Recent progress on light scalar mesons

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Recent progress on light scalar mesons

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Abstract. This is a brief account of the recent developments on the determination of the mass and widths of the much debated scalar mesons, paying particular attention to the causes of major revision of the σ or $f_0(500)$ meson in the last edition of the Review of Particle Physics, which has finally acknowledged that the situation concerning the mass and width of this controversial state has been settled, although this was already well-known to scalar meson practitioners for about a decade. I will briefly comment on the dispersive approach, followed by several groups, which seems to have been the most decisive in support of the existence and precise determinations of scalar meson properties.

Keywords: scalar mesons, resonances
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INTRODUCTION

For researchers outside the field, it may come as a surprise that, despite having established 40 years ago that Quantum Chromodynamics (QCD) is the theory governing the Strong Interaction, its lowest mass spectrum, particularly that of mesons, may be still under debate. Light scalar mesons play a prominent role in the nucleon-nucleon attractive interaction, the QCD spontaneous chiral symmetry breaking as well as in the search for glueballs. In spite of playing such a relevant role, light scalars have suffered a longstanding controversy concerning their properties, spectroscopic classification and even their 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]. In this talk I briefly review how 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. Very slowly, these developments are cautiously being reflected in the RPP. Actually in the latest RPP edition the σ meson has suffered a major revision and the $f_0(980)$ has been significantly updated.

Here I will briefly comment on progress, made after the previous 2009 Chiral Dynamics Workshop, on mass and width determinations of scalars below 1 GeV. Other scalars and the heated controversy concerning their classification in multiplets and composition, lie beyond the scope of this mini-review. 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. Since such analyses exist for other light scalars, I expect further revisions in the near future.

THE MAJOR REVISION OF THE σ OR $f_0(500)$ MESON IN THE RPP.

A light scalar-isoscalar field was postulated 60 years ago [2], to explain the nucleon attraction, and was soon incorporated in the Linear Sigma Model [3], from which it gets its common name: the σ resonance. Nowadays it is called $f_0(500)$. Being linear, this is the simplest realization of an spontaneous chiral symmetry breaking, through a scalar multiplet, where all fields but the σ become Goldstone bosons. On more general grounds, the σ, with the vacuum quantum numbers, is expected to play a relevant role in the QCD spontaneous chiral symmetry breaking.

The latest RPP revision of the σ meson can be considered a major improvement in view of its history: until 1974 the RPP listed the σ as "not-well established", from 1976 it then disappeared for 20 years and came back as the $f_0(600)$ in 1996. The reason for this coming and going is that the nucleon-nucleon interaction is rather insensitive to the details of the exchanged particles, and even less so if they are as wide as the σ. Therefore, light scalars were mostly studied in meson-meson scattering, where they can be produced in the s-channel. Unfortunately, $\pi\pi$ scattering is extracted from $\pi N \to \pi\pi N$ through a complicated analysis full of systematic uncertainties, and the experimental results [4] were

