Heavy-quark production in heavy-ion collisions

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Abstract. We present an overview of the phenomenology and experimental results on open heavy-flavour and quarkonium production in heavy-ion collisions at RHIC and at the LHC.

1. Introduction: what's special about heavy quarks

Heavy-flavour hadrons, containing a charm (c) or beauty (b) quark and a light quark, and quarkonia, bound states of a $c\bar{c}$ or $b\bar{b}$ pair, are effective probes of the properties of the hot and dense strongly-interacting medium formed in high-energy heavy-ion collisions.

Heavy quarks are produced in the early stage of the collision in primary partonic scatterings with large virtuality Q and, thus, on temporal and spatial scales, $\Delta\tau \sim \Delta r \sim 1/Q$, which are sufficiently small for the production to be unaffected by the properties of the medium, in the case of nucleus–nucleus collisions. In fact, the minimum virtuality $Q_{\rm min} = 2\,m_{\rm Q}$ in the production of a $\rm Q\overline{Q}$ pair implies a space-time scale of $\sim 1/(2\,m_{\rm Q}) \simeq 1/3$ GeV^{-1} $\simeq 0.1$ fm (for charm), to be compared to the expected lifetime of a few fm for the hot and dense medium at RHIC and LHC. In contrast to light quarks and gluons that can be produced or annihilated during the entire partonic phase of the medium, heavy quarks preserve their flavour and mass identity while traversing the medium and can be tagged via the measurement of heavy-flavour hadrons in the final state of the collision.

The two historical pillars of the high scientific relevance of heavy-flavour and quarkonium production studies in heavy-ion collisions are:

- The dead cone effect in radiative energy loss [1, 2]. This effect is predicted to suppress medium-induced gluon radiation off heavy quarks at small angles, thus reducing the quenching of heavy-flavour with respect to light-flavour hadrons.
- The colour screening effect on loosely-bound quarkonium states [3]. This mechanism would determine a suppression in the yield of charmonium and bottomonium states with a sequential pattern according to the binding energy of each state.

In the next section we will describe these concepts in more detail, along with briefly summarizing some other aspects of the rich phenomenology of heavy quarks. The rest of this writeup gives a (subjective and incomplete) overview of the most relevant observations made so far by the experimental collaborations at RHIC and LHC.

2. Heavy-quark production from proton–proton to nucleus–nucleus collisions

Given the large virtualities that characterize the production of heavy quarks, the production cross section of heavy-flavour hadrons in proton–proton collisions can be calculated in the framework of collinear factorization and perturbative QCD (pQCD). The ingredients of the calculations are: the parton distribution functions (PDFs) of the proton, evolved with pQCD starting from initial conditions based on deep inelastic scattering ep data; the partonic hard cross section, computed as a perturbative series of the strong coupling constant α_s; the non-perturbative fragmentation functions, which are parametrized from e^+e^- collision data. The state-of-the-art calculations, at fixed-order next-to-leading-log (FONLL) [4], describe well the production cross sections of open heavy-flavour hadrons (D and B mesons) measured at RHIC ($\sqrt{s}$ = 0.2 and 0.5 TeV), Tevatron (1.96 TeV) and LHC (2.76 and 7 TeV). In the case of quarkonia, it is not possible to separate between the partonic hard cross section and the hadronization function, because of the colour neutralization that is required to bind the $\mathrm{Q\overline{Q}}$ pair. This part of the process cannot be parametrized from e^+e^- data and it introduces an additional uncertainty in the calculations. The Colour Singlet + Colour Octet calculations at next-to-leading order, among others, provide a good description of the data [5].

For hard processes, in the absence of nuclear and medium effects, a nucleus–nucleus (AA) or proton–nucleus (pA) collision would behave as a superposition of independent nucleon–nucleon (NN) collisions. The heavy-flavour differential yields would then scale from pp to AA (or pA) proportionally to the number N_{coll} of inelastic NN collisions (binary scaling):

$$\mathrm{d}^2 N^{h_{\mathrm{Q}}}_{\mathrm{AA(pA)}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y = N_{\mathrm{coll}} \cdot \mathrm{d}^2 N^{h_{\mathrm{Q}}}_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y \,. \tag{1}$$

Several effects break down binary scaling. They are usually divided into two classes:

- Initial-state effects, such as nuclear shadowing, the modification of the parton distribution functions in the nucleus due to gluon recombination at small x. Nuclear shadowing is expected to be the dominant effect at RHIC and LHC energies. Other effects include k_{T}-broadening and nuclear absorption of quarkonium states. Initial-state effects (or cold nuclear matter effects) can be studied by comparing pp and pA collisions. Due to space limitations, experimental results on this study are not discussed in this writeup.
- Final-state effects, due to the interaction of the produced partons with the medium formed in the collision. Partonic energy loss by gluon radiation, elastic collisions with the medium constituents and colour screening in the medium are the most relevant effects for the heavy-flavour sector. These effects are expected to depend on the properties of the medium (gluon density, temperature and volume) and should, therefore, provide information on such properties.

