Author(s): Basu, Sumit; Nandi, Basanta K.; Chatterjee, Sandeep; Chatterjee, Rupa; Nayak, Tapan

Title: Beam Energy Scan of Specific Heat Through Temperature Fluctuations in Heavy Ion Collisions

Year: 2016

Version:

Please cite the original version:

Basu, S., Nandi, B. K., Chatterjee, S., Chatterjee, R., & Nayak, T. (2016). Beam Energy Scan of Specific Heat Through Temperature Fluctuations in Heavy Ion Collisions. In D. Alvarez-Castillo, D. Blaschke, V. Kekelidze, V. Matveev, & A. Sorin (Eds.), SQM 2015 : Proceedings of the 15th International Conference on Strangeness in Quark Matter. Institute of Physics Publishing Ltd.. Journal of Physics: Conference Series, 668. https://doi.org/10.1088/1742-6596/668/1/012043

Beam Energy Scan of Specific Heat Through Temperature Fluctuations in Heavy Ion Collisions

2016 J. Phys.: Conf. Ser. 668 012043

(http://iopscience.iop.org/1742-6596/668/1/012043)

15th International Conference on Strangeness in Quark Matter (SQM2015) IOP Publishing
Journal of Physics: Conference Series **668** (2016) 012043 doi:10.1088/1742-6596/668/1/012043

Beam Energy Scan of Specific Heat Through Temperature Fluctuations in Heavy Ion Collisions

Sumit Basu[1], **Basanta K Nandi**[2], **Sandeep Chatterjee**[1], **Rupa Chatterjee**[1,3], **Tapan Nayak**[1]

[1]Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata - 700064, India
[2]Department of Physics, Indian Institute of Technology Bombay, Mumbai - 400067, India
[3]Department of Physics, P.O.Box 35, FI - 40014 University of Jyvāskylā, Finland

E-mail: `sumit.basu@cern.ch`

Abstract. Temperature fluctuations may have two distinct origins, first, quantum fluctuations that are initial state fluctuations, and second, thermodynamical 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 specific heat from data, AMPT and HRG model prediction. Experimental results from NA49, STAR, PHENIX, PHOBOS and ALICE are combined to obtain the specific heat as a function of beam energy. These results are compared to calculations from AMPT event generator, HRG model and lattice calculations, respectively.

1. Introduction

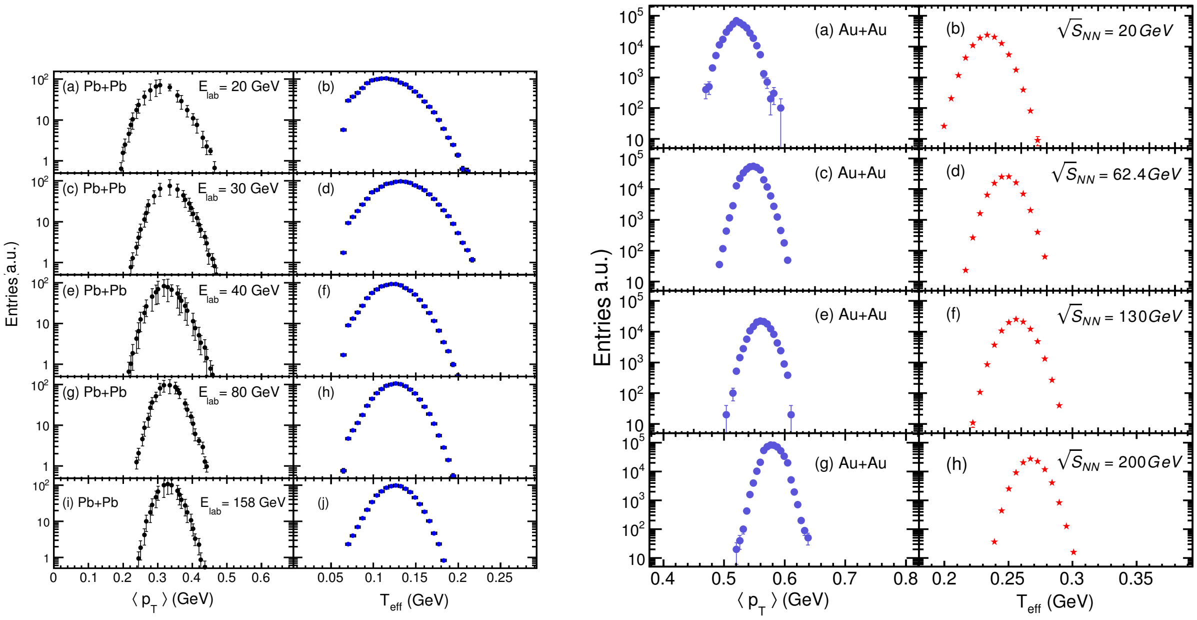
Experiments at RHIC and LHC are on the quest to unearth the nature of the QCD phase transition and to get a glimpse of how matter behaves at such extreme conditions. Phase transitions are governed by a set of thermodynamic parameters, like, temperature (T), pressure, entropy, and energy density (E), 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 $(\Delta E^2) = T^2 C(T)$ [1, 2, 3, 4]. 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: $1/C = (\langle T^2\rangle - \langle T\rangle^2)/\langle T\rangle^2$. 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 ($C_{\rm v}$), which is 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.

