CHARMONIUM AS A PROBE OF HOT QUARK MATTER IN NUCLEAR COLLISIONS WITH ALICE AT THE LHC*

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Received 28 April 2022, accepted 30 May 2022,
published online 9 September 2022

Ultrarelativistic nuclear collisions offer an opportunity to study the properties of the quark–gluon plasma (QGP) by achieving extreme conditions in terms of temperature and energy density in the laboratory. Charmonia, bound states of charm and anti-charm quarks, serve as an efficient probe of the QGP in nuclear collisions. In these proceedings, charmonium measurements performed by the ALICE Collaboration in Pb–Pb collisions are discussed. In particular, observables sensitive to the transport and thermodynamic properties of the QGP, such as nuclear modification factor (R_{AA}) and elliptic flow (v_2) of inclusive J/ψ meson in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, are reported. The measurements are compared with available theoretical models.

DOI:10.5506/APhysPolBSupp.15.3-A37

1. Introduction

At extremely high temperatures and densities, hadronic matter undergoes a phase transition to a state of deconfined quarks and gluons known as quark–gluon plasma (QGP). It is believed that our universe had been in such deconfined state a few microseconds after the Big Bang, when the temperature was of the order of several thousand billion degrees. Such a state of matter might be also present in the inner core of Neutron Stars, where nuclear matter can reach extremely high densities. The production of the QGP in the laboratory is achieved through ultrarelativistic nuclear collisions. Heavy quarks are predominantly produced in the earlier stages of ultrarelativistic nuclear collisions, therefore, they experience the complete evolution of the medium produced. Charmonia (bound states of charm

* Presented at the 28$^{\text{th}}$ Cracow Epiphany Conference on *Recent Advances in Astroparticle Physics*, Cracow, Poland, 10–14 January, 2022.

and anti-charm quarks), such as J/ψ, provide important insights into the different aspects of the QGP. Originally, it was suggested by Matsui and Satz [1] that color Coulomb interactions between the c and $\bar{c}$ quarks are modified by freely moving partons in the deconfined medium, and the corresponding process is known as color Debye screening. Recent theoretical developments describe the melting of charmonia in terms of spectral functions modified in a deconfined medium using lattice QCD calculations [2]. As a result, J/ψ production in Pb–Pb collisions is modified in comparison to the J/ψ yield expected from a binary proton–proton collision scaling at the same energy. This suppression observed for the J/ψ production was considered as one of the direct signatures of the formation of the QGP in Pb–Pb collisions.

In high-energy nuclear collisions at RHIC and LHC, a new production mechanism was proposed [3, 4] as a consequence of the high density of $c\bar{c}$ pairs in medium, which was predicted to be largely enhanced compared to that at SPS [5]. In these conditions, uncorrelated c and $\bar{c}$ quarks, produced in different hard scatterings, can combine to form J/ψ. Consequently, there is enhanced production of inclusive J/ψ, especially at low transverse momentum (p_{T}), where the $c\bar{c}$ production cross section is larger. Theoretical models including J/ψ production via recombination (or regeneration) mechanism, at the chemical equilibrium in statistical models [4] or in microscopic transport approach inside the QGP [3], can predict such enhanced production. In addition, in the recombination scenario, it is expected that charm quarks will inherit some of the medium radial and anisotropic flow. J/ψ anisotropic flow measurements can shed light on the bulk properties of the QGP as well as on the in-medium energy loss of c and $\bar{c}$ quarks at high momentum.

ALICE has measured nuclear modification factor (R_{AA}) and elliptic flow (v_2) of inclusive J/ψ as a function of p_{T}, at midrapidity ($|y| < 0.9$) in the dielectron decay channel and at forward rapidity ($2.5 < y < 4$) in the dimuon decay channel, in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. ALICE has excellent tracking and particle identification capabilities enabling reconstruction of J/ψ down to $p_{\mathrm{T}} \sim 0$. A complete description of ALICE can be found in Ref. [6]. The Time Projection Chamber, a gaseous tracking subdetector of ALICE, is employed for tracking and identification of charged particles, by measuring their specific energy loss in a wide momentum and pseudorapidity (η) range ($|\eta| < 0.9$). The Inner Tracking System (ITS), a six-layered cylindrical subdetector which is the closest to the interaction point, covering $|\eta| < 0.9$, plays a key role in the precise determination of primary and secondary vertices. In the forward region ($2.5 < \eta < 4$), the Muon Spectrometer is installed for muon tracking and triggering. V0 detectors are placed on both sides of the interaction point and cover pseudorapidity ranges of $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. They are used for collision centrality determination, triggering, and background rejection. Reported results are obtained by analyzing data from Pb–Pb collisions collected during LHC Run 2 with an integrated luminosity of 750 $\mu\mathrm{b}^{-1}$ at forward rapidity and 93 $\mu\mathrm{b}^{-1}$ at midrapidity.

