PROCEEDINGS OF SCIENCE

Recent charmonium measurements in Pb–Pb collisions

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Charmonia are key probes to study nuclear matter in extreme conditions, like the quark–gluon plasma formed in heavy-ion collisions. At LHC energies, the regeneration process due to the abundantly produced charm quarks was found to considerably affect measured charmonium observables. Comprehensive measurements of charmonia, including both ground and excited states, are crucial to discriminate among different regeneration scenarios assumed in theoretical calculations. Charmonia can also be sensitive to the initial states of the heavy-ion collisions. In particular, their spin-alignments can be affected by the strong magnetic field generated in the early phase, as well as by the large angular momentum of the medium in non-central collisions. The determination of the component originating from beauty-hadron decays, known as non-prompt charmonium, grants a direct insight into the nuclear modification factor of beauty hadrons, which is expected to be sensitive to the energy loss experienced by the ancestor beauty quarks inside the QGP. Furthermore, once it is subtracted from the inclusive charmonium production, it allows a direct access to prompt charmonia. In this contribution, recent ALICE results on charmonium production are reported. Inclusive J/ψ nuclear modification factors, obtained at mid and forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$= 5.02 TeV, are discussed. Also, prompt and non-prompt J/ψ nuclear modification factors at midrapidity are presented. Results from ψ(2S) nuclear modification factor and J/ψ polarization with respect to a quantization axis orthogonal to the event-plane obtained at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$= 5.02 TeV, are also described. Results are compared to available model calculations.

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1. Introduction

Charmonium states are excellent probes of the quark–gluon plasma (QGP), a state of matter produced in ultrarelativistic nuclear collisions, in which quarks and gluons are not confined into hadrons. In heavy-ion collisions at LHC energies, charmonium production is influenced by the formation of the QGP mainly because of two processes: 1) dissociation of charmonium states by Debye color-screening of $c\bar{c}$ quark pair [1, 2], and, 2) statistical recombination of uncorrelated $c\bar{c}$ pairs within the QGP medium [3] or at the phase boundary [4]. Measuring inclusive J/ψ and ψ(2S) production is essential to understand charmonium production mechanism and its interactions inside the QGP, due to their different binding energies. In addition, the separation of prompt and non-prompt charmonium production is crucial as they probe either the interaction of charm quarks or beauty quarks in the QGP, respectively. Indeed, prompt J/ψ production primarily arises from the direct production of the charm quark-antiquark pair ($c\bar{c}$), while non-prompt J/ψ production involves the decay of hadrons containing beauty quarks. Thus the separation is crucial to quantify the contribution from $c\bar{c}$ recombination on prompt charmonium production.

The charmonium polarization measurements with respect to a quantization axis orthogonal to the event plane of the collision, are also important to probe the initial stages of the heavy-ion collision. The polarization of charmonium states can be influenced by either the presence of strong magnetic fields produced due to fast moving charged nucleons (spectators) in the colliding nuclei or the spin-orbit coupling due to large vorticity of the produced nuclear medium [5, 6].

The ALICE apparatus [7] allows for the reconstruction of inclusive charmonium states down to $p_{\mathrm{T}} = 0$ at midrapidity ($|y| < 0.9$) in the dielectron decay channel and at forward rapidity ($2.5 < y < 4$) in the dimuon decay channel. The Time Projection Chamber (TPC) and Inner Tracking System (ITS) detectors are used for precise tracking of the electron candidates at midrapidity. The TPC offers an excellent particle identification down to very low p_{T} ($\sim$ 200 MeV/c) thanks to the measurement of the specific energy loss in a gaseous medium. The ITS consists of six layers of silicon detectors, with the two innermost layers composed of pixel detectors which provide the spatial resolution needed to separate prompt and non-prompt J/ψ on a statistical basis down to $p_{\mathrm{T}} =$ 1.5 GeV/c at midrapidity, in Pb–Pb collisions. Muon spectrometer is employed to trigger on and reconstruct muon tracks at forward pseudorapidity. Charmonium states, such as, J/ψ, and ψ(2S) are reconstructed through their dilepton decay channel at mid and forward rapidity thanks to the pairing of opposite sign lepton tracks.

