Breaking of the number-of-constituent-quark scaling for identified-particle elliptic flow as a signal of phase change in low-energy data taken at the BNL Relativistic Heavy Ion Collider (RHIC)

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We argue that measurements of identified-particle elliptic flow in a wide energy range could shed light on the possible phase change in high-energy heavy ion collisions at the BNL Relativistic Heavy Ion Collider (RHIC). When the hadronization process is dominated by quark coalescence, the number-of-constituent-quark (NCQ) scaling for the identified-particle elliptic flow can serve as a probe for studying the strong interacting partonic matter. In the upcoming RHIC low-energy runs, the NCQ scaling behavior may be broken because of the change of the effective degrees of freedom of the hot dense matter, which corresponds to the transition from the dominant partonic phase to the dominant hadronic phase. A multiphase transport model is used to present the dependence of NCQ scaling behavior on the different hadronization mechanisms.

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The main purpose of the heavy ion program at the BNL Relativistic Heavy Ion Collider (RHIC) is to study the properties of the high-density matter produced in the heavy ion collisions, in particular, whether it undergoes a transition from the hadronic phase to the quark-gluon plasma (QGP) phase. Recently, many experimental results demonstrated that a hot and dense partonic matter has been indeed formed in ultrarelativistic energy heavy ion collisions at $\sqrt{s_{NN}} =$ 200 GeV [1]. To study this new form of matter, probes are essential to gaining information from the earliest stage of the collisions. Measurements of the collective motion, especially the elliptic flow v_2 of identified particles produced in heavy ion collisions, have long been suggested as a valuable tool for studying the nature of the constituents and the equation of state of the system in the early stage of the reaction [2]. Many significant results in the low-transverse-momentum range for elliptic flow v_2 of final-state particles have been obtained from RHIC experiments [3–7], which agree well with the predictions from ideal hydrodynamics [8]. More interestingly, a number-of-constituent-quark (NCQ) scaling behavior has been observed in the intermediate p_T range ($1.5 < p_T < 5\,\mathrm{GeV}/c$), which can be well reproduced by parton coalescence and recombination model calculations [9–12]. Such scaling indicates that the collective elliptic flow has been developed during the partonic stage and the effective constituent quark degree of freedom plays an important role in the hadronization process.

Simultaneously, some experimental and theoretical developments have suggested that important discoveries are possible at lower collision energies where the physics base may be completely different from the pictures at higher energies. Specifically, calculations from lattice QCD [13,14] predict a transition or fast cross-over between the QGP state and the hadronic matter at $T_c \approx 150 \sim 180$ MeV with vanishing baryon density. In addition, several observables in central Pb + Pb collisions from CERN Super Proton Synchrotron (SPS) experiments show qualitative changes in the energy dependence [15], e.g., the full phase-space ratios $\langle K^+\rangle/\langle\pi^+\rangle$ and $(\langle\Lambda\rangle + \langle K + \overline{K}\rangle)/\langle\pi\rangle$ showed a turnover and a decrease around $\sqrt{s_{NN}} \approx 7.6$ GeV after a steep increase at lower energies.

To gain more information about the existence of the possible phase transition between hadronic matter and partonic matter, the future RHIC physics program includes the Au + Au energy scan extending to low collision energies. Based on this, we shall focus our studies on the NCQ scaling of the identified-particle elliptic flow in a wide energy range. The turning on/off of the NCQ scaling behavior may indicate the onset of deconfinement: the scaling will be retained in the partonic phase at high energy, while it may be broken at lower energies when the system is dominated by hadronic interaction.

In noncentral collisions, the initial asymmetries in the geometry of the system can lead to anisotropies of the particle momentum distributions. Since the spatial asymmetries decrease rapidly with time, anisotropic flow can develop only in the first few fm/c. In that way, the properties of the hot dense matter formed during the initial stage of heavy ion collisions can be learned by measuring the anisotropic flow. The anisotropic flow is defined as the nth Fourier coefficient v_n of the particle distributions in emission azimuthal angle with respect to the reaction plane [16], which can be written as

$$\frac{dN}{d\phi} \propto 1 + 2\sum v_n \cos(n\Delta\phi), \quad (1)$$

where $\Delta\phi$ denotes the angle between the transverse momentum of the particle and the reaction plane. The second Fourier coefficient v_2 represents the elliptic flow that characterizes the eccentricity of the particle distributions in momentum space. At a given rapidity window, the second coefficient is

$$v_2 = \langle\cos(2\Delta\phi)\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle. \quad (2)$$

The measured elliptic flow v_2 as a function of transverse momentum p_T from the minimum-bias Au + Au collisions

