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Quarkonium Production in p-Pb and Pb-Pb Collisions

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Abstract. Quarkonium production in heavy-ion collisions is one of the key tools to study the Quark-Gluon Plasma, the state of matter which is believed to be formed at the high energy density achieved in heavy-ion collisions. The Large Hadron Collider experiments studied quarkonium production in proton-proton, proton-lead and lead-lead collisions at center-of-mass energies of few TeV. Studying quarkonium production in pp, p–Pb and Pb–Pb collisions allows one to disentangle hot (related to the QGP formation) and cold nuclear matter effects. This article summarizes the recent measurements of quarkonium production by the LHC experiments in p–Pb and Pb–Pb collisions.

INTRODUCTION

Production of quarkonia, bound states of quark and anti-quark pairs, is intensively studied in last years. Its suppression in heavy-ion collisions compared to the production expected from pp collisions indicates the formation of a new state of matter, Quark-Gluon Plasma (QGP), which is believed to be formed at high energy densities. It was predicted that at sufficiently high energy densities the color screening of the heavy-quarks potential in deconfined QCD matter will lead to a sequential suppression of the production of different quarkonium states [1]. Contrary to Pb–Pb collisions the quarkonium production in p–Pb collisions is believed to be affected only by the Cold Nuclear Matter (CNM) effects. There are many different models of CNM effects. They all are usually classified into three groups depending on their nature: (a) pure initial-state effects, e.g. shadowing, saturation; (b) pure final-state effects, e.g. nuclear absorption, comover interaction; (c) other effects which cannot be assigned to pure initial-state or pure final-state effects, e.g. coherent parton energy loss.

The measurements in p–Pb collisions allows quantifying the CNM effects which need to be disentangled from the hot, QGP related effects, in Pb–Pb collisions. Usually hot and CNM effects are quantified with the nuclear modification factor, R_{AA}, defined as the ratio of the quarkonium yield in Pb–Pb to that in pp collisions scaled with the average number of binary nucleon-nucleon collisions $\langle N_{\mathrm{coll}} \rangle$ in the corresponding centrality range. In the absence of any nuclear matter effects R_{AA} is equal to unity. For p–Pb collisions R_{pPb} is defined in the same way.

All the four Large Hadron Collider (LHC) experiments measure quarkonium production at the LHC for different collision systems (pp, p–Pb, Pb–Pb). In this review the latest results in p–Pb and Pb–Pb are presented and compared to theoretical models.

QUARKONIUM PRODUCTION IN Pb–Pb COLLISIONS

LHC experiments already produced many results on quarkonium production in Pb–Pb collisions from Run I of the LHC data-taking period. However there are still ongoing analyses which will produce more new results. Figure 1 shows one of the latest LHC results for Pb–Pb collisions performed by ALICE [2]. Left panel shows the ALICE measurement[1] of the J/ψ R_{AA} as a function of the average number of participants $\langle N_{\mathrm{part}} \rangle$, in three p_{T} intervals. For J/ψ with $0.3 \leq p_{\mathrm{T}} < 1$ GeV/c and with $1 \leq p_{\mathrm{T}} < 8$ GeV/c, the measured R_{AA} suggests a similar decreasing trend

[1]Here and later in the text the presented J/ψ production measured by ALICE is the inclusive J/ψ production.

with increasing centrality at $\langle N_{\text{part}} \rangle < 110$, which represents the effect of the QGP. At central collisions ($\langle N_{\text{part}} \rangle > 100$) lower-$p_{\text{T}}$ J/ψ show no centrality dependence of the R_{AA}. Such a behaviour of the J/ψ R_{AA} with similar p_{T} ranges was successfully explained in [3] by transport models [4, 5] including the J/ψ regeneration contribution and by the comover interaction model [6] which also includes a regeneration component. However an excess of the J/ψ production at very low p_{T} for the most peripheral collisions (small $\langle N_{\text{part}} \rangle$) is not expected from these models. The nuclear modification factor R_{AA} reaches 7 in the centrality range 70–90% for $p_{\text{T}} < 0.3$ GeV/c, which is significantly higher than for the other two p_{T} ranges where it is in the range of 0.7-0.8 in the same centrality interval. In the right panel the p_{T}-distribution of opposite-sign dimuons in the J/ψ mass range ($2.8 < m_{\mu^+\mu^-} < 3.4$ GeV/c^2) for 70–90% centrality class is shown. The low-p_{T} excess is well pronounced for centrality interval 70–90%. The calculations of the STARLIGHT Monte Carlo generator [7] that is used to describe the J/ψ photoproduction in ultra-peripheral collisions, is able to reproduce the p_{T}-shape of the low-p_{T} excess, which suggests that it could be dominated by the J/ψ coherent photoproduction mechanism. Such an observation might open new theoretical and experimental challenges and opportunities. In particular, coherent photoproduction accompanying hadronic collisions may provide insight into the dynamics of photoproduction and nuclear reactions.

