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HEAVY FLAVOUR AT RHIC*

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Open and hidden charm and beauty are of outstanding importance for the study of the strongly interacting Quark-Gluon Plasma (sQGP) discovered at RHIC, for example for the understanding of the mass dependence of jet quenching and the measure of the density of the partonic medium, and for the measurement of its temperature through the quarkonia dissociation hierarchy. We review selected highlights on charm and beauty production at RHIC from $p+p$, d+Au and $A+A$ collisions at $\sqrt{s_{NN}} = 200$ GeV, and compare them to model calculations. We focus on two particular issues, jet quenching and quarkonia.

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1. Introduction

The experiments at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory, USA, have been studying nuclear matter at extreme conditions by means of heavy ion collisions over the last decade. One of the main physics projects of RHIC is the exploration of the QCD phase diagram using heavy ion collisions like Au+Au and Cu+Cu collisions up to $\sqrt{s_{NN}} = 200$ GeV as well as using p+p and d+Au collisions at the same energy as a baseline for comparisons to $A+A$ collisions, to prove predictions of Quantum Chromodynamics. In particular, they aim to reproduce and study one of the phase transitions believed to have happened in the early universe 10^{-6} s after the Big Bang, namely the phase transition between hadronic matter and deconfined quark and gluon matter.

There is today evidence [1] that a high density partonic source is built in the initial state of the heavy ion collisions at RHIC, which is strongly interacting. This state is noted in short as sQGP: strongly interacting Quark-

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Gluon Plasma. It has been estimated that in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the initial Bjorken mean energy density reached, is about 5 GeV/fm^3, therefore higher than the critical energy density predicted by lattice QCD of 0.6–1 GeV/fm^3.

Heavy flavours (charm and beauty) play an outstanding role among the signatures for the QGP and the study of its properties. One of the main signatures of QGP that was discovered at CERN SPS has been the anomalous suppression of the J/Ψ in Pb+Pb collisions at $\sqrt{s_{NN}} = 20$ GeV [2, 3]. Heavy flavour continues to play an important role in the study of QGP in higher energies at RHIC and LHC, while new aspects as quarkonia regeneration and open heavy flavour energy loss have to be considered. One of the main discoveries at RHIC, has been the discovery of jet quenching, namely the anomalous energy loss of jets when passing through the dense partonic matter built in the collision. This energy loss allows to estimate the gluon rapidity density of the medium.

In this paper we will review selected highlights on charm and beauty production at RHIC energies, measured with the STAR [4] and PHENIX [5] detectors. In particular we will address two main aspects of heavy flavour physics at RHIC; Firstly, open heavy flavour production through direct and indirect measurements as well as the flavour dependence of jet quenching of heavy quarks and secondly, quarkonia production and their dissociation in the sQGP. At the end we conclude and give an outline of the future plans for heavy flavour physics at RHIC.

2. Open charm and total charm cross-section

Open charm is addressed at RHIC through direct reconstruction of charmed hadrons by their hadronic decays in STAR [6]. Open beauty and charm are addressed indirectly through the measurement of non-photonic electrons (NPE) and muons originating from semileptonic decays of charm and beauty hadrons in PHENIX and STAR. Directly identified D-mesons do not extend at high transverse momenta (p_{T}) in contrast to the non-photonic electron measurement [7].

Recent results of STAR on D-meson reconstruction are using secondary vertex reconstruction taking advantage of the silicon detectors of STAR present in the runs 2005 and 2007 [8, 9].

The total charm cross-section estimated in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX and STAR were showing a discrepancy by a factor of two. The total charm cross-section estimated in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX and STAR both agree with NLO pQCD estimates within the large errors of the latter.

Recent work from STAR addresses the STAR–PHENIX discrepancy and shows that in a new analysis of data [10,11] the cross-section of non-photonic electrons of STAR agree well with those of PHENIX [12] in the common transverse momentum acceptance, and fall below older STAR measurements [13].

Fig. 1, left (b) shows the ratio of the invariant cross-section of non-photonic electrons in $p+p$ collisions over FONLL calculations from STAR and PHENIX which agree with each other within errors.

