CHARM AND BOTTOM QUARK ENERGY LOSS AND FLOW MEASUREMENTS IN Au+Au COLLISIONS BY THE PHENIX EXPERIMENT*

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The energy loss and elliptic flow of heavy quarks provide valuable information for understanding the nature of thermalized quark–gluon plasma. The energy loss of quarks in QGP is expected to depend on their mass. This effect can be investigated by measuring the nuclear modification factors of hadrons made of light and heavy quarks. The coupling between heavy quarks and QGP can also be examined by the measurement of the flow harmonics. The PHENIX experiment measures nuclear modifications and flows of electrons from the semi-leptonic decays of charm and bottom hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Different suppression of charm and bottom electrons is observed in 0–10% most central Au+Au collisions. We report on the nuclear modification of charms and bottoms, and discuss the p_{T} dependence and centrality dependence of the heavy-quark energy loss in QGP.

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1. Introduction

Heavy quarks (charm and bottom quarks) are important probes of the properties of Quark–Gluon Plasma (QGP) created in high-energy heavy-ion collisions. Heavy quarks are primarily produced in the initial hard scattering due to their larger masses relative to the temperature of QGP. Once produced, heavy quarks lose energy due to final-state interactions in the QGP. Both radiative and collisional processes play an important role in the energy loss of heavy quarks. The energy loss of heavy quarks is expected to be suppressed by the "dead cone" effect, where gluon bremsstrahlung is suppressed at an angle smaller than the quark mass-to-energy ratio [1, 2].

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Thus, the energy loss is expected to follow the mass ordering of quarks and gluons, $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$. The medium coupling between heavy quarks and the thermalized QGP is also important in exploring the thermodynamics of QGP. The coupling is investigated by measuring the flow harmonics (v_2) and its dependence on the transverse momentum (p_{T}) and the centrality of the collision.

In PHENIX, single electrons from semi-leptonic decays of charm and bottom hadrons were statistically separated using the distance of closest approach (DCA) from the primary vertex measured by a set of silicon vertex detector at mid-rapidity. The previous results showed that the electrons from charm- and bottom-hadron decays are differently suppressed with the large uncertainty [4]. In the new measurement reported here, the uncertainty is improved by a factor of six larger statistics and the updated $p+p$ reference [5]. In these proceedings, the nuclear modifications and v_2 of electrons from charm- and bottom-hadron decays in 200 GeV Au+Au collisions are presented and their p_{T} and centrality dependence is discussed.

2. Analysis

We analyze data for minimum bias (MB) Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV recorded by the PHENIX experiment in 2014 high luminosity RHIC run.

Charged particle tracks are reconstructed using the PHENIX central arm spectrometer (CNT). The detectors in CNT related to this analysis are the drift chamber (DC), the pad chamber (PC), the ring-imaging Čerenkov Detector (RICH), and the electromagnetic calorimeter (EMCAL). DC and PC measure the trajectory and momentum. Electrons are identified by signals in RICH and energy-momentum matching, where EMCAL measures their energies. An inner silicon tracker (VTX) measures collision vertex and distance of the closest approach ($\mathrm{DCA_T}$) in the transverse plane between the electron track and the vertex. The difference in decay lengths between charm and bottom hadrons ($c\tau_{D^0} = 122.9$ μm and $c\tau_{B^0} = 455.4$ μm) is used to statistically separate electrons from these decays.

In addition to heavy-flavor electrons, there are several sources of electron backgrounds in the electron sample. The main background sources are photonic electrons which are photon conversions in the detector material and the Dalitz decays of light-neutral mesons. The photonic background is mostly removed by an analysis cut with VTX. Non-photonic backgrounds from the three-body decays of kaons, and J/ψ and Υ decays are estimated based on the Geant simulation of the PHENIX detector with measured particle yields as inputs. In a high-multiplicity environment in Au+Au collisions, the tracks reconstructed by the CNT are accidentally associated with the uncorrelated VTX hits. These backgrounds are estimated and subtracted by the event mixing method.

The p_{T} and $\mathrm{DCA_T}$ distributions of heavy-flavor electrons are used to separate charm and bottom contributions by the unfolding method based on the Bayesian inference technique. All the analysis procedures are described in Ref. [3]. Figure 1 shows invariant yields of electrons from charm (left) and bottom (right) hadrons in the MB Au+Au collisions and 0–10%, 10–20%, 20–40%, and 40–60% centralities [3]. The lines and bands represent the median and 1 sigma limits of yield distribution at a given p_{T}. These yields are compared with $p+p$ measurement scaled by nuclear overlap functions (T_{AA}). Charm and bottom electrons are clearly suppressed at high p_{T}.

