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Measurements of open heavy-flavor hadrons in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV with the STAR experiment

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At RHIC energies, heavy-flavor quarks are primarily produced in hard partonic scatterings in the early stages of ultra-relativistic heavy-ion collisions. This makes them an excellent probe of the quark-gluon plasma (QGP) since they experience the whole evolution of the hot and dense medium. The STAR experiment allows studying the production of charm quarks and their interaction with the QGP through direct reconstruction of hadronic decays of open charm hadrons and the topological separation of electrons originating from bottom and charm hadron decays. This is possible thanks to the excellent track pointing resolution provided by the Heavy Flavor Tracker.

In these proceedings, the most recent results on open heavy-flavor hadron production in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV from the STAR experiment are shown. In particular, we will discuss the nuclear modification factor of $\rm D^0$ meson, $\rm D_s^+/D^0$ and $\Lambda_c^+/\rm D^0$ yield ratios as a function of transverse momentum and collision centrality. Additionally, charm- and bottom- hadron decay electron elliptic flow (v_2) are presented. Finally, rapidity-dependent directed flow (v_1) of $\rm D^0$ meson and charm-hadron decay electrons are reported.

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1. Introduction

The quark-gluon plasma (QGP) is the hot and dense nuclear matter of deconfined quarks and gluons that is formed in ultrarelativistic collisions of heavy ions [1]. Heavy-flavor (HF, charm and bottom) quarks are produced primarily in the early stages of collisions [2] and thus experience the entire evolution of the medium. Directed flow of HF mesons allows us to study the initial conditions of heavy-ion collisions, such as the tilt of the QGP medium [3] and the initial electromagnetic (EM) field [4]. Furthermore, understanding the sensitivity of HF quarks to the collective motion of the system, reflected in the elliptic flow of HF mesons, can provide information on the degree of the HF quark thermalization in the QGP and help to constrain the HF-quark diffusion coefficient. Study of open-charm meson yields probes not only the quark mass dependence of energy loss in the QGP, but also its hadronization in the heavy-ion collisions.

The STAR experiment at the Relativistic Heavy Ion Collider (RHIC) performed extensive studies of HF-hadron production. The results from Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV presented in these proceedings were obtained thanks mainly to the presence of Heavy Flavor Tracker (HFT) [5], the high-precision silicon vertex detector installed at the center of the STAR apparatus for data taking in years 2014–2016. It greatly improves the track pointing resolution and enables the topological reconstruction of the secondary vertices of open charm hadron decays through the hadronic channels, such as $\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$, $\Lambda_c^+ \rightarrow \mathrm{K}^-\pi^+\mathrm{p}$ or $\mathrm{D_s} \rightarrow \phi\pi^+ \rightarrow \mathrm{K}^-\mathrm{K}^+\pi^+$. In addition, the HFT enables the measurement of electrons from charm and bottom hadron decays with great precision. HF decay electron fractions are extracted using template fits to distributions of the 3D distance of closest approach of a track to the collision vertex.

2. Heavy-flavor production in Au+Au collisions

Particle production in Au+Au collisions can be studied using the nuclear modification factor R_{AA}, defined as the ratio of the invariant particle yields measured in Au+Au and p+p collisions (where no QGP is expected to be created), scaled by the average number of binary nucleon-nucleon collisions in the investigated Au+Au collision centrality interval. The D^0 meson R_{AA} measured in three collision centrality intervals is shown in Fig. 1 (left) [6]. At high transverse momentum, p_{T}, the yields are greatly suppressed in central collisions, indicating that charm quarks lose a significant amount of energy in the QGP. Towards more peripheral collisions, this suppression at high p_{T} decreases. However, at low p_{T}, R_{AA} has no significant centrality dependence.

Figure 1 (right) shows the charm and bottom decay electron R_{AA}. The data are consistent with the DUKE model prediction [7] which contains the mass dependence of energy loss. Furthermore, bottom decay electron suppression is smaller than that of charm decay electron with a significance larger than 3σ. This suggests a quark mass dependence of the energy loss in the QGP.

In order to understand hadronization of charm quarks, the Λ_c^+/D^0 yield ratio is measured [8] and results are shown in Fig. 2. In Fig. 2 (left), it can be seen that in the measured p_{T} interval, the Λ_c^+/D^0 ratio is comparable to the baryon-to-meson ratios of strange and light flavor hadrons. Additionally, the data are compared to model calculations including different charm quark hadronization mechanisms and QGP medium properties. The data, as well as those calculations that include coalescence hadronization of charm quarks show significant enhancements compared to the PYTHIA

