Squeezed back-to-back correlations of bosons with nonzero widths in relativistic heavy-ion collisions

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We derive the formulas for calculating the squeezed back-to-back correlation (SBBC) between a boson and antiboson with nonzero width produced in relativistic heavy-ion collisions. The SBBCs of D^0 and ϕ mesons with finite in-medium widths are studied. We find that the finite width can change the pattern of the SBBC function of $D^0\bar{D}^0$ with respect to mass. However, the SBBC function of $\phi\phi$ is insensitive to the width. In the high-particle-momentum region, the SBBC function of $\phi\phi$ increases with particle momentum rapidly and can exceed that of $D^0\bar{D}^0$ whether the width is nonzero or not.

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I. INTRODUCTION

The interaction of particles with a medium in relativistic heavy-ion collisions may cause a squeezed back-to-back correlation (SBBC) of detected boson-antiboson pairs [1–8]. This SBBC is related to the in-medium mass modification of the bosons through a Bogoliubov transformation between the annihilation (creation) operators of the quasiparticles in the medium and the corresponding free particles [1–8]. Generally, the in-medium mass modification includes not only a mass shift of the boson but also an increase of its width in the medium. Therefore, the necessity of developing a formulism that can be used to calculate the SBBC between a boson and antiboson with nonzero width in a medium is obvious.

In this work, we derive the formulas for calculating the SBBC function between a boson and antiboson with nonzero width. The influences of the in-medium width on the SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ are investigated. We find that the SBBC function of $D^0\bar{D}^0$ changes obviously for a finite change of width. The SBBC of $\phi\phi$ increases with increasing particle momentum rapidly in a high-momentum region and can exceed the SBBC of $D^0\bar{D}^0$ at high momenta whether the width is nonzero or not. Because of the presence of a charm or strange quark, which is believed to experience the entire evolution of the quark-gluon plasma (QGP) created in relativistic heavy-ion collisions, the analyses of experimental data of D and ϕ mesons have recently attracted great interest [9–30]. However, the bosons with large masses have strong SBBC [6,31–33]. The study of the heavy-meson SBBC is meaningful in relativistic heavy-ion collisions.

The rest of this paper is organized as follows. In Sec. II, we present the formula derivations of the SBBC function for a boson and antiboson with nonzero in-medium width. Then, we show the results of the SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ in Sec. III. Finally, a summary is given in Sec. IV.

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II. FORMULAS

For a system of a boson with mass m_0 in vacuum, the Hamiltonian density is given by

$$\mathcal{H}_0(x) = \tfrac{1}{2}\{\dot{\phi}^2(x) + [\nabla\phi(x)]^2 + m_0^2\phi^2(x)\}, \tag{1}$$

where

$$\phi(x) = \sum_{\mathbf{p}} (2V\omega_{\mathbf{p}})^{-1/2}(e^{-ip\cdot x}a_{\mathbf{p}} + e^{ip\cdot x}a^\dagger_{\mathbf{p}}), \tag{2}$$

where $a_{\mathbf{p}}$ and $a^\dagger_{\mathbf{p}}$ are annihilation and creation operators of the free boson, respectively, $p = (\omega_{\mathbf{p}}, \mathbf{p})$, and $\omega_{\mathbf{p}} = \sqrt{\mathbf{p}^2 + m_0^2}$.

Denoting the in-medium mass shift and width as Δm and Γ, respectively, the boson in-medium energy can be written as

$$\Omega_{\mathbf{p}} = \sqrt{\mathbf{p}^2 + (m_0 + \Delta m - i\Gamma/2)^2} \equiv |\Omega_{\mathbf{p}}|\, e^{i\Theta}, \tag{3}$$

where

$$|\Omega_{\mathbf{p}}| = \left\{\left[\mathbf{p}^2 + (m_0 + \Delta m)^2 - \frac{\Gamma^2}{4}\right]^2 + (m_0 + \Delta m)^2\Gamma^2\right\}^{1/4}, \tag{4}$$

$$\Theta = \frac{1}{2}\tan^{-1}\left[\frac{-(m_0 + \Delta m)\Gamma}{\mathbf{p}^2 + (m_0 + \Delta m)^2 - \Gamma^2/4}\right]. \tag{5}$$

