PHYSICAL REVIEW C **85**, 031903(R) (2012)

Elliptic flow of thermal dileptons as a probe of QCD matter

Payal Mohanty,[1] Victor Roy,[1] Sabyasachi Ghosh,[1] Santosh K. Das,[1] Bedangadas Mohanty,[2] Sourav Sarkar,[1] Jan-e Alam,[1] and Asis K. Chaudhuri[1]

[1]*Theoretical Physics Division, Variable Energy Cyclotron Centre, Kolkata 700064, India*

[2]*Variable Energy Cyclotron Centre, Kolkata 700064, India*

(Received 17 November 2011; revised manuscript received 2 March 2012; published 20 March 2012)

We study the variation of elliptic flow of thermal dileptons with a transverse momentum (p_T) and invariant mass (M) for Pb + Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV for 30%–40% centrality. The dilepton productions from a quark gluon plasma and hot hadrons have been considered, including the spectral change of light vector mesons in the thermal bath. The space-time evolution has been carried out within the framework of $(2+1)$-dimensional ideal hydrodynamics with a lattice + hadron resonance gas equation of state. We find that a judicious selection of M windows can be used to extract the collective properties of quark matter and hadronic matter, and also obtain a distinct signature of medium effects on vector mesons. Results within the ambit of the present work for nuclear collisions at the Large Hadron Collider (LHC) indicate a reduction of elliptic flow (v_2) for M beyond ϕ mass, which, if observed experimentally, would imitate the small momentum anisotropy in the early stage of the collective motion of the partons. We also observe that the magnitude of the elliptic flow is significantly larger at LHC than at Relativistic Heavy Ion Collider (RHIC) collision conditions.

DOI: 10.1103/PhysRevC.85.031903 PACS number(s): 25.75.−q, 12.38.Mh

A collision between nuclei at relativistic energies provides an opportunity to study quantum chromodynamics (QCD) at nonzero temperatures and densities. Calculations based on lattice QCD (LQCD) predict that at high temperatures and/or densities hadronic matter melts down to a state of deconfined thermal quarks and gluons—a phase of matter called a quark gluon plasma (QGP). The weakly interacting picture of the QGP stems from the perception of asymptotic freedom of QCD at high temperatures and densities. However, the LQCD calculations indicate that the deconfined system does not reach the Stefan-Boltzmann limit corresponding to the noninteracting massless gas of quarks, antiquarks, and gluons even at a temperature as high as 1000 MeV [1]. The Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) are the two experimental facilities where the QGP can be created by colliding nuclei at high energies. Several probes to study the properties of QGP have been proposed. Among those the azimuthal anisotropy or the elliptic flow (v_2) of the produced particles have been shown to be sensitive to the initial condition and the equation of state (EOS) of the evolving matter formed in heavy-ion collisions (HICs) (see Refs. [2–4] for reviews).

Noncentral heavy-ion collisions provide an anisotropic spatial configuration which, together with the interactions among the constituents, develop pressure gradients of different magnitudes along different spatial directions. With the expansion the spatial anisotropy reduces and the momentum space anisotropy builds up rapidly. The v_2 is a measure of this momentum space anisotropy, which is defined as $v_2 = \langle \cos[2(\phi - \Psi)] \rangle = \langle p_x^2 - p_y^2 \rangle / \langle p_x^2 + p_y^2 \rangle$, where p_x and p_y are the x and y components of the particle momenta, ϕ is the azimuthal angle of the produced particles, and Ψ is the angle subtended by the plane containing the beam axis and impact parameter in the x direction. A comparison of measured v_2 with those calculated using relativistic hydrodynamic and transport approaches has 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 [5]. The mass ordering of v_2 of identified hadrons, the 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 [6,7]. In contrast to hadrons, which are predominantly emitted from the freeze-out surface of a fireball, the electromagnetically interacting particles (real photons and lepton pairs) are considered as penetrating probes [8] (see Refs. [9–11] for reviews) 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 about the pristine stage of the matter produced in HICs. The v_2 of dileptons [12] and photons [13] have been evaluated for RHIC energies and it has been shown that they can be used as effective probes to extract the properties of the partonic plasmas. The sensitivity of v_2 of lepton pairs on EOS has been elaborated in Ref. [14] for RHIC collision conditions. 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. Further, unlike photons, in addition to p_T, dileptons have an additional kinematic variable M. The evolution of radial flow can be estimated by studying the p_T spectra of lepton pairs for different M windows [15,16]. The radial flow alters the shape of the p_T spectra of dileptons—it kicks the low p_T pairs to the higher p_T domain, making the spectra flatter. Therefore, the presence of large radial flow may diminish the magnitude of v_2 at low p_T [17], and this effect will be larger when the radial flow is large, i.e., in the hadronic phase, which corresponds to lepton pairs with $M \sim m_\rho$.

