

Directed flow of open charm in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using a quark coalescence model

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The directed flow (v_1) of open charm meson (D^0) is studied in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using a multiphase transport model framework with partonic interactions (string melting version). Within this framework, it is found that although the initial spatial eccentricity (ϵ_1) of charm quark is smaller than light quarks, the charm quark v_1 magnitude is found to be approximately seven times larger than that of the light u quark at large rapidity. This indicates that the charm quarks can retain more information from initial condition than the light quarks. We have studied the directed flow of D^0 as a function of rapidity and transverse momentum using quark coalescence as the mechanism for hadron production. Like the charm quark, the D^0 v_1 magnitude is found to be about seven times larger than that of the light (π) hadrons at large rapidity.

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I. INTRODUCTION

The main purpose of relativistic heavy-ion experiments is to understand the formation and evolution of a strongly interacting matter, called quark gluon plasma (QGP) [1], which is expected to be formed a microsecond after the big bang. Experiments at the Brookhaven Relativistic Heavy Ion Collider (RHIC) and at CERN Large Hadron Collider (LHC) facilities established the existence of such strongly interacting matter [2], but the complexity in dynamics of the medium is still being explored. Collective motion of the particles emitted from these collisions is of special interest because it is sensitive to the equation of state of the system. Directed flow (v_1) is characterized by the first harmonic coefficient in the Fourier decomposition of the momentum distribution of emitted particles [3,4],

$$v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle, \quad (1)$$

where ϕ denotes the azimuthal angle of emitted particles and Ψ_{RP} is the reaction plane subtended by the x axis and impact parameter direction. In this paper we consider the rapidity-odd component of directed flow [$v_1^{\text{odd}}(y) = -v_1^{\text{odd}}(-y)$], which refers to a sideward collective motion of emitted particles, and is a repulsive collective deflection in the reaction plane, whereas the fluctuations in the initial state of the colliding nuclei can generate a rapidity-even component of v_1 [$v_1^{\text{even}}(y) = v_1^{\text{even}}(-y)$] and it is unrelated to the reaction plane [5]. In this paper v_1 denotes the rapidity-odd component.

Model calculation [6] suggested that the directed flow near the beam rapidity is initiated during the passage of two colliding nuclei. The typical time scale of passing is $\sim 2R/\gamma \sim 0.1$ fm/ c for a Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV, where R and γ are the radius of nuclei and Lorentz factor, respectively. So the observable of directed flow is sensitive to the dynamics in the early stages of nuclear collisions [7]. Both hydrodynamic [8,10] and transport model [11] calculations have shown that

the directed flow at midrapidity, especially the baryons, are sensitive to the equation of state of the system [9,10]. Several hydrodynamic calculations suggested that the negative v_1 slope near midrapidity (called wiggle [10,12] or antiflow [13]) could be a possible QGP signature [10]. However, there are the hadronic models with partial baryon-stopping and positive space momentum correlations [12], and a hydro model full stopping with a tilted source [14] can also explain the antiflow nature of v_1 . Recently, the STAR experiment at the RHIC has reported the measurements of directed flow of several light hadron species (π , K , K_S^0 , p , Λ and their antiparticles, and ϕ) over the beam energy range 7.7–200 GeV [15,16]. A number of constituent quark (NCQ) scaling has been observed in higher flow harmonics (v_2 and v_3) at both RHIC and LHC energies [17–19]. Such scaling is interpreted as evidence of quark degrees of freedom in the early stages of heavy-ion collisions. The recent v_1 measurements reported by STAR [16] found to be consistent with the particles being formed via coalescence of constituent quarks.

The heavy quarks play a crucial role in probing the QGP medium, because its mass is significantly larger than the typical temperature achieved in such a collision. They are produced in hard partonic scatterings during the early stages of collisions. The probability of thermally produced heavy quarks are expected to be small in the high-temperature phase of QGP. Due to large mass, they decouple in the early stages of the collision. The total number of charm quarks is frozen quite early in the history of collision. So the heavy quarks are capable of retaining information of early time dynamics. The measurement of directed flow of heavy quarks can offer insight into the early time dynamics of the system. Apart from that, recent measurements at the RHIC [20] and LHC [21] have shown significant elliptic flow for the charm hadrons. The flow magnitude of charm hadrons seems to follow that of the light hadrons at midrapidity. The D^0 v_2 from the AMPT model [22] moderately explain recent STAR data at midrapidity [23,24].

