Squeezed correlations of bosons with nonzero widths for expanding sources

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We explore the squeezed back-to-back correlation (SBBC) and investigate how the squeezing effect influences the Hanbury-Brown–Twiss (HBT) interferometry using an expanding Gaussian source with nonzero width. The SBBC and HBT of D^0 and ϕ mesons with finite in-medium widths are studied. The expanding flow of the source may enhance the SBBC strength of $D^0\bar{D}^0$ and $\phi\phi$ in the low momentum region but suppress the SBBC in the larger momentum region. The squeezing effect suppresses the influence of flow on the HBT radii, which is significant for two identical bosons with large pair momentum or with large mass. Due to the squeezing effect, the relationship between the HBT radii and the pair momentum exhibits nonflow behavior for the D^0D^0 pair. Likewise, nonflow behavior also appears in the HBT radii of $\phi\phi$ with large pair momentum. This phenomenon may bring new insights for studying the squeezing effect.

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I. INTRODUCTION

The interactions between bosons and the source medium in high-energy heavy-ion collisions can cause a squeezing effect, resulting in a squeezed back-to-back correlation (SBBC) between boson and antiboson in the particle-emitting source [1–9]. The squeezing effect and SBBC are connected to the in-medium mass modification of bosons through a Bogoliubov transformation. This transformation establishes a connection between the creation (annihilation) operators of quasiparticles within the medium and their corresponding free particles [1–9]. The investigations of the SBBC may offer a fresh perspective for understanding the dynamic and thermal characteristics of the particle source.

Recently, the SBBC function between a boson and antiboson with a nonzero width has been formulated and the influences of the in-medium width on the SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ have been studied in a static homogeneous source [10]. However, the particle-emitting sources created in high-energy heavy-ion collisions are both expansive and inhomogeneous. To create a more realistic model, we extended previous research to the expanding Gaussian source with nonzero width. The results indicate that the expanding flow of the source may enhance the SBBC strength of $D^0\bar{D}^0$ and $\phi\phi$ in the low momentum region but suppress the SBBC in the larger momentum region.

Hanbury-Brown–Twiss (HBT) interferometry has been extensively used for studying the space-time properties and coherence of the particle-emitting sources formed in high-energy heavy-ion collisions [11–26]. The correlation functions between two identical bosons can be obtained by taking the ratio of their two-particle momentum spectrum to that of the product of two single-boson momentum spectra. The squeezing effect may also affect the two-particle momentum spectrum and the single-boson momentum spectra, respectively [2–4]. The squeezing effect on the HBT correlation function of two identical kaon was shown utilizing a nonrelativistic formulism [4]. This paper delves deeper into the study of the effect of squeezing on the HBT correlation functions of D^0D^0 and $\phi\phi$ while accounting for nonzero width using relativistic formalism. In a static source, the HBT radii of two identical bosons show a nearly constant behavior as the pair momentum increases. Conversely, in an expanding source, the HBT radii decrease as the pair momentum increases due to the influence of expanding flow [16,17,20,22–24,27]. The squeezing effect suppresses the influence of flow on the HBT radii and causes them to remain almost unchanged or increase with increasing pair momentum. The phenomenon is referred to as the nonflow behavior of the HBT radii in this paper, which is significant for two identical bosons with large pair momentum or with large mass. Due to the squeezing effect, the relationship between the HBT radii and the pair momentum exhibits nonflow behavior for D^0D^0 pairs. Likewise, nonflow behavior also appears in the HBT radii of $\phi\phi$ with large pair momentum. The recent analyses of experimental data on D and ϕ mesons have garnered significant interest [28–56]. This is due to the presence of a charm or strange quark, which is believed to undergo the complete evolution of the quark-gluon plasma (QGP) formed in high-energy heavy-ion collisions. On the other hand, the in-medium modifications of masses and widths of D and ϕ mesons were expected to exist in the particle-emitting sources formed in high-energy heavy-ion collisions [57–63]. Thus the study of the squeezing effect on D and ϕ mesons is meaningful in high-energy heavy-ion collisions.

In the next section we generalize the formulas of the correlation between two bosons with nonzero width for local-equilibrium expanding sources based on the work in Refs. [2,10]. Then we show the effect of flow on the SBBC of $D^0\bar{D}^0$ and $\phi\phi$ in Sec. III, and the squeezing effect on the HBT interferometry of D^0D^0 and $\phi\phi$ is also shown in Sec. III. Finally, summary and discussion are given in Sec. IV.