2. Results

Medium effects are quantified by the nuclear modification factor (R_{AA}), which is a ratio of invariant particle yields in Pb–Pb collisions to the same in proton–proton (pp) collisions scaled by the average number of binary nucleon–nucleon collisions at the same center of mass collision energy. Figure 1 shows R_{AA} of inclusive J/ψ (left) [8] and prompt and non-prompt J/ψ (right) measured at midrapidity, as a function of the average number of participants in the collisions, $\langle N_{\mathrm{part}} \rangle$. In semicentral collisions, a significant suppression of the inclusive J/ψ yields with respect to the yields in pp collisions is observed. The R_{AA} reaches unity in central collisions indicating a smaller suppression with respect to semicentral collisions. For $1.5 < p_{\mathrm{T}} < 10$ GeV/c, prompt

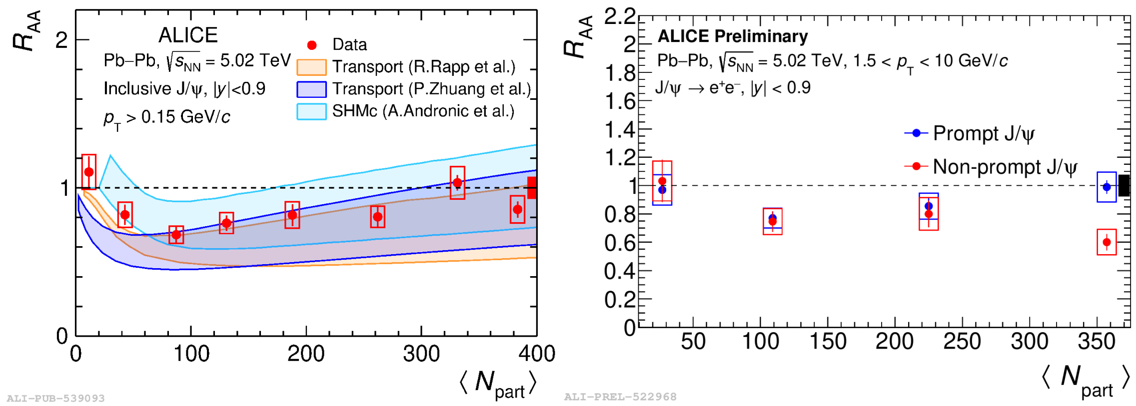

Figure 1: Nuclear modification factor (R_{AA}) of inclusive J/ψ (left) [8], prompt, and non-prompt J/ψ (right) as a function of $\langle N_{part}\rangle$, at midrapidity in Pb–Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV. The inclusive J/ψ R_{AA} is compared to several theoretical predictions [9–11].

and non-prompt J/ψ show similar R_{AA} trends as inclusive J/ψ in non-central collisions, while in most central events, non-prompt J/ψ production exhibits a larger suppression than prompt J/ψ. The inclusive J/ψ R_{AA} is also compared with theoretical models incorporating J/ψ dissociation in the QGP and recombination in the medium [9, 10] or at the phase boundary [11].

The R_{AA} of prompt and non-prompt J/ψ as a function of p_T is shown in the left and right panels of Fig. 2, respectively, in the 0–10% centrality interval in Pb–Pb collisions. The prompt J/ψ production is largely suppressed for p_T larger than 5 GeV/c and the R_{AA} is in agreement with ATLAS [12] and CMS [13] results at midrapidity, where ATLAS results cover a p_T interval larger than 9 GeV/c. At low p_T, the R_{AA} results are close to unity, indicating a reduced suppression in the prompt J/ψ production due to significant recombination probability, which compensates the Debye screening effects. The Statistical Hadronization Model for charm quarks (SHMc) [14] incorporates J/ψ recombination at the QGP phase boundary and all primary charmonia are dissociated in the QGP. While the SHMc model reproduces the prompt J/ψ R_{AA} at low p_T, it fails to describe the results at high p_T. Vitev et. al. [15], which includes charm energy loss in the QGP, provides a good description of the results at high p_T. In the right panel of Fig. 2, the non-prompt J/ψ production exhibits a suppression which increases with increasing p_T. For $7 < p_T < 10$ GeV/c, the results obtained for non-prompt J/ψ R_{AA} shows a slight deviation from ATLAS [12] and CMS [13] results, and also from theoretical predictions [16, 17], which include collisional and radiative b-quark energy loss within the QGP. In contrast, at $5 < p_T < 7$ GeV/c, the R_{AA} is described by the models and consistent with similar measurements by CMS [13]. The non-prompt J/ψ R_{AA} is consistent within uncertainties with the non-prompt D-meson R_{AA} [18] measured by ALICE in the same centrality interval, in Pb–Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV.

