

ALICE results on quarkonium production in pp, p-Pb and Pb-Pb collisions

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Abstract. The study of quarkonia, bound states of heavy (charm or bottom) quark-antiquark pairs such as the J/ψ or the Υ , provides insight into the earliest and hottest stages of high-energy nucleus-nucleus collisions where the formation of a Quark-Gluon Plasma is expected. High-precision data from proton-proton collisions represent an essential baseline for the measurement of nuclear modifications in nucleus-nucleus collisions and serve also as a crucial test for models of quarkonium hadroproduction. Another fundamental tool to understand the quarkonium production in nucleus-nucleus collisions is the the study of proton-nucleus interactions, which allows one to investigate cold nuclear matter effects, such as parton shadowing or gluon saturation. The ALICE detector provides excellent capabilities to study quarkonium production at the Large Hadron Collider at both central and forward rapidity. An overview on ALICE results on quarkonium production in pp, p-Pb and Pb-Pb collisions is presented. Results are compared to theoretical model predictions.

1. Introduction

The ALICE experiment [1] studies proton-proton (pp), proton-nucleus (p-A) and nucleus-nucleus (A-A) collisions at the Large Hadron Collider (LHC), with the main goal of investigating the properties of the high-density, colour-deconfined state of strongly-interacting matter (the Quark-Gluon Plasma, QGP) that is expected to be formed in high-energy nuclear collisions. The suppression of quarkonium states was proposed long ago [2] as a signature of the formation of the QGP: in a deconfined medium, the binding potential between the constituents of a quarkonium state, a heavy quark (Q) and its antiquark (\bar{Q}), is screened by the colour charges of the surrounding light quarks and gluons. In this scenario, quarkonium suppression occurs sequentially, according to the binding energy of each meson: strongly bound states, as the J/ψ and $\Upsilon(1S)$, should melt at higher temperatures with respect to the more loosely bound ones, as the $\psi(2S)$ and χ_c , for the charmonium family, or the $\Upsilon(2S)$ and $\Upsilon(3S)$ for the bottomonium one. The in-medium modification of quarkonium production is usually quantified by the nuclear modification factor: $R_{AA} = \frac{d^2N_{AA}/dp_T dy}{\langle N_{coll} \rangle d^2N_{pp}/dp_T dy}$, where $d^2N/dp_T dy$ denotes the transverse momentum (p_T) and rapidity (y) differential yield of a given particle measured in A-A or pp collisions and $\langle N_{coll} \rangle$ is the average number of nucleon-nucleon collisions over the given centrality interval of A-A collisions; $\langle N_{coll} \rangle$ is calculated using the Glauber model [3]. However, there are further possible effects on the quarkonium production in heavy-ion collisions. On the one hand, the large number of heavy quarks produced in heavy-ion collisions, in particular in the charm sector at the energies accessible by the LHC, may lead to an increased production of

charmonia via (re-)combination in the QGP [4, 5] or at the phase boundary [6, 7]. On the other hand, modifications to the parton distribution functions inside the nucleus (shadowing) and other cold nuclear matter effects can change the production of quarkonia without the presence of a QGP [6, 8]. Hence, for the interpretation of A–A results, data from p–A collisions are crucial because they allow us to disentangle these cold nuclear matter effects from those related to the formation of a hot QCD medium. Finally, besides being the natural reference for A–A studies, quarkonium hadro-production in elementary pp collisions are important *per se*, representing a challenging testing ground for models based on QCD. ALICE results on quarkonium production in pp are therefore also summarized in the following.

2. Experiment, data taking conditions and analysis

The ALICE experiment consists of a central barrel embedded in a solenoidal magnet and a forward muon spectrometer. Details on the experimental set-up can be found in [1]. The measurement of quarkonium production is carried out in the central barrel ($|y| < 0.9$) through their e^+e^- decay, while at forward rapidity ($2.5 < y < 4$) the $\mu^+\mu^-$ decay is studied in the muon spectrometer.

