

Thermal modification of $K_1(1270) \rightarrow \pi^+\pi^-K^+$ in a hot hadronic medium

Seung-il Nam *

Department of Physics, *Pukyong National University (PKNU)*, Busan 48513, Korea
and *Asia Pacific Center for Theoretical Physics (APCTP)*, Pohang 37673, Korea



(Received 30 March 2026; revised 8 June 2026; accepted 26 June 2026; published 28 July 2026)

The thermal modification of the exclusive decay $K_1^+(1270) \rightarrow \pi^+\pi^-K^+$ in a hot hadronic medium is studied. The decay amplitude is constructed from effective hadronic interactions dominated by the ρ - and K^* -pole contributions, thereby enabling a Dalitz-level analysis of the three-body decay in the medium. Thermal effects associated with partial chiral-symmetry restoration are incorporated through a phenomenological interpolation toward vector–axial-vector degeneracy near the chiral crossover. As the temperature increases, the reduction of the parent K_1 mass strongly compresses the available three-body phase space, leading to substantial deformation of the Dalitz distribution and invariant-mass spectra, as well as to a pronounced suppression of $\Gamma_{K_1 \rightarrow \pi^+\pi^-K^+}(T)$. As a further step toward future transport-based phenomenological comparisons, Normalized shape observables are introduced to quantify the thermal evolution of the K^* -dominated πK region, the upper-edge weight of the $\pi\pi$ spectrum, and the compactification of the Dalitz population. The dominant effect identified in the present framework is therefore kinematic: thermal phase-space reduction in the strange axial-vector channel. These results suggest that the exclusive $K_1(1270)$ channel may provide a useful qualitative probe of in-medium strange axial-vector dynamics near the pseudocritical region.

DOI: [10.1103/psq7-hxsj](https://doi.org/10.1103/psq7-hxsj)

I. INTRODUCTION

Understanding how hadronic properties are modified in hot and dense QCD matter is a central goal of contemporary heavy-ion physics. Short-lived resonances are especially useful in this context because their observable yields and line shapes can be altered by in-medium decay, rescattering of decay products, and regeneration before kinetic freeze-out [1–3]. Resonance measurements, therefore, provide sensitive probes of the late hadronic stage of relativistic nucleus-nucleus collisions and of the interplay between hadronization and subsequent hadronic evolution.

Experimentally, this sensitivity is illustrated by the suppression of short-lived resonances relative to longer-lived hadrons in central heavy-ion collisions. A representative example is the reduction of the $K^*(892)^0/K$ ratio with respect to the proton-proton baseline, commonly interpreted as evidence that hadronic rescattering reduces the reconstructable resonance signal [2,3]. Similar suppression patterns observed for other short-lived states, such as $\Lambda(1520)$, further support the view that resonance yields reflect the lifetime and dynamical properties of the hadronic stage between chemical and kinetic freeze-out [4–7].

From the theoretical side, medium modifications of hadrons are closely related to the restoration of chiral symmetry. Since spontaneous chiral-symmetry breaking is a fundamental nonperturbative feature of low-energy QCD, its partial restoration at finite temperature is expected to induce substantial changes in hadronic spectral properties. The vector and axial-vector channels are of particular interest because chiral restoration implies that the corresponding chiral partners should tend toward degeneracy near the pseudocritical temperature [1,8,9]. This idea has been widely explored in studies of spectral functions, dilepton production, and in-medium resonance properties, where the thermal evolution of vector and axial-vector mesons serves as an important indicator of changing chiral dynamics [1]. In this context, the enhancement of the K_1/K^* ratio in heavy-ion collisions has also been proposed as a possible signature of hot-medium effects and chiral dynamics [10,11].

The use of the K_1 - K^* chiral-partner system as a probe of chiral-symmetry restoration in hot and/or dense matter was pioneered in Refs. [12–14]. These works emphasized that the approach toward vector–axial-vector degeneracy in the strange sector may be reflected in the in-medium behavior of the K_1/K^* ratio and related spectral observables. The present study should be viewed as complementary to those pioneering works. Instead of addressing the inclusive K_1/K^* yield ratio, the exclusive decay $K_1(1270)^+ \rightarrow \pi^+\pi^-K^+$ is considered, with particular attention to how an assumed thermal reduction of the K_1 - K^* mass splitting modifies the Dalitz distribution, daughter invariant-mass spectra, and partial decay width.

Against this background, the strange axial-vector meson $K_1(1270)$ is particularly interesting. As a strange member of the axial-vector sector, it provides a complementary

*Contact author: sinam@pknu.ac.kr

perspective on in-medium chiral dynamics beyond the non-strange channels. Its dominant hadronic decays proceed through vector-meson intermediate states, making it sensitive to both the thermal evolution of the strange sector and the available hadronic phase space. At the same time, the physical $K_1(1270)$ state is closely related to the well-known $K_1(1270)$ - $K_1(1400)$ mixing problem, which has been studied in a variety of phenomenological and QCD-based approaches [15,16]. These features make the $K_1(1270)$ meson a potentially useful, although still relatively unexplored, probe of hot hadronic matter.

In this work, the three-body decay process $K_1^+(1270) \rightarrow \pi^+\pi^-K^+$ in a hot hadronic medium is investigated. The decay amplitude is first constructed in vacuum within an effective hadronic framework that includes the dominant ρ - and K^* -pole contributions. Thermal modifications of the relevant vector and axial-vector mesons are then introduced through a phenomenological parametrization inspired by the Weinberg sum rules, such that the chiral-partner pairs (ρ, a_1) and (K^*, K_1) gradually approach degeneracy as the temperature increases. Within this framework, modifications to the Dalitz structure, invariant-mass distributions, and the total three-body decay width in the medium are examined.

Since chemical freeze-out occurs near the QCD crossover region, medium-induced modifications of the parent axial-vector state may leave characteristic traces in exclusive hadronic decay channels before the system reaches kinetic freeze-out [17,18]. The temperature dependence of the K_1 decay width is therefore relevant for understanding how the strange axial-vector channel responds to the hot hadronic environment created in relativistic nucleus-nucleus collisions.

Most previous discussions have focused either on inclusive resonance-yield ratios, such as K_1/K^* , or on global in-medium properties of vector and axial-vector mesons. In contrast, the exclusive decay $K_1(1270)^+ \rightarrow \pi^+\pi^-K^+$ is treated as a decay-level diagnostic quantity, and its temperature dependence is examined through the Dalitz distribution and daughter invariant-mass spectra. A qualification is necessary concerning the interpretation of this temperature dependence. The hadronic final state $\pi^+\pi^-K^+$ is experimentally reconstructed after the late hadronic stage, and the observed distribution is therefore expected to reflect conditions near kinetic freeze-out rather than provide a direct measurement of the decay at an arbitrary temperature inside the fireball.

Therefore, the quantities calculated in this work should not be interpreted as direct heavy-ion observables at fixed T . They should instead be regarded as theoretical diagnostic quantities that indicate how the exclusive Dalitz structure would respond if the effective strange axial-vector mass at the time of hadronic decoupling were modified. Since the kinetic freeze-out temperature can depend on collision system and centrality, as emphasized in studies of the K_1/K^* ratio [11], a temperature scan provides a useful way to characterize the sensitivity of the exclusive channel to different late-stage freeze-out conditions. In this sense, the temperature T in the present calculation should be understood not

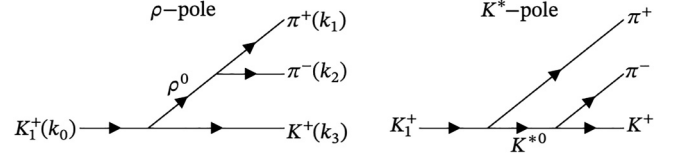


FIG. 1. Relevant Feynman diagrams for the decay $K_1^+ \rightarrow \pi^+\pi^-K^+$, namely, the ρ - and K^* -pole contributions. The four-momentum assignments are also indicated.

as the instantaneous fireball temperature at which the decay occurs, but as a proxy for the effective strange axial-vector mass scale at the moment of hadronic decoupling, which may vary across different collision systems and centrality classes.