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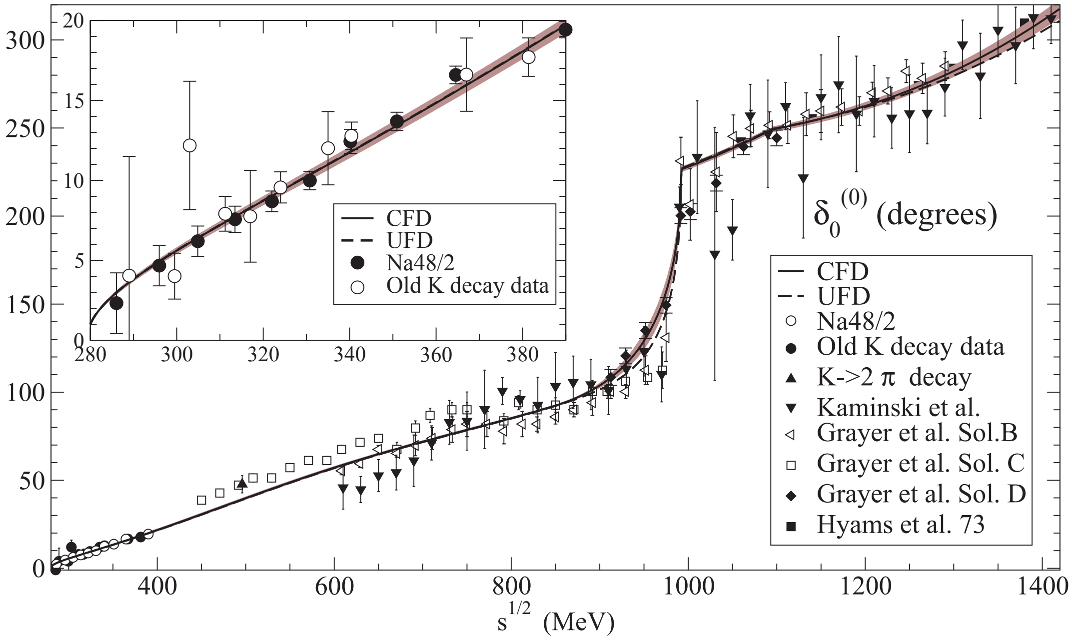

FIGURE 1. Scalar-isoscalar $\pi\pi$ scattering: Data on the $\delta_0^{(0)}$ scattering phase [4, 5, 6] versus the UFD and CFD parametrization [13]. Right: Fulfillment of Roy and GKPY equations for this same wave.

often in conflict. Take a look, for instance, at Fig.1, which shows the scalar-isoscalar $\pi\pi$ scattering phase, and check the large differences between data sets [4], even within the same collaboration. The $f_0(600)$ case gathered enough support before 2002 when it was declared “well established” by the RPP. This came from some theoretical works but mostly from the results of heavy meson decay experiments, which have very different systematics than the scattering experiments, well defined final states and very good statistics, although theoretically their analysis is quite often model dependent. Surprisingly for a "well established" state, it was quoted with a huge uncertainties: from 400 to 1200 MeV for the mass, and from 500 to 1000 MeV, for the width. These huge ranges and the $f_0(600)$ name were kept until the last 2010 RPP edition and are shown as a huge gray square in Fig.2.

Two remarks are in order about Fig.1. First, note the data below 400 MeV coming from $K \to \pi\pi\ell\nu$ decays [5, 6], which have almost no systematic uncertainty compared to those from $\pi N \to \pi\pi N$. Especially relevant are the 2010 precise NA48/2 data [6], since consistency with them is a key requirement for the RPP choice of results in their new estimate. Second, no Breit-Wigner shape is seen around 500-600 MeV. Actually, the σ cannot be described as a Breit-Wigner resonance (nor the $K_0^*(800)$). Hence one uses the mathematically rigorous definition of a resonance by means of its associated pole in the complex plane, whose position s_R is related to the resonance mass and width as $\sqrt{s_R} \simeq M_R - i\Gamma_R/2$. This is why the RPP provides the so-called “t-matrix” pole, although, unfortunately, it also provides a Breit-Wigner pole. To my view, the latter only leads to confusion, and I will only comment “t-matrix” poles. Thus, Fig.2 shows the position of the σ poles in the RPP and the huge light gray area corresponds to the RPP estimate until 2010.

