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# Charge-conjugation asymmetry and molecular content: the $T_{cc}(3875)$ and the $D^*_{s0}(2317)$ in nuclear matter

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We show how the nuclear environment modifies the spectral functions of the $T_{cc}(3875)$ and the $D^*_{s0}(2317)$ exotic hadrons. These states do not have well defined charge-conjugation, and the medium breaks $C-$parity symmetry and induces different particle-antiparticle line-shapes. If these distinctive density dependencies were confirmed experimentally, it would give support to the presence of important molecular components in these exotic resonances. This is because if these hadrons were mostly compact four-quark structures, the density behavior of their line-shapes in the medium, while certainly different, would probably not follow the same patterns found in molecular scenarios.

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## 1. Introduction

Hadron physics, dealing with the structure and dynamics of strongly interacting systems, has always been one of the toughest parts of particle physics. While QCD is universally admitted as the theory behind the hadron-spectrum, the intrinsic non-perturbative nature of hadrons made progress slow. The situation has been reversed lately due to the intense experimental activity with the discovery of new particles that challenge the commonly accepted picture where mesons are made of quark-antiquark pairs and baryons of three quarks. Actually, some hadrons could be molecular states arising from the interaction of more elementary hadrons, in particular in the charm sector [1]. Of special relevance for the field was the discovery in Summer 2021 of a charged tetraquark state $T_{cc}(3875)^+$ by the LHCb Collaboration [2, 3]. This double-charmed state was observed in the $D^0D^0\pi^+$ mass distribution, only $360 \pm 40^{+4}_{-0}$ keV below the $D^{*+}D^0$ threshold and with a width of few tens of keV, and which cannot be obviously accommodated within the simplest quark-antiquark picture for mesons. Different theoretical interpretations of the $T_{cc}$ nature have been postulated (genuine multiquark state, hadronic molecule or a mixture of different components), but the importance of the $DD^*$ hadronic degrees of freedom acquires an special relevance, giving its proximity to this threshold. We will show that these degrees of freedom can be directly tested by analyzing the properties of this exotic hadron embedded inside of a nuclear medium.

In this talk, we adopt a scheme that allows for a sizable $DD^*$ and $\overline{D}\overline{D}^*$ molecular probability for the $T_{cc}(3875)^+$ and its antiparticle $T_{\bar{c}\bar{c}}(3875)^-$ [4–6], and address the spectral functions of these resonances in dense matter that breaks $C-$parity symmetry and induces different particle-antiparticle line-shapes. The asymmetry is induced by the different interaction of $D^{(*)}$ and $\overline{D}^{(*)}$ mesons with nucleons and depends on the molecular content of these exotic states. Hence from such studies one can gain some insight about the nature of the $T_{cc}(3875)^+$. Next, we also pay attention to the particle-antiparticle $D^*_{s0}(2317)^+$ & $D^*_{s0}(2317)^-$ line-shapes. These narrow ($\Gamma < 4$ MeV) scalar-isoscalar mesons, with content $c\bar{s}$ and $\bar{c}s$ respectively, were discovered in 2003 by the BABAR Collaboration [7] at around 40 MeV below the $DK$ threshold. They are exotic since cannot be accommodated in simple constituent quark models [8], and it is commonly accepted that have large (60-80%) $DK$ & $\overline{D}\overline{K}$ molecular components [9–19]. We find in the $D^*_{s0}(2317)^+$ & $D^*_{s0}(2317)^-$ system, an important charge-conjugation asymmetry in dense matter, larger than for the $T_{cc}(3875)^+$ & $T_{\bar{c}\bar{c}}(3875)^-$ pair, which mainly stems from the very different kaon and antikaon interactions with the nucleons of the medium. While the $S$-wave $KN$ interaction is very weak, since the kaon contains an antiquark $\bar{s}$, and it does not produce any resonance at low energies, the $\overline{K}N$ interaction is quite strong, and the $\Lambda(1405)$ and $\Lambda(1670)$ states can be excited.

We will limit here the discussion to the $T_{cc}(3875)$ and the $D^*_{s0}(2317)$, but similar results can be found for their $D^*D^*$ and $D^*K$ heavy quark spin symmetry partners. While the former has been theorized in several works (see for instance Ref. [6]), the latter state is well established, and corresponds to the $D^*_{s1}(2460)$ isoscalar axial resonance.

