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Squeezed back-to-back correlation between bosons and antibosons with different in-medium masses in high-energy heavy-ion collisions

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We derive the formulas of the squeezed back-to-back correlation (SBBC) between a boson and antiboson with different in-medium masses in high-energy heavy-ion collisions. The influence of the in-medium mass difference between a boson and antiboson on the SBBC is investigated. We calculate the SBBC functions of D-meson pairs for the hydrodynamic sources described by the VISH2+1 code for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Our results indicate that the SBBC strengths of D^+D^- and $D^0\bar{D}^0$ are different if there are charge-dependent in-medium interactions.

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Introduction. In high-energy heavy-ion collisions, the in-medium mass shifts of bosons may cause a squeezed back-to-back correlation (SBBC) between a detected boson and an antiboson [1–4]. This SBBC is related to the in-medium energies of the bosons, through a Bogoliubov transformation between the creation (annihilation) operators of the quasiparticles in the medium and the corresponding free particles [1–4]. The study of the SBBC can provide information about boson formations and in-medium interactions in high-energy heavy-ion collisions.

In previous studies of the SBBC, the mass shifts of a boson and antiboson are taken to be the same [1–9]. More generally, the interactions of a boson and antiboson in a medium are different, especially in a medium with a finite baryon chemical potential [10–15]. The in-medium energy difference between a boson and an antiboson leads to a mass difference between the quasiparticles in a medium. It is necessary to check the validity of the previous formulas of the SBBC calculations in this case.

In this work, we derive the formulas for calculating the SBBC function of a boson-antiboson with different in-medium masses. The influence of the in-medium mass difference on the SBBC functions of D-meson pairs is investigated. Since D mesons contain a charm quark, which is believed to experience the entire evolution of the quark-gluon plasma (QGP) created in relativistic heavy-ion collisions, D-meson measurements have recently attracted great interest [16–21]. We calculate the SBBC functions of D-meson pairs for the hydrodynamic sources described by the VISH2+1 code [22] and find that the SBBC strengths of D^+D^- and $D^0\bar{D}^0$ are different in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV if there are charge-dependent in-medium interactions.

In Sec. II, we present the formula derivations of the SBBC function for a boson and antiboson with different in-medium masses. Then, we show the SBBC results of D-meson pairs in Sec. III. Finally, a summary is given in Sec. IV.

Formulas. In the framework of a complex scalar field, the Hamiltonian density of a system for a free boson and antiboson with mass m is given by

$$\mathcal{H} = \dot{\phi}\dot{\phi}^\dagger + \nabla\phi^\dagger \cdot \nabla\phi + m^2\phi^\dagger\phi, \tag{1}$$

where

$$\phi(x) = \sum_{\mathbf{p}} (2V\omega_{\mathbf{p}})^{-\frac{1}{2}} (e^{-ipx} a_{\mathbf{p}} + e^{ipx} b_{\mathbf{p}}^\dagger), \tag{2}$$

$$\phi^\dagger(x) = \sum_{\mathbf{p}} (2V\omega_{\mathbf{p}})^{-\frac{1}{2}} (e^{ipx} a_{\mathbf{p}}^\dagger + e^{-ipx} b_{\mathbf{p}}), \tag{3}$$

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

For a boson and antiboson in a medium with the same mass $m' = \sqrt{m^2 \pm m_1^2}$, where "+" or "−" represents the case that m' is larger or smaller than m, respectively, the Hamiltonian density of system can be written as [1]

$$\mathcal{H}_{\rm M} = \dot{\phi}\dot{\phi}^\dagger + \nabla\phi^\dagger \cdot \nabla\phi + \left(m^2 \pm m_1^2\right)\phi^\dagger\phi, \tag{4}$$

and the Hamiltonian of the system can be diagonalized through a Bogoliubov transformation [1,2].

Generally speaking, the interactions of a boson and antiboson with a medium are somewhat different. Assuming the energy split between the boson and antiboson in the medium is $2\delta'$, we consider the transformation

$$\phi \to e^{i\delta' t}\phi, \quad \phi^\dagger \to e^{-i\delta' t}\phi^\dagger, \tag{5}$$

and have

$$\mathcal{H}_{\rm M} = \dot{\phi}\dot{\phi}^\dagger + \nabla\phi^\dagger \cdot \nabla\phi + m^2\phi^\dagger\phi \pm m_1^2\phi^\dagger\phi + \delta'^2\phi\phi^\dagger - i\delta'(\dot{\phi}\phi^\dagger - \phi\dot{\phi}^\dagger). \tag{6}$$

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It will be seen that δ'^2 provides an additional term of mass square in average energy of the boson and antiboson, which is associated with the different in-medium interactions for both, while m_1^2 reflects the in-medium interaction that is the same for both.

