Quarkonia production at forward rapidities with the ALICE Experiment

Debasish Das[1*]
[1]*Saha Institute of Nuclear Physics,*
1/AF Bidhannagar, Kolkata 700064, INDIA.
**email: debasish.das@saha.ac.in,*
debasish.das@cern.ch
(For the ALICE Collaboration)

The suppression pattern of quarkonia in AA(nucleus-nucleus) collisions (where the plasma of deconfined quarks and gluons, the Quark-Gluon Plasma (QGP) formation is expected), along with the comparative quarkonia production in pp collisions provides important understanding into the properties of the produced medium. Experimental results of Relativistic Heavy Ion Collider(RHIC) indicate a suppression on charmonium production in AA collisions. Muons from the decay of charmonium resonances are detected in the ALICE Experiment at the Large Hadron Collider(LHC) for pp and Pb-Pb collisions with a muon spectrometer, covering the forward rapidity region 2.5< y <4.0. Analysis of the nuclear modification factor ($R_{\rm AA}$) at forward rapidity are presented and compared with mid-rapidity results with electrons in the central barrel covering $|y|$ <0.9. The roles of suppression and regeneration mechanisms are discussed, as well as the importance of the results of the forthcoming p-Pb data taking for the estimate of cold nuclear matter effects on quarkonia. Perspectives for the bottomonia measurements are also given. Quarkonia results via muon channel from CMS experiment at LHC are compared with ALICE quarkonia measurements.

1. Introduction

Quantum Chromo-Dynamics(QCD) is the well-established theory of strong interactions. Quarks are the basic constituents of QCD, which interact through the exchange of gluons. A thermalized system where the properties of the system are governed by the quarks and gluons degrees of freedom is called the $Quark - Gluon\ Plasma(QGP)$ [1]. Lattice QCD predicts this new phase, QGP, at high temperatures($\sim$155-160 MeV) [2, 3]. The motivation of the relativistic heavy ion physics is the experimental study of the hadronic matter under extreme conditions of temperature [4]. This is the main reason for the present heavy ion program ongoing at the Relativistic Heavy-Ion Collider (RHIC, at Brookhaven National Laboratory in New York) and at the Large Hadron Collider (LHC, at the European Organization for Nuclear Research in Geneva).

A wealth of ideas have been proposed in the past few decades on the experimental and theoretical understanding of QGP properties [5–8]. The plasma is short lived and all signals from QGP have background from the hot hadronic phase that follows the QCD phase transition. Therefore, it is important to understand the physics in hot hadronic phase with different experimental probes [4].

2. Quarkonia in heavy-ion collisions

Among the possible probes of the QGP, the interest in heavy quarks is motivated by their unique role in the diagnostics of the highly excited medium created in relativistic heavy-ion collisions. Both experimentally and theoretically for over two decades, the properties of heavy quarkonium states(which are bound states of heavy quark-antiquark pairs, charmonium and bottomonium) in a hot and dense QCD medium have been intensely studied [9, 10]. Heavy-quark mass is large and so heavy-quark production is believed to be occur largely within the earliest phase of the collision. Therefore, the measurement of quarkonia is expected to provide essential information on the properties of the strongly-interacting system formed in the early stages of heavy-ion collisions [11].

If a J/ψ particle(a $c\bar{c}$ bound state) is placed in QGP, the colour charge of the charm quark c will get screened by the quarks, anti-quarks and the gluons of the plasma. The charmonium production was discussed as an important probe of plasma [12, 13], along with the suggestion by Matsui and Satz [14] which affirmed that with increasing centrality in heavy-ion collisions a suppression of the J/ψ is expected. invariant-mass spectrum should happen. The dissociation of the charmonium bound-state in a dense medium is connected with the Debye screening of the binding potential. This is influenced by a deconfinement of color charges and thus intimately connected to the formation of a QGP [15–21].