The modification of the binary scaling is quantified using the nuclear modification factor

$$R_{\mathrm{AA}}(p_{\mathrm{T}}, y) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \cdot \frac{\mathrm{d}^2 N^{h_{\mathrm{Q}}}_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2 N^{h_{\mathrm{Q}}}_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \,. \tag{2}$$

Due to the QCD nature of parton energy loss, quarks are predicted to lose less energy than gluons (that have a higher colour charge) and, in addition, the dead-cone effect is expected to reduce the energy loss of massive quarks with respect to light partons [1,2]. Therefore, one should observe a pattern of gradually decreasing R_{AA} suppression when going from the mostly gluon-originated light-flavour hadrons (e.g. pions) to D and to B mesons [6]: $R^{\pi}_{\mathrm{AA}} < R^{\mathrm{D}}_{\mathrm{AA}} < R^{\mathrm{B}}_{\mathrm{AA}}$. A comparative study of the attenuation of various probes allows one to test the consistency of the interpretation of quenching effects as due to energy loss in a deconfined medium and to investigate the properties (density) of such a medium. Heavy quarks with moderate momenta ($p_{\mathrm{T}} < 10$ GeV/c) could be slowed down by in-medium interactions to the point of being sensitive to the collective expansion of the system and consequently might also reach thermal equilibrium with the medium constituents [7]. In addition, in this momentum range, hadronization may predominantly occur inside the medium via the mechanism of coalescence with other quarks present in the system, rather than via fragmentation in the vacuum outside the medium [7, 8]. The study of this effect may allow the degree of thermal equilibration of the partonic system formed in the collision to be assessed.

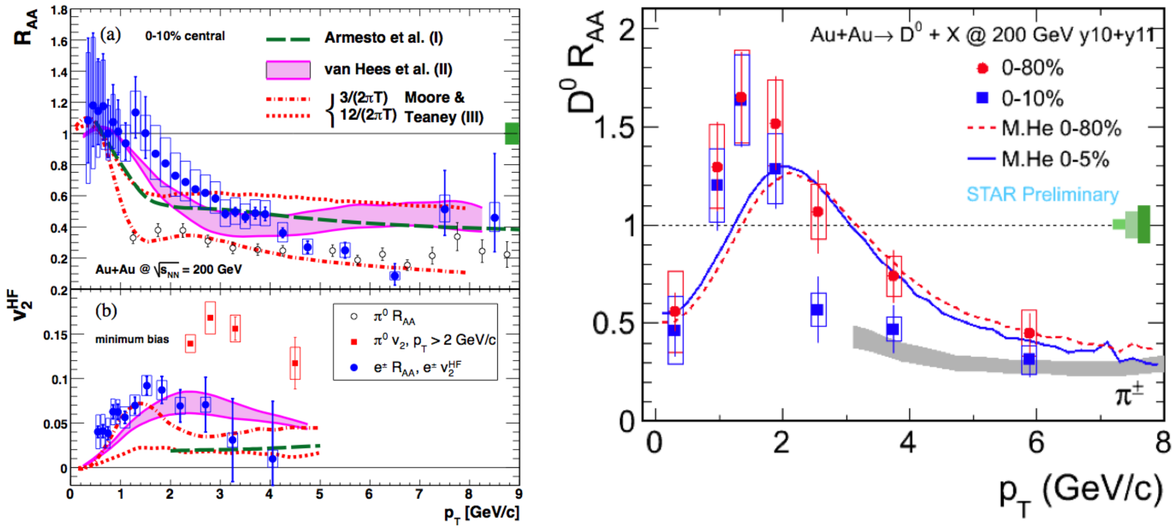

Figure 1. Open heavy-flavour production in Au–Au collisions at top RHIC energy, $\sqrt{s_{\rm NN}} =$ 200 GeV. Left: $R_{\rm AA}$ (top) and v_2 (bottom) of electrons from heavy-flavour decay, measured by PHENIX and compared with the same quantities for pions and with model calculations [13]. Right: $R_{\rm AA}$ of $\rm D^0$ mesons in central and minimum-bias collisions, measured by STAR [15] and compared with model calculations.

