Squeezed K^+K^- correlations in high energy heavy ion collisions

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The hot and dense medium formed in high energy heavy ion collisions may modify some hadronic properties. In particular, if hadron masses are shifted in-medium, it was demonstrated that this could lead to back-to-back squeezed correlations (BBC) of particle-antiparticle pairs. Although well-established theoretically, the squeezed correlations have not yet been discovered experimentally. A method has been suggested for the empirical search of this effect, which was previously illustrated for $\phi\phi$ pairs. We apply here the formalism and the suggested method to the case of K^+K^- pairs, since they may be easier to identify experimentally. The time distribution of the emission process plays a crucial role in the survival of the BBC's. We analyze the cases where the emission is supposed to occur suddenly or via a Lorentzian distribution, and compare with the case of a Lévy distribution in time. Effects of squeezing on the correlation function of identical particles are also analyzed.

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I. INTRODUCTION

Since the beginning of the 1990s, some people started calling attention to the possible existence of a different type of correlation, occurring between particles and their antiparticles. Initially, in 1991, Weiner *et al.* [1] pointed out the surprise existence of a new quantum statistical correlation between $\pi^+\pi^-$, which would be similar to the $\pi^0\pi^0$ case (since π^0 is its own antiparticle), but entirely different from the Bose-Einstein correlations (between $\pi^\pm\pi^\pm$) leading to the Hanbury-Brown–Twiss (HBT) effect. They related those correlations to the expectation values of the annihilation (creator) operators, $\langle \hat{a}^{(\dagger)}(k_1)\hat{a}^{(\dagger)}(k_2)\rangle \neq 0$, which was then estimated by using a density matrix containing squeezed states, analogous to two-particle squeezing in optics. They predicted that such squeezed correlations would have intensities above unity, either for charged or neutral pions, i.e., $C_s(\pi^+\pi^-) > 1$ and $C_s(\pi^0\pi^0) > 1$. Later, Sinyukov [2], discussed a similar effect for $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs, claiming that they would be due to inhomogeneities in the system, in opposition to homogeneity regions in HBT, coming from a hydrodynamical description of the system evolution.

Other tentative models tried to formulate the problem more accurately, and it finally happened at the end of that decade, in a proposition made by Asakawa *et al.* [3]. In their approach, these *squeezed back-to-back correlations* (BBC) of boson-antiboson pairs resulted from a quantum mechanical unitary transformation relating in-medium quasiparticles to two-mode squeezed states of their free counterparts. We discuss it in some more detail below. Shortly after that, Panda *et al.* [4] predicted that a similar BBC between fermion-antifermion pairs should exist, if the masses of these particles were modified in-medium. Both the fermionic (fBBC) and the bosonic (bBBC) back-to-back squeezed correlations are described by analogous formalisms, being both positive correlations with unlimited intensity. This last feature contrasts with the observed quantum statistical correlations of identical bosons and identical fermions, whose intensities are limited to vary between 1 and 2, or 0 and 1, respectively. In the remainder of this paper, we focus our discussion on the bosonic case only.

The correlation reflecting the squeezing is quantified in terms of the ratio of the two-particle distribution by the product of the single-inclusive distributions, i.e., the spectra of the particle and of the antiparticle. For the sake of comprehension, we first briefly discuss the formalism for bosons that are their own antiparticles, such as $\phi\phi$ or $\pi^0\pi^0$ pairs. In this case, the full correlation function, after applying a generalization of Wick's theorem for locally equilibrated systems [5,6] consist of a part reflecting the identity of the particles (HBT), and another one, reflecting the particle-antiparticle squeezed correlation (BBC). This can be written as

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = \frac{N_2(\mathbf{k}_1, \mathbf{k}_2)}{N_1(\mathbf{k}_1)N_1(\mathbf{k}_2)} = 1 + \frac{|G_c(1,2)|^2}{G_c(1,1)G_c(2,2)} + \frac{|G_s(1,2)|^2}{G_c(1,1)G_c(2,2)}. \quad (1)$$

The invariant single-particle and two-particle momentum distributions are given by

$$G_c(i,i) = \omega_{\mathbf{k}_i}\langle \hat{a}^\dagger_{\mathbf{k}_i}\hat{a}_{\mathbf{k}_i}\rangle = \omega_{\mathbf{k}_i}\frac{d^3N}{d\mathbf{k}_i},$$
$$G_c(1,2) = \sqrt{\omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}}\langle \hat{a}^\dagger_{\mathbf{k}_1}\hat{a}_{\mathbf{k}_2}\rangle,$$
$$G_s(1,2) = \sqrt{\omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}}\langle \hat{a}_{\mathbf{k}_1}\hat{a}_{\mathbf{k}_2}\rangle. \quad (2)$$

In the above equations, $\langle \dots \rangle$ represents thermal averages. The first term in Eq. (2) corresponds to the spectrum of each particle, the second is due to the indistinguishability of identical particles, reflecting their quantum statistics. The third term, in the absence of in-medium mass shift is in general identically zero. However, if the particle's mass is modified in-medium, it can contribute significantly, triggering this novel type of particle-antiparticle correlation, yet to be discovered experimentally. This is achieved by means of a Bogoliubov-Valatin (BV) transformation, which relates

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the asymptotic creation (annihilation) operators, $\hat{a}^\dagger_{\mathbf{k}}$ ($\hat{a}_{\mathbf{k}}$), of the observed bosons with momentum $k^\mu = (\omega_k, \mathbf{k})$, to the in-medium operators, $\hat{b}^\dagger_{\mathbf{k}}$ ($\hat{b}_{\mathbf{k}}$), corresponding to thermalized quasiparticles. The BV transformation is given by

$$\hat{a}_k = c_k \hat{b}_k + s^*_{-k} \hat{b}^\dagger_{-k}; \quad \hat{a}^\dagger_k = c^*_k \hat{b}^\dagger_k + s_{-k} \hat{b}_{-k}, \tag{3}$$

being $c_k = \cosh(f_k)$ and $s_k = \sinh(f_k)$; $(-k)$ denotes an opposite sign in the spacial components of the momenta. For conciseness, we keep here the short-hand notation introduced in Ref. [3]. The coefficient

$$f_{i,j}(x) = \frac{1}{2} \log \left[\frac{K^\mu_{i,j}(x)\, u_\mu(x)}{K^{*\nu}_{i,j}(x)\, u_\nu(x)} \right], \tag{4}$$

is the squeezing parameter, where $K^\mu_{i,j}(x) = \frac{1}{2}(k^\mu_i + k^\mu_j)$ is the average of the momenta of each particle, and u_μ is the flow velocity of the system. The BV transformation between the operators is equivalent to a squeezing operation, from which the name of the resulting correlation is derived.

