Chapter 9

Summary and Conclusion

My main research interest is the event-by-event temperature fluctuations for the charged hadrons and identified particles in order to obtain the estimation of specific heat of the system. Other estimations of local temperature fluctuations within the event in order to search for anisotropy pattern in temperature and hot spot in energy density had been performed. Apart from that I had been also involved with various research interests which are associated with the main dissertation topic. So, broadly my dissertation layout is following:

- Temperature fluctuations : Motivation & Theoretical background
  - 1A. Global temperature fluctuation $\rightarrow$ Specific Heat.
  - 1B. Local temperature fluctuation $\rightarrow$ Hot spots and temperature anisotropy pattern searching.
  - 1C. Theoretical model and event generator expectations : Hydro, HRG and AMPT and Lattice.
  - 1D. Estimation of specific heat at RHIC Energies from published results.

- Data Analysis in ALICE experiment : LHC10h
  - 2A. Particle identification.
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- 2B. Efficiency Calculations and Corrections.
- 2C. $p_T$ distributions and calculations of $\langle p_T \rangle$.
- 2D. Mixed event Technique and estimation of statistical error.
- 2E. Centrality–wise estimations of specific heat and temperature fluctuation map.

• Miscellaneous

- 3A. $\Delta p_{Ti}\Delta p_{Tj}$ correlations and $\langle p_T \rangle$ fluctuations.
- 3B. Different fitting function the spectra and associated physics.
- 3C. Particle productions and distributions in Heavy ion collisions in Beam Energy Scan.
- 3D. Higher Harmonic flow for different energy.
- 3E. Multiplicity fluctuations and its effect on temperature fluctuations.

• Experience with PMD-hardware

- 4A. Hardware Experience $\Rightarrow$ Photon Multiplicity Detector Testing and Calibration.
- 4B. PMD: QA and gain calculation analysis.

9.1 Temperature fluctuation: Motivation & Theoretical background

My aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected. The existence of such a phase and its properties are key issues in QCD for the understanding of confinement and of chiral-symmetry restoration. For this purpose, I am carrying out a comprehensive study to address the following questions: How is entropy produced and behaved? Nature of the phase
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transition? What are the properties of the medium?

Answer to all of the above questions are lie in the theory of fluctuations. Also study of fluctuations of various quantities provides a powerful means of observing QCD phase transition as in QCD phase transition associated with a QGP and hadronic phase change. The strength of this fluctuations known as correlation also specify the strength of the collectivity of the medium produced in the heavy ion collisions. Temperature fluctuations have been discussed in the literature as a means of characterizing the evolving system. The fluctuations may have three distinct origins, first, quantum fluctuations that are initial state fluctuations, second, thermodynamical fluctuations which is my prime interest and last statistical fluctuations due to limited number of particles produced in each event due to collisions.

9.1.1 1A. Global temperature fluctuation \(\rightarrow\) Specific Heat

I discuss a method of extracting the thermodynamic temperature from the transverse momentum spectra and mean transverse momentum of charge hadrons, identified pions, by using controllable parameters such as centrality of the system, and range of the transverse momenta and specifying pseudo-rapidity and azimuthal window. Event-by-event fluctuations in global temperature over a large phase space provide the specific heat of the system. 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 \((\Delta E^2) = T^2C(T)\). 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: \(\frac{1}{C} = \frac{(T^2) - (T')^2}{3} \). As specific heat is defined by the heat capacity per unit volume, so we define the specific heat as the heat capacity for a system with number of particles as heat capacity per particle. Like, either per charge particle in case of non-identified hadrons or per identified species like pions, kaons within the available phase space or the experimentally available window in rapidity and azimuth. As the phase space volume is equivalent to the number of interacting particles.
9.1.2 1B. Local temperature fluctuation \( \Rightarrow \) Hot spots and temperature anisotropy pattern searching