2. Results and discussion

2.1. Nuclear modification factor

The nuclear modification factor allows one to quantify nuclear effects on particle production in Pb–Pb collisions in comparison to *pp* collisions. This is defined as

$$R_{AA}(y, p_{\mathrm{T}}) = \frac{1}{\langle T_{AA}\rangle} \frac{\mathrm{d}^2 N_{AA}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}}\,, \tag{1}$$

where $\mathrm{d}^2\sigma_{pp}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}$ is the double-differential cross section in *pp*, $\mathrm{d}^2N_{AA}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}$ is the double-differential yield in Pb–Pb, and $\langle T_{AA}\rangle$ is the average nuclear overlap function [7].

Inclusive J/ψ R_{AA} as a function of p_{T} in central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, measured at midrapidity and at forward rapidity, is shown in the top and bottom panels of Fig. 1, respectively. Results are compared to model predictions from Refs. [4, 8]. In both rapidity intervals, R_{AA} shows less suppression at low p_{T} (< 3 GeV/c) than at higher p_{T}. In addition, relatively larger suppression is observed at forward rapidity compared to midrapidity below 3 GeV/c, while at higher p_{T}, the R_{AA} values become comparable.

The statistical hadronization model (SHM) [4] and transport model [8] including J/ψ dissociation and recombination mechanisms predict similar R_{AA} as a function of p_{T} for both rapidity regions. Inclusive J/ψ R_{AA} is well reproduced by the transport model from [8] over the full p_{T} range at both forward and midrapidity. In this model, J/ψ regeneration occurs via recombination of $c\bar{c}$ quarks throughout the medium evolution. SHM, which considers J/ψ regeneration at the QGP phase boundary where the yields of charmonium states are determined by thermal weights, describes the R_{AA} up to $p_{\mathrm{T}} \sim 4$ GeV/c and underestimates it at higher p_{T}, both at midrapidity and forward rapidity.

2.2. Elliptic flow

In non-central nucleus–nucleus collisions, the nuclear overlap region is spherically asymmetric. This produces a spatial anisotropy in the nuclear matter distribution which transfers later into an azimuthal momentum anisotropy of the produced particles. The Fourier expansion of the produced

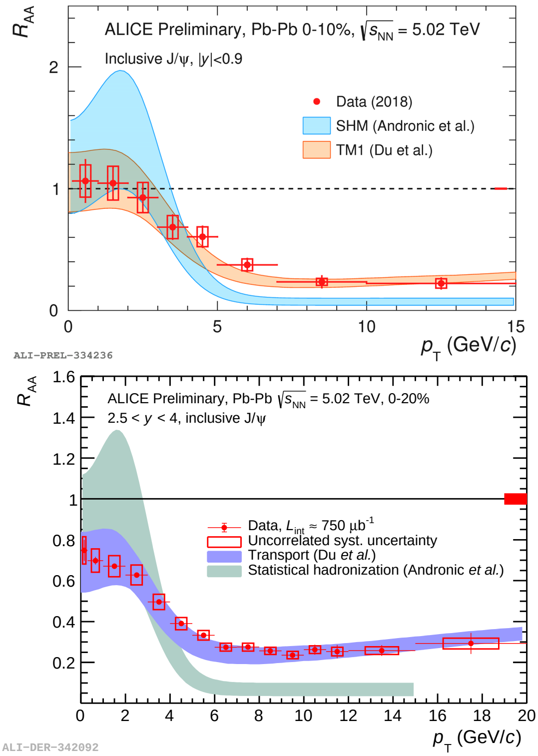

Fig. 1. Nuclear modification factor of inclusive J/ψ as a function of p_{T} at midrapidity (top) and forward rapidity (bottom) in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in comparison to theoretical predictions [4, 8].

particle azimuthal distribution with respect to the reaction plane[1] can be written as

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\,, \tag{2}$$

where v_n are n^{th} order harmonic coefficients that quantify the momentum anisotropy, ϕ is the azimuthal angle of particles, and ψ_n is the reaction plane angle. The second-order harmonic coefficient v_2 is related to the initial almond-shape structure of the overlap region and gives an estimate of the so-called elliptic flow.

Inclusive J/ψ v_2 is measured as a function of p_{T} in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward and midrapidity for several centrality classes [9], as shown in Fig. 2 where it is compared with the v_2 of charged

[1] The reaction plane is defined by the impact parameter vector (b) and the beam direction (z).

pions [10], of prompt D^0 measured by the CMS Collaboration [11] and the v_2 of prompt D mesons computed by the ALICE Collaboration by averaging results of D^0, D^+, and D^{*+} [12]. A positive v_2 for inclusive J/ψ is observed supporting charm quark thermalization in medium and J/ψ regeneration. Measurements of $v_2(p_{\rm T})$ at midrapidity and forward rapidity are compatible with each other within uncertainties. At low $p_{\rm T}$, the J/ψ $v_2(p_{\rm T})$ shows a rising trend then it saturates from $p_{\rm T} \sim 2$–4 GeV/c and drops at larger $p_{\rm T}$. In the $p_{\rm T}$ region below 5 GeV/c, the measured J/ψ v_2 is relatively smaller than that of lighter mesons, *i.e.* pions and prompt D mesons. Such a mass hierarchy suggests a hydrodynamic expansion of the medium and also hints at charm quark thermalization in the medium. For $p_{\rm T} > 5$ GeV/c, it has been observed that all particle species show similar values of v_2, suggesting that anisotropy arises from path-length dependent energy-loss effects [13]. For $p_{\rm T} < 4$ GeV/c, a larger magnitude of J/ψ v_2 is observed in semicentral collisions (30–50%) compared to that in most central collisions (0–10%), as a result of the larger initial anisotropy produced in semicentral collisions.

