HBT size parameters in non-central high energy heavy ion collisions

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Using the dynamic transport model RQMD, the transverse momentum dependence of HBT size parameters in high energy collisions was studied for non-central ($b = 7-9$fm) Au + Au collisions at RHIC energy, $\sqrt{s} = 200$AGeV. We finds that (i) The HBT size parameters reflect the source geometry at freeze-out for such non-central collisions; (ii) HBT size parameter as a function of m_t are insensitive to the pressure develope during the collisions but they are sensitive to the degree of space-momentum correlations.

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In high energy collisions, if hydrodynamical flow had established, a space-momentum correlation will develop. On the other hand, if the space and momentum are found to be correlated, can one draw the conclusion that the system under study is hydro in nature? This is the question we would like to address in this work.

In high energy heavy ion collisions, the measured slope parameters of transverse momentum distributions are found to be particle mass dependent, namely, the higher the mass the larger the value of slope parameter [1]. In addition, such dependence is stronger for heavier colliding systems. This was interpreted as the evidence of collective flow (hydro type) [1,2].

Study the two-particle correlation functions can further shed light on the physics since the observed probability of two particles to close to each other not only depends on their nature on quantum statistics but also on the collision dynamics [11,12], specifically it depends on the space-momentum correlation. Experimental findings are that the extracted size parameters decreases as the transverse momentum increases. This was attributed due to the hydro type collective flow that developed in heavy ion collisions [6,7].

None of the above studies answer the question raised above! Here systematic studies on different colliding systems at different beam energy with different impact parameters are necessary in order to obtain the physics insights.

In this work, we study the pion correlation functions as a function of pair transverse momentum for $Au+Au$ non-central collisions at the RHIC energy. The impact parameter range used here is $b = 7-9$ fm. The RQMD(v2.4) event generator [3] was used to simulate the events and an after-burner was used to calculate the correlation functions [4]. Only pions from mid-rapidity ($|y| \leq 1$) are used in the study.

Before we start our discussion, let us first define different regions that may exist at the beginning of the nuclear collision. The transverse plane of the collision zone is shown in Fig.1 where the in-plane regions are represented as the vertically hatched and the out-of-plane regions are horizontally hatched.

Figure 2 shows the pion HBT size parameters R_{side}, R_{out}, and R_{long} as a function of pair transverse mass m_t for non-central Au + Au collisions ($b = 7-9$ fm) at $\sqrt{s} = 200$ AGeV. The calculations were performed with respect to the reaction plane, see 1. Filled-dots, open-circles and open-squares, respectively, represent the results from events without angle cuts, with in-plane, and out-of-plane cuts.

While no sizable effects is seen in the longitudinal size parameters R_{long}, there clear effects in the transverse directions. In the pair momentum direction, the *out* direction, the values of the R_{out} in the out-of-plane (open squares) are always larger than those from the in-plane (open circles). In the *side* direction, the situation is reversed, namely, the values of the R_{side} from in-plane (open circles) are always larger than those from the out-of-plane (open squares). In terms of the geometry in coordinate space, this means that at the freeze-out, the shape of the source is an ellipse with its longer axis in the y-direction. Note that this shape is similar to the one at the beginning of the collisions, see Fig. 1.

The event anisotropy parameters as a function of transverse mass m_t from the same event sample used for Fig. 2.

$$E\frac{dN}{d\vec{p}} = \frac{1}{2\pi}\frac{dN}{m_t dm_t dy}(1+2\sum_n v_n cos(n\phi)) \qquad (1)$$

In principle the event anisotropy parameters v_n can be constructed using either momentum vectors or coordinate vector. In the later case, we denote it as s_n. Therefore, $v_2 = \langle cos(2\phi_p)\rangle$ and $s_2 = \langle cos(2\phi_s)\rangle$ with $\phi_p = tan^{-1}(\frac{p_x}{p_y})$ and $\phi_s = tan^{-1}(\frac{x}{y})$, respectively.

In Fig. 3 the positive values of the v_2 suggest an in-plane expansion while the negative values of s_2 meaning that the shape of the source is an ellipse with its longer axis in the y-direction, $out-of-plane$. The stress-tensor studies, see Fig. ??, support this interpretation for the observed v_2 distributions.

The s_2 behavior is consistent with the two-particle correlation function measurements seen in Fig. 2. This is the first time that one confirms that the HBT measurement can in deed tell the source shape and its orientation is coordinate space.

Using stress-momentum tensor [17,18], on can in principle analyze the evolution of the collisions within transport calculations. For the RQMD(v2.4) non-central Au+Au (at $\sqrt{s} = 200$ AGeV) collisions, it is found [19] that at the early stage of the collisions, $t = 0.5 \sim 2.5$ fm/c, the in-plane pressure gradients are stronger than that of the out-of-plane ones. In terms of the hydrodynamics, such pressure gradient is the driving force of the observed positive v_2 (Fig. 3) (non-central) and strong radial flow [1] (central) in high energy nuclear collisions. In the same model calculations, the averaged values of the transverse momentum are found to be $\langle p_t \rangle = 0.362$ and 0.353 GeV/c for in-plane and out-of-plane pions, respectively. This is again consistent with a picture that the stronger pressure gradient in the x-direction leads to a positive v_2 and higher mean p_t.