A significant $\rm J/\psi$ suppression beyond the estimated cold nuclear matter effects was first observed at the SPS [9]. At the higher centre-of-mass energies of RHIC and LHC, the most interesting items in the quarkonia sector are: (a) understanding the interplay between colour-screening-induced suppression and statistical regeneration for charmonium production in a medium containing a large number of $\rm c\overline{c}$ pairs [10]; (b) measuring medium effects on the bottomonium states. On this point, the predicted suppression pattern as a function of the medium temperature is particularly interesting: the Υ would melt at $T \approx 2\,T_c$ (where T_c is the critical temperature of the QGP phase transition), a temperature that would be reached only at the LHC, while the Υ' would melt at the same temperature as the $\rm J/\psi$, $T \approx 1.2\,T_c$ (see e.g. [11, 12]). It is thus important to measure also the Υ', because, at variance with the $\rm J/\psi$, it is expected to have a small regeneration probability and it would be very useful to disentangle $\rm J/\psi$ suppression and regeneration. Measuring the in-medium dissociation probability of the different quarkonium states at RHIC and LHC would provide an estimate of the initial medium temperature. Hence, the idea of "quarkonium thermometer".

3. Open heavy-flavour production in nucleus–nucleus collisions at RHIC and LHC

In central Au–Au collisions at centre-of-mass energy $\sqrt{s_{\rm NN}} = 200$ GeV the PHENIX and STAR Collaborations measured a suppression of a factor up to 3–5 ($R_{\rm AA} \approx 0.2$–0.3) at $p_{\rm T} \simeq 5$ GeV/c for electrons from heavy-flavour hadron decays [13, 14]. This suppression is compatible with that of pions of similar transverse momentum. Figure 1 (left) shows in the upper panel the $R_{\rm AA}$ measured by PHENIX. The STAR Collaboration has recently presented also preliminary results for reconstructed $\rm D^0 \to K^-\pi^+$ decays [15]. The $R_{\rm AA}$ is shown in the right-hand panel of Fig. 1 for the central and minimum-bias collisions. For $p_{\rm T} > 3$ GeV/c the suppression of D mesons is consisted with that of pions. At $p_{\rm T} \approx 1$–2 GeV/c, $R_{\rm AA}$ exhibits an enhancement above unity. A model calculation implementing charm quark transport [16] in the medium captures the main features of the data.

At the LHC, the much larger production cross sections (of about a factor 10 for charm and a factor 30 beauty) and the presence of dedicated silicon vertex detectors in the ALICE, ATLAS

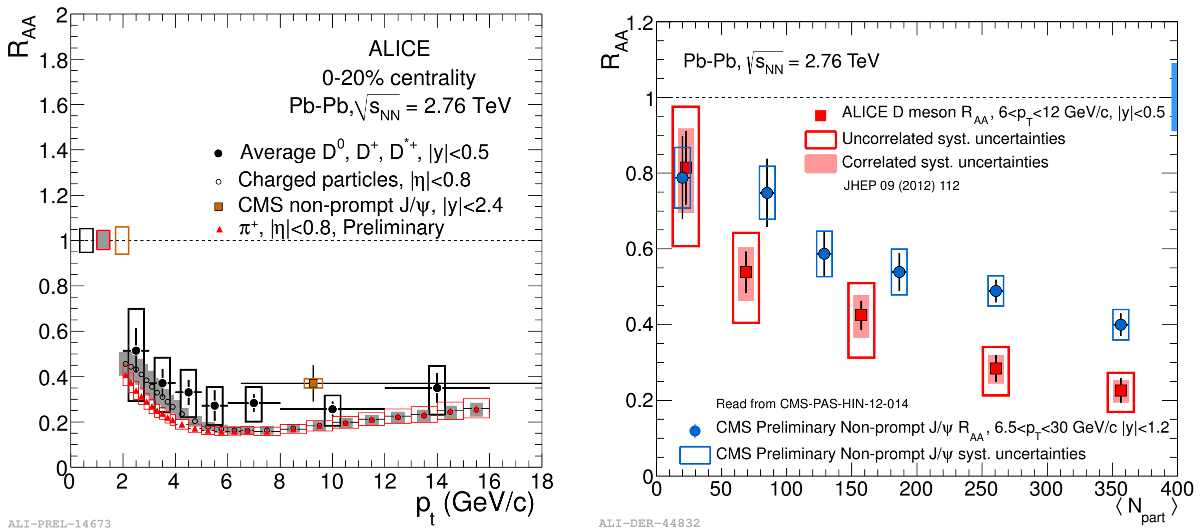

Figure 2. Charm and beauty production in Pb–Pb collisions at the LHC. Left: ALICE measurements of average R_{AA} of D mesons in the 0–20% centrality class [17], compared to that of charged particles [18], π^+, and non-prompt J/ψ from B decays, measured by CMS [19] in the same centrality class. Right: Average R_{AA} of D mesons as a function of centrality (ALICE [17]), compared to that of non-prompt J/ψ from B decays (CMS [20]).

