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Open charm measurements at STAR

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Abstract. We report on the measurements of D^0 meson production via direct reconstruction through the hadronic decay channel $D^0 \to K\pi$ in minimum bias $d+$Au and Au$+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV with p_{T} up to ~ 3 GeV/c. We derive the charm production total cross-section per nucleon–nucleon collision from a combination of three measurements: the D^0 meson spectra, the non-photonic electron spectra from charm semi-leptonic decays obtained in $p+p$, $d+$Au, and Au$+$Au collisions, and the charm-decayed single muon (prompt muon) spectra at low p_{T} in Au$+$Au collisions. The cross-section is found to follow binary scaling, which is a signature of charm production exclusively at the initial impact. The implications of charm quark energy-loss and thermalization in the strongly interacting matter are discussed.

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1 Introduction

Recent experimental studies at the Relativistic Heavy-Ion Collider (RHIC) have given strong evidences that the nuclear matter created in Au$+$Au collisions at $\sqrt{s_{NN}} = 200$ GeV has surprisingly large collectivity and opacity as reflected by its hydrodynamic behavior at low p_{T} [1] and its particle suppression behavior at high p_{T} [2, 3]. This has led to the famous name of this high energy density and high temperature nuclear matter, sQGP, which can be interpreted as strongly-interacting quark gluon plasma [4, 5]. However, many of its important properties are still remain unclear so far, such as whether the newly-created partonic matter has been thermalized or not.

Charm quarks can provide a unique tool to probe the partonic matter created in relativistic heavy-ion collisions at RHIC energies. First, charm quarks are produced in the early stages of high-energy heavy-ion collisions due to their relatively large mass [6]. Thus the charm total cross-section is expected to scale with the number of binary collision, N_{bin}. This scaling behavior should hold from $p+p$ and $d+$Au collisions up to Au$+$Au collisions at RHIC energies if the nuclear modification to the parton structure function, the so-called EMC effect [7], is small. The direct measurement of D^0 mesons with low p_{T} coverage in Au$+$Au collisions will allow us to extract this important information on the scaling properties of the charm production cross-section by comparing with the same measurement in $d+$Au collisions. Secondly, charm quarks interacting with the surrounding partons in the medium could change their flow properties [8, 9], reflected in their p_{T} spectra shape, and could boost the elliptic flow (v_2) of the final observable charmed hadrons besides the v_2 effect picked up by their light constituent quarks. Thus experimental measurements for the p_{T} spectra of the charmed hadrons and/or its decayed non-photonic electrons/positrons together with their elliptic flow properties in Au$+$Au collisions are particularly interesting to interpret the thermalization processes of the light quarks in the partonic matter. Third, charm quarks are believed to lose much smaller energies compared to light quarks in the partonic matter due to the "dead-cone" effect, *i.e.*, the suppression of gluon radiation at small forward angles [10–12]. A measurement of the nuclear modification factor for the charmed hadrons and/or their decayed non-photonic electrons/positrons compared to light hadrons is important to complete the picture of the observed jet-quenching phenomenon and help us better understand the energy-loss mechanisms at parton stage in Au$+$Au collisions at RHIC.

2 Analysis

The data used for this analysis were taken with the STAR experiment during the $\sqrt{s_{NN}} = 200$ GeV Au$+$Au run in 2004 and the $\sqrt{s_{NN}} = 200$ GeV $d+$Au and $p+p$ run in 2003 at RHIC. A minimum bias Au$+$Au collision trigger was defined by requiring coincidences between the two zero degree calorimeters (ZDCs). A 0–12% central Au$+$Au collision trigger was defined using the scintillator CTB (Central Trigger Barrel) and both the ZDCs. A 0–5% central

