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Charm resonance production in heavy-ion collisions

Roberta Arnaldi[1,a]

[1] *INFN, Sezione di Torino, Italy*

Abstract. The production of charmonium states plays an important role among the probes to investigate the formation of a plasma of quarks and gluons (QGP) in heavy-ion collisions. A review of the main J/ψ and $\psi(2S)$ results is presented, focussing on the most recent achievements from the LHC experiments.

1 Introduction

Since thirty years, quarkonia ($c\overline{c}$ or $b\overline{b}$ bound states) are considered important probes of the formation, in heavy-ion collisions, of a strongly interacting medium, the so-called quark gluon plasma (QGP). In a hot and deconfined medium, in fact, quarkonium production is expected to be significantly suppressed with respect to the proton-proton yield, scaled by the number of binary nucleon-nucleon collisions, and the origin of such a suppression, taking place in the QGP, is the color screening of the force which binds the $c\overline{c}$ ($b\overline{b}$) state [1]. In this scenario, quarkonium suppression should occur sequentially, according to the binding energy of each meson: strongly bound states, as the J/ψ, should melt at higher temperatures with respect to the more loosely bound ones, as the ψ(2S) and the χ_c. As a consequence, the in-medium dissociation probability of such states should provide an estimate of the initial temperature reached in the collisions [2]. However, the prediction of a sequential suppression pattern is complicated by several factors as the feed-down contributions from higher-mass resonances into the observed quarkonium yield and the B-hadrons decay into charmonium. Furthermore other hot and cold matter effects can play a role, competing with the suppression mechanism.

On one hand, increasing the center of mass energy of the collisions ($\sqrt{s}$), an increase of the production of c and $\overline{c}$ quarks is expected. Therefore, in high-$\sqrt{s}$ collisions the abundance of c and $\overline{c}$ quarks might lead to a new charmonium production source, due to the (re)combination of these quarks during the collision history [3] or at the hadronization [4, 5]. This additional charmonium production source, taking place in a hot medium, contributes by enhancing the J/ψ yields and might counterbalance the suppression mechanism.

On the other hand, charmonium production is also affected by several effects related to cold matter (the so-called cold nuclear matter effects, CNM). For example, the production cross section of the $q\overline{q}$ pair is influenced by the kinematic distributions of partons in the nuclei, which are different from those in free protons and neutrons (this effect is known as nuclear shadowing [6–9]). In a similar way, approaches based on the Color-Glass Condensate effective theory [10, 11] assume that a gluon saturation effect is expected to set in at high energies. This effect influences the quarkonium production occurring through fusion of gluons carrying small values of the Bjorxen-x in the nuclear target.

[a] e-mail: arnaldi@to.infn.it

Furthermore, parton energy loss may decrease the pair momentum [12, 13], causing a reduction of the quarkonium production at large momenta. Finally, while the $q\bar{q}$ pair evolves towards the final quarkonium state, it may also interact with the medium and eventually break-up. This effect is expected to play a dominant role only for low-$\sqrt{s}$ collisions, where the crossing time of the (pre)-resonant state in the nuclear environement is rather large.

Cold nuclear matter effects are investigated in proton-nucleus collisions, where no hot medium is expected to be formed. Since these effects are present also in nucleus-nucleus interactions, a precise knowledge of their role is crucial in order to correctly quantify the effects related to the formation of a hot QCD medium.

The in-medium modification of quarkonium production, induced by either hot or cold matter effects, is usually quantified through the nuclear modification factor $R_{\rm AA}$ defined as the ratio of the quarkonium yield in A-A collisions ($Y_{\rm AA}^{q\bar{q}}$) and the expected value obtained scaling the pp yield ($Y_{\rm pp}^{q\bar{q}}$) by the average number of nucleon-nucleon collisions ($\langle N_{\rm coll}\rangle$), evaluated through a Glauber model calculation [14]:

$$R_{\rm AA} = \frac{Y_{\rm AA}^{q\bar{q}}}{\langle N_{\rm coll}\rangle \times Y_{\rm pp}^{q\bar{q}}} \qquad (1)$$

$R_{\rm AA}$ is expected to be equal to unity if the quarkonium yield in A-A scales with the number of nucleon-nucleon collisions, while $R_{\rm AA}$ different from unity implies that the quarkonium production is affected by the medium.