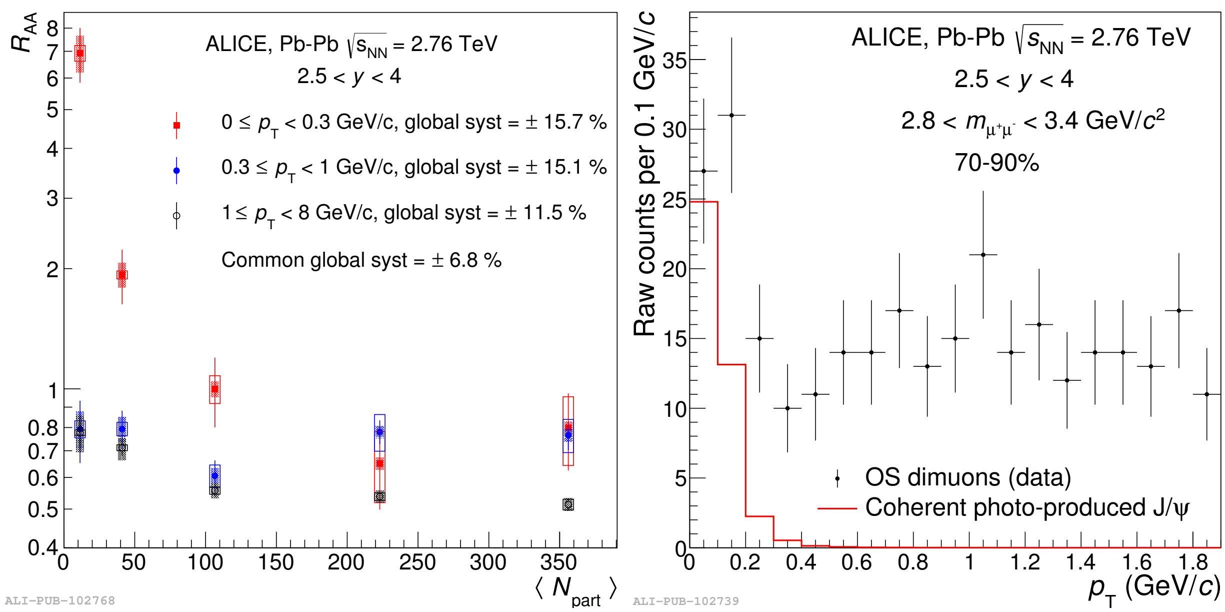

FIGURE 1: (Color online). Low-p_{T} excess of the J/ψ production in Pb–Pb collisions measured by ALICE. Left panel shows the nuclear modification factor R_{AA} as a function of centrality for three p_{T} ranges. Right panel shows the p_{T}-distribution of the opposite-sign dimuons for the most peripheral collisions. Red line in the right panel represents the calculations from STARLIGHT Monte Carlo generator [7]. Both figures are taken from [2].

Another recent Pb–Pb measurement has been performed by CMS [8] and is shown in Fig. 2. These preliminary results represent differential measurements of R_{AA} of Υ(1S) and Υ(2S) as a function of p_{T} (left), y (center) and N_{part} (right). A strong Υ(1S) suppression is observed which is in agreement with the published measurement by ALICE at forward rapidity ($2.5 < y < 4$) [9]. The Υ(2S) is more suppressed than Υ(1S) in all the cases, which is in agreement with the expectations of sequential suppression of quarkonium states depending on their binding energy. There is no p_{T}- nor y-dependence of such a suppression seen for both Υ(1S) and Υ(2S). However a clear trend for a stronger suppression of Υ(1S) with higher centrality is seen. For the Υ(2S) this trend is not so obvious due to larger statistical uncertainties. It is worth mentioning that, in pp collisions, a significant number of the measured Υ(1S) originates in the decay of heavier prompt bottomonium states, like χ_{b} [10], Υ(2S) and Υ(3S) [11], and thus an important part (about 30% for $p_{\text{T}} \lesssim 20$ GeV/c^2 [12]) of the Υ(1S) suppression in nuclear collisions is related to the smaller feed-down contribution.

