

# $\Lambda(1405)$ poles obtained from $\pi^0\Sigma^0$ photoproduction data

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We present a strategy to extract the position of the two  $\Lambda(1405)$  poles from experimental photoproduction data measured recently at different energies in the  $\gamma p \rightarrow K^+ \pi^0 \Sigma^0$  reaction at Jefferson Lab. By means of a chiral dynamics motivated potential but with free parameters, we solve the Bethe Salpeter equation in the coupled channels  $\bar{K}N$  and  $\pi\Sigma$  in isospin  $I=0$  and parameterize the amplitude for the photonuclear reaction in terms of a linear combination of the  $\pi\Sigma \rightarrow \pi\Sigma$  and  $\bar{K}N \rightarrow \pi\Sigma$  scattering amplitudes in  $I=0$ , with a different linear combination for each energy. Good fits to the data are obtained with some sets of parameters, by means of which one can also predict the cross section for the  $K^-p \rightarrow \pi^0\Sigma^0$  reaction. These later results help us decide among the possible solutions. The result is that the different solutions lead to two poles similar to those found in the chiral unitary approach. With the best result we find the two  $\Lambda(1405)$  poles at  $1385 - 68i$  MeV and  $1419 - 22i$  MeV.

## I. INTRODUCTION

The issue of the nature of the  $\Lambda(1405)$  has captured great attention through the years. Very early it was already postulated that it could be a resonance made from the interaction of the coupled channels  $\bar{K}N$  and  $\pi\Sigma$  [1, 2]. Other works followed, looking at the  $\bar{K}N$  interaction from other perspective [3]. A big step forward was made possible with the use of chiral dynamics in its unitarized form, the so called chiral unitary approach, which has brought a new perspective to the problem and has shown the importance of coupled channels and unitarity [4–17]. One of the novel aspects of these works has been the finding of two poles, and thus two states, rather than one, associated to the experimental peaks of the  $\Lambda(1405)$  resonance. Hints of the two poles had been found in [18], using the chiral quark model, and in [7] within the chiral unitary approach. A systematic search and discussion on their origin was done in [11], where it was found that the two poles stem from a  $SU(3)$  singlet and octet of the chiral dynamical theory. One pole is around 1390 MeV, is wide ( $\Gamma > 100$  MeV) and couples mostly to  $\pi\Sigma$ . The other pole appears in all these theories around 1420 MeV, is narrow ( $\Gamma = 30$  MeV) and couples mostly  $\bar{K}N$ . Due to the existence of these two poles, the peak observed in experiments should be different in different reactions, as has been the case in the reactions studied so far [19–26]. The early experiments gave a peak around 1405 MeV, which served to give the nominal mass to the resonance. In view of this, new reactions were devised that would show the peak around 1420 MeV, close to the second pole found in the chiral unitary approach works. The obvious thing was to look for reactions where the  $\Lambda(1405)$  production would be induced by the  $\bar{K}N$  interaction. This seems to be contradictory since the threshold for  $\bar{K}N$ , at 1432 MeV, is higher than the mass of the two poles. Something should be done to remove energy from the initial state while still guaranteeing that the resonance was initiated by the  $\bar{K}N$  channel.

A first suggestion was made in [27], where the radiative production of the  $\Lambda(1405)$  resonance in  $K^-$  collisions on protons was proposed. The photon was radiated from the incoming  $K^-$  and then one still had the  $K^-p$  state to form the resonance. Although the existence of two poles was not well known at that time, the theoretical cross section indeed provided a narrow peak around 1420 MeV. Awaiting for this reaction to be done, an equivalent reaction, the  $K^-p \rightarrow \pi^0\pi^0\Sigma^0$  [22], was measured and a peak was indeed seen around 1420 MeV and narrower than the one observed in [19, 20]. In this case it was the  $\pi^0$  which was emitted from the initial nucleon, and one still had the  $K^-p$  initial state, although with smaller energy, to form the resonance. A theoretical description of this reaction in terms of the chiral unitary approach of [6] was provided in [28]. Further support for the two pole picture came from [29] where the  $K^-d \rightarrow n\pi\Sigma$  reaction was measured and a neat peak was observed around 1420 MeV. The reaction was studied theoretically in [30] and it was found that the mechanism of scattering of the kaon with a neutron, losing some energy, followed by rescattering of the kaon with the proton to produce the  $\Lambda(1405)$ , provided the right strength and shape observed in experiment. It was found that kaons in flight were preferable since they allowed to clearly separate the peaks due to single and double scattering<sup>1</sup>. More difficult but still possible, measuring neutrons in coincidence, was to see the resonance signal with the kaons of the DAFNE facility [32].<sup>2</sup>

As we can see, there is mounting evidence of a state

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<sup>1</sup> An experiment along these lines is being proposed for JPARC [31]

<sup>2</sup> A recent paper [33] questioned the approach of [30], showing problems with threshold behaviour in [30]. In a reply to that work [34], it was shown that the comments were appropriate under the choice of the kinetic energy for  $H_0$  in the deuteron Hamiltonian  $H = H_0 + V$ , but this is not necessary nor convenient in the multiple scattering expansion, and the Watson

around 1420 MeV, complementing another state more around 1400 MeV. Most reactions get contribution from both poles, but some, as those discussed above, give more weight to the pole around 1420 MeV, producing then a peak around this energy.