It has been argued that the anisotropic momentum distribution of the hadrons can show information about the interaction of the dense phase of the system [2] despite the fact that the hadrons are emitted from the freeze-out surfaces when the system is too dilute to support collectivity. Therefore, a suitable dynamical model is required to extrapolate the final hadronic spectra backward in time to obtain the information about the early dense phase. Such an 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 directly provide information about the hot and dense phase. The v_2 of dileptons can also be used to test the validity and efficiency of the extrapolation required for hadronic v_2. We will also see below that the p_T integrated M distribution of lepton pairs with M ($>m_\phi$) originate from the early time, providing information about the partonic phase, and the pairs with $M \lesssim m_\rho$ are chiefly produced later from the hadronic phase. Therefore, the p_T integrated M distribution of lepton pairs may be used 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.

In this Rapid Communication we study the M and p_T dependence of v_2 for dileptons using relativistic ideal hydrodynamics [18], assuming boost invariance along the longitudinal direction [19] for LHC collision conditions. We argue that the v_2 of lepton pairs from QGP and hadronic phases can be estimated with an appropriate choice of M. In addition, we also show that the thermal effects on the ρ spectral function are visible through v_2 in the low-mass (below ρ peak) dileptons.

The elliptic flow of dilepton $v_2(p_T, M)$ can be defined as

$$v_2 = \frac{\sum \int \cos(2\phi)\left(\frac{dN}{d^2p_T dM^2 dy}\Big|_{y=0}\right)d\phi}{\sum \int \left(\frac{dN}{d^2p_T dM^2 dy}\Big|_{y=0}\right)d\phi}, \tag{1}$$

where the $\sum$ stands for summation over quark matter (QM) and hadronic matter (HM) phases. The quantity $dN/d^2p_T dM^2 dy|_{y=0}$ appearing in Eq. (1) can be obtained from the dilepton production per unit four volume $dN/d^4p d^4x$ in a thermalized medium by integrating over the space-time evolution of the system. The quantity $dN/d^4p d^4x$ is given by [8]

$$\frac{dN}{d^4p d^4x} = -\frac{\alpha^2}{6\pi^3}\frac{1}{M^2}L(M^2)\exp\left(-\frac{p_0}{T}\right) g^{\mu\nu}W_{\mu\nu}(p_0,\vec{p}), \tag{2}$$

where $W_{\mu\nu}(p_0,\vec{p})$ is the electromagnetic (EM) current correlator, $g^{\mu\nu}$ is the metric tensor, α is the electromagnetic coupling, $p = (p_0, \vec{p})$ is the four-momentum of the pair, T is the temperature of the thermal bath, $L(M^2) = (1 + 2m_l^2/M^2)\sqrt{1 - 4m_l^2/M^2}$ arises from the Dirac spinors (lepton pair) in the final state, M is the invariant mass of the lepton pair, and m_l is the lepton mass.

