

# Measurements of inclusive $J/\psi$ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE experiment

---

**Antonin Maire\***, for the ALICE Collaboration

*Physikalisches Institut - Heidelberg, Germany*

*E-mail: [antonin.maire@cern.ch](mailto:antonin.maire@cern.ch)*

Charmonium is a prominent probe of the Quark-Gluon Plasma (QGP), expected to be formed in ultrarelativistic heavy-ion (A–A) collisions. It has been predicted that the  $J/\psi(c\bar{c})$  particle is dissolved in the deconfined medium created in A–A systems. However this suppression can be counterbalanced via regeneration of the charm/anti-charm bound state in QGP or via statistical production at the phase boundary. At LHC energies, the latter mechanisms are expected to play a more important role, due to a charm production cross section significantly larger than at lower energies.

Measurements obtained by the ALICE experiment for inclusive  $J/\psi$  production are shown, making use of Pb–Pb data at  $\sqrt{s_{NN}} = 2.76$  TeV, collected in 2010 and 2011. In particular, the focus is given on the nuclear modification factor,  $R_{AA}$ , derived for forward ( $2.5 < y < 4$ ) and mid rapidities ( $|y| < 0.9$ ), both down to zero transverse momentum ( $p_T$ ). The centrality,  $y$  and  $p_T$  dependences of  $R_{AA}$  are presented and discussed in the context of theoretical models, together with PHENIX and CMS results.

*X<sup>th</sup> Quark Confinement and the Hadron Spectrum*

*8–12 October 2012*

*TUM Campus Garching, Munich, Germany*

---

\*Speaker.

## 1. Introduction : studying $J/\psi$ production in ultrarelativistic heavy-ion collisions

Ultrarelativistic heavy-ion (A–A) collisions are expected to give access to a medium where quarks and gluons are deconfined, the so-called Quark-Gluon Plasma (QGP). In order to test experimentally the deconfinement of the created medium, several signatures have been proposed. Among them, the melting of  $J/\psi$  within the QGP [1]. The idea is that colour screening in the medium prevents the bound states  $c\bar{c}$  to form. This results in a  $J/\psi$  production suppressed in A–A relative to the corresponding production in reference systems, like proton-proton (pp) or proton-nucleus (p–A) collisions (hadronic collisions without QGP). The idea developed for  $J/\psi$  can actually be extended to other charmonium and bottomonium states. The resulting suppression hierarchy is expected to depend on the binding energy of the considered quarkonium state. This leads to the notion of the *sequential melting* [2] : the states that are more weakly bound may dissociate in the deconfined medium from lower temperatures on (" $T_{diss}[\psi(2S)] \lesssim T_{diss}[\chi_{cJ}] < T_{diss}[J/\psi] \approx T_{diss}[\Upsilon(2S)] < T_{diss}[\Upsilon(1S)]$ ").

However, with experiments moving towards higher A–A collision energies ( $\sqrt{s_{NN}}$ ), possible scenarios for recombination of  $c$  with  $\bar{c}$  into charmonia must be considered [3]. Indeed, the total production of charm and anti-charm quarks becomes more and more abundant with  $\sqrt{s_{NN}}$  and, if recombination may appear non-negligible already at RHIC energies, it is expected to be sizeable at the LHC. There are basically two complementary approaches to describe the (re)generation of charmonium :

- *thermal models* : charm quarks are thermalised in the QGP and quarkonia are produced at the phase boundary via statistical hadronisation. The implicit hypothesis is that  $c\bar{c}$  is fully dissolved in the medium; the possibility to bind  $q$  with  $\bar{q}$  can only happen at the last stage of the collision [4].
- *transport models* : the binding and dissociation of  $c\bar{c}$  take place directly in the QGP, the competition being described by a transport equation. In other words, a partial survival of charmonium is complemented by a continuous regeneration [5–7].