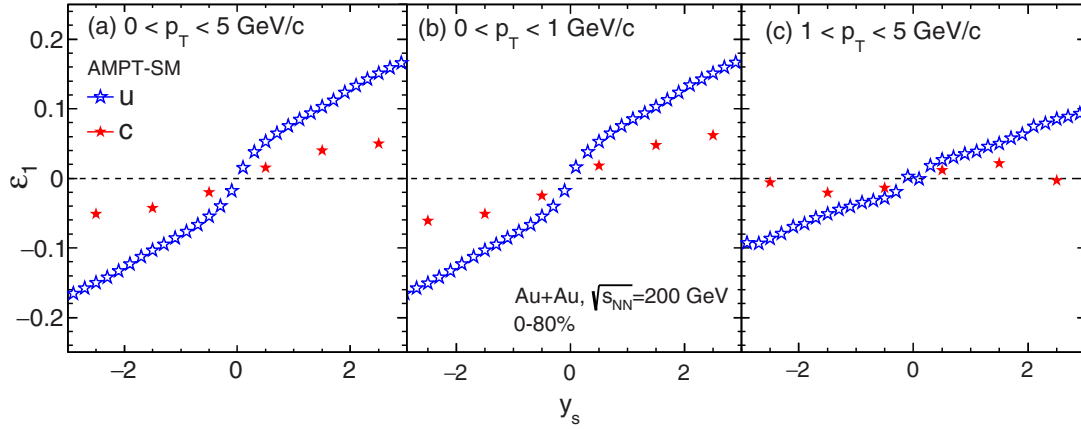


FIG. 1. Initial geometric eccentricity (ϵ_1) as a function of spatial rapidity (y_s) in Au+Au collisions at 200 GeV in three different p_T regions [(a) 0–5 GeV/c, (b) 0–1 GeV/c, and (c) 1–5 GeV/c] for c and u quarks using AMPT-SM model.

In this paper, we aim to study the directed flow of charm mesons [$D^0(\bar{u}c)$] in Au+Au collisions at 200 GeV within the framework of AMPT model. Since the directed flow is generated in early times and also the charm quark production limited to the primordial stage of the collisions, the study of directed flow can offer insight into the initial dynamics of the system. In this work, we have used string melting version (ver. 2.26) of AMPT model [22] (which includes parton coalescence) for the estimation of directed flow. We have studied the $v_1(y, p_T)$ of both heavy and light quarks. We have employed dynamic coalescence mechanism to form hadrons from those quarks.

This paper is organized as follows. In Sec. II, we discuss briefly AMPT model and dynamic coalescence of partons. Section III describes the directed flow v_1 of heavy and light flavor mesons at 200 GeV Au+Au collisions using the AMPT framework (ver. 2.26). Section IV presents a summary of the results.

II. AMPT MODEL

The AMPT is a hybrid transport model [22]. It uses the initial conditions from Heavy Ion Jet Interaction Generator (HIJING) [25]. However, the minijet partons are made to undergo scattering before they are allowed to fragment into hadrons. The string melting (SM) version of the AMPT model (labeled here as AMPT-SM) is based on the idea that for energy densities beyond a critical value of ~ 1 GeV/fm³, it is difficult to visualize the coexistence of strings (or hadrons) and partons, hence the need to melt the strings to partons. Scattering among partons are modeled by Zhang's parton cascade [26]. Once the interactions stop, the partons then hadronize through the mechanism of parton coalescence. The parton-parton interaction cross section in the string-melting version of the AMPT is given by

$$\sigma_{pp} = \frac{9\pi\alpha_S^2}{2\mu^2}. \quad (2)$$

For this study we set the strong coupling constant as $\alpha_S = 0.47$ and the parton screening mass to be $\mu = 3.22$ fm⁻¹. This leads to $\sigma_{pp} = 3$ mb. As the hadronization of heavy quarks is not

implemented in AMPT-SM, we use a dynamical coalescence model to form open charm mesons. Such a model has been extensively used at both intermediate and high energies. In this model we use phase-space information of partons at the freeze out to form open charm mesons based on the Wigner phase-space function [27]. The probability to form a meson from a pair of quark and antiquark is given by,

$$\begin{aligned} \rho^W(\mathbf{r}, \mathbf{k}) &= \int \psi\left(\mathbf{r} + \frac{\mathbf{R}}{2}\right) \psi^*\left(\mathbf{r} - \frac{\mathbf{R}}{2}\right) \exp(-i\mathbf{k} \cdot \mathbf{R}) d^3\mathbf{R} \\ &= 8 \exp\left(-\frac{r^2}{\sigma^2} - \sigma^2 k^2\right), \end{aligned} \quad (3)$$

where R is the center-of-mass coordinate of the quarks or antiquarks and Ψ is the quark wave function. The relative momentum between the two quarks is $\mathbf{k} = \frac{1}{m_1+m_2}(m_2\mathbf{p}_1 - m_1\mathbf{p}_2)$. Here m_i is the mass of i th quark, and p_1 and p_2 are heavy quark and light antiquark transverse momenta, respectively, defined in the center-of-mass frame of produced meson [28]. For quarks, the Wigner phase-space densities are obtained from

