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J/ψ measurements with the ALICE experiment at the LHC

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The hot and dense matter created in nuclear collisions at relativistic energies consists of a plasma of deconfined quarks and gluons. The suppression of quarkonium production in high energy nuclear collisions relative to proton-proton collisions, due to the Debye screening of the quark-antiquark potential, was proposed as a signature of the formation of Quark-Gluon Plasma. However, there are other effects that may impact the observed quarkonia production such as cold nuclear matter effects and statistical coalescence of quark-antiquark pairs. Studies of the production of various quarkonium states in heavy-ion collisions can provide insight into the properties of the hot and dense medium created at the Large Hadron Collider (LHC) energies. In addition, systematic measurement of the quarkonium cross-section for different colliding systems, centralities and collision energies may help to understand the quarkonium production mechanisms as well as the medium properties.

The ALICE experiment at the LHC can measure the J/ψ down to very low transverse momentum in the di-muon and di-electron channels. We will discuss the results on charmonium obtained by ALICE and will provide comparisons with other experimental results and with theoretical calculations.

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PoS(X LASNPA)044

1. Introduction

In ultra-relativistic heavy-ion collisions strongly interacting matter at extreme energy densities and temperatures reaches a phase transition to a deconfined state of quarks and gluons [1].This quantum chromodynamics (QCD) state is called the Quark Gluon Plasma (QGP). The production rates of charmonium states in nucleus-nucleus collisions are sensitive to the dynamics of the formed QCD medium and have long been considered a good probe of this state of strongly interacting matter [2]. The extreme color charge density leads to a color screening effect which is expected to suppress the charmonium and bottomonium formation. Within the hot and dense QCD medium the range of the interaction between heavy quarks (Debye like screening) is inversely proportional to the temperature. Therefore, charmonium resonance states are expected to dissociate at different temperatures according to their binding energy: the $\psi(2S)$ at lower temperature, then the χ_c and finally the J/ψ thus causing a sequential suppression of the $q\bar{q}$ resonant states [3]. Competing factors to this suppression are also present at LHC energies: the inclusive J/ψ yield at the LHC contains a significant contribution from b-hadron decays that do not suffer from color screening; the large multiplicity of charmed partons produced during the heavy-ion collisions may also lead to a regeneration of bound states in the dense medium during the final hadronization phase[4]. On top of these competing phenomena, cold nuclear matter effects can come into play, e.g. initial state energy loss, gluon shadowing due to the small x at LHC energies and nuclear absorption. In order to understand the role of these combined effects in AA collisions, the J/ψ production in pp and in p-Pb collisions are also studied in ALICE.

2. Measurements

The ALICE detector [6] has measured J/ψ in Pb-Pb and pp collisions at a center of mass energy of 2.76 and 7 TeV [9, 10] and in p-Pb collisions at 5.02 TeV [11]. The J/ψ measurements have been done in the central barrel detectors ($\eta < 0.9$) via the dielectron decay channel and in the forward spectrometer ($-4 < \eta < -2.5$) via the dimuon decay channel.

At central rapiity, the inclusive J/ψ yield in pp has been measured at $\sqrt{s} = 7$ TeV in 4 p_T bins and p_T integrated at $\sqrt{s} = 2.76$ TeV. At the highest energy, we recorded 350 millions minimum bias events, corresponding to an integrated luminosity of 5.6 $nb-1$. The yield has been extracted from the invariant mass distribution of opposite sign dielectron pairs, after subtraction of the combinatorial background . The prompt contribution, obtained by removing the secondary J/ψ fraction, can be compared with the results of theoretical models. In particular,the measurements are compatible with next to leading order non relativistic QCD predictions (NRQCD) where color-octet processes play an important role [5]. The measurement at $\sqrt{s}$ = 2.76 TeV was performed on a smaller data set, which is used as a reference for Pb-Pb collision results at the same center of mass energy per nucleon pair. No pp data were taken at $sqrts$ =5.02 TeV, the energy of the p-Pb collisions. The pp cross sections at that energy are obtained by means of an interpolation procedure.

