PROCEEDINGS OF SCIENCE

Measurement of open-charm hadron production in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV with the STAR experiment

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In ultrarelativistic heavy-ion collisions at RHIC energies, charm quarks are predominantly produced in initial hard partonic scatterings. Therefore, they experience the entire evolution of the hot and dense medium produced in these collisions, known as the Quark-Gluon Plasma (QGP). The STAR experiment is capable of studying the production of charm quarks and their interactions with the QGP through the reconstruction of the hadronic decays of D^0, $D^{\pm}$, $D_s^{\pm}$ and $\Lambda_c^{\pm}$ hadrons. These measurements are possible thanks to the excellent track pointing resolution of the Heavy Flavor Tracker (HFT). In these proceedings, we present recent results on open-charm hadron measurements in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. In particular, we discuss the nuclear modification factors of $D^{\pm}$ and D^0 mesons, which provide insights into the energy loss mechanism of charm quarks in the QGP, and the D^0 elliptic and triangular flow coefficients, that probe the charm quark transport in the QGP. We also present the $D_s^{\pm}/D^0$ and $\Lambda_c^{\pm}/D^0$ yield ratios as a function of transverse momentum and collision centrality that help us better understand the charm quark hadronization process in heavy-ion collisions. Finally, we show the rapidity-odd directed flow of D^0 mesons, which is sensitive to the initial tilt of the QGP bulk and can also probe the effects of the initial magnetic field in heavy-ion collisions.

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1. Introduction

A hot and dense medium of deconfined quarks and gluons (usually referred to as the Quark-Gluon Plasma - QGP) is created during the ultrarelativistic collisions of heavy nuclei at the Relativistic Heavy Ion Collider (RHIC) and at the Large Hadron Collider (LHC) [1, 2]. At RHIC, charm quarks are produced in such high-energy collisions predominantly through initial hard partonic scatterings, owing to their large mass. This makes the charm quarks a very valuable probe of the QGP, since they experience the entire evolution of the medium and their number is conserved throughout this process. The interactions between the charm quarks and the QGP can be studied by measuring observables related to the yields and anisotropies of charmed hadrons, such as D^0 (unless stated otherwise, D^0 denotes combined results from D^0 and $\overline{D^0}$), $D^{\pm}$, $D_s^{\pm}$ mesons and $\Lambda_c^{\pm}$ baryon. The measurement of the nuclear modification factor R_{AA}, defined as the ratio of the yield of a given particle species in nucleus-nucleus (A+A) to the yield from proton-proton (p+p) collisions scaled by the mean number of binary collisions $\langle N_{coll} \rangle$, can provide insights into the charm quark energy loss mechanism inside the medium. The so-called dead cone effect is expected to cause less energy loss for the heavy quarks compared to light-flavor quarks [3].

In these proceedings, we will discuss the R_{AA} of D^0 and $D^{\pm}$ mesons. We will also present the recent measurements of the D^0 azimuthal anisotropy coefficients v_2 and v_3, representing the elliptic and triangular flow, respectively. Studying modification of the $\Lambda_c^{\pm}/D^0$ and $D_s^{\pm}/D^0$ yield ratios can help us understand the effects of the coalescence mechanism [4, 5, 6] during the charm quark hadronization. Finally, we will present the results from the measurement of the rapidity-odd directed flow v_1 of D^0 and $\overline{D^0}$ mesons, which is sensitive to the initial tilt of the QGP bulk [7] and could possibly also probe the effects of the initial electromagnetic field [8] generated during heavy-ion collisions. These measurements were conducted by the Solenoidal Tracker at RHIC (STAR) experiment utilizing the STAR Heavy Flavor Tracker (HFT).

2. Experimental Setup

The STAR experiment has a full azimuthal coverage and a pseudorapidity acceptance of $|\eta| < 1$. The Time Projection Chamber (TPC [9]) serves as the main tracking device at STAR and is also capable of identifying charged particles with momentum up to 1 GeV/c via the mean ionization energy loss (dE/dx) measurement. The particle identification is extended up to $p_T = 3$ GeV/c by measuring the particle velocity with the Time-of-Flight detector (TOF [10]). The most important addition in the STAR heavy-flavor program was the HFT, a high-resolution 4-layer silicon detector, which is capable of achieving a track pointing resolution of 40 μm for kaons with momentum of 1 GeV/c [11]. It allows direct topological reconstruction of open-charm-hadron decays with a significant suppression of the combinatorial background. The open-charm hadrons which are used for the analyses presented in these proceedings were reconstructed in their most probable decay channels into charged hadrons [12]. For these analyses, about 900 million minimum-bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV recorded by the STAR experiment during its run in year 2014 and/or about 1 billion events from year 2016 were used.

