

Measurements of open charm hadrons at the STAR experiment

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Abstract. Because of their large masses, charm quarks are predominantly produced in the early stages of the heavy-ion collisions via hard scatterings. Therefore, they experience the entire evolution of the Quark-Gluon Plasma created in such collisions. Compared to light quarks, charm quarks thermalize more slowly. Therefore, the open charm hadrons present a unique probe to the properties of the hot and dense nuclear matter by measuring their energy loss and degree of thermalization in the medium. Furthermore, with the combined measurements of D^0 and D_s mesons, we can study multiple modes of coalescence of charm quarks with light quarks in heavy-ion collisions. Heavy Flavor Tracker at the STAR experiment enables full topological reconstruction of open charm hadrons which greatly improves measurements of D^0 mesons and opens the door to reconstructing the D_s mesons for the first time at RHIC. In this paper, we present the nuclear modification factor and azimuthal anisotropy for the D^0 and D_s mesons as well as the ratio of D_s/D^0 in Au+Au collisions at the center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV.

1. Introduction

Charm quarks are considered to be an excellent probe to study the strongly coupled quark-gluon plasma (sQGP) as they are produced predominantly in hard scatterings during the early stages of heavy-ion collisions due to their large masses which are mostly unaffected by the medium. Thus, they experience the full evolution of the system. Analogous to the Brownian motion, charm quarks are sensitive to the transport properties of the sQGP, e.g. $2\pi T D_s$, where T is the temperature of the system and D_s the spatial diffusion coefficient for the c-quark [1].

The inclusive production of the c-quark has been measured at STAR [2] and exhibits scaling with the number of binary nucleon–nucleon collisions (N_{coll}) in Au+Au collisions. The D^0 meson, being the lightest hadron that contains a charm quark, provides, therefore, an excellent calibrated probe to the behavior of the medium. Recent measurements of the D^0 meson at Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC) [3–5] show suppression of yields at high transverse momenta (p_T) and suggest a non-zero v_2 at intermediate to high p_T . Measurements of better precision are, however, needed to provide more stringent constraints on model calculations.

The D_s meson, which contains a strange quark, provides an additional handle on the hadronization process of charm quarks. Recent calculations [6] suggest an enhancement of the D_s meson yield compared to the D^0 meson because of the process of quark coalescence.



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2. The STAR experiment and open charm hadron reconstruction

The Solenoidal Tracker at RHIC (STAR) is a large-acceptance multi-purpose detector that covers the full azimuth and pseudorapidity range of $|\eta| < 1$ [7]. The main tracking detector of STAR is the Time Projection Chamber, which also provides the dE/dx information for particle identification (PID). The Time-Of-Flight detector is also used to improve the PID capabilities.

Since the beginning of 2014, a new detector, Heavy Flavor Tracker (HFT), has been installed at STAR. The HFT consists of 4 layers of silicon detectors: one layer of double strip, one layer of silicon pad, and finally two layers of PiXeL (PXL) detectors using the state-of-the-art slimmed-down Monolithic Active Pixel Sensor technology for the first time in a collider experiment. It provides excellent distance of closest approach resolution down to $\sim 30 \mu\text{m}$ at high- p_T while maintaining a very small material budget as the first layer of PXL has a radiation length of $\sim 0.4\% X_0$.

The excellent track pointing resolution provided by the HFT allows for a direct topological reconstruction of the secondary vertices of open charm meson decays via hadronic channels, i.e. $D^0 \rightarrow \pi^\pm + K^\mp$, $D_s^\pm \rightarrow \pi^\pm + \phi(1020) \rightarrow \pi^\pm + K^\pm + K^\mp$. This greatly reduces the combinatorial background for these measurements. In the case of the D_s meson, the decay channel via $\phi(1220)$ is used to place an additional constraint on the $K^\pm + K^\mp$ invariant mass and, therefore, to reduce the background even further. STAR has recorded $\sim 3.2\text{B}$ minimum-bias events in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200\text{ GeV}$ in the years 2014 and 2016. Results from $\sim 780\text{M}$ of these events are shown in this paper.

