Hindawi
Advances in High Energy Physics
Volume 2018, Article ID 3794242, 5 pages
https://doi.org/10.1155/2018/3794242

Review Article

HBT Radii: Comparative Studies on Collision Systems and Beam Energies

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Received 12 February 2018; Revised 14 June 2018; Accepted 28 June 2018; Published 15 July 2018

Academic Editor: Fu-Hu Liu

Two-particle Hanbury-Brown-Twiss (HBT) interferometry is an important probe for understanding the space-time structure of particle emission sources in high energy heavy ion collisions. We present the comparative studies of HBT radii in Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV with Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV. To further understand this specific energy regime, we also compare the HBT radii for Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV with Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV. We have found interesting similarity in the $R_{\text{out}}/R_{\text{side}}$ ratio with m_T across the collision systems while comparing the data for this specific energy zone which is interesting as it acts as a bridge from SPS energy regime to the RHIC energy domain.

1. Introduction

A phase transition from a hadronic state to a "plasma" of deconfined quarks and gluons when the energy density exceeds a critical value is predicted from Quantum Chromo-Dynamics (QCD). The complicated structure of nuclear matter at low temperatures, where it is composed of a multitude of hadronic particles, baryons, and mesons, is thus expected to give way at high temperatures to a plasma of weakly composed quarks and gluons, the *Quark–Gluon Plasma* (*QGP*). QGP is a thermalized system where the properties of the system are governed by the quark and gluon degrees of freedom [1].

Understanding the deconfining phase transition in hadronic matter and the QGP properties is a challenging task. For systems created in the relativistic heavy ion collider (RHIC) and large hadron collider (LHC), energy region with high temperatures, and low baryon-chemical potential, Lattice QCD calculations predict a crossover transition between the hadron gas and the QGP phase. Lattice QCD predicts a phase transformation to a quark-gluon plasma at a temperature of approximately $T \approx 170\ MeV (1\ MeV \approx 1.1604 \times 10^{10} K)$ ([1]) corresponding to an energy density $\epsilon \approx 1\ GeV/fm^3$, which is nearly an order of magnitude larger than normal nuclear matter.

Experimental studies in relativistic heavy ion physics aim to study the QCD nature of matter under the conditions of extreme temperature and high energy density both at RHIC and at LHC. The discovery of the QGP can describe the system (governed by the quarks and gluons) in which the degrees of freedom are no more the color neutral hadron states.

The equation of state (EoS) of nuclear matter enables us to understand the relationship between the pressure and the energy at a given net-baryon density. Phase transitions from the hadronic resonance gas phase to the color-deconfined QGP (see, e.g., [2, 3]) contribute to the changes of the EoS. The experimental measurements should also be able to determine the physical characteristics of the transition, for example, the critical temperature, the order of the phase transition, and the speed of the sound along with the nature of the quasi-particles. The EoS of hot and dense QCD matter is still not precisely understood. Modern nuclear physics, has an important goal, that is, to explore the phase diagram of quark matter in various temperatures and baryon density so as to confirm the existence of the new phase of quark matter [4, 5].

The intermediate Super Proton Synchrotron (SPS) energy regime still remains interesting since the onset of deconfinement is expected to happen at those energies. Possibility of a critical endpoint [6, 7] and a first-order phase transition is yet not excluded. Several beam-energy dependent observables such as the particle ratios [8, 9], the flow [10, 11], and the HBT parameters [12, 13] show a nonmonotonic behavior, for which the interpretation still remains unclear. The beam-energy scan (BES) programs at RHIC show that directed flow is strong for both the lowest and the highest RHIC energies as shown by results from STAR experiment [14]. The net-proton $v_1(y)$ slope has a minimum between 11.5 and 19.6 GeV and changing sign twice between 7.7 and 39 GeV, which is quite contrary to the UrQMD transport model predictions for that energy regime. The vanishing of directed flow when the expansion stops and its appearance when the matter has passed through the change constitute the "latent heat", where the predicted "softest point disappearance" of flow can become a possible signature of a first-order phase transition between hadronic matter and a deconfined QGP phase.

