Experimental signals for a second resonance of the Higgs field

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In the region of invariant mass $620 \div 740$ GeV, we have analyzed the ATLAS sample of 4-lepton events that could indicate a new scalar resonance produced mainly via gluon-gluon fusion. These data suggest the existence of a new heavy state $H$ whose mass $660 \div 680$ GeV would fit well with the theoretical range $M_H = 690 \pm 10$ (stat) $\pm 20$ (sys) GeV for the hypothetical second resonance of the Higgs field that has been recently proposed and which would couple to longitudinal W's with the same typical strength of the low-mass state at 125 GeV. Since the total width $\Gamma_H$ is very poorly determined, to sharpen the analysis of the precious ATLAS data, we have considered a particular correlation between resonating peak cross section $\sigma_R(pp \rightarrow H \rightarrow 4l)$ and the ratio $\gamma_H = \Gamma_H/M_H$. This correlation should be nearly insensitive to the precise value of $\Gamma_H$ and mainly determined by the lower mass $m_h = 125$ GeV. Equivalently, if this correlation holds true, one could also fit $m_h$ from the 4-lepton data in the high-mass range $620 \div 740$ GeV. The result $(m_h)^{\text{fit}} \sim (125 \pm 13)$ GeV reproduces the direct measurement of the Higgs particle mass and thus supports the idea that $m_h$ and $M_H$ are the masses of two different excitations of the same field. Therefore, if we combine with the excess at 680 GeV in the ATLAS $\gamma\gamma$ distribution, there are now two signals for a new resonance in the same mass region. Even though, quantitatively, the global statistical significance of each effect is modest, still the sharp correlation $\gamma_H - \sigma_R$ in the 4-lepton channel should induce to consider seriously these indications.

Keywords: Spontaneous Symmetry Breaking; Higgs field mass spectrum; LHC experiments.

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1. Introduction

At present, the excitation spectrum of the Higgs field is described in terms of a single narrow resonance of mass $m_h = 125$ GeV associated with the quadratic shape of the effective potential at its minimum. In a description of Spontaneous Symmetry Breaking (SSB) as a second-order phase transition, this point of view is well summarized in the review of the Particle Data Group where the scalar
potential is expressed as

\[ V_{\text{PDG}}(\varphi) = -\frac{1}{2} m_{\text{PDG}}^2 \varphi^2 + \frac{1}{4} \lambda_{\text{PDG}} \varphi^4 \]  

(1)

By fixing \( m_{\text{PDG}} \sim 88.8 \text{ GeV} \) and \( \lambda_{\text{PDG}} \sim 0.13 \), this has a minimum at \( |\varphi| = \langle \Phi \rangle \sim 246 \text{ GeV} \) and a second derivative \( V''_{\text{PDG}}(\langle \Phi \rangle) \equiv m_h^2 = (125 \text{ GeV})^2 \).

However, recent lattice simulations of \( \Phi^4 \) in 4D support instead the view of SSB as a (weak) first-order phase transition. While in the presence of gauge bosons SSB is often described as a first-order transition, recovering this result in pure \( \Phi^4 \) requires to replace standard perturbation theory with some alternative scheme.

The implications of a first-order scenario in pure \( \Phi^4 \) have not been fully exploited because, with a finite but very large cutoff, besides the 125 GeV resonance, there could be another much larger mass scale \( M_H \). Since vacuum stability would depend on \( M_H \), SSB could originate within the pure scalar sector regardless of the other parameters of the theory, e.g. the vector boson and top quark mass.

To recall how this comes out, we will first summarize the results of refs.\(^{5,7} \) where, as a definite scheme in which \( \Phi^4 \) exhibits a (weak) first-order transition, one explored the original Coleman-Weinberg\(^{8} \) one-loop calculation and the Gaussian effective potential\(^{9,10} \). Indeed, in both cases, SSB takes place when the quanta of the symmetric phase have a very small but still positive mass squared. These two calculations, corresponding to different re-summations of graphs, support each other and admit the same non-perturbative interpretation: an effective potential \( V_{\text{eff}}(\varphi) \) given by some classical background + zero-point energy of a particle with some \( \varphi \)-dependent mass \( M(\varphi) \). The peculiarity is that, in both approximations, by defining \( m_h^2 \) as \( V''_{\text{eff}}(\varphi) \) at the minimum, and \( M_H \) as the value of \( M(\varphi) \) at the minimum, one finds the following trend in terms of the ultraviolet cutoff \( \Lambda_s \):

\[ L = \ln(\Lambda_s/M_H) \sim \frac{1}{\lambda} \quad \quad \text{and} \quad \quad M_H^2 \sim L m_h^2 \gg m_h^2 \]  

(2)