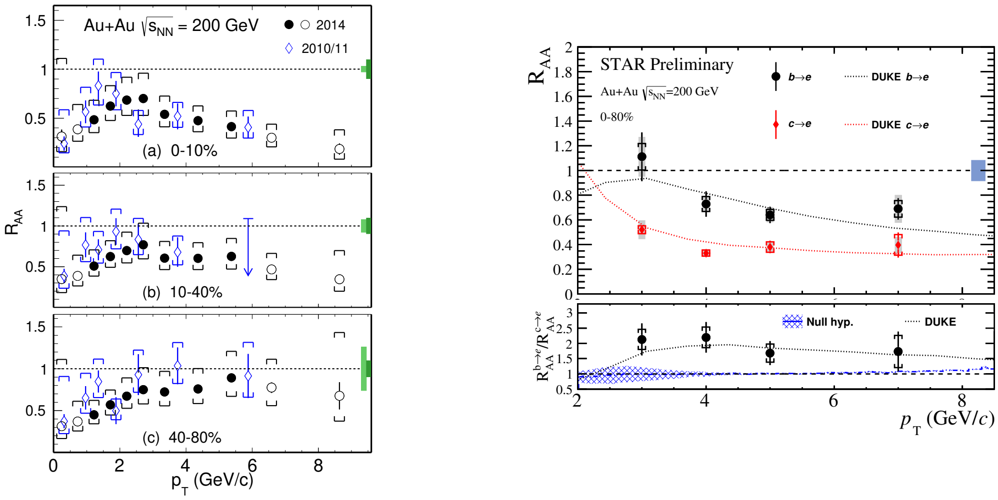

Figure 1: Left: the R_{AA} of D^0 meson as a function of p_T in different centrality classes measured with (year 2014) and without (years 2010/11) the HFT detector installed [6]. Right: the R_{AA} of charm and bottom decay electron (top) and their ratio (bottom), compared to the DUKE model prediction [7].

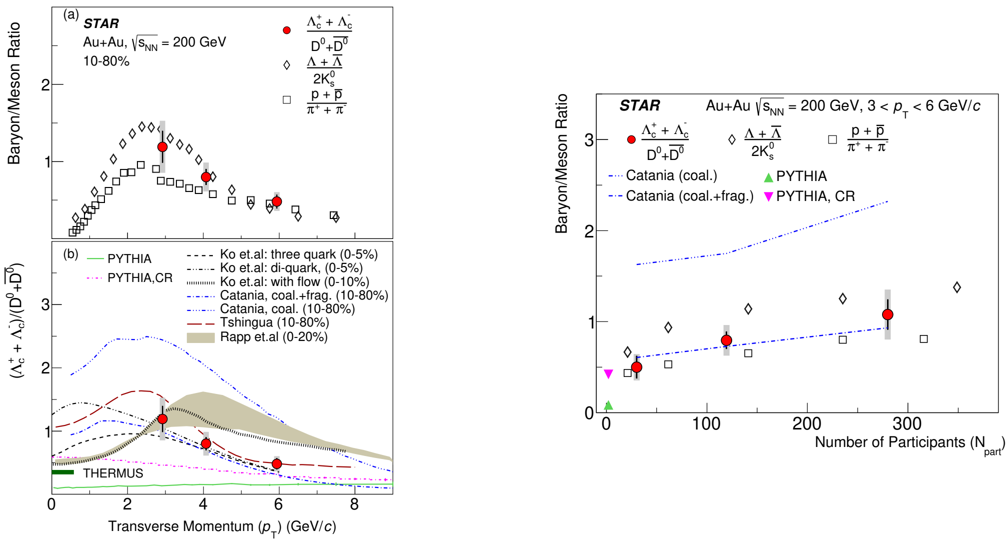

Figure 2: Left: Λ_c^+/D^0 yield ratio as a function of p_T compared to light-hadron results (top) and different model calculations (bottom). Right: Λ_c^+/D^0 yield ratio vs number of participants N_{part}, compared to light-hadron results, PYTHIA calculation with and without color reconnection and the Catania model incorporating coalescence and fragmentation hadronization of the charm quarks [8].

calculations. As displayed in Fig. 2 (right), the centrality dependence of Λ_c^+/D^0 yield ratio shows a similar trend as that of light flavor and strange hadron yield ratios. The data are consistent with the Catania model calculation incorporating coalescence and fragmentation hadronization of charm quarks [9].