Assuming a first-order phase transition, there is a mixed phase of the QGP and hadronic gas. A slow-burning fireball is expected in the absence of pressure gradient, when the initial system is at rest in the mixed phase, and this leads to a time-delay in the system evolution [12, 15–17]. Investigation of the time-delay signatures for the first-order phase transition is henceforth a subject of interest.

Two-particle Hanbury-Brown-Twiss (HBT) interferometry is an important tool for detecting the space-time structure of particle emission sources in high energy heavy ion collisions [18–20]. The occurrence of first-order phase transition between the QGP and hadronic matter will lead to the time-delay of the system evolution, hence making the emission duration of particles more prolonged [12, 15–17]. As explained in [12, 15–17] the three HBT radius parameters, R_{out}, R_{side}, R_{long}, describe the dimensions of a Gaussian source in longitudinal comoving system (LCMS) framework. The $R_{\text{out}}/R_{\text{side}}$ ratio can be related to the emission time [12, 15–17]. We have explored in this paper the energy region of 17.3 GeV to 22.4 GeV through comparative studies of two-pion HBT radii. This energy region has shown interesting results in STAR experiment [14] for other correlation measurements (like flow).

2. Results

The intensity interferometry technique for measuring sizes of stars [21] was formulated by Robert Hanbury Brown and Richard Twiss and is also known as the "Hanbury-Brown-Twiss (HBT) effect". Such technique was extended to particle physics [22] for understanding the angular distributions of pion pairs in $p\overline{p}$ annihilations and thus the quantum statistics causing an enhancement in pairs with low relative momentum. In HBT analyses the method has henceforth evolved into a precision tool for measuring the space-time properties of the regions of homogeneity at kinetic freeze-out in heavy ion collisions [23].

Two-pion interferometry yields HBT radii that describe the geometry of these regions of homogeneity (regions that emit correlated pion pairs). The HBT radii increase for more central collisions due to the increasing volume of the source and hence demonstrate how HBT can probe spatial sizes and shapes [24]. The decrease of HBT radii with mean pair transverse momentum, $k_T(=|\vec{p}_{1\text{T}} + \vec{p}_{2\text{T}}|/2)$, has been due to transverse and longitudinal flow [24]. Flow causes space-momentum correlations since the sizes of the regions emitting the particles do not correspond to the entire fireball created in a relativistic heavy ion collision [24].

In this paper, the results of two-pion HBT analyses of Pb+Pb at 17.3 GeV from NA49 experiment [25] are compared in Figure 1 and discussed with other STAR HBT results from Au+Au 19.6 GeV [26]. Figure 1 shows the HBT radii of SPS and RHIC collision species where Pb+Pb 17.3 GeV(NA49) and Au+Au 19.6 GeV(STAR) show similar trend for R_{side} and R_{long} with m_{T}. For R_{out} the SPS data has a flatter slope when compared with RHIC, but the $R_{\text{out}}/R_{\text{side}}$ ratios with m_{T} $(= \sqrt{k_{\text{T}}^2 + m_\pi^2})$ are very similar for the top central data of both experiments. The $R_{\text{out}}/R_{\text{side}}$ ratios of NA49 and STAR show weak m_{T} dependence and have values close to unity.

The HBT radii from Au+Au 19.6 GeV and Cu+Cu 22.4 GeV, both from STAR experiment, are also included in this paper since they are different collision species with close collision energies. Reference [27] explains the analysis methodology for Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 22.4$ GeV. In Figure 2 we present this comparison of two-pion HBT radii to include central (0-5%) Au+Au collisions at $\sqrt{s_{\text{NN}}} = 19.6$ GeV and central (0-10%) Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 22.4$ GeV from the STAR experiment.