II. FORMULAS

Denote $a^\dagger_{\mathbf{k}}(a_{\mathbf{k}})$ as the creation (annihilation) operators of the boson in vacuum with momentum $\mathbf{k}$, mass m, and width Γ_0. Similarly, denote $b^\dagger_{\mathbf{k}}(b_{\mathbf{k}})$ as the creation (annihilation) operators of the corresponding quasiparticle with momentum $\mathbf{k}$, modified mass m_*, and modified width Γ in the medium. They are related by the transformation [10]

$$e^{i\omega_{\mathbf{k}}t}a^\dagger_{\mathbf{k}} = c^*_{\mathbf{k}}e^{i\Omega_{\mathbf{k}}t}b^\dagger_{\mathbf{k}} + s_{-\mathbf{k}}e^{-i\Omega_{\mathbf{k}}t}b_{-\mathbf{k}}, \tag{1}$$

$$e^{-i\omega_{\mathbf{k}}t}a_{\mathbf{k}} = c_{\mathbf{k}}e^{-i\Omega_{\mathbf{k}}t}b_{\mathbf{k}} + s^*_{-\mathbf{k}}e^{i\Omega_{\mathbf{k}}t}b^\dagger_{-\mathbf{k}}, \tag{2}$$

$$c_{\pm\mathbf{k}} = \frac{\cosh r + i\cosh f}{\sqrt{2}},\qquad s_{\pm\mathbf{k}} = \frac{\sinh r + i\sinh f}{\sqrt{2}}, \tag{3}$$

where r and f are

$$r = \frac{1}{2}\ln\left[\frac{|\omega_{\mathbf{k}}|[1-\sin(\Theta-\theta)]}{|\Omega_{\mathbf{k}}|\cos(\Theta-\theta)}\right], \tag{4}$$

$$f = \frac{1}{2}\ln\left[\frac{|\omega_{\mathbf{k}}|[1+\sin(\Theta-\theta)]}{|\Omega_{\mathbf{k}}|\cos(\Theta-\theta)}\right]. \tag{5}$$

Here $\omega_{\mathbf{k}}$ and $\Omega_{\mathbf{k}}$ are the energy of bosons in vacuum and in medium, respectively,

$$\omega_{\mathbf{k}} = \sqrt{\mathbf{k}^2 + (m_0 - i\Gamma_0/2)^2} = |\omega_{\mathbf{k}}|e^{i\theta}, \tag{6}$$

$$\Omega_{\mathbf{k}} = \sqrt{\mathbf{k}^2 + (m_* - i\Gamma/2)^2} = |\Omega_{\mathbf{k}}|\,e^{i\Theta}, \tag{7}$$

where

$$|\omega_{\mathbf{k}}| = \left\{\left[\mathbf{k}^2 + m_0^2 - \frac{\Gamma_0^2}{4}\right]^2 + m_0^2\Gamma_0^2\right\}^{1/4}, \tag{8}$$

$$|\Omega_{\mathbf{k}}| = \left\{\left[\mathbf{k}^2 + m_*^2 - \frac{\Gamma^2}{4}\right]^2 + m_*^2\Gamma^2\right\}^{1/4}, \tag{9}$$

$$\theta = \frac{1}{2}\tan^{-1}\left[\frac{-m_0\Gamma_0}{\mathbf{k}^2 + m_0^2 - \Gamma_0^2/4}\right], \tag{10}$$

$$\Theta = \frac{1}{2}\tan^{-1}\left[\frac{-m_*\Gamma}{\mathbf{k}^2 + m_*^2 - \Gamma^2/4}\right]. \tag{11}$$

It is necessary to mention that the above transformation can only be regarded as an approximation if the imaginary part of $-2\Omega_{\mathbf{k}}$ $[\mathrm{Im}(-2\Omega_{\mathbf{k}}) \sim m_0\Gamma/\omega_{\mathbf{k}} \sim \Gamma$ for $\mathbf{k}^2 < m_0^2]$ is not considerably large [10].

The correlation function of the two bosons with momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ is defined as [1,2]

$$C(\mathbf{k}_1,\mathbf{k}_2) = 1 + \frac{|G_c(\mathbf{k}_1,\mathbf{k}_2)|^2 + |G_s(\mathbf{k}_1,\mathbf{k}_2)|^2}{G_c(\mathbf{k}_1,\mathbf{k}_1)G_c(\mathbf{k}_2,\mathbf{k}_2)}, \tag{12}$$

where $G_c(\mathbf{k}_1,\mathbf{k}_2)$ and $G_s(\mathbf{k}_1,\mathbf{k}_2)$ are the chaotic and squeezed amplitudes

$$G_c(\mathbf{k}_1,\mathbf{k}_2) = \sqrt{\omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}}\,\langle a^\dagger_{\mathbf{k}_1}a_{\mathbf{k}_2}\rangle, \tag{13}$$

$$G_s(\mathbf{k}_1,\mathbf{k}_2) = \sqrt{\omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}}\,\langle a_{\mathbf{k}_1}a_{\mathbf{k}_2}\rangle. \tag{14}$$

