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New PHENIX results on mid-rapidity bottom and charm production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

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Energy loss of quarks in the hot and dense medium has been studied for decades. Both the experimental and theoretical efforts have hinted that the energy loss is quark mass dependent. Although experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have found that the electrons from heavy quarks are less or similarly suppressed compared to the light hadrons, the mass ordering of the suppression between charm and bottom quarks is not yet clear due to large experimental uncertainties. We have fully exploited the events recorded at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV by the PHENIX experiment at RHIC to study the invariant yield of electrons from open heavy flavors. Latest results on the nuclear modification factors for charm and bottom separated heavy flavor electrons are reviewed in this proceeding. The implications of these results on the understanding of the quark mass and medium size dependence of the energy loss are also discussed.

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1. Introduction

Charm and bottom quarks, together termed as heavy flavors (HF) due to their large masses compared to the QCD scale, are predominantly produced via hard scattering in heavy ion collisions. The dominant production at the Relativistic Heavy Ion Collision (RHIC) is through pair creation and flavor excitation, in contrast to the primary mode of HF production at the Large Hadron Collider (LHC) via gluon splitting [1, 2]. However, once produced, the heavy quarks (HQ) lose their energy energy via radiative and collisional energy loss while propagating through the colored QGP medium formed in these collisions. The combined effect of these two mechanisms, where the former dominates at high p_{T} and the latter dominates at low p_{T}, is expected to give a mass hierarchy to the energy loss mechanism such that lighter parton loses more energy in comparison to the heavier ones i.e. $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ at a given p_{T}. Although measurements at both RHIC and LHC have indicated that heavy flavors might be similarly or less suppressed compared to the light hadrons [3–8], precise measurement of charm and bottom separated final states over wide range of p_{T}, rapidity, and centrality have been deemed necessary to untangle the effects of various mechanisms that affect the yields of HF final states.

The PHENIX experiment at RHIC has measured the yield of single electrons from HF decay, the charm and bottom separated hadron yields using unfolding technique, and their corresponding nuclear modification factors (R_{AA}), using data collected in Run 2004 and 2014. In this report, the latest PHENIX results, and their implications to the understanding of QGP properties are discussed.

2. Analysis

Single electrons from semi-leptonic decay of HF are measured by the PHENIX detector [9] in the central arm covering the rapidity range of $|y| < 0.35$. The central arm consist of electron identification detectors (RICH and EMcal), and silicon vertex detector (VTX) that is responsible for precise tracking and vertex measurement. With a collision vertex resolution of $< 100\ \mu$m, VTX enables precise measurement of the transverse component of Distance of Closest Approach ($\mathrm{DCA_T}$) that is proportional to the lifetime of the decaying particle and is also dependent on the decay kinematics. This allows for a separation of electrons from semi-leptonic decay of charm and bottom hadrons as well as from other sources of background.

The main sources of background to the HF electrons come from misidentified hadrons, mismatching of hits/tracks between central arms and VTX, photonic electrons, kaon decay electrons, and heavy-quarkonia decay electrons. The yields of electrons from background processes are estimated in multiple p_{T} bins using the PHENIX electron cocktail method [10]. Once the background contributions are subtracted from the inclusive electron samples, electrons from charms and bottoms are separated by applying a likelihood-based Bayesian unfolding technique to electron $\mathrm{DCA_T}$ distributions and published HF electron p_{T} spectra [11].

