LIMITS ON A HEAVY HIGGS SECTOR

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For Martin Veltman's 80th birthday

Using the classical argument about tree level unitarity breakdown in combination with the precision electroweak data, it is shown, that if part of the Higgs sector is heavy and strongly interacting, this part is small and is out of range of the LHC. The limits take into account the recent Higgs search results at the LHC.

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1. Introduction

Recently some renewed interest [1, 2, 3, 4] in the possibility of a strongly interacting light Higgs sector has appeared. It was proposed to parametrize the effects of the strong sector by anomalous couplings arising in the form of higher dimensional operators at low energy. Of course, these operators should come from an ultraviolet completion of the theory that gives rise to these effects. The most important operators acting only on the Higgs field itself are

$$\mathcal{O}_1 = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right) , \tag{1}$$

$$\mathcal{O}_2 = \left(\Phi^\dagger \Phi\right)^3 . \tag{2}$$

These operators are automatically invariant under the custodial $\mathrm{SU_L}(2) \times \mathrm{SU_R}(2)$ symmetry, which is highly desirable on phenomenological grounds. The phenomenological effects are as follows. After a rescaling of the fields $\mathcal{O}_1$ gives rise to anomalous Higgs boson couplings, namely every coupling of standard model particles to the Higgs field is multiplied with a common factor. Furthermore $\mathcal{O}_2$ gives rise to a change in the Higgs selfcouplings.

Measuring $\mathcal{O}_2$ would amount to measuring the Higgs self-coupling, which is notoriously difficult at the LHC. In precision tests at LEP, the effects of $\mathcal{O}_2$ appear only at the two-loop level and happen to be actually finite [5], even though the full theory is non-renormalizable. The effect is however very small. In this paper we focus on $\mathcal{O}_1$, since the presence of this operator affects the precision electroweak variables at the one-loop level and can therefore be constrained more easily. Actually the theory with this operator is non-renormalizable and this shows up already at the one-loop level in the electroweak precision tests. The relevant corrections are logarithmically divergent. In order to realistically constrain the theory one, therefore, has to start with an ultraviolet completion, that gives rise to this operator at low energy.

2. The Hill model

Such a completion is given by the Hill model [6], which is actually the simplest possible renormalizable extension of the standard model, having only two extra parameters. The Hill model is described by the following Lagrangian

$$\mathcal{L} = -\frac{1}{2}(D_\mu \Phi)^\dagger (D_\mu \Phi) - \frac{1}{2}(\partial_\mu H)^2 \tag{3}$$

$$-\frac{\lambda_0}{8}\left(\Phi^\dagger \Phi - f_0^2\right)^2 - \frac{\lambda_1}{8}\left(2 f_1 H - \Phi^\dagger \Phi\right)^2 . \tag{4}$$

Working in the unitary gauge one writes $\Phi^\dagger = (\sigma, 0)$, where the σ-field is the physical standard model Higgs field. Both the SM Higgs field σ and the Hill field H receive vacuum expectation values and one ends up with a two-by-two mass matrix to diagonalize, thereby ending with two masses m_- and m_+ and a mixing angle α. There are two equivalent ways to describe this situation. One is to say that one has two Higgs fields with reduced couplings g to standard model particles

$$g_- = g_{\rm SM}\cos(\alpha)\,, \qquad g_+ = g_{\rm SM}\sin(\alpha)\,. \tag{5}$$

The standard model would correspond to $\alpha = 0$ with the light Higgs the standard model Higgs. The other way, which has some practical advantages is not to diagonalize the propagator, but simply keep the σ–σ propagator explicitely. One simply replaces the standard model Higgs propagator, in all calculations of experimental cross sections, by

$$D_{\sigma\sigma}\left(k^2\right) = \cos^2(\alpha)/\left(k^2 + m_-^2\right) + \sin^2(\alpha)/\left(k^2 + m_+^2\right) . \tag{6}$$

The generalization to an arbitrary set of fields H_k is straightforward, one simply replaces the singlet-doublet interaction term by

$$L_{H\Phi} = -\sum \frac{\lambda_k}{8} \left(2 f_k H_k - \Phi^\dagger \Phi\right)^2 . \tag{7}$$

For a finite number of fields H_k no essentially new aspects appear, however dividing the Higgs signal over even a small number of peaks, can make the study of the Higgs field at the LHC somewhat challenging. Having an infinite number of Higgs fields one can also make a continuum [7,8]. A mini-review of this type of models is given in [9]. For the purpose of this paper the precise form of the Higgs propagator is irrelevant. Important is that there is a light piece in the Higgs sector, which is weakly interacting and a heavy piece that is strongly interacting. For this purpose the simple Hill model is sufficient. The Hill field can be considered as an effective description for a technicolour-like composite field, mixing with the standard model Higgs.