For QGP Eq. (2) leads to the standard rate of lepton pair production (in the leading order) from annihilation of $q\bar{q}$ pairs [20]. For the dilepton production from hot hadrons we briefly outline the dilepton production processes here and refer to Ref. [21] for details. For the low-mass dilepton production from HM, the decays of thermal light vector mesons, namely, ρ, ω, and ϕ, have been considered. The change of spectral function of ρ due to its interaction with π, ω, a_1, h_1 (see Refs. [21,22] for details) and baryons [23] have been included in evaluating the production of lepton pairs from HM. For the ω spectral function the width at nonzero temperature is taken from Ref. [24] and medium effects on ϕ are ignored here. The continuum part of the spectral function of ρ and ω has also been included in the dilepton production rate [10,25]. In the present Rapid Communication dileptons from nonthermal sources, e.g., from the Drell-Yan process, and decays of heavy flavors [26] have been ignored in evaluating the elliptic flow of lepton pairs from QM and HM. If the charm and bottom quarks do not thermalize, then they are not part of the flowing QGP and hence do not contribute to the elliptic flow. The model employed in the present work leads to good agreement with NA60 dilepton data [27] for Super Proton Synchrotron (SPS) collision conditions [28].

To evaluate v_2 from Eq. (1) one needs to integrate the production rate given by Eq. (2) over the space-time evolution of the system—from the initial QGP phase to the final hadronic freeze-out state through a phase transition in the intermediate stage. We assume that the matter is formed in the QGP phase with negligible net baryon density. The initial condition required to solve the hydrodynamic equations for the description of the matter produced in a Pb + Pb collision at $\sqrt{s_{\rm NN}} = 2.76$ TeV for 30%–40% centrality are taken as follows: $T_i = 456$ MeV is the value of the initial temperature corresponding to the maximum of the initial energy density profile at the thermalization time $\tau_i = 0.6$ fm/c. The value of the transition temperature T_c for quark hadron conversion is taken as 175 MeV. The EOS required to close the hydrodynamic equations is constructed by complementing the Wuppertal-Budapest lattice simulation [1] with a hadron resonance gas comprising all of the hadronic resonances up to a mass of 2.5 GeV [29,30]. The energy of the lepton pair (p_0) originating from a hydrodynamically expanding system should be replaced by its value ($p \cdot u$) in the comoving frame, which is given by $p \cdot u = \gamma_T(M_T \cosh(y - \eta) - v_x p_T \cos\phi - v_y p_T \sin\phi)$, where $u = (\gamma, \gamma\vec{v})$, is the fluid four-velocity, y is the rapidity, and η is the space-time rapidity, $\gamma_T = (1 - v_T^2)^{-1/2}$, $v_T^2 = v_x^2 + v_y^2$, where v_x and v_y are the x and y components of the velocity. The system is assumed to get out of chemical equilibrium at $T = T_{\rm ch} = 170$ MeV [31]. The kinetic freeze-out temperature $T_F = 130$ MeV is fixed from the p_T spectra of the produced hadrons at the same collision energy of the Pb + Pb system. The EOS and the values of the parameters mentioned above are constrained by the p_T spectra (for 0%–5% centrality) and elliptic flow (for 10%–50% centrality) of charged hadrons [29] measured by the ALICE collaboration [32].

The spatial anisotropy of the matter produced in noncentral HICs is defined as $\epsilon_x = \frac{\langle x^2 - y^2\rangle}{\langle x^2 + y^2\rangle}$, where the average is taken over the energy distribution of the system formed in a collision of a given impact parameter. The resulting momentum anisotropy of the interacting system produced in noncentral HICs is defined as $\epsilon_p = \frac{\int dx \int dy [T^{yy} - T^{xx}]}{\int dx \int dy [T^{yy} + T^{xx}]}$. The variations of ($\epsilon_x$) and ($\epsilon_p$) with time have been displayed in the left-hand panel of Fig. 1 for 30%–40% centrality. We find that ϵ_x (ϵ_p) reduces (increases) with time due to the prevailing pressure gradients which cause the matter to flow. Since $v_2 \propto \epsilon_p$, therefore, the variations of v_2 and ϵ_p with τ are expected to be similar. In Fig. 1 (right-hand side) we depict the constant temperature contours corresponding to $T_c = 175$ MeV and $T_f = 130$ MeV in the τ-x plane (at zero ordinate), indicating the boundaries for

