Evidences for a pseudo scalar resonance at 400 GeV
Possible interpretations

François Richard¹
Université Paris-Saclay, CNRS/IN2P3, IJCLab², 91405 Orsay, France

Abstract: This paper intends to collect the various evidences observed by ATLAS and CMS within searches for heavy scalars and pseudoscalars. These searches in $t\bar{t}$, $hZ$, $\tau\tau$ and $2$ jets$+W$, obtain individual excesses in five channels, each at a modest level of significance, ~$3$ standard deviations, but, put together, give a strong evidence for a pseudoscalar at ~$400$ GeV. Preliminary interpretations are given which suggest that additional observations should appear in the HL-LHC phase.

Introduction

In [1], I have reviewed the various indications for scalar and pseudoscalar resonances shown by ATLAS and CMS. This is an ongoing task since a large fraction of the data has not yet been analysed. The purpose of this work was to examine the present situation and what can still be expected from LHC data, from future HL-LHC data and from $e^+e^-$ colliders under consideration.

The conclusion was unexpected: there is a signal really sticking out, since it is observed in five channels, at a mass ~$400$ GeV. Although each of these observations has a significance at the ~$3$ standard deviation (sd) level, the combination of them gives a significance far above the fatidic $5$ sd level, even taking into account the ‘look elsewhere’ criteria. More precisely, from the following table, the product of probabilities amounts to $7.10^{-15}$. When decreasing by $10\%$ the number of sd, a crude estimate for their uncertainties (numbers in parenthesis), this probability increases to $3.610^{-13}$. If one takes into account the ‘look elsewhere effect’, this figure increases to $50^{-11}$, which is still below a $6$ sd effect, which would correspond to a probability of $10^{-9}$.

| Reaction               | Mass GeV | $\sigma$ fb | # sd (-10%) | Probability % | Luminosity fb-1 |
|-----------------------|----------|-------------|-------------|---------------|-----------------|
| $X(400)\rightarrow tt$ | 400      | ~4000       | 3.5 (3.15)  | 0.02 (0.08)   | 36 CMS [2]      |
| $X(400)\rightarrow \tau\tau$ | 400  | 30          | 2.2 (2)     | 1.4 (2.3)     | 139 ATLAS [3]   |
| $X(400)\rightarrow \tau\tau+bb$ | 400  | 50          | 2.7 (2.4)   | 0.35 (0.8)    | 139 ATLAS [3]   |
| $A(400)\rightarrow h(125)Z+bb$ | 440  | 330         | 3.6 (3.2)   | 0.01 (0.07)   | 36 ATLAS [4]    |
| $X(400)+\text{high pt e}/\mu$ | 400  | 80          | 3(2.7)      | 0.13 (0.35)   | 139 ATLAS [5]   |

¹ richard@lal.in2p3.fr
² Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
The masses reported by the various searches are not very precise, the usual wording being 'around 400 GeV'. This applies to the channel h(125)Z+bb, which may seem (significantly ?) displaced to a higher mass. This channel also shows a ~2 sd and ~200 fb excess in the ggF analysis which I have not taken into account in above table.

The hZ final state allows to identify unambiguously a **CP-odd resonance**. For what concerns the tt analysis, its authors also favour a CP-odd scalar, quote [2]: "The largest SM background is observed for a pseudoscalar Higgs boson with a mass of 400 GeV and a total relative width $\Gamma/M$ of 4%, with a local significance of 3.5±0.3 standard deviations".

Hence, in the following, I will call this resonance A(400) and take it for granted.

The last channel of above list can be interpreted [1], without direct proof, as a heavy charged scalar cascading into A(400)+W, with W decaying leptonically and A(400) decaying into two jets. These two jets are effectively produced in tt, bb and hZ final states, which give the largest contributions, as we shall see.

Since a CP-even scalar H is observed at 660 GeV [1], with more than 4 sd, in the ZZ mode into four charged leptons, one can assume that there could be a charged scalar at a similar mass and that one has H±(660)→A(400)+W, which would explain the inclusive search results from ATLAS.

