Measurements of Open Heavy Flavor Production in STAR

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Abstract. In this article, we report the measurements of $D^0$, $D^*$ in $p+p$ at 0.6 GeV/$c < p_T < 6$ GeV/$c$ and $D^0$ in Au+Au collisions at 0.2 GeV/$c < p_T < 5$ GeV/$c$ via hadronic decays $D^0 \rightarrow K^-\pi^+$, $D^* \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$ and non-photonic electrons spectra at $3 \text{ GeV}/c < p_T < 10 \text{ GeV}/c$ reconstruction in $\sqrt{s_{NN}} = 200 \text{ GeV}$. $p+p$ collisions at mid-rapidity.

1. INTRODUCTION

Heavy quark production is dominated by initial gluon fusion and can be described by perturbative QCD (pQCD) due to their large mass [1]. The measurement of heavy quark production total cross section in $p+p$ and Au+Au collisions is important to understand both open heavy flavor and heavy quarkonia production mechanisms in the nuclear matter. The study of heavy quark production in relativistic nuclear collisions follows two different approaches: (i) the direct reconstruction of heavy flavor mesons and (ii) the identification of electrons from semi-leptonic decays of such mesons.

The data presented in this paper were collected with the Solenoidal Tracker at RHIC (STAR) detector [2] (Figure 1). Main detector subsystems used for these analyses are the large cylindrical time projection chamber (TPC), which is able to track charged particles in the pseudo-rapidity range $|\eta| < 1.8$ with full azimuthal coverage [3], time of flight (TOF) significantly improving charged hadrons identification [4] and barrel electromagnetic calorimeter (BEMC) being able to trigger on high-$p_T$ particles and improving electron-hadron separation [5]. Both TOF and BEMC subsystems provide full azimuthal coverage as TPC, but slightly reduces pseudo-rapidity range $|\eta| < 1.0$. A uniform magnetic field of 0.5 T is applied along the beamline by the surrounding solenoidal coils, allowing the $p_T$ of charged particles to be determined.

2. DATA ANALYSES

2.1. Direct reconstruction

Direct reconstruction of open charm mesons is being performed by the STAR collaboration using decay channels $D^0 \rightarrow K^-\pi^+$ with branching ratio of 3.83%, $D^* \rightarrow D^0\pi^+$ with branching ratio of 67.7% in $p+p$ collisions, and former in $Au+Au$...
collisions at $\sqrt{s_{NN}} = 200$ GeV. Because of the small branching ratio and the lack of dedicated detector determining decay vertices, the direct reconstruction of D-mesons requires the analysis of a large amount of data. The available statistics limits the study of such mesons to the $p_T$ region ($0.6 < p_T < 6$ GeV and $0.2 < p_T < 8$ GeV). Kaons and pions are identified using the TPC $dE/dx$ and TOF $1/\beta$. The resulting invariant mass spectrum of kaon-pion pairs contains a substantial amount of background from random combinatorics that can be subtracted using various independent methods:

(i) **Mixed-Event**: Events are categorized according to the event multiplicity. Pions from one event are paired with kaons from other random events from an event pool with similar global features.

(ii) **Track-Rotation**: Each $\pi$ is paired with $K$ with reversed 3-momenta (within same event).

(iii) **Same-Sign**: pions are paired with same charged kaons (within same event). The geometric mean for positive $N_{++}$ and negative $N_{--}$ pair is calculated as $2\sqrt{N_{++}N_{--}}$. 

**Figure 1.** The STAR detector. TPC (Time Projection Chamber) is main detector for tracking and PID (provides $dE/dx$, $\vec{p}$), TOF (Time Of Flight) is used for PID improvement and pileup tracks removal, BEMC (Barrel Electromagnetic Calorimeter) used for electron identification improvement and pile-up tracks removal.
We used Mixed-Event for Au+Au collisions and an average of Track-Rotation and Same-Sign for p+p collision where difference between raw signals obtained by subtraction of background was the main source of systematic uncertainties. Figure 2 left and center panels show raw $D^0$ signals after combinatorial background reconstruction. A second-order polynomial function is used to fit the residual background. The background fitting with a first-order polynomial function gives negligible difference. A Gaussian function is used to fit the signal. The raw yield of the $D^0$ is obtained by fitting the data (blue solid circles) with a fit function representing the sum of signal and background (red dashed curve) in the mass region of $1.72 < M_{K\pi} < 2.05$ GeV/c$^2$. The signal after the residual background subtraction is shown as the red open circles. The Gaussian function used to describe the signal is shown as the blue dashed curve.