and CMS experiments, allowed for heavy-flavour production measurements already in the first Pb–Pb run in 2010. These measurements are now being extended and improved with data from the 2011 run. The nuclear modification factor of prompt D mesons (average of D^0, D^+ and D^{*+}) in Pb–Pb collisions, measured by the ALICE Collaboration, is shown in Fig. 2: as a function of p_{T} in central collisions (left) and as a function of centrality for $6 < p_{\mathrm{T}} < 12$ GeV/c (right) [17]. A strong suppression is observed in central collisions, reaching a factor about 4 for $p_{\mathrm{T}} > 5$ GeV/c. R_{AA} is compatible with that of charged pions and charged particles [18], although there seems to be a tendency for $R_{\mathrm{AA}}^{\mathrm{D}} > R_{\mathrm{AA}}^{\pi}$ at low p_{T}. In the figure, the nuclear modification of non-prompt J/ψ from B decays, measured by the CMS Collaboration [19, 20], is also shown. The comparison with D mesons indicates a different suppression for charm and beauty hadrons in central collisions, consistent with the expectation $R_{\mathrm{AA}}^{\mathrm{D}} < R_{\mathrm{AA}}^{\mathrm{B}}$. However, the different p_{T} and rapidity ranges still prevent from a clear conclusion on this point.

A large suppression is also observed for heavy-flavour decay muons, at forward rapidity by ALICE [21] and at central rapidity by ATLAS [22], and electrons at central rapidity by ALICE [23,24]. Both lepton species exhibit a suppression of a factor of about 2–3 up to 15 GeV/c in central collisions, as shown in Fig. 3.

The results on heavy-flavour suppression at the LHC are described reasonably well by model calculations that implement various combinations of in-medium interaction mechanisms for heavy quarks, including radiative and collisional processes, as well as in-medium formation and dissociation of heavy-flavour hadrons [6, 16, 25–31].

The possible in-medium thermalization of heavy quarks can be studied by measuring the azimuthal anisotropy of heavy-flavour hadrons and of their decay leptons. The anisotropy is quantified by the second coefficient of the Fourier expansion of the azimuthal distribution, the so-called elliptic flow coefficient v_2. Heavy-flavour anisotropy is observed by PHENIX in Au–Au collisions at RHIC with v_2 values of up to ≈ 0.13 for electrons from heavy-flavour decays [13] (see Fig. 1, bottom-left, and Fig. 4, left). A comparable anisotropy is observed by ALICE at