Comprehensive experimental results at SPS [9, 22] (including feeddown from other less bound resonances like $\psi(2S)$ and χ_c) and RHIC of J/ψ production in AA collisions clearly indicate that even the strongly bound J/ψ ground state is suppressed [23–26]. However at LHC energies the J/ψ production could be even enhanced due to the coalescence of uncorrelated $c\bar{c}$ pairs in the medium [27]. Initial state effects like modifications of the parton distribution functions in the nucleus relative to the nucleon shadowing need to be taken into account. The final state effects like the nuclear absorption are expected to be practically insignificant at the LHC energies. Various statistical and transport models [27–30] are proposed for LHC energies. Studying the pA collisions at the LHC energies is crucial to quantify the role of initial shadowing effects.

A. J/ψ $R_{\rm AA}$

A Large Ion Collider Experiment (ALICE) [31] is a general-purpose heavy-ion experiment to study the nature of the quark matter under extreme temperature ($\geq$ 0.3 GeV) [32, 33] created in nucleus-nucleus collisions at the LHC. In the framework of the ALICE physics program, the goal of the Muon spectrometer is the study of quarkonia production [34–36], along with open heavy flavor production and low mass vector meson properties [37] via the di-muon decay channel in pp, pA and AA collisions. Using the particle identification potential of the central barrel detectors($|\eta|$ <0.9) J/ψ have been also measured in di-electron channel at mid-rapidity [34, 35].

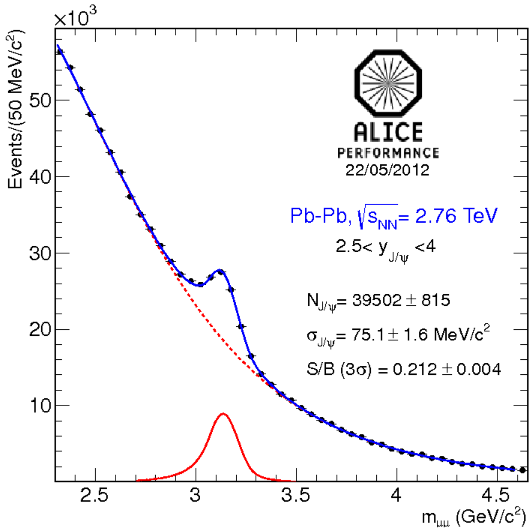

FIG. 1: (Color Online) Opposite sign di-muon invariant mass distribution for the 0%-90% most central collisions for 2.5< y <4, integrated over p_T.

The forward rapidity(2.5< y <4) quarkonia analysis with dimuons in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV is based on a sample corresponding to an integrated luminosity of 70 μb^{-1} which corresponds to 17.7M triggered events. The invariant mass spectrum of $\mu^+\mu^-$ candidates for 0%-90% most central events is shown in Fig. 1. The signal is extracted by performing a combined fit for the background and signal contribution. The background is described by a Gaussian with a width(σ) which varies as a function of the mass value. For the signal description a modified Crystal Ball function was used which is a convolution of a Gaussian and power law functions that can fit the tails of the measured signal.

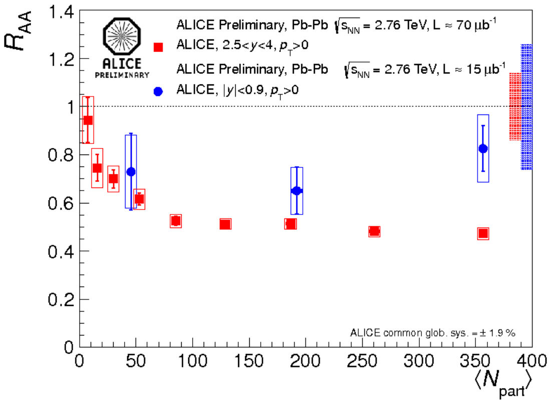

FIG. 2: (Color Online) Inclusive J/ψ R_{AA} for mid-(blue) and forward(red) rapidity as a function of the number of participating nucleons measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