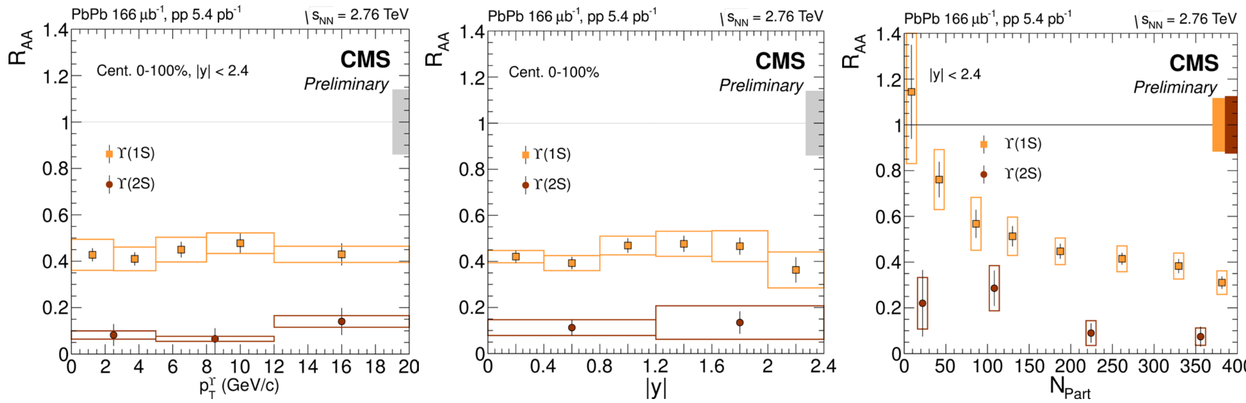

FIGURE 2: (Color online). Nuclear modification factor of $\Upsilon(1S)$ and $\Upsilon(2S)$ in Pb–Pb collisions as a function of p_T (left), y (center) and N_{part} (right), measured by CMS [8].

QUARKONIUM PRODUCTION IN p–Pb COLLISIONS

As mentioned above, one of the main motivations to study p–Pb collisions is to disentangle hot and CNM effects in Pb–Pb collisions. However the first measurements of the J/ψ production in p–Pb collisions at the LHC performed by ALICE [13] and LHCb [14] showed that quarkonium production in p–Pb collisions is an interesting topic by itself. Many theoretical efforts were done to explain the CNM effects seen in the data, e.g. [15, 16, 17, 18]. The ALICE Collaboration recently published its measurement of the centrality dependence of the J/ψ production in p–Pb collisions [19]. One of the main results presented in this paper is shown in Fig. 3. It is the J/ψ nuclear modification factor as a function of centrality[2] at backward (left), mid- (center) and forward (right) rapidity intervals. A strong dependence of the J/ψ suppression with centrality in p–Pb collisions is seen at backward and forward rapidities while at mid-y interval no strong conclusion could be made due to the large statistical uncertainties. While at forward rapidity the J/ψ seems to be suppressed more towards more central collisions, at backward rapidity there is hint for an enhancement of the J/ψ production in p–Pb collisions compared to the scaled pp collisions (i.e. $Q_{pPb} > 1$). Theoretical models of the CNM effects based on shadowing with [17] or without [15, 16, 17] the comover contribution or on parton energy loss [18] fairly agree with the data. The latest preliminary results of the R_{pPb} measured by ATLAS at mid-y interval [21] shown in Fig. 4 show an excess of the prompt J/ψ production in p–Pb collisions while ALICE reports its suppression. Probably, this is due to the difference between prompt and inclusive J/ψ, and the effect of the higher p_T interval used in the ATLAS measurements.