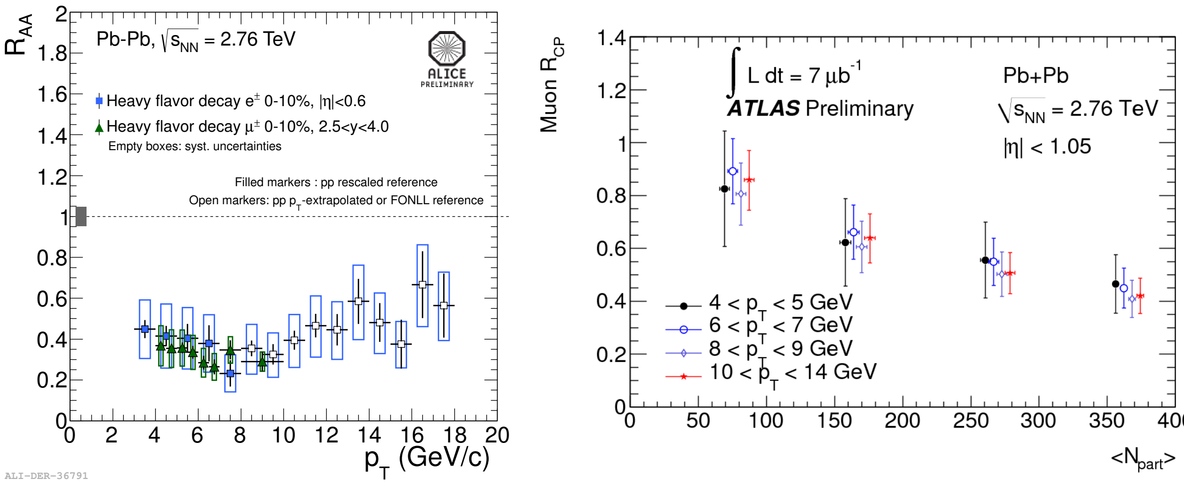

Figure 3. Suppression of heavy-flavour decay leptons at the LHC. Left: ALICE measurements of R_{AA} of heavy-flavour decay muons at forward rapidity [21] and electrons at central rapidity [23] in central (0–10%) Pb–Pb collisions, as a function of p_{T}. Right: ATLAS measurement of R_{CP} of heavy-flavour decay muons at central rapidity, as a function collision centrality [22].

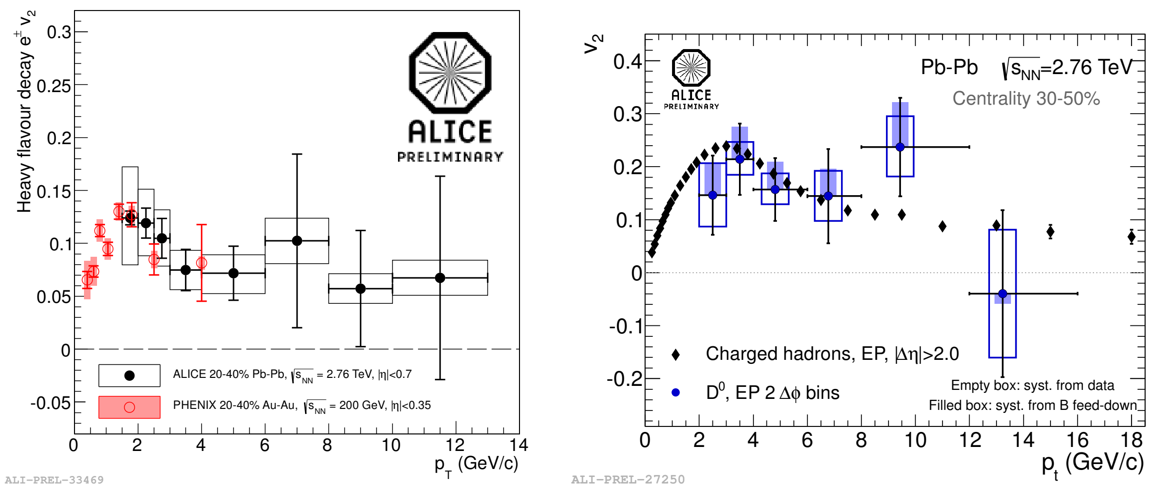

Figure 4. Elliptic flow of open heavy-flavour at RHIC and LHC. Left: v_2 of heavy-flavour decay electrons, measured by ALICE [23] and compared with the same measurement by PHENIX at RHIC [13]. Right: D^0 meson v_2 as a function of p_{T}, measured by ALICE and compared with charged hadrons [23].

the LHC [23, 24], though still with larger experimental uncertainties, as shown in Fig. 4 (left). The ALICE experiment has also carried out a direct measurement of v_2 for D mesons (D^0, D^+ and D^{*+}). The preliminary results, reported in Fig. 4 (right), indicate $v_2 > 0$ for D^0 mesons in the interval $2 < p_{\mathrm{T}} < 6$ GeV/c [23, 32]. The observed anisotropy is comparable to that of charged particles (mostly light-flavour hadrons), although the uncertainties still prevent a precise comparison.

The v_2 measurements at RHIC and LHC are described by several models [16, 28–30] that include heavy-quark transport in the medium, with various implementations of the quark-

