EFFECT OF RADIAL FLOW AND RESONANCE DECAY ON THE TRANSVERSE MOMENTUM DEPENDENCE OF THE HBT PARAMETERS

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Using the Blast-Wave parameterized model in THERMINATOR 2, we study the effect of the radial flow and resonance decay on the transverse momentum dependence of HBT parameters for Au+Au central collisions at the RHIC energy $\sqrt{s_{NN}} = 200$ GeV. The results indicate that the radial flow directly affects the space-momentum correlations and the dependence of the transverse HBT radii on transverse momentum. The rise of α with increasing v_{T} for R_{out} is faster than that for R_{side} which suggests that R_{out} is more susceptible to the radial flow. The pions decayed from resonance increase the HBT radii and strengthen the negative dependence of the radii on transverse momentum.

1. Introduction

Femtoscopy measurements (often called HBT analysis) provide the detailed information on the space-time geometry and dynamics of the interaction regions from the system formed in relativistic heavy-ion collisions [1, 2]. The HBT radii are not equal to the real space size of the source directly, but to a 'region of homogeneity', which allows to extract dynamical information of the particle emission source through the transverse momentum dependence of the HBT parameters [3–5]. A drop of the HBT radii with increasing transverse momentum is observed in the experiments of the heavy-ion collisions and the dependence of the radii is similar for all collision energies, which is directly affected by the space-momentum correlations [3, 6, 7].

It is generally recognized that the space-momentum correlations of the particles are mainly caused by the collective expansion which is embodied in the transverse flow velocity. The effect of the collective flow on the directly freeze-out pions is different from that on the pions decayed from resonance such as ρ and ω [8, 9]. The short-lived resonances increase the HBT radii by about 1 fm, which is caused by the resonance lifetime of 1 fm/c [8, 10].

For studying the effect of the radial flow and resonance decay on the HBT parameters, we use the THERMal heavy IoN generATOR 2 (THERMINATOR 2) model, a Monte Carlo event generator, to generate the simulated events for Au+Au central collisions at the RHIC energy $\sqrt{s_{NN}} = 200$ GeV [11]. Several freeze-out models can be selected in the THERMINATOR model, such as the Blast-Wave model or the Kraków Single Freeze-out model. The Blast-Wave model is based on the Monte-Carlo method, which generates the stable particles and resonances on a freeze-out hypersurface and then the resonances decay by a cascade approach. The velocity profile of the radial flow can be specified in the Blast-Wave model, which is convenient for studying the effect of the different transverse flow velocities on the transverse momentum dependence of the HBT radii and space-momentum correlations. The Blast-Wave parameterized model is used in the THERMINATOR 2 with a linear transverse flow, $v_\mathrm{T}(\rho) = v_\mathrm{T}(\rho/\rho_\mathrm{max})$ and $\rho_\mathrm{max} = 7.43$ fm. The transverse flow velocities are set at $v_\mathrm{T} = 0$, 0.2, 0.4, 0.6 c to compare the transverse momentum dependence of the HBT radii, respectively.

2. The transverse momentum dependence of the HBT parameters

The two-pion correlation function is calculated by the Correlation After Burner (CRAB), without the final-state interactions in the program [12]. For central collisions, the HBT correlation function is often fitted by the Bertsch–Pratt parametrization in the 'out–side–long' coordinate system [13]

$$C(\boldsymbol{q}, \boldsymbol{K}) = 1 + \lambda \exp\left(-q_\mathrm{out}^2 R_\mathrm{out}^2(\boldsymbol{K}) - q_\mathrm{side}^2 R_\mathrm{side}^2(\boldsymbol{K}) - q_\mathrm{long}^2 R_\mathrm{long}^2(\boldsymbol{K})\right),$$
(1)

where $\boldsymbol{q} = \boldsymbol{p_1} - \boldsymbol{p_2}$, $\boldsymbol{K} = (\boldsymbol{p_1} + \boldsymbol{p_2})/2$, and q_out, q_side, q_long are three components of the relative momentum difference $\boldsymbol{q}$ of a pair of pions which are defined in the 'out–side–long' system. By fitting the correlation function, we can obtain size parameters R_out, R_side and R_long which are so-called HBT radii.