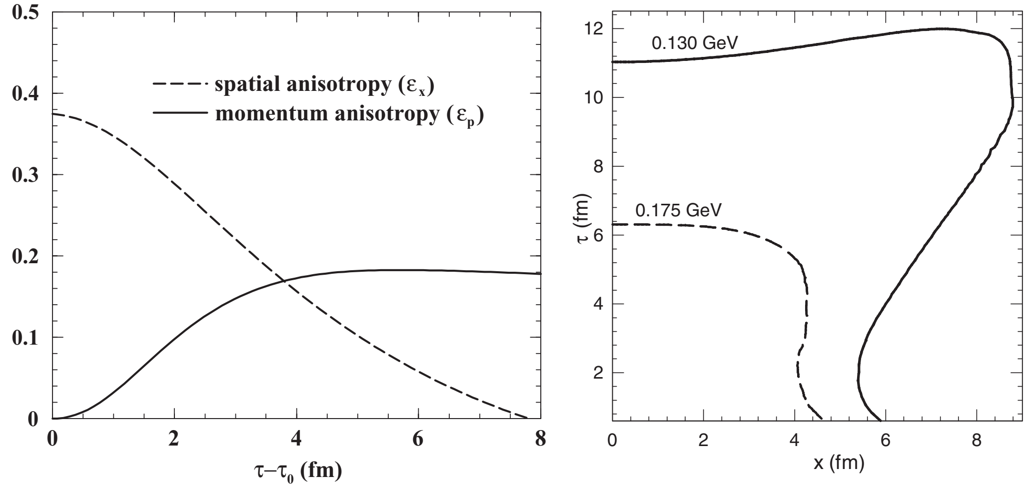

FIG. 1. Left-hand panel: Variations of spatial and momentum space anisotropy with proper time. Right-hand panel: Constant temperature contours denoting the space-time boundaries of the QGP and hadronic phases.

the QM and HM phases, respectively. The lifetime of the QM phase is ~6 fm/c and the duration of the HM is ~6–12 fm/c. Throughout this work "early" and "late" will approximately mean the duration of the QM and HM, respectively.

With all the ingredients mentioned above we evaluate the p_T integrated M distribution of lepton pairs originating from QM and HM (with and without medium effects on the spectral functions of ρ and ω). The results are displayed in Fig. 2 (left-hand side) for the initial conditions and centrality mentioned above. We observe that for $M > M_\phi$ the QM contributions dominate. For $M_\rho \lesssim M \lesssim M_\phi$ the HM shines brighter than QM. For $M < M_\rho$, the HM (solid line) overshines the QM due to the enhanced contributions primarily from the medium-induced broadening of the ρ spectral function. However, the contributions from QM and HM become comparable in this region of M if the medium effects on the ρ spectral function are ignored (dotted line). Therefore, the results depicted in Fig. 2 (left-hand side) indicate that a suitable choice of M window will enable us to unravel the contributions from a particular phase (QM or HM).