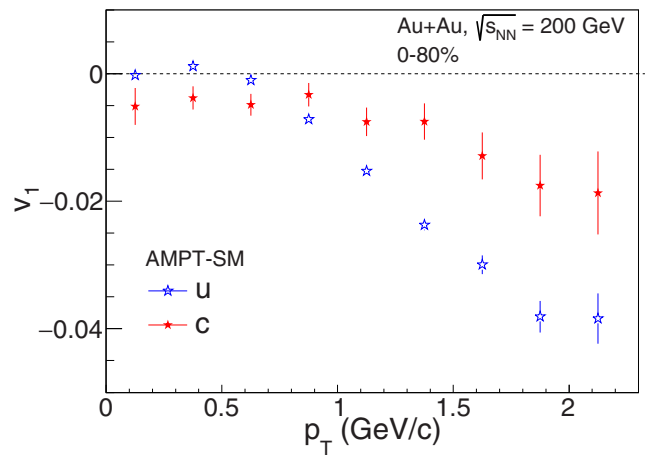


FIG. 2. Comparison of v_1 for c and u quarks as a function of p_T in positive rapidity region ($y > 0$) at 200 GeV Au+Au collisions using AMPT-SM model.

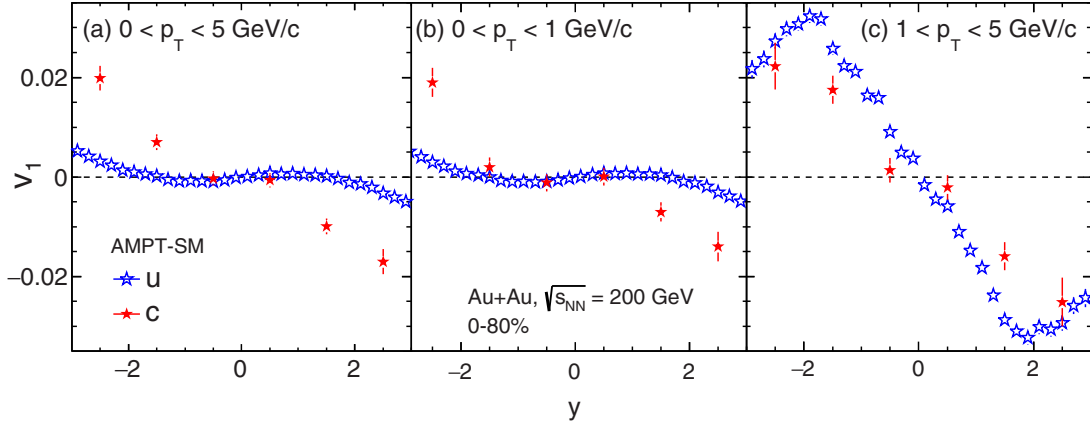


FIG. 3. Comparison of $v_1(y)$ for c and u quarks in three different p_T regions [(a) 0–5 GeV/c, (b) 0–1 GeV/c, and (c) 1–5 GeV/c] at 200 GeV Au+Au collisions using AMPT-SM model.

the spherical harmonic oscillator wave functions,

$$\Psi(\mathbf{r}_1, \mathbf{r}_2) = \frac{1}{(\pi\sigma^2)^{3/4}} \exp\left[-\frac{r^2}{2\sigma^2}\right], \quad (4)$$

where $\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$ and σ is the size parameter related to the root mean square radius as $\langle r^2 \rangle = (3/8)\sigma^2$ [29–31]. In this paper, we have taken $\langle r^2 \rangle = 0.30 \text{ fm}^2$ for D^0 and $\langle r^2 \rangle = 0.44 \text{ fm}^2$ for pion as predicted by the light-front quark model [32].