3. Results

Invariant yields of the HF electrons for minbias (MB) events and those of five different centralities are shown in the left side of Figure 1. The yield decreases with increasing p_{T} and when

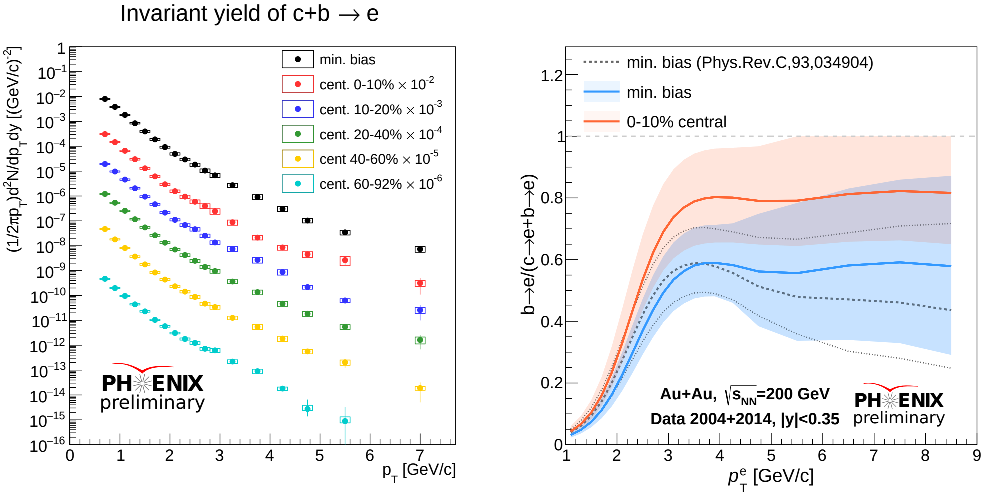

Figure 1: Invariant yield of $c + b \rightarrow e$ for MB events and different centralities (left) and b-fraction (right) for MB (blue) and 0–10% central events (red). The colored bands represent 1σ p_{T} correlated uncertainties in the measurements.

going from central to peripheral events. The charm and bottom separated yields from the unfolding procedure are used to measure the fraction of electrons from bottom decay over the inclusive HF electron yields to get a b-fraction distribution. The right side of Figure 1 shows the b-fraction distribution for MB and 0–10% central events. The b-fraction rapidly increases at low p_{T} and has a small bump at $p_{\mathrm{T}} \sim 3.5$ GeV/c. Both results are consistent with the measurement using 2011 data [11] within the quoted uncertainties of the measurement.

The charm and bottom separated nuclear modification factor, R_{AA}, are calculated for each of these centrality classes and MB events by taking the p+p measurement from the STAR e-h correlation as the baseline [12]. As shown in left side of Figure 2, single electrons from charm decay are more suppressed than those from bottom for p_{T} in the range of 3–5 GeV/c, which is consistent with the expected flavor mass hierarchy for energy loss in QGP. At larger values of p_{T}, electrons from charm and bottom have similar suppression within the uncertainty of the measurement. These results are in agreement with previously published results by PHENIX [10]. The R_{AA} calculations are also made as a function of centrality. R_{AA} for 0–10% central collisions is provided in the right side of Figure 2 and shows better separation between charm and bottom events, particularly at $p_{\mathrm{T}}< 5$ GeV. This result indicates a QGP system size dependence on energy loss mechanism.

To better understand the quark mass dependence on the energy loss mechanism, the R_{AA} and b-fraction distributions for 0–10% central collisions are compared to several theoretical predictions. The b-fraction distribution is compared to T-matrix [13] models with different values of diffusion constant, as well as with DGLV [14] models with different values of gluon density. The T-Matrix model applies heavy quark diffusion in QGP using a non-perturbative T-Matrix approach, where the value of heavy quark diffusion constant, $2\pi TD$, is set to 30, 6, and 4 respectively. Higher value of the constant indicates weakly coupled QGP medium. The b-fraction results are consistent with the T-Matrix models with small diffusion constant, while the models with larger diffusion constant

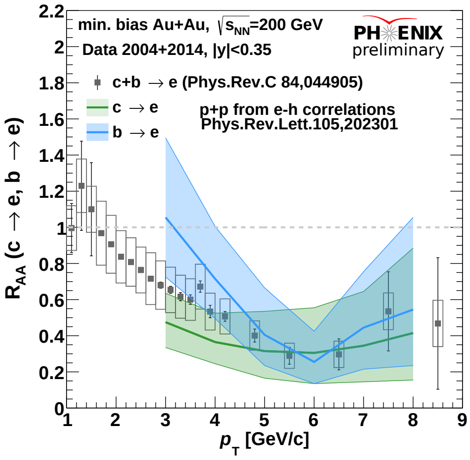

Figure 2: Nuclear modification factor (R_{AA}) for single electrons from charm (green) and bottom (blue) hadron decay in the MB (left) and 0-10% centrality (right) class. Filled color bands represent 1σ p_T uncorrelated uncertainties in the measurements.

