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Charm quarks are more hydrodynamic than light quarks in v_2

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Charm quark v_2 is a useful tool for studying the properties of quark-gluon plasma because charm quarks experience almost the entire evolution history of relativistic heavy ion collisions. Recent studies with transport models suggest that the majority of the overall quark v_2 at RHIC energies comes from the anisotropic escape of partons, not from the hydrodynamic flow. To address whether this is also true for the charm quark v_2, we trace the charm quark v_2 as a function of the number of collisions the charm quark suffers with other quarks in a multi-phase transport model. We find that the common escape mechanism is at work for both the charm and light quark v_2. However, contrary to the naive expectation, the hydrodynamic collective flow contributes more to the charm v_2 than the light quark v_2. Our finding thus highlights the importance of charm v_2 in the study of hydrodynamic properties of the quark-gluon plasma.

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1. Introduction

Collective anisotropic flow is a valuable probe to study the properties of quark-gluon plasma (QGP) in the heavy ion collisions [1, 2, 3, 4]. Large elliptic flow v_2 has been observed and is considered to reflect the hydrodynamic features of the QGP. In the hydrodynamics picture, the pressure gradient would generate an anisotropic expansion resulting in final-state anisotropic flows in momentum space, whose leading term is elliptical [5]. Recent studies within a multi-phase transport (AMPT) model indicate that the large parton v_2 comes mainly from the escape mechanism, where the partons have a larger probability to escape along the shorter axis of the overlap volume and the hydrodynamic contribution is not a major source at RHIC energies [6, 7]. It is further shown in AMPT that the mass splitting of identified hadron elliptic anisotropies mainly comes from hadronic scatterings and thus is not a unique signature of hydrodynamics as naively perceived [8, 9].

In these proceedings, we study the whole evolution history of charm quark v_2 [10, 11] and investigate the flavor dependence of the escape mechanism within the AMPT model. We consider three collision systems: $p+Pb$ collisions at 5 TeV with impact parameter b=0 fm, $Au+Au$ collisions at 200 GeV with b$\in(6.6, 8.1)$fm, and $Pb+Pb$ collisions at 2.76 TeV with b=8 fm. We use the string melting version of AMPT [12] with the same parameters as in our earlier studies.

2. AMPT Results

To trace the complete collision history of quarks with different flavors, we define N_{coll} as the number of collisions suffered by a parton. Fig. 1(a) shows the normalized N_{coll} distribution and the average number of collisions for each quark flavor. It indicates that charm quarks have larger $\langle N_{coll}\rangle$

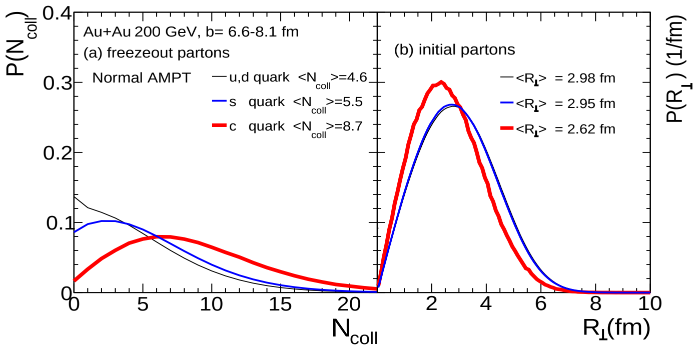

Figure 1: AMPT simulations of $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV with impact parameter $b \in$ 6.6-8.1 fm: (a) normalized N_{coll}-distributions of different quark flavors; (b) normalized probability distributions of the initial transverse radius $R_\perp$ for different quark flavors.

than light quarks. Part of the reason is because charm quarks are produced by hard scatterings at earlier times so having longer time to interact with other partons. The other reason is because charm quarks are produced more in the inner region of the collision volume than light quarks as shown in Fig. 1(b). We find that these features are similar in all three collision systems considered in our study [10, 11].

Figure 2 shows the freezeout parton v_2 of different flavors in both normal AMPT and azimuth-randomized AMPT calculations. We combine the quarks and antiquarks of the same flavor since they have almost identical v_2. In the randomized case, the parton azimuthal angles are randomized after each collision and hence their v_2 comes purely from the anisotropic parton escape. The freeze-out partons still have positive v_2 but the values are reduced from those in the normal case due to the lack of the additional hydrodynamic contribution. Fig. 2 indicates that the escape mechanism contributes to both charm and light quarks v_2. At $N_{coll} = 0$, the parton v_2 comes only from the escape mechanism because no collision has happened, and the charm v_2 is smaller than the light quarks v_2. It implies that the charm v_2 is less sensitive to the anisotropic escape than the light v_2, particularly in large collision systems.