To further quantify these issues we evaluate the following quantity:

$$F = \frac{\int' \left(\frac{dN}{d^4x d^2p_T dM^2 dy}\right) dx dy d\eta \tau d\tau d^2p_T dM^2}{\int \left(\frac{dN}{d^4x d^2p_T dM^2 dy}\right) dx dy d\eta \tau d\tau d^2p_T dM^2}, \tag{3}$$

where the M integration in both the numerator and denominator are performed for selective M windows from M_1 to M_2 with mean M defined as $\langle M\rangle = (M_1 + M_2)/2$. The prime in $\int'$ in the numerator indicates that the τ integration in the numerator is done from $\tau_1 = \tau_i$ to $\tau_2 = \tau_i + \Delta\tau$ with progressive increments of $\Delta\tau$, while in the denominator the integration is done over the entire lifetime of the system. In the right-hand panel of Fig. 2, F is plotted against τ_{av} [=$(\tau_1 + \tau_2)/2$]. The results substantiate the fact that pairs with high $\langle M\rangle \sim 2.5$ GeV originate from QM ($\tau_{av} \lesssim 6$ fm/c, QGP phase) and pairs with $\langle M\rangle \sim 0.77$ GeV mostly emanate from the HM phase ($\tau_{av} \geqslant 6$ fm/c). The change in the properties of ρ due to its interaction with thermal hadrons in the bath is also visible through F evaluated for $\langle M\rangle \sim 0.3$ GeV

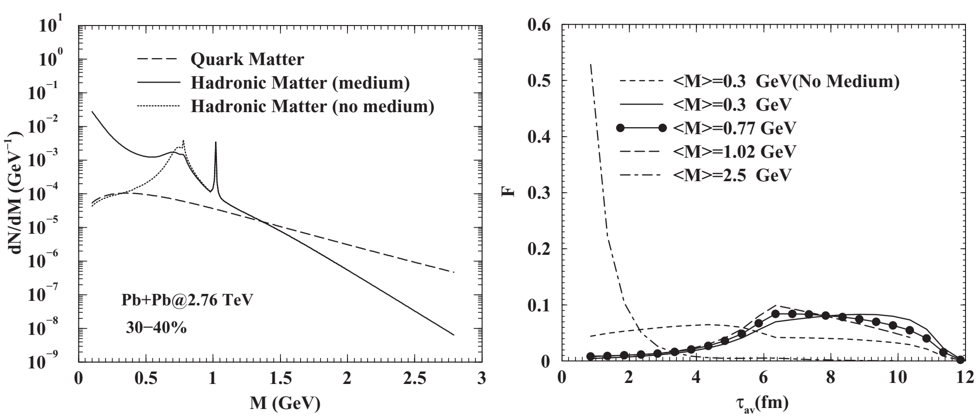

FIG. 2. Left-hand panel: Invariant mass distribution of lepton pairs from quark matter and hadronic matter (with and without medium effects). Right-hand panel: Fractional contribution of lepton pairs for various invariant mass windows as a function of average proper time (see the text for details).

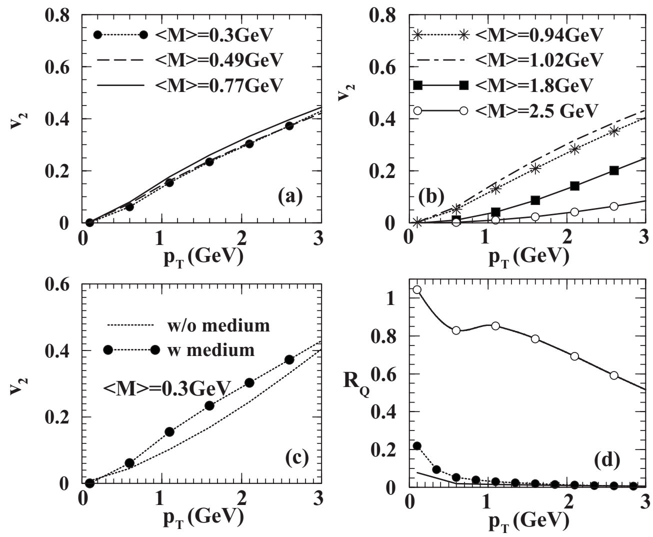

FIG. 3. (a) and (b) indicate the elliptic flow of lepton pairs as a function of p_T for various M windows. (c) displays the effect of the broadening of the ρ spectral function on the elliptic flow for $\langle M\rangle = 300$ MeV. (d) shows the variation of R_Q (see the text) with p_T for $\langle M\rangle = 0.3$ GeV (solid circle), 0.77 GeV (line), and 2.5 GeV (open circle). All the results displayed here are for 30%–40% centrality.

