Five things you should remember about heavy flavor measurements

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Abstract.
Heavy quarks are important tools to study the properties of the hot and dense nuclear matter created in heavy ion collisions. They are produced very early, in the initial interactions with large momentum transfer, and are expected to interact differently from light quarks with the nuclear medium. Measurements of heavy flavor production can provide insights into transport and thermodynamics properties of the created system. In this paper, I give as a brief introduction to the experimental studies of heavy flavor production in relativistic heavy ion collisions and discuss related challenges.

Introduction

Relativistic heavy ion collisions provide a unique opportunity for studying Quark-Gluon Plasma (QGP), a new state of nuclear matter with properties determined by quark and gluon degrees of freedom. In heavy ion collisions, we use an approach analogous to tomography for studying the QGP: We select an external probe, whose properties (production mechanism) are under experimental and theoretical control, which propagates through the medium. Then we can infer properties of the analyzed system from modification of the probe. Heavy quarks, charm and bottom, serve as such external-to-QGP probes. Because of their large masses, they are produced very early in the collision, in the initial interactions with large momentum transfer, before the QGP phase. Their production, both total and differential cross-sections, are well described by perturbative QCD (pQCD). Energy loss and elliptic flow of open heavy flavor are sensitive to the dynamics of the medium; such measurements could be used to determine the fundamental properties of the QGP, for instance transport coefficients (for details, see Ref. [1] and references therein). Elliptic flow of heavy quarks can shed new light on possible collective behavior and degree of thermalization of the created nuclear matter. Measurements of the production of various quarkonium states can provide insight into thermodynamic properties of the QGP ([2] and references therein).

In this paper, I give a brief introduction to the experimental studies of heavy flavor production in relativistic heavy ion collisions and challenges related to these measurements. I present experimental techniques and selected results and discuss their implications.

1. Quarkonium and open heavy flavors are different tools

Quarkonium and open heavy flavors are considered different tools for probing the QGP properties. Quarkonium, which is a bound state of $c\bar{c}$ or $b\bar{b}$ quarks, is a color-neutral object.

Its production can proceed via intermediate color-octet states [3, 4], but after a sufficiently long time a charmonium or bottomonium is formed. Quarkonium production is anticipated to be suppressed in the presence of the QGP, compared to yields in $p+p$ collisions scaled by the number of binary nucleon-nucleon collisions, due to the Debye screening of the quark-antiquark potential in the deconfined, partonic medium [5]. The Debye screening length depends on the temperature of the QGP. Different quarkonium states have different binding energies and thus different radii. Therefore, they are expected to disassociate at different temperatures [6, 7]. Thus measurements of production of various quarkonium states can provide insight into thermodynamic properties of the QGP i.e. its temperature. However, there are other effects that may affect the observed production, such as modifications of a parton distribution function in a nucleus, final state nuclear absorption or secondary production in the QGP, which I discuss in next sections.

Open heavy flavor hadrons are proxies for a single heavy quark, which carry a color charge and thus is expected to interact differently than quarkonium with the QGP. A fast parton traversing QGP will lose its energy due to interaction with the medium. The transport properties of the medium are extracted by comparing energy loss dE/dx observed in the data with models, where dE/dx is related to transport properties of the nuclear medium, for instance mean momentum transfer squared $\hat{q}$ [1].

2. We cannot measure heavy flavor quarks directly

Main complication in using heavy quarks for the QGP research is that we cannot study heavy quark production directly: we measure final state particles. Thus open heavy flavor measurement is always "contaminated" by light quarks. The best case scenario is a direct reconstruction of heavy flavor mesons which gives an access to the kinematics of the parent meson. Such measurement of D-mesons via their hadronic decay channels is feasible both at RHIC and LHC, but it is more difficult for bottom mesons and other means are used for that purpose (however, there are first measurements of exclusive B decays by the CMS collaboration in $p+$Pb collisions [8]). The $B \to J/\psi$ (so-called non-prompt J/ψ) is a popular approach, where J/ψ from B decays are separated from a direct J/ψ production using a pseudo-lifetime discriminating variable. Measurement of electrons from semi-leptonic decays of heavy flavor hadrons, e^{HF} (sometime called non-photonic electrons for historical reasons) is an alternative way to access heavy quarks' production. Such electrons are obtained by first selecting inclusive electron yields and then subtracting electrons from γ conversion (real photons conversion) or Dalitz decays of π^0 and η mesons (virtual photons conversion), called photonic background. Remaining electrons are dominated by open heavy flavor hadron decay, but contain other contributions as well. Hence a conservative name "non-photonic electrons" was invented for such sample, which has to be further corrected for contributions from weak kaon, Drell-Yan and quarkonium decays.

