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)

J. Tian,1,2 J. H. Chen,1 Y. G. Ma,1 X. Z. Cai,1 F. Jin,1,2 G. L. Ma,1 S. Zhang,1,2 and C. Zhong1

1Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
2Graduate School of the Chinese Academy of Sciences, Beijing 100080, China

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 Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL) is to study the properties of the high density matter produced in the heavy ion collisions, in particular, whether it undergoes a transition from hadronic phase to quark gluon plasma (QGP) phase. Recently, many experimental results demonstrated that a hot and dense partonic matter has been indeed formed in ultra-relativistic energy heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV [1]. In order to study this new form of matter, probes are essential to gain 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 to study 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 low transverse momentum range for elliptic flow $v_2$ of final state particles have been obtained from RHIC experiments [3, 1, 5, 6, 7] which consist 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 GeV/c < $p_T$ < 5 GeV/c), which can be well reproduced by parton coalescence and recombination model calculations [9, 10, 11, 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 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 $T_c \approx$ 150~180 MeV with vanishing baryon density. In addition, several observables in central Pb+Pb collisions from SPS experiments show qualitative changes in the energy dependence [15], e.g., the full phase space ratios $\langle K^+ \rangle$/$\langle \pi^+ \rangle$ and $\langle \Lambda \rangle$+$\langle K + \bar{K} \rangle$/$\langle \pi \rangle$ showed a turnover and a decrease around $\sqrt{s_{NN}} \approx$ 7.6 GeV after a steep increase at lower energies.

To gain the further 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 particles 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 in lower energy when the system is dominated by hadronic interaction.

In the non-central collisions, the initial asymmetries in the geometry of the system can lead to the 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 $n$th Fourier coefficient $v_n$ of the particle distributions in emission azimuthal angle with respect to the reaction plane [16], which can be written as

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

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, which characterizes the eccentricity of the particle distributions in momentum space. At a given rapidity window...
the second coefficient is
\[ v_2 = \langle \cos(2\Delta\phi) \rangle = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}; \]  
\[ (2) \]

The measured elliptic flow \( v_2 \) as a function of transverse momentum \( p_T \) from the minimum bias Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV for \( \pi, K^0_S, p, \Lambda, \phi, \Xi, \Omega \) 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 \( p_T \geq 3 \) GeV/c with \( v_2 \sim 0.2 \), while the mesons saturation starts earlier at lower values of \( v_2 \). In addition, from FIG. 1 we can find that although the multi-strange baryons \( \Xi \) and \( \Omega \) tend to undergo less re-scatterings in the hadronic stage, their \( v_2 \) values are as high as others hadrons at given \( p_T \) range, this means that the collectivity should be developed at the partonic stage.

More intriguing phenomenon is that after scaling both values of \( v_2 \) and \( p_T \) by the number of the 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 \[ 17, 18 \]. FIG. 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 values can be fitted with the equation \[ 18 \] given as
\[ f_{v_2} = \frac{a}{1 + \exp(-(x - b)/c)} - d, \]  
\[ (3) \]
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 \[ 9, 10, 11 \] can successfully describe the hadron production in the intermediate \( p_T \) region, where the NCQ-scaling behavior has been observed. According to these models, the 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 \[ 20 \]
\[ v_{2,M}(p_T) \approx 2v_{2,q}(\frac{p_T}{2}), \]  
\[ v_{2,B}(p_T) \approx 3v_{2,q}(\frac{p_T}{3}). \]  
\[ (4)(5) \]
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. Ref. [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 partonic stage, therefore the NCQ-scaling behavior for identified particles will be broken.

In the following, we will use a multi-phase 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 extensively agreement with the RHIC data and AGS data [23, 24, 25, 26, 27, 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 $\phi$ meson as well as di-hadron 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 $\pi$, $k$ and $p$ but also for multi-strange hyperons in the AMPT model with the string melting scenario [26, 28]. The AMPT model is a hybrid model which contains many processes of Monte Carlo simulation. There are four main components in the model: initial conditions, partonic interactions, conversion from partonic matter into 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 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 the partonic matter to the hadronic matter is based on the Lund string fragmentation model [31]. The final-state hadronic scatterings are modeled by the 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 AMPT model in Au+Au collisions at $\sqrt{s_{NN}} = 12.3$ GeV, which assumed to be running at RHIC in the future. Based on the momentum of identified particles, we extract the elliptic flow $v_2$ with formula (2). Accord-
In summary, we proposed to use the NCQ-scaling for identified particles elliptic flow as a unique observable to probe the effective degree of freedom of the system created in heavy ion collisions at RHIC. We argued 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 while it is broken in the default version with dominant hadronic interaction only. The upcoming RHIC low energy measurement will help to disentangle the different physics scenario as discussed.

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