Quarkonium production in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with ALICE

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Abstract. Ultra-relativistic heavy-ion collisions at the Large Hadron Collider provide a unique opportunity to study the properties of matter at extreme energy densities where a phase transition from the hadronic matter to a deconfined medium of quarks and gluons, the Quark-Gluon Plasma (QGP) is predicted. Among the prominent probes of the QGP, heavy quarks play a crucial role since they are created during the initial stages of the collision, before the QGP formation, and their number is conserved throughout the partonic and hadronic phases of the collision. The azimuthal anisotropy of charmonium production, quantified using the second harmonic Fourier coefficient (referred to as elliptic flow), provides important information on the magnitude and dynamics of charmonium production. Measurements of the quarkonium nuclear modification factor at forward rapidity and J/ψ elliptic flow in Pb-Pb collisions as a function of centrality, transverse momentum and rapidity will be presented and compared to different collision energy results and available theoretical calculations.

Keywords: ALICE, heavy-ion collisions, heavy quark, quarkonium, LHC

1 Introduction

Heavy quarks are produced in primary hard-scattering processes and their formation time ($\tau_c \sim 0.08$ fm/c for the charm and $\tau_b \sim 0.02$ fm/c for the bottom quark) is smaller than the QGP formation time ($\tau_f \sim 0.15$ fm/c) [1]. Therefore they experience the medium evolution through interactions with its constituents. Their study is particularly relevant to extract the properties of the QGP since the same number of heavy quarks per binary collision is expected to be produced in proton-proton and nucleus-nucleus collisions [2]. Bound states of heavy quarks — quarkonium (charmonium for $c\bar{c}$ and bottomonium for $b\bar{b}$) — provide remarkable probes of the medium. Quarkonium suppression by color screening was predicted and proposed early as a signature of the QGP formation[3], with different survival probabilities corresponding to the quarkonium binding energies. This suppression scenario framed the studies performed at SPS and RHIC energies. The yield enhancement observed at the LHC at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV led to the introduction of a second production source[4]. The increased energy density and number of $c\bar{c}$ pairs enable quark (re)combination at a later stage of the collision [5–7]. This effect is expected to be more relevant for charmonium than bottomonium states. These two antagonistic mechanisms are required by theoretical models to reproduce experimental

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observations. However many unknowns remain and originate large uncertainties in predictions. The most substantial one corresponds to the charm cross-section but many other parameters are not yet ascertained. Moreover the measurements contain a contribution from higher resonance decays as well as a non-prompt contribution from b hadrons which also require proper estimation. Cold nuclear matter effects can also affect quarkonium production in nucleus-nucleus collisions and their size needs to be precisely quantified.

In non-central collisions the nuclei overlap geometry is anisotropic. If the system is interacting, the density anisotropy will be reflected in the particle momentum distribution. This distribution can be decomposed into a Fourier series whose second coefficient is denoted v_2 and called elliptic flow. The measurement of D meson elliptic flow, recently published by ALICE [8], gives a strong hint of charm quark flow in the medium. Therefore the (re)combined $c\bar{c}$ pairs should inherit the charm quark flow and one can expect the J/ψ v_2 to exhibit large values. First hints of a positive J/ψ v_2 were observed at $\sqrt{s_{\rm NN}} = 2.76$ TeV both by ALICE [9] and CMS [10] experiments. Lower energy measurements with PHENIX [11] or STAR [12] experiments do not exhibit a significant J/ψ elliptic flow, although their systematics are large and the measurements are also compatible with the LHC results.

2 Analysis

The presented results were obtained from ALICE measurements in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV during the Run 2 of the LHC. The recorded data represent an integrated luminosity of $\sim 225\ \mu{\rm b}^{-1}$. A complete description of the ALICE apparatus can be found at [13]. Inclusive quarkonium measurements in the dimuon decay channel are performed at forward rapidity ($2.5 < {\rm y} < 4$) and down to zero $p_{\rm T}$ in the muon spectrometer. The silicon pixel detector (SPD) provides the primary vertex and the event plane estimation for flow measurements. The raw number of reconstructed quarkonia were obtained by fitting the dimuon mass spectra with a superposition of signal and background functions. Systematic uncertainties on the extracted yield are obtained by varying the functions and fitting ranges and detector acceptances as well as efficiencies are taken into account by MC simulations.

