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Higgs doublet(s) as Goldstone bosons

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Summary. — I present, from a very personal and biased point of view, some recent attempts made at building models of ElectroWeak Symmetry Breaking (EWSB) with the Standard Model (SM) Higgs emerging as a pseudo Goldstone Boson of some extended symmetry.

PACS `12.60.Fr` – Extensions of electroweak Higgs sector.

1. – Extending symmetries in the scalar sector (Why and How)

Models of ElectroWeak Symmetry Breaking based on the idea that a Standard Model-like Higgs emerges as a pseudo Goldstone Boson of some extended symmetry have been built with the main purpose of ameliorating the Hierarchy Problem (HP) of the SM. The HP can be brutally stated as follows: $\delta m_h^2 \sim \Lambda^2$, that is the radiative correction to the mass-squared parameter in the scalar potential is quadratically divergent([1]). Clearly, we are facing the question: how is the EWSB scale stabilized?

It is useful to recall how different classes of models perform on this respect: at one loop in SUSY (*e.g.*, in the MSSM) $\delta m_h^2 \sim m_s^2 \log \Lambda$, while Little Higgs (LH) gives $\delta m_h^2 \sim f^2 \log \Lambda$ (f being the scale at which the enlarged symmetry is broken). Thus we see that it *is* possible to obtain better results than the Λ^2-dependence of the SM. Typically, and not surprisingly, this is done making use of symmetries.

The most important symmetry when one is dealing with an attempt to modify the Symmetry Breaking sector of the SM is the so-called *custodial symmetry*. Since it originates from the fact that the scalar sector of the SM has an approximate $SO(4)$ symmetry, which is only violated by the $U(1)_Y$ and Yukawa couplings, it is wise to require that models for EWSB have an *enlarged* invariance group with respect to $SO(4)$, $G \supseteq SO(4)$.

The other primary guideline in our analysis has been Fine Tuning (FT): we have been pursuing the goal to have a 10% or better FT. Once more: we want a stable EWSB scale.

([1]) This is not merely due to the renormalization scheme: in DR one just needs to substitute to Λ the mass m_{NP} of the new particle(s) interacting with h, and the problem is reinstated.

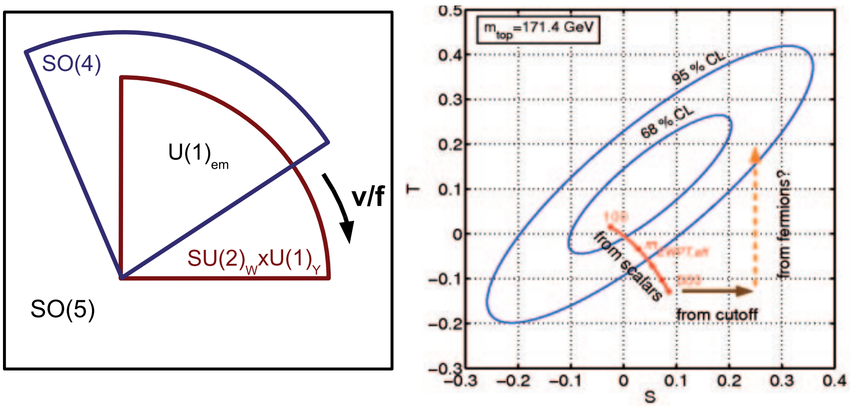

Fig. 1. – Left: pictorial description of the misalignment mechanism for symmetry breaking. Right: behaviour of the $SO(5)$ model in the S, T plane. The contribution marked "from cut-off" comes from new physics at the compositeness scale in the *strong coupling* case, precise values depending on the UV completion. In the *perturbative* case this δS might be significantly smaller.

2. – What we have done (at the beginning)

As a starting point we chose not to construct a LH model (there is no Collective Symmetry Breaking, for instance), nor to perform an EFT analysis (see [1]). Rather, we tried to capture the *essential features* of a *class* of models: we assumed that, given the (extended) symmetry breaking pattern, the minimal setup could give valuable information on more elaborated ones, and later checked this assumption with explicit calculations.

