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A novel model to $D^+ \to K^+K^-K^+$ decay amplitude

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We propose a novel approach to describe the $D^+ \to K^+K^-K^+$ decay amplitude, based on chiral effective Lagrangians, which can be used to extract information about $K\bar{K}$ scattering. Our trial function is an alternative to the widely used isobar model and includes both nonresonant three-body interactions and two-body rescattering amplitudes, based on coupled channels and resonances, for S- and P-waves with isospin 0 and 1. The latter are unitarized in the K-matrix approximation and represent the only source of complex phases in the problem. This approach allows one to disentangle the two-body scalar contributions with different isospins, associated with the $f_0(980)$ and $a_0(980)$ channels.

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PoS(HQL2018)042

1. Introduction

A theoretical description for a three-body nonleptonic decay of a heavy-flavoured meson into light $SU(3)$ pseudoscalars involves two different sets of interactions. In the primary weak vertex the heavy quark emits a W and becomes a light flavour one. The primary vertex is then followed by a purely hadronic final state interactions (FSI), in which the mesons produced initially rescatter in many different ways, before being detected. The usual experimental approach to describe those processes is based on the isobar model and has long been criticised for many reasons among which the lack of two-body unitarity. With the new high precision experiments studying B and D decays from LHCb and Belle II, the amplitude analysis of these processes demands better models.

In a recent work [1] we suggest a novel approach based on effective Lagrangians, whose main new feature is the stress put on multi-meson interactions characteristic of chiral symmetry, and apply it to the $D^+ \to K^+K^-K^+$ decay. We concentrates explicitly on the derivation of two-body scattering amplitudes from three-body decays. This process is interesting because there is very little information available on kaon-kaon scattering, regarding both theory and experiment.

2. Multi-Meson-Model for $D^+ \to K^+K^-K^+$

Our model is based on the assumption that the weak sector of the doubly-Cabibbo-suppressed decay $D^+ \to K^-K^+K^+$ is dominated by the process shown in Fig.1 (left), in which quarks c and $\bar{d}$ in the D^+ annihilate into a W^+, which subsequently hadronizes. In this topology, the decay

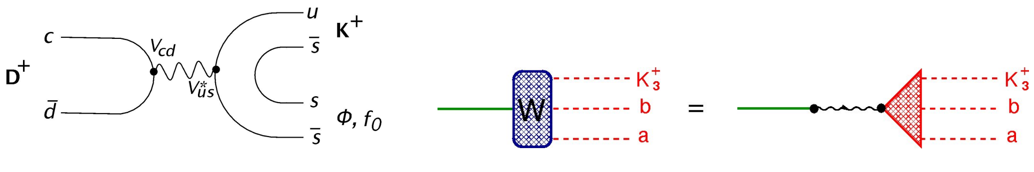

Figure 1: Weak vertex for $D^+ \to K^+K^-K^+$: (left) quark annihilation topology; (right) hadronic diagram.

amplitude is given by

$$T = -\left[\frac{G_F}{\sqrt{2}} \sin^2\theta_C\right] \langle K^-(p_1)K^+(p_2)K^+(p_3)|A^\mu|0\rangle \, \langle 0|A_\mu|D^+(P)\rangle \,, \tag{2.1}$$

where G_F is the Fermi decay constant, θ_C is the Cabibbo angle, the A^μ are axial currents, $P = p_1 + p_2 + p_3$, $\langle 0|A_\mu|D^+(P)\rangle = -i\sqrt{2}F_D P_\mu$ and $\langle (KKK)^+|A_\mu|0\rangle$ is described by what we call Multi-Meson Model, or Triple-M. The decay amplitude can be fully described within chiral effective theory. The universal character of this latter matrix element allows to easily extend this formalism to other heavy meson decays into three kaons or even tau decays.

The primary weak decay is followed by final state interactions (FSI), involving scattering amplitudes. The FSI is considered in the quasi-two-body approximation where the two-body amplitude includes a coupled-channel description appropriate for the quantum numbers of spin-isospin corresponding to (Spin $J = 0,1$; Isospin $I = 0,1$). These channels are associated to the resonances $\rho(770)$, $\phi(1020)$, $a_0(980)$, and two (0,0) $SU(3)$ scalar-isoscalar states- corresponding to an isosinglet and an octet. The decay amplitude T is then given by

$$T \;=\; T_{NR} + \Big[T^{(1,1)} + T^{(1,0)} + T^{(0,1)} + T^{(0,0)} + (2 \leftrightarrow 3)\Big] \tag{2.2}$$

and represented by the diagrams in Fig. 2. Each diagram in Fig. 2 was evaluated using the

