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HEAVY FLAVOR RESULTS AT RHIC — A COMPARATIVE OVERVIEW[*]

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I review the latest heavy flavor measurements at RHIC experiments. Measurements from RHIC together with preliminary results from LHC offer us an opportunity to systematically study the sQGP medium properties. In the end, I will outlook a prospective future on precision heavy flavor measurements with detector upgrades at RHIC.

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1. Introduction

Heavy quarks are expected to be a clean and penetrating probe to study the sQGP matter created in heavy ion collisions because of its intrinsic large mass property. By studying interactions between heavy quarks and medium, one can learn in detail the flavor dependence of parton energy loss mechanism, and also the medium's degree of thermalization by looking at the medium response to heavy quarks. Precision measurements on heavy flavor hadrons in a wide kinematic region will be unique to understand these details. Full reconstruction of charm hadrons has significant advantages over semi-leptonic decay leptons because of complete kinematics and clean interpretations.

Quarkonium suppression due to color screening has been originally proposed as a smoking gun for QGP formation. But various cold and hot medium effects complicate this story and there has not been a direct evidence of color screening so far. Bottomonium (or Υ) production at RHIC may offer us a unique opportunity to directly observe this signature because

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many cold and hot medium effects (cold nuclear absorption, regeneration *etc.*) are expected to be negligible. At LHC, these become complicated, particularly the regeneration process for bottomonium production can be significant, which introduces difficulties in the interpretation.

2. Latest RHIC results

In this paper, I would like to focus on latest RHIC results on charm hadron and quarkonium (J/ψ, Υ) measurements.

2.1. Charm hadron measurements

Figure 1 shows the recent STAR measurements on the charm hadron production cross sections in $p+p$ and minimum bias Au+Au collisions [1]. Charm hadrons were reconstructed via hadronic decays. Although it was not possible to reconstruct secondary decay vertices for charm hadrons in these measurements, STAR managed to overcome the large combinatorial background with large amount of statistics. The left plot shows the mid-rapidity production cross sections for D^0 and D^{*+} scaled to $c\bar{c}$ pairs *vs.* $p_{\rm T}$ and the result is compared to a pQCD FONLL calculation [2]. One can see over a wide $p_{\rm T}$ region, the measurement is consistent with the upper bound of this FONLL calculation. An interesting finding is that the charm hadron cross sections measured by CDF [3] and ALICE [4] at higher energies up to

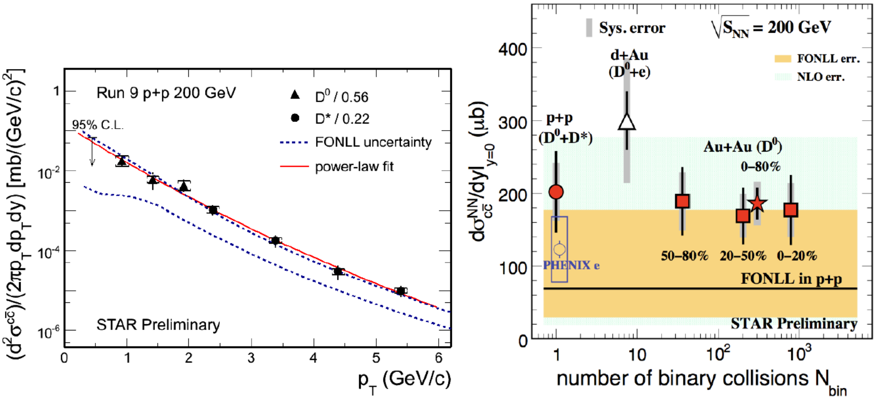

Fig. 1. Left: Charm hadron (D^0 and D^{*+}) production cross section in $p+p$ collisions at $\sqrt{s} = 200$ GeV from STAR. Measurements are consistent with the upper bound of the FONLL pQCD calculation. Right: Total charm production at mid-rapidity per nucleon–nucleon collisions from $p+p$ to central Au+Au collisions from STAR. The measurements demonstrate approximate number of binary collision scaling for the total charm production cross section.

7 TeV are also closer to the upper limits of FONLL calculations. Similarly, the cross section of non-photonic electrons is also consistent with the upper bound of FONLL calculations at $p_{\mathrm{T}}(e) > 1\,\mathrm{GeV}/c$ [5,6]. The STAR D meson measurement covers about 70% of total p_{T} acceptance, leading to a reasonable constraint to the total charm cross section. Fig. 1, right plot shows the total charm cross section per nucleon–nucleon collisions at mid-rapidity from $p+p$ to central Au+Au collisions. Latest STAR Au+Au results were extracted from the D^0 spectrum measurements covering p_{T} from 0.4 up to $\sim 5\,\mathrm{GeV}/c$. The $c\bar{c}$ cross sections were obtained assuming the $c \to D^0$ fragmentation ratio still holds in Au+Au collisions which needs to be tested in future measurements. The results exhibit an approximate N_{bin} scaling indicating charm quarks are predominantly produced from initial hard scatterings.