The HBT radii for Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 22.4$ GeV are smaller than those for Au+Au collisions at $\sqrt{s_{\text{NN}}} = 19.6$ GeV. The variations of the $R_{\text{out}}/R_{\text{side}}$ ratios with m_{T} are similar for the Au+Au and Cu+Cu collision data as we see in Figure 2. The ratios also show weak m_{T} dependence with the values close to unity.

In Figure 3 we present the m_{T} dependence of the ratios of two-pion HBT radii for the most-central Au+Au at $\sqrt{s_{\text{NN}}}$=19.6 GeV and Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 22.4$ GeV. Details about the Cu+Cu systems are explained in [27] and references therein. As seen in Figure 3 the ratios of radii for Au+Au to those for Cu+Cu collisions are ~1.5. Although we see that the individual HBT radii decrease significantly with increasing m_{T}, the ratios in Figure 3 show that the HBT radii for Au+Au and Cu+Cu collisions at 19.6 GeV and 22.4 GeV share a common m_{T} dependence. Such trends can be understood in terms of models [28, 29] where participant scaling is used to predict the HBT radii in Cu+Cu collisions from the measured radii for Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, assuming the radii are proportional to $\text{A}^{1/3}$, where A is the atomic mass number of the colliding nuclei.

3. Summary

The $R_{\text{out}}/R_{\text{side}}$ ratio is important since it is able to provide the information of the emission duration. We also know that the HBT radii are affected by transverse and longitudinal flow. The SPS energy regime is still zone of interest where the recent flow results from STAR experiment [14] (within 11.5 and 19.6 GeV) have shown some new and interesting features. When we compare the HBT (two-particle correlation) radii in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 17.3$ GeV with Au+Au collisions at

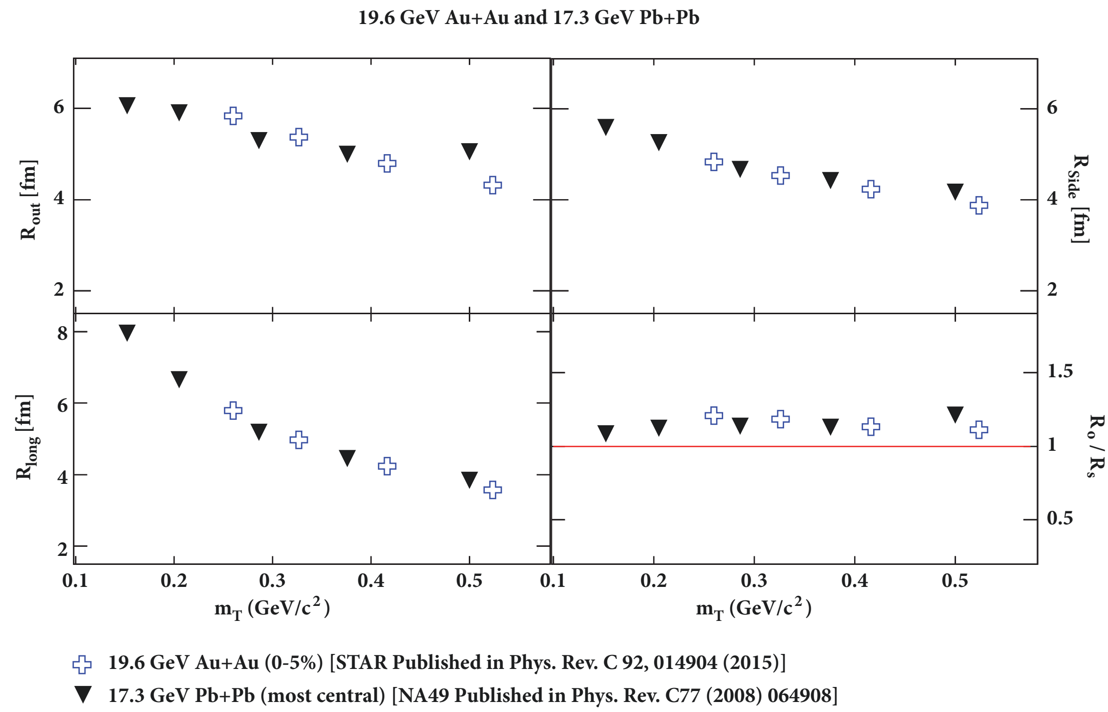

FIGURE 1: The comparison of system size dependence in HBT radii of STAR Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV with NA49 Pb+Pb collisions for 17.3 GeV. Only statistical errors are shown for the top central data of both experiments.

