of the QGP. Because of the larger size and weaker binding energy of the $\psi(2S)$ state, the effects of the nuclear medium on its production due to the interplay between suppression and regeneration mechanisms are expected to be significantly different from those of the $J/\psi$. The regeneration mechanism, described dynamically within the QGP [4] or by thermal weights at the phase boundary [5], is an important ingredient for describing the $J/\psi$ production at LHC energies [6]. $\psi(2S)$ production relative to $J/\psi$ represents one possible discriminator between the two different regeneration scenarios. Measurements of non-prompt charmonium contribution, originating from beauty-hadron decays, can provide insight into the mass dependence of parton energy loss inside the QGP. Polarization measurements also represent a powerful tool for understanding production mechanisms in heavy-ion collisions. The difference of the $J/\psi$ polarization between Pb–Pb [7] and pp collisions [8] at the LHC could be related to the modification of the $J/\psi$ feed-down fractions, due to the suppression of the excited charmonium states in the QGP, but also to the contribution of the regenerated $J/\psi$ in the low transverse momentum ($p_T$) region. Moreover, it has been hypothesized that quarkonium states could be polarized by the strong magnetic field, generated in the early phase of the evolution of the system [9], and by the large angular momentum of the medium in non-central heavy-ion collisions [10]. The measurement is performed by defining an ad hoc reference frame where the quantization axis is orthogonal to the event plane\(^1\) of the collision.

\(^1\) The plane identified by the impact parameter of the collision and the beam axis [11].
2. ALICE detector and data samples

The ALICE detector [12] is able to reconstruct inclusive J/ψ and ψ(2S) down to zero $p_T$ at forward rapidity in Pb–Pb collisions at the centre-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV, through their dimuon decay channel. 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 (ITS), covering the pseudorapidity window $|\eta| < 2$, allow for vertex determination, while forward VZERO scintillators are used for triggering, centrality determination, and background rejection. At midrapidity ($|\eta| < 0.9$), inclusive J/ψ measurement is performed via the dielectron decay channel. The track reconstruction is performed by the central barrel detectors, especially Time Projection Chamber (TPC) and ITS. Particle identification is based on the measurement of specific energy loss in the active volume of the TPC, while primary and secondary vertex reconstruction is done by the innermost layers of the ITS. Prompt and non-prompt J/ψ separation is possible down to $p_T = 1.5$ GeV/$c$ at midrapidity in Pb–Pb collisions.

3. Results

The nuclear modification factors $R_{AA}$ of prompt and non-prompt J/ψ at midrapidity in the 0–10% centrality range are shown in Fig. 1. The results are consistent with the corresponding measurements of CMS and ATLAS at high $p_T$ in the same centrality range. The statistical hadronization model (SHMc) [13, 14] for charm quark including J/ψ regeneration at the phase boundary, reproduces the prompt J/ψ $R_{AA}$ at low $p_T$ ($p_T < 5$ GeV/$c$). Models including J/ψ dissociation and charm quark energy loss in medium [15, 16] are consistent with prompt J/ψ $R_{AA}$ for $p_T > 5$ GeV/$c$. The non-prompt J/ψ $R_{AA}$ shown in the right panel is similar to the non-prompt D$^0$ $R_{AA}$ [17]. Models including radiative and collisional energy losses for b quarks inside the medium [18, 19, 20] describe the non-prompt J/ψ $R_{AA}$ at high $p_T$ within uncertainties.

![Figure 1. $R_{AA}$ of prompt (left) and non-prompt (right) J/ψ as a function of $p_T$ in 0–10% central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and midrapidity compared to CMS and ATLAS results. Non-prompt J/ψ $R_{AA}$ is also compared to non-prompt D$^0$ $R_{AA}$ [17]. The global uncertainties are shown as a filled box around $R_{AA} = 1$. Results are compared with theoretical calculations [13, 14, 15, 16, 18, 19, 20].](image)

The $\psi(2S)$-to-J/ψ cross-section times BR ratio measured by the ALICE Collaboration [21] in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and forward rapidity, as function of centrality is shown in the left panel of Fig. 2. The $\psi(2S)$-to-J/ψ double ratio is shown in the bottom panel of Fig. 2, indicating a suppression effect of about 50% in Pb–Pb with respect to pp collisions. A flat centrality dependence is observed within uncertainties. The centrality dependence of both ratios are compared with NA50 results in Pb–Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV in $0 < y_{Lab} < 1$ [22]. Both single and double ratios from NA50 exhibit a stronger centrality dependence compared to ALICE, reaching smaller values in central collisions. The TAMU model [23] which includes charmonium regeneration in medium, reproduces the centrality dependence of the $\psi(2S)$-to-J/ψ ratio, while SHMc [13, 14] tends to underestimate the result in central Pb–Pb collisions. In the right panel of Fig. 2, the $p_T$

2 The nuclear modification factor represents the ratio between the quarkonium yields in Pb–Pb and those in pp, normalized to the number of binary nucleon–nucleon collisions in Pb–Pb collisions.