Here, $\Theta < 0$, indicating the imaginary part of $\Omega_{\mathbf{p}}$ is negative. The in-medium system Hamiltonian is given by [1]

$$\begin{aligned} H_{\mathrm{M}} &= \int d^3x\, \frac{1}{2}\{\dot{\phi}^2(x) + [\nabla\phi(x)]^2 + (m_0^2 + m_1^2)\phi^2(x)\} \\ &= \sum_{\mathbf{p}} \omega_{\mathbf{p}} a^\dagger_{\mathbf{p}} a_{\mathbf{p}} + \frac{1}{4}\sum_{\mathbf{p}} \frac{m_1^2}{\omega_{\mathbf{p}}}[e^{-i2\omega_{\mathbf{p}}t}a_{\mathbf{p}}a_{-\mathbf{p}} \\ &\quad + e^{i2\omega_{\mathbf{p}}t}a^\dagger_{\mathbf{p}}a^\dagger_{-\mathbf{p}} + 2a^\dagger_{\mathbf{p}}a_{\mathbf{p}}], \end{aligned} \tag{6}$$

where

$$m_1^2 = (m_0 + \Delta m - i\Gamma/2)^2 - m_0^2 = \Omega_{\mathbf{p}}^2 - \omega_{\mathbf{p}}^2. \tag{7}$$

Equation (6) reduces to the case in Ref. [1] when $\Gamma = 0$.

To diagonalize $H_{\rm M}$, we perform the transformation

$$e^{-i\omega_{\mathbf{p}}t}a_{\mathbf{p}} = c_{\mathbf{p}}e^{-i\Omega_{\mathbf{p}}t}b_{\mathbf{p}} + s^*_{-\mathbf{p}}e^{i\Omega_{\mathbf{p}}t}b^\dagger_{-\mathbf{p}}, \tag{8}$$

$$e^{i\omega_{\mathbf{p}}t}a^\dagger_{\mathbf{p}} = c^*_{\mathbf{p}}e^{i\Omega_{\mathbf{p}}t}b^\dagger_{\mathbf{p}} + s_{-\mathbf{p}}e^{-i\Omega_{\mathbf{p}}t}b_{-\mathbf{p}}, \tag{9}$$

and obtain

$$\begin{aligned}H_{\rm M} = \frac{1}{2}\sum_{\mathbf{p}}\frac{m_1^2}{\omega_{\mathbf{p}}}\bigg[(|c_{\mathbf{p}}|^2 + |s_{\mathbf{p}}|^2 + c_{\mathbf{p}}s^*_{\mathbf{p}} + c^*_{\mathbf{p}}s_{\mathbf{p}})\\ + \frac{2\omega^2_{\mathbf{p}}}{m_1^2}(|c_{\mathbf{p}}|^2 + |s_{\mathbf{p}}|^2)\bigg]b^\dagger_{\mathbf{p}}b_{\mathbf{p}}\\ + \frac{1}{4}\sum_{\mathbf{p}}\frac{m_1^2}{\omega_{\mathbf{p}}}\bigg[(c^*_{\mathbf{p}}c^*_{-\mathbf{p}} + s^*_{\mathbf{p}}s^*_{-\mathbf{p}} + 2c^*_{\mathbf{p}}s^*_{-\mathbf{p}})\\ + \frac{4\omega^2_{\mathbf{p}}}{m_1^2}c^*_{\mathbf{p}}s^*_{-\mathbf{p}}\bigg]e^{i2\Omega_{\mathbf{p}}t}b^\dagger_{\mathbf{p}}b^\dagger_{-\mathbf{p}}.\end{aligned} \tag{10}$$

Here, the time-decayed term of $e^{-i2\Omega_{\mathbf{p}}t}b_{\mathbf{p}}b_{-\mathbf{p}}$ has been removed. In Eqs. (8) and (9), the transformation coefficients satisfy

$$|c_{\mathbf{p}}|^2 - |s_{\mathbf{p}}|^2 = 1 \tag{11}$$

to keep the operators b and $b^\dagger$ with the same commutation relation as that of a and $a^\dagger$.

