Measurement of D^0 elliptic and triangular flow in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV at RHIC

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Abstract. Due to their large masses, heavy quarks are predominantly produced through initial hard scatterings in heavy-ion collisions. As such, they experience the entire evolution of the hot and dense medium created in such collisions and are expected to thermalize much more slowly than light flavor quarks. For instance, the azimuthal anisotropy of charm quarks with respect to the reaction plane over a broad momentum range can provide insights into the degree of thermalization and the bulk properties of the system. Specifically at low transverse momenta we can examine the bulk properties in the strongly coupled regime.
In this talk we present the STAR measurement of elliptic (v_2) and triangular flow (v_3) of D^0 mesons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV obtained from the first year of physics running with the new STAR Heavy Flavor Tracker. Comparison with the azimuthal anisotropy of other particle species and a series of model calculations will be shown, and the charm quark dynamics in the sQGP medium will be discussed.

1. Introduction

Heavy flavor quarks are suggested to be an excellent probe to study the strongly coupled quark-gluon plasma (sQGP) as they are predominantly produced early in heavy-ion collisions through hard scattering processes. They experience the full evolution of the system, while their large masses are mostly unaffected by the QCD medium. Furthermore, by studying how the heavy quarks are affected as they propagate through the sQGP we can access information about the transport properties of the medium, for example $2\pi TD_s$, which is given in terms of the temperature T and the charm spatial diffusion coefficient D_s [1].
Recent measurements at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) show that charmed hadron yields at high transverse momenta (p_T) in central collisions are considerably suppressed, suggesting strong charm quark interactions with the bulk, while the elliptic flow (v_2) of charmed hadrons measured at LHC is comparable to that of light hadrons [2, 3, 4]. The enhancement in the nuclear modification factor at intermediate p_T observed at RHIC [2] is suggestive of both charm flow and hadronization via coalescence. Studies of charm flow through semi-leptonic decay channels at RHIC suffer from large uncertainties and, as such, a precise measurement of charmed hadron v_2 is needed to fully understand the properties of the sQGP medium. Furthermore, some model calculations [5] including fluctuations in the initial conditions together with charm quark interactions with the medium have predicted a

non-zero value for charm quark triangular flow (v_3), providing another handle to study the early stages of the collisions.

2. Experimental set-up

The data used in these analyses were recorded in year 2014 by the STAR experiment at RHIC in Brookhaven National Laboratory, USA. The STAR experiment possesses full azimuthal coverage at mid-rapidity using the Time Projection Chamber (TPC) to reconstruct tracks inside a uniform 0.5 T magnetic field. The TPC can also provide excellent particle identification (PID) for hadrons over a broad range in p_T by combining information from the TPC and the Time Of Flight (TOF) detector.

The entire Heavy Flavor Tracker (HFT) was installed for the first time in 2014 and greatly improved STAR's tracking resolution. It provided a track pointing resolution of less than 50 μm for kaons with $p_T = 750$ MeV/c. About 780 million Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with a Minimum-Bias (MB) trigger were analyzed to reconstruct charmed hadrons. A cut on the reconstructed collision position, or primary vertex (PV), along the beam line ($|\mathrm{V_z}| < 6$ cm) is applied to ensure good acceptance in the HFT detector. D^0 mesons are fully reconstructed through the hadronic channel:

$$D^0(\overline{D^0}) \rightarrow K^{\pm}\pi^{\mp},\ c\tau \sim 120\ \mu m,\ \mathrm{B.R.}\ 3.9\%$$

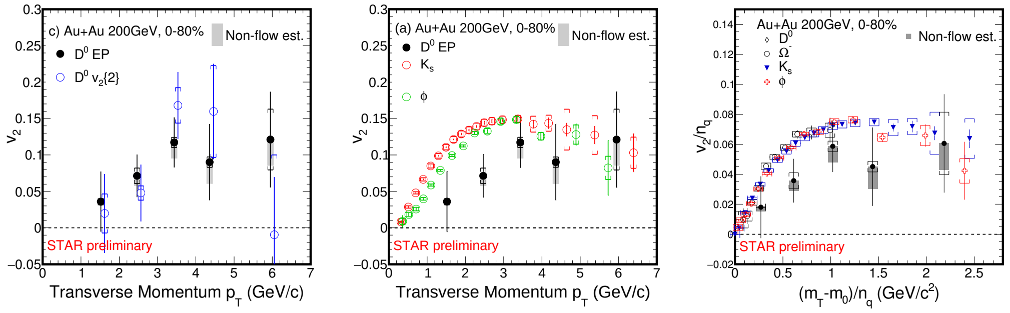
The D^0 daughter tracks are required to have: i) a minimum of 20 space points in the TPC, ii) at least one hit in each of the three inner layers of the HFT, iii) $p_T > 0.6$ GeV/c and iv) pseudorapidity $|\eta| < 1$. Particle identification is done using energy loss (dE/dx) from the TPC, i.e. selecting candidates within 2 to 3 standard deviations from the expected values. It is further enhanced using the TOF when available. The value of $1/\beta$ is estimated from the momentum and the timing measured in the TOF, and is required to be less than 0.03 from the expected values.

