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Scaling of elliptic flow in heavy-ion collisions with the number of constituent quarks in a transport model

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We studied the number of constituent quark scaling (NCQ) behavior of elliptic flow (v_2) under the framework of a multiphase transport model (AMPT) at both top-RHIC and LHC energies. The NCQ-scaling in v_2 holds at top RHIC energy with AMPT string melting version, while it breaks in Pb+Pb collisions at LHC energy using the same framework. The breaking of NCQ scaling at LHC energy has been studied by varying the magnitude of parton-parton scattering cross sections and lifetime of hadronic cascade as implemented in AMPT. We find that the breaking of NCQ scaling in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is independent of the magnitude of parton-parton cross sections and the later stage hadronic interactions. Further we observed that scaling holds in a small collision system like Si+Si at $\sqrt{s_{NN}} = 2.76$ TeV. We discussed that the breaking of NCQ scaling is possibly due to high phase-space density of constituents quarks in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

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I. INTRODUCTION

Relativistic heavy-ion collision experiments aim to study the formation and evolution of a strongly interacting matter called quark gluon plasma (QGP) [1]. Experiments at Brookhaven Relativistic Heavy Ion Collider (RHIC) and at CERN Large Hadron Collider (LHC) established the existence of such strongly interacting matter, which is expected to be formed microseconds after the big bang.

The elliptic flow parameter, v_2, which is defined as a second harmonic coefficient of the azimuthal Fourier decomposition of the momentum distribution of produced particles, has been widely used as an excellent tool for understanding the dynamics of the system formed in the early stages of high-energy heavy-ion collisions [2–8]. This flow parameter v_2 is extracted by studying the correlation of produced particles with respect to the reaction plane (Ψ) as

$$v_2 = \langle \cos[2(\phi - \Psi)] \rangle, \qquad (1)$$

where ϕ is the azimuthal angle of the produced particles [9].

Results from RHIC experiments show that at low transverse momentum ($p_T < 2$ GeV/c), there is a clear mass ordering of v_2 among the identified hadrons [10,11]. It is observed that at fixed p_T, heavier hadrons have smaller values of v_2 than the lighter ones. Hydrodynamic calculations suggest that the interplay between radial and elliptic flow plays an important role in determining the mass ordering of v_2 at low p_T [2–7]. Subsequent later stage hadronic rescattering can also distort v_2 at low p_T [12]. It is observed that in the intermediate-p_T region ($2.0 < p_T < 4.0$ GeV/c), the p_T differential v_2 of baryons and mesons form separate groups [10,11]. Such a baryon-meson splitting in v_2 is successfully reproduced by models where a quark-coalescence mechanism is considered to be the dominant process for hadronization in this p_T regime [13,14]. When both v_2 and p_T of identified hadrons are divided by number of constituent quarks (n_q), all the hadrons follow an approximate scaling behavior. This is known as number of constituent quark (NCQ) scaling. The origin of such scaling is interpreted as an evidence for dominance of quark degrees of freedom in the early stages of heavy-ion collision. Another way of representing NCQ scaling is to plot n_q scaled v_2 as a function of $(m_T - m_0)/n_q$, where m_T is transverse mass and m_0 is the rest mass of hadrons.

Recent v_2 results from LHC [15] show a similar trend of mass ordering among the identified hadrons at low p_T (<3 GeV/c) and about 30% increase in radial flow than the top RHIC energy. But in the intermediate p_T region ($3.0 < p_T < 6.0$ GeV/c), the v_2 results do not seem to follow NCQ scaling as observed in lower energy RHIC experiments. The v_2 of identified hadrons at LHC energy deviates from NCQ scaling at a level of 20%. This observation has triggered theoretical debate over the NCQ scaling.

A multiphase transport (AMPT) model with string melting version (which includes parton coalescence) has been used to reproduce the observed NCQ scaling in v_2 at top RHIC energies [16]. In this paper, we investigated the behavior of NCQ scaling both at top RHIC and LHC energies using the framework of AMPT model to understand the reason behind its breaking at higher energies.

This paper is organized as follows. In Sec. II, we briefly discuss the AMPT model. In Sec. III, we describe the NCQ scaling behavior of v_2 of identified hadrons at top RHIC and LHC energies using the AMPT model (version 1.11). The results are summarized in Sec. IV.

