Chapter 7

Summary and Discussion

The search of QGP has been the major driving force behind research activities in the field of heavy ion collision for the last three decades. The motivation of the present work is to study the signature of formation of quark gluon plasma and its properties. The hot and dense matter expected to be formed in the partonic phase after ultra-relativistic heavy ion collisions dynamically evolve in space and time due to high internal pressure. Consequently the system cools and reverts to hadronic matter from the partonic phase. Just after the formation, the entire energy of the system is thermal in nature and with progress of time some part of the thermal energy gets converted to the collective (flow) energy. In other words, during the expansion stage the total energy of the system is shared by the thermal as well as the collective degrees of freedom. The evolution of the collectivity within the system is sensitive to the Equation of State (EoS). Therefore, the study of the collectivity in the system will be useful to shed light on the EoS and on the nature of the transition that may take place during the evolution process.

It is well known that the average magnitude of radial flow at the freeze-out surface can be extracted from the transverse momentum ($p_T$) spectra of the hadrons. However,
hadrons being strongly interacting objects can bring the information of the state of the system when it is too dilute to support collectivity i.e. the parameters of collectivity extracted from the hadronic spectra are limited to the evolution stage where the collectivity ceases to exist. These collective parameters have hardly any information about the interior of the matter. On the other hand electromagnetic (EM) probes, i.e. photons and dileptons are produced and emitted from each space time points. Therefore, estimating radial flow from the EM probes will shed light on the time evolution of the collectivity in the system.

The photon and dilepton spectra measured at SPS and RHIC energies by different experimental collaborations have been analyzed to understand the evaluation of collectivity in the system. The initial conditions of the evolving matter required to calculate the photon and dilepton spectra have been constrained to reproduce the measured multiplicity in these collisions. The EoS, the other crucial input to the calculations has been taken from lattice QCD calculations. The deviation of the hadronic phase from chemical equilibrium is taken into account by introducing non-zero chemical potential for each hadronic species.

The invariant momentum distribution of photons produced from a thermal source depends on the temperature ($T$) of the source through the thermal phase space distributions of the participants of the reactions that produce photon. As a result the $p_T$ spectra of photon reflects the temperature of the source. Hence ideally the photons with intermediate $p_T$ values ($\sim 2 - 3$ GeV, depending on the value of initial temperature) reflect the properties of QGP (realized when $T > T_c$, $T_c$ is the transition temperature). Therefore, one should look into the $p_T$ spectra for these values of $p_T$ for the detection of QGP. However, for an expanding system the situation is far more complex. The thermal phase space factor changes due to several factors e.g. the transverse kick received by
low $p_T$ photons due to flow originating from the low temperature hadronic phase (realized when $T < T_c$) populates the high $p_T$ part of the spectra. As a consequence the intermediate or the high $p_T$ part of the spectra contains contributions from both QGP and hadrons.

For dilepton the situation is, however, different because in this case we have two kinematic variables - out of these two, the $p_T$ spectra is affected by the flow, however, the $p_T$ integrated invariant mass ($M$) spectra is unaltered by the flow in the system. Moreover, for $M$ below $\rho$ peak and above $\phi$ peak dileptons from QGP dominates over its hadronic counterpart (assuming the contributions from hadronic cocktails are subtracted out and medium effects on the vector meson spectral function are ignored). The invariant mass spectra of lepton pairs may be used in principle to extract (i) the medium effects of the vector meson spectral function, (ii) contributions from the (early) QGP phase by selecting $M > M_\phi$ and (iii) from the (late) hadronic phase. This suggests that the dilepton spectra can be used as a clock for heavy ion collision. As mentioned before, the $p_T$ spectra of the lepton pairs are affected by flow. Therefore the evolution of flow of the evolving QGP may be estimated by studying the transverse momentum spectra with appropriate selection of invariant mass window. Hence the lepton pairs can also be used as flow meter [107, 126, 127] for the system formed in relativistic heavy ion collision. In the present work, two procedures have been proposed to estimate the radial flow of the matter, i.e. (i) ratio of the $p_T$ spectra of thermal photons to dileptons and (ii) HBT radii extracted from the dilepton correlation function.

The calculations of EM probes from thermal sources depend on the parameters like initial temperature ($T_i$), thermalization time ($\tau_i$), chemical freeze-out temperature ($T_{ch}$), kinetic freeze-out temperature ($T_f$) etc, which are not known unambiguously. To minimize the dependence of thermal sources on these parameters the importance of the ratio
of the transverse momentum spectra of photon to dilepton has been considered in order to partially overcome the above mentioned uncertainties. It may be mentioned here that in the limit of $M \to 0$ the lepton pairs (virtual photons) emerge as real photons. Therefore, the evaluation of the ratio of the $p_T$ spectra of photons to dileptons for various invariant mass bins along with a judicious choice of the $p_T$ and $M$ windows will be very useful to extract the properties of QGP as well as that of hadronic phase. This is demonstrated in the present work by analyzing WA98 and PHENIX photons and NA60 and PHENIX dilepton spectra. It is shown that simultaneous measurements of photon and dilepton spectra in heavy ion collisions will enable us to quantify the evolution of the average radial flow velocity for the system and the nature of the variation of radial flow with invariant mass will indicate the formation of partonic phase.

Experimental measurements of two-particle intensity interferometry has been established as a useful tool to characterize the space-time evolution of the heavy-ion reaction. For the case of dileptons, such an interferometry needs to be carried out over dilepton pairs, theoretically representing a study of the correlations between two virtual photons. Although, the dilepton production rate is down by a factor of $\alpha$ compared to real photon, the analysis involving lepton pairs has been successfully used to get direct photon yields at RHIC. In contrast to hadrons, two-particle intensity interferometry of dileptons, like photons, which have almost no interactions with the surrounding hadronic medium hence can provide information on the history of the evolution of the hot matter very efficiently.

