OVERVIEW OF RECENT HEAVY FLAVOR RESULTS FROM STAR

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In relativistic heavy-ion collisions, a new state of matter, consisting of deconfined quarks and gluons, is created, which is also believed to have existed in the early universe $\sim 10^{-6}$ s after the big bang. Among various probes used experimentally to study the medium properties, heavy flavor quarks are a special one since they are dominantly produced at the early stages of the collisions and subsequently experience the entire evolution of the system. In these proceedings, an overview of the latest heavy flavor results from the STAR experiment at the RHIC will be presented. Charm hadrons are found to exhibit significant yield suppression at high transverse momenta (p_{T}) and strong collective behavior, indicating strong interactions between charm quarks and the medium. Moreover, suppression of high-p_{T} J/ψ as well as the sequential melting of the bottomonium family due to the color screening effect is observed, providing evidence for the presence of deconfined partons in the medium.

1 Introduction

A phase transition from confined hadrons to the Quark-Gluon Plasma (QGP), in which quarks and gluons are the relevant degrees of freedom, is predicted by lattice QCD calculations [1], and can be realized via relativistic heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Due to the extremely short lifetime of the QGP phase ($< \sim$10 fm/c), probes produced within the collisions are used exclusively to study the properties of the medium. Among the various probes, heavy flavor quarks make a special one thanks to the following features: i) their masses originate almost entirely from coupling to the Higgs field in the electroweak sector and therefore stay unaltered in the medium; ii) the production cross-section can be calculated with perturbative QCD; and iii) the thermal production is negligible. Experimentally, both open heavy flavor hadrons and quarkonia, sensitive to different aspects of the medium properties, are measured.

2 Experimental setup

The STAR experiment [2] at the RHIC is a general-purpose detector covering the full azimuth within the pseudorapdity range of $|\eta| < 1$. It consists of the Time Projection Chamber (TPC), the Barrel ElectroMagnetic Calorimeter, and the Time-Of-Flight detector to provide charged track reconstruction and particle identification. To harvest the beam time dedicated to heavy flavor physics at the RHIC from 2014 to 2016, two detector updates, the Heavy Flavor Tracker (HFT) [3] and the Muon Telescope Detector (MTD) [4], were deployed at STAR for measuring open heavy flavor hadrons and quarkonia, respectively. The HFT, sitting at the heart of the STAR experiment, is a silicon detector featuring state-of-the-art monolithic active pixel sensors and provides excellent track pointing resolution down to low momenta. The MTD, located outside of the magnet, is used to trigger on and identify muons from quarkonium decays. Results presented in this manuscript are for Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV, and most of the data were taken in 2014 with the HFT and MTD installed.

3 Results

3.1 Open heavy flavor

The parton energy loss, due to interactions with the medium, is sensitive to the transport coefficients of the QGP [5], and depends on the parton color charge and mass, i.e. $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ [6]. It is conventionally measured through the nuclear modification factor ($R_{\rm AA}$):

$$R_{\rm AA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{dN_{\rm AA}/dp_{\rm T}}{dN_{\rm pp}/dp_{\rm T}} \tag{1}$$

where $dN_{\rm AA}/dp_{\rm T}$ and $dN_{\rm pp}/dp_{\rm T}$ are the invariant yields of hadrons in A+A and p+p collisions, and $\langle N_{\rm coll}\rangle$ the average number of binary nucleon-nucleon collisions per A+A collision. The left panel of Fig. 1 shows the D^0 $R_{\rm AA}$ (filled circles) as a function of transverse momentum ($p_{\rm T}$) in 0-10% central Au+Au collisions. A significant suppression of the yield is seen above 2.5 GeV/c, indicating substantial charm quark energy loss in the medium. Also shown in the

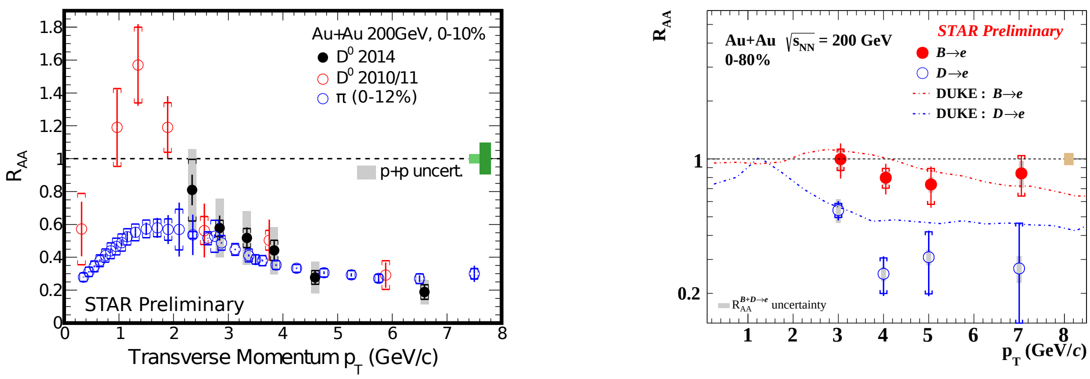

Figure 1 – Left: D^0 $R_{\rm AA}$ in 0-10% central Au+Au collisions, compared to that of pions. Right: $R_{\rm AA}$ of electrons from B and D hadron decays in 0-80% central Au+Au collisions.

