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# Heavy flavours and quarkonia

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## Abstract.

This contribution aims at reviewing the experimental measurements of heavy flavours and quarkonia, prior to the new results presented at the Strange Quark Matter 2013 conference.

Heavy quarks (charm and beauty) are created in the earliest phase of ultra-relativistic heavy-ion collisions. They thus probe the entire evolution of the produced medium often referred to as the quark-gluon plasma. The large fraction of heavy quarks that are separated from their initial antiquark partner, the so-called *open flavour*, are susceptible to interact with the surrounding medium resulting in elliptic flow and/or energy loss, with possibly different magnitudes for different quarks. The small fraction of heavy quark pairs that usually bound themselves into *quarkonia* possibly melt in the plasma and could potentially be formed again when the medium freezes out, from uncorrelated pairs. In addition to these *hot* effects, normal *cold* nuclear effects (modifications of the parton distribution functions, absorption by initial nucleons, etc.) can also affect heavy flavours. The variety of influences the medium can have on heavy flavours makes them an interesting but challenging ground to study its properties.

The current results on open charm and beauty are reviewed in sections 1 and 2, followed by the results on charmonia and bottomonia in sections 3 and 4. For each, the RHIC measurements and conclusions are given first, before presenting the new results produced at LHC.

## 1. Open charm

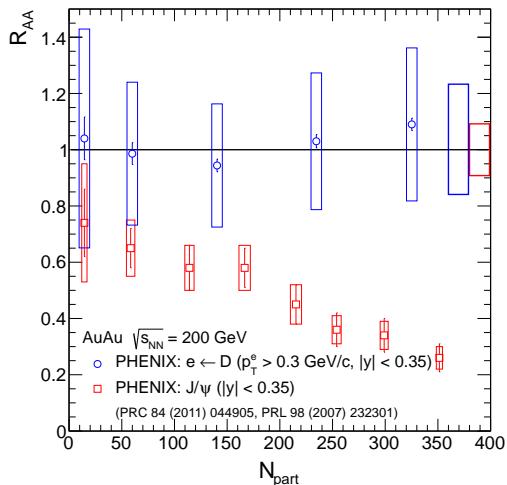
Two ways are typically used to measure open heavy flavour production. One consists in separating so-called *non-photonic electrons*, coming from a mix of charm and beauty leptonic decays, from the copious background coming from lighter quarks and photon conversions. The advantage of this method lays in the fact that electrons are easy to trigger upon, especially if of high transverse momentum ( $p_T$ ). The other way consists in measuring hadronic decays of (hence identified) D or B mesons. These topologies (such as  $D \rightarrow K\pi$ ) are more difficult to trigger on and usually sit on a large background, but provide an unambiguous access to the meson flavour and kinematics. Obviously, the performances of both techniques are dramatically improved if the position where the decay occurs is measured, which is doable with Silicon vertex detectors since D and B mesons have typical proper decay length of the order of hundreds of micrometers.

In 2004, the PHENIX collaboration released an article [1] showing that the total charm production is essentially scaling with the number of elementary nucleon-nucleon collisions. This was based on non-photonic electrons detected at mid-rapidity and of  $p_T$  greater than 300 MeV/c. A more modern version of this result was published in [2] and is shown on Fig. 1, as blue circles. The uncertainty is typically of the order of 25%, mostly due to the lack of a vertex detector.



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The STAR experiment carried out similar studies [3] but is particularly well suited to measure hadronic decays. Thanks to the addition of a Time-of-Flight detector and a massive minimum-bias sample, the scaling of open charm with elementary nucleon-nucleon collisions is now also observed with D mesons, through a STAR preliminary result (see, e.g. Ref. [4]).



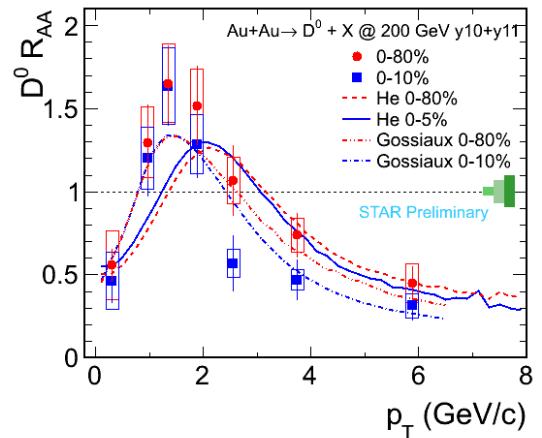
**Figure 1.** At RHIC, nuclear modification factor of low  $p_T$  non-photonic electrons [2] (blue circles) and inclusive  $J/\psi$  [5] (red squares) as a function of centrality depicted as the number of participating nucleons.

