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Inclusive J/ψ production in Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV

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ABSTRACT

Inclusive J/ψ production is studied in Xe–Xe interactions at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\rm NN}} = 5.44$ TeV, using the ALICE detector at the CERN LHC. The J/ψ meson is reconstructed via its decay into a muon pair, in the centre-of-mass rapidity interval $2.5 < y < 4$ and down to zero transverse momentum. In this Letter, the nuclear modification factors $R_{\rm AA}$ for inclusive J/ψ, measured in the centrality range 0–90% as well as in the centrality intervals 0–20% and 20–90% are presented. The $R_{\rm AA}$ values are compared to previously published results for Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and to the calculation of a transport model. A good agreement is found between Xe–Xe and Pb–Pb results as well as between data and the model.

The study of the production of quarkonium states plays an important role in the characterization of the properties of the Quark-Gluon Plasma (QGP) [1]. This state of matter, where quarks and gluons are not confined into hadrons, can be produced in heavy-ion collisions at ultrarelativistic energies. Quarkonia are bound states of heavy quark-antiquark pairs (charmonia, $c\bar{c}$ and bottomonia, $b\bar{b}$) and their production rate is significantly affected by the QGP. In particular, the color force responsible for the binding of heavy quarks is expected to be screened in the QGP, leading to a suppression of quarkonium production which can be related to the initial temperature of the system [2,3]. In addition, at very high energies, such as those available at the LHC, the abundant production of charm-anticharm pairs leads to a recombination process, which may occur both in the QGP phase or when the system cools down and hadrons are formed out of the free quarks and gluons [4,5]. The study of the interplay between suppression and recombination processes offers the possibility of a quantitative investigation of the existence of colorless bound states of heavy quarks in the QGP.

An extended set of results was obtained for the J/ψ, a charmonium state with quantum numbers $J^{PC} = 1^{--}$, at LHC energies ($\sqrt{s_{\rm NN}} = 2.76$ and 5.02 TeV) in Pb–Pb collisions [6–12]. Comparison of these results to theoretical models [13–17] and to lower energy data [18,19] favors the picture described above. The study of the collision of nuclei lighter than Pb may give additional important information on the relative contribution of suppression and recombination mechanisms.

A step in this direction is performed in this Letter, where first results on J/ψ production at LHC energies in Xe–Xe, a collision system ($A_{\rm Xe} = 129$) lighter than Pb–Pb ($A_{\rm Pb} = 208$), are presented. Data were collected by the ALICE Collaboration at the centre-of-mass energy per nucleon pair $\sqrt{s_{\rm NN}} = 5.44$ TeV, during a short run carried out at the end of 2017. Due to the limited integrated luminosity, $L_{\rm int} \sim 0.34\ \mu{\rm b}^{-1}$, the statistical uncertainties are significantly larger than those of the Pb–Pb results [10], but nevertheless allow a meaningful comparison between the two systems, in terms of the nuclear modification factor $R_{\rm AA}$. This quantity is obtained as the ratio between the production yields in nucleus–nucleus collisions and the corresponding proton–proton (pp) cross section, normalized to the nuclear thickness function $\langle T_{\rm AA}\rangle$ [20]. Values of $R_{\rm AA}$ smaller (larger) than unity indicate suppression (enhancement) effects for the particle under study. The results shown in this Letter correspond to the centre-of-mass rapidity range $2.5 < y < 4$, are integrated over transverse momentum ($p_{\rm T}$) and were obtained by studying the J/$\psi \rightarrow \mu^+\mu^-$ decay channel. The nuclear modification factor is studied as a function of the centrality of the collision [21], expressed as a percentage of the hadronic Xe–Xe cross section. The results correspond to inclusive J/ψ production, which is the sum of a prompt component (directly produced J/ψ and feed-down from other charmonium states) and a non-prompt component, due to the decay of particles containing a b quark.

ALICE is the LHC experiment dedicated to the study of nuclear collisions, and is described in detail in Refs. [22,23]. The main detector used in this analysis is a muon spectrometer [24], covering the pseudorapidity range $-4 < \eta < -2.5$.[1] It includes tracking and trigger chambers, and reconstructs muons with $p_{\rm T}$ larger than a

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[1] In the ALICE reference frame, the muon spectrometer covers a negative η range and consequently a negative y range. We have chosen to present our results with a positive y notation.