Thus there are two possible renormalization patterns. A first pattern a) where \( M_H \) is cutoff independent, the effective potential has a finite depth \( |\mathcal{E}| \sim M_H^4 \) and a quadratic shape which vanishes, in units of \( M_H^2 \), when \( \Lambda_s \to \infty \). A second pattern b) where now \( m_h \) is \( \Lambda_s \)-independent and one has the opposite view of a potential with finite curvature at the minimum but an infinite depth. With pattern a), the relations \( m_h^2 = \lambda \langle \Phi \rangle^2 / 3 \) and \( \lambda \sim 16\pi^2/(3L) \), yielding cutoff-independent \( M_H \) and \( \langle \Phi \rangle \), produce the usual non-interacting continuum limit for the fluctuations around the minimum of the potential. However, differently from the 2nd-order scenario, the symmetry-restoring temperature \( T_c \sim |\mathcal{E}|^{1/4} \sim M_H \) is now finite in units of \( \langle \Phi \rangle \). This finiteness can be intuitively explained in terms of an increasing density \( \rho \sim \sqrt{L} \) of \( \langle \Phi \rangle = 0 \) quantum\(^{11} \) which Bose condense in the \( p = 0 \) state and are hidden in the vacuum structure. Therefore \( M_H^2 \sim \rho \sqrt{\lambda} \) remains non-zero when \( \Lambda_s \to \infty \).

\(^{a}\)This somehow resembles superconductivity where the energy gap and the critical temperature depend on a collective coupling \( G = g N_F \) obtained after re-scaling the tiny two-body strength \( g \), of the electrons in a Cooper pair, by the large density of states \( N_F \) at the Fermi surface.
To further clarify the $m_h - M_H$ difference, let us recall that the derivatives of the effective potential produce (minus) the n-point functions at zero external momentum. Hence $m_h^2$, which is $V_{\text{eff}}'(\varphi)$ at the minimum, is directly the 2-point, self-energy function $[\Pi(p = 0)]$. On the other hand, the zero-point energy is (one-half of) the trace of the logarithm of the inverse propagator $G^{-1}(p) = (p^2 - \Pi(p))$. Then, after subtracting constant terms and quadratic divergences, matching the 1-loop zero-point energy ("zpe") at the minimum gives the relation

$$zpe \sim -\frac{1}{4} \int_{p_{\text{min}}}^{p_{\text{max}}} \frac{d^4p}{(2\pi)^4} \frac{\Pi^2(p)}{p^4} \sim -\frac{\Pi^2(0)}{64\pi^2} \ln \frac{p_{\text{max}}^2}{p_{\text{min}}^2} \sim -\frac{M_H^4}{64\pi^2} \ln \frac{\Lambda^2}{M_H^2} \tag{3}$$

This shows that $M_H^2$ effectively refers to some average value $\langle |\Pi(p)| \rangle$ at larger $p^2$. A non-trivial momentum dependence of $\Pi(p)$ would then indicate the coexistence, in the cutoff theory\(^b\), of two kinds of “quasi-particles”, with masses $m_h$ and $M_H$, thus closely resembling the two branches (phonons and rotons) in the energy spectrum of superfluid He-4 which is usually considered the non-relativistic analog of the broken phase.

The existence of a two-mass structure in the cutoff theory was checked with lattice simulations of the scalar propagator\(^b\). Then, by computing $m_h^2$ from the $p \to 0$ limit of $G(p)$ and $M_H^2$ from its behaviour at higher $p^2$, the lattice data are consistent with a transition between two different regimes. By analogy with superfluid He-4, where the observed energy spectrum arises by combining the two quasi-particle spectra of phonons and rotons, the lattice data were well described in the full momentum region by the model form\(^b\)

$$G(p) \sim \frac{1 - I(p)}{2} \frac{1}{p^2 + m_h^2} + \frac{1 + I(p)}{2} \frac{1}{p^2 + M_H^2} \tag{4}$$

with an interpolating function $I(p)$ which depends on an intermediate momentum scale $p_0$ and tends to $+1$ for large $p^2 \gg p_0^2$ and to $-1$ when $p^2 \to 0$. Most notably, the lattice data were also consistent with the expected increasing logarithmic trend $M_H^2 \sim \Lambda \ln^2 \Lambda$ when approaching the continuum limit\(^c\).

\(^b\)This gives one more argument for the different cutoff dependence of $m_h$ and $M_H$. Indeed, it is crucial not to run in contradiction with the “triviality” of $\Phi^4$ which requires a continuum limit with a Gaussian set of Green’s functions and a massive free-field propagator. With this constraint, for a consistent cutoff theory, there are only two possibilities when $\Lambda_s \to \infty$: either the usual perturbative limit $m_h/M_H = 1 + O(\lambda) \to 1$, or a non-uniform scaling of the two masses, see\(^b\).

\(^c\)Note that Eq.\(^b\) closely resembles van der Bij’s two-pole propagator\(^b\) deduced on the basis of very different arguments, quite unrelated to the effective potential and/or lattice simulations. If the Higgs field propagator has really a two-pole structure, radiative corrections will then be sensitive to an effective mass $m_{\text{eff}}$ in the range $m_h \leq m_{\text{eff}} \leq M_H$, see\(^b\). Therefore, it becomes important to understand how well the mass parameter obtained indirectly from radiative corrections agrees with the $m_h = 125$ GeV, measured directly at LHC. Here we just recall that, for a careful check, it is essential to take into account the positive $m_{\text{eff}} - \alpha_s(M_Z)$ correlation\(^b\) where the relevant $\alpha_s(M_Z)$ is the one entering the strong-interaction correction to the quark-parton model in $\sigma(e^- + e^- \to \text{hadrons})$ at center of mass energy $Q = M$. Since the most complete analysis of $e^- + e^- \to \text{hadrons}$ data\(^b\) in the range $20$ GeV $\leq Q \leq 209$ GeV, indicates an overall 4-sigma excess with a
Since, differently from $m_h$, the larger $M_H$ would remain finite in units of the weak scale $\langle \Phi \rangle \sim 246.2$ GeV for an infinite ultraviolet cutoff, one can derive their proportionality relation. To this end, let us express $M_H^2$ in terms of $m_h^2L$ through some constant $c_2$, say

