STAR $D^0$ meson $v_2$ measurement

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Abstract. Experiments at the Relativistic Heavy Ion Collider (RHIC) indicate that a novel QCD matter consistent with a strongly-coupled Quark-Gluon Plasma (sQGP) has been created. Heavy quarks are predominantly created in initial hard scatterings, and thus experience the entire evolution of the system including the sQGP phase. The sensitivity of heavy quarks to the transport properties of sQGP is encoded in experimental observables such as elliptic flow ($v_2$). In this presentation, we present the first measurement of $v_2$ of $D^0$ mesons reconstructed with the STAR Heavy Flavor Tracker (HFT) in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, for a wide transverse momentum range. The measured $D^0$ $v_2$ in 0-80% most central collisions is finite and suggests that the charm quark exhibits collective behavior. Several theoretical calculations with dimensionless spacial diffusion coefficient $(2\pi TD_s)$ for charm quarks in the range of $\sim 2-12$ can simultaneously reproduce our $D^0$ $v_2$ result as well as the previously published $D^0$ nuclear modification factor.

1. Introduction

Heavy quarks (charm and bottom) are predominantly produced during hard scatterings at the early stage of heavy-ion collisions [1]. They thus experience the entire evolution of the medium created in these high energy nuclear collisions. Compared to the nuclear modification factor $R_{AA}$, the anisotropic flow ($v_2$) of heavy quarks at low transverse momenta ($p_T$) is less affected by several cold nuclear matter effects such as shadowing and initial-state energy loss [2]. It can thus be used to probe the strongly-coupled bulk medium. Since the masses of heavy quarks are significantly larger than the medium energy scale, Brownian motion may be one of the approaches to describe the propagation of heavy quarks in the medium. It allows to establish quantitative connections between the heavy-quark spacial diffusion coefficient $(2\pi T D_s)$ and the anisotropic flow [1].

Recent measurements at RHIC and LHC show that yields of high $p_T$ charmed hadron are considerably suppressed in central collisions suggesting strong interactions between charm quarks and the bulk medium [3, 4, 5]. The $D^0$ $v_2$ measured by ALICE [6, 7] is comparable with that of light quarks. At RHIC energy the charm quark flow so far can only be inferred from measurements of semi-leptonic decays, which however suffer from large uncertainties from the experimental background, charm hadron decay kinematics and ambiguity of charm or bottom decays. A precise measurement of charm hadron $v_2$ over a wide momentum range will provide valuable insights into transport properties of sQGP.

2. Experimental setup

The data used for this analysis were collected by the STAR experiment at RHIC in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in 2014. About 780 million events with minimum bias (MB)
trigger are used in this analysis. $D^0$ are reconstructed through the hadronic decay channels $D^0(D^0) \to K^\mp \pi^\pm$, with $c\tau \approx 122.9$ $\mu$m and branching ratio of $3.88 \pm 0.05\%$.

Tracks are reconstructed with the Time Projection Chamber (TPC) and Heavy Flavor Tracker (HFT). The TPC covers the full azimuth at mid-rapidity ($-1 < \eta < 1$). The HFT, a newly installed silicon detector, has about the same coverage as TPC. Figure 1 shows the track pointing resolution of kaon, pion and proton along the transverse direction and beam direction. It is better than 50 $\mu$m for tracks with $p_T > 750$ MeV/c. The tracks in this analysis are required to have at least 20 space points in the TPC and at least one hit on each of three layers of the HFT.

The particle identification for $D^0$ daughters is done with the TPC and the Time of Flight (TOF) detector. The TPC provides energy loss measurement $dE/dx$. Particles are required to be within 2 (for $K^{\pm}$) or 3 (for $\pi^{\pm}$) standard deviations from the expected value. If the TOF information is available, the $1/\beta$ is required to be within 0.03 from the expected value.