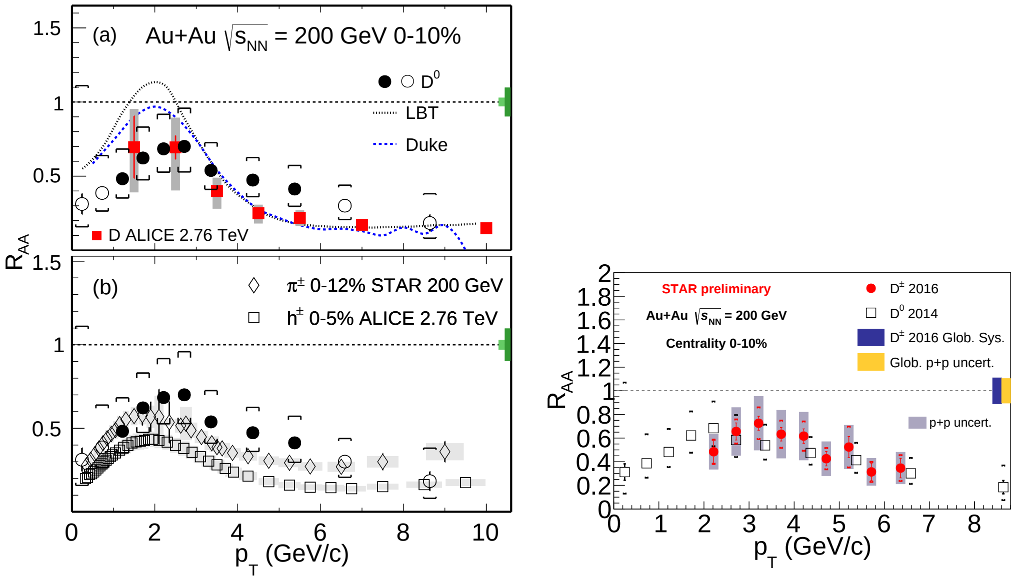

Figure 1: Left: The D^0 R_{AA} (circles) as a function of p_T in 0-10 % most central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [18]. Data are compared to (a) results from ALICE (squares) and the LBT and Duke models (dashed lines), and (b) light-flavor hadrons from STAR (diamonds) and ALICE (squares). Right: The $D^{\pm}$ R_{AA} (circles) as a function of p_T in 0-10 % most central 200 GeV Au+Au collisions. The error bars and boxes/gray bands represent statistical and systematic uncertainties, respectively. The p+p reference is taken from STAR combined D^0 and D^* measurement [19].

3. Results

The left panel of Fig. 1 shows the nuclear modification factor R_{AA} of D^0 mesons as a function of p_T in central Au+Au collisions. The data from 2014 show significant suppression of D^0 production at high p_T ($>$ 4 GeV/c), indicating large charm quark energy loss inside the QGP medium. The overall behavior is well described by the Linearized Boltzmann Transport (LBT [13]) and Duke [14] models, which include both collisional and medium-induced radiative energy losses and collective motion of the charm quarks inside the medium. The data are consistent with ALICE results from a combined D meson measurement [15] and the light-flavor hadrons at RHIC [16], while being less suppressed than light-flavor hadrons at the LHC [17] at intermediate p_T. The right panel of Fig. 1 shows that a very similar behavior is also observed in the $D^{\pm}$ production (from 2016 data), where the $R_{AA}(p_T)$ is consistent with that of D^0 mesons within uncertainties.

STAR has also measured the elliptic (v_2) and triangular (v_3) flow coefficients of D^0 mesons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The left panel of Fig. 2 shows the combined results from 2014 and 2016 data on STAR v_2/n_q as a function of $(m_T - m_0)/n_q$, where m_0 is the particle rest mass, $m_T = \sqrt{m_0^2 + p_T^2}$ and n_q is the number of constituent quarks, from semi-central collisions. These results improve the precision of the published results [20] and show that the charm quarks follow a similar trend as the light-flavor quarks [21]. As seen in the right panel of Fig. 2, the triangular flow of D^0 mesons, when scaled by n_q, is consistent with the light-flavor hadrons, although