In case of charged mesons, such as $\pi^\pm$ or $K^\pm$, the terms in Eq. (1) would act independently, i.e., either the first and the second terms together would lead to the HBT effect (for $\pi^\pm\pi^\pm$ or $K^\pm K^\pm$ pairs), and the first and the last terms, to the BBC effect (for $\pi^+\pi^-$ or K^+K^- pairs).

The in-medium modified mass, m_*, was originally [3] related quadratically to the asymptotic mass, m, i.e., $m^2_*(|\mathbf{k}|) = m^2 - \delta M^2(|\mathbf{k}|)$, where the shifting in the mass, $\delta M(|\mathbf{k}|)$, could depend on the momenta of the particles. Nevertheless, adopting the same simplified assumption as in a few previous studies [7–16], we also consider here a constant mass-shift, homogeneously distributed all over the system, and related linearly to the asymptotic mass by $m_* = m \pm \delta M$.

II. RESULTS FOR K^+K^- PAIRS

Initial studies of the problem were performed for a static, infinite medium [3,4], later extended to a finite-size system, radially expanding with moderate flow [7]. For simplicity, a nonrelativistic approach was considered, assuming flow-independent squeezing parameter. The expansion of the system was described by the emission function from the nonrelativistic hydrodynamical parametrization of Ref. [9], later shown to be a nonrelativistic hydrodynamical solution. In Fig. 1 we illustrate these assumptions with a simple sketch. The flow velocity during the system expansion was considered as $\mathbf{v} = \langle u \rangle \mathbf{r}/R$. The values $\langle u \rangle = 0$ and $\langle u \rangle = 0.5$ are used in the present work. Within the hypotheses described above, analytical results were obtained for the squeezed correlation function [7] of K^+K^- pairs [first and third terms in Eq. (1)], as

$$C_s(\mathbf{k}_1, \mathbf{k}_2) = 1 + \frac{(E_1 + E_2)^2}{4E_1 E_2} |c_0|^2 |s_0|^2 \Bigg| R^3 e^{-\frac{R^2}{2}(\mathbf{k_1}+\mathbf{k_2})^2} + 2n^*_0 R^3_* \exp\left[-\frac{(\mathbf{k_1}-\mathbf{k_2})^2}{8m_* T}\right] \exp\left[-\frac{im\langle u\rangle R}{2m_* T_*}(\mathbf{k_1}+\mathbf{k_2})^2\right] \times \exp\left[-\frac{(\mathbf{k_1}+\mathbf{k_2})^2}{8m_* T_*}\right] \exp\left[-\frac{R^2_*}{2}(\mathbf{k_1}+\mathbf{k_2})^2\right]\Bigg|^2$$

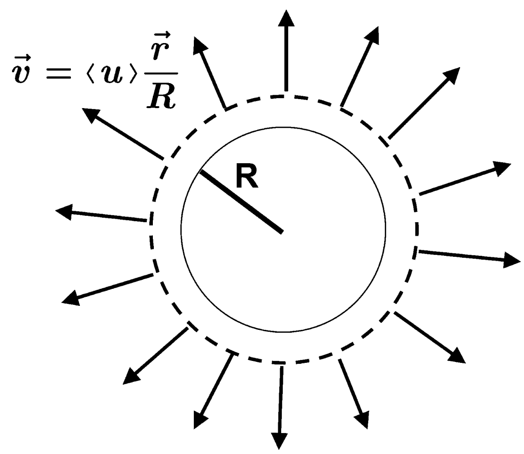

FIG. 1. Sketch illustrating the cross-sectional area of the Gaussian profile ($\sim e^{-\mathbf{r}/(2R)^2}$) of the system expanding with radial flow.

$$\times \left\{\left[|s_0|^2 R^3 + n^*_0 R^3_* (|c_0|^2 + |s_0|^2) \exp\left(-\mathbf{k}^2_1/(2m_* T_*)\right)\right] \left[|s_0|^2 R^3 + n^*_0 R^3_* (|c_0|^2 + |s_0|^2) \exp\left(-\mathbf{k}^2_2/(2m_* T_*)\right)\right]\right\}^{-1}. \tag{5}$$

The medium-modified radius and temperature in Eq. (5) are written, respectively, as $R_* = R\sqrt{T/T_*}$ and $T_* = T + \frac{m^2\langle u\rangle^2}{m_*}$, as introduced in Ref. [7].

As done in the case of $\phi\phi$ correlations [15], it is instructive to analyze the behavior of the correlation function for exactly back-to-back particle-antiparticle pairs, i.e., pairs with exactly opposite momenta, as a function of the shifted mass parameter, m_*, and of the absolute value of their momenta. Therefore, we investigate the behavior of $C_s(\mathbf{k}, -\mathbf{k}, m_*)$ as a function of m_* and $|\mathbf{k}|$. This is obtained by imposing the idealized limit of $\mathbf{k_1} = -\mathbf{k_2} = \mathbf{k}$ in Eq. (5). Consequently, a few simplifications occur at once in that equation, i.e., $\mathbf{k_1} - \mathbf{k_2} = 2\mathbf{k}$ and $\mathbf{k_1} + \mathbf{k_2} \equiv 0$.