3. Limits for a strongly interacting Higgs sector

In order to determine whether the Higgs sector can become strongly interacting, we adapt the classical analysis of [10, 11] to our case. The breakdown of tree level unitarity is used as a criterium for the presence or absence of strong interactions. Studying partial wave unitarity the adapted classical analysis from [10, 11] gives the limit

$$\cos^2(\alpha) m_-^2 + \sin^2(\alpha) m_+^2 \leq \frac{8\pi\sqrt{2}}{3G_{\rm F}} \tag{8}$$

in order to have tree level unitarity. Since we demand that the Higgs sector becomes strongly interacting at high energies we demand that this bound is broken. For this to happen one needs a sufficiently large combination $m_+ \sin(\alpha)$. However one cannot have an arbitrarily large value here, since radiative corrections to low energy precision variables grow logarithmically with the Higgs mass. This is known as Veltman's screening theorem [12]. The correction to a typical electroweak precision observable $\delta_{\rm EW}$ behaves like

$$\delta_{\rm EW} \approx \log\left(m_-^2/m_Z^2\right) + \sin^2(\alpha) \log\left(m_+^2/m_-^2\right) . \tag{9}$$

This must then be smaller than the limit for the standard model

$$\delta_{\rm EW} \leq \log\left(m_{\rm up}^2/m_Z^2\right) . \tag{10}$$

where $m_{\rm up}$ is the upper limit for the Higgs boson mass. From the electroweak working group we take $m_{\rm up} = 157$ GeV. We define $x = m_+^2/m_-^2$ and $m_{\rm min}$

the minimal allowed Higgs mass, which we take to be $m_{\rm min} = 115$ GeV from the direct search. The expectation value v of the Higgs field is given by $v^2 = G_{\rm F}^{-1}/\sqrt{2} = (246~{\rm GeV})^2$. One then derives

$$\frac{x-1}{\log(x)} \geq \frac{16\pi v^2 - 3m_-^2}{3m_-^2 \log(m_{\rm up}^2/m_-^2)}\,. \tag{11}$$

Taking $m_- = m_{\rm min}$ one finds the weakest limits. With the above values one finds

$$m_+ \geq 3285~{\rm GeV} \tag{12}$$

and

$$\sin^2(\alpha) \leq 0.093\,. \tag{13}$$

So the lowest energy where one can find a strongly interacting part of the Higgs sector is at 3285 GeV with a production cross section of only 9.3% of the one for a standard model Higgs field with the same mass.

4. Limits including the LHC Higgs search data

The LHC has shown evidence for the presence of a Higgs particle at about 125 GeV [13, 14]. As the data are not very precise we, therefore, assume that a fraction $f_{\rm LHC}$ of the spectral density is located in this peak and see what the effect on the above analysis will be. We will assume that the rest of the spectral density can still start at 115 GeV. One then derives the following limit

$$\frac{x-1}{\log(x)} \geq \frac{16\pi v^2 - 3(1-f)m_-^2 - 3fm_{\rm LHC}^2}{3m_-^2 \left(\log(m_{\rm up}^2/m_-^2) - f\log\left(m_{\rm LHC}^2/m_-^2\right)\right)}\,. \tag{14}$$

Taking $f_{\rm LHC} = 0.6$, which seems reasonable, given the data, one finds

$$m_+ \geq 3636~{\rm GeV} \tag{15}$$

and

$$\sin^2(\alpha) \leq 0.076\,. \tag{16}$$

Further numbers are given in the table below.

Already without the limits from the direct search such a heavy Higgs boson would be out of reach of the LHC, since it is produced too little because of its high mass and the reduced coupling to the standard model particles. Moreover it is also wide, so there is no clear signal above the background. With the strengthened limits it is hard to imagine any accelerator that could study such a sector.

TABLE I

Lower limit on the Higgs mass m_+, the tree level width Γ_+ and maximal fraction $\sin^2(\alpha)$ of the spectral density in the strongly interacting part of the Higgs sector, as a function of the fraction f_{LHC} of the Higgs sector seen at the LHC.

f_{LHC}	m_+ [GeV]	Γ_+ [GeV]	$\sin^2(\alpha)$ (%)
0.0	3285	1623	9.3
0.1	3337	1648	9.0
0.2	3391	1674	8.7
0.3	3448	1702	8.4
0.4	3508	1731	8.1
0.5	3571	1762	7.8
0.6	3636	1794	7.6
0.7	3705	1827	7.3
0.8	3778	1862	7.0
0.9	3854	1900	6.7
1.0	∞	∞	0.0

The above analysis is, of course, somewhat simplified and could be improved in many ways, for instance, by improving the unitarity bound, applying more accurate formulas for the electroweak tests *etc.* The direct search for the Higgs boson at the LHC could improve the limits if a partial Higgs boson would be found above the limit of about 130 GeV from the present data. Barring this possibility the direct search will not improve on the limits given in the table. An improvement on the precision data however could lower m_{up} and would effect the limits.

However such improvements will not change the conclusion, that strong interactions can only play a very small part in the Higgs propagator in a very high energy region, that is out of the range of the LHC or any machine that is at present under consideration. In combination with the absence of new physics in the LHC data, the argument suggests that, contrary to speculations during the last thirty years, the TeV scale does not appear to play a fundamental role in physics.

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