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# Experimental signals for a new heavy resonance in the ATLAS and CMS data

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The existence of a second resonance of the Higgs field with a mass $(M_H)^{\text{theor}} = 690 \pm 10$ (stat) $\pm$ 20 (sys) GeV has been recently proposed. By analyzing the ATLAS Run2 results on charged 4-lepton final state in the region of invariant mass 620÷740 GeV, we show that they are consistent with the presence of a new resonance of mass $(M_H)^{\text{exp}} = 660 \div 680$ GeV which could represent the hypothetical second resonance. In fact, on the one hand, the observed mass would fit well with the theoretical range. On the other hand, the ATLAS data reproduce to high accuracy the expected correlation, between resonating peak cross section $\sigma_R(pp \to H \to 4l)$ and the ratio $\gamma_H = \Gamma_H/M_H$, which is mainly determined by the lower-resonance mass $m_h = 125$ GeV. Furthermore, indications for a new resonance in the same mass range are also present in i) the ATLAS search for resonances decaying into photon pairs and ii) recent public CMS results. We emphasize that, when comparing with a definite theoretical prediction, local excesses should *not* be downgraded by the look-elsewhere effect. Therefore, considering the presumably small correlation among the different results, the cumulated statistical significance might be close to the traditional 5-sigma discovery level.

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## 1. Introduction

Today, the spectrum of the Higgs field is described as a single resonance of mass $m_h = 125$ GeV defined by the quadratic shape of the effective potential $V_{\rm eff}(\varphi)$, see the PDG review [1]

$$V_{\rm PDG}(\varphi) = -\frac{1}{2}m^2_{\rm PDG}\varphi^2 + \frac{1}{4}\lambda_{\rm PDG}\varphi^4 \tag{1}$$

For $m_{\rm PDG} \sim 88.8$ GeV, $\lambda_{\rm PDG} \sim 0.13$, this has a minimum at $\varphi = \langle\Phi\rangle \sim 246$ GeV with $V''_{\rm PDG}(\langle\Phi\rangle) \equiv m^2_h = (125\ {\rm GeV})^2$. However, there is an alternative description of SSB [2–4] motivated by the basic "triviality" of $\Phi^4$ in 4D, where, instead of perturbatively renormalizing the classical potential, one considers approximations to $V_{\rm eff}(\varphi)$ which are physically equivalent to the 1-loop structure: some classical background + zero-point-energy of a free fluctuation field with some mass $M(\varphi)$. These approximations correspond to different re-summations of graphs but give the same physical picture as at one loop. Namely, by defining $m^2_h = V''_{\rm eff}(\varphi)$ at the minimum, $M_H$ as $M(\varphi)$ at the minimum, and introducing the ultraviolet cutoff $\Lambda_s$, one finds [2–4] ($L = \ln(\Lambda_s/M_H)$)

$$\lambda \sim L^{-1} \qquad\qquad m^2_h \sim \langle\Phi\rangle^2 \cdot L^{-1} \qquad\qquad M^2_H \sim L \cdot m^2_h = K^2\langle\Phi\rangle^2 \tag{2}$$

$K$ being a cutoff-independent constant. Furthermore, the relation $V_{\rm eff}(\langle\Phi\rangle) \sim -M^4_H$ supports the cutoff independence of $M_H$, and therefore of $\langle\Phi\rangle$, because the ground state energy is a Renormalization-Group invariant quantity, see [2–4]. At the same time, since vacuum stability depends on the large $M_H$, and not 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.

Due to their non uniform scaling, $m_h$ and $M_H$ decouple for $\Lambda_s \to \infty$ but refer to different momentum regions in the propagator [1] and could coexist in the cutoff theory. Thus, this two-mass structure was checked with lattice simulations of the propagator [2]. By computing $m^2_h$ from the $p \to 0$ limit of $G(p)$ and $M^2_H$ from its behaviour at higher $p^2$, the lattice data are consistent with the trend $M^2_H \sim L m^2_h$. Therefore, beside the known state with $m_h = 125$ GeV, there could be a second resonance with much larger mass. To this end, by extrapolating from various lattice sizes, the constant was found $K = 2.80 \pm 0.04({\rm stat}) \pm 0.08({\rm sys})$ equivalent to [2–4]

$$(M_H)^{\rm Theor} = 690 \pm 10\ ({\rm stat}) \pm 20\ ({\rm sys})\ {\rm GeV} \tag{3}$$

In the following, we will summarize in Sect.2 the phenomenology of the second resonance and in Sect.3 present experimental evidence for its existence from the ATLAS 4-lepton events [6] for $M_{4l} = 620 \div 740$ GeV. Finally, in Sect.4 we will briefly mention the ATLAS high-mass $\gamma\gamma$ events and other recent CMS results suggesting a new resonance in the same mass region.

