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Open charm hadron production in $p+p$ and Au+Au collisions at STAR

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In relativistic heavy ion collisions at RHIC, heavy quarks are expected to be created from initial hard scatterings. Their large masses are not easily affected by the strong interaction with QCD medium, thus they carry clean information from the system at early stage. The interaction between heavy quarks and the medium is sensitive to the medium dynamics, therefore heavy quarks are suggested as ideal probes to quantify the properties of the strongly interacting QCD matter. In this paper, we present the STAR results of open charm hadron production at mid-rapidity in $p+p$ and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Open charm mesons were reconstructed directly via hadronic decay channels with daughter particles identified by TPC and TOF detectors. With abundant statistics of Au+Au collisions collected by STAR in the year 2010 and 2011, the D-meson is measured at p_T from 0.2 to 6 GeV/c in minimum bias Au+Au collisions. The centrality dependence of D-meson p_T spectra as well as the nuclear modification factor is presented. A first measurement of the D^0 elliptic flow in 200 GeV Au+Au collisions is reported. These measurements are compared to theoretical model calculations and physics implications is discussed. Finally, we discuss the open charm hadron measurement in $\sqrt{s} = 500$ GeV $p+p$ collisions to study the energy dependence of charm production.

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1. Introduction

The heavy quark production at RHIC is dominated by initial gluon fusion at initial hard partonic collisions and can be described by perturbative QCD (pQCD) due to their large mass [1]. The heavy constituent quark mass is almost exclusively generated through its coupling to the Higgs field in the electroweak sector, while masses of (u, d, s) quarks are dominated by spontaneous breaking of chiral symmetry (CS) in QCD [2]. This means that charm quarks remain heavy even if CS is restored, as it likely is in a QGP. One expects therefore that charm production total cross section $\sigma_{c\bar{c}}^{NN}$ should scale as a function of number-of-binary-collisions N_{bin}. In addition, if charm quarks participate in the collective expansion of the medium, there must have been enough interactions to easily thermalize light quarks. Hence, charm quark is an ideal probe to study early dynamics in high-energy nuclear collisions.

2. Analysis Method and Datasets

Invariant yield of charm quark production Inv$Y$ is calculated as

$$\mathrm{Inv}Y \equiv \frac{\mathrm{d}^2 N_{c\bar{c}}}{2\pi p_T \mathrm{d}p_T \mathrm{d}y} = \frac{1}{N_{\mathrm{trig}}} \frac{Y(p_T,y)}{2\pi p_T \Delta p_T \Delta y} \frac{f_{\mathrm{trg}}}{\mathrm{BR}\ f_{\mathrm{frag.}} \varepsilon_{\mathrm{rec}}} \tag{2.1}$$

where N_{trig} is the total number of triggered events used for the analysis. $Y(p_T,y)$ is the raw charm hadron signal in each p_T bin within a rapidity window $\Delta y = 2$. BR is the hadronic decay branching ratio for the channel of interest. $\varepsilon_{\mathrm{rec}}$ is the reconstruction efficiency including geometric acceptance, track selection efficiency, PID efficiency, and analysis cut efficiency. $f_{\mathrm{frag.}}$ represents the the ratio of charm quarks hadronized to open charm mesons. And f_{trg} is the correction factor to account for the bias between the minimum-bias sample used in this analysis and the total NSD sample [3]. f_{trg} is found to be unity in Au+Au, 0.65 in $p+p$ collisions at $\sqrt{s} = 200$ GeV and 0.58 in $p+p$ collisions at $\sqrt{s} = 500$ GeV.

$Y(p_T,y)$ is obtained from fitting the invariant mass spectrum (Fig. 1) of open charm mesons through hadronic decays: $D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$ (BR = 3.89%) and $D^{*\pm} \rightarrow D^0(\overline{D^0})\pi^{\pm}$ (BR = 67.7%) $\rightarrow K^-\pi^+\pi^{\pm}$ (total BR = 2.63%)

The daughter particles were identified by Time Projection Chamber (TPC) and Time Of Flight (TOF) subsystems of the STAR experiment [5] at mid-rapidity $|y| < 1$ at $\sqrt{s_{NN}} = 200$ and 500 GeV. The analysis presented herein is done using three datasets; the first one collected in year 2009 ($N_{\mathrm{trig}} \sim 105$ million 200 GeV $p+p$ collisions), the second one collected in 2010 and 2011 ($N_{\mathrm{trig}} \sim$ 800 million Au+Au 200 GeV collisions), and the third one in 2011 ($N_{\mathrm{MB}} \sim 50$ million 500 GeV p+p collisions).

