PROCEEDINGS OF SCIENCE

Implications of 125 GeV Higgs in Composite Models

Michele Redi∗
INFN, Sezione di Firenze, Via G. Sansone, 1; I-50019 Sesto Fiorentino, Italy
E-mail: michele.redi@fi.infn.it

The discovery of the Higgs boson at 125 GeV has important consequences for the leading alternative to supersymmetry where the Higgs is a pseudo-Goldstone boson of a strongly coupled sector. We show that to obtain a light Higgs boson with mild tuning it is mandatory the presence of light colored fermions. Natural theories require their masses to be around 1 TeV or less, a range that is starting to be probed by the LHC.

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∗Speaker.

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1. Introduction

The discovery of the Higgs boson presented at this conference is an exciting result bound to revolutionize our field. While till recently many options were still conceivable for the mechanism that breaks the electro-weak symmetry, after the discovery of the Higgs boson with couplings compatible with the SM predictions[1] the possibilities essentially boil down to two: The first is the time-honored supersymmetry, that adds to each SM particle a partner of opposite statistics. The other possibility is that the Higgs is a bound state of presently unknown strong dynamics, most likely a pseudo-Goldstone boson (pGB) arising from the spontaneous breaking of a global symmetry.

In supersymmetry the stops play a special role as they cut-off quadratic divergences of the Higgs mass associated to the top loop. For this reason the stops are expected to be light, ideally around 500 GeV leading to various tensions. In this talk I will show that the analogous conclusion applies at a quantitative level in the most promising composite Higgs models (CHM) where the Higgs is a GB and each SM field has at least one partner with same statistic. In particular I will show that the 125 GeV implies that the some fermionic partners must be around the corner and could be found in the near future at the LHC.

2. Higgs Mass in Composite Higgs

The idea of a composite Higgs is a natural extension of technicolor theories first studied by Georgi and Kaplan in the '80s and recently revived, see [1] for nice review and Refs.. Strong dynamics could produce a scalar bound state with the quantum numbers of the Higgs. This can automatically happen if the strong sector has a global symmetry G spontaneously broken to H that generates massless GBs. The chief example on which we will focus also here is $SO(5)/SO(4)$ where a single Higgs doublet is obtained. These scenarios relieve the SM hierarchy problem because quadratic divergences of the Higgs mass are physically cut-off by the compositeness scale. For example the top quadratic divergence that is largest in the SM will produce,

$$\delta m_h^2 \sim \frac{3y_t^2}{8\pi^2} m_\rho^2 \tag{2.1}$$

As a consequence the electro-weak scale can be natural if m_ρ is not too large. Conceptually CHM are similar to technicolor since m_ρ is generated in a full theory by dimensional transmutation but the presence of a physical Higgs allows to ameliorate significantly the phenomenology. With some caveats a reasonable phenomenology can be imagined with a scale of compositeness around 3 TeV. This is necessary for spin-1 resonances that give most of the indirect constraints, however at least some fermions should be lighter as we will see below.

The crucial assumption of phenomenologically successful composite Higgs models is the hypothesis of partial compositeness. This amounts to the fact that the strong sector contains states with identical quantum numbers as the SM fields under the SM gauge group. For gauge fields this is automatic while for fermions it is a strong assumption on the theory. In particular this predicts the

[1] An even bigger revolution is awaiting us if some deviations from SM coupling will be measured.

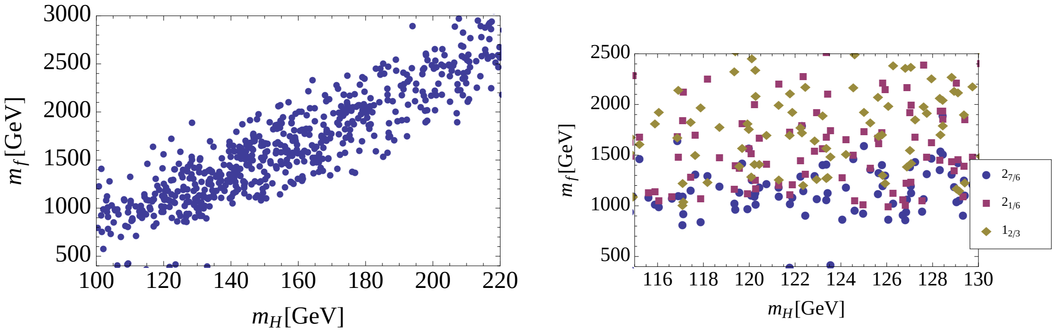


Figure 1: Higgs mass vs. masses of fermionic partners for $f = 800$ GeV in CHM$_5$ [3]. On the left lightest fermionic partners. On the right masses of multiplets with different quantum numbers.

existence colored vectorial fermions that can mix with the SM fermions of particular experimental interest as we will see.

