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Heavy Flavor Measurements at RHIC

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The study of heavy flavor production in relativistic heavy ion collisions is an extreme experimental challenge but provides important information on the properties of the Quark-Gluon Plasma (QGP) created in Au+Au collisions at RHIC. Heavy quarks are believed to be produced in the initial stages of the collision, and are essential on the understanding of parton energy loss in the dense medium created in such environment. Moreover, heavy-flavor quarkonia production is an important tool to understand deconfinement. In this work we review recent results on open heavy flavor and quarkonia production and their interaction with the hot and dense medium at RHIC.

Keywords: Heavy flavors; Heavy-ion collisions

I. INTRODUCTION

High energy nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) [1] have opened a new domain in the exploration of strongly interacting matter at very high energy density. High temperatures and densities are generated in central nuclear collisions, creating the conditions in which a phase of deconfined quarks and gluons should exist [2]. The measurements at RHIC in conjunction with theoretical calculations suggest that a dense, equilibrated system has been generated in the collision and that it expands as an ideal hydrodynamic fluid. The strong suppression phenomena observed for high-p_T hadrons [3–5] suggest that the system early in its evolution is extremely dense and dissipative.

Heavy quark (charm and bottom) measurements further expand the knowledge about the matter produced in nuclear collisions at RHIC. Because of their large masses, their production can be calculated by pertubative QCD (pQCD) [6]. In particular, comparative measurements in p+p, d+Au and Au+Au are sensitive to the initial state gluon densities in these systems [7]. In Au+Au collisions, medium effects such as heavy quark energy loss can be studied through a comparison of the p_T distributions of bottom and charm hadrons with those observed for inclusive hadrons.

Moreover, measuring open charm and bottom production at RHIC provides essential reference data for studies of color screening via quarkonium suppression [8]. The suppression pattern of heavy quarkonium states can provide key information on understanding the medium created in heavy-ion collisions. A full spectroscopy exhibiting suppression of the quarkonium excited states is predicted to be evidence of a strong modification of spectral properties of heavy quarkonia due to deconfinement [9, 10]. The specific pattern can provide experimentalists with a thermometer of the QGP.

II. OPEN HEAVY FLAVOR MEASUREMENTS AT RHIC

The study of heavy flavors in relativistic nuclear collisions follows two different approaches: (i) the direct reconstruction of heavy flavor mesons and (ii) the identification of electrons and muons from semi-leptonic decays of such mesons. STAR and PHENIX explore one or both of these methods.

A. Experimental techniques

Direct reconstruction of heavy-flavor mesons is being performed by the STAR collaboration using the decay channel $D^0 \to K^-\pi^+$ (and c.c.) with branching ratio of 3.83% in d+Au and Au+Au collisions. Because of the small branching ratio and the lack of dedicated detector triggers, the direct reconstruction of D-mesons requires the analysis of a large amount of data. The available statistics limits the study of such mesons to the low-p_T region ($p_T < 3$ GeV/c). Kaons and pions are identified using the STAR Time Projection Chamber (TPC) dE/dx. The resulting invariant mass spectrum of kaon-pion pairs contains a substantial amount of background from random combinatorics that can be subtracted using event mixing methods. Details of the analysis can be found in Ref. [11].

Despite the limitation on p_T and statistics, direct reconstruction of D-mesons is the cleanest probe to investigate heavy quarks in relativistic nuclear collisions.

The use of semi-leptonic decays of heavy flavor mesons (Ex: $D^0 \to e^+ + K^- + \nu$) over a broad p_T range, provide a more efficient measurement of charm and bottom production and overcome the limitations imposed by the direct reconstruction of such mesons. At RHIC two methods are utilized to measure heavy flavor production via semi-leptonic decays: (i) identification of electrons from D and B-meson decays and (ii) identification of muons from D-meson decays.

The analysis of non-photonic electrons (the excess of electrons after subtracting all possible sources of background, such as photon conversions and Dalitz decays) is a technique used by STAR and PHENIX. Electron identification in STAR is done using the dE/dx and momentum information from the TPC and the Time of Flight (ToF) data for low to moderate p_T ($p_T < 4-5$ GeV/c) electrons [11] or the barrel electromagnetic calorimeter (EMCAL) data for moderate to high p_T ($p_T > 1.5$ GeV/c) electrons [12].

