PROCEEDINGS OF SCIENCE

Recent heavy-flavor measurements from STAR

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Heavy quarks, such as charm or bottom quarks, are predominantly produced in the initial hard partonic scatterings of heavy-ion collisions due to their large masses. Therefore, they participate in the entire evolution of the created medium. Moreover, their production cross-sections can be calculated using using perturbative QCD (pQCD), making them ideal probes of the Quark-Gluon Plasma (QGP), the strongly interacting matter under extreme conditions. Heavy quarks can be studied using heavy-flavor hadrons. Heavy-flavor hadrons can be divided into open heavy-flavor hadrons, which carry a single heavy quark, and quarkonia, which are bound states of a heavy quark and its antiquark. Both quarkonia and open heavy-flavor hadrons can be employed as tools for investigating heavy-quark dynamics in the QGP created in heavy-ion collisions.

The observation of quarkonium suppression in heavy-ion collisions has been considered strong evidence of QGP formation and an important probe of the QGP medium's thermodynamic properties. Changes in the production rate of quarkonia in the QGP are indicative of hot matter effects, such as static and dynamic dissociation processes induced by the medium, as well as contributions from regeneration and cold nuclear matter effects. On the other hand, the reduction in production rate and the directional asymmetry of open heavy-flavor hadrons are linked to heavy-quark energy loss and the level of thermalization in the QGP medium.

STAR is a versatile experiment that examines a range of physics phenomena observed in high-energy p+p and heavy-ion collisions. One of the primary objectives of the STAR experiment is to investigate the properties of the QGP. This contribution discusses recent measurements of open heavy-flavor hadrons and quarkonia in p+p and heavy-ion collisions from the STAR experiment at RHIC.

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1. Open heavy-flavor measurements

1.1 D^0-meson production in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV

In order to investigate the dependence of charm quark interaction with the medium on the colliding system size, the STAR experiment has measured the production of the D^0 meson in Zr+Zr and Ru+Ru (isobar) collisions at $\sqrt{s_{NN}}$ = 200 GeV. The preliminary results for the D^0-meson nuclear modification factor (R_{AA}) in the isobar collisions for different centralities are shown in Fig. 1. One can see no obvious centrality dependence for the low transverse momentum (p_{T}) region. This may be due to the interplay of radial flow, cold nuclear matter (CNM) effects, and charm hadrochemistry. Nevertheless, a hint of centrality dependence can be seen for the high p_{T} region. A suppression in central collisions at $p_{\mathrm{T}} > 3$ GeV/c demonstrates significant energy loss of charm quarks in the bulk QCD medium. A similar suppression for the same centrality in both isobar and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [1] is observed despite the different number of participants at a given centrality interval.

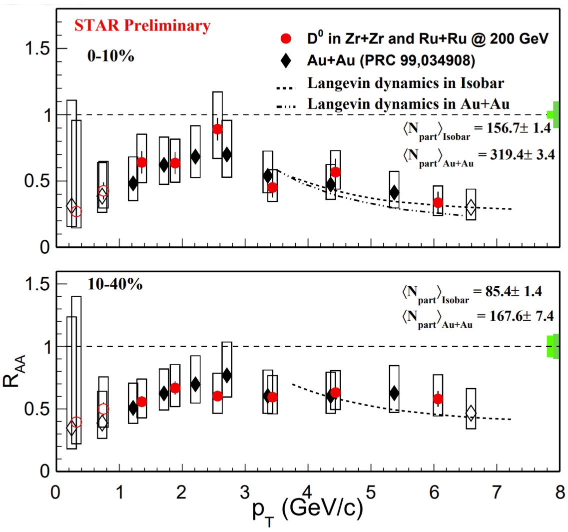

Figure 1: D^0 R_{AA} for 0-10% (top) and 10-40% (bottom) centrality bins in isobar collisions compared to the D^0 R_{AA} in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [1].

1.2 $e^{\pm}$ from open HF hadron decays in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

The STAR experiment has measured the inclusive $e^{\pm}$ from open HF hadron decays in p+p [2] and Au+Au [3] collisions at $\sqrt{s_{NN}}$ = 200 GeV . The left panel of Fig. 2 shows the R_{AA} of heavy-flavor electrons (HFE) in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV as a function of p_{T} for different centrality ranges. A suppression by a factor of two is observed in central collisions, which indicates of significant energy loss of heavy quarks in the QGP medium. Both Duke (modified Langevin transport model) [6] and PHSD (parton-hadron-string dynamics) [7] models agree with the data within uncertainties. The interaction of charm quarks with the medium can be also seen from the elliptic flow results for Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV [4] that are shown in the right panel of Fig. 2. A significant v_2 signal indicates the strong interaction of charm quarks, which are the dominant contribution to the HFE signal at low p_{T}, with the medium and hints charm quarks being close to thermal equilibrium with the medium.