$$M_H^2 = m_h^2L \cdot (c_2)^{-1}$$  \hspace{1cm} (5)$$
and replace the leading-order estimate $\lambda \sim 16\pi^2/(3L)$ in the relation $\lambda = 3m_h^2/\langle \Phi \rangle^2$. Then $M_H$ and $\langle \Phi \rangle$ are related through a cutoff-independent constant $K$

$$M_H = K\langle \Phi \rangle$$  \hspace{1cm} (6)$$
with $K \sim (4\pi/3) \cdot (c_2)^{-1/2}$. Since, from a fit to the lattice propagator, we found $(c_2)^{-1/2} = 0.67 \pm 0.01$ (stat) $\pm 0.02$ (sys) this gives the estimate

$$M_H = 690 \pm 10 \text{ (stat)} \pm 20 \text{ (sys)} \text{ GeV}$$  \hspace{1cm} (7)$$

After having summarized the main theoretical framework of, we will first describe in Sect.2 the expected phenomenology of the new resonance. We will then compare in Sect.3 with the ATLAS 4-lepton data which indicate an excess of events in the same mass region of Eq.(7). Even more significantly, in our picture there is a particular correlation with the lower-resonance mass at 125 GeV which is reproduced to high accuracy by the ATLAS data. Finally, Sect.4 will contain a summary, a discussion of the presently available CMS 4-lepton events and our conclusions, also on the basis of a (local) 3-sigma excess at 680 GeV observed in the ATLAS $\gamma\gamma$ distribution.

2. Basic phenomenology of the new resonance

By accepting the “triviality” of $\Phi^4$ theories in 4D, the $\Lambda_s$—independent combination $3M_H^2/\langle \Phi \rangle^2 = 3K^2$ cannot represent a coupling entering observable processes. Instead, as anticipated, from the relation $|\mathcal{E}| \sim M_H^4$, it would be natural to consider $3K^2$ as a collective self-interaction of the vacuum condensate whose effects are fully re-absorbed into the vacuum structure. In this sense, the constant $3K^2$ is basically different from the coupling $\lambda$ governed by the $\beta$—function

$$\ln \frac{\mu}{\Lambda_s} = \int_{\Lambda_0}^{\Lambda} \frac{dx}{\beta(x)}$$  \hspace{1cm} (8)$$
For $\beta(x) = 3x^2/(16\pi^2) + O(x^3)$, whatever the contact coupling $\lambda_0$ at the asymptotically large $\Lambda_s$, at finite scales $\mu \sim M_H$ this gives $\lambda \sim 16\pi^2/(3L)$ with $L = \ln(\Lambda_s/M_H)$.

As emphasized in, there is no contradiction with the original calculation in the unitary gauge. This could give the impression that, with a mass $M_H$ in the scalar value $\alpha_s(M_Z) \gtrsim 0.128$, the present view, that the Higgs mass parameter extracted indirectly from radiative corrections agrees perfectly with the $m_h = 125$ GeV measured directly at LHC, is not free of ambiguities.
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propagator, very high-energy $W_L W_L$ scattering is indeed similar to $\chi\chi$ Goldstone boson scattering with a contact coupling $\lambda_0 = 3K^2$. However, this is just the result of a tree approximation with the same coupling at all momentum scale. To find the $W_L W_L$ scattering amplitude at some scale $\mu$ one should first use the $\beta$–function to re-sum the higher-order effects in $\chi\chi$ scattering

$$A(\chi\chi \to \chi\chi)|_{g_{\text{gauge}}=0} \sim \lambda \sim \frac{1}{\ln(\Lambda_s/\mu)}$$

and then use the Equivalence Theorem\cite{19–21} which gives

$$A(W_L W_L \to W_L W_L) = [1 + O(g_{\text{gauge}}^2)] A(\chi\chi \to \chi\chi)|_{g_{\text{gauge}}=0} = O(\lambda)$$

Thus the large coupling $\lambda_0 = 3K^2$ is actually replaced by the much smaller coupling

$$\lambda = \frac{3m_h^2}{\langle \Phi \rangle^2} = 3K^2 \frac{m_h^2}{M_H^2} \sim 1/L$$

For the same reason, the conventional large width into longitudinal vector bosons computed with $\lambda_0 = 3K^2$, say $\Gamma_{\text{conv}}(H \to W_L W_L) \sim M_H^3/\langle \Phi \rangle^2$, should instead be rescaled by $(\lambda/3K^2) = m_h^2/M_H^2$. This gives

$$\Gamma(H \to W_L W_L) \sim \frac{m_h^2}{M_H^2} \Gamma_{\text{conv}}(M_H \to W_L W_L) \sim M_H \frac{m_h^2}{\langle \Phi \rangle^2}$$

where $M_H$ indicates the available phase space in the decay and $m_h^2/\langle \Phi \rangle^2$ the interaction strength. If the heavier state couples to longitudinal W’s with the same typical strength of the low-mass state it would represent a relatively narrow resonance.