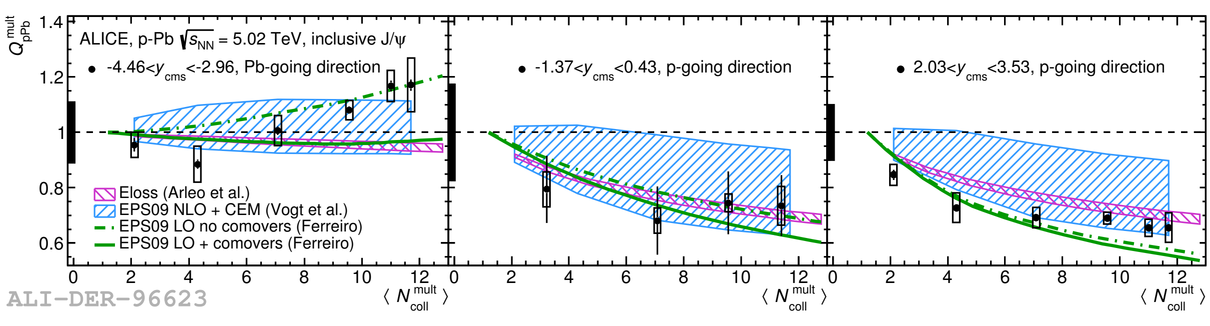

FIGURE 3: (Color online) Nuclear modification factor of J/ψ in p–Pb collisions as a function of centrality at backward (left), mid- (center) and forward (right) y intervals [19]. Bands are theoretical calculations from [15, 16, 17, 18].

[2] ALICE quotes the centrality-dependent nuclear modification factor in p–Pb collisions as Q_{pPb} and not R_{pPb} as it is done by the other LHC experiments. This is to emphasize that the centrality estimation in p–Pb collisions is not a well-defined procedure and all the centrality estimators might have some bias which is difficult to be quantified properly. There is a dedicated ALICE paper describing the ALICE centrality estimation procedure in p–Pb [20].

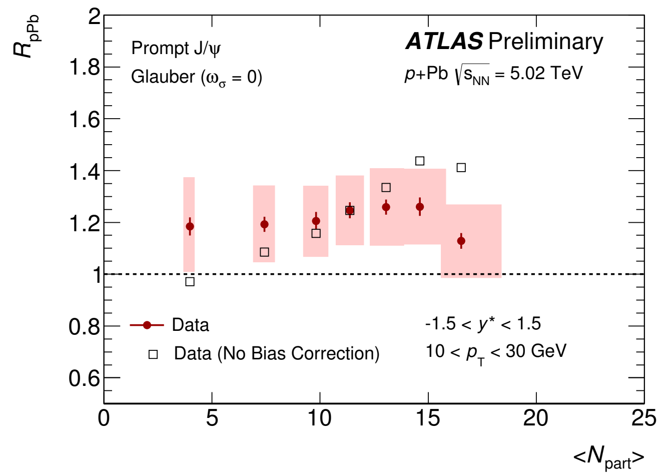

FIGURE 4: (Color online). ATLAS measurement of the nuclear modification factor for the standard Glauber configuration for the production of prompt J/ψ in p–Pb as a function of centrality [21]. Central solid points are corrected for centrality bias. The open points represent the data with no centrality bias correction and are shown as a reference.

Figure 5 shows the nuclear modification factor for inclusive (left) and prompt (right) ψ(2S) as a function of rapidity, measured by ALICE and ATLAS, respectively. Given huge uncertainties in ATLAS measurements, the ALICE and ATLAS measurements are compatible, despite different $p_{\rm T}$ range and the difference between prompt and inclusive ψ(2S) production. Only theoretical models including final state hadronic interactions [17, 22] are able to explain the ψ(2S) production in p–Pb collisions measured by ALICE. It is worth mentioning that the other models like pure shadowing [15, 16] or parton energy loss [18], which were successful in the description of the J/ψ production, are not able to describe the ψ(2S) production presented in Fig. 5. This indicates an importance of the final-state effects to describe the ψ(2S) suppression in p–Pb collisions.