For the measurement in the central barrel described hereafter, events are triggered by a minimum bias (MB) condition, which corresponds roughly to the presence of at least one charged particle in about 8 units of pseudo-rapidity. This condition is defined using the information from the two innermost pixel layers of the silicon Inner Tracking System (ITS) ($|\eta| < 2$ and $|\eta| < 1.4$) and from two arrays of scintillators (VZERO) placed at forward rapidities ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$). In Pb–Pb, several centrality classes can be further defined at the trigger level by means of thresholds on the total signal amplitude in the VZERO. For the measurement with the forward muon spectrometer one can require, in addition to the MB condition, one or two candidate muons to be detected by the muon triggering system.

For Pb–Pb collisions at central rapidity, the analysis is based on a combination of 2010 data, taken with a MB trigger, and 2011 data where, in addition, centrality selections corresponding to central events (0–10%) and semi-central events (10–40%) were performed. The integrated luminosity is $L_{\text{int}} = 15 \mu\text{b}^{-1}$. The Pb–Pb forward rapidity results refer to the 2011 data ($L_{\text{int}} = 70 \mu\text{b}^{-1}$), and were collected by requiring a dimuon trigger, which can select both opposite- and like-sign pairs. In order to define R_{AA} , one needs a sample of pp data collected at the same energy ($\sqrt{s} = 2.76$ TeV) and in the same kinematic domain of Pb–Pb data. Such data were taken in 2011, collecting $L_{\text{int}} = 1.1 \text{ nb}^{-1}$ with a MB trigger for the central rapidity analysis and $L_{\text{int}} = 20 \text{ nb}^{-1}$ with a single-muon trigger for the forward rapidity analysis. Moreover, pp data at $\sqrt{s} = 7$ TeV, the top energy of the 2010 and 2011 LHC data taking, were also collected and analysed, the results discussed here referring to integrated luminosities up to 100 nb^{-1} .

Data were collected in 2013 for p–Pb collisions using, for the quarkonium studies with the muon spectrometer, the dimuon trigger in coincidence with the MB trigger. Due to the energy asymmetry of the LHC beams ($E_p = 4$ TeV, $E_{\text{Pb}} = 1.58 \text{ A TeV}$) the nucleon-nucleon center-of-mass system of the collisions does not coincide with the laboratory system, but is shifted by $\Delta y = 0.465$ in the direction of the proton beam. Data have been taken with two beam configurations, by inverting the direction of the orbits of the two particle species. In this way in the dimuon channel the regions $2.03 < y_{\text{cms}} < 3.53$ and $-4.46 < y_{\text{cms}} < -2.96$ have been studied, where positive rapidities refer to the situation where the proton beam is travelling towards the muon spectrometer (in the following these configurations are referred to as p–Pb and Pb–p, respectively). The integrated luminosities of the analysed data for the two configurations are about 5 nb^{-1} (p–Pb) and 6 nb^{-1} (Pb–p). For the central barrel studies, about 130 M MB events (i.e. an integrated luminosity of about $50 \mu\text{b}^{-1}$) have been collected. In addition, other rarer trigger data sample, of interest for charmonia studies, e.g. that requiring an electron in the Transition Radiation Detector (TRD), corresponding to $L_{\text{int}} \approx 1.5 \text{ nb}^{-1}$ are also available.

These data samples are being analysed at the time of the conference.

In the central barrel the analyses are mainly based on the charged track reconstruction performed with the ITS and Time Projection Chamber (TPC) detectors, on the electron identification via the measurement of the specific energy loss in the TPC and on the auxiliary information from the Time Of Flight (TOF) detector and the TRD for the rejection of hadrons. Thanks to the excellent spatial resolution of the ITS, the non-prompt J/ψ contribution can be separated, thus allowing a measurement of beauty production down to very low p_T ($p_T(J/\psi) \approx 1.5 \text{ GeV}/c$). Details of the analyses are discussed in [9]. In the muon channel, opposite sign (OS) muons, which have been filtered by the hadron absorber and reconstructed in the muon spectrometer, are paired to obtain invariant mass distributions with clean mass peaks for the quarkonium states. Quarkonium signals are extracted by means of fit to the OS mass distribution, using a phenomenological shape for the background, and Crystal Ball shape for the signals. Further details can be found in [10, 11, 12]. Examples of the dileptons invariant mass distributions obtained in Pb–Pb and p–Pb collisions are shown in Fig. 1.