Letting the terms $b^\dagger_{\mathbf{p}}b^\dagger_{-\mathbf{p}}$ and $b^\dagger_{\mathbf{p}}b_{\mathbf{p}}$ in Eq. (10) equal 0 and $\Omega_{\mathbf{p}}b^\dagger_{\mathbf{p}}b_{\mathbf{p}}$, respectively, we have

$$c_{\mathbf{p}} = \frac{\cosh r_1 + i\cosh r_2}{\sqrt{2}}, \quad s_{\mathbf{p}} = \frac{\sinh r_1 + i\sinh r_2}{\sqrt{2}}, \tag{12}$$

where $c_{\mathbf{p}} = c_{-\mathbf{p}}$, $s_{\mathbf{p}} = s_{-\mathbf{p}}$, r_1 and r_2 are two real functions,

$$r_{1,2} = \frac{1}{2}\ln\left[\frac{\omega_{\mathbf{p}}(1 \mp \sin\Theta)}{|\Omega_{\mathbf{p}}|\cos\Theta}\right], \tag{13}$$

and therefore

$$H_{\rm M} = \sum_{\mathbf{p}}\Omega_{\mathbf{p}}b^\dagger_{\mathbf{p}}b_{\mathbf{p}}, \tag{14}$$

i.e., $b_{\mathbf{p}}$ and $b^\dagger_{\mathbf{p}}$ are annihilation and creation operators, respectively, of the quasiparticle in the medium with energy $\Omega_{\mathbf{p}}$. For $\Gamma = 0$, we have $r_1 = r_2 = \frac{1}{2}\ln[\omega_{\mathbf{p}}/\sqrt{\mathbf{p}^2 + (m_0 + \Delta m)^2}]$, and the diagonalization issue reduces to that for the zero-width case.

Next, we further consider the boson with a width Γ_0 in vacuum. In this case, the boson energy in vacuum is

$$\omega'_{\mathbf{p}} = \sqrt{\mathbf{p}^2 + (m_0 - i\Gamma_0/2)^2} \equiv |\omega'_{\mathbf{p}}|e^{i\theta}. \tag{15}$$

Introducing the annihilation and creation operators, $a'_{\mathbf{p}}$ and $a'^\dagger_{\mathbf{p}}$, respectively, by a transformation similar to Eqs. (8) and (9) ($a'_{\mathbf{p}} \to b_{\mathbf{p}}$, $a'^\dagger_{\mathbf{p}} \to b^\dagger_{\mathbf{p}}$, $\omega'_{\mathbf{p}} \to \Omega_{\mathbf{p}}$), we can diagonalize the Hamiltonian of the boson with Γ_0, and therefore write the Hamiltonian density in this case as

$$\mathcal{H}'_0(x) = \tfrac{1}{2}\{\dot{\phi}'^2(x) + [\nabla\phi'(x)]^2 + (m_0 - i\Gamma_0/2)^2\phi'^2(x)\}, \tag{16}$$

where

$$\phi'(x) = \sum_{\mathbf{p}}(2V\omega'_{\mathbf{p}})^{-1/2}(e^{-ip'\cdot x}a'_{\mathbf{p}} + e^{ip'\cdot x}a'^\dagger_{\mathbf{p}}), \tag{17}$$

where $p' = (\omega'_{\mathbf{p}}, \mathbf{p})$.

Again, with the transformation similar to Eqs. (8) and (9),

$$e^{-i\omega'_{\mathbf{p}}t}a'_{\mathbf{p}} = c_{\mathbf{p}}e^{-i\Omega_{\mathbf{p}}t}b'_{\mathbf{p}} + s^*_{-\mathbf{p}}e^{i\Omega_{\mathbf{p}}t}b'^\dagger_{-\mathbf{p}}, \tag{18}$$

$$e^{i\omega'_{\mathbf{p}}t}a'^\dagger_{\mathbf{p}} = c^*_{\mathbf{p}}e^{i\Omega_{\mathbf{p}}t}b'^\dagger_{\mathbf{p}} + s_{-\mathbf{p}}e^{-i\Omega_{\mathbf{p}}t}b'_{-\mathbf{p}}, \tag{19}$$