With these premises, it was proposed\cite{7, 22} that this hypothetical new resonance could naturally fit with some localized excess of 4-lepton events in the ATLAS data around 680 GeV\cite{19} Of course, the 4-lepton channel is just one possible decay channel and, for a complete analysis, one should also look at the other final states. However, this final state fixes the kinematics in an incomparable way and, for this reason, is considered the “golden” channel to exploit the existence of a heavy Higgs resonance. At the same time, the bulk of the effect can be analyzed at an elementary level. Therefore it is natural to start from here.

The main new aspect is the strong reduction of the conventional width in Eq.(12). By assuming for definiteness the reference value $M_H = 700$ GeV, where $\Gamma_{\text{conv}}(H \to ZZ) \sim 56.7$ GeV\cite{23, 24} this gives

$$\Gamma(H \to ZZ) \sim \frac{m_h^2}{(700 \text{ GeV})^2} \sim 56.7 \text{ GeV}$$

so that for $m_h = 125$ GeV one finds $\Gamma(H \to ZZ) \sim 1.8$ GeV.

With this premise, in\cite{7, 22} one was also assuming from refs\cite{23, 24} the values $\Gamma(H \to \text{fermions + gluons + photons...}) \sim 28$ GeV and the ratio $\Gamma(H \to W^+ W^-)/\Gamma(H \to ZZ) \sim 2.03$ deducing a total width $\Gamma(H \to \text{all}) \sim 33.5$ GeV and a fraction $B(H \to ZZ) \sim (1.8 / 33.5) \sim 0.054$. However, these two estimates were not taking into account the new, additional contributions to the total width due to the decays of
the heavier state into the lower-mass state at 125 GeV. These include the two-body process $H \rightarrow hh$, the three-body processes $H \rightarrow hhh$, $H \rightarrow hZZ$, $H \rightarrow hW^+W^-$ and all higher-multiplicity final states allowed by phase space. For this reason, the above value $\Gamma(H \rightarrow all) \sim 33.5$ GeV should only be considered as a lower bound. For the same reason, the fraction $B(H \rightarrow ZZ) \sim (1.8/33.5) \sim 0.054$ should also be considered as an upper bound.

Since it is not easy to evaluate these additional contributions, here, to compare with the ATLAS data, we will perform a test of our picture that does not require the knowledge of the total width but just relies on two assumptions:

a) a resonant 4-lepton production by the hypothetical heavy H which proceeds through the process $H \rightarrow ZZ \rightarrow 4l$

b) the estimate in Eq. (13) together with the linear scaling law of our model for small variations around $M_H = 700$ GeV

$$\Gamma(H \rightarrow ZZ) \sim \frac{M_H}{700 \text{ GeV}} \cdot \frac{m_h^2}{(700 \text{ GeV})^2} \cdot 56.7 \text{ GeV}$$

(14)

Therefore, by defining $\gamma_H = \Gamma(H \rightarrow all)/M_H$, we find a fraction

$$B(H \rightarrow ZZ) = \frac{\Gamma(H \rightarrow ZZ)}{\Gamma(H \rightarrow all)} \sim \frac{1}{\gamma_H} \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700 \text{ GeV})^2}$$

(15)

that will be replaced in the cross section approximated by on-shell branching ratios

$$\sigma_{pp \rightarrow H \rightarrow 4l} \sim \sigma(pp \rightarrow H) \cdot B(H \rightarrow ZZ) \cdot 4B^2(Z \rightarrow l^+l^-)$$

(16)

This should be a good approximation for a relatively narrow resonance, where the effects of its virtuality should be small, so that one gets the anticipated correlation

$$\gamma_H \cdot \sigma_{pp \rightarrow H \rightarrow 4l} \sim \sigma(pp \rightarrow H) \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700 \text{ GeV})^2} \cdot 4B^2(Z \rightarrow l^+l^-)$$

(17)

Since $4B^2(Z \rightarrow l^+l^-) \sim 0.0045$, the last ingredient we need is the total production cross section $\sigma(pp \rightarrow H)$. As discussed in [22], the relevant production mechanism in our picture is through the gluon-gluon Fusion (ggF) process. In fact, the other production through Vector-Boson Fusion (VBF) plays no role. The point is that the $VV \rightarrow H$ process (here $VV = W^+W^-, ZZ$) is the inverse of the $H \rightarrow VV$ decay so that $\sigma^{VBF}(pp \rightarrow H)$ can be expressed [22] as a convolution with the parton densities of the same Higgs resonance decay width. The importance given traditionally to this mechanism depends crucially on the conventional large width into longitudinal $W$’s and $Z$’s computed with the $3K^2$ coupling. In our case, where this width is rescaled by the small ratio $(125/700)^2 \sim 0.032$, one finds $\sigma^{VBF}(pp \rightarrow H) \lesssim 10$ fb which can be safely neglected.