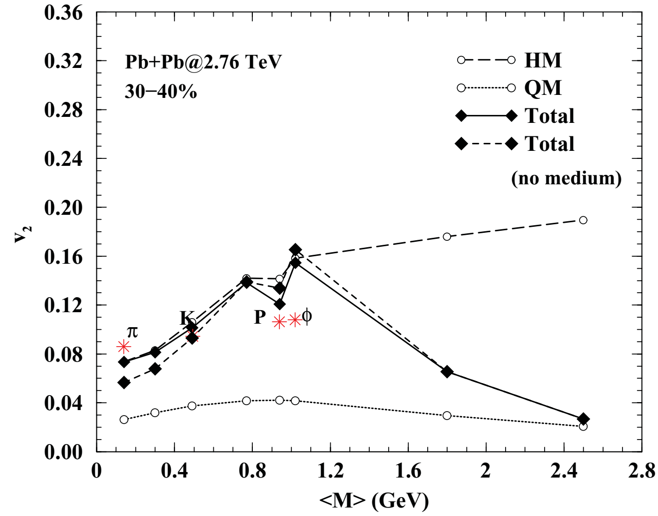

FIG. 4. (Color online) Variation of dilepton elliptic flow as a function of $\langle M\rangle$ for QM, HM (with and without medium effects), and for the entire evolution. The symbol $*$ indicates the value of v_2 for hadrons, e.g., π, kaon, proton, and ϕ.

with and without medium effects. This clearly indicates that the $\langle M\rangle$ distribution of lepton pairs can be exploited to extract the collectivity of different phases of the evolving matter.

Figures 3(a) and 3(b) show the differential elliptic flow $v_2(p_T)$ of dileptons arising from various $\langle M\rangle$ domains. We observe that for $\langle M\rangle = 2.5$ GeV, v_2 is small for the entire p_T range because these pairs arise dominantly from the QM epoch (see Fig. 2, right-hand panel) when the flow is not developed fully. By the time (6–12 fm/c) the pairs are emitted predominantly in the region $\langle M\rangle = 0.77$ GeV, the flow is fully developed, which gives rise to large v_2. It is also interesting to note that the medium-induced enhancement of the ρ spectral function provides a visible modification in v_2 for dileptons below the ρ peak [Fig. 3(c)]. The medium-induced effects lead to an enhancement of v_2 of lepton pairs which is culminating from the "extra" interaction (absent when a vacuum ρ is considered) of the ρ with other thermal hadrons in the bath. We note that the differential elliptic flow $v_2(p_T)$ obtained here at LHC is larger than the values obtained at RHIC [12,14] for all the invariant mass windows. In Fig. 3(d) we depict the variation of R_Q with p_T for $\langle M\rangle = 0.3$ GeV (line with solid circle), 0.77 GeV (solid line), and 2.5 GeV (line with open circle). The quantity R_Q (R_H) is defined as $R_Q = v_2^{\rm QM}/(v_2^{\rm QM} + v_2^{\rm HM})$ [$R_H = v_2^{\rm HM}/(v_2^{\rm QM} + v_2^{\rm HM})$], where $v_2^{\rm QM}$ and $v_2^{\rm HM}$ are the elliptic flows of QM and HM, respectively. The results clearly illustrate that v_2 of lepton pairs in the large $\langle M\rangle$ (=2.5 GeV) domain [open circle in Fig. 3(d)] originate from QM for the entire p_T range considered here. The value of R_Q is large in this domain because of the large (negligibly small) contributions from the QM (HM) phase. It is also clear that the contribution from the QM phase to the elliptic flow for $\langle M\rangle$ (=0.77 GeV) is very small [solid line in Fig. 3(d)]. The value of R_H for $\langle M\rangle = 0.77$ GeV is large (not shown in the figure).