The nuclear modification factor ($R_{\rm AA}$) represents the ratio of the measured yields in Pb–Pb to pp collisions at the same energy, scaled by the number of binary collisions. The measurement of the J/ψ elliptic flow was performed with the event plane method where the event plane Ψ was estimated from flow vectors obtained with detector multiplicities. Non-uniform acceptance effects of the detectors are corrected through an equalization procedure and the resolution is calculated with the three sub-event technique. The total dimuon $v_2 = \langle \cos 2(\varphi - \Psi) \rangle$ distribution as a function of the invariant mass $v_2(m_{\ell\ell})$ is evaluated. The total v_2 is modelled as a contribution from the signal and the background: $v_2(m_{\ell\ell}) = v_2^{\rm sig}\alpha(m_{\ell\ell}) + v_2^{\rm bkg}(m_{\ell\ell})[1 - \alpha(m_{\ell\ell})]$, where the signal fraction $\alpha(m_{\ell\ell})$ is extracted from the invariant mass distribution fit and the background flow $v_2^{\rm bkg}$ is represented with a generic function.

2.1 Results

The J/ψ nuclear modification factor evolution as a function of centrality (Fig.1 left) at $\sqrt{s_{\rm NN}} = 5.02$ TeV is similar to the previous observations at $\sqrt{s_{\rm NN}} = 2.76$ TeV: after an initial decrease, the $R_{\rm AA}$ exhibits almost no centrality dependence for $\langle N_{part} \rangle > 50$. The measurement precision was largely increased. A $p_{\rm T}$ cut below 0.3 GeV/c was applied to reduced the contribution of J/ψ photo-production and the brackets give limits for the remaining contamination [14, 15] on Fig.2 left and right. The $R_{\rm AA}$ dependence with transverse momentum was also studied for different centrality ranges (Fig.2 left). The J/ψ suppression is stronger at high $p_{\rm T}$ and in central collisions. A transport

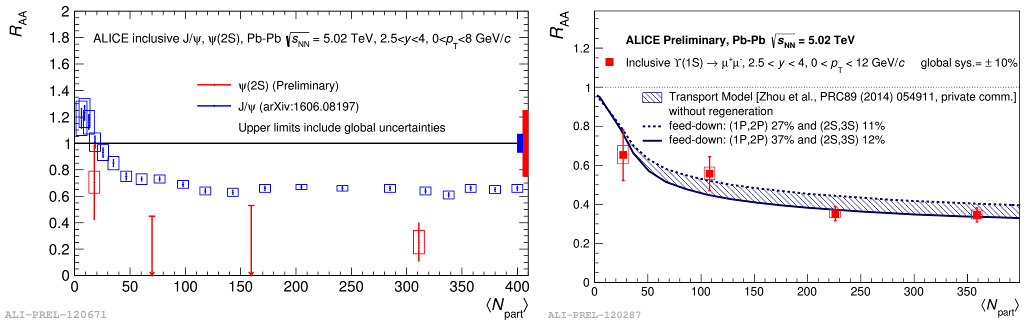

Figure 1. (Left) Comparison of inclusive J/ψ and ψ(2S) R_{AA} and (Right) Υ(1S) R_{AA}vs $\langle N_{\mathrm{part}} \rangle$ at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

model from Du et al. [16, 17] predicts a similar trend. Coherently, the J/ψ $\langle p_{\mathrm{T}} \rangle$ decreases as a function of centrality (Fig.2 right).

