PROCEEDINGS OF SCIENCE

Quarkonium production in nucleus-nucleus collisions with ALICE at the LHC

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Quarkonium studies provide an important insight about the properties of the medium created in high-energy heavy-ion collisions. The ALICE charmonium and bottomonium measurements in nucleus-nucleus collisions, from the LHC Run II data collection, are discussed.

EPS-HEP 2017, European Physical Society conference on High Energy Physics
5-12 July 2017
Venice, Italy

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1. Introduction

Nuclear matter undergoes a phase transition to a deconfined medium of quarks and gluons under extreme energy densities and temperatures as predicted by lattice QCD calculations. The deconfined medium of quarks and gluons is known as Quark Gluon Plasma (QGP) [1, 2]. Experimentally, the high energy-density conditions are reached by colliding heavy ions at ultra-relativistic energies. Matsui and Satz [3] suggested that if a deconfined medium is created in heavy-ion collisions the binding energy between the quark and antiquark of the quarkonium will be screened due to the presence of color charges of the QGP medium. As a consequence, the production of the quarkonium in nucleus-nucleus (A-A) collisions will be suppressed as compared to binary-scaled pp collisions. However, it is also argued that the large production cross section of charm quark in the hot thermalized medium leads to the formation of charmonia via statistical recombination [4, 5] in the phase boundary or through coalescence of charm quarks [6]. The transport models [7, 8] which assume simultaneous interplay of suppression and (re)generation of charmonium in the deconfined medium are able to describe quarkonium measurements in heavy-ion collisions at LHC energies. In addition to the suppression due to the color-screening effect, there can be suppression due to the nuclear shadowing, saturation or energy loss [9, 10, 11, 12] known as Cold Nuclear Matter (CNM) effects. The CNM effects are studied in proton-nucleus collisions and the combined effect of CNM, suppression and (re)generation mechanisms is measured in terms of the nuclear modification factor (R_{AA}) in nucleus-nucleus collisions. The R_{AA} is defined as

$$R_{\mathrm{AA}} = \frac{Y_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \, \sigma_{\mathrm{pp}}} \tag{1.1}$$

where Y_{AA} is the inclusive quarkonium yield in A-A collisions, $\langle T_{\mathrm{AA}} \rangle$ is the nuclear overlap function calculated using the Glauber model and σ_{pp} is the quarkonium production cross section in pp collisions [13].

The following results on charmonium use the reference cross section measured in pp collisions at $\sqrt{s} = 5.02$ TeV. However, the bottomonium measurements were limited by statistics and thus an interpolation method [14] is used to calculate reference cross section for pp collisions at $\sqrt{s} = 5.02$ TeV.

2. Results

The charmonium results are reported for the mid-rapidity ($-0.8 < \eta_{\mathrm{lab}} < 0.8$) and forward rapidity ($-4.0 < \eta_{\mathrm{lab}} < -2.5$) regions as measured via dielectron and dimuon channels, respectively. The bottomonium measurements are obtained only in the dimuon channel. However, for both species of quarkonia ALICE reports the measurement down to $p_{\mathrm{T}} = 0$ GeV/c .

The Inner Tracking System and the Time Projection Chamber [15] are used for the inclusive measurement of J/ψ at mid-rapidity. The Muon Spectrometer measures the inclusive yield of J/ψ, ψ(2S) and Υ(1S) resonances at forward rapidity [15]. Additionally, the V0 detectors are used as minimum-bias trigger detector and for the centrality calculation.

ALICE has measured the nuclear modification factor of inclusive J/ψ, ψ(2S), Υ(1S) production in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in Run-I and $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in Run-II. The Run-I results on quarkonium measurements in Pb-Pb collisions can be found in [16, 17]. In the present article the ALICE quarkonium measurements from the Run-II AA data taking are discussed. The centrality integrated result in case of the e^+e^- decay channel is $R_{\mathrm{AA}}^{0\%-90\%} = 0.86 \pm 0.05(\mathrm{stat.}) \pm 0.16(\mathrm{syst.})$, while for the $\mu^+\mu^-$ channel it is $R_{\mathrm{AA}}^{0\%-90\%} = 0.65 \pm 0.01(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$ [18]. The measured J/ψ R_{AA} in the dielectron decay channel at mid-rapidity (left panel of Fig. 1), does not exhibit any significant dependence with the number of participant nucleons ($\langle N_{\mathrm{part}} \rangle$). The R_{AA} at forward rapidity also shows no centrality dependence for $\langle N_{\mathrm{part}} \rangle$ larger than 100 (right panel of Fig. 1). The J/ψ R_{AA} measurements in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is found to be consistent with the earlier measurements in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [16]. The model predictions which combine the contribution of primordial J/ψ suppression due to color screening and J/ψ enhancement due to full or partial (re)generation of charm quarks reproduce the J/ψ R_{AA} as a function of $\langle N_{\mathrm{part}} \rangle$ well. In Fig. 2, the transport models from two groups [7, 19], the statistical hadronization model [20] and co-movers model [21] are shown with the ALICE results for dielectron (left panel) and dimuon (right panel) decay channels. The models can describe the nuclear modification factor as measured by ALICE. However, the uncertainty of the measured J/ψ R_{AA} is found to be smaller than the uncertainties of the model predictions in Fig. 2. The signal extraction