## 2. Data analysis and experimental remarks

### 2.1 Detector setup and data collection

The  $J/\psi$  analyses presented in these proceedings make use of both di-lepton decay channels of  $J/\psi$  (see Tab. 1). The analysis at mid rapidity ( $|y_{J/\psi}| < 0.9$ ) is based on the  $e^+e^-$  channel. It hinges on the central-barrel detectors of the ALICE experiment [8] : the Inner Tracking System (ITS) and Time Projection Chamber (TPC), for tracking and the TPC and the Time Of Flight detector (TOF), to identify electrons and partially remove contamination by other particle species. The studies at forward rapidity ( $2.5 < y_{J/\psi} < 4$ ) profit from the  $\mu^+\mu^-$  channel. They rely on detectors placed beyond an absorber, *i.e.* muon-tracking and muon-trigger chambers.

In both cases, the analysed data samples are Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. For mid rapidity, this is a combination of data collected in 2010 ( $L_{int} \approx 2 \mu\text{b}^{-1}$ ) and 2011 ( $L_{int} \approx 13 \mu\text{b}^{-1}$ , *i.e.* about 60 % of Pb–Pb data collected that year). For forward rapidity, this is exclusively data taken in 2011 ( $L_{int} \approx 70 \mu\text{b}^{-1}$ ).

## 2.2 Remarks : low- $p_T$ reach and *inclusive* $J/\psi$ measurement...

It must be noted that the ALICE acceptance enables the  $J/\psi$  identification down to zero transverse momentum ( $p_T$ ) in both rapidity ranges, *i.e.* in the phase space region where the bulk of charmonium is produced. This is a unique feature of the experiment for what concerns A–A at the LHC.

	Particles	mass (GeV/ $c^2$ )	$c \cdot \tau$ or width	decay channel	B.R.
prompt ↑ ↓	$J/\psi$ ( $c\bar{c}$ )	3.097	92.9 keV/ $c^2$	$J/\psi \rightarrow e^+e^-$	5.94 %
				$J/\psi \rightarrow \mu^+\mu^-$	5.93 %
	$\chi_{c0}$ ( $c\bar{c}$ )	3.415	10.4 MeV/ $c^2$	$\chi_{c0} \rightarrow J/\psi(1S)\gamma$	1.17 %
	$\chi_{c1}$ ( $c\bar{c}$ )	3.511	0.86 MeV/ $c^2$	$\chi_{c1} \rightarrow J/\psi(1S)\gamma$	34.4 %
	$\chi_{c2}$ ( $c\bar{c}$ )	3.556	1.98 MeV/ $c^2$	$\chi_{c2} \rightarrow J/\psi(1S)\gamma$	19.5 %
	$\psi(2S)$ ( $c\bar{c}$ )	3.686	304 keV/ $c^2$	$\psi(2S) \rightarrow J/\psi + anything$	59.5 %
non-prompt	$B^0$ ( $d\bar{b}$ )	5.280	455 $\mu\text{m}$	$B^0, B^\pm, B_s^0 \rightarrow J/\psi + anything$	1.16 %
	$B^+$ ( $u\bar{b}$ )	5.279	492 $\mu\text{m}$		
	$B_s^0$ ( $s\bar{b}$ )	5.367	449 $\mu\text{m}$		

**Table 1:** Main characteristics of particles contributing to the *inclusive*  $J/\psi$  signal [9]. The table includes mass, decay length or resonance width, as well as considered decay channel and corresponding Branching Ratio (B.R.).

The measurements presented in the following are for *inclusive*  $J/\psi$ , *i.e.* not only for direct  $J/\psi$  production but also  $J/\psi$  fed down from decays of particles with higher mass. As presented in Tab. 1, two components can be distinguished :

- *the prompt component* for which the production vertex cannot be separated experimentally from the primary interaction region; it includes  $J/\psi$  issued by prompt decays of  $\chi_{c_i}$  and  $\psi(2S)$ , together with primary  $J/\psi$ ;
- *the non-prompt component*, originating from beauty mesons, with a decay length which is large enough to allow a possible discrimination between the decay vertex and the primary one.

For an inclusive measurement, with a  $J/\psi$  momentum ranging from  $p_T = 0$  to about 8 GeV/ $c$ , experimental data<sup>1</sup> at TeV scale suggest that the inclusive  $J/\psi$  yield has the following relative contributions: 35-55 % of direct production, 25-35 % from  $\chi_{c_i}$ , 10-15 % from  $\psi(2S)$  and 10-15 % from B mesons.