2. Methodology & Results

The temperature of the system can be obtained from the transverse momentum ($p_{\rm T}$) spectra of the emitted particles. An exponential Boltzmann-type fit to the $p_{\rm T}$ spectra gives a measure of the temperature:

$$F(p_{\rm T}) = \frac{1}{p_{\rm T}}\frac{dN}{dp_{\rm T}} \approx Ae^{-p_{\rm T}/T_{\rm eff}}, \tag{1}$$

where A is a normalization factor and $T_{\rm eff}$ is the apparent or effective temperature of the system [5]. For obtaining the event-by-event fluctuation, the temperature needs to be estimated in every event either by fitting in a specified (thermal) region or by calculating mean transverse momentum ($\langle p_{\rm T}\rangle$) of particles. Since the calculation of the mean value is more stable, this method of temperature estimation can also be used for collisions at RHIC energies. As the $p_{\rm T}$ window is finite, For a range of $p_{\rm T}$ within a to b, we obtain:



(a) NA49 (b) STAR Au-Au

Figure 1: $\langle p_{\rm T}\rangle$ and $T_{\rm eff}$ for both fixed-target and collider energy.

$$\langle p_{\rm T}\rangle = \frac{\int_a^b p_{\rm T}^2 F(p_{\rm T})dp_{\rm T}}{\int_a^b p_{\rm T}F(p_{\rm T})dp_{\rm T}} \tag{2}$$

$$= 2T_{\rm eff} + \frac{a^2e^{-a/T_{\rm eff}} - b^2e^{-b/T_{\rm eff}}}{(a+T_{\rm eff})e^{-a/T_{\rm eff}} - (b+T_{\rm eff})e^{-b/T_{\rm eff}}}. \tag{3}$$

Fig. 1 shows the published [6, 7]. $\langle p_{\rm T}\rangle$ distribution for central (∼ top 5%) of (a) Fixed target experiment in NA49 by Pb+Pb at ($1.1<$ y*< 2.6) with corresponding $T_{\rm eff}$ distribution extracted using 3 and (b) Collider experiment in STAR by Au+Au at mid-rapidity with the range $0.15 < p_{\rm T} < 2.0$.

