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The non-standard model Higgs

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Summary. — This is the write-up of the talk presented at the XXV Rencontres de Physique de La Valle d'Aoste (La Thuile), aimed to introduce the ideas of Composite Higgs Models to an experimental audience. We review the basic features of theories where the Higgs is a composite state and its phenomenological consequences at LHC. We also emphasize the possibility of a heavy Higgs which could provide a first experimental hint on this type of models.

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1. – Introduction

When these proceedings are published the LHC will have hopefully found evidence of the elusive Higgs boson, the only missing piece of the Standard Model (SM). Confirming or rejecting the SM will however likely require significant more work. In this talk I will review Composite Higgs Models (CHM) which are a realistic possibility for the physics beyond the Standard Model. In this scenarios the Higgs boson is a Goldstone boson (GB) of some strongly coupled dynamics, generalizing technicolor ideas. The presence of a physical Higgs allows to obtain models which are in reasonable agreement with experimental data and could be soon tested at the LHC.

2. – Weak or strong dynamics?

The basic question that the LHC will answer is whether the breaking of electro-weak symmetry is due to weak or strong dynamics. In the SM the first option is realized and electro-weak symmetry is broken spontaneously by a scalar doublet of hypercharge 1/2 which acquires a VEV,

$$H(x) = U(x) \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \qquad v = 174\,\text{GeV}. \tag{1}$$

$U(x)$ is an $SU(2)$ matrix and h a real scalar. $U(x)$ describes the 3 GBs associated to the breaking: these degrees of freedom are the longitudinal polarization of W and Z and effectively they have been already discovered since we have measured their masses. One important feature is that the Higgs Lagrangian has an approximate global symmetry $SO(4) \sim SU(2)_L \otimes SU(2)_R$ broken spontaneously to $SU(2)_{L+R}$ by the Higgs VEV. This symmetry, known as "custodial", guarantees the correct ratio of W and Z masses at tree level and is the starting point of any successful theory of electro-weak symmetry breaking. The real scalar $h(x)$ describes the physical Higgs and is the only missing piece within the SM. If the SM is correct the only unknown is the Higgs mass, or equivalently quartic coupling,

$$m_h = \sqrt{\lambda}\, v. \tag{2}$$

In principle a physical Higgs is not needed to break the electro-weak symmetry. In this case the scattering amplitudes of longitudinal gauge bosons become strongly coupled near the electro-weak scale,

$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{1}{2\,v^2}(s+t), \tag{3}$$

and perturbative unitarity is lost around $\Lambda \sim 2\,\text{TeV}$. This simply indicates that new physics must appear below λ but does not require necessarily a Higgs particle.

Indeed electro-weak symmetry breaking without a Higgs is already realized in nature once. In QCD with two massless flavors electro-weak symmetry is broken by the chiral condensate

$$\langle 0|\bar{\Psi}_L^i \Psi_R^j + \bar{\Psi}_R^i \Psi_L^j|0\rangle = \Lambda_{QCD}^3\, \delta_{ij} \longrightarrow \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}}\,. \tag{4}$$

Famously the pions are the GB associated to the spontaneous breaking of chiral symmetry and they would become longitudinal polarizations of W and Z in the absence of other effects. The mass would be only $m_W \simeq g f_\pi \simeq 30\,\text{MeV}$. This clearly does not work phenomenologically but the new strong interaction with the appropriate scale,

$$f = \sqrt{2}\, v, \tag{5}$$

could very well break the electro-weak symmetry and reproduce, because of the unbroken $SU(2)_{L+R}$ symmetry, the known masses of W and Z bosons. This is the idea of technicolor. In this case the longitudinal polarizations of W and Z are the technipions associated to the chiral symmetry breaking of the technicolor theory. Their scattering, as the one pions, is unitary because they are composite objects made of constituents (techniquarks). There is no analog of the Higgs particle but we expect, in analogy with QCD, techni-resonances of various spin which may also partially unitarize scattering of W and Z.