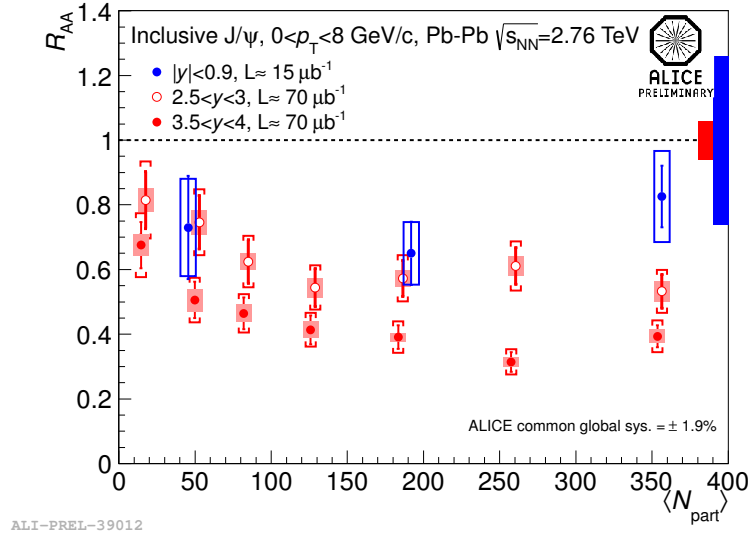
## 3. Experimental results : nuclear modification factor

The comparison of the  $J/\psi$  production in A–A and pp is studied via the nuclear modification factor,  $R_{AA}$ , defined as follows :

<sup>1</sup>In pp at the LHC or  $p\bar{p}$  at the Tevatron; there is no equivalent picture measured in A–A.

$$R_{AA}(p_T, y, \text{centrality class } i) = \frac{d^2N_i^{AA}(J/\psi)/dp_T dy}{\langle T^{AA} \rangle_i d^2\sigma^{PP}(J/\psi)/dp_T dy} \quad (3.1)$$

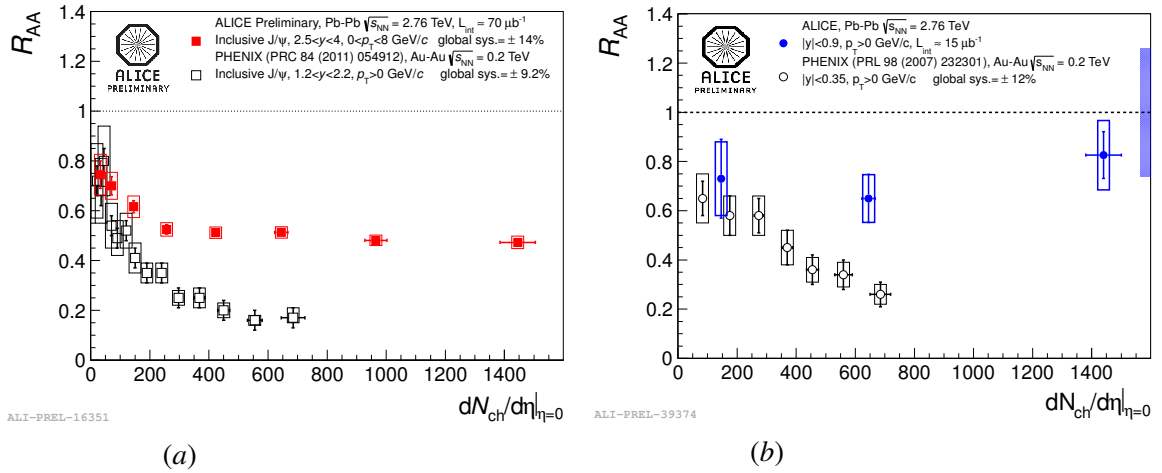
with the  $J/\psi$  yields in Pb–Pb at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV as the basis of the present measurements. The study can be performed differentially as functions of collision centrality, rapidity and/or momentum, depending on the collected data statistics. The values of the nuclear overlap function  $\langle T^{AA} \rangle_i$  are derived from a Glauber Model, for each centrality interval, and correspond to a normalisation of Pb–Pb yields to the adapted number of *binary* nucleon-nucleon collisions. As for the pp reference, the inclusive  $J/\psi$  cross sections,  $\sigma^{PP}(J/\psi)$ , are taken from [10], measured also at  $\sqrt{s} = 2.76$  TeV, for both mid and forward rapidity.



