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ALTERNATIVE ELECTROWEAK SYMMETRY BREAKING MODELS

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Electroweak interactions need three Nambu–Goldstone bosons to provide a mass to the $W^{\pm}$ and the Z gauge bosons but they also need an ultra-violet (UV) moderator or new physics to unitarize the gauge boson scattering amplitudes. I will elaborate on the idea that the Higgs boson can be a composite bound state emerging from a strongly interacting sector, and argue that such composite Higgs scenarios offer a continuous interpolation between the Standard Model and models like technicolor.

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1 The Standard Model and the mass problem

The strong, weak and electromagnetic interactions of elementary particles are described by gauge interactions based on a symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$. Gauge theory is not only a way to classify particles and assign quantum numbers to them but it is also a dynamical principle that predicts particular couplings among particles. And the structure of these interactions has been well tested at LEP, for instance in the process $e^+e^- \to W^+W^-$. While this is certainly true at least for the 3-point functions, namely the interactions involving at least three particles, the gauge structure is actually badly violated at the level of the 2-point functions, namely in the mass spectrum: the observed mass terms for the leptons and the gauge bosons are not gauge invariant since the gauge group is chiral and also acts non-linearly on the gauge fields. This apparent clash calls for a spontaneous breaking of the gauge symmetry.

In the broken phase, a (massive) spin one particle describes three different polarizations: two transverse ones plus an extra longitudinal one which decouples in the massless limit. In the Standard Model (SM), the longitudinal degrees of freedom associated to the $W^{\pm}$ and Z^0 gauge bosons correspond presumably to the eaten Nambu–Goldstone bosons [1,2] resulting from the breaking of the global chiral symmetry $SU(2)_L \times SU(2)_R/SU(2)_V$. This picture still leaves us with the question of the source of the Nambu-Goldstone bosons: What is the sector responsible for the breaking $SU(2)_L \times SU(2)_R \to SU(2)_V$? What is the dynamics of this sector? What are its interactions with the SM particles? The common lore [3,4] is that these extra degrees of freedom are part of a fundamental scalar field transforming as a weak doublet. This Higgs doublet corresponds to 4 real scalar fields: the 3 eaten Nambu–Goldstone bosons and one physical real scalar degree of freedom, the notorious Higgs boson. While this picture is in very good agreement with Electroweak (EW) data [5,6,7] (for a review on the Higgs boson phenomenology, see Ref. [8]), the very fact that its unique prediction, namely the existence of the Higgs boson, has not been verified experimentally yet leaves open the possibility for other origins of the Nambu-Goldstone bosons: e.g., condensates of techniquarks, components of some gauge fields along an extra dimension ... (see Refs. [9,10,11] for recent reviews.)

2 The Higgs boson: the "raison d'être" of the LHC

Some simple numbers can convince us that the Higgs boson is the "raison d'être" of the LHC:

1. Over the last five years, about 500 papers start with an introduction like "the main goal of the LHC is to unveil the mechanism of electroweak symmetry breaking".
2. Spires database contains about 9000 papers which contain "Higgs" in their title.
3. Google gives about 3×10^6 references to "Higgs", which is about 1% of what Michael Jackson gets.
4. ... but there is no Nobel prize associated to the Higgs boson, even though the situation will change hopefully very soon.

What are the reasons of such a success? It is often said that the Higgs boson is the last missing piece of the Standard Model. Well, there is no evidence that the electroweak symmetry breaking sector consists in a single particle and it is more likely that a whole new sector with its own dynamics will trigger this breaking. It is often argued too that the Higgs boson is at the origin of the masses of the elementary particles. This is not quite true since only the Higgs vacuum expectation value is really needed to generate these masses in a gauge invariant way. However, as it was explained in the previous section, a new degree of freedom like the Higgs boson is needed to get a description of these masses that remains valid at high energy. Furthermore, this new degree of freedom should also ensure a proper screening of the radiative corrections to the gauge boson self-energies which otherwise would be logarithmic divergent and in apparent conflict with electroweak precision tests. Therefore something like the SM Higgs boson is likely to exist. The question is how close to reality is this minimal description. What are the possible deformation away from the SM?