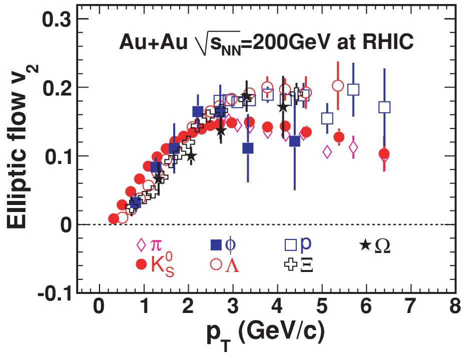

FIG. 1. (Color online) Experimental results of elliptic flow as a function of transverse momentum for π, K_S^0, p, Λ, ϕ, Ξ, and Ω with $|\eta| < 1.0$ in 0–80% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from RHIC. The results are taken from STAR experiments [3–6].

at $\sqrt{s_{NN}} = 200$ GeV for π, K_S^0, p, Λ, Ξ, ϕ, Ω are presented in Fig. 1. The results show that elliptic flow v_2 of all the particles increase with the transverse momentum, while the elliptic flow v_2 becomes saturated in the intermediate transverse momentum region. Moreover, the baryons saturate at $p_T \geqslant 3$ GeV/c with $v_2 \sim 0.2$, while meson saturation starts earlier at lower values of v_2. In addition, from Fig. 1, we find that although the multistrange baryons Ξ and Ω tend to undergo less rescattering in the hadronic stage, their v_2 values are as high as other hadrons at given p_T range, this means that the collectivity should be developed at the partonic stage.

A more intriguing phenomenon is that after scaling the values of both v_2 and p_T by the number of constituent quarks of the corresponding hadron, all particles can fall onto one single curve. However, the pion elliptic flow data are somewhat not following the scaling, which may be caused by the large contribution of pion yield from resonance decays [17,18]. Figure 2 shows elliptic flow v_2 as a function of transverse kinetic energy $(m_T - m)$ for the identified particles ($m_T = \sqrt{m^2 + p_T^2}$ is the transverse mass, while m is the rest mass of the particle), where v_2 and $(m_T - m)$ have been scaled by the number of constituent quarks (n_q). The measured elliptic flow

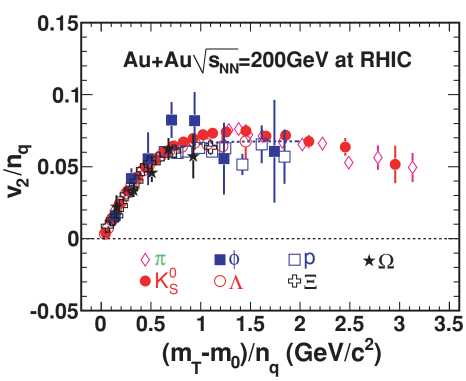

FIG. 2. (Color online) Number of constituent quark (n_q) scaled v_2/n_q vs scaled $(m_T - m)/n_q$. Dashed blue line is the result of fit with function (3).

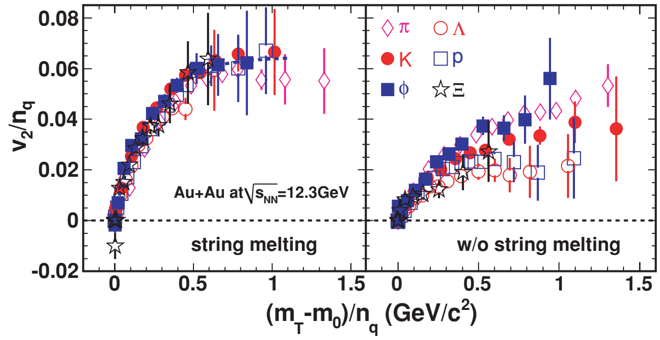

FIG. 3. (Color online) (Left panel) Number of constituent quark (n_q) scaled v_2/n_q vs scaled $(m_T - m)/n_q$ at Au + Au $\sqrt{s_{NN}} =$ 12.3 GeV from the AMPT model with string melting and without string melting. Dashed blue line is the result of fit with the function (3).

values can be fitted with the equation [18] given as

$$f_{v_2} = \frac{a}{1 + \exp[-(x - b)/c]} - d, \tag{3}$$

where a, b, c, and d are the parameters fixed from the fit. This universal curve represents the momentum space anisotropy of constituent quarks prior to hadron formation. However, this simple scaling neglects possible higher harmonics and possible differences between light and heavier quark flow.

Some coalescence or recombination models [9–12] can successfully describe the hadron production in the intermediate p_T region, where the NCQ scaling behavior has been observed. According to these models, hadronization is dominated by coalescence of quarks, and the essential degrees of freedom seem to be effective constituent quarks that have developed a collective elliptic flow during the partonic evolution. There are some common features in the intermediate p_T region below 5 GeV/c [19]: (i) the production probability for a baryon or meson is proportional to the product of local parton densities for the constituent quarks; (ii) baryons with transverse momentum p_T are mainly formed from quarks with transverse momentum $\sim p_T/3$, whereas mesons at p_T are mainly produced from partons with transverse momentum $\sim p_T/2$. Then the meson elliptic flow $v_{2,M}$ and baryon elliptic flow $v_{2,B}$ can be given by those of partons via [20]

$$v_{2,M}(p_T) \approx 2v_{2,q}\left(\frac{p_T}{2}\right), \tag{4}$$

$$v_{2,B}(p_T) \approx 3v_{2,q}\left(\frac{p_T}{3}\right). \tag{5}$$

Consequently, the collectivity of the constituent quarks become the collectivity of the hadrons via quark coalescence during the hadronization. Therefore, by scaling the observed v_2 signal and the transverse momentum with the number of constituent quarks n_q, one obtains the underlying quark flow.