It is important to remark that to determine poles deep in the complex plane, it is not enough to have a good data

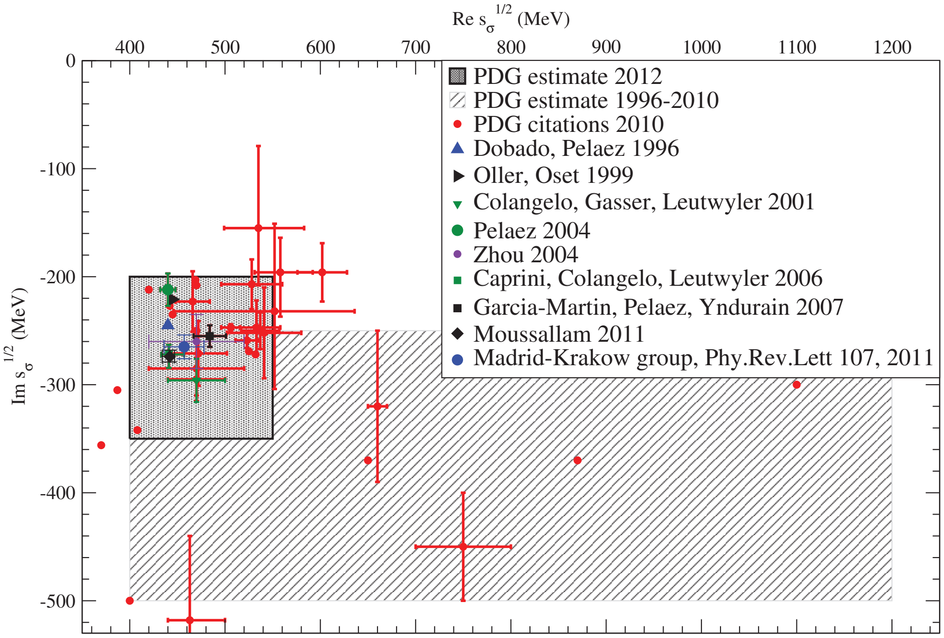

FIGURE 2. $f_0(500)$ poles in the RPP[1]. Non-red poles, obtained from dispersive or analytic approaches [18, 9, 12, 14, 15], fall within the 2012 estimate, which is a major revision with respect to the 2010 RPP estimate.

description, a correct analytic continuation is really needed. Unfortunately this has not been the case of many analyses, leading to unreliable or plain wrong pole determinations. As a matter of fact, most of the disagreement seen in Fig.2 can be attributed to unreliable analytic extrapolations, so that even the same experiment can provide surprisingly different poles. For instance, the poles at 400-i 500 MeV, 1100-i300 MeV and 1100-i 137 MeV (below the legend), both come from [7]. The lesson to learn is that only poles extracted from rigorous analytic or dispersive approaches provide reliable σ pole determinations, which in Fig.2 are plotted in colors other than red. By looking only at those poles it is clear why the existence of a σ pole around 500 MeV was rather well known for many years within the scalar meson community. Dispersive approaches may differ by few tens of MeV, but definitely not by several hundreds. Note that poles obtained from heavy meson decays (with no updates in the 2012 RPP [1]) yield a somewhat higher mass than dispersive approaches, between 500 and 550 MeV. Let me also remark that the analysis of these decays has been frequently performed with models much less rigorous than dispersive analyses.

A rigorous analytic continuation is obtained from dispersion relations that, as a consequence of causality, relate the amplitude at any value with an integral over the real axis, i.e. the data.Thanks to the integral representation the results are independent of the model or functional form parametrizing the data. They can be used to: a) check the consistency of data at a given energy against data in other regions, b) constrain data fits, c) calculate the amplitude at energies where data do not exist, c) use the analytic continuation to look for poles. Of particular interest for spectroscopy are partial wave dispersion relations, since their poles are directly associated to resonances with their same quantum numbers. However, due to crossing symmetry, partial waves have a “left cut” contribution, from the unphysical s region. This is 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 involves an infinite set of coupled integral equations, known as Roy equations [8] for $\pi\pi$ scattering, which have received considerable attention over the last decade [10, 9, 11, 12, 13, 14, 15]. In the 70’s, their accuracy was limited by the quality of threshold data, but this caveat can be circumvented either by the use of Chiral Perturbation Theory (ChPT) at low energy, as in [9], or, if one wants to avoid the use of ChPT as in [13], by using the recent and precise NA48/2 data [6]. The former approach provided a precise σ pole, also showing that Roy Equations yield a consistent analytic continuation to the σ region [12]. The latter, which is just a dispersive data analysis, was followed by our group [13, 14] using another set of Roy-like Equations, called GKPY Equations, with only one subtraction (less energy suppression in the integrals).