When binned in transverse momentum, the above results show that most of the charm yield is concentrated at low  $p_T$ , typically below 2 GeV/c. Concerning D mesons, a preliminary result shows a remarkable feature with a suppression at low  $p_T$  and an enhancement in the moderate  $p_T$  region (1–2 GeV/c), as shown on Fig. 2 and in Ref. [4], a behaviour that could arise from the radial flow of the light quark contained in the D mesons [6, 7]. For non-photonic electrons, this effect dilutes itself in the leptonic decay and the nuclear modification factor is indeed compatible with unity at low  $p_T$  [8]. At higher  $p_T$ , all measurements related to open heavy flavours (such as the blue circles of Fig. 3) exhibit a strong suppression which is attributed to heavy quark energy loss. This is further confirmed when comparing AuAu collisions to dAu, in which no suppression, and even an enhancement [9], is observed.

The last remarkable behaviour of charm at RHIC is its strong elliptic flow, observed in non-photonic electrons [8] and revealing a strong coupling of the heavy quarks to the medium. At high  $p_T$ , STAR shows that the charm  $v_2$  parameter grows above hydrodynamic expectations [4], a behaviour that can probably be attributed to the path-length dependence of energy loss.

Overall, modeling both the quenching and the flow of charm quark observed at RHIC has become a challenge to theorists.

At LHC, the ALICE experiment has released extensive results concerning open charm, using different techniques at mid-rapidity, in particular D meson measurements via hadronic decay [10], but also from muons at forward rapidity [11]. Other complementary preliminary results can be found in Ref. [12]. A strong suppression is observed over the whole probed  $p_T$  range, in particular at 1–3 GeV/c and contrary to RHIC. A possible scaling with the number of elementary nucleon-nucleon collisions is thus not observed but could still lay in the lowest  $p_T$  (below 1 GeV/c) that are not yet accessible. It is to be noted that a violation of this scaling could arise from the modification of parton distribution functions (shadowing).



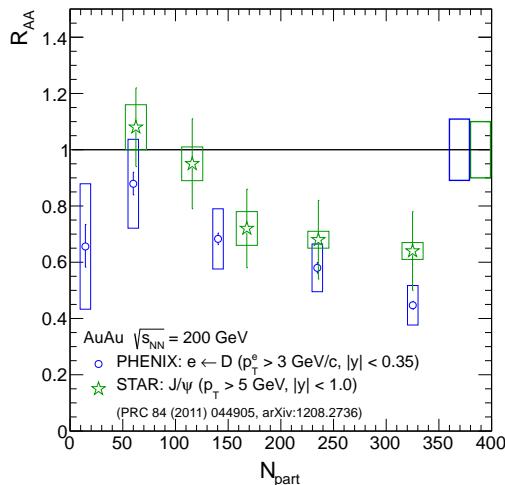
**Figure 2.** At RHIC, (preliminary) nuclear modification factor of D mesons from the STAR experiment [4], as a function of their transverse momentum and for two centrality selections.

The ALICE experiment also showed that D mesons significantly flow at the LHC [13], and the situation is now the same than at RHIC: Theorists are trying to model the energy loss and the collective behaviour of charm quarks in the medium.

