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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

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[1] for the full PHENIX collaboration author list and acknowledgements, see Appendix "collaboration" of this valume
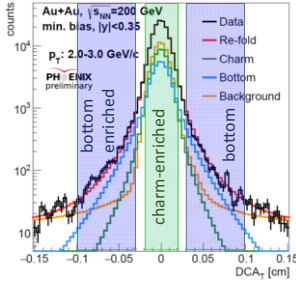
Fig. 1. DCA distribution of electrons for minimum bias Au+Au collisions. The charm and bottom components are determined by the unfolding method. The DCA distributions are split with two regions to separate the charm and bottom $v_2$.
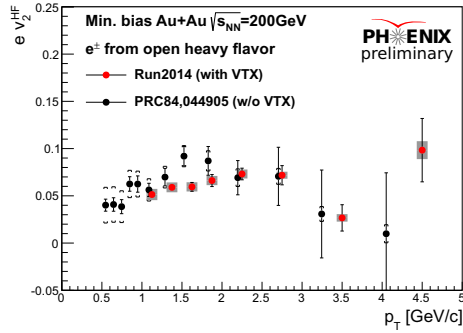


Fig. 2. $v_2$ of electrons from inclusive heavy quark decays for minimum bias Au+Au collisions. The result from this analysis is consistent with the published result[8].

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 $\pi^0$ and $\eta$, and misidentified hadrons. Background electrons from Ke3 decays and random association with VTX hits in high multiplicity make large DCA tail. Electrons from $J/\psi$ 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
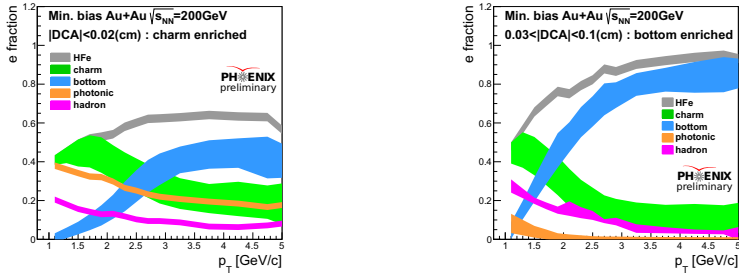
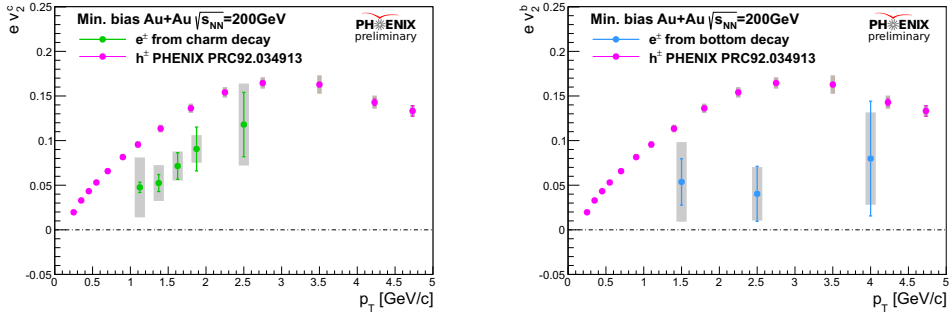Fig. 3. Fractions of charm, bottom, and other backgrounds in charm- (left) and bottom-(right) enriched DCA region.



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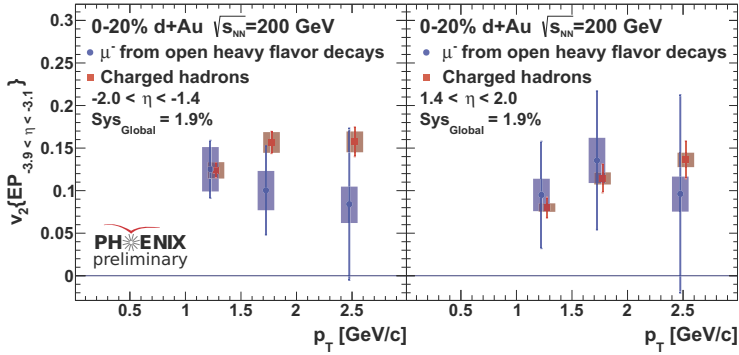
Fig. 5. single muon $v_2$ from heavy quark decays in 0-20% $d$+Au collisions for backward (left) and forward (right) rapidities.

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 $J/\psi$ 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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