The surprising thing is that the theoretical approaches dealing with the  $\bar{K}N$  interaction and predicting the properties of the  $\Lambda(1405)$  have paid little or null attention to the reactions where the resonance is produced. One of the exceptions to this rule is the model constructed for photoproduction of the  $\Lambda(1405)$ , done in [35] before the experiment was performed, which predicted the basic features and strength of the reaction. Similarly, the  $\pi^-p \rightarrow K^0\pi\Sigma$  reaction of [19] was studied theoretically in [36], the  $pp \rightarrow pK^+\pi\Sigma$  reaction of [25] in [37], the  $K^-p \rightarrow \pi^0\pi^0\Sigma^0$  of [22] in [28] and the  $K^-d \rightarrow n\pi\Sigma$  reaction of [29] in [30]. The chiral unitary approach with the potential from the lowest order chiral Lagrangians was used in all these studies. Meanwhile more refined models have been developed [14–17] that contain the next to leading order terms in the potential. It is, however, interesting to observe that the results of [6] with the lowest order potential provide all the observables on cross sections and threshold ratios within the error bands provided by the more refined theoretical potential of [16].

Other theoretical works do not conduct a thorough search of these reactions but try to be consistent with the data of  $\Lambda(1405)$  production commenting that with a reaction amplitude made out from linear combinations of the  $\bar{K}N \rightarrow \pi\Sigma$  and  $\bar{K}N \rightarrow \bar{K}N$  amplitudes one could in principle obtain consistent shapes for the  $\pi\Sigma$  mass distributions where the  $\Lambda(1405)$  is always found. This is the case of [7, 15, 17]. In [7] one goes even further since such a test is demanded in the fit to the data and in [15] even the  $K^-p \rightarrow \pi^0\pi^0\Sigma^0$  reaction of [22] is demanded to be reproduced using the theoretical model of [28]. This comment is most appropriate, since in recent times, apart from the valuable data for the  $K^-p \rightarrow K^-p$  amplitude at threshold of the SIDHARTA experiment [38], no more data on  $\bar{K}N$  induced reactions have been produced. This contrasts with the mounting experimental data on reactions producing the  $\Lambda(1405)$  [21–26].

In the present paper we would like to give a step in the direction of showing the value of the  $\Lambda(1405)$  production reactions to get an insight on the properties of the  $\Lambda(1405)$  states and  $\bar{K}N$  scattering. For this purpose we have taken all the data on photoproduction of  $\Lambda(1405)$  at different energies of the CLAS collaboration at Jefferson Lab [23, 24], with  $\pi^0\Sigma^0$  in the final state, and have performed a fit to these data in terms of linear combinations of the  $\bar{K}N \rightarrow \pi\Sigma$  and  $\pi\Sigma \rightarrow \pi\Sigma$  production mechanisms. For this purpose we have taken the  $\pi\Sigma$  and  $\bar{K}N$  states in isospin  $I=0$  and solved the coupled

channels Bethe Salpeter equations in terms of a potential suggested by chiral dynamics but with free parameters. Note that the  $\pi^0\Sigma^0$  channel has the advantage that only the isospin  $I=0$  is relevant and hence the analysis is simpler. We show that the fit determines the potential with a precision that allows one to conclude that there are two poles, one around 1390 MeV and wide and another one around 1420 MeV and narrow, like most chiral unitary approaches get from the analysis of scattering data. The results of this work are most opportune at a time when some recent fits to the scattering data are providing different pole structures than the so far accepted by the different theoretical groups, but which in our opinion would fail to reproduce the results of the  $\Lambda(1405)$  production data [39, 40].<sup>3</sup>

## II. UNITARIZED MESON-BARYON AMPLITUDE

The main aim of the present work is to propose a way to extract, from experimental photoproduction data, the information of the two  $\Lambda(1405)$  poles predicted by the chiral unitary approach.

In the chiral unitary approach the  $\Lambda(1405)$  is generated dynamically from the final state interaction of the meson-baryon pair. The details for the construction of the meson-baryon unitarized amplitude can be found in Refs. [6, 7, 9, 41]. In the following we summarize the formalism for the sake of completeness and we show the way in which we allow the model to be modified to get a better fine tuning from the fit to photoproduction data.

From the lowest order chiral Lagrangian for the interaction of the octet of Goldstone bosons with the octet of the low lying  $1/2^+$  baryons [42] the tree level transition amplitudes in  $s$ -wave can be obtained [9] and give

$$V_{ij}(\sqrt{s}) = -C_{ij} \frac{1}{4f^2} (2\sqrt{s} - M_i - M_j) \times \left( \frac{M_i + E_i}{2M_i} \right)^{1/2} \left( \frac{M_j + E_j}{2M_j} \right)^{1/2}, \quad (1)$$

with  $\sqrt{s}$  the center of mass energy,  $f$  the averaged meson decay constant  $f = 1.123f_\pi$  [9] with  $f_\pi = 92.4$  MeV,  $E_i$  ( $M_i$ ) the energies (masses) of the baryons of the  $i$ -th channel and  $C_{ij}$  coefficients given, for isospin  $I = 0$ , by

$$C_{ij} = \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix}. \quad (2)$$

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expansion provided an alternative where the interaction of the nucleons in the deuteron was taken into account, leading to the approach of [30].

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<sup>3</sup> In [40] two solutions are proposed, one which is compatible with other results, including also [7], and another one more problematic. If one allows for uncertainties in the normalization, a broad band of the  $\pi\Sigma$  mass distributions is obtained that gives the impression of agreement with the data, but normalized to the peak the deficiencies become more clear.

The  $i$  and  $j$  subscripts represent the channels  $\bar{K}N$  and  $\pi\Sigma$  in isospin-basis. Note that we do not consider the other possible channels in  $I = 0$ ,  $\eta\Lambda$  and  $K\Xi$ , for the sake of simplicity of the approach and because for the energies that we will consider in this work the effect of those channels can be effectively reabsorbed in the subtraction constants, as explained in the next section. We are only interested in the  $I = 0$  channel since we will consider only the  $\pi^0\Sigma^0$  final meson-baryon state in the experiment of CLAS, which can only be in  $I = 0$  and  $I = 2$ , but the  $I = 2$  is non-resonant and negligible. In this way one has not to bother about isospin 1 contributions which would significantly increase the complexity of the analysis.

