Heavy quark flow as better probes of QGP properties

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Abstract. In earlier studies we have proposed that most parton v_2 comes from the anisotropic escape of partons, not from the hydrodynamic flow, even for semi-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Here we study the flavor dependence of this escape mechanism with a multi-phase transport model. In contrast to naive expectations, we find that the charm v_2 is much more sensitive to the hydrodynamic flow than the lighter quark v_2, and the fraction of v_2 from the escape mechanism decreases strongly with the quark mass for large collision systems. We also find that the light quark collective flow is essential for the charm quark v_2. Our finding thus suggests that heavy quark flows are better probes of the quark-gluon-plasma properties than light quark flows.

1 Introduction

Azimuthal anisotropies in heavy ion collisions, such as the elliptic flow v_2, are important tools for the study of the properties of the quark-gluon plasma (QGP). Recent studies with parton transport models suggest [1, 2] that most parton v_2 comes from the anisotropic escape of partons, not from the hydrodynamic flow, even for semi-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This escape mechanism converts the spatial anisotropy in the overlap volume very efficiently into azimuthal anisotropies in final state particles, even though the parton cross section and average number of collisions of each parton are small [1–4]. Thus it naturally explains the similar azimuthal anisotropies observed in small and large collision systems. However, it poses a challenge to the current perfect-fluid paradigm for heavy ion collisions, at least when the collision system and/or energy are not very large.

Our earlier studies [1, 2] looked at all quarks (regardless of their flavors) and only investigated d+Au and Au+Au systems at 200*A* GeV. Here we study the flavor dependence of the parton escape mechanism, especially the charm quarks [5, 6]. As in the earlier studies, we use the string melting version of a multi-phase transport (AMPT) model [7] with the same parameters , which can reasonably describe the experimental data for the bulk matter for high energy heavy ion collisions [8]. We follow the entire evolution history of quarks of different flavors in AMPT and then analyze the developments

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of light (u and d quarks), strange, and charm v_2 in three systems: p+Pb collisions at 5A TeV and impact parameter $b=0$ fm, Au+Au collisions at 200A GeV and $b \in (6.6, 8.1)$ fm, and Pb+Pb collisions at 2.76A TeV and $b=8$ fm. Note that only the results for the Pb+Pb collisions are shown in the figures here, and the results of quarks and antiquarks of the same flavor have been combined.

2 Results

To follow the parton collision history in the AMPT model, we define N_{coll} as the number of collisions suffered by a parton. At any given N_{coll} value, we study three groups of quarks of a given flavor: freezeout partons (partons that freeze out after exactly N_{coll} collisions), non-freezeout partons (partons with more than N_{coll} collisions), and all (active) partons (sum of the previous two groups).

Figure 1a shows the v_2 of light (black), strange (blue), and charm (red) quarks within $|\eta| < 1$ as functions of the number of collisions N_{coll} for 2.76A TeV Pb+Pb collisions at $b = 8$ fm from AMPT simulations. We see a clear mass ordering in that $v_{2,u/d} > v_{2,s} > v_{2,c}$ at low N_{coll} but the opposite at high N_{coll}, indicating that charm quarks need more scatterings to generate their v_2. The normalized N_{coll} distribution and the average number of collisions of each quark flavor (of all pseudorapidities) are shown in Fig. 1b, where we see that charm quarks typically have more collisions than lighter quarks. This should be related to the initial spatial and momentum distributions, which are different for each quark flavor. For example, we find that, in comparison with light quarks, a bigger fraction of charm quarks is produced in the inner region of the overlap volume, consistent with the hard production nature of charm quarks and their scaling with binary collisions. In addition, we find that the above features in Fig.1 are true for all three collision systems in our study.