Thus, we will replace $\sigma(pp \rightarrow H) \rightarrow \sigma^{ggF}(pp \rightarrow H)$ in Eq. (17) and use the ggF cross sections taken from the updated Handbook of Higgs cross sections [26] and reported in Table 1. For 13 TeV pp collisions, and taking into account a typical $\pm 15\%$ uncertainty (due to the choice of the parton distributions, of the QCD scale and other effects), we will adopt here the estimate $\sigma^{ggF}(pp \rightarrow H) = 1180(180)$ fb
Table 1. We report the ggF cross section in fb to produce a heavy Higgs resonance at $\sqrt{s} = 8$ and 13 TeV. The ratios of the two cross sections, respectively 4.311, 4.393 and 4.477, for $M_H = 660, 680$ and 700 GeV, and the 8 TeV values were taken from the updated Handbook of Higgs cross sections in the CERN yellow report. No theoretical uncertainty is reported.

| $M_H$ (GeV) | $\sigma_{gg}(8 \text{ TeV})$ | $\sigma_{gg}(13 \text{ TeV})$ |
|------------|----------------------------|-------------------------------|
| 660        | 315.3                      | 1359.26                       |
| 680        | 268.2                      | 1178.20                       |
| 700        | 229.0                      | 1025.23                       |

which, in our case, also accounts for the range $M_H = 660 \div 700$ GeV. Therefore, by fixing $m_h = 125$ GeV, we arrive to a theoretical prediction which, for not too large $\gamma_H$ where Eq. (16) becomes inadequate, is formally insensitive to the value of the total width and can be compared with the ATLAS data

$$\left[\gamma_H \cdot \sigma_R(pp \to H \to 4l)\right]^{\text{theor}} \sim (0.0137 \pm 0.0021) \text{ fb}$$

(18)

3. Analysis of the ATLAS 4-lepton events

To check the precise correlation in Eq. (18), we have considered the full ATLAS sample of 4-lepton data for luminosity $139 \text{ fb}^{-1}$ and in the region of invariant mass $M_4l = 620 \div 740$ GeV ($l = e, \mu$) which extends about $\pm 60$ GeV around our mass value $M_H = 690 \pm 10 \text{ (stat)} \pm 20 \text{ (sys)}$ GeV.

Now, Eq. (18) accounts only for production through the ggF mechanism and ignores the VBF-production mode which plays no role in our picture. Therefore, we should compare with that subset of data that, for their typical characteristics, admit this interpretation. To this end, the ATLAS experiment has performed a multivariate analysis (MVA) of the ggF production mode which combines a multilayer perceptron (MLP) and one or two recurrent neural networks (rNN). The outputs of the MLP and rNN(s) are concatenated so as to produce an event score. In this way, depending on the score, the ggF events are divided into four mutually exclusive categories: ggF-MVA-high-4$\mu$, ggF-MVA-high-2$e$2$\mu$, ggF-MVA-high-4$e$, ggF-MVA-low. The four sets of events were extracted from the corresponding HEPData file and are reported in Table 2.

By defining $M_4l = E$ and $s = E^2$ we have then transformed the total number of the ggF 4-lepton events in Table 2 into cross sections for the given luminosity $139 \text{ fb}^{-1}$. As in refs. 22 we then assumed the interference of a resonating amplitude $A^R(s) \sim 1/(s - M_R^2)$ with a slowly varying background $A^B(s)$. For a positive interference below peak, setting $M_R^2 = M_H^2 - iM_H\Gamma_H$, this gives a total cross section

$$\sigma_T = \sigma_B - \frac{2(s - M_R^2) \Gamma_H M_H}{(s - M_R^2)^2 + (\Gamma_H M_H)^2} \sqrt{\sigma_B\sigma_R} + \frac{(\Gamma_H M_H)^2}{(s - M_R^2)^2 + (\Gamma_H M_H)^2} \sigma_R$$

(19)
Table 2. At the various 4-lepton invariant mass $M_4 \equiv E$, we report the ATLAS events for the four different categories of the ggF production mode and their total number.

| $M_4$ [GeV] | MVA-high-$4\mu$ | MVA-high-2$e$2$\mu$ | MVA-high-4$e$ | MVA-low | ToT |
|------------|-----------------|-----------------|---------------|---------|-----|
| 635(15)   | 2               | 0               | 1             | 7       | 10  |
| 665(15)   | 0               | 2               | 2             | 17      | 21  |
| 695(15)   | 1               | 0               | 1             | 9       | 11  |
| 725(15)   | 0               | 1               | 0             | 3       | 4   |

where, in principle, both the average background $\sigma_B$, at the central energy 680 GeV, and the resonating peak cross-section $\sigma_R$ can be treated as free parameters.