The p-Pb measurements have been obtained with measurements in the $\mu^+\mu^-$ and e^+e^- decay channels. The events were triggered requiring the coincidence of a signal in two forward detectors [7] and, for the dimuon sample, the detection of two muon candidate tracks in the muon spectrometer. Due to the energy asymmetry of the LHC beams the nucleon-nucleon center-of-mass system

PoS(X LASNPA)044

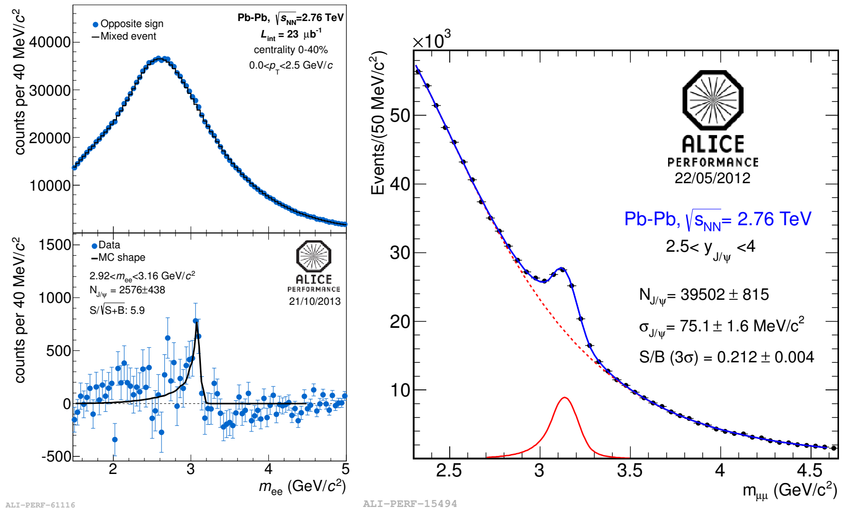

Figure 1: Left, invariant mass distribution $J/\psi \rightarrow e^+ + e^-$ for 0-40% most central events, for Pb-Pb collisions. Right, dimuon invariant mass distribution for 0-90% centrality, also for Pb-Pb collisions.

was 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. The integrated luminosities used in this analysis for the two configurations are 5.03 nb^{-1} (p-Pb) and 5.81 nb^{-1} (Pb-p). For the dimuon sample, the extraction of the number of J/ψ is performed starting from the invariant mass distributions of opposite sign muon pairs, then the distributions are fitted by means of a superposition of a continuum and a resonance shape. The continuum is parameterized either as a polynomial times an exponential function or as a Gaussian with a width linearly varying with mass, while for the resonance a Crystal Ball function is used [8].

The signal extraction in Pb-Pb is challenging due to the presence of a big combinatorial background, especially in central collisions where the highest number of nucleons participate in the interaction. These quantities, centrality and number of participating nucleons (N_{part}), are each determined using the Glauber model [12]. In the e^+e^- decay channel, the J/ψ yields are extracted by counting the number of entries in the invariant mass range $2.92 < m_{e^+e^-} < 3.16$ GeV after subtracting the combinatorial background. Fig. 1 (left) shows the invariant mass distribution of all opposite sign dielectron pairs and the combinatorial background in semi-central collisions ($0-40\%$ most central). Despite the small S/B ratio it is still possible to obtain a signal significance of around 8 sigma. In the $\mu^+\mu^-$ decay channel, the J/ψ raw yield is extracted in each centrality and kinematic interval from the dimuon invariant mass distribution being fitted with the sum of an extended Crystal Ball function to describe the signal and a variable width Gaussian function for the background. Fig. 1 (right) shows a dimuon invariant mass spectrum for 0-90% centrality.