we can diagonalize the in-medium Hamiltonian

$$\begin{aligned}H'_{\rm M} = \sum_{\mathbf{p}}\omega'_{\mathbf{p}}a'^\dagger_{\mathbf{p}}a'_{\mathbf{p}} + \frac{1}{4}\sum_{\mathbf{p}}\frac{m'^2_1}{\omega'_{\mathbf{p}}}[e^{-i2\omega'_{\mathbf{p}}t}a'_{\mathbf{p}}a'_{-\mathbf{p}}\\ + e^{i2\omega'_{\mathbf{p}}t}a'^\dagger_{\mathbf{p}}a'^\dagger_{-\mathbf{p}} + 2a'^\dagger_{\mathbf{p}}a'_{\mathbf{p}}], \quad (m'^2_1 = \Omega^2_{\mathbf{p}} - \omega'^2_{\mathbf{p}})\end{aligned} \tag{20}$$

to

$$H'_{\rm M} = \sum_{\mathbf{p}}\Omega_{\mathbf{p}}b'^\dagger_{\mathbf{p}}b'_{\mathbf{p}}. \tag{21}$$

In Eqs. (18) and (19), the transformation coefficients $c_{\mathbf{p}}$ and $s_{\mathbf{p}}$ have the same expressions as Eq. (12), but r_1 and r_2 are now

$$r_{1,2} = \frac{1}{2}\ln\left[\frac{|\omega'_{\mathbf{p}}|(1 \mp \sin(\Theta - \theta))}{|\Omega_{\mathbf{p}}|\cos(\Theta - \theta)}\right]. \tag{22}$$

The SBBC function of the boson-antiboson with momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ is defined as [2–8]

$$C(\mathbf{p}_1, \mathbf{p}_2) = 1 + \frac{|G_s(\mathbf{p}_1, \mathbf{p}_2)|^2}{G_c(\mathbf{p}_1, \mathbf{p}_1)G_c(\mathbf{p}_2, \mathbf{p}_2)}, \tag{23}$$

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

$$G_c(\mathbf{p}_1, \mathbf{p}_2) = \sqrt{\omega_{\mathbf{p}_1}\omega_{\mathbf{p}_2}}\,\langle a^\dagger_{\mathbf{p}_1}a_{\mathbf{p}_2}\rangle, \tag{24}$$

$$G_s(\mathbf{p}_1, \mathbf{p}_2) = \sqrt{\omega_{\mathbf{p}_1}\omega_{\mathbf{p}_2}}\,\langle a_{\mathbf{p}_1}a_{\mathbf{p}_2}\rangle, \tag{25}$$

where $\langle\cdots\rangle$ indicates the ensemble average and $\omega_{\mathbf{p}}$ is the energy of a boson with average mass m_0 for nonzero Γ_0. The SBBC function for a spatially homogeneous source can be written as [2,3,5–8]

$$C(\mathbf{p}, -\mathbf{p}) = 1 + \frac{|c_{\mathbf{p}}s^*_{\mathbf{p}}n_{\mathbf{p}} + c_{-\mathbf{p}}s^*_{-\mathbf{p}}(n_{-\mathbf{p}} + 1)|^2}{n_1(\mathbf{p})n_1(-\mathbf{p})}|\widetilde{F}(\omega_{\mathbf{p}}, \Delta t)|^2, \tag{26}$$

where $n_{\mathbf{p}}$ is the Bose-Einstein distribution of the quasiparticle with the energy corresponding to in-medium average mass $(m_0 + \Delta m)$, $n_1(\mathbf{p}) = |c_{\mathbf{p}}|^2 n_{\mathbf{p}} + |s_{-\mathbf{p}}|^2(n_{-\mathbf{p}} + 1)$, and $|\widetilde{F}(\omega_{\mathbf{p}}, \Delta t)|^2$ is a time suppression factor. We take $|\widetilde{F}(\omega_{\mathbf{p}}, \Delta t)|^2 = (1 + 4\omega^2_{\mathbf{p}}\Delta t^2)^{-1}$ in the calculations for a time-profile function of exponential decay as in Refs. [2–4,8,32,33]. Generally, $|\widetilde{F}(\omega_{\mathbf{p}}, \Delta t)|^2$ is also related to the spatial distribution of particle-emitting source for an evolving system [5,6], and there is a large difference between the suppression factors from different time-profile functions [5,34].

