Overview of charm production at RHIC

Yifei Zhang
Dept. of Modern Physics, University of Science and Technology of China, Hefei, Anhui, China, 230026
E-mail: yfzhang3@mail.ustc.edu.cn

Abstract.
We present an overview of the recent abundant measurements for charm production at RHIC. The significant information of charm cross sections in different collision system at 200 GeV and charmed hadron freeze-out and flow properties extracted from these measurements are presented. The heavy flavor energy loss in the medium and heavy flavor related azimuthal correlations in heavy ion collisions are also discussed.

PACS numbers: 25.75.Dw, 13.20.Fc, 13.25.Ft, 24.85.+p

1. Introduction
Charm quarks are a unique tool to probe the hot-dense matter created in relativistic heavy-ion collisions at RHIC. Charm quarks are believed to be produced only in the early stages and their production rate is reliably calculable by perturbative QCD [1, 2]. Studies of the binary collision ($N_{\text{bin}}$) scaling of the total charm cross section can be used to test theoretical calculations and determine if charm is indeed a good probe with well-defined initial states. Measurements of charm production at low $p_T$, in particular radial and elliptic flow, probe the QCD medium and are thus sensitive to bulk medium properties like density and the drag constant or viscosity. And charm flow properties may help understand the light flavor thermalization [3]. Due to their large mass ($\simeq 1.3$ GeV/$c^2$), charm quarks are predicted to lose less energy than light quarks by gluon radiation in the medium [4]. Measure heavy quark energy loss via its semileptonic decay electrons may provide us information on the interactions of heavy quarks with the hot dense matter produced in nuclear collisions at RHIC. The strong energy loss of light hadrons modified the di-hadron azimuthal correlation functions [5]. Measurement of the heavy flavor electron-hadron correlation may help look insight the mechanism of heavy quark interactions with the hot dense medium. Bottom quark is much heavier than charm quark, their energy loss and flow behavior may be very different. The separation of the bottom and charm contribution in the non-photonic electron measurement is vital to clearly understand the charm and bottom quark production and their interactions with the medium.

In this paper, instead of going through the details for all the measurements or analyses, we prefer the discussion on those hot physics about charm cross section,
heavy quark flow, energy loss and heavy flavor related correlations from recent abundant observations at RHIC.

2. D-mesons and leptons from heavy flavor decays

STAR experiment has measured open charm via hadronic channel \((D^0 \rightarrow K\pi, \text{B.R.}=3.83\%)\) at low \(p_T (\sim 3 \text{ GeV/c})\) in \(d+Au\) and minbias \(Cu+Cu\) and minbias \(Au+Au\) collisions at 200 GeV. Good signals \((\gtrsim 4\sigma)\) are observed in the \(K\pi\) invariant mass distributions after the combinatorial background subtraction using event-mixing method. Another hadronic channel \((D^0 \rightarrow K\pi\pi^0, \text{B.R.}=14.1\%)\) to reconstruct open charm was measured by PHENIX experiment in \(p+p\) collisions at 200 GeV. In this measurement, the \(\pi^0\) was identified by EMCal trigger via \(\pi^0 \rightarrow \gamma\gamma\) decay, and \(\sim 3\sigma\) signal was seen in the \(p_T\) range of 5-15 GeV/c.

Due to the difficulty to reconstruct D-meson hadronic decay vertex using current detectors, both STAR and PHENIX have measured open charm indirectly via its semileptonic decays to electrons or muons. STAR measured non-photonic electrons using TPC+TOF and TPC+EMC; these two results are consistent with each other but are systematically higher than PHENIX results, which were measured using RICH and EMC in a lower material environment. But the nuclear modification factors \((R_{AA})\) of electrons from heavy quark decays are consistent between STAR and PHENIX. STAR TOF has the capability to measure single muon at very low \(p_T\) range \((0.17-0.21 \text{ GeV/c})\) at mid-rapidity, which constrain 90% of the charm production cross section. PHENIX measured muons at high \(p_T\) \((> 2 \text{ GeV/c})\) using forward muon detector at rapidity \(\langle y\rangle = 1.65\). In addition, the di-electron from heavy flavor decays in \(p+p\) collisions at 200 GeV has been measured by PHENIX experiment using a cocktail method. At mid-rapidity, the charm and bottom cross section are derived from the comparison between the \(e^+e^-\) invariant mass distributions from data and those from PYTHIA simulations.

