PROCEEDINGS OF SCIENCE

Electroweak Symmetry Breaking: status/directions

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This is a brief description[†] of the implications of the 4th of July discovery on electroweak symmetry breaking and the prospects for the future.

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[†]Be aware however of what the Catalan writer Josep Pla used to say: "It is much harder to describe than to give opinions. Infinitely much more. Given this, everybody give opinions".

1. Introduction

The 4th of July of 2012 marked a new milestone in particle physics. A new particle was discovered with properties closely similar to those of the Standard Model (SM) Higgs [1]. Since then more than 500 papers have been written on this new state, a clear sign of the stirring produced in the particle physics community.

Why is the Higgs so important? The SM Higgs corresponds to the radial excitation around the EWSB vacuum. But this is not what makes the Higgs so special. To better appreciate the importance of the SM Higgs, we can ask ourselves how would be the SM without the Higgs. We would find that this is a sick theory! The main problem comes from the electroweak sector where the W and Z, being massive, have an extra degree of freedom as compared to massless gauge bosons, the longitudinal component. And are exactly these states that spoil the nice calculability power of gauge theories, as their scattering amplitudes grow with the energy involved in the process and become strongly coupled at energies around $4\pi v \sim$ TeV (where $v \simeq 246$ GeV is the vacuum expectation value of the Higgs field). The model is not renormalizable, or equivalently, not predictive. With the Higgs, the situation is different. The Higgs-exchange interactions make the SM amplitudes well-behaved, making the SM a renormalizable and predictive model. Of course, we know that the SM is not a final theory due to gravity. At the Planck scale gravity interactions are important and new physics beyond the SM must be present to make a fully consistent quantum theory. Nevertheless, having a theory that is predictive all the way to the Planck scale $M_P \sim 10^{19}$ GeV is, without any doubts, a great theoretical achievement.

In order for the Higgs to be able to play this role of "moderator" of the SM scattering amplitudes, its couplings must be exactly those ones predicted in the SM. Any deviation from these values would make the EW theory sick again at high energies and this scalar would not deserve to be called Higgs boson. We would have to call him "Higgs impostor". Plain and simple, all Higgs couplings are determined in the SM and therefore observing deviations from these predictions automatically implies new physics. This is why is so important to determine the Higgs couplings at the highest precision.

Although the Higgs mechanism is the simplest consistent model of EWSB, it suffers from being too simple. First, we do not understand why the electroweak scale v (or equivalently the Higgs mass) is so much smaller than the Planck scale M_P. And physics is about understanding things! Furthermore, the Higgs is a scalar and, contrary to fermions or gauge bosons, its mass cannot be protected from quantum corrections. This is to say that its mass is sensitive to new physics at the Planck scale, making the small value of m_H, as compared with M_P, difficult to maintain.

Theorists play mainly with two possible scenarios to explain the smallness of the Higgs mass. Either to impose an extra symmetry, called supersymmetry (susy), that relates bosons with fermions and would allow to protect the Higgs mass, or assume that the Higgs is not elementary but a composite state. In both cases one finds important implications for the Higgs sector. In the first case, the minimal supersymmetric Standard Model (MSSM) requires two Higgs doublets. Therefore the duties of the SM Higgs are shared in this case by two scalars with couplings different from those of the single SM Higgs. In the second case the Higgs is assumed to be like a pion in QCD: a composite pseudo-Goldstone boson (PGB) arising from a new strong-sector at the TeV. As a pion,

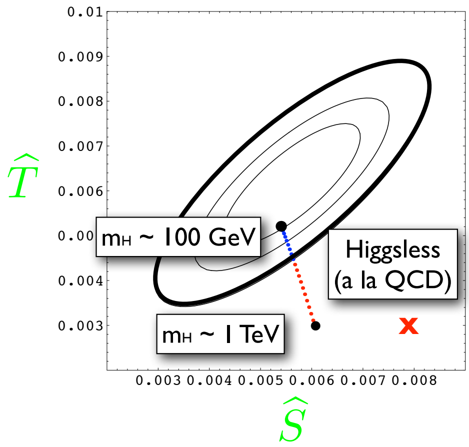

Figure 1: Experimental constraints at 68%, 95% and 99% CL on the $\widehat{S}$ and $\widehat{T}$ parameters following ref. [5], and the SM prediction as a function of the Higgs mass.

the Higgs would be the lightest composite resonance, decaying only to elementary SM particles through small couplings. Nevertheless, if the Higgs were composite, it would have different couplings from those of an elementary state. And this means that a composite Higgs cannot fully play the role of the SM Higgs. Since these deviations are expected to be small [2], the composite PGB Higgs would only be a kind of "mild" impostor. At around few TeVs, other resonances of the new strong-sector would help the composite PGB Higgs to fully moderate the scattering amplitudes, making the theory fully consistent.

