Probing collectivity in ultra-relativistic heavy ion collision by leptons and photons

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Abstract

It has been shown that the evolution of collectivity in ultra-relativistic heavy ion collision is manifested in the variation of various HBT radii with invariant mass \(M\) extracted from the correlation functions of two lepton pairs. The value of the radial velocity \(v_r\) can be estimated from the ratio of the \(p_T\) distributions of single photons to lepton pairs for various \(M\) windows. It has been argued that the variation of radial flow with appropriate kinematic variables can be used as an indicator of a phase transition from initially produced partons to hadrons. We also consider the elliptic flow \(v_{2HF}\) of the matter as probed by the single electron spectra originating from the semileptonic decays of heavy mesons. The measured values of \(v_{2HF}\) and the nuclear suppression factor \(R_{AA}\) at RHIC energy have been reproduced simultaneously by including both the collisional and radiative processes within the scope of perturbative quantum chromodynamics. The \(R_{AA}\) and \(v_{2HF}\) have been predicted for LHC energy.

Key words: Heavy ion collision, quark gluon plasma, photons, dileptons.

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1 Introduction

The hot and dense matter expected to be formed in the partonic phase after ultra-relativistic heavy ion collisions (URHIC) dynamically evolve in space and time due to high internal pressure. The system cools due to expansion and reverts back to hadronic matter from the partonic phase. 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. The electromagnetic (EM) probes, i.e. photons and dileptons on the other hand are produced and emitted \([\text{1}]\) (see \([\text{2}]\) for review) 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 generation of collectivity in
the system depends on EoS - hence this can be used to differentiate partonic and
hadronic phases as the EoS for these two phases are different. In case of EM probes-
dilepton has the advantage over the real photons. Because the low $p_T$ photons from
the hadronic phase receive large transverse kick due to radial flow and consequently
appear in the high $p_T$ domain to mingle with those from the QGP phase, making the
detection of photons from QGP difficult. However, for dileptons there are two kinemat-
ic variables available - the $p_T$ and the invariant mass ($M$). While the $p_T$ spectra
of dilepton is affected by the flow, the $p_T$ integrated $M$ spectra remains unaltered.
This suggests that a careful selection of $p_T$ and $M$ windows will be very useful to
characterize the QGP and hadronic phases. In the present work we will demonstrate
how the development of radial flow can be estimated through the Hanbury-Brown
Twiss (HBT) interferometry with virtual photons (lepton pairs) for different $M$ win-
dows. The radial flow velocity ($v_r$) can be estimated by considering the ratio of the $p_T$
distribution of single photon to lepton pairs for various $M$ windows. We will briefly
discuss the results here and refer to [3] for details.

Single electrons originating from the semi-leptonic decays of heavy mesons carry
the information on the interaction of the heavy quarks (a constituent of the heavy
mesons) with the thermal medium of light quarks and gluons produced in heavy ion
collisions. The $R_{AA}$ and $v_2^{HF}$ can be used to quantify the interaction of the heavy
quarks with the QGP. Several ingredients like inclusions of non-perturbative contrib-
utions from the quasi-hadronic bound state [4], 3-body scattering effects [5], the
dissociation of heavy mesons due to its interaction with the partons in the ther-
mal medium [6] and employment of running coupling constants and realistic Debye
mass [7], the inclusion of both elastic and inelastic collisions along with the path
length fluctuation have been proposed [8] to improve the description of the experi-
mental data. Within the framework of Fokker Planck equation (FPE) we will evaluate
$v_2^{HF}$ and $R_{AA}$ for these electrons. In the present paper we discuss the elliptic flow
of the matter probed by the single electron from the heavy mesons decays. For the
elliptic flow of the matter probed by single photon and lepton pair we refer to [9,10]
for details.

In the next section we will briefly describe the HBT interferometry with virtual pho-
tons. The azimuthal anisotropy of the system probed by single electrons originating
from the heavy flavour decays will be discussed in section 3. Section 4 is devoted to
summary and discussions.

