HIDING THE HIGGS AT THE LHC

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Abstract

We study a simple extension of the standard model where scalar singlets that
mix with the Higgs doublet are added. This modification to the standard
model could have a significant impact on Higgs searches at the LHC. The
Higgs doublet is not a mass eigenstate and therefore the expected nice peak
of the standard model Higgs disappears. We analyze this scenario finding the
required properties of the singlets in order to make the Higgs "invisible" at
the LHC. In some part of the parameter space even one singlet could make
the discovery of the SM Higgs problematic. In other parts, the Higgs can be
discovered even in the presence of many singlets.

1 Introduction

The Higgs particle of the Standard Model (SM) is expected to be discovered at the LHC. In extensions of the standard model, however, the situation could be different. Modifications to the scalar sector alter the experimental signatures of the Higgs boson in a model dependent way. Therefore, there is no guarantee that a very general Higgs boson can be found at the LHC.

The available experimental data provide constraints on the Higgs mass, m_H (for a review see [1]). The strongest lower bound comes from direct searches at LEP2, $m_H > 114.4\ GeV$ at 95% CL [2]. An upper bound is derived from electroweak precision measurements and reads $m_H < 219\ GeV$ at 95% CL [3]. Since the sensitivity of electroweak precision measurements to m_H is logarithmic, we cannot exclude at a very high confidence level the case where m_H is just a factor of a few above this limit.

One of the main goals of the LHC is to discover the Higgs boson. Both the ATLAS and CMS collaborations will search for the Higgs boson in the mass range of $10^2 - 10^3\ GeV$. The Higgs is expected to be discovered through different channels depending on its mass. In the low mass regime, the most promising channel would be $H \to \gamma\gamma$ [4]. For $m_H \gtrsim 150\ GeV$, the preferred decay is $H \to VV^{(*)}$ (with $V = Z, W$) with different substantial decays of the vector bosons. These searches are expected to provide at least a 5σ signal for the Higgs after few years of operation of the LHC.

There are also several theoretical constraints on m_H (see, for example, [5]). For example, the unitarity bound reads $m_H \lesssim 700\ GeV$. One can also consider the possibility that the Higgs does not exist. This possibility gives rise to a constraint on new physics scale $\Lambda \lesssim 1$ TeV. Thus, we expect that the LHC will find either the Higgs boson or some kind of new physics.

What if nothing is found at the LHC, that is, neither the Higgs boson nor new physics? Such a scenario seems to imply that (i) the Higgs boson does not exist; (ii) there is new physics that is responsible for electroweak-symmetry breaking (EWSB); and (iii) the experimental signals of this new physics are such that it cannot be discovered at the LHC. There is, however, another possibility: The Higgs exists and it is responsible for EWSB but there is new physics that "hides" the Higgs signals. Furthermore, this new physics does not show up in any other channel and therefore cannot be discovered at the LHC.

Here we talk about such a scenario which hides the Higgs and does not show any signal of new physics. We extend the scalar sector of the SM by introducing additional SM singlets which mix with the Higgs doublet of the SM. The resulting spectrum consists of many scalars. Each of these scalars

is mainly a singlet with a small component of the SM doublet. Thus, the production rate for any of these mass eigenstates is much smaller than that of a SM Higgs with the same mass. In the limit of many singlets each mass eigenstate produces a very small signal that cannot be separated from the background. In that case the Higgs is practically hidden. For a more detailed description with a numerical analysis of the possible number of scalar fields see [6] which also include a comperhansive review of related works.

2 The model

In order to understand the main features of our scenario we start with a simple case where one singlet, $S(1,1)_0$, is added to the SM. For simplicity we further introduce a Z_2 symmetry such that S is odd under it, while all other fields are even under this Z_2. Denoting the SM Higgs doublet by H, the most general renormalizable scalar potential is

$$\mu_H^2 |H|^2 + \frac{\mu_S^2}{2} S^2 + \lambda_H |H|^4 + \frac{\lambda_S}{4} S^4 + \frac{\eta}{2} S^2 |H|^2. \tag{1}$$

In the following we assume that

$$\mu_H \sim \mu_S, \qquad \lambda_H \sim \lambda_S \sim \eta. \tag{2}$$

While our assumptions, that all dimensionful parameters are at the same scale and all dimensionless couplings are of the same order, are simple and not necessarily fine-tuned, they are not based on a fundamental framework of new physics. We make them because they lead to interesting phenomenology.

