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Nuclear modification factor and flow of charm and bottom quarks in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX Experiment

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Abstract

Experimental results at RHIC and at the LHC show a similar strong suppression for light and heavy quark probes at high p_T, and a possible quark mass dependence of suppression at low p_T. More high precision measurements of separated charm and bottom are needed to quantify the dependence of medium effects on the quark mass. The PHENIX experiment measured separated electrons from bottom and charm decays using displaced vertex distributions at mid-rapidity $|y| < 0.35$. Azimuthal anisotropy of electrons from separated charm and bottom decays are obtained from high statistics Au+Au data taken in 2014. PHENIX also measures muons from heavy quark decays in d+Au collisions at forward rapidity to study collective effects on heavy flavor production in small systems. These proceedings report the azimuthal anisotropy of charm and bottom at mid-rapidity in minimum bias Au+Au collisions and the anisotropy of single muons from heavy quark decays in d+Au collisions.

1. Introduction

Heavy quark measurements, charm and bottom, provide a powerful tool to study the properties of the Quark-Gluon Plasma (QGP) medium created in high-energy heavy-ion collisions. Heavy quarks are mainly produced via initial hard scatterings because of their large mass. Once produced, these heavy quarks probe final state effects such as energy loss and collective flow by the interaction with QGP medium when they traverse it. Therefore the modification of the momentum and angular distributions provides valuable insights of QGP properties.

The PHENIX experiment measured the nuclear modification factor R_{AA} of electrons from charm(c) and bottom(b) decays separately in Au+Au collisions[1]. We found that electrons from bottom decays are less suppressed than charm decays in $3 < p_T < 4$ GeV/c and are similarly suppressed for higher p_T. This

[1]for the full PHENIX collaboration author list and acknowledgements, see Appendix "collaboration" of this valume

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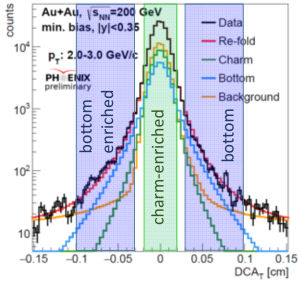

Fig. 1. DCA distribution of electrons for minimum bias Au+Au collisions. The charm and bottom components are determined by the unfolding method. The DCA distributions are split with two regions to separate the charm and bottom v_2.

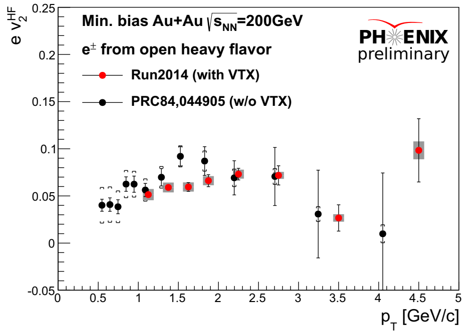

Fig. 2. v_2 of electrons from inclusive heavy quark decays for minimum bias Au+Au collisions. The result from this analysis is consistent with the published result[8].

result is qualitatively consistent with the expected mass ordering of energy loss for quarks(q) and gluons(g), $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$. Both collisional and radiative loss mechanism suggest less energy loss with larger quark mass [2]. To study the energy loss of heavy quarks in more detail, it is essential to measure the centrality dependence of R_{AA} and azimuthal anisotropy of charm and bottom separately. Recently, strong suppression and significant azimuthal anisotropy for charm are reported from RHIC and LHC experiments [3, 4, 6, 5]. Suppression of bottom yield and bottom anisotropy are also under experimentally investigation. The bottom production will provide further information of QGP.

The mass dependence of azimuthal anisotropy for light particles in small collision systems at RHIC is an intriguing observation[7]. To see the extension of this phenomenon in heavy quark particles, we measured single muons from heavy quark decays in d+Au collisions at forward rapidity.

In these proceedings, we report the azimuthal anisotropy (v_2) of separated charm and bottom in the single electron measurement at mid-rapidity in minimum bias Au+Au collisions and the anisotropy of single muons from heavy flavor decays in d+Au collisions at forward rapidity.