In this work, we present a new proposal for carrying out an experimental measurement of dilepton interferometry both for RHIC and LHC. We establish through a hydrodynamical model based space-time evolution the promise of such a dilepton interferometry analysis will be useful to understand the properties of the partonic phase. We
have evaluated the correlation function, $C_2$ for two dilepton pairs for various invariant mass domains and extracted the HBT radii, i.e. $R_{\text{side}}$ and $R_{\text{out}}$ as a function of $M$. These HBT radii show a non-monotonic dependence on the invariant mass, reflecting the evolution of collective flow in the system which can be considered as a signal of the QGP formation in heavy ion collisions. The $M$ dependence of the $R_{\text{out}}/R_{\text{side}}$ and $\sqrt{R_{\text{out}}^2 - R_{\text{side}}^2}$ which can be experimentally measured could be used to characterize the source properties at various instances of the evolution.

Elliptic flow is proposed as an useful tool to characterize Quark-Gluon Plasma. Comparison of measured $v_2$ calculated using relativistic hydrodynamic and transport approaches have lead to several important results. The most important of these is the small shear viscosity to entropy ratio of the QGP compared to other known fluids. The mass ordering of $v_2$ of identified hadrons, clustering of $v_2$ separately for baryons and mesons at intermediate $p_T$ are considered as signatures of partonic coalescence as a mechanism of hadron production. In contrast to hadrons, which are predominantly emitted from the freeze-out surface of fireball, the electromagnetically interacting particles (real photons and lepton pairs) are considered as penetrating probes which can carry information from the hot interior of the system. Therefore, the analysis of $v_2$ of lepton pairs and photons can provide information of the pristine stage of the matter produced in HIC. The lepton pairs are produced from each space time point of the system and hence the study of $v_2$ of lepton pairs will shed light on the time evolution of collectivity in the system.

It has been argued that the anisotropic momentum distribution of the hadrons can bring the information on the interaction of the dense phase of the system despite the fact that the hadrons are emitted from the freeze-out surfaces when the system is too dilute to support collectivity. For hadrons, a suitable dynamical model is required to
extrapolate the final hadronic spectra backward in time to get the information about
the early dense phase. Such extrapolation is not required for lepton pairs because they
are emitted from the entire space-time volume of the system. Therefore, the $v_2$ of lepton
pairs provide information of the hot and dense phase directly. The $v_2$ can also be used
to reassert the conclusion that hadronic $v_2$ can be used as a probe of early dense phase.

It is well known that the $p_T$ integrated $M$ distribution of lepton pairs with $M (> m_\phi)$
originate from the early time, providing information of partonic phase and pairs with
$M \leq m_\rho$ are chiefly produced at late times giving information of the hadronic phase.
Therefore, the study of the $p_T$ integrated $M$ distribution of lepton pairs can act as a
chronometer of the heavy ion collisions. On the other hand, the variation of $v_2$ with $p_T$
for different $M$ windows may be used as a flow meter.

We have evaluated the $v_2$ of dileptons originating from the Pb+Pb collisions at
$\sqrt{s_{NN}} = 2.76$ TeV for 30−40% centrality. Here, the (2+1) dimensional hydrodynamical
model has been used for space-time dynamics. The dilepton emission rate used for the
evaluation of $v_2$ of dilepton includes the medium effect on the spectral function of the
vector mesons. However, the spectral function of low mass vector mesons (mainly $\rho$)
may shift toward lower invariant mass region due to non-zero temperature and density
effects. As a consequence the contributions from the decays of such vector mesons to
lepton pairs could populate the low $M (< M_\rho)$ window and may dominate over the
contributions from the QGP phase.

The differential elliptic flow, $v_2(p_T)$ has been evaluated for different invariant mass
windows. We found an increasing trend of $v_2$ with $p_T$. Our study shows that $v_2(M)$
provides useful information on the collective motion of the evolving QCD matter formed
in high energy heavy-ion collisions. Our calculation indicates that a reduction of $v_2(M)$
with increasing $M$ beyond $\phi$ mass would reflect the presence of small momentum space
anisotropy through modest collective motion in the QM phase. We observe that $v_2(\langle M \rangle)$ of the penetrating probe (lepton pairs) for $\langle M \rangle = m_\pi$ and $m_K$ is similar to the hadronic $v_2^\pi$ and $v_2^K$ when the medium induced change in the $\rho$ spectral function is included in evaluating the dilepton spectra. The medium effects are large during the dense phase of the hadronic system, therefore, this validates the findings that the hadronic $v_2$ carry the information of the dense part of the hadronic phase. Our study also establishes the fact that the invariant mass dependence of dilepton $v_2$ can in principle act as a clock for the space time evolution of the system formed in HIC.

Some comments on the initial conditions used in this work are in order here. For the results presented here, different initial conditions have been used. In the chapter-3, the main focus is to describe the available experimental data of $p_T$ spectra of photon and dilepton at SPS and RHIC energies. So the initial conditions taken in this chapter are constrained to specific collision energy, centrality and final multiplicity. These set of initial conditions are also used in chaper-4, where the $p_T$ spectra of photon and dilepton which reproduce the experimental data are used to evaluate the ratio ($R_{em}$) and quantify the radial flow. For the analysis of HBT radii (in chapter-5) we have used different set of initial condition for RHIC and LHC energies which is for most central collision. Again, for the evaluation of $v_2$ of dilepton, the initial condition is taken for LHC energies for a peripheral collision (30-40 % centrality). Therefore, in summary, the initial conditions have been made to vary to suit different collision centralities and beam energies.