Studies performed since thirty years first at the SPS ($\sqrt{s_{NN}}$=17 GeV) and then at RHIC facilities ($\sqrt{s_{NN}}$=39-200 GeV) have, indeed, shown a reduction of the J/ψ production yield beyond the expectations due to cold nuclear matter effects (as nuclear shadowing and $c\bar{c}$ break-up) [15–18]. Even if the center of mass energies are very different, the amount of suppression observed by SPS and RHIC experiments is similar [19]. Furthermore, unexpectedly, a stronger J/ψ suppression has been measured, at RHIC, at forward with respect to mid-rapidity (y), in spite of the higher energy density which is reached close to y ~0. These observations suggest the existence of the previously mentioned (re)combination process, which might set in already at RHIC energies and which can counteract the quarkonium suppression in the QGP.

The measurement of charmonium production is, therefore, especially promising at the LHC, where the high-energy density of the medium and the large number of $c\bar{c}$ pairs produced in central Pb-Pb collisions should help to disentangle suppression and (re)combination scenarios.

2 Charmonium studies at LHC energies

All the four main LHC experiments (ALICE, ATLAS, CMS and LHCb) have carried out studies on quarkonium production either in Pb-Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV or in p-A collisions at $\sqrt{s_{NN}}$= 5.02 TeV. Quarkonium production has also been investigated in pp interactions at various energies as $\sqrt{s}$= 2.76, 7 and 8 TeV (not covered in this proceeding). The four experiments are characterized by different kinematic coverages, allowing us to investigate quarkonium production over ~4 rapidity units, from 0 to high transverse momentum ($p_{\rm T}$).

ATLAS [20] and CMS [21–23] are designed to measure quarkonium production reconstructing the various states in their dimuon decay channel. They both cover the mid-rapidity region: depending on the quarkonium state under study and on the $p_{\rm T}$ range investigated, the CMS rapidity coverage can reach up to $|y|$<2.4, and a similar y range is also covered by ATLAS. ALICE [24, 25] measures quarkonium in two rapidity regions: at mid-rapidity ($|y|$<0.9) in the dielectron decay channel and at forward rapidity (2.5<y<4) in the dimuon decay channel, in both cases down to zero transverse momentum. LHCb has taken part only to the pp and p-A LHC programs and results on quarkonium production, reconstructed through the dimuon decay channel, are provided at forward rapidity, i.e. 2<y<4.5 [26].

2.1 J/ψ production in Pb-Pb collisions

ALICE has studied the centrality dependence of the inclusive J/ψ (prompt J/ψ plus those coming from B-hadron decays) production in Pb-Pb collisions. The corresponding nuclear modification factor, as a function of the number of participant nucleons (N_{part}) [25], is shown in Fig. 1 for the forward (left) and the mid-rapidity (right) regions. The R_{AA} centrality dependence is compared to the one observed by the PHENIX experiment [18] in similar kinematic ranges. At low energy there is an increasing

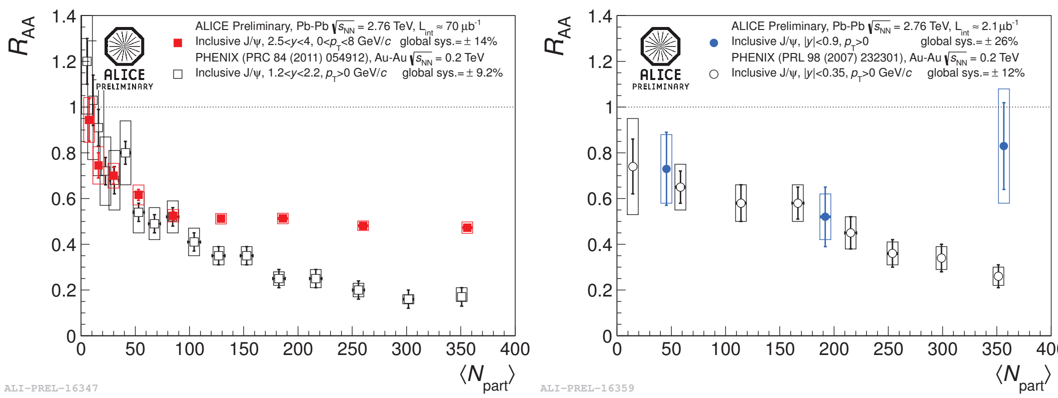

Figure 1. ALICE [25] (closed symbols) and PHENIX [18] (open symbols) inclusive J/ψ nuclear modification factor versus the number of participant nucleons, at forward rapidity (left) and at mid-rapidity (right).