Many experimental results [15] have shown anomalous dependence on the collision energy in the SPS energy range, especially the sharp changes around $\sqrt{s_{NN}} \approx 7.6$ GeV. All those phenomena suggest that a common underlying physics process is responsible for these changes. The authors of Refs. [21,22] argue that this anomaly is probably caused by the modification of the equation of state in the transition region between confined and deconfined matter. The low-energy runs at RHIC offer us opportunities to study the possible phase transition, thus the NCQ scaling behavior for the identified particles may be considered as a new signal of the onset of deconfinement located in the low-energy domain. We suppose that at lower collision energies, there would be no phase transition from hadronic matter to partonic matter. In this case, the hadrons are not produced from the coalescence of deconfined partons, and the collective flow does not stem from the partonic stage; therefore the NCQ scaling behavior for identified particles will be broken.

In the following, we will use a multiphase transport (AMPT) model [23] to investigate the NCQ scaling behavior of the identified particles under different hadronization mechanisms in Au + Au collisions. The AMPT model has an extensive agreement with data from the RHIC and the BNL Alternating Gradient Synchrotron (AGS) [23–28]. For example, by using parton-scattering cross sections of 6–10 mb, it was able to reproduce both the centrality and transverse momentum (below 2 GeV/c) dependence of the elliptic flow and pion interferometry measured in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV. It can explain the measured p_T dependence of both v_2 and v_4 of midrapidity charged hadrons and v_2 for ϕ meson as well as the dihadron correlation in the same collisions at $\sqrt{s_{NN}} = 200$ GeV. It was also demonstrated that there exists the NCQ scaling of v_2 not only for π, k, and p but also for multistrange hyperons in the AMPT model with the string melting scenario [26,28]. The AMPT model is a hybrid model that contains many processes of Monte Carlo simulation. There are four main components in the model: initial conditions, partonic interactions, conversion from partonic matter to hadronic matter, and hadronic interactions in collision evolution. First the hybrid model uses the minijet partons from the hard processes and the strings from the soft processes in the HIJING model as the initial phase [29], then the dynamical evolution of partons are modeled by the ZPC [30] parton cascade model, which calculates two-body parton scatterings using cross sections from pQCD with screening masses. The transition from partonic to hadronic matter is based on the Lund string fragmentation model [31]. The final-state hadronic scatterings are modeled by the A /Another Relativistic Transport (ART) model [32]. In the default AMPT model, minijets coexist with the remaining part of their parent nucleons, and together they form new excited strings; then the resulting strings fragment into hadrons according to the Lund string fragmentation. In the AMPT model with the string melting scenario, these strings are converted to soft partons, and their hadronization is based on a naive quark coalescence model.

We calculated the elliptic flow v_2 with different versions of the AMPT model in Au + Au collisions at $\sqrt{s_{NN}} =$ 12.3 GeV, which we assume will be running at RHIC in the future. Based on the momentum of identified particles, we extract the elliptic flow v_2 with formula (2). According to the discussion above, when there is a phase transition from hadron matter to quark-gluon plasma, the essential degrees of freedom at the hadronization seem to be effective constituent quarks, then we use the AMPT model with string melting to calculate the elliptic flow. The left panel of Fig. 3 shows the elliptic flow v_2 for identified particles calculated with the string melting scenario; it seems that the elliptic flow v_2 of the identified particles have a nice NCQ scaling behavior due to the coalescence of partons in the hadronization. On the other hand, if the degree of freedom of the system is dominated by the hadronic interaction, we will use the default AMPT model to calculate the elliptic flow; the right panel of Fig. 3 shows the elliptic flow v_2 of identified particles without string melting, and the NCQ scaling of elliptic flow v_2 is broken since hadrons are directly from the fragmentation of excited strings. In comparison with the string melting case, the v_2 values of identified particles show significant decreasing in the case without the string melting, which reflects that the partonic stage makes an important contribution to the development of sizable elliptic flow in the early stage.

In summary, we propose to use NCQ scaling for identified-particle elliptic flow as a unique observable to probe the effective degree of freedom of the system created in heavy ion collisions at RHIC. We argue that the presence or absence of the NCQ scaling behavior might indicate the turn on or turn off of the partonic degree of freedom of the system. The AMPT simulation has further confirmed our argument: the NCQ scaling is observed in the string melting scenario where full partonic evolution has been included, whereas it is broken in the default version with dominant hadronic interaction only. The upcoming RHIC low-energy measurement will help disentangle the different physics scenario as discussed.

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