Global and Local Temperature Fluctuations in High Energy Heavy-ion Collisions

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Abstract:

Temperature fluctuations may have two distinct origins, first, quantum fluctuations that are initial state fluctuations, and second, thermo-dynamical fluctuations. We discuss a method of extracting the thermodynamic temperature from the mean transverse momentum of pions, by using controllable parameters such as centrality of the system, and range of the transverse momenta. Event-by-event fluctuations in global temperature over a large phase space provide the specific heat of the system. We present Beam Energy Scan of sp. heat from data, AMPT and HRG model prediction. The production of a large number of particles in every event, it is possible to divide the phase space into small bins and obtain local temperature for each bin. The origin of the local fluctuations has been studied with the help of event-by-event hydrodynamic calculations, which diminishes with the elapse of time. We discuss the hydrodynamic calculations and a feasibility study at LHC using AMPT simulated data.

Introduction:

Experiments at RHIC and LHC are on the quest to unearth the nature of the QCD phase transition and to get a glimpse of how matter behaves at such extreme conditions. Phase transitions are governed by a set of thermodynamic parameters, like, temperature (T), pressure, entropy, and energy density (E), and can be further characterized by their response functions, like, specific heat, compressibility, and susceptibility. In thermodynamics, the heat capacity (C) is defined in terms of the ratio of the event-by-event fluctuations of the energy of a part of a finite system in thermal equilibrium to the energy (ΔE^2) = $T^2C(T)$. This can be applied for a locally thermalized system produced during the evolution of heavy-ion collisions. But for a system at freeze-out, specific heat can expressed in terms of the event-by-event fluctuations in temperature of the system where volume is fixed:

$$\frac{1}{C}=\frac{\langle T^2\rangle-\langle T\rangle^2}{\langle T\rangle^2}$$

We define the specific heat as the heat capacity per pion multiplicity within the experimentally available phase space in rapidity and azimuth. For a system in equilibrium, the mean values of temperature and energy density are related by an equation of state. However, the fluctuations in energy and temperature have quite different behavior. Energy being an extensive quantity, its fluctuations have a component arising from the volume fluctuations, and not directly suited for obtaining the heat capacity. The heat capacity (C_v), which defined as the amount of heat required to change the temperature of the system by one unit. The specific heat is the heat capacity per unit mass or per particle in the system.

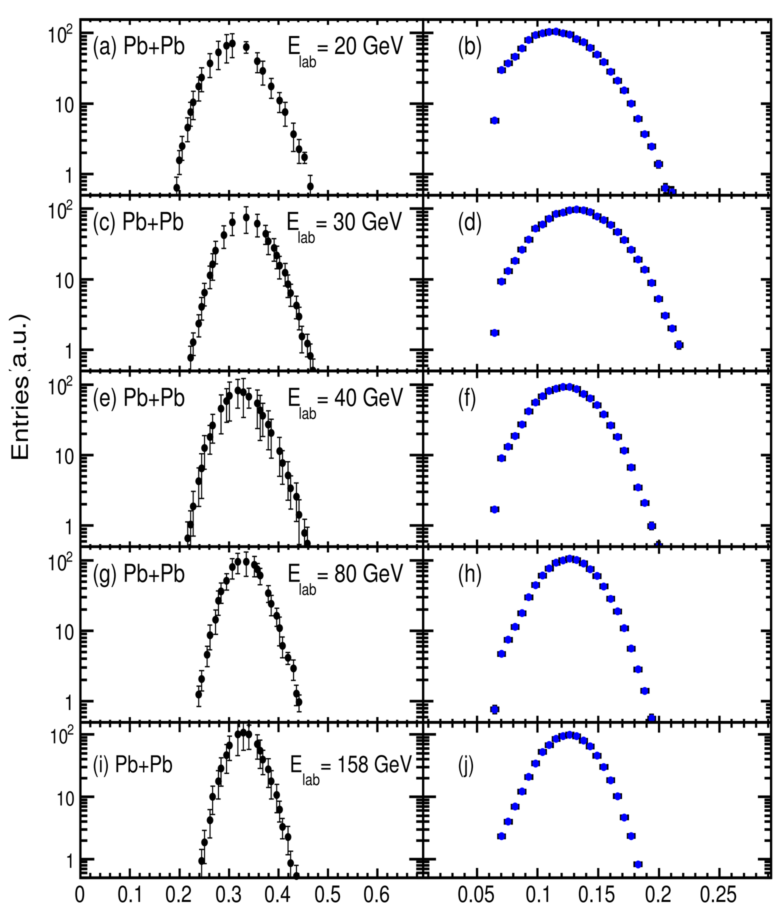

Fig: 1

Fixed target experiment by NA49. The published results are of mean transverse momentum of top 6.5% centrality at 1.1 < y*< 2.6 and the T_{eff} distribution are derived from it.