The implementation of unitarity in coupled channels of the scattering amplitude is one of the crucial points of the chiral unitary approach. This can be accomplished by means of the Inverse Amplitude Method [43, 44] or the N/D method [7, 45, 46]. In this latter work the equivalence with the Bethe-Salpeter equation used in [47] was established. Based on the N/D method, the coupled-channel scattering amplitude  $T_{ij}$  is given by the matrix equation

$$T = [1 - VG]^{-1}V, \quad (3)$$

where  $V_{ij}$  is the interaction kernel of Eq. (1) and the function  $G_i$ , or unitary bubble, is given by the dispersion integral of the two-body phase space  $\rho_i(s) = 2M_i q_i / (8\pi W)$ , in a diagonal matrix form, with  $M_i$  the mass of the baryon of the meson baryon loop,  $q_i$  the on shell momentum of the particles of the loop and  $W$  the center of mass energy.

This  $G_i$  function is equivalent to the meson-baryon loop function

$$G_i = i \int \frac{d^4 q}{(2\pi)^4} \frac{M_i}{E_i(\vec{q})} \times \frac{1}{k^0 + p^0 - q^0 - E_i(\vec{q}) + i\epsilon} \frac{1}{q^2 - m_i^2 + i\epsilon}. \quad (4)$$

The integral above is divergent, and therefore it has to be regularized, which can be done either with a three momentum cutoff, or with dimensional regularization in terms of a subtraction constant  $a_i$ . The connection between both methods was shown in Refs. [7, 44]. In ref. [9, 11] the values  $a_{KN} = -1.84$ ,  $a_{\pi\Sigma} = -2$  where used. In the present case, since we do not consider the  $\eta\Lambda$  and  $K\Xi$  channels these subtraction constants may differ slightly but we will allow to vary these constants in the fit below.

The amplitudes  $T_{\bar{K}N \rightarrow \pi\Sigma}$  and  $T_{\pi\Sigma \rightarrow \pi\Sigma}$  for  $I = 0$  are shown in fig. 1. They produce two poles in the second Riemann sheet of the complex energy plane at the positions  $\sqrt{s_0} = 1387 - 67i$  MeV, and  $1437 - 13i$  MeV. Note that the poles come dynamically from the non-linear dynamics involved in the implementation of unitarity in the meson-baryon scattering amplitude, without the need to include the poles as explicit degrees of freedom. This is

what is usually called *dynamically generated* resonance or meson-baryon molecule. It is worth mentioning that the

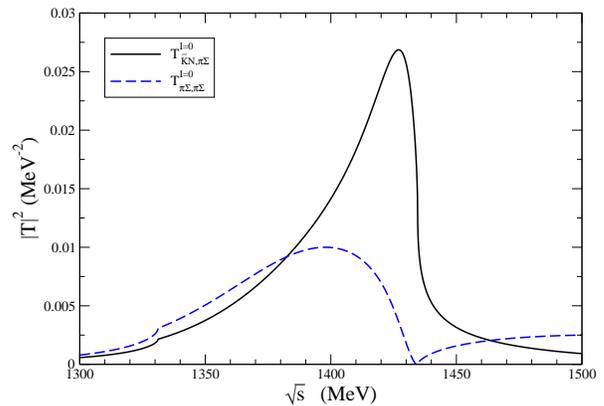


FIG. 1. Modulus squared of the meson-baryon unitarized amplitudes  $T_{\bar{K}N, \pi\Sigma}^{I=0}$  (solid line) and  $T_{\pi\Sigma, \pi\Sigma}^{I=0}$  (dashed line).

unitarized amplitudes provide the actual meson-baryon scattering amplitudes, not only the poles of the resonance in the complex plane. Indeed the resonant shape of the amplitudes around the 1400 MeV region are far from a Breit-Wigner-like shape. Therefore a fit assuming Breit-Wigner resonant shapes to experimental data is not suitable for this resonance and a model like the present one, in the line of implementing unitarity in coupled channels, is called for in order to reproduce or fit experimental data where these amplitudes are relevant.

### III. FIT TO PHOTOPRODUCTION DATA

In ref. [24], data for the  $\gamma p \rightarrow K^+\pi^+\Sigma^-$ ,  $\gamma p \rightarrow K^+\pi^-\Sigma^+$  and  $\gamma p \rightarrow K^+\pi^0\Sigma^0$  reactions were taken at different photon energies. The  $\gamma p \rightarrow K^+\pi^0\Sigma^0$  reaction filters  $I=0$  and these are the data that we will use. The main observable measured for this reaction is the  $\pi^0\Sigma^0$  invariant mass distribution (see fig. 3 below).

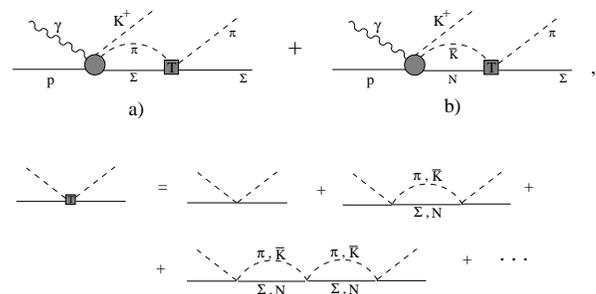


FIG. 2. General mechanisms for the  $\Lambda(1405)$  photoproduction in  $\gamma p \rightarrow K^+\pi^0\Sigma^0$  reaction.