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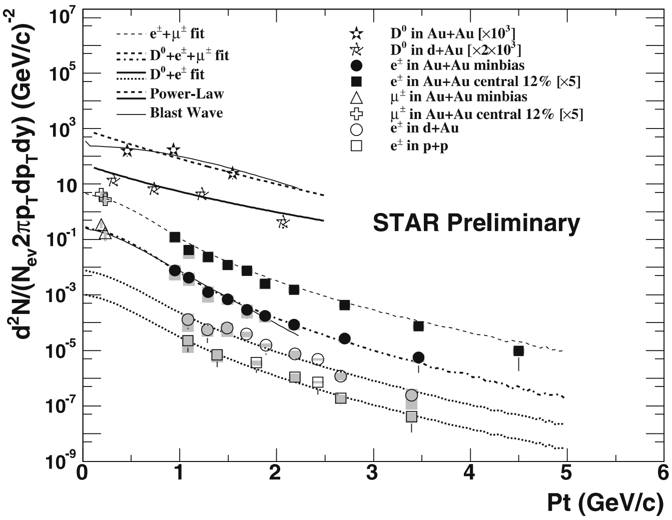

Fig. 1. p_{T} distributions of invariant yields for D^0 mesons in minimum bias Au + Au (*solid stars*) and d + Au (*open stars*) collisions, charm-decayed prompt muons in 0–12% central Au + Au (open crosses) and minimum bias Au + Au (*open triangles*) collisions and non-photonic electrons in 0–12% central Au + Au (*solid squares*), minimum bias Au + Au (*solid circles*), d + Au (*open circles*) and $p+p$ (*open squares*) collisions measured by the TOF detector

data set is further selected by cutting on the event multiplicity in the 0–12% central data sample. A minimum bias d + Au collision trigger was defined by requiring at least one spectator neutron in the outgoing Au beam direction depositing energy in a ZDC. A minimum bias $p+p$ collision trigger was defined by coincidences between two BBCs (beam–beam counter).

The low p_{T} ($< 3\,\mathrm{GeV}/c$) D^0 mesons were reconstructed in minimum bias Au + Au and d + Au collisions through their decay $D^0 \to K^-\pi^+$ ($\bar{D}^0 \to K^+\pi^-$) with a branching ratio of 3.83%. Analysis details can be found in [13, 14]. Figure 1 shows the p_{T} distributions of invariant yields for the D^0 mesons in minimum bias Au + Au (solid stars) and d + Au (open stars) collisions.

The charm-decayed prompt muons ($\mu^{\pm}$) at $0.17 < p_{\mathrm{T}} < 0.25\,\mathrm{GeV}/c$ were analyzed by combining the energy-loss information measured by the STAR Time Projection Chamber (TPC) and the mass-square (m^2) information measured by the TOF detector. Analysis details can be found in [15–17]. The p_{T} distribution for $\mu^{\pm}$ invariant yields in 0–12% central and minimum bias Au + Au collisions is shown in Fig. 1.

By using the combined information from the STAR TPC and TOF detectors, electrons can be identified and their transverse momentum distribution measured. Detailed analysis for the inclusive, photonic and non-photonic electron reconstruction can be found in [13, 16]. The p_{T} spectra for non-photonic electrons measured by TOF in 0–12% central Au + Au (solid squares), minimum bias Au + Au (solid circles), d + Au (open circles) and $p+p$ (open squares) collisions are shown in Fig. 1.

Electrons can also be identified by using the STAR TPC and BEMC detectors. Details of this measurement can be found in [18–20].

