Evidence of the true Higgs boson $H_T$ at the LHC Run 2

Paolo Cea

INFN - Sezione di Bari, Via Amendola 173 - 70126 Bari, Italy

Abstract

The aim of the present note is to compare the recent LHC data at $\sqrt{s} = 13\, TeV$ with our previous theoretical proposal that the true Higgs boson $H_T$ should be a broad heavy resonance with mass around 750 GeV. We focus on the so-called golden channel $H_T \to ZZ$ where the pair of Z bosons decay leptonically to $\ell^+\ell^-\ell^+\ell^-$, $\ell$ being either an electron or a muon. We use the data collected by the ATLAS and CMS Collaborations at $\sqrt{s} = 13\, TeV$ with an integrated luminosity of 36.1 fb$^{-1}$ and 77.4 fb$^{-1}$ respectively. We find that the experimental data from both the LHC Collaborations do display in the golden channel a rather broad resonance structure around 700 GeV with a sizeable statistical significance. Our theoretical expectations seem to be in fair good agreement with the experimental observations. Combining the data from both the ATLAS and CMS Collaborations we obtain an evidence of the heavy Higgs boson in this channel with an estimated statistical significance of more than five standard deviations.

Keywords: Higgs Boson; Large Hadron Collider.

PACS Nos.: 11.15.Ex; 14.80.Bn; 12.15.-y

\[\text{Electronic address: Paolo.Cea@ba.infn.it}\]
1 Introduction

The mechanism of spontaneous symmetry breaking, now called the Brout-Englert-Higgs mechanism \cite{1,2,3,4}, is a fundamental aspect of the Standard Model Physics. Actually, the first runs of proton-proton collisions at the CERN Large Hadron Collider (LHC) with center-of-mass energies $\sqrt{s} = 7, 8 \text{ TeV}$ (Run 1) has brought the confirmation of the existence of a spin-zero boson $H$ with mass $m_H \simeq 125 \text{ GeV}$ which resembles the one which breaks the electroweak symmetry in the Standard Model \cite{5,6}.

Usually the spontaneous symmetry breaking in the Standard Model is implemented within the perturbation theory which leads to predict that the Higgs boson mass squared is proportional to $\lambda v^2$, where $\lambda$ is the renormalised scalar self-coupling and $v \simeq 246 \text{ GeV}$ is the known weak scale. On the other hand, it is known that, within the non-perturbative description of spontaneous symmetry breaking in the Standard Model, self-interacting scalar fields are subject to the triviality problem \cite{7}, namely the renormalised self-coupling $\lambda \to 0$ when the ultraviolet cutoff is sent to infinity. Strictly speaking, there are no rigorous proof of triviality. Nevertheless, there exist several numerical studies which leave little doubt on the triviality conjecture. As a consequence, within the perturbative approach, the scalar sector of the Standard Model represents just an effective description valid only up to some cut-off scale.

If the renormalised self-coupling of the scalar fields vanishes, then one faces with the problem of the spontaneous symmetry breaking mechanism and the related scalar Higgs boson. In fact, naively, one expects that the spontaneous symmetry breaking mechanism cannot be implemented without the scalar self-coupling $\lambda$. However, in Ref. \cite{8}, by means of non-perturbative numerical simulations of the $\lambda\Phi^4$ theory on the lattice, it was enlightened the scenario where the Higgs boson without self-interaction could coexist with spontaneous symmetry breaking. This means that the Higgs boson condensation triggering the spontaneous breaking of the local gauge symmetries needs to be dealt with non-perturbatively. If this is the case, from one hand there is no stability problem for the condensate ground state, on the other hand the Higgs mass is finitely related to the vacuum expectation value of the quantum scalar field and it can be evaluated from first principles. Indeed, precise non-perturbative numerical simulations indicated that the true Higgs boson, denoted as $H_T$ in Ref. \cite{9}, is a rather heavy resonance with mass \cite{8}:

