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2014 J. Phys.: Conf. Ser. 562 012012

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Status of light scalar mesons as non-ordinary mesons

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Abstract. In this talk I briefly review the status of the $f_0(500)$ and $f_0(980)$ together with the other light scalar resonances, as well as the emerging picture of a non-ordinary light meson multiplet, paying particular attention to unitarized Chiral Perturbation Theory, large N_c , semi-local duality and Regge theory arguments.

1. Introduction and present status

The lightest scalar meson, recently renamed $f_0(500)$, but traditionally known as the σ meson, has been a longstanding puzzle in our understanding of strong interactions. This resonance is very relevant both for Nuclear and Particle Physics. For the former because, on a first approximation, it is largely responsible for nucleon-nucleon attraction, and for the latter due to its role in spontaneous chiral symmetry breaking and the identification of glueballs - two fundamental features of QCD. Moreover, there is an ongoing worldwide experimental program on strong interactions (CERN, China, Germany, Japan & USA), even looking for New Physics, where many results depend crucially on final state interactions of pions, producing scalar mesons in general and the $f_0(500)$ in particular. Despite this relevance, the σ properties, nature, and even its very existence have been controversial for decades, since it was first proposed almost 60 years ago. As an example of this debate, the σ (with different names) appeared listed in the early editions of the Particle Data Tables (PDT) [1], disappeared for quite some time of those lists, and made it back to the tables in 2002. Surprisingly, despite being quoted with a huge mass uncertainty from 400 to 1200 MeV and a huge uncertainty in the width, it was nevertheless considered a “well established state”.

Finally, and after more than five decades, the controversy on the $f_0(500)$ mass and width seems to be settled. This has been rather well known to specialists for quite some time [2, 4, 5, 6, 3, 7, 8, 9, 10] but remained less well known to the Particle and Nuclear Physics community at large. Actually, this situation has been finally acknowledged with a major revision of its properties in the 2012 edition of the PDT[1], where, after more than a decade of quoting such a disproportionately huge mass uncertainty, it has been reduced by a factor of more than five (and the width uncertainty by more than two), settling the case for the so-called “light sigma” scenario, and opening the door for an even more radical revision in the future, in terms of current dispersive analyses (see the “Note on light scalars” in the PDT).

Of course, the evidence that supports this recent recognition has been accumulating over many years both from the experimental and theoretical side, using a wide variety of techniques, which not only have allowed for precise and model independent determinations of the mass and width of this meson, but which have advanced our understanding of its non-ordinary features.



In addition, in the 2012 PDT edition, the $f_0(980)$ has also suffered a minor revision, by changing the central value of its mass from 980 to 990 MeV whereas its mass uncertainty has doubled to 20 MeV. Other possible multiplet partners of the $f_0(500)$, as the $a_0(980)$ and $K(800)$ have not suffered any changes in their quoted parameters in the last PDT edition. Note that the $K(800)$ is still considered as "not well established" despite its pole has already been well established within a rigorous dispersive approach [36]. The $K(800)$ is therefore in a situation somewhat similar to that of the $f_0(500)$ a few years ago: Its existence is widely accepted by the "scalar-community" but it just lacks recognition in the PDT.

Historically, the first proposal of a scalar isoscalar field was made in the 50's [11] and it was soon realized by J. Schwinger that expectation values of such a scalar singlet field, which he called σ [12], could be of relevance for the breaking of symmetries. Actually it soon became relevant for simple models of the attractive part of the nucleon-nucleon interaction and for the spontaneous chiral symmetry breaking of QCD. For the latter one should mention the traditional Linear Sigma Model [13], but also the more modern and systematic approach of Chiral Perturbation Theory [15], including its unitarization [16, 17, 4, 5, 6, 18], which is needed to generate resonances. Apart from the questioning of their existence, light scalars have faced the controversy on their classification in multiplets [19, 2, 9, 10] leading to the suggestion that they may have a predominantly non-ordinary quark-antiquark nature [19, 20], which has received a recent strong support based on the N_c dependence [21, 22, 23, 24, 25], unusual Regge behavior [26], etc... On the experimental side, the clarification of these controversial issues was hindered by the difficult observation from nucleon-nucleon interactions and the large systematic uncertainties in traditional pion-nucleon experiments used to extract pion-pion scattering [27]. However, more recent "production" experiments, with different systematics from scattering processes, have been very relevant in the recent clarification in the PDT (like [28]) although these also may have problems of their own (use of Breit-Wigner parametrizations, isobar models, etc...). Finally, the results that have partly driven the major σ revision in the PDT have been the latest NA48/2 data on [30] $K \rightarrow \pi\pi\ell\nu$ experiments (some older can be found on [29]) together with the most recent dispersive approaches that have provided a rigorous treatment of this resonance.

2. The $f_0(500)$ parameters

As just commented, one of the main difficulties to present a convincing case for the existence of a σ resonance pole around 500 MeV and not higher —the so-called "light sigma" scenario— were due to: i) the poor data on $\pi\pi$ scattering [27], ii) its large width and iii) the fact that the σ does not present the familiar peak and shape of a Breit-Wigner resonance. A description in terms of poles in the complex plane is more appropriate, although, being so wide, its associated pole is deep in the complex plane. This demands a careful, rigorous and model independent analytic extension after the amplitudes that describe the data have been constrained with dispersion relations. The precise analyses of $\pi\pi$ scattering with dispersion relations [38, 33, 40] and their later use to find the associated poles [33, 34, 35, 36] have driven the major revision in the PDT [1], which now reads 400–550 MeV for the mass and 400–700 MeV for the width, as defined from the associated pole. Actually, the PDT mass and with new estimates are "conservative", and the PDT also provides a "more radical point of view", relying only on such model independent dispersive approaches, yielding a mass of 446 ± 6 MeV and a width of 552 ± 10 MeV.