The Higgs boson itself is certainly not the end of the story. After all, it is only an "emergency tire" [12] that allows us to rescue the SM for a limited range of energy until the next territory of physics beyond the SM. Theorists very often rely on the "naturalness" criterion to guess what the structure of this new physics above the Terascale could be. The aim is to understand how the quadratically divergent radiative corrections to the Higgs boson mass are cancelled. It could be the result of a new symmetry which prevents the occurrence a Higgs mass until this symmetry is broken, examples along this line include supersymmetric models [13,14], gauge–Higgs unification models and models which see the Higgs a a pseudo Nambu–Goldstone boson. Another solution to the hierarchy problem is to lower the scale of quantum gravity either by diluting gravity in large extra dimensions [14] or by introducing many-many new degrees of freedom. A third and may be more radical approach is to remove the Higgs boson from the physical spectrum and to assume that EW symmetry is broken dynamically by some strong dynamics [15,16,17].

3 Elementary vs. composite Higgs boson. Strong vs. weak EWSB

What is unitarizing the WW scattering amplitude? Supersymmetric models, Little Higgs models and many other models take for granted that the Higgs boson provides the answer to this pressing question of the origin of EWSB. I said earlier that the masses of the $W^\pm$ and Z gauge bosons break the gauge symmetry. Actually, in the presence of these masses, the gauge symmetry is realized non-linearly: the longitudinal $W_L^\pm, Z_L$ can be described by the Nambu–Goldstone bosons, or pions, associated to the coset $SU(2)_L \times SU(2)_R/SU(2)_{\text{isospin}}$ and the gauge boson mass terms correspond to the pions kinetic term (σ^a, $a = 1, 2, 3$, are the usual Pauli matrices):

$$\mathcal{L}_{\text{mass}} = \frac{v^2}{4}\text{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \quad \text{with} \quad \Sigma = e^{i\sigma^a \pi^a / v}. \tag{1}$$

Thanks to this Goldstone boson equivalence[18], the non-trivial scattering of the longitudinal W's (W generically denotes $W^\pm$ as well as Z) now simply follows for the contact interactions among four pions obtained by expanding the Lagrangian (1) and leads to amplitudes that grow with the energy:

$$\mathcal{A}(W_L^a W_L^b \to W_L^c W_L^d) = \mathcal{A}(s)\delta^{ab}\delta^{cd} + \mathcal{A}(t)\delta^{ac}\delta^{bd} + \mathcal{A}(u)\delta^{ad}\delta^{bc} \quad \text{with} \quad \mathcal{A}(s) \approx \frac{s}{v^2}. \tag{2}$$

In the absence of any new weakly coupled elementary degrees of freedom canceling this growth, perturbative unitarity will be lost around 1.2 TeV[a] and new strong dynamics will kick in and soften the UV behavior of the amplitude, for instance via the exchange of massive bound states similar to the ρ meson of QCD. In any circumstances, by measuring the $W^\pm$ and Z masses, we have been guaranteed to find new physics around the Fermi scale to ensure the proper decoupling of the longitudinal polarizations at very high energy.

The simplest example of new dynamics that can restore perturbative unitarity consists of a single scalar field, h, singlet under $SU(2)_L \times SU(2)_R/SU(2)_V$ and coupled to the longitudinal W's as[19]:

$$\mathcal{L}_{\text{EWSB}} = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{v^2}{4}\text{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \times \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right). \tag{3}$$

Via its linear coupling, a, to the W_L's, the scalar gives an additional contribution to the WW scattering amplitude

$$\mathcal{A}_{\text{scalar exchange}}(s) = -\frac{a^2 s^2}{v^2(s - m_h^2)}, \tag{4}$$

which, for $a = 1$, cancels the leading contact term at high energy. This is not the end of the story yet: perturbative unitarity should be maintained in inelastic channels too, like $W_L W_L \to hh$. Both the linear and quadratic couplings, a and b, contribute to this amplitude and the terms growing with the energy are canceled for the particular choice $b = a^2$. The point $a = b = 1$ defines the SM Higgs boson and it can be shown that the scalar resonance and the pions then combine together to form a doublet transforming *linearly* under $SU(2)_L \times SU(2)_R$.

The Lagrangian (3) describes either an elementary or a composite Higgs boson. As soon as the couplings deviate from $a = b = 1$, the Higgs exchange alone will fail to fully unitarize the WW scattering amplitude irrespectively whether or not the effective Lagrangian (3) emerges from a perturbative theory (see for instance Ref. [20]) or from a strongly interacting dynamics. Therefore and contrary to a general belief, the question of strong vs weak dynamics at the origin of the EWSB is decoupled from the question of the existence of a light and narrow Higgs-like scalar. In composite Higgs models, the deviations from $a = b = 1$ are controlled (see Section 4) by the ratio of the weak scale over the Higgs compositeness scale, f, which can be rather low (a few hundreds of GeV), and strong WW scattering above the Higgs mass is therefore expected.