3 Results

We obtain the mid-rapidity D^0 yield through a combined fit applied to the D^0, the prompt muon, and the non-photonic electron spectra in 0–12% central Au + Au, minimum bias Au + Au and d + Au collisions. This yield is then converted to the total mid-rapidity charm cross-section per nucleon–nucleon collision ($\mathrm{d}\sigma_{c\bar{c}}^{NN}/\mathrm{d}y$). The charm total

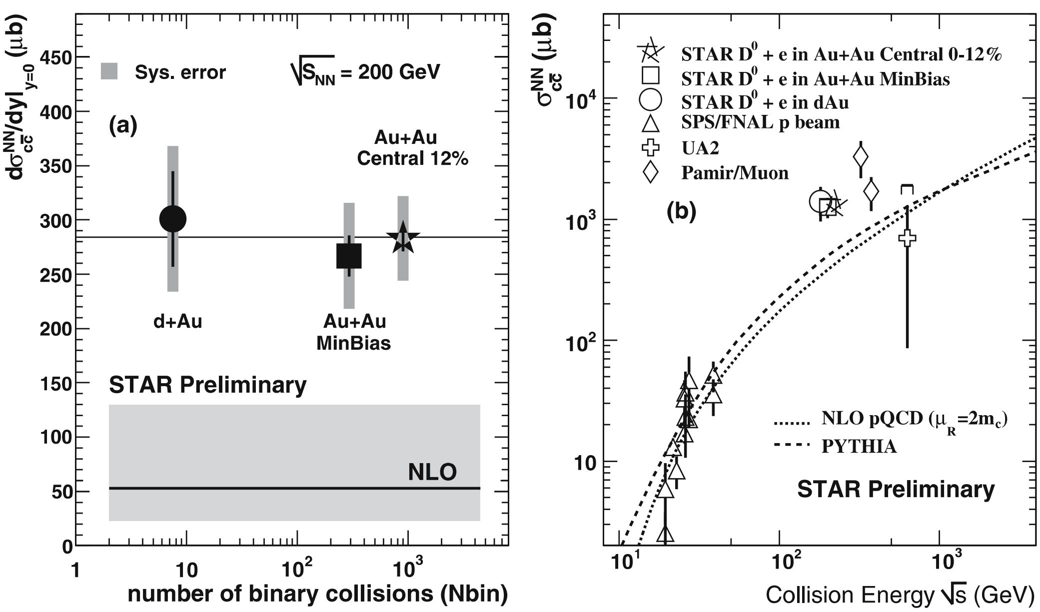

Fig. 2. a Mid-rapidity charm total cross-section per nucleon–nucleon collision as a function of number of binary collisions (N_{bin}) in d + Au, minimum bias and 0–12% central Au + Au collisions; **b** Charm total cross-section per nucleon–nucleon collision as a function of collision energy ($\sqrt{s}$) in d + Au, minimum bias and 0–12% central Au + Au collisions compared various collision systems with various collision energies

cross-section per nucleon–nucleon collision ($\sigma_{c\bar{c}}^{NN}$) is finally derived following the method addressed in [13]. $\sigma_{c\bar{c}}^{NN}$ is measured to be $1.33 \pm 0.06(\text{stat.}) \pm 0.18(\text{sys.})$ mb in 0–12% central Au + Au, $1.26 \pm 0.09 \pm 0.23$ mb in minimum bias Au + Au collisions and $1.4 \pm 0.2 \pm 0.2$ mb in minimum bias d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Panel a of Fig. 2 shows the $\mathrm{d}\sigma_{c\bar{c}}^{NN}/\mathrm{d}y$ as a function of N_{bin} for minimum bias d + Au, minimum bias Au + Au and 0–12% central Au + Au collisions. It can be observed that the charm total cross-section roughly follows the N_{bin} scaling from d + Au to Au + Au collisions which supports the conjecture that charm quarks are produced at early stages in relativistic heavy-ion collisions. Panel b of Fig. 2 shows the $\sigma_{c\bar{c}}^{NN}$ as a function of $\sqrt{s}$ for minimum bias d + Au, minimum bias Au + Au and 0–12% central Au + Au collisions compared various collision systems at various collision energies as well as theoretical predictions. However, one can clearly see from Fig. 2 that the $\mathrm{d}\sigma_{c\bar{c}}^{NN}/\mathrm{d}y$ in the three measured collision systems are about a factor of 5 larger than the NLO predictions [21, 22] depicted by the light green band in panel a.