Once daughter candidates have been identified, the (displaced) decay vertex is reconstructed at the mid-point on their distance of closest approach (DCA). The combinatorial background is greatly suppressed by imposing criteria on the following topological variables: decay length (distance between primary and decay vertices), DCA between daughter tracks, DCA between reconstructed D^0 candidate and the PV, and DCA between daughter tracks and the PV.

3. Azimuthal anisotropy

Once the D^0 candidates have been selected, the second (v_2) and third (v_3) order azimuthal anisotropies are studied. In the case of v_2 the results obtained using two different methods were compared: the event plane method and the two particle correlation method, which will be discussed briefly in the following paragraphs. For the measurement of v_3 only the event plane method was used.

In the event plane method the second (third) order event plane, $\Psi_{2(3)}$, is reconstructed using TPC tracks and corrected for the non-uniform detector efficiency [6]. To reduce the contributions from non-flow effects originating from other two or multi-particle correlations, all tracks within a relative pseudorapidity gap $|\Delta\eta| \leq 0.15$ around the reconstructed D^0 candidates are removed from the event plane reconstruction. The azimuthal distribution of D^0 mesons with respect to the event plane $\phi - \Psi_n$ is obtained and weighted by $1/(\epsilon R)$, where ϵ is the D^0 reconstruction efficiency and R is the event plane resolution for each centrality. In each $\phi - \Psi_n$ bin, the mixed-event background is subtracted from the unlike-sign invariant mass spectrum. The D^0 yield is obtained by either the fitting or sideband method: at low p_T the invariant mass spectrum is fitted with a Gaussian function, representing the signal, and a first order polynomial function describing the correlated background; for the last p_T bin (5-10 GeV/c) fitting is limited by low background statistics, and the D^0 yield is obtained by subtracting scaled unlike-sign counts in



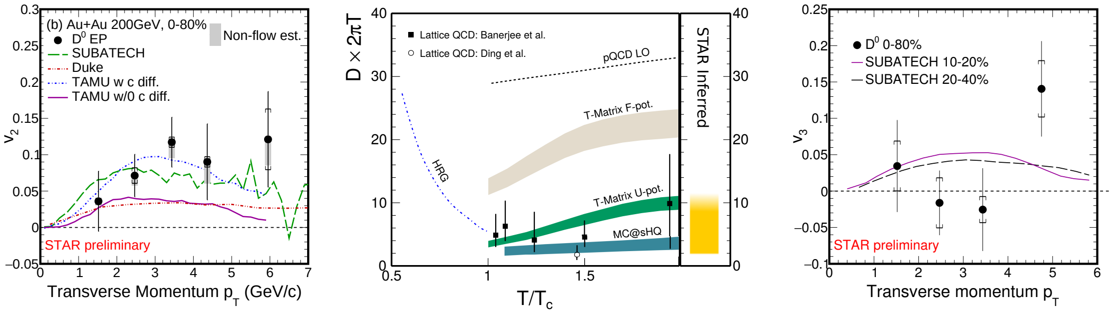
(a) (b) (c)

Figure 1: a) Comparison between v_2 from event plane and two particle correlation methods. b) Measured v_2 for D^0 compared to that of light hadrons. c) v_2/n_q vs $(m_T - m_0)/n_q$ for D^0 and other particle species.

two invariant mass regions around the signal region. The observed v_n^{obs} is then obtained by fitting the yield versus $\phi - \Psi_n$ with the functional form $A(1 + 2v_n \cos(n(\phi - \Psi_n)))$. Finally, the observed v_n^{obs} is corrected for the average event plane resolution $\langle 1/R \rangle$ to obtain the true value of the azimuthal anisotropy.