3. Results

3.1. D^0 measurements

Although the inclusive charm quark production scales with N_{coll} [2], the D^0 spectrum shape is significantly modified in Au+Au collisions. Fig. 1a shows the D^0 nuclear modification factor R_{AA} as a function of p_T in the most central (0–10%) collisions, where R_{AA} is the ratio between the yield in Au+Au collisions and that in p+p collisions scaled by N_{coll} . The new results (black full circles) obtained with the HFT are consistent with the published R_{AA} from 1.1B minimum-bias events taken in the years 2010 and 2011 without the HFT (red empty circles) [3]. For the new results, a much better precision is achieved despite the less statistics used. The D^0 production is significantly suppressed at high- p_T which indicates strong interactions between charm quarks and the medium in this kinematic region. In the intermediate p_T range ($\sim 0.7\text{--}2\text{ GeV}/c$), data show an enhancement which can be described by models including coalescence of charm quarks.

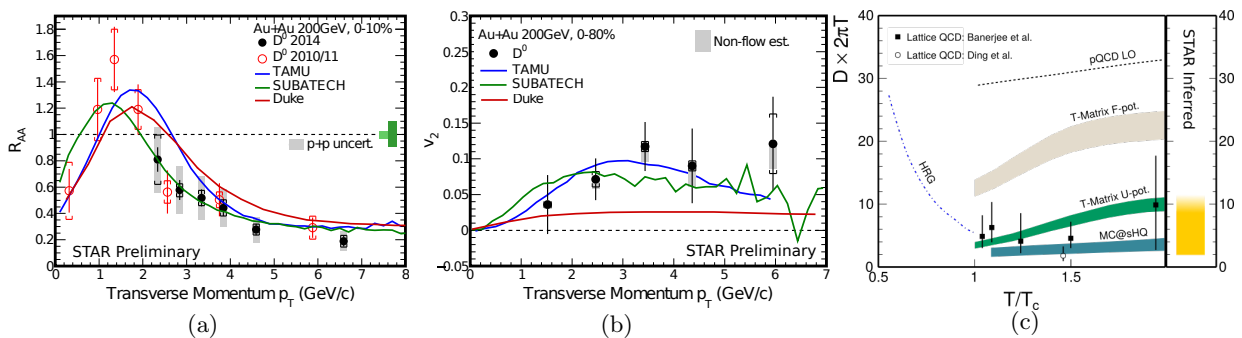


Figure 1. (a) D^0 R_{AA} as a function of p_T for 0–10% central Au+Au collisions. The gray bands are systematic uncertainties from the p+p baseline and the light and dark green vertical bands around unity are uncertainties related to the N_{coll} in Au+Au collisions and the global normalization in the p+p collisions, respectively; (b) D^0 v_2 as a function of p_T for Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200\text{ GeV}$; (c) Charm-quark diffusion coefficient used in various models compared to that inferred from the STAR data.

The HFT also enables the measurement of the D^0 v_2 for the first time at RHIC, as shown in Fig. 1b. The vertical bars (brackets) indicate the statistical (systematic) uncertainties while the gray bands represent the estimated non-flow contribution inferred from D meson–hadron correlations in p+p collisions. The data show that the v_2 is significantly larger than 0 above 2 GeV/c.

Several models, which use different approaches to determine the charm quark diffusion coefficient, are compared to the measurements of R_{AA} and v_2 . The group from TAMU [8] (blue) employs a non-perturbative T-matrix approach with the assumption that two body interactions can be described by a potential, which is a function of the transferred 4-momentum. This model predicts the charm quark diffusion coefficient multiplied by temperature as $3 \leq 2\pi TD_s \lesssim 11$. The SUBATECH group [9] (green) uses a pQCD approach with the Hard Thermal Loop approximation for soft collisions. In this approach, the diffusion coefficient is within $2 \leq 2\pi TD_s \leq 4$. The model by the Duke university group [11] uses $2\pi TD_s$ as a free parameter. The red curves shown in Figs. 1a and 1b use the value $2\pi TD_s = 7$ which is fixed to match the D^0 R_{AA} measured at the LHC. The Duke model can describe the shape of R_{AA} well, however it systematically underestimates the v_2 . The other two models are consistent with both R_{AA} and v_2 data. Fig. 1c shows the $2\pi TD_s$ values obtained from different models [8, 12–17] compared to the range inferred from the STAR data which is drawn as the yellow band. The STAR inferred range of $2 \leq 2\pi TD_s \lesssim 12$ is consistent with the lattice QCD calculations [16, 17] shown as the black points.

3.2. D_s measurements

Thanks to the HFT, the D_s meson, consisting of a charm quark and a strange quark, is measured for the first time at RHIC. Such measurements are expected to shed more light on the mechanism of the charm quark coalescence.