III. RESULTS

We plot in Figs. 1(a) and 1(b) the SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ with respect to in-medium mass $m_0 + \Delta m$ for different Γ values, respectively. Here, the particle momentum is fixed at 1000 MeV/c and we take $\Delta t = 2$ fm/c in calculations as in Refs. [2–5,8]. The mass and width of D^0 meson in vacuum, m_0 and Γ_0, are taken to be 1864.86 and 0 MeV/c^2 (Particle Data Group (PDG [35,36]): 1.60×10^{-9} MeV/c,

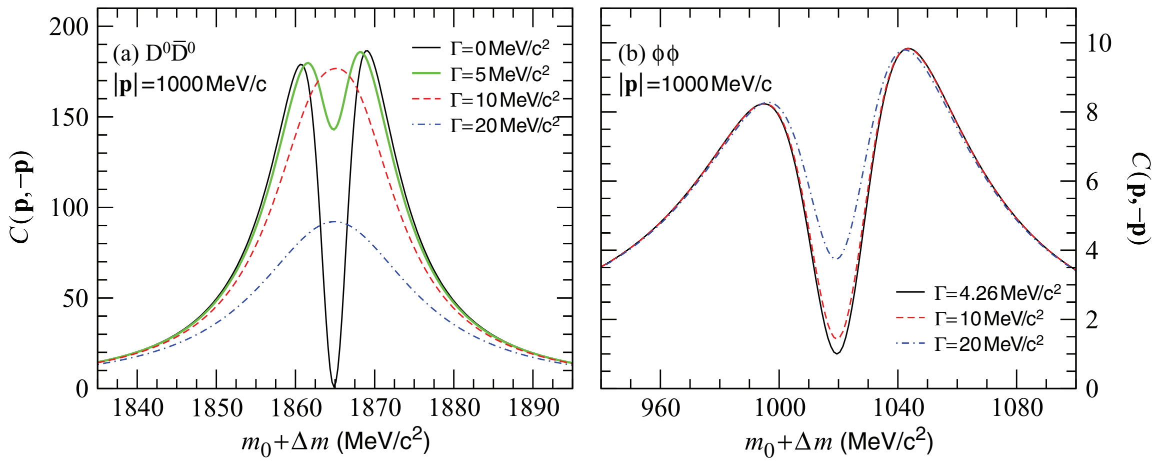

FIG. 1. SBBC functions of $D^0\bar{D}^0$ (a) and $\phi\phi$ (b) with respect to in-medium particle mass ($m_0 + \Delta m$) for particle momentum $|\mathbf{p}| = 1000$ MeV/c and different Γ values.

corresponding to a mean life 4.10×10^{-15} s) respectively, and the m_0 and Γ_0 of ϕ meson are taken to be 1019.46 and 4.26 MeV/c^2 respectively [35,36].

We see from Fig. 1(a) that the pattern of the SBBC function of $D^0\bar{D}^0$ changes significantly with in-medium width Γ. For $\Gamma = 0$, the SBBC function has a typical two-peak structure [2–4,8]. It is 1 (no correlation) at m_0 ($\Delta m = 0$) and approaches 1 when $\Delta m \to \pm\infty$. However, the two peaks of the SBBC function move to m_0 and form one peak rapidly with increasing Γ. Then, the peak declines with increasing Γ. For $\Gamma \neq 0$, the SBBC always exists even though $\Delta m = 0$. By comparing the SBBC functions in Figs. 1(a) and 1(b), we see that the SBBC functions of $\phi\phi$ with respect to mass are much wider than those of $D^0\bar{D}^0$. This is because the SBBC function becomes wide with decreasing boson mass [6,32,33]. We also see that the influence of Γ on the SBBC function of $\phi\phi$ is small. Because the SBBC function of $\phi\phi$ has a wide mass distribution, it is insensitive to a mass-distribution change caused by a change of Γ. However, the nonzero Γ_0 of ϕ will also counteract the effect of Γ on the SBBC function [see Eq. (22) $\theta \neq 0$].

We plot in Fig. 2 the SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ with respect to particle momentum for the in-medium mass shift $\Delta m = -10$ MeV/c^2 and in-medium width $\Gamma = \Gamma_0$ and 10 MeV/c^2. We see that the SBBC functions increase with increasing particle momentum, and the influence of Γ increases with increasing particle momentum. Because the momentum distribution $n_{\mathbf{p}} = n_{-\mathbf{p}}$ approaches zero when $|\mathbf{p}| \to \infty$, the behavior of the SBBC function at very high momenta is mainly determined by $(|c_{\mathbf{p}} s^*_{\mathbf{p}}|^2/|s_{\mathbf{p}}|^4)$ [2,6], which is approximately $16\mathbf{p}^4/[4m_0^2\Delta m^2 + m_0^2(\Gamma - \Gamma_0)^2]$. Therefore, the SBBC functions of $\phi\phi$ increase with increasing particle momentum more rapidly than that of $D^0\bar{D}^0$ in the high-momentum region and can exceed the SBBC of $D^0\bar{D}^0$ at high momenta.

