Chapter 1

Introduction

The behaviour of matter under extreme conditions is governed by its equation of state. Equivalently, probing the matter in extreme conditions enables the determination of the equation of state. There is evidence of dense nuclear matter in the core of neutron star with density many times the density of normal nuclear matter [1]. The Big Bang Model of the creation of the Universe also assumes an evolution that includes a phase of dense nuclear matter of unconfined quarks and gluons. Thus, it is of interest to study nuclear matter under extreme conditions in controlled experiments. Such experiments can be done by colliding nuclear matter, heavy-ions, at extremely high energies in laboratories [2]. Measuring the final state particles and their distribution in the phase space can provide information about the different evolutionary stages of the collision, including the possible formation of dense nuclear matter. Quarks and gluons may be deconfined in this dense state of matter, producing a new phase of matter called the Quark-Gluon Plasma [3].

Earlier experiments on heavy-ion collisions were limited to exposing photographic emulsions to cosmic rays, and measuring the final state particles [4]. With the advent of technology to accelerate heavy ions at high energies, experiments could be conducted under controlled conditions. A systematic study of heavy-ion collisions started more than three decades ago. Such systematic study was conducted in fixed target experiments by accelerating heavy-ions at the Alternating Gradient Synchrotron at Brookhaven National Laboratory in New York [2, 5] and at the
Super Proton Synchrotron at the European Organisation for Nuclear Research in Geneva [6]. A wealth of data and results were obtained in fixed target experiments for collisions up to nucleon-nucleon centre of mass energies of about 19 GeV with nuclei as large as Lead (Pb) [7, 8].

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the first heavy-ion collider, and has been in use since the year 2000 [9–11]. RHIC has provided nucleon-nucleon centre of mass energies of up to 200 GeV for nuclei as large as Gold (Au). Two beams of Au nuclei accelerated to 100 GeV per nucleon, are made to collide with each other, giving the total centre of mass energy of 200 GeV per nucleon. During the collisions, the nuclei may compress, pass through each other, create a violent collision converting the incident energy into particles of mass, form dense nuclear matter, or a combination of all of the above. Study of matter created in these collisions helps to understand the phase diagram [12, 13].

1.1 The Phase Diagram of Hadronic Matter

Quarks and leptons are the basic building blocks of matter. The quarks carry a colour charge, and their interactions with each other, and with the gluons, are described by the currently accepted theory of strong interactions, Quantum Chromodynamics (QCD). Due to colour confinement, free quarks and gluons can not be observed in nuclear matter under normal conditions. Lattice QCD predicts that quarks will be deconfined and a new state of matter called Quark-Gluon Plasma (QGP) will be created if the temperature is extremely high.

The QCD phase diagram is shown in Figure 1.1 [14]. The horizontal axis is the net baryon density, which is closely related to the baryochemical potential $\mu_b$. Baryochemical potential is the amount of energy needed to add an additional baryon to the existing matter. Three different forms of nuclear matter are shown in this diagram.

- normal nuclear matter at low temperatures and density.

- quark-gluon plasma at high temperatures,
Figure 1.1: The QCD phase diagram

- color superconductor at low temperatures and high baryon density (e.g. neutron stars) [15].

Heavy-ion collisions lead to production of dense system which can reach energy densities and temperatures high enough for a phase transition to occur [16–18]. If \( \mu_B \) is relatively small and temperature is high, a cross over to deconfined quark-gluon plasma phase is expected [19–21]. At higher \( \mu_B \), the phase transition is expected to be a first order transition. On the boundary of the hadronic and QGP phase, there is expected a critical point [22–24] where the phase transition would change from cross over to first order. However, due to the difficulty of lattice QCD calculations at finite \( \mu_B \), accurate predictions of the location of critical point in the phase diagram are still lacking.

