EPJ Web of Conferences **73**, 03003 (2014)
DOI: 10.1051/epjconf/20147303003

Present status of the $f_0(500)$ or σ meson

J.R. Peláez[a]

Dep. de Física Teórica II, Facultad de CC. Físicas, Universidad Complutense, 28040 Madrid, Spain

Abstract. In this talk I will very briefly comment on the major revision of the σ or $f_0(500)$ meson in the Review of Particle Physics, driven by new data and rigorous dispersive studies. The long debate on the mass, width and very existence of this meson is settled.

In the talk I gave at this Conference I reviewed all members of the lightest scalar nonet but due to space limitations in this written version I will focus on the lightest scalar meson, the $f_0(500)$ or σ resonance. Despite playing a prominent role in the nucleon-nucleon attraction, the QCD spontaneous chiral symmetry breaking as well as in the search for glueballs, it has suffered a longstanding controversy concerning its properties, spectroscopic classification and even its very existence as it has been nicely summarized in the "Note on light scalars below 2 GeV" in the Review of Particle Properties (RPP) [1]. Recently, the combination of new data with rigorous and model independent approaches has finally provided very convincing evidence of the existence and properties of these states. As a matter of fact, in the latest RPP edition the σ meson has suffered a major revison, and that is why I will only comment on progress made after the previous 12$^{\text{th}}$ Conference on Meson-Nucleon Physics and the Structure of the Nucleon in 2010, and only in relation to mass and width determinations of the σ. I will follow two paths: a conservative one, based on the RPP updates, and my personal view, less conservative but probably closer to the "scalar community", for long well aware of the situation now acknowledged by the RPP revisions. I will explain how the RPP updates have been driven, not only by new data, but by the consistency of rigorous dispersive approaches. Similar analyses exist for other light scalars and I expect further revisions soon.

Already 60 years ago a light scalar-isoscalar field was postulated [2] in order to explain the inter-nucleon attraction. To describe chiral symmetry in pion-pion interactions, this field was soon included within the Linear Sigma Model [3], from which it gets its usual name: the σ meson, its modern name being $f_0(500)$. The linear sigma model is a simple realization of an spontaneous chiral symmetry breaking, where all fields but the σ become Goldstone bosons, i.e. pions. Generically, the σ, having the vacuum quantum numbers, plays a relevant role for the understanding of the QCD spontaneous chiral symmetry breaking. The significance of the latest RPP major revision of the σ meson can be illustrated as follows: until 1974 the σ was listed as "not-well established", disappeared for 20 years after 1976 and came back as the $f_0(600)$ in 1996. The reason is that nucleon-nucleon interactions are not sensitive to the details of the exchanged particles, even less so if they are as wide as the σ and thus it was studied in $\pi\pi$ scattering, where it can be produced in the s-channel. Unfortunately, $\pi\pi$ scattering is extracted from

[a]e-mail: `jrpelaez@fis.ucm.es`

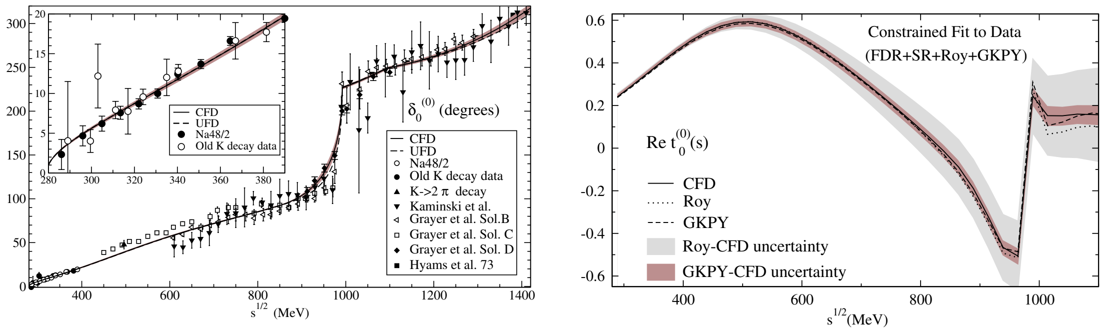

Figure 1. Scalar-isoscalar $\pi\pi$ scattering. Left: data on the $\delta_0^{(0)}$ scattering phase [4–6] versus the UFD and CFD parametrization [13]. Right: fulfillment of Roy and GKPY equations for this same wave.