As was already mentioned in [1], one should give up the usual MSSM interpretation of these scalars. The main reason comes from observing that, in this model, A(400)→hZ and H(660)→ZZ should vanish in the so called decoupling or alignment approximations, a requirement to get the SM couplings for h(125). This behaviour can, for instance, be interpreted by saying that A(400) and H(660) are iso-singlets, with small mixing with h(125). Something radically different is therefore happening here, irreducible to MSSM, and I will come back to what could be an explanation of this phenomenon in the next section.

Another unusual feature, examined in the following, are the Yukawa couplings, which are large for both top and bottom quarks.

In the following sections, I will recall, in more detail than in [1], some of these observations and try to reach a quantitative interpretation of the A(400) properties.

Finally, I will try to sketch what remains to be done with available LHC data and the consequences for HL-LHC and e+e- programs.

**Phenomenological speculations**

Before engaging in a quantitative interpretation, let me recall what can be said if we give up on the standard picture of elementary scalars, the SM or SUSY paradigms.

In [1], it was assumed that **compositeness** was at work to interpret the origin of the Higgs boson discovered at LHC. There are however many avenues towards compositeness.

The most naïve one is to assume bound states of a new type of elementary particles called partons, which are the constituents of the SM particles.

Without explicitly defining the particles composing the Higgs boson, one can, on general grounds, invoke a dynamical mechanism which describes h(125) as a **pseudo-Nambu-Golstone boson**, pNGB,
originating from a broken symmetry in a composite world operating at a much higher scale. This particle would therefore play the role of pions within QCD, the lightest bound states resulting from chiral symmetry breaking.

Alternatively, influenced by the heaviness of the top quark, which has the largest Yukawa coupling to the Higgs boson, one has speculated that the Higgs boson is itself a bound state of top quarks or from many top quarks, up to 6 in [6]. Gravitation has also been invoked to predict a very large set of scalar bound states [7]. I will not discuss any further examples of these composite scenarios. As for QCD with pions, there is an obvious next step in a composite picture. If Higgs bosons like h(125) are composite particles, it is conceivable that they can form a bound state like h-h or even h-Z and h-W, assuming that the bosons Z/W, intimately related to the BEH mechanism, are also composite. This could generate neutral scalar H (h-h) or pseudoscalar A (h-Z) resonances. This could also generate charged scalars H± by h-W or A-W bonding.

As recalled in ref [8], one even speculates that this mechanism could happen within the SM, recalling the standard case of positronium, which does not require new strong forces. Admittedly these SM resonances, not observed so far, could be too wide to be detected but one needs to be sure that this is the case to avoid further misinterpretations.

Leaving the SM picture and speculating that there are new composite force operating at the ~TeV scale, some authors provide an explicit mechanism to generate an ‘Higgsinium’ bound state, [9] and [10], not necessarily very wide, in a mass region ranging between 450 to 650 GeV. Generalizing these ideas, one then gets, presumably, an interpretation of A(400) as a h-Z bound state and of H(660) as a A(400)-Z bound state.

Note that since these states are observed with a sizeable cross section at LHC, they are presumably produced by gluon-gluon annihilation, as the SM h(125), through a top loop, therefore they will presumably decay into top pairs. Due to the interference effects discussed in [1], these top pair final states are less easy to observe than in bosonic pairs like hh or hZ or in a fermion pair like ττ.

One can speculate that A(400)W would form a charged state at about the same mass as H(660), which would explain the cascade observed by ATLAS, X(660)±→A(400)+W, in its inclusive search. Other combinations are of course possible but have so far not been detected. In particular H(400) is not observed into ZZ nor hh final states. In top pairs, CMS favours a CP-odd interpretation of the 400 GeV resonance. One should however remember that, at 400 GeV, the top pair decay of H(400) would be suppressed by a p-wave factor. Therefore, it is not possible to make a definite conclusion about its non-existence.

**Quantitative interpretation of the A(400) observations**

**Determining gAbb/gAtt**

There are two main processes which allow to produce A(400). The gluon fusion process ggF, which goes like the square of the Yukawa coupling gAtt and the associated production A+bb, where A is radiated from a b quark, which goes like the square of the Yukawa coupling gAbb. The ggF cross section goes approximately like ~9000gAtt² in fb, while A+bb goes like ~16000gAbb² in fb.