The heavy-ion collisions at different colliding energies probe different regions of the QCD phase diagram. The main interest in theory and in experiments in high energy heavy-ion collision is to search for the QCD critical point and the effort to locate the QCD phase boundary in the phase diagram. At present, the experimental collaborations that are focusing on these exciting physics issues are STAR...
(Solenoidal Tracker At RHIC) [12] and PHENIX (Pioneering High Energy Nuclear Interaction experiment) [25] at RHIC, and SHINE (SPS Heavy Ion and Neutrino Experiment) at SPS (the Super Proton Synchrotron) at CERN in Switzerland [26, 27]. The near future experiments which aim to search for a possible critical point are CBM (Compressed Baryonic Matter) [28] at FAIR (Facility for Antiproton and Ion Research) at Darmstadt in Germany, and NICA (Nuclotron-based Ion Collider facility) at Dubna in Russia [29]. All these experiments cover different regions of the phase diagram and hence complement each other. During the initial operation of the RHIC and at the Large Hadron Collider at CERN, the high temperature region is probed. To see the nature of the transition, and obtain the threshold conditions for the transition, it is important to study the collisions at varying energies. To meet this goal, the RHIC studied the collisions at a scan of beam energies from 39 A GeV to 7.7 A GeV, known as the Beam Energy Scan (BES) program.

1.2 High Energy Heavy-Ion Collisions

When two heavy nuclei approach each other at ultra-relativistic energies, they appear to be Lorentz contracted. The overlap region of the two nuclei depends upon impact parameter. The nucleons in the overlap region are called participants and those which are not participating are called spectators as shown in Figure 1.2.

![Figure 1.2: Schematic diagram showing collision of two nuclei with non zero impact parameter. The participants and the spectators are also shown.](image)
Figure 1.3: Space time diagram and different evolution stages of a relativistic heavy-ion collision.

When the impact parameter is small, the overlap is large, the collision is called a 'central' collision. When the impact parameter is large, the overlap is small, the collision is called a 'peripheral' collision. For intermediate range of impact parameters, these are generally termed as semi-central collisions. The number of participating nucleons decreases as the impact parameter increases.

The dynamics of nucleus-nucleus collision can be viewed by space time diagram [30] with the longitudinal coordinate $z$ (marked as space) and the time coordinate $t$ as shown in Figure 1.3. The projectile and target nucleus both meet at $z = 0$ and $t = 0$. At very high energy, when a collision occurs, the large amount of energy is deposited in a small region of space for a short time, called the fireball. The energy deposited can produce a large number of quarks and gluons which, at sufficiently high temperature and particle density, can move freely over nuclear instead of nucleonic volumes. The quarks and gluons can interact strongly and may lead to a locally equilibrated state, quark gluon plasma, which is shown by the red band in Figure 1.3. The matter expands under its own strong internal pressure and cools down. When its temperature comes down to around $T_c$ (critical temperature), the phase transition from QGP to hadronic matter occurs (hadronization). When the system cools further, below a certain temperature, there are no more elastic
or inelastic interactions. After this final freezeout, the particles stream through freely to the detector.

1.3 Evolution of Heavy-Ion Collisions

The heavy ions being extended objects, the geometry plays an important role in the evolution dynamics of the collision. Different stages of the collision can be probed using different measurements. The results of measurements reflect the initial geometry of the collision. The entire evolution of the collision can be described by an initial state governed by geometry, an expansion of matter depending upon its equation of state and the subsequent interactions, and the freezeout.

1.3.1 Initial Geometry and Characterisation

When two nuclei collide, the overlap region is decided by the impact parameter of the collision. The number of participating nucleons, $N_{\text{part}}$, in the collision affect the total energy deposited in the overlap region, and hence also the total number of particles produced. The measurement of the number of particles produced, to the first order, is a good estimate of the impact parameter of the collision, and of the energy density obtained in the system.

Various model calculations describe that with increasing collision energy, the produced particle multiplicity also increases. Measurements by PHENIX experiment at $\sqrt{s_{NN}} = 130$ GeV, reveal that collisions at RHIC generates $\sim 0.8$ GeV of transverse energy per produced charge particle near midrapidity and independent of collision centrality. Under certain assumptions, suggested by Bjorken, the estimate of the initial spatial energy density [30] of the bulk matter is given by:

$$\epsilon_{Bj} = \frac{dE_T}{dy} \frac{1}{\tau_0 \pi R^2}$$

(1.1)
where $\tau_0$ is the formation time and $R$ is the initial radius of the expanding system.