$\pi N \to \pi\pi N$ through a complicated analysis plagued with systematic uncertainties, and experiments [4] produced conflicting data sets. For instance, note in Fig.1, which shows the scalar-isoscalar $\pi\pi$ scattering phase, the large differences between data sets [4], even within the same collaboration. Strong support for a σ below 1 GeV came from heavy meson decays, making the $f_0(600)$ case sufficiently convincing to be considered "well established" in 2002, although with a huge mass uncertainty ranging from 400 to 1200 MeV and a similarly large range, from 500 to 1000 MeV, for the width. These huge ranges and the $f_0(600)$ name were kept until the 2012 RPP edition.

Note that data below 400 MeV coming from $K \to \pi\pi\ell\nu$ decays [5, 6], have almost no systematic uncertainty compared to those from $\pi N \to \pi\pi N$. Particularly important are the NA48/2 precise data from 2010 [6], since being consistent with them is a criterion for the RPP choice of results in their 2012 estimate. In addition, nothing like a Breit-Wigner shape is seen around 500–600 MeV in Fig. 1 and the σ should not be described as a Breit-Wigner resonance, but with a mathematically rigorous definition through its associated pole in the complex plane, whose position s_R is related to the resonance mass and width as $\sqrt{s_R} \simeq M_R - i\Gamma_R/2$. For this reason the RPP provides a "t-matrix" pole, although, unfortunately, it also provides a Breit-Wigner pole. Obviously, the latter only leads to confusion, and thus I will only comment "t-matrix" poles. Hence, Fig. 2 displays the position of the σ poles in the RPP and the light gray area stands for the huge RPP uncertainty estimate until 2010.

In order to determine poles deep in the complex plane, a good data description is not enough, but also a correct analytic continuation is needed. Indeed, a significant part of the disagreement seen in Fig. 2 is due to unreliable extrapolations to the complex plane, so that even the same experiment can provide dramatically different poles. For example, the poles at 400-i 500 MeV, 1100-i300 MeV and 1100-i 137 MeV (below the legend), all come from [7]. To my view, only poles extracted from analytic or dispersive approaches provide reliable and precise σ pole determinations, which are highlighted in colors other than red in Fig. 2, although within the light scalar community, the existence of a σ pole around 500 MeV was rather well known for many years. Poles determined from heavy meson decays (no updates in the 2012 RPP [1]) yield a somewhat higher mass than dispersive approaches, between 500 and 550 MeV. Unfortunately the analysis of these decays has been usually performed with models less rigorous than dispersive approaches, which may differ by a couple of tens of MeV, at most.

A correct analytic continuation is obtained from dispersion relations. These are just a consequence of causality and relate the amplitude at any value with its integral over the real axis, i.e. the data. Thanks to the integral representation the results are independent of the model or functional form parameterizing the data. Dispersion relations can be used to: i) check the data consistency at a given energy versus data in other regions, ii) constrain the fits to data, iii) obtain the value of the amplitude at energies where

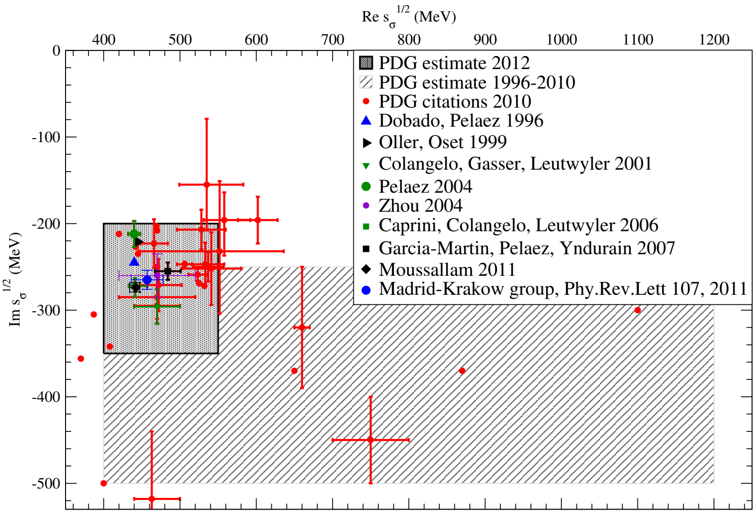

Figure 2. $f_0(500)$ poles in the RPP [1]. Non-red poles, obtained from dispersive or analytic approaches [9, 12, 14, 15, 18], fall within the 2012 estimate, which is a major revision with respect to the 2010 RPP estimate.