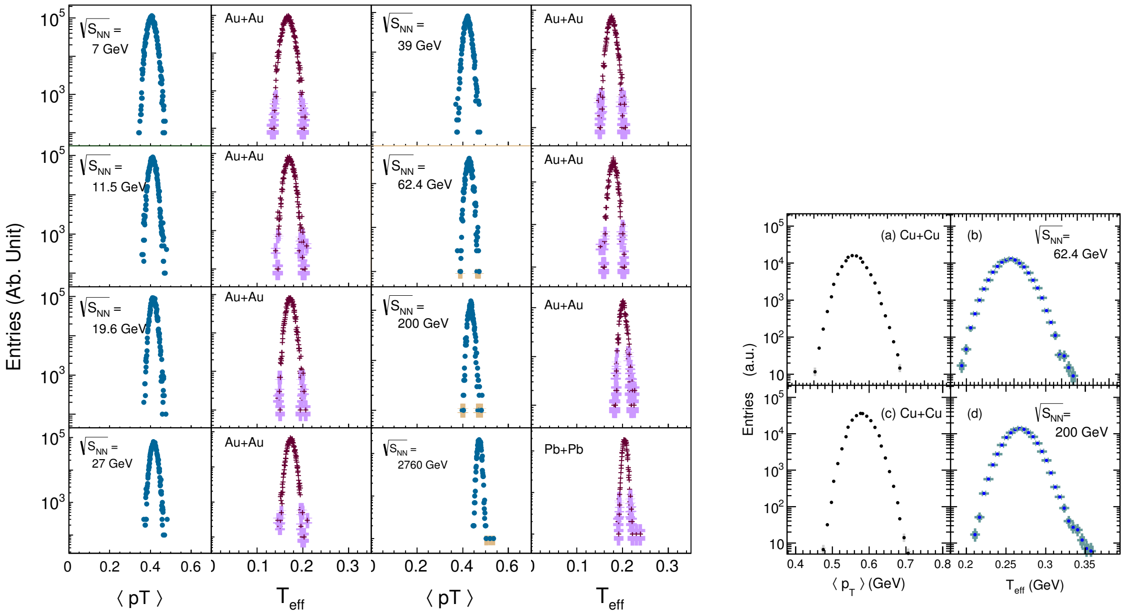
The event-by-event fluctuations of $\beta_{\rm T}$ need to be taken into account for calculating the fluctuation in kinetic temperature. Fluctuation in $\beta_{\rm T}$ has been discussed in the literature lately.

Experimental determination is only possible by a fitting event-by-event $p_{\rm T}$ distribution by a blast-wave fit. This has not yet been done. For the present work, we have assigned an error to the value of $\beta_{\rm T}$ from the available data and calculated its effect on heat capacity. We calculate $C_{\rm v}$ using the equation,

$$\frac{1}{C_v} = \frac{(\langle T_{\rm kin}^2\rangle - \langle T_{\rm kin}\rangle^2)}{\langle T_{\rm kin}\rangle^2} \approx \frac{(\langle T_{\rm eff}^2\rangle - \langle T_{\rm eff}\rangle^2)}{\langle T_{\rm kin}\rangle^2}, \tag{4}$$

and assign an error to $C_{\rm v}$ corresponding to the fluctuations in $\beta_{\rm T}$. The values of $\langle T_{\rm kin}\rangle$ can be obtained from the Blast Wave fits to the experimental data for large number events. Knowing the heat capacity, the specific heat ($c_{\rm v}$) is calculated as the heat capacity per particle [5] in the system and expressed in terms of $c_{\rm v}/T_{\rm kin}^3$ as a dimensionless quantity.

Fig. 2 shows the $\langle p_{\rm T}\rangle$ and $T_{\rm eff}$distribution for central ($\sim$ top 5%)(a) AMPT model with string melting (SM) mode ranging from 7GeV to 200GeV by Au+Au at mid-rapidity and by Pb+Pb at 2760 GeV [8, 9]. While (b) shows the same in a different system size at colliding mode via Cu+Cu [10]. Due to finite multiplicity, within a centrality window in the heavy-ion collisions contribute to the statistical fluctuations in temperature fluctuations. The temperature fluctuations arising from statistical effects have been calculated in terms of a statistical model calculation. It can be either done via a synthetic event assuming similar slope of corresponding collision energy with zero fluctuations on $T_{\rm eff}$ and only fluctuation in its event multiplicity with a realistic approach or via mix event analysis. Then following the same mechanism of analysis one can estimate the statistical fluctuations in temperature ($\Delta T_{\rm stat}$). Now, $\Delta T_{\rm eff}^2 = \Delta T_{\rm dyn}^2 + \Delta T_{\rm stat}^2$. Knowing the $\Delta T_{\rm dyn}$ one can crudely assume that within a narrow centrality if the $\beta_{\rm T}$ varies too little event-to-event then $\Delta T_{\rm dyn}$ is solely arieses due to $\Delta T_{\rm kin}$. Even if $\beta_{\rm T}$ varies within the error one can calculate the modified contribution from $\Delta T_{\rm kin}$ and put it as a error. A similar estimation could be possible in a much simple way $\Delta T_{\rm stat}^2 = \frac{1}{M}$ where M is the particle number within specified pseudo-rapidity and $p_{\rm T}$ range [11].