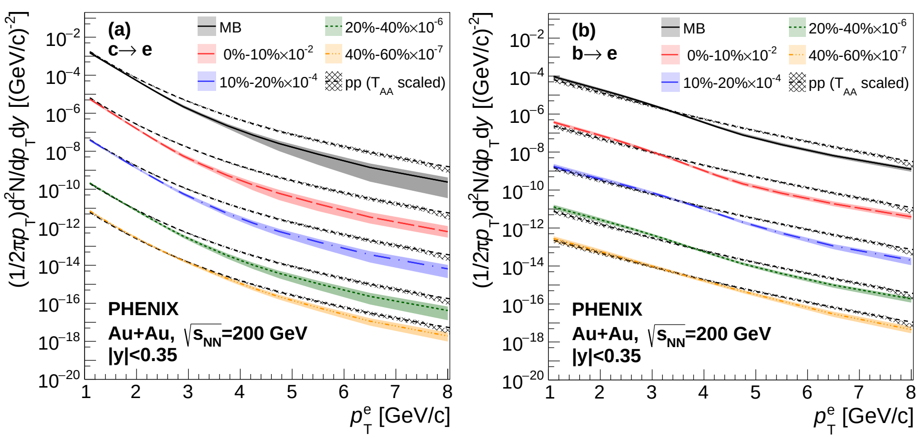

Fig. 1. Invariant yields of electrons from charm (left) and bottom (right) hadron decays in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The yields in MB and four centralities are compared with T_{AA}-scaled $p+p$ result.

3. Results

3.1. Heavy flavor suppression

To quantitatively evaluate the yield suppression of charm and bottom quarks in QGP, nuclear modification factors (R_{AA}) are calculated. Figure 2 shows R_{AA} of charm and bottom electrons as a function of p_{T} in 0–10% and 40–60% Au+Au collisions. In 0–10% centrality, the suppression for charm electrons is stronger than that for bottom electrons at $1 < p_{\mathrm{T}} < 5$ GeV/c, while at 40–60% centrality, a modest suppression for charm and bottom electrons is observed.

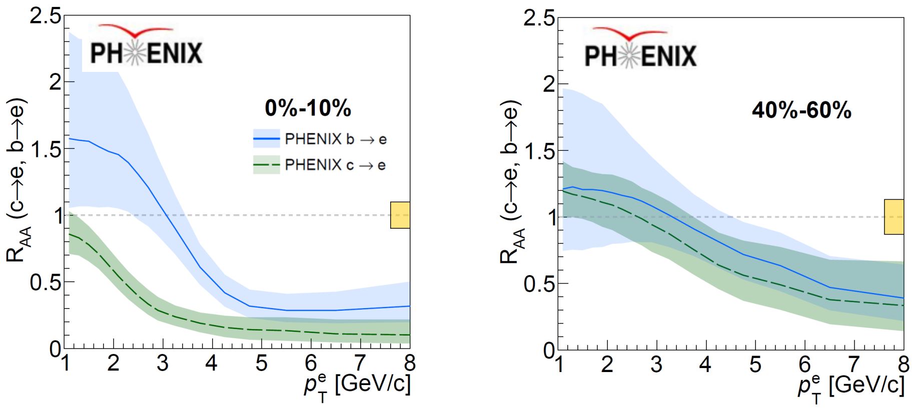

Fig. 2. R_{AA} for charm and bottom electrons in 0–10% (left) and 40–60% centralities (right).

To examine the centrality dependence of suppression, charm and bottom R_{AA} in three different p_T intervals are plotted as a function of number of participant nucleons ($N_{\rm part}$) in Fig. 3. In the low-p_T region, R_{AA} for both charm and bottom electrons is consistent with unity for all $N_{\rm part}$. In the mid-p_T region, the suppression of charm electrons increases with $N_{\rm part}$ but there is no suppression of bottom electrons. At high p_T, the suppression of the bottom electron is also observed to increase with $N_{\rm part}$. These comparisons indicate that there is a clear $N_{\rm part}$ dependence on the suppression of charm and bottom electrons.