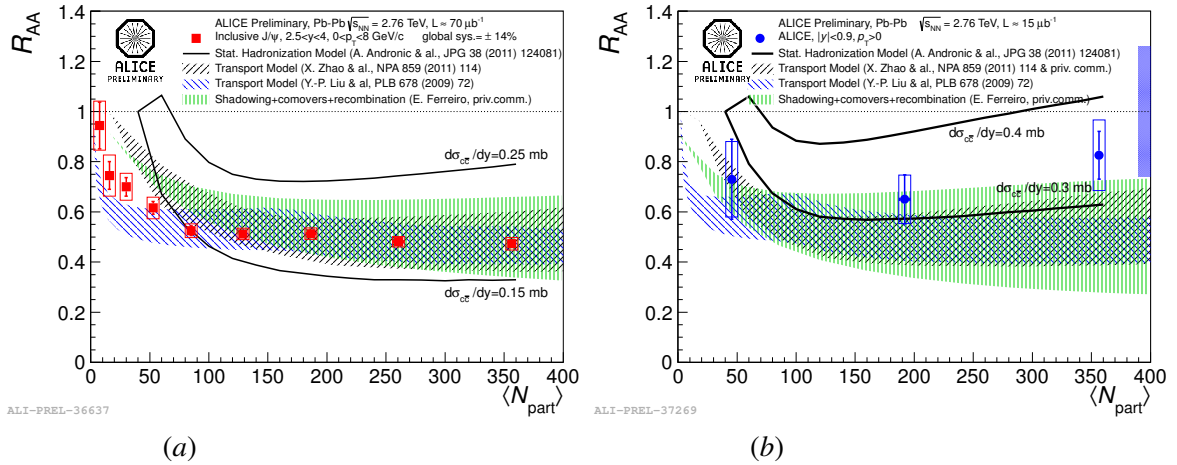
**Figure 1:** Nuclear modification factor  $R_{AA}$  for inclusive  $J/\psi$  as a function of collision centrality, measured by the ALICE experiment in Pb–Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV, in three rapidity intervals ranging from forward to mid rapidity. Vertical error bars stand for statistical uncertainties; blue empty boxes, for systematic uncertainties; red brackets and shaded boxes, for partially correlated and uncorrelated systematic uncertainties, respectively. The filled boxes sitting at unity indicate the respective pp reference uncertainties.

The figure 1 shows  $R_{AA}$  of inclusive  $J/\psi$  extracted for three rapidity ranges – from most forward to mid  $y$  – as a function of centrality, embodied here by the average number of nucleons participating in a Pb–Pb collision,  $\langle N_{part} \rangle$ . One can observe a weak centrality dependence of the suppression, for each rapidity interval, and a suppression which seems less and less pronounced while going towards mid rapidity. Note that, for the results derived at mid rapidity, the uncertainties remain rather significant and dominated by systematic uncertainties related to the pp reference as well as the signal extraction in Pb–Pb.

The centrality dependence of  $R_{AA}$  in ALICE can be compared to PHENIX results obtained for Au–Au collisions at lower energies ( $\sqrt{s_{\text{NN}}} = 0.2$  TeV). This is presented in Fig. 2, where the charge particle density,  $dN_{ch}/d\eta$ , at mid rapidity is used as centrality observable. The figure exhibits a centrality dependence which is clearly different between ALICE and PHENIX data; in particular, the 0.2 TeV  $R_{AA}$  in most central collisions appears noticeably lower, in each rapidity region, than the equivalent quantity at 2.76 TeV. This pattern is in contrast with the expectations based solely on



**Figure 2:** Centrality dependence of ALICE  $R_{AA}$  (inclusive  $J/\psi$ ) at (a) forward rapidity, compared with equivalent PHENIX results [11] and (b) mid rapidity, compared with corresponding PHENIX results [12].