STAR also measured the D_s^+/D^0 yield ratio, which probes both strangeness enhancement and coalescence of charm quarks with strange quarks in the QGP. Figure 3 (top left) shows that this ratio

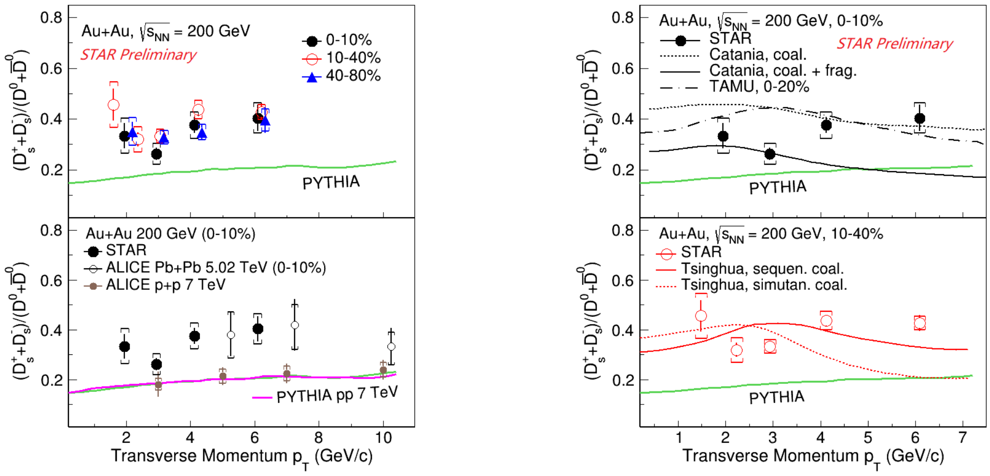

Figure 3: D_s^+/D^0 yield ratio as a function of p_T in different centralities of Au+Au collisions compared to PYTHIA p+p calculations and to an ALICE measurement [10, 11] (left) and to various models incorporating coalescence and fragmentation hadronization of charm quarks [9, 12, 13] (right).

has no significant centrality dependence and is significantly larger than the fragmentation baseline, represented by a PYTHIA8 calculation. In Fig. 3 (bottom left), STAR results in central Au+Au collisions are compared to the ALICE result in central Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The results are consistent in the overlapping region. Additionally, ALICE p+p data at $\sqrt{s}$ = 7 TeV are consistent with a PYTHIA calculation at the same energy.

Figure 3 (right) shows the comparison of the STAR results in central (top right) and semi-central collisions (bottom right) with model calculations. The Catania model calculation with only coalescence hadronization describes data for $p_T > 4$ GeV/c, while the Catania model calculation with both coalescence and fragmentation hadronization describes data for lower p_T. Furthermore, the Tsinghua model with sequential coalescence hadronization of charm quarks qualitatively describes data in 10–40% semi-central collisions.

3. Anisotropic flow of heavy-flavor decay electrons

To quantify the transport properties of the hot medium produced in heavy-ion collisions, the collective motion of partons is studied via the measurement of the elliptic flow v_2 of produced particles [14]. This is the second coefficient of the Fourier decomposition of the azimuthal distribution of the particle yield with respect to the event plane. The D^0 meson v_2 measured by STAR in Au+Au collisions was found to follow the number-of-constituent-quark scaling [15].

Figure 4 shows the HF decay electron v_2. In this analysis, non-flow effects are calculated using electron-hadron correlations with electrons from semileptonic charm and bottom decays simulated with PYTHIA. Charm decay electron v_2, shown in Fig. 4 (left) is consistent with the D^0 v_2 [15] folded to account for decay-kinematic effects and the Duke model [7]. For bottom decay electron v_2, shown in Fig. 4 (right), two approaches for the event plane reconstruction are compared. One of them uses tracks reconstructed in the Time Projection Chamber (TPC) in the pseudorapidity range of $|\eta| < 1$, the latter one uses hits in the Forward Meson Spectrometer (FMS) in $-2.5 < \eta < 4$. The

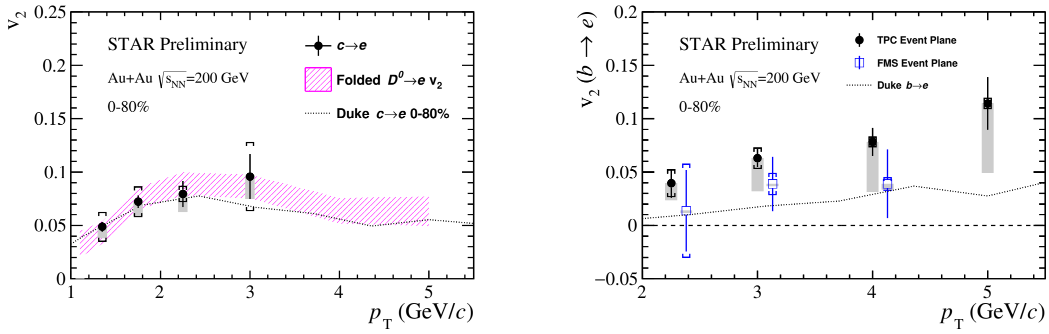

Figure 4: Elliptic flow v_2 of charm decay (left) and bottom decay electrons (right) as a function of p_T, compared to folded D^0 meson v_2 [15] and DUKE model calculations [7]. Gray boxes show the estimated non-flow contributions.