3. Results

An observable that quantifies possible medium effects in Pb-Pb collisions with respect to elementary pp collisions is the nuclear modification factor, R_{AA}, which is the ratio between the trans-

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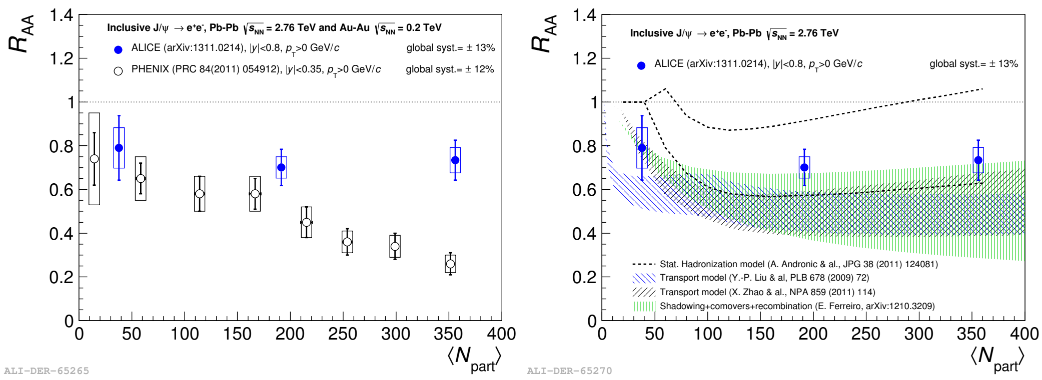

Figure 2: Left : Measurement of R_{AA} as a function of N_{part} for central rapidity. The ALICE measurement is shown together with results by the PHENIX collaboration. Right: R_{AA} vs. N_{part} compared with the predictions by several theoretical models, some models are in reasonable agreement with the data.

verse momentum and rapidity differential yield of J/ψ in Pb-Pb collisions over that in pp collisions times the average nuclear overlap function ($\langle T_{AA}\rangle$) as estimated by the Glauber model.

$$R_{AA} = \frac{d^2N^{AA}_{J/\psi}/dp_T dy}{\langle T_{AA}\rangle d^2N^{pp}_{J/\psi}/dp_T dy} \tag{3.1}$$

Results of the nuclear modification factor for RHIC energies (PHENIX [13]) show a dependence of the J/ψ R_{AA} on the centrality or number of participating nucleons (N_{part}) as expected within a suppression scenario (left panel Fig. 2). The measurements at LHC energies, on the other, hand show a negligible dependence on the centrality for the dielectron channel, which qualitatively agrees with the regeneration scenario (left panel Fig. 2). The same features are observed in the dimuon analysis. Several theoretical models have made predictions for the J/ψ R_{AA} as a function of centrality. Figure 2 (right) shows some of them which have a good agreement with the data. These are based on two different approaches. For the statistical hadronization model (SHM) [14], given the high number of $c\bar{c}$ pairs during the plasma phase, it is assumed that the charmed hadrons hadronize according to statistical weights in the hot medium, thus increasing the final J/ψ yield. On the other hand the J/ψ production can be described with a transport equation which includes dissociation and regeneration processes. The collision dissociation occurs at the initial stages and is due to the interactions with gluons, whereas the recreation of the resonant $c\bar{c}$ state happens later and is provided by free heavy quarks thermalized in a hot medium. The final J/ψ yield is described within an hydrodynamical scenario by integrating the dissociation and regeneration rates over time. Figure 2 (right) shows the predictions of the R_{AA} from both the SHM or transport models.

The results of the first approach (dashed line) are calculated taking into acount the shadowing contribution for the $c\bar{c}$ production. The results from the transport model approaches are in fair agreement between them, in spite of the differences in the calculation details. In particular, the first two (Liu, Zhao) differ in the rates of dissociation and regeneration. The last one (Ferreiro) still considers the dissociation and regeneration rates, but within the scenario assuming no thermal equilibrium [15]. The main uncertainties of all the models are from the $c\bar{c}$ cross section and the shadowing contribution, which can be investigated using the results from p-Pb collisions.