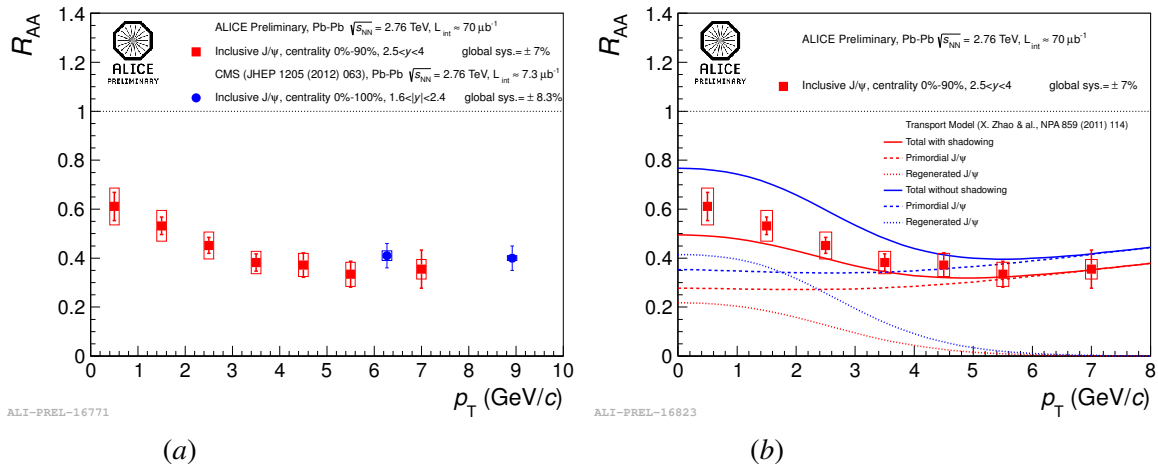


**Figure 3:** ALICE centrality dependence for  $R_{AA}$  (inclusive  $J/\psi$ ) compared with several models (thermal [13], transport [7, 14] and co-movers [15]), at (a) forward rapidity and (b) mid rapidity.

the colour screening model, for which higher energy density (higher  $dN_{ch}/d\eta$ ) implies a stronger suppression.

This trend indicating less suppression at the LHC can be explained by several models, as plotted in Fig. 3 : whether it deals with statistical hadronisation [13], transport [7, 14] or co-mover [15] models, a fair agreement seems to be found between LHC data and phenomenological descriptions. It should be noticed that every model incorporates a significant fraction<sup>2</sup> of  $c$  and  $\bar{c}$  recombination for most central collisions. Any further interpretation and discrimination between models is precluded by uncertainties, on data, but also on models. For instance, all of them are almost equivalently affected by the uncertainty of the total  $c, \bar{c}$  production cross section, *i.e.* the absence of accurate measurements covering open charm ( $D^0, D^+, D^*, D_s^+$  mesons and  $\Lambda_c^+$  baryon) and hidden charm (the whole charmonium family) over a wide region of phase space.

<sup>2</sup>By construction, it is 100 % in the case of statistical models.



**Figure 4:**  $p_T$  dependence of ALICE  $R_{AA}$ (inclusive  $J/\psi$ ) at forward rapidity, integrated over all collision centralities (a) compared with CMS [16] and (b) compared to a transport model [7].

With the current data, a last item to complement the description of  $R_{AA}$ (inclusive  $J/\psi$ ) can be added though. The figure 4 displays the  $p_T$  dependence of the nuclear modification factor, for the forward rapidity region, in a wide centrality interval (0-90%). The resulting differential measurements span from 0 to 8 GeV/c and overlap at high  $p_T$  with the corresponding result (under similar centrality and rapidity selections) by the CMS collaboration [16] (Fig. 4 a). Looking at the detailed comparison with one transport approach [7] (Fig. 4 b), data seem to be correctly reproduced by theory. Based on the given model, the agreement suggests that  $J/\psi$  regeneration phenomena may essentially vanish from 5-6 GeV/c on, whereas they should account for a sizeable contribution ( $\approx 50\%$ ) for  $p_T < 3$  GeV/c. Considering recombination as a mechanism preferentially working at low momentum, this emphasizes the importance of measuring  $J/\psi$  down to  $p_T = 0$  to test this kind of prediction.