panel is a similar measurement for pions (blue open circles) [7], which is consistent with the D^0 results for $p_{\rm T} > 3$ GeV/c. Taking into account the shapes of parton distribution functions and fragmentation functions, the observed consistency can be explained by the expected energy loss hierarchy for gluons, light and charm quarks[8]. Figure 1, right panel, shows the $R_{\rm AA}$ for electrons from B (filled circles) and D (open circles) hadron decays in 0-80% Au+Au collisions. The $R_{\rm AA}$ of B-decayed electrons is about a factor of 2 larger than that of D-decayed electrons, which again follows the expectation that heavier quarks lose less energy.

The collective behavior of charm quarks can be measured through the second Fourier coefficient (v_2) of the D^0 meson distribution in the momentum space with respect to the reaction plane. Specifically, Fig. 2 shows v_2/n_q as a function of $(m_{\rm T} - m_0)/n_q$ for D^0 (filled circles) and light hadrons (open markers) in 10-40% Au+Au collisions, where n_q is the number of constituent quarks in hadrons, m_0 the rest mass and $m_{\rm T} = \sqrt{m_0^2 + p_{\rm T}^2}$ [9]. The large non-zero D^0 v_2 again indicates strong interactions between charm quarks and the QGP. Furthermore, the D^0 meson v_2 follows the empirical n_q scaling as light hadrons as shown in Fig. 2, suggesting that charm quarks might have gained similar amount of flow as light quarks.

Thanks to the HFT, the first ever Λ_c signal in heavy-ion collisions is reconstructed, and the ratio of its yield to that of D^0 is shown in Fig. 3 for the 10-60% centrality bin to study the hadronization mechanism of charm quarks in the hot and dense matter. The measured value is

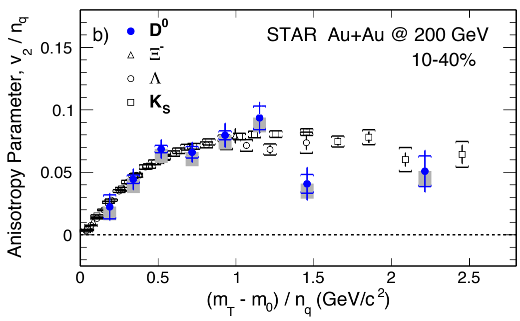

Figure 2 – D^0 v_2 in 10-40% central Au+Au collisions, compared to those of light hadrons.

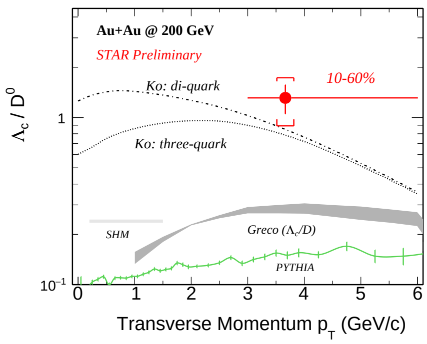

Figure 3 – Λ_c/D^0 ratio as a function of $p_{\rm T}$ in 10-60% Au+Au collisions along with model predictions.

significantly larger than the PYTHIA prediction, which can be attributed to the participation of charm quarks in the coalescence hadronization as previously observed for light quarks. The Ko model calculation [10] for the 0-5% centrality bin with thermalized charm quarks taking part in the coalescence is consistent with the measurement.

3.2 Quarkonium

Quarkonium dissociation due to the color screening of the potential between quark and anti-quark was proposed as a direct evidence of the QGP formation [11]. However, besides cold nuclear matter (CNM) effects, a competing mechanism due to the regeneration of quarkonia by deconfined quarks and anti-quarks further complicates the interpretation of the measured quarkonium suppression in heavy-ion collisions. The left and right panels of Fig. 4 show the J/ψ $R_{\rm AA}$ as a function of the average number of participating nucleons ($N_{\rm part}$) per A+A collision at the RHIC (stars and circles) and the LHC (blue squares) [12,13] for $p_{\rm T} > 0$ GeV/c and high $p_{\rm T}$, respectively. At both $p_{\rm T}$ ranges, the J/ψ $R_{\rm AA}$ at the RHIC decreases towards more central collisions, where