Figure 1 shows the pion HBT radii R_out, R_side, R_long, the ratio $R_\mathrm{out}/R_\mathrm{side}$ and λ parameter as a function of the pair average transverse mass m_T in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the transverse flow velocity $v_\mathrm{T} = 0$, 0.2, 0.4, 0.6 c, where $m_\mathrm{T} = \sqrt{\boldsymbol{K}^2 + m_\pi^2}$ and m_π is the mass of pion. v_T reduces the values of radii R_out, increases the values of
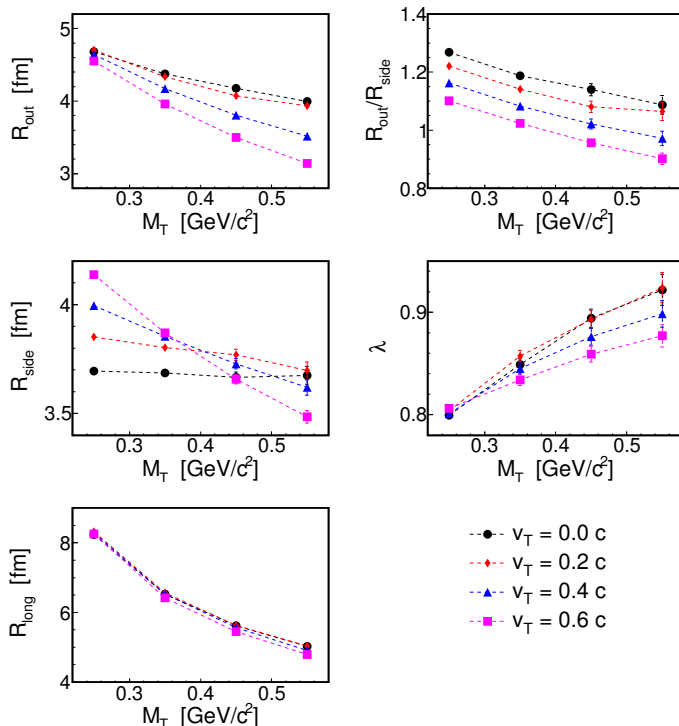
Fig. 1. The HBT parameters at mid-rapidity as functions of m_T with different v_T for Au+Au central collisions at the RHIC energy of $\sqrt{s_{NN}} = 200$ GeV.

radii R_{side}, and does not affect the radii R_{long}. The radii R_{out} and R_{side} decrease with m_T and the decrease is now rapid as v_T increases. The value of v_T does not affect the drop of R_{long}. When v_T is set to zero, R_{side} remains unchanged as m_T increases and R_{out} decreases with increasing m_T, which indicates the drop of R_{side} is caused by the radial flow and the transverse momentum dependence of R_{side} is not only affected by the radial flow, but also by the other space-momentum correlations [5, 15].

Figure 2 shows the HBT radii with different v_T and the fitted results using the power-law function $R_i(m_T) = R_i'(m_\pi/m_T)^\alpha$. The power-law fit is derived by the ideal hydrodynamical simulation, in which $\alpha = 0.5$ [16]. It is obvious that the fitted results are close to the HBT radii, which indicates that the power-law function is appropriate to fitting the HBT radii.

