

# Single electrons from semi-leptonic charm and bottom hadron decays in Au+Au collisions at PHENIX

**Takashi Hachiya for the PHENIX collaboration**

RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

E-mail: [hachiya@ribf.riken.jp](mailto:hachiya@ribf.riken.jp)

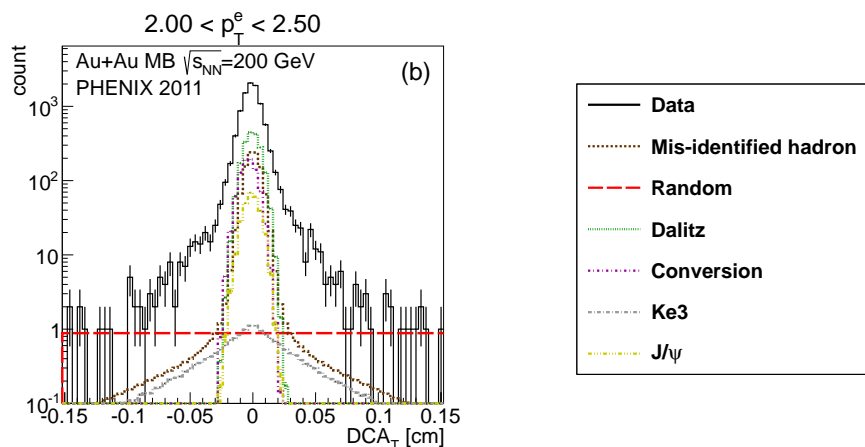
**Abstract.** Heavy quarks are clean probes to explore the nature of strongly coupled quark gluon plasma created in high energy heavy ion collisions. The strong suppression of single electrons from semi-leptonic decays of heavy flavor hadrons was observed. To further understand the heavy quark suppressions, PHENIX installed the silicon vertex detector (VTX) which allows us to measure the bottom and charm productions separately from measurement of displaced tracks. For the first time, we observed the electrons from bottom hadron decays are less suppressed than those from charms for  $3 < p_T < 4$  GeV/ $c$  and are similarly strongly suppressed for higher  $p_T$  in minimum bias Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. We present the results of separated bottom and charm productions using the 2011 dataset with the VTX.

## 1. Introduction

Heavy quarks are clean probes to explore the nature of strongly coupled quark gluon plasma (QGP) created in relativistic high energy heavy ion collisions. Heavy quarks, bottom and charm quarks, are mainly produced via initial hard scattering in the collisions because of their large masses ( $M_b \approx 4.2$  GeV/ $c^2$  and  $M_c \approx 1.3$  GeV/ $c^2$ ). Once produced, heavy quarks interact with QGP when they traverse it. Therefore, heavy quarks probe the property of QGP during its entire space-time evolution.

PHENIX previously measured a strong suppression of the heavy quark production at high transverse momentum ( $p_T$ ) and a substantial flow in the measurement of single electrons from semi-leptonic decays of bottom and charm hadrons[1, 2]. The observed suppression of heavy quarks was found to be similar to that of light quarks. Before this discovery, it was expected that heavy quarks suffer less energy loss in QGP than light quarks and gluons via radiative energy loss due to “dead cone effect” [3], which provides a mass ordering of energy loss ( $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ ). Collisional energy loss is also considered to describe the suppressions in addition to radiative energy loss. To understand the phenomena of the heavy quark suppressions in detail, PHENIX installed a barrel silicon vertex detector (VTX) in 2011 to measure the bottom and charm components separately in the single electron measurement. VTX can disentangle the relative contributions between the radiative and collisional energy losses. In this article, the data analysis method are described and the results are discussed.