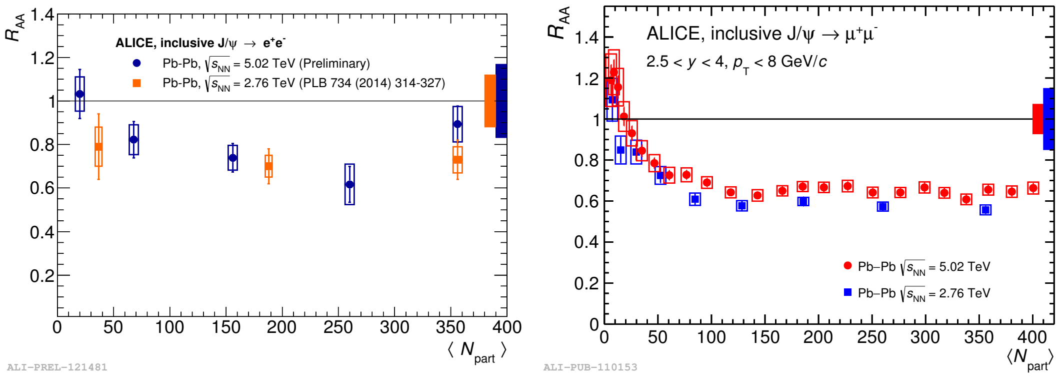

Figure 1: The J/ψ R_{AA} as a function of the number of participating nucleons at mid-rapidity (left panel) and forward rapidity (right panel) [16, 18].

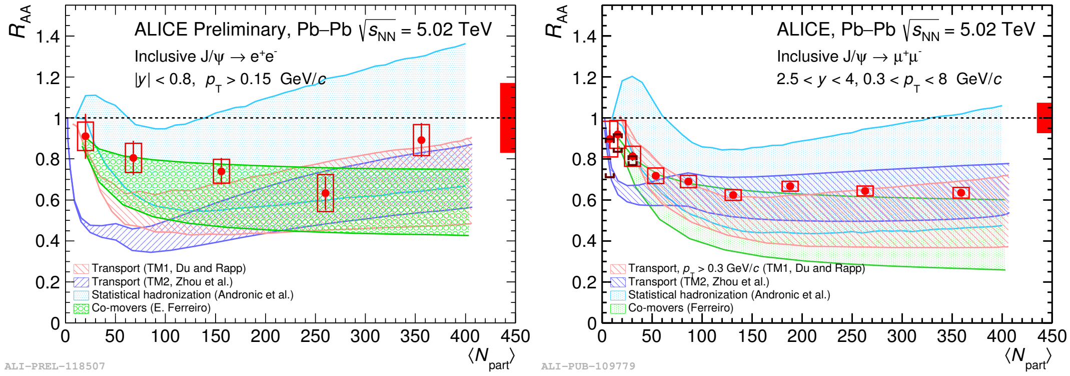

Figure 2: The J/ψ R_{AA} as a function of number of participating nucleons with model predictions at mid-rapidity (left panel) and forward rapidity (right panel) [18]

for $\psi(2S)$ is challenging compared to J/ψ and therefore only confidence level results are provided for two data points in Fig. 3. However, a stronger suppression has been observed for $\psi(2S)$ compared to J/ψ, as visible in the ratio of the nuclear modification factor of $\psi(2S)$ to J/ψ in the left plot of Fig. 3. The measurement of J/ψ elliptic flow [22] provides another observable to understand the interplay of suppression and (re)generation in heavy-ion collisions. The elliptic flow of J/ψ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [23] is shown in the right panel of Fig. 3. The large statistics of J/ψ signals allows the measurement of elliptic flow to higher p_T with higher precision than Pb-Pb results at $\sqrt{s_{NN}} = 2.76$ TeV. The transport (re)generation model [7] can describe the data at low-p_T but fails at high-p_T.