$$m_{H_T} = 754 \pm 20 \text{ GeV}. \quad (1.1)$$

In our previous paper \cite{9} we elaborated some phenomenological consequences of the massive Higgs boson proposal. In particular, we discussed the couplings of the $H_T$ Higgs boson to the massive vector bosons and to fermions, the expected production mechanisms, and the main decay modes. We also attempted a quantitative comparison in the so-called golden channel with available LHC data at $\sqrt{s} = 13 \text{ TeV}$ from both ATLAS and CMS Collaborations corresponding to an integrated luminosity of 36.1 $fb^{-1}$ and 35.9 $fb^{-1}$ respectively. The aim of the present paper is to extend such a comparison to the data collected by the CMS Collaboration in the 2016 and 2017 runs at LHC corresponding to an integrated luminosity of 77.4 $fb^{-1}$. The main results of the present note is that the experimental data from both the LHC Collaborations do display in the golden channel a rather broad resonance structure around 700 GeV with statistical significances well above four standard deviations for CMS and three standard deviations for ATLAS. Moreover, we find that our theoretical expectations seem to be in fair good agreement with the
experimental observations. We also try a combination of the data from the ATLAS and CMS Collaborations corresponding to 113.5 fb\(^{-1}\) and obtain an evidence of the heavy Higgs boson in this channel with an estimated statistical significance exceeding five standard deviations.

We organise the paper as follows. In Sect. 2, following Ref. [9], we briefly discuss the couplings of our massive Higgs boson proposal to the Standard Model gauge fields, the main decay channels, and the production mechanisms. In Sect. 3 we compare our theoretical proposal with the recent data collected by the ATLAS and CMS Collaborations at \(\sqrt{s} = 13\) TeV in the golden channel. Finally, our concluding remarks are relegated to Sect. 4.

## 2 Physics of the \(H_T\) boson

The phenomenological signatures of the massive \(H_T\) Higgs boson are determined by the couplings with the gauge and fermion fields of the Standard Model. As already argued in Ref. [9], the coupling of the Higgs field to the gauge vector bosons is fixed by the gauge symmetries. As a consequence the couplings of the \(H_T\) Higgs boson to the gauge vector bosons are the same as in perturbation theory notwithstanding the non-perturbative Higgs condensation driving the spontaneous breaking of the gauge symmetries. Given the rather large mass of the \(H_T\) Higgs boson, the main decay modes are the decays into two massive vector bosons (see, e.g., Refs. [10, 11]):

\[
\Gamma(H_T \to W^+ W^-) \simeq \frac{G_F m_{H_T}^3}{8\pi \sqrt{2}} \left[ 1 - 4 \frac{m_W^2}{m_{H_T}^2} \left( 1 - 4 \frac{m_W^2}{m_{H_T}^2} + 12 \frac{m_W^4}{m_{H_T}^4} \right) \right]
\]

(2.1)

and

\[
\Gamma(H_T \to Z^0 Z^0) \simeq \frac{G_F m_{H_T}^3}{16\pi \sqrt{2}} \left[ 1 - 4 \frac{m_Z^2}{m_{H_T}^2} \left( 1 - 4 \frac{m_Z^2}{m_{H_T}^2} + 12 \frac{m_Z^4}{m_{H_T}^4} \right) \right].
\]

(2.2)

Note that for heavy Higgs the radiative corrections to the decay widths can be safely neglected [12, 13, 14].

The couplings of the \(H_T\) Higgs boson to the fermions are given by the Yukawa couplings \(\lambda_f\). Unfortunately, there are not reliable lattice non-perturbative simulations on the continuum limit of the Yukawa couplings. If we follow the perturbative approximation, then the fermion Yukawa couplings turn out to be proportional to the fermion mass, \(\lambda_f = \sqrt{2} m_f / v\). Thus, for heavy Higgs the only relevant fermion coupling is the top Yukawa coupling \(\lambda_t\). On the other hand, we cannot exclude that the couplings of the physical Higgs field to the fermions could be very different from perturbation theory. Therefore, in Ref. [9] we introduced the parameter:

\[
\kappa = \lambda_t^2 \frac{v^2}{2 m_t^2}.
\]

(2.3)