The R_{AA} of inclusive ψ(2S) [20] and J/ψ [21] measured at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV are shown in Fig. 3, as a function of $\langle N_{part}\rangle$ (left panel) and p_T in the 0–90% centrality interval (right panel). More precise J/ψ measurements as a function of p_T can be found in Ref. [8]. Cold nuclear matter (CNM) effects, as quantified in p–Pb collisions, are considered for interpreting the obtained results. Overall, the ψ(2S) production is more suppressed than the J/ψ one, in line with the expectation from the sequential suppression of charmonium states in the

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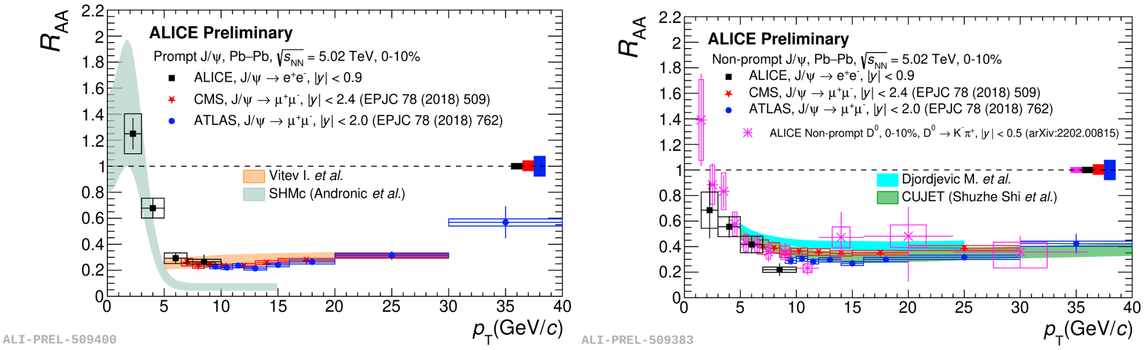

Figure 2: R_{AA} of prompt (left) and non-prompt (right) J/ψ as a function of p_T at midrapidity in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV. Data are compared to models [14–17, 19] including several nuclear modification effects. Similar measurements carried out by the CMS [13] and ATLAS [12] Collaborations are also shown along with non-prompt D^0 measurements from the ALICE Collaboration [18].

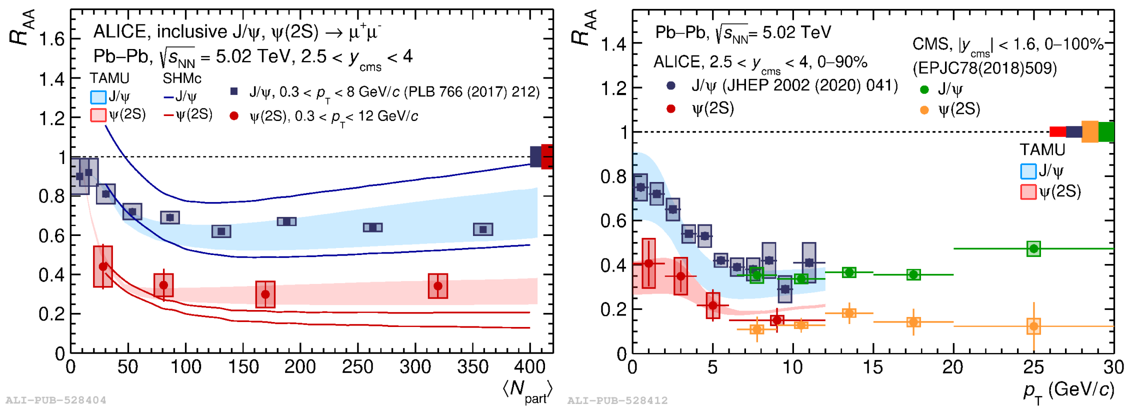

Figure 3: R_{AA} of inclusive ψ(2S) [20] and inclusive J/ψ [21] as a function of $\langle N_{part} \rangle$ (left) and p_T (right) at forward rapidity, in Pb–Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV. These results are compared to TAMU [23] and SHMc [11, 24] theoretical models and also to CMS results [13] at high p_T.

QGP [22]. There is no clear centrality dependence of the ψ(2S) R_{AA} and the TAMU transport model [23], which includes recombination of charm quarks in the QGP, and describes this trend within uncertainties. The SHMc underpredicts the ψ(2S) R_{AA} in the most central collisions while it agrees with results in peripheral collisions. The inclusive J/ψ R_{AA} shows a larger suppression in central collisions than peripheral ones. This trend is described by the TAMU transport model and SHMc model within uncertainty bands. At high p_T, there is a larger suppression of the ψ(2S) production yields and the R_{AA} is consistent with the CMS results [13] at midrapidity. The R_{AA} increases at low p_T suggesting that for both J/ψ and ψ(2S) $c\bar{c}$ recombination can be a relevant production mechanism at low p_T. The TAMU model describes the J/ψ and ψ(2S) R_{AA} as a function of p_T within uncertainties. In addition, further model comparisons are available in Ref. [8].