For further discussion, the labeling convention for particles and antiparticles is as follows: "+" denotes particles, "−" denotes antiparticles (unless the antiparticle of the particle is itself, in which case "0" is used for both). The correlation functions of the two bosons for pairs of (0 0), (+ −), and (+ +) become [2]

$$C^{00}(\mathbf{k}_1,\mathbf{k}_2) = 1 + \frac{|G_c(\mathbf{k}_1,\mathbf{k}_2)|^2 + |G_s(\mathbf{k}_1,\mathbf{k}_2)|^2}{G_c(\mathbf{k}_1,\mathbf{k}_1)G_c(\mathbf{k}_2,\mathbf{k}_2)}, \tag{15}$$

$$C^{+-}(\mathbf{k}_1,\mathbf{k}_2) = 1 + \frac{|G_s(\mathbf{k}_1,\mathbf{k}_2)|^2}{G_c(\mathbf{k}_1,\mathbf{k}_1)G_c(\mathbf{k}_2,\mathbf{k}_2)}, \tag{16}$$

$$C^{++}(\mathbf{k}_1,\mathbf{k}_2) = 1 + \frac{|G_c(\mathbf{k}_1,\mathbf{k}_2)|^2}{G_c(\mathbf{k}_1,\mathbf{k}_1)G_c(\mathbf{k}_2,\mathbf{k}_2)}. \tag{17}$$

Equation (15) describes the correlation function of two particles where the antiparticle is itself. Equation (16) describes the correlation function of boson and antiboson, and it is also known as SBBC when $\mathbf{k}_1 = -\mathbf{k}_2$. Equation (17) describes the correlation function of two identical bosons, and it is also called HBT interferometry.

For local-equilibrium expanding sources, $G_c(\mathbf{k}_1,\mathbf{k}_2)$ and $G_s(\mathbf{k}_1,\mathbf{k}_2)$ can be expressed as [2–8]

$$G_c(\mathbf{k}_1,\mathbf{k}_2) = \int \frac{d^4\sigma_\mu(x)}{(2\pi)^3}K^\mu_{1,2}e^{i\,q_{1,2}\cdot x}\Big\{\big|c'_{\mathbf{k}'_1,\mathbf{k}'_2}\big|^2 n'_{\mathbf{k}'_1,\mathbf{k}'_2} + \big|s'_{-\mathbf{k}'_1,-\mathbf{k}'_2}\big|^2\big[n'_{-\mathbf{k}'_1,-\mathbf{k}'_2} + 1\big]\Big\}, \tag{18}$$

$$G_s(\mathbf{k}_1,\mathbf{k}_2) = \int \frac{d^4\sigma_\mu(x)}{(2\pi)^3}K^\mu_{1,2}e^{2i\,K_{1,2}\cdot x}\Big\{s'^*_{-\mathbf{k}'_1,\mathbf{k}'_2}c'_{\mathbf{k}'_2,-\mathbf{k}'_1}\times n'_{-\mathbf{k}'_1,\mathbf{k}'_2} + c'_{\mathbf{k}'_1,-\mathbf{k}'_2}s'^*_{-\mathbf{k}'_2,\mathbf{k}'_1}\big[n'_{\mathbf{k}'_1,-\mathbf{k}'_2} + 1\big]\Big\}, \tag{19}$$

where $\mathbf{k}'_i$ is the local-frame momentum corresponding to $\mathbf{k}_i\,(i = 1, 2)$. The other local variables are

$$c'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} = \frac{\cosh r'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} + i\cosh f'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2}}{\sqrt{2}}, \tag{20}$$

$$s'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} = \frac{\sinh r'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} + i\sinh f'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2}}{\sqrt{2}}, \tag{21}$$

$$r'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} = \frac{1}{2}\ln\left[\frac{\big|\omega'_{\mathbf{k}'_1,\mathbf{k}'_2}\big|\big[1-\sin\big(\Theta'_{\mathbf{k}'_1,\mathbf{k}'_2}-\theta'_{\mathbf{k}'_1,\mathbf{k}'_2}\big)\big]}{\big|\Omega'_{\mathbf{k}'_1,\mathbf{k}'_2}\big|\cos\big(\Theta'_{\mathbf{k}'_1,\mathbf{k}'_2}-\theta'_{\mathbf{k}'_1,\mathbf{k}'_2}\big)}\right], \tag{22}$$

$$f'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} = \frac{1}{2}\ln\left[\frac{\big|\omega'_{\mathbf{k}'_1,\mathbf{k}'_2}\big|\big[1+\sin\big(\Theta'_{\mathbf{k}'_1,\mathbf{k}'_2}-\theta'_{\mathbf{k}'_1,\mathbf{k}'_2}\big)\big]}{\big|\Omega'_{\mathbf{k}'_1,\mathbf{k}'_2}\big|\cos\big(\Theta'_{\mathbf{k}'_1,\mathbf{k}'_2}-\theta'_{\mathbf{k}'_1,\mathbf{k}'_2}\big)}\right], \tag{23}$$