(a) AMPT

(b) STAR
Cu+Cu

Figure 2: AMPT SM modes and system size dependence of $\langle p_{\rm T}\rangle$ and extraction of $T_{\rm eff}$.

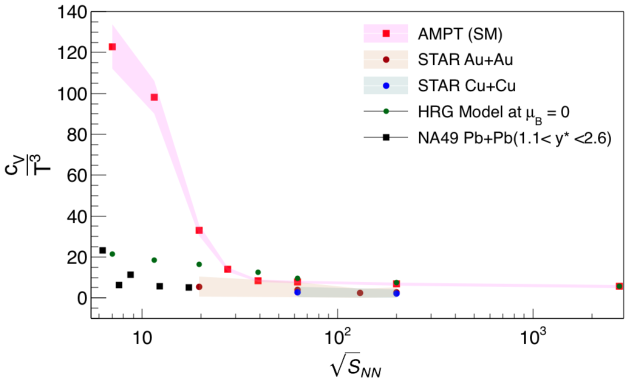


Figure 3: Beam energy dependence of $c_{\rm v}/T_{\rm kin}^3$ with data and model comparisons.

After subtracting out the statistical estimations, one can find out the heat capacity $C_{\rm v}$ via (4) and having the $c_{\rm v}$ by knowing the particle or pion numbers. Calculating the $c_{\rm v}$, we can measure the dimensionless quantity $c_{\rm v}/T_{\rm kin}^3$ and directly compare the values with theoretical prediction like thermal Hadron Gas (HRG) model at corresponding energy considering baryonic potential is zero ($\mu_{\rm B} = 0$). Fig. 3 shows that the variation of $c_{\rm v}/T_{\rm kin}^3$ with different beam energy and system size with one microscopic event generator (AMPT SM) and thermal model (HRG) prediction. This is the first result which can be experimentally measurable.

3. Discussions

This result is very important to understand the critical point and other transitions at phase boundary. This is also first time some result of specific heat form experimental result. Normally $\frac{c_{\rm v}}{T_{\rm kin}^3}$ quantity is widely used by the theoretical study assuming the chemical freeze-out. Also if the experimental results matches with the theory prediction, it would help to understand the QGP partonic phase and the equation of state more deeply. It should be observed that by increasing the energy then $\langle p_{\rm T}\rangle$ increases but the $\Delta\langle p_{\rm T}\rangle$ decreases, which is expected as chance of achieving thermalization is being higher. Thus specific heat from temperature fluctuation could play a key role in the order to fix the remaining mystery of the QGP and heavy ion collisions.

References

[1] L.D. Landau.and E.M. Lifshitz, STATISTICAL PHYSICS, (Course of Theoretical Physics, v. 5, 3rd, rev. and enlarged ed.) Pergamon Press (1980).
[2] L. Stodolsky, Phys. Rev. Lett. **75**, 1044 (1995).
[3] E.V. Shuryak, Phys. Lett. B **423**, 9 (1998).
[4] M.A. Stephanov, K. Rajagopal and E. V. Shuryak, Phys. Rev. Lett. **81**, 4816 (1998).
[5] B-H Sa, X-M Li, S-Y Hu, S-P Li, J. Feng, and D-M Zhou, Phys. Rev. **75**, 054912 (2007).
[6] J. Adams *et al.* (STAR Collaboration) Phys. Rev. C **79** 044904 (2009).
[7] J. Adams *et al.* (STAR Collaboration) Phys. Rev. C**72** 044902 (2005).
[8] D. Solanki *et al.* Phys. Lett. **B720** 352-357 (2013).
[9] S. Basu *et al.* arXiv:1504.04502 [nucl-ex] (2015).
[10] B. I. Abelev *et al.* (STAR Collaboration) Phys. Rev. C**79** 034909 (2009).
[11] S. A. Voloshin *et al.* Phys. Rev. **C60** 024901 (1999).