Can parameters of f_0-mesons be determined correctly analyzing only $\pi\pi$ scattering?

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(Received 27 September 2012; published 3 December 2012)

The coupled processes—the $\pi\pi$ scattering and $\pi\pi \to K\bar{K}$ in the $I^G J^{PC} = 0^+0^{++}$ channel—are analyzed (both separately and combined) in a model-independent approach based on analyticity and unitarity and using a uniformization procedure. We show that (1) a structure of the Riemann surface of the S matrix for considered coupled processes must be allowed for calculating both amplitudes and resonance parameters, such as the mass and width; and (2) the combined analysis of coupled processes is needed as the analysis of only the $\pi\pi$ channel does not give correct values of resonance parameters even if the Riemann surface structure is included.

DOI: 10.1103/PhysRevD.86.116002 PACS numbers: 11.55.Bq, 11.80.Gw, 14.40.−n

The study of scalar mesons is very important for such profound topics in particle physics as the QCD vacuum. However, despite a big effort devoted to studying various aspects of the problem [1] (for recent reviews see Refs. [2–5]), a description of this sector is far from being complete. Parameters of the scalar mesons, their nature, and status of some of them are still not well settled [1]. For example, applying our model-independent method in three-channel analyses of processes $\pi\pi \to \pi\pi$, $K\bar{K}$, $\eta\eta(\eta\eta')$ [6,7] we have obtained parameters of the $f_0(600)$ and $f_0(1500)$ which differ considerably from results of analyses utilizing other methods (mainly those based on the dispersion relations and Breit-Wigner approaches). Reasons of this difference should be understood because our method is based only on a demand for analyticity and unitarity of the amplitudes using a uniformization procedure. The construction of amplitudes is practically free from any dynamical (model) assumptions using only the *mathematical* fact that a local behavior of analytic functions determined on the Riemann surface is governed by the nearest singularities on all corresponding sheets, i.e., the obtained parameters of resonances can be considered as free from theoretical prejudice.

First note that in our previous three-channel analyses with the uniformizing variables [6,7] we were forced to construct a four-sheeted model of the eight-sheeted Riemann surface. This we achieved by neglecting the $\pi\pi$-threshold branch point, which means that we have considered the nearest to the physical region semisheets of the initial Riemann surface. This is in the line with our approach of a consistent account of the nearest singularities on all relevant sheets. The two-channel analysis utilizes the full Riemann surface and is, therefore, free of these approximations. To verify a plausibility of our assumptions in the three-channel calculations, we have performed a combined two-channel analysis of data on $\pi\pi \to \pi\pi$, $K\bar{K}$ to check whether the results of our three-channel analyses [6,7] are also obtained in the two-channel consideration. Moreover, to better understand reasons for the above-indicated difference in results, we have performed first the analysis only of the $\pi\pi$ scattering data in the two-channel approach.

The two-channel S matrix is determined on the four-sheeted Riemann surface. The matrix elements S_{ij}, where $i, j = 1(\pi\pi), 2(K\bar{K})$ denote channels, have the right-hand cuts along the real axis of the s complex plane (s is the invariant total energy squared), starting with the channel thresholds s_i, and the left-hand cuts related to the crossed channels. The Riemann-surface sheets are numbered according to the signs of analytic continuations of the roots $\sqrt{s - s_i}$ as follows: signs$(\mathrm{Im}\sqrt{s - s_1}, \mathrm{Im}\sqrt{s - s_2}) = ++, -+, --, +-$ correspond to sheets I, II, III, IV.

