Origin of the Mass Ordering of v_n from a Multi-Phase Transport (AMPT)

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Abstract

The mass splitting of v_2 at low $p_\perp$ is often considered as a hallmark of hydrodynamic collective flow. We investigate the mass splitting with a multiphase transport model, where the azimuthal anisotropies v_n are mainly generated by the anisotropic parton escape mechanism instead of hydrodynamic flow. We demonstrate that the v_2 mass splitting in AMPT is small right after the hadronization; the mass splitting mainly comes from hadronic rescatterings, even though their contribution to the overall charged hadron v_2 is small. These findings are qualitatively the same as those from hybrid models that combine hydrodynamics with a hadron cascade. We further show that there is no qualitative difference between heavy ion collisions and small-system collisions, or between elliptic (v_2) and triangular (v_3) anisotropies. Our studies thus demonstrate that the mass splitting of v_2 and v_3 at low $p_\perp$ is not a unique signature of hydrodynamic collective flow but can be the interplay of several physics effects.

Introduction

The quark-gluon plasma has been created in relativistic heavy ion collisions. Of particular interests are non-central collisions, where the overlap volume of the colliding nuclei is anisotropic in the transverse plane perpendicular to the beam direction.
The pressure gradient and/or particle interactions would generate an anisotropic expansion, which converts the anisotropic geometry into the final-state elliptic flow. The mass splitting of hadron v_2 at low transverse momentum ($p_\perp$) is also observed in the experimental data.
It is often considered as a hallmark of the hydrodynamic description of relativistic heavy ion collisions, where a common but anisotropic transverse velocity field coupled with the Cooper-Frye hadronization and hadronic scatterings leads to the mass splitting [1-3].

A multiphase transport model (AMPT) can also reasonably reproduce the bulk experimental data at low $p_\perp$ including the azimuthal anisotropies v_n [4-6]. However, we recently found [7] that the azimuthal anisotropies v_n in transport models such as AMPT are mainly generated by the anisotropic parton escape, while hydrodynamics may play only a minor role. This escape mechanism naturally explains the similar azimuthal anisotropies in heavy ion and small system collisions. Since the mass splitting of hadron v_2 is also present in AMPT, it suggests that the hydrodynamic collective flow may not be the only mechanism that can generate the mass splitting of hadron v_n in collisions with high energy densities.
Our goal here [8] is to find the underlying reason for the mass splitting of v_n in AMPT.

The AMPT Model and Analysis Method

We employ the same string melting version of AMPT (v2.26t5, available online [9]) as in our earlier studies [7]. The model consists of fluctuating initial conditions, two-body parton elastic scatterings, quark coalescence for hadronization, and hadronic interactions. A parton scattering cross section of σ=3 mb is used. This version of AMPT [4] has been shown to reasonably reproduce particle yields, $p_\perp$ spectra, and v_2 of low-$p_\perp$ pions and kaons in central and mid-central Au+Au collisions at 200A GeV and Pb+Pb collisions at 2760A GeV.

We simulate three collision systems: Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with b=6.6-8.1 fm (representing the 20%-30% centrality), d+Au collisions at 200 GeV with b=0 fm, and p+Pb collisions at 5 TeV with b=0 fm. We compute the n_{th} harmonic plane of each event from its initial configuration of all partons in the transverse plane via

$$\psi_n^{(r)} = \frac{1}{n}\left[\mathrm{atan2}(\langle r_\perp^2 \sin n\phi_r\rangle, \langle r_\perp^2 \cos n\phi_r\rangle) + \pi\right]$$

The momentum anisotropies are then characterized by the Fourier coefficients as

$$v_n^{\mathrm{obs}} = \langle \cos n(\phi - \psi_n^{(r)})\rangle$$

where ϕ is the azimuthal angle of the parton or hadron momentum. All results shown here are for particles within the pseudo-rapidity window of $|\eta| < 1$.

Mass Splitting in Parton v_n

Fig.1 shows the v_2 and v_3 of light (u and d) quarks and strange (s) quarks in the three collision systems. The quark and antiquark anisotropies are found to be the same, so they are combined. At low $p_\perp$, the light quark v_2 (and v_3) is larger than the s quark's in the normal AMPT results (solid curves). This is qualitatively consistent with the picture where particles tend to move with a common collective flow velocity due to their interactions.

Dashed curves in Fig.1 represent the test results when we randomize the outgoing parton azimuthal directions after each parton scattering, where the final-state parton anisotropy is entirely due to the escape mechanism [7]. We also see clear mass splitting from this ϕ−randomized AMPT; this suggests that the mass splitting is caused by the mass or kinematic difference in the parton scatterings rather than the collective flow.

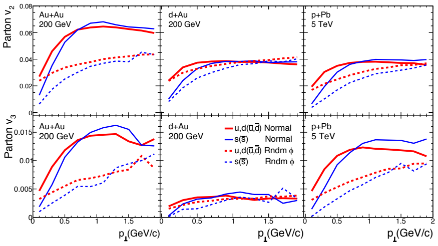

Fig.1 Massing splitting of parton v_n. Parton v_2 (*upper panels*) and v_3 (*lower panels*) as functions of $p_\perp$ for light (u and d) and strange (s) quarks in the final state from string melting AMPT.

