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Detecting the long-distance structure of the $X(3872)$

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Abstract

In this work we focus on the analysis of the $X(3872) \to D^0\bar{D}^0\pi^0$ decay assuming a molecular picture for the $X(3872)$ state within an effective field theory (EFT) approach. This decay is sensitive to the long-distance structure of the $X(3872)$; in sharp contrast with the main decay channels: $J/\psi\pi\pi$ and $J/\psi 3\pi$. We show that the final state interactions in the $D\bar{D}$ system can be important and that the measurement of this partial decay width can provide a constrain on the low energy constants (LECs) of the $D^{(*)}\bar{D}^{(*)}$ EFT.

1. Introduction

The discovery of the $X(3872)$ in 2003 by the Belle collaboration [1] was a huge milestone in the understanding of the QCD spectrum. This resonance did not fit into the conventional quark model so an exotic explanation was required. Since then, a lot of theoretical work has been done under tetraquark, mesonic molecular nature and hybrid assumptions. In this work, we will assume a $D\bar{D}^*$ molecular structure for this resonance, as suggested by its proximity to the threshold of these two mesons, and $J^{PC} = 1^{++}$ quantum numbers [3].

The main decay channels of this resonance are $J/\psi\pi\pi$ and $J/\psi 3\pi$. The comparable branching ratios of these two modes point out to a large isospin violation. Nevertheless, these two decays only provide information about the short-distance part of the molecular $X(3872)$ wave function [3]. This is because the two heavy-light mesons should be close enough to recombine and give rise to J/ψ in the final state.

One way to obtain information about the $X(3872)$ long-distance part of the wave function is to study decay channels where one of the constituent hadrons is in the final state and the rest of the final particles are products of the decay of the other constituent hadron of the X(3872) molecule. One of these modes is the $X(3872) \to D^0\bar{D}^0\pi^0$. It is important to notice that the charged decay mode is kinematically forbidden.

2. Heavy meson-Heavy Antimeson EFT

We study the $X(3872) \to D^0\bar{D}^0\pi^0$ within an EFT approach. This EFT approach is based on the different light and heavy quark symmetries a heavy meson-heavy antimeson molecular system should approximately fulfill. This EFT has already been used in [4, 5, 6, 7] to predict a whole family of resonances heavy quark spin-flavour partners of the $X(3872)$ and the $Z_b(10610)/Z_b'(10650)$ states, understood as a $D\bar{D}^*$ and isovector $B\bar{B}^*$ / $B^*\bar{B}^*$ molecules, respectively.. In these works, the $X(3872)$ is described as a $D\bar{D}^*$ molecule without a well defined isospin to account for the experimental ratio of $J/\psi\pi\pi$ and $J/\psi 3\pi$ branching fractions. We are summarizing the formalism here, and further information can be seen in the original works.

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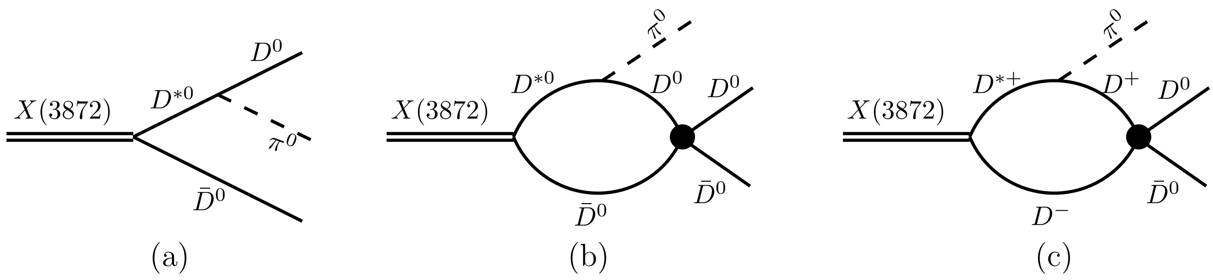

Figure 1: Feynman diagrams for the decay $X(3872) \to D^0\bar{D}^0\pi^0$. The charge conjugate channel is not shown but included in the calculations.