The origin of the local fluctuations has been studied within a event. Here main idea is to find some hot spot pattern in the phase space in terms of energy density and temperature, which is done via \( \langle p_T \rangle \) distribution in a grid like \( \eta - \phi \) zone. The correlation in multiplicity of each small of these bins are connected to the isothermal compressibility. The effect of multiplicity in local temperature had been studied for both non identified charged hadrons and identified pions. The map of this temperature fluctuation contains hot spots and cold spots. This irregularities in temperature or \( p_T \) may have their origin from the extreme regions of phase space, which existed during the early stages of the reaction. This may indicate that the observed fluctuations are remnants of the initial energy density fluctuations and are not washed out until the freeze-out stage. From this maps of temperature fluctuations and \( \langle p_T \rangle \) are constructed from large number of events of similar multiplicity class could be used for making power spectrum analysis.

9.1.3 1C. Theoretical model and event generator expectations : Hydro, HRG and AMPT and Lattice

The result from different experiments are explained successfully from different school of thoughts of various theoretical models and even generators. Mainly hydrodynamics and microscopic models are used for explaining different observables to understand the properties of the matter produced due to collisions.

Hydrodynamics has been used extensively and to a large extent successfully to explain majority of these experimental results Use of a (2+1)-dimensional event-by-event ideal hydrodynamical framework developed by the Finland group with lattice-based equation of state. The formation time of the plasma is taken to be 0.14 fm in this purpose. A wounded nucleon (WN) profile is considered where the initial entropy density is distributed using a 2-dimensional Gaussian
distribution function. The size of the density fluctuations is taken to be 0.4 fm. The transition
temperature from the QGP to the hadronic phase is chosen to be 0.170 GeV via cooper-fry for-
malism and the kinetic freeze-out temperature is taken as 0.160 GeV. Both the free streaming
and defining freezeout hyper surface has been used to study the fluctuation in energy density
and temperature with the elapsed time.

Also, Hadron Resonance Gas (HRG) model analysis of the particle yields indicate the formation
of a thermal source for the produced particles in heavy-ion collisions. Similar way lattice results
are very promising at higher temperature and lower baryonic potential region. A comparison of
these models has been studied in temperature fluctuations view point.

Similarly there are some heavy ion event generators which explains most of the experimental
observables nicely at different collision energies, viz. HIJING, URQMD and AMPT. Some of
these models are completely microscopic, some are hybrid in origin. In-spite of different origin
and mechanism adopted by these event generators, most of them explains the $p_T$ distributions
for different flavour. A detailed study of AMPT model calculation for this regard is done. The
AMPT model provides two modes: Default and String Melting. In both the cases these two
modes taken initial condition from HIJING with two Wood-Saxon type radial density profile
colliding nuclei. The multiple scattering among the nucleons of two heavy ion nuclei, are gov-
erned by the eikonal formalism. In both mode, energetic patrons cascading (Zhang’s Parton
Cascade) before the strings and partons are recombined. Default mode is fragmentation dom-
inated (Lund string fragmentation function) and String Melting is quark coalescence process
dominated to mimicking the realistic hadronization scenario transported from the patrons.

Global and local fluctuations in temperature had been studied by using these theoretical models
and event generator. Both beam energy and centrality dependence of said fluctuations have
been estimated as a model based expectations.
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9.1.4 1D. Estimation of specific heat at RHIC Energies from published results

Experimental results from NA49, CERES, STAR, PHENIX, PHOBOS and ALICE are combined to obtain the specific heat as a function of beam energy for event-by-event global temperature fluctuations. In this regard, \( \langle p_T \rangle \) distributions from the published results are used for charged hadrons. The distribution of \( \langle p_T \rangle \) from data and mixed event helps to find out the dynamical fluctuations in \( \langle p_T \rangle \) and subsequently fluctuations in temperature. These calculation gives the excitation function of specific heat over a large collisional energy. The blast-wave mechanism is used further to determine the kinetic temperature from the effective temperature decoupling the radial flow part. Results shows below 19.6 GeV energy (NA49, CERES) the temperature fluctuations dominated by the statistical fluctuations due to low multiplicity. A detailed methodology and combined results from these published data and different model expectation has been reported.