The present framework is intentionally exploratory. It is not designed to provide a quantitative description of experimentally reconstructed K_1 yields in heavy-ion collisions because it does not account for regeneration, daughter-particle rescattering, coupled-channel dynamics, detector acceptance, and combinatorial backgrounds. Instead, the objective is to identify robust qualitative signatures of thermal phase-space suppression in the exclusive channel $K_1(1270)^+ \rightarrow \pi^+\pi^-K^+$. This paper is organized as follows: Section II formulates the decay in vacuum, introduces the temperature-dependent meson properties, and defines the shape observables. Section III presents numerical results for the Dalitz plots, invariant-mass spectra, thermal decay width, and related quantities, together with a detailed discussion. Section IV provides the summary and outlook.

II. THEORETICAL FRAMEWORK

A. $K_1^+ \rightarrow \pi^+\pi^-K^+$ decay

In this section, the vacuum decay $K_1^+(1270) \rightarrow \pi^+\pi^-K^+$ is formulated as the baseline for the finite-temperature analysis presented below. The dominant contributions are assumed to arise from the two resonant processes shown in Fig. 1, namely, the ρ -pole and K^* -pole channels. These correspond to the sequential decays $K_1^+ \rightarrow \rho K^+$ followed by $\rho \rightarrow \pi^+\pi^-$, and $K_1^+ \rightarrow K^*\pi$ followed by $K^* \rightarrow K\pi$, respectively. The decay amplitude is described in an effective hadronic framework that incorporates axial-vector, vector, and pseudoscalar meson degrees of freedom.

The relevant interaction vertices are introduced through the effective Lagrangians

$$\begin{aligned}\mathcal{L}_{VPP} &= ig_{VPP} V^\mu (P \partial_\mu P^\dagger - P^\dagger \partial_\mu P) + \text{H.c.}, \\ \mathcal{L}_{AVP} &= ig_{AVP} A^\mu V_\mu P + \text{H.c.},\end{aligned}\quad (1)$$

where A , V , and P denote the axial-vector, vector, and pseudoscalar meson fields, respectively. The interaction $\mathcal{L}_{VPP}$ generates the $\rho\pi\pi$ and $K^*K\pi$ vertices, while $\mathcal{L}_{AVP}$ describes the $K_1\rho K$ and $K_1K^*\pi$ transitions. Because of the derivative structure of $\mathcal{L}_{VPP}$, the resulting amplitudes depend on momentum differences of the outgoing pseudoscalar mesons, as expected for intermediate spin-1 states.

Using Eq. (1), one obtains the invariant amplitudes for the ρ - and K^* -pole diagrams in Fig. 1 as

$$i\mathcal{M}_\rho = \frac{g_{K\rho K_1} g_{\pi\pi\rho} (\epsilon \cdot q_{1-2})}{q_{1+2}^2 - M_\rho^2 + i\Gamma_\rho M_\rho},$$

$$i\mathcal{M}_{K^*} = \frac{g_{\pi K^* K_1} g_{\pi K K^*} [\epsilon \cdot q_{2-3} - (\frac{M_\pi^2 - M_{K^*}^2}{M_{K^*}^2}) \epsilon \cdot q_{2+3}]}{q_{2+3}^2 - M_{K^*}^2 + i\Gamma_{K^*} M_{K^*}}, \quad (2)$$

where $q_{i\pm j} \equiv k_i \pm k_j$, with k_1 , k_2 , and k_3 denoting the four-momenta of π^+ , π^- , and K^+ , respectively. The intermediate ρ meson carries $q_{1+2}^2 = (k_1 + k_2)^2 = M_{\pi^+\pi^-}^2$, whereas the intermediate K^* meson carries $q_{2+3}^2 = (k_2 + k_3)^2 = M_{\pi^-K^+}^2$. The denominators are of Breit-Wigner form and encode the finite widths of the unstable intermediate resonances.

The momentum structure in Eq. (2) follows directly from the derivative VPP interaction. In the ρ -pole channel, the $\rho \rightarrow \pi^+\pi^-$ vertex yields $(k_1 - k_2)^\mu \equiv q_{1-2}^\mu$, so that the numerator is proportional to $\epsilon \cdot q_{1-2}$. In the K^* -pole channel, the transverse part of the vector propagator gives the expected term $\epsilon \cdot q_{2-3}$, while the longitudinal projector $q_\mu q_\nu / M_{K^*}^2$ with $q = q_{2+3}$ generates the additional contribution proportional to $\epsilon \cdot q_{2+3}$. Using

$$q \cdot (k_2 - k_3) = (k_2 + k_3) \cdot (k_2 - k_3) = M_\pi^2 - M_{K^*}^2, \quad (3)$$

one obtains the mass-dependent correction appearing in the numerator of $\mathcal{M}_{K^*}$. Numerically, this term is subleading, but it is retained for completeness and preserves the covariant form of the amplitude in the unequal-mass $K\pi$ channel.

The total decay amplitude is written as the coherent sum

$$\mathcal{M}_{\rho+K^*}(\epsilon) = \mathcal{M}_\rho(\epsilon) + \mathcal{M}_{K^*}(\epsilon) + \mathcal{M}_{\text{BKG}}, \quad (4)$$

so that interference between the two resonant channels is fully accounted for. Here, $\mathcal{M}_{\text{BKG}}$ denotes a constant nonresonant background term introduced to absorb smooth contributions not explicitly described by the dominant ρ - and K^* -pole amplitudes. In the present phenomenological treatment, this term is not meant to represent a specific microscopic mechanism, but rather to parametrize residual direct three-body or broad nonresonant effects at the amplitude level. Its value will be fixed to reproduce a reasonable K_1 partial decay width in Sec. III. For completeness, the propagator of an intermediate vector meson with four-momentum q is given by

$$iD_{V\mu\nu}(q) = \frac{i}{q^2 - M_V^2 + i\Gamma_V M_V} \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{M_V^2} \right). \quad (5)$$

For the initial K_1 meson at rest, the polarization vectors are chosen as [19]

$$\epsilon_+ = \left(0, -\frac{1}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0 \right),$$

$$\epsilon_0 = (0, 0, 0, 1), \quad \epsilon_- = \left(0, \frac{1}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0 \right). \quad (6)$$

These satisfy the standard orthonormality and completeness relations for a massive spin-1 particle. In the decay-width calculation, the squared amplitude is averaged over the three spin states of the initial K_1 , which leads to the factor $1/3$ in the expression below.

The strong-coupling constants are taken from Refs. [11,20], where the physical $K_1(1270)$ and $K_1(1400)$ states were analyzed, including their mixing structure. The numerical values used here are listed in Table I. Since these couplings already encode the phenomenological effects of $K_1(1270)$ - $K_1(1400)$ mixing, I do not introduce additional mixing parameters in the present work. Our purpose is instead to examine how thermal phase-space reduction modifies the decay once a phenomenologically acceptable set of physical couplings is adopted.

To describe the three-body kinematics, the two independent invariant masses $M_{\pi^+\pi^-}^2 = (k_1 + k_2)^2$ and $M_{\pi^-K^+}^2 = (k_2 + k_3)^2$, which span the Dalitz plot, are employed. The double-differential decay width is then given by

$$\Gamma_{K_1(1270) \rightarrow \pi^+\pi^-K^+} \equiv \frac{d^2\Gamma_{K_1(1270) \rightarrow \pi^+\pi^-K^+}}{dM_{\pi^+\pi^-} dM_{\pi^-K^+}} = \frac{1}{3} \sum_{x=0,\pm 1} \frac{M_{\pi^+\pi^-} M_{\pi^-K^+}}{64\pi^3 M_{K_1}^3} |\mathcal{M}_{\rho+K^*+\text{BKG}}|^2. \quad (7)$$

This expression contains the full resonance and interference structure of the three-body decay in terms of the two Dalitz variables. The factor $M_{\pi^+\pi^-} M_{\pi^-K^+} / (64\pi^3 M_{K_1}^3)$ arises from the Lorentz-invariant three-body phase-space measure written in terms of the two independent invariant masses. Integration of Eq. (7) over the kinematically allowed Dalitz region yields the total vacuum decay width.

This vacuum formalism provides the starting point for the finite-temperature analysis. Once thermal modifications of hadron masses and widths are incorporated, the pole positions and available phase space in Eq. (2) are altered accordingly, which leads to corresponding changes in both the Dalitz distribution and the total decay width.