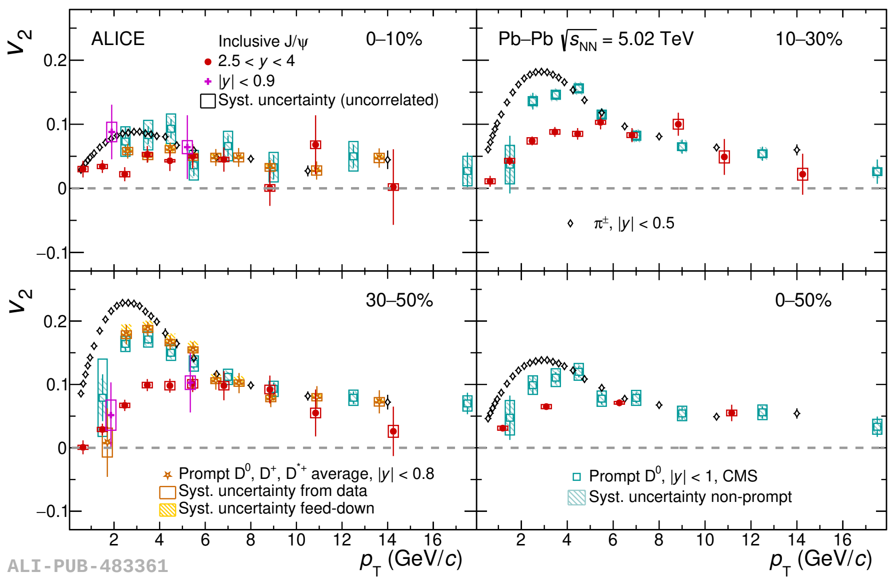

Fig. 2. Elliptic flow (v_2) of inclusive J/ψ measured as a function of $p_{\rm T}$ from the most central to semicentral Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in $2.5 < y < 4.0$ and in $|y| < 0.9$, compared to the v_2 of charged pions and prompt D^0 from the CMS Collaboration [11] and prompt D mesons (average of D^0, D^+ and D^{*+}) from the ALICE Collaboration [12].

Elliptic flow $v_2(p_{\mathrm{T}})$ of inclusive J/ψ is also measured at forward rapidity in the centrality interval 20–40%, in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. It is shown in Fig. 3 and compared to transport calculations which incorporate resonance recombination model [14]. In this model, space-momentum correlations of charm and anti-charm quarks in a collectively expanding medium are taken into account. Measurements are compatible with the model predictions within uncertainties.

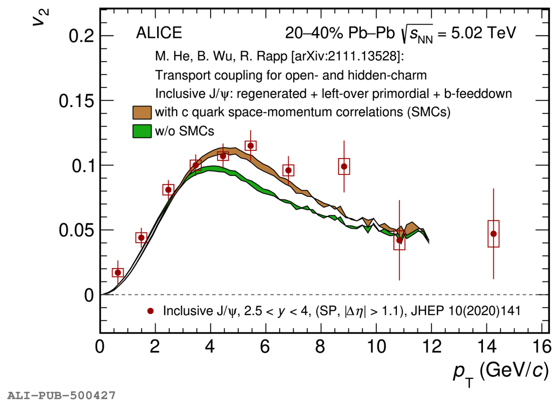

Fig. 3. Elliptic flow (v_2) of inclusive J/ψ as a function of p_{T}, for $2.5 < y < 4$, in Pb–Pb collisions (20–40%) at $\sqrt{s_{NN}} = 5.02$ TeV compared to theoretical calculations [14].

3. Summary

In summary, medium effects on inclusive J/ψ production have been measured by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, at midrapidity and forward rapidity. In the most central collisions, J/ψ production exhibits a significant contribution from regeneration more visible at low p_{T} and at midrapidity. A positive v_2 of J/ψ at low p_{T} has been observed which supports charm quark thermalization in the medium. R_{AA} and v_2 measurements are compatible with theoretical models within uncertainties in both rapidity regions.

More precise charmonium measurements are expected in Pb–Pb collisions during the LHC Run 3 (2022–2026) with a larger statistics by a factor of 10–100. In addition, ALICE has improved the precision for charged particle tracking and impact parameter resolution especially at low p_{T} in the central barrel, where the separation between prompt and non-prompt J/ψ is already possible. The newly installed Muon Forward tracker will allow one to separate prompt and non-prompt charmonia in the forward pseudorapidity ($-3.6 < \eta < -2.5$) region. ALICE is looking forward to achieve new physics milestones in charmonium production during the physics program of the recently started LHC Run 3.

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