Mass Splitting in Hadron v_n Before Hadronic Rescatterings

Fig.2 shows the initial hadron v_n directly after quark coalescence. For example, primordial pions have a larger v_2 at low $p_\perp$ than primordial ρ mesons due to the larger opening angles between the coalescing partons for the heavier ρ meson. Primordial protons have a larger v_2 at high $p_\perp$ than primordial π or ρ mesons because of the number of constituent quarks. Also, the decay product v_2 is usually smaller than the parent hadron v_2.

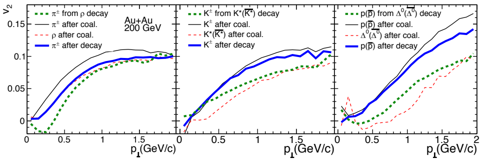

Fig.2 Initial hadron v_2 and the effect of resonance decays. The v_2 of primordial hadrons (black curves), resonances (red curves), decay products (green curves), and the total v_2 (including both the primordial hadrons and decay products, blue curves).

Mass Splitting in Hadron v_n After Hadronic Rescatterings

Fig.3 shows the initial hadron $v_2(p_\perp)$ before hadronic rescatterings (including resonance decays) and the final hadron $v_2(p_\perp)$ after hadronic rescatterings.
For Au+Au collisions, the pion v_2 at low $p_\perp$ increases after hadronic rescatterings, the proton v_2 decreases, while the kaon v_2 does not change significantly. This can be understood as the consequence of hadron interactions. For example, pions and protons tend to flow together at the same velocity due to their interactions. Thus, pions and protons at the same velocity (i.e. small-$p_\perp$ pions and large-$p_\perp$ protons) will tend to have the same anisotropy after rescatterings. This will then lead to lower v_2 for protons and higher v_2 for pions at the same $p_\perp$ value.

For d+Au collisions, however, the pion v_2 increases significantly with hadronic scatterings while the proton v_2 remains roughly unchanged. We find that the overall gain in the charged hadron v_2 in the hadron cascade is larger in d+Au than Au+Au collisions (see Fig4) due to the larger eccentricity in the d+Au system at the start of hadron cascade. Therefore the changes in the pion and proton v_2 in d+Au are a net effect of the mass splitting due to pion-proton interactions (i.e. increase in the pion v_2 and decrease in the proton v_2) and the overall gain of v_2 for charged hadrons.

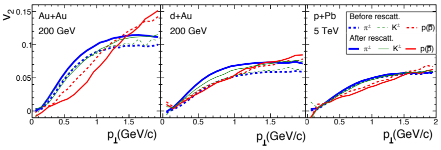

Fig.3 Effect of hadronic rescatterings. The v_2 of pions, kaons, and (anti-)protons as functions of $p_\perp$ before (*dashed curves*) and after (*solid curves*) hadron rescatterings in AMPT.

Fig.4 shows the time evolutions of v_2's and v_3's in the hadron cascade for hadrons within 0.8 < $p_\perp$ < 1.2 GeV/c as an example. Points in the shaded region represent primordial particles (right after the quark coalescence); points at t_{max}~0 represent initial particles including resonance decays (right after the quark coalescence); then hadron v_2's and v_3's (including resonance decays) are plotted as functions of the hadron cascade ending time t_{max}. We see that the mass splitting before hadron cascade is typically small. This small mass splitting does not change significantly during the first 5 fm/c in Au+Au collisions, since the partonic stage dominates the early evolution. Then a significant mass splitting is built up during the time of 5-20 fm/c in the hadron cascade. On the other hand, most of the charged particle overall v_n is built up in the parton phase; the additional gain from hadronic rescatterings is small. We see no qualitative difference between heavy ion collisions and small-system collisions, or between elliptic (v_2) and triangular (v_3) anisotropies.

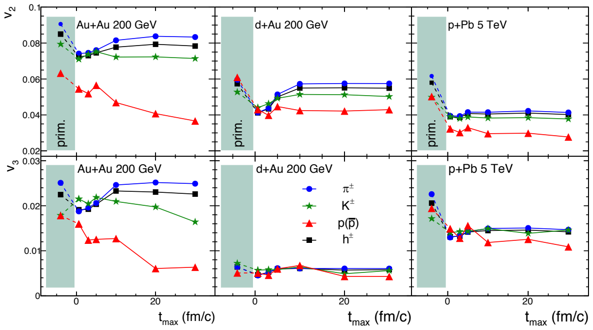

Fig.4 Origin of the mass splitting of v_n. The v_2 (*upper panels*) and v_3 (*lower panels*) of pions, kaons, (anti-)protons, and charged hadrons within 0.8<$p_\perp$<1.2 GeV/c at different stages of the hadronic evolution.

Conclusions

We have investigated the origin and development of the mass ordering of hadron v_2 and v_3 in heavy ion collisions and small system collisions with a multi-phase transport model AMPT. We show that a fraction of the mass ordering comes from kinematics in the quark coalescence process, while resonance decays tend to reduce the mass ordering. We find that the majority of the mass ordering comes from hadronic rescatterings, although they have little effect on the overall magnitude of charged hadron v_n. These findings are qualitatively the same as those from hybrid models that couple hydrodynamics to a hadron cascade, even though in transport models such as AMPT the anisotropic parton escape is the major source of v_n. Our results thus demonstrate that the v_n mass ordering may not be a distinctive signature of hydrodynamic collective flow, but can be a quantitative interplay of several physics processes.

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[9] AMPT source files are available at http://myweb.ecu.edu/linz/ampt/

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