Figure 3 shows the extracted parameters R' and α by the power-law fit as a function of the transverse velocities, where solid lines and dashed lines show the results of the pions with resonance decay and the directly freeze-out pions, respectively. In order to quantify the effect of the radial flow on the HBT radii, we apply the power-law fit to extract the parameters
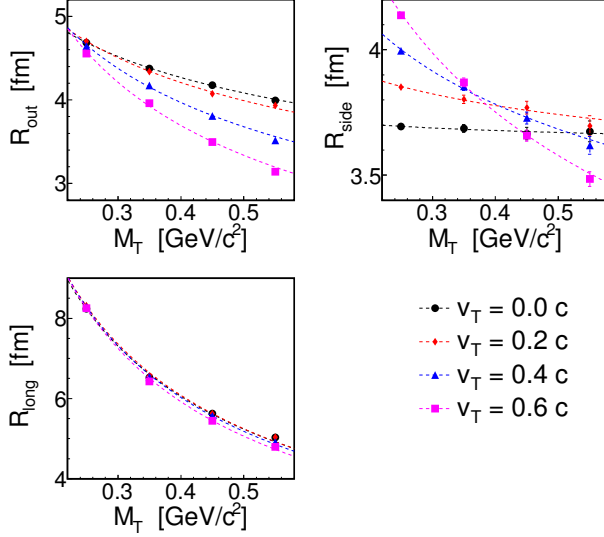
Fig. 2. The HBT radii with different v_T. Lines represent the fitted results using the power-law function $R_i(m_T) = R'_i(m_\pi/m_T)^\alpha$.

R' and α. The dependence of parameter α with increasing v_T can reflect the effect of the radial flow on the transverse momentum dependence of the HBT radii. Compared with the results of the pions with resonance decay, R' of the directly freeze-out pions does not depend on v_T, which indicates that the radial flow affects only the drop of the HBT radii on the transverse momentum and does not change the value of the radii for the directly freeze-out pions. The rise of α with increasing v_T for R_{out} is faster than that for R_{side} which suggests that R_{out} is more susceptible to the radial flow. R_{out} contains the information on space and time which leads R_{out} to be more
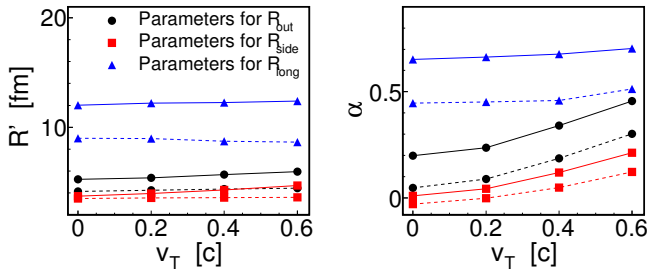

Fig. 3. Parameters R' in the left panel and α in the right panel as a function of v_T are extracted by the power-law fits from the HBT radii, where solid lines and dashed lines show the results of the directly freeze-out pions and the pions with resonance decay, respectively.

susceptible than R_{side} and R_{long}. It is necessary to mention that α is almost constant for the radii R_{long}, because the radial flow does not affect the longitudinal radii. The drop of R_{long} is mainly caused by the longitudinal flow and the longitudinal direction of the source is satisfied with the boost-invariant in the THERMINATOR model [11, 17].