II. THE AMPT MODEL

The AMPT model, which is a hybrid transport model, has four main stages: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and hadronic interactions [16]. It uses the same initial conditions as HIJING [17]. Scattering among partons are modeled by Zhang's parton cascade [18], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. In the default AMPT model, partons are recombined with their parent strings and when they stop interacting,

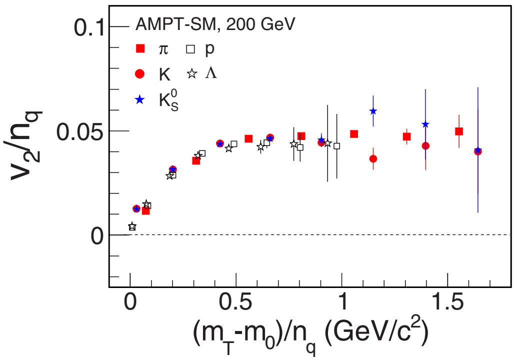

FIG. 1. v_2/n_q as a function of $(m_T - m_0)/n_q$ for some selected hadrons (π, K, K^0_S, p, and Λ) in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the AMPT-SM model. The parton-parton cross section is taken as 3 mb with hadronic cascade time =30 fm in the AMPT-SM model.

the resulting strings fragment into hadrons according to the Lund string fragmentation model [19]. However, in the string melting scenario (labeled as AMPT-SM), these strings are converted to soft partons and a quark coalescence model is used to combine partons into hadrons. The evolution dynamics of the hadronic matter is described by a relativistic transport (ART) model. The interactions between the minijet partons in the AMPT default model and those between partons in the AMPT-SM could give rise to substantial v_2. The parton-parton interaction cross section in the string-melting version of the AMPT is taken to be 3 and 10 mb. In this study, approximately 500 K (50 K) events for each configuration were generated for minimum-bias Au+Au (Pb+Pb) collisions.

III. RESULTS AND DISCUSSION

It has been observed that NCQ scaling in v_2 holds for AMPT with the string melting scenario, which incorporates partonic coalescence mechanism, but no such scaling occurs in the default AMPT [20]. We studied the energy dependence of such scaling using AMPT-SM, mainly at top RHIC and LHC energies. Figure 1 shows v_2/n_q as a function of $(m_T - m_0)/n_q$ for some selected hadrons (π, K, K^0_S, p, and Λ) in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using the AMPT-SM model. A clear scaling is observed among all hadrons consistent with the observation in Ref. [20]. Here we used parton-parton cross section (σ_{PP}) equal to 3 mb and hadron cascade time (τ) equal to 30 fm in these results.

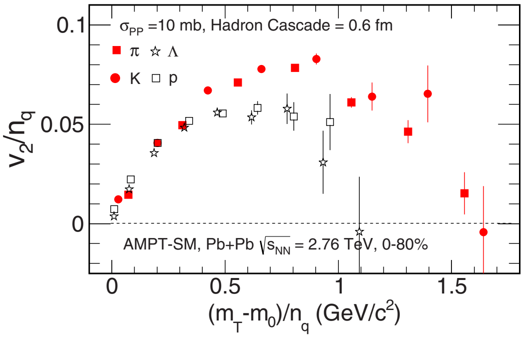

FIG. 3. v_2/n_q as a function of $(m_T - m_0)/n_q$ for some selected hadrons (π, K, p, and Λ) in minimum bias Pb+Pb collisions at 2.76 TeV using AMPT-SM model ($\sigma_{PP} = 10$ mb, $\tau = 0.6$ fm).

After observing a clear scaling at 200 GeV, we studied NCQ scaling in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using AMPT-SM model as shown in Fig. 2. A clear breaking of scaling is observed for $(m_T - m_0)/n_q > 0.4$ GeV/c^2, which is very striking and interesting as we have used the AMPT-SM model. Figures 2(a) and 2(b) show scaling results where the magnitudes of σ_{PP} have been taken as 3 and 10 mb, respectively, keeping same hadron cascade time (30 fm). It is clear that scaling breaks down for both the values of σ_{PP}. This indicates that the breakdown of NCQ scaling at $\sqrt{s_{NN}} = 2.76$ TeV is independent of the magnitude of the parton-parton cross section.