A striking feature of the ττ cross section is that it is, within a factor 2, similar for the two processes [3], meaning that both Yukawa constants are large. This is also true for the hZ signal which is indicated by the data but not advocated by [4] which only mentions the prominent channel A+bb.
These observations give $g_{Abb}/g_{Att} \approx 0.5$ and we will see that $g_{Att} \approx 0.8$ allows to interpret available results.

In the usual MSSM interpretation, the large $g_{Abb}$ coupling can be interpreted by saying that $\tan\beta \approx 24$. This value would lead to a very small value of $g_{Att}$, incompatible with $ggF$ signals. This is another proof that we are not dealing with this model.

**Determining $g_{Att}$**

While the $\tau \tau$ and $hZ$ modes are relatively straightforward to interpret, the top pair final pair does not come out simply, due to interference effects with the $gg \to tt$ background [1].

Let us start by repeating the CMS statements [2]: “The largest deviation from the SM background is observed for a pseudoscalar Higgs boson with a mass of 400 GeV and a total relative width $\Gamma/M$ of 4%, with a local significance of 3.5±0.3 standard deviations.”

| $g_{Att}$ | $\tau \tau$ % | miss % | $hZ$ % | $\tau \tau$ % | $bb$ % | $gg$ % | $\sigma_A$ fb | $\Gamma_{tot}$ GeV | $\Gamma_{res}/M$ % |
|-----------|----------------|--------|--------|----------------|------|-------|-------------|------------------|-----------------|
| 1         | 42             | 37     | 3.7    | 0.55          | 16.5 | 0.04  | 9000        | 28               | 7               |
| 0.9       | 52             | 22     | 4.5    | 0.7           | 20.5 | 0.04  | 7300        | 18.3             | 5               |
| 0.8       | 66             | 1.4    | 5.7    | 0.87          | 26   | 0.06  | 5700        | 11.4             | 3.5             |
| 0.7       | 86             | -      | 7.5    | 1.1           | 34   | 0.07  | 4400        | 6.7              | 2.6             |

The table shows the results which can be deduced from the available data for different values of $g_{Att}$ and assuming $g_{Abb}/g_{Att} \approx 0.5$. Taking into account uncertainties, one can accommodate a range of $g_{Att}$ couplings, between 0.8 and 1, noting that the solution $g_{Att}=0.7$ is logically excluded and $g_{Att}=1$ disfavoured since it corresponds to a relative width which goes beyond the CMS observation.

The 4% width is compatible with a CP-odd $A(400)$, knowing that [2] quotes a ~2% value for the mass resolution width. The measured width is therefore compatible with expectation for $g_{Att}=0.8$ and $g_{Att}=0.9$. This result is at variance to what would be obtained with a CP-even Higgs which, in a $p$-wave, would give a width four times smaller.

We know from [1] that there could be another scalar candidate at 96 GeV, which would give $A(400) \to h(96)Z$, with a branching ratio similar to $hZ$, therefore in conformity with the solution $g_{Att}=0.8$.

Taking $g_{Att}=0.8$ as a solution which satisfies all observations, without leaving too much missing modes, one has $g_{A\tau\tau}=0.11$, $g_{Abb}=0.4$.

These results are notoriously distinct from an MSSM situation, which would say that with $\tan\beta \approx 1.25$ to ‘explain’ $g_{Att}=0.8$, one should have $g_{A\tau\tau}=0.013$ and $g_{Abb}=0.022$.

**Inclusive production of $A(400)$**

I assume [1] that there is a decay:

$$H\pm(660) \to A(400) + W \ , \text{with } W \to e\nu, \mu\nu$$
One also has \( H(660) \rightarrow A + Z \), with \( Z \rightarrow \ell \ell, \mu \mu \), which contributes 3 times less, given the \( Z \) branching ratio into leptons. Furthermore, one assumes that the charged scalar, which is produced through the processes \( gb \rightarrow H - t \) and \( gg \rightarrow H - t b \), provides a spectator top, which also gives an additional \( W \) for tagging.

Since ATLAS observes an excess at 400 GeV with a cross section \( \sim 80 \) fb, including an acceptance factor and the branching ratio for the lepton tag, one needs to have a production cross section in excess of \( \sim 300 \) fb to interpret the resulting cross section. This cross section seems to be on the high side, although there is a large uncertainty due to our ignorance of the \( H^\pm(660)tb \) coupling.