2. What data tell us?

2.1 Before the 4th of July

Before the 4th of July, we already knew, of course, that the vacuum does not respect the EW symmetry, since the W and Z bosons and the SM fermions are massive. We also knew that, as in superconductors, this was due to a spin-zero condensate, although we did not know if this condensate was made of something else (as Cooper pairs are known to be made of pairs of electrons) or was a new elementary field. We also knew that the angular excitations around this EWSB vacuum, the Goldstones, correspond to the longitudinal component of the massive gauge bosons, but we didn't know anything about the radial excitations. Of course, we knew that those excitations were there (you can always excite a vacuum in a particular direction creating new waves/particles), but we had not yet measured them so we were not aware of their masses or couplings.

Two very important pieces of information on the EWSB sector were, however, known before the 4th of July. The first one was the experimental evidence for the relation $m_W^2 \simeq m_Z^2 \cos^2\theta_W$. Deviations from this relation, parametrized by the T-parameter [3], were known to be very small. Recall that, after EWSB, the W and Z masses are a priori two independent parameters. Nevertheless, the fact that their masses were related implied that the EWSB sector had an extra symmetry remaining after EWSB. This symmetry was called custodial symmetry [4] and it was known to be

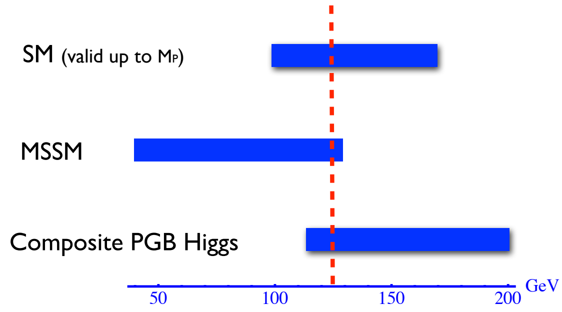

Figure 2: Rough ranges of the Higgs mass for three possible scenarios: The SM, the MSSM and the minimal composite PGB Higgs of ref. [9].

(approximately) respected, for example, if the Higgs field was a doublet, but not if it was a triplet. The other important piece of information was the S-parameter [3], a measured of the $\gamma - Z$ kinetic mixing. The Higgs boson contributes to this quantity at the one-loop level. Experimentally, the S and T parameters were constrained as shown in fig. 1, where the theoretical prediction is also shown as a function of the Higgs mass. From the plot we see that data was already telling us that a light Higgs was favored and simple Higgsless models (*à la* QCD) were already ruled out. But "one swallow does not make a spring", so we needed more data to definitely discard or favour different EWSB models.

2.2 After the 4th of July

The 4th of July a new boson was discovered with a mass around 125 GeV. Today, after most of the 2012 data analysed, we find that its measured couplings are in reasonable good agreement with those predicted for the SM Higgs.

2.2.1 What does $m_H \sim 125$ GeV tell us?

First of all, $m_H \sim 125$ GeV tells us that the Higgs is a relatively light particle (below the "cut-off" mentioned above $4\pi v \sim$ TeV), that is equivalent to say, a weakly self-coupled state. Indeed, writing $m_H^2 = \lambda v^2$, one obtains $\lambda \sim 0.26 \ll 4\pi$ where λ is the Higgs self-interaction. This tells us that Higgsless models of EWSB [6], in which no light Higgs-like state is expected, are definitely ruled out. After 33 years with us, Higgsless models finally rest in peace! There is, however, the Higgsless fan's hope that this new boson is not a Higgs but a dilaton, the Goldstone boson of spontaneously broken scale invariance that could be present in Higgsless models. A dilaton can mimic very well a Higgs (is one of our best impostors) since it can couple like a Higgs up to an overall scale-factor v/f, where f is the decay-constant of the dilaton. In principle, f has no relation with v, so one expects v/f be different from one. Nevertheless, as we will see, experimental data are already telling us that $v/f \simeq 1$, indicating that both scales are the same thing, favoring then the Higgs hypothesis.