## 2. Basic phenomenology of the second resonance

In spite of their substantial difference, $m_h$ and $M_H$ represent excitations of the *same* Higgs field. The observable interactions of this field with the other fluctuations, as the Goldstone bosons, are

[1]The zero-point energy is (one-half of) the trace of the logarithm of $G^{-1}(p)$. Therefore $M_H$, reflecting also the behaviour of the propagator at large Euclidean $p^2$, in general differs from $m^2_h \equiv V''_{\rm eff}(\langle\Phi\rangle) = |G^{-1}(p=0)|$.

thus governed by a single coupling: the parameter $m_h^2$, defined by expanding the potential around its minimum,which provides the boundary condition at the Fermi scale for the scalar self-coupling $\lambda = 3m_h^2/\langle\Phi\rangle^2$. As such, the heavier state would couple to longitudinal W's with the same strength as the low-mass state at 125 GeV and represent a relatively narrow resonance. This means to replace the conventional width $\Gamma^{\rm conv}(H \to WW + ZZ) \sim G_F M_H^3$ with $\Gamma(H \to WW + ZZ) \sim M_H(G_F m_h^2)$ which retains the phase-space factor $M_H$ with a coupling re-scaled by $m_h^2/M_H^2 \sim 0.032$. Numerically, for $M_H \sim 700$ GeV, from ref.[8], this gives

$$\Gamma(H \to ZZ) \sim \frac{M_H}{700\ \text{GeV}} \cdot \frac{m_h^2}{(700\ \text{GeV})^2}\, 56.7\ \text{GeV} \sim \frac{M_H}{700\ \text{GeV}} \cdot\ 1.8\ \text{GeV} \tag{4}$$

and $\Gamma(H \to WW) \sim 2.03 \cdot \Gamma(H \to ZZ)$. Instead, the decays into fermions, gluons, photons..., depending only on the gauge and yukawa couplings, are unchanged and can be taken from [8] yielding $\Gamma(H \to \text{fermions} + \text{gluons} + \text{photons}...) \sim (M_H/700\ \text{GeV}) \cdot 27$ GeV. Therefore, one could expect a total width $\Gamma_H \equiv \Gamma(H \to all) \sim 32(1)$ GeV. However, this is not considering the new decays of the heavier state into the lower-mass state at 125 GeV, $H \to hh$, $H \to hhh$, $H \to hZZ$, $H \to hW^+W^-$... so that the estimate $\Gamma_H \sim 32(1)$ GeV is only a lower bound. It is not easy to evaluate these new contributions mostly because the overlapping of the two states $H - h$ makes this a non-perturbative problem. For this reason, in ref.[5], one considered a test in the 4-lepton channel that does *not* require the total width but just relies on two assumptions: i) a resonant 4-lepton production through the chain $H \to ZZ \to 4l$ and ii) the estimate of $\Gamma(H \to ZZ)$ in Eq.(4)

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

$$B(H \to ZZ) = \frac{\Gamma(H \to ZZ)}{\Gamma(H \to all)} \sim \frac{1}{\gamma_H} \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700\ \text{GeV})^2} \tag{5}$$

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

$$\sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot B(H \to ZZ) \cdot 4B^2(Z \to l^+l^-) \tag{6}$$

thus obtaining the correlation

$$\gamma_H \cdot \sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700\ \text{GeV})^2} \cdot 4B^2(Z \to l^+l^-) \tag{7}$$

Since $4B^2(Z \to l^+l^-) \sim 0.0045$, we only need the production cross section $\sigma(pp \to H)$. As discussed in [4], here the $H-$production mechanism is mainly through the gluon-gluon Fusion (ggF) process. In fact, Vector-Boson Fusion (VBF), being rescaled by the ratio $(m_h/M_H)^2 \sim 0.032$, can be safely neglected. Thus, we can replace $\sigma(pp \to H) \to \sigma^{\rm ggF}(pp \to H)$ in Eq.(7) and use the ggF cross sections taken from [9]. For 13 TeV pp collisions, with a typical ±15% uncertainty, this gives the estimate $\sigma^{\rm ggF}(pp \to H) \sim 1180(180)$ fb which also accounts for $M_H = 660 \div 700$ GeV. Therefore, for $m_h = 125$ GeV, we predict