Using the Bogoliubov transformation between the operators $(a_{\mathbf{p}}, a_{\mathbf{p}}^\dagger, b_{\mathbf{p}}, b_{\mathbf{p}}^\dagger)$ for the free particles and $(a'_{\mathbf{p}}, a'^\dagger_{\mathbf{p}}, b'_{\mathbf{p}}, b'^\dagger_{\mathbf{p}})$ for the quasiparticles,

$$a_{\mathbf{p}} = c_{\mathbf{p}} a'_{\mathbf{p}} + s^*_{-\mathbf{p}} b'^\dagger_{-\mathbf{p}}, \quad b_{\mathbf{p}} = \bar{c}_{\mathbf{p}} b'_{\mathbf{p}} + \bar{s}^*_{-\mathbf{p}} a'^\dagger_{-\mathbf{p}}, \tag{7}$$

where

$$c^*_{\pm\mathbf{p}} = c_{\pm\mathbf{p}} = \bar{c}^*_{\pm\mathbf{p}} = \bar{c}_{\pm\mathbf{p}} = \cosh r_{\mathbf{p}}, \tag{8}$$

$$s^*_{\pm\mathbf{p}} = s_{\pm\mathbf{p}} = \bar{s}^*_{\pm\mathbf{p}} = \bar{s}_{\pm\mathbf{p}} = \sinh r_{\mathbf{p}}, \tag{9}$$

$$r_{\mathbf{p}} = \tfrac{1}{2}\ln(\omega_{\mathbf{p}}/\Omega_{\mathbf{p}}), \tag{10}$$

$$\Omega_{\mathbf{p}} = \sqrt{\mathbf{p}^2 + m^2 \pm m_1^2 + \delta'^2}, \tag{11}$$

we can diagonalize the Hamiltonian of the system for the boson and antiboson with an energy split $2\delta'$ in the medium as

$$H_{\rm M} = \sum_{\mathbf{p}} [(\Omega_{\mathbf{p}} + \delta') a'^\dagger_{\mathbf{p}} a'_{\mathbf{p}} + (\Omega_{\mathbf{p}} - \delta') b'^\dagger_{\mathbf{p}} b'_{\mathbf{p}}]. \tag{12}$$

The in-medium masses of the boson and antiboson are

$$m'_\pm = (\Omega_{\mathbf{p}} \pm \delta')\big|_{\mathbf{p}=0} = \sqrt{m^2 \pm m_1^2 + \delta'^2} \pm \delta', \tag{13}$$

and the in-medium mass difference between the boson and antiboson with the same momentum is also the split $2\delta'$.

It can be seen that the Bogoliubov transformation involves only the average in-medium energy of the boson and antiboson. Furthermore, the average energy $\Omega_{\mathbf{p}}$ is not only related to m_1 associated with the in-medium interactions that are the same for the boson and antiboson, but it is also related to the δ' associated with the in-medium interactions that are different for the boson and antiboson.

The SBBC function of the boson-antiboson with momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ is defined as [2,3]

$$C(\mathbf{p}_1, \mathbf{p}_2) = 1 + \frac{|G_s(\mathbf{p}_1, \mathbf{p}_2)|^2}{G_c(\mathbf{p}_1, \mathbf{p}_1) G_c(\mathbf{p}_2, \mathbf{p}_2)}, \tag{14}$$

where $G_c(\mathbf{p}_1, \mathbf{p}_2)$ and $G_s(\mathbf{p}_1, \mathbf{p}_2)$ are the so-called chaotic and squeezed amplitudes [2,3], respectively. They are given by [2–4,23]