These observations demonstrate the substantial energy loss of heavy quarks in the QGP medium and their interaction with the medium for different collisional energies and system sizes.

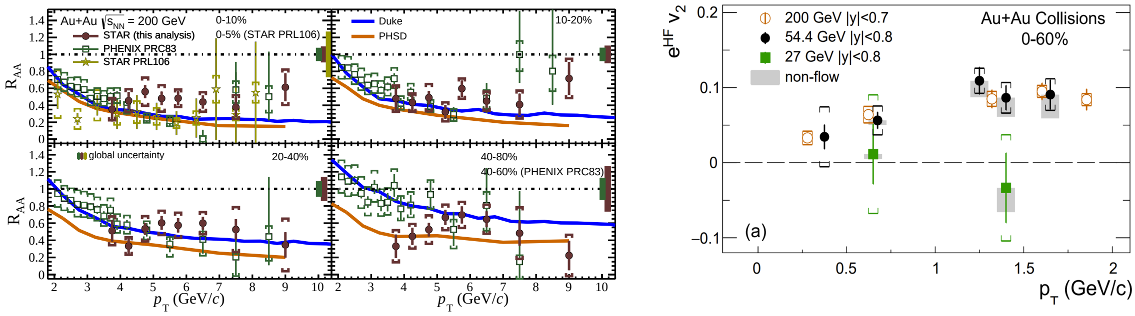

Figure 2: (left) Heavy-flavor electron $R_{\rm AA}$ as a function of $p_{\rm T}$ in different centrality intervals of Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [3]. (right) The elliptic flow of heavy-flavor electrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 and 27 GeV [4] compared to 200 GeV [5].

2. Quarkonium measurements

2.1 Cold nuclear matter effects on J/ψ production in p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

In order to quantify the CNM effect on the J/ψ production, the STAR experiment has measured the inclusive J/ψ nuclear modification factor in p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The preliminary results of J/ψ $R_{p\rm Au}$ measured through the di-electron channel are shown in Fig. 3 (left). The data are consistent with unity in the high $p_{\rm T}$ region, indicating a limited impact of the

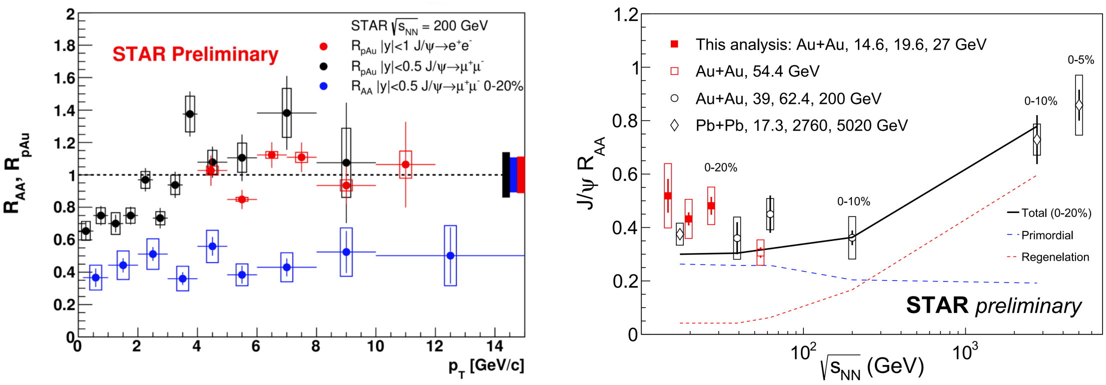

Figure 3: (left) Comparison of di-electron $R_{p\rm Au}$ to di-muon $R_{p\rm Au}$ [8] and $R_{\rm AA}$ [9] results at $\sqrt{s_{NN}}$ = 200 GeV. (right) The energy dependence of the J/ψ $R_{\rm AA}$ in Au+Au collisions at low center-of-mass collisional energies compared to the higher energy results from STAR [9] and ALICE [10].

CNM on the J/ψ production. The results are also compared to the previously published di-muon $R_{p\rm Au}$ [8] and $R_{\rm AA}$ [9]. A suppression of the J/ψ $R_{p\rm Au}$ measured through the di-muon channel at low $p_{\rm T}$ indicates significant CNM effects on the J/ψ production in p+Au collisions. At the high $p_{\rm T}$ region both di-muon and di-electron results are seen to be consistent. A strong suppression in Au+Au collisions above $p_{\rm T}$ of 3 GeV/c is a consequence of the hot medium effects. The p+Au results are consistent with the different model calculations that include CNM, transport properties, CGC, comovers, etc. [8] within uncertainites.

