Quarkonium measurements at forward rapidity with ALICE at the LHC

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Introduction and apparatus

Quarkonia serve as an important probe to study the Quark–Gluon Plasma (QGP), a deconfined state of quarks and gluons created at extreme energy-densities, in high-energy heavy-ion collisions. ALICE records the snapshots of high-energy collisions of various colliding beams such as pp, p–Pb, Pb–Pb and Xe–Xe at LHC energies. This allows us to explore different phase space domains of heavy-quark (c, b and their anti-quarks) production by hard-scattering processes describable using a perturbative QCD framework. The bound states of heavy quarks (charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$)) are formed via non-perturbative processes as long distance soft momentum scales are involved [1]. The production of the heavy-quark bound states can be modified in the presence of a QGP leading to an interplay of suppression [2] and (re)generation [3, 4] of quarkonium states, commonly known as hot-matter effects. A complete understanding of the hot-matter effects requires a detailed study of Cold Nuclear Matter (CNM) effects such as nuclear shadowing, energy loss, gluon saturation or hadronic/nuclear break-up [5] of the heavy-quark resonance states.

ALICE is a general purpose apparatus whose detectors identify and measure hadrons, electrons, photons and muons produced in the above mentioned hadronic collisions [6, 7]. In ALICE, quarkonia are detected by their decay products, a) electrons in the pseudorapidity $|\eta| < 1$ and b) muons at the forward pseudorapidity $(-4.0 < \eta < -2.5)$. The Muon Spectrometer is designed to run at the highest interaction rate in heavy-ion collisions at the LHC [8]. It consists of the following components: a passive front absorber to stop hadrons coming from the interaction vertex; a high granularity tracking system of 5 stations each with two detection planes; a large warm dipole magnet; a passive muon filter wall, followed by four planes of muon trigger chambers and an inner beam shield surrounding the beam pipe to protect the chambers from high particle flux at large rapidities.

Analysis and results

The opposite sign muons are used to reconstruct the dimuon invariant mass spectrum so that the dimuon rapidity is within $(-4.0 < y_{\mu^+\mu^-} < -2.5)$. The invariant mass spectrum is then fitted with a combined function composed of a pseudo-gaussian signal function and an adhoc background function. The production yield of the quarkonium is obtained by dividing the number of signal counts obtained from the fit by the acceptance times efficiency calculated via Monte Carlo simulations [9].

The quarkonium yield measured in pp collisions provides the reference knowledge for the subsequent studies of CNM and hot-matter effects. The extent of the medium modification for heavy-quark production in heavy-ion collisions is measured in terms of a nuclear modification factor R_{AA}, defined as the quarkonium yield in heavy-ion collisions divided by the pp cross section scaled by the nuclear overlap function. In the absence of hot medium effects R_{AA} equals to unity, whereas the combined effect of suppression and (re)generation results in an $R_{\mathrm{AA}} = 0.65 \pm 0.01(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$ [11] and $R_{\mathrm{AA}} = 0.37 \pm 0.02(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$ [9] for J/ψ and Υ(1S), respectively, in Pb–Pb collisions at

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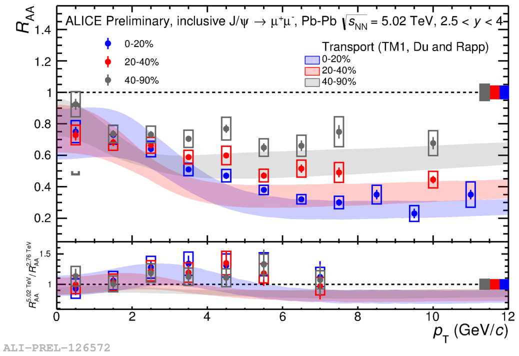

FIG. 1: $p_{\rm T}$–Differential J/ψ $R_{\rm AA}$ in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [12].

$\sqrt{s_{\rm NN}} = 5.02$ TeV. The differential J/ψ $R_{\rm AA}$ when plotted as a function of $p_{\rm T}$ for different centrality intervals displayed in Fig. 1 shows a (re)generation effect at low-$p_{\rm T}$ and stronger suppression for most central collisions. A consistent J/ψ $R_{\rm AA}$ within 1σ of that of Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV was reported for Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV [10]. The viscous nature of the QGP medium sets a preferred quarkonium emission angle in the azimuthal direction with respect to the reaction plane of the heavy-ion collisions, which is measured in terms of the elliptic flow coefficient (v_2) of the quarkonia. The largest measured v_2 value is 0.113 ± 0.015(stat.) $\pm$ 0.008(syst.) at $4 < p_{\rm T} < 6$ GeV/c for J/ψ in semi-central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [13]. The elliptic flow for Υ(1S) is reported to be consistent with zero [14]. The heavy-quark production in nucleus–nucleus collisions can also have contributions of CNM effects, which is therefore studied in proton–nucleus collisions. The nuclear modification factor of J/ψ in p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV [15] for forward ($2.03 < y_{\rm cms} < 3.53$) and backward ($-4.46 < y_{\rm cms} < -2.96$) rapidities are $R_{\rm pPb} = 0.700 \pm 0.005({\rm stat.}) \pm 0.065({\rm syst.})$ and $R_{\rm Pbp} = 1.018 \pm 0.004({\rm stat.}) \pm 0.098({\rm syst.})$, respectively.

Conclusion and outlook

A decade long effort has been invested to understand the QGP and CNM effects in heavy-ion collisions by ALICE using its Muon Spectrometer. The color screening mechanism and the (re)combination effects are both found essential in explaining the measurements performed in different kinematic regions, in terms of both the nuclear modification factor and elliptic flow. The CNM effects of shadowing, energy loss, gluon saturation and nuclear break-up can explain the data in p–Pb collisions. At present, ALICE is going through an upgrade phase where the Muon Spectrometer readout upgrade is an important activity to record Pb–Pb collisions at the highest rate of 50 kHz. In addition, a five layer silicon pixel detector named Muon Forward Tracker is being installed [8]. This will improve the vertex finding capability resulting in a better track resolution of muons and identification of prompt J/ψ at forward rapidities.

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