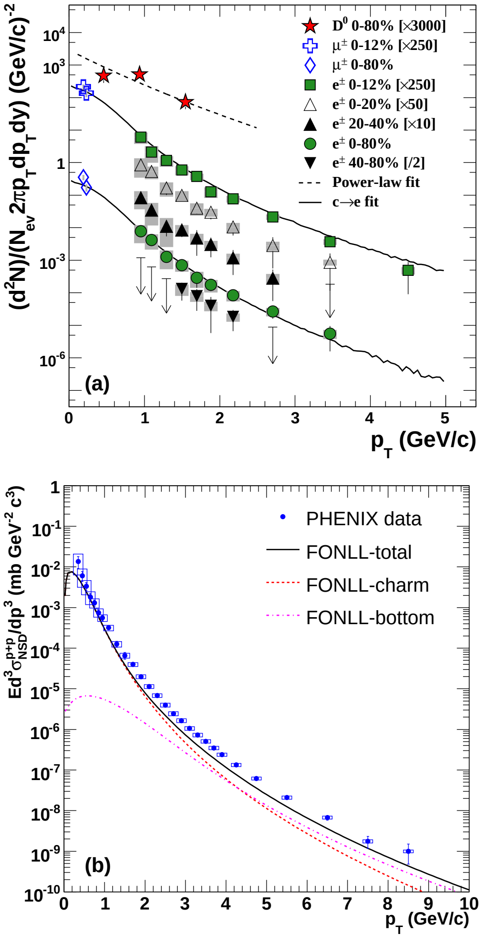

FIG. 1: Data used by STAR and PHENIX to study total charm production at RHIC. (a) D^0, μ and electron data used in a combined fit from STAR. (b) electron data used by PHENIX. Curves are FONLL prediction used by PHENIX to extrapolate the electron spectra to $p_T = 0$.

Electron identification in PHENIX [13, 14] is largely based on the Ring Imaging Cherenkov detector (RICH) in conjunction with a highly granular EMC (electromagnetic calorimeter). The momentum is derived from the curvature (due to a magnetic field up to 1.15 T) of tracks reconstructed from drift and pad chambers.

A major difficulty in the electron analysis by both collaborations is the fact that there are many sources of electrons other than semi-leptonic decays of heavy-flavor mesons. A substantial effort is being made to overcome this difficulty. The main sources of background are photon conversion in the detector material (less significant in PHENIX due to the reduced amount of material when compared to STAR) and π^0 and η Dalitz decays. Other sources of background, such as ω, ϕ and ρ decays are also taken into account. These background sources are usually called photonic electrons.

Background subtraction in the PHENIX experiment is performed by two different methods: (i) the converter method, in which a well defined amount of material is added to the detector to increase the amount of background electrons. (ii) the cocktail method, with which PHENIX simulates the spectra of the main sources of background (photons, π^0 and η). Both methods agree with each other very well.

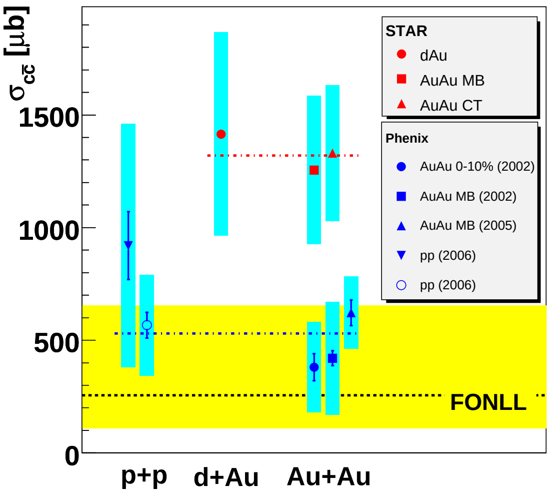

FIG. 2: Overview of the experimental charm cross section measured by STAR and PHENIX from p+p to central Au+Au collisions at RHIC.

Due to the large acceptance and tracking efficiency, STAR can directly reconstruct the photonic background by performing invariant mass reconstruction of e^+e^- pairs with high efficiency. For photon conversion, π^0 and η Dalitz decays the invariant mass spectrum shows a peak near zero. Other background sources are evaluated by simulations and account for a very small fraction of the total background.

Muon identification at low-p_T ($p_T < 0.25$ GeV/c) plays an important role because this p_T range imposes a significant constraint on the measurement of the charm cross section [15]. This measurement is being done by STAR using dE/dx and momentum information from the TPC and mass reconstruction from the ToF detector. Background from π and K decays can be subtracted by looking at the DCA (distance of closest approach) between the muon and the primary vertex of the collision.