![Figure 2. Left and center panels: $D^0$ signals in p+p and Au+Au 0-80% minbias collisions after same-sign and mix-event background subtraction, respectively. Right panel: $D^*$ signal in p+p collisions. Combinatorial background is reproduced by the distributions from the wrong-sign (black dotted) and side-band (blue solid) methods.](image)

In the case of $D^*$, we followed the same analysis technique as described in [6]. Compared to the cuts used in [6], the $p_T$ threshold cut for the $\pi^+$ (from $D^*$ decays), denoted as $\pi^+_s$, was lowered to 0.15 GeV/c. The ratio, $r$, of transverse momenta from the $D^0$ and $\pi^+_s$ was required to be $7 < r < 20$. These two changes were implemented to improve the statistics near the lower bound in $p_T$. The invariant mass difference $\Delta M = M(K\pi\pi) - M(K\pi)$ was calculated in reconstructing the $D^*$ signal to take advantage of the partial cancellation in the detector resolution in measured mass distributions. The $\Delta M$ distributions are shown in the right panel of Fig. 2. The right-sign combinations $K^\pm\pi^\pm\pi^\pm_s$ were used to select the $D^{*\pm}$ candidates. Two independent methods wrong-sign combinations (opposite sign of $\pi_s$) and $D^0$ side-band combinations - were used for combinatorial background reconstruction. The plot illustrates that both methods reproduce the combinatorial background very well.

2.2. Identification of electrons from semi-leptonic decays
The analysis of non-photonic electrons consists of three main steps: selection of a clean electron sample; subtraction of electron background arising from interactions in material and decays; and residual corrections of the signal yield. The inclusive electron
identification was done using TPC dE/dx + BEMC information (matching of track momentum and electromagnetic energy) + Shower Max Detector (SMD) information (the shape of the electromagnetic shower, that is much wider for electrons). The analysis details and a discussion of the sources of uncertainty can be found in [9]. The main background in this analysis is the substantial flux of photonic electrons from photon conversion in the detector material and Dalitz decay of $\pi^0$ and $\eta$ mesons. These contributions need to be subtracted in order to extract the non-photonic electron yield according to formula

$$N_{\text{npe}} = N_{\text{inc}} \cdot \varepsilon_{\text{purity}} - N_{\text{pho}} \varepsilon_{\text{pho}},$$

where $N_{\text{npe}}$ is the non-photonic electron yield, $N_{\text{inc}}$ is the inclusive electron yield, $N_{\text{pho}}$ is the photonic electron yield, $\varepsilon_{\text{pho}}$ is the photonic electron reconstruction efficiency defined as the fraction of the photonic electrons identified through invariant mass reconstruction, and $\varepsilon_{\text{purity}}$ is the purity reflecting hadron contamination in the inclusive electron sample.

3. RESULTS

3.1. Direct reconstruction

Raw Yields $N_{\text{D mesons}}^{\text{raw}}$ were calculated in 7 $p_T$ bins (3 for $D^0$, 4 for $D^*$) for p+p data and 5 $p_T$ bins for Au+Au data. Then the invariant charm cross section $d\sigma_{\text{c}/c}/(2\pi p_T dp_T dy)$ was calculated by formula

$$\frac{d\sigma_{\text{c}/c}}{2\pi p_T dp_T dy} = \frac{N_{\text{D mesons}}^{\text{raw}} \sigma_{\text{NSD}}^{\text{raw}}}{2\pi p_T \Delta p_T \Delta y \text{BR} N_{\text{frag.}}} \epsilon_T f_{\text{frag.}},$$