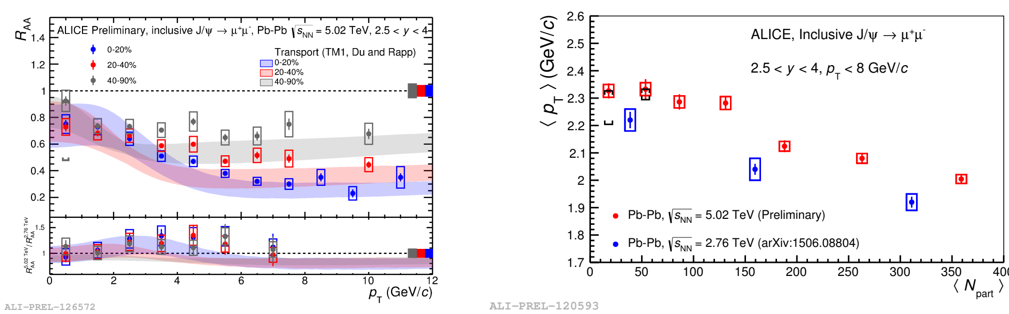

Figure 2. (Left) Differential J/ψ R_{AA} in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV for 3 centrality classes (0–20%, 20–40% and 40–90%) with comparison to transport model prediction from Du and al. and ratio to $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. (Right) J/ψ $\langle p_{\mathrm{T}} \rangle$ vs $\langle N_{\mathrm{part}} \rangle$ comparison between $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV and $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

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The ψ(2S), a losely bound charmonium state, is more suppressed than the J/ψ. Data shows a stronger suppression for semi-central and central collisions. The Run 3 campaign should bring additional statistics and improve the signal over background ratio although the ψ(2S) signal extraction represents a challenging measurement. The Υ(1S) suppression increases as a function of centrality (Fig. 1 right). The observation is compatible with transport models including or not a (re)generation contribution. Precise feed-down measurement from higher resonances (2S and 3S states) are required to further improve the results and discriminate between models.

The J/ψ v_2 as a function of p_{T} is presented on Fig.3. Different centrality classes (5–20%, 20–40% and 40–60%) were studied. Significant values are observed for various centrality and p_{T} bins. The highest J/ψ v_2 is obtained for semi-central collisions (20–40%), with a significance reaching 6.6σ for the 4–6 GeV/c p_{T} class. The comparison to a transport model shows that the v_2 amplitude can only be achieved by including a strong contribution of J/ψ (re)generation. The comparison to open charm flow (Fig.3 right) result is a strong hint of charm (re)combination and thermalization in the medium.

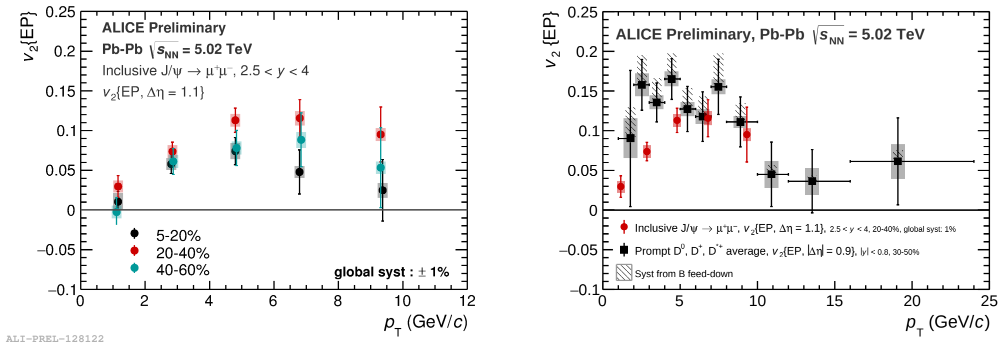

Figure 3. (Left) Inclusive J/ψ v_2 at forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV for 3 centrality classes. (Right) Comparison of inclusive J/ψ v_2 at forward rapidity (20–40%) with D mesons v_2 (30–50%)

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3 Conclusion

The interplay between suppression and (re)generation mechanisms is investigated through quarkonium measurements. Precise results on the J/ψ nuclear modification factor at $\sqrt{s_{\rm NN}}$ = 5.02 TeV, compatible with previous measurements at $\sqrt{s_{\rm NN}}$ = 2.76 TeV, were obtained. Furthermore the J/ψ elliptic flow was asserted with a 6.6 σ significance. Concerning the $\psi(2S)$, a stronger suppression than the J/ψ was observed. The greater centrality dependence of Υ(1S) nuclear modification factor may imply that the suppression plays a dominant role with a minor (re)generation contribution for bottomonium.

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