3. Results

3.1. pp

ALICE has measured the production cross section of inclusive J/ψ at $\sqrt{s} = 7$ and 2.76 TeV [13, 14]. At $\sqrt{s} = 2.76$ TeV a p_T differential study was possible only in the forward region, due to the rather small MB integrated luminosity. At central rapidity, the fraction of J/ψ from beauty hadron decay could be separated at low p_T [15], which also led to an estimation of the total $b\bar{b}$ cross section at $\sqrt{s} = 7$ TeV. The first LHC study of the inclusive J/ψ polarization has been performed at forward rapidity, showing that the J/ψ production is essentially unpolarized up to $p_T = 8 \text{ GeV}/c$ [16]. The comparisons of these results with NLO NRQCD calculations that include color octet processes show good agreement. We have also performed a unique measurement of the J/ψ yield as a function of the charged particle multiplicity [17, 18], which shows an almost linear increase of the yield with the multiplicity. The latter result may either indicate that J/ψ production in pp is connected with strong hadronic activity, or that multiparton interactions could also affect the harder momentum scales relevant for quarkonium production.

Preliminary results on Υ production in pp collisions at $\sqrt{s} = 7$ TeV have also been delivered [11], which are in good agreement with the published LHCb results [19].

Reference pp data at the same energies of the p–Pb ($\sqrt{s_{NN}} = 5.02$ TeV) and Pb–Pb ($\sqrt{s_{NN}} = 2.76$ TeV) interactions are, respectively, not available and of limited statistics (a few days of data taking was devoted to the study of pp collisions at $\sqrt{s} = 2.76$ TeV). Therefore, interpolation procedures are often introduced (except for the forward rapidity J/ψ results at $\sqrt{s} = 2.76$ TeV) to estimate the production cross section of quarkonium states at these energies, which lead to large uncertainties.

3.2. $Pb-Pb$

The inclusive J/ψ nuclear modification factor as a function of centrality, p_T and y in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, has been measured down to zero p_T [9]. At forward rapidity, R_{AA} shows a clear suppression of the J/ψ yield, with no significant dependence on centrality for $\langle N_{part} \rangle$ larger than 70 (left panel of Fig. 2). At mid rapidity the J/ψ R_{AA} is compatible with a constant value (middle panel of Fig. 2). At forward rapidity the J/ψ R_{AA} exhibits a strong p_T dependence and decreases by a factor of 2 from low p_T to high p_T . This behavior shows a striking difference with the one observed by the PHENIX experiment at RHIC energy [21], which measured a larger suppression at low p_T than that measured by ALICE at the LHC. The measurement of the inclusive J/ψ elliptic flow at forward rapidity [22] has provided an indication of non-zero v_2 in semi-central Pb–Pb collisions. Both results are in agreement with the global