4 (Pseudo Nambu–Goldstone) composite Higgs models

4.1 Effective chiral description

Notwithstanding its simplicity, the appeal of the SM Higgs picture comes from its successful agreement with EW precision data, provided that the Higgs boson is rather light. In this regard, being an elementary scalar is not a virtue but rather a flaw because of the quadratic

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[a] Defining the breakdown of perturbativity is subject to arbitrary choices: the 1.2 TeV($= 2\sqrt{2\pi}v$) number follows from requiring that the real part of the partial waves of the iso-amplitudes remains smaller than $\frac{1}{2}$, while demanding that the tree-level amplitude remains bigger than the one-loop one leads to the more conventional scale, $4\pi v (\approx 3.1$ TeV), associated to a non-linear σ-model with a breaking scale v.

divergence destabilizing the Higgs mass. It is thus tantalizing to consider the Higgs boson as a composite bound state emerging from a strongly-interacting sector. In order to maintain a good agreement with EW data, it is sufficient that a mass gap separates the Higgs resonance from the other resonances of strong sector (the resonances that will ultimately enforce a good behavior of the WW scattering amplitudes). Such a mass gap can naturally follow from dynamics if the strongly-interacting sector possesses a global symmetry, G, spontaneously broken at a scale f to a subgroup H, such that the coset G/H contains a fourth Nambu–Goldstone bosons that can be identified with the Higgs boson. Simple examples of such coset are $SU(3)/SU(2)$ or $SO(5)/SO(4)$, the latter being favored since it is invariant under the custodial symmetry (some non-minimal models with extra Nambu–Goldstone bosons have also been constructed[21]). Attempts to construct composite Higgs models in 4D have been made by Georgi and Kaplan (see for instance Ref.[22]) and modern incarnations have been recently investigated in the framework of 5D warped models where, according to the principles of the AdS/CFT correspondence, the holographic composite Higgs boson now originates from a component of a gauge field along the 5th dimension with appropriate boundary conditions

The composite Higgs models offer a nice and continuous interpolation between the SM and technicolor type models. The dynamical scale f defines the compositeness scale of the Higgs boson: when $\xi = v^2/f^2 \to 0$, the Higgs boson appears essentially as a light elementary particle (and its couplings approach the ones predicted by the SM) while the other resonances of the strong sector become heavier and heavier and decouple; on the other hand, when $\xi \to 1$, the couplings of the Higgs boson to the W_L's go to zero and unitarity in gauge boson scattering is ensured by the exchange of the heavy resoances.

At the eve of the LHC operation, I would like to give a description of the physics of such a composite Higgs boson rather than presenting the details of the construction of an explicit model. In the same way that we do not need the refinements of QCD to describe the physics of the pions, I will rely on an effective Lagrangian to capture the relevant physics. This effective Lagrangian involves higher dimensional operators for the low energy degrees of freedom (the SM particles and a unique Higgs boson in the minimal case) and the strong sector will be broadly parametrized by two quantities: the typical mass scale, m_ρ, of the heavy resonances and the dynamical scale, f, associated to the coset G/H (for maximally strongly coupled sectors, we expect $m_\rho \approx 4\pi f$; here, I will simply assume that m_ρ is parametrically larger than f). There are two classes of higher dimensional operators: (i) those that are genuinely sensitive to the new strong force and will affect qualitatively the physics of the Higgs boson and (ii) those that are sensitive to the spectrum of the resonances only and will simply act as form factors. Simple rules control the size of these different operators, see Ref.[23], and the effective Lagrangian generically takes the form (g, g' are the SM EW gauge couplings, λ is the SM Higgs quartic coupling and y_f is the SM Yukawa coupling to the fermions $f_{L,R}$):

$$\begin{aligned}\mathcal{L}_{\text{SILH}} = {}& \frac{c_H}{2f^2}\left(\partial_\mu\left(H^\dagger H\right)\right)^2 + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) \\ & + \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) + \ldots \end{aligned} \tag{5}$$

All the coefficients, $c_H, c_T \ldots$, appearing in Eq. (5) are expected to be of order one.