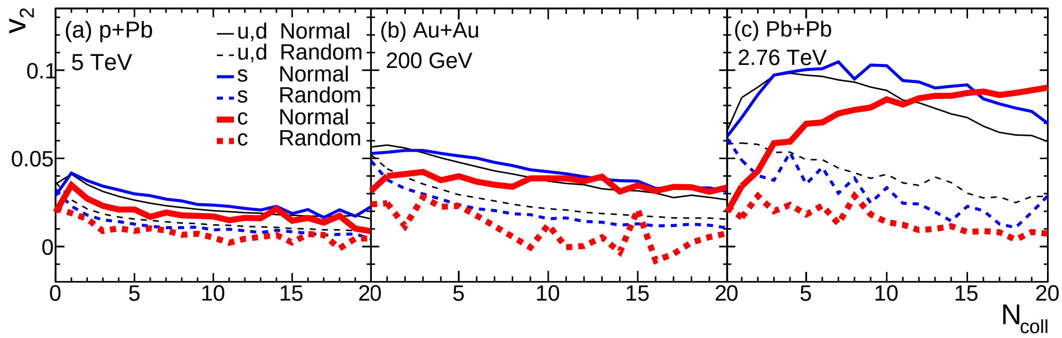

Figure 2: Freezeout parton v_2 within $|\eta| < 1$ as a function of N_{coll} in (a) $p+Pb$ collisions with $b = 0$ fm at $\sqrt{s_{\rm NN}} = 5$ TeV, (b) $Au+Au$ collisions with $b \in 6.6$-8.1 fm at $\sqrt{s_{\rm NN}} = 200$ GeV, and (c) $Pb+Pb$ collisions with $b = 8$ fm at $\sqrt{s_{\rm NN}} = 2.76$ TeV in normal (solid curves) and ϕ-randomized (dashed curves) AMPT.

We further calculate $\langle N_{\rm coll} \rangle$ and the ratios of v_2 from azimuth-randomized AMPT to that from normal AMPT as shown in Table 1. The $\langle N_{\rm coll} \rangle$ value of freezeout partons of a given flavor increases with the collision system size and beam energy as expected. The ratio of v_2 from ϕ-randomized AMPT to that from normal AMPT represents the fraction of v_2 that comes from the escape mechanism. It shows that the escape mechanism contribution to the light quark v_2 is larger than that to charm quark v_2 for the same collision system. Consequently, the hydrodynamic contribution to the light quark v_2 is more important for charm quarks. This result suggests that the charm v_2 better reflects the hydrodynamic properties of the quark-gluon plasma, especially for large systems at high energies. Similar conclusions have been reached by other authors [13, 14].

	pPb ($b = 0$ fm)			AuAu ($b \in 6.6$-8.1 fm)			PbPb ($b = 8$ fm)		
Quark flavor	u,d	s	c	u,d	s	c	u,d	s	c
$\langle N_{\rm coll} \rangle$	2.0	2.5	4.2	4.6	5.5	8.7	9.8	11.	15.
$v_{2_{Random}}/v_{2_{Normal}}$	73%	59%	57%	66%	47%	22%	43%	27%	8.5%

Table 1: $\langle N_{coll} \rangle$ and the ratio of v_2 from ϕ-randomized AMPT to that from normal AMPT for freezeout partons of different flavors within $|\eta| < 1$ in three collision systems.

3. Toy model study

To further understand the hydrodynamic contribution to charm v_2 and light quark v_2 in the large systems, we evaluate the root-mean-square (rms) change of the azimuth angle ($\sigma_{\Delta\phi}$) as a function of $N_{\rm coll}$ for different quark flavors in $Au+Au$ and $Pb+Pb$ collisions as shown in Fig. 3(left pannel). The rms change is approximately $\sigma_{\Delta\phi}$=1.0, 0.65, 0.25 for light, strange, and charm quarks, respectively; it is significantly smaller for heavier quarks [15]. To gain insights, we construct a toy model where partons start from the center $(x,y) = (0,0)$ and propagate out to the boundary of an ellipse that has an eccentricity $\varepsilon_2 = 0.17$ (corresponding to semi-central $Au+Au$ collisions). The number of collisions a parton suffers, assuming a straightline propagation (i.e. assuming a small total deflection angle), can be written as

$$N_{\rm coll}(\phi_i) = \langle N_{\rm coll}\rangle\,(1-2\varepsilon_2\cos 2\phi_i)\,,$$