However, the larger pressure gradient in the in-plane direction does not lead to the stranger m_t dependence of the size parameters. As it can be seen in Fig.2 (b), the m_t dependence in the in-plane direction (open circles) is in fact weaker than that in the out-of-plane (open squares). This observation certainly disprove the flow effect in the m_t dependence statement. In addition, we observed that for a given particle, if one randomized the cooresponding momentum and space vetors, the m_t distribution becomes flat. Note that, this operation of randomization does not alter the momentum distributions and only the relative angle[1] is changed. In fact, the values of the $\langle cos\theta \rangle$ aore found to be large in the out-of-plane direction than that of the in-plane direction: $\langle cos\theta \rangle = 0.565 \mid_x, 0.580 \mid_y$. This observation indicating that what behind the m_t dependence of the HBT size parameters is the space momentum correlation, not necessary the hydrodynamic pressure.

With such collision geometry, it is not surprise that the angular correlation is stronger in the out-of-plane direction. Since the longer axis in in the $y-$direction (out-of-plane direction), if particles are freeze-out from the surface of the overlaped region, the averaged angle between their spactor vector and momentum vectors will be smaller in the y-direction than in the x-direction leading to the larger values of $\langle cos\theta \rangle$. Such correlation was also found to be responsible for high yield of out-of-plane anti-deuteron productions in non-central heavy ion collisions [?].

Using the dynamic transport model RQMD(v2.4) generated RHIC events, $Au + Au$ at $\sqrt{s} = 200$ AGeV, mid-rapidity pion two-particle correlation functions as a function of transverse mass m_t with respective to the reaction plane were stidied. Coupling with the event anisotropy studies, one found that the size parameters do reflect the source grometry at freeze-out. This for the first time demonstrated that one can access the shape of the source via the experimentally measured HBT parameters. The senond finding in this work is that the m_t-dependence of the size parameters do not reflect the pressur that developed at the early stage of the collisions, rather, they are very sensitive to the space-momentum correlation created in the collision.

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[1]The angle between the space vector and momentum vector

$$\theta = cos^{-1}(\frac{\vec{p_t} \cdot \vec{r_t}}{p_t r_t}) \tag{2}$$

[1] I.G. Bearden *et al.*, (NA44 Collaboration), Phys. Rev. Lett. **78**, 2080 (1997).

[2] Yu. M. Sinyukov, S.V. Akkelin, and N. Xu, Phys. Rev. **C59**, 3437(1999).

[3] H. Sorge, Phys. Rev. C **52**, 3291 (1995); and references therein.

[4] S. Pratt, free codes of correlation after burner (http://www.nscl.msu.edu/~pratt/freecodes/crab/v3).

[5] D. Hardtke, S.A. Voloshin, submitted to Phys. Rev. **C**; nucl-th/9906033, 1999.

[6] H. Beker *et al.*, (NA44 collaboration), Phys. Rev. Lett. **74**, 3340(1995).

[7] Th. Alber *et al.*, (NA35 Collaboration), Phys. Rev. Lett. **74**, 1303(1995).

[8] S. Esumi, U. Heinz, and N. Xu, Phys. Lett. **B403**, 145(1997).
[9] S. Esumi, S. Chapmann, H. van Hecke, and N. Xu, Phys. Rev. **C55**, R1(1997).
[10] E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. **C48**, 2462(1993), and E. Schnedermann, J. Sollfrank, and U. Heinz, *Particle Production in Highly Excited Matter*, ed. H. Gutbrod and J. Rafelski (Plenum Press, New York, 1992) p. 175.
[11] B. Monreal et al., Phys. Rev. **C60**, (1999); nucl-th/9904080, 1999.
[12] B. Monreal et al., Phys. Rev. **C**, in print (1999); nucl-th/9907071, 1999.
[13] U. Heinz and B.V. Jacak, Ann. Rev. Nucl. Part. Sci. 49 (1999).
[14] G. Alexander, I. Cohen, and E. Levin, Phys. Lett. **B452**, 159(1999); G. Alexander and I. Cohen, LANL Preprint hep-ph/9909288, Sept. 1999.
[15] I.G. Bearden *et al.*, (NA44 Collaboration), Phys. Rev. C **58**, 1656 (1998).
[16] H. Appelshäuser *et al.*, (NA49 Collaboration), Eur. Phys. J. C **2**, 661 (1998).
[17] G. Baym, Privation communications, 1995.
[18] L.D. Landau and E.M. Lifshitz, *'Fliud Dynamics'*, Pergamon Press, 1959.
[19] Q. Li, Y. Pang, and N. Xu, To appear in Nucl. Phys. **A** (1999) and in preparation.
[20] M. Bleicher, C. Spieles, A. Jahns, R. Mattiello, H. Sorge, H. Stoöcker, and W. Greiner, Phys. Lett. **B361**, 10(1995).
[21] B.R. Schlei and N. Xu, Phys. Rev. **C54**, R2155(1996).