A blast-wave model [23] fit to the D^0, prompt muons and non-photonic electron p_{T} spectra at $p_{\mathrm{T}} < 2$ GeV/c in minimum bias Au + Au collisions is performed to estimate the charm hadron kinetic freeze-out temperature T_{fo} and the maximum flow velocity β_m. Figure 3 shows the T_{fo} versus β_{m} for charm hadrons in minimum bias Au + Au collisions. The 1σ contour from the blast-wave fit with quadratic sum of statistical and systematic errors of the spectra is shown as the magenta curve in Fig. 3. A larger T_{fo} (> 140 MeV) and a smaller β_{m} (~ 0.21) compared to those of light hadrons [24] is observed. This may hint that charm hadrons may kinetically freeze-out early and may not be in complete equilibrium with the rest of the system at kinetic freeze-out in minimum bias Au + Au collisions.

The nuclear modification factors, $R_{AA}(p_{\mathrm{T}})$, of D^0 mesons (stars in Fig. 4) are calculated by dividing the

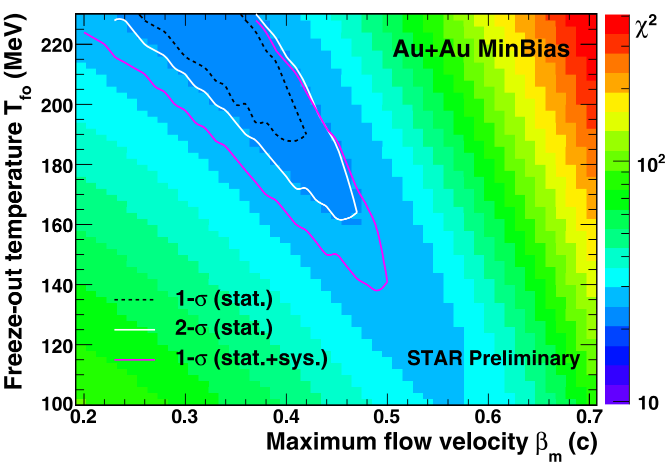

Fig. 3. Charmed hadron freeze-out temperature (T_{fo}) versus maximum flow velocity (β_{m}) in minimum bias Au + Au collisions. The *magenta solid line* shows the 1σ contour fit with quadratic sum of statistical and systematic errors. The fit gives a velocity $\langle\beta_{\mathrm{T}}\rangle$ of ~ 0.21 and $T_{\text{fo}} > 140$ MeV

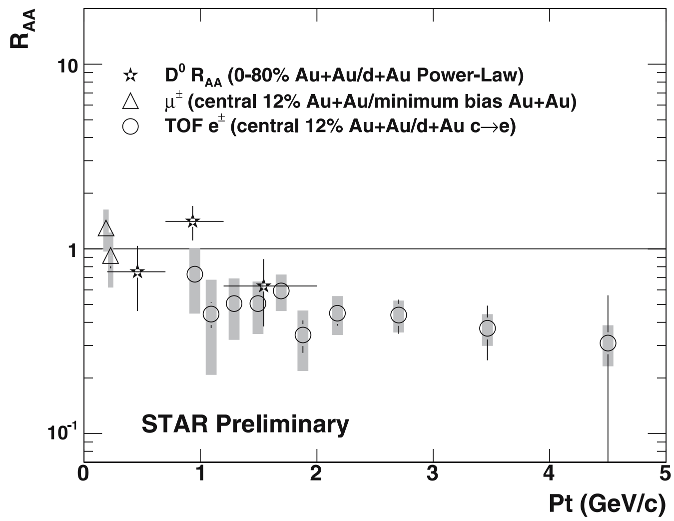

Fig. 4. p_{T} distributions of the nuclear modification factor (R_{AA}) for D^0, charm-decayed prompt muons and single electrons measured by the TOF detector. The normalization uncertainty is 8% for D^0 R_{AA} and 6% for $\mu^{\pm}$ and $e^{\pm}$ R_{AA}

