

# New physics: theoretical developments

*Christophe Grojean*

CERN, Physics Department, Theory Unit, CH-1211 Geneve 23, Switzerland  
Institut de Physique Théorique, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France

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 present various recent models of physics at the Fermi scale, 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.

## 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  $e^+e^- \rightarrow W^+W^-$ . 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  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$ ? 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] for recent reviews.)

## 2 The Higgs boson: a simple picture that calls for new physics

The Higgs mechanism is at best a description, but certainly not an explanation, of electroweak symmetry breaking (EWSB) since there is no dynamics that would explain the instability of the Higgs potential at the origin. Moreover, it also jeopardizes our current understanding of the SM at the quantum level since the Higgs potential suffers from two sources of radiative instabilities: (i) the mass term is quadratically divergent while (ii) the quartic Higgs-self interactions could easily be driven to a Landau pole or to a rolling vacuum at very large value of the Higgs field if the Higgs mass does not lie in the window around 130 and 170 GeV. New physics is required to solve these “naturalness” [11, 12, 13], “triviality” [14, 15] and “(meta)stability” [16, 17] problems. In particular the naturalness problem, also known as gauge hierarchy problem, has been the main source of inspiration/excuse for theoretical speculations on the structure of new physics above the weak scale. In the presence of generic new physics, the Higgs mass becomes UV sensitive unless a symmetry prevents it, in which radiative corrections will generate a contribution that is screened by this symmetry breaking scale and not by the UV scale of new physics. Such a symmetry should act non-linearly on the Higgs field and examples include (i) supersymmetry (SUSY), (ii) global symmetry when the Higgs appears as a pseudo Nambu–Goldstone bosons, (iii) gauge symmetry when the Higgs appears as a component of the gauge field along an extra spatial dimension [18, 19] (see Refs. [20, 21] for modern realizations of this idea in the context of branes and orbifold symmetry breaking and see Ref. [22] for a recent review), . . .

There are of course additional arguments for the existence of new physics beyond the SM: (i) at the level of  $2 \div 3$  standard deviations, there are a few discrepancies between EW data and the SM predictions for quantities like  $g_\mu - 2$  or the left-right asymmetries in the hadronic and leptonic sectors; (ii) the neutrino masses can be generated only if new states are added to the SM or if a new scale is introduced; (iii) the SM does not provide any dynamics to generate the observed matter-antimatter asymmetry; (iv) no SM particle can account for the dark matter (DM) relic abundance; (v) with may be the exception of the Higgs boson itself [23], no SM particle can drive inflation; (vi) there is no rationale for the pattern of fermion masses and mixing angles; (vii) the strong CP problem remains unexplained; (viii) the charge quantization most likely requires an embedding of the SM gauge group into a bigger symmetry which would unify all the fundamental interactions; (ix) gravity is left aside.

## 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 ( $\sigma^a$ ,  $a = 1, 2, 3$ , are the usual Pauli matrices):

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

Thanks to this Goldstone boson equivalence [25], 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:

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

In the absence of any new weakly coupled elementary degrees of freedom canceling this growth, perturbative unitarity will be lost around<sup>1</sup> 1.2 TeV 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  $\rho$  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 [26]:

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

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

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

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  $W_L W_L \rightarrow hh$ . 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 Refs. [?, 27]) 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.

<sup>1</sup>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  $\sigma$ -model with a breaking scale  $v$ .

## 4 (Pseudo Nambu–Goldstone) composite Higgs models

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 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 [28]). Attempts to construct composite Higgs models in 4D have been made by Georgi and Kaplan (see for instance Ref. [29]) 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<sup>2</sup>.

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  $\xi = v^2/f^2 \rightarrow 0$ , 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  $\xi \rightarrow 1$ , 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 resonances.