Given the premises, it was a logical first step to move from our starting-point $SO(4)$ to $G = SO(5)$ symmetry. We replaced the SM scalar potential with the following one([2]) ($\phi = (\vec{\phi}, \phi_5)^T$ is a real 5-plet, and $\vec{\phi}$ has the quantum numbers of the SM Higgs doublet):

$$V(\phi) = \lambda(\phi^2 - f^2)^2 - Af^2\vec{\phi}^2 + Bf^3\phi_5. \tag{1}$$

In the nonperturbative limit $\lambda \to \infty$ the low energy particle content is that of the SM (albeit the Higgs has a *compositeness* scale $\sim 3\,\text{TeV}$): this we call the *strong coupling regime*. On the other hand, for small λ one has a complex scalar doublet plus a singlet and two physical states in the spectrum: h and σ (each of them an admixture of $\phi_3 \subset \vec{\phi}$ and ϕ_5). This is, clearly, a *perturbative* extension of the SM. But how do we get EWSB? Formally, we need $\langle \vec{\phi}^2 \rangle = 2v^2 \neq 0$. This is guaranteed by the presence of the B term in V, hence we call this a *tadpole* mechanism to misalign the vevs of the components of ϕ.

In practice, we gauge a subgroup of $SO(5)$, and the vev of $\vec{\phi}$, v, measures the misalignment between $SO(4)$ and the gauged $SU(2)_L \times U(1)_Y$: the intersection between those two groups (for $v \neq 0$) gives the residual $U(1)_{em}$, as required (see fig. 1).

In *strong coupling* $\Delta = \frac{A}{v^2}\frac{\partial v^2}{\partial A} \simeq \frac{f^2}{v^2}$, *i.e.* 10% FT for a benchmark value $f \simeq 500\,\text{GeV}$.

Also, a suppression factor $\cos\alpha = \sqrt{(1 - 2v^2/f^2)}$ to the Higgs couplings to SM

([2]) V is renormalizable and it contains the most general soft-breaking terms consistent with the gauge symmetry and up to dimension 2. See [2] for a detailed discussion of these terms.

TABLE I. – *Properties of the* $SU(3)$ *SUSY models studied in* [3].

Model I	Model II
large Y's trigger radiative EWSB cut-off $\to$ GUT scale	tadpole mechanism, as before cut-off $\simeq 20\,\text{TeV}$
phenomenology $\sim$ decoupling regime of MSSM light (200–300 GeV) $\pm\pm$ Charginos high $\tan\beta$ (≥ 10)	new scalars with $300\,\text{GeV} \leq m_{S_i} \leq 1000\,\text{GeV}$ light Higgsinos (100–200 GeV) low $\tan\beta$ ($\sim$ a few)
$f \geq 2\,\text{TeV}$ gives optimal FT (better than 10)	low f ($\sim 350\,\text{GeV}$) allows to have 10% FT

particles is present (due to noncanonical kinetic terms for h). The unitarization of gauge boson longitudinal scattering amplitudes is then reduced, and some new physics is required to cut off the growth of $\sigma(WW \to WW)$ at a scale $\Lambda \sim 3\,\text{TeV}$.

Interestingly, the usual formulae for the dependence of the S and T parameters on the Higgs mass ($\hat{S}, \hat{T} = a_{S,T} \log m_h + b_{S,T}$) still apply, provided one substitutes m_h with an effective mass given by $m_{\text{EWPT,eff}} = m_h (\Lambda/m_h)^{\sin^2\alpha}$.

In the *perturbative case* the FT formula reads, approximately, $\Delta \simeq \frac{f^2}{v^2}(1 + \frac{3A}{4\lambda})$. It is clear that low Fine Tuning requires small values of the ratio A/λ, however 10% is still reasonable in a large fraction of the parameter space.