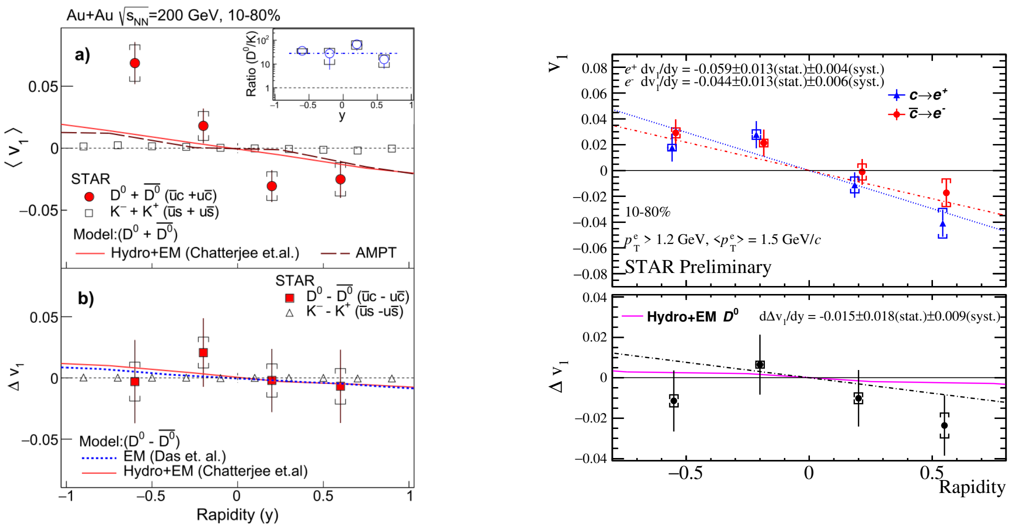

Figure 5: Directed flow v_1 of D^0 and $\overline{D^0}$ for p_T > 1.5 GeV/c compared to that of kaons for p_T > 0.2 GeV/c [16] (left) and v_1 of charm decay positrons and anti-charm decay electron for p_T > 1.2 GeV/c as a function of rapidity in 10–80% central Au+Au collisions compared to model calculations (right).

TPC event plane measurement with non-flow subtraction results in non-zero v_2 of bottom decay electrons with a significance of 3.4σ. The usage of the FMS significantly reduces the non-flow contribution to 0.5%. However, this measurement has a larger uncertainty due to the poorer event-plane resolution and smaller statistics analyzed because the FMS being present only in part of the data recorded.

The initial conditions of heavy-ion collisions could be accessed via measurement of directed flow, v_1, whose magnitude is affected by the initial tilt of the QGP bulk and viscous drag on charm quarks. Furthermore, the initial EM field is predicted to induce larger v_1 for charm quarks than for light flavor quarks due to the early production of charm quarks and gives opposite contributions to charm and anti-charm quarks.

Figure 5 (left) shows the v_1 of combined D^0 and $\overline{D^0}$ (top) and the difference between D^0 and $\overline{D^0}$ v_1 (bottom) [16]. A separate measurement of D^0 and $\overline{D^0}$ is done via topological reconstruction of decays $D^0 \rightarrow K^-\pi^+$ and $\overline{D^0} \rightarrow K^+\pi^-$. The absolute value of the D^0 v_1 is observed to be about 25 times larger than that of the kaons with a 3.4σ significance. Model calculations with a tilted source predict the correct sign of dv_1/dy, but the v_1 magnitudes are lower than in data. Study of the initial EM field induced splitting for charm decay electrons is shown in Fig. 5 (right). The v_1 for charm and anti-charm is accessed by separate measurements of charm decay e^+ and anti-charm decay e^-. Within the uncertainties, no splitting due to EM field is observed in both measurements.

4. Summary

The STAR experiment, thanks to the HFT detector, measured open heavy-flavor production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV via the topological reconstruction of charmed hadrons and extraction of HF decay electrons. The results on the open-charm hadron production suggest that charm quarks hadronize via coalescence with light quarks in the QGP and strongly interact with the created medium. Additionally, measurements of charm and beauty decay electron R_{AA} suggest that parton energy loss in the QGP depends on quark mass. Charm decay electron v_2, consistent with D^0 v_2, indicate that charm quarks gain significant flow in the QGP. Firstly observed non-zero bottom decay electron v_2 is consistent with the Duke model incorporating bottom quark transport in the QGP. The predicted charm and anti-charm splitting due to the initial EM field is not observed in measured v_1 of D^0 and $\overline{D^0}$, as well as charm (anti-charm) decay e^+ (e^-).

Acknowledgments

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