In the case of quarkonium, the main issue is a feed-down from excited states to ground state. Such decays amount to 40% of J/ψ (10% comes from ψ' and 30% from $\chi_c(1P)$) and $\sim 40\%$ for $\Upsilon(1S)$ mostly due to χ_{b1}, χ_{b2} decays. This feed-down is extremely difficult to measure in heavy ion collisions because χ decays involve soft photons (energy ~ 0.5 GeV) that are lost in a large background from the underlying event.

3. It is crucial to understand the reference

We use nuclear modification factors R_{pA} and R_{AA} to quantify modification of the production in $p+A$ and $A+A$ collisions (such as $p+$ Pb, $d+$ Au, Pb+Pb or Au+Au), respectively, compared to $p+p$ interactions. They are defined as

$$R_{\mathrm{pA}}(R_{\mathrm{AA}})(p_T) = \frac{\sigma_{\mathrm{inel}}}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{pA(AA)}}/\mathrm{d}y\mathrm{d}p_T}{\mathrm{d}^2 \sigma_{pp}/\mathrm{d}y\mathrm{d}p_T} \tag{1}$$

where σ_{inel} is the inelastic cross section in $p+p$ collisions, $N_{\text{pA(AA)}}$ is a yield in $p+A$ or $A+A$ collisions, respectively, σ_{pp} is the corresponding cross section in $p+p$ collisions, and $\langle N_{\text{coll}} \rangle$ is an average number of binary collisions.

In the case of $p+A$ collisions, we generally do not expect a formation of a hot and dense matter. Thus $p+$Pb or $d+$Au measurements were introduced as a null experiments to quantify modification of the particle yields not related to the QGP formation, so called cold nuclear matter (CNM) effects. These include initial and final state effects. The former affect parton distributions in a nucleus (for instance shadowing) and thus the initial production yields. The latter modify yields or momentum distributions of final state particles. A Cronin effect (an enhancement of transverse momentum in $p+A$ with respect to $p+p$ collisions) is an example of such effect. These effects play an important role at SPS, RHIC and LHC. A significant quarkonium suppression was observed at midrapidity and forward rapidity at SPS [9], RHIC [10, 2] and at LHC [11, 12, 13, 14]. Overall, the suppression for J/ψ and Υ(nS) as a function of rapidity at LHC is consistent with model calculations based on a pure nuclear shadowing scenario [15, 16] and with models including a contribution from coherent partonic energy loss [17, 18]. An additional final breakup cross section is needed to explain the SPS [19] and RHIC data [10].

Experiments at RHIC and LHC recently reported collective behavior of light hadrons in high multiplicity $d+$Au [20] and $p+$Pb collisions [21], where these hadrons have significant elliptic flow v_2 with a characteristic mass-splitting pattern [22]. These observations triggered speculations that an enhancement of the e^{HF} production in central and minimum bias $d+$Au collisions at midrapidity at RHIC [23] could indicate a collective phenomena (radial flow) of heavy quarks in $d+$Au [24]. However, this phenomenon could also be owing to the CNM effects: The enhancement at low p_T is reproduced assuming Cronin effect for charm quarks [25]. No significant suppression/enhancement for open charmed and bottom hadrons is observed at LHC [26, 8, 11]: nuclear modification factor R_{pPb} for D-mesons measured by ALICE is shown in Fig. 4 (right panel).