Figure 4 shows the HBT radii from the directly freeze-out pions and the pions with resonance decay for different v_{T}. The values of v_{T} have different effects on the transverse momentum dependence of HBT radii with or without pions decayed from resonance. As $v_{\text{T}} = 0$, R_{out} from the directly freeze-
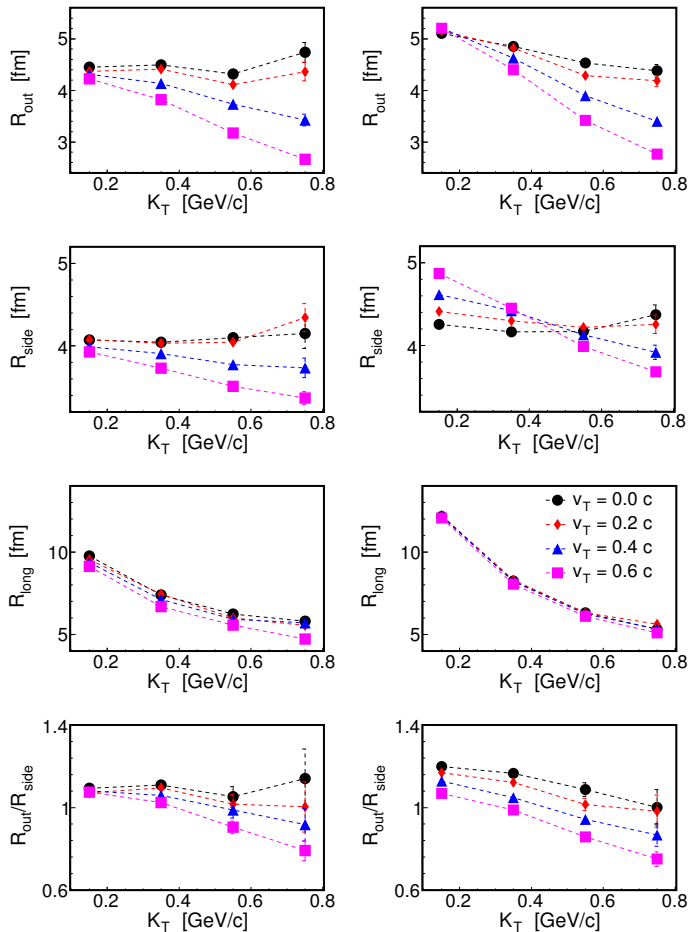

Fig. 4. The dependence of the HBT radii R_{out}, R_{side}, R_{long} on transverse momentum of the pion pair is extracted from the directly freeze-out pions (left panel) and the pions with resonance decay (right panel) for different v_{T}. The model parameters are as follows: $T = 165.6$ MeV, $\mu_{\text{B}} = 28.5$ MeV, $\tau = 9.91$ fm, $\rho = 7.43$ fm.

out pions stays constant with the increasing transverse momentum, but the drop of R_{out} appears for the pions with resonance decay. The stronger radial flow makes the drop of R_{out} more pronounced with increasing K_{T}. As $v_{\mathrm{T}} = 0$, R_{side} stays constant with increasing K_{T} with or without pions decayed from resonance. With increasing v_{T}, the radial flow reduces the value of R_{side} from the directly freeze-out pions, but increases R_{side} with resonance decays. The larger v_{T} makes the drop of R_{out} with increasing K_{T} more pronounced than that of R_{side} and reduces the ratio of $R_{\mathrm{out}}/R_{\mathrm{side}}$. The drop of $R_{\mathrm{out}}/R_{\mathrm{side}}$ with increasing v_{T} from pions with resonance decay is more obvious than that from the directly freeze-out pions.

Figure 5 shows the dependence of the HBT radii R_{out}, R_{side} and the ratio of $R_{\mathrm{out}}/R_{\mathrm{side}}$ on the transverse momentum for the directly freeze-out pions, the pions decayed from resonance and the pions with resonance decay which include both all. As $v_{\mathrm{T}} = 0$, R_{out} and R_{side} from the directly freeze-out pions stays constant, but R_{out} of the pions decayed from resonance reduces with increasing K_{T} which leads to the drop of R_{out} on K_{T} for the pions
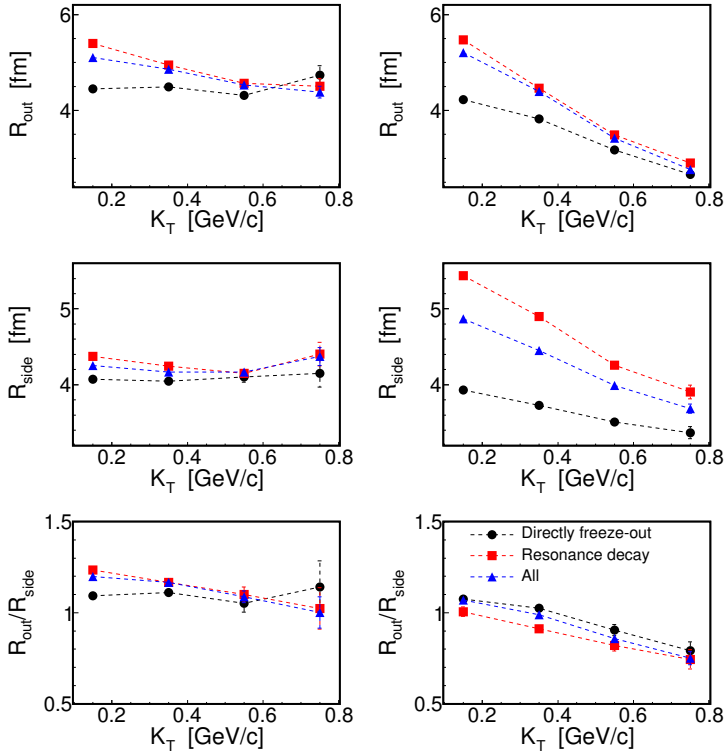
Fig. 5. The dependence of the HBT radii R_{out}, R_{side} and the ratio of $R_{\mathrm{out}}/R_{\mathrm{side}}$ on transverse momentum with and without resonance decays. Left panel is for $v_{\mathrm{T}} = 0\ c$, and right panel is for $v_{\mathrm{T}} = 0.6\ c$.