Methodology:

If the transverse momentum spectra is thermal (exponential) with a definite (user defined) region from a to b, then the relation with mean of the to slope is given like:

$$\langle p_T\rangle=\frac{\int_a^b p_T^2F(p_T)dp_T}{\int_a^b p_TF(p_T)dp_T}=2T_{eff}+\frac{a^2e^{-\frac{a}{T_{eff}}}-b^2e^{-\frac{b}{T_{eff}}}}{(a+T_{eff})e^{-\frac{a}{T_{eff}}}-(b+T_{eff})e^{-\frac{b}{T_{eff}}}}$$

Using above equations, we can have the T_{eff} distribution from the published transverse momentum distribution of charge particle (mostly pions).
Now this T_{eff} has both the component from kinematic temperature T_{kin} and radial flow velocity β. The only associated part of the thermal fluctuation is responsible for specific heat. For this work, for 0-5% top central assuming β is not fluctuation much and the fluctuation of T_{eff} is solely due to the fluctuation of T_{kin}. Thus,

$$\frac{1}{C_V}=\frac{(\langle T_{kin}^2\rangle-\langle T_{kin}\rangle^2)}{\langle T_{kin}\rangle^2}\approx\frac{(\langle T_{eff}^2\rangle-\langle T_{eff}\rangle^2)}{\langle T_{kin}\rangle^2}$$

We now define, the specific heat (c_v) is calculated as the heat capacity per particle and calculate the dimensionless quantity $\frac{c_v}{T_{kin}^3}$

We also compare this for HRG model and AMPT string melting(SM) for a wide energy range from 7GeV and 2760GeV.

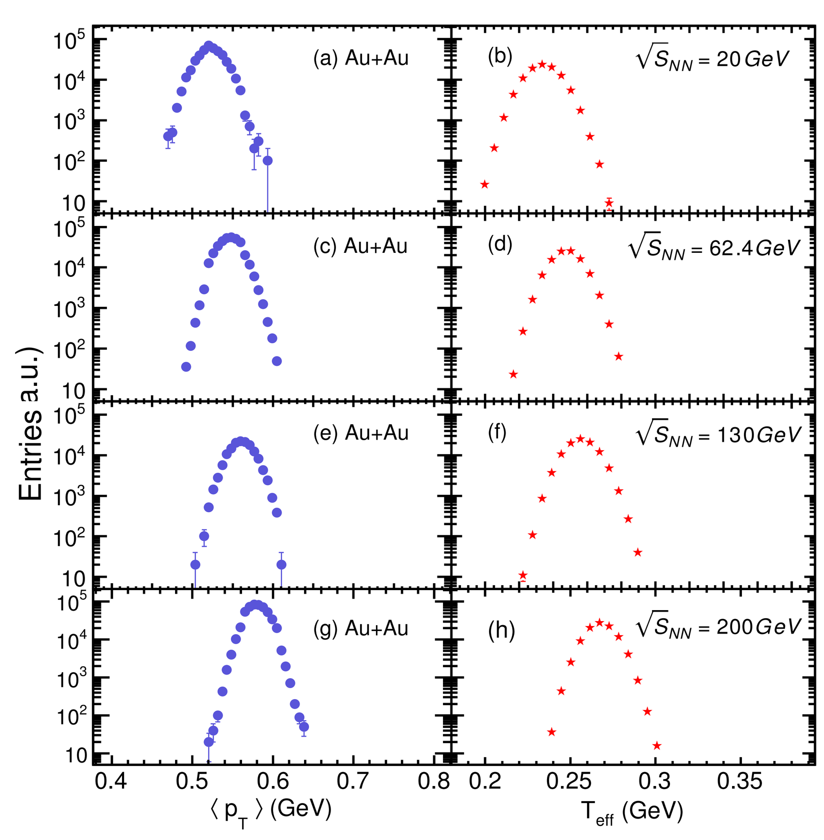

Fig: 2

Collider experiment by STAR Au-Au 0-5% centrality published results of mean transverse momentum and the T_{eff} distribution are derived from it.