The resonance representations on the Riemann surface are obtained from formulas [8] that express analytic continuations of the S matrix elements to unphysical sheets in terms of those on the physical (I) sheet having only resonance zeros (beyond the real axis). Then, starting from the resonance zeros on sheet I, one can obtain an arrangement of poles and zeros of a resonance on the whole Riemann surface (''pole clusters''). In the two-channel case, according to these formulas and a real analyticity, amplitudes of all coupled processes have conjugate poles at the same points of complex energy on sheets II, III, and IV if $S^{\mathrm{I}}_{11} = 0$, $S^{\mathrm{I}}_{11}S^{\mathrm{I}}_{22} - (S^{\mathrm{I}}_{12})^2 = 0$, and $S^{\mathrm{I}}_{22} = 0$, respectively (the superscript I means the matrix elements on sheet I). Therefore three types of pole clusters representing states of different nature arise: (a) when there is a pair of conjugate zeros only in $S^{\mathrm{I}}_{11} = 0$, (b) only in $S^{\mathrm{I}}_{22} = 0$, and (c) in both the $S^{\mathrm{I}}_{11} = 0$ and $S^{\mathrm{I}}_{22} = 0$. If the coupling of channels is present ($S_{12} \neq 0$) (i.e., a state decays into both channels

TABLE I. The pole positions of resonances $\sqrt{s_r} = \mathrm{E}_r - i\Gamma_r/2$ [MeV] on sheets II and IV in the $\sqrt{s}$ plane in the analysis of only $\pi\pi$ scattering.

Sheet	II	IV
$f_0(600)$	$447.5 \pm 5.9 - \mathrm{i}(267 \pm 6.5)$	
$f_0(980)$	$1001.1 \pm 3.7 - \mathrm{i}(20.3 \pm 2.6)$	
$f_0(1370)$		$1301.1 \pm 47.9 - \mathrm{i}(224 \pm 49.3)$
$f_0(1500)$		$1503.7 \pm 45.1 - \mathrm{i}(56.5 \pm 39.4)$
$f_0'(1500)$	$1511.4 \pm 11.2 - \mathrm{i}(200.5 \pm 11)$	$1505.9 \pm 38.5 - \mathrm{i}(168 \pm 40.6)$
$f_0(1710)$		$1720 \pm 32.2 - \mathrm{i}(64.9 \pm 30.1)$

and/or is exchanged in crossing channels), then type a is represented in S_{11} by a pair of conjugate poles on sheet II and a pair of conjugate zeros on sheet I and also by a pair of conjugate poles on sheet III and a pair of conjugate zeros on sheet IV at the same complex-energy points, which are to be shifted with respect to the zeros on sheet I. For states of type b, the pair of conjugate poles on sheet III is shifted relative to the pair of poles on sheet IV. For the states of type c, one must consider two pairs of conjugate poles on sheet III. Generally, wide multichannel states are most adequately represented by pole clusters, because the pole positions are rather stable characteristics for various models, whereas masses and widths are very model dependent [9]. For calculation of the latter, one must use the poles on those sheets where they are not shifted (due to the channel couplings) with respect to the zero position on sheet I. For resonances of types a and b these poles are on sheets II and IV, respectively. For resonance of type c the poles can be used on both of these sheets. In the case of N channels, the poles only on the sheets with the numbers 2^i ($i = 1, \ldots, N$ is the number of channel), i.e., II, IV, VIII,..., should be used for calculating resonance parameters [7,8].

It is convenient to use the Le Couteur-Newton relations [10]. They express the S-matrix elements of all coupled processes in terms of the Jost matrix determinant $d(\sqrt{s - s_1}, \ldots, \sqrt{s - s_N})$ that is a real analytic function with the only square-root branch points at $\sqrt{s - s_\alpha} = 0$.

A necessary and sufficient condition for existence of the multichannel resonance is its representation by one of the types of pole clusters. To use this representation of resonances, which is very important for the wide multichannel states, a uniformizing variable is applied. Analyzing $\pi\pi \to \pi\pi$, $K\bar{K}$ we applied the uniformizing variable [9] that takes into account, in addition to the $\pi\pi$- and $K\bar{K}$-threshold branch points, the left-hand branch point at $s = 0$, related to the $\pi\pi$ crossed channels:

$$\upsilon = \frac{m_K\sqrt{s - 4m_\pi^2} + m_\pi\sqrt{s - 4m_K^2}}{\sqrt{s(m_K^2 - m_\pi^2)}}. \tag{1}$$

It maps the four-sheeted Riemann surface with two unitary cuts and the left-hand cut onto the υ plane. Representation of resonances of various types on the uniformization υ plane can be found in Ref. [11].