We emphasize that this is the only truly satisfactory explanation of the separation of fundamental scales that we are aware of. Starting from order one gauge couplings at a high scale, perhaps the Planck scale $M_p = 10^{19}\,\text{GeV}$, the coupling grows in the infrared due to the logarithmic running becoming non-perturbative at an exponentially smaller scale. When this happens, similarly to QCD, we expect confinement to take place and a mass gap to be generated. This phenomenon, known as dimensional transmutation,

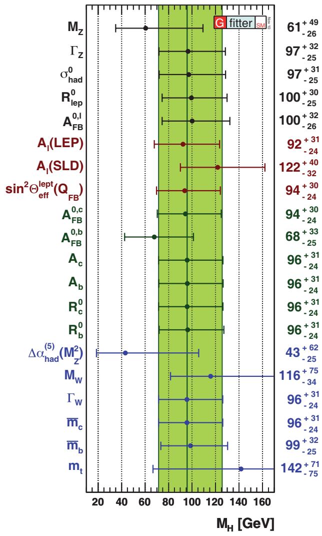

Fig. 1. – Central value of the Higgs mass removing different observables [1].

explains dynamically why the proton is so much lighter than M_p so that there is no hierarchy problem in QCD. It is natural to suspect that a similar mechanism might be at work for the electro-weak scale.

Sadly, at least the simplest versions of technicolor are ruled out: precision electro-weak measurements are problematic and even worse the standard realization of fermion masses generically leads to unacceptably large flavor changing neutral currents which are excluded by experiments by many orders of magnitude.

The situation is very different in the SM. Due to the presence of the physical Higgs there are new diagrams contributing to the scattering of longitudinal gauge bosons. For example one finds,

$$A(W_L^+W_L^- \to W_L^+W_L^-) = \frac{1}{2\,v^2}\left[s - \frac{s^2}{s-m_h^2} + (s \to t)\right], \tag{6}$$

so that the amplitude does not grow indefinitely at high energies and the theory remains weakly coupled above the electro-weak scale. Indeed, due to the fact that the theory is renormalizable, it can mathematically be consistent up to very large energies with no need for new physics.

However the SM has without doubts its weaknesses: hierarchy problem, dark matter, origin of flavor and CP violation, etc. Moreover while the SM fits the data extremely well it does not explain why electro-weak symmetry breaking happens. Of these arguments only the first clearly requires new physic at the weak scale. This might be taken as a theoretical prejudice by some so it is worth having a look at the data. The SM model provides a reasonable fit though not perfect. Statistically the probability of the fit is 15% but if only observables most directly related to the Higgs are included this drops to just 2%. In particular the b asymmetry, which is 3σ away from the SM value (the largest deviation), is necessary to pull up the central preferred value of the Higgs mass, in any case below the LEP exclusion limit, see fig. 1. This situation can only be improved with new physics in the TeV range.

3. – Composite Higgs

The idea of a composite Higgs is a natural extension of technicolor theories first studied by Georgi and Kaplan in the '80s and recently revived, see [2] for nice review and references therein. Among the states of the strong sector there could be a scalar doublet which plays the role of the Higgs. This relieves the SM naturalness problem because quadratic divergences of the Higgs mass are physically cut off by the compositeness scale. For example the top quadratic divergence

$$\delta m_h^2 \sim \frac{3y_t^2}{4\pi^2} m_\rho^2. \tag{7}$$

As a consequence the electro-weak scale can be natural if m_ρ is not too large. Conceptually composite Higgs is similar to technicolor since m_ρ can be generated by dimensional transmutation but the presence of a physical Higgs allows to improve significantly the phenomenology as we will see.

This picture is particularly compelling when the Higgs is an approximate Goldstone boson (GB) as it is massless at leading order and its existence is guaranteed by the symmetries. In the simplest realization the strong sector has a global symmetry $SO(5)$ broken spontaneously to $SO(4) \sim SU(2)_L \otimes SU(2)_R$ [3]. This delivers precisely 4 GBs with the quantum numbers of the Higgs doublet and custodially symmetric interactions. Other patterns of symmetry breaking can also be considered [4],

$$\frac{SO(6)}{SO(4)\otimes U(1)}, \qquad \frac{SU(5)}{SU(4)\otimes U(1)}, \qquad \frac{SU(5)}{SO(5)}, \qquad + \dots, \tag{8}$$

leading to an extended Higgs sector. The interaction of GBs are determined by the symmetries and by their decay constant f (analogous to the one of the pions) which is related to the compositeness scale by

$$m_\rho = g_\rho f, \tag{9}$$

g_ρ being the coupling of the strong sector.