## 2. Theoretical framework

We present results from Refs. [20] and [21], where the nuclear-medium $T_{cc}(3875)^+$ & $T_{\bar{c}\bar{c}}(3875)^-$ and the $D^*_{s0}(2317)^+$ & $D^*_{s0}(2317)^-$ spectral functions are computed, respectively,

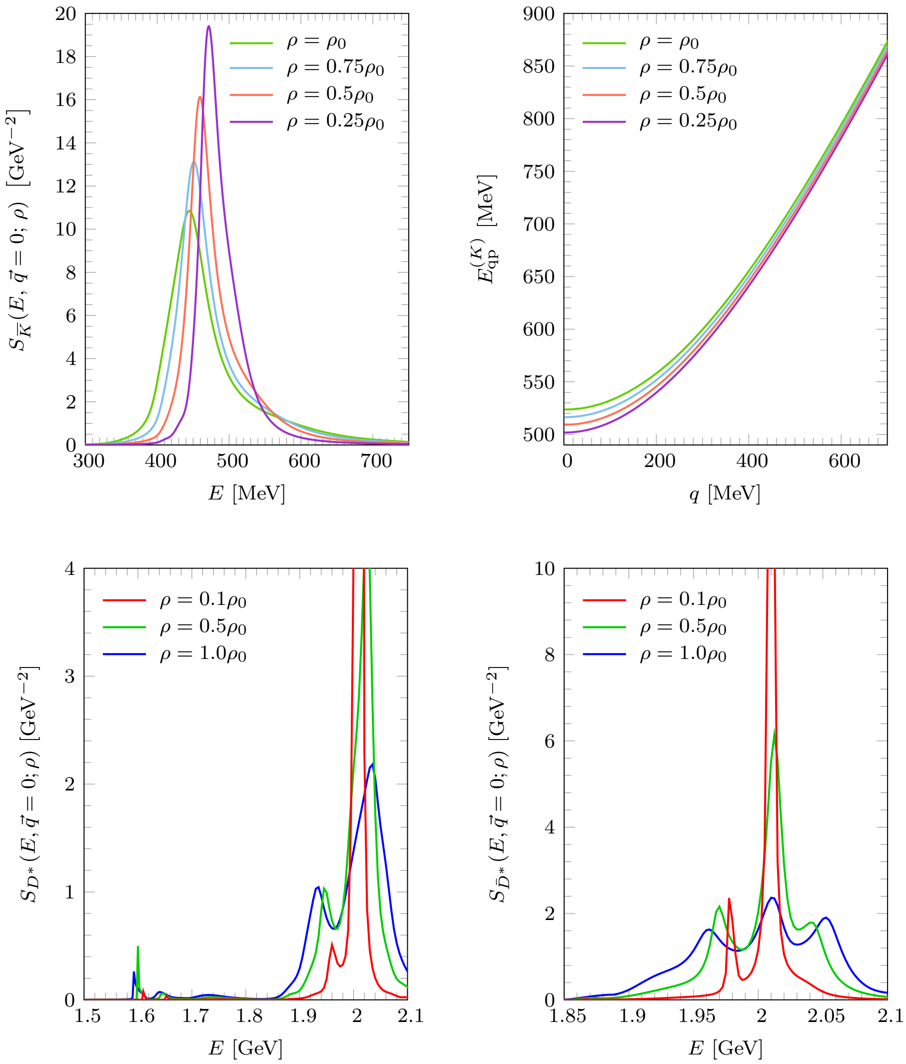


**Figure 1:** Top left: Energy ($q^0$) dependence of the $\overline{K}$ spectral function at zero three-momentum ($\mathbf{q} = 0$) for different values of the nuclear density in units of $\rho_0 = 0.17$ fm$^{-3}$. Top right: $K$ quasi-particle energy, $E_{\rm qp}$ (see text), as a function of the modulus of the kaon three-momentum $q$ (= $|\mathbf{q}\,|$) for different densities. Bottom left (right) $D^*$ ($\overline{D}^*$) spectral functions for zero three-momentum as a function of the (anti-)charm meson energy for three different densities $\rho = 0.1\rho_0$, $0.5\rho_0$ and $\rho_0$. Plots are taken from Refs. [20] and [21].

using a formalism derived in Ref. [22] to account for the in-medium modifications of $D^*\overline{D}$ scattering and the $X(3872)$ properties. The scheme of Ref. [22] employs the nuclear-medium self-energies $\Pi_\phi(q^0,\ \mathbf{q};\ \rho)$ of the mesons that form the exotic hadron-molecule, which depend on the meson energy[1] ($q^0$), three-momentum ($\mathbf{q}$ ) and the isospin-symmetric nuclear density $\rho$. For the $K$ and $\overline{K}$ nuclear self-energies, we use a coupled-channel self-consistent chiral unitary approach [23], while those of the $D^{(*)}$ and $\overline{D}^{(*)}$ mesons are obtained following a unitarized self-consistent procedure in coupled channels, as described in Refs. [24, 25] and in Ref. [26], respectively.