Thus, the 2012 RPP has finally made a major revision of the σ mass range, reduced by a factor of more than

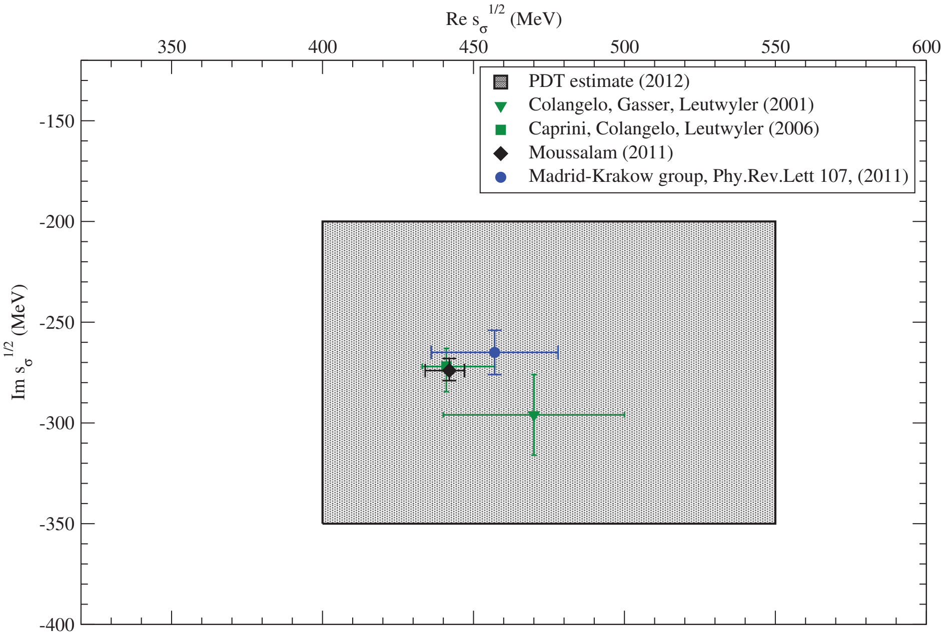

FIGURE 3. The four "most advanced dispersive analyses" [9, 12, 14, 15] which according to the "Note on light scalars" of the 2012 RPP lead to their "more radical" average $\sqrt{s_\sigma} = (446 \pm 6) - (276 \pm 5)$ MeV. The gray square is the uncertainty estimate of the RPP.

five, down to 400 to 550 MeV, and by almost a factor of two for the width, now estimated between 400 and 700 MeV. This change has been triggered by the consistency of dispersive results, together with the new 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 like heavy meson decays, which, as commented above, use models and yield somewhat larger masses than dispersive approaches. Note that even the name of the particle has been changed to $f_0(500)$. The RPP also provides Breit-Wigner parameters but I have argued above why I think they should be avoided. Definitely, this $f_0(500)$ update should be considered a major revision which was long awaited, and improves considerably the previous situation. Nevertheless, in my opinion, these RPP criteria are still too conservative, and for the σ I would rely on pole extractions based on rigorous dispersive techniques only. In fact, even the RPP 'Note on light scalars" offers the possibility to "take the more radical point of view and just average the most advanced dispersive analyses", which according to the RPP are [9, 12, 14, 15]), yielding: $\sqrt{s_\sigma} = (446 \pm 6) - (276 \pm 5)$ MeV. These poles are shown here in Fig.3, inside the new uncertainty estimate of the RPP.