2. Azimuthal anisotropy of single electrons from separated bottom and charm decays

We analyzed the dataset from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV recorded in 2014. The analysis performs a statistical separation of electrons from charm and bottom decays utilizing the difference of their decay lengths measured by a silicon vertex detector (VTX). The VTX provides precise tracking information in the form of the distance of closest approach (DCA) of electrons to the collision vertex. The DCA is proportional to the decay length, thus the shape of the DCA is broader for electrons from bottom decays than that from charm decays. The DCA distributions are measured for $1 < p_T < 8$ GeV/c.

Inclusive electrons contains not only the bottom and charm electrons but also electrons from several backgrounds. The main sources of these backgrounds are photon conversions, Dalitz decays of π^0 and η, and misidentified hadrons. Background electrons from Ke3 decays and random association with VTX hits in high multiplicity make large DCA tail. Electrons from J/ψ decays are also a non-negligible background for high p_T. Those backgrounds are estimated by event driven methods and the PHENIX detector simulations. To separate the bottom and charm components, the unfolding method fits the DCA distributions simultaneously with the invariant yield of electrons from inclusive heavy quark decays. The analysis methods (the background subtraction and the unfolding) are described in the article[1]. Figure 1 shows the DCA distribution of electron for minimum bias Au+Au collisions. The bottom and charm components obtained by the unfolding method are also plotted as well as the sum of the all background components.

The inclusive electron v_2 was measured with the reaction plane method. The reaction plane was determined from the multiplicity in the forward silicon vertex detector (FVTX). The background v_2 from photonic electrons and misidentified hadrons are subtracted. The dilution effect of v_2 due to the finite resolution of the

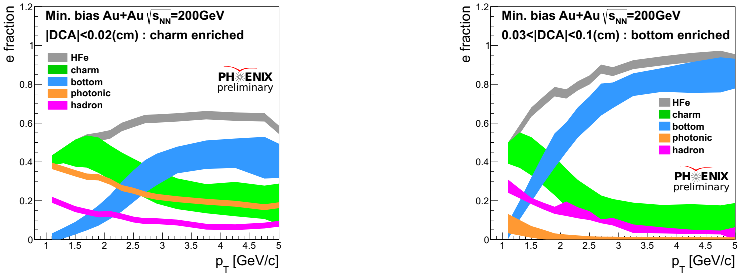

Fig. 3. Fractions of charm, bottom, and other backgrounds in charm- (left) and bottom-(right) enriched DCA region.

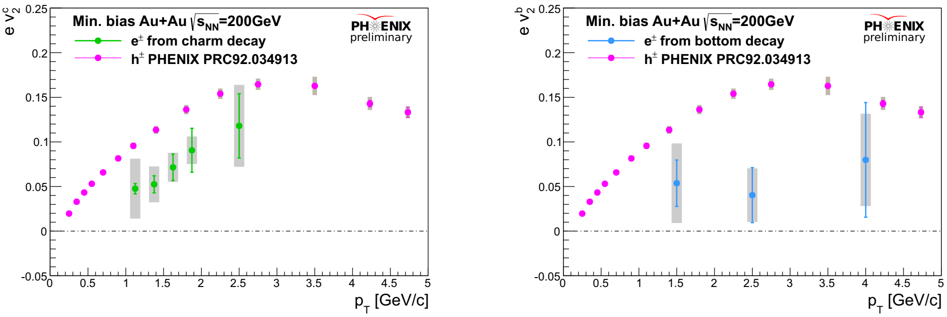

Fig. 4. electron v_2 for charm(left) and bottom(right) decays in minimum bias Au+Au collisions. The results are compared with the charged hadron v_2[9].

reaction plane measured by FVTX is corrected. Figure 2 shows the electron v_2 from inclusive heavy quark decays in minimum bias Au+Au collisions. The result from this analysis is found to be consistent with the previous published result[8].

To separate electron v_2 from charm and bottom decays, we split the electron sample into two DCA ranges, $|DCA| < 200\ \mu m$ and $300 < |DCA| < 1000\ \mu m$, as shown in Fig. 1. These DCA regions are called charm-enriched and bottom-enriched region because charm component is mostly contained in the DCA peak but bottom component has broad DCA tail. Figure 3 shows the fraction of charm and bottom components as well as other background for charm enriched (left) and bottom enriched (right) DCA region. These fractions are obtained using the DCA distributions and determining the charm and bottom components with the unfolding method.

