Quark Matter 2017

Investigating the scaling of higher-order flows in relativistic heavy-ion collisions

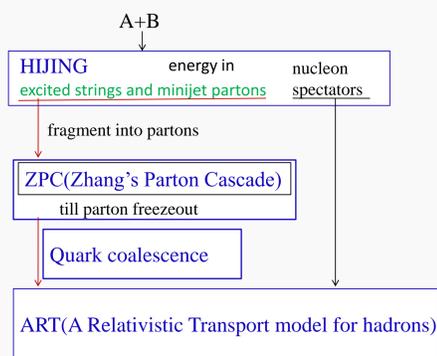Chun-Jian Zhang, and Jun Xu*

Abstract

The modified number of constituent quark (NCQ) scaling $\upsilon_n/n_q^{n/2} \sim KE_T/n_q$ for mesons and baryons and the scaling relation $\upsilon_n \sim \upsilon_2^{n/2}$ for higher-order anisotropic flows, which were observed experimentally, have been investigated at the top energy of Relativistic Heavy-Ion Collider. It has been found that the modified NCQ scaling cannot be obtained from the naive coalescence even by taking into account event-by-event fluctuations but may be due to hadronic afterburner or thermal freeze-out. In addition, we observed that the behavior of the $\upsilon_n/\upsilon_2^{n/2}$ ratio is sensitive to the partonic interaction. Further insights about the relation between the two scalings are discussed.

Models and Formalism

AMPT model

The AMPT model with string melting scenario is utilized in this work which is used to give a reasonable final parton-phase distribution and serves as a useful tool to test the effect of hadronic afterburner. It consists of four main stages of high-energy heavy-ion collisions: the initial conditions, parton cascade, hadronization, and hadronic rescattering.

A+B

HIJING — energy in excited strings and minijet partons, nucleon spectators

fragment into partons

ZPC(Zhang's Parton Cascade)
till parton freezeout

Quark coalescence

ART(A Relativistic Transport model for hadrons)

Analytical coalescence

Azimuthal distribution of the parton transverse momentum spectra considering fluctuation:

$$f(p_T,\phi) \propto 1 + 2\sum_{n=1}^{\infty}\upsilon_n(p_T)\cos[n(\phi-\psi_n)]$$

In this limit the azimuthal distribution of mesons and baryons can be expressed respectively as:

$$F(2p_T,\phi) \propto f^2(p_T,\phi) \propto 1+\sum_{n=1}^{\infty}V_n(2p_T)\cos[n(\phi-\psi_n)]$$

$$\tilde{F}(3p_T,\phi) \propto f^3(p_T,\phi) \propto 1+2\sum_{n=1}^{\infty}\tilde{V}_n(3p_T)\cos[n(\phi-\psi_n)]$$

Ψ_n is the nth-order event plane angle, ϕ is the azimuthal angle, and υ_n is the nth-order anisotropic flow.

Blast wave model

Lorentz invariant one-particle distribution function:

$$f(\vec{r},\vec{p}) \propto \exp(p^\mu u_\mu / T_f)$$

The nth-order azimuthal velocity:

$$\rho(n,\phi,r) = \rho_0\left\{1+\sum_{n=1}^{\infty}\rho_n\cos[n(\phi-\psi_n)]\right\}\frac{r}{R_{\max}}$$

The spatial density anisotropies:

$$S(n,\phi) = 1+\sum_{n=1}^{\infty}s_n\cos[n(\phi-\psi_n)]$$

T_f is the freeze-out temperature, $p^\mu = \{E,p_x,p_y,p_z\}$ is the four-momentum, $u^\mu=\gamma\{1,\rho_x,\rho_y,\rho_z\}$ is the four-velocity field with $\gamma = 1/\sqrt{1-\rho_x^2-\rho_y^2-\rho_z^2}$. ψ_n is the event plane but is set to 0, we simply set $\rho_n = 0.43$ and $s_n = -0.05$ fm to be the same for different orders n. The values of the other parameters are used to describe the initial hadron distribution before hadronic evolution in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and they are $T_f = 175$ MeV, R = 5.0 fm, and $\rho_0 = 0.55$.

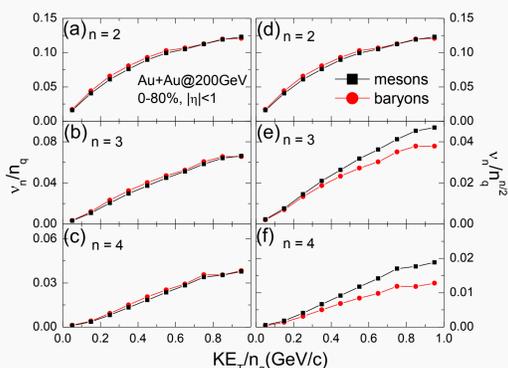## Results and Discussions

The modified NCQ scaling

FIG. 1. Scaling relations of hadrons $\upsilon_n \sim KE_T$ in minibias Au+Au collisions at $\sqrt{sNN} = 200$ GeV from the analytical coalescence scenario.