with resonance decay. R_{out} and R_{side} decrease as K_T increases at $v_T = 0.6\,c$ for the directly freeze-out pions and the pions decayed from resonance, but the values of the radii for the pions decayed from resonance are much larger than those for the directly freeze-out pions.

Figures 6 and 7 show the dependence of the mean radial expansion flow value $\langle v_T \rangle$, the mean cosine value of angle between freeze-out momentum and the radial direction $\langle \cos(\theta) \rangle$, $\langle x_{\mathrm{out}} \rangle$ and $\langle x_{\mathrm{side}} \rangle$ on the transverse momentum with $v_T = 0\,c$ and $0.6\,c$, where

$$x_{\mathrm{out}} = \frac{|\boldsymbol{r} \cdot \boldsymbol{p}_T|}{|\boldsymbol{p}_T|}\,, \qquad x_{\mathrm{side}} = \frac{|\boldsymbol{r} \times \boldsymbol{p}_T|}{|\boldsymbol{p}_T|}\,. \tag{2}$$

As $v_T = 0$, the results of the directly freeze-out pions are quite different from those of the pions decayed from resonance. The values of $\langle v_T \rangle$, $\langle \cos(\theta) \rangle$, $\langle x_{\mathrm{out}} \rangle$ and $\langle x_{\mathrm{side}} \rangle$ stay constant with increasing K_T for the pions which directly freeze out on the hypersurface. For the pions decayed from resonance, the dependence of those values on K_T is different. The values of $\langle v_T \rangle$ and $\langle \cos(\theta) \rangle$ for the pions decayed from resonance are larger than those for the directly freeze-out pions with the K_T increase, which suggests the pions decayed from resonance have a different kind of collective motion along the radial direction, such as the space-momentum correlation, and increase the value of $\langle x_{\mathrm{out}} \rangle$ and $\langle x_{\mathrm{side}} \rangle$. As $v_T = 0.6\,c$, the results of $\langle v_T \rangle$ and $\langle \cos(\theta) \rangle$ for the directly freeze-out pions are similar to those for the pions decayed
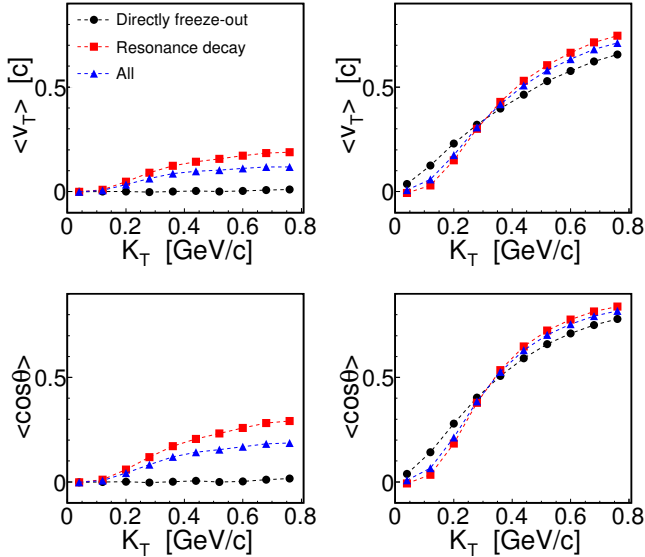

