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The dynamics of Composite Higgses

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Abstract. The nature of the 125 GeV Higgs recently discovered at CERN has not been established yet. One intriguing possibility is that it may arise as a light composite state from a confining dynamics at the TeV scale. I will review the recent progress in understanding the dynamics that may be behind this mechanism, focusing on what we can learn by knowing its details. The masses of the spin-1 resonances can in fact be extracted from lattice calculations thus providing an estimate of the mass scale of new states. Furthermore, a lot can be learned about the physics of eventual top partners.

1. Introduction
The discovery of the 125 Higgs boson at the LHC has undoubtedly opened a new era in particle physics. By analyzing its decay products, mainly from the golden channels \( h \to \gamma\gamma \) and \( h \to ZZ^* \to \text{leptons} \), experimentalists at CMS and ATLAS have been able to establish with good accuracy that it is a spin-0 and CP-even state, which couples to particles proportionally to their mass, thus fulfilling the properties of the Higgs boson in the Standard Model (SM). In this sense, this discovery completes the list of particles expected in the SM after 50 years from its proposal. However, the discovery of the Higgs boson has not improved our comprehension of the Brout-Englert-Higgs mechanism \([1, 2]\) responsible for the breaking of the electroweak (EW) symmetry: the SM contains a mere description of the spontaneous symmetry breaking via an elementary weakly-coupled scalar field transforming as a doublet of the weak SU(2) gauge symmetry, which develops a vacuum expectation value thanks to a mass term tuned to have “wrong” sign in the Lagrangian. Only a precise determination of the couplings of the discovered Higgs boson would allow to confirm this description of the EW symmetry breaking sector of the SM. However, the most recent data at the end of Run I of the LHC has allowed us to determine the couplings with an accuracy of 15–20% in the best channels \([3, 4]\). Even though the central values are in very good agreement with the SM predictions, there is plenty of space for New Physics effects. For comparison, the accuracy in the test of the EW gauge sector of the SM is of the order of 0.1%.

Furthermore, the discovery of a light scalar associated to the Higgs has brought in the realm of reality the old questions of naturalness, and the hierarchy problem. The mass of a scalar field is in fact very sensitive to quantum corrections deriving from its couplings to other particles in the model, the underlying reason being the absence of spin. For particles with spin, like fermions and vector bosons, sending the mass to zero allows for the recovery of a symmetry: chiral symmetry in the case of fermions and gauge symmetry in the case of vectors. In such cases one always finds, therefore, that loop corrections to the masses are proportional to the bare masses of the
particles, thus a small mass-parameter in the Lagrangian stays small after quantum corrections are included. This is not true for scalar fields: their mass receives corrections proportional to the mass of any physics they couple to. For a generic scalar field $\phi$, therefore, we can write that

$$m_{\phi}^2 = m_{\text{bare}}^2 + \frac{g^2}{16\pi^2}M^2,$$

where $M$ is a mass scale associated to a sector of the model that couples to $\phi$ with coupling strength $g$. In the SM, we know that any field will ultimately couple to gravity, which carries an intrinsic scale $M = M_{\text{Planck}} = 10^{19}$ GeV. Following quantum corrections, thus, the mass of the Higgs boson should be very close to the Planck mass, unless the bare mass in the Lagrangian is tuned with a high accuracy to cancel the quantum corrections.

So far, the only mechanisms we know that can keep the Higgs mass (and thus the EW scale) under control are either based on a symmetry that relates the scalars to states carrying spin, or one that sets the Higgs mass to zero:

A- boson-fermion symmetry, dubbed supersymmetry [5], is an extension of space-time symmetries that allows to associate scalar fields to fermions, thus their masses enjoy the same protection from chiral symmetry;

B- extra dimensions, another extension of space time symmetry allowing for additional space-like dimensions, allow to associate 4-dimensional scalars to the additional polarisation of vector bosons, so that their masses are also protected by the extended gauge symmetry [6];

C- compositeness, where the scalar field is replaced by a bound state of fermions, whose mass is associated to a non-perturbative dynamical mass (like the condensation scale in QCD);

D- Goldstone symmetry, associating the scalar with the massless Goldstone boson of a spontaneously broken global symmetry.

In this contribution, we will focus on the possibility that the Higgs boson arises as a composite state: this is a very rich scenario that offers many qualitatively different candidates for the Higgs:

- **composite Higgs**, arising as a massive bound state in models where the dynamics breaks the EW symmetry at the condensation scale. This scenario is realized in old-school QCD-like Technicolor models [7, 8].