**Figure 1.**  $DCA_T$  distribution for electrons in  $2 < p_T < 2.5$  GeV/ $c$  in minimum bias Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. Also shown are the normalized components for the various background sources

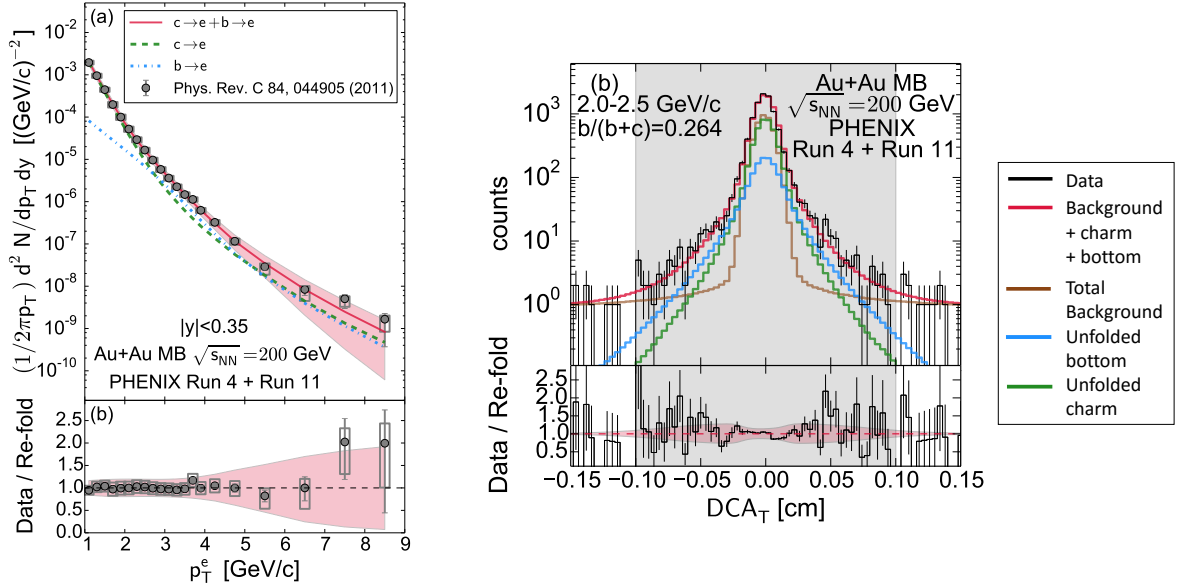
## 2. Data analysis and bottom/charm separation

We measured single electrons using the data on Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV recorded in 2011[4]. Electron identification and tracking are performed by the PHENIX two central arm detectors. The analysis utilizes the difference of the decay lengths of  $B$  and  $D$  mesons ( $c\tau_{B^0} \approx 455 \mu m$  and  $c\tau_{D^0} \approx 123 \mu m$ ). VTX measures the distance of closest approach ( $DCA$ ) of the track from the collision vertex. The  $DCA$  is calculated in the transverse ( $DCA_T$ ) and longitudinal ( $DCA_L$ ) planes separately because VTX has better resolution in transverse plane by detector design. We use  $DCA_T$  for the analysis, where the  $DCA_T$  resolution is  $\approx 60 \mu m$  for tracks with  $p_T > 2$  GeV/ $c$ .

The data analysis is performed in three steps. First, we measure the  $DCA_T$  of inclusive electrons for  $1.5 < p_T < 5.0$  GeV/ $c$  in five  $p_T$  bins. The electrons contain a large amount of backgrounds that originate from non-desired physics processes such as Dalitz decays of  $\pi^0$  and  $\eta$ , photon conversions,  $K_{e3}$  decays, and  $J/\psi \rightarrow e^+e^-$  decays as well as detector effects such as mis-identified hadrons and high multiplicity background. Most of them are rejected by vetoing pair-wise hits in VTX because very close pairs of hits are created by  $e^+e^-$  pairs from Dalitz decays and photon conversions, which are main background sources.