As an illustration of the dispersive techniques, let me sketch the methods of our group [13, 14]. We start from a set of "Unconstrained Fits to Data" (UFD), which we showed 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. This procedure leads to a set of "Constrained Fits to Data" (CFD). Both the CFD and UFD for the scalar-isoscalar $\pi\pi$ scattering phase shift were already shown on 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. In addition, we show in Fig.4 how well the CFD satisfies the Roy and GKPY equations for the real part of the scalar-isoscalar wave. The continuous line is the CFD input, whereas the dotted and dashed lines are the output of the Roy and GKPY equations, respectively. Note that the once-subtracted GKPY equations are more precise in the resonance region, say above 500 MeV, whereas Roy equations are more accurate below that energy, given the same input. In summary, the CFD describes the data and is consistent with a whole set of dispersion relations, unitarity and symmetry constraints, etc... We then use this CFD inside the dispersion relation to obtain the analytical continuation of the partial wave into the complex plane, where

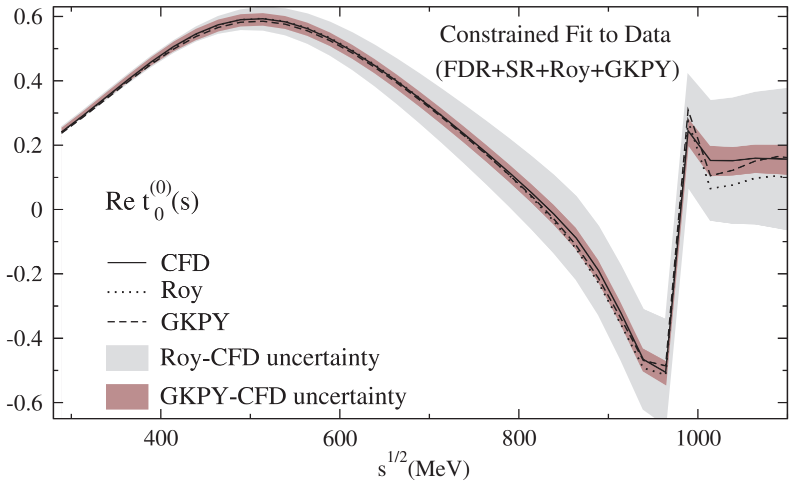

FIGURE 4. Scalar-isoscalar $\pi\pi$ scattering: Fulfillment of Roy and GKPY equations for this same wave.

the following poles are found[14]:

$$\sqrt{s_\sigma} = (457^{+14}_{-13}) - i(279^{+11}_{-7})\ \text{MeV}(\text{from GKPY eqs.})$$

and $(445 \pm 25) - i(278^{+22}_{-18})$ MeV (from Roy eqs.), very consistent between them.

Our two pole determinations just given above are two of the five new entries in the 2012 RPP edition. The other new entries 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. Finally, the other new result in the 2012 RPP is $(442^{+5}_{-8}) - i(274^{+6}_{-5})$ 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.3 here.

THE $f_0(980)$

The existence and parameters of the $f_0(980)$ have been much less controversial, since this resonance is narrow and clearly seen in many processes. For example, in Fig.1, although it is slightly distorted by the nearby $\bar{K}K$ threshold, a Breit-Wigner-like shape can be seen over a background phase of about 100^o around 980 MeV. This is nothing but the $f_0(980)$.

Nevertheless, after almost two decades of keeping the same estimate, the 2012 RPP has updated the $f_0(980)$ mass to 990 ± 20 MeV. As pointed out in the 2012 "Note on light scalars", the 10 MeV higher update on the mass, and the doubling of the uncertainty, was made to accommodate the dispersive analysis by our group [13, 14]. We obtain an $f_0(980)$ pole (in the second Riemann sheet) at: $\sqrt{s_{f_0(980)}} = (996 \pm 7) - i(25^{+10}_{-6})$ MeV if we use GKPY equations and $\sqrt{s_{f_0(980)}} = (1003^{+5}_{-27}) - i(21^{+10}_{-8})$ MeV from Roy equations. The relevance of our study is that it has settled a longstanding conflict between the "dip" and "no-dip" scenarios for the elasticity parameter in $\pi\pi$ scattering, shown in Fig.5. In [13] it was shown that the dip scenario satisfies well the GKPY dispersion relations as seen in Fig.5, whereas it is not possible to accommodate the non-dip scenario. This was confirmed later in [15] using Roy equations and obtaining a pole at: $(996^{+4}_{-14}) - i(24^{+11}_{-3})$ MeV. Actually, these three dispersive values together with the one from the "analytic K-matrix" approach in [17], $(981 \pm 43) - i(18 \pm 11)$ MeV, are the only new additions to the $f_0(980)$ in the 2012 RPP .

