What if Susy is not right? Non-susy signals at the LHC

Antonio Delgado
Department of Physics
University of Notre Dame
Notre Dame, IN 46556, USA

1 Introduction: the Hierarchy Problem

It is clear that the Standard Model (SM) of particle physics has proved it success beyond any doubt. It is based on a $SU(3) \times SU(2) \times U(1)$ gauge theory, the first factor describing QCD and the other two the electroweak interaction. In order to correctly describe the behavior of the electroweak part one has to spontaneously break $SU(2) \times U(1)$ to $U(1)_{em}$. In the SM this is achieved by adding a field ϕ which transforms as a $(1, 2, 1/2)$ and has the following potential:

$$V_{higgs} = -\mu^2|\phi|^2 + \lambda|\phi|^4 \tag{1}$$

Since that potential is unstable at the origin it develops a vacuum expectation value (VEV) that breaks the electroweak symmetry in the desired way giving mass to the W and Z bosons. In order to reproduce the observed values of the masses and not to relay on big values of λ which will violate perturbation theory one demands $\mu \sim O(100 \text{ GeV})$. Having a mass scale for a boson of that size introduces what is called *the hierarchy problem*, i.e., why μ is of that size and not equal to any higher scale, like the GUT scale (10^{16} GeV) or the Planck mass (10^{19} GeV). For the case of fermions there is an explanation, *chiral symmetry.* And for gauge bosons there is another one, *gauge symmetry.* But it is a fact that, within the SM, there is no symmetry protecting the Higgs mass, therefore the *natural* value for μ is much larger than expected, even if one sets the value to something of electroweak size radiative corrections will lift it:

$$\delta\mu^2 \sim \frac{\Lambda^2}{16\pi^2} \tag{2}$$

where Λ represents a high scale. One can then suppose that there is a cancelation between the classical tree-level value of μ and its quantum corrections leading to a final value close to what is required to correctly explain the electroweak scale. For this to happen one requires a cancelation between very large numbers, $O(M_{GUT})$ or

$O(M_{Pl})$ to give rise to a number O(100 GeV), this is clearly a fine tuning in the parameters of the theory. And since the Higgs mass term sets the scale for all other SM particles, any fine-tuning of the Higgs mass is really a fine-tuning of the entire SM spectrum.

One of the reasons to go beyond the SM is precisely to explain that fine tuning, i.e., to give a reason why the Higgs mass is *NOT* proportional to the cut-off of the SM. There are several avenues one can take in order to explain the hierarchy problem, some of them relay on introducing a new symmetry to explain why the Higgs mass is protected, namely *supersymmetry.* In this note we are going not to pursue that direction but rather other ones which also provide with a (partial) solution to the hierarchy problem.

2 Little Higgs Models

In little Higgs models [1], on tries to realize the old idea of the Higgs being a pseudo-goldstone boson of a new gauge symmetry. In this way the Higgs mass is partially protected due to that symmetry.

For this idea to work one has to enhance the symmetry group of the SM to a bigger group under which the Higgs will transform non trivially in such a way that when that symmetry is broken to the SM then the Higgs will arise as a goldstone boson. If that was all then the Higgs would be exactly massless and it would have only derivative interactions, both of those properties are something that the Higgs *can not* have. We know that the Higgs has a mass and it was normal couplings to fields. The way out is to gauge part of the extra symmetry. Enlarging the symmetries of the standard model and gauging part of it has the immediate consequence of enlarging the spectrum of particles. The exact spectrum is very model dependent but in general there are a set of new gauge bosons. W', Z', an enlarged number of Higgses, in some cases even doubly charged, and a set of new fermions, particularly copies of the top quark.

In this way the one loop contribution to the Higgs mass parameters cancels for a careful choice of couplings. But it should be pointed out that the cancelation occurs only at the one-loop level, therefore

$$\delta\mu^2 \sim \frac{\Lambda^2}{(16\pi^2)^2} \tag{3}$$

in this sense the Little Higgs models are just a partial solution to the little hierarchy problem. These models postpone the cut-off of the theory to tens of TeV, sufficiently to be hidden at the LHC but not to the next generation of accelerators.