The Higgs cannot be an exact GB. In general GBs shift under the *spontaneously* broken symmetries and this symmetry is certainly not respected in the SM, being *explicitly* broken by the SM Yukawas, gauge couplings and by the Higgs potential. The general picture in these models is the following [6]: there is a strong sector which delivers various resonances among which GBs with quantum numbers of the Higgs. At the level of the strong sector the Higgs doublet might be an exact GB in which case it is massless. One important ingredient of modern constructions is the mechanism of partial compositeness. The SM fermions and gauge fields are mostly elementary states([1]) which mix with states of the strong sector as allowed by the SM gauge symmetry. This generates Yukawas,

$$y \sim \frac{\lambda_L \lambda_R}{g_\rho}. \tag{10}$$

([1]) For the top quark its large mass requires that at least one of the chiralities must be strongly composite, in certain cases it can even be part of the strong sector.

The mixings break explicitly the global symmetry of the strong sector that guarantees the Higgs to be massless. As a consequence a potential is generated at loop level. The main contribution to the potential is normally associated to the top which breaks the global symmetry most strongly but one should keep in mind that other contributions to the potential, not associated to SM interactions, may exist.

Phenomenologically there are two main differences with respect to old technicolor theories which make these models phenomenologically appealing. First, the scale of new resonances m_ρ is not directly linked to the electro-weak VEV. If $m_\rho \gg v$ the composite Higgs approaches the SM Higgs allowing to successfully reproduce all the successes of the SM. In practice however the scale m_ρ should not be very large if the theory shall remain natural (at most few TeV). Secondly, contrary to technicolor, the SM flavor structure is generated by the mixings and this greatly reduces flavor problems. Indeed flavor changing neutral currents turn out to be proportional to the mixing SM fermions which are small for the light generations.

With some caveats a reasonable phenomenology can be imagined with a scale of compositeness of around 3 TeV. Overall the models are far from perfect but the general picture is compelling and worth taking seriously.

4. – Signatures

In the LHC era the relevant question is whether CHM can be distinguished from an elementary SM Higgs. In CHM, as in technicolor, we expect the existence of resonances whose mass roughly determines the compositeness scale. As a consequence at least some of these resonances are expected to be seen, even though this may require high energy and luminosity.

One robust feature is the presence of spin 1 resonances (electro-weak and gluonic) and spin 1/2 resonances of SM fermions. The latter are required by the mechanism of partial compositeness. An important experimental feature, at least in standard scenarios, is that the new resonances are mostly coupled to third generation quarks and to the Higgs, so they will decay into these states.

The main production mechanism of spin 1 resonances is through mixing of SM gauge bosons to composite spin 1 resonances. Colored spin 1/2 resonances could either be produced in pairs through the strong interactions or singly produced through weak-interactions. In certain cases the mass of these states could be lower than the overall dynamical scale making their discovery less changeling.

The other crucial experimental difference of CHM relative to the SM are the modified couplings. The coupling of the Higgs to gauge and matter fields can be parametrized as,

$$
\begin{aligned}
g_{hW^+W^-} &= i\sqrt{2}\frac{m_W^2}{v}\,a, \\
g_{h^2W^+W^-} &= i\frac{m_W^2}{2v^2}\,b, \\
g_{hf\bar{f}} &= -i\frac{m_f}{\sqrt{2}v}\,c.
\end{aligned} \tag{11}
$$

The SM model predicts $a = b = c = 1$. This choice also guarantees that the theory remains perturbative, since the Higgs exactly unitarizes WW scattering and the theory is renormalizable.

This does not hold in CHM because the SM vertices are corrected, proportionally to v^2/f^2 to leading order. These corrections are moreover calculable, depending on the symmetry structure and representations of the theory. Measuring deviations from $a = b = c = 1$ would directly test the idea of a composite Higgs. In particular, WW scattering is only partially unitarized and, as in technicolor, new strong interactions are necessary, even though at a higher energy scale. Moreover production and decay of the Higgs will be modified. Practically however, unless $f \sim v$ these deviations from SM couplings will be very hard to be seen at the LHC and will likely require precision measurements at the linear collider.

There might be however a short-cut. The experimental success of the SM requires the Higgs to be light, most likely below 200 GeV. A discovery of a heavy Higgs would immediately rule out the SM and would require new physics at a relatively low scale in order to reproduce precision tests.