PoS(X LASNPA)044

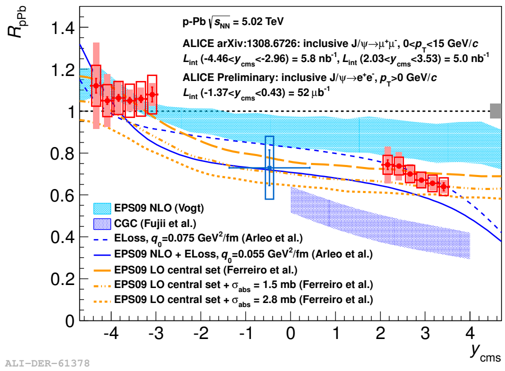

Figure 3: The nuclear modification of inclusive J/ψ as a function of rapidity compared with theory predictions. The open boxes indicate the uncorrelated systematical uncertainties, the filled areas the partially correlated systematical uncertainties and the grey box at unity the common normalization uncertainty due to the T_{pA}-uncertainty. The theory predictions can be found in [17, 18, 19, 20]

Figure 3 shows the nuclear modification factor R_{pA} as a function of rapidity integrated over p_T compared to models. The forward and backward results are consistent with those obtained by the LHCb Collaboration [16]. The depicted result at forward rapidity indicates a suppression of J/ψ, while the backward rapidity data shows no significant suppression within the uncertainties. The central rapidity measurement is consistent with the forward rapidity result albeit with larger uncertainties. The predictions by R. Vogt employing NLO nPDF EPS09 and the Colour Evaporation Model (CEM) [17] as well as the calculations by E. Ferreiro with EPS09 at LO assuming $gg \to J/\psi g$ production mechanism [18] are consistent with the experimental results. In the case of the model by E. Ferreiro, the possible impact of a finite effective nuclear absorption of J/ψ resonance or the precursor state is also shown. The data can be described within this model without this absorption mechanism. The coherent energy loss model [19] is also consistent with data, with or without inclusion of shadowing as an additional effect. The prediction by H. Fujii [20] employing the CEM in a Color Glass Condensate (CGC) framework is, on the other, hand disfavored by the data.

Figure 4 shows the p_T-dependence of R_{pA} at backward, mid and forward rapidity. At forward rapidity, the suppression observed at low p_T is gradually weakens with increasing p_T and becomes consistent with no suppression at high p_T. A similar pattern seems to be present at central rapidity, although uncertainties prevent a firm conclusion. At backward rapidity, a weak p_T dependence seems to be present considering the partially correlated uncertainties with R_{pA}-values close to unity. The CGC-model for forward rapidity by H. Fujii is disfavored by the data. The coherent energy loss model [21] is not consistent with the data in the two lowest p_T-bins, but compatible with it at high p_T. At backward rapidity, the latter model is in agreement with our data despite some tension at low p_T. The calculations by R. Vogt for the p_T-dependence are consistent with the ALICE results for all three rapidity domains in the provided transverse momentum ranges ($p_T > 2.5$ GeV/c).

The Bjorken x-values of the lead nucleus probed under a $2 \to 1$ production mechanism assumption $gg \to J/\psi$ are approximately matching between the recorded Pb-Pb and p-Pb collision data. Therefore, an expectation for the R_{AA} based on the R_{pA} under those kinematic assumptions

PoS(X LASNPA)044

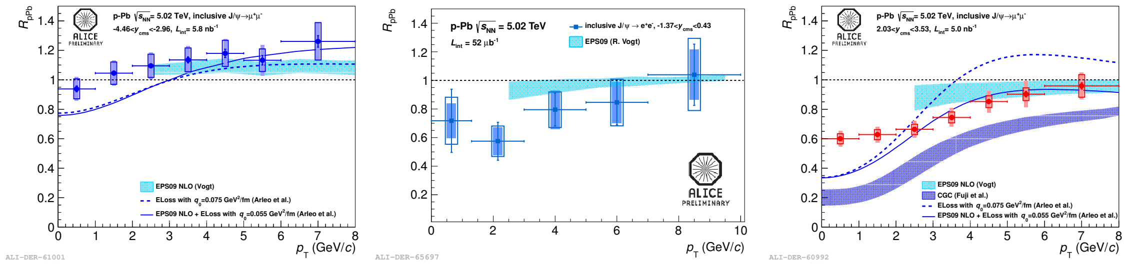

Figure 4: The J/ψ nuclear modification factor in p-Pb as a function of p_T at backward rapidity, central rapidity and forward rapidity compared with theory predictions. The open boxes represent the uncorrelated systematic uncertainties, the filled areas the partially correlated systematical uncertainties. The theory predictions are taken from [20, 21].