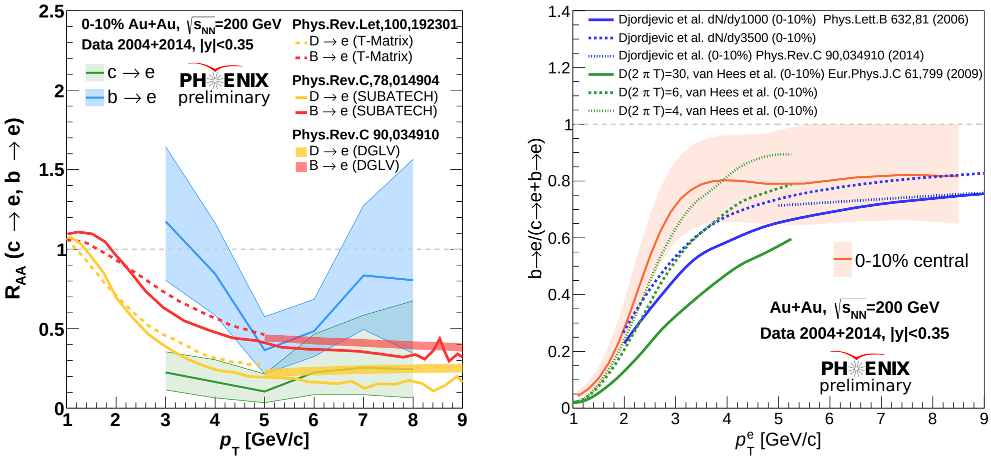

Figure 3: The R_{AA} (left) and b-fraction (right) measurements for 0–10% central events overlaid with different theoretical models.

do not describe the p_T dependence well. The DGLV model employs energy loss via gluon emission and is based on the GLV model. This model assumes mostly static medium characterized by the gluon density, whose values are varied and compared separately. All DGLV models under-perform at mid and low p_T regions, where uncertainties on measurement are the smallest, while the one corresponding to $dN_g/d\eta = 3500$ models the distribution the best.

The most central R_{AA} distribution comparisons are made with T-Matrix, SUBATECH [15] and DGLV models. The SUBATECH model incorporates collisional energy loss using Boltzmann transport equation with a running coupling constant and a more realistic hard thermal loop calculations replacing the Debye screening mass. The measured R_{AA} for $c \rightarrow e$ is well described by models shown here, whereas the R_{AA} for $b \rightarrow e$ at low p_T is not well described. More precise measurements at higher values of p_{T} are necessary to distinguish between the different models.

4. Summary and Future Plans

PHENIX has measured charm and bottom separated heavy flavor electron yield, bottom electron fraction over inclusive HF electrons, and their respective nuclear modification factors using data collected in Run 2004 and 2014 Au+Au collisions. Comparison of b-fraction for central events with different theoretical models show preference for T-Matrix models with stronger coupling of heavy quark with the QGP, while the R_{AA} measurements are in good agreement with DGLV models at high values of p_{T}. These comparisons suggest that the QGP behaves like a strongly coupled plasma, and the energy loss in QGP is quark mass dependent. More precise measurements are underway at PHENIX using p+p baseline measurement [16] by PHENIX using similar methodology as the analysis covered in this report. In addition to the reduced uncertainties, this would extend the measurement to much lower values of $p_{\mathrm{T}} \sim 1$ GeV/c.

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