2 HBT interferometry with dileptons

The interferometry of the dilepton pairs actually reflect correlation between two
virtual photons, the analysis then can proceed by computing the Bose-Einstein cor-
relation (BEC) function for two virtual photons which can be defined as, \( C_2(\vec{p}_1, \vec{p}_2) = P_2(\vec{p}_1, \vec{p}_2) / [P_1(\vec{p}_1)P_1(\vec{p}_2)] \), where \( p_i \) is momentum of the individual lepton pair, \( P_1(\vec{p}_i) \) and \( P_2(\vec{p}_1, \vec{p}_2) \) represent the one- and two- particle inclusive lepton pair spectra respectively, which can be evaluated form the source function for various invariant mass windows of the pair [11]. For the productions of lepton pairs from QGP the annihilation of thermal quarks and from the hadronic phase the decays of thermal light vector mesons (\( \rho, \omega \) and \( \phi \)) have been considered.

For the space time evolution of the system relativistic hydrodynamical model with cylindrical symmetry [12] and boost invariance along the longitudinal direction [13] has been used. For a system undergoing isentropic expansion, the initial temperature \( (T_i) \) and proper thermalization time \( (\tau_i) \) of the system may be constrained by the measured hadronic multiplicity, \( dN/dy \sim T_i^3 \tau_i \). For Relativistic Heavy Ion Collider (RHIC) we have taken \( T_i = 290 \) MeV and \( \tau_i = 0.6 \) fm/c. The EoS which controls the rate of expansion/cooling has been taken from the lattice QCD calculations [14]. The chemical \( (T_{ch}=170 \) MeV) and kinetic \( (T_f=120 \) MeV) freeze-out temperatures are fixed by the particle ratios and the slope of the \( p_T \) spectra of hadrons [15]. With all these ingredients the correlation function \( C_2 \) has been evaluated for different (average) invariant mass windows, \( \langle M \rangle = (M_1 + M_2)/2 \) as a function of \( q_{side} \) and \( q_{out} \) [11] which are related to the transverse momentum of individual pair. The HBT radii, \( R_{side} \) and \( R_{out} \) corresponding to \( q_{side} \) and \( q_{out} \) extracted from the (Gaussian) parametrization of \( C_2 \).

The \( R_{side} \) is related to the transverse size of the system whereas the \( R_{out} \) measures both the transverse size and duration of particle emission ( [16] for review). The \( R_{side} \) shows non-monotonic dependence on \( \langle M \rangle \) (Fig. 1, left panel). It can be shown that \( R_{side} \sim 1/(1 + E_{collective}/E_{thermal}) \). The high \( \langle M \rangle \) regions are dominated

Fig. 1. Left panel: variation of \( R_{side} \) and \( R_{out} \) as a function of \( \langle M \rangle \). The dashed (solidi with asterisk) line indicates HBT radii for QGP (total=QGP+hadron) phase. Right panel: variation of the radial velocity with \( \langle M \rangle \) extracted from the ratio of the \( p_T \) distribution of photons to lepton pairs (see [3] for details).
by the early partonic phase [16] where the collective flow has not been developed fully consequently the ratio of collective \((E_{\text{collective}})\) to thermal \((E_{\text{thermal}})\) energies is small- hence a larger \(R_{\text{side}}\) is obtained for large \(M\). In contrast, the lepton pairs with \(M \sim m_\rho\) are emitted from the late hadronic phase where the collective flow or \(1 + E_{\text{collective}}/E_{\text{thermal}}\) is large, which is reflected as a dip in \(R_{\text{side}}\) for \(\langle M \rangle \sim m_\rho\). Thus the variation of \(R_{\text{side}}\) with \(M\) can be used as an efficient tool to measure the collectivity in various phases of matter. We observe that by keeping the \(\rho\) and \(\omega\) contributions and setting radial velocity, \(v_r = 0\), the dip in \(R_{\text{side}}\) vanishes, confirming the fact that the dip is caused by the large radial flow of the hadronic matter. The \(R_{\text{out}}\) probes both the transverse dimension as well as the duration of emission and unlike \(R_{\text{side}}\), \(R_{\text{out}}\) does not remain constant even in the absence of radial flow. The large \(\langle M \rangle\) regions are populated by lepton pairs from early partonic phase where the effect of flow is small and the duration of emission is also small - resulting in smaller values of \(R_{\text{out}}\). For lepton pair from \(\langle M \rangle \sim m_\rho\) region the flow is large which could have resulted in a dip as in \(R_{\text{side}}\) in this \(M\) region. However, \(R_{\text{out}}\) probes the duration of emission too, which is large for hadronic phase. The larger duration overwhelms the reduction of \(R_{\text{out}}\) due to flow in the hadronic phase resulting in a bump in \(R_{\text{out}}\) in this region of \(\langle M \rangle\).