$$G_c(\mathbf{p}_1, \mathbf{p}_2) = \int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K^\mu_{1,2}\, e^{i\, q_{1,2}\cdot r} \left\{ \left|c'_{\mathbf{p}'_1,\mathbf{p}'_2}\right|^2 n'_{\mathbf{p}'_1,\mathbf{p}'_2} + \left|s'_{-\mathbf{p}'_1,-\mathbf{p}'_2}\right|^2 \left[n'_{-\mathbf{p}'_1,-\mathbf{p}'_2} + 1 \right] \right\}, \tag{15}$$

$$G_s(\mathbf{p}_1, \mathbf{p}_2) = \int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K^\mu_{1,2}\, e^{2i\, K_{1,2}\cdot r} \left\{ s'^*_{-\mathbf{p}'_1,\mathbf{p}'_2} c'_{\mathbf{p}'_2,-\mathbf{p}'_1} \times n'_{-\mathbf{p}'_1,\mathbf{p}'_2} + c'_{\mathbf{p}'_1,-\mathbf{p}'_2} s'^*_{-\mathbf{p}'_2,\mathbf{p}'_1} \left[n'_{\mathbf{p}'_1,-\mathbf{p}'_2} + 1 \right] \right\}, \tag{16}$$

for an evolving source. Here, $d^4\sigma_\mu(r)$ is the four-dimensional element of the freeze-out hypersurface, $q^\mu_{1,2} = p^\mu_1 - p^\mu_2$, $K^\mu_{1,2} = (p^\mu_1 + p^\mu_2)/2$, and $\mathbf{p}'_i$ is the local-frame momentum corresponding to $\mathbf{p}_i (i = 1, 2)$. In Eqs. (15) and (16), the quantities $c'_{\mathbf{p}'_1,\mathbf{p}'_2}$ and $s'_{\mathbf{p}'_1,\mathbf{p}'_2}$ are the coefficients of the Bogoliubov transformation between the creation (annihilation) operators of the quasiparticles and the free particles, respectively, and $n'_{\mathbf{p}'_1,\mathbf{p}'_2}$ is the boson distribution of the quasiparticle pair [2–5].

Results. We first consider a simple case, namely, a rest particle-emitting source with a fixed freeze-out temperature T_f, a Gaussian spatial distribution $[e^{-r^2/2R^2}/(\sqrt{2\pi}R)^3]$, and a temporal distribution of exponential decay $[\theta(t - t_0)e^{-(t-t_0)/\Delta t}/\Delta t]$ [2,3,5]. In this case, the SBBC function of the boson-antiboson emitted from the source with momenta $\mathbf{p}_1$ and $\mathbf{p}_2$, and under the condition $|\mathbf{p}_1| = |\mathbf{p}_2| = |\mathbf{p}|$, can be given analytically by [24]

$$\begin{aligned} C(\mathbf{p}_1, \mathbf{p}_2) &= 1 + e^{-2\mathbf{p}^2 R^2 [1+\cos(\alpha)]} B(\mathbf{p}) \\ &\equiv 1 + f(\alpha) B(\mathbf{p}), \end{aligned} \tag{17}$$

where $\alpha (0 < \alpha < \pi)$ is the angle between momenta $\mathbf{p}_1$ and $\mathbf{p}_2$, and

$$B(\mathbf{p}) = \frac{|c_{\mathbf{p}}\, s^*_{\mathbf{p}}\, n_{\mathbf{p}} + c_{\mathbf{p}} s^*_{\mathbf{p}}\, (n_{\mathbf{p}} + 1)|^2}{\left(1 + 4\omega^2_{\mathbf{p}} \Delta t^2\right) n_1(\mathbf{p})\, n_1(\mathbf{p})}, \tag{18}$$

where $n_{\mathbf{p}}$ is the boson distribution of the quasiparticle pair with average energy $\Omega_{\mathbf{p}}$, and $n_1(\mathbf{p}) = |c_{\mathbf{p}}|^2 n_{\mathbf{p}} + |s_{\mathbf{p}}|^2 (n_{\mathbf{p}} + 1)$. Here, it should be mentioned that we have used an approximation that replaces the boson or antiboson momentum distribution with the pair momentum distribution $n_{\mathbf{p}}$ in the denominator of Eq. (18). The SBBC function $C(\mathbf{p}_1, \mathbf{p}_2)$ approaches its maximum $[1 + B(\mathbf{p})]$ when the boson and antiboson approach antiparallelism, and decreases with increasing $\cos\alpha$ exponentiality. For the case of incomplete antiparallelism $\mathbf{p}_1$ and $\mathbf{p}_2$, the mass-shift-caused SBBC still exists, except for very large sources.