Obviously, in perturbation theory we have \(\kappa = 1\). Nevertheless, in our previous work [9] we found that the experimental data pointed to strongly suppressed fermion Yukawa couplings. Indeed, in Ref. [9] we assumed \(\kappa \simeq 0\). Actually, the available experimental
The width for the decays of the $H_T$ boson into a $t\bar{t}$ pairs is easily found \cite{10, 11}:

$$
\Gamma(H_T \to t\bar{t}) \simeq \kappa \frac{3 G_F m_{H_T} m_t^2}{4\pi \sqrt{2}} \left(1 - 4 \frac{m_t^2}{m_{H_T}^2}\right)^{\frac{3}{2}}.
$$

(2.4)

So that, to a good approximation, the Higgs total width is given by:

$$
\Gamma_{H_T} \simeq \Gamma(H_T \to W^+ W^-) + \Gamma(H_T \to Z^0 Z^0) + \Gamma(H_T \to t\bar{t}) .
$$

(2.5)

To evaluate the Higgs event production at LHC we need the inclusive Higgs production cross section. As in perturbation theory, for large Higgs masses the main production processes are by vector-boson fusion and gluon-gluon fusion. In fact, the $H_T$ Higgs production cross section by vector-boson fusion is the same as in the perturbative Standard Model calculations. Moreover, for Higgs mass in the range 700 – 800 GeV the main production mechanism at LHC is expected to be by the gluon fusion mechanism. The gluon coupling to the Higgs boson in the Standard Model is mediated by triangular loops of top and bottom quarks. Since in perturbation theory the Yukawa couplings of the Higgs particle to heavy quarks grows with quark mass, thus balancing the decrease of the triangle amplitude, the effective gluon coupling approaches a non-zero value for large loop-quark masses. This means that for heavy Higgs the gluon fusion inclusive cross section is almost completely determined by the top quark. Therefore, according to our approximations the total inclusive cross section for the production of the $H_T$ Higgs boson can be written as:

$$
\sigma(pp \to H_T + X) \simeq \sigma_{VV}(pp \to H_T + X) + \kappa \sigma_{gg}(pp \to H_T + X),
$$

(2.6)

where $\sigma_{VV}$ and $\sigma_{gg}$ are the vector-boson fusion and gluon-gluon fusion inclusive cross sections respectively.

The calculations of the cross sections computed at next-to-next-to-leading and next-to-leading order for heavy Higgs boson with Standard Model-like coupling at $\sqrt{s} = 13$ TeV can be found in Ref. \cite{15}. As concern the gluon-gluon fusion cross section we found \cite{9} that this cross section can be parametrised as:

$$
\sigma_{gg}(pp \to H_T + X) \simeq \left\{ \begin{array}{ll}
\left(\frac{a_1}{M_{H_T}} + a_2 M_{H_T}^3\right) \exp(-a_3 M_{H_T}) & M_{H_T} \leq 300 \text{ GeV} \\
\frac{a_4}{M_{H_T}} \exp[-a_5(M_{H_T} - 400 \text{ GeV})] & 300 \text{ GeV} \leq M_{H_T} \leq 400 \text{ GeV} \\
\frac{a_4}{M_{H_T}} \exp[-a_5(400 \text{ GeV} - M_{H_T})] & 400 \text{ GeV} \leq M_{H_T} \end{array} \right.
$$

(2.7)

where $M_{H_T}$ is expressed in GeV and

$$
a_1 \simeq 1.24 \times 10^4 \text{ pb GeV} , \quad a_2 \simeq 1.49 \times 10^{-6} \text{ pb GeV}^{-3} ,
$$

$$
a_3 \simeq 7.06 \times 10^{-3} \text{ GeV}^{-1} , \quad a_4 \simeq 9.80 \text{ pb} ,
$$

$$
a_5 \simeq 7.63 \times 10^{-3} \text{ GeV}^{-1} .
$$

(2.8)

Likewise, the dependence of the vector-boson fusion cross section can be parametrised as:

$$
\sigma_{VV}(pp \to H_T + X) \simeq \left( b_1 + \frac{b_2}{M_{H_T}} + \frac{b_3}{M_{H_T}^2}\right) \exp(-b_4 M_{H_T}) ,
$$

(2.9)
where \[ b_1 \simeq -2.69 \times 10^{-6} \text{ pb} \], \[ b_2 \simeq 8.08 \times 10^2 \text{ pb GeV} \],
\[ b_3 \simeq -1.98 \times 10^4 \text{ pb GeV}^2 \], \[ b_4 \simeq 2.26 \times 10^{-3} \text{ GeV}^{-1} \].