As mentioned before the \(v_r\) can be estimated from the ratio of the \(p_T\) spectra of real photons to lepton pairs. Fig. 1(right panel) shows the variation of \(v_r\) with \(\langle M \rangle\) both for SPS and RHIC conditions. The individual spectra of photons and lepton pairs are constrained by the available experimental data [3]. The \(v_r\) increases with \(M\) up to \(M = M_\rho\) then drops. From the invariant mass spectra it is known that the low \(M\) (below \(\rho\) mass) and high \(M\) (above \(\phi\) peak) pairs originate from a partonic source [3]. The collectivity (or flow) does not develop fully in the QGP resulting in smaller values of \(v_r\) at both low and high \(M\) regions. Lepton pairs for \(M \sim m_\rho\) originate from the late hadronic source which are largely affected by the flow resulting in higher values of \(v_r\). In summary, the value of \(v_r\) for \(M\) below and above the \(\rho\)-peak is small but around the \(\rho\) peak is large - the resulting behaviour is displayed in Fig. 1(right panel). Similar non-monotonic variation of the effective slope parameter of the \(p_T\) distribution of lepton pairs for various \(M\) windows is observed in [17]. The evolution of \(v_r\) as observed in Fig. 1(right panel) is responsible for such behaviour.

3 Elliptic flow probed by single electron spectra

The heavy flavors, namely, charm and bottom quarks, play a crucial role in characterizing the QGP (see also [18]). As the relaxation time is larger for heavy quarks than light partons, the light quarks and the gluons thermalize faster. Therefore, the propagation of heavy quarks through QGP may be treated as the interactions between equilibrium and non-equilibrium degrees of freedom and the FPE provides an appropriate framework [19] for such studies. In this work we would like to evaluate \(v_2^{HF}\) and \(R_{AA}\) of heavy flavours within the framework of FPE and contrast the results
with the available experimental data. The evolution of heavy quarks momentum distribution function, while propagating through the QGP are assumed to be governed by the FPE, which reads,

\[
\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_i} \left[ A_i(p) f + \frac{\partial}{\partial p_j} [B_{ij}(p) f] \right]
\]

(1)

where the kernels \(A_i\) and \(B_{ij}\) are given by, \(A_i = \int d^3k \omega(p, k)k_i\) and \(B_{ij} = \int d^3k \omega(p, k)k_i k_j\), for \(|p| \to 0\), \(A_i \to \gamma p_i\) and \(B_{ij} \to D \delta_{ij}\), where \(\gamma\) and \(D\) stand for drag and diffusion co-efficients respectively.

The basic inputs required for solving the FP equation are the dissipative co-efficients and initial momentum distributions of the heavy quarks. The (effective) drag and diffusion coefficients have been evaluated by taking in to account both the collisional and radiative processes [20]. In the radiative process the dead cone and LPM effects are included. In evaluating the drag co-efficient we have used temperature dependent strong coupling, \(\alpha_s(T)\) [21]. The Debye mass, \(\sim g(T)T\) also a temperature dependent quantity used as a cut-off to shield the infrared divergences arising due to the exchange of massless gluons. The initial momentum distribution of heavy quarks in pp collisions have been taken from the NLO MNR [22] code. The solution of the FPE for the heavy quarks is convoluted with the fragmentation functions of the heavy quarks to obtain the \(p_T\) distribution of the \(D\) and \(B\) mesons. For heavy-quark fragmentation function, the Peterson function has been used. The solution of the FPE has been used to predict the \(p_T\) spectra of the \(D\) mesons by following the procedure similar to blast wave method [23], the result is compared with experimental data [24] (Fig. 2, left panel) which indicate that the present data can not distinguish between the equilibrium and non-equilibrium scenario. The \(p_T\) distribution of the electrons from the semi-leptonic decays of \(D\) and \(B\) meson are evaluated using the standard techniques available in the literature. The ratio of the \(p_T\) distribution of the electron from the decays of heavy flavours produced in heavy ion collisions to the corresponding (appropriately scaled by the number of collisions) quantities from the pp collisions is defined as: \(R_{AA}(p_T) = \frac{dN^e_{Au+Au}/dp_Tdy}{[N_{coll} \times dN^e_{pp}/dp_Tdy]}\), which will be unity in the absence of re-scattering. The STAR [25] and the PHENIX [26] collaborations have measured the \(R_{AA}(p_T)\) for non-photonic single electron as a function of \(p_T\) for \(Au+Au\) at \(\sqrt{s_{NN}} = 200\) GeV. The experimental data from both the collaborations show \(R_{AA} < 1\) for \(p_T \geq 2\) GeV indicating substantial interaction of the heavy quarks with the plasma particles. The spectra evaluated using the formalism described above reproduces the data reasonably well (Fig. 2, right panel).