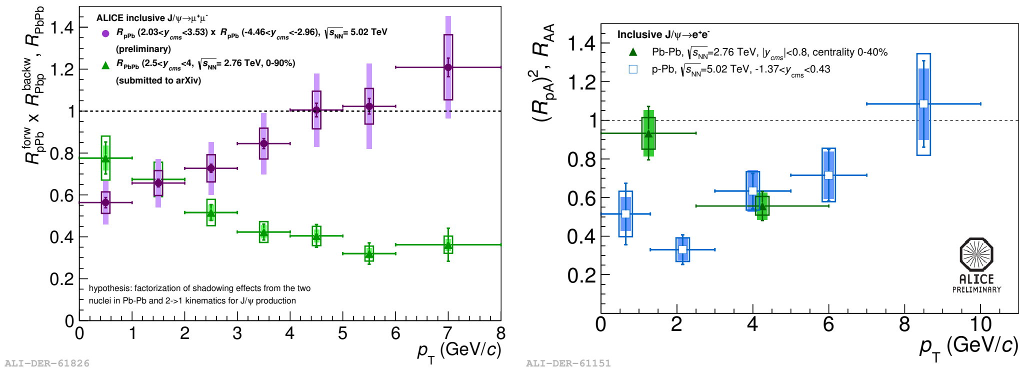

Figure 5: The product of R_{pA}, forward(p_T) $\times$ R_{pA},backward(p_T) compared to the $R_{AA}(p_T)$ at forward rapidity and the comparison of $R_{pA}2$ with R_{AA}, mid-rapidity. The centrality ranges explored in the Pb-Pb collision case are from 0 to 40% at midrapidity and from 0-90% at forward rapidity, and 0-100% for the p-Pb collisions.

and the hypothesis of factorization of nuclear effects can be derived by comparing the R_{pA} backward $\times$ R_{pA} forward ($R_{pA}{}^2$, mid-rapidity) with R_{AA} forward (R_{AA}, mid-rapidity) assuming that the Bjorken x is the relevant scaling variable. This comparison is depicted in Fig. 5. It is worth noticing that theoretical expectations of the factorization can be different from unity even in pure shadowing scenarios due to the finite bin size in rapidity and transverse momentum. Furthermore, there are theoretical models, which do not predict a "factorization" of cold nuclear matter effects, when one extrapolates from pA to AA collisions at LHC energies [22]. Under the given assumptions, the observed behavior is in qualitative agreement with expectations from models incorporating non-primordial J/ψ production: there is a hint of enhancement of the R_{AA} results with respect to R_{pA} backward $\times$ R_{pA} forward ($R_{pA}{}^2$) in the the rapidity region explored by the muon spectrometer acceptance at low p_T and a strong suppression at high p_T. These results are also valid at low p_T for the dielectron results.

4. Conclusions

Detailed measurements of J/ψ production as a function of centrality, p_T and rapidity have

PoS(X LASNPA)044

been performed by the ALICE experiment. They are unique at the LHC since they provide a determination of the inclusive J/ψ cross section at mid rapidity down to $p_T = 0$. For the Pb-Pb collisions , the J/ψ R_{AA} as a function of N_{part} shows a value smaller than unity without a dependence on the centrality. From a theoretical point of view, the regeneration contribution seems to be necessary to describe the ALICE data; nevertheless the shadowing affects the theoretical predictions. The nuclear modification factor of J/ψ in p-Pb collisions has been measured by the ALICE collaboration as a function of rapidity and as a function of p_T in the rapidity ranges accessible to the experiment. The results are consistent with shadowing and/or coherent energy loss in the case of the rapidity dependence. The coherent energy loss model and the calculations based solely on shadowing provide a reasonable description of the experimental data at $p_T > 2.5$ GeV/c, whereas the low-p_T results at forward rapidity are underestimated by the present version of the coherent energy loss model.

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