Fig. 6. The dependence of $\langle v_T \rangle$, $\langle \cos(\theta) \rangle$ on transverse momentum with and without resonance decays. Left panel is for $v_T = 0\,c$, and right panel is for $v_T = 0.6\,c$.
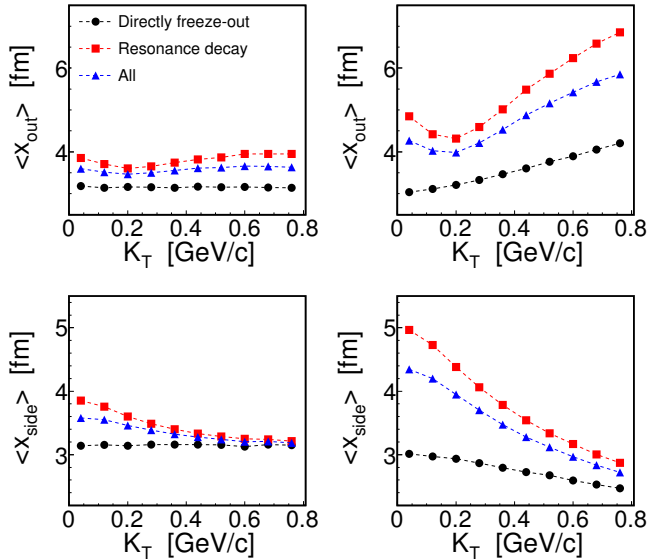
Fig. 7. The dependence of $\langle x_{\mathrm{out}} \rangle$, $\langle x_{\mathrm{side}} \rangle$ on transverse momentum with and without resonance decays. Left panel is for $v_{\mathrm{T}} = 0$ c, and right panel is for $v_{\mathrm{T}} = 0.6$ c.

from resonance, which suggests the effect of the space-momentum correlation is weaker than that of the radial flow. $\langle x_{\mathrm{out}} \rangle$ and $\langle x_{\mathrm{side}} \rangle$ of the pions decayed from resonance are much larger than those of the directly freeze-out pions, which indicates the space size of the source in the radial direction for the pions decayed from resonance is more sensitive to the increase of the radial flow. The pions decayed from resonance increase the HBT radii and strengthen the negative dependence of the radii on transverse momentum.

3. Summary

Based on the Blast-Wave parameterized model in THERMINATOR 2, we calculate the HBT parameters with different transverse velocities for Au+Au central collisions at the RHIC energy $\sqrt{s_{NN}} = 200$ GeV and study the effect of the radial flow and resonance decay on the HBT radii. The radial flow reduces the value of radii R_{out} and increases the value of radii R_{side}. The drop of the radii R_{out} and R_{side} decrease rapidly with increasing v_{T}. The rise of α with increasing v_{T} for R_{out} is faster than that for R_{side} which suggests that R_{out} is more susceptible to the radial flow. The larger v_{T} makes the drop of R_{out} with increasing K_{T} more pronounced than that of R_{side} and reduces the ratio of $R_{\mathrm{out}}/R_{\mathrm{side}}$. The pions decayed from resonance have a different kind of collective motion along the radial direction, such as

the space-momentum correlation, and increase the size of the source in the radial direction, which increase the HBT radii and strengthen the negative dependence of the radii on transverse momentum.

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