suppression moving towards central collisions, while ALICE result indicates a saturation both at forward and at mid-rapidity. In the two y ranges there is a clear evidence for a smaller suppression at LHC with respect to RHIC energy. However, no final conclusion can be drawn on the relative size of the suppression measured in ALICE at forward or mid-rapidity, mainly due to the large normalization error corresponding to the uncertainty associated to the reference pp cross section used in the R_{AA} evaluation. Partonic transport models which include a (re)generation process for J/ψ due to the (re)combination of $c\bar{c}$ pairs along the history of the collisions indeed predict such a behaviour [27–29], the smaller suppression at the LHC being due to the larger $c\bar{c}$ pair multiplicity which compensates the suppression from color screening in the deconfined phase. A similar behaviour is expected by the statistical model [5], where the J/ψ yield is completely determined by the chemical freeze-out conditions and by the abundance of $c\bar{c}$ pairs.

The (re)combination process is expected to be dominant in central collisions and, for kinematical reasons, it should contribute mainly at low p_T, becoming negligible as the J/ψ p_T increases. This behaviour is investigated by further studying the R_{AA} p_T-dependence, as shown in Fig.2 (left). Models including a p_T-dependent contribution from (re)combination, amounting to ~50% [27, 28] at low p_T, provide, also in this case, a reasonable description of the data.

CMS measures high-p_T prompt J/ψ (p_T>6 GeV/c) [21–23], i.e. J/ψ in a kinematic region where (re)combination should play a negligible role. Contrarily to what is observed by ALICE, the J/ψ

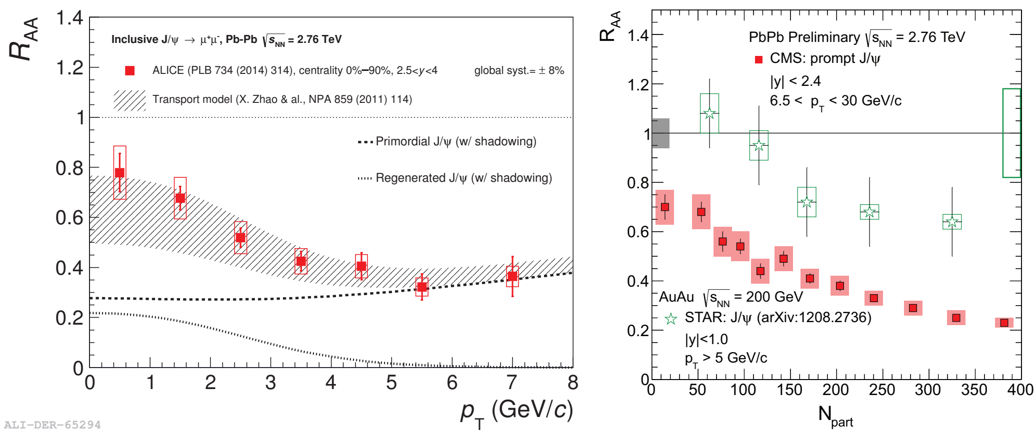

Figure 2. ALICE inclusive J/ψ R_{AA}, measured in the forward rapidity region, versus p_T [25], compared to theoretical calculations [27] (left). CMS prompt J/ψ R_{AA} versus centrality [21, 22] compared to the results of the STAR experiment [30] (right).

yield is indeed increasingly suppressed towards the most central collisions, as shown in Fig. 2 (right). Furthermore, as expected in a scenario where the (re)combination process is not dominant, for high p_T J/ψ the suppression is stronger at LHC energies by up to a factor ~3 with respect to RHIC energies, as it can be deduced from the comparison with the results from the STAR experiment, obtained in Au-Au collisions at $\sqrt{s_{NN}}$= 200 GeV [30].