$$\omega'_{\mathbf{k}'_1,\mathbf{k}'_2}(x) = \frac{1}{2}\left[\omega'_{\mathbf{k}'_1}(x) + \omega'_{\mathbf{k}'_2}(x)\right] = \left|\omega'_{\mathbf{k}'_1,\mathbf{k}'_2}\right| e^{i\theta'_{\mathbf{k}'_1,\mathbf{k}'_2}}, \tag{24}$$

$$\Omega'_{\mathbf{k}'_1,\mathbf{k}'_2}(x) = \frac{1}{2}\left[\Omega'_{\mathbf{k}'_1}(x) + \Omega'_{\mathbf{k}'_2}(x)\right] = \left|\Omega'_{\mathbf{k}'_1,\mathbf{k}'_2}\right| e^{i\Theta'_{\mathbf{k}'_1,\mathbf{k}'_2}}, \tag{25}$$

$$\omega'_{\mathbf{k}'_i}(x) = \sqrt{\mathbf{k}'^2_i(x) + (m_0 - i\Gamma_0/2)^2} = k^\mu_i u_\mu(x) = \gamma_\mathbf{v}\left[\,\omega_{\mathbf{k}_i} - \mathbf{k}_i \cdot \mathbf{v}(x)\,\right], \tag{26}$$

$$\Omega'_{\mathbf{k}'_i}(x) = \sqrt{\mathbf{k}'^2_i(x) + (m_* - i\Gamma/2)^2} = \sqrt{\left[k^\mu_i u_\mu(x)\right]^2 - (m_0 - i\Gamma_0/2)^2 + (m_* - i\Gamma/2)^2}, \tag{27}$$

$$n'_{\pm\mathbf{k}'_1,\pm\mathbf{k}'_2} = \exp\left\{-\left[\Omega'_{\mathbf{k}'_1,\mathbf{k}'_2}(x) - \mu_{1,2}(x)\right]/T(x)\right\}. \tag{28}$$

In this paper, the spatial distribution of the source is taken as $\rho(x) = Ce^{-\mathbf{r}^2/(2R^2)}\,\theta(r - 2R)$. R and C are the source radius and the normalization constant, respectively. $\mathbf{v} = \frac{u}{2R}\mathbf{r}$ is used to represent the expanding velocity of the source, and u is a parameter. The time distribution of source is assumed to be the typical exponential decay [2–4]

$$F(t) = \frac{\theta(t - t_0)}{\Delta t}\, e^{-(t-t_0)/\Delta t}, \tag{29}$$

where Δt is a parameter, and the time distribution of the source widens as the parameter Δt increases.

III. RESULTS

In this section all results are based on Monte Carlo simulation calculations using a spherically symmetric Gaussian expanding source. The parameter R, which is chosen to be 7 fm [3,64], determines the spatial radius of the source. The radial expanding flow of the source is determined by the parameter u, and when $u = 0$, it represents a static source. The time distribution of the source is independent of the spatial distribution and is described by the parameter Δt. In all figures except for Fig. 6, Δt is set to 2 fm/c [3,64].

The freeze-out temperatures of D^0 meson and ϕ meson are taken as 150 and 140 MeV, respectively [3,7]. The mass and width of D^0 meson in a vacuum, denoted by m_0 and Γ_0, respectively, are taken as 1864.86 and 0 MeV, respectively, and the m_0 and Γ_0 of ϕ meson are taken as 1019.46 and 4.26 MeV, respectively [65,66]. The modified mass and width in the medium are represented by m_* and Γ, respectively. The in-medium mass shift is denoted as δm, and $\delta m = m_* - m_0$. When $\delta m = 0$ and $\Gamma = \Gamma_0$, the mass and width of bosons in the medium are identical to those in vacuum. This indicates the squeezing effect is not considered in the calculation.

A. Effect of flow on SBBC

In Fig. 1 the SBBC results of $D^0\bar{D}^0$ (top panels) and $\phi\phi$ (bottom panels) with respect to modified mass m_* for flow parameter $u = 0$ and 0.5 are shown. From Fig. 1 it can be seen that a change of width can lead to a SBBC signal even for $\delta m = 0$, especially for the $D^0\bar{D}^0$ pair. The SBBC function of $D^0\bar{D}^0$ is enhanced by the expanding flow for $k = 0.5$ and 1 GeV. The expanding flow enhances the SBBC signal of $\phi\phi$ for $k = 0.5$ GeV but suppresses the SBBC signal of $\phi\phi$ for $k = 1$ GeV. In Fig. 2 we plot the SBBC results of $D^0\bar{D}^0$ [(a)] and the correlation of $\phi\phi$ [(b)] with respect to momentum k for flow parameter $u = 0$ and 0.5. Here, $\delta m = -10$ MeV and $\Gamma = 10$ MeV. Flow has opposite effects on SBBC of $D^0\bar{D}^0$, depending on the value of momentum k; it enhances SBBC when k is less than 1.2 GeV but suppresses it when k is greater than 1.2 GeV. For the $\phi\phi$ pair, flow suppresses the SBBC signal for $k > 0.7$ GeV but slightly enhances the SBBC signal for $k < 0.7$ GeV. This phenomenon is similar to the situation without considering the width [3,64]. It is necessary to mention that Eq. (15) is used for calculating the correlation of $\phi\phi$. Since the correlations of $\phi\phi$ were shown for $k_1 = -k_2$ in Figs. 1 and 2, the square of chaotic amplitude $|G_c(\mathbf{k}_1, \mathbf{k}_2)|^2$ is almost 0 and does not contribute to the value