The SBBC is expected to be strong for the mesons with large masses [7,25], under the same source size and freeze-out temperature. We plot $B(\mathbf{p})$ in Fig. 1 as functions of mass shift $\Delta m_1 = (m' - m_0)$ for D^+D^- pairs with different momenta and in-medium mass differences. Here, the solid and dashed lines are for $\delta' = 0$ and 60 MeV, respectively. In the calculations, the source freeze-out temperature is taken to be 150 MeV and we take $\Delta t = 2$ fm. It can be seen that δ' leads to a shift of $B(\mathbf{p})$ toward decreasing Δm_1. The function width decreases with increasing momentum.

In Fig. 2 we plot $B(\mathbf{p})$ as functions of δ' for D^+D^- pairs with momenta 0.8 and 1.2 GeV/c. Here, the source parameters are the same as in Fig. 1. Based on the results [24] calculated in the framework used by Fuchs, Martemyanov, Faessler, and Krivoruchenko [26,27], the mass of the D meson in a hadronic medium in relativistic heavy-ion collisions is approximately $3 \sim 5$ MeV/c^2 smaller than its value at a free state. Thus, we compare the $B(\mathbf{p})$ functions at $\Delta m_1 = -3$ and -5 MeV/c^2. For the lower momentum $|\mathbf{p}| = 0.8$ GeV/c, $B(\mathbf{p})$ decreases with increasing δ'. However, for the higher momentum $\mathbf{p} = 1.2$ GeV/c, the result of $B(\mathbf{p})$ for $\Delta m_1 = -5$ MeV/c^2 increases with increasing δ', while the result for $\Delta m_1 = -3$ decreases more rapidly with increasing δ' when $\delta' > 40$ MeV. The results of $B(\mathbf{p})$ are sensitive to the mass shift Δm_1, mass difference δ', and particle momentum $|\mathbf{p}|$.

We show in Fig. 3 the SBBC functions of D-meson pairs for the source as in Figs. 1 and 2 and with a Gaussian radius $R = 3$ fm. It can be seen that the influence of δ' on the SBBC

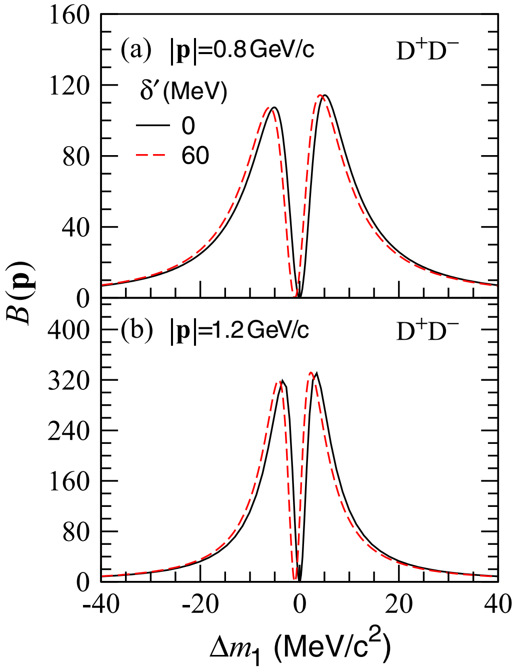

FIG. 1. $B(\mathbf{p})$ as functions of mass shift $\Delta m_1 = (m' - m_0)$ for D^+D^- pairs with momenta 0.8 and 1.2 GeV/c and the splits $\delta' = 0$ and 60 MeV (solid and dashed lines).