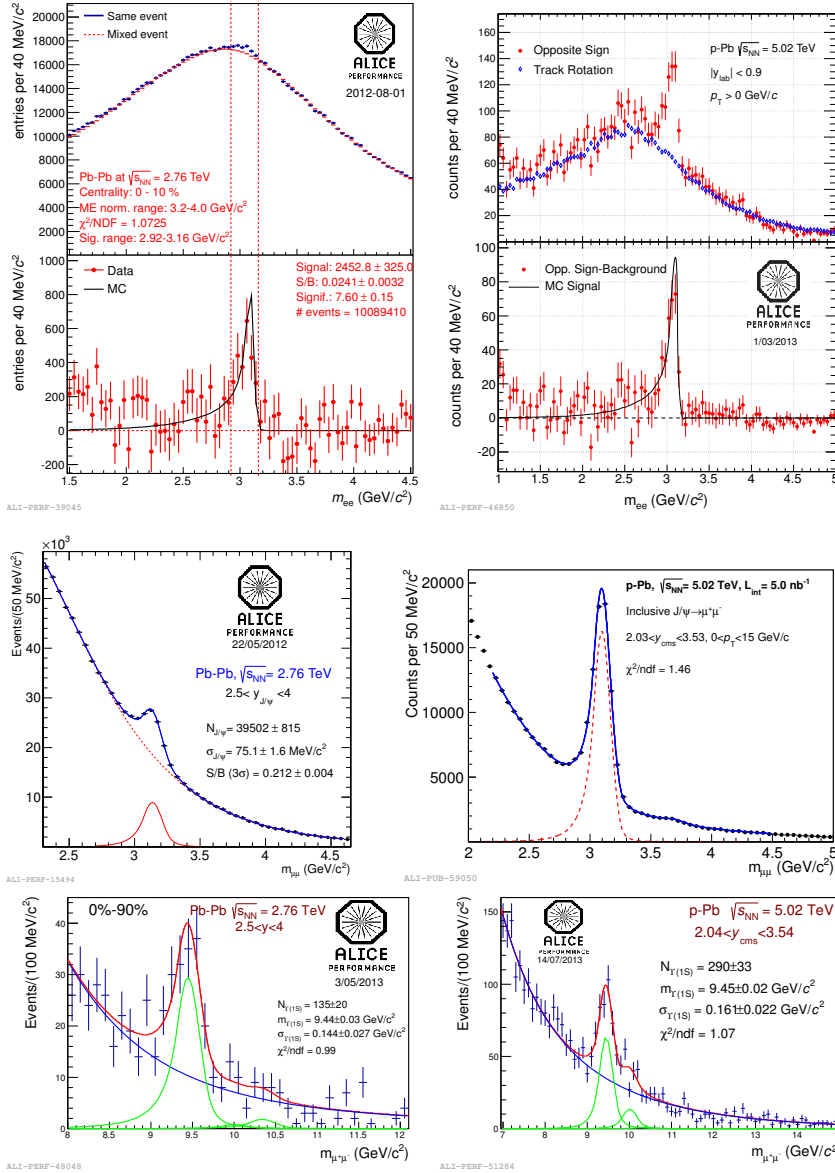


Figure 1. Invariant mass distributions of opposite sign electron (top panels) or muon (middle and bottom panels) pairs in Pb–Pb (left panels) and p–Pb (right panels) collisions. In the dielectron channel the combinatorial background is described with the event mixing or the track rotation methods and subtracted from the same-event opposite-sign distributions.

picture in which a significant fraction of the observed J/ψ is produced from (re-)combination of charm quarks in the QGP phase or at the phase boundary.

The fraction of non-prompt J/ψ (f_B) has been measured at central rapidity in the range $2 < p_T < 10$ GeV/c [9]. No significant dependence of f_B on centrality could be determined. Considering the ALICE and CMS results [23] together, an indication for a similar trend of f_B as a function of p_T in pp and Pb–Pb collisions is observed. The preliminary results on the $\Upsilon(2S)$ are discussed in [20]. The nuclear modification factor of the $\Upsilon(1S)$ has been measured at forward rapidity ($2.5 < y < 4.0$) for $p_T > 0$ [11]. Within the uncertainty a similar suppression as that measured for inclusive J/ψ is observed. The suppression is stronger for central than

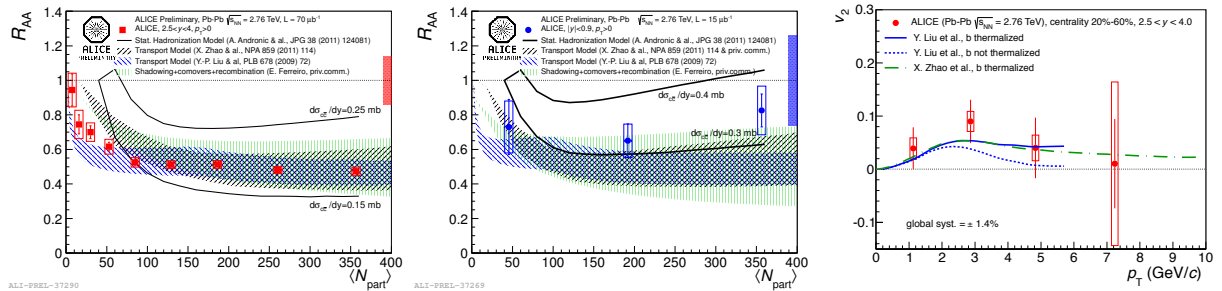


Figure 2. Inclusive J/ψ R_{AA} measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at forward (left panel) and central (middle panel) rapidity and inclusive J/ψ $v_2(p_T)$ for semi-central Pb–Pb collisions (right panel) compared to theoretical models.

semi-peripheral collisions. Combining this measurement with that of CMS [24] performed for $|y| < 2.4$, no rapidity dependence of the $\Upsilon(1S)$ suppression is observed within the large rapidity range probed by the two experiments.

