Charm and Beauty production at RHIC

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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. Anomalous energy loss (jet quenching) of quarks passing through the dense and hot matter built in heavy ion collisions is one of the outstanding discoveries made at RHIC. This phenomenon allows for an estimate of the initial gluon density. Furthermore, color screening of hidden charm and beauty states is a key signature of the QCD phase transition, allowing an estimate of the initial temperature. We present results on the flavour dependence of jet quenching. Heavy flavour production in A+A as compared to p+p collisions will be discussed for open and hidden charm.

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 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} sec 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 build 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 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 as shown in fig. 1 [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].

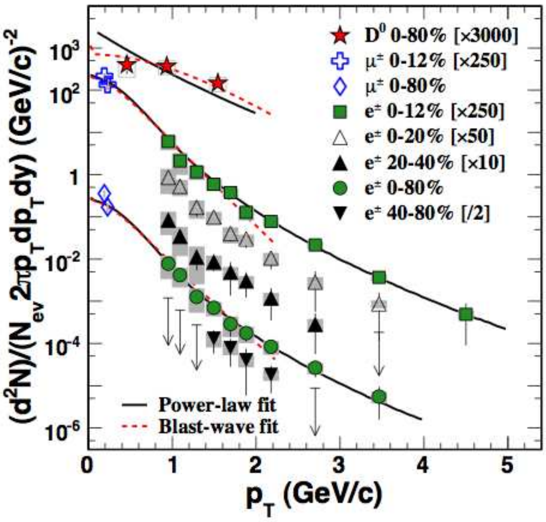

Figure 1. p_T distributions of invariant yields for D, charm-decayed prompt muons and NPE in different centralities. Solid curves are power-law combined fit for D0 and leptons. Dashed curves are blast-wave fit. The gray bands are bin-to-bin systematic uncertainties [7].

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 later.

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

The non-photonic electron transverse momentum spectrum of both STAR and PHENIX agree with FONLL estimates [13] within the errors [10,14]. Both PHENIX and STAR have shown that the total cross section of charm is scaling with the number of binary collisions [15].

3. Jet quenching of open Charm and Beauty from non-photonic electron measurements

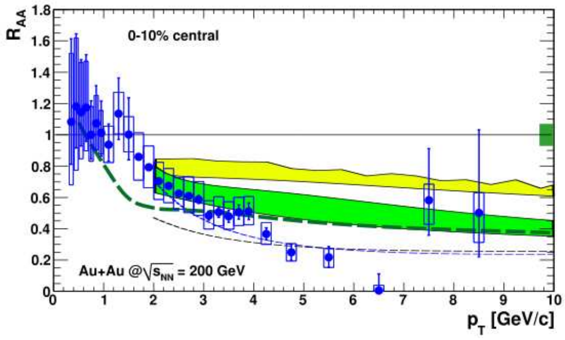

Figure 2. R_{AuAu} in 0-10% centrality class compared with energy loss models [14]. The thick dashed curve is calculation for electrons from D and B decays from reference [36]. The bands are DGLV [18] calculations for electrons from D and B decays. The lower band contains collisional energy loss as well as radiative energy loss. The thin dashed curves are DGLV calculations for electrons from D decays only.

It is expected that jet quenching due to radiative energy loss is mass dependend and in particular it increases with decreasing quark mass [16]. 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 [17,12].

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.

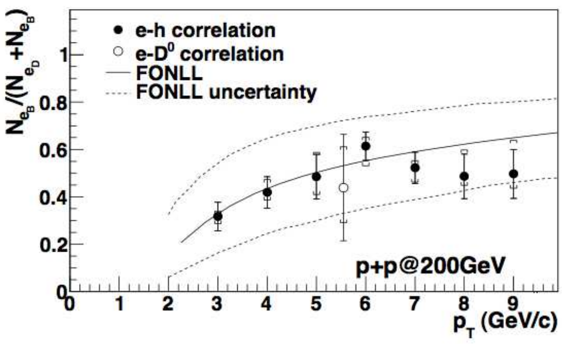

Figure 3. Transverse momentum dependence of the relative contribution of NPE from B meson decay to the total NPE yields. Error bars are statistical and brackets are systematic uncertainties. The solid line is the FONLL calculation [13]. The dashed curves indicate the theoretical uncertainties.

Fig. 2 shows that the R_{AA} of non-photonic electrons is suppressed at high p_T for most central Au+Au collisions [14]. 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 e.g. collisional energy loss is assumed (lower band) [18].

Other models which achieve an agreement with these data are e.g. a model assuming elastic scattering mediated by resonance excitations of D and B-like states in the medium [19], a collisional dissociation model [20], a model assuming enhancement in the Λ_c production in the heavy ion collisions [21], or models using a running coupling constant and replacing the Debye mass with a hard thermal loop calculation [22].