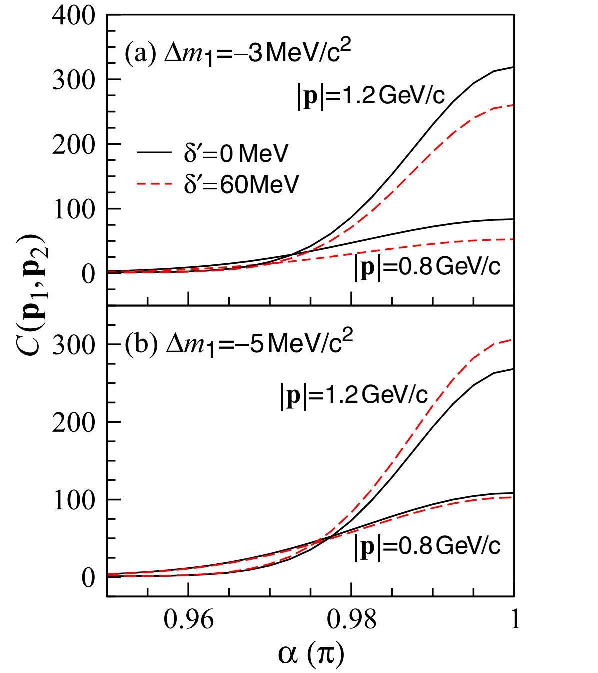

FIG. 3. SBBC functions of D-meson pairs for the Gaussian source as in Figs. 1 and 2 and with $R = 3$ fm.

functions at the higher momentum is different when $\Delta m_1 = -3$ and -5 MeV/c^2. For $\Delta m_1 = -3$ MeV/c^2, δ' makes the SBBC function at high momentum decrease. However, δ' makes the SBBC function at high momentum increase for $\Delta m_1 = -5$ MeV/c^2.

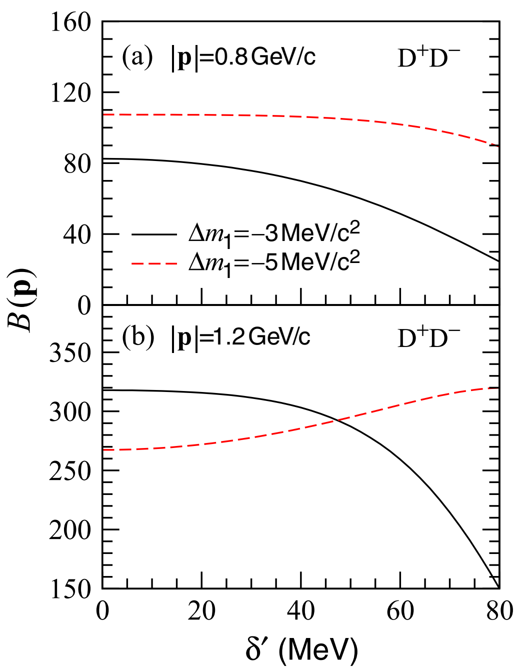

FIG. 2. $B(\mathbf{p})$ as functions of δ' for D^+D^- pairs with momenta 0.8 and 1.2 GeV/c and $\Delta m_1 = -3$ and -5 MeV/c.

As discussed above, δ' is associated with the in-medium interactions, which are different for a boson and antiboson. If assuming these in-medium interactions are particle-charge dependent, the split δ' will be zero for a $D^0\bar{D}^0$ pair. For a D^+D^- pair, the split may reach a few tens of MeV [11,15]. In this case, it can be seen that the SBBC of D^+D^- at high momentum is weaker or stronger than that of $D^0\bar{D}^0$ when $\Delta m_1 = -3$ or -5 MeV/c^2 in the simple source model, where Δm_1 is the mass shift related to the in-medium interactions, which are the same for the particles and antiparticles.

We next investigate the SBBC functions for the evolving sources described by the viscous hydrodynamic model VISH2+1 [22] under the Monte Carlo Glauber (MCGlb) initial conditions fluctuating event by event [28]. Figures 4 and 5 show the SBBC functions $C(\Delta\phi)$ of D-meson pairs for the hydrodynamic sources for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions with centralities 0%–80% and 40%–80%, respectively. Here, $\Delta\phi$ is the angle between the transverse momenta of the two D mesons, the ratio of the shear viscosity to entropy density of QGP is taken to be 0.08 [29,30], and we take the freeze-out temperature to be 150 MeV based on comparisons of the transverse-momentum spectra of D mesons [24] with the RHIC experimental data [16].

It can be seen that the results of the SBBC function for nonzero δ' are smaller than those for zero δ' when $\Delta m_1 = -3$ MeV. In addition, the results of the SBBC function for nonzero δ' are slightly larger than those for zero δ' when $\Delta m_1 = -5$ MeV. Assuming that there the split δ' associated with the charge-depend in-medium interactions exists, we conclude that the SBBC of D^+D^- and $D^0\bar{D}^0$ pairs are different for the different Δm_1. This may provide a probe with which to study the in-medium interactions in detail.