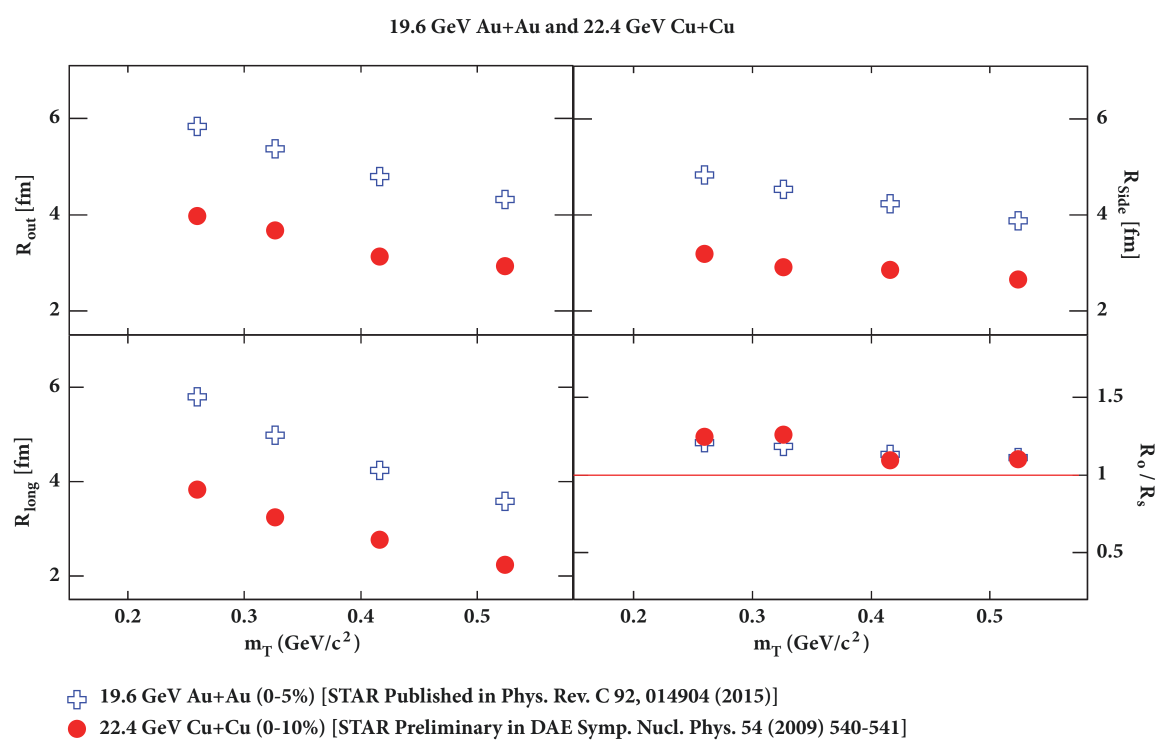

FIGURE 2: The comparison of system size dependence in HBT radii of STAR Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV with Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV. Only statistical errors are shown for the top central data of both the Au+Au and Cu+Cu datasets.