Another essential assumption is underlying the above result. The solution in Eq. (5) follows when an instantaneous process is considered for the particles' emission. We adopt throughout the paper $\hbar = c = 1$. In the case of instantaneous emission, the time factor is given by

$$|e^{-i(E_1+E_2)\tau_0}|^2 = 1, \tag{6}$$

which results from the Fourier transform of an emission distribution described by a δ function. Nevertheless, it is not expected that it this corresponds to a realistic situation. An emission lasting for a finite time interval seems more appropriate. Naturally, *a priori* it is not known which functional form better describes the particle emission process. In what follows, we consider two other types of distribution. One of them is a Lorentzian form,

$$|F(\Delta t)|^2 = [1 + (\omega_1 + \omega_2)^2 \Delta t^2]^{-1}, \tag{7}$$

where $\omega_i = \sqrt{\mathbf{k}^2_i + m^2}$. The Lorentzian emission distribution in Eq. (7) was suggested in Ref. [3] and adopted in previous studies [4,7,8,11–16]. Either of the factors in Eq. (6) or (7) should multiply the second term in Eq. (5). As discussed in Ref. [3], in the adiabatic limit, $\Delta t \to \infty$, the time factor in

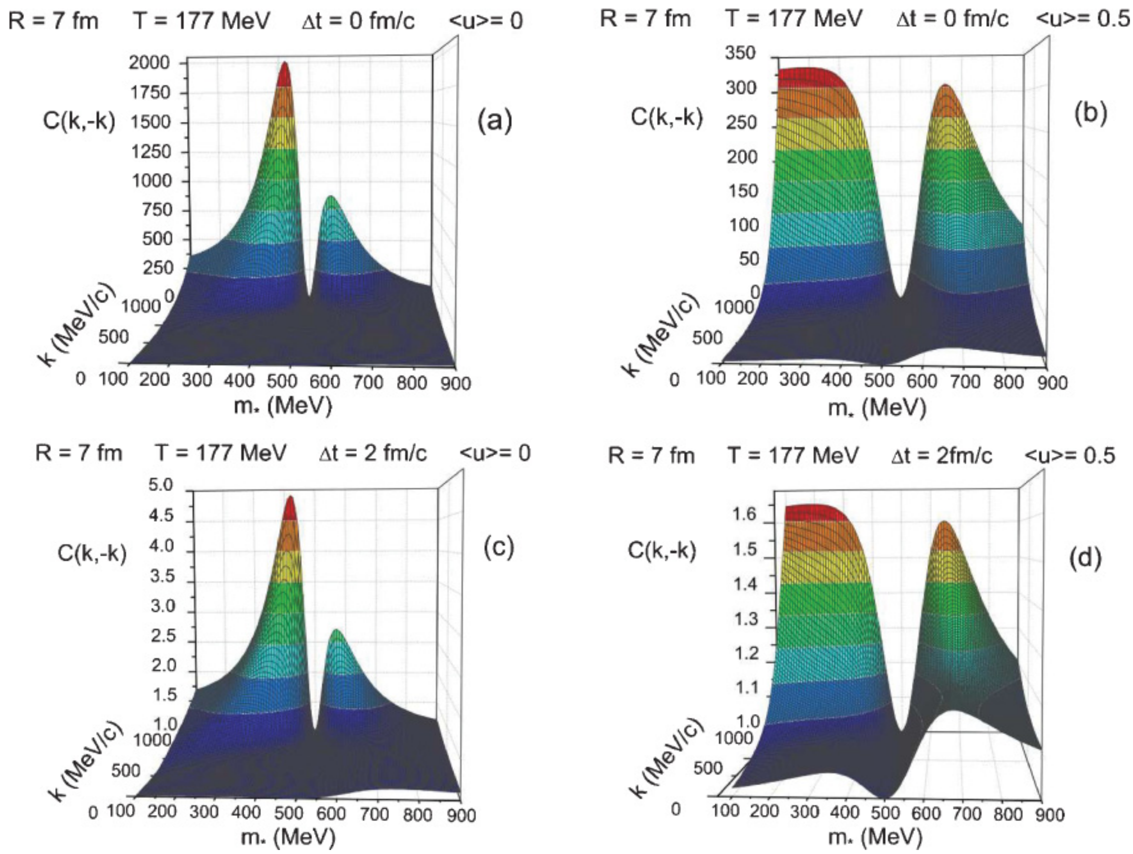

FIG. 2. (Color online) $C(\mathbf{k}, -\mathbf{k}) \times m_* \times |\mathbf{k}|$ comparing the instantaneous and the Lorentzian distributions for both the static case, $\langle u \rangle = 0$, and for an expanding system with radial flow parameter $\langle u \rangle = 0.5$.

Eq. (7) completely suppresses the back-to-back correlation (BBC). On the contrary, in the instantaneous approximation, either from Eq. (6) or in the limit $\Delta t \to 0$ of Eq. (7), the result returns to the form written in Eq. (5), fully preserving the strength of the BBC.

The third type of particle emission that we consider here is a symmetric, α-stable Lévy distribution, i.e.,

$$|F(\Delta t)|^2 = \exp\{-[\Delta t(\omega_1 + \omega_2)]^\alpha\}. \tag{8}$$

This functional form was used in the analysis made by the PHENIX Collaboration [18] to fit two- and three-particle Bose-Einstein correlation functions. According to that analysis, depending on the region investigated of the particles' transverse momentum or transverse mass, a good confidence level was obtained in the fit for different values of α. They found $\alpha \sim 1$ for $0.2 < m_T < 0.3$ GeV or $\alpha = 1.35$ for $0.2 < p_T < 2.0$ GeV$/c$. Therefore, we investigate here the time emission factor of Eq. (8) for these two values of the distribution index, α. The Lévy distribution in Eq. (8) should also multiply the second term in Eq. (5). We will see in what follows that the reduction effect of this distribution on the squeezed correlation function is even more dramatic than the effect of the Lorentzian in Eq. (7).

We show in Fig. 2 results comparing the time emission distributions of Eqs. (6) and (7). The freeze-out temperature ($T = 177$ MeV) and radial flow ($\langle u \rangle \approx 0.5$) parameters were suggested by experimental fits of kaon data obtained by the PHENIX experiment [19].

Comparing parts (a) and (b) in the top panel of Fig. 2 with parts (c) and (d) in the bottom, we see that the strength of the BBC, $C(\mathbf{k}, -\mathbf{k}) \times m_* \times |\mathbf{k}|$, decreases almost three orders of magnitude due the Lorentzian time factor, as compared to the instantaneous emission. However, the resulting signal is still strong enough to allow for its experimental search. Another interesting outcome of the calculation is shown in the left panel in Fig. 2 [(a) and (c)] as compared to the right panel [(b) and (d)]. In this case, we see the effect of the expansion of the system on the squeezed correlation function. The growth of the squeezed correlation for increasing values of $|\mathbf{k}|$ is faster in the static case as compared to when $\langle u \rangle = 0.5$, especially at high values of $|\mathbf{k}|$. Nevertheless, the presence of flow seems to enhance the intensity of $Cs(\mathbf{k}, -\mathbf{k}, m_*)$ in the whole region of the $(m_*, |\mathbf{k}|)$ plane investigated, mainly in the lower $|\mathbf{k}|$ region. Naturally, at $m_* = m_{K^\pm} \sim 494$ MeV, the squeezing disappears, i.e., $C_s(\mathbf{k}, -\mathbf{k}, m_* = m_{K^\pm}) \equiv 1$.