To compare the invariant mass spectrum of our \( H_T \) Higgs with the experimental data, we note that:

\[
N_{H_T}(E_1, E_2) \simeq \mathcal{L} \int_{E_1}^{E_2} \text{Br}(E) \, \varepsilon(E) \, \sigma(p \, p \to \, H_T \, + \, X) \, L_{H_T}(E) \, dE ,
\]  

(2.11)

where \( N_{H_T} \) is the number of Higgs events in the energy interval \( E_1, E_2 \), corresponding to an integrated luminosity \( \mathcal{L} \), in the given channel with branching ratio \( \text{Br}(E) \). The parameter \( \varepsilon(E) \) accounts for the efficiency of trigger, acceptance of the detectors, the kinematic selections, and so on. Thus, in general \( \varepsilon(E) \) depends on the energy, the selected channel and the detector. In Eq. (2.11) \( L_{H_T} \) is the Lorentzian distribution:

\[
L_{H_T}(E) \simeq \frac{1}{1.0325 \, \pi} \frac{\Gamma_{H_T}(E)}{\left( E - 730 \text{ GeV} \right)^2 + \left( \frac{\Gamma_{H_T}(E)}{2} \right)^2} ,
\]  

(2.12)

where \( \Gamma_{H_T}(E) \) is given by Eq. (2.5), and the normalisation is such that:

\[
\int_{0}^{\infty} L_{H_T}(E) \, dE = 1 .
\]  

(2.13)

We assumed a slightly smaller value for the heavy Higgs boson central mass, namely \( m_{H_T} \simeq 730 \text{ GeV} \) that, however, is within the statistical uncertainties of the lattice determination Eq. (1.1).

### 3 Comparison with the LHC data from Run 2

In the present Section we compare our theoretical expectations with the available experimental data from LHC Run 2 in the so-called golden channel corresponding to the decays \( H_T \to ZZ \to \ell\ell\ell\ell \), where \( \ell \) is either an electron or a muon. Indeed, the four-lepton channel, albeit rare, has the clearest and cleanest signature of all the possible Higgs boson decay modes due to the small background contamination.

In Fig. 1 we show the invariant mass distribution for the golden channel obtained from the CMS experiment with an integrated luminosity of \( 77.4 \, fb^{-1} \) [16, 17] (left top panel) and the ATLAS experiment with an integrated luminosity of \( 36.1 \, fb^{-1} \) [18] (right top panel). From our estimate of the background (dashed lines in Fig. 1) we see that, indeed, in the high invariant mass region \( m_{ZZ} \gtrsim 600 \text{ GeV} \), the background is strongly suppressed.

To compare with our theoretical expectations, we display in Fig. 1 bottom panels, the signal distribution of the invariant mass \( m_{ZZ} \) in the golden channel. The signal distributions have been obtained from the event distributions by subtracting the relevant backgrounds. Moreover, with the aim of a comparison between the CMS and ATLAS data, we have rebinned the CMS data with a bin of size 20 GeV.