B. Temperature-dependent meson properties

To model thermal modifications of the vector (V) and axial-vector (A) mesons, a phenomenological framework motivated by partial chiral restoration is adopted. Qualitative guidance is provided by the first and second Weinberg sum rules,

$$\int_0^\infty ds [\rho_V(s) - \rho_A(s)] = f_\pi^2,$$

$$\int_0^\infty ds s [\rho_V(s) - \rho_A(s)] = 0, \quad (8)$$

where $\rho_V(s)$ and $\rho_A(s)$ denote the vector and axial-vector spectral functions, respectively, and f_π is the pion weak-decay constant. As the system approaches the chiral-restoration region, the difference between the vector and axial-vector channels is expected to diminish. In the present work, however, these sum rules are used only as qualitative motivation for the tendency toward vector-axial-vector degeneracy, i.e., a microscopic calculation of the in-medium spectral functions is not attempted. The present thermal setup is therefore constructed as an effective interpolation scheme designed to isolate the leading kinematic consequence of axial-vector mass reduction for the exclusive three-body decay $K_1^+ \rightarrow$

TABLE I. Relevant coupling constants and widths for $K_1(1270)$ and $K_1(1400)$ decays.

State	$g_{\pi K^* K_1}$ [GeV]	$g_{K \rho K_1}$ [GeV]	$g_{\pi K K^*}$	$g_{\pi \pi \rho}$	Γ_{K^*} [MeV]	Γ_ρ [MeV]
$K_1(1270)$	0.92	4.10	4.48	8.49	47.3	147.7
$K_1(1400)$	4.34	0.92			same as above	

$\pi^+ \pi^- K^+$. The purpose is not to provide a precise description of strange-sector spectroscopy in medium but to examine how a smooth crossover-driven approach toward vector–axial-vector degeneracy modifies the available Dalitz phase space and the resulting decay width.

A simplified description is adopted in which the pseudoscalar meson masses are kept approximately constant, $M_P(T) \approx M_P(0)$ with $P = (\pi, K)$, while the vector-meson masses and widths are also assumed to remain close to their vacuum values, $M_V(T) \approx M_V(0)$ and $\Gamma_V(T) \approx \Gamma_V(0)$. This choice reflects the expectation that, in the temperature range relevant to the present study, the dominant thermal effect arises from the axial-vector sector, whereas the pseudoscalar mesons are comparatively less sensitive to the medium. Although the kaon is not an exact Nambu-Goldstone boson and vector mesons may acquire collision-induced broadening in a realistic hadronic environment, these effects are expected to be subleading for the present purpose, namely, to isolate the leading phase-space suppression induced by the reduction of the parent axial-vector mass. Mesonic thermal properties in the Polyakov-loop-extended Nambu–Jona-Lasinio (PNJL) model were studied in Ref. [21], which exhibit a trend qualitatively consistent with the assumptions adopted here: the axial-vector channel changes more strongly than the vector channel.

To parametrize the temperature dependence of the axial-vector masses, their evolution is assumed to follow the thermal crossover profile of the constituent light-quark mass, $M_A(T) \propto M_{q=u,d}(T)$, where $M_q(T)$ denotes the effective light-quark mass at temperature T . The temperature dependence of $M_q(T)$ is determined using the two-flavor Nambu–Jona-Lasinio (NJL) model in medium. The NJL Lagrangian is given by

$$\mathcal{L}_{\text{NJL}} = \bar{q}(i\gamma^\mu \partial_\mu - m_q)q + G[(\bar{q}q)^2 + (\bar{q}i\gamma_5 \tau q)^2], \quad (9)$$

where $q = (u, d)^T$ denotes the light-quark doublet, m_q is the current quark mass, and G is the effective $2N_f$ coupling constant. Although the NJL model does not incorporate confinement, it captures the essential mechanism of spontaneous chiral-symmetry breaking through dynamical mass generation. The constituent quark mass is determined self-consistently as

$$M_q = m_q - 2G\langle \bar{q}q \rangle. \quad (10)$$

The use of the NJL model as an effective description of dynamical chiral-symmetry breaking and its restoration at finite temperature follows the standard framework reviewed in Refs. [22–24]. In the present work, however, the two-flavor NJL model is not used as a microscopic model for the full strange-meson spectrum. It is employed only to provide a smooth, normalized light-sector crossover profile through

$M_q(T)/M_q(0)$, which is then mapped phenomenologically onto the strange axial-vector sector.

At finite temperature T and quark chemical potential μ_q , the constituent mass is obtained in the Matsubara formalism as

$$M_q(T, \mu_q) = m_q - 2G\langle \bar{q}q \rangle, \\ \langle \bar{q}q \rangle = -4N_c N_f \int_0^\Lambda \frac{d^3 \vec{k}}{(2\pi)^3} \frac{M_q}{E_k} [1 - n_+ - n_-], \quad (11)$$

where

$$E_k = \sqrt{\vec{k}^2 + M_q^2}, \quad n_F(E_k \pm \mu_q) = \frac{1}{e^{(E_k \pm \mu_q)/T} + 1} \equiv n_\mp. \quad (12)$$

As T or μ_q increases, the quark condensate decreases, which reduces M_q and signals partial chiral restoration.

Here, one focuses on the $\mu_q = 0$ case and uses the standard NJL parameter set $m_q = 5.25$ MeV, $\Lambda = 631.4$ MeV, and $G\Lambda^2 = 2.14$ [22]. The parameter dependence is also checked by varying $\Lambda = (630 \pm 30)$ MeV and $G\Lambda^2 = 2.1 \pm 0.1$, and the qualitative behavior and the pseudocritical region remain essentially unchanged. In the present analysis, the two-flavor NJL input is used solely to provide a smooth, normalized crossover profile of $M_q(T)$. The strange-sector mass scale itself is not predicted by the model but is introduced phenomenologically through an interpolation between M_A and its vector partner M_V . The corresponding interpretation of this construction in the strange axial-vector sector is discussed in the Appendix.

To implement this idea in a compact form, one parametrizes the normalized quark-mass profile $M_q(T)/M_q(0)$ by a Richards-type generalized logistic function,

$$F(T) = A + B \left[1 + \exp \left(\frac{T - T_0}{\Delta T} \right) \right]^{-\nu}, \quad (13)$$

where $A = 0.08299$, $B = 0.9180$, $\Delta T = 0.02668$ GeV, and $\nu = 0.1988$. Here, T_0 [GeV] is a fit parameter controlling the midpoint of the crossover profile. Using this function, the axial-vector mass is interpolated between its vacuum value and the corresponding vector-meson mass as

$$M_A(T) = M_V + [M_A(0) - M_V] \frac{[F(T) - F(T_{\text{pc}})]}{[F(0) - F(T_{\text{pc}})]}. \quad (14)$$

Here, T_{pc} denotes the pseudocritical temperature that sets the onset of approximate vector–axial-vector degeneracy in the present model. Throughout this work, T_c and T_{pc} are used interchangeably as the same crossover scale, with $T_c \approx T_{\text{pc}} \approx 184$ MeV. This construction ensures that $M_A(T)$ approaches M_V as the system moves toward the chiral-restoration region. It is also verified that alternative smooth parametrizations,

such as hyperbolic-tangent forms, do not qualitatively alter the numerical results, indicating that the dominant conclusion is determined by the existence of a smooth crossover profile rather than by the specific functional form adopted.

The thermal decay widths are then updated consistently with the changing kinematics. Rather than keeping the axial-vector widths fixed, their dominant temperature dependence is assumed to originate from the available two-body phase space for the decay $A \rightarrow VP$. Accordingly, one writes

$$\Gamma_A(T) = \Gamma_A(0) \left[\frac{M_A(0)}{M_A(T)} \right] \left[\frac{p_A(T)}{p_A(0)} \right]^3, \quad \Gamma_V(T) \approx \Gamma_V(0), \quad (15)$$

where the factor $p_A^3(T)$ reflects the P -wave nature of the decay. The center-of-mass momentum is given by

$$p_A(T) = \frac{\sqrt{[M_A^2(T) - (M_V + M_P)^2][M_A^2(T) - (M_V - M_P)^2]}}{2M_A(T)}. \quad (16)$$

As $M_A(T)$ decreases toward M_V , the available phase space shrinks, and the axial-vector width is correspondingly reduced.

