

## 83. Pole Structure of the $\Lambda(1405)$ Region

Revised June 2021 by T. Hyodo (Tokyo Metropolitan U.) and U.-G. Meißner (Bonn U.; Jülich).

The  $\Lambda(1405)$  resonance emerges in the meson-baryon scattering amplitude with the strangeness  $S = -1$  and isospin  $I = 0$ . It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and systematic approach for the low-energy regime of the strong interactions is chiral perturbation theory (ChPT), see e.g. Ref. [2]. A perturbative calculation is, however, not applicable to this sector because of the existence of the  $\Lambda(1405)$  just below the  $\bar{K}N$  threshold. In this case, ChPT has to be combined with a non-perturbative resummation technique, just as in the case of the nuclear forces. By solving the Lippmann-Schwinger equation with the interaction kernel determined by ChPT and using a particular regularization, in Ref. [3] a successful description of the low-energy  $K^-p$  scattering data as well as the mass distribution of the  $\Lambda(1405)$  was achieved (for further developments, see Ref. [4–7] and references therein).

The study of the pole structure was initiated by Ref. [8], which finds two poles of the scattering amplitude in the complex energy plane between the  $\bar{K}N$  and  $\pi\Sigma$  thresholds. The spectrum in experiments exhibits one effective resonance shape, while the existence of two poles results in the reaction-dependent lineshape [9]. The origin of this two-pole structure is attributed to the two attractive channels of the leading order interaction in the SU(3) basis (singlet and octet) [9] and in the isospin basis ( $\bar{K}N$  and  $\pi\Sigma$ ) [10]. It is remarkable that the sign and the strength of the leading order interaction is determined by a low-energy theorem of chiral symmetry, i.e. the so-called Weinberg-Tomozawa term. The two-pole nature of the  $\Lambda(1405)$  is qualitatively different from the case of the N(1440) resonance. Two poles of the N(1440) appear on different Riemann sheets of the complex energy plane separated by the  $\pi\Delta$  branch point. These poles reflect a single state, with a nearby pole and a more distant shadow pole. In contrast, the two poles in the  $\Lambda(1405)$  region on the same Riemann sheet (where  $\pi\Sigma$  channels are unphysical and all other channels physical, correspondingly to the one, connected to the real axis between the  $\pi\Sigma$  and  $\bar{K}N$  thresholds) are generated from two attractive forces mentioned above [9, 10].

Recently, various new experimental results on the  $\Lambda(1405)$  have become available [4]. Among these, the most striking measurement is the precise determination of the energy shift and width of kaonic hydrogen by the SIDDHARTA collaboration [11, 12], which provides a quantitative and stringent constraint on the  $K^-p$  amplitude at threshold through the improved Deser formula [13]. Systematic studies with error analyses based on the next-to-leading order ChPT interaction including the SIDDHARTA constraint have been performed by various groups [14–18]. All these studies confirm that the new kaonic hydrogen data are compatible with the scattering data above threshold.

The results of the pole positions of  $\Lambda(1405)$  in the various approaches are summarized in Table 83.1. We may regard the difference among the calculations as a systematic error, which stems from the various approximations of the Bethe-Salpeter equation, the fitting procedure, and also the inclusion of SU(3) breaking effects such as the choice of the various meson decay constants, and so on. A detailed comparison of the various approaches that enter the table is given in Ref. [19]. A recent analysis including also the  $J^P = 1/2^+$  P-wave contribution (and also an explicit  $\Sigma(1385)$   $3/2^+$  state) gives results consistent with the findings reported above, with the pole positions at  $(1364 - i43)$  MeV and  $(1430 - i15)$  MeV, respectively [20].

The main component for the  $\Lambda(1405)$  is the pole 1, whose position converges within a relatively small region near the  $\bar{K}N$  threshold. On the other hand, the position of the pole 2 shows a sizeable scatter. Detailed studies of the  $\pi\Sigma$  spectrum in various reaction processes, together with the precise experimental lineshape (see e.g. the recent precise photoproduction data from the

LEPS collaboration [21] and from the CLAS collaboration [22, 23], electroproduction data from the CLAS collaboration [24], and proton-proton collision data from COSY [25] and the HADES collaboration [26]), will shed light on the position of the second pole. The  $\pi\Sigma$  spectra from the CLAS data are analyzed in Ref. [27] and Ref. [18]. It was shown in Ref. [18] that several solutions, which agree with the scattering data, are ruled out if confronted with the recent CLAS data. The remaining solutions are collected as solution #2 and solution #4 in Table 83.1. The HADES data are analyzed in Ref. [28] and Ref [29]. Although the result of the pole found in Ref. [28] is not compatible with other results, the authors of Ref. [29] invoke the anomalous triangle singularity mechanism to argue that the invariant mass distribution of the  $\pi\Sigma$  system is found at lower masses than in other reactions. It is thus desirable to perform more comprehensive analyses of  $\pi\Sigma$  spectra together with the systematic error analysis of the scattering data.

**Table 83.1:** Comparison of the pole positions of  $\Lambda(1405)$  in the complex energy plane from next-to-leading order chiral unitary coupled-channel approaches including the SIDDHARTA constraint. The lower two results also include the CLAS photoproduction data.

approach	pole 1 [MeV]	pole 2 [MeV]
Refs. [14, 15], NLO	$1424_{-23}^{+7} - i 26_{-14}^{+3}$	$1381_{-6}^{+18} - i 81_{-8}^{+19}$
Ref. [17], Fit II	$1421_{-2}^{+3} - i 19_{-5}^{+8}$	$1388_{-9}^{+9} - i 114_{-25}^{+24}$
Ref. [18], solution #2	$1434_{-2}^{+2} - i 10_{-1}^{+2}$	$1330_{-5}^{+4} - i 56_{-11}^{+17}$
Ref. [18], solution #4	$1429_{-7}^{+8} - i 12_{-3}^{+2}$	$1325_{-15}^{+15} - i 90_{-18}^{+12}$

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