In the case of the Lévy distribution, the essential features of finite emission interval as compared to the sudden freeze-out are similar to the ones discussed with regard to Fig. 2. The same is valid when comparing expanding systems with the static case, for which $\langle u \rangle = 0$. Therefore, we show only results for $\langle u \rangle = 0.5$ in Fig. 3. We compare $C(\mathbf{k}, -\mathbf{k}) \times m_* \times |\mathbf{k}|$ for $\alpha = 1$ and $\alpha = 1.35$, considering that the duration of the emission could last either $\Delta t = 1$ fm$/c$ or $\Delta t = 2$ fm$/c$. We

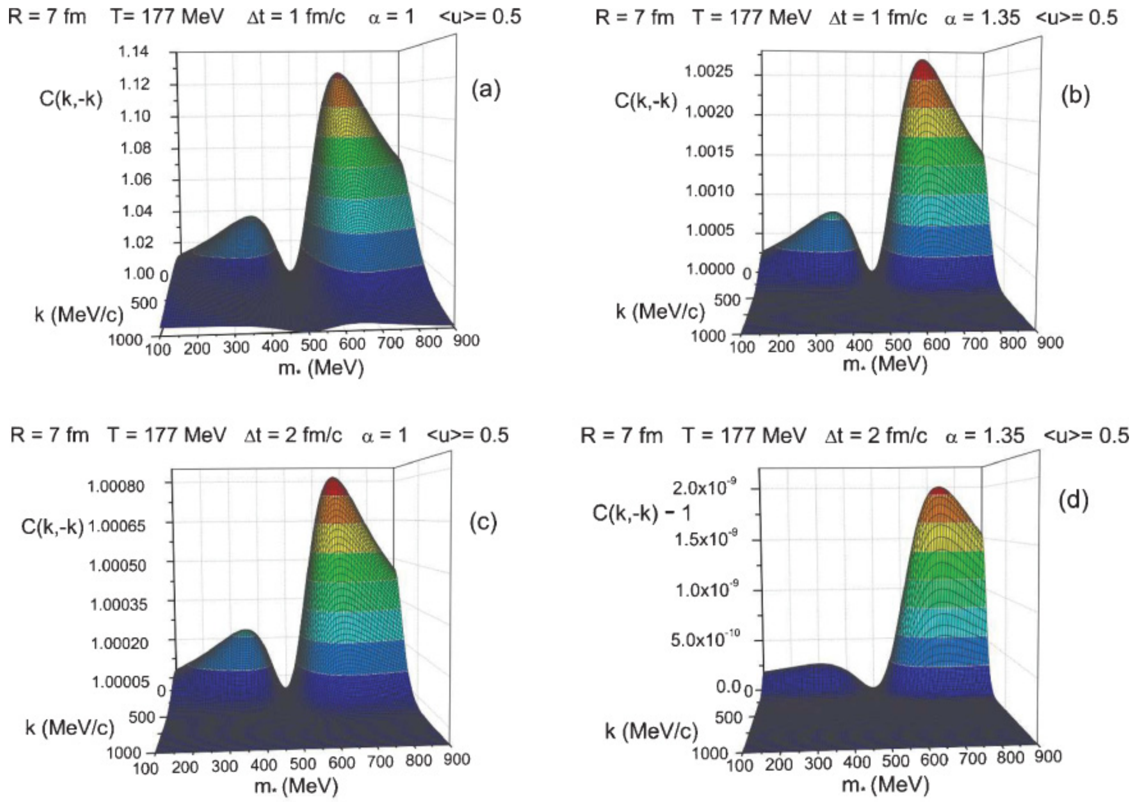

FIG. 3. (Color online) $C(\mathbf{k}, -\mathbf{k}) \times m_* \times |\mathbf{k}|$ for the symmetric, α-stable Lévy distribution with parameters $\alpha = 1.0$ and $\alpha = 1.35$.

see that, even for a short-lived system, with $\Delta t = 1$ fm/c and $\alpha = 1$, the reduction of the squeezed correlation intensity due to the Lévy distribution is even more dramatic than that due to the Lorentzian time emission. For $\alpha = 1.35$, that strength is driven to values probably unmeasurable in a first tentative search. For $\Delta t = 2$ fm/c, the situation is considerably worse, even if $\alpha = 1$. Finally, combining $\Delta t = 2$ fm/c with $\alpha = 1.35$ reduced the signal basically to unity, the first nonzero decimal digit being too small for the precision of the axis scale, if we tried to plot $C(\mathbf{k}, -\mathbf{k})$ as in the other parts of Fig. 3. That is why in Fig. 3(a) we plot $C(\mathbf{k}, -\mathbf{k}) - 1$. We see that the resulting squeezed correlation function acquires values too small to be measured by this method. Therefore, if nature favors the Lévy distribution and if the emission lasts a short period, i.e., $\Delta t = 1$ fm/c, then the predicted strength of $C(\mathbf{k}, -\mathbf{k}) \times m_* \times |\mathbf{k}|$ from Fig. 3 makes it still possible to search for the signal, if $\alpha = 1$. However, if $\alpha = 1.35$, even if the emission lasts for this short period, it would basically wash the effect out. For illustrating the procedure to search for the BBC's, and supposing that nature is kind enough to let us envisage the squeezing effect also for hadron-antihadron pairs, we restrict our discussion, from now on, to the Lorentzian type of distribution.