B. Charm production at RHIC

The measurement of the total charm cross section via non-photonic electrons requires precise measurements down to very low-p_T. This is an experimental challenge because the lower the p_T, the higher the amount of photonic electrons that contaminate the measurement, resulting in large systematic uncertainties. In order to overcome this limitation, STAR per-

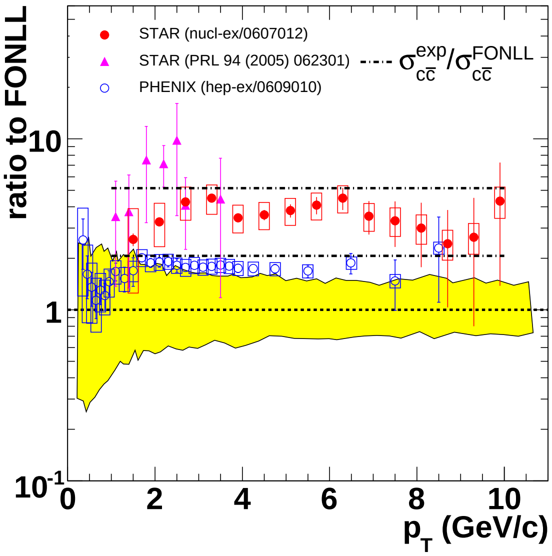

FIG. 3: Ratio between the measured non-photonic electron yield and FONLL pQCD calculations for *p*+*p* collisions.

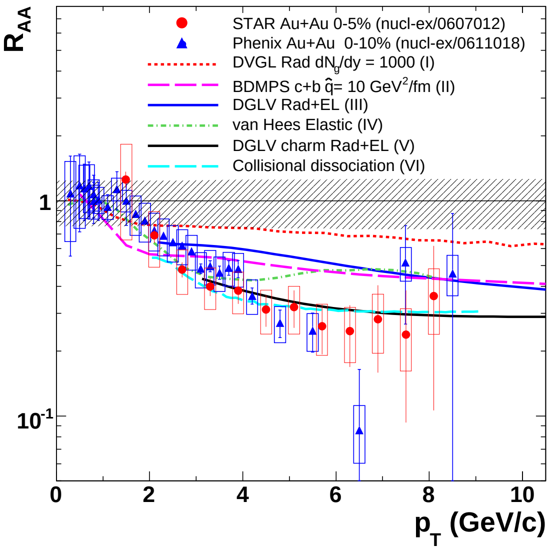

FIG. 4: R_{AA} as function of p_T for central collisions. Curves are described in the text.

forms three independent measurements: direct reconstruction of D-mesons and μ and $e^\pm$ from semi-leptonic decays. The total charm cross section is obtained from a combined fit of these measurements [15] as illustrated in Fig. 1-a. PHENIX, on the other hand, uses its $e^\pm$ measurements to extract total cross sections [14]. To overcome the large background at low-p_T PHENIX reduced the amount of material in its detector, therefore reducing the amount of electrons from photon conversions. This resulted in a decrease in the minimum p_T that can be measured by PHENIX from ~ 0.8 to ~ 0.4 GeV/c (Fig. 1-b).

Figure 2 summarizes all charm cross section measurements from *p*+*p* to central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC [11, 13–16]. Shown is the total cross section per binary nucleon-nucleon collision. Fig. 2 makes evident a factor of ~ 2 between STAR and PHENIX, this difference being larger than the combined systematic uncertainties in the case of central Au+Au collisions. The dashed line in this figure depicts the average prediction from FONLL calculations for charm production at RHIC energies, being the yellow band its uncertainty determined by independent variation of quark masses and of renormalization and factorization scales. The dash-dotted lines correspond to average values for each experiment. Despite the differences between experiments the results, for each experiment, suggest that charm production follows a binary scaling from *p*+*p* to central Au+Au collisions. This is a strong indication that charm is predominantly produced in the early stages of the collision evolution and other processes, such as thermal production in the QGP, are not significant.

Figure 3 shows the ratio of STAR [12] and PHENIX [14] measurements to FONLL calculations [17] for high-p_T electrons in *p*+*p* collisions at RHIC. The dash-dotted lines correspond to the ratio of the experimental to FONLL cross sections. This makes evident that the factor of ~ 2 discrepancy in the cross section extends up to large p_T values. It is also possible to note that, despite this normalization discrepancy FONLL describes the shape of the measured spectra well in both cases, suggesting that the differences between the measurements may be related to an experimental normalization effect.

Future RHIC measurements should address this experimental discrepancy. STAR is planning a run without its inner tracking detectors (SVT and SSD) in the next 1-2 years that will reduce the amount of photon conversion and will address in detail some of the systematic uncertainties in the background removal of the electron measurements. Added to that, both STAR and PHENIX are developing detector upgrades visioning drastic improvements in secondary vertex reconstruction which will allow the use of displaced vertex techniques to directly measure *D* and *B* mesons with high precision and efficiency.