III. RESULTS AND DISCUSSION

The flow harmonic, v_1 , quantifies the first-order anisotropy of particles of interest in the momentum space, and its magnitude is a response of the initial anisotropy, the expansion dynamics and the equation of state of the medium. Figure 1 presents the initial odd eccentricity (ϵ_1) of u and c quarks as function of spatial rapidity (y_s) in Au+Au collisions at 200 GeV in three different transverse momentum (p_T) regions. The ϵ_1 can be extracted following the equation [33,34]:

$$\epsilon_1 = \langle \cos(\phi_s - \Psi_{RP}) \rangle, \quad (5)$$

where ϕ_s denotes the particle azimuthal angle, $\langle \dots \rangle$ denotes the average at a given rapidity and Ψ_{RP} is the reaction plane. In this paper, we have used the theoretical reaction plane $\Psi_{RP} = 0$ for the v_1 . It is observed that the ϵ_1 for c quarks is about 2–3 times smaller than that for the u quarks in all p_T regions. Next we try to see how this eccentricity is being transferred to the directed flow.

Figure 2 presents the p_T differential v_1 for the c and u quarks in the forward rapidity region. We observed that the u quark v_1 has a very strong p_T dependence, while the c quark shows a weak dependence on p_T . Figure 3 shows the rapidity dependence of c and u quarks in three different p_T regions. Motivation for showing $v_1(y)$ in three different p_T intervals comes from p_T dependence of v_1 , as shown in Fig. 2. Figure 3(a) presents $v_1(y)$ for $0 < p_T < 5 \text{ GeV}/c$. The magnitude of v_1 (first-order anisotropy in momentum space) for u quarks is a few orders smaller than the magnitude of ϵ_1 (first-order anisotropy in coordinate space) with opposite sign in the forward and backward rapidities. Whereas for the c quarks the magnitude of ϵ_1 and v_1 is of similar order. This

is due to the effect of system evolution in the partonic phase in the AMPT model. Although the parton-parton interaction cross section in the AMPT model is taken to be same (3 mb) for all types of quarks, the charm quark is less affected by the scattering due to its heavy mass. Therefore, the change in momentum (or $v_1 = \langle p_x \rangle / \langle p_T \rangle$) of charm quarks is less during the interaction with other light quarks. We observe that full p_T integrated v_1 values for c quarks (0.02) is about seven times larger than that of the u quark (0.003) within the range $2.0 < |y| < 3.0$. This indicates that the heavy c quarks retain more information about the initial anisotropy than light u quarks, since initial ϵ_1 of u quarks is larger than c quarks. However, we do not see any significant difference between v_1 of u and c quarks at midrapidity. Our model calculation suggested that rapidity dependence of flow harmonics of various identified hadrons need to be measured in experiment to better understand the dynamics of the produced medium. In this paper, we have concentrated our calculation only on the v_1 coefficient. Figures 3(b) and 3(c) presents the $v_1(y)$ in low ($0 < p_T < 1 \text{ GeV}/c$) and higher p_T ($1 < p_T < 5 \text{ GeV}/c$) regions. While at low p_T the magnitude of c quark v_1 is larger than the u quarks,

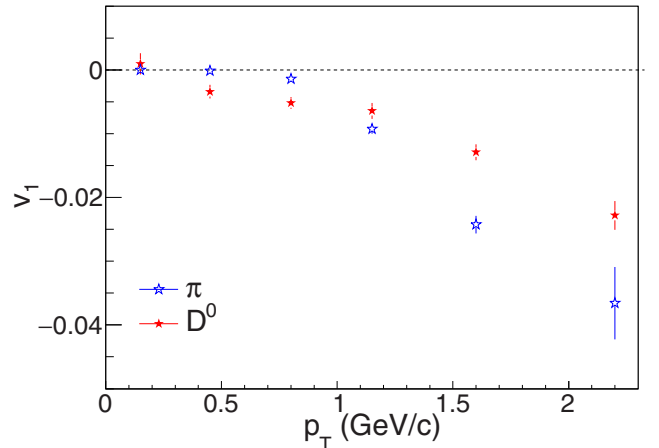


FIG. 4. Comparison of $v_1(p_T)$ in positive rapidity region ($y > 0$) for D^0 and π in 200 GeV Au+Au collisions using AMPT-SM model.