The electron v_2 (v_2^{HQ}) from heavy quark decays for charm-enriched (bottom-) region is expressed as

$$v_2^{HQ}(c) = F_b(c) \cdot v_2^b + F_c(c) \cdot v_2^c \tag{1}$$
$$v_2^{HQ}(b) = F_b(b) \cdot v_2^b + F_c(b) \cdot v_2^c. \tag{2}$$

Here, F_b(c) and F_c(c) are the fraction of the charm and bottom components in these DCA regions where (c) and (b) denote the charm- and bottom- enriched region. v_2^b and v_2^c are electron v_2 from bottom and charm decays which are signals of interest, and they are extracted by solving these equations simultaneously.

Figure 4 shows electron v_2 for charm(left) and bottom(right) decays at mid-rapidity in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These results are compared with charged hadron v_2[9]. Charm electron v_2 is larger than zero and increasing with p_T and smaller than charged hadron v_2 for the entire p_T range. Bottom electron v_2 data shows a hint of positive value of v_2 but it is also consistent with zero within large uncertainty. From the comparison with v_2^c, bottom electron v_2 is likely to be smaller than charm electron v_2. This result is consistent with the LHC results which show small bottom v_2[10, 11]. The analysis of separated v_2^b and v_2^c is in progress with the improvement of analysis method and the uncertainty would be

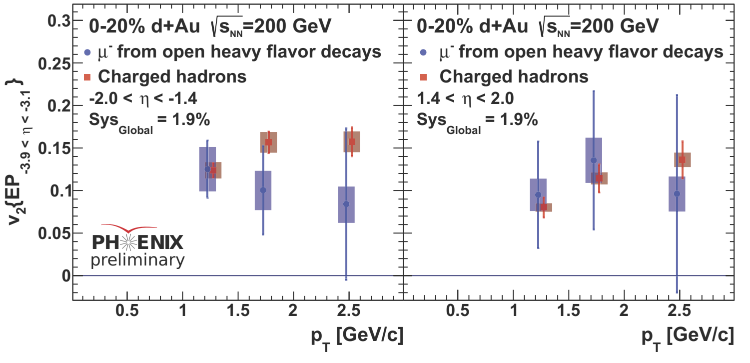

Fig. 5. single muon v_2 from heavy quark decays in 0-20% d+Au collisions for backward (left) and forward (right) rapidities.

reduced.

3. Muon anisotropy from heavy quark decays in d+Au collisions for forward rapidity

The analysis of single muon from heavy quark decays was performed with the data on d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV recorded in 2008. Muons are measured with the PHENIX muon spectrometer. The analysis is described in [12]. The inclusive muon v_2 and charged hadron v_2 was measured with the reaction plane method. Background muon v_2 from mis-identified hadrons, light hadron decays and J/ψ decays are subtracted by the detector simulation. It uses the charged hadron v_2 as input and includes their decay kinematics and the detector response. Figure 5 shows single muon v_2 from inclusive heavy quark decays in 0-20% central d+Au collisions for backward (left, Au-going) and forward (right, d-going) rapidities. The results are compared with charged hadron v_2. From the results, we found the single muon v_2 from heavy quark decays are positive for both backward and forward rapidities with 99.9% and 98.6% confidence level.

4. Summary

PHENIX measured azimuthal anisotropy, v_2, of bottom and charm in Au+Au and d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. In Au+Au, we measured for the first time the separated charm and bottom electron v_2 in minimum bias Au+Au collisions. The results show that charm electron v_2 is positive and bottom electron v_2 is consistent with zero within the uncertainty. Bottom electron v_2 is likely smaller than charm electron v_2. In 0-20% central d+Au collisions, we found that the significant v_2 of single muons from heavy quark decays for forward and backward rapidities. In 2015 and 2016, we recorded high statistics dataset in $p + p$ and Au+Au collisions. These new dataset will provide a more precise measurement of suppression and azimuthal anisotropy for charm and bottom and allow quantitative constraints on the transport properties of QGP.

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