At present, STAR does not have the capability to reconstruct the secondary vertex of D^0 decay; one must calculate the invariant mass of all $K\pi$ pairs coming from the vicinity of the primary vertex. This results in a large combinatorial background which was reconstructed via the mixed-event method (Au+Au dataset), same-charge-sign, and kaon momentum-rotation ($p+p$ dataset) and subtracted from invariant mass spectra of all particle pairs [6]. To reconstruct D^*, one may exploit the softness of $D^* \rightarrow D^0\pi$ decay; combine low momentum pions with D^0 candidates, i.e. pairs with $1.82 < M(K\pi) < 1.9$ GeV/c^2, and plot difference $M(K\pi\pi) - M(K\pi)$ whose resolution is determined by mostly the soft pion high momentum resolution. The combinatorial background is reconstructed by side-band (picking $K\pi$ pair outside the D^0 mass region) and wrong-sign (picking soft pion with opposite charge) methods. The dominant source of systematic uncertainties for both D^0 and D^* analyses is the difference between yields obtained from subtractions of combinatorial background from all particle combinations.

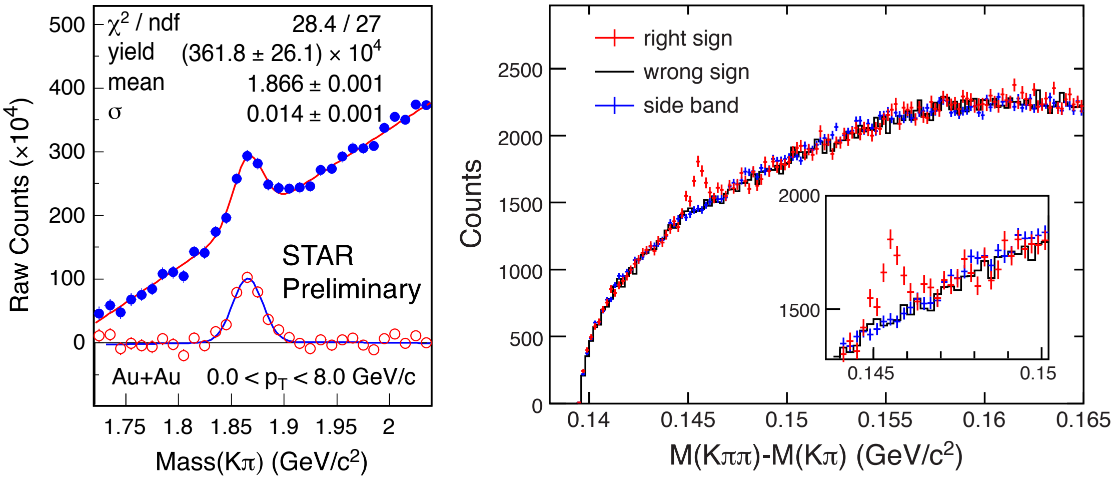

Figure 1: Left panel: D^0 signal in Au+Au 200 GeV collisions after mixed-event background subtraction. Right panel: D^* signal in $p+p$ 200 GeV collisions with comb. background reproduced by wrong-sign and side-band methods [3].

3. Results

3.1 D meson production in $p+p$ collisions

Yields $Y(p_T, y)$ are calculated in six p_T bins (first two for D^0, the next four for D^*) in $p+p$ 200 GeV and five p_T bins (first for D^0, the next four for D^*) in $p+p$ 500 GeV. The charm cross section at mid-rapidity $\mathrm{d}\sigma^{c\bar{c}}/\mathrm{d}y$ was obtained from the power-law function

$$\frac{\mathrm{d}^2\sigma^{c\bar{c}}}{2\pi p_T \mathrm{d}p_T \mathrm{d}y} = 4\frac{\mathrm{d}\sigma^{c\bar{c}}}{\mathrm{d}y}\frac{(n-1)(n-2)}{\langle p_T\rangle^2(n-3)^2}\left(1+\frac{2p_T}{\langle p_T\rangle(n-3)}\right)^{-n}$$