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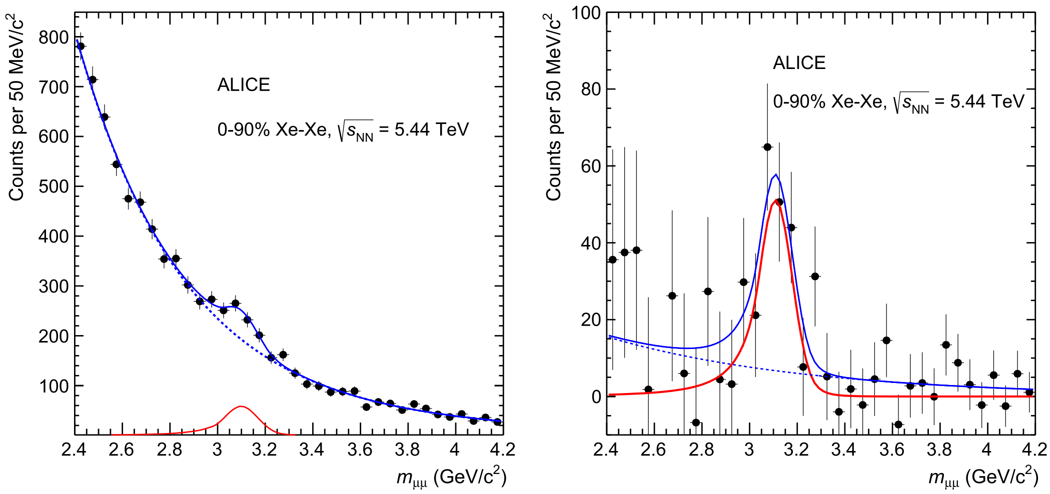

Fig. 1. Fits to invariant mass distributions of opposite-sign dimuons, for 0–90% Xe–Xe collisions. In the left panel, the result of a fit to the raw invariant mass spectrum is shown, while in the right panel the fit to the same distribution after subtraction of the mixed-event background is presented. The fit curves shown in blue represent the sum of the signal and background shapes, while the red lines correspond to the J/ψ signal and the blue dashed ones to the background (see text for details). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

given threshold, which is set at the trigger level. In addition, the V0 [25], a set of scintillator detectors covering $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, is used to define the minimum bias (MB) interaction trigger via a coincidence of signals at positive and negative η values. The V0 is also used for the centrality estimate via a fit of the distribution of the total signal amplitudes in the framework of the Glauber model [21]. The reconstruction of the primary collision vertex is carried out in the two layers of the Silicon Pixel Detector (SPD), the innermost part of the Inner Tracking System of the experiment [26], covering $|\eta| < 2$ and $|\eta| < 1.4$ respectively. Finally, rejection of non-hadronic Xe–Xe collisions is performed using the Zero Degree Calorimeters (ZDC) [27], which identifies electromagnetic interactions, while the V0 detects beam-gas collisions occurring outside the nominal interaction point region.

The data analyzed in this Letter are taken with a trigger formed by the coincidence of the MB trigger signal and of at least one muon triggered in the muon spectrometer, with a $p_T = 0.5$ GeV/c threshold. The definition of the trigger is less restrictive than the one usually adopted for Pb–Pb data taking (1 GeV/c threshold and two detected muons), due to the much smaller instantaneous luminosity for Xe–Xe collisions. Standard selection criteria [10] are then applied to such events and to the muon candidates. In particular, it is required (i) that two opposite-sign tracks reconstructed in the tracking chambers of the muon spectrometer are matched to track segments in the trigger system, (ii) that both muons belonging to the pair (dimuon) have $-4 < \eta_\mu < -2.5$, and (iii) that their transverse position R_{abs} at the end of the hadron absorber of the muon spectrometer satisfies the condition $17.6 < R_{abs} < 89.5$ cm. Finally, the reconstructed dimuon should lay in the fiducial rapidity region of the muon spectrometer, $2.5 < y < 4$.

