Open Heavy Flavor Production in Heavy-ion Collisions from STAR

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Abstract. We report on the STAR measurements of open charm hadron and heavy flavor decay electron (NPE) production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The centrality dependences of D-meson and NPE p_T spectra, nuclear modification factors as well as the NPE elliptic flow v_2 are presented. The model comparisons and interpreted physics are discussed.

1. Introduction

Charm quarks are a unique tool to probe the strongly interacting matter created in relativistic heavy-ion collisions at RHIC energies, which consists of the carriers (quarks) and the mediators (gluons) of the strong force [1]. Their large masses ($\simeq$1.3 GeV/c^2) are not easily affected by the strong interaction with QCD medium. They are believed to be created mainly via initial hard parton scatterings. Therefore they carry clean information of the system at early stage in heavy-ion collisions [2]. Energetic charm quarks are predicted to lose less energy than light quarks, due to the suppression of gluon radiation by the large mass, when they traverse a Quark-Gluon Plasma [3, 4]. In contrast, recent measurements of non-photonic electrons (NPE) from heavy quark decays at high transverse momentum (p_T) show a jet quenching level similar to that of the light hadrons [5, 6]. This observation renews the interest in charm production and the interactions of heavy charm quarks with the hot and dense matter produced in nuclear collisions at RHIC. Open charm production at low p_T , in particular in the kinematic region sensitive to the radial flow in hot QCD medium or cold nuclear matter effect, is crucial for understanding the charm and light quark hadronization mechanisms and the bulk/cold medium propterties.

In this proceedings, we present the measurements of open charm via two independent decay channels: hadronic $D^0 \rightarrow K\pi$ and semi-leptonic ($c\&b \rightarrow e + X$). The centrality depdence of the transverse momentum distributions as well as the nuclear modification factor respect to p + p result show less suppression in perpheral collisions but strong suppression in most central collisions above p_T = 3 GeV/c for both D^0 and NPE measurements, which indicates significant energy loss of charm quark in the hot dense medium. However, this remain us a puzzle whether bottom lose similar amount of energy as charm quark, since in the NPE measurement, especially at high p_T, charm and bottom is hardly to be separated. Benifit from our D^0 measurement, the first preliminary separation of charm and bottom in NPE measurement without model constraints will be presented. The first observation of the low p_T bump structure is consistent with model calculations assuming strong charm-medium interactions.

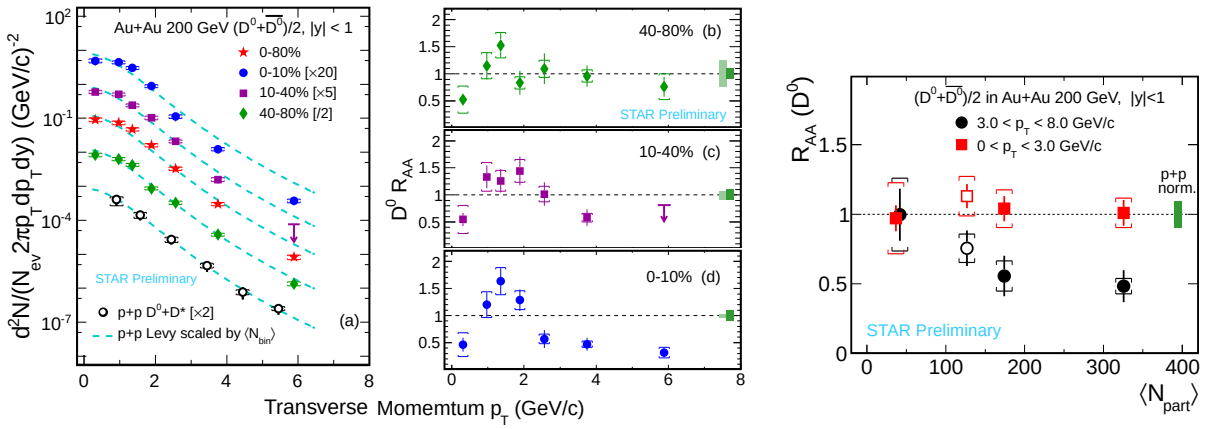

Figure 1. Left panel: (a) Centrality dependence of D^0 p_T differential invariant cross section. Data from peripheral (40-80%) to central (0-10%) are shown from bottom to top. The curves are number of binary collisions scaled Levy function from fitting to the p+p result (open circles). D^0 R_{AA} are shown in 40-80% (b), 10-40% (c) and 0-10% (d) centrality. Right panel: Integrated D^0 R_{AA} as a function of number of participants.