Second, we determined the background contributions remained in the  $DCA_T$  distributions. The background from mis-identified hadrons is evaluated by the event swap method and the high-multiplicity background is evaluated by embedding single simulated electrons into the real events. The backgrounds from Dalitz decays of  $\pi^0$  and  $\eta$ , photon conversions,  $K_{e3}$ , and  $J/\psi$  decays are determined using a GEANT simulation of PHENIX detector with the inputs of measured spectra.  $DCA_T$  distributions from these backgrounds are normalized based on the background yields by cocktail calculations, which is similar with previous PHENIX single electron measurement in 2004[1, 2]. Figure 1 shows the  $DCA_T$  distribution for electrons in  $2.0 < p_T < 2.5$  GeV/ $c$ . The normalized background components are also plotted in Fig. 1.

Third, to separate the bottom and charm components, we developed a new statistical separation method based on the Bayesian inference technique, which is called as an unfolding method. The unfolding method performs a simultaneous fitting to the  $DCA_T$  distributions from the 2014 data set and the published PHENIX invariant yield of inclusive heavy flavor electrons measured using the data recorded in 2004[2]. In the unfolding method, a set of trial parent bottom and charm hadron yields are chosen and converted to  $DCA_T$  distributions and



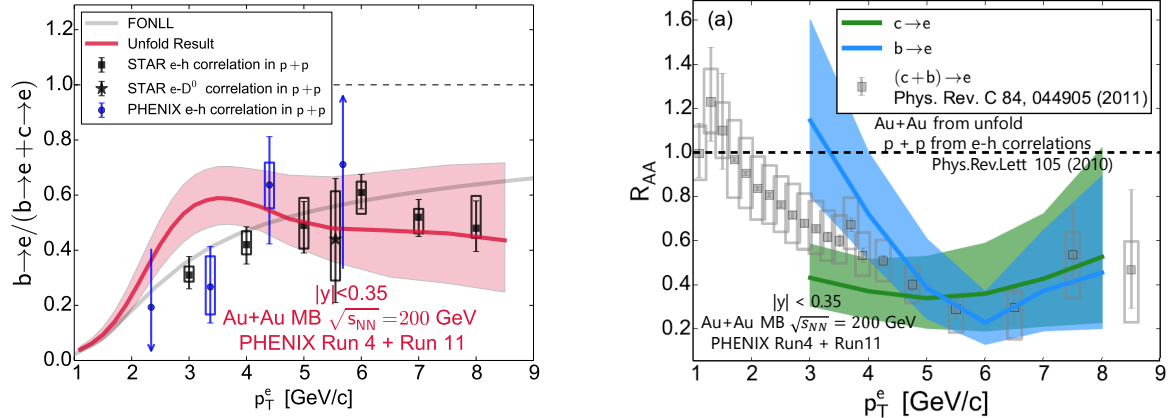
**Figure 2.** (Left) Invariant yield of inclusive heavy flavor electrons measured using the data recorded in 2004[2]. (Right)  $DCA_T$  distribution for single electrons measured in this analysis. The invariant yield and  $DCA_T$  distributions are compared with the calculated bottom and charm components from the unfolding method as well as their backgrounds. Bottom panels in left and right plots show the ratio between the data and the results from the unfolding method. The results are in good agreement with the measure data within the uncertainties.

invariant yield of electrons decayed from these parents using a decay matrix. The resulting distributions of electron  $DCA_T$  and invariant yield are compared with the measured data using a likelihood function. The benefit of the unfolding method is to constrain the bottom and charm components in both the  $DCA_T$  and the invariant yield spaces using the parent hadron yields because both the  $DCA_T$  shape and invariant yield of electrons are sensitive to the  $p_T$  distributions of parent bottom and charm hadrons. Figure 2 shows the comparisons between measured electrons and electrons calculated by the unfolding method in  $p_T$  (left) and  $DCA_T$  distribution (right), respectively. The bottom panels of Fig. 2 are the ratio between them. We found a good agreement in both invariant yield and  $DCA_T$  within the uncertainties.