The couplings of SM fields to the strong sector explicitly break the global symmetry associated to the GB nature of the Higgs. One consequence is the generation of the SM Yukawas proportional to the mixing of left and right chiralities,

$$y \sim \varepsilon_L \cdot g_\rho \cdot \varepsilon_R \tag{2.2}$$

where $\varepsilon_{L,R}$ are the mixings. For this reason it is typically assumed that the light generations are mostly elementary while the top is strongly composite. The second effect of the explicit breaking is the generation of a potential for the Higgs at 1-loop. Since the largest coupling is the one of the top the potential is typically (though not always) dominated by the top Yukawa. Upon tuning the electro-weak VEV one finds in most models,

$$m_h \sim \frac{\sqrt{N_c}}{4\pi} \frac{m_\rho}{f} y_t v \tag{2.3}$$

To obtain a Higgs mass around 125 GeV one can see that this demands the fermion partner of the top to be light $m_\rho \sim f$. This can be checked more quantitatively in explicit calculable models such as [2]. In Fig. 2 we show a scan extracted from Ref. [3] of the Higgs mass as a function of the lightest fermion in the theory. This corresponds to the model where the composite fermions belong to the 5 of $SO(5)$. As expected from the estimate the lightest fermions required by a light Higgs are around the decay constant f of the Higgs. For a typical (relatively conservative) choice $f = 800$ GeV this corresponds to fermions significantly lighter than spin-1 resonances.

In Fig. 2 a dedicated scan over points that reproduce the 125 GeV Higgs is presented On the left is shown the correlation of the masses of singlet and doublet fermions. We can also quantify the tuning similarly to supersymmetric theories evaluating the logarithmic derivative of the electro-weak VEV with respect to the parameters of the theory. The result is presented on the righthand side. The numbers are comparable to the ones found in supersymmetric theories that realize natural supersymmetry. One can easily show that the tuning will grow proportionally to f^2 so that,

$$\text{TUNING} = k(m_i) \frac{f^2}{v^2} \tag{2.4}$$

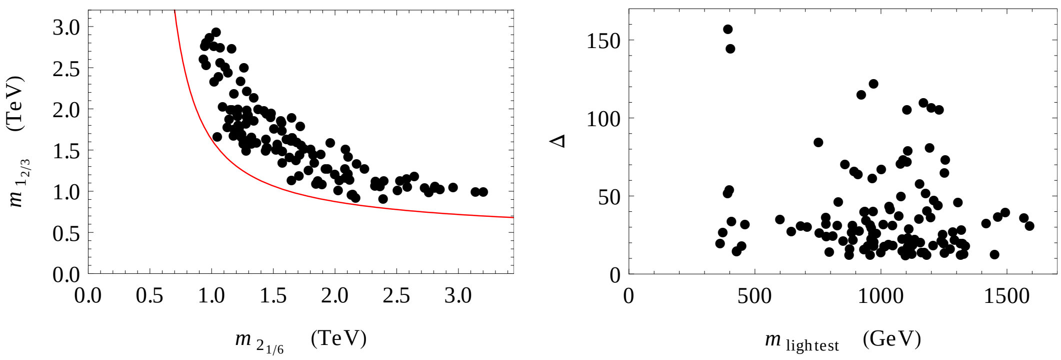


Figure 2: Scatter plots for 125 GeV Higgs in CHM_5 from [4]. On the left mass of the lightest singlets and doublets. On the right tuning as a function of the mass of the lightest resonance.

where k is function of the masses of the heavy fermions.

To conclude this part we wish to comment on the relation with supersymmetry. A priori one could have expected the composite Higgs to be heavy if the composite sector is characterized by a single scale and coupling. The opposite is true in supersymmetry where the natural value is given the Z mass and the observed Higgs is unexpectedly heavy. From the point of view of naturalness however the two theories are similar and to accommodate LHC bounds they both require a hierarchical spectrum where the partners of SM gauge fields are heavier than the top partners.

3. Signatures

In the LHC era the relevant question is whether CHM can be distinguished from the elementary SM Higgs. The distance between SM and composite Higgs is measured roughly by the ratio v^2/f^2. As this goes to zero the composite Higgs approaches the SM. At the same time the tuning becomes large.

Compositeness has two practical effects. The first is modified couplings. The coupling of the Higgs to gauge and matter fields can be parametrized as,

$$\begin{aligned} g_{hW^+W^-} &= i\sqrt{2}\frac{m_W^2}{v}\,a \\ g_{h^2W^+W^-} &= i\frac{m_W^2}{2v^2}\,b \\ g_{hf\bar{f}} &= -i\frac{m_f}{\sqrt{2}v}\,c \end{aligned} \tag{3.1}$$

The SM model predicts $a = b = c = 1$. This point in parameter space is special because the theory remains perturbative up to a very high scale since the Higgs exactly unitarizes the growth of WW scattering. Related to this the theory is renormalizable.