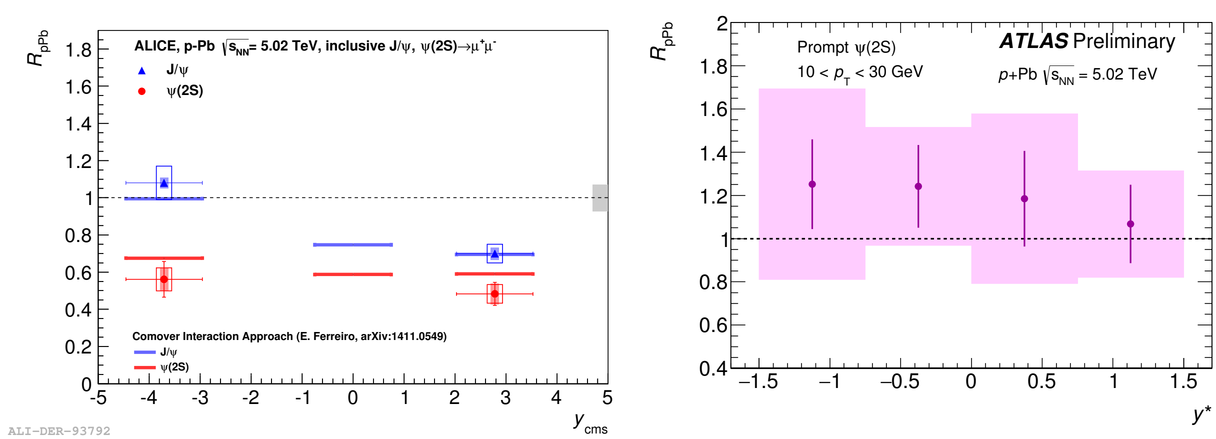

FIGURE 5: (Color online). Nuclear modification factor of inclusive (left) and prompt (right) ψ(2S) as a function of rapidity, measured by ALICE (left) and ATLAS (right). Left panel also contains J/ψ measurements from [13]. ALICE ψ(2S) data points are from [23], ATLAS points are preliminary results from [21]. Model calculations in the left panel are from [17].

In Fig. 6 the LHCb p–Pb results on the nuclear modification factor of inclusive Υ(1S) [24] are compared to its prompt and non-prompt J/ψ measurements [14]. The Υ(1S) state seems to be slightly less suppressed than prompt J/ψ. Shadowing model [16] fairly agrees with the data for both Υ(1S) and prompt J/ψ, however slightly underestimates the prompt J/ψ suppression at forward rapidity. These LHCb measurements agree within uncertainties with the ALICE measurements of the Upsilon(1S) production in p–Pb collisions at similar rapidity ranges [25].

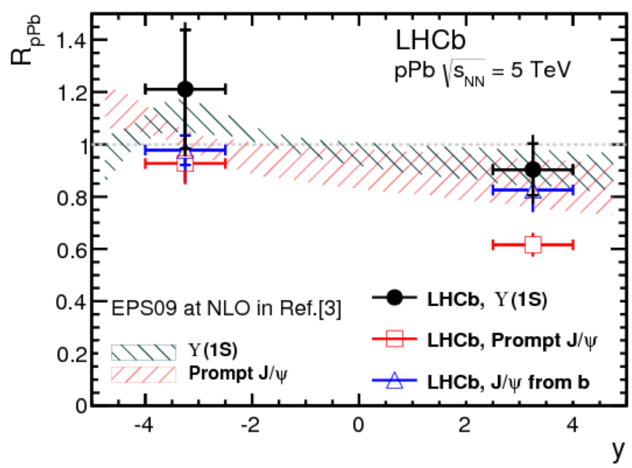

FIGURE 6: (Color online). Nuclear modification factor of inclusive $\Upsilon(1S)$, prompt J/ψ and J/ψ from b in p-Pb collisions as a function of rapidity, measured by LHCb and compared to theoretical calculations from [16]. Figure is taken from [24].

FROM p–Pb TO Pb–Pb

As mentioned above, one of the main motivations to study p–Pb collisions is to estimate the contribution from CNM effects to the quarkonium production in Pb–Pb collisions. ALICE performed this exercise for inclusive J/ψ production [26]. The following assumptions have been made assuming also that the shadowing is the dominant CNM effect:

- Similar Bjorken-x ranges in Pb-nucleus for both Pb–Pb collisions at 2.76 TeV and p–Pb collisions at 5.02 TeV.
- Factorization of shadowing effects in p–Pb and Pb–Pb collisions.