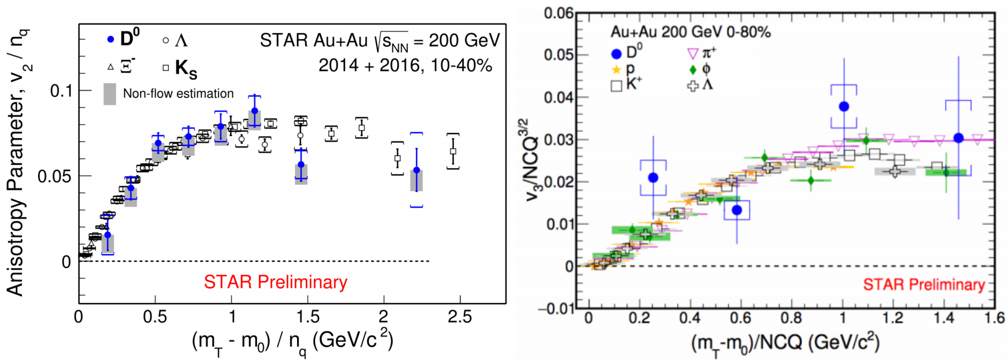

Figure 2: Left: The elliptic flow coefficient v_2 scaled by the number of constituent quarks n_q for D^0 mesons (full circles) and light-flavor hadrons as a function of $(m_T - m_0)/n_q$ in the 10-40 % most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: The triangular flow coefficient v_3 scaled by the number of constituent quarks $NCQ^{\frac{3}{2}}$ for D^0 mesons (full circles) and light flavor hadrons as a function of $(m_T - m_0)/NCQ$ in the 0-80 % most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The error bars and brackets represent statistical and systematic uncertainties, respectively.

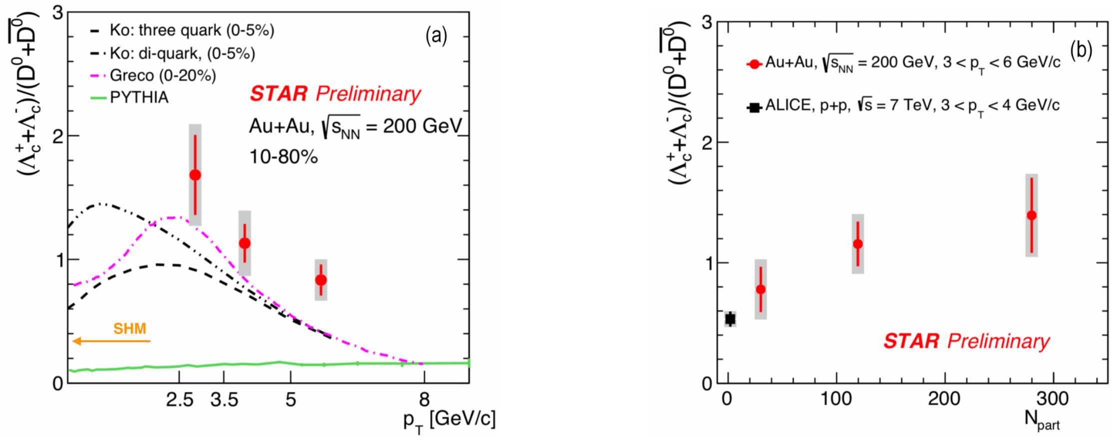

Figure 3: The $\Lambda_c^{\pm}/D^0$ ratio (circles) as a function of (a) p_T in the 10-80 % centrality class of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (years 2014+2016), compared to Ko (0-5 %) and Greco (0-20 %) models and PYTHIA p+p reference, and (b) N_{part} for $3 < p_T < 6$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The error bars and gray bands represent statistical and systematic uncertainties, respectively.

the uncertainty of this measurement is larger. Both the v_2 and v_3 results indicate that the charm quarks show similar collectivity as light-flavor quarks and that they may thermalize in the medium.

Figure 3 shows the $\Lambda_c^{\pm}/D^0$ yield ratio as a function of p_T and centrality. The $\Lambda_c^{\pm}$ baryon production is significantly enhanced compared to D^0 in Au+Au collisions and the magnitude of the enhancement increases from peripheral to central collisions. The p_T dependence of the enhancement is qualitatively described by models (Ko [5], Greco [22]), which take into account coalescence during charm quark hadronization, while the data are in significant disagreement with the PYTHIA p+p baseline.

The $D_s^{\pm}/D^0$ ratio as a function of p_T in central and semi-central Au+Au collisions (from year

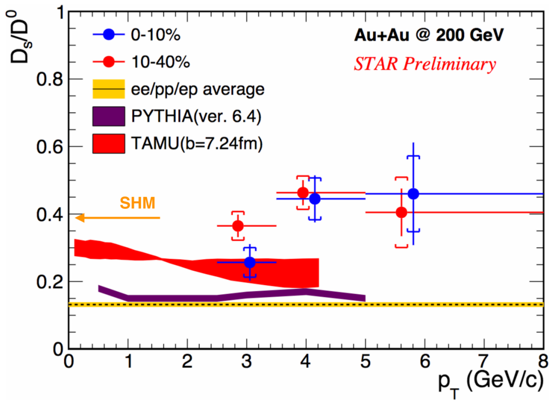

Figure 4: The $D_S^{\pm}/D^0$ ratio as a function of p_T in the 0-10 and 10-40 % centrality classes of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, compared to elementary collisions average, TAMU model and PYTHIA p+p reference. The error bars and boxes represent statistical and systematic uncertainties, respectively.