For $\phi_1\phi_2 \to \phi_1\phi_2$ scattering in the nuclear-medium, we obtain the unitary isoscalar S-wave

[1] Variables are referred to the reference system where the nuclear matter is at rest.

$T$-matrix from the solution of the on-shell Bethe-Salpeter equation [27],

$$T^{-1}_{\phi_1\phi_2}(s;\rho) = V^{-1}_{\phi_1\phi_2}(s) - \Sigma_{\phi_1\phi_2}(s;\rho), \tag{1}$$

where $s = P^2$, with $P^\mu$ the total four-momentum of the $\phi_1\phi_2$ meson pair, $V_{\phi_1\phi_2}(s)$ is their mutual interaction and $\Sigma_{\phi_1\phi_2}(s;\rho)$ is the two-meson loop function in the medium,

$$\Sigma_{\phi_1\phi_2}(s;\rho) = i\int \frac{d^4q}{(2\pi)^4}\Delta_{\phi_1}(P-q;\rho)\Delta_{\phi_2}(q;\rho), \tag{2}$$

$$\Delta_\phi(q;\rho) = \frac{1}{(q^0)^2 - \mathbf{q}^2 - m^2_\phi - \Pi_\phi(q^0,\,\mathbf{q};\,\rho)}, \tag{3}$$

with $m_\phi$ the meson mass. The computation of $\Sigma_{\phi_1\phi_2}(s;\rho)$ requires to introduce an ultraviolet (UV) regulator in the $d^3q$ integration to make the vacuum two-point function $\Sigma_{\phi_1\phi_2}(s;\rho=0)$ finite.

The $\Pi_\phi(q^0,\,\mathbf{q};\,\rho)$ self-energies vanish in the free space [$\Pi_\phi(q^0,\,\mathbf{q};\,\rho=0)\to -i\epsilon$], but they produce significant changes in the dispersion relations of the mesons inside of nuclear matter of density $\rho$. Indeed, when the mesons are embedded in the medium, their spectral functions

$$S_\phi(q;\rho) = -\frac{1}{\pi}\,\mathrm{Im}\Delta_\phi(q;\rho) \tag{4}$$

depart from the $\delta(q^2 - m^2_\phi)$ delta function, with the position of the quasi-particle peaks being displaced with respect to the free mass position, and becoming broader as the density increases. In addition, richer structures are produced by several resonant-hole excitations that appear around the quasi-particle positions [23–26]. These effects can be appreciated in Fig. 1. The kaon spectral function has little structure, being a Dirac delta function peaked around the quasi-particle energy[2] $E_{\rm qp}$ an excellent approximation, i.e. $S_K(E,\,q;\,\rho) \approx \delta\left(E - E_{\rm qp}(q;\,\rho)\right)/(2E_{\rm qp}(q;\,\rho)$. In sharp contrast, the energy dependence of the $\bar K$ spectral function is much more complex and observe that the $\bar K$ quasi-particle peak energy is located in dense matter at a lower energy than the free $\bar K$ mass. In addition, the $\Lambda(1405)N^{-1}$ excitation for energies above the quasi-particle energy is clearly visible. As density increases, the quasi-particle peak gains attraction whereas the spectral function becomes wider due to the dilution of the $\Lambda(1405)$ with density, as thoroughly discussed in Refs. [23, 28, 29]. In the bottom plots of Fig. 1, we show the $S_{D^*}$ (left) and $S_{\overline{D}^*}$ for different densities, where we can also appreciate the distinctive and different density behavior of the vector charmed and anticharmed meson spectral functions.