fit [3] to $\mathrm{d}^2\sigma^{c\bar{c}}/(2\pi p_T \mathrm{d}p_T \mathrm{d}y) = \mathrm{Inv}Y \cdot \sigma_{\mathrm{NSD}}$, where $\mathrm{Inv}Y$ is obtained from (2.1). σ^{NSD} is the total Non-single Diffractive (NSD) cross section, which is measured at STAR to be 30.0 ± 2.4 mb at $\sqrt{s} = 200$ GeV [7]. In the case of $\sqrt{s} = 500$ GeV, there's no STAR measurement yet; σ^{NSD} is extrapolated from 200 GeV measurement with the help of PYTHIA simulation to be 34 mb. The charm production cross section at mid rapidity $\left.\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y}\right|_{y=0}$ is $170 \pm 45(\mathrm{stat.})^{+37}_{-51}(\mathrm{sys.})$ μb at $\sqrt{s} = 200$ GeV and is $217 \pm 86(\mathrm{stat.}) \pm 73(\mathrm{sys.})$ μb at $\sqrt{s} = 500$ GeV. Fixed-order Next-to-leading Logarithm (FONLL) predictions for p_T spectra [8] shown in Fig. 2.

In order to compare STAR results with other experiments, we extrapolated $\left.\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y}\right|_{y=0}$ to $\sigma^{\mathrm{NN}}_{c\bar{c}}$ using PYTHIA simulations with various parameter tunings giving extrapolation factors 4.7 ± 0.7 for 200 GeV and 5.6 ± 0.1 for 500 GeV collisions. The results are shown in Figure 2.

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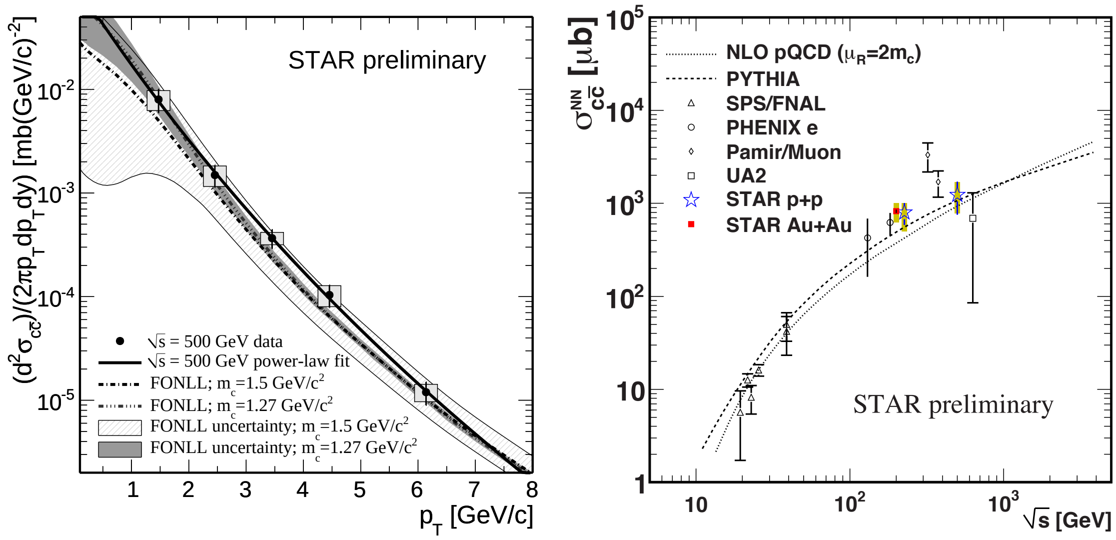

Figure 2: Left Panel: Charm quark production invariant cross section as a function of D meson p_T in 500 GeV p+p collisions with two FONLL predictions [8] using normalization and factorization scale equal to charm quark mass m_c. Right Panel: Total charm cross section as a function of $\sqrt{s}$