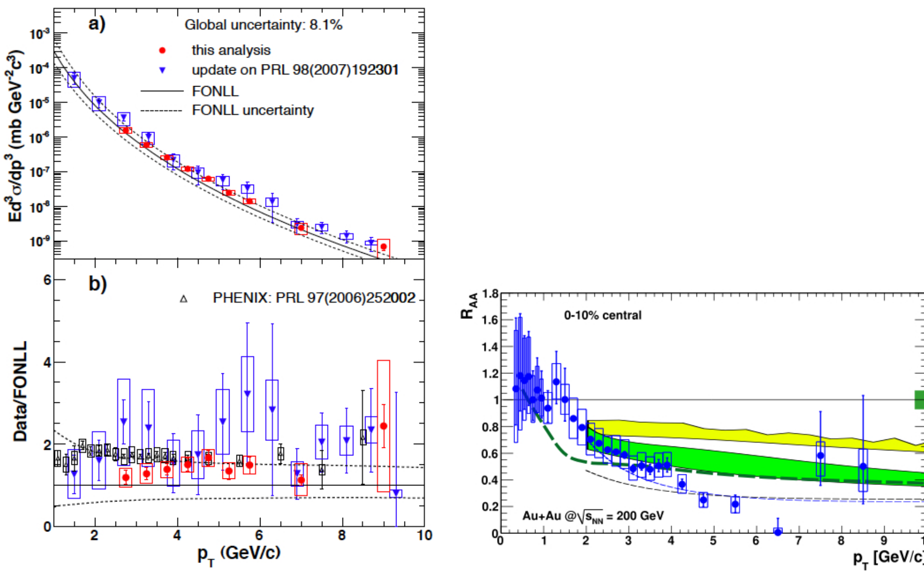

Fig. 1. Left (a): Invariant cross-section of non-photonic electrons in $p+p$ collisions at 200 GeV from [11] (closed circles) and from older STAR results (closed triangles) [13]. Left (b): Ratio of the invariant cross-section of non-photonic electrons in $p+p$ collisions over FONLL calculations from STAR and PHENIX (open triangles) [12]. Right: R_{AuAu} in 0–10% centrality class compared with energy loss models [15]. The thick dashed curve is calculation for electrons from D and B decays from reference [39]. The bands are DGLV [19] calculations for electrons from D and B decays. The lower band contains collisional energy loss as well as radiative energy loss. The thin dashed curves are DGLV calculations for electrons from D decays only.

The non-photonic electron transverse momentum spectrum of both STAR and PHENIX agree with FONLL estimates [14] within the errors [10,11,15]. Both PHENIX and STAR have shown that the total cross-section of charm is scaling with the number of binary collisions [16].

3. Jet quenching of open charm and beauty from non-photonic electron measurements

It is expected that jet quenching due to radiative energy loss is mass dependent and, in particular, it increases with decreasing quark mass [17]. One expects, therefore, an hierarchy in the amount of jet quenching as a function of the mass of the parton. As a consequence, one of the main puzzles at RHIC in the last years has been the measurement of jet quenching of the sum of charm and beauty, which appears to be the same as for light quarks [18, 13].

Jet quenching of charm and beauty are measured through the p_{T} dependence of the nuclear modification factor R_{AA} which is defined as the yield of charm and beauty in heavy ion collisions, divided by the yield in $p+p$ collisions at same energy scaled by the average number of binary collisions. For the study of R_{AA} at high p_{T} charm and beauty are measured through non-photonic electron measurements.

Fig. 1, right shows that the R_{AA} of non-photonic electrons is suppressed at high p_{T} for most central Au+Au collisions [15]. It is shown that models with radiative energy loss are overestimating the R_{AA} (upper band), while the agreement with the data becomes better when collisional energy loss is assumed (lower band) [19].

Other models which achieve an agreement with these data are a model assuming elastic scattering mediated by resonance excitations of D- and B-like states in the medium [20], a collisional dissociation model [21], a model assuming enhancement in the Λ_c production in the heavy ion collisions [22], or models using a running coupling constant and replacing the Debye mass with a hard thermal loop calculation [23].

Some models [20, 23, 24, 25] are able to describe the p_{T} dependence of the observed elliptic flow (v_2) of non-photonic electrons [15], while a coalescence model [26] describes well the low p_{T} part of v_2.

4. Disentangling charm and beauty and consequences for jet quenching

To clarify the origin of the anomalous quenching of charm and beauty mentioned above, a measurement of the quenching of charm and beauty separately is of great interest. Charm and beauty can be disentangled using electron–hadron and electron-D^0 azimuthal correlations.

The relative contribution from B decays to the non-photonic electron spectrum has been measured in $p+p$ collisions at 200 GeV with these two methods and is shown in Fig. 2, left [27].