On the other hand, we assume that the $\phi_1\phi_2$–interaction $V_{\phi_1\phi_2}(s)$ is not modified by the nuclear medium and it is fixed by the free-space properties of the $T_{cc}(3875)$ and $D^*_{s0}(2317)$ resonances, which show up as poles in the first Riemann sheet of the elastic isoscalar S-wave $D\bar K$ and $DD^*$ amplitudes, respectively. Note that even though the $V_{\phi_1\phi_2}(s)$ potential is charge-conjugation invariant, i.e., elastic $\bar D K$ and $\bar D\bar D^*$ interactions are identical to the $D\bar K$ and $DD^*$ ones, the nuclear matter breaks the $C-$ parity invariance of the in-medium $T_{\phi_1\phi_2}(s;\rho)$–amplitudes calculated using Eq. (1). This is because meson $\Pi_\phi(q^0,\,\mathbf{q};\,\rho)$ and antimeson $\Pi_{\bar\phi}(q^0,\,\mathbf{q};\,\rho)$ nuclear self-energies are different owing to different $\phi N$ and $\bar\phi N$ interactions.

The pole position of the $T_{cc}(3875)$ and the $D^*_{s0}(2317)$ exotic hadrons do not completely determine the potentials $V_{\phi_1\phi_2}(s)$, which also depend of the coupling of these states to the $DD^*$ or

[2] Solution of the equation $E^2_{\rm qp} - q^2 - m^2_K - \mathrm{Re}\left[\Pi_K(E_{\rm qp},\,q;\,\rho)\right] = 0$.

$D\overline{K}$ channels, respectively, and that in turn, it is related to the molecular probability content $P_0$ of the exotic resonance [30–32]. After fixing $P_0$, we have considered two-term expansions of $V_{\phi_1\phi_2}(s)$ or $V^{-1}_{\phi_1\phi_2}(s)$ around threshold $s_0 = (m_{\phi_1} + m_{\phi_1})^2$. Though both approaches provide the same positions of the $T_{cc}(3875)$ and $D^*_{s0}(2317)$ poles in the free space, they however lead to different nuclear medium amplitudes $T_{\phi_1\phi_2}(s;\rho)$ for small molecular probability content scenarios [20–22].