The approximation $\Gamma_V(T) \approx \Gamma_V(0)$ also deserves comment. In a realistic hadronic medium, vector mesons such as the ρ and K^* are expected to acquire additional collision-induced broadening. However, the dominant effect in the present analysis comes from the reduction of the parent axial-vector mass $M_{K_1}(T)$, which shrinks the available Dalitz domain and suppresses the $A \rightarrow VP$ phase space entering Eq. (15). By contrast, moderate thermal broadening of the intermediate K^* mainly redistributes spectral strength around the resonance pole and smooths the corresponding ridge structure in the Dalitz plot, without reversing the overall reduction of the total three-body phase space caused by the decreasing K_1 mass. Neglecting vector broadening is therefore not expected to alter the qualitative trend, although it can affect detailed line shapes and should be incorporated in a more quantitative treatment. Nonetheless, a mild broadening of vector-meson widths in the numerical calculations is tested, as shown in Sec. III.

A similar remark applies to the approximation $M_P(T) \approx M_P(0)$. Even if moderate thermal shifts of the pseudoscalar masses are allowed, their impact on the present decay kinematics is expected to remain subleading compared with the axial-vector mass reduction. The three-body threshold for $K_1^+ \rightarrow \pi^+\pi^-K^+$ is $2M_\pi + M_K \approx 0.77$ GeV in vacuum, whereas the decrease of $M_{K_1}(T)$ in Fig. 3(a) is of order 0.2 GeV over the temperature range considered. By comparison, even a conservative thermal increase of (10–20) MeV per pseudoscalar would raise the threshold only by (30–60) MeV. Keeping the pseudoscalar masses fixed is therefore a reasonable first approximation for isolating the dominant phase-space effect, while explicit thermal shifts in pseudoscalar masses are left for future refinement.

Within this framework, the thermal modification of the K_1 mass and width directly affects the three-body decay $K_1^+ \rightarrow \pi^+\pi^-K^+$ through the intermediate ρ - and K^* -pole channels.

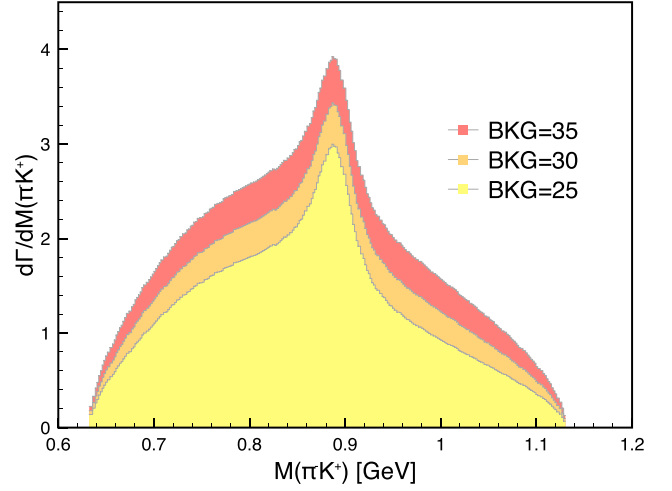


FIG. 2. Invariant-mass distribution $d\Gamma/dM(\pi^-K^+)$ for $K_1(1270)^+ \rightarrow \pi^+\pi^-K^+$ with $\mathcal{M}_{\text{BKG}} = 25, 30$, and 35 at $T = 0$. The background mainly changes the overall strength, while the spectral shape remains nearly unchanged.

Both the resonance structure and the kinematically allowed Dalitz region are therefore altered at finite temperature. As shown below, the resulting decay width $\Gamma_{K_1 \rightarrow \pi^+\pi^-K^+}(T)$ is strongly suppressed with increasing temperature, primarily because the decreasing parent axial-vector mass rapidly contracts the available three-body phase space.

C. Experiment-oriented shape observables

While the present framework is not intended to provide quantitative predictions for experimentally reconstructed heavy-ion yields, it is nevertheless useful to define normalized shape observables as intermediate decay-level quantities. These observables are designed to facilitate future comparisons with exclusive-reconstruction data once a full transport-based description that accounts for production, regeneration, rescattering, and detector effects becomes available. This is particularly important because the present analysis more reliably isolates decay-level thermal distortions than absolute yield modifications. Since the dominant thermal effect identified here is the shrinking of the available Dalitz support, the most natural observables are shape-based quantities that are less sensitive to the overall normalization uncertainty associated with the nonresonant background.

A first example is the fraction of events inside a K^* -dominated window of the $M_{\pi^-K^+}$ spectrum,

$$R_{K^*}(T; \Delta_{K^*}) \equiv \frac{\int_{M_{K^*} - \Delta_{K^*}}^{M_{K^*} + \Delta_{K^*}} dM_{\pi^-K^+} \frac{d\Gamma(T)}{dM_{\pi^-K^+}}}{\int dM_{\pi^-K^+} \frac{d\Gamma(T)}{dM_{\pi^-K^+}}}. \quad (17)$$

This quantity measures how strongly the reconstructed event population remains concentrated around the resonance-enhanced K^* region as the temperature increases. A second useful observable is the relative spectral weight near the upper

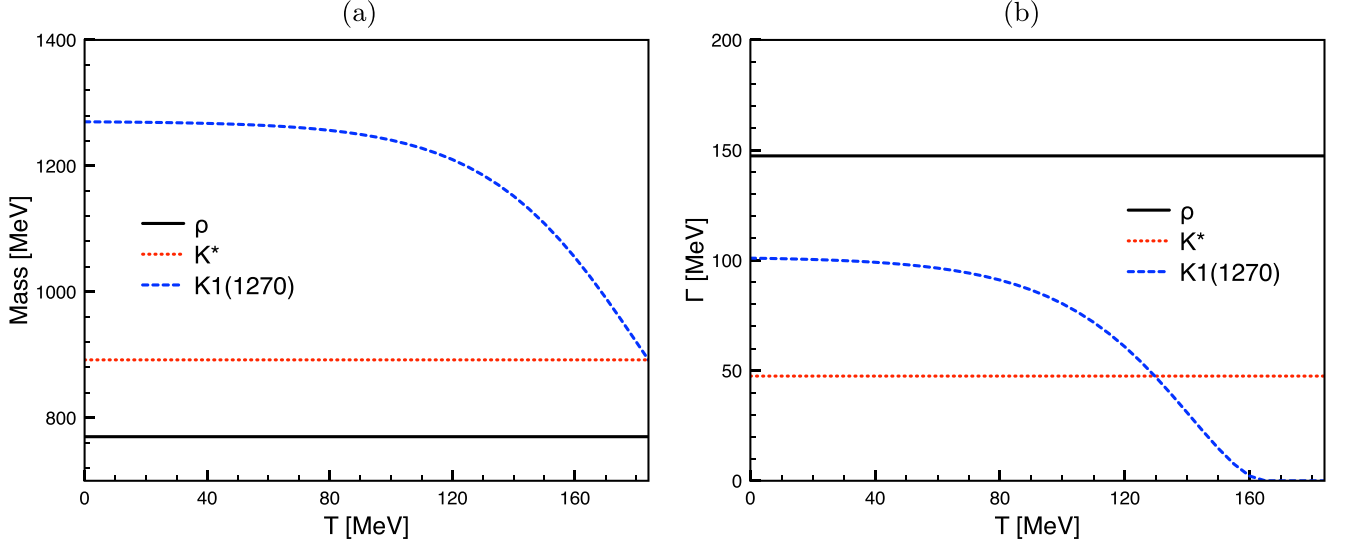


FIG. 3. Temperature dependence of the meson properties used in the present calculation: (a) masses of the ρ , K^* , and $K_1(1270)$ mesons, and (b) their corresponding decay widths. The more rapid variation in the range $T = (120-160)$ MeV reflects the approach to the pseudocritical region, where approximate vector-axial-vector degeneracy sets in, and the K_1 channel begins to show strong suppression.

edge of the $M_{\pi^+\pi^-}$ distribution,

$$R_{\text{edge}}(T; M_{\text{cut}}) \equiv \frac{\int_{M_{\text{cut}}}^{M_{\pi\pi}^{\text{max}}(T)} dM_{\pi^+\pi^-} \frac{d\Gamma(T)}{dM_{\pi^+\pi^-}}}{\int dM_{\pi^+\pi^-} \frac{d\Gamma(T)}{dM_{\pi^+\pi^-}}}. \quad (18)$$

This observable is designed to capture the progressive suppression of the upper-bound enhancement in the $\pi^+\pi^-$ channel as the available phase space becomes compressed.

