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Non-supersymmetric extensions of the SM

A. Pomarol

Departament de Física and IFAE, Universitat Autònoma de Barcelona - 08193 Bellaterra Barcelona, Spain

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Summary. — We discuss the implications of having the Higgs particle arising as a composite pseudo-Goldstone boson, either from a new strong interacting sector at the TeV, or from the 5th-component of a gauge field in extra dimensional models.

PACS 12.60.-i – Models beyond the standard model.

1. – Introduction

In most people's mind the Minimal Supersymmetric Standard Model (MSSM) is the ideal (and, sometimes, unique) candidate for physics beyond the SM, becoming, in recent times, the new orthodoxy. The MSSM gained its present status after LEP1, where electroweak precision tests (EWPT) of the SM left behind its main competitors such as Technicolor models. A manifestation of this strong feelings towards supersymmetric theories, that arose around the end of the nineties, can be found in Veneziano's summary talk at the SUSY 98 conference in Paris: "To conclude, the score on precision tests puts the MSSM first, with the SM itself a close second. Technicolour theories appear to lag far behind and ... there is not much else in the race."

But after LEP1, it came LEP2 and Tevatron II and those expectations for finding supersymmetric states or, at least, the light MSSM Higgs at energies $\sim 100\,\mathrm{GeV}$, were not met. At present we can claim that almost any MSSM model must be tuned at the 1–10% in order to pass all the experimental constraints.

Due to this new situation the obvious question is, in the words of Veneciano, is there something else in the "race"? In the last 10 years several new solutions to the hierarchy problem have been proposed: Large extra dimensions, Randall-Sundrum models, ... In this talk I will review the only one that, I think, can provide some clues on the origin of electroweak symmetry breaking: the idea that the Higgs arises as a Pseudo-Goldstone Boson (PGB) of a new sector. This scenario is clearly inspired by QCD where one observes that the (pseudo) scalar states, *e.g.*, the pions, are the lightest particles. We understand the reason for this: the pions are Goldstone states arising from the chiral symmetry breaking $SU(2)_L \times SU(2)_R \to SU(2)_V$ of QCD. This symmetry, however,

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is explicitly broken by the gauging of electromagnetism and the quark masses, giving to the pions a mass around 100 MeV, smaller than the masses of the other resonances $m_\rho \sim 1\,\text{GeV}$. In other words, the pion mass is protected by the global chiral symmetry under which the pion fields shift, and, for this reason, is smaller than the QCD mass gap.

Could we have a similar scenario in which the Higgs arises as a PGB [1]? This could work in the following way [2]. Let us assume that at the TeV we have a new strong sector whose global symmetry-breaking pattern, induced by the condensation of some composite scalar operator, is $SO(5) \to SO(4)$. This implies that the Goldstone spectrum corresponds to a unique weak-doublet, the Higgs. Two bonus come automatically from this idea. First, the electroweak interactions and the SM fermion couplings to the Higgs must explicitly break the global $SO(5)$-symmetry that protects the Higgs mass. Correspondingly, a Higgs potential will be induced at the one-loop level. The heaviness of the top plays here an important role. Since fermionic loops give negative contributions to the Higgs mass, a vacuum expectation value (VEV) will be induced for the Higgs, breaking the electroweak symmetry (EWSB). Therefore, this scenario predicts inevitably EWSB, as observed in nature. Second, the VEV of the Higgs will be of the order of the decay constant of the PGB, f, that can be smaller than the mass of the other resonances of the model. For $f \sim 500\,\text{GeV}$, that is roughly the lowest value allowed by EWPT [2], one obtains that the lightest resonance has a mass around 2 TeV, out of the reach of past colliders (*e.g.*, LEP and Tevatron). This could explain the absence of new states at any collider before the LHC. Finally, the physical Higgs mass arises in these models at the one-loop level and therefore is predicted to be around 100–200 GeV.

2. – Unraveling the composite nature of the Higgs

If the Higgs arises as a PGB from a strongly interacting sector, we expect it will show properties of a composite particle. In an ideal collider we could easily differentiate between an elementary and a composite Higgs, in the same way as we do with pions: we probe them with photons at large virtual momentum q^2; if the electromagnetic form factor stays (almost) constant for large q^2, we claim to see an elementary state; if it drops to zero, we claim we have a composite state. Although the Higgs does not couple at tree-level to photons, we could probe it with the reaction $Wh \to Wh$ where the large q^2 must go from the incoming W to the ingoing h. If we could measure this cross-section at very high energies, we could easily determine the nature of the Higgs. Nevertheless, in a real collider (LHC) we cannot probe the Higgs form factor at sufficiently high energies to see whether it goes or not to zero. We must look therefore for other signatures of compositeness.