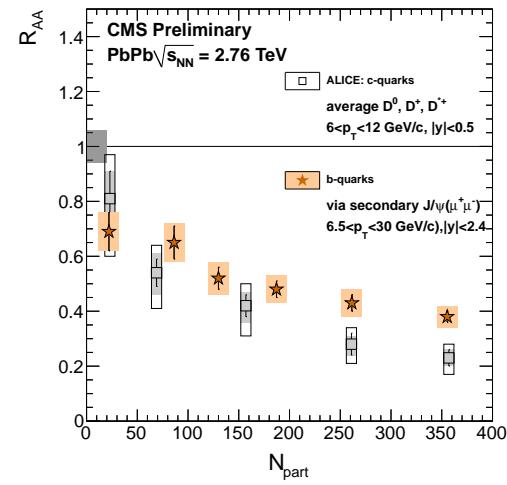
## 2. Open beauty

Open beauty was marginally accessible at RHIC, though non-photonic electrons at high  $p_T$  must come from a mix of charm and beauty decays. At LHC, the CMS experiment provided the first unambiguous  $b$ -quark measurements in heavy-ion collisions. The (published) *non-prompt* component of  $J/\psi$  mesons [14] and (preliminary) topologically-identified jets from  $b$  quarks [15] provide information on the fate of beauty at relatively low and high  $p_T$ , respectively. Both show a significant suppression (of the same order of the inclusive jet in the later case), pointing to an important energy loss of  $b$  quarks in the medium.

A comparison of the measurements from the CMS and ALICE experiments indicate that D mesons are more suppressed than B mesons, as shown on Fig. 4. This is often quoted as reflecting a stronger energy loss of the  $c$  quarks, though a quantitative analysis is yet to be done, with a proper treatment of the quark fragmentation, production spectrum and decay kinematics.



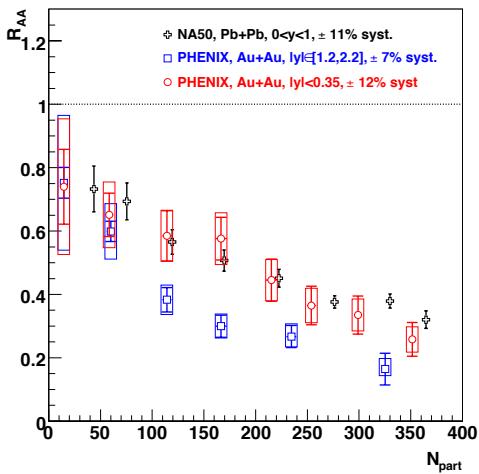
**Figure 3.** At RHIC, nuclear modification factor of high  $p_T$  non-photonic electrons [2] (blue circles) and high  $p_T$   $J/\psi$  [16] (green stars) as a function of centrality depicted as the number of participating nucleons.



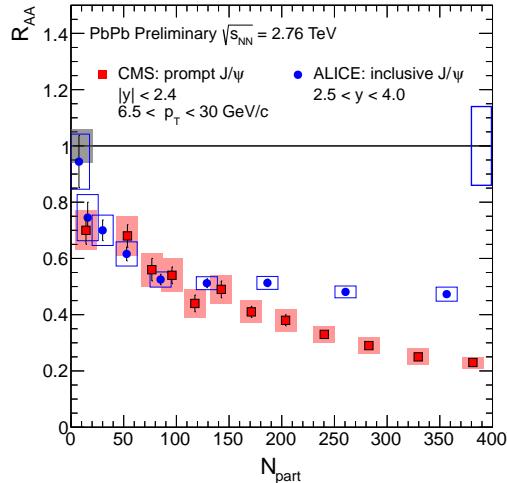
**Figure 4.** At LHC, nuclear modification factor of D mesons [12] (stars) and non-prompt  $J/\psi$  [17] (squares) as a function of centrality depicted as the number of participating nucleons.

## 3. Charmonia

In 2006, the first  $J/\psi$  significant measurements at RHIC brought up two surprises [5] that were later confirmed with more statistics [18] and are illustrated by Fig. 5. First,  $J/\psi$  are as suppressed at RHIC (red circles) than at SPS (black cross) [19], at mid rapidity. Second, the suppression is stronger at forward rapidity (blue squares), where the  $J/\psi$  should rather see lower densities. Two popular answers were proposed to solve this puzzle. On one hand,  $J/\psi$  mesons could be regenerated, especially at mid-rapidity, from initially-uncorrelated  $c$  and  $\bar{c}$  quarks streaming through the medium and meeting at hadronization. On the other hand, shadowing or saturation could further suppress the forward  $J/\psi$ . In this second case, it is possible that directly produced  $J/\psi$  survive at both SPS and RHIC, the observed suppression being due to the melting of the higher states decaying into  $J/\psi$  (feed-down).



**Figure 5.** Nuclear modification factor of  $J/\psi$  from the first PHENIX [5] and last NA50 [19] publications, as a function of centrality depicted as the number of participating nucleons.