The properties shown in Figs. 2 and 3 were important for understanding the expected behavior of the squeezed correlation function for different values of the shifted mass, m_*, and back-to-back momenta of the pair, $\mathbf{k_1} = -\mathbf{k_2} = \mathbf{k}$. This approach, however, focuses the study on the behavior of the maximum value of $C_s(\mathbf{k}, -\mathbf{k}, m_*)$. In other words, if we make an analogy to the HBT effect between identical particles, this corresponds to investigate the behavior of the correlation function's intercept. Nevertheless, it is not efficient for the purpose of searching for the BBC experimentally, since the modified mass of particles is not an observable quantity, existing only inside the hot and dense medium. Besides, the measurement of particle-antiparticle pairs with exactly back-to-back momenta has zero probability of happening in practice. It would be more realistic to look for distinct values of the momenta of the particles, $\mathbf{k}_1$ and $\mathbf{k}_2$, and combine in an appropriate manner. Therefore, following previous knowledge of identical particle correlations (HBT), the first natural tentative method would be to measure the squeezed correlation function in terms of the momenta of the particles combined as their average, $\mathbf{K}_{12} = \frac{1}{2}(\mathbf{k}_1 + \mathbf{k}_2)$, and their relative momenta, $\mathbf{q}_{12} = (\mathbf{k}_1 - \mathbf{k}_2)$ [12–15]. However, this proposition considers nonrelativistic momenta and therefore has its application constrained to this limit. For a relativistic treatment, Nagy [12] proposed to construct a momentum variable defined as $Q^{\mu}_{back} = (\omega_1 - \omega_2, \mathbf{k}_1 + \mathbf{k}_2) = (q^0, 2\mathbf{K})$. In fact, it is preferable to redefine this variable as $Q^2_{bbc} = -(Q^{\mu}_{back})^2 = 4(\omega_1\omega_2 - K^{\mu}K_{\mu})$, whose nonrelativistic limit is $Q^2_{bbc} \to (2\mathbf{K}_{12})^2$, returning to the average momentum variable proposed above. Although not invariant, the advantage of constructing Q^2_{bbc} as indicated is that the squeezed correlation function would have its maximum around the zero of this variable, keeping a close analogy to the HBT procedures and to its nonrelativistic counterpart. In the remainder of this paper, we attain our study to the nonrelativistic limit, where the

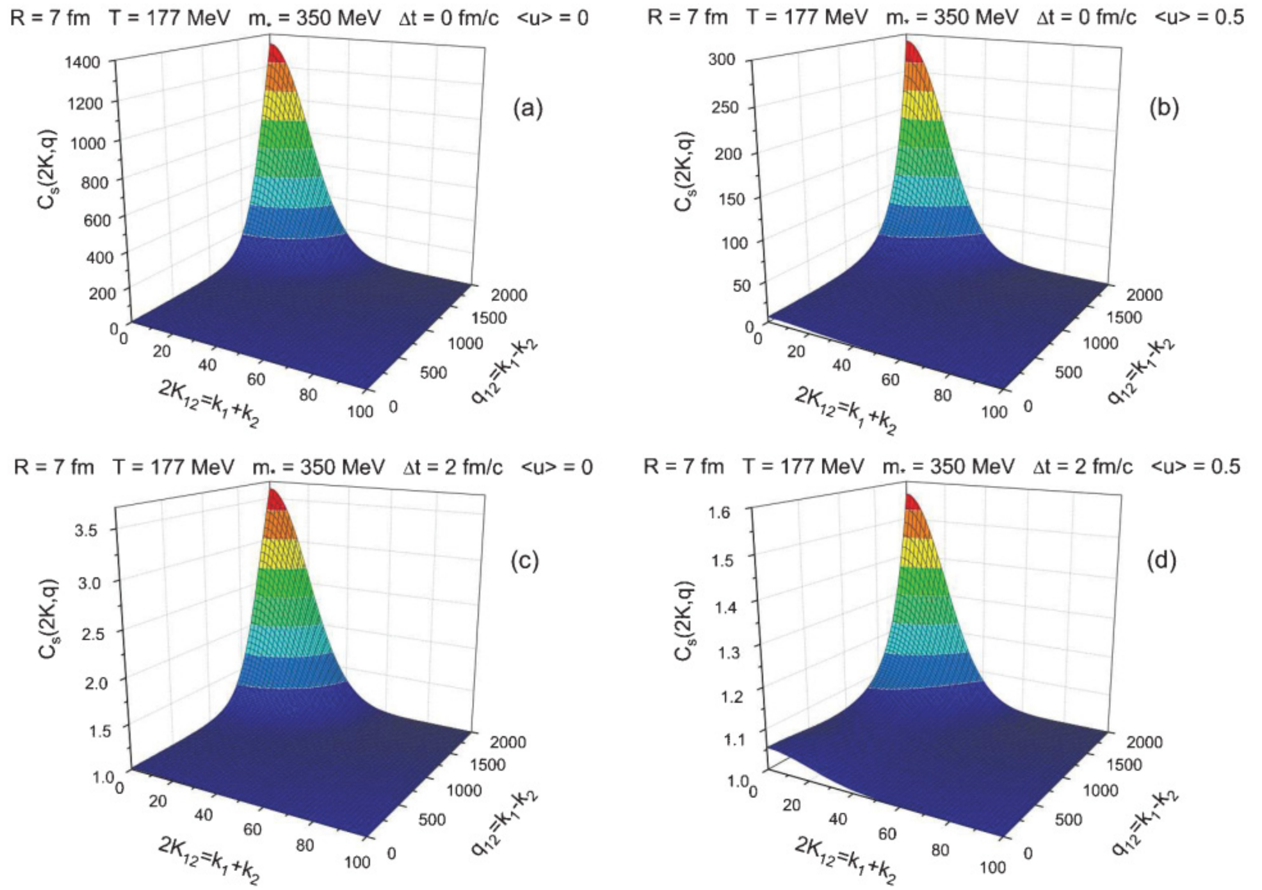

FIG. 4. (Color online) Behavior of the squeezed correlation function in the ($\mathbf{K}_{12}$, $\mathbf{q}_{12}$) plane, fixing the modified mass to $m_* = 350$ MeV.

analytical results of the model under discussion, written in Eq. (5) and related ones, are safely applicable.

The analogy with the HBT method is not completely transferred to the study of the BBC effect. In HBT experimental analyses a common practice is to replace the product of the two spectra by mixed events, since these are the reference sample not containing statistically correlated pairs. However, we see that the second line in Eq. (5), representing the product of the particle and the antiparticle spectra in BBC, does contain the squeezing factor $f_{i,j}$ as well. Therefore, the mixed events technique would not be an appropriate reference sample in constructing the BBC correlation function.