Since the  $\Lambda(1405)$  is dynamically generated from the final state interaction of the meson-baryon produced, the

most general mechanisms for the photoproduction reaction are those depicted in fig. 2, a) and b). The photoproduction can proceed by the production of either a  $\pi\Sigma$ , (fig. 2a), or  $\bar{K}N$  (fig. 2b) pair, thick circle in fig. 2, which rescatter to produce the final  $\pi\Sigma$ , accounted for by the unitarized scattering amplitude explained in previous section. Note that a possible contact mechanism of direct  $\pi\Sigma$  production would contribute to the background and we do not consider it since a proper background subtraction has been done in the experimental analysis.

Based on fig. 2 it is immediate to realize that the amplitude for the photoproduction process can be generally written as

$$t(W) = b(W)G_{\pi\Sigma}T_{\pi\Sigma,\pi\Sigma}^{I=0} + c(W)G_{\bar{K}N}T_{\bar{K}N,\pi\Sigma}^{I=0}, \quad (5)$$

with  $W$  the energy of the  $\gamma p$  interaction. The coefficients  $b$  and  $c$  may in general depend on  $W$  and hence we consider 9 sets of them labeled  $b_j$  and  $c_j$ , with  $j$  from 1 to 9, in order to account for the 9 different energies  $W$  provided by the experimental result of CLAS [24]. On the other hand the relative weight between the  $G_{\pi\Sigma}T_{\pi\Sigma,\pi\Sigma}$  and  $G_{\bar{K}N}T_{\bar{K}N,\pi\Sigma}$  amplitudes must be complex in general, therefore we allow the  $c_j$  to be complex and keep  $b_j$  real since a global phase in the total amplitude is irrelevant. Note that we have intentionally avoided proposing any model for the initial photoproduction mechanisms since we aim at suggesting a way to extract physical poles of the  $\Lambda(1405)$  resonance from experimental data in a way as model independent as possible to ease the implementation by experimental groups. Indeed these initial photoproduction mechanisms are encoded in the coefficients  $b$  and  $c$ . Since we are fitting 9 different energies we have thus in total 27 parameters. This may look large but none of them affect the meson-baryon scattering amplitude and the number is smaller than in other possible experiments where mixing with isospin 1 could be allowed, like for instance  $\gamma p \rightarrow K^+\pi^+\Sigma^\mp$  in the same CLAS experiment.

One has to view the fit from the perspective that the data for one energy will provide the three coefficients,  $b$  and  $c$  (complex) at this energy. Only the parameters of the potential affect all the data. This problem is similar to the fit conducted to pionic atoms to extract neutron radii in [48]. In that problem there were 19 parameters for 19 neutron radii and 6 parameters for the potential. Again, each of these 19 parameters affected only the data on shifts and widths of a single pionic atom and the 6 parameters of the potential affected all the data. The fits worked without problems and the set of neutron radii obtained is considered nowadays the most valuable experimental source of neutron radii, together with the information obtained from antiprotonic atoms in [49].

We first fit the  $b$  and  $c$  coefficients to the photoproduction  $\pi^0\Sigma^0$  invariant mass distribution data using for the unitarized amplitudes the expression and parameters explained in the previous section. Note that in this first step the chiral unitary amplitudes for the meson-baryon interaction are kept constant (see fig. 1). Only the pho-

toproduction vertex is allowed to vary. The results of this fit is shown in fig. 3. In the evaluation of the theoretical invariant mass distribution the three body phase space has been averaged within the experimental  $W$  bin,  $[W - 0.05, W + 0.05]$  GeV, for every  $W$ . In the fit the range  $M_{\pi\Sigma} \in [1350, 1475]$  MeV is considered. The fit is fair for most of the energies, ( $\chi^2/dof = 1.76$ ), which means that an actual full physical meson-baryon amplitudes must not be much far from those predicted by the chiral unitary approach<sup>4</sup>. But what we actually want in the present work is not to calculate what the chiral unitary approach predicts for the poles of the  $\Lambda(1405)$  but to extract them from the experimental photoproduction data. Therefore we can try to get results with  $\chi^2/dof \simeq 1$  by allowing the basic chiral unitary model to vary slightly. In this way we could obtain a fine tuning of the chiral unitary model and then of the position of the  $\Lambda(1405)$  poles. In order to do this we multiply each coefficient of the potentials of the unitary amplitudes, Eq. (6), by one parameter  $\alpha_i$  and hence the new coefficient matrix that we consider now is given by

$$C_{ij} = \begin{pmatrix} 3\alpha_1 & -\sqrt{\frac{3}{2}}\alpha_2 \\ -\sqrt{\frac{3}{2}}\alpha_2 & 4\alpha_3 \end{pmatrix}. \quad (6)$$

Furthermore we also allow to vary the subtraction constants from the regularization of the loop function by multiplying both of them by a free parameter,  $\alpha_4, \alpha_5$ :  $a_{KN} \rightarrow \alpha_4 a_{KN}$ ,  $a_{\pi\Sigma} \rightarrow \alpha_5 a_{\pi\Sigma}$ . Therefore, the chiral unitary amplitudes depend on 5 free parameters,  $\alpha_i$ , to be fitted and with the potential obtained we shall search for the positions of the two  $\Lambda(1405)$  poles.