The nuclear modification factor R_{AA} for the collision system under study is defined, for the centrality interval i, as

$$R^i_{AA} = \frac{N^i_{J/\psi}}{BR_{J/\psi\to\mu^+\mu^-} N^i_{MB} A\varepsilon^i \langle T^i_{AA}\rangle \sigma^{pp}_{J/\psi}}, \quad (1)$$

where $N^i_{J/\psi}$ is the number of detected J/ψ in the i-th centrality interval, $BR_{J/\psi\to\mu^+\mu^-} = (5.96 \pm 0.03)\%$ is the branching ratio of the dimuon decay channel [28], N^i_{MB} is the number of MB events corresponding to the analyzed triggered event sample, $A\varepsilon^i$ is the product of the detector acceptance times the reconstruction efficiency, $\langle T^i_{AA}\rangle$ is the average nuclear thickness function [29], and $\sigma^{pp}_{J/\psi}$ is the inclusive J/ψ cross section for pp collisions, at the same energy and in the same kinematic range as the Xe–Xe data. Results are given for the centrality interval 0–90% and for the two sub-intervals 0–20% and 20–90%.

Except for the determination of $\sigma^{pp}_{J/\psi}$, the other quantities entering the definition of R_{AA} are evaluated following the same procedure used for the analysis of the Pb–Pb data sample and detailed in Ref. [10].

The extraction of $N_{J/\psi}$ is performed with two different approaches. In the first, the raw opposite-sign dimuon invariant mass distribution is fitted with a superposition of resonance and background shapes [30], the former being tuned to Monte Carlo (MC) simulations and the latter corresponding to empirical functions. In the second, the background is estimated via a mixed-event invariant mass distribution, obtained from the collected sample of muon-triggered events and subtracted from the raw spectrum [9]. The resulting distribution is then fitted with the sum of a resonance shape and a continuum function accounting for the small residual background component. Due to the low statistical significance of the present data sample, the width of the J/ψ meson, which is usually kept as a free parameter in the invariant mass fits, is fixed to $\sigma_{J/\psi} = 70$ MeV/c^2, corresponding to the value of this quantity obtained in previous analyses [10,31,32]. For each of the two approaches, several fits were performed varying the fit mass range, the signal and background shapes and the J/ψ width by ± 1 MeV/c^2. The obtained value for the centrality interval 0–90% is $N_{J/\psi} = 241 \pm 47(\text{stat.}) \pm 26(\text{syst.})$, where the central value and the statistical uncertainty correspond to the average of the fit results and to the average of the corresponding statistical uncertainties, respectively. The systematic uncertainty is obtained as the root mean square of the distribution of the $N_{J/\psi}$ values obtained with the various fits. The corresponding values for the 0–20% and 20–90% centrality sub-intervals are $N_{J/\psi} = 175 \pm 42(\text{stat.}) \pm 23(\text{syst.})$ and $N_{J/\psi} = 77 \pm 20(\text{stat.}) \pm 7(\text{syst.})$, respectively.

Fig. 1 shows as an example the results of two fits to the 0–90% Xe–Xe dimuon invariant mass distribution, corresponding to fitting the raw spectrum (left panel) or the mixed-event background subtracted mass distribution (right panel).

The product of the acceptance times the reconstruction efficiency $A\varepsilon$ for J/ψ is evaluated via a MC simulation, based on the GEANT3 transport model [33], which takes into account the alignment of the muon spectrometer detectors and their efficiency. The input p_T and y distributions for the J/ψ acceptance calculation cannot be tuned directly to data, due to the low integrated luminosity of the data sample. It is therefore assumed that the shape of the y and p_T distributions is similar for different collision systems in centrality intervals corresponding to the same average number of participant nucleons, weighted by the corresponding number of nucleon–nucleon collisions, $\langle N^{w}_{part} \rangle$. The weighting is introduced to take into account that the J/ψ production cross section is proportional to the number of nucleon–nucleon collisions and that therefore the average N_{part} in wide centrality bins is systematically shifted towards higher values. Following this argument, the differential distributions measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [10] for the 20–40% centrality range are used as input distribution for the MC calculation, since $\langle N^{w}_{part} \rangle_{PbPb,20-40\%}$ is equal, within $\sim 2\%$, to $\langle N^{w}_{part} \rangle_{XeXe,0-90\%}$, estimated via a Glauber MC calculation. The systematic uncertainty on the J/ψ acceptance value due to the choice of the J/ψ rapidity and transverse momentum distributions amounts to 2% and is evaluated by choosing alternative input shapes corresponding to other Pb–Pb centrality ranges.