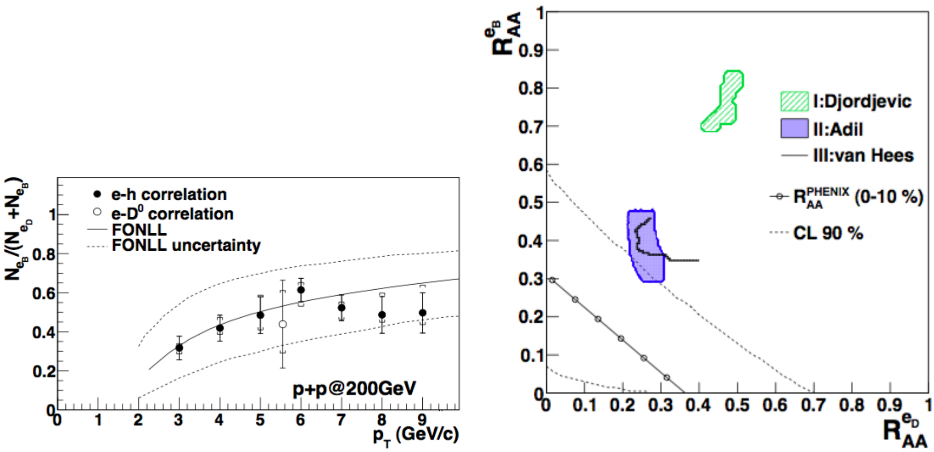

Fig. 2. Left: Transverse momentum dependence of the relative contribution of NPE from B-meson decay to the total NPE yields [27]. Error bars are statistical and brackets are systematic uncertainties. The solid line is the FONLL calculation [14]. The dashed curves indicate the theoretical uncertainties. Right: Confidence level contours for nuclear modification factor R_{AA} for electrons from D- and B-meson decays in central Au+Au collisions at 200 GeV for $p_{\rm T} > 5$ GeV [27].

These results agree with PHENIX measurements at $p_{\rm T}$ up to 5 GeV [28]. The B decay contribution is seen to increase with $p_{\rm T}$ and becomes comparable to the contribution from D-meson decay at $p_{\rm T} \geq 5$ GeV. The ratio of NPE from B decay to all NPE is in agreement with FONLL calculations within errors.

Fig. 2, right from [27] combining the measurement shown in Fig. 2, left and in [15], indicates that the R_{AA} for NPE from B decays in Au+Au collisions at 200 GeV is below 0.6 at 90% confidence level. Therefore, beauty as well as charm is suppressed at high $p_{\rm T}$ ($p_{\rm T} > 5$ GeV) in central Au+Au collisions at 200 GeV. Models with only radiative energy loss, like the "Model I" shown in the Fig. 2, right, are excluded by these data.

5. Quarkonia

Dissociation of quarkonia in the dense and hot partonic matter allows to establish the phase transition and to measure the temperature of QGP reached in a collision through the hierarchy of their dissociation temperature [3, 29]. Next to colour screening, many other effects may play a role in the suppression of quarkonia in heavy ion collisions, in particular, cold matter absorption, recombination/coalescence from quark–antiquark pairs in the source, heavy resonances, *etc.*

There are two major puzzles concerning the J/Ψ suppression measured at RHIC; One is that the dependence of the J/Ψ suppression on the number of participant nucleon N_{part} obtained in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV RHIC is similar to that measured in Pb+Pb collisions at $\sqrt{s_{NN}} = 20$ GeV [2], as shown in Fig. 3, left.

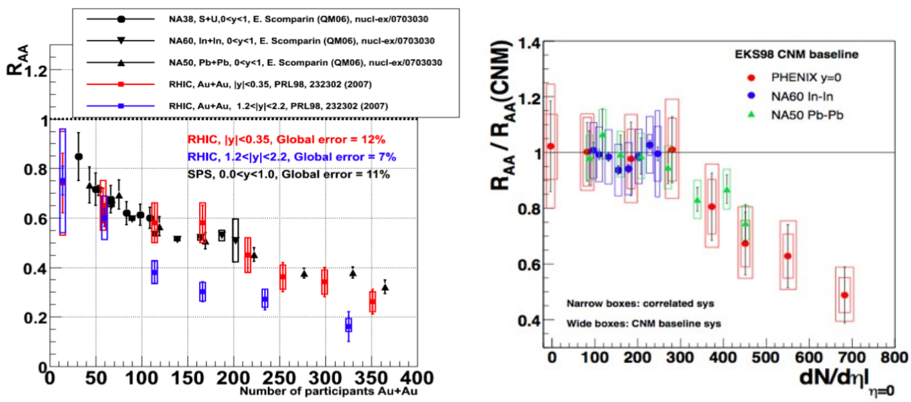

Fig. 3. Left: Nuclear modification factor for J/Ψ in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV at $|y| = 0.35$ and $1.2 < |y| < 2.2$, as well as data from CERN SPS as a function of the number of participating nucleons. Right: Nuclear modification factor for J/Ψ corrected for cold nuclear matter effects as a function of the charged particle $dN/d\eta$ at $\eta = 0$ in Au+Au collisions at 200 GeV at RHIC and at SPS energies (preliminary) [31].