If at this point we carry on a global fit allowing for all the parameters to be free from the beginning in the fitting algorithm, there are many local minima of the  $\chi^2$  function, most of them having clearly unphysical values of the parameters. Therefore it is very difficult to get and identify an absolute minimum. Actually many minima have  $\chi^2$  very similar but with very different values of the parameters, which spoils the statistical significance of the fit and the possible physical conclusions. In order to get physically meaningful results, we implement the following strategy: The previous fit of fig. 3, i.e. fixing  $\alpha_i = 1$ , is already reasonably fair, and the potential is consistent with data of scattering [6], hence a good physical global fit should not be very far from having values of  $\alpha_i \sim 1$ . Therefore, in a first step, we start from the fit of fig. 3, which was obtained fixing  $\alpha_i = 1$ , but fixing now the  $b_j$  and  $c_j$  parameters and allowing only the  $\alpha_i$  parameters to change. Next, fixing the new  $\alpha_i$  parameters obtained in the previous step, we fit again the  $b_j$  and  $c_j$  parameters and iterate the process till we get a  $\chi^2/dof \simeq 1$  (which we call solution 1 in the following). After this iteration

<sup>4</sup> This value of the  $\chi^2/dof$  is already better than the one of the best fit in [24],  $\chi^2/dof = 2.15$ .

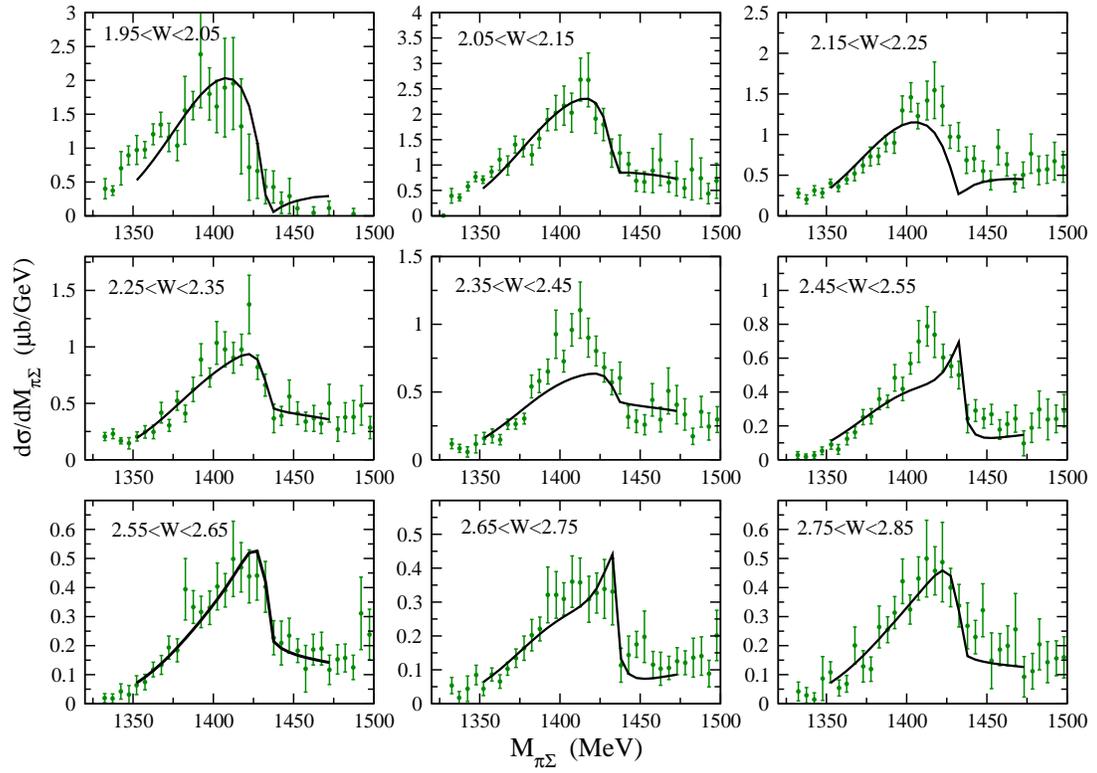


FIG. 3. Fit with fix unitary amplitudes,  $\alpha_i = 1$ .

we get the result shown in fig. 4 and the  $\alpha_i$  parameters obtained are shown in table I besides the corresponding poles of the  $\Lambda(1405)$ .

	$\alpha_1$	$\alpha_2$	$\alpha_3$	$\alpha_4$	$\alpha_5$	$\Lambda(1405)$ poles [MeV]	
solution 1	1.15	1.17	1.15	1.03	0.88	1385-68i	1419-22i
solution 2	1.88	1.89	1.57	0.93	0.87	1347-28i	1409-33i

TABLE I. Parameters of the unitarized amplitudes and pole positions of the  $\Lambda(1405)$  for both solutions discussed in the text

We can see that the parameters obtained are not very different from 1 for solution 1. This means that allowing for a small variation in the parameters of the chiral unitary approach the photoproduction data can be properly reproduced. In other words, a small freedom in changing the  $\alpha_i$  coefficients allows for extracting the pole positions for the two  $\Lambda(1405)$  from experimental photoproduction data. The results obtained for the poles are 1385 – 68i MeV and 1419 – 22i MeV. The solution 1 shown above does not actually correspond to the minimum  $\chi^2/dof$  but to a  $\chi^2/dof \simeq 1$ . The absolute minimum that we find after iterating the process described above many times has  $\chi^2/dof = 0.60$  (solution 2) but since it is smaller than 1 it is not more statistically significant than the one with  $\chi^2/dof \simeq 1$  (solution 1). The fit for photoproduction for solution 2 is represented by the dashed-line in fig. 4 and the coefficients and corresponding poles in table I. The  $\alpha_i$  coefficients for solution 2 differ more from the chiral unitary approach predictions, ( $\alpha_i = 1$ ), than those from solution 1. The pole positions obtained with these parameters are not far from those of solution 1. Anyway we could consider the difference between solutions 1 and 2 as a conservative estimate of the uncertainties of the procedure. Yet, a visual inspection to fig. 4 induces us to accept the solution 1 as better than solution 2 because it respects much better the Flatté behaviour (with a fast fall of the cross section in the upper side of the mass distribution) exhibited by the experimental data.