IV. SUMMARY AND DISCUSSION

We derived the formulas for calculating the SBBC between a boson and antiboson with nonzero width produced in relativistic heavy-ion collisions. The influences of the in-medium width on the SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ are investigated. It is found that the pattern of the SBBC function of $D^0\bar{D}^0$ with respect to mass changes significantly with the width. However, the SBBC function of $\phi\phi$ changes slightly with the width. The influence of the width on the SBBC increases with particle momentum. Whether the width is nonzero or not, the SBBC function of $\phi\phi$ increases with increasing particle momentum more rapidly than that of $D^0\bar{D}^0$ in the high-momentum region and can exceed the SBBC function of $D^0\bar{D}^0$ at high momenta.

Finally, it is necessary to mention that we have removed the time-decayed term of $e^{-i2\Omega_{\mathbf{p}}t} b_{\mathbf{p}} b_{-\mathbf{p}}$ in diagonalizing the in-medium Hamiltonian [Eq. (10)]. Therefore, the diagonalization is an approximation unless the imaginary part of $-2\Omega_{\mathbf{p}}$ [$\mathrm{Im}(-2\Omega_{\mathbf{p}}) \sim m_0\Gamma/\omega_{\mathbf{p}} \sim \Gamma$ for $\mathbf{p}^2 < m_0^2$] is very large. This problem does not appear in the diagonalization for the

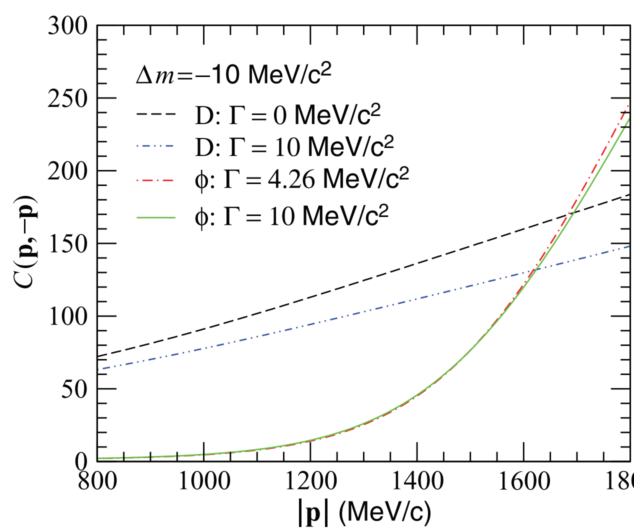

FIG. 2. SBBC functions of $D^0\bar{D}^0$ and $\phi\phi$ with respect to particle momentum for the in-medium mass shift $\Delta m = -10$ MeV/c^2 and in-medium widths $\Gamma = \Gamma_0$ and 10 MeV/c^2.

bosons without width. There, the terms of $b_{\mathbf{p}}b_{-\mathbf{p}}$ and $b^{\dagger}_{\mathbf{p}}b^{\dagger}_{-\mathbf{p}}$ can become zero simultaneously with the reduced transform quantity, $r_1 = r_2 = \frac{1}{2}\ln[\omega_{\mathbf{p}}/\sqrt{\mathbf{p}^2 + (m_0 + \Delta m)^2}]$. The recent measurements of D^0 in heavy-ion collisions at the RHIC and LHC indicate that the average width of D^0 is approximately 30 MeV/c^2 [9–16]. The corresponding characteristic size is $c\tau \sim 6.6$ fm, which is smaller than the typical size of the particle-emitting source in relativistic heavy-ion collisions. Therefore, the diagonalization is a good approximation and the influence of the in-medium width on the SBBC of $D^0\bar{D}^0$ must be considered in the heavy-ion collisions. For the ϕ meson, its $c\tau$ is comparable to the typical size of the source. Our work is a key step forward to solve the problem. In addition, it will be of interest to expand the approach presented in the case that the particle and antiparticle with different in-medium mass modifications.

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