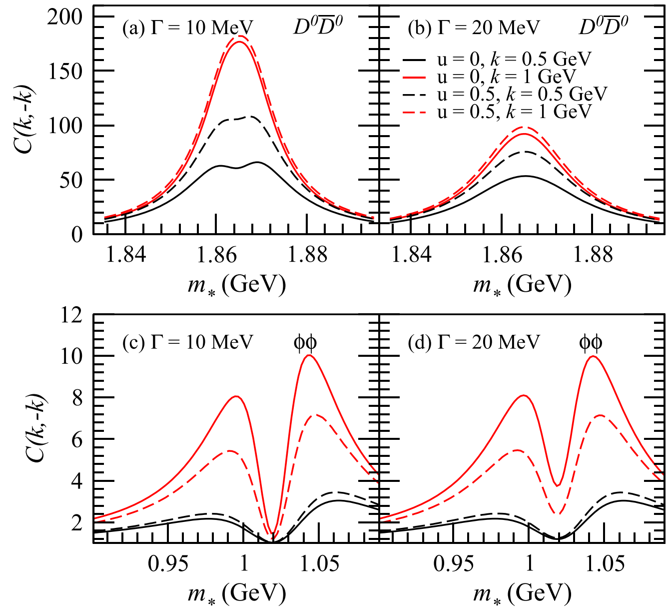

FIG. 1. SBBC results of $D^0\bar{D}^0$ (top panels) and $\phi\phi$ (bottom panels) with respect to modified mass m_* for flow parameter $u = 0$ and 0.5.

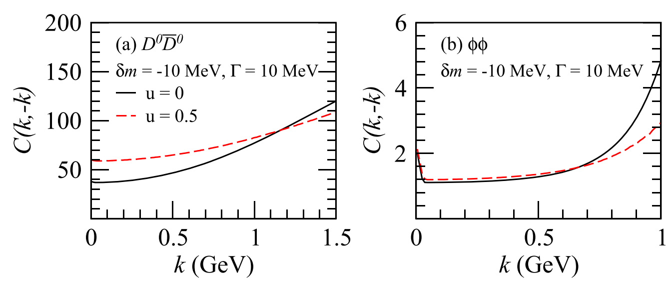

FIG. 2. SBBC results of $D^0\bar{D}^0$ (a) and the correlation of $\phi\phi$ (b) with respect to momentum k for flow parameter $u = 0$ and 0.5. Here, $\delta m = -10$ MeV and $\Gamma = 10$ MeV.

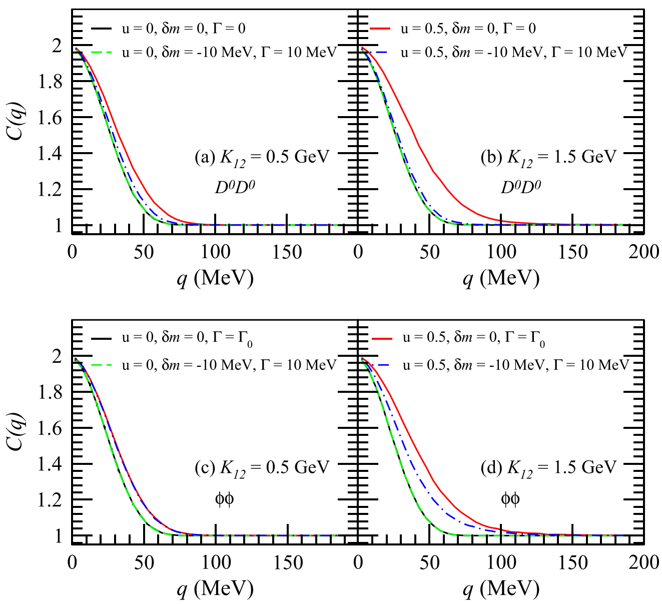

FIG. 3. HBT results of D^0D^0 (top panels) and the correlation of $\phi\phi$ (bottom panels) with respect to relative momentum q. Here, K_{12} is the pair momentum and $2K_{12} = |\mathbf{k}_1 + \mathbf{k}_2|$.

of the correlation function of $\phi\phi$ unless the momentum k is very small [see Fig. 2(b)].