With reasonable estimates for these parameter values ($\tau_0 \approx 1 \text{fm}/c, R \approx 1.2A^{1/3}$), the energy density in Au+Au collisions at RHIC is $\sim 5 \text{ GeV}/\text{fm}^3$, which is well above the critical energy density $\sim 1 \text{ GeV}/\text{fm}^3$ expected from LQCD for the transition to the QGP phase.

The number of participating nucleons can be estimated on an average in a Glauber model approach [31]. Assuming a uniform density of the nuclei, the number of protons and neutrons can be estimated within a certain overlap region by using the nuclear thickness function. However, this approach provides only the mean number of participating nucleons. The distribution of the number of participating nucleons and the total (identified) particle multiplicity show a very similar characteristic behaviour, indicating a possible correspondence between multiplicity and impact parameter in minimum bias collisions. While the above may be correct on an average, fluctuations in particle production processes, and in the number of participating nucleons at a given impact parameter, inhibit a unique correspondence between the measured multiplicity and the impact parameter.

As a first approximation, it is tempting to consider nuclear collisions to be a superposition of nucleon nucleon collisions. Considering that there are two participants in a pp collision, it is interesting to study the multiplicity in a nucleus - nucleus collision, scaled by the number of participants, or scaled by the number of collisions. If the observed multiplicity demonstrates scaling with the number of participants, then the dominant process for particle production is 'soft', where the momentum transfer is small. However, if the multiplicity is seen to scale with the number of collisions, then the dominant process for particle production is 'hard', where the momentum transfer is large. Multiplicities and rapidity densities are characterised by estimates of $N_{\text{part}}$ and $N_{\text{coll}}$. The initial shape of the colliding zone is decided by the positions of the nucleons. Both multiplicity and the initial shape are closely related to the expansion and subsequent freezeout of the nuclear matter.

PHOBOS experiment searched for a possible scaling of pseudorapidity density with $N_{\text{part}}$ over a large pseudorapidity window [32]. The centrality dependence of charged particle density from PHOBOS experiment is shown in Figure 1.4. Panel (a) of Figure 1.4 shows the total charge particle multiplicity measured within the
Figure 1.4: PHOBOS result on centrality dependence of $dN_{ch}/d\eta$ for different eta ranges in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [32].

range $|\eta| < 5.4$ for Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV. Panel (b)-(f) shows the $< N_{part} >$ dependence of $dN_{ch}/d\eta$ per participant nucleon pair, plotted for five different eta bins. In all figures, PHOBOS has also shown predictions from an event generator HIJING as a solid line. Considering that the data shows behaviour that changes with the $\eta$ region, the dependence on $N_{part}$ is not the same everywhere. Further studies have attempted to explain the pseudorapidity density by considering a contribution that depends upon $N_{part}$ and another that depends on $N_{coll}$.

Even in the case of symmetric nuclei, the overlap region is asymmetric because of density fluctuations inside nuclei. Many event generators that use the Glauber approach, generate positions of the nucleons in the nuclei using Monte Carlo methods, and assume a straight line trajectory for the nucleons. When two nucleons from different nuclei approach a distance less than the corresponding radius of a geometrical cross section of interaction, then the nucleons are considered to be
interacting, or participating. Such a simulation of nuclear positions and their approach towards each other is considered as one event in simulated data. Different event generators model the dynamics of collisions differently. By simulating a large number of events, the event generators can provide a distribution of the number of participants in a given impact parameter range. For each event, the information on the number of nucleons participating $N_{\text{part}}$, and the number of nucleon-nucleon collisions $N_{\text{coll}}$ can be recorded. The same Monte Carlo event generators can provide an event-by-event position (spatial) map of the nucleons in the overlap region. The fluctuations in the number of nucleons, and in their positions, both contribute to the final state observables as will be discussed in the next section(s).

Further, features of particle production at different rapidities in collision of different beam energies may demonstrate the phenomena of 'limiting fragmentation' [33], and will be discussed in the next section(s).

1.3.2 Expansion of Matter and Freezeout

After the initial collision, the large energy deposited in the fireball materialises in thousands of partons interacting strongly. These interactions may lead to a thermal equilibrium. The expansion can be modeled using hydrodynamical evolution [34–36]. Any solution of hydrodynamical evolution requires an equation of state of the system, which along with the initial conditions, define the starting point of the system. Due to high parton density, the mean free path $\lambda$ between the interactions is much smaller than the size of the fireball. This allows to assume that the system is in local thermodynamic equilibrium.