Once defined the choice of plotting variables as $\mathbf{K}_{12}$ and $\mathbf{q}_{12}$, we can proceed to study the squeezed correlation function. For emphasizing the characteristics to be searched for, we focus the study to values of the shifted mass corresponding to the two maxima located more or less symmetrically below and above the kaon asymptotic mass, $m = m_{K^\pm} \sim 494$ MeV. They correspond to $m_* = 350$ MeV and $m_* = 650$ MeV, respectively. We then calculate the squeezed correlation for K^+K^- pairs using Eq. (5). From it, it is easily envisaged that we should replace $\mathbf{k_1} + \mathbf{k_2} = 2\mathbf{K}_{12}$ and $\mathbf{k}_1 - \mathbf{k}_2 = \mathbf{q}_{12}$ in the numerator, at the same time as replacing $\mathbf{k}_1 = \mathbf{K}_{12} + \mathbf{q}_{12}/2$ and $\mathbf{k}_2 = \mathbf{K}_{12} - \mathbf{q}_{12}/2$ in the denominator. The result of this calculation is shown in Figs. 4 and 5. In both cases we can observe similar behavior of the squeezed correlation functions. The difference resides mainly in the low q_{12} region, where $C_s(\mathbf{K}_{12}, \mathbf{q}_{12}, m_*)$ reaches much higher intensities for $m_* = 650$ MeV than for $m_* = 350$, including for its intercept at $K_{12} = 0$. In both cases we see that the presence of flow enhances the strength of $C_s(\mathbf{K}_{12}, \mathbf{q}_{12}, m_*)$, potentially facilitating its detection in an experimental search of the effect.

In all the investigation and results discussed above, the mass-shifting was considered homogeneously distributed over the entire squeezing region, whose size was fixed to $R = 7$ fm, the radius of the cross-sectional area depicted in Fig. 1. The squeezed correlation function is actually sensitive to that size. In fact, this is reflected in its inverse width of the squeezed correlation functions plotted in terms of the average momentum, $2K_{12}$. In Ref. [15] we illustrate this sensitivity by considering two values for the radii, $R = 7$ fm and $R = 3$ fm. The resulting squeezed correlation function is shown to be broader for smaller systems than for larger ones.

III. RESULTS FOR $K^\pm K^\pm$ PAIRS

Next, we discuss our findings about the effects of in-medium mass-shift and resulting squeezing on the HBT correlation function of $K^\pm K^\pm$ pairs. Usual expectations were that thermalization would wash out any trace of mass-shift in these type of correlations. However, as it was demonstrated

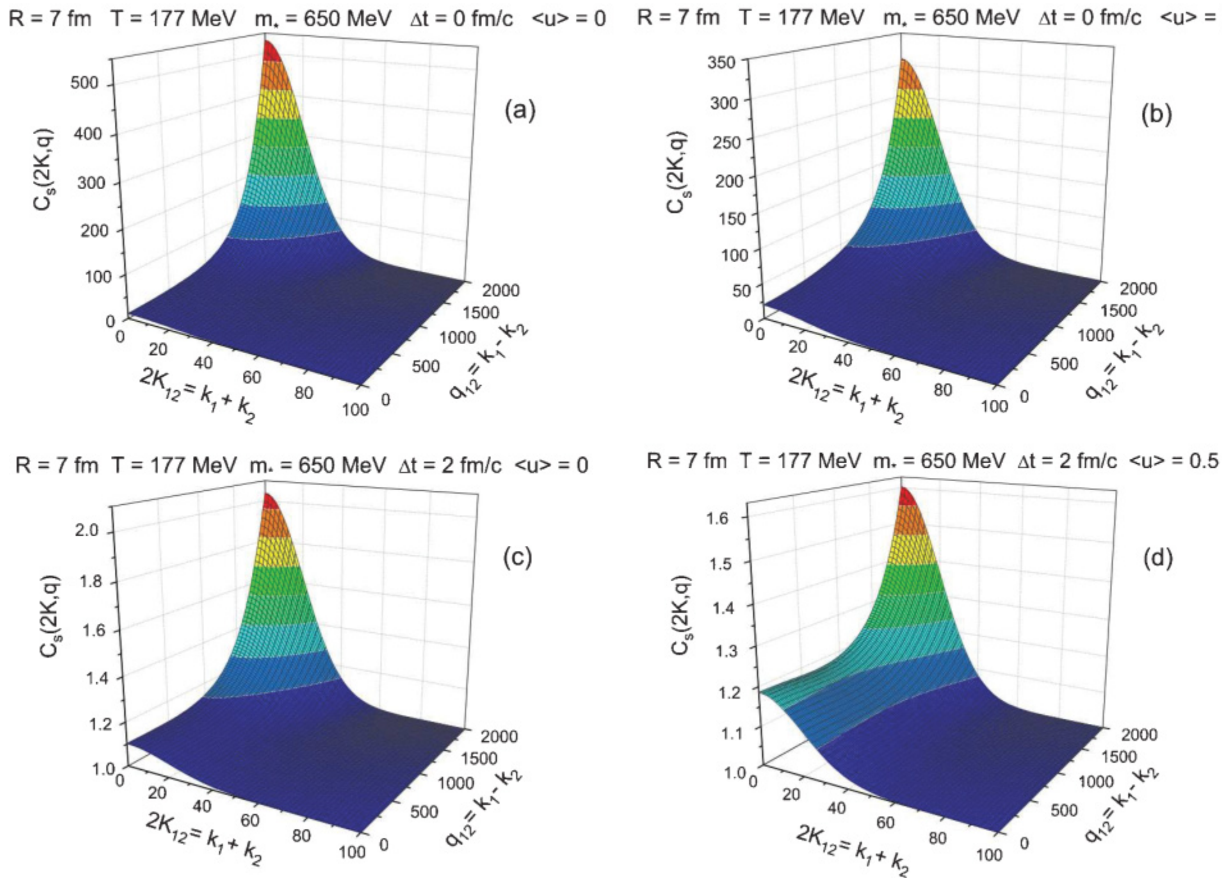

FIG. 5. (Color online) Behavior of the squeezed correlation function in the $(\mathbf{K}_{12}, \mathbf{q}_{12})$ plane, fixing the modified mass to $m_* = 650$ MeV.

analytically in Refs. [3,4], the HBT correlation function also depends on the squeezing parameter, $f_{i,j}(m, m_*)$.