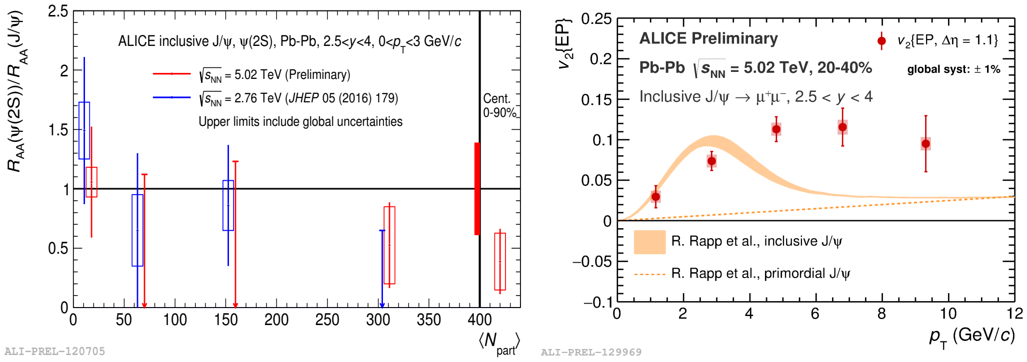

Figure 3: The ratio of the nuclear modification factors of $\psi(2S)$ to J/ψ is plotted for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (blue) and $\sqrt{s_{NN}} = 5.02$ TeV (red) in the left panel. The right panel shows the elliptic flow of J/ψ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and the model calculation.

A strong suppression is reported for the $\Upsilon(1S)$ and $\Upsilon(2S)$. The centrality, p_T and rapidity integrated R_{AA} measured for $\Upsilon(1S)$ and $\Upsilon(2S)$ are $0.40 \pm 0.03(\text{stat.}) \pm 0.04(\text{syst.})$ and $0.26 \pm 0.12(\text{stat.}) \pm 0.06(\text{syst.})$, respectively. The transport model prediction for the transverse momentum dependence [24] of $\Upsilon(1S)$ (left panel of Fig. 4) supports a negligible (re)generation component. The $\Upsilon(1S)$ R_{AA} measured as a function of rapidity is plotted in the right side plot of Fig. 4. The model based on the anisotropic hydrodynamical expansion [25] of plasma can explain the data, although with a different trend at forward rapidity.

3. Conclusion

ALICE continued the measurements of charmonium and bottomonium states in the Run-II phase of LHC. The combined effect of suppression and (re)generation are observed for charmonium, where the effect of (re)generation is found to be stronger in the most central collisions. The medium effects due to hot and cold nuclear matter in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is found to be consistent with the charmonium R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The excited states of charmonium $\psi(2S)$ shows stronger suppression than J/ψ, which has been predicted by the sequential suppression mechanism and statistical hadronization model. The elliptic flow measurement of J/ψ in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV confirms the observation of non-zero elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The transport model which explains the nuclear modification factor of J/ψ is able to explain the J/ψ elliptic flow in the low-p_T region. A

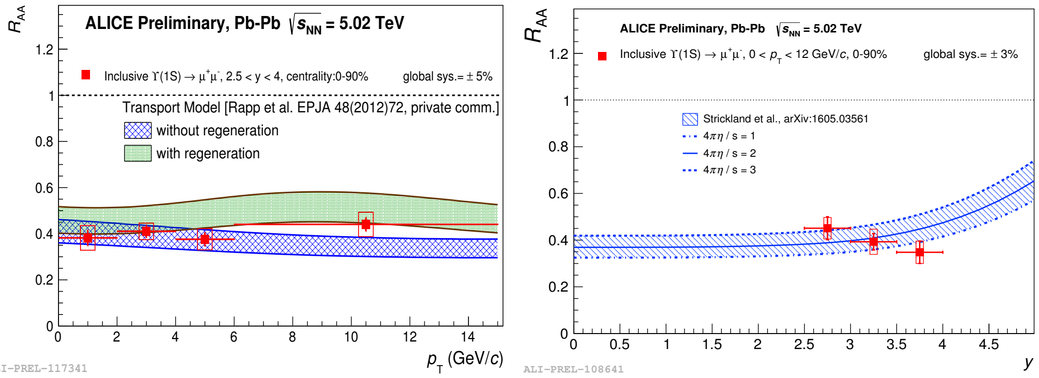

Figure 4: The ϒ(1S) R_{AA} as a function of p_T (left panel) and y (right panel) in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The transport and anisotropic hydrodynamical models [24, 25] are shown for the p_T and y dependence of ϒ(1S) R_{AA} in the left and right panels, respectively.

negligible (re)generation contribution is observed compared to suppression in the bottomonia R_{AA} measurement. The excited bottomonium state, i.e. ϒ(2S), shows stronger suppression than the 1S ground state. ALICE plans to upgrade in the Long Shutdown 2, which will allow more precise track momentum calculation in the forward and mid-rapidity regions. This upgrade will improve the quarkonium measurements by improving the signal-to-background ratio. The measurement of prompt J/ψ R_{AA} will be also possible along with J/ψ from B meson decays. This will help to study the effect of suppression and (re)generation for quarkonium with higher precision in the coming years.

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