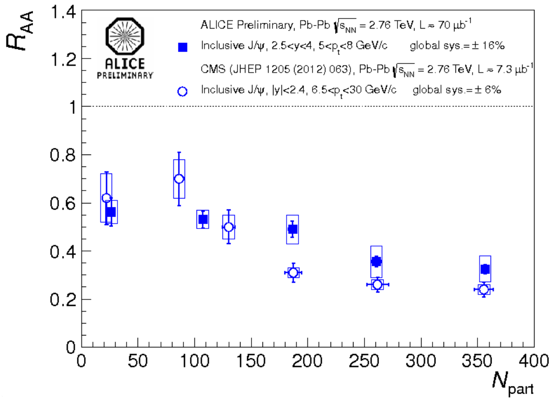

FIG. 4: (Color online) J/ψ R_{AA} for high-p_T($5<p_T<8$ GeV/c) in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV as a function of the number of participating nucleons and compared with CMS results [39].

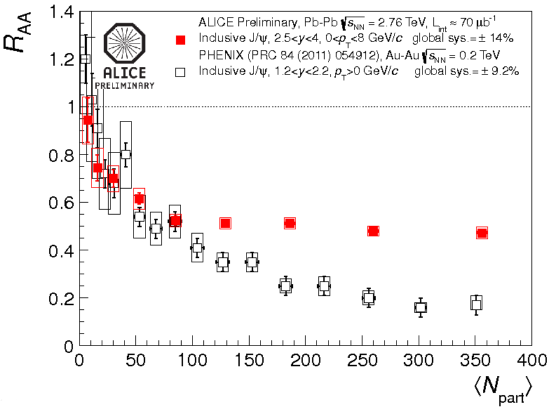

FIG. 3: (Color Online) J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded in 2011 as a function of the number of participating nucleons and compared with PHENIX results [38] in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

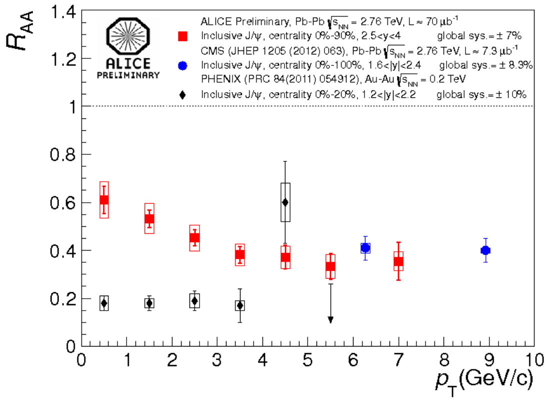

FIG. 5: (Color online) Inclusive J/ψ R_{AA} as a function of the J/ψ p_T for $2.5<y<4.0$ and centrality 0%-90% compared with CMS [39] and PHENIX [38] data.

The nuclear modification factor(R_{AA}) allow us to quantify the medium effects on the production of J/ψ. R_{AA} gives the deviation in J/ψ yield in AA collisions relative to the scaled (according to the number of binary nucleon-nucleon collisions) yield of J/ψ in pp collisions. The raw yield has been corrected for acceptance and efficiency.

Figure 2 shows the inclusive J/ψ R_{AA} for mid- and forward rapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, as a function of the average number of nucleons participating to the collision ($N_{\rm part}$) which has been calculated using the Glauber model [40]. Its important to note that in ALICE for both the di-muon and di-electron channel the J/ψ production can be measured down to $p_T = 0$ GeV/c. The di-muon data sample analysed and shown

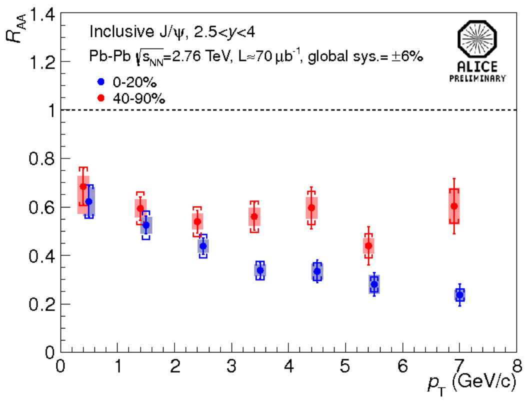

FIG. 6: (Color online) Comparison of R_{AA} as a function of the J/ψ p_T for 2.5<y<4.0 in two centrality classes of 0%-20% and 40%-90%.