## 3. Results and discussion

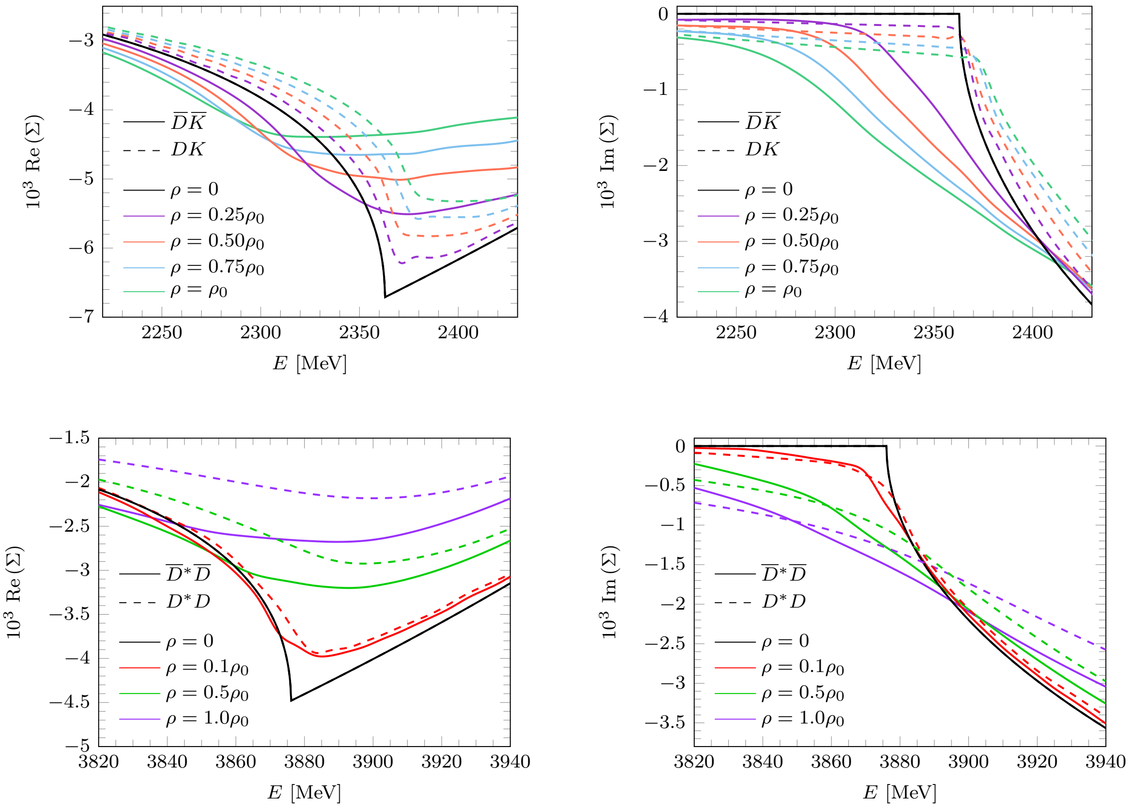


**Figure 2:** Medium two-meson loop function $\Sigma_{\phi_1\phi_2}(s;\rho)$ for different values of the nuclear density (in units of $\rho_0 = 0.17$ fm$^{-3}$), as a function of the center of mass energy of the corresponding meson pair ($s = E^2$). In the top [bottom] panels, the real (left) and imaginary (right) parts of the $\overline{D}\overline{K}$ [$\overline{D}^*\overline{D}$] (solid lines) and $DK$ [$D^*D$] (dashed lines) loop functions are shown. Plots are taken from Refs. [20] and [21].

In Fig. 2 we compare the $\overline{D}\overline{K}$ & $DK$ (top) and $DD^*$ & $\overline{D}\overline{D}^*$ (bottom) loop functions for different values of the nuclear density. Two point-functions for charged-conjugated channels coincide in the vacuum, as imposed by $C-$symmetry. However, we observe that both real (left plots) and imaginary parts (right plots) significantly deviate as the density increases. The charge-conjugation asymmetry pattern found for the $\overline{D}\overline{K}$-$DK$ sector is much more pronounced than in the $D^*D$-$\overline{D}^*\overline{D}$ one.

Next in Fig. 3, we show the modulus square of the medium amplitudes for two different values of $P_0$. These represent two quite opposite scenarios, and the one with higher molecular probability would roughly correspond to that found employing unitarized heavy-meson chiral perturbation theory in Ref. [16]. With increasing densities and molecular probabilities, we find that the $D^*_{s0}(2317)^+$