In order to make further checks that the fits obtained are physically acceptable and to decide between the different solutions obtained above, we calculate now the cross section for  $K^-p \rightarrow \pi^0\Sigma^0$  interaction which is the only one that does not mix with  $I = 1$ . The amplitude for this reaction is purely  $I = 0$ , which is the isospin involved in the fit to photoproduction data, (since the  $I = 2$  is negligible). The result is shown in fig.5 in comparison to experimental data from refs. [50, 51]. It can be seen that the best result corresponds to solution 1. Note, however, that as the energy increases other channels like  $\eta\Lambda$  and  $K\Xi$  are needed to be explicitly included as well as higher order contributions in the chiral potentials, but for low energies, and particularly to determine the position of the poles of the  $\Lambda(1405)$ , our analysis, with the channels chosen and the freedom of the potential is sufficient.

Since we have been concerned about the poles of the  $\Lambda(1405)$ , our analysis using only the I=0 data is appropriate. In the future one can think of using also the  $\gamma p \rightarrow K^+\pi^+\Sigma^-$  and  $\gamma p \rightarrow K^+\pi^-\Sigma^+$  data to try to induce the I=1 potential. In this case one can also use the large set of  $K^-p$  scattering data to constrain further the potential. A global fit to all the data and using potentials beyond the lowest order would certainly be most welcome and one could hopefully determine whether there is or not an I=1 state around 1430 MeV, which has been hinted in [7] and [11] and also obtained by the fit of [24].

One should note that the global fit obtained in [24] is admittedly rather imperfect and, as quoted there, the authors are unable to get a reduced  $\chi^2$  smaller than 2.15. Instead we get fits of high quality with the reduced  $\chi^2$  of the order of 1. Furthermore, an inspection of the results of our fit in Fig. 4 and those of Fig. 21 of [24] for  $\gamma p \rightarrow K^+\pi^0\Sigma^0$  clearly shows that the fit to the data is much better in our analysis.

It is interesting to see why our fit to the data of [24] is better than the one obtained in this latter work. There is an essential difference between our analysis and the one of [24]. In [24] the  $\gamma p \rightarrow K^+\pi\Sigma$  amplitudes are parametrized as (Eq.(19) of [24])

$$t_I(m) = C_I(W)e^{i\Delta\phi_I}B_I(m), \quad (7)$$

where  $C_I(W)$  is a weight factor,  $\Delta\phi_I$  a phase and  $B_I(m)$  a Breit-Wigner function. As one can see, the weight is allowed to depend on the photon energy,  $W$ , but not its phase. But even more restrictive is the fact that the shape of the resonance,  $B_I(m)$ , is chosen independent of the photon energy. This neglects the possibility that one has two poles of the  $\Lambda(1405)$  resonance and that the amplitudes  $\gamma p \rightarrow K^+\pi\Sigma$  are superpositions of the amplitudes corresponding to these poles with relative weights that depend on the photon energy. Since this is what happens in the theories that predict two poles, it is then important that an analysis of the data takes this into account and this is done in our analysis. In our analysis the amplitude is given by Eq. (5) as a superposition of the  $T_{\pi\Sigma,\pi\Sigma}^{I=0}$  and  $T_{\bar{K}N,\pi\Sigma}^{I=0}$  amplitudes, which have a very different shape as seen in Fig. 1. With  $b(W)$  and  $c(W)$  depending on the photon energy, we allow the freedom to change the shape of the resonance as the photon energy changes.

#### IV. CONCLUSIONS

We have studied the  $\gamma p \rightarrow K^+\pi^0\Sigma^0$  reaction at different energies from a semiempirical point of view in order to illustrate the possibility to obtain the position of the two  $\Lambda(1405)$  poles from experimental production data. We have taken an amplitude for this reaction which consists of a linear combination of the  $\pi\Sigma \rightarrow \pi\Sigma$  and  $\bar{K}N \rightarrow \pi\Sigma$  scattering amplitudes in I=0. The parameters of this