After considering the Heavy Quark Spin Symmetry (HQSS) arising in the QCD lagrangian in the $m_Q \to \infty$ limit, at leading order, the interaction among heavy-light mesons is described by a contact potential, since pion exchanges and coupled channels are higher-order effects [4, 8]. This leading order contact interaction is written in its most general form in Eq.(1) and it is important to notice that it only depends on four undetermined LECs (rewritten without loss of generality as C_{0A}, C_{0B}, C_{1A} and C_{1B}). The LECs are determined from the masses of some resonances assumed molecules: the $X(3872)$ as a $J^{PC} = 1^{++}$ $D\bar{D}^*$ molecule and the $Z_b(10610)/Z_b'(10650)$ as isovector $B\bar{B}^*/B^*\bar{B}^*$ molecules. These two hypothesis are sound as both resonances are close to its corresponding threshold.

$$\begin{aligned} V_4 &= \frac{C_A}{4}\, Tr\left[\bar{H}_a^{(Q)} H_a^{(Q)} \gamma_\mu\right] Tr\left[H_a^{(\bar{Q})} \bar{H}_a^{(\bar{Q})} \gamma^\mu\right] \quad (1) \\ &+ \frac{C_A^\lambda}{4}\, Tr\left[\bar{H}_a^{(Q)} \lambda_{ab}^i H_b^{(Q)} \gamma_\mu\right] Tr\left[H_c^{(\bar{Q})} \lambda_{cd}^i \bar{H}_d^{(\bar{Q})} \gamma^\mu\right] + \\ &+ \frac{C_B}{4}\, Tr\left[\bar{H}_a^{(Q)} H_a^{(Q)} \gamma_\mu \gamma_5\right] Tr\left[H_a^{(\bar{Q})} \bar{H}_a^{(\bar{Q})} \gamma^\mu \gamma_5\right] \\ &+ \frac{C_B^\lambda}{4}\, Tr\left[\bar{H}_a^{(Q)} \lambda_{ab}^j H_b^{(Q)} \gamma_\mu \gamma_5\right] Tr\left[H_c^{(\bar{Q})} \lambda_{cd}^j \bar{H}_d^{(\bar{Q})} \gamma^\mu \gamma_5\right] \end{aligned}$$

The above interaction is used as a kernel of the Lippmann-Schwinger Equation (LSE). We look for poles in the LSE amplitudes, whose positions provide the mases of the generated molecular states. In this way, we fix three linear combinations of the LECs can be fixed: $C_{0X} = C_{0A} + C_{0B}$, $C_{1X} = C_{1A} + C_{1B}$ and $C_Z = C_{1A} - C_{1B}$. Note that, a gaussian regulator Λ has to be included to treat the UV divergences in the LSE thus the LECs depend on the gaussian regulator Λ. The important thing is that physical results (masses and decay widths) must be regulator-independent.

Finally, the lagrangian in Eq. (1) gives the interactions for the $D\bar{D}$ system. However, in this interaction is appears also the undetermined LEC C_{0A}.

3. $X(3872)$ long-distance decays.

Compared to the main short-distance decays, the long-distance decays are more interesting to probe the molecular nature of the resonance. For this reason, it is worth studying of the $X(3872) \to D^0\bar{D}^0\pi^0$ decay, where a $D^* \to D\pi$ decay has occurred. This decay channel has already been observed in [9].

The contributions to the decay width of this channel are depicted in Fig. 1. For the numerical evaluation of the decay width the $X(3872) \to D\bar{D}^*$ couplings are needed. In our scheme, we find [4, 5]:

$$g_0^X = 0.35^{+0.08}_{-0.29}\,(0.34^{+0.07}_{-0.29})\ \text{GeV}^{-1/2}, \quad (2)$$
$$g_c^X = 0.32^{+0.07}_{-0.26}\,(0.26^{+0.05}_{-0.22})\ \text{GeV}^{-1/2}, \quad (3)$$

for $\Lambda = 0.5(1.0)$ GeV. If we now only take into account the tree level contribution without any kind of final state interaction (FSI), the partial decay width for the three-body decay $X(3872) \to D^0\bar{D}^0\pi^0$ at tree level is predicted to be

$$\Gamma_{\text{tree}} = 44.0^{+2.4}_{-7.2}\left(42.0^{+3.6}_{-7.3}\right)\ \text{keV}, \quad (4)$$

at $\Lambda = 0.5(1.0)$ GeV, respectively (see [10] for details).