Beam Energy Scan of sp. heat from data, AMPT and HRG model prediction. For Pb-Pb collisions at the Large Hadron Collider (LHC) energies, because of 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. Event-by-event fluctuations in local temperature can be obtained by following a novel procedure of making fluctuation map of each event.

The origin of the local fluctuations has been studied with the help of event-by-event hydrodynamic calculations, which shows that the system exhibits fiercely large fluctuations at early times after the collision, which diminishes with the elapse of time. Any observation of non-zero local fluctuations may imply that a part of the early fluctuations might have survived till freeze-out. We discuss the hydrodynamic calculations and a feasibility study at LHC using AMPT simulated data.
9.2 Data Analysis in ALICE experiment : LHC10h

ALICE Experiments at LHC in CERN are on the quest to unearth the nature of the QCD phase transition and to get a glimpse of how matter behaves at extreme conditions of temperature and energy density. The temperature fluctuation can also be studied in heavy-ion physics at TeV energy scale in ALICE experiment as for mainly three reasons. First high temperature, secondly a very large number of events and very large multiplicity at each event which will lead to a better control in statistical fluctuations and third it is in the cross-over region in the phase space diagram where baryonic potential is almost zero.

9.2.1 2A. Particle identification

In ALICE experiment from the slope of the $p_T$ spectrum of charged hadrons and identified particles for every event fit with different functions such as exponential, Boltzmann Gibbs Blast Wave etc. The slope parameter can also be obtained from $\langle p_T \rangle$ of each event at mid rapidity. From there the distribution for a large number of events, heat capacity and specific heat had been calculated for charged hadrons and identified pions. For local temperature fluctuation specified phase space ($\eta$-$\phi$) or ($\gamma$-$\phi$). For particle identification Time projection Chamber(TPC) and Time of Flight(ToF) detectors has been used. For the data sets of Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2760 GeV, 0.15($p_T$<2.0) cuts are used for kinematic cut. V0 detector has been used for the centrality cuts at mid rapidity $-0.8<\eta<0.8$. Particle identification has been done via only TPC upto 0.15 $\langle p_T \rangle$<0.6 and combined TPC+TOF has been used 0.6$\langle p_T \rangle$<0.6 via NSigma method.

9.2.2 2B. Efficiency Calculations and Corrections

The efficiency calculation is important to get the corrected spectra. In order to get a efficiency estimation species wise and for charged hadrons for different primary vertex, centrality, kinematic cuts LHC11a10a_bis Monte Carlo (MC) data set has been used, which is basically HIJING tuned for ALICE. This MC in the generator level called as MC Truth and when it passes through Geant ALICE detector labeled as MC reconstructed. Ratio of which with respect to $p_T$ in primary
particles gives the efficiency x acceptance ($\epsilon$). The detailed study for secondary particle from weak decay, material and mis identification has been performed to obtain the contamination factor($c$). Now the raw uncorrected spectra from the data has been corrected by dividing the correction factor $G = \frac{1-c}{\epsilon}$.

9.2.3 2C. \( p_T \) distributions and calculations of \( \langle p_T \rangle \)

Applying the above methodology with different kinematic with different centrality once corrected spectra (\( p_T \)) is obtained for each of the event. With full azimuth and \(-0.8 \langle \eta \rangle 0.8 \) from each event corrected \( p_T \) distribution is giving \( \langle p_T \rangle \) for both identified pions, kaons and charged hadrons. From there I calculate the slope for each of the event and making distribution of both \( \langle p_T \rangle \) and \( T_{eff} \).

9.2.4 2D. Mixed event Technique and estimation of statistical error

In order to calculated the dynamical component once has to take out the statistical fluctuation from the \( \langle p_T \rangle \) and \( T_{eff} \) distribution. For this mixed event technique is adopted. Here mixed event are produced by mixing the events in track level of same multiplicity class keeping other cuts similar to that of the data and then following the same techniques to produces spectra and subsequently the distribution of \( \langle p_T \rangle \) and \( T_{eff} \). By doing this one could get rid off from the statistical fluctuations due to limited number of charge particles or identified species, and also from other auto correlation and resonance effect. The effect of jet and mini jets in the fluctuations are studied via varying the window of the \( p_T \) distributions.