Note that if one assumes that there is a similar situation as for \( A \) couplings, with \( g_{tt} = 0.8 \) and \( g_{bb} = 0.4 \), the cross section for \( H(660)tb \), which goes like \( g_{tt}^2 + g_{bb}^2 \), is enhanced by a factor 3 with respect to the MSSM case where one would take \( \tan \beta = 30 \) to accommodate \( g_{bb} \).

One can estimate that the two processes giving \( H^\pm(660) \) have a total cross section of about 320 fb. Since the final state \( A + W + t \) contains two charged \( W \), one is entitled to expect a high tagging efficiency.

**Future LHC results**

LHC results are still not fully analysed. In particular, the top result only relies on one-fourth the luminosity collected by CMS, also awaiting for ATLAS results. \( A(400) \) into \( hZ \) and \( \tau \tau \) remain to be analysed by CMS.

For what concerns \( H(660) \), ATLAS can provide more data in \( ZZ \) which would allow to cross the 5 sd border. Combining the two experiments, one may hope to confirm a weak indication in \( h-h \) from ATLAS, still marginal at the present level [11]. A confirmation from CMS for the inclusive search \( A(400) + W + t \) would also be very welcome.

Demonstrating that there is a transition \( H(660) \rightarrow A(400) + Z \) appears very challenging. Chasing the charged Higgs in the \( tb \) mode seems to suffer interference problems [12] analogue to those in top pairs [1].

Under these circumstances, the data coming from HL-LHC will be very welcome.

Finally, one should not forget the \( h(96) \) puzzle [1]. Completing the CMS analysis with all available data is needed as well as a more performing ATLAS analysis. If this resonance is confirmed, it will bring several additional possibilities within this type of investigation. One should however be aware that it is not possible to distinguish \( h(96) \rightarrow bb \) and \( Z \rightarrow bb \), which makes life difficult to separate, in \( 4b, h(96)-h(96) \) or \( h(96)-Z(96) \) from standard ZZ final states.

**Production of \( A(400) \) at \( e^+e^- \) colliders**

Given that there is a \( ZhA \) coupling, the process \( e^+e^- \rightarrow Z \rightarrow A(400)h(125) \) allows to produce \( A(400) \) for a centre of mass energy above 525 GeV. Knowing the coupling \( g_{AH} \) from the the measured width \( \Gamma A \rightarrow hZ \) at LHC, one can determine the cross section. For \( g_{Att} = 0.8 \), our table gives \( \Gamma A \rightarrow hZ = 0.65 \) GeV, which I will use in the following calculations.

The amount of data is governed:
- by the phase space which goes like $\lambda^{3/2}$, where $\lambda=(1-(m_h^2/s-m_A^2/s)^2-4(m_A m_h/s)^2$.
- by the cross section $\sigma=150\lambda^{3/2}/s\text{TeV}^2$ in fb.
- by the ILC integrated luminosity, which grows from 4 ab-1 to 8ab-1 from 500 GeV to 1 TeV.

With these figures, one predicts that the accumulated number of events will grow from $1.510^5$ events at 600 GeV to $6.7\,10^5$ events at one TeV.

**Summary**

One is probably living in an exciting time for searches of heavy scalars at LHC, charged or neutral.

I hope that this type of spectroscopy cannot trivially be explained within the SM and opens an unexpected BSM window and a bright future for HEP.

The CP-odd resonance $A(400)$ observed by ATLAS and CMS has a variety of final states which allow an interpretation clearly outside the usual MSSM model.

One is eagerly awaiting for a completion of the ongoing LHC analyses and for a harvest of new data collected by HL-LHC.

If confirmed, this resonance would motivate a Linear Collider reaching at least 600 GeV, which seems achievable with the technology already planned for ILC.

**Apologies**, for quoting very partially the rich literature on compositeness, which goes beyond my competences. Two papers, [13] [14], dealing with 2 HDM scenarios, could be relevant for $A(400)$. They were kindly brought to my attention by their authors.