The dispersive results are also responsible for the minor change in the $f_0(980)$ parameters and, when applied to πK scattering, for the most reliable $K(800)$ determination [36]. I have no space to discuss them here in detail but can only refer to the appropriate references on Roy equations [39, 38, 33, 36], GKPY equations [40], Forward Dispersion relations [32, 41] and some pedagogical introductions [31, 32].

3. Chiral Symmetry and the $f_0(500)$

Within Particle Physics, part of the interest on the $f_0(500)$ is due to its role in the spontaneous chiral symmetry breaking of QCD. Actually, the traditional name “sigma”, given by J.Schwinger [12], was later adopted by the classic ‘Linear Sigma Model’ (LSM) formulation of such a breaking [13]. The LSM has played a very important role in our phenomenological and more intuitive description of low energy hadronic interactions, which has its success and shortcomings, leading to multiple variations, i.e. [3]. Similarly, a relatively light scalar-isoscalar meson coupling strongly to $\pi\pi$, and therefore very wide, also seems to be generated in a Nambu-Jona-Lasinio (NJL) model or its modifications within Hadron Physics [14]. Still, both the LSM and NJL are simple models that, despite capturing many relevant features, do not provide a systematic description of low energy hadron Physics and a clear connection to QCD, and usually require some ad-hoc modifications. Nevertheless, a systematic analysis exists under the form of the more modern Chiral Perturbation Theory (ChPT), which is the low energy effective Theory of QCD. Within standard ChPT [15], only Goldstone modes appear explicitly in the Lagrangian, and the dynamics is encoded in a set of “low energy parameters”, whose values are saturated [37] by heavier resonances, but not by the sigma, which is another hint of its non-ordinary nature. ChPT is limited to low energies and resonances are not present in its Lagrangian, but can be generated when combined with some dispersive techniques. This approach, less systematic, known as unitarized Chiral Perturbation Theory [16, 17], has been very successful in the description of light scalars and is particularly simple in the case of the $f_0(500)$ [4]. These unitarization techniques allow to study the quark mass dependence of the σ [42], also recently studied on the lattice despite the difficulties in providing results for physical quark masses [43]. Other models in the literature deal with the $f_0(500)$ together with the other light scalars, like extended linear sigma models [3], non-linear models [9, 10], as well as the simple but very successful Chiral Unitary Approach [5, 6], which is tightly connected to Unitarized Chiral Perturbation Theory described before. The lesson to learn from all them is that even very simple descriptions of low energy data, when implementing some basic chiral symmetry constraints and using a decent analytic extrapolation, yield a $f_0(500)$ pole in fair agreement with the precise and model independent dispersive determinations commented in the previous section.

4. The spectroscopy and nature of light scalars

These are the $f_0(500)$ features that are still under some discussion, although the situation has also clarified considerably over the last years. The first problem with spectroscopy is how light scalars are assigned to U(3) multiplets. There is a very strong support [19, 2, 3, 5, 6, 8] for the sigma to belong to a nonet with the other lightest scalars, namely the $f_0(980)$, $a_0(980)$ and $K(800)$. Still, this assignment is obscured by the possible different mixing schemes [45, 10] within states of the multiplet (or even other multiplets) as well as by the controversial status of some scalar mesons, like the $K(800)$ or the $f_0(1370)$.

Somewhat more controversial is the composition of these resonances in terms of quarks and gluons. It was long ago suggested that the ordinary identification of mesons as $q\bar{q}$ states did not match well the light scalars due to their inverted hierarchy [19] as well as their large widths and couplings [44]. Of course, attention has to be paid to what is meant by “composition”, since the intuitive Fock space decomposition is not always well defined. Most interpretations are made within some kind of “constituent models”. However there are recent attempts to tackle this problem from QCD via the $1/N_c$ behavior of the $f_0(500)$ pole generated from unitarized ChPT [22, 8, 23], or, more recently, also on the lattice [49]. Unitarized ChPT supports a predominantly non- $q\bar{q}$ nature for the $f_0(500)$ providing a very strong support for the $f_0(500)$ meson, since it depends on N_c in a rather different way than predicted from QCD for $q\bar{q}$ mesons [46]. This effect was also observed in $\pi\pi$ scattering by explicit introduction of resonant states [21, 24]. Furthermore, the same conclusion can be obtained without using a particular model, but just

from data, the pole positions and the general behavior of $q\bar{q}$ states in QCD [25]. Moreover, larger N_c extrapolations [50] suggest that, even if it is not predominantly an ordinary meson, it might contain some small admixture of a heavier $q\bar{q}$ state [23]. Note this is the $1/N_c$ expansion around $N_c = 3$ [47], although some results are also available for the "large N_c limit" [48].

Finally, since the $f_0(500)$ has not been commonly included in the ordinary classifications of hadrons into linear Regge trajectories with a universal slope [51], its Regge trajectory has been shown not to follow a straight line and that its slope is of a very different order of magnitude than ordinary mesons [26], once again supporting the non-ordinary nature of this state.

5. Acknowledgements

I thank the organizers of Troia14 for their kind hospitality and for creating such a nice scientific environment. Work supported by the Spanish Research contract FPA2011-27853-C02-02 and the EU-Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (acronym HadronPhysics2, Grant Agreement n. 227431, 7th Framework Programme).

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