On the υ plane, $S_{11}(\upsilon)$ has no cuts; $S_{12}^2(\upsilon)$ and $S_{22}(\upsilon)$ do have the cuts that arise from the left-hand cut on the s plane, starting at $s = 4(m_K^2 - m_\pi^2)$, which is further approximated by a pole

$$d_L = \upsilon^{-4}\left(1 - \left(p - i\sqrt{1 - p^2}\right)\upsilon\right)^4\left(1 + \left(p + i\sqrt{1 - p^2}\right)\upsilon\right)^4,$$

where $p = 0.903 \pm 0.0004$ from analysis. An explanation of the fourth power of this pole can be found in Ref. [11].

On the υ plane, the function $d(\upsilon)$ in the Le Couteur-Newton relations [9,10] does not possess any branch points. The main model-independent contribution of resonances, given by the pole clusters, is factorized in the S matrix elements from the background. The possible remaining small (model-dependent) contributions of resonances are supposed to be included in the background. Therefore, $d(\upsilon)$ is taken as $d = d_{res}d_L d_{bg}$ where the resonance part is

$$d_{\mathrm{res}} = \upsilon^{-M}\prod_{n=1}^{M}(1 - \upsilon_n^*\upsilon)(1 + \upsilon_n\upsilon) \tag{2}$$

with M the number of pairs of the conjugate zeros. The background part is

$$d_{bg} = \exp\left[-i\sum_{n=1}^{3}(\sqrt{s - s_n}/2m_n)(\alpha_n + i\beta_n)\right],$$
$$\alpha_n, \beta_n = a_{n1}, b_{n1} + \sum_{k=\eta,\sigma,\upsilon} a_{nk}, b_{nk}(s/s_k - 1)\theta(s - s_k) \tag{3}$$

with s_η and s_σ the $\eta\eta$ and $\sigma\sigma$ thresholds, respectively, s_υ a combined threshold of the $\eta\eta'$, $\rho\rho$, and $\omega\omega$ thresholds; from the analysis, $s_\sigma = 1.6558\ \mathrm{GeV}^2$, $s_\upsilon = 2.1293\ \mathrm{GeV}^2$.

At present in the scalar sector, there are alternative data for the $\pi\pi$ scattering—Refs. [12,13]—which are different considerably in the 0.76 GeV region and especially above 1.45 GeV. Therefore, separate analyses using these alternative data are needed. Here we performed the analysis taking for the $\pi\pi$ scattering in interval $0.575\ \mathrm{GeV} < \sqrt{s} < 1.89\ \mathrm{GeV}$ data from Ref. [12] and for $\sqrt{s} < 1$ GeV from many works. References to the latter and to practically all accessible $\pi\pi \to K\bar{K}$ data used can be found in Ref. [11]. Analysis using the data [13] will be presented in another paper.

First analyzing only the $\pi\pi$ scattering, we supposed an existence of two states [narrow $f_0(1500)$ and wide $f_0'(1500)$] and achieved an excellent description for the phase shift δ_{11} and modulus $|S_{11}|$ (the total $\chi^2/\mathrm{NDF} \approx 1.07$) with the resonance parameters (Table I) that largely coincide with estimations of the PDG [1] (cf. also Ref. [14]). The only distinction is observation of the wide $f_0'(1500)$. The fact that this state is not observed in works cited by the PDG is related, it seems, with peculiarities of analysis of data therein.