Table 3. For each $\gamma_H$ we report the values of $M_H$, the resonating cross section $\sigma_R$ and the corresponding product $k = \gamma_H \cdot \sigma_R$ which are obtained from a fit with Eq. (19) to the total number of ATLAS events in Table 2.

| $\gamma_H$ | $M_H$ [GeV] | $\sigma_R$ [fb] | $k = \gamma_H \cdot \sigma_R$ [fb] |
|------------|-------------|-----------------|---------------------------------|
| 0.05       | 678(6)      | 0.218(39)       | 0.0109(20)                      |
| 0.06       | 676(7)      | 0.191(30)       | 0.0115(18)                      |
| 0.07       | 673(10)     | 0.174(26)       | 0.0122(18)                      |
| 0.08       | 669(20)     | 0.161(24)       | 0.0129(19)                      |
| 0.09       | 668(16)     | 0.151(22)       | 0.0136(20)                      |
| 0.10       | 668(15)     | 0.141(21)       | 0.0141(21)                      |
| 0.11       | 669(15)     | 0.133(21)       | 0.0146(23)                      |
| 0.12       | 670(16)     | 0.125(22)       | 0.0150(26)                      |
| 0.13       | 672(17)     | 0.118(23)       | 0.0153(30)                      |
| 0.14       | 673(19)     | 0.112(26)       | 0.0157(36)                      |
| 0.15       | 674(20)     | 0.106(29)       | 0.0159(43)                      |

In a first series of fits to the ATLAS data, for each given $\gamma_H = \Gamma_H/M_H$, there were 3 free parameters, namely $M_H, \sigma_R$ and $\sigma_B$. As a control, to check the stability of the results, we then repeated the analysis by assuming the background to be a decreasing function of energy. To this end, for each given $\gamma_H$, we considered the central value $\langle \sigma_B \rangle$ from the first series of fits and replaced the constant background with a function depending on a slope parameter $\Delta \sigma_B \geq 0$

$$\sigma_B(E) = \langle \sigma_B \rangle - \Delta \sigma_B \cdot \frac{(E - 680)}{680}$$

(20)

In this second series of fits, $\Delta \sigma_B$ was further constrained by $0 \leq \Delta \sigma_B \leq \langle \sigma_B \rangle (680/45)$ imposing the positivity of $\sigma_B(E)$ at the upper limit of the energy range. Therefore, again, for each given $\gamma_H$, there were 3 free parameters: $M_H, \sigma_R$, and $\Delta \sigma_B$.

The second series of fits did not show any appreciable evidence for an energy-decreasing background so that we reported in Table 3 the results obtained with a constant average background. The profile of the $\chi^2$ as function of $\gamma_H$ and the fit to
Fig. 1. At the various values of $\gamma_H$, we report the chi-square of the fit with Eq.(19) to the ATLAS data.

Fig. 2. For $\gamma_H = 0.09$, we show the fit with Eq.(19) to the ATLAS cross sections in fb.

the ATLAS cross sections for $\gamma_H = 0.09$ are reported respectively in Fig.1 and in Fig.2.

Finally, to show the very good consistency with our theoretical prediction

dThe fitted average background shows some mild dependence on the input $\gamma_H$ value. In all cases, however, we found $\langle \sigma_B \rangle_{\text{fit}} \lesssim 0.03$ fb, thus indicating an average total background events $\langle N_B \rangle_{\text{fit}} \lesssim 17$. This is about twice as small as the background estimated by ATLAS $\langle N_B \rangle_{\text{estimated}} \sim 36$. As a partial explanation for this difference, we observe that the two external bins at 635(15) and 725(15) GeV of [16] which are less sensitive to the presence of a resonance, have less events than expected.
Fig. 3. The $\sigma_R$’s of Table 3 are compared with our theoretical prediction Eq. (18) represented by the shaded area enclosed by the two hyperbolae $\sigma_R = (0.0137 \pm 0.0021)/\gamma_H$. Eq. (18), we have reported in Fig. 3 the peak cross sections of Table 3 and compared with the shaded area enclosed by the two hyperbolae $\sigma_R = (0.0137 \pm 0.0021)/\gamma_H$. This picture illustrates how well the observed $\gamma_H - \sigma_R$ correlation in Table 3 is reproduced in our model. In particular, notice the excellent agreement between Eq. (18) and the value $k = \gamma_H \cdot \sigma_R = 0.0136$ for $\gamma_H = 0.09$ which gives the minimum $\chi^2$. Finally, a fit to all entries in Table 3 with $\chi^2 < 1$ gives

$$[\gamma_H \cdot \sigma_{R(\text{pp} \rightarrow H \rightarrow 4l)}]_{\text{fit}} = k \sim (0.0137 \pm 0.0008) \text{ fb}$$

(21)

This value can then be replaced in the left-hand side of Eq. (17) by providing the combined determination

$$[\sigma(\text{pp} \rightarrow H) \cdot m_h^2]_{\text{fit}} = (1.84 \pm 0.11) \cdot 10^7 \text{ fb} \cdot \text{GeV}^2$$

(22)

Therefore, with the previous estimate $\sigma(\text{pp} \rightarrow H) \sim \sigma_{ggF}(\text{pp} \rightarrow H) \sim 1180(180) \text{ fb}$, we find

$$(m_h)_{\text{fit}} \sim (125 \pm 13) \text{ GeV}$$

(23)

whose central value coincides with the measured Higgs particle mass.