One possible reason for the violation may be the distortion of initially developed v_2 by later hadronic interaction. To check this effect, we turn off hadronic cascade in AMPT model. This can be done by setting input parameter $Nt = 3$, which gives hadron cascade time equal to 0.6 fm (minimum hadron cascade time in AMPT). The NCQ scaling result from AMPT-SM ($\sigma_{PP} = 10$ mb) with hadron cascade time 0.6 fm is shown in Fig. 3. In this case too we have observed that the scaling

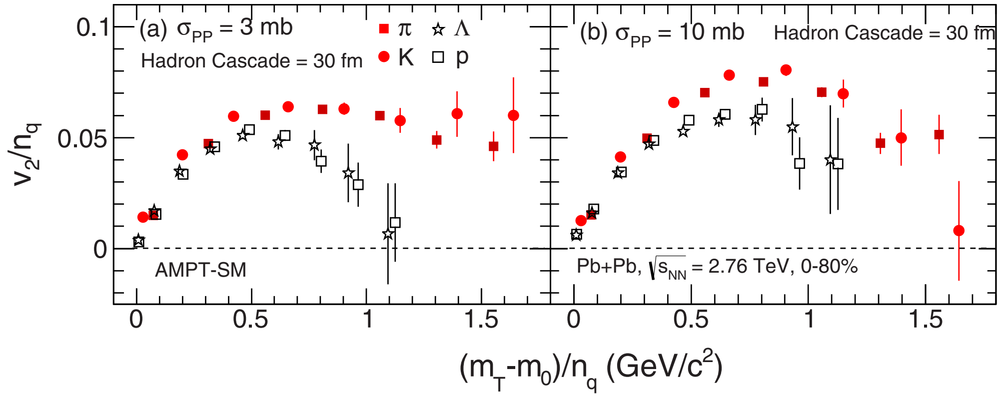

FIG. 2. v_2/n_q as a function of $(m_T - m_0)/n_q$ for some selected hadrons (π, K, p, and Λ) in minimum bias (a) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and (b) Pb+Pb collisions at 2.76 TeV using the AMPT-SM model.

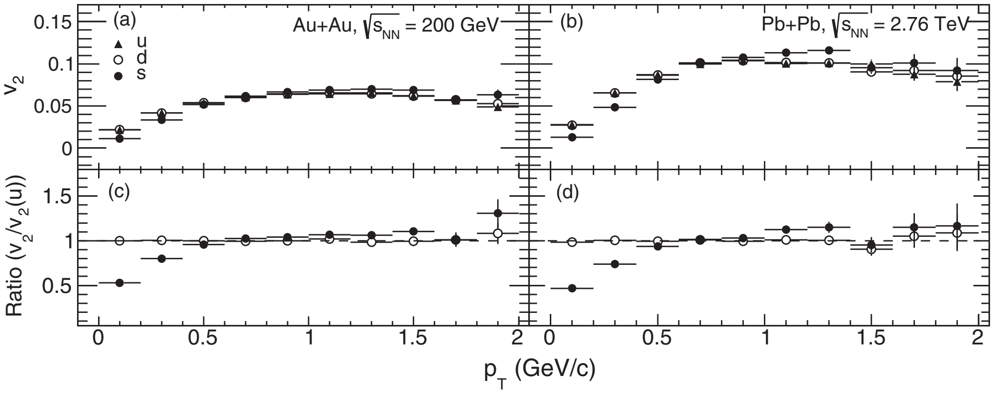

FIG. 4. The v_2 of u, d, and s quarks as a function of p_T in AMPT-SM model ($\sigma_{PP} = 3$ mb) for minimum bias (a) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and (b) Pb+Pb collisions at 2.76 TeV. Ratios with respect to u-quark v_2 are shown in the corresponding lower panel.

breaks, indicating that it is not due to the hadronic interactions at $\sqrt{s_{NN}} = 2.76$ TeV.

A. Quark-$v_2(p_T)$ distributions in AMPT model

According to coalescence model the relation between quark-v_2 (v_2^q) and hadrons-v_2 (v_2^h) is as follows:

$$v_2^h(p_T) = n_q v_2^q(p_T/n_q), \tag{2}$$

where p_T is the transverse momentum of hadron. The violation of NCQ scaling at LHC energy within a parton coalescence approach was first predicted in Ref. [21]. According to Ref. [21], modifications of the underlying light and heavy quark $v_2(p_T)$ due to the strong transverse expansion at LHC energy could be the reason for NCQ scaling violation. To understand such behavior in Pb+Pb collisions at 2.76 TeV, we have checked underlying $v_2(p_T)$ for different quark flavors in the AMPT-SM model.