### 3. Results

From the results of the unfolding method, the fraction of electrons from bottom decays to inclusive heavy flavors (both bottoms and charms) is calculated. The resulting bottom electron fraction is shown in the left panel of Fig. 3 and compared with FONLL perturbative QCD calculations for  $p+p$  collisions at  $\sqrt{s} = 200$  GeV[5]. We find that the measured bottom electron fraction in Au + Au collisions shows a steep rise in  $2 < p_T < 4$  GeV/c with a possible peak at  $p_T \sim 3$  GeV/c compared with the FONLL calculation. In Fig. 3, the bottom electron fraction in  $p+p$  collisions at  $\sqrt{s} = 200$  GeV [6, 7] is also plotted and found that they are in good agreement with the FONLL calculations within uncertainties.

We can calculate the nuclear modification factor ( $R_{AA}$ ) for electrons from bottom and charm hadron decays separately using the bottom electron fraction in Au + Au and  $p+p$ , and  $R_{AA}$  of inclusive heavy flavor electrons. The resulting  $R_{AA}$  is shown in the right panel of Fig. 3. We find that electrons from bottom decays are less suppressed than that from charm decays for  $p_T < 4$  GeV/c and similarly strongly suppressed for higher  $p_T$ . However, it is difficult to compare with



**Figure 3.** (Left) The unfolded result of bottom electron fraction in minimum bias Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV[4], which are compared with the FONLL calculation[5]. Also shown are the bottom electron fraction in  $p + p$  collisions at  $\sqrt{s} = 200$  GeV from PHENIX[6] and STAR[7]. (Right)  $R_{AA}$  for electrons from separated bottom and charm hadron decays as well as inclusive heavy flavor electrons

the theoretical calculations in detail because of the relatively large uncertainties.

#### 4. Summary and Outlook

PHENIX has measured the electron yield from bottom and charm hadron decays separately. The VTX detector installed in 2011 enables us to separate the bottom and charm components in single electrons by measuring the  $DCA_T$  distributions. Using the  $DCA_T$  distributions and previous PHENIX results of invariant yield of heavy flavor electrons, the unfolding method successfully extracted the fraction of bottom electrons to inclusive heavy flavors as a function of  $p_T$ . From the comparison of the bottom electron fractions in Au + Au and  $p + p$ , we find a less suppression of electrons from bottom decays than that from charm decays for  $p_T < 4$  GeV/c and a similar strong suppression for higher  $p_T$ .

This is the first measurement of the strong bottom suppression in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. However the uncertainties in the current measurement is relatively large so as to disentangle the energy loss mechanisms in detail. We collected approximately 10 times larger amount of Au + Au data in 2014 and large statistics  $p + p$  data in 2015. These data sets should provide definitive measurements of separated bottom and charm electron suppressions.

#### References

- [1] A. Adare *et al.* Energy Loss and Flow of Heavy Quarks in Au + Au Collisions at  $\sqrt{s_{NN}} = 200$  GeV *Phys. Rev. Lett.* **98** 172301 (2007)
- [2] A. Adare *et al.* Heavy-quark production in  $p + p$  and energy loss and flow of heavy quarks in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV *Phys. Rev. C* **84**, 044905 (2011)
- [3] Y. L. Dokshitzer and D. E. Kharzeev *Phys. Lett. B* 519, 199 (2001)
- [4] A. Adare *et al.* Single electron yields from semileptonic charm and bottom hadron decays in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV *Phys. Rev. C* **93** 034904 (2016)
- [5] M. Cacciari, P. Nason, and R. Vogt, QCD Predictions for Charm and Bottom Quark Production at RHIC *Phys. Rev. Lett.* **95** 122001 (2005)
- [6] A. Adare *et al.* Measurement of Bottom versus Charm as a Function of Transverse Momentum with Electron-Hadron Correlations in  $p + p$  Collisions at  $\sqrt{s} = 200$  GeV *Phys. Rev. Lett.* 103 082002 (2009)
- [7] M. Aggarwal *et al.* Measurement of the Bottom contribution to non-photonic electron production in  $p + p$  collisions at  $\sqrt{s} = 200$  GeV *Phys. Rev. Lett.* 105 202301 (2010)