B. Squeezing effect on HBT interferometry

In Fig. 3 we plot the HBT results of D^0D^0 (top panels) and the correlation of $\phi\phi$ (bottom panels) with respect to relative momentum q. Here the angle between the momentum of two particles is taken as zero, and the square of squeezed amplitude $|G_s(\mathbf{k}_1, \mathbf{k}_2)|^2$ is almost zero and does not contribute to the value of the correlation function of $\phi\phi$. The HBT correlation of D^0D^0 or $\phi\phi$ is not affected by the squeezing effect for static sources. Comparing the results for $u = 0$ and $u = 0.5$, it can be concluded that the HBT curves are widened by the expanding flow and the HBT radii also decrease. The squeezing effect suppresses the widening effect of flow on the HBT curve of D^0D^0 for $K_{12} = 0.5$ and 1.5 GeV. The squeezing effect does not affect the HBT result of $\phi\phi$ for $K_{12} = 0.5$ GeV. The widening effect of flow is suppressed by the squeezing effect for $K_{12} = 1.5$ GeV for the $\phi\phi$ pair. The phenomenon of ϕ meson is similar to the nonrelativistic results of kaon [4].

We show in Fig. 4 the normalized distributions of radial coordinates of the sources of D and ϕ for $k = 0.5$ and 1.5 GeV. For static sources, the squeezing effect does not affect the distributions of radial coordinates of the sources of D and ϕ. Generally, particles with low momentum tend to be generated in greater numbers at lower flow velocities, whereas locations with higher flow velocities tend to generate more particles with high momentum. In the model of this paper, the expanding flow increases as the radial position increases. Hence, the expanding flow leads to a shift in the source distributions for a momentum of 0.5 GeV towards smaller radial positions. This can be observed by comparing the black solid

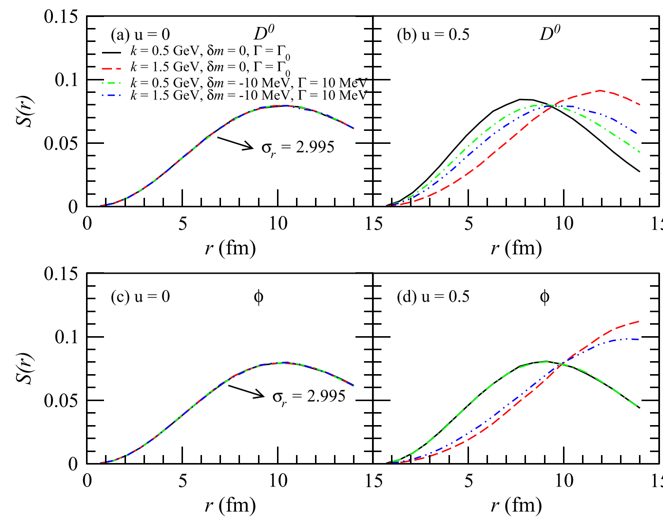

FIG. 4. Normalized distributions of radial coordinates of the sources of D (top panels) and ϕ (bottom panels) for $k = 0.5$ and 1.5 GeV.

lines in Figs. 4(a) and 4(b), or in Figs. 4(c) and 4(d). Similarly, the expanding flow causes a shift in the source distributions for a momentum of 1.5 GeV towards larger radial positions. This can be observed by comparing the red dashed lines in Figs. 4(a) and 4(b), or in Figs. 4(c) and 4(d). For expanding sources, the squeezing effect suppresses the influence of flow on the spatial distribution of D. Similarly, it also mitigates the influence of flow on the spatial distribution of ϕ for a momentum of 1.5 GeV. However, it is important to note that the squeezing effect does not alter the influence of flow on the spatial distribution of ϕ for a momentum of 0.5 GeV. The above phenomenon can be attributed to the fact that the response of $|s'_{-\mathbf{k}'_1,-\mathbf{k}'_2}|^2$ to flow velocity is significantly lower compared to that of $n'_{-\mathbf{k}'_1,-\mathbf{k}'_2}$ in $G_c(\mathbf{k}_1, \mathbf{k}_2)$ in Eq. (18) [67], since the $G_c(\mathbf{k}_1, \mathbf{k}_2)$ is the single-particle momentum distribution for $\mathbf{k}_1 = \mathbf{k}_2$. In Table I we show the standard deviation σ_r of emission source of D and ϕ for $u = 0.5$, where $\sigma_r = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(r_i - \bar{r})^2}$, and it can qualitatively describe the relative spatial distribution of the source. Here N is the total number of D or ϕ emitted from the source, r_i is the radial coordinate of the particle denoted by i, and $\bar{r}$ is the average radial coordinate. When squeezing off, the value of σ_r at $u = 0.5$ is less than that at $u = 0$ [σ_r for $u = 0$ is shown in Figs. 4(a) and 4(c)], which is more obvious for $k = 1.5$ GeV.