The v_2 of u, d, and s quarks as a function of p_T in the AMPT-SM model ($\sigma_{PP} = 3$ mb) are shown in Figs. 4(a) and 4(b) for $\sqrt{s_{NN}} = 200$ GeV (Au+Au) and 2.76 TeV (Pb+Pb), respectively. Ratios with respect to u-quark v_2 are shown in the corresponding lower panel. We have observed that the $v_2(p_T)$ of u, d, and s quarks are the same for both the energies in AMPT-SM model. However, for $p_T < 0.5$ GeV/c, magnitude of s-quark v_2 is slightly lower than that of u and d. It is clear from Fig. 4 that the $v_2(p_T)$ distribution for different quark flavors is similar for both Au+Au and Pb+Pb collisions at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV, respectively. Therefore, the breaking of NCQ scaling in the AMPT-SM model for Pb+Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV is not due to change in $v_2(p_T)$ of underlying quarks.

B. Effect of parton density in coalescence mechanism

Let us recall the formalism of coalescence mechanism. In a simplified coalescence scenario, the probability that the constituents a and b will form a composite object C [13] is

$$f_C(P_C,R,t_c) \approx f_a(m_aP_C/(m_a+m_b),R,t_c) \times f_b(m_bP_C/(m_a+m_b),R,t_c). \tag{3}$$

Here f_i denotes phase densities, P_C is the momentum of the composite particle, t_c is the coalescence time, and R is the center of mass. Masses of constituents are denoted by m_i. Within the regime of coalescence mechanism, the invariant spectrum of produced particles is proportional to the product of the invariant spectra of constituents. Therefore, the yields of mesons and baryons produced by coalescence of quarks (q) are given by

$$\frac{dN_B}{d^2p_T}(p_T) = f_B(p_T)\left[\frac{dN_q}{d^2p_T}(p_T/3)\right]^3, \tag{4}$$

$$\frac{dN_M}{d^2p_T}(p_T) = f_M(p_T)\left[\frac{dN_q}{d^2p_T}(p_T/2)\right]^2, \tag{5}$$

where the coefficients f_M and f_B are the probabilities for meson and baryon coalescence. Note that Eqs. (2), (4), and (5) are valid only when the phase-space density is very small [13]. When phase-space density of quarks is very high, the probability of finding another quark in the vicinity will be close to unity, so the final composite v_2 of hadron will be linear in terms of the quark's v_2 and hence break the scaling relation. On the other hand, for low density, a quark has a small probability of finding another quark to coalesce, and Eqs. (2), (4), and (5) will be valid.

So the change in phase space density of quarks can affect the coalescence mechanism and it can be studied using the AMPT model. We generated 2 million Si+Si collision events at $\sqrt{s_{NN}} = 2.76$ TeV using the same AMPT-SM configuration ($\sigma_{PP} = 3$ mb, $\tau = 0.6$ fm). Because of small system size, we would expect a smaller density compared to that in Pb+Pb collisions. So if NCQ scaling at LHC energies in Pb+Pb collisions breaks due to the high density of partons, the scaling might hold in Si+Si collision system at the same center-of-mass energy. Figure 5 shows the NCQ scaling plot for the minimum-bias Si+Si system at $\sqrt{s_{NN}} = 2.76$ TeV. We can see that NCQ scaling holds much better than the Pb+Pb system. This confirms that the breaking of NCQ scaling of v_2 in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is due to very high phase-space density of initially produced quarks.

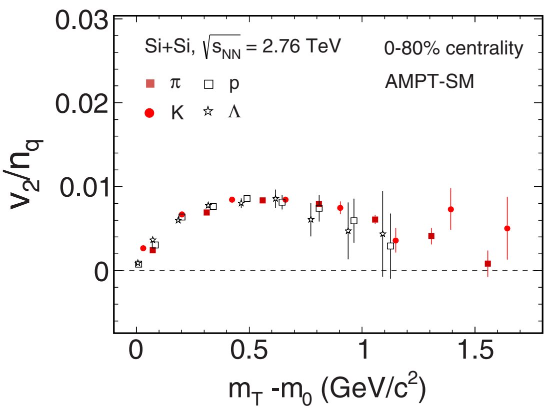

FIG. 5. v_2/n_q as a function of $(m_T - m_0)/n_q$ for some selected hadrons (π, K, p, and Λ) in minimum-bias Si+Si collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the AMPT-SM model ($\sigma_{PP} = 3$ mb, $\tau = 0.6$ fm).