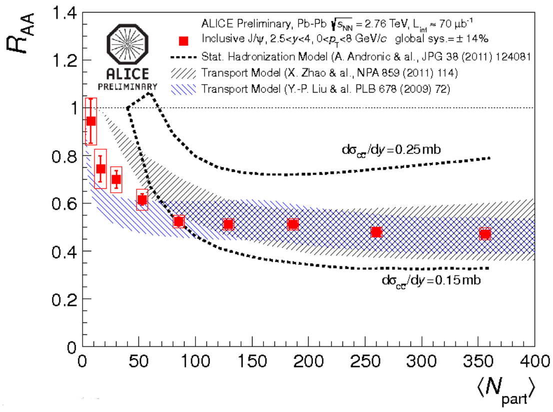

FIG. 7: (Color Online) Inclusive J/ψ R_{AA} as a function of the number of participating nucleons measured in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. These results are compared with statistical hadronization model [28] along with transport models by Zhao *et al.* [29] and Liu *et al.* [30] respectively.

here are for nine centrality classes from 0%-10%(central collisions) to 80%-90%(peripheral collisions). For the dielectron analysis the three centrality classes of 0%-10%, 10%-40% and 40%-80% are shown here. At forward rapidity the centrality integrated value of $R_{\mathrm{AA}}^{0\%-90\%} = 0.497 \pm 0.006(\mathrm{stat.}) \pm 0.078(\mathrm{syst.})$ indicate J/ψ suppression, improving the statistical significance of the R_{AA} measurements obtained with 2010 data [36]. The centrality integrated mid-rapidity value is $R_{\mathrm{AA}}^{0\%-80\%} = 0.66 \pm 0.10(\mathrm{stat.}) \pm 0.24(\mathrm{syst.})$. The systematic error is dominated by the pp reference both for mid- and forward rapidity measurements.

Comparison with the RHIC measurements at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [38] from the PHENIX experiment shown in Fig. 3 exhibit that the inclusive J/ψ R_{AA} at 2.76 TeV in the ALICE forward rapidity region are higher than that measured at 200 GeV in the rapidity domain of $1.2 < |y| < 2.2$. High-p_T J/ψ R_{AA} measured in ALICE for 5<p_T<8 GeV/c range is compared with CMS measurements at central rapidity($|y|$ <0.9) for 6.5<p_T<30 GeV/c in Fig. 4. For ALICE the J/ψ R_{AA} at most central collisions is ~ 0.35 and the integrated value of $R_{\mathrm{AA}}^{0\%-90\%} = 0.384 \pm 0.014(\mathrm{stat.}) \pm 0.074(\mathrm{syst.})$. We observe from Fig. 4 that selecting high-p_T drives down the R_{AA}.

Figure 5 shows R_{AA} as a function of p_T as measured by ALICE(red) results are compared to the CMS data [39](blue) as well as results from the PHENIX [38] (black) at a lower collision energy. The R_{AA} is decreasing from 0.6 for low p_T to about 0.4 at higher p_T. The CMS results (0%-100% centrality, $1.6 < |y| < 2.4$, $p_T > 6.5$ GeV/c) are in agreement with the ALICE measurements (0%-90% centrality, 2.5<y<4, $p_T > 0$) in the overlapping transverse momentum range whereas the lower energy results from PHENIX (0-20% centrality, $1.2 < |y| < 2.2$) show a significantly smaller R_{AA}. Figure 6 shows the p_T dependence of R_{AA} obtained in the most central (0%-20%) and most peripheral (40%-90%) centrality classes. The J/ψ suppression pattern depends on the centrality of the collisions. In the most central collisions (0%-20%), the suppression increases with the transverse momentum of the J/ψ. For the peripheral collisions (40%-90%), the p_T dependence of the R_{AA} is weaker and compatible with a flat behaviour. Thus, for $p_T > 3$ GeV/c the J/ψ suppression is larger in central collisions.