- **radion/dilaton scenario**, where the Higgs [9] can be associated to a classical conformal invariance of the theory in 4 dimensions, or extra dimensional models. This scenario is similar to the Technicolor case if the underlying dynamics is near conformal.

- **pNGB scenario**, where the Higgs is associated to a pseudo-Nambu-Goldstone-boson (pNGB) of the spontaneously broken global symmetry of the dynamics [10]. The mass is then generated by small explicit breaking of the global symmetry, like the gauging of the EW and the couplings responsible for the generation of the top mass. Holography allows to associate this case to models in (warped) extra dimensions, where the Higgs arise as a gauge boson.

- **holographic Higgs**, where the Higgs arises as a particle-like state associated with an operator of an underlying conformal field theory which couples marginally to the SM [11]. The AdS/CFT correspondence allows to relate this scenario with models in extra dimensions.

It should be noted here that the name “composite Higgs” [12] is currently associated to models of holographic Higgses, and that any dynamical model of pNGB Higgs automatically enjoys a Technicolor-like limit [13] where the Higgs arises as a composite bound state. So, in a sense, all these scenarios, are related to each other and have similar phenomenology.
A new approach to understanding the physics of a composite Higgs is to rely on a well-defined underlying dynamics based on confining gauge interactions with matter fermions (thus qualitatively similar to QCD). This allows to work in a well-defined scenario where the global symmetries and properties of the composite states are determined \cite{13}. In the following we will review the latest development achieved thanks to this approach.

2. Fundamental dynamics and the Higgs boson

Let us postulate the existence of a dynamics that is invariant under a global symmetry group $G$, which is spontaneously broken to a subgroup $H$. No matter what the details of the dynamics are, the spectrum of the theory will contain a number of massless Goldstone bosons, equal to the dimension of the coset $G/H$. One can further imagine to couple the dynamics to the SM by partially gauging the global symmetries. As a first example, we will assume that the EW symmetry is broken by the dynamics, thus it is sufficient to have

$$G \supset SU(2)_L \times U(1)_Y,$$

(2)

This is exactly what happens in Technicolor models: for instance, in QCD with 2 quarks, $G = SU(2)_L \times SU(2)_R$, and $H = SU(2)_D \supset U(1)_{em}$. In this case, $\dim G/H = 3$, and one obtains exactly the 3 Goldstone bosons needed to give mass to the $W$ and $Z$.

We can however be more ambitious and imagine a situation where

$$G \supset H \supset SO(4) \supset SU(2)_L \times U(1)_Y,$$

(3)

where we extended the electroweak symmetry to the custodial $SO(4) \sim SU(2)_L \times SU(2)_R$ in order to avoid three level corrections to the $\rho$ ($T$) parameter \cite{14}. If we properly choose the global symmetries, the coset may contain 4 scalars which transform as a bi-doublet of the custodial $SO(4)$, and can thus play the role of the Higgs field. Giving a vacuum expectation value to such states would therefore be equivalent to misaligning the vacuum of the dynamics that breaks $G \rightarrow H$ along the direction of the generators of $G$ associated to the Higgs field \cite{10}. The misaligned vacuum will now break the EW symmetry in a way similar to Technicolor. The degree of misalignment can be described by an angular variable $\theta$, so that:

- $\theta = 0$ corresponds to the vacuum that does not break the EW symmetry, and the coset contains a full bi-doublet of $SO(4)$;
- $\theta = \pi/2$ corresponds to the Technicolor alignment that breaks the EW symmetry at the scale of the dynamics $f \sim v$;
- for intermediate $\theta$, the breaking along the Higgs direction is $f \sin \theta \sim v$, so that $v/f < 1$.