$\upsilon_n = C_n^m \upsilon_2^{n/2}$,(for mesons)

$\upsilon_n = C_n^b \upsilon_2^{n/2}$,(for baryons)

If the NCQ scaling for v_n is satisfied, i.e., $\upsilon_2/n_q = g(KE_T/n_q)$ we automatically get the modified NCQ scaling relation for higher-order flows (n > 2):

$\upsilon_n^m/n_q^{n/2} = C_n^m g^{n/2}(KE_T/n_q)$,(for mesons)

$\upsilon_n^b/n_q^{n/2} = C_n^b g^{n/2}(KE_T/n_q)$,(for baryons)

If the value of $F_0/\tilde{F}_0$ is approximated to be 1,

$C_n^m/C_n^b \approx \sqrt{3/2}$,(for n=3)

$C_n^m/C_n^b \approx \sqrt{3/2}$,(for n=4)

The analytical coalescence scenario leads to the original NCQ scaling, $\upsilon_n/n_q \sim KE_T/n_q$ instead of the modified one $\upsilon_n/n_q^{n/2} \sim KE_T/n_q$. To understand the relation between the modified NCQ scaling $\upsilon_n/n_q^{n/2} \sim KE_T/n_q$ and the scaling relation $\upsilon_n \sim \upsilon_2^{n/2}$, we can go into further details of the results in Fig. 1 in a semianalytical way. The modified NCQ scaling relation is satisfied only if $C_n^m = C_n^b$, which is not the case from the analytical coalescence scenario.
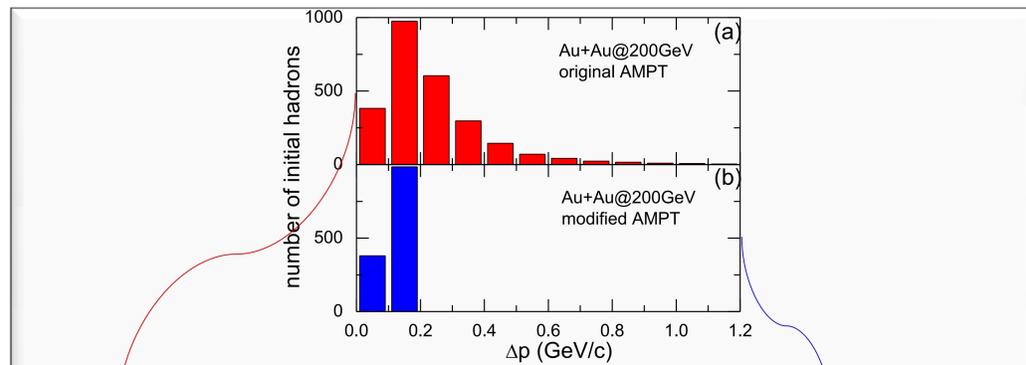

FIG. 2. Histogram of the momentum distance Δp between valence quarks in the hadronization process from the original (a) and the modified AMPT model (b) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
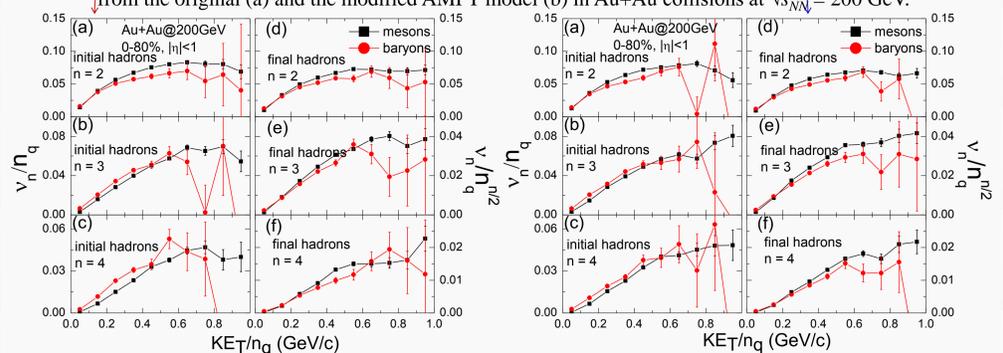

FIG. 3. Scaling relation of $v_n \sim KE_T$ for initial hadrons right after hadronization and final hadrons after hadronic evolution in minibias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the original AMPT model (left) and the modified AMPT (right).