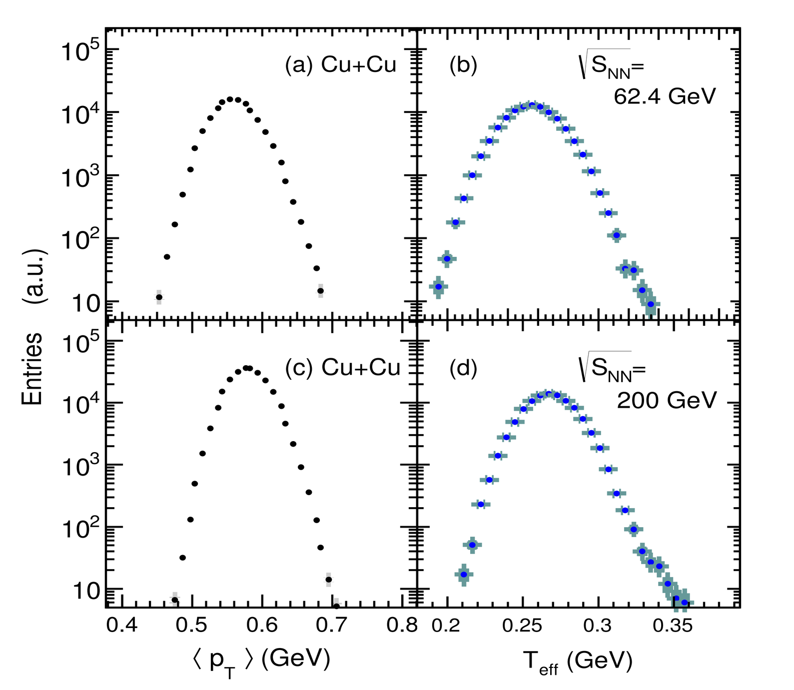

Fig: 3

Collider experiment by STAR Cu-Cu 0-5% centrality published results of mean transverse momentum and the T_{eff} distribution are derived from it. This gives a confidence of changing system size and how the specific heat depends on the system size.

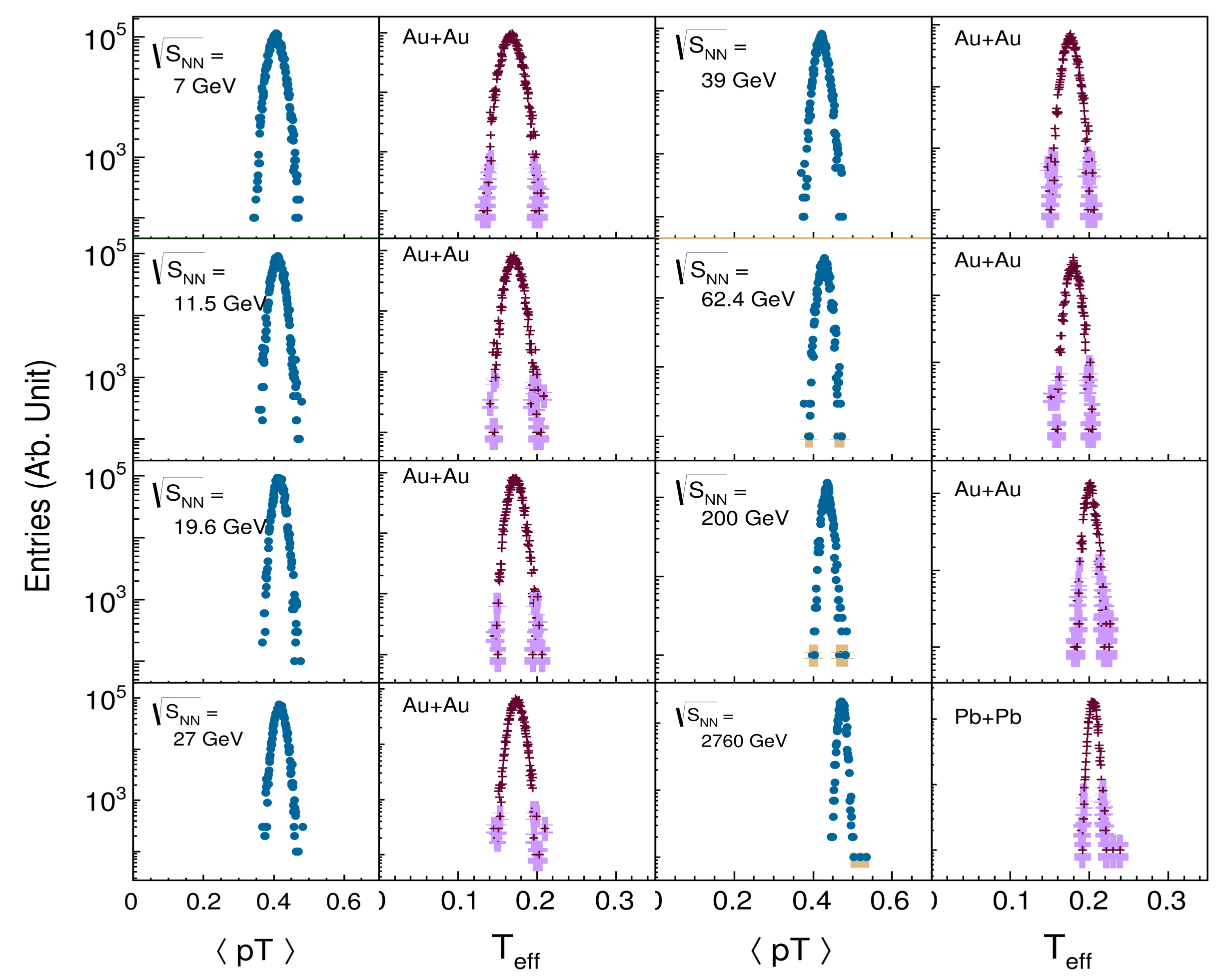

Fig: 3

Au-Au 0-5% centrality & Pb-Pb 0-5% centrality by AMPT SM model of mean transverse momentum and the T_{eff} distribution . A clear observation is the mean transverse momentum increases with energy and the width of the fluctuations is decreases which energy for both the distribution, which is expected

