PHENIX measurements of heavy quark anisotropic flow in Au+Au and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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The measurement of heavy quark collective motion in heavy-ion collisions is a powerful tool to reveal key QGP properties, such as shear viscosity and quark diffusion. PHENIX has new measurements of the second Fourier harmonic, $v_2$, of separated charm and bottom quarks at mid-rapidity $|y| < 0.35$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The technique utilized in these measurements makes use of the distance of the closest approach of electrons from the semileptonic decays of charm and bottom hadrons. In addition, measurements of $v_2$ of inclusive heavy-flavor particles were performed in the small d + Au system using muon decays at forward and backward rapidities covering the range $1.2 < |y| < 2.2$. The experimental study in small systems will help the understanding of the origins of particle collectivity in hadronic collisions. This presentation will show these results and discuss them in the view of the current theoretical calculations.
1. Introduction

Heavy quark provides an important information on the properties of the Quark-Gluon Plasma (QGP). They are mainly produced in the initial stage of the heavy-ion collisions and propagates the QGP. Since heavy quark propagate thorough the QGP with a strong coupling, the modification of their phase space distribution strongly reflects the QGP dynamics.

Ten years ago, we have measured the nuclear modification factor $R_{AA}$ of $c + b \rightarrow e$ in Au+Au and $d + Au$ collisions which reflects the modification of a momentum distribution as shown in Figure 1 (left) [1]. $R_{AA}$ of $c + b \rightarrow e$ in Au+Au collisions indicates a strong yield suppression at high $p_T$ compared with that in $d + Au$ collisions. It was not expected and we need to reconsider the energy loss mechanism and understand its quark-mass dependence. Recently, we have measured $R_{AA}$ of $c \rightarrow e$ and $b \rightarrow e$ and observed a quark-mass dependence of the suppression, namely a suppression less pronounced for bottom quarks than for charm quarks [2, 3, 4].

On the other hand, we have also found a large azimuthal anisotropy $v_2$ of $c + b \rightarrow e$ in Au+Au collisions ten years ago as shown in Figure 1 (right) [1]. It indicates that heavy flavors are strongly coupled in the QGP which was also not expected. We now are interested in the quark-mass dependence of the elliptic flow in the QGP. Especially, whether a very heavy bottom quark can be strongly coupled with the QGP is an object of interest. In addition, a heavy-flavor flow in small collision systems is also an object of interest because the flow in small collision systems was found at both RHIC [5] and LHC [6].

![Figure 1](image-url)  
*Figure 1:* Left: The nuclear modification factor for $c + b \rightarrow e$, $c \rightarrow e$ and $b \rightarrow e$ in $d + Au$ and $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: The azimuthal anisotropy of $c + b \rightarrow e$ in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

2. Result

2.1 Azimuthal Anisotropy of $c + b \rightarrow \mu$ in $d + Au$ collisions

We have measured the azimuthal anisotropy $v_2$ of $c + b \rightarrow \mu$ in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$
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The invariant yield of single muons is measured with the PHENIX muon spectrometer (1.2 < $\eta$ < 2.2) and background components which are hadron decay muons, punch through hadrons, and $J/\psi$ decay muons are subtracted to extract muons from heavy-flavor decays. Focusing on the 0-20% central $d+Au$ collisions, the azimuthal anisotropy $v_2$ of $c + b \rightarrow \mu$ with respect to the reaction plane is observed for 1.0 < $p_T$ < 3.0 GeV/c as shown in Figure 2. $v_2$ in Au-direction ($d$-direction) is observed with 99.9% (98.6%) confidence level, indicating the non-zero flow of heavy flavors in the small collision systems. The order of magnitude is similar to charged hadron $v_2$ [7]. This new result is one of the keys to understand flow in small collision systems.

![Figure 2](image)

Figure 2: The azimuthal anisotropy of $c + b \rightarrow \mu$ (blue points) in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV for Au-direction (left panel) and $d$-direction (right panel). Red squares correspond to charged hadron $v_2$ measured in same $\eta$ range [7].