For quarkonium, the most surprising CNM results are the strong suppression of ψ' production in $d+$Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV [27] (Fig. 1) and $p+$Pb at $\sqrt{s_{NN}} = 5.02$ TeV [28] and event activity dependence of Υ(nS) production in $p+p$ and $p+$Pb interactions [13]. The ψ' production is significantly more suppressed compared to J/ψ in $p+$Pb and $d+$Au collisions. One possible explanation is a breakup in the final state, either due to interaction with nuclear matter or with co-moving hadrons. Since this effect is significant in central $p+$Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, it has to be understood and taken into account in the interpretation of the quarkonium suppression pattern in heavy ion collisions. In the case of of Υ(nS) production in $p+$Pb (and also in $p+p$) interactions, the excited-to-ground-states cross section ratios Υ(nS)/Υ(1S) decrease with increasing charged-particle multiplicity measured at midrapidity (Fig. 2, left panel). The double ratios measured by the CMS collaborations, $[\Upsilon(nS)/\Upsilon(1S)]_{\text{pPb}}/[\Upsilon(nS)/\Upsilon(1S)]_{p+p}$ points to final-state suppression effects in the $p+$Pb which affect more strongly the excited states than the ground state [13]. Another piece of the puzzle is Υ(1S) production in $d+$Au at 200 GeV collisions. A suppression of magnitude similar to that in central Au+Au collisions is observed there, which is difficult to explain by models.

Overall, the CNM effects are difficult to quantify because they depend on the kinematic range (longitudinal momentum fraction $x_{1,2}$ carried by the initial parton), energy and production mechanism (i.e. kinematics) [29]. The NA60 results for J/ψ production [9] provide an example how important it is to have a good handle on the reference measurement. Moreover, extrapolation of these effects from $p+A$ to $A+A$ is not straightforward [30].
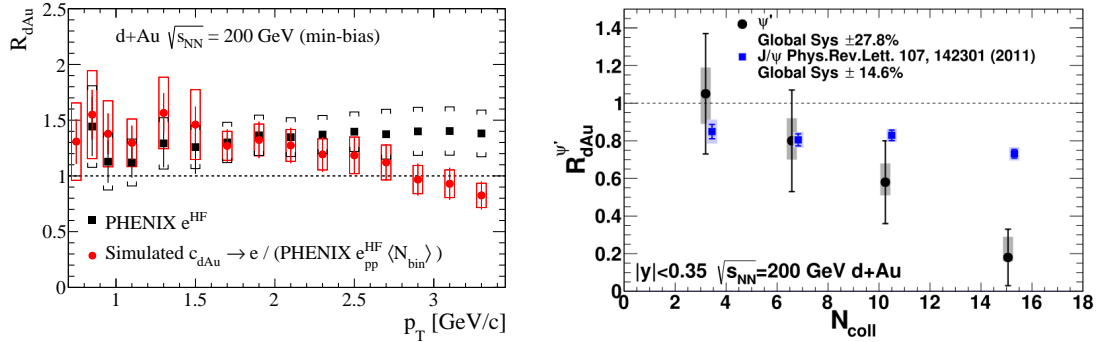
Figure 1. Cold nuclear matter effects at RHIC. Left panel: R_{dAu} for heavy flavor decay electrons compared to calculations which assume a Cronin effect for charm quarks [25]. Right panel: R_{dAu} for charmonium (ψ' and J/ψ) [27].

4. Color screening is a hypothesis

Quarkonium production is anticipated to be suppressed in the presence of the QGP and measurement of different quarkonium states in $A+A$ collisions gives a handle on the QGP temperature. This is a well established and popular idea, which served as a motivation for J/ψ measurements at SPS, RHIC and LHC and can be found in any conference talk on this topic. However, this hypothesis is still to be validated, because there are other possible scenarios. For the comprehensive review see [2, 31], here I list a few approaches successfully applied to describe the experimental data.

In the statistical hadronization model [32], the charm and bottom quarks thermalize in QGP and no quarkonium state is present in the deconfined state. All quarkonium states are produced during hadronization stage, together with all other hadrons. The comovers interaction model [33] does not assume thermal equilibrium and it does not use thermodynamical concepts. The quarkonium suppression is caused by the final state interactions of the $c\bar{c}$ pairs with the dense medium created in the collision. Quarkonium could be also created in the QGP, by (re)combination charm or bottom quarks [34, 35, 36]. In the transport approach [37, 38], the evolution of the quarkonium yield and spectrum is described by a transport relation, which includes terms for both quarkonium dissociation and formation reactions in the deconfined stage.