3. Charm production cross section

Both STAR and PHENIX have measured charm production cross section in several collision systems. Left panel of Fig. shows \(d\sigma^{NN}/dy\) as a function of number of binary collisions \(N_{bin}\). The STAR previous result, the charm production cross section at mid-rapidity in \(d+Au\) collisions is shown as the red circle. The charm cross section in \(Au+Au\) minbias collisions, derived by combining three independent measurements of \(D^0 \rightarrow K\pi (p_T < 3 \text{ GeV/c}),\) muon \((0.17 < p_T < 0.21 \text{ GeV/c})\) from charm decay and non-photonic electron \((0.9 < p_T < 4 \text{ GeV/c})\) from heavy flavor decays, is shown as the red square. The result in \(Au+Au\) central collisions (red star) is from combing the muon and electron measurements. The new result from \(Cu+Cu\) minbias collisions is obtained from the \(D^0 (p_T < 3.3 \text{ GeV/c})\) measurement with statistics only (red triangle). The results from non-photonic electron measurements in 200 GeV \(p+p\) \((0.3 \leq p_T \leq 9.0\)
Overview of charm production at RHIC

3

GeV/c [12] and Au+Au (0.4 \( \leq p_T \leq 4.0 \) GeV/c) [13] collisions at PHENIX, are shown as the blue circle and the blue square, respectively. The charm production cross section at mid-rapidity scales with number of binary interactions both in STAR and PHENIX experiments. This indicates that charm quarks are produced in the early stage of relativistic heavy-ion collisions. The FONLL calculation [17] shown as the band. Both the STAR and PHENIX results are higher than the central value (thick line) of the FONLL calculation, but the upper theory value reproduces the experimental results. The central values of the cross sections reported by PHENIX [12, 13] are a factor of about two smaller than STAR at all measured \( p_T \) [10]. The difference is approximately 1.5 times the combined uncertainties, also shown in the right panel of Fig. 1 at mid-rapidity. Right panel of Fig. 1 shows the charm cross section as a function of rapidity compared to theoretical calculations [18], the clear difference is seen between STAR and PHENIX results at mid-rapidity with systematical errors dominated. PHENIX also obtained the charm cross section from muon measurement at forward rapidity (\( \langle y \rangle = 1.65, 1.0 \leq p_T \leq 3.0 \) GeV/c) in 200 GeV p + p collisions, shown as the triangles. The new result has smaller systematical error and consistent with theory curves [15].

4. Flow and energy loss

In the hot dense medium created at Au+Au collisions, heavy quark is consider as an intruder, put into the hot medium with relatively very high density of light quarks. Due to their large mass, such a heavy quark may acquire flow from the sufficient interactions with the constituents of a dense medium in analog to Brownian motion. Theoretical calculations have shown that interactions between the surrounding partons in the medium and heavy quarks could change the measurable kinematics [3, 19], and could boost the radial and elliptic flow resulting in a different heavy quark \( p_T \) spectrum shape. Panel (a) of Fig. 2 shows the \( m_T \) spectra for light hadrons (\( \pi, K, p \)), \( \Lambda, \Xi \) and multi-strange hadrons (\( \phi, \Omega \)) in 200 GeV central Au+Au collisions [21, 22], and charmed hadron (\( D^0 \)) in 200 GeV minbias Au+Au collisions in symbols [8]. Due to
Overview of charm production at RHIC

relatively heavy quark mass and smaller hadronic scattering cross section, heavy flavor hadrons are expected to freeze-out early and difficultly participate in collective motion. Thus the larger freeze-out temperature and smaller flow velocity are expected for heavy flavor hadrons. The blast wave [20] fit results (curves) show significant dependence of the hadron species. From bottom (light hadrons) to top (charmed hadron), the freeze-out temperature is getting higher and the flow velocity becomes smaller, shown as the arrows, which is consistent with our expectations.

**Figure 2.** Panel (a): Hadron species dependent freeze-out and flow parameters from blast wave fits to the hadron \( m_T \) spectra. Panel (b): Nuclear modification factor \( (R_{\text{AuAu}}/d\text{Au}) \) for 0–12% Au+Au collisions.