**References**

[1] Indications for extra scalars at LHC? — BSM physics at future e+e− colliders
François Richard (IJCLab, Orsay). Jan 14, 2020. 22 pp.
e-Print: arXiv:2001.04770
[2] Search for heavy Higgs bosons decaying to a top quark pair in proton-proton collisions at $\sqrt{s}=13$ TeV
CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) et al.). Aug 2, 2019. 45 pp.
CMS-HIG-17-027, CERN-EP-2019-147
e-Print: arXiv: 1908.01115
[3] Search for heavy Higgs bosons decaying into two tau leptons with the ATLAS detector using pp collisions at $\sqrt{s}=13$ TeV
ATLAS Collaboration (Georges Aad (Marseille, CPPM) et al.). Feb 27, 2020. 32 pp.
e-Print: arXiv:2002.12223
[4] Search for heavy resonances decaying into a W or Z boson and a Higgs boson in final states with leptons and b-jets in 36 fb−1 of $\sqrt{s}=13$ TeV pp collisions with the ATLAS detector
ATLAS Collaboration (Morad Aaboud (Oujda U.) et al.). Dec 18, 2017. 52 pp.
Published in JHEP 1803 (2018) 174, Erratum: JHEP 1811 (2018) 051
e-Print: arXiv:1712.06518
[5] Search for dijet resonances in events with an isolated charged lepton using $s\sqrt{s}=13$ TeV proton-proton collision data collected by the ATLAS detector
ATLAS Collaboration (Georges Aad (Marseille, CPPM) et al.). Feb 26, 2020. 41 pp.
CERN-EP-2019-276
e-Print: arXiv:2002.11325

[6] New Resonances at LHC are possible. Multiple Point Principle and New Bound States in the Standard Model
L.V. Laperashvili (Moscow, ITEP), H.B. Nielsen (Bohr Inst.), C.D. Froggatt (Glasgow U.), B.G. Sidharth (Birla Sci.
Ctr., Hyderabad), C.R. Das (Dubna, JINR). Mar 6, 2017. 18 pp.
e-Print: arXiv:1703.01757

[7] Composite Higgs Bosons and Mini Black Holes
Christopher T. Hill (Fermilab). Mar 2, 2020. 9 pp.
FERMILAB-PUB-20-086-T
e-Print: arXiv:2002.11547

[8] Bound-state/elementary-particle duality in the Higgs sector and the case for an excited 'Higgs' within the standard model
Axel Maas (Jena U., TPI). May 30, 2012. 15 pp.
Published in Mod.Phys.Lett. A28 (2013) 1350103
DOI: 10.1142/S0217732313501034
e-Print: arXiv:1205.6625

[9] A Higgs-Higgs bound state due to new physics at a TeV
Benjamin Grinstein, Michael Trott (UC, San Diego). Apr 2007. 32 pp.
Published in Phys.Rev. D76 (2007) 073002
e-Print: arXiv:0704.1505

[10] Is Higgsium a possibility in 2HDMs?
Ambalika Biswas (Vivekananda Coll.). Jan 15, 2019. 23 pp.
Published in Nucl.Phys. B951 (2020) 114885
DOI: 10.1016/j.nuclphysb.2019.114885
e-Print: arXiv:1901.05325 [hep-ph]

[11] Search for the $HH\rightarrow bb^-bb^-$ process via vector-boson fusion production using proton-proton collisions at $s\sqrt{s}=13$ TeV with the ATLAS detector
ATLAS Collaboration (Georges Aad (Marseille, CPPM) et al.). Jan 15, 2020. 37 pp.
CERN-EP-2019-267
e-Print: arXiv:2001.05178

[12] Scattering Interference effects on $H\rightarrow tb^-$ Signals in MSSM Benchmark Scenarios
Abdesslam Arhrib, Duarte Azevedo, Rachid Benbrik, Hicham Harouiz, Stefano Moretti, Riley Patrick, Rui Santos.
Mar 5, 2020. 8 pp.
Conference: C19-11-04
e-Print: arXiv:2003.02435

[13] Phenomenology of the new light Higgs bosons in Gildener-Weinberg model
Kenneth Lane (Boston U.), Eric Pilon (Annecy, LAPTH). Sep 4, 2019. 25 pp.
e-Print: arXiv:1909.02111

[14] Enhanced Di-Higgs Production in the Two Higgs Doublet Model
K.S. Babu, Sudip Jana (Oklahoma State U.). Dec 31, 2018. 46 pp.
Published in JHEP 1902 (2019) 193
OSU-HEP-18-07
DOI: 10.1007/JHEP02(2019)193
e-Print: arXiv:1812.11943