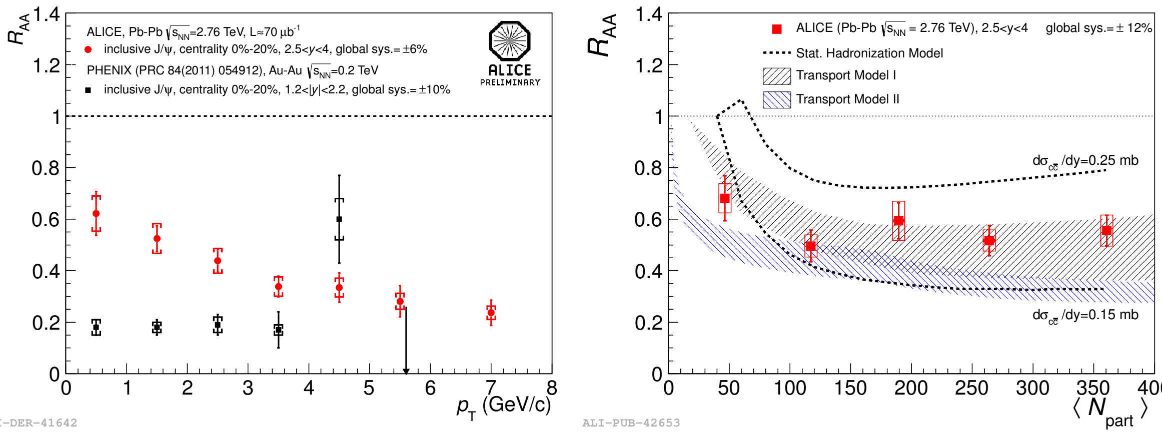

Figure 5. J/ψ suppression at RHIC and LHC. Left: J/ψ R_{AA} as a function of p_T, measured by the PHENIX experiment at RHIC [38] and by the ALICE [35] experiment at LHC. Right: J/ψ R_{AA} for $p_T > 0$ at forward rapidity, as a function of centrality, measured by ALICE [36] and compared with theoretical models including a component of regeneration [39–41].

medium interaction.

The upgrades of the silicon vertex detectors at RHIC and LHC, along with the envisaged increase in heavy-ion luminosities at both machines, are expected to open a new era in terms of both high-precision measurements of the observables presented here and qualitatively new measurements, such as the production of heavy-flavour baryons and the flow of B mesons (see e.g. [33]).

4. Quarkonium production in nucleus–nucleus collisions at RHIC and LHC

The measurements of J/ψ production in Au–Au and d–Au collisions at RHIC have strengthened the conclusions, indicated by the SPS data, on the observation of a medium-induced suppression beyond the expectation from cold nuclear matter effects. However, they leave many open questions: why is the suppression the same at the SPS and at RHIC? why is the suppression at RHIC larger at forward rapidity, where the medium density should be smaller? See e.g. [34] for a review. Model calculations including cold nuclear matter effects, colour screening and a small component of regeneration can describe the data, but it is difficult to disentangle the relative weight of these effects, from data alone.

A clear indication of the relevance of the various effects is provided by the measurements at the LHC, where the ALICE experiment observed a J/ψ suppression much smaller than at RHIC in the low p_T region, as shown in Fig. 5 (left) [35, 37]. Since the medium temperature, thus its screening power, is expected to be larger at the LHC, this observation is an indication of the presumably important contribution of charmonium regeneration from initially-uncorrelated c and $\bar{c}$ quarks that are freely roaming in the deconfined medium. Indeed, models that include this contribution can describe the data [39–41], see e.g. the comparison with R_{AA} at forward rapidity and low p_T in Fig. 5 (right) [36]. A further hint on the relevance of regeneration is provided by the possible observation of positive v_2 for J/ψ at the LHC. This would be consistent with the $v_2 > 0$ that is measured for D mesons. The ALICE measurement [35, 37] is compared in Fig. 6 with models and with the measurement by the STAR experiment at RHIC [42], which shows a v_2 consistent with zero.

Another important break-through at the LHC, carried out by the CMS experiment, is the first measurement of the suppression for all three states of the Υ family. Figure 7 (left) shows the dimuon invariant mass distribution in Pb–Pb collisions compared with the expected distribution obtained from the a binary (N_{coll}) scaling of the pp data [44]. This results gives a first indication of the expected sequential suppression pattern for charmonium and bottomonium

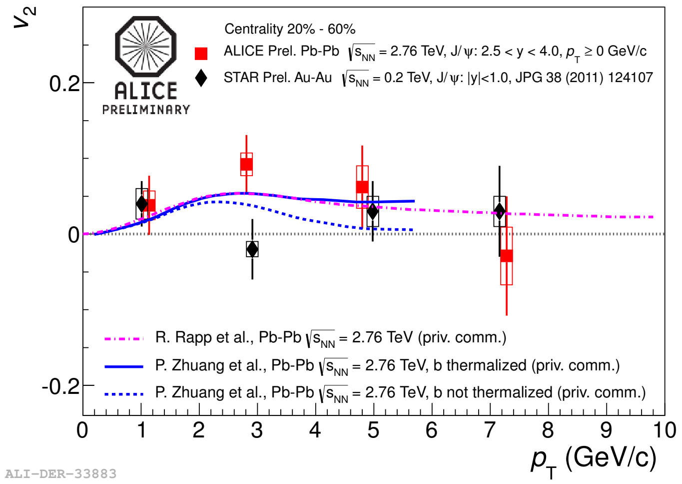

Figure 6. J/ψ elliptic flow coefficient v_2, measured by the STAR experiment [42] at RHIC and by the ALICE experiment [35] at LHC and compared with model calculations.