The second puzzle is that the J/Ψ suppression in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is larger at forward rapidity as compared to midrapidity, also shown in Fig. 3, left. Therefore, the suppression of J/Ψ does not increase with the expected local density of the medium.

A possible solution to these puzzles is suggested by taking into account cold nuclear matter effects [30, 31, 32] using the d+Au data of run 2009.

A representation of the J/Ψ suppression after correcting for cold nuclear matter effects and as a function of $dN/d\eta$ instead of N_{part} depicted in Fig. 3, right shows a more consistent way to compare the different energies [31]. Indeed the N_{part} variable describes centrality but it does not account for the different energies of SPS and RHIC data.

One possible interpretation of these data is that the suppression of J/Ψ, which occurs at low p_{T}, may come from the dissociation of excited states (ψ', χ_c) which have a smaller dissociation temperature and which decay into J/Ψ. In particular 60% of all J/Ψ is direct, while 30% comes from χ_c and 10% from ψ'. In that case directly produced J/Ψ may not be suppressed at RHIC, and more J/Ψ suppression is expected at the LHC in which the directly produced J/Ψ should dissociate, while one should take into account also the regeneration of J/Ψ from $c\bar{c}$ coalescence.

Another possible interpretation is addressed in [33] in which the J/Ψ is assumed completely suppressed at RHIC and is regenerated by $c\bar{c}$ coalescence. This estimate agrees with the data at RHIC and predict a great enhancement of R_{AA} of J/Ψ at the LHC.

The nuclear modification factor of J/Ψ at high $p_{\rm T}$ has been measured by STAR in Cu+Cu collisions at 200 GeV [34] and it is demonstrated that it is consistent with 1 namely with no suppression above a $p_{\rm T}$ of ~ 5 GeV. This measurement excludes predictions of AdS/CFT+Hydro model [35]. The two component model with finite J/Ψ formation time describes the increasing tendency of the R_{AA} of the J/Ψ [36].

Furthermore, the $\Upsilon \rightarrow e^+e^-$ state has been measured by STAR and PHENIX [37, 38]. The Υ(1S) state has a high dissociation temperature and is not expected to dissociate at RHIC while the (2S, 3S) states may dissociate. The measurements at RHIC cannot distinguish the (1S, 2S, 3S) states. The production cross-section of Υ extracted in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX and STAR agree with the trend seen in other data as a function of collision energy.

The R_{AA} of Υ in d+Au collisions is consistent with unity. An upper limit of 0.64 at 90% confidence level on the R_{AA} of Υ produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV has been estimated by PHENIX [38].

6. Conclusions and outlook

Heavy flavour physics in heavy ion collisions at RHIC exhibits several outstanding results as well as puzzles to be resolved with new detectors and new data at RHIC and at LHC. One highlighted puzzle is the strong unexpected suppression of non-photonic electrons from charm and beauty which is similar to that seen in light hadrons. This puzzle is central to the understanding of jet quenching flavour dependence.

New data on the beauty contribution to non-photonic electrons in $p+p$ collisions and the nuclear modification factor of non-photonic electrons in central Au+Au collisions allow to constraint the nuclear modification factor of charm and beauty at $p_{\rm T} > 5$ GeV to be below 0.7 respectively 0.6 at 90% confidence level. Therefore, not only charm but also beauty is suppressed in central Au+Au collisions. As next, a direct measure of the R_{AA} of charm and beauty at RHIC would be needed to give a definitive answer to that puzzle and allow to establish together with theory the different components of radiative *versus* other types of energy loss.

The suppression of J/Ψ in Au+Au collisions constitutes another puzzle, as it does not seem to follow the local density: the suppression is the same at RHIC and SPS as a function of participant nucleons, and becomes larger in forward rapidity at RHIC. Corrections for cold nuclear matter effects are important for the understanding of these data. An interpretation, appearing as possible, is that directly produced J/Ψ may not be dissociated at RHIC, while χ_c and $\psi^{'}$ which give feeding into J/Ψ, are completely suppressed. In that case the direct J/Ψ is expected to be completely suppressed at LHC, while it will reappear due to J/Ψ regeneration from $c, \bar{c}$ coalescence. J/Ψ regeneration if large, gives an alternative scenario in which all J/Ψ may be completely suppressed already at RHIC. New RHIC and LHC data will be able to give important input to resolve this issue. The Υ (1S+2S+3S) has been measured at RHIC and its nuclear modification factor in Au+Au collisions is found to be less than 0.64 at 90% confidence limit.

Both the PHENIX and STAR collaborations at RHIC have an extended program to explore Heavy Flavour physics in the next few years by means of new dedicated silicon vertex detectors allowing high precision measurements.

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