RHIC data for J/ψ production at $\sqrt{s_{NN}} = 200$ GeV [39] were surprising because the level of suppression is similar as at SPS ($\sqrt{s_{NN}} = 17.3$ GeV) and suppression at forward rapidity was larger than at midrapidity (Fig. 3, right panel). This observation was consistent with the hypothesis that there is a significant secondary production of J/ψ via coalescence of uncorrelated charm quarks, which is now an important ingredient of various models [2, 31]. Such a trend with rapidity can be also explained by Debye screening mechanism together with a larger suppression due to stronger shadowing (or other CNM effects) at forward rapidity compared to midrapidity.

The J/ψ suppression as a function of p_T has different trends at RHIC ($\sqrt{s_{NN}} = 200$ GeV) and LHC ($\sqrt{s_{NN}} = 2.76$ TeV). At RHIC, J/ψ is strongly suppressed at low p_T and then R_{AA} increases with transverse momentum, with a hint of suppression at high p_T in central collisions [40, 39]. At LHC, J/ψ is less suppressed at low p_T than at RHIC, and suppression increases with p_T [41, 42]. Such a trend is consistent with a significant contribution from J/ψ regeneration to the measured yields.

Upsilon states are better probes of the color screening hypothesis because they are less susceptible to CNM effects: Shadowing and final state absorption are expected to be smaller than in the case of J/ψ (the absorption due to interaction with co-moving hadrons was predicted

to be minimal [43]). Moreover, the Υ(nS) regeneration is expected to be small and the initial-state effects are likely to cancel in a double ratio of excited-to-ground state in heavy ion and $p+p$ collisions. Quarkonium suppression pattern in heavy ion collisions at RHIC and LHC is consistent with the color screening scenario: there is a larger suppression for loosely bound excited states compared to ground states J/ψ and Υ(1S) (Fig. 2(right panel)). However, there are observations which cannot be explained by color screening alone. Firstly, a ratio of excited-to-ground state as a function of event activity in $p+p$, $p+$Pb and Pb $+$ Pb follows the same trend (Fig. 2(left panel)), which may suggest that there is a significant final state adsorption due to interactions with co-moving hadrons. Then, the nuclear modification factor Υ(1S) as a function of rapidity at LHC [44] (Fig. 3, left panel) exhibits a similar trend as J/ψ at RHIC: there is a larger suppression at forward rapidity than at midrapidity. These data present a challenge to models which successfully described J/ψ production at RHIC and LHC assuming a color screening and regeneration scenario [44] (Fig. 3) because secondary production of Υ(1S) via b-quarks coalescence is expected to be small. Such a trend could also originate from stronger CNM effects (shadowing) at forward rapidity compared to midrapidity (where even an anti-shadowing i.e. enhancement could be expected).

The jury is still out on the question of the nature of the quarkonium interactions with a hot nuclear matter.
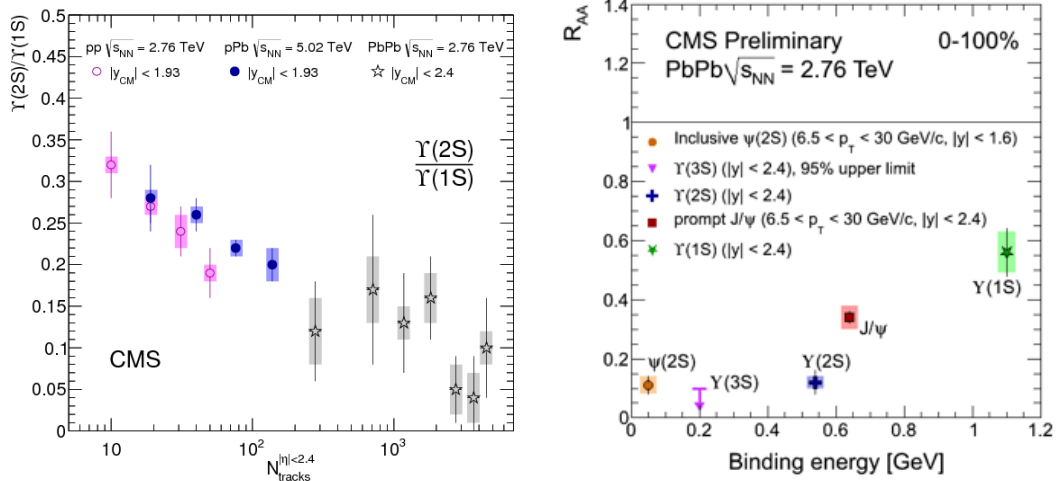
Figure 2. Left panel: Single cross section ratios Υ(2S)/Υ(1S) versus charged-particle multiplicity $p+p$ collisions at $\sqrt{s}=2.76$ TeV, $p+$Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV and Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. Right panel: Nuclear modification factor as a function of binding energy for various quarkonium states at LHC [45].

