A resonance of the Higgs field at 700 GeV and a new phenomenology

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Abstract
It has been recently proposed that, besides the known resonance with mass $m_h \sim 125$ GeV, the Higgs field could exhibit a new excitation with a larger mass $M_h$ related by $M_h^2 \sim m_h^2 \ln(\Lambda_s/M_h)$, where $\Lambda_s$ is the ultraviolet cutoff of the scalar sector. Lattice simulations performed in the 4D Ising limit of the theory support this two-mass picture and lead to the estimate $M_h \sim 700$ GeV. In spite of its large mass, however, the heavier state would couple to longitudinal vector bosons with the same typical strength of the low-mass state and thus would represent a relatively narrow resonance. We argue that this hypothetical new resonance would naturally be associated with the peak in the 4-lepton channel observed by ATLAS at 700 GeV.
1. Introduction

Spontaneous Symmetry Breaking (SSB) through the vacuum expectation value $\langle \Phi \rangle \neq 0$ of a scalar field, is a basic ingredient of the Standard Model. This old idea of a fundamental scalar field [1, 2] has more recently found an important experimental confirmation after the observation, at the Large Hadron Collider of CERN [3, 4] of a narrow scalar resonance, of mass $m_h \sim 125 \text{ GeV}$ whose phenomenology fits well with the perturbative predictions of the theory. This has produced the widespread conviction that, by now, any modification of this general picture can only come from new physics.

Though, this is not necessarily true. So far only the gauge and Yukawa couplings of the 125 GeV resonance have been tested. Instead, the effects of a genuine scalar self-coupling $\lambda$ are still below the accuracy of the measurements. For this reason, an uncertainty about the mechanisms producing SSB may still persist.

At the beginning, the driving mechanism was identified in a classical scalar potential with a double-well shape. But, after Coleman and Weinberg [5], the phenomenon started to be described at the quantum level and the classical potential was replaced by the effective potential $V_{\text{eff}}(\varphi)$ which includes the zero-point energy of all particles in the spectrum. But SSB could still be determined by the pure $\lambda \Phi^4$ sector if the contributions of the other fields to the vacuum energy are negligible. As recently pointed out in ref.[6], this becomes a natural perspective if one takes into account the indications of most recent lattice simulations of pure $\lambda \Phi^4$ in 4D [7, 8, 9]. These calculations, performed in the Ising limit of the theory with different algorithms, indicate that on the largest lattices available so far the SSB phase transition is (weakly) first order, as in the one-loop and Gaussian approximations.

The crucial point is that, in these approximations, the resulting effective potential has two mass scales: i) a lower mass $m_h$, defined by its quadratic shape at the minima and related to the zero-momentum self-energy $\Pi(p = 0)$ and ii) a larger mass $M_h$, defined by the zero-point energy and related to a typical average value $\langle \Pi(p) \rangle$ at larger $|p|$. Although always considered as a single mass, they turn out to be related by $M_h^2 \sim Lm_h^2 \gg m_h^2$, where $L = \ln(\Lambda_s/M_h)$ and $\Lambda_s$ is the ultraviolet cutoff of the scalar sector. Since vacuum stability depends on the much larger $M_h$, and not on $m_h$, spontaneous symmetry breaking could well originate within the pure scalar sector regardless of the other parameters of the theory (e.g. the vector boson and top quark mass).
This two-mass picture, which resembles the coexistence of phonons and rotons in the energy spectrum of superfluid He-4, has been checked \cite{6} with lattice simulations of the propagator in the 4D Ising limit of the theory. This limit, always considered as a convenient laboratory to exploit the non-perturbative aspects of the theory, corresponds to a $\lambda \Phi^4$ with an infinite bare coupling $\lambda_B = +\infty$, as if one were sitting precisely at the Landau pole.

In this sense, for any finite cutoff $\Lambda_s$, it provides the best definition of the local limit for a given non-zero, low-energy coupling $\lambda \sim 1/L$. Then, once $m_h^2$ is directly computed from the zero-momentum limit of the propagator $G(p) = (p^2 - \Pi(p))^{-1}$ and $M_h$ is extracted from the behaviour of $G(p)$ at higher momentum, the lattice data confirm the expected increasing logarithmic trend $M_h^2 \sim Lm_h^2$.