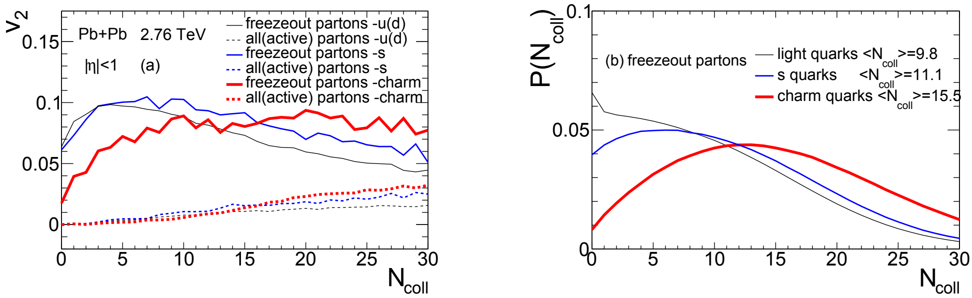

Figure 1. AMPT simulations of Pb+Pb collisions at 2.76A TeV and $b=8$ fm: (a) v_2 of light, strange, and charm quarks within $|\eta| < 1$ as functions of N_{coll}, where solid curves represent freezeout parton and dashed curves represent all (active) partons; (b) normalized N_{coll}-distributions of different quark flavors.

For partons that freeze out (i.e. hadronize) at $N_{coll} = 0$, their finite positive v_2, as shown in Fig. 1a, is due to the fact that it is easier to avoid collisions along the impact parameter direction in the transverse plane. As these partons have not been affected by the collective flow, their v_2 comes purely from the anisotropic escape probability, an interaction-induced response to the anisotropic geometrical shape that we named the escape mechanism. For partons that freeze out at $N_{coll} \neq 0$, however, their v_2 comes partly from the interaction-induced response to geometry and partly from the collective flow that is also anisotropic. In order to identify the contribution from the escape mechanism, we have designed the azimuth-randomized test to remove the collective flow [1, 2], where we randomize the azimuth angle of each of the two final state partons after every parton scattering. As a result, anisotropic flows in the azimuth-randomized simulations are generated only by the escape mechanism.

We show in Fig. 2 the v_2 as functions of N_{coll} for light, strange, and charm quarks within $|\eta| < 1$ from both normal AMPT simulations (solid curves) and azimuth-randomized AMPT simulations (dashed curves) of Pb+Pb collisions. Note that the average parton v_2 is the freezeout v_2 shown here summed with the weight given by the N_{coll}-distribution shown in Fig. 1b. First we see that the v_2 results from azimuth-randomized calculations are finite, although they are mostly lower than that from normal calculations due to the lack of the anisotropic collective flow. We also see that the reduction of v_2 going from normal to azimuth-randomized calculations is more obvious for heavier quarks, indicating that a smaller fraction of v_2 comes from the escape mechanism for heavier quarks.

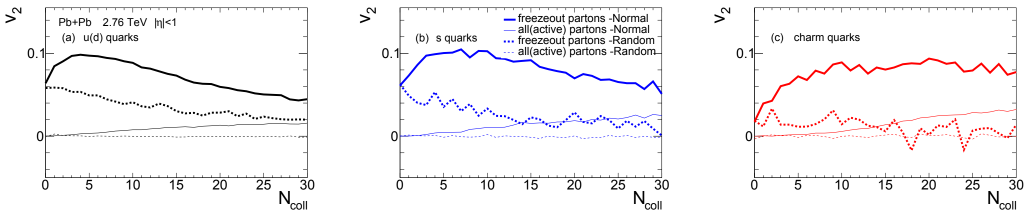

Figure 2. The v_2 of (a) light, (b) strange, and (c) charm quarks within $|\eta| < 1$ as functions of N_{coll} for Pb+Pb collisions at 2.76A TeV and $b = 8$ fm.

Another interesting test is to do azimuth-randomized calculations only for u/d/s quarks and antiquarks but not on charm, i.e., only charm quarks and antiquarks are allowed to keep their collective flow developed in the parton cascade. Results from this test are shown in Fig. 3a for charm quarks within $|\eta| < 1$ in Pb+Pb collisions, where we see that the freezeout charm v_2 is much reduced when compared to the normal charm v_2 (thick solid curve in Fig 2c) and is similar to the freezeout charm v_2 when all quark flavors are azimuth-randomized (thick dashed curve in Fig 2c). This means that charm quarks cannot develop a significant v_2 without the light quark collective flow.