TABLE I. Standard deviation σ_r of emission source of D and ϕ for $u = 0.5$. When squeezing on, the values of δ and Γ are -10 and 10 MeV, respectively.

	D		ϕ	
Momentum	Squeezing off	Squeezing on	Squeezing off	Squeezing on
0.5 GeV	2.939	2.998	2.990	2.988
1.5 GeV	2.833	2.993	2.729	2.842

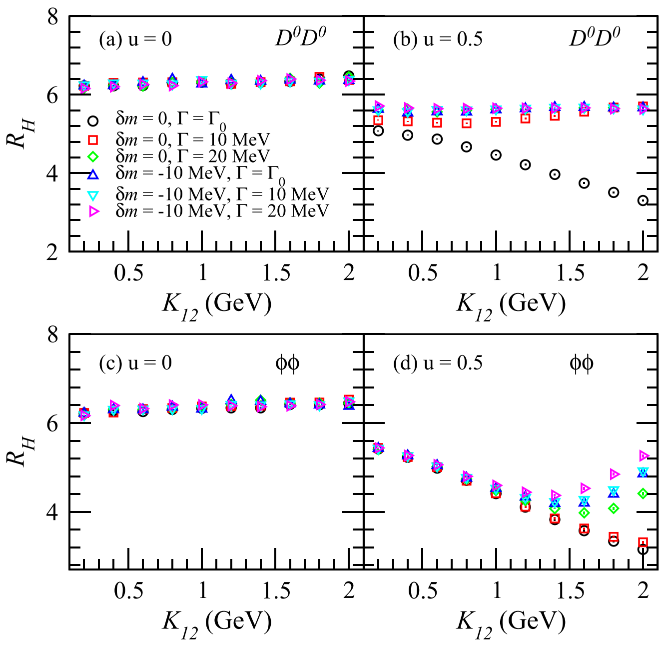

FIG. 5. HBT radii of D^0D^0 (top panels) and $\phi\phi$ (bottom panels) for $u = 0$ and $u = 0.5$.

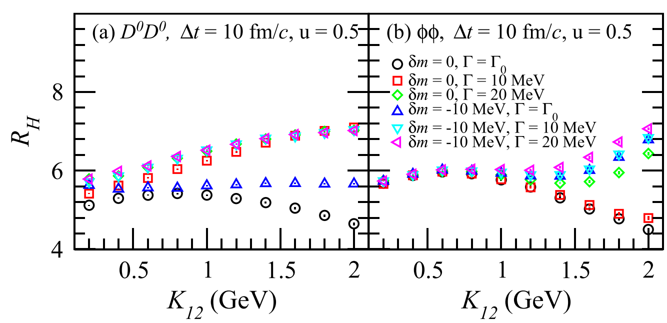

FIG. 6. HBT radii of D^0D^0 (a) and $\phi\phi$ (b) for $\Delta t = 10\,\mathrm{fm}/c$ and $u = 0.5$.

For expanding the source ($u = 0.5$), the squeezing effect suppresses the influence of flow on the spatial distribution of the sources and leads to a larger σ_r. From the results of Figs. 3 and 4 and Table I, it can be concluded that the expanding flow causes the HBT correlation curve to appear wider by reducing the spatial distribution width of the particle source. However, the squeezing effect suppresses the influence of flow on the spatial distribution of the sources and leads to a narrower HBT correlation curve compared to the case without the squeezing effect.

To conduct a more in-depth analysis of the influence of the squeezing effect on the HBT correlation, we extract the one-dimensional HBT radius R_H by fitting the correlation function with the parametrized formula

$$C(q) = 1 + \lambda e^{-q^2 R_H^2}. \tag{30}$$

It is worth mentioning that D^0 and ϕ mesons are electrically neutral, rendering them unaffected by the Coulomb effect. Consequently, these mesons serve as ideal probes for investigating the squeezing effect compared to charged bosons. Additionally, when performing HBT radii fitting for D^0 and ϕ mesons, there is no need to account for the Coulomb effect [16,21]. In Fig. 5 we plot the HBT radii of D^0D^0 (top panels) and $\phi\phi$ (bottom panels) for $u = 0$ and $u = 0.5$. For static sources, the HBT radii remain almost unchanged as pair momentum K_{12} increases, and it is not affected by the squeezing effect. The reduction of the HBT radii are caused by the expanding flow, and this phenomenon intensifies as the pair momentum K_{12} increases. Thus the HBT radii decrease as the pair momentum K_{12} increases for the expanding sources without the squeezing effect. For expanding sources with the squeezing effect, the HBT radii of the D^0D^0 pair remain almost unchanged as pair momentum K_{12} increases, and this phenomenon exists even for $\delta m = 0$ and $\Gamma \neq \Gamma_0$. For expanding sources, the squeezing effect does not influence the HBT radii of $\phi\phi$ when the pair momentum is small. However, it can result in larger HBT radii of $\phi\phi$ for greater pair momentum, and as the δm or Γ increases, this phenomenon becomes more noticeable. It should be noted that even though the σ_r of the D source is slightly greater for δ =–10 MeV, $\Gamma = 10$ MeV, and $u = 0.5$ compared to $u = 0$ at $k = 0.5$ GeV, the HBT radius of D^0D^0 is actually less than the HBT radius for $u = 0$. This occurs because the fitting analysis relies on a Gaussian form, where the flow and squeezing effect affect the width of the source distribution while also resulting in deviations from the Gaussian distribution of the source. Moreover, the non-Gaussian characteristics of the source introduce certain impacts on the fitting results.