In fact, this identical particle correlation is obtained by inputting in Eq. (1) the chaotic amplitude,

$$G_c(\mathbf{k}_1, \mathbf{k}_2) = \frac{E_1 + E_2}{2(2\pi)^{\frac{3}{2}}} \Bigg\{ |s_0|^2 R^3 e^{-\frac{1}{2}R^2 \mathbf{q}_{12}^2} + n_0^* R_*^3 (|c_0|^2 + |s_0|^2) \times \exp\left(-\frac{\mathbf{K}_{12}^2}{2m_* T_*}\right) \exp\left[-\left(\frac{R_*^2}{2} + \frac{\mathbf{1}}{8m_* T}\right)\mathbf{q}_{12}^2\right] \times \exp\left[-\frac{im\langle u\rangle R}{m_* T_*}\mathbf{K}_{12}.\mathbf{q}_{12}\right]\Bigg\}, \quad (9)$$

as well as the expression for the spectrum of each particle, $G_c(k_i, k_i) = \frac{E_i}{(2\pi)^{\frac{3}{2}}}\{|s_0|^2 R^3 + n_0^* R_*^3 (|c_0|^2 + |s_0|^2) \exp(-\frac{k_i^2}{2m_* T_*})\}$. Since it involves the identical kaons in this case, the third term in Eq. (1) gives no contribution. The plots corresponding to such results are shown in Fig. 6, for two values of the average momentum, $|\mathbf{K_{12}}| = 0.5$ GeV/c and $|\mathbf{K_{12}}| = 2.0$ GeV/c. The plots in the top panel simply illustrate the behavior of the identical particle correlation function if no in-medium mass modification occurs. In (a) for the sudden emission hypothesis, and in (b) for emission with finite duration (with $\Delta t = 2$ fm/c). Finite emission intervals are also described by a Lorentzian distribution similar to that in Eq. (7) obtained as the Fourier transform of an exponential distribution in time, but in this case, obtained in terms of the relative energy, $q^0 = \omega_1 - \omega_2$, i.e.,

$$|F(\Delta t)|^2 = [1 + (\omega_1 - \omega_2)^2 \Delta t^2]^{-1}, \quad (10)$$

where $\omega_i = \sqrt{\mathbf{k}_i^2 + m^2}$. The factor in Eq. (10) multiplies the second term in Eq. (1).

In Fig. 6(a), with $\Delta t = 0$, no sensitivity to the two values of $|\mathbf{K_{12}}|$ is seen, only the effect of flow is evident. In the absence of mass-shift and squeezing, the flow broadens the curves, as expected, since it is well-known that the expansion reduces the size of the region accessible to interferometry. In part (b), we see that a finite duration of the emission separates the curves for each value of $|\mathbf{K_{12}}|$, both in presence and in absence of flow. This effect is also well known, and comes from the coupling of the average momentum of the pair to the emission duration, Δt. Therefore, when there is no mass-shift and no squeezing, the relations describe correctly the expansion effects on the identical particle correlation function.

When squeezing is present, the flow broadening is seen in Fig. 6(c) for $|\mathbf{K_{12}}| = 0.5$ GeV/c, but apparently disappears for $|\mathbf{K_{12}}| = 2.0$ GeV/c. Therefore, it seems that the squeezing effects tend to oppose those of flow, practically canceling the broadening of the correlation function due to flow for large $|\mathbf{K}_{12}|$. Part (d) essentially repeats what is seen in (c), except for devising a modest effect related to the finite duration of the emission, which slightly separates the curves corresponding to the two values of $|\mathbf{K_{12}}|$, when $\langle u\rangle = 0$.