There were three EWSB scenarios that predicted a light Higgs. In fig. 2 we show the ranges of the predicted Higgs mass. The first one is to assume that the SM is a valid theory all the way to the Planck scale. This is possible if the Higgs mass takes a value in the window $100 - 170$ GeV

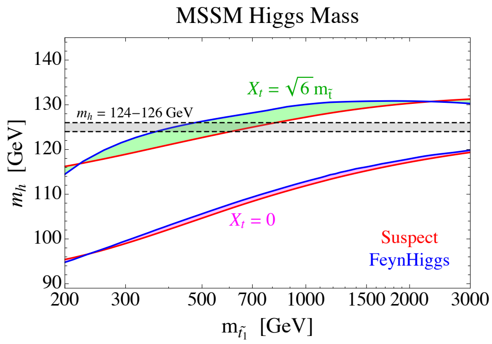

Figure 3: Lightest-Higgs mass as a function of the lightest-stop mass in the MSSM for $X_t \equiv A_t - \mu \cot\beta$ equal to zero or taking the maximal value [15].

[7]. Interestingly, the discovered boson is in this window permitting then this simple possibility. As already discussed, this seems very unnatural, although it could well find an explanation within the multiverse idea.

The second possibility, the MSSM, predicts that one of the Higgses must be below ~ 130 GeV [6]. Therefore, just by few GeVs, a 125 GeV Higgs could be one of these. One must be aware, however, that the MSSM Higgs-mass squared upper-bound has two contributions, a tree-level supersymmetric one, m_Z^2, and a one-loop susy-breaking one, Δm^2:

$$m_h^2 \leq m_Z^2 + \Delta m^2\,. \tag{2.1}$$

Knowing that $m_h \simeq 125$ GeV, we learn that $\Delta m^2 \gtrsim (86\text{ GeV})^2$. This is similar in size to the susy-preserving contribution $m_Z^2 \simeq (91\text{ GeV})^2$, indicating that in the MSSM supersymmetry must be "badly" broken. By this I mean that stops must be much heavier than the Higgs (when these are the main Higgs "body-guards" that had to be closer to the Higgs to protect its mass) as fig. 3 shows, otherwise trilinear susy-breaking terms A_t must be close to maximal. In both cases a high-degree of tuning (of at least 1%) is required to keep the EW scale at its present value. Then if we want to stay within natural supersymmetric models, we must abandon the MSSM for some non-minimal alternatives such as the NMSSM [6].

A light Higgs was also predicted in composite Higgs models. The Higgs is in this case a PGB that means that its mass does not receive contributions from the TeV strong-sector, but only at the one-loop level due to the SM couplings that break the global symmetry protecting the Higgs mass. It is difficult to get predictions in these models due to the intractable strong dynamics. Nevertheless, using similar techniques as used in the past in QCD to calculate the charged pion mass [8], one obtains, for example, in one of the minimal composite Higgs models (MCHM) [10, 11, 12]:

$$m_H^2 \simeq \frac{3}{\pi^2}\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right), \tag{2.2}$$

where f is the Higgs decay-constant expected to take a value around v, and Q_4 and Q_1 are fermionic color resonances, a bi-doublet with $Y = 1/6, 7/6$ and a singlet with $Y = -1/3$ respectively. A $m_H \simeq 125$ GeV can be obtained if at least one of the fermionic resonance is lighter than 700 GeV

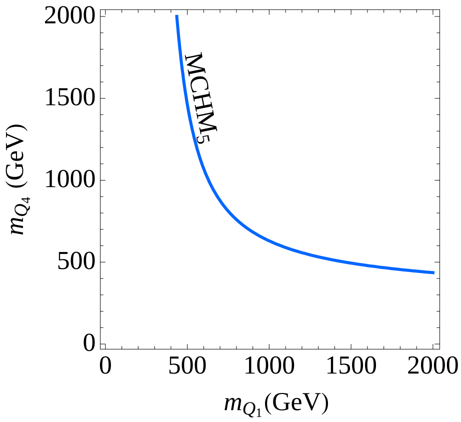

Figure 4: Mass of the fermionic color resonances Q_1 and Q_4 for $m_H = 125$ GeV and $f = 500$ GeV in the MCHM$_5$ [11].