We can get again some inspiration from QCD. We know that at small q^2, the form factor of the pion goes approximately as $F(q^2) \sim 1 - q^2/m_\rho^2$, so deviations from 1 arise suppressed by the mass of the lowest QCD resonance, $m_\rho \sim 1\,\text{GeV}$. Nevertheless, we have other types of pion interactions that are not suppressed by m_ρ but by f, the decay constant of the pion. For example, the amplitude of $\pi\pi \to \pi\pi$ grows with the energy as E^2/f^2. For $f \sim 100\,\text{MeV}$, this process seems to be enhanced by a factor 10 as compare to deviations on the gauge form factors.

For a composite PGB Higgs we also expect this kind of behavior arising from the low-energy operator $\mathcal{O}_H \equiv (\partial_\mu(H^\dagger H))^2/f^2$ where H is the Higgs doublet [3]. This, however, does not seem to be very useful since a $hh \to hh$ process is not at the reach of the LHC. Nevertheless, there is, as we said, an important difference between the Higgs and the pions; the Higgs is expected to get a VEV and therefore the operator

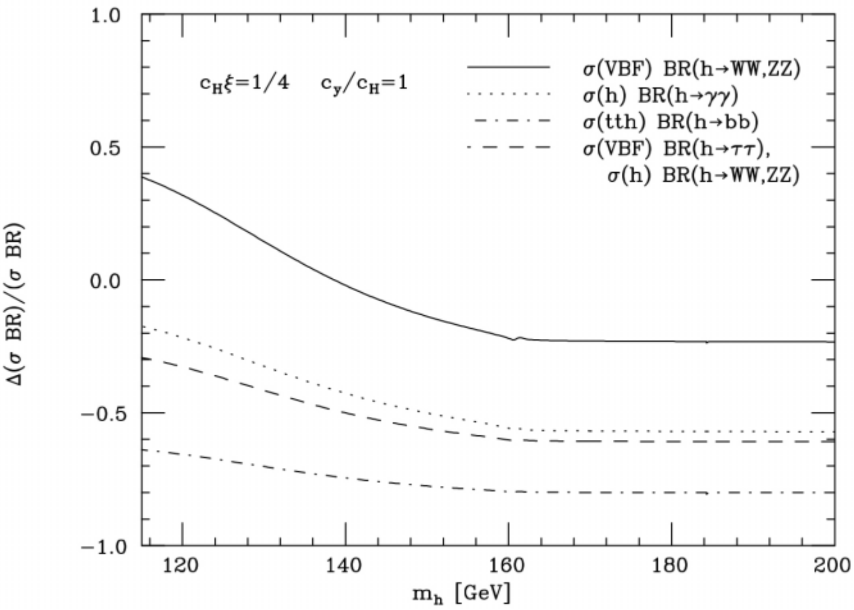

Fig. 1. – Deviations from the SM predictions of Higgs production cross-sections and decay branching ratios expected in composite Higgs models. See [3] for details.

$\mathcal{O}_H$ gives a modification to the Higgs propagator $\xi(\partial_\mu h)^2$ where $\xi = \langle H\rangle^2/f^2$. This has several important implications. First, this Higgs will not completely unitarize the WW interaction, and therefore this is expected to grow at high energies $\mathcal{M}(WW \to WW) \sim E^2/f^2$. Secondly, the Higgs partial widths will be modified (see fig. 1).

Can this be seen at the LHC? Clearly, this is going to be difficult. For $f > 500\,\mathrm{GeV}$, we have $\xi < 0.2$; this suppression, although small, makes already very difficult to see the composite nature of the Higgs at the LHC. First studies show that with about 300/fb of integrated luminosity, it is possible to measure Higgs production rate times branching ratio in different channels with only a 20–40% precision [4]. For the WW interaction, the signal of Higgsless models, that corresponds to $\xi = 1$, can be only measured with a 30–50% accuracy for 200/fb.