**Figure 6.** Nuclear modification factor of  $J/\psi$  from the ALICE [20] (all  $p_T$ ) and CMS [17] (prompt, high  $p_T$ ) preliminary results, as a function of centrality depicted as the number of participating nucleons.

The dAu collisions indeed revealed a similar effect, with more suppression in the forward region [21] but a detailed understanding of the observed yields is still missing. In particular, a simple combination of nuclear shadowing and nuclear absorption does not reproduce the modification factors observed in different rapidity ranges [22]. This makes a quantitative extrapolation of the nuclear effects observed in pA to AA collisions difficult.

An important finding at RHIC is the fact that  $J/\psi$  are less suppressed at high  $p_T$ , both in AuAu [16] and dAu [23] collisions. For AuAu collisions, this can be seen by comparing PHENIX low  $p_T$   $J/\psi$  from Fig. 1 and STAR high  $p_T$   $J/\psi$  from Fig. 3. The latter shows that the  $D$  and  $J/\psi$   $R_{AA}$  somewhat meet for selected  $p_T$  thresholds, but this has to happen for an increasing and decreasing suppression as a function of  $p_T$ .

There was a hope that the situation will be clearer at LHC, with a centrality-growing modification factor in case of regeneration, and a step-like behaviour in case of sequential suppression, as frequently advertised by a popular but naive cartoon. The suppression of low  $p_T$  (inclusive)  $J/\psi$  was reported by the ALICE collaboration at forward rapidity and shows a remarkably saturating nuclear modification factor  $R_{AA} \simeq 0.5$  ([24] even more remarkable in the new preliminary result with finer centrality binning shown on Fig. 6). At mid-rapidity, statistically-limited results show a similar feature, with a higher  $R_{AA}$  [20]. Though the observed plateau reminds the topology of a long-awaited sequential melting, the current interpretation is the opposite: regeneration is at play at LHC! This twist is justified by three related observations: 1) These low  $p_T$   $J/\psi$  are *less* suppressed than at RHIC, as can be seen by comparing Figs. 5 and 6, while nuclear effects (shadowing) should be larger, 2) High  $p_T$   $J/\psi$  are *more* suppressed than at RHIC, as seen for instance by the CMS experiment [14] and displayed also on Fig. 6, 3) A hint of  $J/\psi$  elliptic flow is observed [25] which is supposed to arise from inheriting the individual charm quark flow at hadronization time.

In pPb collisions, the adventure is just beginning at LHC, with results from the ALICE [26] and LHCb [27] collaborations showing a  $J/\psi$  backward/forward asymmetry, which is compatible with various predictions of cold nuclear matter effects, within (large) uncertainties.

The study of pp collisions at LHC also revealed interesting features. The average yield of  $J/\psi$  was shown by the ALICE collaboration to grow with the average multiplicity of the events [28]. In other words, events with more multiplicity also produce more  $J/\psi$  mesons on average, which is interpreted as a consequence of multi-parton interaction. A preliminary result also showed this behaviour for D mesons [12] and a comprehensive study of all heavy and hard probes versus pp event multiplicity will be interesting.

Both at RHIC and LHC, the excited  $\psi'$  state brought up surprises. At RHIC, the PHENIX collaboration has published its nuclear modification factor in dAu collisions [29], showing a dramatic dependence on event centrality, with a rather strong suppression in the most central collisions. At LHC, the CMS collaboration released a preliminary results showing that, in PbPb collisions,  $\psi'$  are more suppressed than  $J/\psi$  at high  $p_T$  (more than 6.5 GeV/c) but might be less suppressed at lower  $p_T$  (down to 3 GeV/c) [30]. This is not observed on a preliminary result by the ALICE collaboration [20], though the two results are not incompatible. These  $\psi'$  results call for more statistics. The CMS result in particular suffered from the low statistics of the first pp sample at 2.76 TeV and should be updated with the larger sample.

#### 4. Bottomonia

The available bottomonium statistics were marginal at RHIC, and the three  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states unresolved. However a few results exist, such as the nuclear modification factor of the (grouped) three states in dAu collisions from PHENIX [31] and a corresponding preliminary result on AuAu collisions from STAR [4]. They show, within large uncertainties, no sizeable effect in dAu collisions and a significant suppression in AuAu collisions ( $R_{AA} \simeq 0.3 - 0.6$ ).