The advantage of this scenario is in the possibility to induce a small hierarchy between the mass scale of the dynamics, where the spontaneous breaking takes place, and the EW scale $v$. Furthermore, one would naturally obtain

$$m_{W,Z} \sim m_h \sim f \sin \theta \sim v.$$

(4)

For the Higgs, this relation is due to the fact that for $\theta \rightarrow 0$, the EW symmetry is recovered and the fourth component of the bi-doublet must become an exact Goldstone boson, like the 3 eaten by $W$ and $Z$. Note that the mass of the Higgs, and the alignment of the vacuum, are determined by explicit breaking of the global symmetry $G$, which must be small in order not to deform the dynamics: as examples, one should mention the gauging of the EW symmetry, and the coupling to the standard fermions (primarily the top) apt to generate their mass (analogous to the Yukawa couplings in the standard model). If ones wants to generate a largish hierarchy between $v$ and $f$, a certain degree of fine tuning is necessary in the explicit breaking terms.
For a review of the possible global symmetries and a discussion of the fine tuning, we refer to the review in Ref. [12]. The minimal coset, in terms of dimension, is SO(5)/SO(4) [11], which contains exactly 4 states transforming as a bi-doublet of SO(4), and has been extensively studied in the literature.

3. The minimal dynamical model: SU(4) → Sp(4)

In the following, we will focus on the minimal dynamical model, which features the coset SU(4)/Sp(4) [15]: the microscopic model can be based on a very simple construction based on a hypercolor group $G_{TC} = SU(2)^{TC}$ with two Dirac fermions transforming as doublets. This microscopical model has been first proposed as a UV completion of Little Higgs models in Ref. [16], then as a candidate for a minimal Technicolor in Ref. [17], and finally as a candidate for pNGB Higgs in Ref. [18]. A list of other non-minimal model is in Table 1. One of the greatest advantaged of this model is that, due to its simplicity, it can be put on the lattice [19]: in fact, the symmetry breaking SU(4)/Sp(4) has been observed in lattice results, thus giving us confidence that the dynamics does what we need it for. Also, the model can be pushed close to the conformal limit by adding one or two extra fermions transforming as an adjoint of SU(2)$_{TC}$ [20].

Embedding the electroweak interactions $SU(2)_L \times U(1)_Y$ can be done by assigning EW quantum numbers to the fundamental quarks $\psi$: a minimal and consistent choice is to take the left-handed components $\psi_L$ to transform as a doublet of $SU(2)_L$, while the right-handed ones $\psi_R$ as a doublet of $SU(2)_R$ (i.e. they have opposite hypercharge equal to $\pm 1/2$). With this assignments, no gauge anomalies are introduced. The global $G = SU(4)$ symmetry becomes evident once one builds a 4-component object with $\psi^j = (\psi_L^j, \psi_R^j)$. The condensate $\langle \psi^j \psi^j \rangle$ transforms as:

$$\langle \psi^j \psi^j \rangle = 6_{SU(4)} = 5_{Sp(4)} \oplus 1_{Sp(4)}.$$

The five-plet of Sp(4) contains the Goldstone bosons of the SU(4)/Sp(4) breaking, and they decompose under the custodial SO(4) $\subset$ Sp(4) group as

$$5_{Sp(4)} = (2,2)_{SO(4)} \oplus (1,1)_{SO(4)}.$$

The spectrum, therefore, contains a bi-doublet (associable to the Higgs field) and an extra singlet $\eta$. On the other hand, the Sp(4) singlet corresponds to a massive scalar, similar to the $\sigma$ in QCD: this is the candidate for the observed Higgs boson in the Technicolor limit. The most general alignment for the condensate can be obtained starting from the vacuum that preserves the EW symmetry, and applying a rotation generated by the broken generators:

$$\Sigma_0 = e^{i\gamma_5} \begin{pmatrix} i\sigma_2 \cos \theta & \sin \theta \\ -\sin \theta & -i\sigma_2 \cos \theta \end{pmatrix},$$

**Table 1.** List of the smallest models of composite Higgs based on a simple underlying dynamics.
where $\sigma_2$ is the second Pauli matrix, and $\theta$ is the angle determining the alignment ($\theta = \pi/2$ corresponding to the Technicolor limit). The phase $\gamma$ is generated by an anomalous global $U(1)$ acting on the fermions $\psi$, and it potentially induces CP violation (therefore we will set it to zero in the following). In principle, a rotation along the singlet direction can also introduce a new parameter, however this direction commutes with the EW gauge generators and therefore will not affect the physics in the EW sector. From this vacuum, one can obtain the masses for the $W$ and $Z$, and a Lagrangian for the Goldstone bosons (we refer the reader to Ref. [13]):

$$m_W^2 = m_Z^2 c_W^2 = 2g^2 f^2 \sin^2 \theta, \quad v = 2\sqrt{2} f \sin \theta.$$  \hspace{1cm} (8)