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,  $m_\rho$ , 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  $m_\rho$  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. [33], and the effective Lagrangian generically takes the form ( $g, g'$  are the SM EW gauge couplings,  $\lambda$  is the SM Higgs quartic

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<sup>2</sup>A Higgs localized on the IR brane of a warped model, like in the original models of Randall–Sundrum [30], would also correspond to a 4D composite Higgs boson in the dual interpretation [31, 32]. However, this composite Higgs state would not be a pseudo Nambu–Goldstone boson and there is no reason why it would be lighter than the other resonances of the strong sector (in other words, the original Randall–Sundrum models solve the gauge hierarchy problem but they do not address the little hierarchy problem. Hence the need to rely on the  $A_5$  degree of freedom.

coupling and  $y_f$  is the SM Yukawa coupling to the fermions  $f_{L,R}$ )<sup>3</sup>:

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

All the coefficients,  $c_H, c_T, \dots$ , 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 [34] (the divergence in  $T$  will eventually be screened by resonance states if the strong sector is invariant under the custodial symmetry). Typically, this one-loop IR contribution imposes [35, 36]  $f^2/v^2 \geq 3 \div 4$  (see Refs. [37, 38, 39, 40] 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 [41].

One may worry that because of the modified Yukawa interactions induced by the operator  $c_y$ , the mass matrices and the Yukawa interaction matrices are not simultaneously diagonalizable, leading to potentially dangerous flavor changing neutral currents (FCNC). Actually, the coefficient  $c_y$  is flavor universal (at least among the light fermions) and the flavor structure of the higher dimensional Yukawa interactions are proportional to the SM Yukawa interactions. In other words, the effective Lagrangian (5) satisfies the minimal flavor violation hypothesis [42]. And therefore no Higgs-mediated FCNC is generated at the leading level (see however Refs. [43, 44] for a detailed discussion on this subject). Besides the Higgs boson, the other resonances of the strong sector can generate too large flavor violating amplitude. The extra dimensional realizations of the composite Higgs models provide some clues on this issue. In these setups, the hierarchy among the fermion masses and mixing angles is the result of flavor dependent wavefunctions [45, 46] (the dual interpretation is that the light fermions are only *partially* composite [47]). At the same time, a built-in RS–GIM mechanism [48, 49] highly suppress the FCNC processes and the KK scale, equivalent to  $m_\rho$ , can be lowered to 20 TeV [50] or even to 5–6 TeV [51] (to be compared to the generic  $10^{4\div 5}$  TeV scale in the absence of any suppression), the stringent constraint actually coming for CP violation in the kaon sector [52].

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

<sup>3</sup>This effective Lagrangian captures the physics of a Higgs boson identified as pseudo Nambu–Goldstone boson emerging from a *strongly* interacting sector. The scaling of the operators will be different in perturbative theories. For instance, in Little Higgs models with a product group gauge symmetry, there will be sizable corrections to the non-linear  $\sigma$ -model structure when none of the gauge couplings is strong. The Higgs potential, in the case of a strongly interacting light Higgs (SILH), is also fully saturated by quantum effects, i.e., generated radiatively, while in Little Higgs models, the quartic interactions can be larger [33].

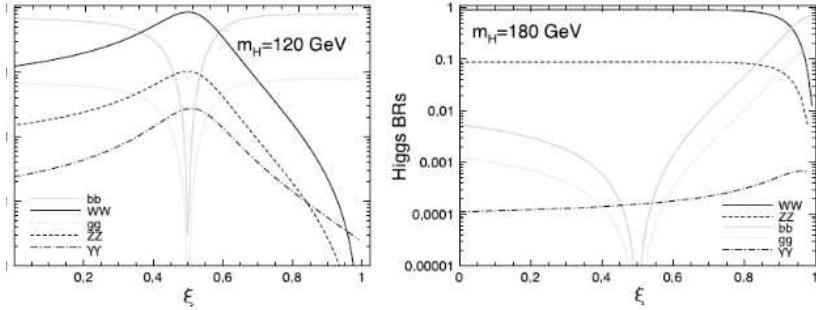


Figure 1: Higgs decay branching ratios as a function of  $\xi = v^2/f^2$  for SM fermions embedded into fundamental representations of  $SO(5)$  for two benchmark Higgs masses:  $m_h = 120$  GeV (left plot) and  $m_h = 180$  GeV (right plot). For  $\xi = 0.5$ , the Higgs is fermiophobic, while in the technicolor limit,  $\xi \rightarrow 1$ , the Higgs becomes gaugephobic. From Ref. [26].