In the two particle correlation method, the average D^0-hadron correlation is calculated according to $V_2^{D-h} \equiv \langle \cos 2(\phi_D - \phi_h) \rangle$. Assuming that the D^0 and hadrons have no correlation other than through the event plane, it can be shown that $V_2^{D-h} = V_2^D V_2^h$. Finally, together with the hadron-hadron correlation, $V_2^{h_1-h_2} \equiv \langle \cos 2(\phi_{h1} - \phi_{h2}) \rangle$ the elliptic flow of D^0 can be obtained $v_2^D = V_2^{D-h}/(V_2^{h1-h2})^{1/2} = \langle \cos 2(\phi_D - \phi_h) \rangle / \langle \cos 2(\phi_{h1} - \phi_{h2}) \rangle^{1/2}$. The D^0 background is estimated by averaging both the like- and unlike-sign sidebands as well as the like-sign invariant mass in the D^0 signal range. As in the case of the event plane method, the contribution from non-flow effects is suppressed by introducing a gap $|\Delta\eta| > 0.2$ in the measurement of $D - h$ correlations, while only particles in opposite ends of the TPC are used in the hadron-hadron correlations (i.e. $h_1 \in \eta > 0$ and $h_2 \in \eta < 0$). The event plane and two particle correlation methods show good overall agreement within systematic uncertainties, as is shown in figure 1a. However, non-flow effects may still contribute to the measured v_2. This contribution is estimated by scaling the non-flow contribution estimated in p+p collisions to Au+Au collisions [7], in which case it can be written as $\langle \sum_i \cos(2(\phi_D - \phi_h)) \rangle / M v_2$ where M and v_2 are the average multiplicity and hadron v_2 measured in Au+Au collisions. Figure 1b shows the v_2 of D^0 mesons compared with that of other particle species [8]. The D^0 v_2 is non-zero for $p_T > 2$ GeV/c and is systematically below that of light hadrons in the range $1 < p_T < 4$ GeV/c within large uncertainties. To account for the different particle masses and number of constituent quarks (n_q), the comparison is done in figure 1c by plotting v_2/n_q vs $(m_T - m_0)/n_q$ where $m_T = \sqrt{p_T^2 + m_0^2}$. Once the scaling has been done the difference among particle species is reduced, although D^0 is still systematically below the light particle species in 0-80% centrality.

In figure 2a the results for D^0 are compared with four theoretical models. The TAMU model [9] uses a non-perturbative T-matrix approach assuming the two-body interactions can be described by a potential as a function of the transferred 4-momentum. Two curves from TAMU are shown: the scenario including charm diffusion (blue) agrees with the data while the predictions without charm diffusion (magenta) are systematically lower. The calculation by the SUBATECH group [5] employs pQCD with Hard Thermal Loop approximation for soft collisions and can also describe the measurement over the whole p_T range. In the model developed by the Duke group [10] the diffusion coefficient $2\pi T D_s$ is a free parameter which, in the case of the red curve shown,



(a) (b) (c)

Figure 2: a) D^0 v_2 in 0-80% centrality compared to model calculations. b) Diffusion coefficient from model calculations and the inferred range from STAR measurements. c) D^0 v_3 measured in 0-80% centrality compared to model calculations in 10-20% and 20-40% central events.

has been constrained using the R_{AA} measured at LHC to be roughly 7. It is seen that this model underpredicts the v_2 observed in our data. Figure 2b shows the extracted diffusion coefficient from different model calculations compared to the yellow band on the far right showing the range of inferred values that are compatible with the measurement presented here. Figure 2c shows the D^0 triangular flow in 0-80% central events compared with model calculations in 10-20% and 20-40% central events from the SUBATECH group. The uncertainties in the current results are, however, too large to draw any firm conclusion.

4. Summary

STAR has carried out the first heavy flavor measurements in heavy-ion collisions using the newly installed, state-of-the-art vertexing detector, the HFT. The measured charmed meson v_2 in Au+Au collisions is found to be non-zero, but systematically below v_2 of light hadrons in 0-80% centrality. Comparison to a series of models shows that they are able to describe the data, favoring the scenario where charm quarks flow with the medium. The models infer a range of the charm diffusion coefficient $2\pi T D_s$ between 2 and ~12. An expected factor of 2-4 improvement in D^0 significance is expected from the reprocessed 2014 data as well as another factor of 2-3 from the 2016 data set. Together these should allow a more thorough centrality dependent study of the azimuthal anisotropy and may also provide an answer to whether the D^0 v_3 is non-zero.

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