3. – Models for Higgs as PGB

There could be other indirect signals of Higgs compositeness. For example, in QCD, the pions are accompanied by a rich hadronic spectrum. Therefore, we could try to measure the heavy states accompanying the Higgs. What are the expected masses and quantum numbers of these states? It is very difficult to answer this question. As in QCD, it is very difficult to calculate the spectrum in strongly interacting theories. This has been the main reason that has discouraged particle physicist to pursue this kind of models since they were proposed in the 80's.

The situation, however, has changed in the last years. The AdS/CFT correspondence [5] has afforded a new tool to calculate within strongly interacting theories. The most important feature that emerges from this correspondence is that strongly coupled gauge theories in the limit in which the number of colors, N_c, and the 'tHooft coupling, $g^2 N_c$, are both large, can be described by weakly coupled theories living in extra dimensions.

This has boosted the studies of 5D models with the Higgs as PGB. The simplest version of these models is a five-dimensional gauge theory compactified by two 4D boundaries, the UV-boundary and IR-boundary, and with the following symmetry pattern [2]:

$$\begin{array}{ll} \text{UV-boundary:} & SU(2)_L \otimes U(1)_Y \otimes SU(3)_c, \\ \text{5D Bulk:} & SO(5) \otimes U(1)_X \otimes SU(3)_c, \\ \text{IR-boundary:} & O(4) \otimes U(1)_X \otimes SU(3)_c, \end{array}$$

where $Y = T_R^3 + X$, with T_R^3 being the 3rd component generator of one of the two $SU(2)$ inside the $SO(5)$. This is the minimal scenario that accomplishes three things: it delivers a PGB being a **2** of $SU(2)_L$, the Higgs, it has a custodial $SU(2)_V$ symmetry after EWSB (up to UV-boundary terms), and it contains the SM gauge group. The SM fermions are embedded into 5D Dirac spinors which live in the bulk and belong to the **5** representation of $SO(5)$. By an appropriate determination of the bulk and boundary masses we can obtain a realistic theory of fermion masses. In AdS_5 small fermion masses can be naturally obtained since the Higgs is localized towards the IR-boundary. Therefore small Yukawas can be obtained for the 1st and 2nd family by localizing the zero-mode fermions towards the UV-boundary and then having a small overlapping with the Higgs. The most interesting features of the heavy spectrum that come out of this model is the following: We have a light Higgs, with a mass around 110–180 GeV; there are fermionic resonances in the $\mathbf{2_{1/6}}$ and $\mathbf{2_{7/6}}$ representations of the SM with masses ranging around 500–1500 GeV; vector resonances appear around 2–3 TeV, while spin 2 states are much heavier, around 4 TeV.

Another different approach towards models with PGB Higgs that has been pursued in the last years comes with the name of "Little Higgs" (LH) [6]. The idea is to generate a Higgs quartic coupling at the one-loop level, but engineer a model such that the Higgs mass-term appears only at the two-loop level. If so, the EW scale will be two loops below the strongly interacting scale, that can be then around 100 TeV. To accomplish this, however, new states must be introduced in the theory around the TeV (heavy vector bosons and color fermions). Present fully realistic models realizing this idea are, however, too complicated to be described here.

3˙1. *LHC phenomenology.* – In most of the models in which the Higgs appears as a PGB we have extra W and Z resonances, W' and Z', with masses around the TeV. In 5D models these states mostly decay to tops, Higgs or W_{long} and Z_{long}, while for LH models they decay to leptons. LHC will be able to reach them if they are not heavier than ~ 2 TeV.

In 5D models we also have gluonic resonances, g'. They decay mostly into a pair of tops, and could be reached at the LHC if their masses are not higher than ~ 4 TeV. Also color fermionic resonances are present in all PGB models. In LH there is, for example, a resonance of the t_R-quark, t'_R, that decays mostly to Wb. Nevertheless extradimensional models predict the existence of extra exotic color states. In particular, a colored fermion with electromagnetic charge of 5/3 is the most distinctive signal of 5D composite Higgs models.

4. – Conclusion

There is light beyond supersymmetry. The idea presented here of composite PGB Higgs is not only theoretically well motivated, but, at present, we can find models realizing this idea in a realistic and predictive way. Most importantly, they give clear signals for the LHC worthy to fully explore.

* * *

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