We are interested in the vacuum structure of this potential. Since the Higgs vev is responsible for EWSB we demand $\langle H \rangle \neq 0$. As for the vev of S, the solution $\langle S \rangle = 0$ is not interesting as there is no mixing between S and H. Thus, we consider only solutions where $\langle H \rangle \neq 0$ and $\langle S \rangle \neq 0$. It is worth mentioning that in general there is a large part of the parameter space where both fields acquire a vev.

Next, we analyze the mass spectrum. We substitute

$$\mathcal{R}e(H) \rightarrow \frac{h + v_H}{\sqrt{2}}, \qquad S \rightarrow s + v_S, \tag{3}$$

where h and s are real scalar fields and v_H and v_S are the vacuum expectation values of H and S respectively. The mass-squared matrix in the (h, s) basis is

$$M^2 = \begin{pmatrix} \mu_H^2 + 3\lambda_H v_H^2 + \frac{1}{2}\eta\, v_S^2 & \eta v_H v_S \\ \eta v_H v_S & \mu_S^2 + 3\lambda_S v_S^2 + \frac{1}{2}\eta\, v_H^2 \end{pmatrix}. \tag{4}$$

Diagonalizing M^2, we get two mass eigenstates, ϕ_0 and ϕ_1 with masses m_0 and m_1. We define $m_0 \leq m_1$ and due to our assumptions we expect $m_0 \sim m_1$. We further consider only cases where the two mass eigenstates are not close to be degenerate, that is, $m_1 - m_0 \gg \Gamma_0, \Gamma_1$. The two mass eigenstates are related to the weak eigenstates h and s by a 2×2 orthogonal rotation matrix V

$$\begin{pmatrix} h \\ s \end{pmatrix} = V \begin{pmatrix} \phi_0 \\ \phi_1 \end{pmatrix}, \qquad V = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \tag{5}$$

Note that θ can assume any value between 0 and $\pi/2$. In general θ can be very small, but due to our assumption, Eq. (2), we expect $\theta \sim O(1)$. The model discussed here contains five parameters. They can be chosen to be the five parameters in (1). Instead, we can chose them to be the two masses, m_0 and m_1, the two vevs, v_S and v_H and the mixing angle θ.

We are now in position to study the phenomenology of the model. The couplings of the scalars to the SM fields can be obtained from that of the SM Higgs by projecting onto the doublet component. In particular, we are interested in the coupling of a scalar to a pair of SM fields, either fermions or vector bosons

$$\frac{V_{hi}}{v_H} \left(m_f \, \phi_i \bar{f} f + m_Z^2 \, \phi_i \, Z_\mu Z^\mu + 2 m_W^2 \, \phi_i \, W_\mu^+ W^{\mu-} \right). \tag{6}$$

We see that the couplings are just the SM couplings projected by V_{hi}. The couplings between two scalars and two gauge bosons are given by the SM ones multiplied by $V_{hi} V_{hj}$

$$\frac{V_{hi} V_{hj}}{2 v_H^2} \left(m_Z^2 \, \phi_i \phi_j \, Z_\mu Z^\mu + 2 m_W^2 \, \phi_i \phi_j \, W_\mu^+ W^{\mu-} \right). \tag{7}$$

Last we need the self interactions term, i.e., interaction that involve only scalars. The interesting part for our study is the couplings that can be responsible for decays of a heavy scalar into light scalars, $\phi_1 \to 2\phi_0$ and $\phi_1 \to 3\phi_0$. These couplings are given by

$$\frac{1}{4} \Big[(\lambda_S - \lambda_H - (\lambda_S + \lambda_H - \eta) \cos 2\theta) \sin 2\theta \Big] \phi_1 \phi_0^3 +$$
$$[v_\phi \cos\theta \left((3\lambda_S - \eta) \sin^2\theta + \frac{\eta}{2} \cos^2\theta \right)$$
$$- v_H \sin\theta \left((3\lambda_H - \eta) \cos^2\theta + \frac{\eta}{2} \sin^2\theta \right)] \phi_1 \phi_0^2. \tag{8}$$