In CHM the situation is different because the SM vertices are corrected, proportionally to v^2/f^2 to leading order. These corrections are moreover calculable, depending on the symmetry structure and representations of the theory. Measuring deviations from $a = b = c = 1$ would directly test the idea of a composite Higgs. In particular, WW scattering is only partially unitarized and, as in technicolor, new strong interactions are necessary, even though at a higher energy scale. Also production and decay of the Higgs will be modified. Practically however, unless $f \sim v$ these deviations from SM couplings will be very hard to be seen at the LHC and will likely require precision measurements at the linear collider.

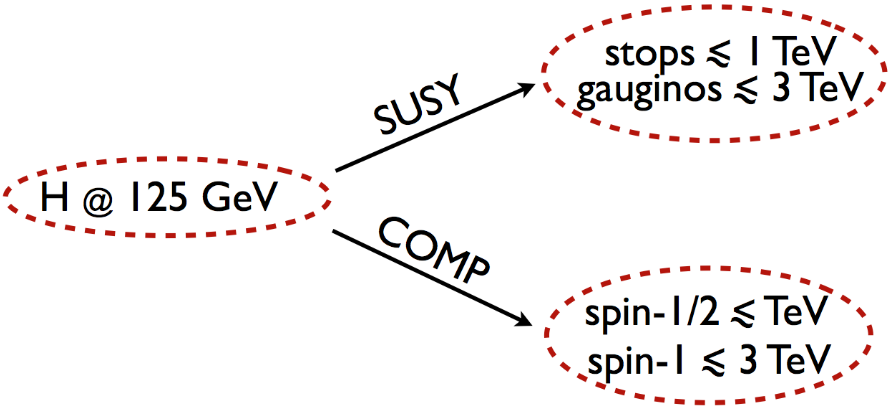
The second experimental feature is the production of composite resonances of various. This is a more exciting avenue for the LHC. We focus here on spin-1 and spin 1/2 states. The main production mechanism of spin-1 resonances is through mixing of SM gauge bosons. At least in standard scenarios, it is assumed that the new resonances are mostly coupled to third generation quarks and to the Higgs so they will decay into these states. Indirect tests from flavor physics and precision tests indicate that the scale of these resonances must be at least 3 TeV. Present bounds are around 1.5 TeV so these states will be probably accessible in the second run of LHC.

Potentially more easily accessible are spin 1/2 resonances. As we have seen the small Higgs mass is naturally obtained if the lightest fermions are around 1 TeV, often even below. These resonances can be either produced by single or double production and decay into W, Z or Higgs plus third generation quarks. In particular in many models the presence of states with exotic charges is strongly motivated. For example in the model considered above with fermions in the 5 there is state with electric charge 5/3 that decays in $W+t$ giving rise to the experimentally clear signature of same sign di-leptons. These states can be either be produced through double production by QCD interaction or singly produced by electro-weak processes. At present energies for a realistic coupling of the strong sector double production provides the strongest bound despite being disfavored energetically. This happens because double production can be initiated by gluon fusion while single production requires the scattering of W Z and a top which penalized by the PDFs. The situation could however change in the next run of LHC where higher energy could allow single production to become dominant. We should however also consider that while double production is model independent being determined by QCD, single production depends on the couplings and mixings of the strong sector.

Current experimental exclusion of top partners is around 700 GeV [5, 6]. This implies that the LHC is already probing the natural region of the composite Higgs. Given the correlation with the Higgs mass the direct exclusion of top partners can be translated into an exclusion on the scale f that in turn implies larger tuning of the theory. f is the scale that c Excluding top partners up to 1 TeV that could perhaps be achieved in the present LHC run would have a deep impact on the credibility of these models. This should be one of the top priorities of the LHC since it is the only alternative to supersymmetry for a natural theory of electro-weak symmetry breaking that is left.

4. Summary

With the discovery of a light Higgs naturalness of the electro-weak scale requires light top partners that can either be of bosonic of fermionic nature. We have shown in particular that in composite Higgs models where the Higgs is a pseudo-Goldstone boson fermions should be in the TeV range. This is an exciting opportunity for the LHC that can already probe some regions of parameter space of these theories. If these theories are correct the other states, particular spin-1 resonances, will be probably heavier and only accessible in the second run of the LHC. This leads to hierarchical spectrum analogous to the one of natural supersymmetry depicted below.



To summarize two roads are still conceivable for naturalness of the electro-weak scale: supersymmetry and composite Higgs. None of them looks perfect but hopefully nature has chosen one of them.

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