## 5. Open heavy flavor production at high p_T is suppressed at RHIC and LHC

Heavy flavor production at RHIC (D^0 and e^{HF}) in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV and at LHC (D-mesons and $B \to J/\psi$ in Pb+Pb collisions at $\sqrt{s_{NN}}=2.7$ TeV) is suppressed at high p_T (Fig. 4 and Fig. 5). This suppression is comparable to that for light hadrons. This was a surprising result. Models, which described the light flavor data well assuming gluon radiation (radiative energy loss, $dE/dx_{\rm rad}$) predicted that the heavy quark production will be less suppressed than light partons [46]. This lead to introduction of collisional energy loss $dE/dx_{\rm coll}$ due to binary interactions of partons with other objects in the QGP. Moreover, D-mesons at LHC and e^{HF} at RHIC have a significant positive elliptic flow [47, 48, 49]. These
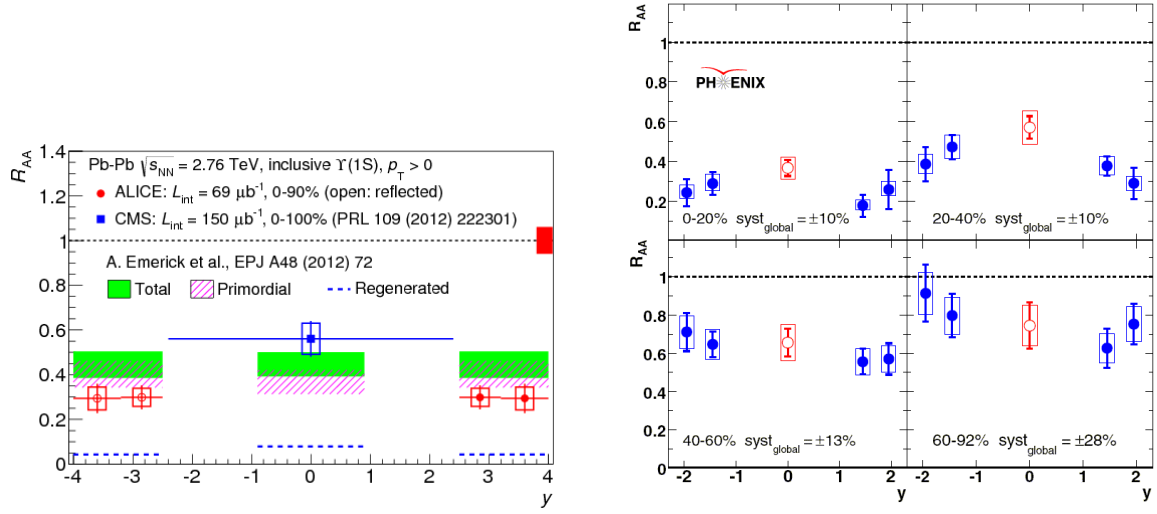
Figure 3. Nuclear modification factor as a function of rapidity for $\Upsilon(1S)$ at LHC [44] and J/ψ at RHIC [39].

observations suggest that charm quarks are strongly coupled with the medium: heavy quarks loose a large amount of energy and acquire a significant elliptic flow during interaction with matter created at top RHIC energy and at LHC.