From a phenomenological point of view, the lattice simulations indicate that in a cutoff theory, where $m_h$ and $M_h$ are both finite albeit vastly different scales, the scalar propagator interpolates between these two masses so that, by increasing the energy, one should see a transition from a relatively low value, e.g. $m_h=125$ GeV, to a much larger $M_h$. At the same time since, differently from $m_h$, the larger mass $M_h$ would remain finite in units of the weak scale $\langle \Phi \rangle \sim 246$ GeV in the continuum limit, one can write a proportionality relation, say $M_h = K \langle \Phi \rangle$, and extract the constant $K$ from the same lattice data. As discussed in \cite{6}, this leads to a final estimate $M_h \sim 720 \pm 30$ GeV which includes various statistical and theoretical uncertainties and updates the previous work of refs.\cite{11,12}.

We emphasize that with the relation $M_h = K \langle \Phi \rangle$ we are not introducing a new large coupling $K^2 = O(10)$ in the picture of symmetry breaking. This $K^2 = (M_h^2 / \langle \Phi \rangle)^2$ is clearly quite distinct from the usual low-energy coupling $\lambda \sim (m_h^2 / \langle \Phi \rangle)^2 \sim 1/L$ but should not be viewed as a coupling constant which produces observable interactions in the broken-symmetry phase. Since $M_h^4$ reflects the magnitude of the vacuum energy density, the natural interpretation is to consider $K^2 \sim \lambda L$ as a collective self-interaction of the scalar condensate which, differently from $\lambda$, persists in the $\Lambda_s \rightarrow \infty$ limit. This original view \cite{13,14,15} has now been made more transparent after the RG-analysis of the effective potential in ref.\cite{6}.

\footnote{The simultaneous presence of two different mass scales in the scalar propagator would also require some interpolating form in the loop corrections. Since some precision measurements (e.g. the b-quark forward-backward asymmetry or the value of $\sin^2 \theta_w$ from neutral current experiments) still point to a rather large mass of the Higgs boson mass, this could provide an alternative way to improve the overall quality of a Standard Model fit. For a general discussion of the various quantities and of systematic errors see ref.\cite{10}.}
On the other hand $\lambda \sim 1/L$ remains as the appropriate coupling to describe the individual interactions of the elementary excitations of the vacuum, i.e. the Higgs field and the Goldstone bosons. Consistently with the “triviality” of $\lambda \Phi^4$ theory, these remain weakly interacting entities with a strength which becomes weaker and weaker when $\Lambda_s \to \infty$.

By assuming this description of the scalar sector, and using the Equivalence Theorem \cite{16, 17}, the same conclusion applies to the high-energy interactions of the Higgs field with the longitudinal vector bosons in the full $g_{\text{gauge}} \neq 0$ theory. In fact, the limit of zero gauge coupling is smooth \cite{18}. Therefore, up to corrections proportional to $g_{\text{gauge}}$, a heavy Higgs particle will interact exactly with the same strength as in the $g_{\text{gauge}} = 0$ theory \cite{19}. In the language of the present paper, this could be rephrased by saying that for $M_h \sim 700$ GeV, the conventional estimate $\Gamma_{\text{conv}}(M_h \to WW + ZZ) \sim M_h^3 G_{\text{Fermi}} \sim 172$ GeV becomes the much smaller value $\Gamma(M_h \to WW + ZZ) \sim M_h(m_h^2 G_{\text{Fermi}})$ where $M_h$ is from phase space and $m_h^2 G_{\text{Fermi}} \sim 1/L$ is the strength of the interaction.

By addressing to refs.\cite{6, 19} for more details, we arrive to the main point of this Letter. Suppose to take seriously this two-mass picture and the prediction of a second heavier excitation of the Higgs field with mass $M_h \sim 700$ GeV. Is there any experimental indication for such a resonance? Furthermore, if there were some potentially interesting signal, what kind of phenomenology should we expect? Finally, is there any support for the identification $m_h \sim 125$ GeV, implicitly assumed for the magnitude of our lower mass scale?

In the following Sect.2, we will consider these questions by using a definite piece of experimental evidence: the peak observed by the ATLAS Collaboration \cite{20} in the 4-lepton channel for an invariant mass $\mu_{4l} = 700$ GeV. This should be seriously considered because an independent analysis of these data and their combination \cite{21} with the corresponding ones of the CMS Collaboration \cite{22} indicates an evident excess, with respect to the background.