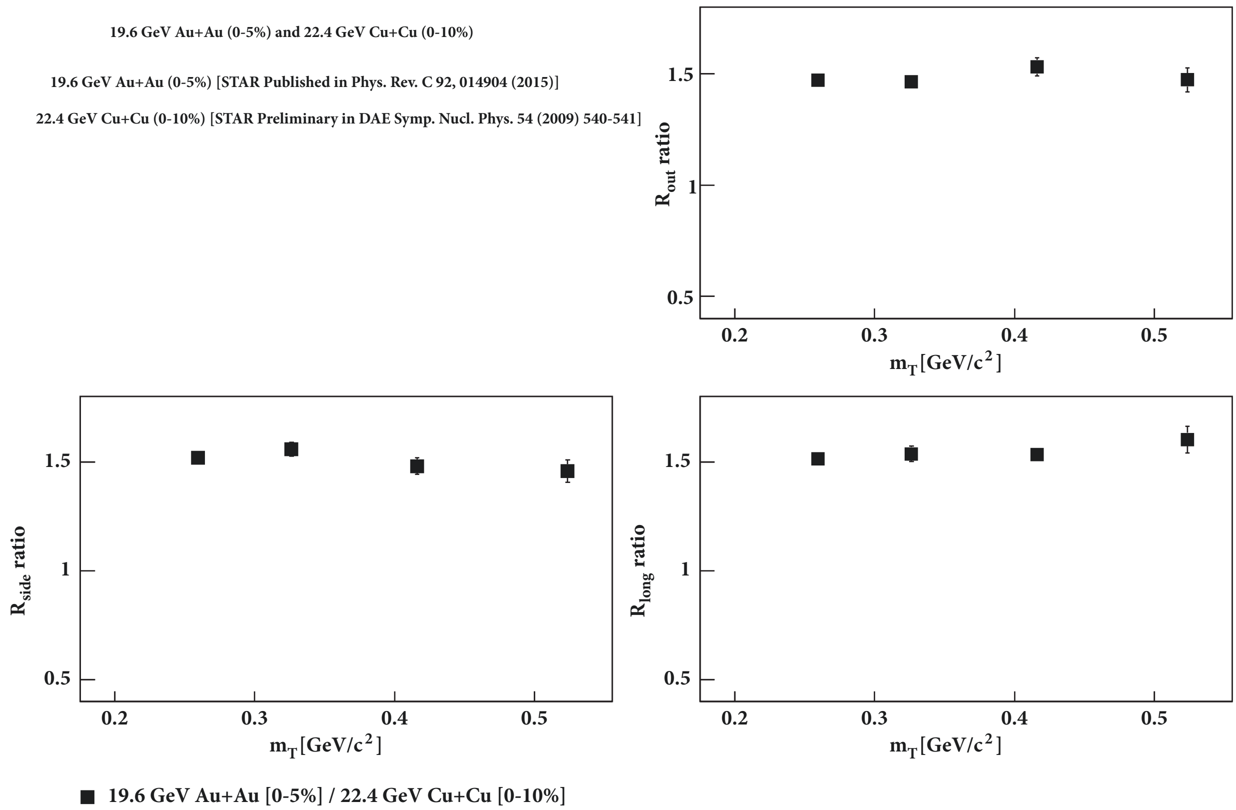

FIGURE 3: Ratios of HBT radii at top centralities for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 19.6$ and 22.4 GeV versus m_T. Only statistical errors are shown for Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV and Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$ for their top central datasets.

$\sqrt{s_{NN}} = 19.6$ GeV, we find very similar R_{out}/R_{side} ratio with m_T. To explore this interesting energy regime we have compared the HBT radii for Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV with Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV. The similarity in the R_{out}/R_{side} ratio with m_T persists across the collision systems from SPS to RHIC energies and even in close RHIC energies for Au+Au and Cu+Cu systems as well. The rise of the ratio R_{out}/R_{side} with collision energy which was predicted [12] due to a possible phase transition is not observed. Such inferences establish that HBT radii R_{out}/R_{side} ratios are very much comparable and consistent across the different colliding species in (an exciting zone of interest of the RHIC BES program) the energy region of 17.3 GeV to 22.4 GeV.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The author acknowledges the facilities of Saha Institute of Nuclear Physics, Kolkata, India.

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