2. Open charm measurement with STAR

The Solenoidal Tracker at RHIC (STAR) covers large acceptance with mid-rapidity within ± 1 and full azimuth. The main subsystems used in this analysis are the Time Projection Chamber (TPC) [7], the Time-Of-Flight (TOF) detector [8], the Barrel Electromagnetic Calorimeter (BEMC) and the Barrel Shower Maximum Detector (BSMD) [9]. The TPC measures the track momentum and ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) for particle identification. The TOF detector greatly extends the particle identification kinematics via measuring time of flight, especially for low p_T pion and kaon separation up to 1.7 GeV/c, which is crucial for current D^0 reconstruction statistically without any vertex detector. The BEMC and BSMD are effective for high p_T electron trigger and hadron rejection, which is used for high p_T NPE analysis. The other detector used is the Vertex Position Detectors (VPD) for the online minimum bias trigger. The central trigger was defined with a combination cut using the spectator signals in the Zero Degree Calorimeter (ZDC) and the multiplicity signal in the Time-Of-Flight (TOF) at midrapidity.

The pion-kaon invariant mass was reconstructed by combinning all pion and kaon candidates with large combinatorial background. A mix-event technique was used to reproduce the combinatorial background. The D^0 signals are then obtained after the mix-event background subtraction in each centrality and transverse momentum bin. The D^0 reconstruction efficiency and detector acceptance were studied via Monte Carlo simulation with full STAR detector geometry. The other detailed techniques, such as signal extraction, cut efficiency, tof matching efficiency, double-counting effect, etc, are similar as the D^0 measurement in $p+p$ collisions [10].

The electron was identified via $\mathrm{d}E/\mathrm{d}x$ and momentum over energy ratio from combination of TPC and BEMC. The further hadron rejection was done according to the different shower size between electrons and hadrons in the BSMD. The photonic electron background was reconstructed by pairing the electron and positron and select small mass (less than 150 MeV) region, which covers almost all the photon conversions and large fraction of π^0 and η Dalitz decays. The photonic electron reconstruction efficiency was also studied via standard STAR simulation. The NPE signals are obainted by subtracting the photonic background from the inclusive electron candidates corrected by the purity. The details are similar as the NPE analysis in $p+p$ collisions [11].

3. Results

The D^0 p_T spectra in each centrality bin in Au+Au collisions are shown as solid symbols in Fig. 1(a). From bottom to top are 40-80% (diamonds), 0-80% (stars), 10-40% (squares) and 0-10% (circles). The open circles represent the D-meson p_T spectrum in p+p collisions [10]. The dashed curves are number of binary collisions ($N_{\rm bin}$) scaled Levy function from fitting to the p+p result. Peripheral 40-80% is consistent with th e curve, while central 0-10% deviates from the curve at high p_T. Fig. 1(b),(c),(d) show the D^0 R_{AA} for 40-80%, 10-40% and 0-10%, respectively. Within uncertainties there is no obvious suppression in peripheral collisions but strong suppression in central collisions observed. Vertical lines denote statistic uncertainties while brackets are for bin-by-bin systematic uncertainties. The vertical bars around unity from left to right represent the overall uncertainty for Au+Au and p+p collisions, respectively. In 0-10% central collisions, the suppression level is around 0.4, which is consistent with NPE measurement [5, 6] and light hadron R_{AA} [12]. This indicates strong interactions between charm quark and the surrounding medium in Au+Au central collisions at RHIC. Figure 1 right panel shows the integrated R_{AA} as a function of number of participants. The low p_T data points (0-3 GeV/c, squares) agree with unity and show a number-of-binary-collisions scaling behavior. The high p_T data points (3-8 GeV/c, circles) show strongly centrality dependent: no suppression in peripheral collisions and strong suppression (∼0.5) in central collisions. Open symbols are for minimum bias 0-80%.