At the moment it is challenging for models to describe the heavy flavor elliptic flow and high p_T suppression simultaneously. One difficulty is that the relative contributions of dE/dx_{coll} and dE/dx_{rad} is unknown. To overcome this problem, multiplication factors for dE/dx_{coll} and dE/dx_{rad} are adjusted based on the comparison with data. To understand better the interplay of these two processes, precise measurements of suppression of charm and bottom separately are necessary. New observables (for instance azimuthal correlations of charmed mesons [50]) could also help to address this issue.
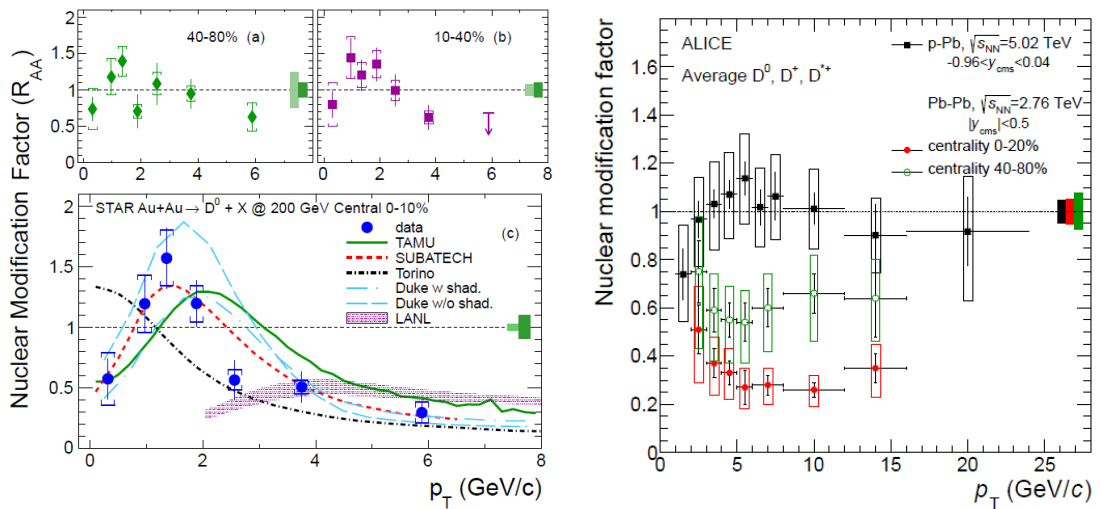
Figure 4. Charmed meson suppression at RHIC [51] and LHC [26].

The Beam Energy Scan (BES) program at RHIC was carried out recently to study the phase diagram of nuclear matter and search for a phase transition and a critical point. BES results show that elliptic flow of inclusive charged hadrons is approximately independent of beam energy (the difference is less than 10% for $0.5 < p_T < 3$ GeV/c) and light hadron production is suppressed at high p_T in the energy range of $39 - 200$ GeV. In Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV, production of e^{HF} is not suppressed (Fig. 5, right panel). Moreover, contrary to results for light hadrons, where a positive v_2 is observed and the difference between 200 GeV and 39 GeV is small, STAR measurements in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ and 39 GeV [48] indicate that the v_2 of e^{HF} is consistent with zero. Furthermore, the difference between 200 GeV and results at those lower energies is statistically significant for $p_T < 1$ GeV/c.

These results indicate that there is a difference in the interactions of the heavy quarks with the surrounding nuclear matter at 200 GeV compared to the two lower energies and there is already a change of the nuclear matter properties in the energy range of $62.4 - 200$ GeV.
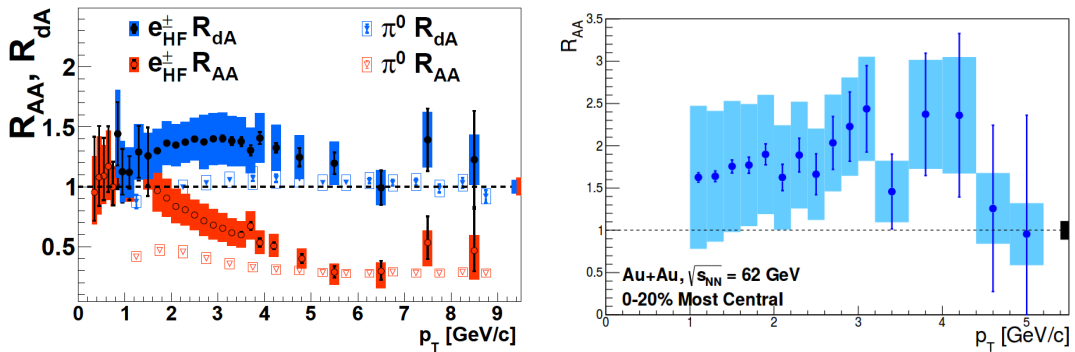
Figure 5. Nuclear modification factor for electrons from semi-leptonic heavy flavor hadron decays in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [23] and 62.4 GeV [52].