At forward rapidity, the non-prompt J/ψ was measured by the LHCb collaboration to be about 10% in pp collisions at $\sqrt{s} = 7$

TeV [41] in the p_T range of the present analysis. Neglecting the shadowing effects and considering the scaling of beauty production with the number of binary nucleon-nucleon collisions, the prompt J/ψ R_{AA} is estimated to be(upper limit), 11% smaller than the inclusive measurement. While estimating the influence of non-prompt J/ψ as a function of p_T and y on the inclusive $R_{\rm AA}$ results, the LHCb measurement at $\sqrt{s}$ = 2.76 TeV is interpolated using CDF and CMS data. J/ψ from beauty hadrons have a negligible influence on the present measurements while assuming a range of energy loss for the b-quarks from $R_{\rm AA}({\rm b}) = 0.2$ to $R_{\rm AA}({\rm b}) = 1$.

Figure 7 compares the ALICE results with results from a statistical hadronization model [28], as well as two different transport models [29, 30]. The models describe the data within uncertainties for $N_{\rm part}$ larger than 70. The Statistical Hadronization Model [28] assumes deconfinement and a thermal equilibration of the bulk of the $c\bar{c}$ pairs. Then the charmonium production occurs at the phase boundary by statistical hadronization of charm quarks. The two transport model from Zhao *et al.* [29] and Liu *et al.* [30] differ mostly in the rate equation controlling the J/ψ dissociation and regeneration. Both the transport model calculations are shown as a band which connects the results obtained with (lower limit) and without (higher limit) shadowing, which can be interpreted as the uncertainty of the prediction. The model from Zhao *et al.* incorporates a simple shadowing estimate leading to a 30% suppression for the most central Pb-Pb collisions assuming the charm cross-section $d\sigma_{c\bar{c}}/dy \approx 0.5$ mb at y = 3.25. The J/ψ from beauty hadrons is estimated at 10% and no quenching is assumed. The model from Liu *et al.* has shadowing from EKS98 and a smaller charm cross-section $d\sigma_{c\bar{c}}/dy \approx 0.38$ mb is used.

B. $\psi(2S)$

The study of $\psi(2S)$ provides an interesting comparison with J/ψ production [42, 43]. In particular, a substantial fraction of the J/ψ's is known to originate from $\psi(2S)$ and χ_c decays [44]. Examining the ratio of $\psi(2S)$ to

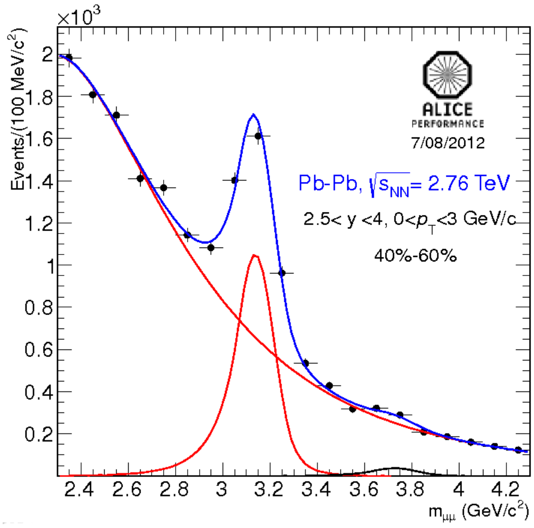

FIG. 8: (Color Online) Opposite sign dimuon invariant mass distribution for the 40%-60% most central collisions and $0<p_T<3$ GeV/c range in $2.5< y <4$.