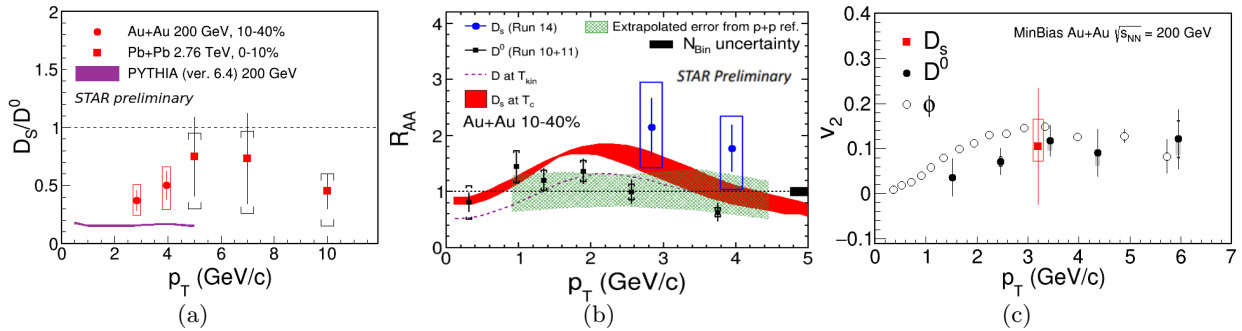


Figure 2. (a) The ratio between D_s and D^0 yield in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for 10–40% centrality; (b) D_s R_{AA} in the 10–40% centrality class; (c) D_s v_2 in minimum-bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

In Fig. 2a, the yield ratio of produced D_s to D^0 is shown as a function of p_T in 10–40% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (red circles). The D^0 spectrum is obtained from the published STAR data [3]. The measured D_s/D^0 ratios are compared to similar measurements at the LHC for minimum-bias Pb+Pb collisions [18] (red squares). Both of the measurements are consistent with each other within uncertainties. To compare our measurement to the D_s/D^0 in p+p collisions, PYTHIA 6.4 [19] (purple curve) is used. The STAR measurement is slightly enhanced compared to the p+p ratio; however, the enhancement is statistically insignificant.

In Fig. 2b, the nuclear modification factor for D_s is shown as blue points. The p+p baseline is obtained from the measured total charm cross-section by STAR [2] multiplied by the $c \rightarrow D_s$ fragmentation factor obtained from the measurements at HERA [20, 21]. The uncertainty of the baseline is indicated by the green hashed band and the uncertainty on N_{coll} is plotted as the

black rectangle. The $D_s R_{AA}$ is compared to the calculation done by the TAMU group [6] and the published $D^0 R_{AA}$ by STAR [3]. Again, we observe a hint of D_s enhancement compared to D^0 , which can be described by the TAMU model within uncertainties; however, more data is needed to draw firmer conclusions.

Fig. 2c shows the first result of $D_s v_2$ at RHIC as the red filled square. The data slightly prefer a non-zero v_2 , albeit not significantly. The $D_s v_2$ is compared to the v_2 of D^0 and ϕ meson [22] which, like the D_s , contains strange quarks. The $D_s v_2$ is consistent with both measurements within uncertainties.

4. Summary and outlook

We report the first measurements of the open charm hadrons using the state-of-the-art vertex detector HFT. $D^0 v_2$ is measured for the first time at RHIC. These data are significantly above zero and favor models with charm diffusion. Moreover, the $D^0 R_{AA}$ is measured with a much improved precision, compared to the previous measurements without the HFT. Comparing both R_{AA} and v_2 measurements to different models, STAR is able to infer the value of the charm spatial diffusion coefficient D_s multiplied by the temperature T to be $2 \leq 2\pi T D_s \lesssim 12$, which is consistent with the lattice QCD calculations.

The first measurement of the D_s meson at RHIC is enabled by the HFT. The ratio of the production yield of D_s/D^0 is compatible with a similar LHC measurement and indicates an enhancement of the D_s mesons in Au+Au collisions compared to the p+p collisions. The R_{AA} of the D_s is measured and is consistent with model calculations. Moreover, the $D_s v_2$ is also measured for the first time at RHIC.

In the years 2014 and 2016, ~ 4 times more minimum-bias Au+Au events were recorded compared to the shown results. All of these measurements will benefit greatly from the increased statistics. In addition, there have been significant improvements in terms of HFT performance in 2016 as well as offline software, which greatly enhance the tracking efficiency. In 2015, STAR took reference p+p and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, which will provide a baseline of better precision and help to quantify the cold nuclear matter effects.

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