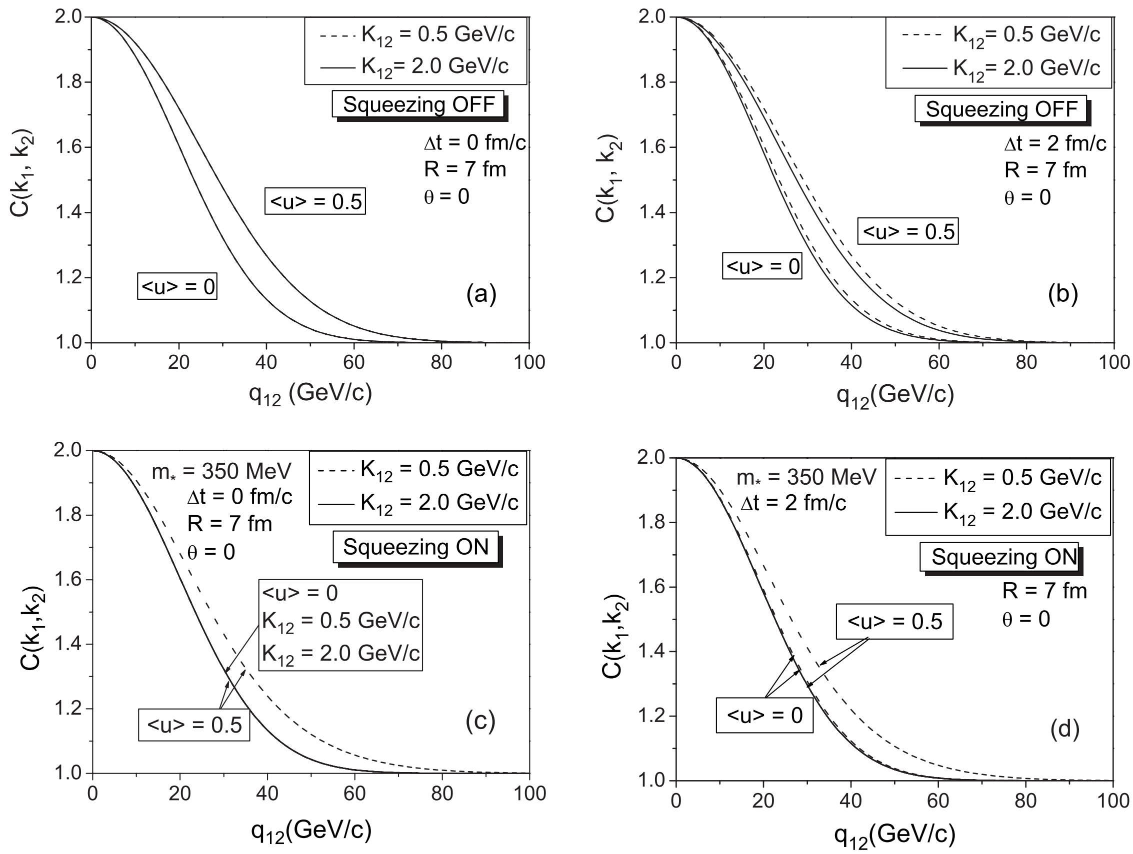

FIG. 6. Identical particle correlation functions for two values of $|\mathbf{K}_{12}|$, both for sudden emission ($\Delta t = 0$) and for a Lorentzian distribution in time, from Eq. (10), with $\Delta t = 2$ fm/c. (a) and (b) show results in the absence of in-medium mass modification. (c) and (d) consider a shifted mass of $m_* = 350\,\mathrm{MeV}$.

We remark that we did not include the Coulomb final state interactions in the above analysis. In the case of K^+K^- pairs, even the Gamow factor which overpredicts the strength of the effect for finite distances would be very small. In general, the effect of the Coulomb interactions is more pronounced for small values of $|\mathbf{q}_{12}|$, which corresponds to the region where the hadron-antihadron squeezing correlation is less favored, therefore being less significant to this analysis. Also in the case of $K^\pm K^\pm$ pairs, the squeezing affects the width of the HBT correlation function and, since the Coulomb effect is mostly concentrated in the region where $|\mathbf{q}_{12}|$ is small [17], it is not expected to be relevant in this context.

IV. SUMMARY AND CONCLUSIONS

In this work we discuss an effective way to search for K^+K^- squeezed correlations in heavy ion collisions, currently at RHIC, and soon at the LHC. We use suitable variables introduced previously [8,10–15] to investigate the expected behavior of the squeezed correlation function in an experimental search of the effect. This is studied by plotting $C_s(\mathbf{K}_{12}, \mathbf{q}_{12}, m_*)$ in terms of the average momentum of the pair, $2|\mathbf{K}_{12}|$, and its relative momentum, $|\mathbf{q}_{12}|$. These variables are combinations of the momenta of the particle and the antiparticle of each pair, and $2|\mathbf{K}_{12}|$, is the nonrelativistic limit of $Q^2_{bbc} = 4(\omega_1\omega_2 - K^\mu K_\mu)$, as discussed previously [12].

We started by investigating the general behavior of $C_s(\mathbf{k}, -\mathbf{k}, m_*)$ for exactly back-to-back K^+K^- pairs, as a function of both $|\mathbf{k}|$ and the in-medium shifted mass, m_*. This was showing in Fig. 2 comparing the cases of sudden particle emission and a finite emission interval described by a Lorentzian distribution. A Lévy distribution was also studied, with results shown in Fig. 3. We could see the striking reduction effect of finite emission intervals, even for the Lorentzian distribution. The Lévy type causes an even more dramatic suppression of the effect. If this distribution is the one favored by nature, the hadronic squeezed correlation function could still be searched for, if the duration of the emission process is short, not longer than $\Delta t \simeq 1$ fm/c. For longer emission time intervals, such suppression would probably destroy the effect.

For illustrating the procedure to be followed in the experimental search of the hadronic squeezing effect, we suppose that the emission could be considered either sudden or following a Lorentzian distribution. We then analyze the behavior of the particle-antiparticle correlation function, $C_s(\mathbf{K}_{12}, \mathbf{q}_{12}, m_*)$, in the $(\mathbf{K}_{12}, \mathbf{q}_{12})$ plane. We find that, in the presence of flow, the signal is expected to be stronger over the momentum regions shown in the plots, i.e., roughly for $0 \leqslant 2|\mathbf{K}| \leqslant$ 60–150 MeV/c (depending on the size of the squeezing region) and $500 \leqslant |\mathbf{q}| \leqslant 2000$ MeV/c, suggesting that flow may enhance the probability of observing the squeezing effect.

Another important point discovered within this simplified model and in the nonrelativistic limit considered here is that the squeezing could distort the HBT correlation function as well. It tends to oppose to the effects of flow on those curves, practically neutralizing them for large values of $|\mathbf{K}_{12}|$.

Finally, it is worth emphasizing that the results shown here correspond to the signals of the squeezing expected if the particles have their mass shifted in the hot and dense medium formed in high energy collisions. If the particle's properties, such as its mass, are not modified in the medium, the squeezed correlation functions would be unity for all values of $2|\mathbf{K}|$, and therefore, no signal would be observed. It that is the case, then the HBT correlation functions would behave as usual, both in the presence or absence of flow. However, if the particles' masses are indeed shifted in-medium, the experimental discovery of squeezed particle-antiparticle correlation (and the distortions pointed out in the HBT correlations) would be an unequivocal signature of these modifications, by means of hadronic probes. The values of the modified mass, m_*, adopted here for illustrating the squeezing effects for K^+K^- pairs, correspond approximately to the maximum values shown in Fig. 2. However, if the modified mass turns to be shifted away from the maximum values considered in the above calculations, $C_s(2\mathbf{K}_{12}, \mathbf{q}_{12})$ would attain smaller intensities than the ones shown, but the signal could still be high enough to be observed experimentally. The squeezed correlations are very sensitive to the form of the emission distribution in time, as shown above. Instant emissions would fully preserve the signal. Lorentzian time distributions would drastically reduce it and Lévy-type distributions would attenuate it more dramatically or even make the searched signal unmeasurable. Another important point that needs emphasis is that the squeezed correlation function should be plotted in the $(\mathbf{K}_{12}, \mathbf{q}_{12})$ plane. If plotted as function of $\mathbf{K}_{12}$ only, this means that all the variations in each bin of $\mathbf{q}_{12}$ are averaged out, as they are projected in the $\mathbf{K}_{12}$ axis. This could enlarge the error bars and decrease the signal substantially, depending on the region of $\mathbf{q}_{12}$ selected for the plot. Therefore, the experimental search for the squeezed hadronic correlations should aim at good statistics of the events for enhancing the chances of its discovery.

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