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

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In this work we use an effective field theory (EFT) approach to study the $X(3872)$ resonance, assuming a heavy meson-heavy antimeson molecule as its inner structure. From this EFT we extract some direct consequences for the hidden charm and bottom hadronic spectrum.

Within this EFT we also study the decay $X(3872) \to D^0\bar{D}^0\pi^0$. This decay is unique since it is more sensitive to the long-distance part of the $X(3872)$ wave function than the $X(3872) \to J/\psi\pi\pi$ and $X(3872) \to J/\psi\pi\pi\pi$ modes. We also show that the possible $D\bar{D}$ Final State Interactions (FSI) effects can lead to experimental constrains on the Low Energy Constants (LECs) that appear in the EFT and the possible existence of a loosely $D\bar{D}$ bound state.

1 Introduction

The current understanding of the hadronic spectrum is a milestone in particle physics. The success of the conventional quark model (where mesons and baryons are the only possible quark composites) in the classification of known particles and the prediction of different states is outstanding. However, beyond the quark model there are other exotic possibilities that QCD allows. These exotics (glueballs, tetraquarks, hadronic molecules...), though theoretically predicted, have not been experimentally confirmed yet.

The existence of hadronic molecules, first predicted in the mid-70s by Voloshin and Okun [1] was based on the similarities these systems shared with the deuteron. The best candidate to fit this hadronic molecule description is the $X(3872)$, discovered by Belle in 2003 [2] in the $J/\psi\pi\pi$ channel. Based on the closeness to the $D\bar{D}^*$ threshold this resonance is thought to be a $D\bar{D}^*$ with quantum numbers $J^{PC} = 1^{++}$. These quantum numbers were later confirmed in 2011 by the LHCb collaboration [3]. Taking into account this experimental information, it seems likely that the hadronic molecule component of the $X(3872)$ wave function plays an important role in the description of the resonance.

In this work we use an EFT to describe these heavy meson-heavy antimeson molecules. In Sec. 2 the main features of this EFT are briefly explained since they have been extensively covered in previous works. In Sec. 3, the computation of the $X(3872) \to D^0\bar{D}^0\pi^0$ decay width is carried out. Finally some conclusions are established in Sec. 4.

2 The heavy meson-heavy antimeson EFT

In this section the EFT that is going to be used along this work is introduced. At leading order (LO), the description of heavy meson-heavy antimeson molecules can be done with a contact potential determined by Heavy Quark Spin Symmetry (HQSS) as proposed in [4]. This LO lagrangian, when considering the isospin degrees of freedom, depends exclusively on four undetermined LECs. Other subleading effects such as pion exchanges and coupled channel effects are less important than expected and can be taken into account by the errors of the order $\mathcal{O}\left(\frac{1}{m_Q}\right)$, that will be introduced to account for not considering the next order in the EFT expansion [5].

The lagrangian provides the kernel that is employed in a Lippmann-Schwinger Equation (LSE). Poles in the T-matrix give rise to the different molecular states. The LSE, however, has a ultraviolet divergent two-body loop function. This divergence can be treated employing several regularization methods. We are using a gaussian regulator Λ and we choose two different gaussian regulators $\Lambda = 0.5(1.0)$ GeV, see [6, 7] for details.

Now, assuming some experimental resonances are heavy meson-heavy antimeson molecules we can fix some linear combination of the four undetermined LECs in the lagrangian. For that purpose, we find that the $X(3872)$ and the $Z_b(10610)/Z_b'(10650)$ [10] are perfect candidates. As already said, the $X(3872)$ can be thought as a $D\bar{D}^*$ with quantum numbers $J^{PC} = 1^{++}$. In the Z_bs case, we are dealing with resonances whose quark content must be of, at least, four quarks since they have $I_{Z_b} = 1$. Even more, its closeness to the $B\bar{B}^*$ and $B^*\bar{B}^*$ threshold respectively, suggest that a molecular interpretation with quantum numbers $J^{PC} = 1^{+-}$ is very sensible.

Thanks to these two assumptions we can fix three different linear combinations on LECs. Two of them come from the $X(3872)$ assumption (where we have also taken into account the isospin violating decays in the fit, see [7] for further information) and the third one comes from the experimental masses of the Z_bs resonances. This means that there is still an undetermined LEC in our model, that we will call C_{0A} without loss of generality.

We have used this scheme in previous works, predictions for HQSS heavy meson-heavy antimeson molecules [6, 7, 8] and pentaquark-like states that will be partners of the $X(3872)$ and $Z_b(10610)/Z_b'(10650)$ resonances [9]. In these works we found that there was almost no dependence on the regulation method used and that the small differences that appear can be accounted in the expansion errors too.

3 $X(3872) \to D^0\bar{D}^0\pi^0$ decay

So far, the only experimental information about the $X(3872)$ we have used in the analysis is its mass and the ratio of its $X(3872) \to J/\psi\pi\pi$ and $X(3872) \to J/\psi\pi\pi\pi$ decay widths. In these decays, the $D(\bar{D})$ and $\bar{D}^*(D^*)$ components of the $X(3872)$ have to be close so its charm quark and antiquark can form a charmonium state. Therefore, we can extract little information about the long-distance structure of the $X(3872)$. This long-distance structure of the resonance could become a very important piece of information to differenciate between two exotic structures like tetraquarks and hadronic molecules.