In the Unitary gauge, the spectrum contains two light scalars: a pNGB Higgs $h$, and the extra singlet $\eta$. On top of this, we have the heavy scalar $\sigma$, being a singlet of Sp(4). The masses of these states depend on the explicit breaking of the global symmetry, and we refer the reader to Ref.s [18, 13] for more details. Here, we will simply recap the main features. The breaking terms introduced by the coupling to standard model particles are due to gauge interactions (i.e. the partial gauging of SU(4)), and the coupling to the top. The latter can be introduced in the form of a four-fermion interaction

$$\frac{y_t}{\Lambda^2} (q_L t_R) (\psi_L \psi_R),$$  \hspace{1cm} (9)

i.e. a coupling of the elementary fermions $q_L$ and $t_R$ to the combination of $\psi$'s that transforms like the Higgs doublet. After bosonizing the theory, the above four-fermion interaction will generate a mass for the top in the form

$$m_t = y_t' f \sin \theta,$$  \hspace{1cm} (10)

where $y_t'$ is an effective Yukawa coupling.

### 3.1. Potential and fine tuning

This interaction in Eq.(9) is crucial for the model, as loops of the elementary top induce an effective potential for the vacuum. Another breaking term is due to a mass for the fermions $\psi$, allowed by gauge interactions. The contribution of the top and $\psi$-mass to the potential is given by (here we neglect the contribution of gauge loops, which are of the same form of the top ones but smaller):

$$V(\theta) = y_t^2 C_t \cos^2 \theta - 4C_m \cos \theta,$$  \hspace{1cm} (11)

where $C_t$ and $C_m$ are $O(1)$ loop coefficients determined by the dynamics, and the second term is generated by the mass term. This potential fixes the value of $\theta$: the minimum is

$$|\cos \theta|_{\text{min}} = \frac{2C_m}{y_t'^2 C_t}, \quad \text{for} \quad y_t'^2 C_t > 2|C_m|,$$  \hspace{1cm} (12)

else $\theta_{\text{min}} = 0$. We can see here that obtaining a small $\theta$, corresponding to a pNGB Higgs limit, requires a certain level of fine tuning between two terms whose origin is of very different nature. For instance, $\sin \theta = 0.2$ requires $\cos \theta = 0.98$, thus the two terms must be equal up to a 2%. It is also interesting to study the contribution to the masses of the two pNGBs $h$ and $\eta$: the top loop and $\psi$-mass contribute

$$m_h^2 = \frac{f^2}{4} \left( 2C_m \cos \theta - y_t'^2 C_t \cos(2\theta) \right) = \frac{y_t'^2 C_t f^2}{4} \sin^2 \theta_{\text{min}}.$$  \hspace{1cm} (13)
In the second expression we have used the minimum condition to eliminate $C_m$ in favor of $\theta$. This formula is remarkable as if shows the pNGB mechanism at work: the naïve expectation for the top loop contribution to the Higgs mass in this model should be

$$\delta m^2_h|_{\text{naïve}}^{\text{(top)}} \sim -\frac{y_t^2 \Lambda_T C}{16\pi^2} = -y_t^2 f^2,$$

(14)

using $\Lambda_T \sim 4\pi f$ as a cut-off, which is thus proportional to the scale of the condensate $f$. However, the minimization, which requires a tuning between the top loop and the $\psi$-mass to achieve a small $\theta$, automatically generates an extra factor $\sin^2 \theta$ in the Higgs mass, thus lowering the scale to $v$. In this model, also, the Higgs mass can be rewritten as

$$m^2_h = \frac{y_t^2 C_t f^2 \sin^2 \theta}{4} = \frac{C_t m^2_t}{4},$$

(15)

thus $m_h = 125$ GeV requires $C_t \sim 2$, which is a well reasonable value.

For the singlet, the mass reads

$$m^2_\eta = \frac{f^2}{4} \left( 2 C_m \cos \theta + y_t^2 C_t \sin^2 \theta \right)$$

$$= \frac{y_t^2 C_t f^2}{4} = \frac{m^2_\eta}{\sin^2 \theta}.$$

(16)

It is interesting to notice that in models where this symmetry breaking is achieved in a renormalizable way, these estimates change drastically [21]: in fact, the quadratic divergences would be renormalized (even though the naturalness problem is not solved) and the value of the masses will be determined by higher order terms in the $\theta$-expansion.