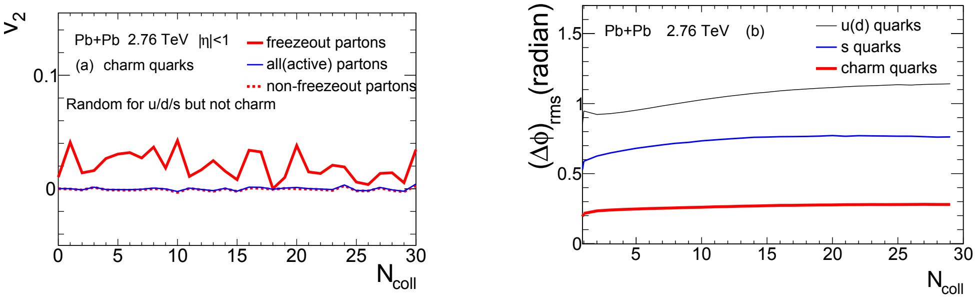

Figure 3. AMPT results of 2.76A TeV Pb+Pb collisions at $b = 8$ fm: (a) v_2 of three charm quark groups within $|\eta| < 1$ as functions of N_{coll} in simulations where u/d/s (but not charm) (anti)quarks are azimuth-randomized; (b) the rms change of azimuth due to the $N_{coll}-th$ collision for different quark flavors in normal simulations.

To further understand the flavor dependence, we have also looked at the effect of each parton collision on the azimuth of different flavors. Figure 3b shows the root-mean-square (rms) change of the azimuth angle, in radian, as a function of N_{coll} for different quark flavors (of all pseudorapidities) in Pb+Pb collisions. There is a clear mass ordering in that the average azimuth change is much smaller for heavier quarks, consistent with the expectation that it is more difficult to deflect a heavier quark in the parton cascade. Note that AMPT uses the same light quark mass as PYTHIA [9]: $m_u = 5.6, m_d = 9.9$, $m_s = 199$ MeV/c^2, and we use $m_c = 1.2$ GeV/c^2 for charm in this study.

Table 1 lists the ratios of the $\langle v_2 \rangle$ from azimuth-randomized AMPT over that from normal AMPT, where $\langle v_2 \rangle$ represents the v_2 averaged over all partons within $|\eta| < 1$, in four different collision systems at RHIC and LHC energies. This ratio represents the fraction of v_2 that comes from the escape

Table 1. Ratio of the averaged v_2 from azimuth-randomized simulations over that from normal simulations, which represents the fraction from the escape mechanism.

	d+Au at 200 GeV ($b=0$ fm)	p+Pb at 5 TeV ($b=0$ fm)	Au+Au at 200 GeV ($b=6.6-8.1$ fm)	Pb+Pb at 2.76 TeV ($b=8$ fm)
u/d	93% (all flavors)	72.9%	65.6%	42.5%
s		59.1%	47.4%	26.5%
c		56.8%	21.8%	8.5%

mechanism, i.e., from the interaction-induced response to the anisotropic geometry. Note that the d+Au result comes from our earlier study on quarks of all flavors [1]. We can see that the escape contribution decreases with the quark mass, more strongly for larger systems. It also decreases with the collision energy and/or system size, which is expected. Therefore these results show that the hydrodynamical collective flow contributes more to the v_2 of heavier quarks, especially in large systems at high energies, suggesting that heavy quark flows can better reflect the properties of the quark-gluon plasma. We note that similar claims have been made in studies from other points of view [10, 11].

3 Summary

We have followed the complete parton collision history to study the v_2 of light, strange and charm quarks in small and large collision systems at both RHIC and LHC energies using the string melting version of the AMPT model. We find that the fraction from the interaction-induced response to the anisotropic spatial geometry (the escape mechanism) decreases not only with the system size and collision energy but also with the quark mass (especially for large systems at high energies). The escape mechanism is no longer dominant for the light quark average v_2 in semi-central Pb+Pb collisions at 2.76 TeV but its contribution is stil significant. On the other hand, most of the charm quark v_2 comes from the hydrodynamical collective flow for the large systems covered in this study. We also find that the collective flow of light quarks is essential for the generation of charm quark v_2. These results indicate that heavy quark flows are better probes of QGP properties than light quark flows.

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