The main difference concerns the spectrum: there are now two physical scalars below the cut-off, h and σ. The growth of the longitudinal WW cross-section is cut off by h and(3) σ at $\sqrt{s} \simeq m_\sigma$ (with typical values $1\,\text{TeV} \leq m_\sigma \leq 2.5\,\text{TeV}$).

As for the ElectroWeak Precision Tests (EWPT), everything goes on as before, provided one uses the corrected formula $m_{\text{EWPT,eff}} = m_h (m_\sigma/m_h)^{\sin^2\alpha}$.

Unfortunately, this construction does not seem to perform well with respect to the EWPT. In the strong coupling regime it is clear that a sizeable contribution from fermions is needed: this, in turn, with *minimal* assignments for fermion representations, leads to a clash with constraints coming from Flavour physics ($Z \to b\bar{b}$, etc.).

The perturbative case looks slightly better, but still the *minimal* set-up looks in trouble (as anticipated, checks have been made: tree level estimates in the deconstructed and 5-dimensional siblings of the present model give comparable results, so that the situation seems pretty general). Also, a low production of σ particles is predicted, so that it might be difficult to discriminate the two regimes at the LHC.

3. – Something(s) richer (more by us, and by others)

As a next step, we tried to combine SUSY with the extended symmetry [3]. The main ingredients can be summarized as follows: $SU(3)$ is used(4) instead of $SO(5)$; one now has two Higgs multiplets (as required by supersymmetry); the effect of having employed both SUSY and an enlarged symmetry is the so-called *double protection*, which ensures perturbativity up to a higher scale (depending on the details it can be $O(10)\,\text{TeV}$ or

(3) The suppression factor $\cos\alpha$ to Higgs couplings is still present, due to the mixing with the singlet. The presence of σ compensates for this.
(4) For a usual, non-supersymmetric, ϕ^4 potential this would amount to choosing $SO(6)$.

even M_{GUT}). We explored two possible realizations: one is based on radiative EWSB (analogously to the MSSM), the other is a SUSY version of the *tadpole* mechanism outlined above. The salient features of those two models are summarized in table I.

More elaborated attempts have been performed, and it seems worth (and logical) to mention at least two of them. First of all, the $SU(3)$-based supersymmetric model has been modified [4] by including non-decoupling D-terms of an extra symmetry: this generates an enhanced quartic for the Higgs, while preserving the double protection.

It is then easier to get a heavier Higgs, without affecting perturbativity. The spectrum consists mainly of light MSSM-like states plus some exotics (*little partners*).

Another line of investigation is that of the non-minimal composite Higgs. In particular, an $SO(6)/SO(5)$-based model was studied [5]. The spectrum could comprise a very light ($O(10)$ GeV) scalar, η, with interesting discovery potential. Moreover the LEP bound on the Higgs mass might be lowered (due to the $H \to \eta\eta$ decay mode). It has also been emphasized that there are possible sources of explicit or spontaneous CP violation.

4. – Conclusions—What we have learned, and we hope

On the bad news side, the most economical ($SO(5)/SO(4)$) model(s) seem to be in troubles. A complicated fermion sector is needed to satisfy at the same time the constraints imposed by EWPT and Flavour. Also, one must not be fooled by the fact that radiative corrections to m_H^2 now depend on a scale that can be as low as a few hundred GeV: the Hierarchy Problem might be reintroduced, at the scale f.

On the other hand, more elaborated models (for instance supersymmetric ones, or with a non-minimal choice for the extended symmetry) look promising. It must be stressed that, after all, EWPT and Flavour can be accommodated, at the price of complicating the fermion sector. Definitely on the *plus* side one has a predicted rich (and possibly distinctive) phenomenology. As for the Hierarchy, at the beginning of the LHC era it is probably wiser to first explore 10 TeV region, both experimentally and theoretically. The information we will gather should allow us not only to distinguish between the two main options of a fundamental or composite Higgs: it could also provide new guidelines for the construction of more satisfactory UV completions of our EWSB models.

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