Panel (b) shows \( R_{\text{AuAu}}/d\text{Au} \) for 0–12% Au+Au collisions. To study whether charmed hadrons have similar radial flow to light hadrons, we have included curves for the expected nuclear modification factor from a blast-wave model, using the freeze-out parameters for light hadrons [21] (BW3 in Fig. 2 Panel (b)) and multi-strange hadrons [22] (BW2). The data and best blast-wave fit (BW1) show large deviations from both these curves for \( p_T > 1 \text{ GeV/c} \), which suggests that the charmed hadron freeze-out and flow are different from light hadrons. We scanned the parameters to a 2-dimensional \( T_{fo}, \langle \beta_t \rangle \) space, the results show little sensitivity to freeze-out temperature, but disfavor large radial flow. These findings, together with the observation of large charm elliptic flow [11], are consistent with the recent prediction from hydrodynamics [23]: elliptic flow is built up at partonic stage, and radial flow dominantly comes from hadronic scattering at later stage where charm may have already decoupled from the system.

Since there is no direct charmed meson measurement at high \( p_T \) currently, the \( R_{\text{AA}} \) of non-photonic electrons from heavy flavor decays was used to reveal heavy quark energy loss indirectly. The strong suppression similar to light hadrons of the non-photonic electrons \( R_{\text{AA}} \) at high \( p_T > 4 \text{ GeV/c} \) has been observed in several experiments [10] [11]. In this case, STAR and PHENIX are consistent with each other. Theoretical calculation predicts that heavy quark lose less energy in the medium than light quarks due to small gluon radiation angle [4]. As presented in Fig. 2 Panel (b), model calculations of coalescence and fragmentation [24] (double-dotted curves), and collisional dissociation
of heavy meson $[25]$ (double-dashed curves) describe the experimental data.

![Figure 3](image)

**Figure 3.** Non-photonic electron elliptic flow $v_2$ in minbias Au+Au collisions at 200 GeV. Error bars are statistical and the shaded boxes are systematical errors.

In the mean time, due to the strong angular correlation between heavy flavor hadron and electron from its semileptonic decay at high $p_T$, the non-photonic electron elliptic flow $v_2$ can be used to measure heavy flavor hadron $v_2$. None zero $v_2$ of electron from heavy flavor decays was observed at PHENIX. Fig. shows the non-photonic electron $v_2$ measured from run4 $[11]$ and run7 $[26]$. This may indicate that the heavy quark strongly interact with the dense medium at early stage of heavy ion collisions and the partonic level collective motion has been observed at RHIC. The none zero but smaller non-photonic electron $v_2$ is consistent with the none zero but smaller radial flow velocity $\langle \beta_t \rangle$ compared to light hadrons. Both the observations may suggest that the light flavor thermalization at partonic stage in the hot dense matter created in heavy ion collisions.

5. Correlations

The large amount of energy loss of high $p_T$ partons in the dense medium created in central $A + A$ collisions was observed at RHIC $[27]$. And their azimuthal correlations with low $p_T$ hadrons are also modified by interacting with the medium, showing a broad or even double-peak structure on the away-side di-hadron correlation $[5]$. Since the similar level of non-photonic electron energy loss as light hadrons was observed at RHIC $[10, 11]$, the study of the e-h azimuthal correlation distribution could help us to understand the mechanism of heavy quark energy loss in the dense medium and the corresponding correlation pattern.

The azimuthal angular correlation of non-photonic electron and charged hadrons has been measured at STAR $[28]$. Left panel of Fig. 4 shows non-photonic e-h correlations at 200 GeV Au+Au collisions. Here the $v_2$ background has been subtracted. Despite large statistical errors, the azimuthal correlation distribution shows clear structure. On the near side, there is one single peak representing the heavy quark fragmentation, and possible interactions with the medium. On the away side, instead of one peak around $\pi$ as in $p + p$ collisions, the correlation functions are modified to be a broad even a double-peak structure, which is similar to the di-hadron correlation in Au+Au $[5]$. A single peak structure expected from PYTHIA calculations can not
describe the measured away side correlations. This observation of non-photonic e-h correlation probably indicates heavy quark interaction with the dense medium and the heavy quark energy loss may generate conical emission in the hot dense matter created in heavy ion collisions at RHIC.