2.2 Energy dependence of J/ψ suppression in Au+Au collisions

The energy dependence of the J/ψ suppression in Au+Au collisions is of interest to understand the interplay of CNM and the hot medium effects. The right panel of Fig. 3 shows the energy dependence of the J/ψ R_{AA} in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6, 19.6, 27 and 54.4 GeV compared to the higher energy results from STAR [9] and ALICE [10]. One can see no significant energy dependence within uncertainties up to $\sqrt{s_{NN}}$ = 200 GeV. This could be due to the interplay of dissociation, regeneration, and CNM effects.

2.3 Υ and $\psi(2S)$ production in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV

The sequential suppression of Υ states was previously observed at RHIC energies in Au+Au collisions [11] and the LHC [12]. It is now of interest to study the production of the Υ in a smaller system, such as an isobar. The left plot in Fig. 4 depicts a comparison of $\Upsilon(1S)$ R_{AA} in isobar collisions to Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [11]. The indication of centrality dependence can be seen for both system sizes. The similar suppression of $\Upsilon(1S)$ and $\Upsilon(2S)$ in isobar and Au+Au collisions at the same energy suggests there is no significant species dependence when considering similar number of participants.

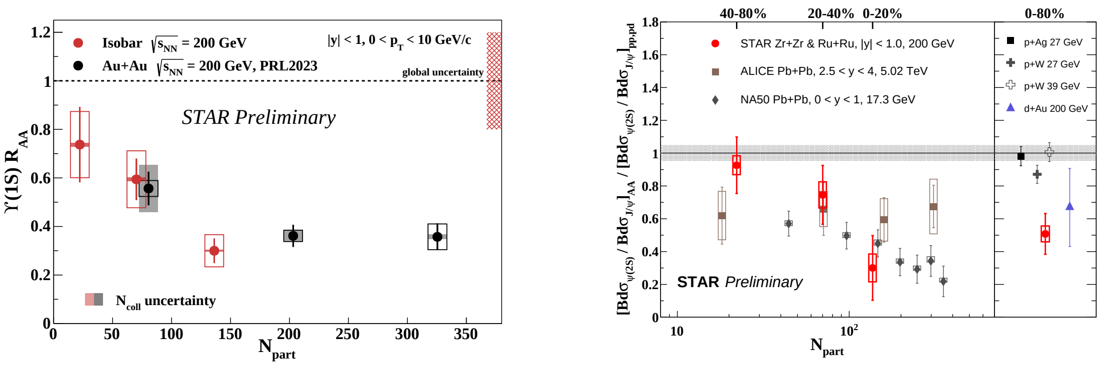

Figure 4: (left) The R_{AA} of the $\Upsilon(1S)$ in isobar collisions compared to Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV[11]. (right) The double ratio of the $\psi(2S)$ to J/ψ in isobar collisions as a function of centrality compared to ALICE and NA50 results [12].

The STAR experiment at RHIC has also observed the sequential suppression of charmonia, by studying $\psi(2S)$ production. As the $\psi(2S)$ is less bound than the J/ψ, it is expected to be more suppressed. The right panel of Fig. 4 shows preliminary results of the first observation of charmonium sequential suppression in heavy-ion collisions at RHIC. The double ratio of the $\psi(2S)$ to J/ψ in A+A collisions over p+p collisions is presented as a function of centrality. The p+p reference is the average of measurements in p+p(d) by NA51 [13], ISR [14] and PHENIX [15]. It can be seen that the double ratio in isobar collisions decreases towards central collisions. This indicates that the $\psi(2S)$ is more suppressed than the J/ψ in central nucleus-nucleus collisions than in p+p. This is consistent with the sequential suppression of charmonia in Pb+Pb collisions at LHC.

3. Summary

The STAR experiment has measured open heavy-flavor hadrons and quarkonium production in p+p and heavy-ion collisions. The results indicate significant energy loss of heavy quarks in the QGP medium and their interaction with the medium across different collision energies and system sizes. Additionally, the results demonstrate substantial CNM effects on quarkonia production in p+Au collisions at low p_{T} and hot nuclear matter effects in Au+Au collisions. Furthermore, sequential suppression of both charmonia and bottomonia is observed in heavy-ion collisions at the top RHIC energy.

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