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:

$$g_{h\bar{f}\bar{f}}^\xi = g_{h\bar{f}\bar{f}}^{\text{SM}} \times (1 - (c_y + c_H/2)v^2/f^2), \quad (6)$$

$$g_{hWW}^\xi = g_{hWW}^{\text{SM}} \times (1 - c_H v^2/(2f^2)). \quad (7)$$

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 effective Lagrangian (5) should be viewed as the first terms in an expansion in  $\xi = v^2/f^2$ . When departing significantly from the SM limit,  $v^2/f^2 \sim \mathcal{O}(1)$ , the series has to be resummed. Explicit models, like the ones constructed in 5D warped space [53], provide examples of such a resummation, allowing to study the effects of the anomalous Higgs couplings up to the technicolor limit. Figure 1 shows the modification in the branching ratios for the Higgs decays to SM particles in the minimal composite Higgs model with fermions embedded into fundamental representations of  $SO(5)$ .

The Higgs anomalous couplings affect the decay rates as well as the production cross sections of the Higgs [33, 54, 55]. 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. [56] and Answers to questions).

Will the LHC be able to probe these deviations in the couplings<sup>4</sup> of the Higgs? The contribution of the operator  $c_H$  is universal for all Higgs couplings and therefore it does not affect

<sup>4</sup>The physics of the composite models, as captured by the effective Lagrangian (5), selects the operators  $c_H$  and  $c_y$  as the most important ones for LHC studies, as opposed to totally model-independent operator analyses [57, 58] which often lead to the conclusion that the dominant effects should appear in the vertices  $h\gamma\gamma$  and  $hgg$ , since their SM contribution occurs only at loop level.

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  $b, \tau, \gamma$  and (virtual) weak gauge bosons. At the LHC with about  $300 \text{ fb}^{-1}$ , it is possible to measure Higgs production rate times branching ratio in the various channels with 20–40 % precision [59, 60]. 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  $5 \div 7 \text{ TeV}$ .

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 the very high-energy regime. 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

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

The growth with energy of the amplitudes is strictly valid only up to the maximum energy of our effective theory, namely  $m_\rho$ . The behaviour above  $m_\rho$  depends on the specific model realization. In 5D models, the growth of the elastic amplitude is softened by Kaluza–Klein modes exchange [61], 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 [62]. The most promising channels correspond to purely leptonic decays of the  $W$ 's, though semileptonic decay channels have also been considered recently [63, 64]. 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 [26].

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

$$\mathcal{A}(Z_L^0 Z_L^0 \rightarrow hh) = \mathcal{A}(W_L^+ W_L^- \rightarrow hh) = \frac{c_H s}{f^2}. \quad (9)$$

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 [26] has shown that the best channel for discovery involves 3 leptons in the final states, with both Higgs bosons decaying to  $W^+ W^-$ :  $pp \rightarrow hhjj \rightarrow 4Wjj \rightarrow l^+l^-l^\pm \not{p}_T 4j$ . 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):  $a = 1 - c_H v^2 / (2f^2)$ ,  $b = 1 - 2c_H v^2 / f^2$ . A Monte-Carlo simulation with simple kinematic cuts concludes [26] that the signal significance at the LHC operating at  $\sqrt{s} = 14$  TeV with  $300 \text{ fb}^{-1}$  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  $5\sigma$  discovery can be reached with less than  $1 \text{ ab}^{-1}$  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 [65].

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 [35, 39, 66, 67, 68, 69, 70, 71]. In particular the same-sign dilepton final states offer a sensitive probe to the top partners [67, 71] with a discovery potential up to 500 GeV (resp. 1 TeV) with about  $50 \text{ pb}^{-1}$  (resp.  $15 \text{ fb}^{-1}$ ).

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 [72] together with the sLHC [73] can be easily made.

## 5 5D Higgsless models

In composite models, when the compositeness scale gets close to the weak scale, the Higgs boson effectively decouples. This Higgsless limit is easily reached in 5D dimensional setups and offers a new point of view on the mass problem. In a sense, the EWSB itself is achieved via boundary conditions (rather than by a Higgs vacuum expectation value). According to the Einstein's relation between the mass and the momentum ( $\vec{p}_3$  denotes the momentum along the usual 3 spatial dimension and  $p_\perp$  is the momentum along the extra dimension):