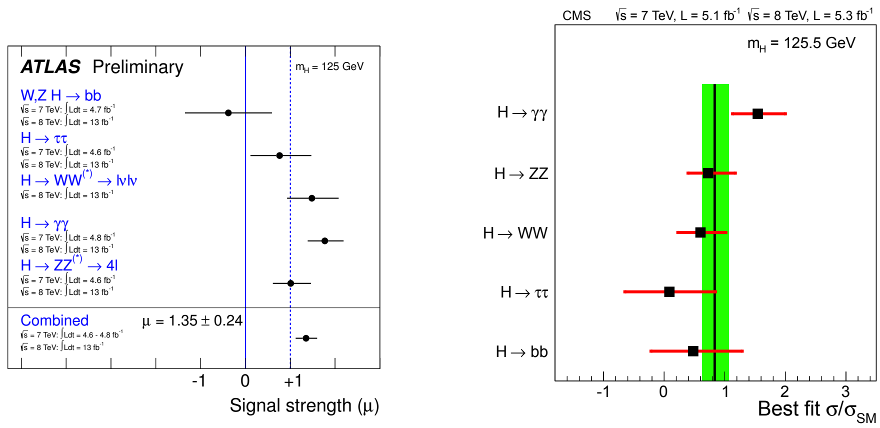

Figure 5: Left: Signal strengths (production cross-section times the relevant branching fraction relative to the SM expectation) as measured by ATLAS for $m_H = 125$ GeV [13]. Right: Same for CMS for $m_H = 125.5$ GeV [14]. The vertical band shows the overall value 0.87 ± 0.23.

(for $f = 500$ GeV), as shown in fig. 4. Holographic techniques [9] or other composite Higgs models [11] lead to similar results. This are good news for LHC resonance hunters that could see these fermionic color states already at the 8 TeV LHC.

2.2.2 What Higgs-coupling measurements tell us?

As fig. 5 shows, the present measurements of the Higgs couplings are quite close to those predicted by the SM. This favors the idea that this is the SM Higgs and not another exotic state such as the dilaton. There are however some small discrepancies with the SM predictions, the most pronounced one being the coupling to photons, that could favor, if it persists in the future, scenarios beyond the SM.

What are the main pieces of information to be extracted from data (in this first LHC run)? The first and most important one is the Higgs coupling to massive vector bosons $V = W, Z$. If this new

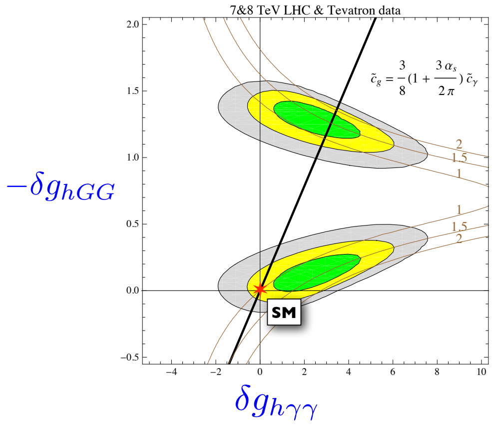

Figure 6: Global fit for the Higgs coupling to gluons and photons and predictions from stop loops (solid straight line). See details in ref. [16].