A few comments are in order. Firstly, both the LHC experiments display almost the same shape for the signal distributions. Secondly, both ATLAS and CMS data do show
Figure 1: (color online) Comparison to the LHC data of the distribution of the invariant mass $m_{ZZ}$ for the process $H_T \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ ($\ell = e, \mu$) in the high-mass region $m_{ZZ} \gtrsim 600 \text{GeV}$. The CMS data (left top panel) have been obtained from Fig. 3, left panel, in Ref. [16] and Fig. 2, left panel, in Ref. [17] corresponding to a total integrated luminosity of $\mathcal{L} = 77.4 \text{ fb}^{-1}$. The ATLAS data (right top panel), corresponding to an integrated luminosity of $\mathcal{L} = 36.1 \text{ fb}^{-1}$, have been obtained from Fig. 4, left panel, in Ref. [18]. The dashed (green) lines are our estimate of the background. The signal distribution of the invariant mass $m_{ZZ}$ for CMS (left bottom panel) and ATLAS (right bottom panel). The CMS data have been binned with bin of size 20 GeV to facilitate the comparison with the ATLAS data. The signal distributions have been obtained from the event distributions by subtracting the relevant backgrounds. The continuum (red) lines are the expected signal histograms obtained with Eq. (2.11) by assuming $\varepsilon(E) \simeq 0.80$ and $\kappa \simeq 0.15$. 
Figure 2: (color online) Comparison to the LHC data of the distribution of the invariant mass $m_{ZZ}$ in the high-mass region $m_{ZZ} \gtrsim 600\,\text{GeV}$ for the process $H_T \to ZZ \to \ell\ell\ell\ell$ ($\ell = e, \mu$). The signal distribution has been obtained from the combination of the ATLAS and CMS event distributions by subtracting the relevant background. The continuum (red) line is the expected signal histogram assuming $\varepsilon(E) \simeq 0.80$ and $\kappa \simeq 0.15$.

a rather broad structure around $m_{ZZ} \sim 700\,\text{GeV}$. Finally, the observed signal distributions seem to compare quite well with our theoretical proposal. In fact, in Fig. 1, bottom panels, we display the expected signal histograms obtained with Eq. (2.11) by assuming $\kappa \simeq 0.15$ and $\varepsilon(E) \simeq 0.80$ to take care of the fact that the detectors do not cover the full phase space. To be quantitative, we may estimate the total number of events in the invariant mass interval $650\,\text{GeV} \lesssim m_{ZZ} \lesssim 800\,\text{GeV}$ and compare with our theoretical expectations. We find:

\begin{align}
N_{\text{obs}}^{\text{sign}} &= 20.74^{+9.33}_{-4.39}, \quad N_{\text{sign}}^{\text{th}} = 17.30 \quad \text{CMS} \quad \mathcal{L} = 77.4\,\text{fb}^{-1} \quad (3.1)
\end{align}

\begin{align}
N_{\text{obs}}^{\text{sign}} &= 13.47^{+8.73}_{-4.14}, \quad N_{\text{sign}}^{\text{th}} = 8.10 \quad \text{ATLAS} \quad \mathcal{L} = 36.1\,\text{fb}^{-1} \quad (3.2)
\end{align}

where, to be conservative, the quoted errors have been obtained by adding in quadrature the experimental errors. We see that CMS has an evidence of a signal reaching a statistical significance well above four standard deviations, while the signal significance of ATLAS is about three standard deviations. Moreover, the observed and predicted event counts are in quite good agreement. Since the signal distributions from both the LHC experiments are compatible, we may try to combine both LHC datasets. In Fig. 2 we compare the resulting signal distribution with our theoretical estimates. It is, now, evident, that the signal distribution displays a broad peak structure around $m_{ZZ} \sim 700\,\text{GeV}$ with a high statistical significance that compare favourably with our theoretical signal distribution (continuum line in Fig. 2). In this case we find:

\begin{align}
N_{\text{obs}}^{\text{sign}} &= 34.21^{+12.78}_{-6.03}, \quad N_{\text{sign}}^{\text{th}} = 25.40 \quad \text{ATLAS} + \text{CMS} \quad \mathcal{L} = 113.5\,\text{fb}^{-1} \quad . \quad (3.3)
\end{align}
We see that there is an evidence of a signal reaching a statistical significance well above five standard deviations, and the overall observed and predicted event counts agree within 1.5 standard deviations. Therefore, we may conclude that our proposal for the heavy $H_T$ Higgs boson is finding in the golden channel the first clear confirmation.

4 Conclusion

It is widely believed that the new LHC resonance at 125 GeV is the Standard Model Higgs boson. However, stemming from the known triviality problem, i.e. vanishing self-coupling, that affects self-interacting scalar quantum fields in four space-time dimensions, we evidenced that the Higgs boson condensation triggering the spontaneous breaking of the local gauge symmetries needs to be dealt with non-perturbatively. It is worthwhile to notice that if this is the case, from one hand there is no stability problem for the condensate ground state, on the other hand the Higgs mass is finitely related to the vacuum expectation value of the quantum scalar field and, in principle, it can be evaluated from first principles.