$$m^2 = E^2 - \vec{p}_3^2 - p_\perp^2, \quad (10)$$

a transverse momentum,  $p_\perp$ , simply appears as a mass from the 4D point of view. And the mass problem reduces to a problem of quantum mechanics in a box: suitable boundary conditions will generate a transverse momentum for the appropriate particles. Nonetheless, an immediate question arises: is it better to generate a transverse momentum than to introduce by hand a symmetry breaking mass for the gauge field? In other words, how is unitarity restored? In full generality, the elastic scattering amplitude of a massive Kaluza–Klein (KK) gauge field would have terms that grow with the fourth and the second powers of the energy

$$\mathcal{A} = \mathcal{A}^{(4)} \left( \frac{E}{M} \right)^4 + \mathcal{A}^{(2)} \left( \frac{E}{M} \right)^2 + \mathcal{A}^{(0)} + \dots \quad (11)$$

In the SM,  $\mathcal{A}^{(4)}$  is automatically vanishing due to gauge invariance, while  $\mathcal{A}^{(2)}$  vanishes via the exchange of the physical Higgs boson. In 5D Higgsless models [74, 75], the unitarization of the  $WW$  scattering amplitudes follows from the exchange of all the KK excitations of the  $W$ . In order for this unitarization to actually happen, the couplings and the masses of the KK excitations have to obey the following sum rules<sup>5</sup> [74]:

$$\begin{aligned} g_{WWWW}^2 &= g_{WW\gamma}^2 + g_{WWZ}^2 + \sum_n g_{WWZ^{(n)}}^2 \\ 4g_{WWWW}^2 M_W^2 &= 3g_{WWZ}^2 M_Z^2 + 3 \sum_n g_{WWZ^{(n)}}^2 M_{Z^{(n)}}^2. \end{aligned} \quad (12)$$

The effective couplings among the KK states are dictated by the gauge structure of the 5D theory and it is easy to show that the two sum rules are automatically satisfied, provided there is no hard breaking of gauge invariance, i.e., if the 5D gauge fields obey Dirichlet or Neumann boundary conditions at the end points of the 5<sup>th</sup> dimension.

The most distinctive feature of the Higgsless models is, of course, the absence of a physical scalar state in the spectrum. Yet, *the absence of proof is not the proof of the absence* and some other models exist in which the Higgs is unobservable at the LHC (for a recent review, see for instance Ref. [76]). Fortunately, Higgsless models are characterized by other distinctive features, such as (i) the presence of spin-1 KK resonances with the  $W, Z$  quantum numbers, (ii) some slight deviations in the universality of the light fermion couplings to the SM gauge bosons and (iii) some deviations in the gauge boson self-interactions compared with the SM. References [77, 78] studied the production of the lightest KK excitations of the  $W$  and the  $Z$  via vector boson fusion. The most recent study [79] included also the more model-dependent possibility of Drell–Yan production. At the LHC, about  $10 \text{ fb}^{-1}$  of luminosity will be necessary for the discovery of the resonances in the 700 GeV mass range. A precise measurement of the couplings of these resonances or the search for some deviations in the SM couplings will require a more precise machine, such as an ILC or CLIC.

## 6 Conclusion

The SM has emerged as a successful description, at the quantum level, of the interactions among the elementary particles but it is at odds in what concerns the masses of these elementary

<sup>5</sup> $g_{WWWW}^2$  is the quartic  $W$  self-coupling,  $g_{WWX}$  is the cubic coupling between two  $W$ 's and  $X$  and  $Z^{(n)}$  denote the KK excitations of the  $Z$ . The two sum rules (12) correspond to the  $W^\pm W^\pm \rightarrow W^\pm W^\pm$  channel and similar sum rules will apply to other  $WZ$  channels.

particles. EW interactions certainly need three Nambu–Goldstone bosons to provide a mass to the  $W^\pm$  and the  $Z$  gauge bosons. But they also need new dynamics to act as a UV moderator and ensure a proper decoupling at high energy of the extra polarizations associated to the mass of these spin-1 fields. After many years of theoretical speculations and in the absence of any direct experimental evidences, it is not yet possible to tell whether the strength of this new dynamics is weak or strong. In many regards, this question is equivalent to asking whether a light Higgs boson exists or not. However it is also possible and plausible that a light and narrow Higgs-like scalar does exist but it is actually a bound state from some strong dynamics not much above the weak scale. Such composite models provide a continuous dynamical deformation of the SM, with the same spectrum as the SM up to 2÷3 TeV.