2014), as seen in Fig. 4, shows a significant enhancement with respect to the PYTHIA p+p prediction and also to the average from e+e, e+p and p+p collisions [23]. While the TAMU model [6], which includes coalescence, predicts an enhancement of the $D_S^{\pm}/D^0$ ratio, it still underpredicts the data. Together with the $\Lambda_C^{\pm}$ results, the $D_S^{\pm}$ results support the idea of charm quark hadronization via coalescence. After measuring the D^0 production cross-section down to zero p_T, extrapolating the $D^{\pm}$ and $D_S^{\pm}$ production using Levy fits and calculating the $\Lambda_C^{\pm}$ production cross-section using the $\Lambda_C^{\pm}/D^0$ ratio, we conclude that the total charm quark cross section per binary nucleon-nucleon collision at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV ($d\sigma^{c\bar{c}}/dy|_{y=0} = 152 \pm 13 \pm 29\ \mu$b) is consistent with the result from p+p collisions at the same energy ($d\sigma^{c\bar{c}}/dy|_{y=0} = 130 \pm 30 \pm 26\ \mu$b). Given the suppression of the D^0 yield at low p_T (Fig. 1) and the enhancements of $\Lambda_c^{\pm}$ and $D_s^{\pm}$, this suggests that the charm quark distribution among different hadron species during hadronization is significantly modified in the presence of the QGP.

The final result presented in these proceedings is the rapidity-odd component of the D^0 meson directed flow (v_1) shown in Fig. 5 [24]. The v_1 exhibits a negative slope for both D^0 and $\overline{D^0}$ mesons with the magnitude being significantly larger than that of kaons. This behavior is consistent with the hydrodynamical prediction [7], which takes into account the different longitudinal profiles of the charm quark production and the QGP bulk. The splitting between v_1 of D^0 and $\overline{D^0}$ as a result of charm quark and antiquark interaction with the initial electromagnetic field as predicted in [8] has not been observed within uncertainties.

4. Summary

The STAR experiment has extensively studied the production of open-charm hadrons, utilizing large data samples of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the excellent pointing resolution of the HFT. Both the nuclear modification factors of $D^{\pm}$ and D^0 mesons show a significant suppression at high transverse momentum, indicating large charm quark energy loss in the QGP, comparable to light-flavor hadrons. The measurements of D^0 elliptic and triangular flow coefficients, which

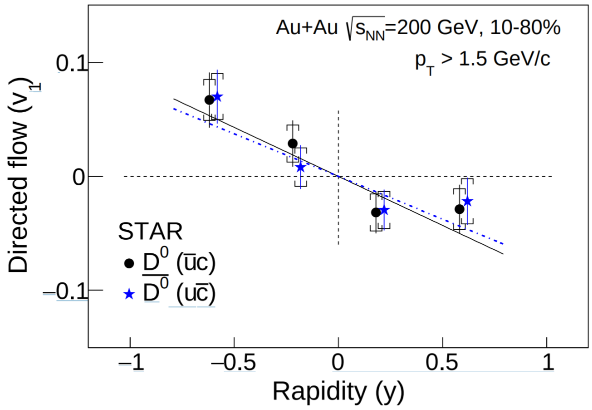

Figure 5: The D^0 directed flow coefficient v_1 as a function of rapidity y for particles with $p_T > 1.5$ GeV/c in the 10-80 % most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The lines represent linear fits to the data. The error bars and boxes represent statistical and systematic uncertainties, respectively.

follow the number-of-constituent-quarks scaling, indicate significant collective motion of charm quarks inside the medium and suggest that the charm quarks may achieve thermal equilibrium with the QGP at RHIC. The $\Lambda_c^{\pm}/D^0$ and $D_s^{\pm}/D^0$ ratios are significantly enhanced in Au+Au collisions compared to their p+p baselines and favor models which include coalescence during the charm quark hadronization. The results on the total charm cross-section confirm significant modification of charm hadrochemistry during hadronization. The measurement of the rapidity-odd component of the directed flow shows a large negative slope for both D^0 and $\overline{D^0}$ mesons, supporting the hydrodynamical prediction with a tilted QGP bulk, while the role of the initial electromagnetic field remains inconclusive.

Acknowledgments

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