The R_{AA} results previously discussed can be considered as strong hints for an important contribution of (re)combined J/ψ at low p_T, setting in at LHC energies. An independent confirmation of this hypothesis comes from the study of the J/ψ elliptic flow (v_2). If (re)combination effects are sizeable, then the corresponding J/ψ would inherit the flow related to the collective expansion, which is experienced by the charm quarks contained in the fireball [31]. Theoretical models predict in this case a non-zero v_2 for the J/ψ at intermediate p_T [32]. While STAR results for the v_2 of the inclusive J/ψ are compatible with zero everywhere [33], a hint for a non-zero v_2 can be appreciated at intermediate p_T in the ALICE results [34], as shown in Fig. 3 (left). Depending on the adopted binning for the study, the significance, of the ALICE results for non-zero v_2 reaches about 3σ. This result, complementing the study of the R_{AA} behaviour, suggests that a large fraction of the observed J/ψ is produced from deconfined charm quarks in the QGP phase. Also CMS measures a significant J/ψ v_2 [35]. However, since CMS measures charmonium in a kinematic region where (re)combination should be negligible, this observation can be interpreted in terms of path-length dependence of the J/ψ suppression.

2.2 ψ(2S) production in Pb-Pb collisions

Further insight on charmonium production in Pb-Pb collisions can be achieved comparing the production yields of a higher mass resonance, as the ψ(2S), to the J/ψ ones. Results, presented as a double ratio of the ψ(2S) to J/ψ yields in Pb-Pb and in pp collisions as a function of centrality, are shown in Fig.3 (right) for both ALICE [25] and CMS [36]. CMS observes values higher than one in the region $1.6<|y|<2.4$, $3<p_T<30$ GeV/c, while results obtained in the range $|y|<1.6$ and $6.5<p_T<30$ GeV/c show a decreasing pattern towards most central collisions. ALICE explores a contiguous range in rapidity ($2.5<y<4$) and also extend the p_T reach of this measurement down to zero. Unfortunately, the

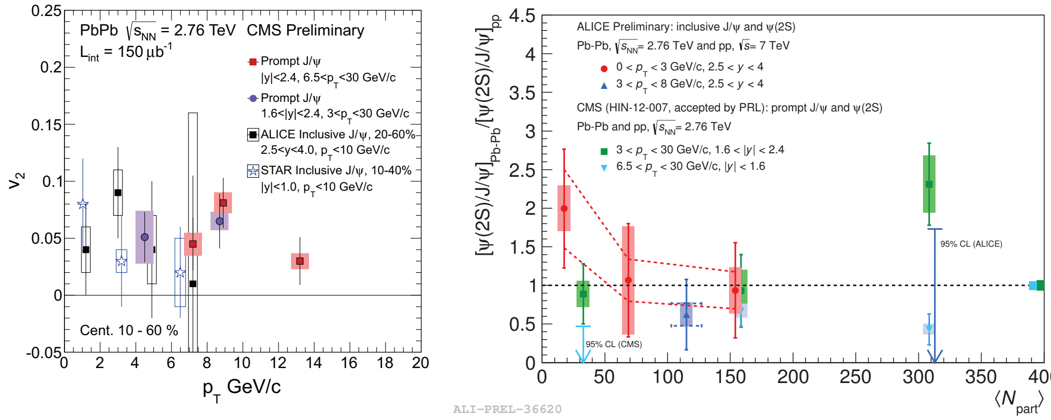

Figure 3. J/ψ v_2 versus p_T measured by ALICE [34], CMS [35] and STAR [33] experiments (left). ALICE and CMS double ratio ψ(2S) to J/ψ in Pb-Pb and pp collisions as a function of centrality and in p_T bins [25, 36] (right).

large statistics and systematic uncertainties associated to the ψ(2S) measurement preclude the drawing of strong conclusions on the $\psi(2S)$ behavior and on its kinematic dependence. The incoming LHC Run-II will surely be helpful to get further insight on this topic.

2.3 J/ψ production in p-Pb collisions

To correctly quantify the influence of hot matter effects, a precise knowledge of the cold matter effects is needed. This study can be addressed thanks to the recent LHC p-Pb run at $\sqrt{s_{NN}}$= 5.02 TeV. Similarly to what is done to quantify how the medium affects quarkonium production in Pb-Pb collisions, cold nuclear matter effects are investigated through the nuclear modification factor $R_{\rm pA}$. In this case, since no pp data at $\sqrt{s}$= 5.02 TeV were collected, the pp reference is obtained interpolating at $\sqrt{s}$= 5.02 TeV results collected at higher and lower energies.