The LHC is prepared to discover the Higgs boson or whatever replaces it. To this end, the collaboration between experimentalists and theorists is more important than ever to make sure, for instance, that no unexpected physics is missed because of triggers and cuts. In this regards, signature-motivated approaches like ‘unparticles’ [80], ‘hidden valleys’ [81] or ‘quirks’ [82] should be encouraged.

Also, it should not be forgotten that the LHC will be a top(-quark) machine. And there are many reasons to believe that the top quark can be an important agent in the dynamics triggering the electroweak symmetry breaking.

Finally, it is also worth mentioning that most theories for the Fermi scale can be probed outside of colliders. The numerous experiments searching for Dark Matter nicely exemplify the strong cosmo-astro particle connection, and, for sure, if weakly interacting massive particles (WIMPs) are part of the dynamics of EWSB, their direct or indirect detections would provide valuable information. An intriguing signature [83] arises when the WIMPs can annihilate directly into a photon and a Higgs boson, giving rise to a line in the gamma ray spectrum whose position reflects the Higgs mass: the observation of such a line would be the first direct observation of a Higgs production process! The complementarity between astrophysics and collider physics is not restricted to Dark Matter. Another compelling example concerns gravitational waves: a background of stochastic gravitational waves peaked around mHz frequencies would be an indication of a strong EW phase transition due for instance to enhanced Higgs self-couplings [84, 85].

In any case, more than ever, experimental data are eagerly awaited to disentangle what may be the most pressing question faced by particle physics today: How is electroweak symmetry broken?

## Acknowledgements

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## Discussion

**Majid Hashemi (University of Antwerp):** What changes at the LHC if there are additional contributions from coupling constant terms in the Higgs sector? Is it only branching ratios or kinematics?

**Answer:** Obviously, when the Higgs couplings are modified compared to the Standard Model, the Higgs production cross sections and the Higgs decay branching ratios are affected [1]. Therefore, the searches for the Higgs boson at the LHC, as well as the LEP/Tevatron exclusion bounds are modified [2]. Figure 2 for instance reports the amount of luminosity needed for discovery in the most promising channels for the minimal composite Higgs models of Ref. [3]. Notwithstanding the fact that, in composite Higgs models, the Higgs boson emerges from a strongly interacting sector, in processes with a single Higgs boson involved the kinematics of the signal is not modified. As example, the  $p_T$  distribution in the gluon fusion process will be exactly the same as in the SM model up to an overall normalization factor. The reason is that the  $p_T$  distribution is obtained from the three processes: (i)  $gg \rightarrow h + g$ , (ii)  $gq \rightarrow h + q$  and  $g\bar{q} \rightarrow h + \bar{q}$  and (iii)  $q\bar{q} \rightarrow h + g$ . The three processes will rescaled the same way and therefore the overall normalization of the  $p_T$  distribution will change but not its shape. The situation is totally different when two particles from the strong sector are involved [1, 4, 5]. Two typical examples are the scattering of longitudinally polarized massive gauge bosons or the double Higgs production via vector boson fusion. The strong sector makes the signal much harder. Figure 3 depicts the differential cross section for  $pp \rightarrow WW jj$  as function of the invariant mass of the  $WW$  pair for the SM model ( $\xi = 0$ ) and for the technicolor limit of composite Higgs model ( $\xi = 1$ ).

**Guido Altarelli (University of Roma III and CERN):** In composite Higgs models you have bounds on the couplings of new operators from precision tests, flavour physics and so on. This implies the need for fine-tuning. How would you quantify the amount of necessary fine-tuning in these models? How does it compare with SUSY?