3.2. EWPTs and LHC signatures

At this point, the value of the minimum $\theta$ is one of the free parameters of the model. The main constraint on it comes from effects on electroweak precision measurements, mainly to the $S$ parameter. The value of $\theta$ that can be attained is crucial for predicting the LHC phenomenology of this model, because it allows to determine the mass of the additional pNGB $\eta$, and of the heavier spin-1 resonances. The correction to $S$ can be estimated by calculating the effect of the modified couplings of the 125 GeV Higgs, and of the heavier singlet $\sigma$, while the contribution of the dynamics can be approximated by a loop of $\psi$'s. Such an estimate makes sense if the contribution of heavier resonances is dominated by the lightest vector ones. The numerical impact of electroweak precision tests (EWPTs) has been studied in [22], and it depends crucially on the couplings of the $\sigma$ to the SM particles. Neglecting the contribution of $\sigma$, we find that EWPTs prefer values $\sin \theta < 0.24$.

With this range in mind, we can estimate the production cross section for the $\eta$ at the Run II at the LHC [22], which will collide protons at a center of mass energy of 13 TeV. The results, for the two leading channels, are shown in Figure 1: in blue we show the pair production by vector boson fusion (VBF), $pp \rightarrow jj\eta$, as a function of the mass, where $j$ are jets produced by forward light quarks from the proton and the two singlets couple to EW gauge bosons at tree level. We see that in the whole range considered, the cross section is always smaller than 0.5 fb, which would correspond to about 50 events produced after 100/fb of collected data (3 years of Run II). The second best channel is single production by gluon fusion, triggered by a top loop. We should also stress that in the region preferred by EWPTs, $m_\eta > 528$ GeV and the cross sections drop to very small values: $\sigma_{\text{VBF}} < 5$ ab and $\sigma_{\text{ggfusion}} < 1.5$ ab. We can therefore conclude that the singlet $\eta$ cannot be observed at the LHC due to the too feeble production rates.
The model also contains spin-1 states, whose masses can be calculated on the Lattice [19]. By properly rescaling the Lattice results, the masses are predicted to lie in the range

\[ m_{\alpha} = \frac{3.3 \pm 0.7}{\sin \theta} \text{ TeV} > 14 \pm 3 \text{ TeV}, \]  
\[ m_{\rho} = \frac{2.5 \pm 0.5}{\sin \theta} \text{ TeV} > 10 \pm 2 \text{ TeV}, \]  

(17)  
(18)

where \( \rho \) and \( \alpha \) label the vector and axial-vector resonances, and the lower limit corresponds to the EWPT preferred region. From these values we can immediately see that the LHC, even during Run II, does not have enough energy to produce on-shell resonances.

4. Conclusions

The possibility that the discovered 125 GeV Higgs is a composite state of an underlying strong dynamics is still viable, especially if the Higgs arises as a pseudo-Nambu-Goldstone boson of the breaking of a large global symmetry of the dynamics. In this paper we follow a new approach relying on the existence of a simple underlying dynamics based on a simple confining gauge group and fermionic matter. This approach allows some calculability, in the sense that the symmetry breaking pattern can be predicted uniquely and that Lattice results can be used to constrain the masses of some of the resonances.

We showed that the minimal case, based on a confining SU(2) gauge symmetry with 2 Dirac fermions in the fundamental representation, can lead to a realistic model for the discovered Higgs boson, which arises as a pNGB of the global symmetry breaking SU(4)/Sp(4). Electroweak precision tests can be evaded with a mild fine tuning in the potential, of the order of a few \%. We also showed that the model predicts the absence of signals of new physics at the LHC, both Run I and Run II. In fact, the only new light state is a singlet \( \eta \) which can be pair and singly produced at the LHC with feeble sub-fb cross-sections. The event rates are therefore too small to yield detectable signals. At the same time, Lattice results show that heavier spin-1 states are too heavy to be produced, as their mass range is expected above 10 TeV. Therefore, this model
is a good benchmark for a higher energy proton collider, following the recent proposals of 100 TeV center of mass energies.

We conclude by stressing that other possible symmetry patterns, and underlying dynamical models, are possible, which lead to additional light pNGBs. Thus, we can still hope that new scalar states can be observed at the LHC in these extended scenarios, and that maybe one such state can play the role of the Dark Matter in the Universe.

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