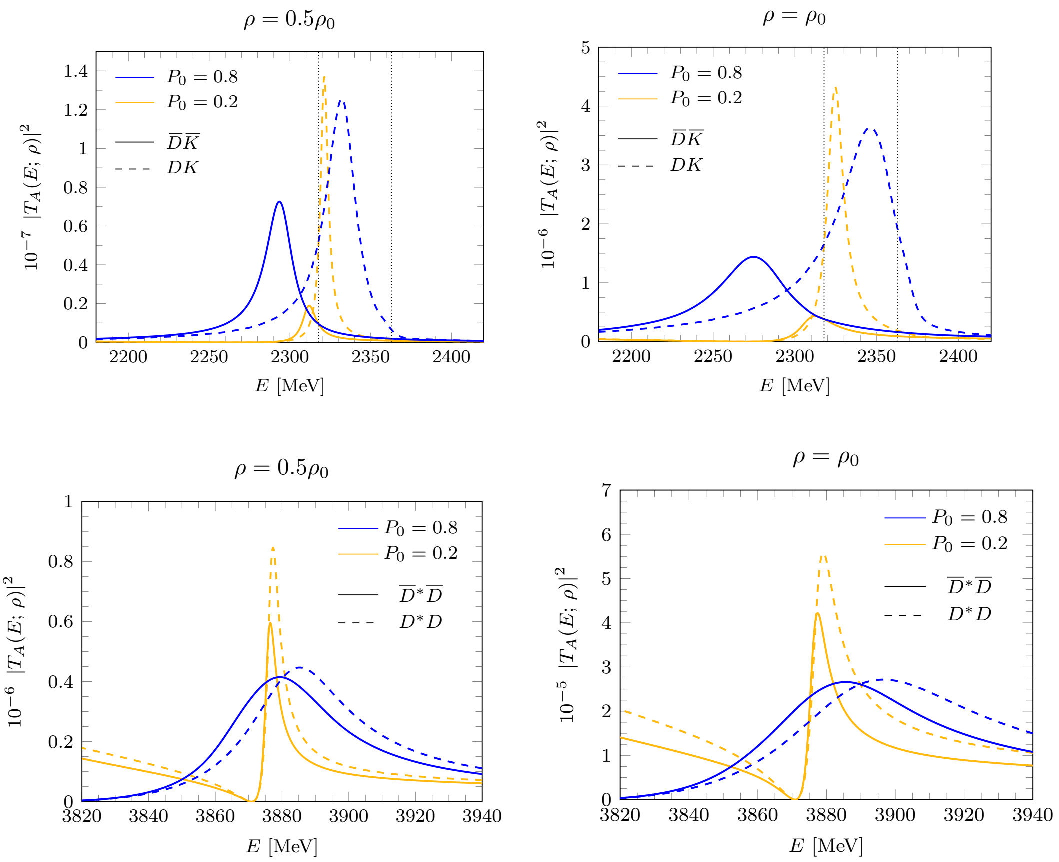


**Figure 3:** Medium $|T_{\phi_1\phi_2}(s;\rho)|^2$ for different values of the nuclear density and molecular contents, as function of the center of mass energy of the corresponding meson pair. In the top [bottom] panels, the solid and dashed lines show the $\overline{D}\overline{K}$ [$\overline{D}\overline{D}^*$] and $DK$ [$DD^*$] modulus squared amplitudes, respectively, for vacuum molecular probabilities $P_0 = 0.2$ (orange) and $P_0 = 0.8$ (blue), and for nuclear densities $\rho = 0.5\rho_0$ (left panels) and $\rho = \rho_0$ (right panels). In the top plots the dotted vertical lines correspond, from left to right, to the vacuum $D^*_{s0}(2317)^\pm$ mass and $DK$ (and $\overline{D}\overline{K}$) threshold. In all cases, we have considered a two-term expansion of the potential $V_{\phi_1\phi_2}(s)$ around threshold [20, 21]. Plots are taken from the latter references.

peak shifts towards higher energies and becomes less broad than its charge-conjugation partner $D^*_{s0}(2317)^-$, whose wider Breit-Wigner-like shape moves more noticeably at lower energies. At half normal nuclear matter density, the change is already so drastic for high molecular component scenarios that the $D^*_{s0}(2317)^+$ and $D^*_{s0}(2317)^-$ lineshapes hardly overlap.

We also observe that the widths of the $T^+_{cc}$ and $T^-_{\bar{c}\bar{c}}$ grow with increasing density, being this effect more notable for high values of $P_0$. We find that the position of the $T^-_{\bar{c}\bar{c}}$ peak always lies below the $T^+_{cc}$ one when considering high enough values of the molecular probability and density. However, the difference in energy between both states is almost not noticeable for low values of $P_0$ and density, as expected. On the other hand, we observe that the $T^-_{\bar{c}\bar{c}}$ state tends to be narrower than the $T^+_{cc}$ for high enough values of the molecular probability and density.

In summary, if these distinctive density dependencies of the particle-antiparticle line-shapes were confirmed experimentally, they would give qualitative and quantitative support to the presence of important molecular components in the $T_{cc}(3875)$ and the $D^*_{s0}(2317)$ exotic hadrons.

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## References

[1] F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, and B.-S. Zou, Rev. Mod. Phys. **90**, 015004 (2018), [Erratum: Rev.Mod.Phys. 94, 029901 (2022)], arXiv:1705.00141 [hep-ph] .

[2] R. Aaij *et al.* (LHCb), Nature Phys. **18**, 751 (2022), arXiv:2109.01038 [hep-ex] .

[3] R. Aaij *et al.* (LHCb), Nature Commun. **13**, 3351 (2022), arXiv:2109.01056 [hep-ex] .

[4] A. Feijoo, W. H. Liang, and E. Oset, Phys. Rev. D **104**, 114015 (2021), arXiv:2108.02730 [hep-ph] .

[5] M. Albaladejo, Phys. Lett. B **829**, 137052 (2022), arXiv:2110.02944 [hep-ph] .

[6] M.-L. Du, V. Baru, X.-K. Dong, A. Filin, F.-K. Guo, C. Hanhart, A. Nefediev, J. Nieves, and Q. Wang, Phys. Rev. D **105**, 014024 (2022), arXiv:2110.13765 [hep-ph] .

[7] B. Aubert *et al.* (BaBar), Phys. Rev. Lett. **90**, 242001 (2003), arXiv:hep-ex/0304021 .

[8] S. Godfrey and R. Kokoski, Phys. Rev. D **43**, 1679 (1991).