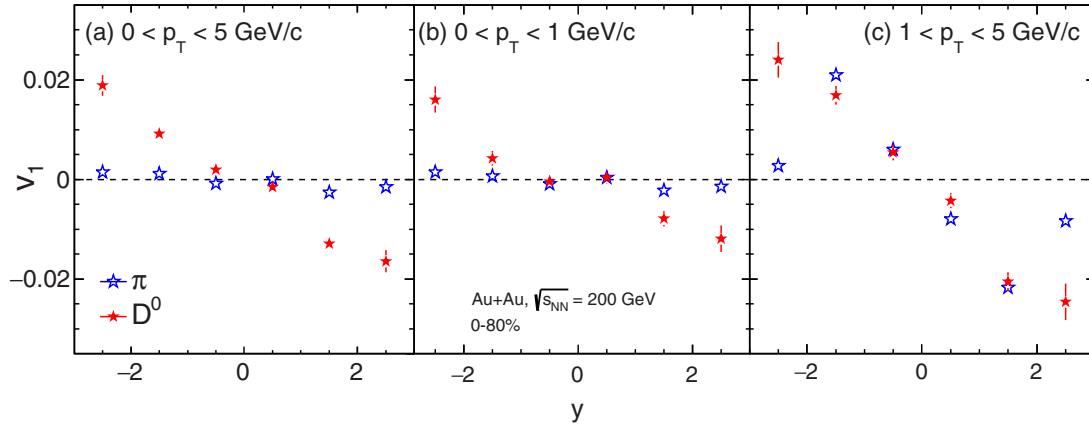


FIG. 5. Comparison of $v_1(y)$ for D^0 and π in three different p_T intervals [(a) 0–5 GeV, (b) 0–1 GeV, and (c) 1–5 GeV] in 200 GeV Au+Au collisions using AMPT-SM model.

at higher p_T their magnitudes are comparable. In AMPT-SM model, the p_T integrated $v_1(y)$ of pions are actually dominated by the low p_T (< 1.0 GeV/c) pions due to a very sharp fall in pion p_T spectra after $p_T = 1.0$ GeV/c. We have observed that the p_T spectra for charm quarks are harder than the light quarks. Although u quarks have large v_1 in the range $p_T > 1.0$ GeV/c, the p_T integrated $v_1(y)$ for $p_T > 1.0$ GeV/c [Fig. 3(c)] shows nearly the same magnitude for both charm and up quarks.

Next, we employ dynamic coalescence mechanism, as described in Sec. II, to form mesons from the quarks at the freeze out. The u and \bar{d} quarks are used to form pions, while c and \bar{u} quarks are used to get the D^0 . Figure 4 presents p_T differential v_1 for D^0 and π 's in the forward rapidity region ($y > 0$). The π 's have a stronger (p_T) dependence of v_1 than for the D^0 's, which reflects the similar behavior of the constituent quarks, which is shown in Fig. 2.

Figure 5 shows the rapidity dependence of v_1 for D^0 and π 's in three different p_T intervals. Figures 5(a)–5(c) present $v_1(y)$ for $0 < p_T < 5$ GeV/c, $0 < p_T < 1$ GeV/c, and $1 < p_T < 5$ GeV/c, respectively. Figure 5(a) shows that the D^0 v_1 has large magnitude than that of pions for $|y| > 1.0$. The full p_T integrated D^0 v_1 is found to be factor seven times larger than that of pions within the range $2.0 < |y| < 3.0$. Figures 5(b) and 5(c) represent similar observation as shows for partons in Fig. 3. Our observation from AMPT model calculation suggest that $D^0 v_1$ can be used as a useful probe, in addition to light hadrons v_1 , to study the initial state effect in heavy-ion collisions. There are recent hydro calculations [36] that suggests that the v_1 slope of heavy flavors can be sensitive probe of the initial matter distribution. The AMPT model with different dynamics for the charm quarks hints towards the same direction.

A recent paper [35] predicted that the transient magnetic field in heavy-ion collisions can induce a larger v_1 in heavy quarks than for light quarks. Model also predicts opposite sign for charm and anticharm quarks due to the magnetic field. In future, one can study these effect on charm v_1 within the AMPT model framework. We also look forward to the measurement of charm v_1 at both RHIC and LHC energies.

IV. SUMMARY AND CONCLUSION

In summary, we have presented the directed flow of heavy and light flavor hadrons, and their constituent quark species in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the string melting version of AMPT model. Although the initial rapidity-odd eccentricity (ϵ_1) in spatial coordinates for heavy quarks are smaller than for the light quarks, the v_1 magnitude for heavy flavor hadrons is approximately seven times larger than that of the light hadrons at large rapidity. This is an interesting observation, which tells us that the charm hadrons are capable of retaining more information of the initial dynamics than the light ones. Any future measurement of D^0 v_1 in a large rapidity window would be interesting to understand the initial dynamics in heavy-ion collisions.

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