If full Dalitz-level information is available, one may also define a compactification measure of the event population through an intensity-weighted second moment,

$$C(T) \equiv \frac{\int dM_{\pi^+\pi^-} dM_{\pi^-K^+} W(M_{\pi^+\pi^-}, M_{\pi^-K^+}) \frac{d^2\Gamma(T)}{dM_{\pi^+\pi^-} dM_{\pi^-K^+}}}{\int dM_{\pi^+\pi^-} dM_{\pi^-K^+} \frac{d^2\Gamma(T)}{dM_{\pi^+\pi^-} dM_{\pi^-K^+}}}, \quad (19)$$

where a natural choice for the weight function is

$$W(M_{\pi^+\pi^-}, M_{\pi^-K^+}) = [M_{\pi^+\pi^-} - \bar{M}_{\pi\pi}^{(0)}]^2 + [M_{\pi^-K^+} - \bar{M}_{\pi K}^{(0)}]^2, \quad (20)$$

with $\bar{M}_{\pi\pi}^{(0)}$ and $\bar{M}_{\pi K}^{(0)}$ denoting the centroid of the vacuum Dalitz distribution. In this form, $C(T)$ quantifies the thermal contraction of the event population relative to the vacuum kinematic support.

For practical implementation, the reference choices are adopted as

$$\Delta_{K^*} = 50 \text{ MeV}, \quad M_{\text{cut}} = 0.65 \text{ GeV}, \quad (21)$$

which are intended to capture, respectively, the resonance-dominated region around the K^* peak in the $M_{\pi^-K^+}$ spectrum and the upper-edge enhancement region in the $M_{\pi^+\pi^-}$ spectrum. These observables are not meant to replace a full transport-based description of experimentally reconstructed heavy-ion signals. Rather, they provide intermediate decay-level quantities that are directly sensitive to the weakening

and narrowing of the resonance-enhanced structures and to the shrinking of the Dalitz support. In this sense, they offer a practical bridge between the present phenomenological analysis and future comparisons with reconstructed exclusive data.

III. NUMERICAL RESULTS

In this section, the numerical results obtained within the temperature-dependent framework described above are presented, and their implications for the decay process $K_1^+(1270) \rightarrow \pi^+\pi^-K^+$ in a hot hadronic medium are discussed. Our focus is on the thermal deformation of the Dalitz structure, the invariant-mass spectra, the integrated three-body decay width, and the normalized shape observables.

Before turning to the thermal results, the background amplitude $\mathcal{M}_{\text{BKG}}$ is estimated. Since the exclusive partial width for the channel $K_1(1270)^+ \rightarrow K^+\pi^+\pi^-$ is not listed directly by the particle data group (PDG) [20], a representative value is inferred from the total width and the dominant quasitwo-body branching fractions. As a bookkeeping estimate, the charged final state is decomposed into the leading intermediate channels,

$$\begin{aligned} \mathcal{B}_{\text{est}}[K_1(1270)^+ \rightarrow K^+\pi^+\pi^-] \\ \approx \mathcal{B}[K_1^+ \rightarrow K^+\rho^0] \mathcal{B}[\rho^0 \rightarrow \pi^+\pi^-] \\ + \mathcal{B}[K_1^+ \rightarrow K^{*0}\pi^+] \mathcal{B}[K^{*0} \rightarrow K^+\pi^-] \\ + \mathcal{B}[K_1^+ \rightarrow K_0^{*0}(1430)\pi^+] \mathcal{B}[K_0^{*0}(1430) \rightarrow K^+\pi^-], \end{aligned} \quad (22)$$

where only the charge combinations contributing to the final state $K^+\pi^+\pi^-$ are retained. The corresponding partial width is approximated as

$$\begin{aligned} \Gamma_{\text{est}}^{\text{PDG}}[K_1(1270)^+ \rightarrow K^+\pi^+\pi^-] \\ = \mathcal{B}_{\text{est}}[K_1(1270)^+ \rightarrow K^+\pi^+\pi^-] \Gamma_{K_1(1270)}^{\text{tot}}. \end{aligned} \quad (23)$$

Using $\Gamma_{K_1(1270)}^{\text{tot}} \approx 101$ MeV together with the PDG-listed branching fractions for the dominant quasitwo-body channels, an estimated branching fraction $\mathcal{B}_{\text{est}}[K_1(1270)^+ \rightarrow K^+\pi^+\pi^-] \approx 0.4$ is obtained, within the corresponding experimental uncertainties. Accordingly,

$$\Gamma_{\text{est}}^{\text{PDG}}[K_1(1270)^+ \rightarrow K^+\pi^+\pi^-] \approx 40 \text{ MeV}. \quad (24)$$

This estimate should be regarded as only indicative, since it neglects coherent interference among the intermediate resonances as well as possible nonresonant contributions. In the full amplitude-level treatment of Eq. (2), by contrast, the ρ - and K^* -pole terms interfere coherently over the entire Dalitz domain. Numerically, the partial width is found to be $\Gamma[K_1(1270)^+ \rightarrow \pi^+\pi^-K^+] \approx (32\text{--}47)$ MeV for $\mathcal{M} * \text{BKG} \approx (25\text{--}35)$. In the following analysis, $\mathcal{M} * \text{BKG} = 30$ is adopted, yielding $\Gamma[K_1(1270)^+ \rightarrow \pi^+\pi^-K^+] \approx 39.5$ MeV and reproducing the PDG-based estimate at a reasonable level. It has also been verified that varying the background strength within this range does not produce any significant change in the Dalitz-plot topology. As shown in Fig. 2, the π^-K^+ invariant-mass distributions for $\mathcal{M}_{\text{BKG}} = 25, 30$, and 35 at $T = 0$ exhibit mainly an overall enhancement of the spectral strength, while the resonance structure remains essentially unchanged.

The absolute normalization, therefore, retains some background dependence, but the decreasing trend with temperature remains stable within this range. Although a more complete treatment of the nonresonant amplitude may modify the detailed normalization and local Dalitz-profile intensity, the qualitative temperature dependence obtained here is not driven by the specific choice of $\mathcal{M}_{\text{BKG}}$ but by the kinematic reduction of the available three-body phase space as $M_{K_1}(T)$ decreases.

The thermal behavior of the meson properties entering the present calculation is examined first. Figure 3 shows the temperature dependence of the masses and decay widths of the relevant vector and axial-vector mesons. By construction, the vector-meson masses remain nearly constant, whereas the axial-vector masses decrease with temperature and gradually approach their corresponding vector partners. The associated axial-vector widths are also strongly reduced because they are updated through the shrinking phase space for the $A \rightarrow VP$ channel. In the present parametrization, this evolution remains mild at low temperature and becomes much steeper only in the pseudocritical region. For the K_1 channel in particular, the reduction of both $M_{K_1}(T)$ and $\Gamma_{K_1}(T)$ becomes pronounced around $T = (120\text{--}130)$ MeV and accelerates toward chemical freeze-out.

The modification of the meson properties is reflected directly in the Dalitz distribution for the three-body decay $K_1^+ \rightarrow \pi^+\pi^-K^+$. Figure 4 shows the Dalitz plots for $T = (0\text{--}160)$ MeV. At zero temperature, the allowed kinematic region is broad, and the event distribution exhibits a pronounced ridge associated mainly with the K^* -pole contribution, together with a weaker structure related to the ρ channel. As the temperature increases, the Dalitz domain shrinks steadily because the decreasing K_1 mass reduces the total energy available to the final-state particles. At the

same time, the high-intensity ridge narrows and shifts toward lower invariant masses. The medium, therefore, modifies both the overall decay strength and the detailed kinematic profile through shifted pole positions and reduced phase space.

The same trend appears in the one-dimensional invariant-mass distributions shown in Fig. 5. In the $M_{\pi^+\pi^-}$ distribution [Fig. 5(a)], the enhancement near the upper kinematic boundary is progressively suppressed as T increases. Likewise, the $M_{\pi^-K^+}$ spectrum [Fig. 5(b)] shows a pronounced peak around the K^* region at low temperature, but this peak becomes reduced and compressed at higher temperatures. These results indicate that thermal modification affects not only the integrated strength of the decay but also the shapes of phenomenologically relevant invariant-mass spectra.