4. Summary and conclusions

From the phenomenological analysis of Sect. 3, we can draw the following conclusions:

i) by inspection of Table 3, the ATLAS 4-lepton data suggest the existence of a new resonance $H$ whose mass $M_H = 660 \pm 680 \text{ GeV}$ is consistent with our prediction Eq. (7). Quantitatively, if we look at Fig. 2 and compare with the estimated background, the local significance of this $M_H$ is about 2.5 $\sigma$ and almost entirely
due to the central peak at 665(15) GeV. However, the global significance, estimated along the lines of ref.\[28\] is considerably smaller, about 1.4 $\sigma$;

ii) by assuming a partial width $\Gamma(H \rightarrow ZZ)$ which scales as in Eq.\[14\], we obtain the theoretical prediction Eq.\[18\] which is well consistent with the corresponding Eq.\[21\] obtained from a fit to the ATLAS data in the high-mass range $620 \div 740$ GeV. Equivalently, the central value of the fitted lower-resonance mass $(m_h)_f^{\text{fit}} \sim (125 \pm 13)$ GeV in Eq.\[23\] coincides with the direct, experimental determination $m_h = 125$ GeV;

iii) consistently with our picture, in the ATLAS analysis there is no sizeable contribution from the VBF production mode to the new resonance (on average, only 2 VBF-like events vs. 46 ggF-like events, see Fig.2e of ref.\[16\]);

iv) re-obtaining exactly the same central value $m_h = 125$ GeV means that, for $M_H \sim 680$ GeV, a ggF cross section of about 1180 fb and the ATLAS selection criteria of ggF-like events are consistent to a high degree of precision;

v) the correlation successfully reproduced in Fig.3 effectively eliminates the spin-zero vs. spin-2 ambiguity in the interpretation of the heavy state.

Therefore, our picture of a second resonance of the Higgs field finds support in the present ATLAS data. Given the importance of the issue, we have also attempted a comparison with CMS and looked for their 4-lepton data in the relevant energy region $E=650\div700$ GeV. Right now, this can only be done with smaller statistical samples because in the full $137$ fb$^{-1}$ CMS analysis all data in the range $600\div800$ GeV were summarized into a single bin of 200 GeV. We have thus compared with previous reports, for instance the $35.9$ fb$^{-1}$ sample shown in Fig.3 (left) of\[30\]. In spite of its smaller statistics, this plot is useful because it shows an event distribution strongly peaked around 660 GeV and which does not slowly decrease with energy, as expected from the modeled background (on average, there are 8 events in the range $600\div700$ GeV and only 1 marginal event at the very end of the range near 800 GeV).

At present, the largest existing CMS sample which can serve for our scope refers to integrated luminosity $77.4$ fb$^{-1}$ corresponding to the 2016+2017 data only, see Fig.9 of\[31\]. Since the very compressed scale prevents a straightforward interpretation, we have taken advantage of Cea’s paper\[32\] where these CMS data, in bins of 4 GeV, were extracted and plotted in an expanded scale, see his Fig.1a) here reported as our Fig.4\[e\].

To solve the problem of overlapping events, we have then grouped these data

\footnote{For the whole range $600\div800$ GeV, the $77.4$ fb$^{-1}$ sample in Fig.4 gives an average number of events $\langle N_{\text{obs}}(4l)\rangle = 21\div24$, depending upon the inclusion or not of 3 marginal events at the extreme left and extreme right of the reported energy range. After re-scaling by the factor $(137/77.4)=1.77$, this measured number corresponds to an extrapolated value $\langle N(4l)\rangle_{\text{extrapolated}} = 37\div42$ which is well consistent with the actual measurement $N_{\text{data}}(4l) \sim 40\pm7$ for the full $137$ fb$^{-1}$ statistics in ref.\[29\]. While this shows that the data in Fig.4 form a consistent subset of the full $137$ fb$^{-1}$ sample, still the event distribution in Fig.4 has not the slowly decreasing trend expected from the modeled background.}
The 4-lepton data observed by CMS, for integrated luminosity 77.4 fb$^{-1}$, given in Fig. 9 of [21] as plotted in an expanded scale by Cea [22] for the range 600 ÷ 1000 GeV. The interval in red color corresponds to 655 ÷ 715 GeV and solves the problem of overlapping events.

in a single bin of 60 GeV which corresponds approximately to the range formed by the two central ATLAS bins at E=665(15) and E=695(15) GeV. On average, there are 14 events that, when scaled by the luminosity ratio 139/77.4= 1.8, would imply 25 ATLAS events. This would be in excellent agreement with the ggF-MVA-low category in Table 2 which give indeed 17+9=26. However, the correspondence between the two sets of data is still to be clarified and, hopefully, postponed to a combined analysis of the two Collaborations.

Finally, we cannot close this paper without mentioning the (local) 3-sigma excess, see Fig.3 of [23] which is present in the ATLAS $\gamma \gamma$ distribution for the same invariant-mass $M_{\gamma \gamma} \sim 680$ GeV obtained from our analysis of the 4-lepton data. Even though the global statistical significance is reduced to about 1.5 $\sigma$, by the looking-elsewhere effect [25] still this particular excess of events represents the highest peak in Fig.3 of [23]. Nevertheless, the strong indication for $M_H$ is the sharp $\gamma_H - \sigma_R$ correlation in the ATLAS 4-lepton channel.