In Fig. 6 we plot the HBT radii of D^0D^0 [(a)] and $\phi\phi$ [(b)] for $\Delta t = 10\,\mathrm{fm}/c$ and $u = 0.5$. For expanding sources without the squeezing effect, the HBT radii exhibit a slight increase as the pair momentum increases for small values of K_{12}. For the D^0D^0 pair, the squeezing effect leads to an increase in the HBT radii and causes the HBT radii to increase with the increasing pair momentum K_{12}. The squeezing effect has no impact on the HBT radii for small pair momentum in the $\phi\phi$ pair; however, it results in an increase in the HBT radii for large pair momentum and leads the HBT radii to increase with the increasing pair momentum K_{12}. According to the above results, the squeezing effect diminishes the impact of flow on the HBT radii, particularly for larger pair momentum values. As the collision energy increases, the bosons may experience a more pronounced medium effect, and the time distribution of the source becomes wider. The SBBC is very sensitive to the time distribution of the source and may be suppressed to no signal for a wide temporal distribution [3–6]. Thus the above phenomenon of HBT radii caused by the squeezing effect may provide evidence of the existence of the squeezing effect for the sources with wide temporal distribution.

The results in this section indicate that the squeezing effect suppresses the influence of flow on the spatial distribution of bosons, resulting in a nonflow behavior observed in the relationship between HBT radii and the pair momentum. In the calculation, the time distribution of the source is assumed to be independent of the spatial distribution. However, the temporal distribution is correlated with the spatial distribution [5,6,68]. Consequently, the squeezing effect not only affects the spatial distribution but may also influence the time distribution of the source. Unfortunately, the model employed in this paper is unable to capture the influence of the squeezing effect on the time distribution.

IV. SUMMARY AND DISCUSSION

The interactions between bosons and the source medium in high-energy heavy-ion collisions can cause a squeezing effect, resulting in a SBBC between boson and antiboson in the particle-emitting source. In this paper we explore the SBBC and investigate how the squeezing effect influences the HBT using an expanding Gaussian source with nonzero width. The results indicate that the expanding flow of the source may enhance the SBBC strength of $D^0\bar{D}^0$ and $\phi\phi$ in the low momentum region but suppress the SBBC in the larger momentum region. For static sources, the squeezing effect does not affect the HBT, and the HBT radii remain almost unchanged with the increasing pair momentum K_{12}. For expanding sources, the HBT radii decrease as the pair momentum K_{12} increases due to the influence of expanding flow. The squeezing effect suppresses the influence of flow on the HBT radii, which is significant for two identical bosons with large pair momentum or with large mass. Due to the squeezing effect, the relationship between the HBT radii and the pair momentum exhibits nonflow behavior for the $D^0\bar{D}^0$ pair. Likewise, nonflow behavior also appears in the HBT radii of $\phi\phi$ with large pair momentum.

As the collision energy increases, the source medium becomes hotter and denser. Consequently, the bosons may experience a more pronounced medium effect and the time distribution of the source becomes wider. For sources with wide temporal distribution, the SBBC may be suppressed to no signal but the nonflow behavior of the HBT radii persist. The results presented in this paper are solely based on theoretical simulations. Unfortunately, there is currently no SBBC and HBT experimental data available for the D^0 meson and the ϕ meson for comparative purposes. The significance of the study lies in the fact that, apart from SBBC, the nonflow behavior of the HBT radii may introduce a novel way to investigate squeezing effects.

In this paper the expanding Gaussian source with nonzero width was used to studied the SBBC. Exploring the SBBC of bosons with nonzero width using more realistic sources, such as the hydrodynamical sources, would offer a highly intriguing avenue for further investigation. To study the influence of the squeezing effect on HBT radii, a one-dimensional Gaussian fitting formula is utilized. However, the spatial distribution of the source may deviate from a Gaussian shape. Further analysis is needed on the impact of the squeezing effect using fitting formulas that include the form of the source distribution, such as a Lévy-type formula [69–71]. It would also be interesting to conduct additional research on the influence of the squeezing effect on three-dimensional HBT radii.

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