The decay vertex is reconstructed as the mid point of DCA between $K^{\pm}$ and $\pi^{\mp}$. Topological cuts are used to suppress the combinatorial background. The topological cuts are:

- decay length (distance from decay vertex to primary vertex)
- DCA between $K^{\pm}$ and $\pi^{\mp}$
- DCA of $K^{\pm}$ ($\pi^{\mp}$) to primary vertex
- DCA of $D^0$ candidates to primary vertex

The TMVA (Toolkit for MultiVariate Analysis) is used to optimize cuts to achieve best signal significance for each $p_T(K\pi)$ bin. The optimized cuts are listed in Table 1.

| $D^0 p_T$ (GeV/c) | 0-1 | 1-2 | 2-3 | 3-5 | 5-10 |
|-------------------|-----|-----|-----|-----|-----|
| decay length ($\mu$m) | 145 | 181 | 212 | 247 | 259 |
| DCA($K,\pi$) ($\mu$m) | 84  | 66  | 57  | 50  | 60  |
| DCA($K, PV$) ($\mu$m) | 103 | 91  | 95  | 79  | 58  |
| DCA($\pi, PV$) ($\mu$m) | 110 | 111 | 86  | 81  | 62  |
| DCA($V_0, PV$) ($\mu$m) | 61  | 49  | 38  | 38  | 40  |

Table 1. Topological cuts used for $D^0$ reconstruction.

![Figure 1](image-url). Track pointing resolution along beam direction (left) and transverse direction (right) as a function of the particle momentum.
3. Azimuthal anisotropy
Two different methods are used to measure $D^0 v_2$: event plane method and two-particle correlation method. In the event plane method, the second order event plane $\Psi_2$ is reconstructed using TPC tracks and corrected for the non-uniform detector efficiency $[8]$. A minimum pseudorapidity ($\eta$) gap of 0.15 around the $D^0$ candidate is applied to the tracks used for event plane reconstruction to suppress non-flow effect. For different $p_T$ bins the yields of $D^0$ candidates are measured in azimuth relative to the event plane $\Psi$. In order to avoid bias from $D^0$ reconstruction efficiency and event plane resolution, $D^0$ candidates are weighted by a factor of $1/(\epsilon * R)$, where $\epsilon$ is the $D^0$ reconstruction efficiency and $R$ is the event plane resolution $[8]$. The background is estimated from mixed events $[9]$ scaled to the like-sign yield within the invariant mass range of 1.6-2.1 GeV/$c^2$. For $1 < p_T < 5$ GeV/$c$, the $D^0$ yield is obtained by fitting invariant mass distribution of $K\pi$ unlike-sign pairs with a Gaussian function (representing $D^0$ signal) plus a first-order polynomial function (for background). In $5 < p_T < 10$ GeV/$c$ bin, the $D^0$ yield is obtained by subtracting scaled counts in side-band regions (1.71-1.80 and 1.93-2.02 GeV/$c^2$) from counts in the signal region (1.82-1.91 GeV/$c^2$). Figure 2 shows the $D^0$ yield as a function of $\phi - \Psi$ for $3 < p_T < 4$ GeV/$c$, where $\phi$ is the azimuthal angle of $D^0$, $v_2^{observed}$ is obtained by fitting the data with $A(1 + 2v_2 \cos(2(\phi - \Psi)))$. The observed $v_2$ is scaled by $(1/R)$ to obtain the final $v_2$ $[10]$.

In the correlation method $[11,12]$, $D^0 v_2$ is calculated through the $D^0$-hadron azimuthal cumulant $V_2^{D^0,h} \equiv \langle \cos(2\phi_{D^0} - 2\phi_h) \rangle$. $D^0 v_2$ can be obtained via $v_2^{D^0} = \frac{V_2^{D^0,h}}{v_2^h}$, $v_2^h$ is measured using the same method, as $v_2^h = \sqrt{V_2^{h,h}}$. To suppress the non-flow contribution, $|\Delta \eta| > 0.15$ between $D^0$ and correlated hadrons is applied in $D^0$-hadron azimuthal cumulant calculation. The hadron-hadron cumulant uses particles on opposite sides of the TPC in $\eta$. $D^0$ candidate $v_2$ and background $v_2$ are measured with the same method. $D^0$ candidates are unlike-sign $K\pi$ pairs within $D^0$ mass window ($\pm 3\sigma$); and background is represented by like-sign $K\pi$ pairs under $D^0$ peak and side bands ($4 - 9\sigma$ around $D^0$ peak using both like-sign and unlike-sign $K\pi$ pairs). Figure 2 shows the azimuthal cumulant of both $D^0$ candidate and background. With $v_2$ of $D^0$ candidate and background, as well as the yield of $D^0$ signal from the fitting, the signal $v_2$ is calculated as $v_2^{signal} = (N_{\text{cand}} \cdot v_2^{\text{cand}} - N_{\text{bg}} \cdot v_2^{\text{bg}}) / N_{\text{signal}}$, where $N_{\text{cand}}$ is the count under $D^0$ peak and $N_{\text{bg}} = N_{\text{cand}} - N_{\text{signal}}$.