The D^0 spectrum in Au+Au collisions can be compared to the reference $p+p$ data to calculate the nuclear modification factor R_{AA}. Figure 2, left panel shows the recent results from the STAR measurements. The R_{AA} covers p_{T} up to $\sim 5\,\mathrm{GeV}/c$. Although the values are consistent with unity given current uncertainties, there seems to be a hint of modification for D^0 production in this p_{T} region. The dashed (blue) line depicts the R_{AA} calculated based on the Blast–Wave fit to the Au+Au spectrum. If one uses the

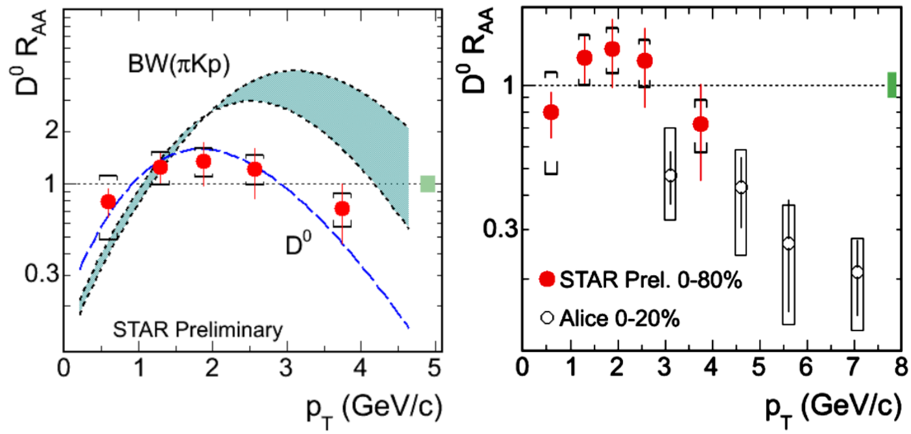

Fig. 2. Left: D^0 meson R_{AA} in 0–80% minimum bias Au+Au collisions at RHIC from STAR. The dashed (blue) line depicts the R_{AA} with the Au+Au D^0 spectrum fit to the Blast–Wave model. The shaded area depicts the R_{AA} with Au+Au spectrum calculated in the Blast–Wave model with light hadron freeze-out parameters. Right: D^0 meson R_{AA} in 0–80% Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ from STAR and D meson R_{AA} in 0–20% Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ from ALICE.

Blast–Wave model with light hadron freeze-out parameters and calculates the R_{AA}, the result is shown as shaded area in the plot. The data points are significantly different from this prediction indicating the charm hadrons freeze-out differently from the system compared to light hadrons. When going towards higher p_{T}, the data points tend to show a slight suppression, however, the uncertainties are large. The right panel of Fig. 2 plots the D^0 R_{AA} from STAR together with the high p_{T} measurement from central (0–20%) Pb+Pb collisions by ALICE [4]. One should note the difference in the centrality for these two sets of data points. After considering this, there seems to be a consistent trend of D^0 R_{AA} between RHIC and LHC although the uncertainties need to be smaller for detailed investigation. One should be aware that D^0 R_{AA} less than unity does not necessarily mean the suppression of charm quark production in heavy ion collisions. The sQGP medium in heavy ion collision may modify the distributions of charm quarks into different charm hadrons compared to $p+p$ collisions because hadronization scheme other than fragmentation (*e.g.* coalescence) can be significant as has already been observed for light flavor hadrons. A complete understanding of charm quark energy loss requires measurements of all ground state charm hadrons in heavy ion collisions.

2.2. J/ψ measurements

J/ψ production has been reported by the PHENIX Collaboration, focusing on the low p_{T} suppression observation [7]. With a couple of subsystem upgrades, STAR has been able to measure J/ψ production with improved statistics, particularly with significant capability of covering high p_{T} up to $\sim 10\,\mathrm{GeV}/c$. A combination of both PHENIX and STAR measurements covers significant large acceptance in 4π [8, 9, 10], offering us a great opportunity to constrain the quarkonium production mechanism as well as to learn the cold and hot medium properties. Most newly developed models can produce the cross section data points within accessible kinematic region. Precision cross section measurements provide constrains on model calculations. In the meantime, more differential measurements (*e.g.* polarization) and/or with more extended kinematic coverage can allow us to disentangle different models and pin down the quarkonium production mechanism.