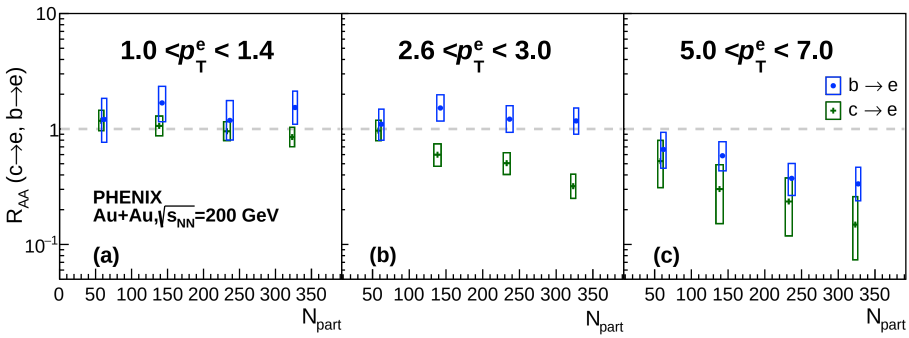

Fig. 3. $N_{\rm part}$ dependence of R_{AA} for charm and bottom electrons. The panels correspond to three different p_T intervals: 1–1.4 GeV/c (left), 2.6–3 GeV/c, and 5–7 GeV/c, respectively.

Figure 4 compares data with three theoretical models: the T-matrix approach [6], the SUBATECH model [7], and the DGLV model [8]. These models include a quark mass ordering of energy loss in QGP. The model calculations reproduce the trend for charm and bottom suppression. This suggests that the energy loss of charm quarks is larger than that of bottom quarks in QGP. There is a difference between data and the models at $p_T <$ 4 GeV/c. The models overpredict the bottom suppression although the uncertainty is large.

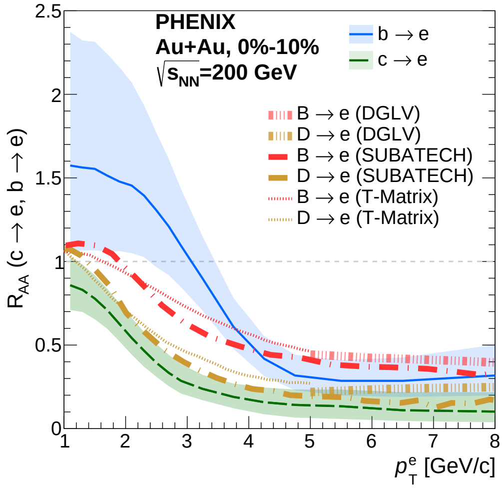

Fig. 4. Comparison of charm and bottom R_{AA} with the T-Matrix approach, SUBATECH model, and DGLV model.

3.2. Elliptic flows of heavy flavors

Using the same dataset of Au+Au collisions recorded in 2014, the v_2 of electrons from charm and bottom decays are measured [9]. Figure 5 shows v_2 as a function of p_T for charm (left) and bottom (right) electrons, respectively. These results are found to be smaller than the charged hadron v_2. The v_2 of charm electrons is positive at 3.5σ, while a positive v_2 for bottom electrons

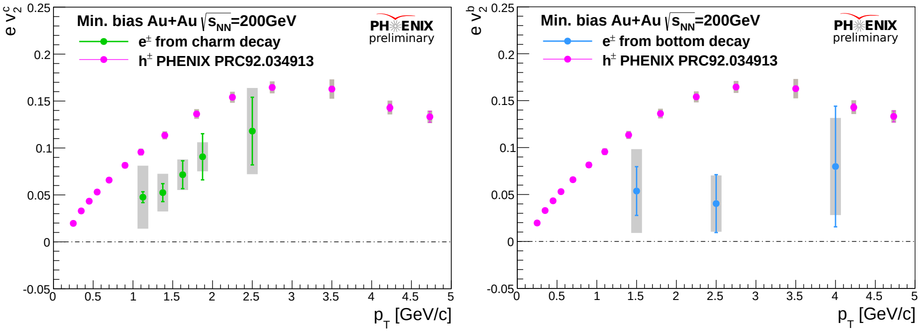

Fig. 5. v_2 for charm (left) and bottom (right) electrons. The results are compared with charged hadron v_2.

is suggested at 1.1σ. The v_2 of charm electrons is larger than that of bottom electrons, but the uncertainty is large. Further analysis of v_2 of electrons is underway with a factor of two larger statistics from the 2014 and 2016 runs.

4. Summary

PHENIX measured nuclear modifications and elliptic flows of electrons from charm- and bottom-hadron decays in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. A comparison of R_{AA} for charm and bottom electrons shows that charm electrons are more suppressed than bottom electrons in 0–10% centrality. These results are described by the theoretical models including mass ordering of energy loss in QGP. This suggests that charm quarks lose more energy than bottom quarks. We also observe a different centrality dependence of suppression for charm and bottom electrons. In the v_2 measurements, we observed that the v_2 of charm and bottom electron is positive with the significance of 3.5 and 1.1σ. The v_2 of charm electrons is larger than that of bottom electrons. High statistics dataset of Au+Au collisions was recorded in the 2016 RHIC runs. This dataset will allow us to more accurately measure R_{AA} and v_2 for charm and bottom electrons.

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