ALICE measured the polarization of inclusive J/ψ at forward rapidity down to p_T = 2 GeV/c by measuring the angular distribution of its decay products. These are the first polarization measurements performed in Pb–Pb collisions for several centrality intervals, using as quantization axis the

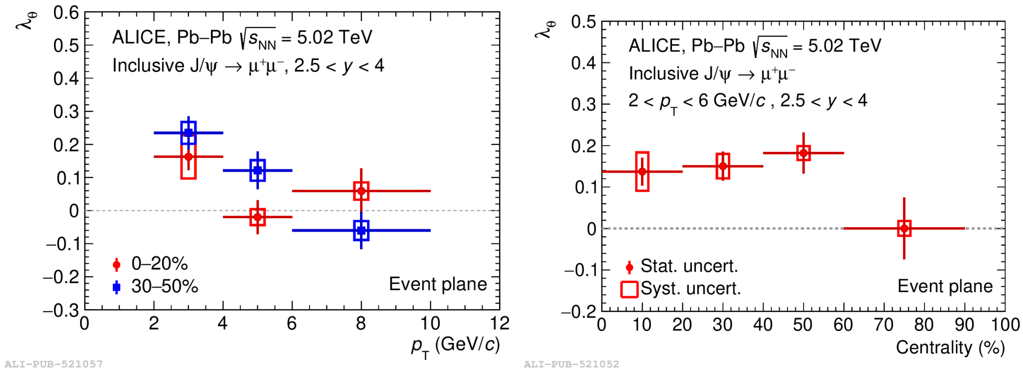

Figure 4: λ_θ parameter for inclusive J/ψ as a function of p_T (left) and centrality (right) at forward rapidity in Pb–Pb collisions measured using a quantization axis orthogonal to the event plane [25].

direction perpendicular to event plane [1]. Figure 4 illustrates the p_T dependence of the λ_θ parameter [25] in 0–20% and 30–50% centrality intervals (left panel) and its centrality dependence for the $2 < p_T < 6$ GeV/c interval (right panel). At low p_T, the data show the largest deviation from $\lambda_\theta = 0$, with a significance of 3.9 σ for the 30-50% centrality interval. This hints to a non-zero polarization of inclusive J/ψ production at low p_T. Also, a significant transverse polarization has been observed in the 0–60% centrality range. These observations are consistent with those from the measurement of the spin alignment of light vector mesons [26], but require further theoretical guidance to interpret the data.

3. Summary

The recent charmonium production results in Pb–Pb collisions from the ALICE experiment were described. The R_{AA} of inclusive, prompt and non-prompt J/ψ has been described as a function of p_T and $\langle N_{part} \rangle$. In most central collisions, a smaller suppression of both the inclusive and prompt J/ψ production at low p_T compared to medium/high p_T, supports a significant contribution to J/ψ production from the $c\bar{c}$ recombination mechanism. At high p_T, the inclusive, prompt and non-prompt J/ψ yields are largely suppressed. A stronger suppression in the ψ(2S) production with respect to the J/ψ is consistent with the expectation of sequential suppression of charmonium states in QGP while considering the CNM effects. The TAMU transport model, which includes charmonium dissociation and $c\bar{c}$ recombination in the medium, describes the inclusive J/ψ and ψ(2S) production in Pb–Pb collisions. Models with b quark energy loss are consistent with non-prompt J/ψ production at high p_T. The first measurements of J/ψ polarization using a quantization axis orthogonal to the event plane, in Pb–Pb collisions, suggest a significant polarization of J/ψ at low p_T in non-central collisions.

The ALICE detector has been upgraded during the Long Shutdown 2 and it is prepared for the data collection at higher interaction rates (~ 50 kHz in Pb–Pb collisions) in LHC Run 3. Presently, the ALICE experiment is collecting data from Pb–Pb collisions at $\sqrt{s_{NN}}$= 5.36 TeV that will be used to realise its exciting physics program with many new quarkonium measurements [27]. Thanks

[1]Event plane is characterized by the impact parameter vector and the beam direction.

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to the upgrade of the ITS, the resolution of the impact parameter sees a threefold improvement in the transverse direction and a sixfold improvement along the beam direction. This will boost the capability of separating prompt and non-prompt J/ψ components. In addition, the new Muon Forward Tracker detector [28] will allow one to separate prompt and non-prompt charmonia for the first time also at forward rapidity ($2.5 < y < 3.6$).

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