data are not available, iv) implement the analytic continuation in order to look for poles. Particularly useful for spectroscopy are partial wave dispersion relations, since their poles are directly associated to resonances with their same quantum numbers. Unfortunately, due to crossing symmetry, partial waves have additional singularities from the unphysical s region, like the "left cut" contribution or even a circular one in case of unequal masses. These may be numerically relevant for precise studies of the σ and the $K_0^*(800)$, which are relatively close to threshold and the left cut. Dealing rigorously with the left cut requires an infinite set of coupled integral equations, known as Roy equations [8] for $\pi\pi$ scattering, which have shown to be very powerful, particularly over the last decade [9–15]. The reason is that in the 70's, their accuracy was limited by the quality of threshold data, but this caveat can be circumvented either by means of Chiral Perturbation Theory (ChPT) at low energy, as in [9], or, if one wants to avoid ChPT as in [13], by using the recent and precise NA48/2 data [6]. The former approach yielded a precise σ pole in [12], where it was also shown that Roy eqs. provide a consistent analytic continuation down to the σ pole. The latter approach is merely a dispersive data analysis, was carried out by our group [13, 14] using another set of Roy-like Equations with only one subtraction (less energy suppression in the integrals), called GKPY Equations.

Thus, the 2012 RPP has finally reduced the uncertainties of the σ mass, by a factor of more than five, down to 400 to 550 MeV, and width, by a factor of two, now estimated between 400 and 700 MeV. This was triggered by the consistency of dispersive results, together with the NA48/2 data close to $\pi\pi$ threshold [6]. The new RPP "estimate", shown in Fig. 2 as the smaller and darker rectangle, takes into account, not only the most recent dispersive analyses, but other results from models which are required to be at least consistent with the accurate $K \to \pi\pi\ell\nu$ data [6, 16], as well as values from other processes which, as commented above, yield somewhat larger masses than dispersive approaches, extracted using models. This considerable revision, which has even changed the name of the particleto $f_0(500)$, constitutes a long awaited improvement upon the previous situation. But, to my view, these RPP criteria are still rather conservative, and for the σ I would only rely on pole extractions based on rigorous analytic methods. Furthermore, the RPP "Note on light scalars" suggests that one could "take the more radical point of view and just average the most advanced dispersive analyses" (here correspond to [9, 12, 14, 15], shown in Fig. 2), to find: $\sqrt{s_\sigma} = (446 \pm 6) - (276 \pm 5)\,\text{MeV}$.

Dispersive techniques can be illustrated with the method of group [13, 14]: We start from a set of "Unconstrained Fits to Data" (UFD), shown not to be too inconsistent with forward dispersion relations. Next, we slightly modify the fit to satisfy dispersion relations without spoiling the description of the experimental data resulting in a set of "Constrained Fits to Data" (CFD). Both the CFD and UFD for the scalar-isoscalar $\pi\pi$ scattering phase shift are shown in Fig. 1. The only noticeable differences between the UFD and CFD appear in or above the 1 GeV region, but both sets describe data very well. Let us remark that, given the same input, in the resonance region above 500 MeV the once-subtracted GKPY equations are more precise, whereas Roy equations are more accurate below that energy. In summary, the CFD describes the data and is consistent with a whole set of dispersion relations, unitarity and symmetry constraints, etc. This CFD is then used inside the GKPY dispersion relation to obtain the analytical continuation of the partial wave into the complex plane, where the following pole is found [14]: $\sqrt{s_\sigma} = (457^{+14}_{-13}) - i(279^{+11}_{-7})$ MeV and $(445 \pm 25) - i(278^{+22}_{-18})$ MeV if using Roy eqs.

These are two of the five new entries in the 2012 RPP edition. The other ones are two results from an "analytic K-matrix model" in [17]: $(452 \pm 13) - i(259 \pm 16)$ MeV and $(448 \pm 43) - i(266 \pm 43)$ MeV, depending on what data sets and different variants of the K-matrix model are averaged, together with $(442^{+5}_{-8}) - i(274^{+6}_{-5})$ MeV from [15]. The latter is also based on Roy equations using as input for other waves and higher energies the Roy equations output of [9] and is therefore very consistent with the older result in [12]: $\sqrt{s_\sigma} = (441^{+16}_{-8}) - i(272^{+9}_{-12.5})$ MeV, which used ChPT input, as well as with that even older in [10]: $(452 \pm 13) - i(259 \pm 16)$ MeV. These last three results, based on Roy equations, together with our two results in the paragraph above, are precisely the ones considered by the RPP as the "most advances dispersive analyses", shown in Fig. 2 here.

Let me thank the organizers for nice Conference and their kid invitation. Work supported by the Spanish Research contract FPA2011-27853-C02-02 and the EU FP7 HadronPhysics3 project.

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