In general there are no specific relations between the strength of the scalar couplings, Eq. (8), and the couplings between scalars and gauge bosons, Eqs. (6)

and (7). For example, the coupling of $\phi_1\phi_0^2$ can be similar, smaller or larger to that of $\phi_1 W^+ W^-$.

We can generalize the above model by introducing N new singlets, S_α, with $\alpha = 1..N$. Again, we analyze the most interesting case where all the scalar fields acquire vevs. The algebra is more cumbersome, but we end up with a result similar to the case of one extra singlet. There are $N+1$ mass eigenstates ϕ_i ($i = 0..N$). We expand around the vacuum in a similar way as Eq. (3). In terms of the weak eigenstates, $\phi^W \equiv (h, s_\alpha)$, the mass eigenstates ϕ are given by $\phi = V\phi^W$, such that V is an $(N+1) \times (N+1)$ orthogonal matrix. The couplings to the SM fields are then given as in the one singlet case by Eqs. (6) and (7). The analog of Eq. (8) is more complicated. It can be obtained in a straightforward way and we do not write it explicitly here. We only mention that also in the more general case considered here the couplings between the scalars can be smaller, similar, or larger with respect to other couplings which involves gauge bosons.

3   Phenomenology of the model

Next we study the phenomenology of the N singlets model. We first look at the effect of this model on electroweak precision measurements (see also [7]) and then move to discuss the collider signatures.

The SM Higgs contribution to electroweak precision measurements comes through the S and T parameters. [8] That is, the gauge boson self energies are the only numerically relevant diagrams with the Higgs. Of course varying m_H affects all observables, but in a way consistent with changing just S and T. Thus, in order to see the effects of our model, all we need to do is to replace the SM Higgs contributions to S and T with the sum of all contributions weighted by the mixing angles. Consider a one-loop diagram with the ith mass eigenstate. Its contribution to S and T is equal to that of the corresponding SM diagram multiplied by $|V_{hi}|^2$. In the leading log approximation, we therefore substitute

$$\log(m_h^2) \to \sum_i |V_{hi}|^2 \log(m_i^2). \tag{9}$$

Thus, the bound on the Higgs mass in the SM is replaced by a bound on a function of the masses and mixing angles. In particular, we can have heavy mass eigenstates up to 1 TeV without violating the electroweak data.

In order to discuss the implications of our model on collider searches of the Higgs, we recall some issues regarding the search for the SM Higgs. Depending on the Higgs mass, there are several decay channels that are used to search for the Higgs. They are discussed at length in Ref. [1] and are summarized in figs. 22 and 23 there. Roughly speaking, we can say that

1. At the low mass range, the Higgs is mainly searched for by looking into a resonance in different channels (like $H \to \gamma\gamma$ or $H \to ZZ^{(*)} \to 4l$).

2. For $m_h \gtrsim 400$ GeV the search channels are mainly $H \to ZZ \to ll\nu\nu$ and $H \to WW \to l\nu jj$ where the search is for missing mass/momentum.

A relevant point to the Higgs search is the width of the Higgs, Γ_h. The experimental resolution is expected to be $\sigma \sim 2$ GeV [9] which is roughly the width of a Higgs with $m_h \sim 200$ GeV. For $\Gamma_h < \sigma$ a reduction of the Higgs width due to added singlets is practically impossible to detected, while for $\Gamma_h > \sigma$ this effect is more noticeble.

Now we move back to our model. The main effect of our model on collider searches for the Higgs is that the cross section of each mass eigenstate is suppressed compared to a SM Higgs of the same mass. The leading production process at the LHC is gluon fusion through one-loop triangle diagram. Thus, the production cross section for each mass eigenstate is suppressed by a factor of $|V_{hi}|^2$. In the limit of many new singlets, $|V_{hi}|$ is small, and thus the cross section become very small.