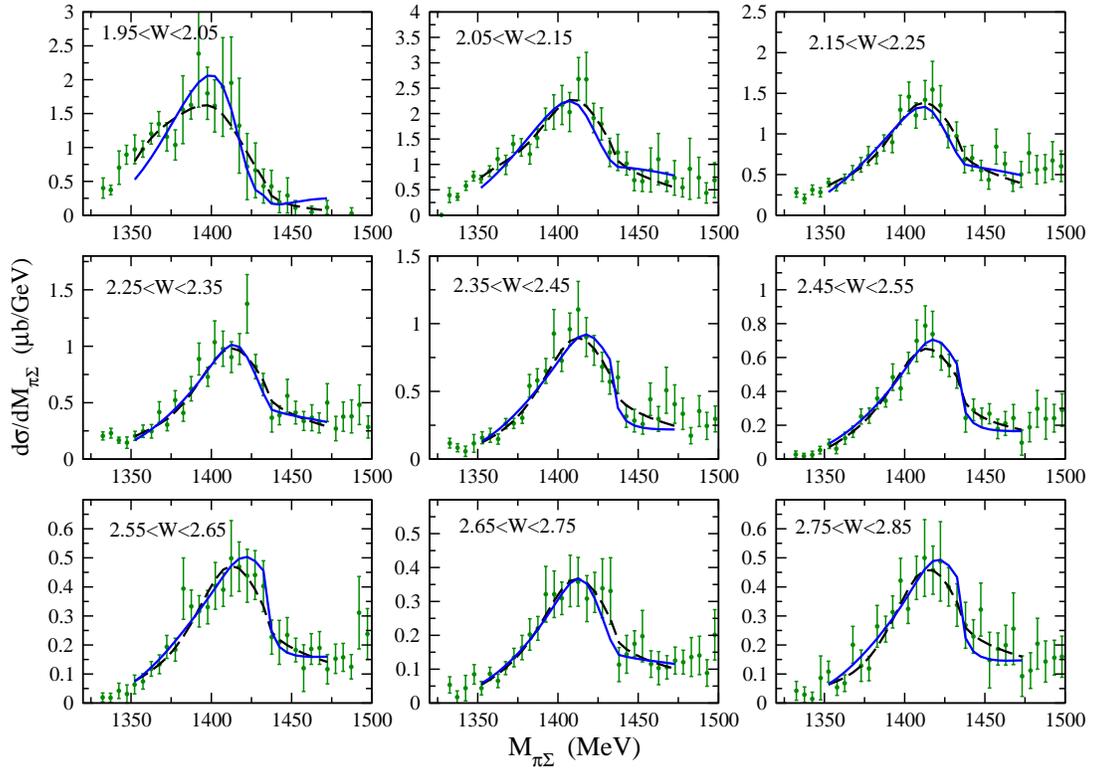


FIG. 4. Results from solutions 1 (solid line) and 2 (dashed line) explained in the text.

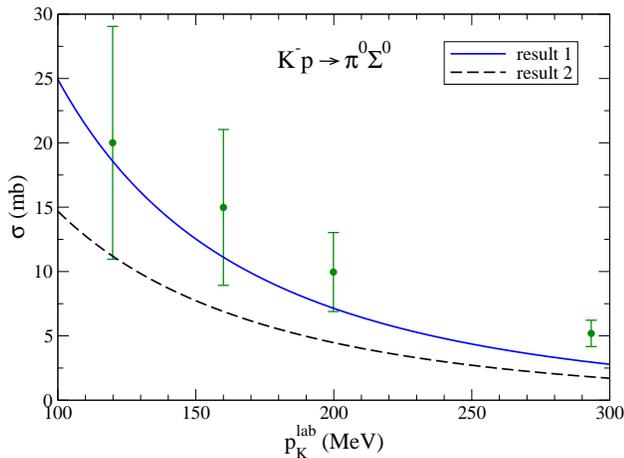


FIG. 5. Predicted  $K^-p \rightarrow \pi^0\Sigma^0$  cross section for solutions 1 and 2. Experimental data from refs. [50, 51].

combination are free and different for each energy. The  $\pi\Sigma \rightarrow \pi\Sigma$  and  $\bar{K}N \rightarrow \pi\Sigma$  amplitudes are constructed using the Bethe Salpeter equations in the coupled channels of  $\bar{K}N$  and  $\pi\Sigma$  in isospin  $I=0$ . For this we used a  $2 \times 2$  potential matrix inspired by the chiral unitary approach but slightly modified with free coefficients. These coefficients and those of the linear combinations were fitted to the data and good solutions were obtained. It was interesting to see that these solutions gave fair results for the cross section of the  $K^-p \rightarrow \pi^0\Sigma^0$  reaction and provided two poles very close to those provided by the chiral uni-

tary approaches. By choosing the set of parameters that also provides best results for the  $K^-p \rightarrow \pi^0\Sigma^0$  reaction we could decide the best results and we found for the two poles of the  $\Lambda(1405)$   $1385 - 68i$  MeV and  $1419 - 22i$  MeV in the complex energy plane. The exercise conducted in the present work is orthogonal and complementary to the usual one performed so far where the scattering data are used to fit the parameters of the chiral theory. We find that the photoproduction data at several energies have enough information to provide the  $\Lambda(1405)$  poles, without the need to develop a detailed model for the reaction. After this work, two lines of progress look most advisable: Elaborating a detailed model to describe the data theoretically and performing simultaneous fits to the scattering data and  $\Lambda(1405)$  production data. The present work has shown clearly that the information contained in the  $\Lambda(1405)$  production data is extremely valuable to learn about the position of the  $\Lambda(1405)$  poles and the nature of these states.

