Flow correlation as a measure of phase transition

Ashutosh Dash* and Victor Roy†
National Institute of Science Education and Research, HBNI, 752050 Odisha, India.

1. Introduction

It is well known that at low temperature and baryon chemical potential the degrees of freedom of nuclear matter are color-neutral hadrons and at high temperature or at large baryon chemical potential matter is in the form of a quark-gluon plasma (QGP) in which the fundamental degrees of freedom are colored objects such as quarks and gluons. Nuclear matter at at small baryon chemical potential (μ_B) and finite temperature (T) is believed to undergo a crossover transition from the hadronic phase to the QGP phase and a first order phase transition at relatively larger μ_B and the first order phase transition line terminates at a critical point [1].

The present study aims to find a unique observable which connects QCD Equation of State (EoS) and the experimental data of heavy-ion collisions using hydrodynamical model. We find the linear/Pearson correlation (defined later) of initial geometric asymmetry of colliding nuclei to the corresponding flow coefficient (particularly the second-order flow coefficient v_2, Eq. 3) is a unique observable which can differentiate between EoS with a first-order phase transition to that with a crossover transition irrespective of the initial condition used. It has been known that the event averaged v_2, and the eccentricity of the averaged initial state, ϵ_2, Eq. 2 are approximately linearly correlated [2], and the Pearson correlation is quite insensitive to the shear viscosity of the fluid and the initial condition used [2], which makes it a robust observable to disentangle between the two different EoSs.

*Electronic address: ashutosh.dash@niser.ac.in
†Electronic address: victor@niser.ac.in

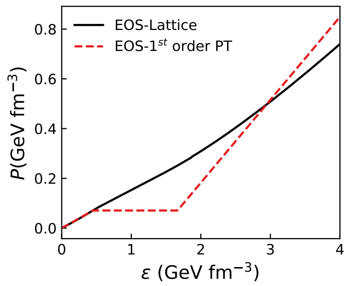

FIG. 1: Equation of state with a cross-over transition (solid black line) and with first order phase transition (dashed red line), at $\mu_B = 0$ MeV.

Results and Discussion

In the present work, we will be using two kinds of EoSs (shown in Fig. 1):
(i) A parameterized EoS (EoS Lattice) which has a cross-over transition between high temperature QGP phase obtained from lattice QCD and a hadron resonance gas below the crossover temperature.
(ii) An EoS (EoS 1^{st} order PT) connecting a non-interacting massless QGP gas at high temperature to a hadron resonance gas at low temperatures through a first order phase transition. The bag constant B is a parameter adjusted to yield a critical temperature $T_c = 164$ MeV. Similarly, we consider here two initial conditions, where the initial energy density $\varepsilon(x, y)$ is obtained at initial time $\tau_0 = 0.6$ fm from the MC-Glauber model using Gaussian smearing,

$$\varepsilon(x, y) = \kappa \sum_{i=1}^{N_{\text{BC, WN}}} \exp\left(\frac{-(\vec{r} - \vec{r}_i)^2}{(2\sigma^2)}\right), \quad (1)$$

where $\vec{r}_i = (x_i, y_i)$ are the spatial coordinates of either wounded nucleons (initial condition ε_{WN}) or binary collisions (initial condition ε_{BC}). κ is a normalization constant fixed to

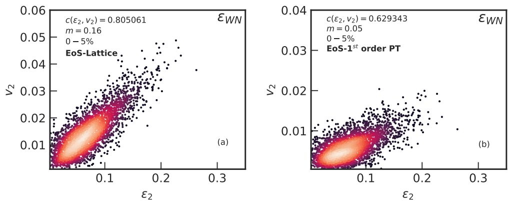

FIG. 2: (a) Event-by-event distribution of v_2 vs ϵ_2 for $0-5\%$ Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. (b) Same as left panel but for EoS with first order phase transition.

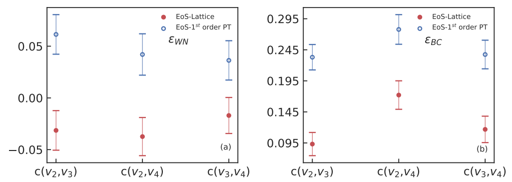

FIG. 3: (a) Pearson correlation coefficient $c(v_n, v_m)$ for EoS-Lattice (solid red circles), and first order phase transition (open blue circle) for $20-30\%$ collision centrality. (b) same as left panel but for ε_{BC}. Error bars are statistical.

provide the observed multiplicity of pions and $\sigma=0.7$ fm is the spatial scale of a wounded nucleon or a binary collision. The initial geometry/anisotropy of the overlap zone of two colliding nucleus is quantified in terms of coefficients ϵ_n

$$\epsilon_n e^{in\Phi_n} = -\frac{\int dxdyr^n e^{in\phi}\varepsilon(x,y)}{\int dxdyr^n\varepsilon(x,y)}. \quad (2)$$

where $\varepsilon(x,y)$ is as defined in Eq. 1. The final azimuthal momentum anisotropy is characterized in terms of the coefficients v_n and is defined as Fourier expansion of the single particle azimuthal distribution

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1+2\sum_{n=1}^{\infty} v_n^{\mathrm{obs}}\cos n\left(\phi-\Psi_n^{\mathrm{obs}}\right) \quad (3)$$

where Ψ_n^{obs} is the event plane angle. In order to quantify the linear correlation we use Pearson's correlation coefficient which is defined as

$$c(x,y) = \left\langle \frac{(x-\langle x\rangle_{\mathrm{ev}})(y-\langle y\rangle_{\mathrm{ev}})}{\sigma_x\sigma_y}\right\rangle_{\mathrm{ev}}, \quad (4)$$

where σ_x and σ_y are the standard deviations of the quantities x and y. A value of $1(-1)$ implies that a linear (anti-linear) correlation between x and y. A value of 0 implies that there is no linear correlation between the variables.

For centrality $0-5\%$ as shown in Fig. 2, using two different EoS we found $\sim 15\%$ decrease in $c(\epsilon_2, v_2)$ for first order phase transition compared to a crossover transition, which clearly indicates that $c(\epsilon_2, v_2)$ can be treated as a good signal of phase transition in the nuclear matter. However, the initial eccentricities ϵ_n are not accessible in real experiments (and are model dependent) which makes $c(v_n, v_m)$ more interesting (shown in Fig. 3). We found in the mid central collisions always show higher values of $c(v_n, v_m)$ for the EoS with first order phase transition than crossover transition irrespective of the initial conditions. For example we can calculate $c(v_n, v_m)$ from available experimental data for various $\sqrt{s_{NN}}$ and pinpoint the energies where $c(v_n, v_m)$ shows an enhancement. These observations may be attributed to very different evolutionary dynamics of the system for the two different EoS, as the speed of sound becomes zero in first-order phase transition hence the linear/non-linear coupling of ϵ_n - v_n and v_n - v_m is different in the two scenario.

Acknowledgments

V.R. is supported by the DST-INSPIRE Faculty research grant, India. A.D. acknowledges financial support from DAE, Government of India.

References

[1] R. V. Gavai and S. Gupta, Phys. Rev. D **71**, 114014 (2005)

[2] H. Niemi, G. S. Denicol, H. Holopainen and P. Huovinen, Phys. Rev. C **87**, no. 5, 054901 (2013)

[3] A. Dash and V. Roy, arXiv:1908.05292 [hep-ph].