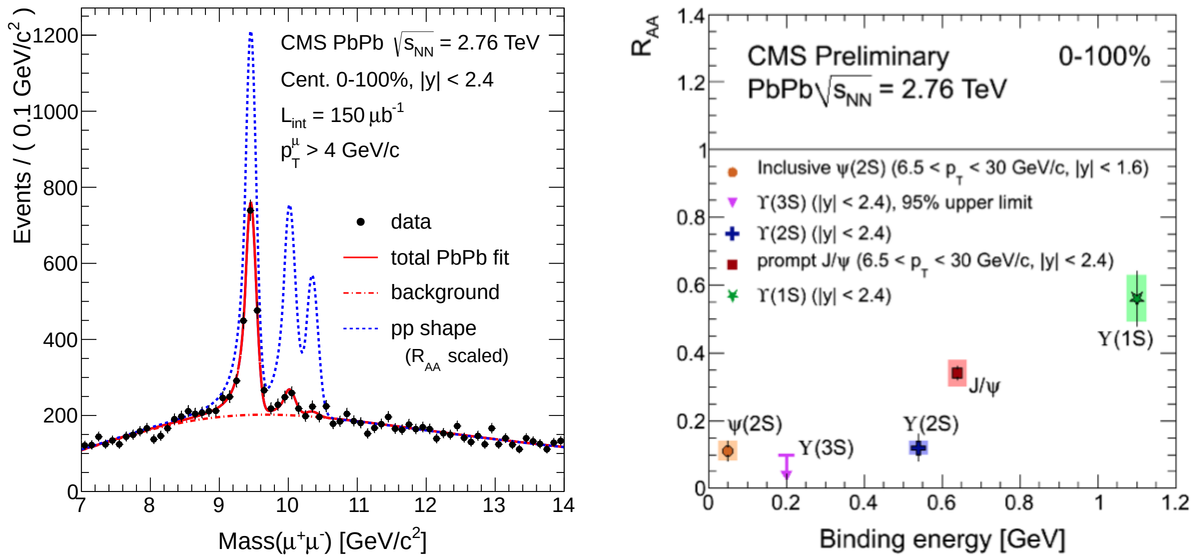

Figure 7. Left: CMS measurement of the dimuon invariant mass distribution in the Υ region in Pb–Pb collisions compared with the expected distribution obtained from the a binary ($N_{\rm coll}$) scaling of the pp data [44]. Right: CMS measurements of the suppression of various quarkonium states as a function of their estimated binding energy [20, 43, 44].

states according to their binding energy. Figure 7 (right) shows $R_{\rm AA}$ in minimum-bias Pb–Pb collisions for the five states J/ψ, ψ', Υ, Υ' and Υ'' [20,43,44]. Υ suppression is also observed also at RHIC by the STAR experiment [45]. This "quarkonium thermometer" of the medium will be refined with future data, using the same kinematic ranges for all particles, applying feed-down corrections and disentangling cold nuclear matter effects using p–Pb measurements. At the same time, the upgraded PHENIX and STAR detectors should allow for the same measurements to be carried out also at RHIC energy.

5. Summary

We have discussed how heavy quarks, abundantly produced at RHIC and LHC energies, allow us to address several physics issues in heavy-ion collisions. In particular, they provide tools to probe the density, via parton energy loss and its predicted mass dependence, and temperature, via quarkonia successive dissociation patterns, of the high-density QCD medium formed in ultra-relativistic heavy-ion collisions.

From the experimental point of view, we have just entered the "golden age" of heavy-flavour observables, thanks to the LHC detectors and to the upgrades at RHIC. Heavy quarks promise to be a hot topic for many Hot Quarks workshops to come.