In addition to the radial flow of matter during the expansion, there is also an anisotropic flow caused due to the azimuthally anisotropic collision zone. The spatial anisotropy causes different pressure gradients in the direction along the impact parameter and perpendicular to it. Re-scattering processes amongst the produced particles transform this spatial deformation into momentum space with more matter flowing out along the reaction plane (i.e. in the plane defined by impact parameter and beam direction) than perpendicular to it. This causes the azimuthal distribution of particles to be anisotropic and correlated with the
reaction plane. This is termed as anisotropic flow \cite{37–39}. As more particles push out along the event plane, the initial asymmetry of the fireball vanishes. This is called the self-quenching behaviour of flow. The anisotropic flow predominantly develops in the initial stages, can be measured in the final state particles, and serves as a probe to study the initial stages of expansion in the evolution of heavy-ion collision.

Once the system expands, the hydrodynamic fluid is transformed to particles, a process modeled by the Cooper-Frye freezeout mechanism. These particles continue to interact inelastically until they cool down such that inelastic collisions do not occur. At this point, the hadron composition of the matter is frozen, the relative ratio of different hadron species are fixed, and this is referred to as the chemical freezeout. Subsequently, the particles continue to interact elastically until kinetic freezeout, beyond which the particles stream away freely. Since the particle ratios are fixed at the chemical freezeout, the measurement of their yields can provide information about the system during this stage \cite{9}.

![Figure 1.5: STAR results on ratios of $p_T$ integrated mid-rapidity yields for different hadron species for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The horizontal bars represent statistical model fits to the measured yield ratios. The fit parameters are $T_{ch} = 163 \pm 4$ MeV, $\mu_B = 24 \pm 4$ MeV, $\gamma_s = 0.99 \pm 0.07$. The variation of $\gamma_s$ with centrality is shown in the inset \cite{9}.
At chemical freezeout, the measured ratio can be used to constrain the system temperature and the baryonic chemical potential $\mu_B$. The statistical model assumes that the system is in chemical and thermal equilibrium [40]. A comparison of the experimental $p_T$ integrated hadron yield ratios measured by STAR experiment for central Au+Au collisions, with statistical model fits is given in Figure 1.5. The good fit obtained in describing the ratios by model calculations indicates that the light flavors have reached chemical equilibrium for central and semi-central collisions at temperature $T_{ch} = 163.5$ MeV [9].

Statistical model is able to explain the ratios of a large number of particle species using few parameters like baryon chemical potential, chemical freezeout temperature, and strangeness chemical potential. The strange particle ratios do not fit well, suggesting that these might freezeout at a different temperature. By including an additional factor, termed as the strangeness suppression factor $\gamma_s$, the statistical model is able to fit the strange particle ratios also. The variation of $\gamma_s$ with centrality is shown in Figure 1.5. The value of $\gamma_s$ reaches $\sim 1$ for most central collisions.

Figure 1.6: STAR results on the $\chi^2$ contours for temperature $T_{fo}$ and radial flow velocity $\beta_T$ extracted from thermal and radial flow fits for hadrons produced in Au+Au collisions at 200 GeV. The centrality selection are indicated on the top of the plot [9].
Particles which are formed as a result of chemical freezeout, interact with each other and their space time evolution is modeled using hydrodynamics. The characteristics of the system at kinetic freezeout can be explored by studying the transverse momentum distributions for various hadron species [9]. The transverse momentum distribution of hadrons reflects the later conditions in the evolution as well as the integrated effect of expansion from the beginning of the collision. The result on spectra have shown that the details of the spectra are a combined effect of collective radial flow and a thermalised system yielding a temperature termed as the kinetic freezeout temperature $T_{fo}$. For each event centrality, the spectra of $\pi$, $K$, $p$ were fit to a blast wave model using a single value of radial flow velocity $<\beta_T>$ and temperature $T_{fo}$, as can be seen in Figure 1.6 for Au+Au collisions at 200 GeV. It has been observed that the bulk of the system which consists of kaons, pions and protons become cooler at kinetic freezeout and develop a stronger collective flow.