Due to finite multiplicity of produced particles the statistical fluctuations should be taken out. It could be done by either using a toy model and having same formalism with similar multiplicity and T_{eff} for each colliding energy or by using simple estimation that, $\Delta T_{stat}^2=\frac{1}{\langle M\rangle}$ Where M is the particle multiplicity within the specified pT range.
Now applying the idea, $\Delta T_{eff}^2=\Delta T_{dyn}^2+\Delta T_{stat}^2$ one can calculate the dynamical part of T_{eff}.
After extracting all the ΔT from different experimental data and model (AMPT) we calculate the T_{kin} and β are determined from the identified particle spectra using combined Blast-Wave model. This depends on centrality and collision energy. After getting the $\frac{\Delta T_{eff}}{T_{kin}}$ one can calculate the heat capacity of the system. Now as we define,

the specific heat (c_v) = $\frac{C}{\langle n\rangle}$

Where n is the number of charge particle within that spectral range. From there is a source of error in c_v comes as n appears n ± Δn.

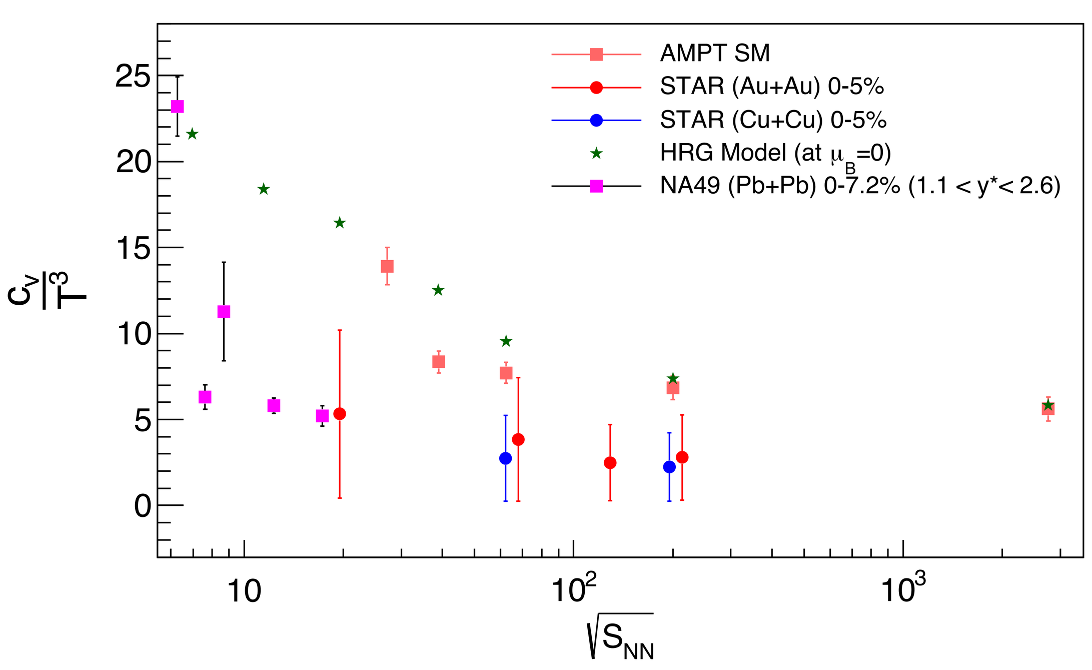

Fig: 4

The dimensionless quantity related to specific heat is $\frac{c_v}{T_{kin}^3}$ is measured for all the experimental data from fixed target to collider system with different beam energy , different system size. 62.4 and 200 GeV Au and Cu points placed with shifted X axis for better representation. A thermal model Hadron Resonance Gas (HRG) prediction with zero baryonic potential calculation along with one microscopic model AMPT SM is given.

Discussion & Conclusions:

A beam energy dependence of specific heat is shown from the available data set from different experiment like Collider(STAR) to Fixed Target(NA49). System size dependence of the same from Au-Au to Cu-Cu system form STAR experiment at 2 different energies are also shown. A thermal model calculation at zero baryonic potential (HRG model) is compared at similar energies. Also a microscopic model AMPT string melting mode is compared. All shows a reasonable agreement with one another.

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