C. Modifications of heavy flavors in the medium

Putting aside the discrepancies in the absolute cross section measurements between STAR and PHENIX we now investigate how heavy quarks interact with the dense QCD medium formed in Au+Au collisions at RHIC. Over the last few years RHIC is providing interesting information on how the partons behave in such a hot and dense medium. The study of flavor dependence of these interactions will further expand our knowledge about the properties of the nuclear matter under such extreme conditions.

Nuclear effects in non-photonic electron production are measured through the comparison of spectra from *d*+Au and

Au+Au collisions to the equivalent spectrum in p+p; the relevant quantity is the ratio $R_{AA}(p_T) = (dN_{AA}/dp_T)/(T_{AA} \times dN_{pp}/dp_T)$, where dN_{AA}/dp_T is the differential yield in Au+Au (d+Au) and dN_{pp}/dp_T the corresponding yield in p+p collisions. T_{AA} is the nuclear overlap integral, derived from Glauber calculations [18]. In the absence of nuclear effects, such as shadowing, Cronin effect, or gluon saturation, hard processes, such as heavy flavor production are expected to scale with the number of binary collisions and, hence, $R_{AA}(p_T)$ = 1. Fig. 4 shows R_{AA} as a function of p_T for non-photonic electrons in central Au+Au collisions from STAR and PHENIX data. Despite the cross section discrepancies between STAR and PHENIX, R_{AA} results are consistent with each other. R_{AA} for non-photonic electrons shows a large suppression in central Au+Au collisions, indicating an unexpectedly large energy loss of heavy quarks in the medium.

The suppression of non-photonic electrons in central Au+Au collisions can be, to some degree, explained in terms of heavy-quark energy loss in the medium. Fig. 4 also shows different theoretical predictions for the non-photonic electron suppression in central Au+Au collisions considering different energy loss mechanisms. Curves (I) and (II) correspond to the expected heavy quark suppression when the energy loss mechanism is induced gluon radiation, considering electrons from decays of D and B mesons decays. Curve (I) corresponds to the average value of DVGL radiative energy loss calculation in which the medium gluon density is $dN_g/dy = 1000$ [19]. In this case, the radiative energy loss does not account for the observed suppression, although the uncertainties, both in the data and theory, are large. On the other hand, Curve (II) [20] shows a larger suppression than Curve (I). In this case, however, the sensitivity of R_{AA} to the time averaged transport coefficient $\hat{q}$ becomes smaller as $\hat{q}$ increases. In fact, the variation in R_{AA} for $4 < \hat{q}$ (GeV^2/fm) < 14 at $p_T > 3$ GeV/c is only ~ 0.15 [20]. This saturation of the suppression for high values of $\hat{q}$ can be attributed to the highly opacity of the medium, biasing the particle production towards its surface. Although gluon radiation is still expected to be a significant energy loss mechanism, other processes may become important to describe the suppression observed in central Au+Au collisions. Curve (III) is a prediction for electrons from D and B mesons decays and includes both DVGL radiative and elastic energy loss, as well as jet path length fluctuations [21]. In contrast with light quarks, the elastic energy loss for heavy quarks is comparable to the radiative one [22] and the effect on R_{AA} is significant. In fact, theoretical predictions for elastic rescattering of partons in the medium that can create resonant D and B meson states via quark coalescence [23] in the medium can lead to a significant suppression at moderate p_T as seen in Curve (IV). In this case, the amount of suppression depends on the resonances width. Generally, all current models overpredict R_{AA} at high p_T.It is important to note that, in all calculations, charm quarks are substantially more quenched than bottom quarks. Curve (V) in Fig. 4, which is based only on electrons from D decays, describes the data best. It is the dominance of electrons from B decays for $p_T > 4-5$ GeV$/c$ that pushes the predicted R_{AA} to higher values. All theoretical calculations use the relative contribution of D and B as predicted by pQCD calculations [17]. Other processes, such as in-medium fragmentation [24], shown in Curve (VI), may also contribute to the observed suppression in central Au+Au collisions.