1.4 Experimental Observables to Study Heavy-Ion Collisions

Systematic experimental studies and theoretical advances have provided a large number of experimental observables to discern the mechanism of heavy-ion collisions. Depending upon the various stages of collisions and evolution process, these signatures reveal insights about the collision processes and its different stages. The signals which are produced in the first stages of the collision are known as hard probes. There is a high momentum transfer between the colliding partons. This includes the signatures such as jet quenching and nuclear modification factor, direct photons and dileptons. The signals which are produced in the later stage of the collision are known as soft probes. These signals are affected primarily by the hadronization stage and may contain information about the properties of phase transition and the QGP. Results on particle multiplicities and their rapidity distributions provide information about particle production mechanism through scaling and limiting fragmentation. Initial state anisotropies determine the measurements of flow. Participant scaling and limiting fragmentation, and azimuthal anisotropy
are the two topics that are addressed in the present thesis using measurements of photons in the completely indigenous Photon Multiplicity Detector (PMD), and using data from event generators. These are discussed in greater detail in the following sub-sections. Some observables due to hard probes are also mentioned briefly.

1.4.1 Participant Scaling and Limiting Fragmentation

If the particle multiplicity scales with $<N_{\text{part}}>$, it shows that the particle production is due to soft processes whereas the scaling with $<N_{\text{coll}}>$ indicates that the particle production is due to hard processes. The results of PHENIX experiment showed that the charged particle production scales with a combination of $<N_{\text{part}}>$ and $<N_{\text{coll}}>$ at mid-rapidity, which indicates a significant contribution of hard processes in the particle production as shown in Figure 1.7 [41]. The data is fitted by a function $dN_{\text{ch}}/d\eta = A \times N_{\text{part}} + B \times N_{\text{coll}}$ and the details of obtaining the values of $N_{\text{part}}$ and $N_{\text{coll}}$ can be seen in [41].

![Figure 1.7: PHENIX results on charged-particle pseudorapidity density per participant pair vs. the number of participants. Predictions from model calculations are also shown. The shaded area represents the systematic errors on $dN_{\text{ch}}/d\eta$ and $N_p$. [41]](image)
Figure 1.8 shows the variation of photon multiplicity per average number of participating nucleon pairs with \(<N_{\text{part}}\rangle\) for Au+Au and Cu+Cu at \(\sqrt{s_{NN}} = 200\) and 62.4 GeV within eta range \(-3.7 \leq \eta \leq -2.3\) [42, 43]. Results from HIJING [44] are shown by solid line for Au+Au and dashed line for Cu+Cu collisions in the same figure. The photon multiplicity is seen to scale with \(<N_{\text{part}}\rangle\) at forward rapidity, which indicates that the photon production at forward rapidity is due to soft processes.

In relativistic heavy-ion collisions, large number of particles are produced. One convenient way to describe heavy-ion collisions is by measuring particle density in rapidity or pseudorapidity. The particle multiplicity contain information about the entropy of the system and the gluon density in the heavy-ion collisions. Photon pseudorapidity distribution are measured for Au+Au and Cu+Cu collisions at \(\sqrt{s_{NN}} = 200\) and 62.4 GeV [42, 43] for all centrality bins and are shown in Figure 1.9. The photon multiplicity is found to increase from peripheral to central collisions. The result have been compared to those obtained from HIJING event
Figure 1.9: STAR results on photon pseudorapidity distributions for Au+Au and Cu+Cu at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The solid lines are result from HIJING for central (0-5% for Au+Au and 0-10% for Cu+Cu) and 30-40% mid-central collisions [42, 43].

With increase in the center of mass energy the rapidity distribution of all particles is expected and observed to become broader due to kinematics. To observe more interesting physics at forward rapidity, it was proposed that the rapidity distribution should be observed in the frame of reference of one of beam nuclei. This can be checked by shifting the distribution by beam rapidity and study it as a function of $\eta - y_{beam}$. Model predictions suggest that with increasing energy the rapidity distributions would reach a limiting value beyond which they will not grow any further. This behaviour is also called longitudinal scaling. This has been observed in a number of different experiments for different particle species and the physics phenomenon which is causing this is still being explored. In order to study
limiting fragmentation in different colliding systems, the rapidity distribution is scaled with the number of participant pairs. Normalizing with the number of participant pairs also allows us to study limiting fragmentation as a function of event centrality.