[9] E. E. Kolomeitsev and M. F. M. Lutz, Phys. Lett. B **582**, 39 (2004), arXiv:hep-ph/0307133 .

[10] F.-K. Guo, P.-N. Shen, H.-C. Chiang, R.-G. Ping, and B.-S. Zou, Phys. Lett. B **641**, 278 (2006), arXiv:hep-ph/0603072 .

[11] D. Gamermann, E. Oset, D. Strottman, and M. J. Vicente Vacas, Phys. Rev. D **76**, 074016 (2007), arXiv:hep-ph/0612179 .

[12] J. M. Flynn and J. Nieves, Phys. Rev. D **75**, 074024 (2007), arXiv:hep-ph/0703047 .

[13] C. B. Lang, L. Leskovec, D. Mohler, S. Prelovsek, and R. M. Woloshyn, Phys. Rev. D **90**, 034510 (2014), arXiv:1403.8103 [hep-lat] .

[14] A. Martínez Torres, E. Oset, S. Prelovsek, and A. Ramos, JHEP **05**, 153 (2015), arXiv:1412.1706 [hep-lat] .

[15] M. Albaladejo, P. Fernandez-Soler, F.-K. Guo, and J. Nieves, Phys. Lett. B **767**, 465 (2017), arXiv:1610.06727 [hep-ph] .

[16] M. Albaladejo, D. Jido, J. Nieves, and E. Oset, Eur. Phys. J. C **76**, 300 (2016), arXiv:1604.01193 [hep-ph] .

[17] G. S. Bali, S. Collins, A. Cox, and A. Schäfer, Phys. Rev. D **96**, 074501 (2017), arXiv:1706.01247 [hep-lat] .

[18] M.-L. Du, M. Albaladejo, P. Fernández-Soler, F.-K. Guo, C. Hanhart, U.-G. Meißner, J. Nieves, and D.-L. Yao, Phys. Rev. D **98**, 094018 (2018), arXiv:1712.07957 [hep-ph] .

[19] M. Albaladejo, P. Fernandez-Soler, J. Nieves, and P. G. Ortega, Eur. Phys. J. C **78**, 722 (2018), arXiv:1805.07104 [hep-ph] .

[20] V. Montesinos, M. Albaladejo, J. Nieves, and L. Tolos, Phys. Rev. C **108**, 035205 (2023), arXiv:2306.17673 [hep-ph] .

[21] V. Montesinos, M. Albaladejo, J. Nieves, and L. Tolos, Phys. Lett. B **853**, 138656 (2024), arXiv:2403.00451 [hep-ph] .

[22] M. Albaladejo, J. M. Nieves, and L. Tolos, Phys. Rev. C **104**, 035203 (2021), arXiv:2102.08589 [hep-ph] .

[23] L. Tolos, D. Cabrera, and A. Ramos, Phys. Rev. C **78**, 045205 (2008), arXiv:0807.2947 [nucl-th] .

[24] L. Tolos, C. Garcia-Recio, and J. Nieves, Phys. Rev. C **80**, 065202 (2009), arXiv:0905.4859 [nucl-th] .

[25] C. Garcia-Recio, J. Nieves, and L. Tolos, Phys. Lett. B **690**, 369 (2010), arXiv:1004.2634 [nucl-th] .

[26] C. Garcia-Recio, J. Nieves, L. L. Salcedo, and L. Tolos, Phys. Rev. C **85**, 025203 (2012), arXiv:1111.6535 [nucl-th] .

[27] J. Nieves and E. Ruiz Arriola, Nucl. Phys. A **679**, 57 (2000), arXiv:hep-ph/9907469 .

[28] L. Tolos, A. Ramos, and E. Oset, Phys. Rev. C **74**, 015203 (2006), arXiv:nucl-th/0603033 .

[29] D. Cabrera, L. Tolós, J. Aichelin, and E. Bratkovskaya, Phys. Rev. C **90**, 055207 (2014), arXiv:1406.2570 [hep-ph] .

[30] S. Weinberg, Phys. Rev. **137**, B672 (1965).

[31] I. Matuschek, V. Baru, F.-K. Guo, and C. Hanhart, Eur. Phys. J. A **57**, 101 (2021), arXiv:2007.05329 [hep-ph] .

[32] M. Albaladejo and J. Nieves, Eur. Phys. J. C **82**, 724 (2022), arXiv:2203.04864 [hep-ph] .