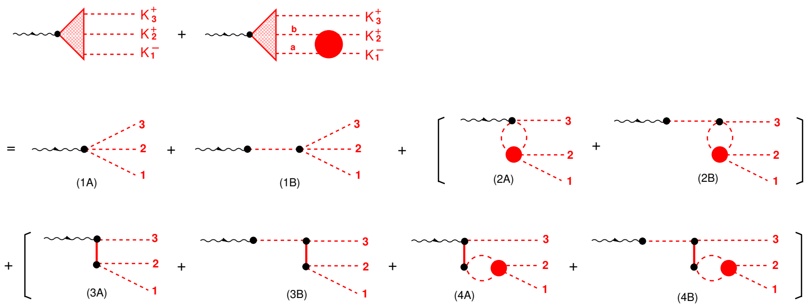

Figure 2: Dynamical structure of triangle vertices in Fig. 1(right); the wavy line is the W^+, dashed lines are mesons, continuous lines are resonances and the full red blob represent meson-meson scattering amplitudes, described in Fig. 3; all diagrams within square brackets should be symmetrized, by making $2 \leftrightarrow 3$.

techniques described in Refs. [3, 4]. In chiral perturbation theory, the primary couplings of the W^+ to the $K^-K^+K^+$ system always involve a direct interaction, accompanied by a kaon-pole term, denoted by (A) and (B) in the figure. Only their joint contribution is compatible with PCAC. Diagrams (1A+1B) are LO and describe a non-resonant term, a proper three body interaction, which goes beyond the $(2+1)$ approximation, whereas diagrams (2A+2B) allow for the possibility that two of the mesons rescatter, after being produced in the primary weak vertex. Diagrams (3A+3B) are NLO and describe the *production* of bare resonances at the weak vertex, whereas final state rescattering processes (4A+4B) endow them with widths.

2.1 2-body unitary and coupled-channel

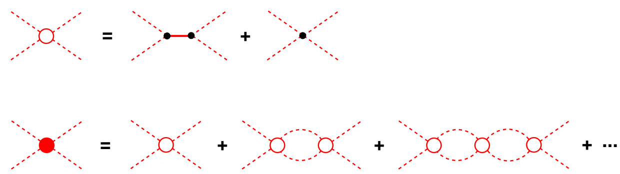

Figure 3: (a) Tree-level two-body interaction kernel $\mathscr{K}^{(J,I)}_{ab\to cd}$ - a NLO s-channel resonance, added to a LO contact term. (b) Structure of the unitarized scattering amplitude.

The basic meson-meson intermediate interactions $P^aP^b \to P^cP^d$ are described by *kernels* $\mathscr{K}^{(J,I)}_{ab|cd}$ and their simple dynamical structure is shown in Fig. 3, as LO four point terms, typical of chiral symmetry [3], supplemented by NLO resonance exchanges in the s-channel. Just in the $(J=0, I=0)$ channel two resonances, S_1 and S_o, are needed. In these diagrams, all *vertices* represent interactions derived from chiral lagrangians [4]. Kernels are then functions depending on just masses and coupling constants. The evaluation of amplitudes involves the iteration of the basic kernels by means of two-meson propagators, as in Fig. 3(b). The propagators, denoted by $\bar{\Omega}$,

PoS(HQL2018)042

have both real and imaginary components. The former contain divergent contributions and their regularization brings unknown parameters into the problem. This considerable nuisance is avoided by working in the K-matrix approximation, whereby just the imaginary parts of the two-meson propagators are kept.

The resonance masses and coupling constants derived from the basic lagrangian adopted [4] are potentially free parameter of our amplitude T. The former include m_ρ, m_ϕ, m_{a0}, m_{S1} and m_{So}, whereas the latter involve F, the pseudoscalar decay constant, G_V, the coupling constant of vector mesons to pseudoscalars, an angle θ, associated with $\omega\!-\!\phi$ mixing, c_d, c_m, describing the couplings of both a_0 and S_o to pseudoscalars, and $\tilde{c}_d, \tilde{c}_m$, implementing the couplings of S_1 to pseudoscalars. These parameters can not have the same meaning as their low-energy counterparts, since they are designed to be used into a mathematical structure which is different from ChPT. The former correspond to effective parameters describing the physics within the energy ranges defined by Dalitz plots and should not be expected to have the same values as the latter.