J/ψ $R_{\rm pA}$ has been studied by both ALICE [37] and LHCb [26]. ALICE results in the center of mass rapidity ranges 2.03<$y_{\rm cms}$<3.53 and -4.46<$y_{\rm cms}$<-2.96 are shown in Fig.4 (left). The positive (negative) rapidity region corresponds to the data collected, inverting the beam directions, with the proton (Pb) beam going towards the ALICE muon spectrometer. While at forward rapidity a suppression of the J/ψ yield with respect to the pp binary scaled one is observed, no suppression in visible in the backward region. LHCb has also evaluated the prompt J/ψ $R_{\rm pA}$ [26], showing a similar trend as the one observed by ALICE. Results are compared with theory predictions, based on a pure nuclear shadowing scenario [38], as well as partonic energy loss, either in addition to shadowing or as the only nuclear effect [39]. A model including pure nuclear shadowing and a suppression term due to the break-up of the $c\bar{c}$ pair is also compared to the data [40], showing that the at LHC energies this latter contribution should be very small or even negligible. Finally, results from a calculation in the CGC framework [41] are also shown. Within the $R_{\rm pA}$ uncertainties, both the model based on shadowing only and the coherent energy loss approach are able to reasonably describe the data, while the CGC-based prediction overestimates the observed suppression.

The J/ψ nuclear modification factor has also been studied as a function of the transverse momentum, in the rapidity ranges covered by ALICE (2.03<$y_{\rm cms}$<3.53, -1.37<$y_{\rm cms}$<0.43 and -4.46<$y_{\rm cms}$<-

2.96). Forward and mid-rapidity results show a suppression with respect to the pp yield, which decreases with increasing p_T, while at backward rapidity no significant suppression is observed.

The R_{pA} results are a valuable tool to improve our understanding of the cold nuclear matter effects underlying the J/ψ suppression observed in Pb-Pb collisions. Under the reasonable assumption that shadowing is the main CNM effect and that its effect on the two colliding nuclei in Pb-Pb collisions can be factorized, the product of the forward and backward nuclear modification factors ($R_{pA} \times R_{Ap}$) can be qualitatively considered as an estimate of the CNM effects in Pb-Pb collisions at forward rapidity. As shown in Fig. 4 (right), the extrapolation of CNM effects shows a clear p_T-dependence, corresponding to a strong suppression at low p_T, vanishing at high p_T. The measured R_{AA} trend is rather different, indicating that at high-p_T the suppression observed in Pb-Pb is much larger than the one induced by CNM effects. At low p_T there might be even a hint of suppression smaller than the one due to CNM effects, consistent with the presence of (re)combination effects.

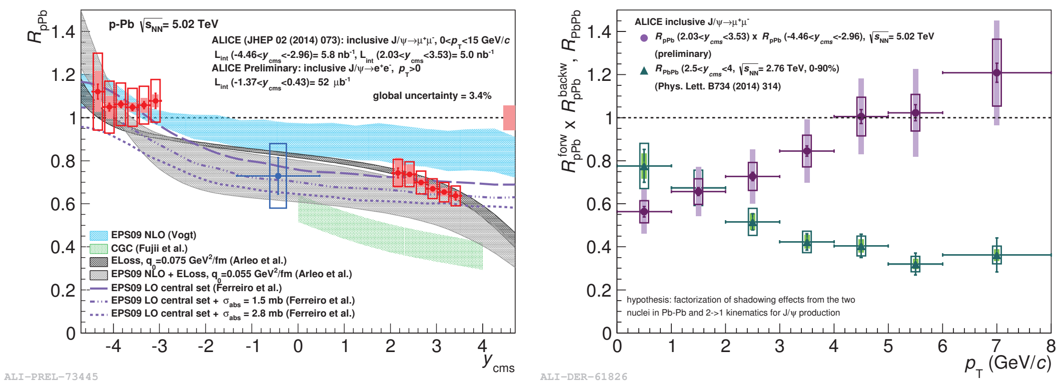

Figure 4. J/ψ R_{pA} as a function of rapidity, compared to various theoretical calculations (see text for details) (left). Estimate of the p_T-dependence of the CNM effects evaluated as $R_{pA} \times R_{Ap}$, compared to the R_{AA} (right).