in each $p_T$ bin ($\sigma_{\text{NSD}}^{\text{raw}}$ is non-single diffractive p+p inelastic cross section, $f_{\text{frag.}}$ is the ratio of charm quarks hadronized to open charm mesons and $\epsilon_T$ represents the trigger bias correction including the vertex reconstruction efficiency in the measurement). The charm cross section at mid rapidity $d\sigma_{\text{c}/c}/dy$ was obtained from power-law function fit to $d\sigma_{\text{c}/c}/(2\pi p_T dp_T dy)$ points (see Fig. 3) as $202 \pm 56$(stat.) $\pm 40$(sys.) $\pm 20$(norm.) $\mu$b. In Au+Au collisions we calculate invariant yield $d^2N/(N_{\text{ev}} dp_T dy)$.

The $d\sigma_{\text{c}/c}/dy$ at mid-rapidity in Au+Au collisions was extracted, from the average of a power-law(dot-dashed curve) and a blast-wave (dashed curve) fit (Fig. 4) as $186 \pm 22$(stat.) $\pm 30$(sys.) $\pm 18$(norm.) $\mu$b assuming that the $f_{\text{frag.}}$ does not change from p+p to Au+Au collisions. The power-law fit to p+p scaled by the average number of binary collisions ($N_{\text{bin}}$) is shown as solid curve. The charm cross section for three centrality bins, 0-20%, 20-50% and 50-80%, is obtained according to the integrated yields. The charm production cross section per nucleon-nucleon collision at mid-rapidity as a function of $N_{\text{bin}}$ is shown in the right panel of Fig. 3. Within errors, the results are in agreement and follow the number of binary collisions scaling, which indicates that charm quark is produced via initial hard scatterings at early stage of the collisions at RHIC. The FONLL(orange band)and NLO [7] (light-blue band) uncertainties are also shown here for comparison.
The $R_{AA}^{D^0}$ was obtained via dividing $D^0$ yields in Au+Au 0-80% minbias collisions by the power-law fit to p+p yields scaled by $N_{\text{bin}}$, shown in right panel of Fig. 4. The uncertainty of the p+p power-law shape is taken into account as systematic error. No suppression is observed at $p_T < 3$ GeV/c. The dashed curve shows the blast-wave fit. The shaded band is the predicted $R_{AA}^{D^0}$ blast-wave parameters from light-quark hadrons [8], which is different from data. This might indicate that $D^0$ mesons freeze out earlier than light flavor hadrons or has less radial flow.
3.2. Identification of electrons from semi-leptonic decays

The invariant cross section for non-photonic electron production is calculated according to

$$E^3 \frac{d^3 \sigma}{dp^3} = \frac{1}{L} \frac{1}{2 \pi p_T \Delta p_T \Delta y} \frac{N_{npe}}{\varepsilon_{\text{rec}} \varepsilon_{\text{trig}} \varepsilon_{\text{eid}} \varepsilon_{\text{BBC}}}$$

where $N_{npe}$ is the non-photonic electron raw yield, $\varepsilon_{\text{rec}}$ is the product of the single electron reconstruction efficiency and the correction factor for momentum resolution and finite spectrum bin width, $\varepsilon_{\text{trig}}$ is the high-tower trigger efficiency, $\varepsilon_{\text{eid}}$ is the electron identification efficiency, $L$ is the integrated luminosity with the z-position of vertex cuts, and $\varepsilon_{\text{BBC}} = 0.87 \pm 0.08$ is the BBC trigger efficiency.

Figure 5(a) shows the non-photonic electron ($\frac{e^+ + e^-}{2}$) invariant cross section obtained by combining the Run2008 and the Run2005 results using the "best linear unbiased estimate" [10]. The corrected result of our early published measurement using year 2003 data [11] is shown in the plot as well. Fig. 5(b) shows the ratio of each individual measurement, including PHENIX results, to the FONLL calculation. One can see that all measurements at RHIC on non-photonic electron production in $p+p$ collisions are now consistent with each other. The corrected run 2003 data points have large uncertainties because of the small integrated luminosity (100nb$^{-1}$) in that run. FONLL is able to describe the RHIC measurements within its theoretical uncertainties.