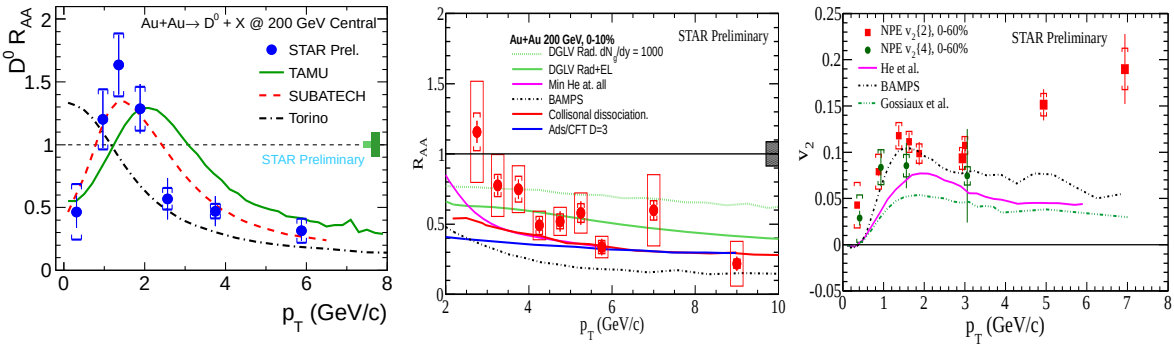

Figure 2. Left panel: D^0 R_{AA} for Au+Au central 0-10% (blue circles) compare with model calculations. The vertical bars around unity denote the uncertainties for N_{coll} in central 0-10% and p+p normalization from left to right, respectively. Right panel: NPE elliptic flow v_2 in 200 GeV Au+Au collisions. Curves are theoretical calculations.

Recent model calculations present interesting results compared with our data, especially for most central collisions, see Fig. 2 left panel. For example, the calculations from M. He and R. Rapp, performed a T-Matrix dynamic evolution of the charm quark in a Langevin + Hydro simulation plus a coalescence at low and intermediate p_T and fragmentation at high p_T for the D-meson hadronization [13, 14]. Their calculations can also reproduce the high p_T suppression with elastic scatterings. In the model of P. B. Gossiaux et. al from SUBATECH group [15, 16], the low p_T bump structure is mainly caused by the charm quark recombined with light quark in the medium with strong radial flow. In their calculation they used pure collisional energy loss and collisional + radiative energy loss (LPM) can both describe the D^0 data with different rescaling factor K. The calculations from Torino group [17, 18] with tuned transport coefficients can not reproduce the low p_T bump structure due to the pure fragmentation without any quark coalescence mechanism. Such a "bump" structure could also be explained by cold nuclear matter effect, such as Cronin effect with p_T broadening.

The NPE p_T spectra with improved statistics was reported in [19]. The NPE R_{AA} is strong

suppressed in central 0-10% collisions, similar as D^0 and light hadrons, shown in 2 middle panel. The detailed comparison with models is illustrated in [19]. Figure 2 right panel shows the NPE elliptic flow v_2 in 200 GeV Au+Au collisions. Each of the models predicts a non-zero v_2 of charm quarks. The finite NPE v_2 at low p_T suggest strong charm-medium interactions. At $p_T > 3$ GeV/c, v_2 increases with p_T which is likely due to jet-like correlations.

4. Conclusions

In summary, we report the STAR preliminary results on the charmed meson (D^0) and NPE production at mid-rapidity in Au+Au collisions at $\sqrt{s} = 200$ GeV. The charm production cross sections at low p_T (< 3 GeV/c) show number of binary collisions scaling, which indicates that charm quark is mainly produced via initial hard scatterings. The centrality dependence of the transverse momentum distributions as well as the nuclear modification factor respect to p+p result show less suppression in peripheral collisions but strong suppression in most central collisions for both D^0 and NPE, which indicates significant energy loss of charm quark in the hot dense medium. The first observation of the low p_T bump structure of D^0 R_{AA} is consistent with models with strong charm-medium interactions. However, current precision of the data does not allow us to distinguish the coalescence approach and the cold nuclear matter effect. The strong charm-medium interactions result in the sizeable NPE v_2 at low p_T.

5. Acknowledgment

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