**Answer:** Electroweak precision tests and flavor data certainly restrict the parameter space of any composite Higgs models. The dominant effects arise at tree-level from the exchange of the resonances of the strong sector. For instance, the vector spin-1 resonances give rise to a contribution to the Peskin–Takeuchi parameter<sup>1</sup>  $S$  scaling like  $m_W^2/m_\rho^2$ ,  $m_\rho = g_\rho f$  being the mass scale of the resonances ( $g_\rho$  is the typical coupling of the strong sector and  $f$  is the decay constant of the strong sector the Higgs is emerging from). The scale that controls the Higgs physics is the strong decay constant  $f$  and not the mass scale of the resonances, so that the large UV dominated contribution to  $S$  can be screened by increasing the coupling of the strong sector: this is a huge advantage

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<sup>1</sup> $T$  can always be protected by custodial symmetry in the strong sector. Actually, a careful analysis [6] of complete electroweak constraint reveals that the deviation of the coupling of the left-handed  $b$  quark to the  $Z$  gauge boson gives more stringent constraints than corrections to the oblique parameters. A particular realization of the custodial symmetry [7] can however relax significantly this constraint [8].

of composite Higgs models over regular technicolor models. However, there is a second contribution to  $S$  emerging at one-loop from the IR degrees of freedom as a result of the modifications of the Higgs couplings: the cancellation occurring in the SM between the gauge and the Higgs contributions to  $S$  does not hold anymore and it results in a logarithmic divergence proportional to the Higgs anomalous coupling [9]. Typically, this IR contribution imposes a lower bound on the compositeness scale of the Higgs:  $\xi = v^2/f^2 \approx 0.2 \div 0.3$ . Since the ratio  $\xi$  is the result of the dynamics generating the Higgs potential, forbidding larger values of  $\xi$  certainly restricts the allowed parameter space compatible with data. For instance, a typical Higgs potential has the form  $V(h) = A \sin^2 h/f - B \sin^2 h/f \cos^2 h/f$  which, for  $B > |A|$ , has a global minimum at  $\xi = \langle \sin^2 h/f \rangle = (1 - A/B)/2$ . This certainly amounts to some level of fine-tuning in any particular model. For instance, Fig. 4 displays the region of parameter space fulfilling the electroweak constraints in a concrete model built in warped 5D: it gives a feeling of the fine-tuning necessary in these models, which can be estimated to be of the order of 20÷30%, compared to a typical  $\mathcal{O}(1\%)$  fine-tuning in SUSY models. But it is also true that the outcome of the SUSY models are more predictive while the composite Higgs models do not offer a complete description of the strong sector at the origin of EWSB above the scale  $4\pi f$ .

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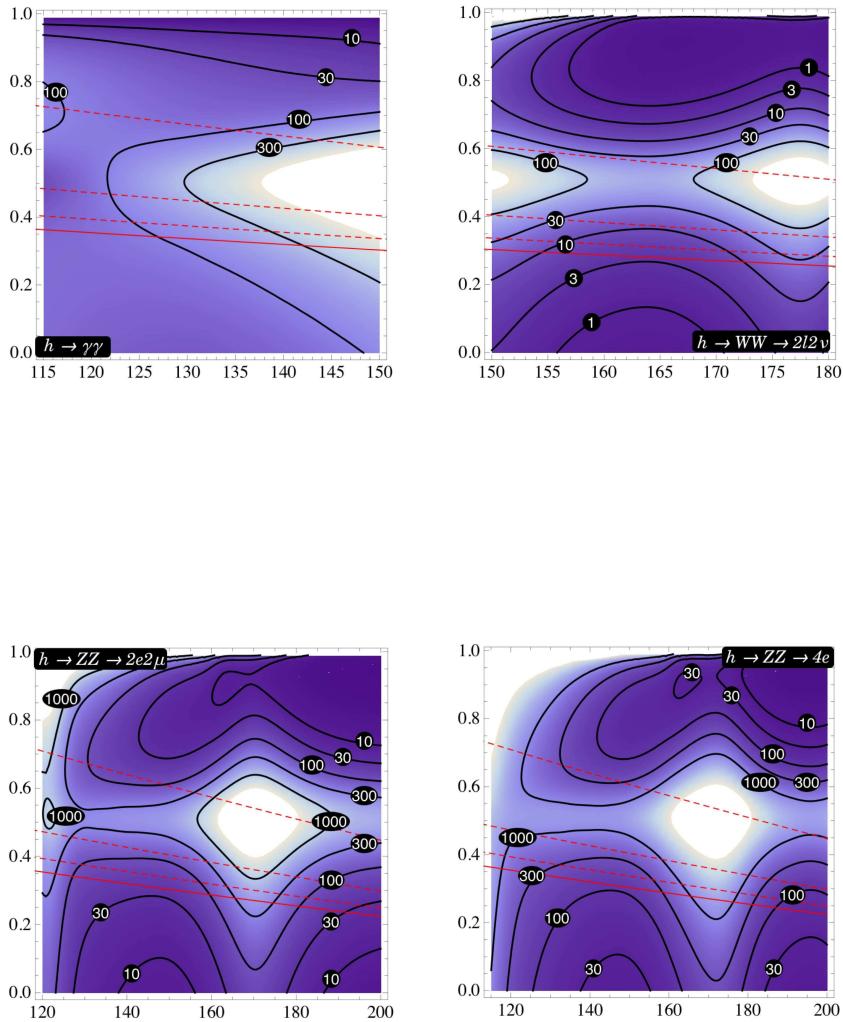