With significantly improved statistics at high p_{T}, RHIC experiments are now able to study the p_{T} dependent J/ψ R_{AA} [7, 10, 11]. Figure 3 shows the J/ψ R_{AA} results *vs.* centrality (left) and p_{T} (right). On the left plot, the latest STAR Au+Au results were divided into two p_{T} bins. The low p_{T} (2–5 GeV/c) data show consistency with the PHENIX published data points. High p_{T} ($> 5\,\mathrm{GeV}/c$) data show systematically higher R_{AA} compared to low p_{T}. In peripheral Au+Au collisions, the high p_{T} data are consistent with no suppression, while in central collisions, J/ψs are still significantly suppressed, which may be due to the color-screening effect. On the right, the R_{AA} values are plotted *vs.* p_{T} for two centrality bins and one can see the p_{T} dependent structure more clearly. Also plotted on these two plots are theoretical model calculations which include the J/ψ dissociation in the QGP phase as well as the regeneration process [12, 13]. Both model calculations generally describe the data well. The system size and p_{T} dependence of J/ψ R_{AA} can be attributed to the formation time and/or leakage effects.

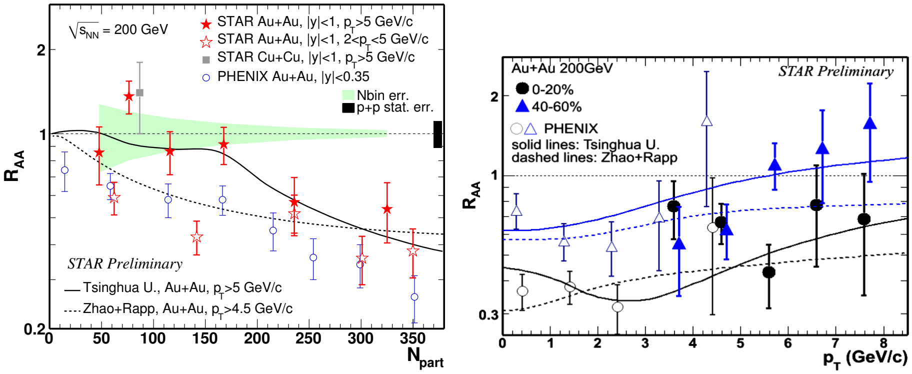

Fig. 3. Left: Nuclear modification factor R_{AA} of J/ψ *vs.* centrality. Measurements include PHENIX and STAR low p_{T} results in Au+Au collisions, STAR high p_{T} results in Cu+Cu and Au+Au collisions. Curves shown in the plot are two model calculations which include both J/ψ dissociation and recombination processes. Right: R_{AA} of J/ψ *vs.* p_{T} in Au+Au collisions from RHIC measurements compared to model calculations.

There have been many interesting results from LHC experiments recently. ATLAS and CMS also observed large suppression of high p_{T} J/ψ in central Pb+Pb collisions [14, 15], and the suppression seems to be stronger than that of RHIC high p_{T} J/ψs, consistent with more suppression in a larger size system. ALICE reported low p_{T} J/ψ R_{AA} at forward rapidity [16]. Comparing to the PHENIX result, the higher R_{AA} values observed are consistent with more regeneration at LHC than at RHIC. Although current observations seem to qualitatively agree with expectations, but quantitatively, we need further systematic studies at both RHIC and LHC to understand the quarkonium production mechanism as well as the medium properties. This also requires precision measurements in $p(d) + A$ collisions to control the shadowing and the cold nuclear absorption effects.

Another striking result reported by STAR is the J/ψ elliptic flow (v_2) measurement [17]. It has a significant improvement in term of precision compared to previous PHENIX measurement [18]. Figure 4 shows the J/ψ v_2 results from both PHENIX and STAR in 20–60% Au+Au collisions and they are compared to various model predictions. Data show that $p_T >$ 2 GeV$/c$, there is no sizable v_2 for J/ψ, which disfavors coalescence production from thermalized charm quarks.

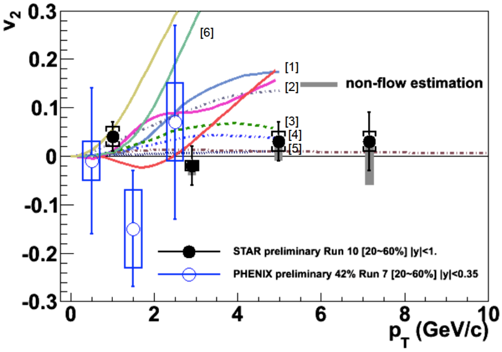

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Fig. 4. J/ψ elliptic flow (v_2) measurements from RHIC experiments in 20–60% Au+Au collisions compared with various model predictions.