The other effects depend on the parameters of the model. First consider the scenario where decays of the form $\phi_i \to 2\phi_j$ are forbidden or negligible. Then, all the decay rates of the ith mass eigenstate are suppressed by the same factor of $|V_{hi}|^2$. Thus, the branching ratios are the same as those of a SM Higgs with the same mass. The total width of each mass eigenstate is smaller by a factor of $|V_{hi}|^2$ compared to the width of a SM Higgs with the same mass.

We can think about three different cases for the above scenario. First we discuss the low mass range where the Higgs is searched for by a resonance and the width of the Higgs is small compared to the experimental resolution. Then the signal of each mass eigenstates is reduced by $|V_{hi}|^2$. (The width is also reduced by the same amount but this reduction cannot be noticed.) With many singlets, when $|V_{hi}|^2$ is very small for all i, the signal significance will drop below detection level. With about ten singlets no signal of the Higgs can be found if all mass eigenstates are below about 300 GeV. In some cases even one singlet is enough to "hide" the Higgs, while in other cases more than ten singlets are needed.

When the width of each mass eigenstate, Γ_i, is large, $\Gamma_i > \sigma$ the division of the signal between the singlets reduces the significance of each resonance $|V_{hi}|$. The reason is that while the total signal is reduced by $|V_{hi}|^2$, this reduction simultaneously affects the width of the resonance. Indeed in our study we found that when we have masses above about 300 GeV, more singlets are needed in order to hide the Higgs signals then in the lower mass case.

The third case is where some of the mass eigenstates are heavy with $m_i \gtrsim 400$ GeV. All these mass eigenstates contribute to the missing energy

signal. Hence, the combined excess of these eigenstates over the background will be similar to that of a SM Higgs with $m_h \gtrsim 400$ GeV. In this case it is possible to hide the Higgs signal by adding light mass eigenstates whose signals are reduced by the $|V_{hi}|^2$ factors.

Last we discuss the scenario where decays like $\phi_i \rightarrow 2\phi_j$ are important. In particular, the interesting case is when all the heavy scalars decay almost entirely to the lightest one. In that case the situation is similar to the SM Higgs. Only one mass eigenstate is produced and its branching ratios are the same as a SM Higgs with the same mass. Yet, the production cross section and width are smaller than for a SM Higgs. This is because the production cross section for a heavy mass eigenstate is always less than half that of the light one. Thus, the fact that a heavy mass eigenstate decays into two light scalars cannot compensate for the reduction in the production rate and the parameter spcae allow for the possibility of the Higgs being hidden.

4   Discussion and conclusions

The Higgs boson is expected to be discovered at the LHC. Depending on its mass, different channels will be used to discover it. The standard model will be in a very bad position if the Higgs is not found. In this work we have shown that additional singlets might explain an absence of a Higgs signal without any signal of new physics. We analyzed scenarios corresponding to different masses in the range of $10^2 \lesssim m_i \lesssim 10^3$ GeV. We assumed that all dimension-full parameters are of the order of the weak scale and all dimensionless parameters are of order one. In particular we asked how many singlets are needed in order to "hide" the Higgs. The answer depends crucially on the model parameters. In some cases, in particular when the mass eigenstates are close to 100 GeV, we found that a single additional singlet could reduce the significance below discovery level. In other cases, mainly when many of the masses are roughly above 300 GeV we found that tens of singlets are needed to hide the Higgs.

We have concentrated on the Higgs search at the LHC. In fact, it could affect the searches for the Higgs also at LEP and the Tevatron and it is possible that the Higgs signal is hidden by a many-singlet solution. Yet, we did not investigate this issue in details. For the case of one extra singlet such a study was done in. [10]

To conclude, we present a model in which the standard model Higgs field generates electroweak symmetry breaking but still the Higgs particle cannot be discovered at the LHC. Our model is very simple, and while it is not based on a well motivated theoretical framework, it serves as an example that the SM Higgs mechanism can escape detection at the LHC.

Acknowledgments

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