The v_2 at the HM phase (either at the ρ or ϕ peak) is larger than its value in the QGP phase (at $\langle M\rangle = 2.5$ GeV, say) for the entire p_T range considered here. Therefore, the p_T integrated values of v_2 should also retain this character at the corresponding values of $\langle M\rangle$, which is clearly observed in Fig. 4, which displays the variation of $v_2(\langle M\rangle)$ with $\langle M\rangle$. The v_2 ($\propto\epsilon_p$) of QM is small because of the small pressure gradient in the QGP phase. The v_2 resulting from the hadronic phase has a peak around the ρ pole, indicating the full development of the flow in the HM phase. For $\langle M\rangle > m_\phi$ the v_2 obtained from the combined phases approach the value corresponding to the v_2 for QGP. Therefore, a measurement of v_2 for large $\langle M\rangle$ will show information about the QGP phase at the earliest time of the evolution. It is important to note that the p_T integrated $v_2(\langle M\rangle)$ of lepton pairs with $\langle M\rangle \sim m_\pi, m_K$ is close to the hadronic v_2^π and v_2^K (symbol $*$ in Fig. 4) if the thermal effects on the ρ properties are included. The exclusion of medium effects give lower v_2 for lepton pairs compared to hadrons. The fact that the v_2 of the (penetrating) lepton pairs are similar in magnitude to the v_2 of hadrons for ($\langle M\rangle \sim m_\pi, m_K, m_{\rm proton}$, etc.) ascertains that the anisotropic momentum distribution of hadrons carries the information about the HM phase with a duration of $\sim$6–12 fm/c (left-hand panel of Fig. 1). We also observe that the variation of $v_2(\langle M\rangle)$ with $\langle M\rangle$ has a structure similar to dN/dM vs M. As indicated by Eq. (1), we can write $v_2(\langle M\rangle) \sim \sum_{i={\rm QM,HM}} v_2^{\rm i} \times f_{\rm i}$, where f_i is the fraction of QM or HM from various space-time regions. The structure of dN/dM is reflected in $v_2(\langle M\rangle)$ through f_i. We find that the magnitude of $v_2(\langle M\rangle)$ at LHC is larger than its value at RHIC.

In conclusion, we have evaluated the v_2 of dileptons originating from the Pb + Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV for 30%–40% centrality. Our study shows that $v_2(M)$ provides useful information about the collective motion of the evolving

QCD matter formed in high-energy heavy-ion collisions. If the heavy quarks (charm and bottom) produced in HIC do not thermalize and hence do not become part of the flowing QGP, then the lepton pairs which originate from the decays of heavy flavors will not contribute to the v_2 of lepton pairs. In such a scenario an experimental observation of the reduction of $v_2(M)$ with increasing M beyond ϕ mass would reflect the presence of small momentum space anisotropy through a 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^π and v_2^K when the medium-induced change in the ρ spectral function is included in evaluating the dilepton spectra. The medium effects are large during the dense phase of the hadronic system, and therefore, this validates the findings that the hadronic v_2 carry information about 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.

P.M., S.K.D., and J.A. are partially supported by DAE-BRNS Project Sanction No. 2005/21/5-BRNS/2455. B.M. is partially supported by DAE-BRNS Project Sanction No. 2010/21/15-BRNS/2026.