Concerning the reconstruction efficiency, it slightly depends on the collision centrality, due to the detector occupancy in the muon spectrometer. The effect was evaluated in the analysis of Pb–Pb events [10] by embedding the simulated J/ψ signal into real events corresponding to various centralities. For this analysis, starting from the Pb–Pb results, the decrease in $A\varepsilon_{XeXe,0-90\%}$ with respect to a simulation containing only J/ψ is estimated to be 4.2% (values for 0–20% and 20–90% centrality ranges are 5.5% and 1.6%, respectively). The systematic uncertainty on the reconstruction efficiency is evaluated following the procedure used in Ref. [10], leading to a 3.6% effect.

The resulting value for the product of acceptance times reconstruction efficiency for J/ψ production in 0–90% Xe–Xe collisions is $A\varepsilon_{XeXe,0-90\%} = 0.228 \pm 0.009(\text{syst.})$, with a negligible statistical uncertainty.

The normalization factor N_{MB} is evaluated by multiplying the number of opposite-sign dimuon triggers by a factor F_{norm}, corresponding to the inverse of the probability of having a triggered muon in a MB event. This quantity is computed from the event trigger input information and the level-0 trigger mask. The procedure and the evaluation of the systematic uncertainty are described in Ref. [10]. The obtained value is $F_{norm} = 2.428 \pm 0.001(\text{stat.}) \pm 0.024(\text{syst.})$.

The reference cross section for the calculation of R_{AA} is obtained starting from the measured value of the inclusive J/ψ cross section in pp collisions at $\sqrt{s} = 5.02$ TeV [10]. This quantity is then corrected to account for the different centre-of-mass energy of the Xe–Xe data, using an interpolation of available ALICE pp results at $\sqrt{s}$ =2.76, 5.02, 7, 8 and 13 TeV [32]. The obtained value is $\sigma^{pp}_{J/\psi} = 5.99 \pm 0.09(\text{stat.}) \pm 0.30(\text{syst.})$ μb^{-1}, where the systematic uncertainty contains a small term (0.4%) related to the interpolation procedure, calculated as the maximum spread between results obtained with various interpolating functions [34].

The nuclear thickness function $\langle T_{AA} \rangle$ is evaluated for the various centrality intervals via a Glauber model calculation, and its uncertainty is estimated by varying within uncertainties the density parameters of the Xe nucleus [29,35]. For 0–90% centrality its value amounts to $\langle T_{AA} \rangle = 3.25 \pm 0.25$ mb^{-1}, while for 0–20% and 20–90% one obtains $\langle T_{AA} \rangle = 9.90 \pm 0.62$ mb^{-1} and $\langle T_{AA} \rangle = 1.35 \pm 0.14$ mb^{-1}, respectively.

Finally, a systematic uncertainty on the definition of the centrality intervals is evaluated by varying the value of the V0 signal amplitude corresponding to 90% centrality by ±0.5% and recalculating correspondingly the centrality intervals.

Table 1
Summary of systematic uncertainties on the calculation of the nuclear modification factors. The tracking efficiency term includes a 1% contribution due to the choice of the χ^2 cut of the matching between the information of tracking and trigger detectors. All the uncertainties are correlated among the various centrality ranges, except those on the signal extraction, $\langle T_{AA} \rangle$ and the definition of the centrality intervals.