To illustrate the cumulative effect of the thermal evolution, Figs. 6(a) and 6(b) compare the vacuum Dalitz plot with the thermally averaged one, respectively, over the range $T = (0\text{--}T_c)$. The thermal average shown here denotes a simple numerical average over the temperature grid, not a dynamical fireball-weighted average. The thermally averaged distribution is visibly smeared and reduced relative to the vacuum case, reflecting that decays at different temperatures sample different effective masses, widths, and phase-space boundaries. If a mild broadening of the vector-meson width is taken into account as indicated in the PNJL model calculation [21], the widths for ρ^0 and K^{*0} can be parametrized simply as follows:

$$\Gamma_V(T) = \Gamma_V \left[1 + 0.2 \left(\frac{T}{T_c} \right)^2 \right]. \quad (25)$$

Figure 6(c) shows the thermally averaged Dalitz plot including the thermal broadening of Γ_V in Eq. (25). The mild broadening produces only a negligible difference compared with the result obtained without it. Figure 6(d) provides a purely illustrative cross-check obtained by including the $K_1(1400)$ contribution. Although the detailed ridge intensity and overall event distribution are modified by admixture with the heavier strange axial-vector state, the main thermal trend remains unchanged: the resonance-enhanced structure is smeared, and the suppression associated with the shrinking effective phase space persists. In the present paper, the $K_1(1400)$ contribution is included only for illustration, rather than as part of a systematic in-medium treatment of $K_1(1270)$ - $K_1(1400)$ mixing.

Integrating the double-differential decay width over the Dalitz region yields the total three-body decay width $\Gamma_{K_1 \rightarrow \pi^+\pi^-K^+}(T)$ for the central choice $\mathcal{M}_{\text{BKG}} = 30$, shown in Fig. 7(a). The solid and dashed lines denote the decay widths with and without the vector-meson width broadening, respectively, defined by Eq. (25). Consistent with Fig. 6(c), the broadening produces no visible change in the integrated width. The shaded band indicates the variation obtained by changing the nonresonant background amplitude in the range $\mathcal{M}_{\text{BKG}} = (25\text{--}35)$. The result is well described by

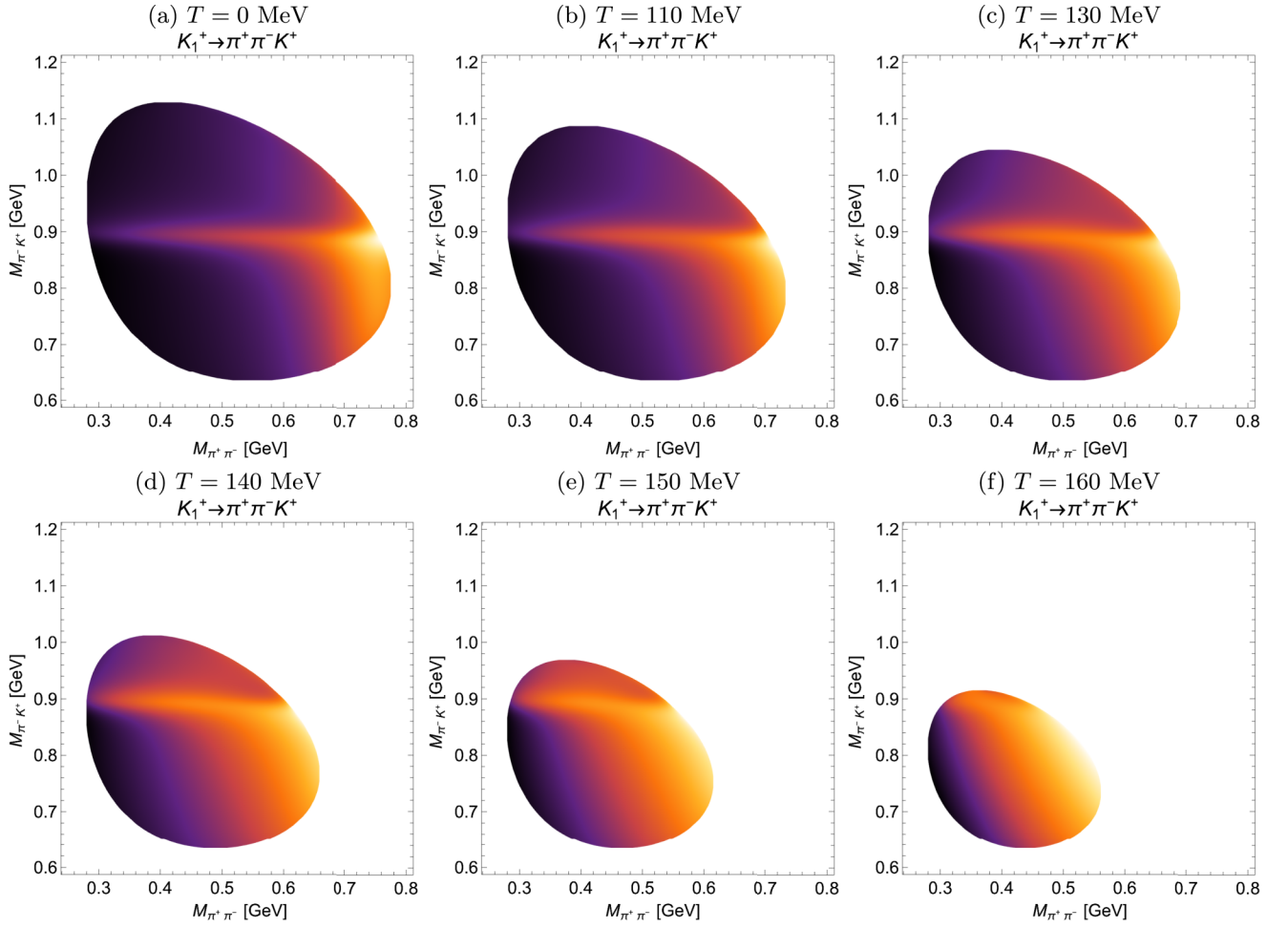


FIG. 4. Dalitz plots for $K_1^+(1270) \rightarrow \pi^+\pi^-K^+$ as functions of the invariant masses $M_{\pi^+\pi^-}$ and $M_{\pi^-K^+}$, shown with a common color normalization for different temperatures $T = (0-160)$ MeV.

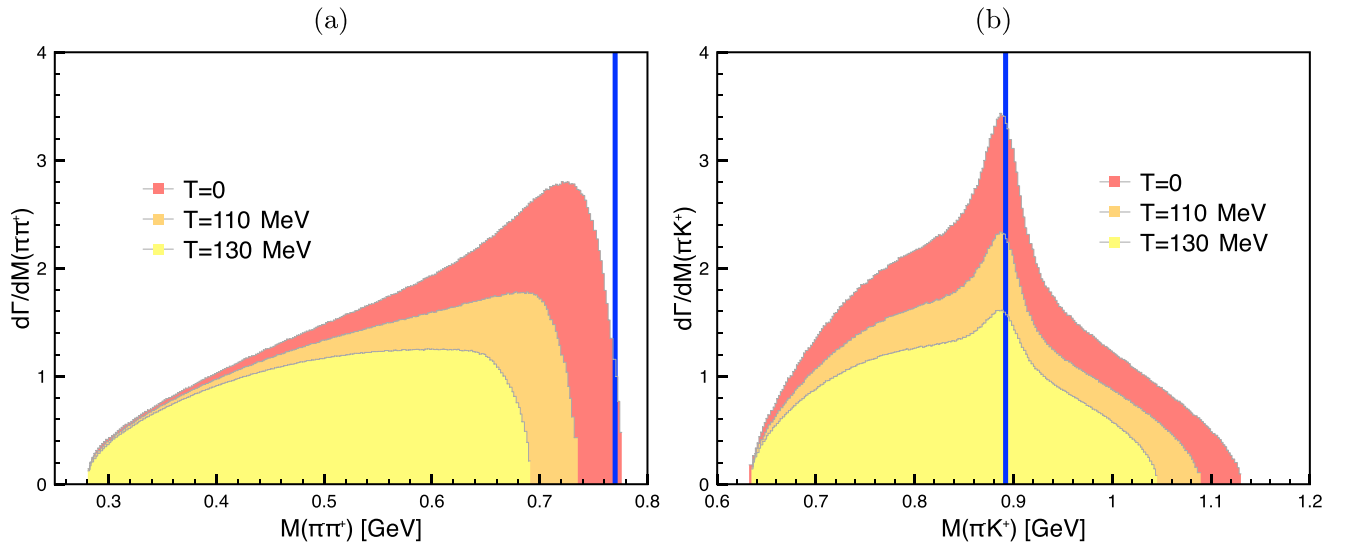


FIG. 5. Invariant-mass distributions for $K_1^+ \rightarrow \pi^+\pi^-K^+$ at several temperatures: (a) $d\Gamma/dM_{\pi^+\pi^-}$ and (b) $d\Gamma/dM_{\pi^-K^+}$. The vertical thick lines stand for the mass of $\rho^0(770)$ and $K^{*0}(892)$.