[1] S. Borsanyi *et al.*, J. High Energy Phys. 11 (2010) 077.
[2] P. Huovinen and P. V. Ruuskanen, Annu. Rev. Nucl. Part. Sci. **56**, 163 (2006).
[3] D. A. Teaney, arXiv:0905.2433v1 [nucl-th].
[4] T. Hirano, N. van der Kolk, and A. Bilandzic, in *The Physics of the Quark-Gluon Plasma*, edited by S. Sarkar, H. Satz, and B. Sinha (Springer, Heidelberg, 2009).
[5] R. Averbeck (PHENIX Collaboration), J. Phys. G **35**, 104115 (2008).
[6] B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. C **77**, 054901 (2007).
[7] A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **98**, 162301 (2007).
[8] L. D. McLerran and T. Toimela, Phys. Rev. D **31**, 545 (1985).
[9] J. Alam, S. Raha, and B. Sinha, Phys. Rep. **273**, 243 (1996).
[10] J. Alam, S. Sarkar, P. Roy, T. Hatsuda, and B. Sinha, Ann. Phys. **286**, 159 (2001).
[11] R. Rapp and J. Wambach, Adv. Nucl. Phys. **25**, 1 (2000).
[12] R. Chatterjee, D. K. Srivastava, U. W. Heinz, and C. Gale, Phys. Rev. C **75**, 054909 (2007).
[13] R. Chatterjee, E. S. Frodermann, U. W. Heinz, and D. K. Srivastava, Phys. Rev. Lett. **96**, 202302 (2006).
[14] J. Deng, Q. Wang, N. Xu, and P. Zhuang, Phys. Lett. B **701**, 581 (2011).
[15] T. Renk and J. Ruppert, Phys. Rev. C **77**, 024907 (2008).
[16] J. K. Nayak and J. Alam, Phys. Rev. C **80**, 064906 (2009); P. Mohanty, J. K. Nayak, J. Alam, and S. K. Das, *ibid.* **82**, 034901 (2010); P. Mohanty, J. Alam, and B. Mohanty, *ibid.* **84**, 024903 (2011).
[17] P. Huovinen, P. F. Kolb, U. Heinz, P. V. Ruuskanen, and S. A. Voloshin, Phys. Lett. B **503**, 58 (2001).
[18] P. F. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev. C **62**, 054909 (2000); P. F. Kolb and R. Rapp, *ibid.* **67**, 044903 (2003); P. F. Kolb and U. Heinz, arXiv:nucl-th/0305084; J. Sollfrank, P. Koch, and U. Heinz, Phys. Lett. B **252**, 256 (1990); Z. Phys. C **52**, 593 (1991).
[19] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).
[20] J. Cleymans, J. Fingberg, and K. Redlich, Phys. Rev. D **35**, 2153 (1987).
[21] S. Ghosh, S. Sarkar, and J. Alam, Eur. Phys. J. C **71**, 176 (2011).
[22] S. Ghosh, S. Mallik, and S. Sarkar, Eur. Phys. J. C **70**, 251 (2010).
[23] V. L. Eletsky, M. Belkacem, P. J. Ellis, and J. I. Kapusta, Phys. Rev. C **64**, 035202 (2001).
[24] R. A. Schneider and W. Weise, Phys. Lett. B **515**, 89 (2001)
[25] E. V. Shuryak, Rev. Mod. Phys. **65**, 1 (1993).
[26] H. van Hess and R. Rapp, J. Phys. G **35**, 054001 (2008).
[27] R. Arnaldi *et al.* (NA60 Collaboration), Phys. Rev. Lett. **96**, 162302 (2006); **100**, 022302 (2008).
[28] J. K. Nayak, J. Alam, T. Hirano, S. Sarkar, and B. Sinha, arXiv:0902.0446.
[29] V. Roy and A. K. Choudhuri, Phys. Lett. B **703**, 313 (2011).
[30] B. Mohanty and J. Alam, Phys. Rev. C **68**, 064903 (2003).
[31] T. Hirano and K. Tsuda, Phys. Rev. C **66**, 054905 (2002).
[32] K. Aamodt *et al.* (ALICE Collaboration), Phys. Rev. Lett. **106**, 032301 (2011); Phys. Lett. B **696**, 30 (2011).