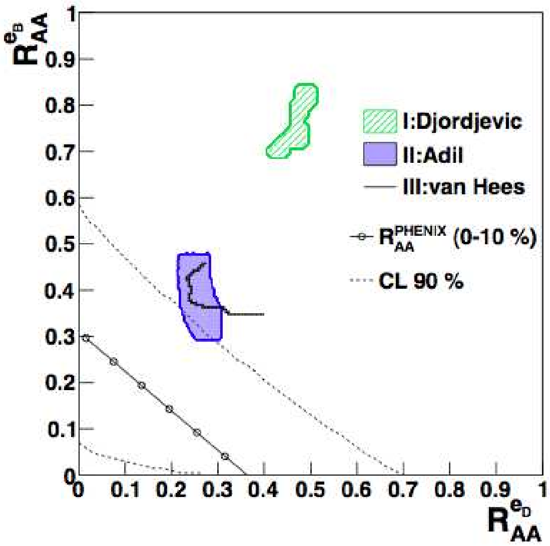

Figure 4. Confidence level contours for nuclear modification factor R_{AA} for electrons from D and B meson decays in central Au+Au collisions at 200 GeV for $p_T > 5$ GeV [26].

Some models e.g. [19,22–24] are able to describe the p_T dependence of the observed elliptic flow (v_2) of non-photonic electrons [14], while a coalescence model [25] 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

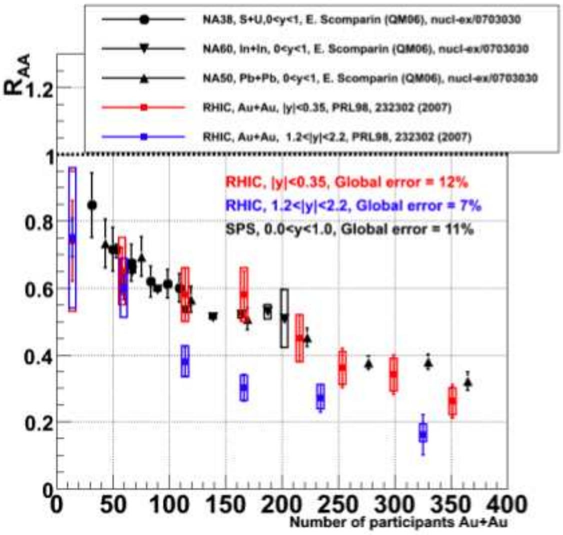

Figure 5. Nuclear modification factor for J/Ψ in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV at $|y|$ =0.35 and $1.2 < |y| < 2.2$, as well as data from CERN SPS as a function of the number of participating nucleons.

non-photonic electron spectrum has been measured in p+p collisions at 200 GeV with these two methods and is shown in fig. 3 [26]. These results agree with PHENIX measurements at p_T up to 5 GeV [27]. The B decay contribution is seen to increase with p_T and becomes comparable to the contribution from D meson decay at $p_T >= 5$ GeV. The ratio of NPE from B decay to all NPE is in agreement with FONLL calculations within errors.

Fig. 4 from [26] combining the measurement shown in fig. 3 and in [14], 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_T ($p_T > 5GeV$) in central Au+Au collisions at 200 GeV. Models with only radiative energy loss, like the "Model I" shown in the fig. 4, are excluded by these data.

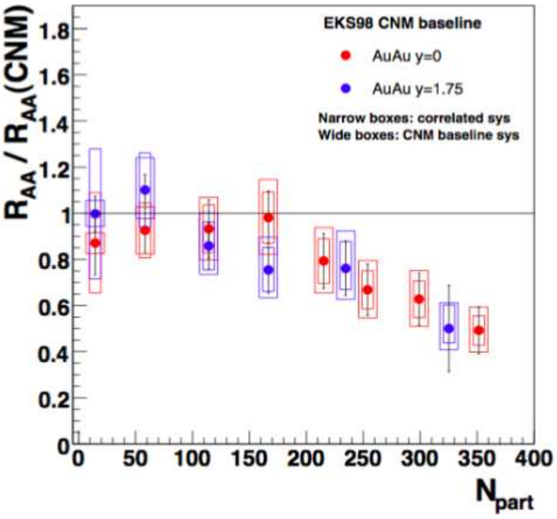

Figure 6. Nuclear modification factor for J/Ψ corrected for cold nuclear matter effects as a function of the number of participant nucleons in Au+Au collisions at 200 GeV at y=0 and at y=1.75 [29].

5. Quarkonia

Dissociation of quarkonia in the dense and hot partonic matter allow to establish the phase transition and to measure the temperature of QGP reached in a collision through the hierarchy of their dissociation temperature [3,28]. Next to color screening, many other effects may play a role in the suppression of quarkonia in heavy ion collisions in particular cold matter absorbtion, 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. 5. 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. 5. Therefore the suppression of J/Ψ does not increase with the expected local density of the

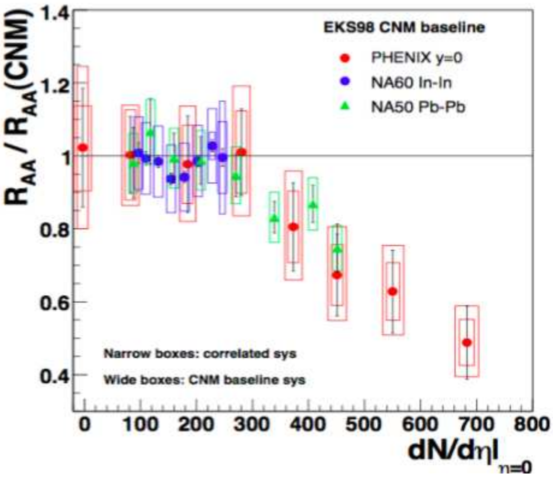

Figure 7. Nuclear modification factor for J/Ψ corrected for cold nuclear matter effects as a function of the charged particle $dN/d\eta$ at $\eta = 0$ in Au+Au collisions at 200 GeV at RHIC and at SPS energies [29].

medium.