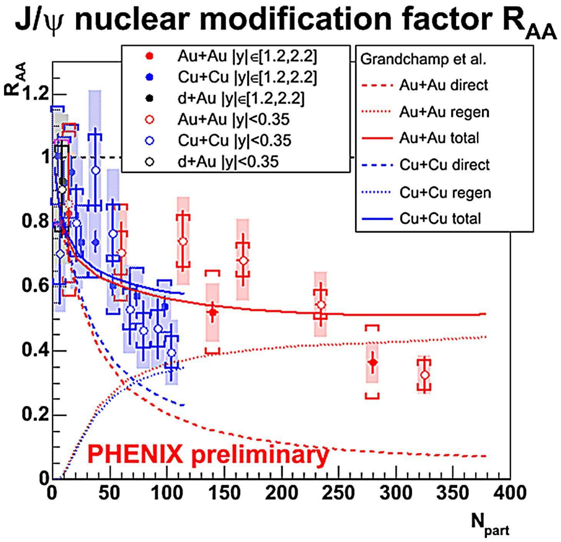

FIG. 5: J/ψ R_{AA} as function of N_{part} for Au+Au and Cu+Cu collisions [28]. Curves are described in the text.

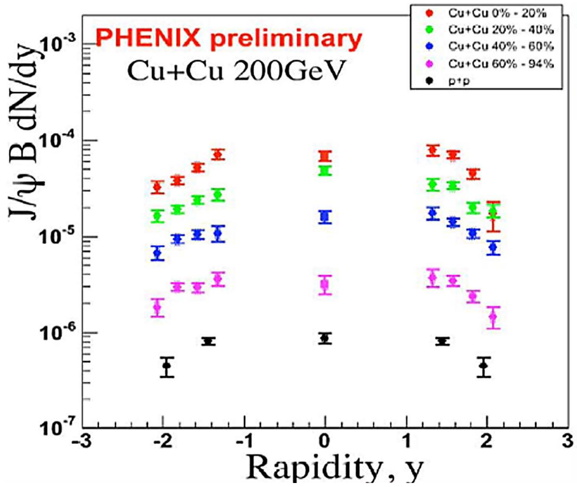

FIG. 6: J/ψ rapidity distribution for p+p and Cu+Cu collisions [28].

The understanding of the observed suppression of non-photonic electrons requires independent measurements of D and B mesons at high-p_T. The full understanding of the energy loss mechanisms is a fundamental milestone for the characterization of the medium properties. Heavy flavors provide an important tool to investigate these mechanisms.

III. QUARKONIA MEASUREMENTS

Since the original idea about color screening by Matsui and Satz [25] quarkonia measurements at relativistic nuclear collisions are taken as important tools for deconfinement investigation in a dense QCD matter. In this framework, the amount of suppression observed for any quarkonia (charmonium and bottomonium) state depends on the medium temperature and the binding energy of such state. However, many other processes, such as cold nuclear matter absorption, shadowing [26] and recombination [27] can lead to suppression or to enhancement of quarkonium production, meaning the investigation more complex. In this scenario, a complete scan (energy, rapidity and p_T) of all quarkonia states is necessary to disentangle the different production/suppression mechanisms.

Both PHENIX and STAR are performing quarkonia measurements at RHIC. STAR relies on special trigger developments for these measurements because of data acquisition limitations. Over the last few years PHENIX is making systematic studies on J/ψ production from p+p to central Au+Au collisions. Most recent results from PHENIX include R_{AA} distributions for Au+Au and Cu+Cu collisions [28] (Fig. 5). The data shows an increasing suppression with N_{part}. At central Au+Au collisions the suppression is larger than predicted by normal absorption in cold nuclear matter [26]. Theoretical models that roughly reproduce the anomalous suppression observed in SPS data [29] predict a suppression stronger than observed but this might be partially compensated by the increase of production predicted by recombination models. However, recombination models also predict a narrowing in the J/ψ rapidity distribution, not observed by PHENIX (Fig. 6) [28]. Significant progress in uderstanding the effect of the medium in quarkonium production is still to come with new measurements at RHIC. Recent results from PHENIX and STAR indicate that other quarkonia states, such as $\psi\prime$ and Υ will be available in the near future, once the integrated luminosities required by these measurements will be reached at RHIC.

IV. FINAL REMARKS

RHIC is providing challenging data on heavy flavor production and its interplay with the medium. Recent results show that this interaction with the medium is more complex than previously expected, resulting in a large energy loss in central Au+Au collisions. In order to make substantial progress it is imperative to independently measure the interaction of D and B mesons with the medium. However, experimental discrepancies are evident in the report of absolute charm cross sections. Detailed and systematic measurements are required to address these discrepancies and are fundamental in our understanding of heavy flavor production at RHIC. First results on J/ψ production and modifications in the medium show increasing suppression from peripheral to central collisions. The final understanding of this suppression needs systematic investigation and the measurement of other heavy flavor quarkonia states.

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