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- [1] R. H. Dalitz, S. F. Tuan, *Annals Phys.* **10**, 307-351 (1960).
  - [2] R. H. Dalitz, T. C. Wong, G. Rajasekaran, *Phys. Rev.* **153**, 1617-1623 (1967).
  - [3] E. A. Veit, B. K. Jennings, R. C. Barrett, A. W. Thomas, *Phys. Lett.* **B137**, 415 (1984).
  - [4] N. Kaiser, P. B. Siegel and W. Weise, *Nucl. Phys. A* **594**, 325 (1995).
  - [5] N. Kaiser, T. Waas and W. Weise, *Nucl. Phys. A* **612**, 297 (1997) [hep-ph/9607459].
  - [6] E. Oset and A. Ramos, *Nucl. Phys. A* **635**, 99 (1998).
  - [7] J. A. Oller and U. G. Meissner, *Phys. Lett. B* **500**, 263 (2001).
  - [8] M. F. M. Lutz and E. E. Kolomeitsev, *Nucl. Phys. A* **700**, 193 (2002).
  - [9] E. Oset, A. Ramos and C. Bennhold, *Phys. Lett. B* **527**, 99 (2002) [Erratum-ibid. *B* **530**, 260 (2002)].
  - [10] T. Hyodo, S. I. Nam, D. Jido and A. Hosaka, *Phys. Rev. C* **68**, 018201 (2003).
  - [11] D. Jido, J. A. Oller, E. Oset, A. Ramos, U. G. Meissner, *Nucl. Phys. A* **725**, 181-200 (2003).
  - [12] C. Garcia-Recio, J. Nieves, E. Ruiz Arriola and M. J. Vicente Vacas, *Phys. Rev. D* **67**, 076009 (2003).
  - [13] C. Garcia-Recio, J. Nieves and L. L. Salcedo, *Phys. Rev. D* **74**, 034025 (2006) [hep-ph/0505233].
  - [14] B. Borasoy, R. Nissler and W. Weise, *Eur. Phys. J. A* **25**, 79 (2005).
  - [15] J. A. Oller, *Eur. Phys. J. A* **28**, 63 (2006).
  - [16] B. Borasoy, U. G. Meissner and R. Nissler, *Phys. Rev. C* **74**, 055201 (2006).
  - [17] Y. Ikeda, T. Hyodo and W. Weise, *Nucl. Phys. A* **881**, 98 (2012).
  - [18] P. J. Fink, Jr., G. He, R. H. Landau and J. W. Schnick, *Phys. Rev. C* **41**, 2720 (1990).
  - [19] D. W. Thomas, A. Engler, H. E. Fisk and R. W. Kraemer, *Nucl. Phys. B* **56**, 15 (1973).
  - [20] R. J. Hemingway, *Nucl. Phys. B* **253**, 742 (1985).
  - [21] M. Niiyama, H. Fujimura, D. S. Ahn, J. K. Ahn, S. Ajimura, H. C. Bhang, T. H. Chang and W. C. Chang *et al.*, *Phys. Rev. C* **78**, 035202 (2008).
  - [22] S. Prakhov *et al.* [Crystal Ball Collaboration], *Phys. Rev. C* **70**, 034605 (2004).
  - [23] K. Moriya *et al.* [CLAS Collaboration], *AIP Conf. Proc.* **1441**, 296 (2012).
  - [24] K. Moriya *et al.* [CLAS Collaboration], arXiv:1301.5000 [nucl-ex].

- [25] I. Zychor, M. Buscher, M. Hartmann, A. Kacharava, I. Keshelashvili, A. Khoukaz, V. Kleber and V. Koptev *et al.*, Phys. Lett. B **660**, 167 (2008).
- [26] G. Agakishiev, A. Balanda, D. Belver, A. V. Belyaev, J. C. Berger-Chen, A. Blanco, M. Bohmer and J. L. Boyard *et al.*, arXiv:1208.0205 [nucl-ex].
- [27] J. C. Nacher, E. Oset, H. Toki and A. Ramos, Phys. Lett. B **461**, 299 (1999).
- [28] V. K. Magas, E. Oset and A. Ramos, Phys. Rev. Lett. **95**, 052301 (2005).
- [29] O. Braun, H. J. Grimm, V. Hepp, H. Strobele, C. Thol, T. J. Thouw, D. Capps and F. Gandini *et al.*, Nucl. Phys. B **129**, 1 (1977).
- [30] D. Jido, E. Oset and T. Sekihara, Eur. Phys. J. A **42**, 257 (2009).
- [31] M. Noumi *et al.*. Spectroscopic study of hyperon resonances below KN threshold via the ( $K^-$ ,  $n$ ) reaction on Deuteron - J-PARC proposal E31 (2009).
- [32] D. Jido, E. Oset and T. Sekihara, Eur. Phys. J. A **47**, 42 (2011).
- [33] K. Miyagawa and J. Haidenbauer, Phys. Rev. C **85**, 065201 (2012).
- [34] D. Jido, E. Oset and T. Sekihara, arXiv:1207.5350 [nucl-th].
- [35] J. C. Nacher, E. Oset, H. Toki and A. Ramos, Phys. Lett. B **455**, 55 (1999).
- [36] T. Hyodo, A. Hosaka, E. Oset, A. Ramos and M. J. Vicente Vacas, Phys. Rev. C **68**, 065203 (2003).
- [37] L. S. Geng and E. Oset, Eur. Phys. J. A **34**, 405 (2007).
- [38] M. Bazzi, G. Beer, L. Bombelli, A. M. Bragadireanu, M. Cargnelli, G. Corradi, C. Curceanu (Petrascu) and A. d'Uffizi *et al.*, Phys. Lett. B **704**, 113 (2011).
- [39] M. Mai and U. -G. Meissner, arXiv:1202.2030 [nucl-th].
- [40] Z. -H. Guo and J. A. Oller, arXiv:1210.3485 [hep-ph].
- [41] T. Hyodo, D. Jido, and A. Hosaka, Phys. Rev. **D75**, 034002 (2007).
- [42] V. Bernard, N. Kaiser and U. G. Meissner, Int. J. Mod. Phys. E **4** (1995) 193.
- [43] A. Dobado and J. R. Peláez, Phys. Rev. D **56** (1997) 3057.
- [44] J. A. Oller, E. Oset and J. R. Pelaez, Phys. Rev. D **59** (1999) 074001 [Erratum-ibid. D **60** (1999) 099906].
- [45] J. A. Oller and E. Oset, Phys. Rev. D **60** (1999) 074023.
- [46] T. Hyodo, S. I. Nam, D. Jido, and A. Hosaka, Prog. Theor. Phys. **112**, 73 (2004).
- [47] J. A. Oller and E. Oset, Nucl. Phys. A **620** (1997) 438 [Erratum-ibid. A **652** (1999) 407].
- [48] C. Garcia-Recio, J. Nieves and E. Oset, Nucl. Phys. A **547**, 473 (1992).
- [49] A. Trzcinska, J. Jastrzebski, P. Lubinski, F. J. Hartmann, R. Schmidt, T. von Egidy and B. Klos, Phys. Rev. Lett. **87**, 082501 (2001).
- [50] W. E. Humphrey and R. R. Ross, Phys. Rev. **127** (1962) 1305.
- [51] J. K. Kim, Columbia University Report No. NEVIS-149, 1966