3.2 D^0 production in Au+Au collisions

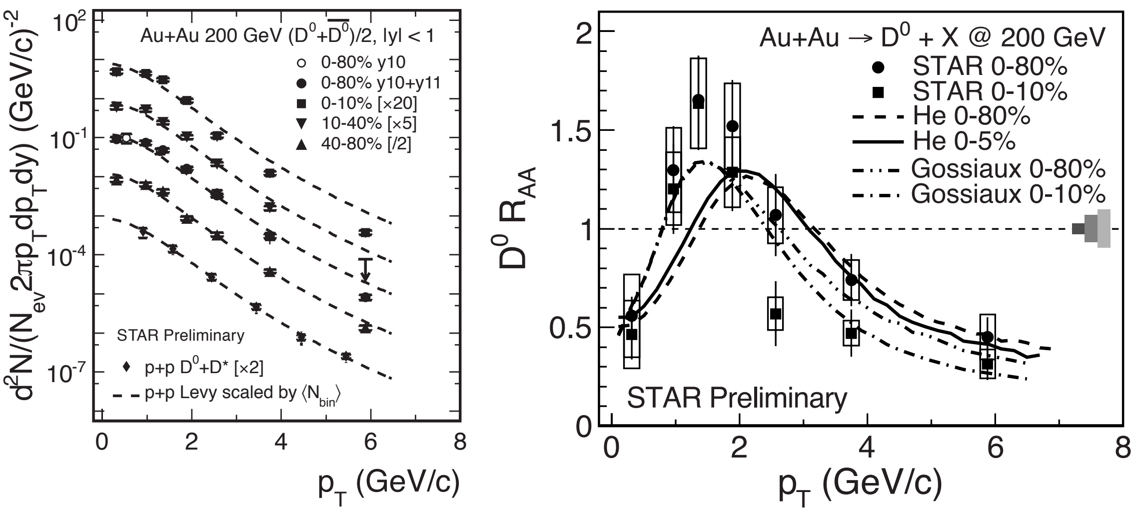

Figure 3: Left Panel: D^0 Invariant Yield spectra for various centralities, The last four p_T bins in $p+p$ collisions are from D^{+*}. Right panel: D^0 nuclear modification factor R_{AA} as a function of p_T for most central (blue) and minimum-bias (red) Au+Au collisions with theoretical predictions from two models [11, 12]. Gray rectangles around unity represent systematic uncertainties, from left to right, N_{bin} definition uncertainty for the most central (2.8%), N_{bin} definition uncertainty for all Au+Au (7%), and $p+p$ normalization error (8.1%).

Yields $Y(p_T, y)$ were calculated in eight p_T and three centrality bins. $\mathrm{d}\sigma^{\mathrm{NN}}_{c\bar{c}}/\mathrm{d}y$ was obtained from the integral of

$$\mathrm{d}^2\sigma^{\mathrm{NN}}_{c\bar{c}}/(2\pi p_T \mathrm{d}p_T \mathrm{d}y) = \mathrm{Inv}Y \cdot \sigma^{\mathrm{inel}}/N_{\mathrm{bin}} \tag{3.1}$$

over p_T and is measured to be $\frac{d\sigma_{c\bar{c}}}{dy}\Big|_{y=0} = 175 \pm 13(\text{stat.}) \pm 23(\text{sys.})\ \mu$b. Inv$Y$ is obtained from (2.1) and $\sigma^{\text{inel}} = 42$ mb is the total inelastic cross section [9]. To calculate the D^0 nuclear modification factor R_{AA} in various centrality bins, we scaled the Levy function [10]

$$\frac{1}{2\pi p_T}\frac{d^2\sigma_{c\bar{c}}}{dp_T dy} = \frac{d\sigma_{c\bar{c}}}{dy}\frac{(n-1)(n-2)}{2\pi nC[nC+m_0(n-2)]}\left(1+\frac{\sqrt{p_T^2+m_0^2}-m_0}{nC}\right)^{-n}$$

fit to $p+p$ data by N_{bin}, as shown in the left panel of Fig. 3, and follow the same process for the original power-law function as discussed in section 3.1. Since enhanced statistics allow more p_T bins in Au+Au collisions, we rely on the extrapolation from the two fits to estimate one source of systematic uncertainty. The $p+p$ baseline for R_{AA} calculation is the arithmetic average of the Levy and the power-law fit results. The measurement, shown in the right panel of Fig. 3, reveals strong suppression in the most central collisions for $p_T > 2$ GeV/c consistent with the prediction of the SUBATECH group (Gossiaux) model [12] and exhibits the maximum of the R_{AA} around $p_T \simeq 1.5$ GeV/c. This agreement with [12] might indicate that the maximum is induced by the transverse flow picked up from the expanding medium through coalescence with light-quarks.