3.3. p – Pb

The nuclear modification factor in p – Pb collisions, R_{pPb} , has been measured in the muon spectrometer for the J/ψ and $\Upsilon(1S)$ states [11, 12]. Since no pp collisions at $\sqrt{s} = 5.02$ TeV have been delivered, the pp references are obtained interpolating the results collected at higher and lower energies, and these pp references introduce an important contribution to the total uncertainty on R_{pPb} , especially for the J/ψ . The variable R_{FB} , which is defined as the ratio of the J/ψ (and similarly for the Υ) forward to backward yields measured in the common J/ψ rapidity range $2.96 < |y_{cms}| < 3.53$, has been introduced to avoid the need of the pp reference, and its relative large uncertainty. The drawback of this observable, which is measured in a restricted rapidity interval, is a minor sensitivity to discriminate among models that can describe the cold nuclear matter effects, with respect to R_{pPb} .

The nuclear modification factors for the J/ψ and $\Upsilon(1S)$ as a function of the quarkonium rapidity y_{cms} are shown in the left panel of Fig. 3. The R_{FB} of J/ψ as a function of p_T is shown in the right hand panel of Fig. 3. The results are compared with theory predictions, based on a pure nuclear shadowing scenario, as well as partonic energy loss, either in addition to shadowing or as the only nuclear effect (see [11, 12] for a detailed discussion, and references therein). Within the uncertainties, both the models based on shadowing only and the coherent energy loss approach are in fair agreement with the data. The present theoretical and experimental uncertainties prevent from drawing more precise conclusions on the role of the different contributions. The prediction based on the Color Glass Condensate model underestimates our results (not shown in Fig. 3, see [12] and references therein).

4. Conclusions

ALICE has measured the production of quarkonia in pp , p – Pb and Pb – Pb collisions at the energies of the LHC. Recent NLO NRQCD calculations that include color octet processes describe well the production in pp collisions. In Pb – Pb interactions, the results suggest that the (re-)combination of $c\bar{c}$ pairs in the QGP or at the phase boundary plays a sizeable role in the J/ψ production. The $\Upsilon(1S)$ has been found to be suppressed at forward rapidity to the same extent as measured at midrapidity by the CMS Collaboration. First p – Pb results are in fair agreement with predictions of models based on nuclear shadowing and coherent energy loss.

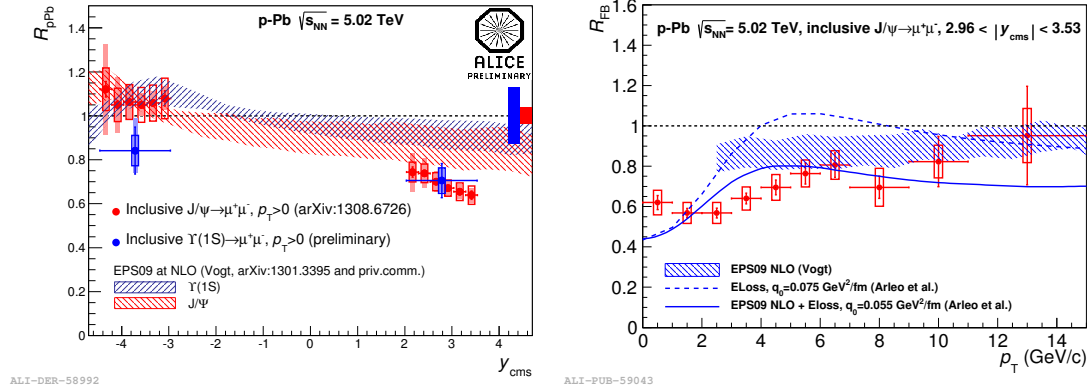


Figure 3. Left panel: the nuclear modification factor for $\Upsilon(1S)$ and inclusive J/ψ as a function of y_{cms} in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Error bars correspond to statistical uncertainties, open boxes represent uncorrelated systematic uncertainties, shaded boxes show partially correlated systematic uncertainties and the boxes around $R_{pPb} = 1$ shows the fully correlated uncertainties. Right panel: the forward to backward ratio for inclusive J/ψ production as a function of p_T . Statistical uncertainties are shown as bars, uncorrelated systematic uncertainties correspond to open boxes. Theoretical model predictions are superimposed, see text for details.

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