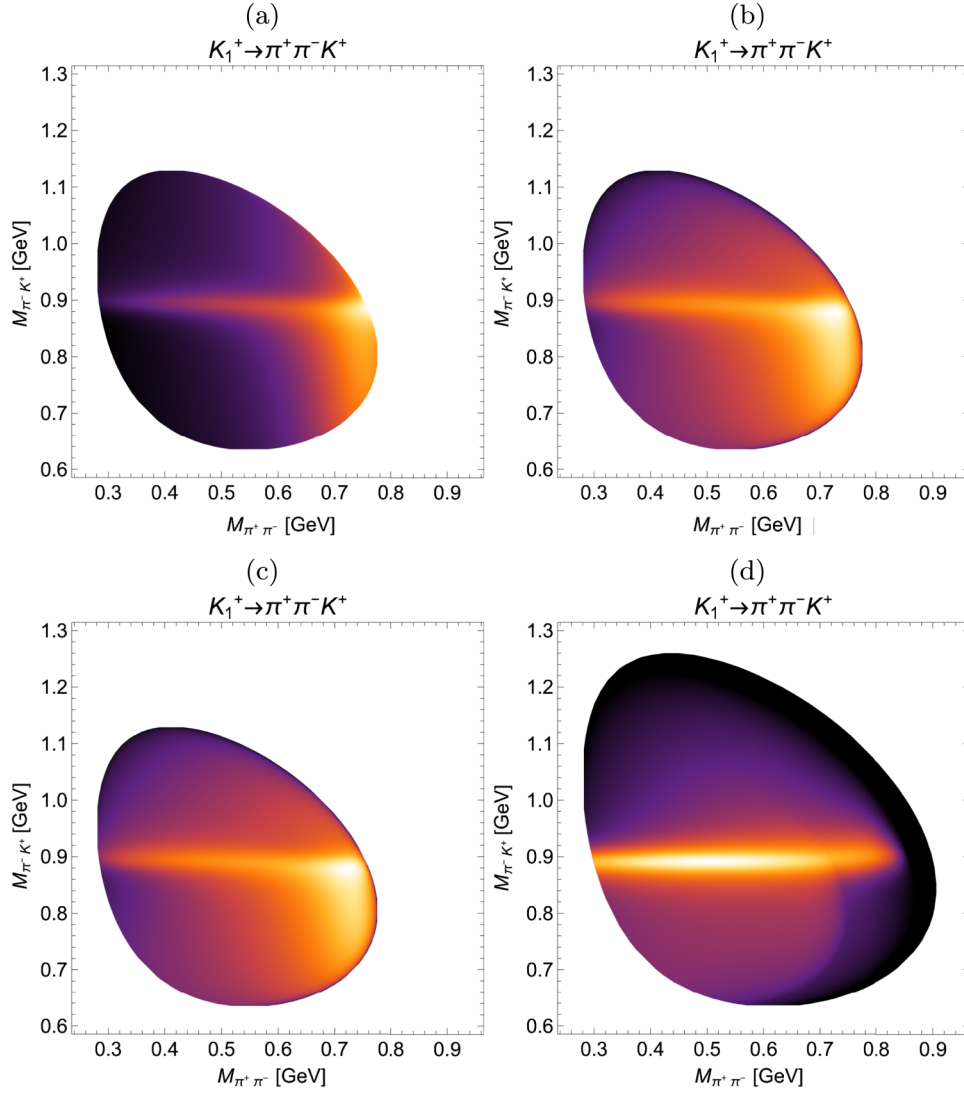


FIG. 6. (a) Dalitz plot at $T = 0$, (b) thermally averaged one for $T = (0 - T_c)$, and (c) that with the vector-meson width broadening in Eq. (25). (d) Thermally averaged one including $K_1(1400)$.

the Richards-type parametrization (square):

$$\begin{aligned} \Gamma_{K_1^+ \rightarrow \pi^+ \pi^- K^+}(T) \\ = \Gamma_{K_1^+ \rightarrow \pi^+ \pi^- K^+}(0) \left\{ a + b \left[1 + \exp \left(\frac{T - T_c}{\Delta T} \right) \right]^{-\nu} \right\}, \end{aligned} \quad (26)$$

with $a = -2.461$, $b = 41.73$, $T_c = 142.4$ MeV, $\Delta T = 25.90$ MeV, and $\nu = 1.292$. The suppression becomes increasingly pronounced toward the pseudocritical region, where the reduction of $M_{K_1}(T)$ rapidly compresses the available three-body phase space. The dominant conclusion is therefore kinematic: within the present phenomenological framework, the thermal suppression of the exclusive channel is controlled primarily by the shrinking Dalitz volume induced by the decreasing axial-vector mass.

To complement this integrated measure, the normalized shape observables introduced in Eqs. (17)–(19) are also

evaluated. These quantities allow one to track how the thermal suppression is distributed across different regions of the daughter invariant-mass spectra and the Dalitz plane, rather than only through the total decay strength. Figure 7(b) summarizes the thermal evolution of the normalized shape observables. The upper-edge weight R_{edge} decreases earlier and more rapidly than the K^* -window fraction R_{K^*} , indicating that the enhancement near the upper boundary of the $M_{\pi^+ \pi^-}$ spectrum is more sensitive to the initial compression of the available phase space. By contrast, the resonance-dominated K^* structure in the $M_{\pi^- K^+}$ channel remains relatively stable up to higher temperatures and is strongly reduced only near the pseudocritical region. Meanwhile, the increase in C shows that the Dalitz event population is progressively redistributed as the allowed kinematic support shrinks and deforms. These results demonstrate that the thermal effect identified here manifests itself not only as an overall suppression of the decay width but also as a nontrivial reshaping of normalized exclusive observables.