2.4 ψ(2S) production in p-Pb collisions

ALICE has also investigated the ψ(2S) production in p-Pb collisions [42] and results are compared to the J/ψ ones. At RHIC or LHC energies, the time spent by the $c\bar{c}$ pair in the created medium is much shorter that the time needed to the pair to evolve into a fully formed resonance state as the J/ψ or the ψ(2S). Therefore, cold nuclear matter effects affect only the pre-resonant state and are expected to be very similar for the two charmonium states. ψ(2S) measurements performed by the PHENIX experiment [43], as double ratio of the ψ(2S) and J/ψ yields in d-Au and pp collisions, indicates that the ψ(2S) is unexpectedly affected by the medium in a stronger way than the J/ψ. As visible in Fig. 5 (left), a similar effect is observed also at LHC energies: the ALICE result shows a ψ(2S) more suppressed than the J/ψ to a 2.1 σ (3.5 σ) level at forward (backward) rapidity, while the PHENIX result show a similar feature at a 1.3 σ level. The suppression of charmonium states with respect to the corresponding pp yields can be quantified through the nuclear modification factors as shown in Fig. 5 (right). The ψ(2S) suppression is much stronger than the J/ψ one and it reaches a factor two with respect to pp. Results are compared to the aforementioned theoretical calculations based on nuclear shadowing and/or energy loss. All three models would predict an almost identical suppression for the ψ(2S) and the J/ψ over the full rapidity range. This prediction is in strong disagreement with

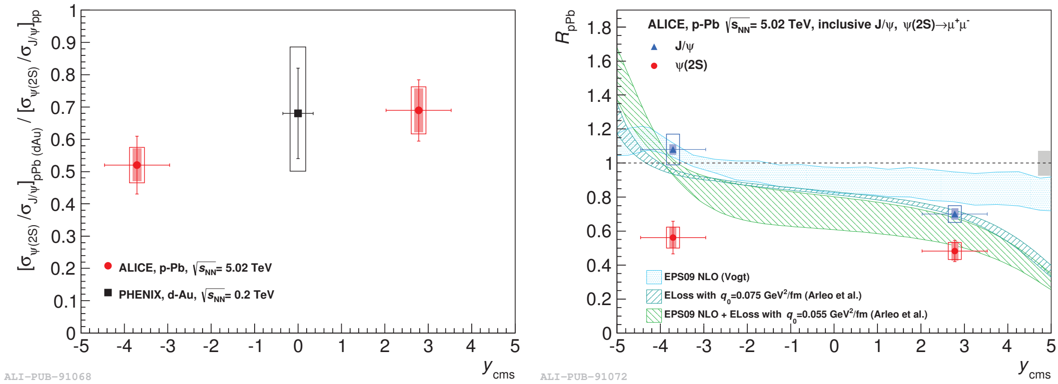

Figure 5. Double ratio of the ψ(2S) and J/ψ yields in p-Pb and pp collisions measured by PHENIX and ALICE (left). J/ψ and ψ(2S) nuclear modification factors as a function of rapidity, compared to theoretical calculations. See text for models'details (right).

the ALICE result, and clearly indicates that initial state nuclear effects alone cannot account for the modification of the ψ(2S) yields. Final state effects, such as the pair break-up by interactions with cold nuclear matter, might in principle lead to the observed effect, but the extremely short crossing times for the $c\bar{c}$ pair, in particular at forward rapidity, make such an explanation unlikely. Consequently, other final state effects should be considered, including the interaction of the $c\bar{c}$ pair with the final state hadronic system created in the proton-nucleus collisions.

3 Conclusions

First quarkonia measurements in heavy-ion collisions date back thirty years and have now been enriched by a large wealth of data from the LHC experiments, complementing SPS and RHIC results. A step further in the knowledge of how quarkonium is affected by the hot created medium can now be achieved, at LHC, comparing several quarkonium states in different, but complementary, kinematic regions. Results have shown that there are two competing processes playing a role in nucleus-nucleus collisions: the suppression in the deconfined medium and the (re)combination of q and $\overline{q}$ states. These two mechanisms have a different role depending on the quarkonium states and on the kinematic region under study. A deeper understanding of hot medium effects requires the knowledge of the underlying effects related to cold matter and present also in p-A interactions. The investigation of the J/ψ behaviour in proton-nucleus collisions has shown that several effects are at play, as nuclear shadowing and energy loss. These results can be used to provide a qualitative estimate of the influence of cold nuclear matter effects on the J/ψ suppression observed in Pb-Pb collisions. Under the assumption that shadowing represents the main CNM contribution, we find that it cannot account for the observed suppression in Pb-Pb, in particular at high p_{T}. The incoming Run-II at LHC will benefit of higher $\sqrt{s}$ energies, and the expected results will allow us to sharpen our knowledge, aiming to a coherent description of quarkonium production in a hot and deconfined medium, from low to very high energies.

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