D^0 data points in minimum bias Au + Au collisions by the power-law fit results of the D^0 p_{T} spectrum in d + Au collisions scaled by N_{bin}. The prompt muon $R_{AA}(p_{\mathrm{T}})$ is calculated by dividing the p_{T} spectrum in 0–12% central Au + Au collisions by that obtained in minimum bias Au + Au collisions assuming N_{bin} scaling. It is depicted by triangles in Fig. 4. The TOF-measured single electron R_{AA} is also calculated by dividing the p_{T} spectra in 0–12% central Au + Au collisions to the $D^0 \to e^{\pm}$ decayed shape in d + Au collisions scaled by N_{bin}, shown as open circles in Fig. 4. The R_{AA}'s for D^0 and muons at low p_{T} are consistent with unity considering uncertainties. The non-photonic electron R_{AA} in 0–12% central Au + Au collisions is observed to be significantly below unity at $1 < p_{\mathrm{T}} < 4$ GeV/c. The R_{AA} in 0–12% central Au + Au collisions is suppressed as strongly as that of light hadrons [2], which indicates a large amount of energy-loss for heavy quarks in central Au + Au collisions.

According to the "dead-cone" effect [10–12], bottom quarks should lose smaller energy than charm quarks due to their mass difference. Theoretical calculations [12, 25] considering only the charm contributions to the non-photonic electrons agree with the measured non-photonic electron R_{AA}, while calculations with single electrons decayed from both bottom and charm quarks give larger R_{AA} values. However, in most theoretical models, the amount of bottom quark and charm quark contributions to the non-photonic electron spectra, respectively, still remains uncertain. Thus, an experimental measurement of the R_{AA}'s from directly reconstructed charm hadrons (D^0, $D^{\pm}$, D_S, Λ_C, etc.) at high p_{T} is necessary. A detector upgrade plan for a silicon pixel detector, the Heavy Flavor Tracker (HFT) [26], at STAR will allow us to directly measure the charm hadron R_{AA} in the near future.

4 Conclusion

We present measurements on D^0 meson production via direct reconstruction of its hadronic decay channel $D^0 \rightarrow K\pi$ in minimum bias $d+\mathrm{Au}$ and $\mathrm{Au}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV with p_T up to ~ 3 GeV/c. Non-photonic electron spectra from the charm semi-leptonic decays are analyzed from the same data set as well as in $p+p$ collision at $\sqrt{s} = 200$ GeV using the STAR time-of-flight (TOF) detector. Results of the charm-decayed prompt muon spectra are also presented at low p_T in $\mathrm{Au}+\mathrm{Au}$ collisions measured by the TOF detector. The charm production total cross-section per nucleon–nucleon collision is measured to be $1.26 \pm 0.09(\mathrm{stat.}) \pm 0.23(\mathrm{sys.})$ mb in minimum bias $\mathrm{Au}+\mathrm{Au}$ collisions, which is consistent with the N_bin scaling compared to $1.4 \pm 0.2 \pm 0.4$ mb in minimum bias $d+\mathrm{Au}$ collisions, and supports the idea that charm quarks should be produced mostly via parton fusion at early stage in relativistic heavy-ion collisions. A blast-wave model fit to the low p_T (< 2 GeV/c) non-photonic electrons, prompt muons and D^0 spectra shows that charm hadrons may kinetically freeze-out earlier than light hadrons with a smaller collective velocity. The nuclear modification factors (R_{AA}) of the non-photonic electrons in central $\mathrm{Au}+\mathrm{Au}$ collisions are significantly below unity at $p_\mathrm{T} >\sim 2$ GeV/c, which indicates a significant amount of energy loss for heavy quarks in $\mathrm{Au}+\mathrm{Au}$ collisions. The charm transverse momentum distribution must have been modified by the hot and dense matter created in central $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC.

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