In the analysis, the $f_0(600)$ and $f_0(980)$ are described by the clusters of type a; $f_0(1370)$, $f_0(1500)$, and $f_0(1710)$, type b; and $f_0'(1500)$, type c. The received background parameters are $a_{11} = -0.0895 \pm 0.0030$, $a_{1\eta} = 0.04 \pm 0.03$, $a_{1\sigma} = 0.0 \pm 0.8$, $a_{1v} = 0.0 \pm 0.7$, $b_{11} = 0.0 \pm 0.007$, $b_{1\eta} = 0.0 \pm 0.01$, $b_{1\sigma} = 0.0 \pm 0.02$, and $b_{1v} = 0.054 \pm 0.036$.

In Fig. 1, we show the fitting only to the $\pi\pi$ scattering data and energy behavior of the phase shift ϕ_{12} and modulus of S_{12} calculated using the resonance parameters from this analysis. In spite of the very good description of data and the very good agreement of obtained $\pi\pi$ scattering length a_0^0 with the experimental results and with the chiral perturbation theory (ChPT) calculations (see Table III), this analysis shows two important flaws: (1) The negative background phase shift beginning at the $\pi\pi$ threshold ($a_{11} = -0.0895$) is necessary for a successful description of the data. This should not be the case because, in the uniformizing variable, we have allowed for the left-hand branch point at $s = 0$ that gives a main contribution to the $\pi\pi$ background below 1 GeV. Other possible contributions of the left-hand cut from exchanges by the nearest ρ and $f_0(600)$ mesons practically obliterate each other [9] because vector and scalar particles contribute with the opposite signs due to gauge invariance. (2) Description of the $\pi\pi \to K\bar{K}$ data, using the same parameters of resonances as in the $\pi\pi$ channel, is satisfactory only for the phase shift ϕ_{12} that is due to the approximation of the left-hand cut in S_{12} and S_{22} by the fourth-power pole. The modulus $|S_{12}|$ is described well only from the $K\bar{K}$ threshold to about 1.15 GeV as it should be due to the two-channel unitarity. Above this energy the description fails even qualitatively (Fig. 1).

From this we conclude the following: If the data are consistent, for obtaining correct parameters of wide resonances the combined analysis of coupled processes is needed. Further that analysis of $\pi\pi \to \pi\pi$, $K\bar{K}$ is performed successfully. The data for the $\pi\pi$ scattering below 1 GeV admit two solutions for the phase shift—A and B—which differ mainly in the pole position on sheet II of the $f_0(600)$. The total χ^2/NDF is 1.53 for the A solution and 1.44 for B solution. The resonances are described by pole clusters of the same types as in the analysis only of the $\pi\pi$ scattering. In Table II we show the pole positions of resonances on sheets II and IV on the $\sqrt{s}$ plane. The obtained background parameters for the