It is seen from the right Fig. 3 that the flows of initial hadrons are closer to the NCQ scaling relation $\upsilon_n/n_q \sim KE_T/n_q$ compared with that from the original AMPT model shown in left Fig. 3, consistent with the results from the analytical coalescence scenario.

Despite the weaker hadronic afterburner effect compared with that from the original AMPT calculation, the flows of final hadrons again follow the relation $\upsilon_n/n_q^{n/2} \sim KE_T/n_q$, after hadronic evolution including elastic and inelastic scatterings as well as resonance decays.
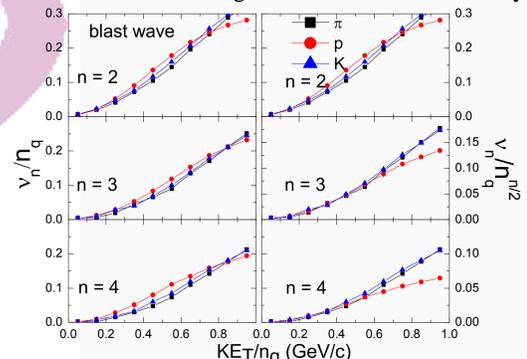

FIG. 4. Scaling relation of $v_n \sim KE_T$ for pions, kaons, and protons from a generalized blast wave model.

Fig. 4 shows flows of pions, kaons, and protons do not deviate from the NCQ scaling relation $\upsilon_n/n_q \sim KE_T/n_q$ by much even from a thermal blast wave model. Furthermore, the modified NCQ scaling $\upsilon_n/n_q^{n/2} \sim KE_T/n_q$ is well satisfied for higher-order anisotropic flows at smaller KE_T.
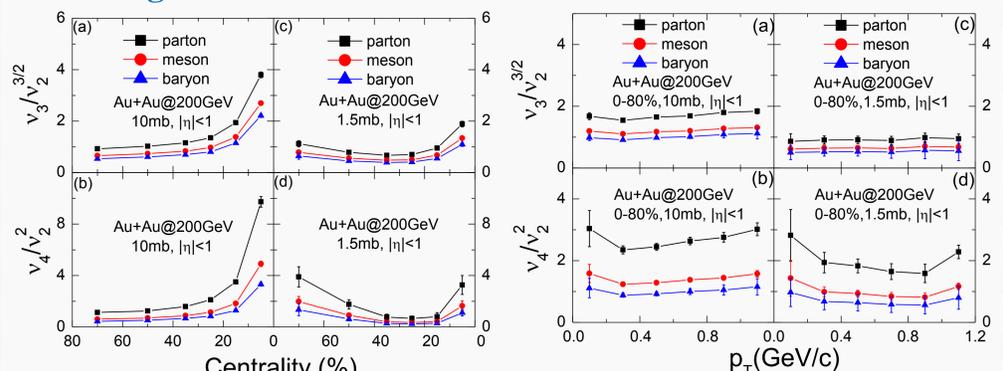
The scaling ratio

FIG. 5. Centrality dependence (left) and transverse momentum (p_T) of $\upsilon_n/\upsilon_2^{n/2}$ for partons, mesons, and baryons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the analytical coalescence scenario with partonic flows from the parton scattering cross section of 10 mb and 1.5 mb (right).

The $\upsilon_n/\upsilon_2^{n/2}$ ratio decreases with increasing centrality because of similar centrality dependence of initial anisotropy ratio $\varepsilon_n/\varepsilon_2^{n/2}$ for 10 mb. While it shows a non-monotonical behaviour for 1.5mb because the correlation between the initial anisotropies ε_n and the final collective flows v_n is not that strong. The QGP interaction generates the anisotropic flows simultaneously in a p_T-independent way according to the relation $\upsilon_n/\upsilon_2^{n/2} \sim (\upsilon_2/\varepsilon_2)^{n/2}$ from initial anisotropies v_n.

Conclusions

‣ The modified NCQ scaling **cannot be obtained** from the naive analytical coalescence scenario, even if event-by-event fluctuations are taken into account.

‣ This is related to the different scaling coefficients for mesons and baryons in the scaling relation $\upsilon_n \sim \upsilon_2^{n/2}$, while experimentally they are expected to be almost the same.

‣ The modified NCQ scaling may stem from **the hadronic afterburner effect** or **thermal freeze-out** rather than the coalescence mechanism.

‣ The centrality dependence of the $\upsilon_n/\upsilon_2^{n/2}$ ratio has been shown to be sensitive to the parton scattering cross section, while the p_T independency of the ratio seems to be a robust phenomena.

*more details see Phys. Rev. C 93, 024906 (2016).