discovered boson is the Higgs, this coupling must be sizeable and proportional to the vector mass ($2m_V^2/v$). If it is not a Higgs but an impostor, the coupling to vectors must arise from a higher-dimensional operator and then is expected to be smaller. The fact that we have measured it in reasonable good agreement with the SM prediction is the strongest argument in favor of a Higgs-like state. The second piece of information is the Higgs coupling to photons and gluons, $H\gamma\gamma$ and HGG. Being the Higgs chargeless and colorless, these couplings arise at the one-loop level. In the SM they are mainly induced by W and top loops, but could be affected by other charged or color states if present. Another piece of information is the Higgs coupling to fermions: top, bottom and taus. At present the coupling to tops is indirectly extracted from the measurements of $H\gamma\gamma$ and HGG since, as said before, it enters in these couplings through loop effects. The coupling to bottoms is also at present not very well measured from $H \to bb$, but it can be inferred indirectly from the total Higgs width (where $\Gamma(H \to bb)$ gives the main contribution) that can be extracted from the measurements of the different branching ratios (BR). Finally, the Higgs could decay to new light and neutral states that, if were stable, would escape detection. An interesting example is Higgs decaying into dark matter that can occur in certain scenarios. This gives an invisible partial width to the Higgs that, if large, can be at present extracted from the total Higgs width.

We then conclude that there are 7 important pieces of information to be extracted: Higgs couplings to fermions (top, bottom and tau), Higgs coupling to vectors [1], Higgs coupling to photons, Higgs coupling to gluons and Higgs coupling to invisible particles. One can find in the literature a global fit for these 7 Higgs-couplings. It is however not only cumbersome, but also not be very illuminating to present it here. Instead, I think it is better to show fits of the Higgs couplings two by two motivated by the predictions of some EWSB scenarios.

Let us start with supersymmetric models in the limit in which the only light superpartners are the stops, as motivated by naturalness arguments. In this limit the couplings of the light Higgs

[1] For simplicity and motivated by the need of a custodial symmetry in the EWSB sector, we can assume that the Higgs coupling to Z and W are related according to this custodial symmetry: $g_{HWW}/m_W^2 = g_{HZZ}/m_Z^2$. This is also motivated by a higher-dimensional operator analysis, as shown later.

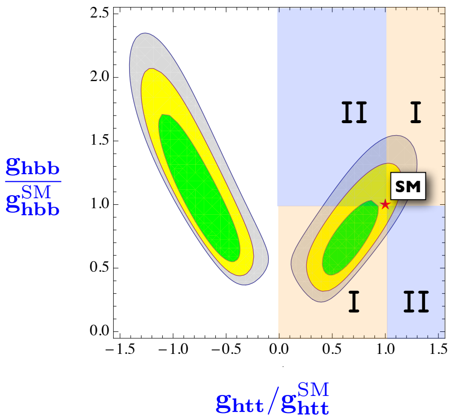

Figure 7: Global fit for the Higgs coupling to bottoms and tops [20] and areas predicted by Type-I and Type-II THDM.

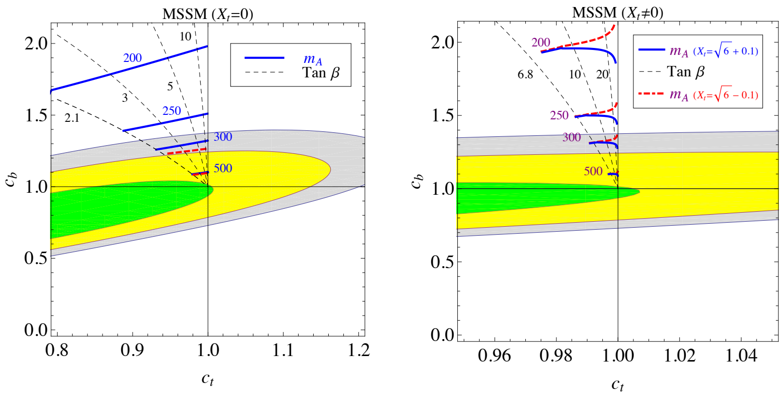

Figure 8: Predictions of the MSSM Higgs coupling to bottoms and tops, $c_{t(b)} = g_{htt(bb)}/g^{SM}_{htt(bb)}$, for different values of m_A and $\tan\beta$. Large stop masses are assumed with $X_t = 0$ (left) or $X_t \neq 0$ (right). See details in ref. [19].