#### 4. Final considerations : complementing the picture

While testing the original idea by Matsui and Satz of  $J/\psi$  suppression in QGP, the study of  $J/\psi$  in A–A collisions at LHC energies may be examined from two other angles.

On the one hand, at high  $p_T$ ,  $J/\psi$  appears as the "hidden charm" piece in the puzzle of identified-hadron  $R_{AA}$ . Can we confirm or invalidate with proper accuracy a high- $p_T$  picture like :

$$R_{AA}[h^\pm] < R_{AA}[D] \approx R_{AA}[\text{prompt } J/\psi] \approx R_{AA}[\psi(2S)] < R_{AA}[B \rightarrow J/\psi] < R_{AA}[\Upsilon(1S)]$$

The question is the flavour dependence and hierarchy of the suppression for particles at high momentum ( $p_T > 6$  GeV/c), ranging from gluons ( $R_{AA}[h^\pm]$ , [17]) up to the hidden beauty ( $R_{AA}[\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)]$ , [18]) via open charm ( $R_{AA}[D]$ , [19]) and open beauty ( $R_{AA}[J/\psi \text{ from } B]$ , [16]).

On the other hand, at low  $p_T$ , studies may address the question related to thermalisation of charm quarks. On this aspect, the discussion must be enriched by  $R_{AA}$  measurements of other charmonium (*e.g.*  $\psi(2S)$  [20]) together with measurement of elliptic flow of charm species. In that sense, the ALICE Preliminary measurement indicating a non-zero elliptic flow (significance close to  $3\text{-}\sigma$  in 20-40 % Pb–Pb collisions with  $p_T(J/\psi) > 1.5$  GeV/c [21]) is certainly a prominent result

that will be closely followed in the future.

Last but not least, one should conclude the discussion with the relevance of  $J/\psi$  measurements in p–A collisions. Nothing has been mentioned so far on the studies related to this system whereas p–A collisions define a crucial experimental milestone on the way going from pp to A–A collisions. There are *non-QGP* effects foreseen in A–A collisions : parton distribution functions in nuclei can be modified (lowering of the  $J/\psi$  production probability due to parton shadowing in the nucleus), incident parton can loose energy in nucleus before the hard scattering, ... All these phenomena can be labelled as *Cold Nuclear Matter* (CNM) effects.

In RHIC data, CNM effects are expected to explain for a large part the inclusive  $J/\psi$  suppression seen in most central Au–Au collisions at  $\sqrt{s_{NN}} = 0.2$  TeV (see for instance Fig. 87 and 88, p. 126 of [22]). At LHC energies, the same phenomena may account for a less dramatic effect but this has to be confirmed experimentally. For that purpose, results from p–A data taking occurring at the LHC early 2013 will certainly act as as the keystone of the  $J/\psi$  picture currently emerging with A–A data at TeV scale.