3 The centrality is expressed in terms of average number of participant nucleons $\langle N_{\text{part}} \rangle$. 
dependence of the $\psi(2S)$-to-$J/\psi$ ratio 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 smaller compared to the one measured in $pp$ [21]. The corresponding double ratio shown in the bottom panel, indicates a significant relative suppression in Pb–Pb with respect to $pp$, with no strong $p_T$ dependence and reaching a value of $\sim 0.5$ at high $p_T$.

**Figure 2.** $\psi(2S)$-to-$J/\psi$ cross-section times BR ratio measured by the ALICE Collaboration in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of $\langle N_{\text{part}} \rangle$ (left) and $p_T$ (right) [21]. In the left panel, NA50 measurements at SPS carried out at $\sqrt{s_{NN}} = 17.3$ GeV [22] are also shown. The results, are compared with theoretical predictions from TAMU [23] and SHMc [13, 14]. Bottom panels show the $\psi(2S)$-to-$J/\psi$ ratio normalized to the corresponding $pp$ value (double ratio). The filled boxes around the line at unity indicate the global systematic uncertainties.

**Figure 3.** The $R_{AA}$ of $J/\psi$ and $\psi(2S)$ measured by the ALICE Collaboration as a function of $\langle N_{\text{part}} \rangle$ (left panel) and $p_T$ (right panel) [21]. The ALICE data are compared with CMS results for $|y| < 1.6$, $6.5 < p_T < 30$ GeV/$c$ and centrality 0–100%. The global uncertainties are shown as a filled box around $R_{AA} = 1$. The results are also compared with theoretical predictions from TAMU [23] (left and right plots) and SHMc [13, 14] (left plot).

$R_{AA}$ shows no dependence on centrality, consistent with an $R_{AA}$ value of about 0.4. The TAMU model [23] and SHMc [13, 14] qualitatively describe the centrality dependence of the $R_{AA}$ for both $J/\psi$ and $\psi(2S)$, some tension for SHMc to describe the $\psi(2S)$ $R_{AA}$ in central Pb–Pb collisions.
collisions. In the right panel of Fig. 3, the $R_{AA}$ of both charmonium states shows an increasing trend towards low $p_T$. This is a requirement for $\psi(2S)$ regeneration at low $p_T$. The result is in good agreement with CMS measurements for $|y| < 1.6$, $6.5 < p_T < 30$ GeV/$c$ and centrality $0–100\%$. The TAMU [23] model qualitatively describes the $p_T$ dependence of the $R_{AA}$ for both $J/\psi$ and $\psi(2S)$.

$J/\psi$ polarization measurement has been recently extended by ALICE to a reference frame where the quantization axis corresponds to the direction orthogonal to the event plane [11]. This allows one to investigate potential effects related to the magnetic field due to the spectator and participant nucleons [9] as well as the large angular momentum associated to the rotation of the medium produced in the collision [10]. The polarization parameter $\lambda_\theta$ shown in Fig. 4 exhibits a maximum deviation of $\sim 3.9\sigma$ with respect to $\lambda_\theta = 0$ in semi-central (30-50\%) collisions for $2 < p_T < 4$ GeV/$c$. The absence of theoretical predictions prevents from drawing a definitive conclusion on the origin of such significant non-zero polarization.

4. Summary

The nuclear modification factors of prompt and non-prompt $J/\psi$ are measured at midrapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Prompt $J/\psi R_{AA}$ results are described by models including regeneration at low $p_T$ and dissociation at high $p_T$. The strong suppression for non-prompt $J/\psi$ at high $p_T$ is described by models implementing parton energy loss in medium. The first accurate measurement of the $\psi(2S)$ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been reported by ALICE at forward rapidity. The $\psi(2S)$ is more suppressed than the $J/\psi$ as a function of $p_T$ and centrality. Transport model (TAMU), which includes recombination of charm quarks in the QGP phase, is in agreement with the $\psi(2S)$-to-$J/\psi$ ratio, while the SMc model tends to underestimate the ratio in central events. A significant $J/\psi$ polarization with respect to the event plane is observed in Pb–Pb collisions, which urgently calls for inputs from theory.

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