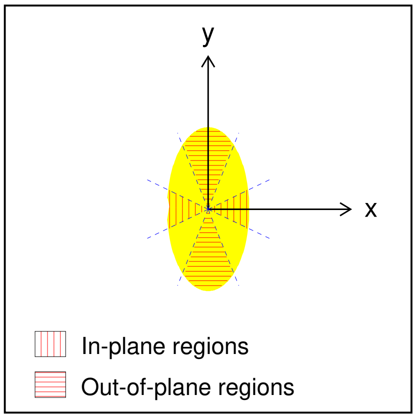

FIG. 1. Transverse plane of the nuclear overlap region at the beginning of the collision. In-plane means $|\phi| \leq 30$ and $150 \leq \phi \leq 210$; out-of-plane means the regions $60 \leq |\phi| \leq 120$. The beam direction is perpendicular to the $x-y$ plane.

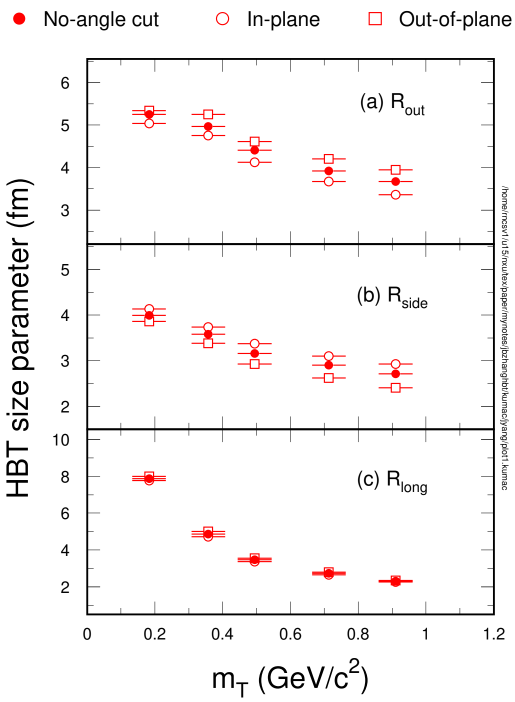

FIG. 2. The pion HBT size parameters R_{side}, R_{out}, and R_{long} as a function of pair transverse mass m_t for Au + Au non-central collisions ($b = 7 - 9$ fm) at $\sqrt{s} = 200$ AGeV. The calculations were performed with respect to the reaction plane, see 1. Filled-dots, open-circles and open-squares, respectively, represent the results from events with out angle cuts, with in-plane, and out-of-plane cuts. While no sizable effects is seen in the longitudinal size parameters R_{long}, there clear effects in the transverse directions. In the pair momentum direction, the *out* direction, the values of the R_{out} in the out-of-plane (open squares) are always larger than those from the in-plane (open circles). In the *side* direction, the situation is reversed, namely, the values of the R_{side} from in-plane (open circles) are always larger than those from the out-of-plane (open squares). In terms of the geometry in coordinate space, this means that the shape of the source is an ellipse with its longer axis in the y-direction.

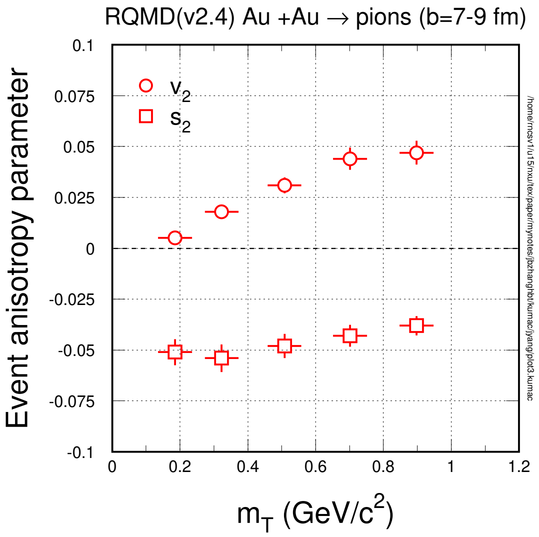

FIG. 3. The event anisotropy parameters as a function of transverse mass m_t for Au + Au non-central collisions ($b = 7 - 9$ fm) at $\sqrt{s} = 200$ AGeV. v_2 (open circles) and s_2 (open squares) are constructed from momentum and coordinate spaces, respectively. The positive values of the v_2 suggest an in-plane expansion while the negative values of s_2 meaning that the shape of the source is an ellipse with its longer axis in the y-direction, $out-of-plane$. The s_2 behavior is consistent with the two-particle correlation function measurements seen in Fig. 2. The values of s_2 starts at about zero when impact parameter b is small and when b increases, the s_2 continuous becomes more and more negative, indicating that the ratio of the longer axis over shorter axis of the ellipse becomes larger and larger. On the contrary, the v_2 values increases in the positive direction as the b increases and till $b = 7 - 9$ fm, they reach their maximum. Further increasing in b leads to decrease of the v_2 values.