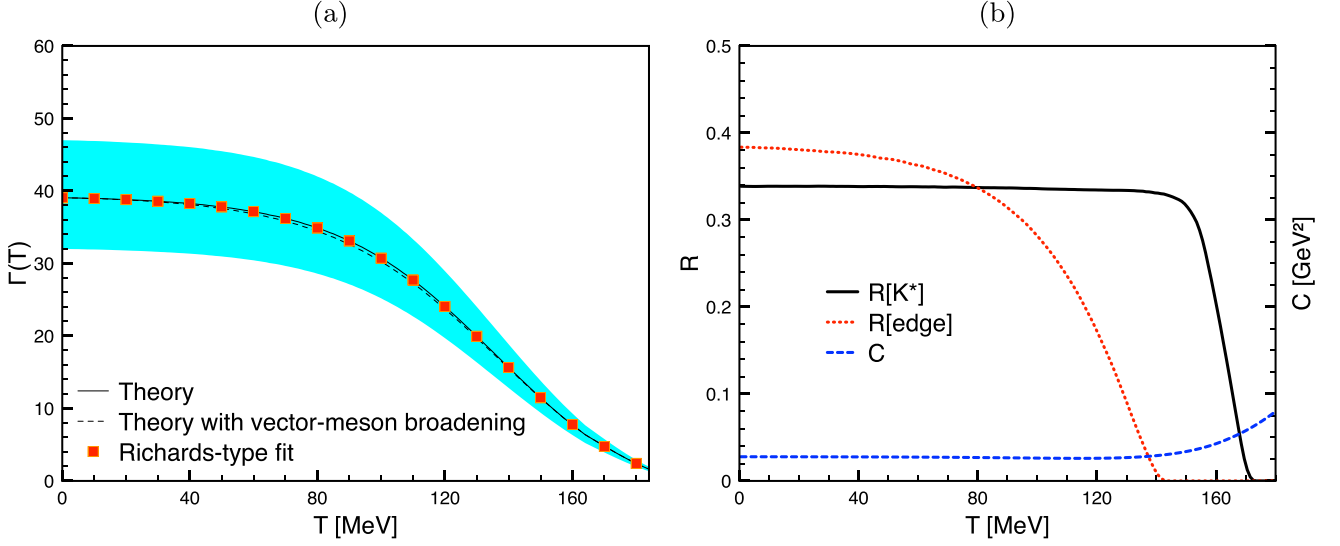


FIG. 7. (a) Temperature dependence of the integrated decay width $\Gamma_{K_1 \rightarrow \pi^+ \pi^- K^+}(T)$ for the central choice $\mathcal{M}_{\text{BKG}} = 30$, together with the Richards-type fit. The shaded band indicates the variation obtained for $\mathcal{M}_{\text{BKG}} = (25-35)$. (b) Normalized shape observables R_{K^*} , R_{edge} , and C , defined by Eqs. (17)–(19).

Overall, the numerical results show that thermal reduction of the available Dalitz phase space deforms the invariant-mass spectra and significantly suppresses the integrated decay width of $K_1^+ \rightarrow \pi^+ \pi^- K^+$. This indicates that the $K_1(1270)$ channel can serve as a qualitative probe of in-medium strange axial-vector dynamics and the approach to chiral restoration. From an experimental perspective, the present results imply not only an overall suppression of reconstructable $K_1(1270)^+ \rightarrow \pi^+ \pi^- K^+$ candidates, but also characteristic modifications of the daughter invariant-mass spectra. As the parent axial-vector mass decreases, the three-body phase space becomes increasingly compressed, driving events into a narrower kinematic region. In particular, the $M_{\pi^- K^+}$ distribution would show a weakened and compressed K^* -dominated structure if the effective K_1 mass at the time of hadronic decoupling were reduced, while the enhancement in the $M_{\pi^+ \pi^-}$ spectrum near the upper kinematic boundary would become progressively less pronounced under such conditions.

The thermal effect is therefore reflected not only in the integrated width but also in qualitative changes in shape that may remain visible in reconstructed exclusive channels, provided that the freeze-out conditions are sufficiently close to the pseudocritical region.

IV. SUMMARY AND OUTLOOK

I have investigated the three-body decay process $K_1(1270)^+ \rightarrow \pi^+ \pi^- K^+$ in a hot hadronic medium as a decay-level probe of the strange axial-vector channel. The calculation was formulated in an effective hadronic framework including the dominant ρ - and K^* -pole contributions. Thermal effects were incorporated through a phenomenological interpolation motivated by partial chiral-symmetry restoration, in which the effective K_1 - K^* splitting decreases toward the pseudocritical region. In this setup, reducing the parent K_1 mass contracts the available

three-body phase space and suppresses the partial decay width. It should be emphasized from the outset that the present results constitute decay-level diagnostics rather than quantitative predictions for reconstructed heavy-ion observables; a realistic comparison with data would additionally require dynamical modeling of production, regeneration, daughter-particle rescattering, detector acceptance, and kinetic freeze-out, which are beyond the scope of the present work.

Our numerical analysis shows that both the Dalitz plot and the corresponding one-dimensional invariant-mass spectra are significantly modified as temperature increases. The kinematically allowed region becomes progressively smaller, while the resonance-enhanced structures, particularly those associated with the K^* channel, become narrower and weaker. The medium, therefore, affects not only the overall magnitude of the decay rate but also the detailed kinematic profile of the decay. To characterize this effect beyond the integrated width, I introduced normalized shape observables that quantify the thermal evolution of the K^* -dominated πK region, the upper-edge weight of the $\pi\pi$ spectrum, and the compactification of the Dalitz population. These observables demonstrate that the thermal modification identified here is not limited to an overall suppression of the decay rate but also manifests as a structured reshaping of the exclusive decay kinematics.

The thermal setup adopted here is intentionally phenomenological and is not derived from a microscopic finite-temperature calculation of strange spectral functions. Its purpose is to isolate the leading decay-level consequence of a smooth reduction of the K_1 - K^* mass splitting as the system approaches vector-axial-vector degeneracy. Under this interpretation, the sign and overall trend of the suppression are expected to be more robust than its detailed magnitude, whereas the quantitative size of the effect and the detailed line shapes may still depend on thermal broadening in the intermediate vector channels, finite-temperature pseudoscalar-mass

shifts, and a more microscopic treatment of the strange-sector thermal input.

Several limitations of the present analysis should be noted. First, the nonresonant background term $\mathcal{M}_{\text{BKG}}$ was introduced only phenomenologically as a temperature-independent contribution and should not be regarded as a microscopic description of direct three-body dynamics. Although a more realistic treatment could affect quantitative details of the Dalitz distribution and the partial width, the present results suggest that the dominant thermal effect is driven primarily by the reduction in the available three-body phase space as $M_{K_1}(T)$ decreases.

Second, the present treatment of the $K_1(1270)$ - $K_1(1400)$ system remains schematic. While the adopted vacuum couplings already contain phenomenological information related to their mixing, a dynamical in-medium evolution of the mixing pattern has not been included [25]. A more complete treatment of the strange axial-vector sector would therefore be desirable in future work.

Even within this simplified framework, however, the present results suggest possible qualitative shape distortions that may be relevant for reconstructed exclusive candidates. In addition to an overall reduction in the decay strength, the shrinking Dalitz support implies characteristic distortions in the invariant-mass distributions. These shape changes may provide useful observables that are less sensitive to overall normalization uncertainties. A more quantitative connection to experimentally reconstructed heavy-ion observables will require implementing the in-medium spectral modifications in realistic dynamical transport simulations, such as UrQMD [26] or SMASH [27]. Related works are in progress and will appear elsewhere.

The present results should therefore be regarded as a decay-level map of how the exclusive $K_1(1270)^+ \rightarrow \pi^+\pi^-K^+$ Dalitz structure changes as the effective K_1-K^* splitting is reduced. Such information may be useful as an input or benchmark for future transport calculations in which production, regeneration, rescattering, detector effects, freeze-out temperature, and centrality dependence are treated explicitly.

ACKNOWLEDGMENTS

The author is grateful to Su-Jeong Ji, Sanghoon Lim, and Su Houn Lee (Yonsei University) for fruitful discussions. This work was supported by the National Research Founda-

tion of Korea (NRF) grant funded by the Korean government (MSIT) (Grant No. RS-2025-16065906).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX

Phenomenological crossover profile for the strange axial-vector sector (Drop 1).

1. Phenomenological implementation of the $N_f = 2$ NJL crossover profile in the strange axial-vector sector

In the present work, the two-flavor NJL model is not used as a microscopic theory for the in-medium strange-meson spectrum. It is employed only as a source of a smooth, normalized crossover profile through $M_q(T)/M_q(0)$. The strange-sector mass scale itself is not predicted by the model, but is introduced phenomenologically through

$$M_A(T) = M_V + [M_A(0) - M_V] \left[\frac{F(T) - F(T_{\text{pc}})}{F(0) - F(T_{\text{pc}})} \right]. \quad (\text{A1})$$

Thus, the NJL input fixes only the location and smoothness of the crossover, not the absolute strange-meson spectroscopy.

The motivation is that the K_1 and K^* states contain one light quark, so their vector-axial-vector splitting is expected to respond qualitatively to light-sector chiral restoration in the same pseudocritical region. The present ansatz should therefore be understood as a phenomenological crossover-scale mapping rather than a microscopic strange-sector model. Its purpose is to isolate the dominant kinematic consequence of decreasing K_1 - K^* splitting. In the exclusive channel studied here, the main effect is the rapid contraction of the available three-body phase space as $M_{K_1}(T)$ decreases, which suppresses the decay width. A more microscopic treatment may alter the detailed thermal trajectory, but the overall suppression trend is expected to remain, provided the effective K_1 - K^* splitting decreases smoothly toward the pseudocritical region, because the dominant effect is the associated phase-space contraction.

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