The phenomenology of these models can be very rich but before discussing it one has to discuss the impact on electroweak observables. Since there are a set of new gauge bosons that has to have couplings to the Higgs in order to cancel the different contributions to the quadratic divergences those new gauge bosons mixed with the W and Z which leads to big contribution to the ρ parameter, that is the ration of the Z mass to the W mass. Since the experimental value of ρ is very close to 1 then the only way to suppress dangerous contributions to the ρ parameter is to supposed that the masses of these new gauge bosons are sufficiently high so as the mixing between the W and Z and these new states is small. However if one increases the mass of these new gauge bosons then the cancelation of the one loop quadratic diverges are jeopardized so a new fine tuning is reintroduced. Another way out is to implement a Z_2 parity, similar to R-parity, to avoid this dangerous mixing. One can prove that models of with this parity, called T-parity, have no problems passing the electroweak constrains but another consequence of this T-parity is that the lightest new particle, usually called lightest T-odd particle (LTP), is stable, in the same way of the LSP in supersymmetric models. In order to avoid cosmological problems the LTP has to be neutral so it can be a natural candidate for dark matter but from the collider point of view it will mean that T-odd particles has to be produced in pairs and they will have to decay to another T-odd particle therefore the collider signatures are going to be very similar to the ones of supersymmetry, lots of missing energy. A possible process could be:

$$pp \to W_H^+ Z_H \to (W^+ A_H)(h A_H) \tag{4}$$

where the subscript H indicates the new gauge bosons and A_H is the LTP. This process has a similar signal as one where gauginos or higgsinos are produced, therefore good techniques to try to measure the spin of the decaying particle to be able to distinguish between supersymmetry or the little Higgs. On the other hand there are particular realizations of the little higgs paradigm where there are extra states which are T-even and therefore these states can be singly produced, one example includes copies of the top quark:

$$qb \to qt'_+ \quad t_+ \to Zt \tag{5}$$

in this case a resonant peak can be reconstructed.

To summarize the little Higgs models build and extra gauge symmetry to postpone the hierarchy problem but it does not solve it completely.

3 Composite Higgs Models

Another possible way of solving the hierarchy problem related to the Higgs is to supposed that the Higgs is, in fact, not a fundamental particle but something similar to the proton, a composite of more fundamental degrees of freedom that, similar to quarks, are confined due to a new strong interaction. Until ten years ago this approach to solve the hierarchy problem had to face the same problems that QCD has, namely, the non-perturbative regime that made calculations very difficult. Ten years ago is was shown that a particular type of strong interactions can be thought as theories that exist on extra dimensions where calculations can be made, this is called the AdS/CFT correspondence. Since then there has been a resurrection of those models. On this new way of understanding strongly couple theories one supposes that there is an extra dimension where fields can propagate. The general framework is to suppose that there is a group in the bulk that it is broken via boundary conditions [2]:

$$SO(5) \to SO(4) \equiv SU(2)_L \times SU(2)_R \to SU(2)_L \tag{6}$$

The fifth components of the 4 zero modes of $SO(5)/SO(4)$ become the degree of freedom of the Higgs and the hierarchy problem is solved due to the bigger $SO(5)$ symmetry. Because of the enlarge symmetry on the model one has to include extra top partners to till out a representation of $S0(4)$. It turns out that one of the partners has the same quantum number of the top so one can repeat the same analysis as in the little higgs models. On the other hand there is also an exotic quark with charge $q = 5/3$ that can be discovered looking for same sign dileptons coming from decays of W's:

$$T_{5/3} \to W^+ t \to W^+ b \tag{7}$$

These models do not need any T-parity because they have $SU(2)_R$, the custodial symmetry, embedded into the framework therefore any dangerous contributions to the T parameter are naturally suppressed.

To summarize one can implement the idea of the Higgs being a composite field in the context of extra dimensions and have predictive models that could be tested at the LHC.

4 Higgsless

One step further is to build a model where there is no Higgs, that it the old idea of technicolor, in these extra dimensional models it can be implemented via boundary conditions [3]. The electroweak group is broken by the compactification in such a way that the W and Z bosons do not have a zero massless mode because the boundary conditions break the symmetry. Since there is no Higgs in these models one may question if there is unitarization in WW scattering because the Higgs plays a central role in that calculation. In these higgsless models unitarization is achieved via the KK states (excited states) of W and Z, The main experimental signature of these models come from the production of these KK modes that can be reconstructed completely into a resonance.

5 Conclusions

The LHC is about to start proving the scale where the realm of electroweak symmetry breaking has to be uncovered.

Several possibilities exits for explaining the nature of the mechanism:

- Just the SM: one Higgs and no reason for it to be light.
- SUSY: the paradigm of a weak explanation of the weak scale.
- Alternative explanations: Little Higgs, composite Higgs or no Higgs.

In this review paper I have summarized several of the non-susy models and their signals a the LHC. Some of them are somewhat similar to susy (MET), like the LH (or UED), others rely more on resonances. It is important to have multiple observations in order to correctly identify the physics BSM.

References

[1] N. Arkani-Hamed, A. G. Cohen, E. Katz, A. E. Nelson, JHEP **0207** (2002) 034. [hep-ph/0206021].

[2] K. Agashe, R. Contino, A. Pomarol, Nucl. Phys. **B719** (2005) 165-187. [hep-ph/0412089].

[3] C. Csaki, C. Grojean, H. Murayama, L. Pilo, J. Terning, Phys. Rev. **D69** (2004) 055006. [hep-ph/0305237].