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2To help physical intuition, it may be useful to compare SSB to the phenomenon of superconductivity in non-relativistic solid state physics. There, the transition to the superconductive phase represents an essential instability occurring for any infinitesimal two-body attraction $\epsilon$ between the two electrons forming a Cooper pair. At the same time, however, the energy density of the superconductive phase and all global quantities of the system (energy gap, critical temperature, etc.) depend on the much larger collective coupling $\epsilon N$ obtained after re-scaling the tiny 2-body strength by the large number of states near the Fermi surface. This means that, in principle, the same macroscopic description could be obtained with smaller and smaller $\epsilon$ and Fermi systems of corresponding larger and larger $N$. In this comparison $\lambda$ is the analog of $\epsilon$ and $K^2$ is the analog of $\epsilon N$. 4
with a statistical significance of about 5 sigma.

Of course, the 4-lepton channel is just one of the possible decay channels of a hypothetical heavier Higgs resonance and, for a comprehensive analysis, one should also look at the other final states. For instance, at the 2-photon channel which, in the past, has been showing some intriguing signal at the close energy of 750 GeV. However, the 4-lepton channel, as compared to other final states, has the advantage of being experimentally clean and, for this reason, is considered the “golden” channel to explore the possible existence of a heavy Higgs resonance. Moreover, the bulk of the effect can be analyzed at an elementary level. Thus it makes sense to start from here.

2. A new phenomenology

Let us now consider the peak in the number of events observed by ATLAS in the 4-lepton channel for invariant mass $\mu_{4l} = 700$ GeV. From Fig.4a of [20] this corresponds to the range

$$3 \lesssim n_{\text{peak}}^{(l^+l^-l^+l^-)} \lesssim 9 \quad \text{ATLAS} - 700 \text{ GeV}$$

above the small background $n_{\text{bkg}} \sim 1$ event. By subtracting this background and considering symmetric errors we get a number of (non-background) events

$$n_{\text{peak}}^{(l^+l^-l^+l^-)} \sim 5 \pm 3 \quad (\text{non} - \text{bkg}) \; \text{EXP}$$

Now, the ATLAS efficiency for events with reconstructed leptons at large transverse momentum is nearly 100%. Therefore, for a luminosity of 36.1 $fb^{-1}$, this peak is equivalent to a (non-background) peak cross-section

$$\sigma_{\text{peak}}^{pp \rightarrow l^+l^-l^+l^-} \sim (0.14 \pm 0.08) \; fb$$

In our estimates, we will make the oversimplified assumption that the invariant mass $\mu_{4l} = 700$ GeV is exactly the same pole mass $M_h = 700$ GeV of our heavier excitation of the Higgs field. Moreover, if we consider this to be a relatively narrow resonance, the corrections due to its virtuality [23] should be small and this cross-section could be factorized in terms of on-shell branching ratios as

$$\sigma(pp \rightarrow M_h \rightarrow l^+l^-l^+l^-) \sim \sigma(pp \rightarrow M_h) \cdot B(M_h \rightarrow ZZ) \cdot 4B^2(Z \rightarrow l^+l^-)$$

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In this relation, the $Z-$boson branching ratio into charged leptons is precisely known and yields $4B^2(Z \rightarrow l^+l^-) \sim 0.0045$.

Concerning the other branching ratio $B(M_h \rightarrow ZZ)$, for $M_h = 700$ GeV, we recall that the only unconventional aspect of our picture concerns the coupling of the heavy Higgs resonance to longitudinal vector bosons which is proportional to $m_h^2 G_{\text{Fermi}} \sim 1/L$ and not to $M_h^2 G_{\text{Fermi}}$. Therefore, given a decay width $\Gamma(M_h \rightarrow ZZ)$, we could use the conventional estimate for $M_h = 700$ GeV \cite{24,25}

$$\Gamma^{\text{conv}}(M_h \rightarrow ZZ) \sim M_h^3 G_{\text{Fermi}} \sim 56.7 \text{ GeV} \quad (5)$$

and obtain $m_h$ as

$$m_h = \sqrt{\frac{\Gamma(M_h \rightarrow ZZ)}{56.7 \text{ GeV}}} \times 700 \text{ GeV} \quad (6)$$

Equivalently, we could insert a given value for $m_h$ and compute

$$\Gamma(M_h \rightarrow ZZ) = \frac{m_h^2}{(700 \text{ GeV})^2} \times 56.7 \text{ GeV} \quad (7)$$