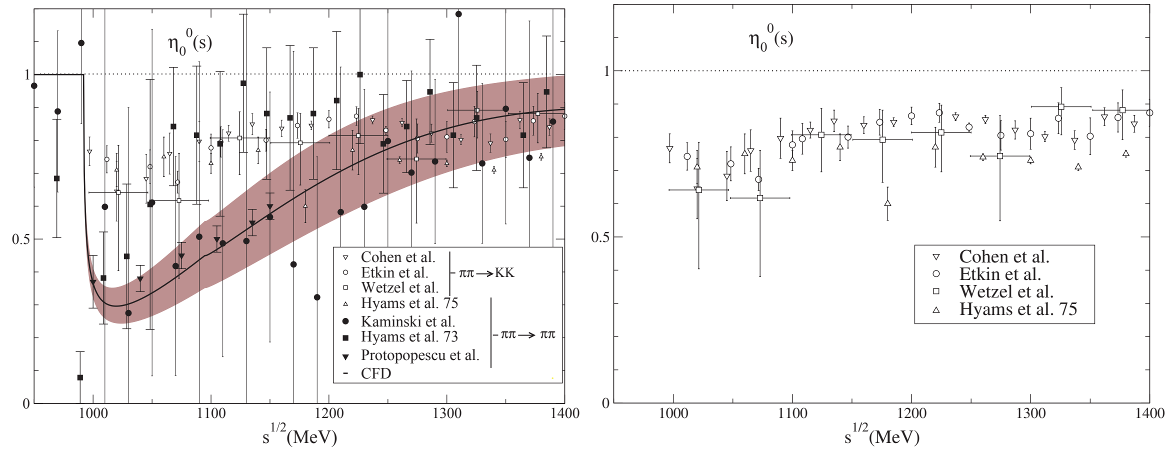

FIGURE 5. Left: Favored "Dip" solution (CFD) for the $\pi\pi$ scattering inelasticity around the $f_0(980)$ resonance region. Original figures and references in [13]. Right: data only for the disfavored "no-dip" scenario.

THE $a_0(980)$ AND THE κ OR $K_0^*(800)$

There were no changes for the $a_0(980)$ parameters in the latest RPP.

Concerning the $K_0^*(800)$ meson or κ, it is listed in the RPP under the "needs confirmation" label. This occurs despite being rather similar to the σ. In fact either within fairly reasonable models or rigorous Roy-like dispersive analyses [19], the $K_0^*(800)$ appears as a wide pole (not a Breit Wigner) around 650 to 770 MeV, with a 550 MeV width or larger. Furthermore, as with the $f_0(500)$, a pole is consistently seen in heavy meson decays. In my opinion then, it deserves the same treatment as the σ and should be considered as another "well established" light scalar meson resonance.

Unfortunately, the additions the 2012 RPP come from Breit-Wigner parameters of two studies of J/Ψ decays at BES2 [20]. Fortunately this Collaboration [20] also provides a $t-matrix$ pole position $764 \pm^{+71}_{-54} - i(306 \pm 149^{+143}_{-85})$ MeV. This is quite consistent with the value from rigorous dispersive approaches $(658 \pm 13) - i(278.5 \pm 12)$ MeV [19]. The 2012 RPP keeps the previous estimates: 685 ± 29 MeV for the mass and 547 ± 24 for the width.

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