![Figure 1.10: STAR results on photon pseudorapidity distributions normalized by the average number of participating nucleon pairs for different collision centralities are plotted as a function of pseudorapidity shifted by the beam rapidity for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The solid line is a second order polynomial fit to the data [42, 43].](image)

Charged particles exhibit energy independent limiting fragmentation behaviour. This has been observed in central Au+Au collisions in BRAHMS [45, 46] and PHOBOS experiments [32, 47]. BRAHMS experiment reported that the longitudinal scaling is also independent of collision centrality, while PHOBOS observed a centrality dependent limiting fragmentation behaviour. When photon pseudorapidity density normalized by $<N_{part}/2>$ are plotted as a function of $\eta - y_{beam}$ for Au+Au and Cu+Cu collision at $\sqrt{s_{NN}} = 200$ and 62.4 GeV and show longitudinal scaling, independent of beam energy and collision centrality as shown in Figure 1.10. The solid line is a second order polynomial fit to the data. It was
also shown that the longitudinal scaling for produced photons is independent of colliding ion species.

These features of photon production are to be investigated at other energies, results of which will facilitate the complete understanding of the nuclear equation of state.

### 1.4.2 Azimuthal Anisotropy and Fluctuations

When two heavy nuclei collide the reaction volume is azimuthally asymmetric. Strong interaction in this volume convert this initial spatial anisotropy to momentum anisotropy as shown in Figure 1.11. As a result the distributions of particle in the azimuthal plane become anisotropic [37–39]. The anisotropy of the particle yield can be characterized by a Fourier expansion [48, 49]

\[
\frac{dN}{d(\phi - \Psi_R)} \propto 1 + 2 \sum_n v_n \cos[n(\phi - \Psi_R)]
\] (1.2)

where \(\phi\) is the azimuthal angle of the particle, \(\psi_R\) is the reaction plane angle, where the reaction plane is the plane containing the impact parameter direction and the beam direction, \(v_n\)'s are the n Fourier coefficients.

Measurement of the Fourier coefficients \(v_n\) for different hadrons provides information on the phase present in the initial stages of evolution of the collision and degree of thermalisation. These coefficients can be determined using different techniques, few of which are discussed in Chapter 5. The first few coefficients are \(v_1\) the directed flow, \(v_2\) the elliptic and \(v_3\) the triangular flow. Figure 1.12 gives the geometric representation of the origin of these three coefficients for a realistic positions of the nucleons.

Some of the important features of the observed elliptic flow at higher energy are:

(i) \(v_2\) values measured for each centrality were observed to be large at RHIC energies and were found to be scale with the geometric eccentricity of the
Figure 1.11: Schematic diagram showing event anisotropy in spatial and momentum space with respect to reaction plane overlap volume. This established that $v_2$ is arising from the initial anisotropic conditions.

(ii) $v_2$ as a function of transverse momentum ($p_T$) for various particle species for $p_T < 1.0$ GeV/c showed mass ordering in Figure 1.13. At a given $p_T$, the hadron with higher mass has a lower value of $v_2$. This observation can be understood using hydrodynamical models [50].

(iii) For $p_T > 2.0$ GeV/c the $v_2$ values for all hadrons saturated, with mesons and baryons showing a clear split and saturating at different values as shown in Figure 1.14. This suggested a number of constituent quark ($n_q$) scaling (NCQ scaling) i.e when $v_2/n_q$ was studied as a function of $p_T/n_q$ all particles species showed exactly the same trend as shown in Figure 1.15. This is interpreted as a possibility that during the initial stages of evolution, when flow was developing, the system showed partonic degrees of freedom. During hadronization, three quarks coalesce to form baryons and a quark and anti-quark form a meson [50].
It is expected that at lower energies, the NCQ scaling would disappear if the matter does not pass through the partonic phase. This was also observed by STAR Collaboration which studied elliptic flow of charged particles as well as identified particles at all the BES energies [51–53]. At the BES energies, $v_2$ of the particle and antiparticle were systematically studied and were found to be different, indicating a breakdown of NCQ scaling, providing a possibility of determining the threshold for production of the partonic medium.
2. STAR results of the $p_T$ dependence of the elliptic flow parameter $v_2$ in Au+Au collisions at 200 GeV. The hydrodynamic calculations are shown in dot-dashed lines. The figure is taken from [50].