As discussed above, the mechanism of the heavy quark interactions with the dense medium is still not very clear. Thus it is of great interest to separate non-photonic electron energy loss into the contributions from charm and bottom quarks. Since the near-side e-h azimuthal correlation from B decays is much wider than that from D decays for the same electron \( p_T \), STAR’s previous study [29] compared the experimental correlation results in p+p collisions with PYTHIA simulations, and found a substantial B contribution to non-photonic electrons up to electron \( p_T \sim 6 \text{ GeV/c} \) (blue circles in the right panel of Fig. 4). And in Run7 this measurement has been extended to \( p_T \sim 9 \text{ GeV/c} \) (blue triangles). Furthermore, STAR presents another analysis technique to separate charm and bottom quark contributions in the non-photonic electron measurement via triggering on the leading non-photonic electron azimuthal correlations with the balancing heavy quark identified by the \( D^0 \) meson (Red circle and STAR) [30]. The azimuthal correlation distribution was studied using PYTHIA simulations and simulations including NLO process [30, 31], the charm and bottom quark contribution can be separately estimated by comparing the azimuthal correlation function from simulation and data. PHENIX also presents similar analysis to separate charm and bottom contribution in non-photonic electron measurement (purple circles). A clear peak structure has been seen around 1.2 GeV/\( c^2 \) in the invariant mass distribution of triggered non-photonic electron and correlated charged hadrons. By comparing to the data, the difference of the invariant mass peaks of triggered electrons and correlated charged hadrons from simulation can be used to estimate the contributions from bottom and charm quark for the same electron \( p_T \) [32]. All the experimental results are consistent with the FONLL calculation shown as the curves [2].
Table 1. Charm production cross sections before and after bottom subtraction in minbias and central Au+Au collisions at 200 GeV. The first error is statistical, the second is systematical.

|                  | before bottom subtraction | after bottom subtraction |
|------------------|---------------------------|--------------------------|
| 0-12% central Au+Au | 297 ± 24 ± 63µb           | 301 ± 24 ± 66µb          |
| 0-80% minbias Au+Au | 274 ± 25 ± 60µb           | 285 ± 26 ± 70µb          |

The upper limit of the FONLL calculation was used to estimate the maximum contribution of electrons from bottom decays in the non-photonic electron spectra, which were used to extract charm cross section in a combined fit. In Fig. ??, the solid squares and solid circles are the non-photonic electron spectra in 0-12% central and 0-80% minbias Au+Au collisions at 200 GeV, respectively. The open symbols present the non-photonic electron spectra after the subtraction of the bottom contribution from the upper limit of FONLL calculation. Then the bottom-excluded non-photonic electron spectra were used in the new combined fit to extract the charm production cross section. Table 1 shows the charm production cross sections before and after bottom subtraction in minbias and central Au+Au collisions at 200 GeV. The difference is within ~5%. Since the low $p_T$ muon measurement sample most fraction of the charm cross section [14], the high $p_T$ bottom contribution does not change it.

Figure 5. Combined fit to extract charm production cross section using $D^0$, $\mu$ and non-photonic electron spectra before (solid squares and circles) and after (open squares and circles) bottom contribution subtraction.

6. Conclusions
The results of charm production from analysis of D meson reconstruction and leptons from heavy flavor semileptonic decays at RHIC were reported. The charm production cross section was found to scale with number of binary collisions both in STAR and PHENIX, which indicates that charm quark produced at early stage of the system. But the discrepancy remains between STAR and PHENIX. The blast-wave fits and the direct
comparisons of the spectra suggest that charmed hadrons interact with and decouple from the system differently from the light hadrons. The non-zero radial and elliptic flow observed at RHIC may suggest that the light flavor thermalization at partonic stage in the hot dense matter created in heavy ion collisions. The strong electron suppression was observed both in STAR and PHENIX, the heavy quark energy loss mechanism is not really understood. The broad structure shown on the away-side e-h correlation may suggest the heavy quark energy loss generates the conical emission in the medium. The bottom contribution in the non-photonic electron spectrum was studied by the e-h or e-D correlations, but the high $p_T$ bottom contribution does not affect the charm production cross section.

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