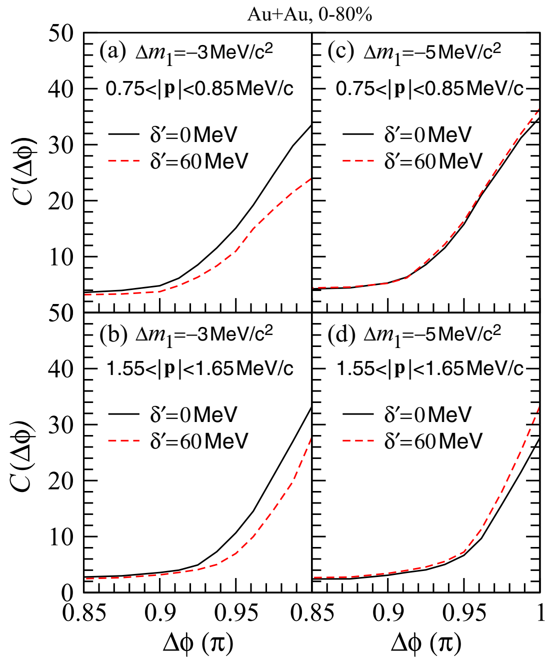

FIG. 4. SBBC functions of D-meson pairs for viscous hydrodynamic sources for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions with 0%–80% centrality.

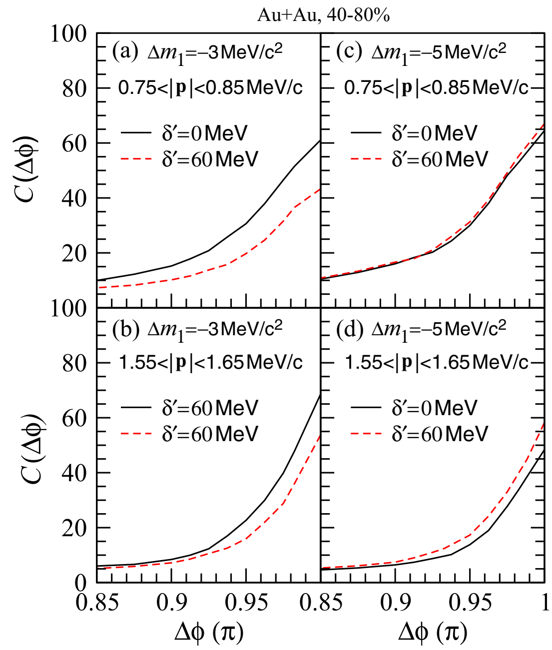

FIG. 5. Same as Fig. 4, but with 40%–80% centrality.

The dependence of SBBC on particle momentum is complicated for the hydrodynamic sources with fluctuating initial conditions. The more serious oscillations of single-event SBBC functions at higher momentum [4] may lead to a lower SBBC function after being averaged over events [7,24], although the intercept of the SBBC function $C(\mathbf{p}, -\mathbf{p})$ increases with increasing particle momentum [1–9]. It can be seen that the widths of the SBBC functions $C(\Delta\phi)$ for higher momentum are narrower than those for lower momentum, which is similar to that for the simple source in Fig. 3. By comparing the SBBC functions in Figs. 4 and 5, we find that the SBBC functions for the peripheral collisions are higher than those for the central collisions. This is because the averaged source lifetime is smaller for the peripheral collisions [7].

Summary. We derived the formulas of SBBC between a boson and antiboson with different in-medium masses. The SBBC is related to the average in-medium energy of the boson and antiboson, which is the same as for quasiparticles having the same mass. However, the more general formulas developed in this paper indicate that the SBBC is associated with both in-medium interactions, one is the same for a boson and antiboson and the other one is different for the boson and antiboson, respectively. Due to the high strength, the SBBC of heavy-meson pairs provides a possible probe with which to study the in-medium interactions of the heavy mesons in detail in relativistic heavy-ion collisions. Our results calculated with the VISH2+1 code for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV indicate that the SBBC strengths of D^+D^- and $D^0\bar{D}^0$ pairs are different if there are charge-dependent in-medium interactions.

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