Some oblique corrections are generated, at tree-level, by the operators of this effective Lagrangian: (i) the operator c_T gives a contribution to the T Peskin–Takeuchi parameter, $\hat{T} = c_T v^2/f^2$, which would impose a very large compositeness scale; however, assuming that the custodial symmetry is preserved by the strong sector, the coefficient of this operator is vanishing automatically; (ii) a contribution to the S parameter is generated by the form factor operators only, $\hat{S} = (c_W + c_B) m_W^2/m_\rho^2$, and will simply impose a lower bound on the mass of the heavy resonances, $m_\rho \geq 2.5$ TeV. At the loop level, the situation is getting a bit more complicated: as

I am going to show below, the couplings of the Higgs to the SM vectors receive some corrections of the order v^2/f^2, and these corrections prevent the nice cancelation occurring in the SM between the Higgs and the gauge boson contributions and S and T are logarithmically divergent[24] (the divergence in T will enventually be screened by resonance states if the strong sector is invariant under the custodial symmetry). Typically, this one-loop IR contribution imposes[25,26] $f^2/v^2 \geq 3 \div 4$ (see Refs. [27,28,29,30] for careful discussions of electroweak precision tests in composite models built in 5D). Overall, $\xi = v^2/f^2$ is a good estimate of the amount of fine-tuning of these models[31].

4.2 Higgs anomalous couplings

The effective Lagrangian (5) does induce some corrections to the Higgs couplings to the SM particles. In particular, the operator c_H gives a correction to the Higgs kinetic term which can be brought back to its canonical form at the price of a proper rescaling of the Higgs field inducing an universal shift of the Higgs couplings by a factor $1 - c_H\, v^2/(2f^2)$. For the fermions, this universal shift adds up to the modification of the Yukawa interactions:

$$g^{\xi}_{hf\bar{f}} = g^{\mathrm{SM}}_{hf\bar{f}} \times (1 - (c_y + c_H/2)v^2/f^2), \tag{6}$$

$$g^{\xi}_{hWW} = g^{\mathrm{SM}}_{hWW} \times (1 - c_H\, v^2/(2f^2)). \tag{7}$$

All the dominant corrections, i.e. the ones controlled by the strong operators, preserve the Lorentz structure of the SM interactions, while the form factor operators will also introduce couplings with a different Lorentz structure.

The Higgs anomalous couplings affect the decay rates as well as the production cross sections of the Higgs[23,32,33]. Therefore, the searches for the Higgs boson at the LHC, as well as the LEP/Tevatron exclusion bounds are modified as compared to the SM case (see Ref. [34] for a detailed study).

Will the LHC be able to probe these deviations in the couplings of the Higgs? The contribution of the operator c_H is universal for all Higgs couplings and therefore it does not affect the Higgs branching ratios, but only the total decay width and the production cross section. The measure of the Higgs decay width at the LHC is very difficult and it can be reasonably done only for rather heavy Higgs bosons, well above the two gauge boson threshold, a region which is not of particular interest since we consider the Higgs as a pseudo-Goldstone boson, and therefore relatively light. However, for a light Higgs, LHC experiments can measure the product $\sigma_h \times BR_h$ in many different channels: production through gluon, gauge-boson fusion, and top-strahlung; decay into b, τ, γ and (virtual) weak gauge bosons. At the LHC with about 300 fb^{-1}, it is possible to measure Higgs production rate times branching ratio in the various channels with 20–40 % precision[35,36]. For c_H and c_y of order one, this will translate into a sensitivity on the compositeness scale of the Higgs, $4\pi f$, up to $5 \div 7$ TeV. It was shown recently[37] that, taking into account the particular pattern of the deviations of the Higgs couplings as predicted in the composite models, the same sensitivity can be achieved with 30 fb^{-1} only.

4.3 Strong pair productions

Deviations from the SM predictions of Higgs production and decay rates could be a hint towards models with strong dynamics, especially if no new light particles are discovered at the LHC. However, they do not unambiguously imply the existence of a new strong interaction. The most characteristic signals of a composite Higgs model have to be found in pair production os states that belong to the strongly interacting sector like $W_L\, h$. Indeed, as already announced in Section 3, a peculiarity of a composite Higgs boson is that it fails to fully unitarize the $W_L W_L$ scattering amplitudes which have thus a residual growth with energy and the corresponding interaction becomes strong, eventually violating tree-level unitarity at the cutoff scale. Indeed, the extra contribution to the Higgs kinetic term from the c_H operator prevents Higgs exchange diagrams from accomplishing the exact cancellation, present in the SM, of the terms growing with energy in the amplitudes. Therefore, although the Higgs is light, we obtain strong WW scattering at high energies.