Here, we will follow the latter strategy and assume, tentatively, the exact identification $m_h = 125$ GeV which gives

$$\Gamma(M_h \rightarrow ZZ) \sim 1.8 \text{ GeV} \quad (8)$$

Thus, to obtain $B(M_h \rightarrow ZZ)$, we only need an estimate of the total width. To this end, we will maintain exactly the other contributions reported in the literature \cite{24,25} for $M_h = 700$ GeV, namely

$$\Gamma(M_h \rightarrow \text{fermions + gluons + photons...}) \sim 28 \text{ GeV} \quad (9)$$

and the same ratio

$$\frac{\Gamma(M_h \rightarrow WW)}{\Gamma(M_h \rightarrow ZZ)} \sim 2.03 \quad (10)$$

\footnote{The quoted value refers to a top-quark mass of 173.7 which averages between the two determinations 173.2(6) GeV and 174.2(1.4) GeV reported by the Particle Data Group \cite{26} and replaces the values 171.4 and 172.5 GeV used respectively in \cite{24,25}.}
Table 1: For $M_h = 700\text{GeV}$ and $m_h = 125\text{GeV}$, and for two values of the total cross-section, we report our predictions for the peak cross section $\sigma(pp \rightarrow 4l)$ and the number of events at two values of the luminosity.

| $\sigma(pp \rightarrow M_h)$ | $\sigma(pp \rightarrow 4l)$ | $n[4l](\mathcal{L}=36.1\text{ fb}^{-1})$ | $n[4l](\mathcal{L}=139\text{ fb}^{-1})$ |
|----------------------------|---------------------------|--------------------------------|--------------------------------|
| 950(100) fb               | 0.23(2) fb               | 8.3 ± 0.8                      | 32.1 ± 3.3                     |
| 1200(150) fb              | 0.29(4) fb               | 10.5 ± 1.4                     | 40.4 ± 5.1                     |

These input numbers (which have very small uncertainties) will thus produce a total decay width

$$\Gamma(M_h \rightarrow all) = 28\text{ GeV} + 3.03 \Gamma(M_h \rightarrow ZZ) \sim 33.5\text{ GeV}$$  \hspace{1cm} (11)

and a branching ratio

$$B(M_h \rightarrow ZZ) = \frac{1.8}{33.5} \sim 0.054$$  \hspace{1cm} (12)

Finally, let us consider the total inclusive cross section $\sigma(pp \rightarrow M_h)$, for production of a heavy Higgs resonance of 700 GeV at 13 TeV. Here, there is no unambiguous prediction confirmed by experimental tests. Therefore, we will separately compare with two slightly different estimates. On the one hand, the value $\sigma(pp \rightarrow M_h) = 1080(100)\text{ fb}$ of ref.\[24\] and on the other hand the other value $\sigma(pp \rightarrow M_h) = 1365(150)\text{ fb}$ of ref.\[25\]. These predictions refer to $\sqrt{s} = 14\text{ TeV}$ and will be rescaled by about $-12\%$ for the actual center of mass energy of 13 TeV. In both cases, errors include various uncertainties due to the choice of the normalization scale and the parametrization of the parton distributions.

Altogether, for $B(M_h \rightarrow ZZ) = 0.054$ and $4B^2(Z \rightarrow l^+l^-) \sim 0.0045$, our predictions for the 4-lepton peak cross section and the associated number of events (for luminosity of 36.1 fb$^{-1}$ and 139 fb$^{-1}$) are reported in Table 1.

From this comparison, we conclude that, without the introduction of any free parameter, our model can easily reproduce the order of magnitude of the presently observed peak $n[4l] = 5 \pm 3$. However, the statistics analyzed so far is not sufficient to draw a firm conclusion. Therefore, a test of our picture is postponed to the analysis of the entire luminosity $\mathcal{L} = 139\text{ fb}^{-1}$. If our new $M_h \sim 700\text{ GeV}$ is really there, the number of events at the peak should
become four times bigger, while remaining well above the background which is very small in that region. Thus the line shape of the resonance should become visible and direct determinations of the total width should be possible. An experimental result $\Gamma_{\text{exp}}(M_h \to \text{all}) = 33\div34$ GeV would support an experimental branching ratio $B_{\text{exp}}(M_h \to ZZ)$ close to our reference value 0.054 and, in turn, sharpen the agreement of our smaller $m_h$ with the value 125 GeV measured directly at LHC.

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