2.2 Azimuthal Anisotropy of $c \rightarrow e$ and $b \rightarrow e$ in Au+Au collisions

We have measured the azimuthal anisotropy $v_2$ of $c \rightarrow e$ and $b \rightarrow e$ via a displaced vertex analysis in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Firstly, we measure the $p_T$ spectrum and DCA$_T$ distributions of single electrons and estimate background contributions which include non-electrons, internal and external conversion electrons, $J/\psi$ decay electrons, Kaon decay electrons, and electron tracks mis-associated with uncorrelated inner tracker hits. These background components and DCA$_T$ shapes are estimated by the data-driven method and the PHENIX detector full-simulation. Secondly, each component of $c \rightarrow e$ and $b \rightarrow e$ are extracted in DCA$_T$ distributions. In this analysis, we employ our Bayesian inference technique [2, 3] and unfold the $p_T$ spectrum of parent charm and bottom hadrons because DCA$_T$ shapes depend on parent hadron $p_T$ spectrum shape. The refold DCA$_T$ shape from unfolded $p_T$ spectrum of parent charm and bottom hadrons describes well the measured DCA$_T$ distribution of electrons as shown in Figure 3 (left). Thirdly, the DCA$_T$ distribution is divided to charm enriched region ($|DCA_T| < 200$ $\mu$m) and bottom enriched region ($300 < |DCA_T| < 1000$ $\mu$m) as shown in Figure 3 to extract the azimuthal anisotropy of $c \rightarrow e$ and
For both charm and bottom enriched region, the azimuthal anisotropy of $c + b \to e$ as a function of $p_T$ is measured with the background $v_2$ subtraction as shown in Figure 3 (right).

These $v_2$ of $c + b \to e$ in charm and bottom enriched regions are expressed as

$$v_{2,\text{rich}}^c = F_{c,\text{rich}}^c \times v_2^c + F_{b,\text{rich}}^c \times v_2^b$$

(2.1)

$$v_{2,\text{rich}}^b = F_{c,\text{rich}}^b \times v_2^c + F_{b,\text{rich}}^b \times v_2^b$$

(2.2)

where $F_c$ ($F_b$) is the fraction of $c \to e$ ($b \to e$) in each DCA$_T$ regions, $v_2^c$ ($v_2^b$) is true azimuthal anisotropy of $c \to e$ ($b \to e$). Simultaneous equations can be solved with each fraction and inclusive $v_2$ values to extract $v_2$ of $c \to e$ and $b \to e$. Figure 4 shows extracted $v_2$ of $c \to e$ and $b \to e$ as a function of $p_T$ which is the first measurement at RHIC energy. $v_2$ of $c \to e$ increases with increasing $p_T$ and indicates the large elliptic flow of charm quarks in the QGP. The order of magnitude is less than the charged hadron $v_2$ [8]. To a direct comparison, an unfolding of parent hadron $v_2$ and Quark-Constituent-Number scaling are needed. On the other hand, $v_2$ of $b \to e$ indicates no strong $p_T$ dependence and non-zero flow of bottom quarks which is consistent with LHC result [9]. Measured $v_2$ of $b \to e$ is likely smaller than $v_2$ for $c \to e$, indicating the quark-mass dependence of flow in the QGP. However, $v_2$ of $b \to e$ is consistent with zero and $v_2$ of $c \to e$ within the large uncertainty. The analysis method will be improved to reduce the uncertainty and better understand the quark-mass dependence of flow.

3. Summary

We have observed $v_2$ of $c + b \to \mu$ in $d + A$ collisions and separated $v_2$ of $c \to e$ and $b \to e$
in Au + Au at $\sqrt{s_{NN}} = 200$ GeV. Large $v_2$ of $c + b \rightarrow \mu$ in $d + Au$ collisions is found for both Au-direction and $d$-direction. It indicates that heavy flavors flow in small collision system. We also find large $v_2$ of $c \rightarrow e$ in Au + Au collisions, which indicates that charm quark is strongly coupled in the QGP. On the other hands, $v_2$ of $b \rightarrow e$ in Au + Au collisions show no strong $p_T$ dependence and very small $v_2$ which is likely smaller than $v_2$ of $c \rightarrow e$. The analysis method will be improved to reduce the uncertainty and better understand the quark-mass dependence of flow in the QGP.

References