Thanks to the enhanced production cross section and high luminosity, bottomonia are copiously produced at LHC. A first publication by the CMS collaboration indicated that the excited states ( $2S$  and  $3S$ ) were more suppressed than the ground ( $1S$ ) state [32]. It was further confirmed in Ref. [33], which shows a clear sequential pattern in the nuclear modification factors, with  $0.56 \pm 0.08 \pm 0.07$ ,  $0.12 \pm 0.04 \pm 0.02$  and less than 0.10 with a 95% confidence level, for the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$ , respectively, as shown on the right sub panel of Fig. 7. Also on this figure is the centrality dependence of the  $\Upsilon(1S)$  and  $\Upsilon(2S)$ , together with a preliminary  $\Upsilon(1S)$  result from the ALICE collaboration [20]. With possibly half of the  $\Upsilon(1S)$  coming from the decay of higher-mass bottomonia (in particular from  $\chi_b$ ), this result leaves open the possibility that the  $\Upsilon(1S)$  ground state survives in the plasma created at LHC.

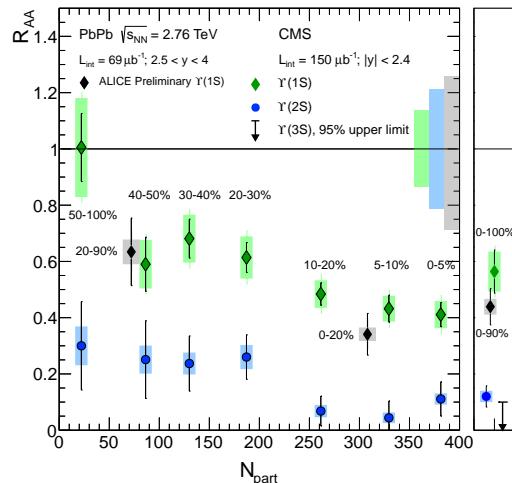
Five quarkonia are thus now accessible, as shown for instance on Fig. 8 which summarizes the nuclear modification factors observed with the CMS experiment (hence for high  $p_T$   $\psi$  and inclusive  $\Upsilon$ ). Taken as such, the quarkonium suppression shows an ordering as a function of their binding energy, hence materializing the old dream suggested in the seminal quarkonium suppression paper [34]. If one considers that selecting high  $p_T$  charmonia is a way of going away from the regeneration regime, it might indeed be relevant, but it is far too premature to come to such a conclusion and works need to be carried out to disentangle all cold and hot effects, on the five quarkonia.

#### Conclusions

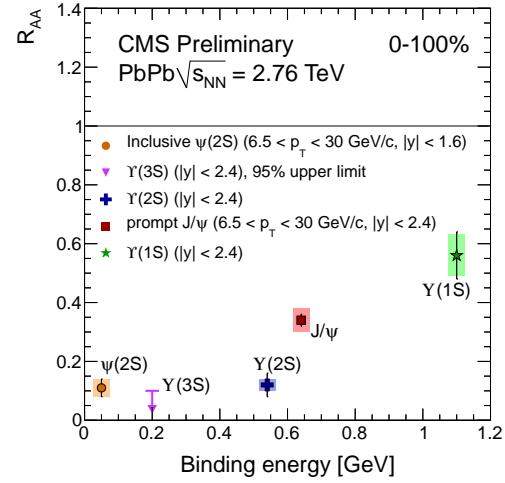
Heavy flavours have proven themselves to be an interesting and surprising playground at RHIC energies. With the arrival of LHC and the wide opening of the  $b$ -quark sector, both for open heavy flavour and bottomonia, a rich phenomenology should arise in the near future.

#### Acknowledgements

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**Figure 7.** Nuclear modification factor of  $\Upsilon(1S)$  (diamonds, CMS in green, ALICE in black [20]) and  $\Upsilon(2S)$  (blue circles, CMS [33]) versus centrality depicted as the number of participating nucleons.



**Figure 8.** Nuclear modification factors of 5 quarkonia from the CMS experiment [14, 30, 33], in minimum bias collisions and versus their binding energy. Bottomonia are inclusive but charmonia lay at high  $p_T$ .

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