A possible solution to these puzzles is suggested by taking into account cold nuclear matter effects [29] using the d+Au data of run 2009. Fig. 6 show that after correcting for cold nuclear matter effects the J/Ψ suppression at midrapidity and y=1.75 agree within errors [29].

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} shown in fig. 7 shows a more consistent way to compare the different energies [29]. Indeed the N_{part} variable describes well 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 ($\psi^{'}$, 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 $\psi^{'}$. 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.

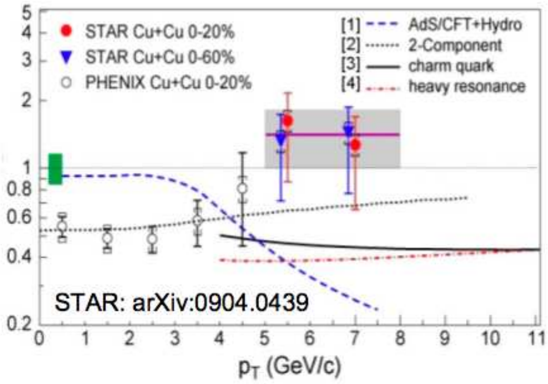

Figure 8. R_{AA} of J/Ψ vs p_T in Cu+Cu collisions at 200 GeV [31].

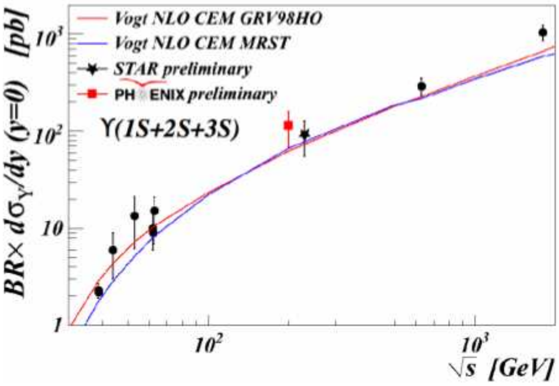

Figure 9. Cross section of Υ in p+p collisions as a function of $\sqrt{s_{NN}}$ of the collision.

Another possible interpretation is addressed in [30] 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_T has been measured by STAR in Cu+Cu collisions at 200 GeV as seen in fig. 8 [31] and it is demonstrated that it is consistent with 1 namely with no suppression above a p_T of ~5 GeV. This mesurement excludes predictions of

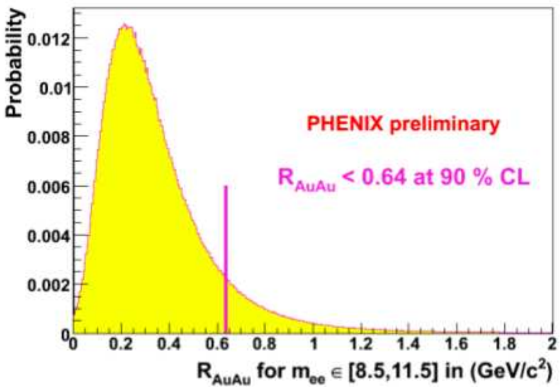

Figure 10. Probability estimate for the R_{AA} of Υ in Au+Au collisions at 200 GeV leading to a limit of R_{AA} being below 0.64 at the 90% confidence level.

AdS/CFT+Hydro model [32]. The two component model with finite J/Ψ formation time describes the increasing tendency of the R_{AA} of the J/Ψ [33].

Furthemore the $\Upsilon \rightarrow e^{+}e^{-}$ state has been measured by STAR and PHENIX [34,35]. 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 as seen in fig. 9.

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 as seen in fig. 10 [35].

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 $p_T > 5$ 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.

Another highlighted puzzle is the suppression of J/Ψ in Au+Au collisions which seemed to not 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. The dissociation of J/Ψ and other quarkonia in the QGP is an outstanding probe and signature of the QGP, in particular the expected sequencial dissociation of quarkonia depending on their dissociation temperature constitutes a unique thermometer of the initial temperature of the partonic medium.

Recent work taking into account cold nuclear mater effects and using as a scaling variable the midrapidity hadron density which is energy dependend, seem able to resolve this puzzle.

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 $c, \overline{c}$ coalescence. J/Ψ regeneration if large, gives an alternative scenario in which all J/Ψ maybe 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. This program will run parallel to the heavy ion data taking from LHC, where a new area in Heavy Flavour physics for QGP searches is initiated this year.

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