(h) approach to those of the SM Higgs. The only relevant correction comes from stop loops that mainly affect the $h\gamma\gamma$ and hGG couplings. In fig. 6 we show a global fit, extracted from ref. [16], to possible new contributions to the $h\gamma\gamma$ and hGG couplings. As expected, data suggest (although not very significantly) that a better fit than the SM can be obtained by increasing the effective Higgs coupling to photons. The stop loop contributions, shown by the solid straight line in fig. 6, can do this, but at the same time it modifies the hGG coupling, worsening the fit, unless we make the stop effects large enough to reach the second favored island in fig. 6. This however leads to problems with vacuum stability [17]. Therefore supersymmetric theories with light stops do not seem to improve the SM fit.

Other interesting extensions of the SM are two-Higgs-doublet models (THDM), since they can arise as low-energy manifestations of supersymmetric or composite Higgs scenarios. There are two main types of THDM depending on how the Higgs doublets couple to quarks [6]: Type-I and

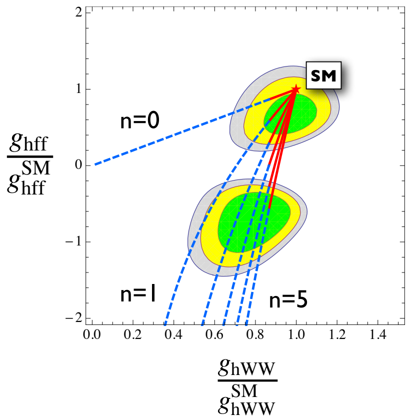

Figure 9: Global fit for the Higgs coupling to fermions and vectors and predictions from the MCHM [20].

Type-II [2]. In particular, the MSSM belongs to Type-II. In THDM the couplings of the Higgses can be, in principle, very different from those of the SM. Nevertheless, motivated by the experimental absence of large deviations from the SM, we will assume that only one Higgs is light (h) and the other Higgses (H) are heavier, such that the couplings of h will only differ from those of the SM Higgs by effects of order m_h^2/M_H^2. At the leading order in an expansion in m_h^2/M_H^2 one finds that only the Higgs couplings to tops and bottoms are modified with respect to the SM values, but not that to vectors. We can then look for deviations in the $g_{htt}-g_{hbb}$ plane alone. A fit of the data in this two-parameter space is shown in fig. 7. One can see that a better fit than the SM can be obtained if, for example, the couplings of h to the top and bottom are smaller than those of a SM Higgs. Interestingly, the sign of these corrections depends on the type of THDM. Type-II can only give corrections in the blue areas of fig. 7, while Type-I only in the orange ones [18]. At present, Type-I seems to be favored. As a concrete example, we show the predictions of the MSSM (fig. 8) taken from ref. [19] that seems to go in the wrong direction to improve the fit of the data. Notice also that a second disconnected favored island can be achieved by flipping the sign of the top coupling. But only Higgs impostors can be in that island.

Let us finally consider models in which the Higgs is composite. In the MCHM, based on the SO(5)/SO(4) coset, only the Higgs coupling to vectors and fermions are modified according to [2, 11]

$$\frac{g_{hWW}}{g^{SM}_{hWW}}=\sqrt{1-\frac{v^2}{f^2}}\,,\qquad \frac{g_{hff}}{g^{SM}_{hff}}=\frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}\qquad n=0,1,2,\dots,\tag{2.3}$$

where the different values of the integer n depend on how the SM fermions couple to the TeV strong-sector fields [11]. In fig. 9 we show the fit of the Higgs coupling to vectors and fermions taken from ref. [20]. First, notice that a better fit than the SM can be achieved by reducing the Higgs coupling to vectors and fermions, unless we overshoot and reach the second island (the island of Higgs impostors) where the coupling to fermions has opposite sign. The predictions (2.3) of the

[2]There are other well-motivated possibilities that depend on the couplings to leptons. Since the measurement of the Higgs coupling to taus is not yet very precise, we will not consider these possibilities.

MCHM, shown in fig. 9 in a red solid line for $v/f < 1/2$ and blue dashed line for $1/2 < v/f < 1$, seems to (slightly) improve the fit.

These examples show that a better determination of the Higgs couplings will be extremely useful to learn about the origin of EWSB. Possible future discrepancies with respect to the SM predictions will allow us to discriminate between different EWSB scenarios; otherwise this will still be useful to put strong constraints on these models.