Next we discuss the elliptic flow resulting from non-central collisions of nuclei. When a heavy quark propagates along the major axis of an ellipsoidal domain of QGP (resulting from the non-central collisions) then the number of interactions it encounters or in other words the amount of energy it dissipates or the amount of momentum degradation that takes place is different from when it propagates along the minor axis. Therefore, the momentum distribution of electrons originating from
Fig. 2. Left panel: $p_T$ distribution of $D$ mesons. $\beta_s$ indicates the value of $v_r$ which appears as a parameter in the blast wave model. FP stands for the results obtained from the solution of FP equation. The experimental data from STAR collaboration \cite{24} is compared with the theoretical results. Right panel: variation of $R_{AA}$ with $p_T$. The initial temperature and thermalization time are taken as 400 MeV and 0.2 fm/c respectively.

Fig. 3. Left panel: variation of $v_2^{HF}$ with $p_T$ for for RHIC energy. Right panel: $v_2^{HF}$ is plotted as a function of $p_T$ for LHC energy for 0-10% centrality. The values of $T_i$ and $\tau_i$ are taken as 700 MeV and 0.08 fm/c respectively.

the decays of heavy flavoured hadrons produced from the fragmentation of heavy quarks propagating through an anisotropic domain will reflect such anisotropy. The degree of momentum anisotropy will depend on both the spatial anisotropy and more importantly on the coupling strength of the interactions between the heavy quarks and the QGP. The drag and diffusion coefficients depend on the temperature of the background medium (QGP) which evolves in space and time due to expansion. Therefore, the drag and diffusion will also change due to the flow of the background. The flow of the background has been treated within the ambit of (2+1) dimensional hydrodynamics \cite{27}. The coefficient of elliptic flow, $v_2^{HF}$ is defined as: $v_2^{HF} (p_T) = \langle \cos(2\phi) \rangle = \int d\phi dN/dy dp_T d\phi|_{y=0} \cos(2\phi) / \left[ \int d\phi dN/dy dp_T d\phi|_{y=0} \right]$. We evaluate $v_2^{HF}$ in the current formalism \cite{28} and compare the results with experimental data \cite{29} (Fig. 3 left panel). The prediction for the elliptic flow of the heavy quarks to be measured at Large Hadron Collider (LHC) energy through the semi-leptonic decays is depicted in Fig. 3 (right panel). The value of $v_2^{HF}$ at LHC is similar to that of at RHIC. The prediction for the $R_{AA}$ at LHC has been displayed in Fig. 4 separately for $D$ and $B$ mesons. The sensitivity of the results on the equation of state (EoS), i.e. on the velocity of sound is also considered. Lowering of $c_s$ gives
Fig. 4. Variation of $R_{AA}$ with $p_T$ for LHC for 0-10% centrality. Left panel for charm and right panel bottom quarks. The values of $T_i$ and $\tau_i$ are taken as 700 MeV and 0.1 fm/c respectively.

more suppressions as observed in Fig. 4. Lower value of velocity of sound, $c_s$ makes the expansion of the plasma slower enabling the propagating heavy quarks to spend more time to interact in the medium and hence lose more energy before exiting from the plasma resulting in more suppression.

4 Summary

We have shown that the variation of various HBT radii with invariant mass extracted from the correlation functions of two lepton pairs can be used to understand the evolution of collectivity in ultra-relativistic heavy ion collision. The evolution of the radial flow in the system produced in URHIC has been discussed and demonstrated that the non-monotonic variation of $v_r$ with $M$ can be used as a signal for parton to hadron transition. The elliptic flow of the matter probed by the single electrons originating from the heavy flavour decays has been studied. The elliptic flow and the nuclear suppression factor measured at RHIC have been reproduced and predictions for LHC have been given including both the radiative and the collisional processes of energy loss in evaluating the effective drag and diffusion coefficients. The sensitivity of the results on the EoS has also been studied.

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