3. $v_2$ as a function of $p_T$ for different hadrons in minimum bias Au+Au collisions at 200 GeV. Here hydrodynamical calculations are shown by solid and dotted curves. The figure is taken from [50].

### 1.4.3 Jet Quenching and Nuclear Modification Factor

In a heavy-ion collision, hard scattering between two incoming partons can create a pair of energetic high $p_T$ fast partons which move back to back in the centre of
momentum (CM) Frame. Fragmentation of these partons leads to production of hadrons which are observed as a "jet" around the position of the initial parton. If a parton pair is produced in an AA collision, it is likely that one of the resulting jets passes through the dense medium formed in the interaction. If the medium making up the fireball is QGP the initially produced parton undergoes multiple interactions with the medium and looses its energy in the process. This partial or complete "disappearance" of jet is called as "jet quenching" [54, 55]. The degree of quenching of jet, therefore provides information on the properties of the medium and its interactions. Jet quenching has been studied extensively by RHIC experiments [56, 57]. To estimate the effect of medium on observables, the results are compared with corresponding results in pp collisions. The ratio of the two, normalised to the number of collisions in A+A, is termed as the nuclear modification factor $R_{AA}$. For cold nuclear matter, $R_{AA}$ is expected to yield a value of 1. Smaller than 1 values of $R_{AA}$ indicate the effect of medium on the observable.
It is now standard practice to estimate the medium effects using this method for all observables, including those mentioned in the following.

1.4.4 Strangeness Enhancement

The colliding nuclei are normal nuclear matter, and consist of protons and neutrons which in turn are made of up and down quarks. Strange quarks are only produced in the collision of partons. While $s\bar{s}$ pairs can be formed by collision of quarks (up and down) the dominant mode of production is through gluon gluon collisions ($gg \rightarrow s\bar{s}$) which are present if the Quark-Gluon Plasma is formed [58]. This makes the abundance of strange quarks sensitive to the state of matter formed during the collision. Formation of a large number of ssbar pairs leads to a larger number of strange and multistrange hadrons. Strangeness enhancement is experimentally measured by comparing the yield in AA collisions per participant pair to the yield in pp collisions. Enhancement factors of 2-3 as compared to pp collisions have been reported in AuAu collisions at 200 GeV by STAR experiment. The enhancement is even larger 5-7 for multi-strange particles in central CuCu and AuAu collisions at 200 GeV [59].

1.4.5 $J/\Psi$ Suppression

$J/\Psi$ is a bound state of charm and anticharm quark [60]. Like $s\bar{s}$, $c\bar{c}$ are also produced during a heavy-ion collision by $gg \rightarrow c\bar{c}$. Interactions of $J/\Psi$ with other hadrons during AA collision can cause them to breakup, leading to "normal" suppression of their yield to a small extent. In a high density environment of QGP, the $c$ and cbar are Debye screened from each other due to presence of other color charges. This is similar to screening of two charged particles in a di-electric medium due to polarization of the medium. As a result even though a large number of hadrons with single charm ( or anticharm) are produced, the production of $J/\Psi$ is suppressed and is termed as anomalous suppression. Features of anomalous suppression observed at SPS energies [61, 62] could not be explained by hadronic models. Anomalous suppression has also been confirmed at RHIC energies [62].
1.4.6 Fluctuations and Critical Phenomena

When a system approaches a critical point of continuous phase transformation the correlation length $\xi$ diverges and microscopic details become irrelevant [22–24]. Such critical states of matter are highly correlated, and particularly sensitive to external perturbation.