Figure 3 presents the $D^0 v_2$ measured with the event plane and correlation methods. The results from two different methods show good agreement within systematic uncertainties. The grey band is an estimation of non-flow contribution. It is deduced from $D^*$-hadron correlation measured with $p+p$ data taken by STAR in the year 2012, and corrected for different feed-down effects for $D^0$ and $D^*$ using simulation. The systematic uncertainty on $D^0 v_2$ is dominated by background treatment. In the event plane method, the systematic uncertainty is estimated by varying several aspects of fit and side band methods mentioned above. In the correlation method, the uncertainty is estimated as the largest difference between using like-sign pairs and side bands. The yield difference from using different fitting functions (Gaussian plus exponential) is also considered as a contribution to systematic uncertainty in the correlation method.

4. Discussion
Figure 4 compares the $D^0 v_2$ with $K_s$ $[13]$, $\Omega$ and $\phi$ $[14]$. In order to eliminate the effects of different particle masses and different number of constituent quarks (NCQ), Figure 4 plots $v_2/NCQ$ as a function of $(m_T - m_0)/NCQ$, where $m_0$ is the rest mass of particle and $m_T = \sqrt{p_T^2 + m_0^2}$. $v_2/NCQ$ of $K_s$, $\Omega$ and $\phi$ fall into same trend. There is an indication that $D^0 v_2$ is systematically lower than those of the light flavor particles, which might suggest that charm quark is not fully thermalized in the medium.

Figure 4, right panel, shows the comparison of $D^0 v_2$ to different model calculations.
Figure 2. Left:$D^0$ yield as a function of $\phi - \Psi$ in $3 < p_T < 4$ GeV/c bin; Right:Azimuthal cumulant of $D^0$ candidates and background as a function of $p_T$.

Figure 3. Comparison of $v_2$ using event plane method and two-particle correlation method.

The models use different treatments of charm-medium interaction and have different effective diffusion coefficient $2\pi TD_s$. The SUBATECH model [15, 16] uses pQCD with Hard Thermal Loop (HTL) describing soft processes. The TAMU model [17, 18] is a non-perturbative model, using T-matrix with internal energy potential. Two curves of TAMU models are shown: the blue curve includes charm diffusion while the pink curve does not. Table 2 summarizes the $\chi^2/n.d.f$ measuring the difference between the measured $D^0 v_2$ and those from different models. The model developed by Duke group [19, 20] has a fixed diffusion coefficient $2\pi TD_s = 7$. The Parton-Hadron-String Dynamic (PHSD) model [21] is a transport model. From the comparison of $D^0 v_2$ with models, the measurement agrees with most of the models with diffusion coefficient
Table 2. The fitting result of different models to $D^0 v_2$ measurement.

| Model                        | diffusion coefficient | $\chi^2/n.d.f.$ |
|------------------------------|-----------------------|-----------------|
| SUBATECH                     | 2-4                   | 2.8/5           |
| TAMU c quark diff.           | 2-7                   | 2.1/5           |
| TAMU no c quark diff.        | N/A                   | 7.4/5           |
| DUKE                         | 7                     | 9.3/5           |
| PHSD                         | 5-12                  | 0.46/4          |

ranging from 2-12.

![Figure 4. Left: Comparison of $v_2$ of $D^0$ with light flavor particles; Right: Comparison of $D^0 v_2$ with different models.](image)

5. Summary

$D^0 v_2$ is measured by STAR with the newly installed HFT, for 0-80% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measurement is carried out in a $p_T$ range from 1 to 10 GeV/c. The measured $D^0 v_2$ is finite. The smaller $D^0 v_2$ compared to the light hadrons indicates that charm quarks may not be fully thermalized. Different models with charm diffusion coefficient $2\pi T D_s$ ranging from 2 to 12 are consistent with the measured $D^0 v_2$. The model comparisons suggest that charm quarks have collective behavior.

As part of continuing heavy flavor program in STAR, 2 billion Au+Au minimum bias events have been recorded in 2016 with thinner aluminum cables used for the innermost silicon layer of the HFT. An expected factor of 2-3 improvement in the $D^0$ significance at $p_T = 1$ GeV/c will allow for the study of the centrality dependence of $D^0 v_2$ in heavy ion collisions.

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