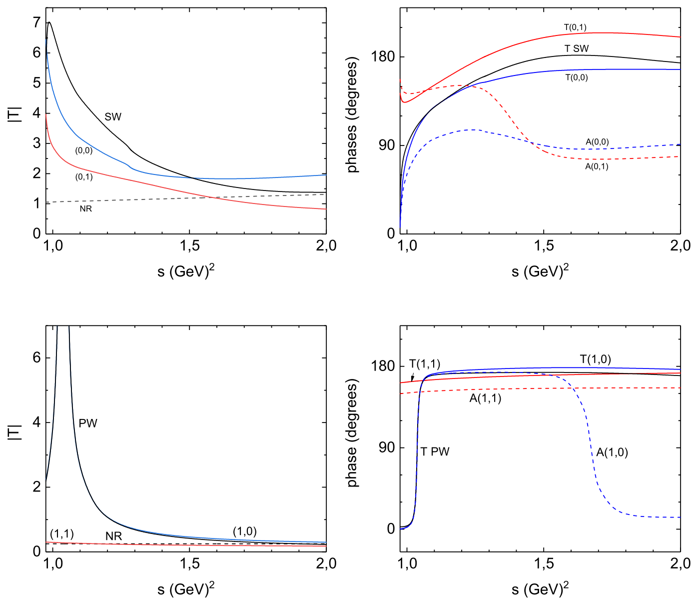

Figure 4: Results for S- (top) and P-wave(bottom) $D^+ \to K^+K^-K^+$ decay amplitude (left) and phase (right): continuous black curve (SW) is the decay amplitude, whereas other curves are the spin-isospin partial contributions; phases are compared with the $K\bar{K}$ scatterig amplitudes $A^{(J,I)}$.

3. Results - TOY parameters

The Triple-M is aimed at predicting scattering amplitudes by using parameters obtained from fits to decay data [2]. by using those suited to problems at low-energies [4]. The results for magnitude and phase at S and P-wave are given in Fig. 4. These figures illustrate the usefulness of the lagrangian approach: one can access partial contributions in different isospin channels. Moreover, it is also clear that $K\bar{K}$ scattering amplitudes $A^{(J,I)}$, are very different and cannot be guessed from the decay components. For more details of all the calculations please go to Ref. [1]. One interesting outcome of this model are the predictions for $K\bar{K}$. In Fig. 5 we present the phase shifts and inelasticity results where, even with toy parameters, one can see the role of the coupled channel structures.

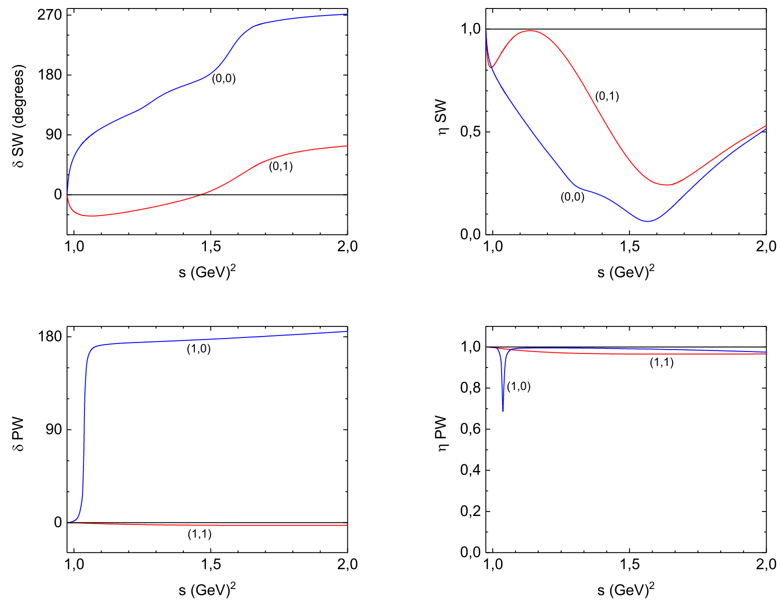

Figure 5: Phase shifts δ and inelasticity parameter η for $K\bar{K}$ scattering - top: S-waves; bottom: P-waves; blue and red curves correspond respectively to isospin I=0 and I=1.

4. Final remarks

The model developed for $D^+ \to K^+K^-K^+$ relies on factorization and its main novel feature is the role played by multimeson interactions characteristic of chiral symmetry. The nonresonant component, given by chiral symmetry as a real polynomial, is an important prediction of the model, which goes beyond the (2+1) approximation.

In the Triple-M amplitude, the relative contribution and phase of each component is a consequence of the theory, which represents an important difference to the isobar model. At present, the values of masses and couplings are given by the basic chiral lagrangian but, ultimately, they should be determined by a fit to data [2]. One striking feature of Triple-M is the ability of disentangle the different Isospin contributions from $a_0(980)$ and $f_0(980)$.

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