Summary
Heavy quarks are important tools to study the properties of the nuclear matter under extreme conditions but their measurements in heavy ion collisions are challenging and interpretation of the results is model dependent. Precision measurements of elliptic flow and production for charmed and bottom hadrons separately are necessary to further constrain models and to advance our understanding of the partonic medium properties. New vertex detectors at RHIC (Heavy Flavor Tracker at STAR and Silicon Vertex Tracker and Forward Silicon Vertex Detector at PHENIX) and LHC (new Inner Tracking System at ALICE) will provide data which will allow to address these issues.

References
[1] Rapp R and van Hees H 2010 *Heavy Quarks in the Quark-Gluon Plasma* in *Quark-Gluon Plasma 4* (World Scientific) chap 3, p 111 (*Preprint* 0903.1096)
[2] Rapp R, Blaschke D and Crochet P 2010 *Prog. Part. Nucl. Phys.* **65** 209
[3] Lansberg J 2006 *Int. J. Mod. Phys. A* **21** 3857 (*Preprint* hep-ph/0602091)

[4] Conesa del Valle Z, Corcella G, Fleuret F, Ferreiro E, Kartvelishvili V *et al.* 2011 *Nucl. Phys. Proc. Suppl.* **214** 3 (*Preprint* 1105.4545)

[5] Matsui T and Satz H 1986 *Phys Lett. B* **178** 416

[6] Digal S, Petreczky P and Satz H 2001 *Phys. Lett. B* **514** 57 (*Preprint* hep-ph/0105234)

[7] Mocsy A 2009 *Eur. Phys. J. C* **61** 705 (*Preprint* 0811.0337)

[8] Kim H (CMS Collaboration) 2014 *Nucl. Phys. A* **931** 558

[9] Scomparin E (NA60 Collaboration) 2009 *Nucl. Phys. A* **830** 239C (*Preprint* 0907.3682)

[10] Adare A *et al.* (PHENIX Collaboration) 2011 *Phys. Rev. Lett.* **107** 142301 (*Preprint* 1010.1246)

[11] Yang Z 2014 *Nuclear Physics A* **931** 643

[12] Abelev B B *et al.* (ALICE Collaboration) 2014 *JHEP* **1402** 073 (*Preprint* 1308.6726)

[13] Chatrchyan S *et al.* (CMS Collaboration) 2014 *JHEP* **1404** 103 (*Preprint* 1312.6300)

[14] Abelev B B *et al.* (ALICE Collaboration) 2015 *Phys. Lett. B* **740** 105 (*Preprint* 1410.2234)

[15] Ferreiro E G, Fleuret F, Lansberg J P and Rakotozafindrabe A 2013 *Phys. Rev. C* **88** 047901

[16] Ferreiro E, Fleuret F, Lansberg J, Matagne N and Rakotozafindrabe A 2013 *Eur. Phys. J. C* **73**

[17] Arleo F and Peigné S 2012 *Phys. Rev. Lett.* **109** 122301

[18] Arleo F and Peign S 2013 *JHEP* **2013**

[19] Loureno C, Vogt R and Whri H K 2009 *JHEP* **2009** 014

[20] Adare A *et al.* 2013 *Phys. Rev. Lett.* **111** 212301

[21] Chatrchyan S *et al.* (CMS Collaboration) 2013 *Phys. Lett. B* **724** 213 (*Preprint* 1305.0609)