IV. SUMMARY AND CONCLUSION

In summary, we have studied the number of constituent quark scaling in v_2 for hadrons at top RHIC and LHC energies using the AMPT-SM model. We have observed that while NCQ scaling holds at $\sqrt{s_{NN}} = 200$ GeV, the model fails to reproduce the same in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. We have observed the breaking in NCQ scaling at $\sqrt{s_{NN}} = 2.76$ TeV is independent of the magnitude of parton-parton cross sections and also not due to later-stage hadronic interactions. We also compared v_2 of u, d, and s quarks as a function of p_T for Au+Au and Pb+Pb collisions in the AMPT-SM model to see any possible change in underlying quark $v_2(p_T)$ due large radial flow at LHC energy. We find $v_2(p_T)$ of u, d, and s quarks shows similar behaviors for both Au+Au and Pb+Pb collisions. Therefore, the violation in NCQ scaling is not due to change in underlying quark $v_2(p_T)$ in Pb+Pb collisions at LHC energy. Further, we checked the effect of parton's phase-space density on NCQ scaling behavior within the framework of coalescence. We observed that the scaling holds in a small collision system like Si+Si at $\sqrt{s_{NN}} = 2.76$ TeV where the phase-space density of constituent quarks is not very high as compared to Pb+Pb. This observation can be well understood in the framework of coalescence mechanism. Our study shows that the NCQ scaling in v_2 is not a necessary condition for quark coalescence when phase-space density of constituent quarks is very high, e.g., Pb+Pb collision at LHC energies.

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[1] I. Arsene *et al.* (BRAHMS Collaboration), Nucl. Phys. A **757**, 1 (2005); B. B. Back *et al.* (PHOBOS Collaboration), *ibid.* **757**, 28 (2005); J. Adams *et al.* (STAR Collaboration), *ibid.* **757**, 102 (2005); K. Adcox *et al.* (PHENIX Collaboration), *ibid.* **757**, 184 (2005).
[2] P. F. Kolb *et al.*, Nucl. Phys. A **715**, 653c (2003).
[3] D. Teaney, J. Lauret, and E. V. Shuryak, Phys. Rev. Lett. **86**, 4783 (2001).
[4] P. F. Kolb and U. Heinz, arXiv:nucl-th/0305084.
[5] P. F. Kolb *et al.*, Phys. Lett. B **500**, 232 (2001).
[6] H. Sorge, Phys. Rev. Lett. **78**, 2309 (1997).
[7] P. Huovinen *et al.*, Phys. Lett. B **503**, 58 (2001).
[8] B. Zhang *et al.*, Phys. Lett. B **455**, 45 (1999).
[9] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998).
[10] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92**, 052302 (2004); B. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **75**, 054906 (2007); J. Adams *et al.* (STAR Collaboration), *ibid.* **72**, 014904 (2005); B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **99**, 112301 (2007).
[11] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 182301 (2003); S. Afanasiev *et al.* (PHENIX Collaboration), *ibid.* **99**, 052301 (2007); A. Adare *et al.* (PHENIX Collaboration), *ibid.* **98**, 162301 (2007); Phys. Rev. C **85**, 064914 (2012).
[12] T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey, and Y. Nara, Phys. Lett. B **636**, 299 (2006).
[13] D. Molnar and S. A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003); S. Pratt and S. Pal, Phys. Rev. C **71**, 014905 (2005).
[14] C. Nonaka *et al.*, Phys. Lett. B **583**, 73 (2004); V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003); R. J. Fries *et al.*, Ann. Rev. Nucl. Part. Sci. **58**, 177 (2008); R. C. Hwa and C. B. Yang, *ibid.* **70**, 024904 (2004).
[15] B. Abelev *et al.* (ALICE Collaboration), J. High Energy Phys. 06 (2015) 190; K. Aamodt *et al.* (ALICE Collaboration), Phys. Rev. Lett. **105**, 252302 (2010).
[16] Z.-W. Lin and C. M. Ko, Phys. Rev. C **65**, 034904 (2002); Z.-W. Lin *et al.*, *ibid.* **72**, 064901 (2005); L.-W. Chen *et al.*, Phys. Lett. B **605**, 95 (2005).
[17] X. N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991).
[18] B. Zhang, Comput. Phys. Commun. **109**, 193 (1998).
[19] B. Andersson *et al.*, Phys. Rep. **97**, 31 (1983).
[20] B. Mohanty and N. Xu, J. Phys. G **36**, 064022 (2009).
[21] D. Krieg and M. Bleicher, Phys. Rev. C **78**, 054903 (2008).