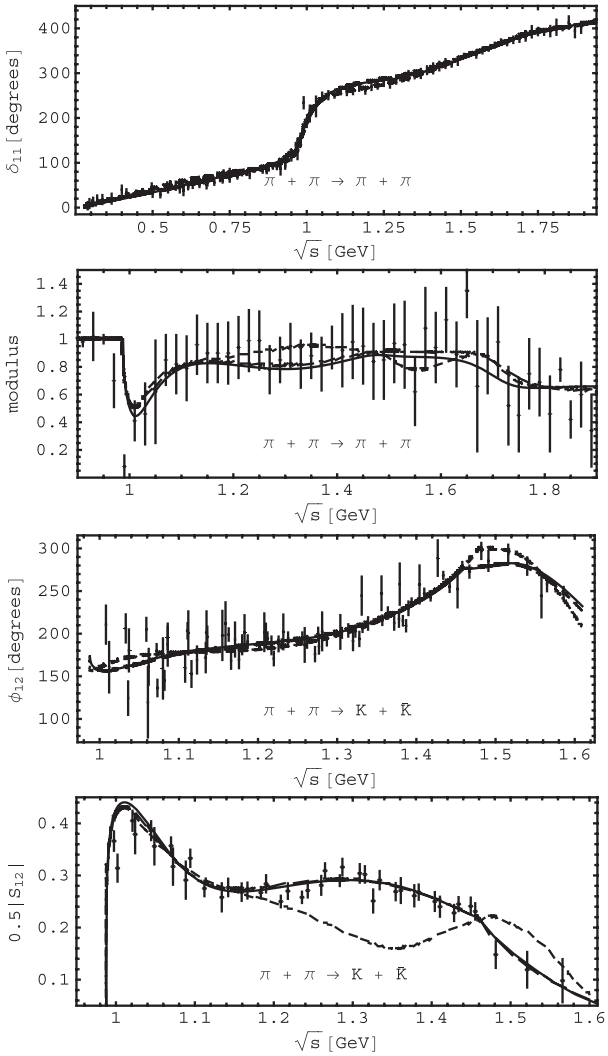

FIG. 1. The S-wave phase shifts and modules of the $\pi\pi$ scattering and $\pi\pi \to K\bar{K}$ matrix elements. The short-dashed lines correspond to the analysis only of the $\pi\pi$ scattering. The long-dashed and solid lines correspond to solutions A and B of the combined analysis of $\pi\pi \to \pi\pi$, $K\bar{K}$, respectively. The data are from Refs. [11,12,15,16].

A solution are $a_{11} = 0.0 \pm 0.003$, $a_{1\eta} = -0.1004 \pm 0.0301$, $a_{1\sigma} = 0.2148 \pm 0.0822$, $a_{1v} = 0.0 \pm 0.07$, $b_{11} = b_{1\eta} = b_{1\sigma} = 0$, $b_{1v} = 0.012 \pm 0.0287$, $a_{21} = -0.919 \pm 0.107$, $a_{2\eta} = -1.399 \pm 0.348$, $a_{2\sigma} = 0.0 \pm 0.7$, $a_{2v} = -11.45 \pm 0.75$, $b_{21} = 0.0747 \pm 0.0503$, $b_{2\eta} = b_{2\sigma} = 0$, $b_{2v} = 4.83 \pm 1.94$; and for the B solution are $a_{11} = 0.0 \pm 0.003$, $a_{1\eta} = -0.0913 \pm 0.0327$, $a_{1\sigma} = 0.1707 \pm 0.0899$, $a_{1v} = 0.0 \pm 0.07$, $b_{11} = b_{1\eta} = b_{1\sigma} = 0$, $b_{1v} = 0.006 \pm 0.029$, $a_{21} = -1.338 \pm 0.111$, $a_{2\eta} = -1.119 \pm 0.376$, $a_{2\sigma} = 0.0 \pm 0.8$, $a_{2v} = -12.13 \pm 0.77$, $b_{21} = 0.018 \pm 0.050$, $b_{2\eta} = b_{2\sigma} = 0$, $b_{2v} = 4.48 \pm 1.98$.

In the combined analysis both flaws of the only $\pi\pi$-scattering analysis are cured. Now the $\pi\pi$ background below the $K\bar{K}$ threshold is absent ($a_{11} = 0.0$). An arising

TABLE II. The pole positions of resonances on sheets II and IV in the $\sqrt{s}$ plane in the combined analysis of the $\pi\pi \to \pi\pi$, $K\bar{K}$ data. The complete pole clusters of resonances can be found in Ref. [11].

Sheet	II	IV
	A solution	
$f_0(600)$	$517 \pm 7.8 - i(393.9 \pm 6)$	
$f_0(980)$	$1004.6 \pm 3.9 - i(25.0 \pm 2.3)$	
$f_0(1370)$		$1342.9 \pm 12.2 - i(221.6 \pm 30.7)$
$f_0(1500)$		$1501.1 \pm 6.4 - i(56.6 \pm 6.0)$
$f_0'(1500)$	$1532.2 \pm 12.4 - i(323.2 \pm 21)$	$1519.3 \pm 18.7 - i(339.5 \pm 42.2)$
$f_0(1710)$		$1717 \pm 34.9 - i(72.9 \pm 16.2)$
	B solution	
$f_0(600)$	$550.6 \pm 9 - i(502.1 \pm 7.2)$	
$f_0(980)$	$1003.2 \pm 3 - i(28.9 \pm 2)$	
$f_0(1370)$		$1336.7 \pm 14 - i(251.9 \pm 27.5)$
$f_0(1500)$		$1500.3 \pm 6.3 - i(57.0 \pm 6.4)$
$f_0'(1500)$	$1528.4 \pm 12.5 - i(328 \pm 20.2)$	$1515.6 \pm 17 - i(340.3 \pm 34.9)$
$f_0(1710)$		$1722 \pm 35.7 - i(92.3 \pm 20.3)$