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\rm theor} \sim (0.0137 \pm 0.0021)\ \text{fb} \tag{8}$$

**Table 1:** *The values of $M_H$, $\sigma_R$, $k = \gamma_H \cdot \sigma_R$ from a fit with Eq.(9) to the 4-lepton cross sections.*

| $\gamma_H$ | $M_H$ [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) |

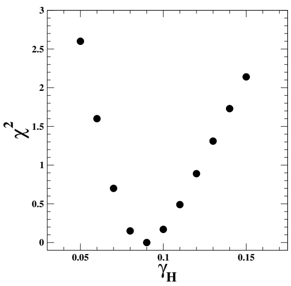


**Figure 1:** Chi-square of the fit with Eq.(9) to the ATLAS data as function of $\gamma_H$.

## 3. Analysis of the ATLAS 4-lepton results

To check Eq.(8), we considered [5] the ATLAS [6] ggF-like 4-lepton events for invariant mass $M_{4l} = 620 \div 740$ GeV ($l = e, \mu$) extending about $\pm$ 60 GeV around our central value Eq.(3). For luminosity 139 fb$^{-1}$, the number of events observed by ATLAS is $N_{4l} = 10, 21, 11, 4$ respectively for $M_{4l} \equiv E = 635(15), 665(15), 695(15)$ and 725(15) GeV. By transforming into cross sections, and with $s = E^2$, one assumed [5] a resonating amplitude $A^R(s) \sim 1/(s - M_R^2)$ interfering with a background $A^B(s)$. Setting $M_R^2 = M_H^2 - iM_H\Gamma_H$, this gives a total cross section

$$\sigma_T = \sigma_B - \frac{2(s - M_H^2)\,\Gamma_H M_H}{(s - M_H^2)^2 + (\Gamma_H M_H)^2}\sqrt{\sigma_B \sigma_R} + \frac{(\Gamma_H M_H)^2}{(s - M_H^2)^2 + (\Gamma_H M_H)^2}\,\sigma_R \tag{9}$$

where, in principle, both the background $\sigma_B$, at the central energy 680 GeV, and the resonating peak $\sigma_R$ can be treated as free parameters. For the parametrization of the background and other details we address to [5]. Here, we just report in Table 1 the results of the fit to the ATLAS data and, in Figs.1 and 2, respectively the chi-square and the optimal fit for $\gamma_H = 0.09$. Finally, in Fig.3 the peak cross sections of Table 1 are compared with the prediction Eq.(8). The excellent agreement implies that, if we leave $m_h$ as a free parameter, from all entries in Table 1 (with $\chi^2 < 1$) and production cross section $\sigma(pp \to H) \sim \sigma^{\rm ggF}(pp \to H) \sim 1180(180)$ fb, the fitted value $(m_h)^{\rm fit} \sim (125 \pm 13)$ GeV coincides with the direct measurement of the Higgs particle mass. We emphasize that, 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.[6]). Also, the correlation successfully reproduced in Fig.3 effectively eliminates the spin-zero vs. spin-2 ambiguity in the interpretation of the heavy state. Thus, this remarkable correlation

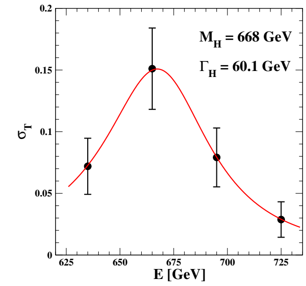


**Figure 2:** For $\gamma_H = 0.09$, we show the fit with Eq.(9) to the 4-lepton cross sections (in fb).

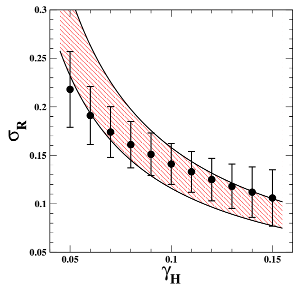


**Figure 3:** The $\sigma_R$'s of Table 1 vs. the prediction Eq.(8) represented by the area within the hyperbolae $\sigma_R = (0.0137 \pm 0.0021)/\gamma_H$.

becomes a guiding principle to look for other small excesses which could seem negligible. This will be illustrated in Sect.4.