From the operator c_H, using the Goldstone equivalence theorem, it is easy to derive the following high-energy limit of the scattering amplitudes for longitudinal gauge bosons

$$\mathcal{A}(W_L^a W_L^b \to W_L^c W_L^d) = \mathcal{A}(s)\delta^{ab}\delta^{cd} + \mathcal{A}(t)\delta^{ac}\delta^{bd} + \mathcal{A}(u)\delta^{ad}\delta^{bc} \quad \text{with} \quad \mathcal{A}(s) \approx \frac{c_H\, s}{f^2}. \qquad (8)$$

The growth with energy of the amplitudes is strictly valid only up to the maximum energy of our effective theory, namely m_ρ. The behaviour above m_ρ depends on the specific model realization. In 5D models, the growth of the elastic amplitude is softened by Kaluza–Klein modes exchange[38] like in 5D Higgsless models [39,40], but the inelastic channels dominate and strong coupling is reached at a scale $\sim 4\pi f$. Notice that the amplitudes (8) are exactly proportional to the scattering amplitudes obtained in a Higgsless SM, the growth being controlled by the strong coupling scale, f, and not the weak scale itself, v.

Will the LHC be able to measure the growth of these scattering amplitudes? Contrary to a naive belief, it is a notoriously difficult measurement which requires some large integrated luminosity [41]. The most promising channels correspond to purely leptonic decays of the W's, though semileptonic decay channels have also been considered recently[42,43]. The rapid falloff of the W luminosity inside the proton and the numerous SM backgrounds that can fake the signal certainly make the measurement harder, but, as a matter of fact, already at the partonic level, the onset of the strong scattering is delayed to higher energies due to a large pollution from the scattering of the transverse polarizations [19].

In composite Higgs models, another direct probe of the strong dynamics at the origin of EWSB is the cross section for the double Higgs production. Indeed, the Higgs boson appears as a pseudo Nambu–Goldstone boson and its properties are directly related to those of the other exact (eaten) Goldstones, corresponding to the longitudinal W, Z gauge bosons. Thus, a generic prediction is that the strong gauge boson scattering is accompanied by strong production of Higgs pairs.The amplitudes for double Higgs production grow with the center-of-mass energy as

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}. \qquad (9)$$

Therefore a significant enhancement over the (negligible) SM rate for the production of two Higgs bosons at high p_T, along with two forward jets associated with the two primary partons that radiated the $W_L W_L$ pair, is expected. An explorative analysis[19] has shown that the best channel for discovery involves 3 leptons in the final states, with both Higgs bosons decaying to W^+W^-: $pp \to hhjj \to 4Wjj \to l^+l^-l^\pm \not{E}_T\, 4j$. The final states are undeniably more complicated than in the analyses of gauge boson scattering and come with smaller branching ratios, but at least the double Higgs production does not suffer from pollution from the transverse modes and it is the only process that gives access to the quadratic coupling b of the Lagrangian (3) and allows to test its relation to the linear coupling, a, as predicted by the structure of the higher dimension operators (5) and characteristic of a linear realization of the $SU(2)_L$ symmetry: $a = 1 - c_H v^2/(2f^2), b = 1 - 2c_H v^2/f^2$. A Monte-Carlo simulation with simple kinematic cuts concludes [19] that the signal significance at the LHC operating at $\sqrt{s} = 14$ TeV with 300 fb^{-1} will be limited to about 2.5 standard deviations for $v^2/f^2 = 0.8$. With an upgrade of the LHC luminosity (sLHC program), a 5σ discovery can be reached with less than 1 ab^{-1} of integrated luminosity.

While the effective Lagrangian 5 elegantly captures the LHC physics of composite Higgs models up to a scale of the order of 10 TeV, explicit holographic models constructed in 5D warped space provide a valid description in the far UV up to the energies close to the Planck scale and give a new and interesting twist to the question of gauge coupling unification. Not only the running of the gauge couplings receives a contribution from all the resonances of the strong sector (the KK states in the 5D picture) but it also loses the contribution of the Higgs (and the top) above the weak scale. And an appealing unification seems to follow from this minimal set-up with a degree of accuracy comparable to the one reached in the MSSM[44].

While my presentation has been focussed on the gauge sector, the fermionic sector of composite Higgs models, in particular in the top sector, provides also very interesting signatures easily accessible at the first stages of the LHC operation [25,29,45,46,47,48,49,50]. In particular the same-sign dilepton final states offer a sensitive probe to the top partners [46,50] with a discovery potential up to 500 GeV (resp. 1 TeV) with about 50 pb^{-1} (resp. 15 fb^{-1}).

In conclusion, in the plausible situation that the LHC sees a Higgs boson and no other direct evidence of new physics, it will not be immediate to determine the true nature of this Higgs boson and tell for sure if it is an elementary particle or a composite bound state emerging from a strongly interacting sector. In that situation, a physics case for a linear collider [51] together with the sLHC [52] can be easily made [53].

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