![Figure 1.16: Collision energy and centrality dependence of the net-proton $S\sigma$ and $K\sigma^2$ from Au+Au and p+p collisions at RHIC. The width of the bands represents statistical uncertainties. The hadron resonance gas model (HRG) values for $S\sigma$ and $K\sigma^2$/Skellam are unity. The error bars are statistical and caps are systematic errors [63].](image)

Any external perturbation is likely to cause large fluctuations. Experiments measure multiplicities $N_\pi$ and $N_p$ event by event. These quantities fluctuate event by event and their distribution is Gaussian. The fluctuations conform to a Gaussian
distribution. At critical point the fluctuations deviate from those expected from a Gaussian distribution. The correlation length is seen to affect the moments of the fluctuations, the second moment $< (\delta N)^2 > \sim \xi^2$. The higher moments have an even stronger dependence on $\xi$. Therefore study of the higher moments for various conserved quantities as a function energy of collision is a sensitive probe for locating the critical point on Hadron-QGP Phase transformation boundary. Experimentally, instead of moments of distributions of conserved quantities, it is easier to study ratios of the moments $\kappa \sigma^2$ and $S \sigma$, since the effects due to finite volume cancel out. One of the main goals of RHIC BES program was to search for the critical point. STAR experiment has studied the higher moments of net proton distributions [63] for a range of center of mass energy from 7.7 to 200 A GeV as shown in Figure 1.16. The measurements are carried out at mid-rapidity for various event centrality. The experimental observations are not reproduced by models that do not include a critical point in the phase diagram. More studies with higher statistics are underway for understanding the results. Fluctuations in net charge and net strangeness distributions are also being studied.

1.5 Beam Energy Scan (BES) at RHIC

The main goal of the beam energy scan at RHIC is to:

(i) To locate the existence of the critical point in the QCD phase diagram

(ii) To search of the evidence of the first order phase transition in the QCD phase diagram

(iii) To understand the properties of QGP

The BES phase-one recorded data successfully in 2010 (Run10) and in 2011 (Run11). STAR took data for Au+Au collision at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV in year 2010 and at $\sqrt{s_{NN}} = 19.6$ and 27 GeV in year 2011. For these energies, the corresponding $\mu_B$ coverage is estimated from 112 to 410 MeV. This program provides a suitable access to most interesting region in QCD phase diagram to understand the bulk properties of the QGP. The measurements and the analyses in the present thesis correspond to data recorded as a part of the BES programme.
### 1.6 Organization of the Thesis

The work presented in the thesis deals with results of investigation of scaling and limiting fragmentation in photons in forward rapidity region in the BES energies. The thesis also investigates the ability of AMPT event generator to explain the published results on $v_2$ and $v_3$ of charged particles from BES energies to the energies at the Large Hadron Collider (2.76 A TeV). The elliptic flow, $v_2$, of photons has been measured at 39 A GeV and compared with AMPT predictions. To meet this aim, the data at BES energies from the Photon Multiplicity Detector in the STAR experiment is used. The results presented in this thesis are preliminary results of STAR Collaboration.

Chapter 2 contains a brief overview of the STAR detector and its subsystems which are connected with the analyses in the present work, and provides some details of working of PMD. Chapter 2 also contains the details of centrality selection for the various energies, as adopted by STAR, and the parameters characterising the centrality ($N_{\text{part}}$). In Chapter 3, the details of raw data, identification of bad channels and gain normalisation process has been provided. To correct the measured values of photon yield for efficiency and purity, simulations have been performed for different centralities, rapidity windows and the correction factors obtained for different occupancies in the detector. The procedure has been systematically shown in this chapter. The chapter also includes results on photon rapidity density distributions in Au+Au collisions at 39, 27 and 19.6 A GeV. Detailed estimates of systematic errors on rapidity densities are also included in this chapter. In Chapter 4, the results on photon multiplicity and rapidity density distributions for the three energies are compared with event generators, and the data investigated for possible scaling and limiting fragmentation. Possible explanation for the observed deviation from limiting fragmentation at lower energies have been discussed, along with comparison with published data at higher energies. A new parametrisation for different contributions to the total yield of photons has been proposed, which describes the data at five energies using two free parameters. Chapter 5 deals with the results of AMPT model to describe the $v_2$ and $v_3$ of charged particles for a wide range of energies. The model parameters were tuned to reproduce multiplicity and the details are discussed here. In Chapter 6, the results on photon flow for
Au+Au collisions at 39 GeV are presented, along with comparison with AMPT data. The thesis ends with the conclusions in Chapter 7.