## 4. Further signals in the ATLAS and CMS data

The ATLAS $\gamma\gamma$ events [7] in the range $\mu(\gamma\gamma) = 600 \div 770$ GeV were considered in ref. [10], to which we address for all details. Again, with Eq.(9), a fit was performed to the corresponding cross sections. In $\gamma\gamma$ , however, the background is so large that, instead of the Breit-Wigner form of Fig.2, one can only detect the interference with the resonance which is made visible by the 3.3-sigma excess at 684 GeV. With the exception of the mass $M_H = 695(10)$ GeV, the other two parameters are very poorly determined: $\Gamma_H = 15^{+30}_{-10}$ GeV and $\sigma_R(pp \to H \to \gamma\gamma) = 0.025^{+0.055}_{-0.023}$ fb. In fact the visible effect of the resonance is concentrated in the interference $\sigma_{\rm int}(E) = O(10^{-1})$ fb which, in turn, is much smaller than the background in the resonance region $\sigma_B \sim 1.3$ fb. Nevertheless, when combined with the 4-lepton data which provide $\Gamma_H \sim 60(20)$ GeV, the $\gamma\gamma$ events constrain the total width from above giving $(\Gamma_H)^{\rm Exp} \sim 45(15)$ GeV [2]. The analogous determination for the mass from the two channels is $(M_H)^{\rm Exp} \sim 680(15)$ GeV.

Of course, new data are needed. Meanwhile, one can also search in other channels, for instance in $\gamma\gamma$ pairs produced in $pp$ diffractive scattering, i.e. in the process $p+p \to p+X+p$ when both final protons are tagged and have large $x_F$. The final state $X$ can be considered a "diffractive excitation of the vacuum" [11] and one could check if there is an excess for $\mu(\gamma\gamma) \sim M_H$. Remarkably, an excess with respect to the background is present at $\mu(\gamma\gamma) = 650(40)$ GeV in the CMS analysis [12]. In fact, from Fig.5 fourth panel, the number of $\gamma\gamma$ events was $N_{\rm obs} \sim 76(9)$ vs. an estimated background $N_{\rm BKG} \sim 40(6)$ with a local excess of 3.3-sigma significance.

[2]This is also consistent with the previous theoretical lower bound $(\Gamma_H)^{\rm Theor} > 30$ GeV.

Finally, the CMS search [13] for new resonances decaying, through two intermediate scalars, into a $b\bar{b}$ quark pair + $\gamma\gamma$ pair. In particular, the cross section for the full process

$$\sigma(\text{full}) = \sigma(pp \to H \to hh \to b\bar{b} + \gamma\gamma) \tag{10}$$

(with respect to the CMS paper we denote $X \equiv H$ and the 125 GeV resonance is here defined $h = h(125)$). For a spin-zero resonance (see Fig.4 top panel) the 95% limit $\sigma(\text{full}) < 0.16$ fb, at 600 GeV, increases up to $\sigma(\text{full}) < 0.30$ fb in the plateau $650 \div 700$ GeV and then decreases at larger energies. The local significance is modest, about 1.6-sigma, but the mass region 675(25) GeV is precise and agrees well with our analysis of the ATLAS data. Altogether, the two CMS searches suggest a new resonance with $(M_H)^{\text{Exp}} \sim 670(20)$ GeV.

Summarizing, our idea of a second Higgs resonance finds support in the LHC data. In fact, the two indications we have obtained, respectively 680(15) GeV from ATLAS and 670(20) GeV from CMS, fit well with the theoretical Eq.(3). Moreover, see Fig.3, the ATLAS 4-lepton data reproduce to high accuracy the theoretical correlation Eq.(8). We emphasize that, by comparing with a *definite theoretical prediction*, as Eq.(3), local excesses should *not* be downgraded by the look-elsewhere effect. Thus, from all excesses (2.5-sigma at 665(15) GeV in the ATLAS 4-leptons, 3.3-sigma at 684(8) GeV in the ATLAS $\gamma\gamma$, 1.6-sigma at 675(25) GeV in the CMS $b\bar{b} + \gamma\gamma$ channel and 3.3-sigma at 650(40) GeV in the CMS $\gamma\gamma$ produced in $pp$ diffractive scattering), and considering that the correlation is presumably small, the cumulated statistical significance might be close to the traditional 5-sigma level.

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