One should note the valid centrality and p_T regions for this statement. Based on model calculations [12] which generally reproduce the J/ψ R_{AA} and v_2, the coalescence contribution in 20–60% Au+Au collision at RHIC is not dominant, and it mostly contributes in low p_T ($< 3\,\mathrm{GeV}/c$) region. High p_T region is still dominated by the initial J/ψ production plus possible dissociation in the medium. To get insight of the clean charm quark v_2 from the measurement of J/ψ at RHIC energy, one needs to focus on the p_T region below $\sim 3\,\mathrm{GeV}/c$ and central collisions. This requires further improvement in the experimental precision. Another alternate way to learn the charm quark v_2 will be to measure the charm hadron v_2 experimentally, and it will be achievable with great precision with help of the future silicon vertex detector.

2.3. Υ measurements

Study of bottomonium production at RHIC is a unique way to get insight of the originally proposed QGP color screen signature. The challenge for RHIC experiments is the statistics which makes this measurement likely to be a multi-year program. Both PHENIX and STAR have reported Υ ($1S+2S+3S$ states if not specified) signals from $p+p$ and Au+Au collisions since QM2009. The STAR published and PHENIX preliminary Υ cross sections in $p+p$ collisions are consistent with pQCD model calculations and lie on the trend of energy dependence curve [19, 20]. Recently, with significantly improved statistics in Au+Au collisions, STAR was able to measure the centrality dependence of Υ R_{AA} [21].

Figure 5 shows the Υ R_{AA} *vs.* centrality. It shows a trend of Υ suppression in central Au+Au collisions. Taking into account all current uncertainties from Au+Au and $p+p$ reference, the measured value is $\sim 3\,\sigma$ below unity. The dotted (red) line depicts a naive expectation assuming 2S and 3S states completely melt based on pQCD cross sections and PDG branching ratios. The dashed (blue) line depicts the expected value when all excited bottomonium states (including χ_b) melt and only $\Upsilon(1S)$ survives [22]. The data now seem to favor the scenario that only $\Upsilon(1S)$ survives, but to learn quantitatively the suppression levels of different bottomonium states requires significantly improved statistics in the future.

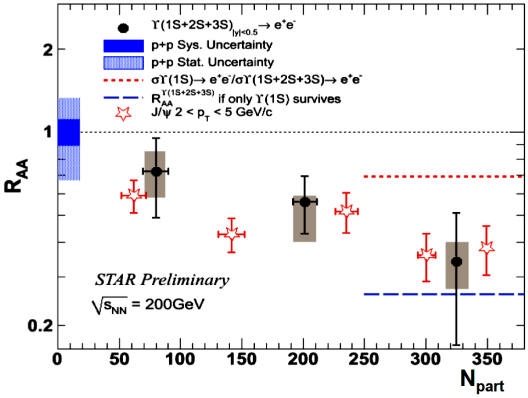

Fig. 5. $\Upsilon(1S+2S+3S)$ R_{AA} *vs.* centrality from STAR compared to expectations from two naive Υ melting scenarios.

With good mass resolution, CMS Collaboration has managed to separate $(2S+3S)$ states from 1S state and they reported the separate R_{AA} values in minbias Pb+Pb collisions at 2.76 TeV [23]. When combining them together to compare with RHIC results, the expected R_{AA} for central collisions should be less than 0.42, which is generally in line with the STAR result. However, one should note that the cold and hot medium effects may be significantly different between RHIC and LHC.

3. Summary and outlook

In summary, RHIC heavy flavor program has achieved many significant results particularly in the past couple of years. It will remain as one of the focuses of RHIC heavy ion program in the upcoming RHIC II era. Both PHENIX and STAR are building significant detector subsystem upgrades now or in the coming years, *e.g.* PHENIX VTX and FVTX, STAR HFT and MTD upgrades *etc.* These are all aiming for precision measurements of both open heavy flavor and quarkonium production at RHIC II. With the LHC experiments ongoing, RHIC heavy flavor program will be complementary and remain competitive in many aspects. Some of the measurements will be unique at RHIC, including: (a) high precision open charm hadron measurements at low p_{T} to address charm-medium interactions, (b) bottomonium production measurements as bottomonia are expected to be clean at RHIC because of negligible contribution from regeneration, (c) heavy quark correlation measurements as heavy quarks are expected to be back-to-back correlated in $p+p$ collisions which allows clean interpretations for results in heavy ion collisions. These systematic study of heavy flavor measurements at RHIC and LHC will significantly improve our understanding of the sQGP matter by quantifying its physical properties with controlled accuracy.

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