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References

1. Particle Data Group Collaboration (M. Tanabashi et al.), Phys. Rev. D 98, 030001 (2018), doi:10.1103/PhysRevD.98.030001.

2. P. H. Lundow and K. Markström, Physical Review E 80, 031104 (2009).
3. P. H. Lundow and K. Markström, *Nucl. Phys.* B845, 120 (2011), arXiv:1010.5958 [cond-mat.stat-mech] doi:10.1016/j.nuclphysb.2010.12.002.
4. S. Akiyama, Y. Kuramashi, T. Yamashita and Y. Yoshimura, *Physical Review D* 100, 054510 (2019).
5. M. Consoli and L. Cosmai, *International Journal of Modern Physics A* 35, 2050103 (Jul 2020), doi:10.1142/s0217751x20501031.
6. M. Consoli and L. Cosmai, *Symmetry* 12, 2037 (2020), doi:10.3390/sym12122037.
7. M. Consoli, *Acta Physica Polonica B* 52, 763 (2021), doi:10.5506/aaphyspolb.52.763.
8. S. R. Coleman and E. J. Weinberg, *Phys. Rev.* D7, 1888 (1973), doi:10.1103/PhysRevD.7.1888.
9. T. Barnes and G. I. Ghandour, *Phys. Rev.* D22, 924 (1980), doi:10.1103/PhysRevD.22.924.
10. P. M. Stevenson, *Phys. Rev.* D32, 1389 (1985), doi:10.1103/PhysRevD.32.1389.
11. M. Consoli and P. M. Stevenson, *Int. J. Mod. Phys.* A15, 133 (2000), arXiv:hep-ph/9905427 [hep-ph] doi:10.1142/S0217732300000910.
12. J. J. van der Bij, *Acta Phys. Polon. Supp.* 11, 397 (2018), arXiv:1711.03898 [hep-ph] doi:10.5506/APhysPolBSupp.11.397.
13. M. Consoli and Z. Hioki, *Modern Physics Letters A* 10, 845?852 (Mar 1995), doi:10.1142/s0217732395000910.
14. M. Consoli and Z. Hioki Modern Physics Letters A 10, 2245?2252 (Sep 1995), doi:10.1142/s0217732395002404.
15. M. Schmitt, Apparent excess in e+e→ hadrons, arXiv:hep-ex/0401034v2.
16. ATLAS Collaboration (G. Aad et al.), *Eur. Phys. J. C* 81, 332 (2021), arXiv:2009.14791 [hep-ex] doi:10.1140/epjc/s10052-021-09013-y.
17. P. Castorina, M. Consoli and D. Zappala, *J. Phys.* G35, 075010 (2008), arXiv:0710.0458 [hep-ph] doi:10.1088/0954-3899/35/7/075010.
18. B. W. Lee, C. Quigg and H. B. Thacker, *Phys. Rev. D* 16, 1519 (Sep 1977), doi:10.1103/PhysRevD.16.1519.
19. J. M. Cornwall, D. N. Levin and G. Tiktopoulos, *Phys. Rev. D* 10, 1145 (Aug 1974), doi:10.1103/PhysRevD.10.1145.
20. M. S. Chanowitz and M. K. Gaillard, *Nucl. Phys. B* 261, 379 (1985), doi:10.1016/0550-3213(85)90580-2.
21. J. Bagger and C. Schmidt, *Phys. Rev. D* 41, 264 (1990), doi:10.1103/PhysRevD.41.264.
22. M. Consoli and L. Cosmai, A resonance of the higgs field at 700 gev and a new phenomenology (2020).
23. A. Djouadi, *Phys. Rept.* 457, 1 (2008), arXiv:hep-ph/0503172 doi:10.1016/j.physrep.2007.10.004.
24. LHC Higgs Cross Section Working Group Collaboration (S. Dittmaier et al.) (1 2011), arXiv:1101.0593 [hep-ph] doi:10.5170/CERN-2011-002.
25. G. L. Kane, W. W. Repko and W. B. Rolnick, *Phys. Lett. B* 148, 367 (1984), doi:10.1016/0370-2693(84)90105-9.
26. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014.
27. https://www.hepdata.net/record/ins1820316.
28. E. Gross, O. Vitells, *Eur. Phys. J. C* 70, 525 (2010) https://doi.org/10.48550/arXiv.1005.1891
29. CMS Collaboration, *Eur. Phys. J. C* 81, 200 (2021), arXiv:2009.01186 [hep-ex] doi:10.1140/epjc/s10052-020-08817-8.
30. CMS Collaboration, *JHEP* 11, 047 (2017), arXiv:1706.09938 [hep-ex] doi:10.1007/JHEP11(2017)047.
31. CMS Collaboration, Report CMS PAS HIG-18-001, 2018/06/03.
32. P. Cea, *Mod. Phys. Lett. A* 34, 1950137 (2019), arXiv:1806.04529 [hep-ph], doi: 10.1142/S0217732319501372.
33. ATLAS Collaboration (G. Aad et al.), *Phys. Lett. B* 822, 136651 (2021), arXiv:2102.13405 [hep-ex], doi:10.1016/j.physletb.2021.136651.