## References

- [1] T. Matsui and H. Satz, *J/ψ suppression by Quark-Gluon Plasma formation*, *Phys. Lett. B* **178** (1986) 416. [DOI link](#).
- [2] A. Mocsy and P. Petreczky, *Color Screening Melts Quarkonium*, *Phys. Rev. Lett.* **99** (2007) 211602, [[arXiv:0706.2183](#)]. [DOI link](#).
- [3] P. Braun-Munzinger and J. Stachel, *(Non)Thermal Aspects of Charmonium Production and a New Look at J/ψ Suppression*, *Phys. Lett. B* **490** (2000) 196–202, [[nucl-th/0007059](#)]. [DOI link](#).
- [4] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, *Evidence for charmonium generation at the phase boundary in ultra-relativistic nuclear collisions*, *Phys. Lett. B* **652** (2007) 259–261, [[nucl-th/0701079](#)]. [DOI link](#).
- [5] R. L. Thews, M. Schroedter, and J. Rafelski, *Enhanced J/ψ Production in Deconfined Quark Matter*, *Phys. Rev. C* **63** (2001) 054905, [[hep-ph/0007323](#)]. [DOI link](#).
- [6] B. Chen, K. Zhou, and P. Zhuang, *Mean Field Effect on J/ψ Production in Heavy Ion Collisions*, *Phys. Rev. C* **86** (2012) 034906, [[arXiv:1202.3523](#)]. [DOI link](#).
- [7] X. Zhao and R. Rapp, *Medium Modifications and Production of Charmonia at LHC*, *Nucl. Phys. A* **859** (June, 2011) 114–125, [[arXiv:1102.2194](#)]. [DOI link](#).
- [8] ALICE collab., *The ALICE experiment at the CERN LHC*, *J. of Instrum.* **3** (2008) S08002. [DOI link](#).
- [9] Particle Data Group collab., *Review of Particle Physics*, *Phys. Rev. D* **86** (2012) 010001. [pdg.lbl.gov](#), [DOI link](#).
- [10] ALICE collab., *Inclusive J/ψ production in pp collisions at  $\sqrt{s} = 2.76$  TeV*, *Phys. Lett. B* **718** (2012) 295–306, [[arXiv:1203.3641](#)]. [DOI link](#).
- [11] PHENIX collab., *J/ψ suppression at forward rapidity in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV*, *Phys. Rev. C* **84** (2011) 054912, [[arXiv:1103.6269](#)]. [DOI link](#).
- [12] PHENIX collab., *J/ψ production vs centrality, transverse momentum, and rapidity in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV*, *Phys. Rev. Lett.* **98** (2007) 232301, [[nucl-ex/0611020](#)]. [DOI link](#).

- [13] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, *The thermal model on the verge of the ultimate test: particle production in Pb–Pb collisions at the LHC*, in *Quark Matter 2011*, vol. 38, p. 124081, J. Phys. G, 2011. [[arXiv:1106.6321](#)]. [DOI link](#).
- [14] Y. Liu, Z. Qu, N. Xu, and P. Zhuang,  *$J/\psi$  transverse momentum distribution in high energy nuclear collisions*, *Phys. Lett. B* **678** (2009) 72–76, [[arXiv:0901.2757](#)]. [DOI link](#).
- [15] E. Ferreira, *Charmonium dissociation and recombination at LHC: Revisiting comovers*, arXiv note, Update of arXiv:0712.4331, Dec. 2012. [arXiv:1210.3209](#).
- [16] CMS collab., *Suppression of non-prompt  $J/\psi$ , prompt  $J/\psi$ , and  $\Upsilon(1S)$  in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV*, *J. High Energy Phys.* **5** (2012) 63, [[arXiv:1201.5069](#)]. [DOI link](#).
- [17] ALICE collab., *Centrality dependence of charged particle production at large transverse momentum in Pb–Pb Collisions at  $\sqrt{s_{NN}} = 2.76$  TeV*, [arXiv:1208.2711](#).
- [18] CMS collab., *Observation of sequential  $\Upsilon$  suppression in PbPb collisions*, [arXiv:1208.2826](#).
- [19] ALICE collab., *Suppression of high transverse momentum  $D$  mesons in central Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV*, *J. High Energy Phys.* **09** (2012) 112, [[arXiv:1203.2160](#)]. [DOI link](#).
- [20] R. Arnaldi (for the ALICE Collaboration),  *$J/\psi$  and  $\psi(2S)$  production in Pb-Pb collisions with the ALICE Muon spectrometer at the LHC*, in *Quark Matter 2012*. [[arXiv:1211.2578](#)].
- [21] H. Yang (for the ALICE Collaboration), *Elliptic flow of  $J/\psi$  at forward rapidity in Pb-Pb Collisions at  $\sqrt{s_{NN}} = 2.76$  TeV with the ALICE experiment*, in *Quark Matter 2012*. [[arXiv:1211.0799](#)].
- [22] N. Brambilla, S. Eidelman, B. Heltsley, R. Vogt, G. Bodwin, et al., *Heavy quarkonium: progress, puzzles, and opportunities*, *Eur. Phys. J. C* **71** (2011) 1534, [[arXiv:1010.5827](#)]. [DOI link](#).