Electrons from bottom and charm meson decays are the two dominant components of the non-photonic electrons. Mostly due to the decay kinematics, the azimuthal...
correlations between the daughter electron and daughter hadron are different for bottom meson decays and charm meson decays. A study of these azimuthal correlations has been carried out on STAR data and is compared with a PYTHIA simulation to obtain the ratio of the bottom electron yield to the heavy-flavor decay electron yield $\frac{e_b}{e_b+e_c}$ [13], where PYTHIA was tuned to reproduce STAR measurements of $D$ mesons $p_T$ spectra [14]. Using the measured $e_b/(e_b+e_c)$ together with the measured non-photonic electron cross section with the electrons from $J/\Psi$, $\Upsilon$ decay and Drell-Yan processes subtracted, we are able to disentangle these two components. Figure 6 shows the invariant cross section of electrons $\left(\frac{e^+ + e^-}{2}\right)$ from bottom (upper left) and charm (upper right) mesons as a function of $p_T$ and the corresponding FONLL predictions, along with the ratio of each measurement to the FONLL calculations (lower panels).

![Invariant cross section of electrons](image)

**Figure 6.** Invariant cross section of electrons $\left(\frac{e^+ + e^-}{2}\right)$ from bottom (upper left) and charm meson (upper right) decay, together with the ratio of the corresponding measurements to the FONLL predictions for bottom (lower left) and charm electrons (lower right). The solid circles are experimental measurements. The error bars and the boxes are, respectively, the statistical and systematic uncertainties. The solid and dotted curves are the FONLL predictions and their uncertainties. The dashed and dot-dashed curves are the FONLL prediction for $B \to D \to e$

From the measured spectrum, we determine the integrated cross section of electrons $\left(\frac{e^+ + e^-}{2}\right)$ at $3\text{ GeV}/c < p_T < 10\text{ GeV}/c$ from bottom and charm meson decays to be,
respectively,
\[
\begin{align*}
\left. \frac{d\sigma(B\to e)+ (B\to D\to e)}{dy} \right|_{y_t=0} & = 4.0 \pm 0.5 \text{(stat)} \pm 1.1 \text{(syst)} \text{ nb} \\
\left. \frac{d\sigma_{D\to e}}{dy} \right|_{y_t=0} & = 6.2 \pm 0.7 \text{(stat)} \pm 1.5 \text{(syst)} \text{ nb}
\end{align*}
\]

4. CONCLUSIONS

Open charm mesons ($D^0, D^{*+}$) are measured in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at STAR. Charm cross sections per nucleon-nucleon collision at mid-rapidity follow the number of binary collisions scaling. The charm pair production cross sections per nucleon-nucleon collision at mid rapidity are measured to be $d\sigma_{cc}/(2\pi p_T dp_T dy) = 202 \pm 56 \text{(stat.)} \pm 40 \text{(sys.)} \pm 20 \text{(norm.)} \mu b$ in p+p and $186 \pm 22 \text{(stat.)} \pm 30 \text{(sys.)} \pm 18 \text{(norm.)} \mu b$ in Au+Au minimum bias collisions. Blast-wave predictions with light-quark hadron parameters are different from data, which might indicate that $D^0$ mesons freeze out earlier than light flavor hadrons or have less radial flow.

STAR measurements of high $p_T$ non-photonic electron production in $p+p$ collisions at $\sqrt{s} = 200$ GeV using data from Run2005 and Run2008 and PHENIX result are consistent with each other. We are able to disentangle the electrons from bottom and charm meson decays in the non-photonic electron spectrum using the measured ratio of $e_B/(e_B + e_D)$ and the measured non-photonic cross section.

In the near future the STAR Heavy Flavor Tracker [15] will provide the necessary resolution to reconstruct secondary vertices of charm mesons, which will increase the precision of charm measurements.

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