[22] Abelev B B *et al.* (ALICE Collaboration) 2013 *Phys. Lett. B* **726** 164 (*Preprint* 1307.3237)

[23] Adare A *et al.* (PHENIX Collaboration) 2012 *Phys. Rev. Lett.* **109** 242301 (*Preprint* 1208.1293)

[24] Sickles A M 2014 *Phys. Lett. B* **731** 51 (*Preprint* 1309.6924)

[25] Kikola D and Lipiec A 2014 (*Preprint* 1410.6503)

[26] Abelev B B *et al.* (ALICE Collaboration) 2014 *Phys. Rev. Lett.* **113** 232301 (*Preprint* 1405.3452)

[27] Adare A *et al.* (PHENIX Collaboration) 2013 *Phys. Rev. Lett.* **111** 202301 (*Preprint* 1305.5516)

[28] Abelev B B *et al.* (ALICE Collaboration) 2014 *JHEP* **1412** 073 (*Preprint* 1405.3796)

[29] Rakotozafindrabe A, Ferreiro E, Fleuret F and Lansberg J 2010 *J. Phys. G* **37** 094055 (*Preprint* 1002.2351)

[30] Kopeliovich B, Potashnikova I, Pirner H and Schmidt I 2011 *Phys. Rev. C* **83** 014912 (*Preprint* 1008.4272)

[31] Andronic A 2014 *Nucl. Phys. A* **931** 135 (*Preprint* 1409.5778)

[32] Andronic A, Braun-Munzinger P, Redlich K and Stachel J 2011 *J. Phys. G* **38** 124081 (*Preprint* 1106.6321)

[33] Capella A, Bravina L, Ferreiro E, Kaidalov A, Tywoniuk K *et al.* 2008 *Eur. Phys. J. C* **58** 437 (*Preprint* 0712.4331)

[34] Thews R L, Schroedter M and Rafelski J 2001 *Phys. Rev. C* **63** 054905

[35] Grandchamp L, Rapp R and Brown G E 2004 *Phys. Rev. Lett.* **92** 212301

[36] Gupta S and Sharma R 2014 *Phys. Rev. C* **89** 057901

[37] Liu Y, Qu Z, Xu N and Zhuang P 2009 *Physics Letters B* **678** 72

[38] Zhao X and Rapp R 2011 *Nuclear Physics A* **859** 114

[39] Adare A *et al.* (PHENIX Collaboration) 2007 *Phys. Rev. Lett.* **98** 232301 (*Preprint* nucl-ex/0611020)

[40] Adamczyk L *et al.* (STAR Collaboration) 2013 *Phys. Lett. B* **722** 55 (*Preprint* 1208.2736)

[41] Chatrchyan S *et al.* (CMS Collaboration) 2012 *JHEP* **1205** 063 (*Preprint* 1201.5069)

[42] Collaboration A 2014 *Physics Letters B* **734** 314

[43] Lin Z and Ko C 2001 *Physics Letters B* **503** 104

[44] Abelev B B *et al.* (ALICE Collaboration) 2014 *Phys. Lett. B* **738** 361 (*Preprint* 1405.4493)

[45] Caldern de la Barca Snchez M (CMS Collaboration) 2013 *J. Phys. Conf. Ser.* **458** 012011 (*Preprint* 1305.5560)

[46] Djordjevic M, Gyulassy M, Vogt R and Wicks S 2006 *Phys. Lett. B* **632** 81

[47] Abelev B *et al.* (ALICE Collaboration) 2013 *Phys. Rev. Lett.* **111** 102301 (*Preprint* 1305.2707)

[48] Adamczyk L *et al.* (STAR Collaboration) 2014 (*Preprint* 1405.6348)

[49] Adare A *et al.* (PHENIX Collaboration) 2011 *Phys. Rev. C* **84** 044905

[50] Nahrgang M, Aichelin J, Gossiaux P B and Werner K 2014 *Phys. Rev. C* **90**(2) 024907

[51] Adamczyk L *et al.* (STAR Collaboration) 2014 *Phys. Rev. Lett.* **113** 142301 (*Preprint* 1404.6185)

[52] Adare A *et al.* (PHENIX Collaboration) 2014 (*Preprint* 1405.3301)