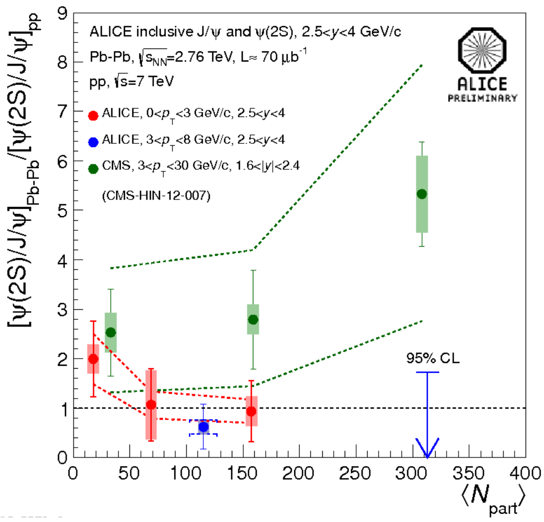

FIG. 9: (Color Online) ALICE results for $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$ obtained in $0<p_T<3$ and $3<p_T<8$ GeV/c for Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV recorded in 2011. ALICE results are compared with CMS [47] values for $3<p_T<30$ GeV/c and $1.6< y <2.4$.

J/ψ production can render a further insight on the mechanism affecting quarkonium in a hot and dense medium which was studied in detail at SPS energies [45, 46]. In a scenario, in which quarkonium states are suppressed by a Debye screening mechanism, the $\psi(2S)$ meson melts at lower temperatures, being a less bound state with respect to the J/ψ [42]. A reduction of the $\psi(2S)$ nuclear modification factor, with respect to the J/ψ can infer on this sequential melting [42]. However this picture might be complicated by charmonium production via recombination mechanisms at LHC, which can affect both the J/ψ and the $\psi(2S)$. Production via recombination mechanisms should contribute mostly in the low-p_T region which can be studied by the ALICE experiment.

The invariant mass spectrum of $\mu^+\mu^-$ candidates for 40%-60% most central events and $0<p_T<3$ GeV/c is shown in Fig. 8. Figure 9 shows the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, which compares the ratio of $\psi(2S)$ over J/ψ yields in Pb-Pb and pp. ALICE results which do not show large enhancement in central collisions are obtained in $0<p_T<3$ GeV/c and $3<p_T<8$ GeV/c for Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV and compared with CMS [47] values for $3<p_T<30$ GeV/c and 1.6<y<2.4 as a function of centrality. SPS measurements have indicated that $\psi(2S)$ is more suppressed than J/ψ [46].

3. Summary and Outlook

Nuclear modification factor $R_{\rm AA}$ of J/ψ have been measured in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV at forward rapidity and compared with mid-rapidity. It was shown that $R_{\rm AA}$ decreases with increasing p_T and towards larger rapidity. Several models that take into account a recombination of $c\bar{c}$-pairs are compared with the ALICE results.

The inclusive J/ψ production in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV show less suppression compared to PHENIX results at RHIC energies. The regeneration mechanism explain these experimental results. But a more quantitative calculation requires the study of cold nuclear matter. There the roles of the suppression and regeneration mechanisms will be disentangled by quantifying the initial shadowing effect with data from the forthcoming p-Pb run at LHC, planned in early 2013.

Studying the bottomonia ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$) states and their suppression are important at LHC energies. Since the Υ is smaller and has larger binding energy than the J/ψ, the states will provide valuable information complementary to the study of charmonium. The smaller $b\bar{b}$ rate results in a lower probability for production by coalescence. In terms of AA collisions, the Υ is expected to dissociate at a higher temperature [48–50] than all the other quarkonium states, thus proving to be a more effective thermometer of the system [51, 52].

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