9.2.5 2E. Centrality-wise estimations of specific heat and temperature fluctuation map

Following the above methodology of getting corrected spectra and estimation of dynamical fluctuations of \( \langle p_T \rangle \) and \( T_{eff} \) distributions the analysis divided into two main categories. First for global temperature fluctuations, I use then simultaneous Boltzmann-Gibbs Blast Wave fit
to different species for estimation of kinetic temperature and radial flow velocity. Then using
\[ \frac{1}{c^2} = \frac{(\Delta T_{\text{had}})^2}{(T_{\text{kin}})^2}, \]
heat capacity is calculated. Divided by the average number of charged hadron or identified particles within the available phase space, the specific heat is obtained for different centrality from most central to peripheral. Second, the available phase space $\eta-\phi$ for each of the event is subdivided into $4\times4, 5\times5$ and $6\times6$ grid like zone for local temperature fluctuations. This division being optimised in for constructing the $p_T$ distributions and multiplicity. Now similar approach as global is followed to make map of $(p_T)$ and $T_{\text{eff}}$ in order to search for local hotspot. Repeating the same for a large event sample on similar centrality I tried find some pattern in local temperature fluctuation maps. This methodology is limited only for charged hadrons and identified pions. For kaons and protons it can not be applied as the number of production of these species for each event is very less compared to other two.

9.3 Miscellaneous

In addition of the main research work, the following detailed studies have been performed as a part thesis work:

3A. Transverse Momentum spectra for identified particles with $p_T$ correlations: Several experiments involves with the basic observables like transverse momentum. Although it has very rich physics goal. During the detailed research work, we try to relate the $p_T$ correlation with it. It has been observed that different experiments uses different observables for this study. A inter-relation and comparative study has been made on this basis. A system size and energy dependence helps a lot for characterizing and understanding the evolving fire ball. Also a centrality scan may address the effect of mini jets and degree of hadronizations.

3B. Spectra–fitting functions and associated physics.

Different spectra fitting functions are available for addressing the different physics aspects. Mainly these are used for calculated the particle yield, temperature and flow. Combined blast wave are used for decoupling the radial boost from the kinematic freeze-out temperature in heavy ion collisions where as Tsallis are used for non–extensive type spectra or non thermalized
spectra. An extensive study has been made for both the data and different event generators.

3C. Theoretical baseline studies using Hydro, HRG and AMPT.

To understand various sources of fluctuation related to heavy ion collision, various model simulations have been performed for the Temperature fluctuations. Those models are HIJING, AMPT and Event by event Hydro. These models are based upon certain known physics processes like, jet-interaction, transport phenomena, coalescence mechanism, thermal equilibrium etc., which are blind to the CP phenomena. These models may serve as baseline studies for the Temperature fluctuation analysis and other baseline studies.

3D. Higher harmonic anisotropic flow.

A beam energy scan from RHIC to LHC energies of anisotropic flow had been performed. The detailed study of elliptic, triangular and other higher harmonic flow are done in models and compared with different published results. These study are very important to understand for NCQ scaling, quark coalescence and other phenomena to fixing the initial conditions and also the shear viscosity of the system.

3E. Multiplicity fluctuations.

Detailed study of total charge multiplicity, $\eta$ distributions and its fluctuations had been studied for having the nature of the evolution of these observable with the centrality and collision beam energy. It could also help to predict the same for the intermediate or higher energy. The event—by—event basis study of net charge, particle ratio, net baryon is related to some susceptibility as these are the conserved quantities. From there one can achieve the corresponding observable which are directly comparable with the Lattice QCD results.

9.4 Experience with PMD-hardware

Hardware and software associated with PMD is one part of my dissertation. High voltage testing, detector building is performed for part of the full detectors. The modules which had been prepare and tested now taking data in ALICE experiments at CERN. The detailed QA test for these detector data set has been performed for gain calculations and other characteristics.