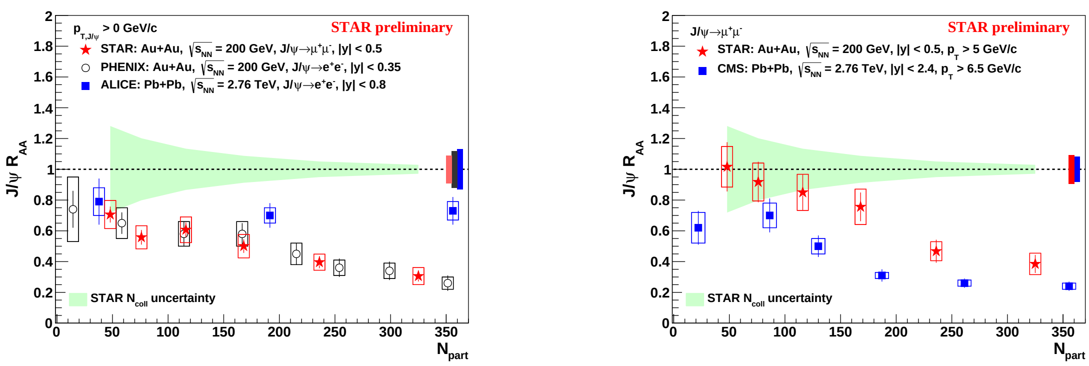

Figure 4 – J/ψ $R_{\rm AA}$ as a function of $N_{\rm part}$ at the RHIC and the LHC for $p_{\rm T} > 0$ GeV/c (left) and high $p_{\rm T}$ (right).

larger medium effects are expected. In central collisions, the strong suppression of high-$p_{\rm T}$ J/ψ, for which CNM effects and the regeneration contribution are small, is a clear evidence of J/ψ dissociation in the medium. Comparing to the LHC results, the smaller J/ψ $R_{\rm AA}$ for $p_{\rm T} > 0$ GeV/c in central collisions at the RHIC could arise from a smaller regeneration contribution due to the smaller charm quark cross-section. On the contrary, the J/ψ $R_{\rm AA}$ is larger for high-$p_{\rm T}$ J/ψ at the RHIC, which might be a result of a lower medium temperature leading to a lower dissociation rate.

For bottomonia, the three Υ states of different binding energies are expected to dissociate at different temperatures, and the measurement of this "sequential melting" was envisioned as a thermometer for the QGP. The $R_{\rm AA}$ for the ground (left) and excited (right) Υ states as a

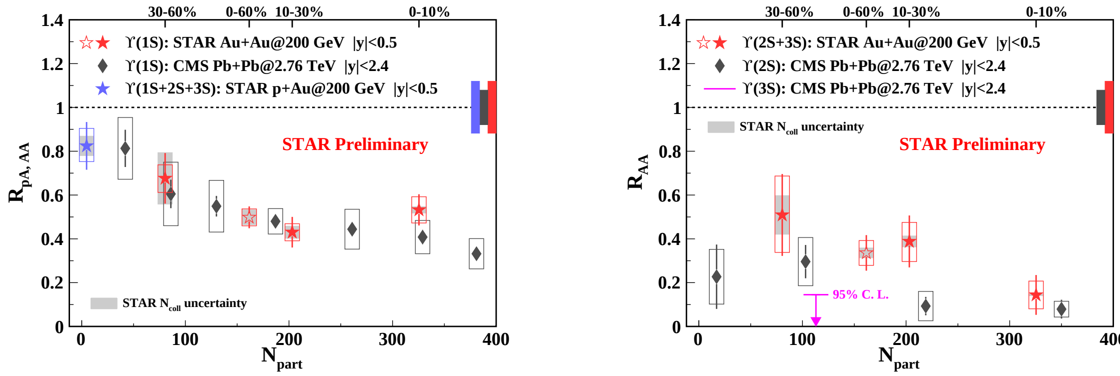

Figure 5 – Υ $R_{\rm AA}$ as a function of $N_{\rm part}$ at the RHIC and LHC for ground (left) and excited (right) states.

function of $N_{\rm part}$ are shown in Fig. 5 for Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV and Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [14]. For Υ(1S), there is decreasing trend for $R_{\rm AA}$ towards central collisions at both RHIC and LHC energies, and the magnitudes of suppression are compatible at the two energies. It is worth noting that the feed-down contributions are not subtracted in these results, and CNM effects could be different. For the excited states, they are significantly more suppressed than the ground state in central collisions, which is consistent with the "sequential melting" picture. There is also a hint that the excited states might be less suppressed at the RHIC than at the LHC.

4 Summary

The heavy flavor program launched at the RHIC during 2014-2016, accompanied by the STAR HFT and MTD upgrades, has generated a series of high impact physics results with the 2014 data. The measured D^0 $R_{\rm AA}$ and v_2 reveal strong interactions between charm quarks and the QGP, resulting possibly in charm quark thermalization. An enhancement to the baryon-to-meson ratio in the charm section is observed for the first time, which is consistent with the expectation by the coalescence hadronization. For quarkonia, the clear suppression of high-$p_{\rm T}$ J/ψ and Υ provides a strong evidence of deconfinement, which is further backed up by the observation of the "sequential melting" for excited Υ states. With the 2015 and 2016 data to be analyzed, the understanding of QGP properties is expected to be further advanced using heavy flavor probes.

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