TABLE III. The $\pi\pi$ scattering length a_0^0.

a_0^0 $[m_{\pi^+}^{-1}]$	Remarks	References
0.222 ± 0.008	Analysis only of $\pi\pi$ scattering	This work
0.230 ± 0.004	A solution	This work
0.282 ± 0.003	B solution	This work
0.26 ± 0.05	Analysis of the $K \to \pi\pi e\nu$ using Roy's equations	[15]
0.24 ± 0.09	Analysis of $\pi^- p \to \pi^+ \pi^- n$	[16]
$0.2220 \pm 0.0128_{\text{stat}} \pm 0.0050_{\text{syst}} \pm 0.0037_{\text{th}}$	Experiment on K_{e4} decay	[17]
0.220 ± 0.005	ChPT + Roy's equations	[18,19]
0.220 ± 0.008	Dispersion relations and K_{e4} data	[20]
0.26	NJL model (I)	[21]
0.28	NJL model (II)	[22]

pseudobackground at the $\eta\eta$ threshold ($a_{1\eta} < 0$) is also clear: this is a direct indication to consider explicitly the $\eta\eta$-threshold branch point. This was already done in our work [7]. In the combined analysis the $f_0(600)$ parameters are changed considerably receiving new values closer to those obtained in our three-channel analysis [7]. Earlier one noted that wide resonance parameters are largely controlled by the nonresonant background [23]. In part this problem is removed due to allowing for the left-hand branch point at $s = 0$ in the uniformizing variable.

In Table III we compare our results for the $\pi\pi$ scattering length a_0^0 with results of some other theoretical and experimental works. In the analysis only of $\pi\pi$ scattering and in the A solution we reproduced with a high accuracy the ChPT results [18,19] including constraints imposed by the Roy equations. On the other hand, the B solution is similar to the predictions of the chiral approaches based on the linear realization of chiral symmetry (models of the Nambu–Jona-Lasinio type [21,22]). Taking into account very precise experiments at CERN performed by the NA48/2 [17] and the DIRAC [24] collaborations, which confirmed the ChPT prediction [18,19], one ought to prefer the A solution.

In summary, a structure of the Riemann surface of the S matrix for coupled processes must be included properly. To calculate resonance parameters, such as masses and widths, one must use poles on those sheets where they are not shifted (due to the channel coupling) in respect to the zeros on sheet I. In the two-channel case, the relevant poles are on sheets II and/or IV depending on the resonance type. Moreover, the combined analysis of coupled processes is needed as the analysis of only the $\pi\pi$ channel does not give correct values of resonance parameters even if the Riemann surface structure is included. Finally, in order to be concrete, the main scope of the paper is the scalar mesons; however, the method and conclusions of the paper can be applied to other wide resonances, e.g., to vector mesons.

This work was supported in part by the Heisenberg-Landau Program, RFBR Grant No. 10-02-00368-a, the Votruba-Blokhintsev Program for Cooperation of Czech Republic with JINR, GACR Grant No. P203/12/2126, the Grant Program of Plenipotentiary of Slovak Republic at JINR, the Bogoliubov-Infeld Program for Cooperation of Poland with JINR, the Polish Ministry of Science and Higher Education (Grant No. N N202 101 368), and by the DFG under Contract No. LY 114/2-1.

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