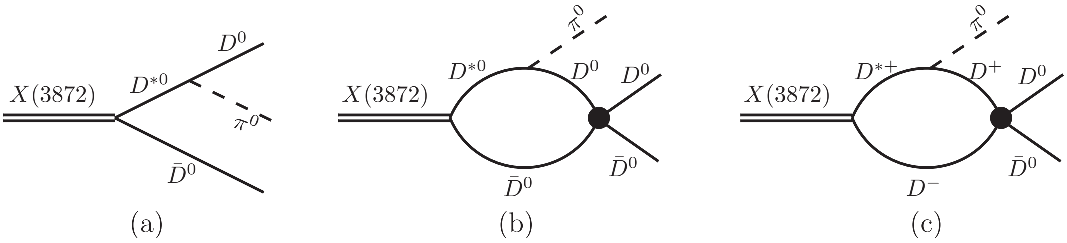

Figure 1: Feynman diagrams for the decay $X(3872) \to D^0\bar{D}^0\pi^0$. The charge conjugate channel is not shown but included in the calculations.

Hence, the detailed analysis of different decays where the $X(3872)$ inner components keep their individual properties is crucial for the full comprehension of the resonance. The $X(3872) \to D^0\bar{D}^0\pi^0$ (already observed in [11]) decay looks like a perfect probe of the long-distance structure of the $X(3872)$. As it can be seen in Fig.1, the $X(3872)$ can decay despite its $D^{*0}(\bar{D}^{*0})$ and $\bar{D}^0(D^0)$ inner components are substancially separated. It should already be noticed that this is the only $X(3872) \to D\bar{D}\pi$ decay channel since the charged decays are kinematically forbidden.

In this decay, there are two contributions. The tree level contribution is depicted in Fig.1a (and its corresponding charge conjugated diagram). From the $X(3872)$ pole residue we determine the $X(3872)D^0\bar{D}^0$ coupling and we obtain [12]:

$$\Gamma(X(3872) \to D^0\bar{D}^0\pi^0)_{\rm tree} = 44.0^{+2.4}_{-7.2}\left(42.0^{+3.6}_{-7.3}\right)\ \text{keV}, \tag{1}$$

for $\Lambda = 0.5$ (1.0) GeV, respectively. Next, we include the possible FSI between the D-mesons and the $\bar{D}$-antimesons, as shown in the Feynman diagrams of Fig.1b and Fig.1c. In this case, we need for the computation of the decay width the four LECs of our model. Our results, therefore, will be a function of the undetermined LEC C_{0A}. The results obtained are displayed in Fig.2, being the grey band the results coming from the tree level calculation.

As can be observed, there is no appreciable dependence on the gaussian regulator in the results. However, the inclusion of FSI mechanism has created a *bump* in the decay width curve. This is caused by the interferences due to the possible existence of a $D\bar{D}$ bound state with quantum numbers $J^{PC} = 0^{++}$. For that reason, a precise experimental value of the $X(3872) \to D^0\bar{D}^0\pi^0$ decay width could be an important asset in the determination of the fourth, still undetermined, LEC and can also rule out or confirm the existence of this $D\bar{D}$ bound state, predicted in several theoretical models.

4 Conclusions

In this work, we have studied the decay of the $X(3872)$ resonance into $D^0\bar{D}^0\pi^0$ using an EFT based on a hadronic molecule assumption for the $X(3872)$ and HQSS. We show that $D\bar{D}$ FSI effects can be important specially if a near threshold pole exists. Besides, this decay may be used to measure the so far unknown parameter C_{0A} of the HQSS EFT employed in this work. Such information is valuable to better understand the interaction between heavy-light mesons and heavy-light antimesons.

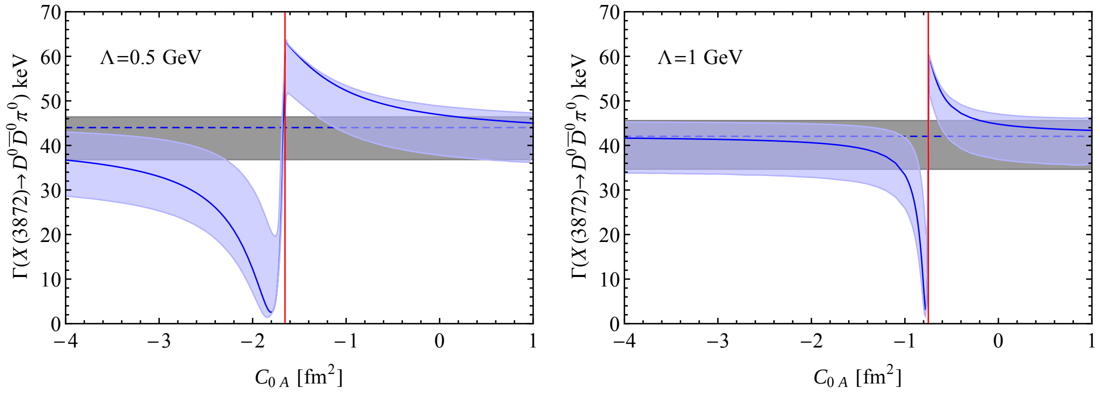

Figure 2: Dependence of the $X(3872) \to D^0\bar{D}^0\pi^0$ partial decay width on the C_{0A} LEC. The UV cutoff is set to $\Lambda = 0.5$ GeV (1 GeV) in the left (right) panel. The blue error bands contain $D\bar{D}$ FSI effects, while the grey bands stand for the tree level prediction. The vertical 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.

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