Source	0–90%	0–20%	20–90%
Signal extraction	11%	13%	8%
MC input	2%	2%	2%
Tracking efficiency	2%	2%	2%
Trigger efficiency	3%	3%	3%
F_{norm}	1%	1%	1%
$\langle T_{AA} \rangle$	8%	6%	10%
Centrality	0%	0%	1%
pp reference	5%	5%	5%

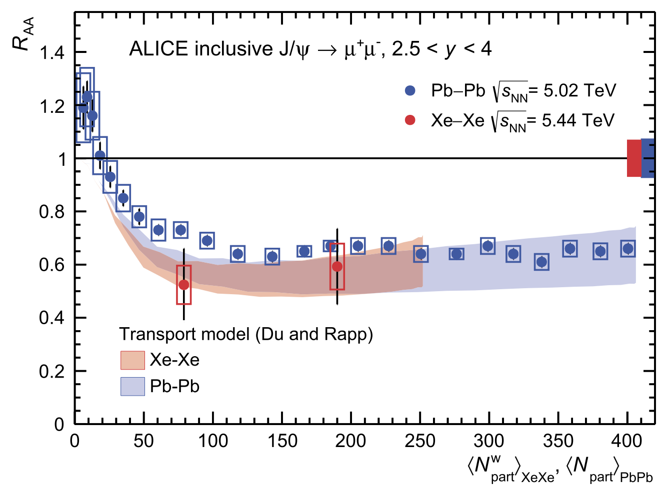

Fig. 2. The inclusive J/ψ nuclear modification factor for Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The results are plotted using as centrality variable $\langle N^{w}_{part} \rangle$, obtained by weighting, in each centrality interval, the N_{part} distribution with the corresponding distribution of the number of nucleon–nucleon collisions. The error bars represent the statistical uncertainties, the boxes around the points the uncorrelated systematic uncertainties. Correlated uncertainties are shown as a filled box around unity. The results are compared with the same quantity for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [10] and to the results of the calculation of a transport model [13,14]. For Pb–Pb, the weighting of N_{part} with the number of nucleon–nucleon collisions was not performed, since it leads to a negligible effect when the centrality intervals are narrow.

Table 1 shows a summary of the systematic uncertainties for the R_{AA} measurement for the three analyzed centrality ranges. The main contributions come from the estimate of $\langle T_{AA} \rangle$ and from the signal extraction. The former is dominated by the uncertainty on the surface thickness of the Xe nucleus. The latter, being estimated in a data-driven way as detailed above, may suffer from the statistical limitations of the data sample. The quoted values can therefore be considered to be a conservative estimate.

The p_T-integrated nuclear modification factor for inclusive J/ψ production in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, measured in $2.5 < y < 4$ and in the 0–90% centrality range, is $R_{AA} = 0.54 \pm 0.11(\text{stat.}) \pm 0.08(\text{syst.})$. This value can be compared with the corresponding one for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, $R^{PbPb}_{AA} = 0.65 \pm 0.01(\text{stat.}) \pm 0.04(\text{syst.})$ [10]. Their ratio amounts to $0.84 \pm 0.16(\text{stat.}) \pm 0.13(\text{syst.})$, showing that the two values agree within about 0.8σ. Following the approach of Ref. [9], it can be shown that the Xe–Xe nuclear modification factor for prompt J/ψ could be up to 10% higher (lower) than the inclusive R_{AA} if the non-prompt J/ψ component from the decays of hadrons containing a b quark is not (completely) suppressed. In Fig. 2 the R_{AA} values for 0–20% and 20–90% Xe–Xe collisions are plotted, and compared with the centrality dependence of the nuclear modification factor for Pb–Pb collisions [10]. The latter shows, after a decrease up to $N_{\mathrm{part}} \sim 100$, a saturation at $R_{\mathrm{AA}} \sim 0.65$–$0.7$ towards more central events, and the two Xe–Xe points are found to be in agreement, within their larger uncertainties, with the Pb–Pb results. The Xe–Xe and Pb–Pb results are also compared with the calculation of a transport model by Du and Rapp [13,14]. A close similarity of the predicted suppression patterns for Pb–Pb and Xe–Xe is observed, which fairly reproduces the experimental results.

In summary, we have measured inclusive J/ψ production in Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV. Results on the nuclear modification factors were given for various centrality selections and compared to corresponding results for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and to a theoretical model. Within the experimental uncertainties, a good agreement is found between the R_{AA} measured in the two systems and with the calculation. These results show that the relative contribution of suppression and regeneration processes is similar for collisions producing similar N_{part} values from different collision systems.

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