Including the full calculation instead, a dependence on C_{0A} arises from the $D\bar{D}$ FSI, as previously advanced. These results are shown in Fig. 2. First of all, the results are quite regulator-independent. Second, we can see no obvious deviations from the tree level behavior except for some values of C_{0A}, for which a close to threshold $D\bar{D}$ bound state is generated. This behavior is common to every value of the Λ regulator; the only difference is that the interference effects appear at different values of the C_{0A} LEC, as can be appreciated in Fig. 2.

Therefore, deviations from the tree level prediction of a precise experimental measurement of the $X(3872) \to D^0\bar{D}^0\pi^0$ partial decay width will constrain the possible values for the C_{0A} LEC and the existence of a possible $D\bar{D}$ bound state.

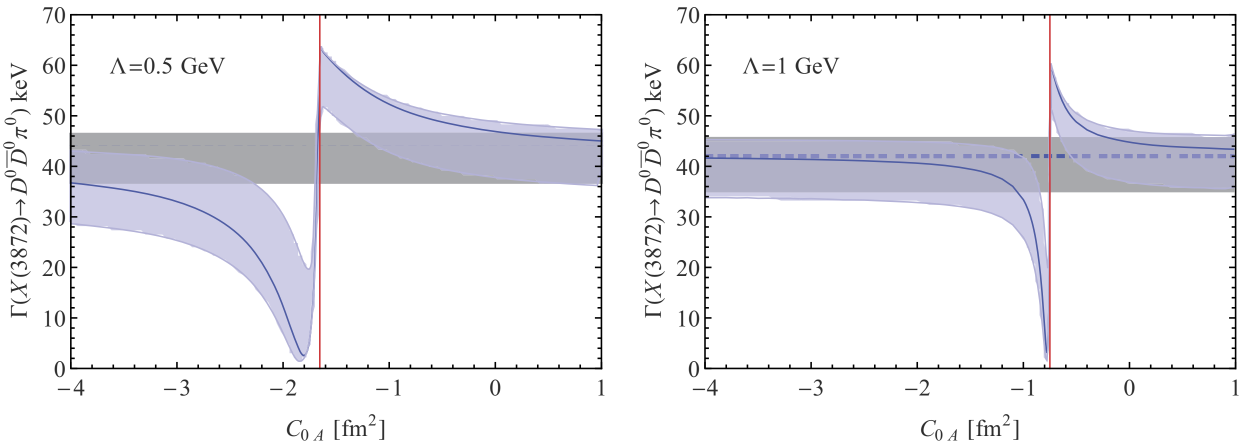

Figure 2: Dependence of the $X(3872) \to D^0\bar{D}^0\pi^0$ partial decay width on the low-energy constant C_{0A}. The UV cutoff is set to $\Lambda = 0.5$ GeV (1 GeV) in the left (right) panel. The blue error bands contain $D\bar{D}$ FSI effects, while the grey bands stand for the tree level predictions of Eq. (4). The solid (full calculation) and dashed (tree level) lines stand for the results obtained with the central values of the parameters. The vertical lines denote the values of C_{0A} for which a $D\bar{D}$ bound state is generated at the $D^0\bar{D}^0$ threshold.

4. Conclusions

In this work, we explored the decay of the $X(3872)$ into $D^0\bar{D}^0\pi^0$ using an EFT based on the hadronic molecule assumption for the $X(3872)$. This decay is unique in the sense that it is sensitive to the long-distance structure of the $X(3872)$ as well as the strength of the S-wave interaction between the D and $\bar{D}$.

We show that if there was a near threshold pole in the $D\bar{D}$ system, the partial decay width can be very different from the result neglecting the FSI effects. Thus, this decay may be used to constrain the so far unknown parameter C_{0A} in this situation. Such is valuable to better understand the interaction between a heavy-light meson and a heavy-light antimeson and it would be very useful to predict of symmetric partners of the $X(3872)$ that could be thought as mesonic molecules too. Thus, we conclude that the study of this decay could become a useful tool to achieve a more precise knowledge of the exotic XYZ states.

It is also worth mentioning that the contribution of the $X(3872)$ charged component $(D^+D^{*-} - D^{*+}D^-)$ is not important even when the $D\bar{D}$ FSI mechanisms are taken into account. This could be expected since the binding energy of the charged channel is much larger than the binding energy of the neutral channel.

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