Figure 2: Luminosity (in  $\text{fb}^{-1}$ ) needed for discovery in the most promising channels with the CMS detector as a function of the Higgs mass (horizontal axis, in GeV) and the parameter  $\xi = v^2/f^2$  (vertical axis), measuring the amount of compositeness of the Higgs boson. From Ref. [2].

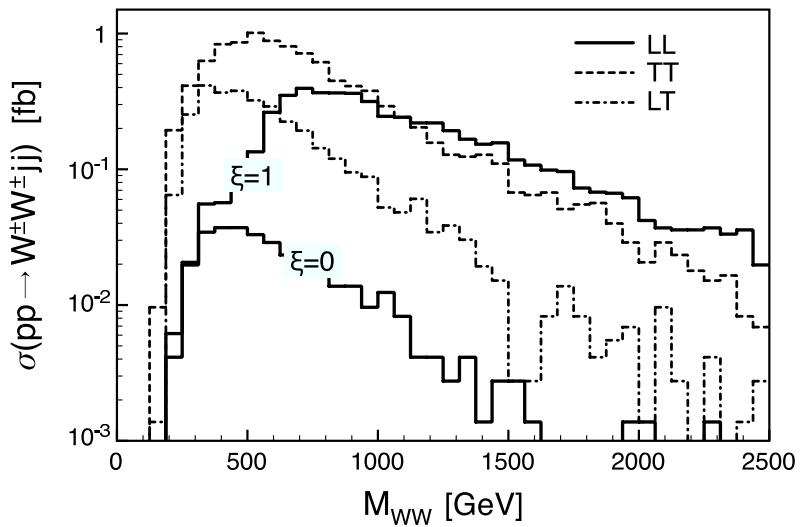


Figure 3: The differential cross section for  $pp \rightarrow WW\bar{q}q$  as function of the invariant mass of the  $WW$  pair for the SM model ( $\xi = 0$ ) and for the technicolor limit of composite Higgs model ( $\xi = 1$ ). The strong interaction makes the signal much harder. From Ref. [4].

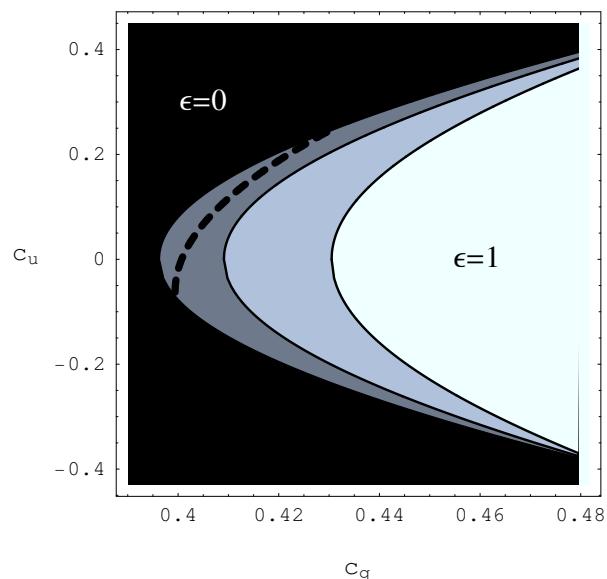


Figure 4: The electroweak precision data exclude large portions of the parameter space of a typical composite Higgs models built in warped 5D: in the dark region, no EWSB occurs, while in the white region EWSB is maximal ( $v \sim f$ ). Only the dark-grey area is compatible with all electroweak constraints. From Ref. [8].