In that case the nuclear modification factor in Pb–Pb collisions estimated from shadowing, $R^{\mathrm{Shad}}_{\mathrm{PbPb}}$, can be found as a simple factor of nuclear modification factors in p–Pb collisions at forward and backward rapidities: $R_{\mathrm{pPb}}(y \geq 0) \cdot R_{\mathrm{pPb}}(y \leq 0)$. The result of this estimation is shown in Fig. 7 at forward (left) and mid- (right) rapidity intervals as magenta points. It is compared to the real measurements of the nuclear modification factor in Pb–Pb collisions (in green) performed by ALICE [27, 28]. As seen from this comparison, a huge J/ψ suppression seen in Pb–Pb at high p_T should be considered as a pure QGP-related effect since the estimated shadowing effect at high p_T is negligible: $R^{\mathrm{Shad}}_{\mathrm{PbPb}} \simeq 1$. In the low-$p_T$ region the estimated J/ψ suppression is similar to the measured one which suggests that the J/ψ production scales with the number of binary collisions. However it does not necessarily mean that hot nuclear matter effects do not play a role. Indeed, at low p_T some other effects enter the game, for instance, regeneration of the J/ψ pairs. In that case the hot nuclear matter effects are compensated, yielding in a zero effect on the J/ψ suppression.

CONCLUSIONS

In this review we summarized the recent measurements of quarkonium production in p–Pb and Pb–Pb collisions performed by the four LHC experiments: ALICE, ATLAS, CMS and LHCb. All of them produced lots of exciting results using the data from the Run I data-taking period at the LHC. Now the heavy-ion community is preparing for the next bunch of the quarkonium production results from Run II. The following measurements are of particular interest:

- the relative suppression of different quarkonium states;
- low-pt J/ψ measurements;
- quarkonium production in pp collisions at 5.02 TeV expected to be used as a reference for both p–Pb collisions and Pb–Pb collisions at the same energy;
- and many others.

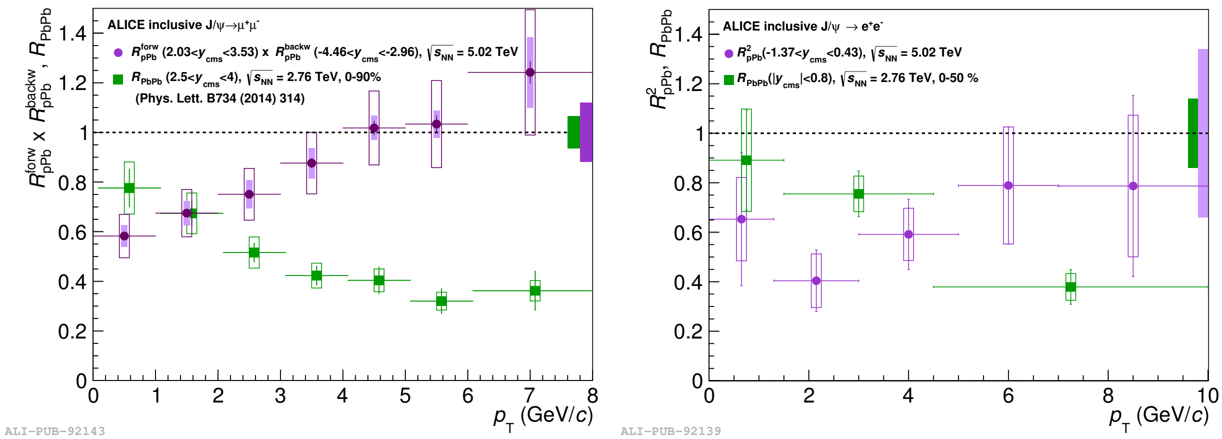

FIGURE 7: (Color online). Nuclear modification factor of J/ψ in Pb–Pb collisions at forward (left) and mid- (right) rapidity intervals. Green points are the measurements performed by ALICE [27, 28] while magenta points are the estimated results from shadowing (see text for details).

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