In the present and previous papers we elaborated some phenomenological aspects of the heavy Higgs boson scenario. We have critically discussed the couplings of the $H_T$ Higgs boson to the massive vector bosons and to fermions. We have also estimated the expected production mechanism and the main decay modes. Comparing with the available LHC Run 2 data we concluded that the coupling of the $H_T$ Higgs boson to fermions were strongly suppressed. We compared our proposal with the recent results in the golden channel from both ATLAS and CMS Collaborations. We found that the available experimental observations were consistent with our scenario. We are confident that forthcoming data from LHC Run 2 will add further support to the heavy Higgs proposal. However, it remains the problem of unraveling the true nature of the new LHC resonance at 125 GeV. Even though we are still convinced that the H boson cannot be the Higgs boson of the Standard Model, nevertheless up to now all the experimental informations from the LHC experiments seem to confirm that the H boson resembles quite closely the Standard Model Higgs boson. Thus, we see that the presence of two (perturbative and non-perturbative) Higgs bosons indicates that some fundamental and crucial aspects of the Standard Model spontaneous symmetry breaking mechanism are still missing. In this respect, an interesting suggestion has been advanced in Ref. [19] motivated by the stability analysis of the theory in a class of approximations to the effective potential that are consistent with the triviality property. Indeed, it could well be that the elementary excitation of the scalar condensate is a Higgs boson doublet that consists of the heavy Higgs boson from the upward rescaling and the a light Higgs boson from the downward rescaling. We hope that the forthcoming data from LHC will help to shed light on this fundamental aspect of the Standard Model.

References

[1] F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964).
[2] P. Higgs, Phys. Lett. 12, 132 (1964).
[3] G. Guralnik, C. Hagen and T. Kibble, Phys. Rev. Lett. 13, 585 (1964).
[4] P. Higgs, Phys. Rev. 145, 1156 (1966).

[5] The ATLAS Collaboration, G. Aad, et al., Phys. Lett. B 716, 1 (2012).

[6] The CMS Collaboration, S. Chatrchyan, et al., Phys. Lett. B 716, 30 (2012).

[7] R. Fernandez, J. Fröhlich, and A. D. Sokal, Random Walks, Critical Phenomena, and Triviality in Quantum Field Theory, Springer, Berlin, Germany, 1992.

[8] P. Cea and L. Cosmai, The Higgs boson: From the lattice to LHC, ISRN High Energy Physics, vol. 2012, Article ID 637950, arXiv:0911.5220.

[9] P. Cea, The $H_T$ Higgs boson at the LHC Run 2, arXiv:1707.05605 [hep-ph].

[10] J. F. Gunion, H. E. Haber, G. Kane, and S. Dawson, The Higgs Hunter’s Guide, Perseus Publishing, Cambridge, Massachusetts (1990).

[11] A. Djouadi, Phys. Rept. 457, 1 (2008).

[12] J. Fleischer and F. Jegerlehmer, Phys. Rev. D 23, 2001 (1981).

[13] J. Fleischer and F. Jegerlehmer, Nucl. Phys. B 216, 469 (1983).

[14] W. J. Marciano and S. D. Willenbrok, Phys. Rev. D 37, 2509 (1988).

[15] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBSMAt13TeV.

[16] The CMS Collaboration, Measurements of properties of the Higgs boson in the four-lepton final state at $\sqrt{s} = 13$ TeV, CMS PAS HIG-16-041 (2017).

[17] The CMS Collaboration, Measurements of properties of the Higgs boson in the four-lepton final state at $\sqrt{s} = 13$ TeV, CMS PAS HIG-18-001 (2018).

[18] The ATLAS Collaboration, Eur. Phys. J. C 78 293 (2018).

[19] P. Castorina, M. Consoli, and D. Zappala, J.Phys. G 35 075010 (2008).