Addendum: Higher-dimensional operator analysis

The fact that the couplings of this new discovered state are so close to those of the SM Higgs makes us to think that this is indeed part of a Higgs doublet, $H = (G^+, h + iG_3)^T$, where G^+, G_3 are the SM Goldstones. If so, and no new light states ($\lesssim m_h$) are present, we can parametrize deviations from the SM by higher-dimensional operators suppressed by the scale of new physics $\Lambda \gg m_h$. The good thing of this approach is that it is model-independent; furthermore, allows us to relate possible deviations from SM Higgs physics with deviations from SM gauge-boson physics that are more constrained by experiments (mainly LEP) [5].

At the leading order in m_h^2/Λ^2, we must only consider dimension-6 operators. It is very important to choose the right basis for these operators. An appropriate one, relevant for Higgs physics, is given in ref. [2] that classifies operators according to the expected size of their coefficients [3]. A first class of operators are those involving extra powers of Higgs doublets and are generically suppressed by $g_H^2/\Lambda^2 \equiv 1/f^2$, where g_H is the Higgs coupling to the new-physics sector responsible for generating the operators:

$$\begin{aligned}\Delta\mathscr{L}_1 &= \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\ &- \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2}H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right). \qquad (2.4)\end{aligned}$$

A second class of operators are those involving extra (covariant) derivatives or gauge bosons and are generically suppressed by $1/\Lambda^2$:

$$\Delta\mathscr{L}_2 = \frac{ic_W g}{2\Lambda^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2\Lambda^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}). \qquad (2.5)$$

I separate in a different group those operators that in all known UV-consistent theories are induced at the loop level:

$$\begin{aligned}\Delta\mathscr{L}_3 &= \frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \qquad (2.6) \\ &+ \frac{c_\gamma g'^2}{16\pi^2 f^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_s^2}{16\pi^2 f^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}. \qquad (2.7)\end{aligned}$$

All c_i are coefficients expected to be of order one. For $1 \ll g_H \lesssim 4\pi$, we have $f \ll \Lambda$ and the most relevant operators are (2.4). The operators (2.7), however, cannot be neglected in a Higgs physics

[3] Basis that mixes these different types of operators make the extraction of new-physics implications more obscure.

analysis, since, although they are expected to be generated at the loop level, they enter respectively in $BR(h \to \gamma\gamma)$ and $\sigma(gg \to h)$ that have been measured at the LHC with a loop-level sensitivity (as also in the SM are generated at one-loop). Constraints from electroweak precision data on the operators (2.4) and (2.7) are quite weak. Only c_T, that contributes to the T-parameter, is highly constrained, so we don't expect large effects in Higgs physics from c_T. We can then conclude that for $f \ll \Lambda$ deviations from SM Higgs physics can be mainly parametrized by the coefficients c_H, c_y, c_γ and c_g [4]. This corresponds to one parameter for each Higgs coupling [2], except for the Higgs couplings to W and Z whose deviations are both parametrized by c_H. If $f \sim \Lambda$, the operators (2.5) can also be relevant. The combination $c_W + c_B$, however, is constrained by the S-parameter [2]. We could allow for cancellations in the sum $c_W + c_B$ and then sizeable values for $c_W - c_B$. There have been a lot of attempts to find theories with this property without success. For example, in theories with custodial $O(4)$-symmetry we have $c_W = c_B$. Therefore we do not expect this cancellation to happen. Even though, we can include the extra parameter $c_W \approx -c_B$ in the analysis. This breaks the custodial symmetry and allows for different deviations for the hWW and hZZ couplings, although suppressed by $\tan^2\theta_W$ [2].

Let us briefly comment on what operators can be induced in different EWSB scenarios. Let us first consider "universal" theories, those with extra fields coupled only to the boson sector of the SM. In these theories all operators (2.4)-(2.7) can in principle be induced [5]. At tree-level, by integrating out heavy scalars, the operators (2.4) can be generated, while heavy vector bosons can generate (2.4) and (2.5) [21]. The MSSM gives at tree-level only contributions to two coefficients, $c_y y_f$ with $f = t, c, u$ and $f = b, s, d, l$. The NMSSM, however, due to the presence of the singlet, can also give sizeable contributions to c_H. The main contributions from composite Higgs models are to the two coefficients c_H and c_y (flavor independently) [4] [2].

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