where ϕ_i is the initial azimuthal angle of the parton. Note that $\langle N_{\rm coll}\rangle$ reflects the size of system. Assuming that the deflection angle from each scattering follows a Gaussian distribution, the cumulative deflection in the azimuth angle after the parton leaves the elliptical area is then Gaussian-distributed with the width of $\sigma_{\Delta\phi}\sqrt{N_{\rm coll}(\phi_i)}$. The parton average elliptic flow $\langle v_2\rangle$ can be calculated as

$$\langle v_2\rangle = \frac{1}{(2\pi)^{3/2}\sigma_{\Delta\phi}\sqrt{\langle N_{\rm coll}\rangle}}\int\frac{\cos 2(\phi_i+\delta\phi)}{\sqrt{1-2\varepsilon_2\cos 2\phi_i}}\exp\left(-\frac{\delta\phi^2}{2\sigma^2_{\Delta\phi}\langle N_{\rm coll}\rangle(1-2\varepsilon_2\cos 2\phi_i)}\right)d\phi_i d\delta\phi\,.$$

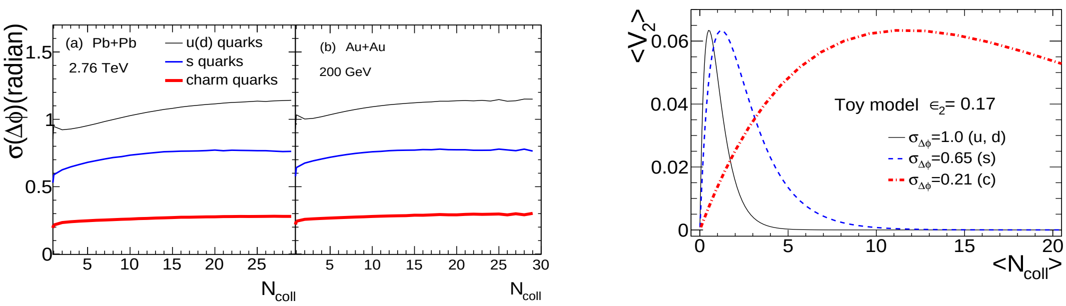

Figure 3: (left panel) The rms change of azimuth due to the $N_{coll}-th$ collision for different quark flavors in normal AMPT calculations of (a) $Pb+Pb$ and (b) $Au+Au$ collisions. (right panel) The freezeout partons $\langle v_2\rangle$ as a function of $\langle N_{coll}\rangle$ for quarks with different flavors from a toy model calculation for a transverse geometry at a given ε_2.

The $\langle v_2\rangle$ of light quarks is larger than that of charm quarks at small $\langle N_{\rm coll}\rangle$ but becomes smaller at large $\langle N_{\rm coll}\rangle$ as shown in Fig. 3 (right pannel). Partons along the longer y-axis suffer more collisions than those along the x-axis, and each collision deflects the parton from its original direction to a range of directions. As a result, more y-going partons will be deflected towards an isotropic distribution. Since $\sigma_{\Delta\phi}$ is large for light quarks, a small number of collisions is already strong enough to reshuffle the ϕ directions to produce a large v_2. However, also because $\sigma_{\Delta\phi}$ is large, light quarks easily forget their original direction, so the light quark v_2 quickly drops to zero at modest $\langle N_{\rm coll}\rangle$ in this toy model calculation. For charm quarks, on the other hand, it takes many collisions to build up a sizable v_2 because each collision can hardly deflect the charm quark direction. Moreover, $\langle v_2 \rangle$ only depends on the variable $\sigma_{\Delta\phi}\sqrt{\langle N_{\text{coll}} \rangle}$, therefore the average elliptic flow $\langle v_2 \rangle$ has the same peak value for all flavors while the peak occurs at a larger $\langle N_{\text{coll}} \rangle$ value for heavier quarks. Note that the v_2 from the toy model basically represents the v_2 generated by the escape mechanism, and after a large number of collisions partons of all flavors will be randomized and reach zero $\langle v_2 \rangle$. Our toy model calculation helps to illustrate the importance of the average scattering deflection angle, thus also the importance of quark mass, for the generation of v_2 by parton scatterings.

4. Summary

We have followed the entire parton collision history in the AMPT model to study the flavor dependence of parton v_2 in small and large collision systems from RHIC to LHC energies. We find that the escape mechanism contributes to both charm and light quark v_2. However, our results indicate that the charm v_2 mainly comes from the hydrodynamic collective flow for large systems. We further find that the fraction of the hydrodynamic contribution to the final partons v_2 is closely related to the parton average deflection angle from each collision. Our results suggest that the charm v_2 contains more information about the hydrodynamic properties of the QGP.

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