$d\sigma_{c\bar{c}}^{\text{NN}}/dy|_{y=0}$ as a function of N_{bin} is shown in the right panel of Fig. 4. 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 (darker band) and NLO [13] (gradient band) uncertainties are also shown here for comparison.

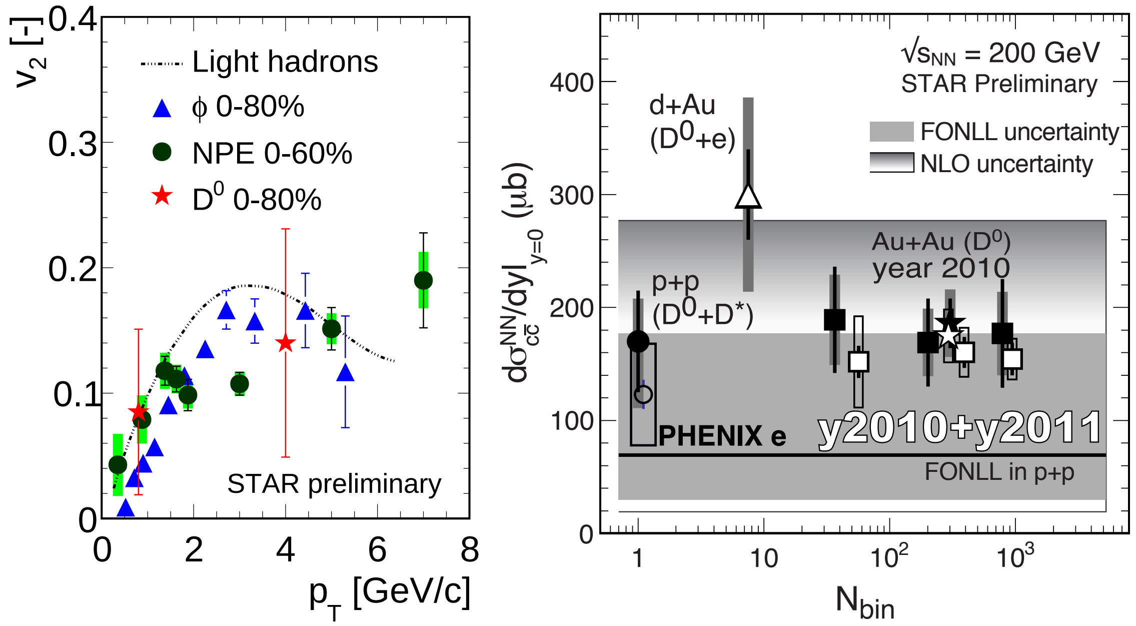

Figure 4: Left Panel: Elliptic flow as a function of p_T. Right panel: The charm production cross section per N_{bin} as a function of N_{bin}.

In the Left panel of Fig. 4, the measurement of D^0 elliptic flow v_2 is shown. Within large statistical error bars, D^0 v_2 is consistent with the STAR Non-photonic electrons v_2.

4. Conclusions

New open charm hadrons (D^0, D^{*+}) measurements in $p+p$ and Au+Au minimum bias collisions at $\sqrt{s_{\rm NN}} = 200$ GeV from STAR shows the $N_{\rm bin}$ scaling of the charm quark production cross section at mid rapidity. The differential invariant open charm cross section at mid rapidity is measured as $170 \pm 45(\text{stat.})^{+37}_{-51}(\text{sys.})$ μb in $p+p$, $175 \pm 13(\text{stat.}) \pm 23(\text{sys.})$ μb in Au+Au collisions at 200 GeV and $217 \pm 86(\text{stat.}) \pm 73(\text{sys.})$ μb in $p+p$ collisions at 500 GeV. Results of the total charm cross section are within statistical and systematic uncertainties consistent with both PYTHIA and NLO pQCD predictions.

The new D^0 nuclear modification factor $R_{\rm AA}$ measurement reveals strong suppression in the most central collisions for $p_T > 2$ GeV/c consistent with the prediction of the model [12] and exhibits the maximum of the $R_{\rm AA}$ around $p_T \simeq 1.5$ GeV/c.

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Acknowledgments

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