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References

[1] Dokshitzer Y L, Kharzeev D E 2001 *Phys. Lett.* **B519** 199-206
[2] Armesto N, Salgado C A, Wiedemann U A 2004 *Phys. Rev.* **D69** 114003
[3] Matsui T and Satz H 1986 *Phys. Lett.* **B178** 416
[4] Cacciari M *et al.* 2012 *JHEP* **1210** 137
[5] Butenschoen M and Kniehl B A 2012 *Nucl. Phys. Proc. Suppl.* **222-224** 151
[6] Armesto N, Dainese A, Salgado C A, Wiedemann U A 2005 *Phys. Rev.* **D71** 054027
[7] Greco V, Ko C M and Rapp R 2004 *Phys. Lett.* **B595** 202
[8] Andronic A, Braun-Munzinger P, Redlich K and Stachel J 2003 *Phys. Lett.* **B571** 36
[9] Alessandro B *et al.* [NA50 Collaboration] 2005 *Eur. Phys. J.* **C39** 335
[10] Braun-Munzinger P and Stachel J 2000 *Phys. Lett.* **B490** 196
[11] Digal S, Petreczky P and Satz H 2001 *Phys. Rev.* **D64** 094015
[12] Mocsy A and Petreczky P 2007 *Phys. Rev. Lett.* **99** 211602
[13] Adler S S *et al.* [PHENIX Collaboration] 2006 *Phys. Rev. Lett.* **96** 032301
Adare A *et al.* [PHENIX Collaboration] 2011 *Phys. Rev.* **C84** 044905
[14] Abelev B I *et al.* [STAR Collaboration] 2007 *Phys. Rev. Lett.* **98** 192301
[15] Tlusty D [STAR Collaboration] 2012 arXiv:1211.5995 [hep-ex]
[16] He M, Fries R J and Rapp R 2012 *Phys. Rev.* **C86** 014903
[17] Abelev B *et al.* [ALICE Collaboration] 2012 *JHEP* **1209** 112
[18] Abelev B *et al.* [ALICE Collaboration] 2012 arXiv:1208.2711 [hep-ex]
[19] CMS Collaboration 2012 *JHEP* **1205** 063
[20] CMS Collaboration 2012 CMS-PAS-HIN-12-014
[21] Abelev B *et al.* [ALICE Collaboration] 2012 *Phys. Rev. Lett.* **109** 112301
[22] ATLAS Collaboration 2012 ATLAS-CONF-2012-050
[23] Conesa del Valle Z [ALICE Collaboration], to appear in the proceedings of the Quark Matter 2012 conference
[24] Fasel M [ALICE Collaboration], these proceedings
[25] Sharma R, Vitev I and Zhang B-W 2009 *Phys. Rev.* **C80** 054902
[26] He Y, Vitev I and Zhang B-W 2012 *Phys. Lett.* **B713** 224
[27] Horowitz W A and Gyulassy M 2011 *J. Phys.* **G38** 124114
[28] Alberico W M *et al.* 2011 *Eur. Phys. J.* **C71** 1666; 2011 *J. Phys.* **G38** 124144
[29] Gossiaux P B, Aichelin J, Gousset T and Guiho V 2010 *J. Phys.* **G37** 094019
[30] Fochler O, Uphoff J, Xu Z and Greiner C 2011 *J. Phys.* **G38** 124152
[31] Buzzatti A and Gyulassy M 2012 *Phys. Rev. Lett.* **108** 022301
[32] Luparello G [ALICE Collaboration], these proceedings
[33] Stiller J H [ALICE Collaboration], these proceedings
[34] Granier de Cassagnac R 2008 *J. Phys.* **G35** 104023
[35] Scomparin E [ALICE Collaboration] 2012 arXiv:1211.1623 [nucl-ex]
[36] Abelev A *et al.* [ALICE Collaboration], 2012 *Phys. Rev. Lett.* **109** 072301
[37] Lardeux A [ALICE Collaboration], these proceedings
[38] Adare A *et al.* [PHENIX Collaboration] 2011 *Phys.Rev.* **C84** 054912
[39] Andronic A, Braun-Munzinger P, Redlich K and Stachel J 2011 *J. Phys.* **G38** 124081
[40] Zhao X and Rapp R 2011 *Nucl. Phys.* **A859** 114
[41] Liu Y-P, Qu Z, Xu N, and Zhuang P-F 2009 *Phys. Lett.* **B678** 72
[42] Adamczyk L *et al.* [STAR Collaboration] 2012 arXiv:1212.3304 [nucl-ex]
[43] CMS Collaboration 2012 CMS-PAS-HIN-12-007
[44] Chatrchyan S *et al.* [CMS Collaboration] 2012 *Phys. Rev. Lett.* **109** 222301
[45] Kesich A [STAR Collaboration] 2012 *J. Phys. Conf. Ser.* **389** 012025