In CHM there is no *a priori* reason why the Higgs should be light. Indeed if the Higgs mass is natural a heavy Higgs is favored. Consider the quadratic divergences associated to the top (7). The fine tuning required to have a mass m_h can be estimated as,

$$\text{tuning} \equiv \frac{m_h^2}{\delta m_h^2} \approx \left(\frac{4\, m_h}{m_\rho}\right)^2 . \tag{12}$$

Phenomenologically the compositeness scale m_ρ should be at least 3 TeV so that the tuning is already few percent. A small fine tuning can be achieved if the Higgs is somewhat heavy. Alternatively the top quadric divergences should be cut off at a lower scale which can be realized in specific models but is not generic.

One can see that the Higgs is naturally heavy if the coupling of the strong sector is large. There can be in general several contributions to the potential [6]. One unavoidable contribution is due to the Yukawa couplings, the top being the largest. The GB nature of the Higgs allows to estimate the potential to all orders in the Higgs as

$$N_c\, \frac{y_t^2}{8\pi^2} \times \frac{m_\rho^4}{g_\rho^2} \times \hat{V}_{yuk}(H/f), \tag{13}$$

where $N_c = 3$ is the number of colors. This can be obtained by naturalness matching with the quadratic term (7). In absence of tuning $\hat{V}$ will have no hierarchies and the natural VEV of H is f. In practice one accepts a modest fine tuning of the quadratic terms so that $f > v$. This implies that one can expand the potential to quartic order to determine the Higgs VEV. Extracting the quartic from the potential one obtains the estimate

$$m_h^2 \sim N_c \left(\frac{g_\rho}{4\pi}\right)^2 y_t^2 v^2. \tag{14}$$

For large g_ρ the Higgs can already be above 200 GeV. Depending on the model even larger contributions to the potential may exist, generating an heavier Higgs. For example Higgs dependent kinetic terms by naturalness generate contributions to the potential

$$N_c\, \frac{\lambda_{L,R}^2}{16\pi^2} \times \frac{m_\rho^4}{g_\rho^2} \times \hat{V}_{kin}(H/f) \tag{15}$$

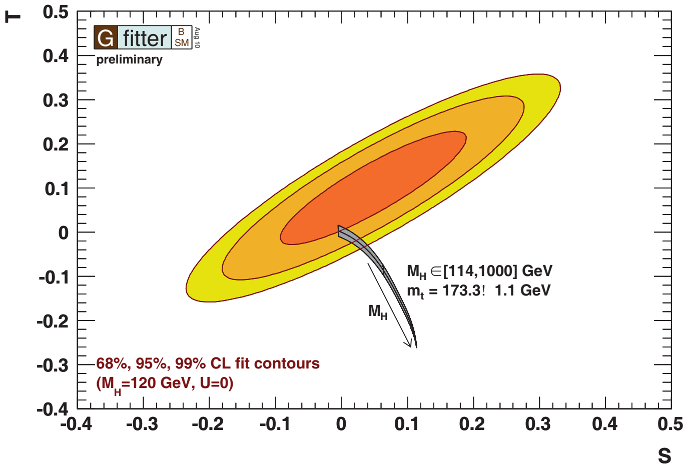

Fig. 2. – Standard Model S and T plane [1]. Large Higgs mass quickly drives the SM out of the allowed region.

which can be larger than the previous if $\lambda_L > y_t$. In this case one finds

$$m_h^2 \sim N_c \left(\frac{g_\rho}{4\pi}\right)^2 y_t g_\rho v^2, \tag{16}$$

which is easily above 200 GeV.

Inserting the Higgs mass in (12) we obtain,

$$\text{tuning} \sim \frac{v^2}{f^2}, \tag{17}$$

which shows that the tuning is controlled by f (smaller than m_ρ at strong coupling), despite the fact that physically that loops are cut off at m_ρ. This is consistent with the fact that the Higgs is heavy.

As shown in fig. 2, in the SM a heavy Higgs is ruled out by the data. While the contribution to S of a heavy Higgs is relatively small, the negative contribution to T drives quickly the SM outside of the allowed region. Within the SM this strongly favors the presence of a light a Higgs which must be lighter than 158 GeV at 2σ CL (225 GeV at 3σ CL). As a consequence a heavy Higgs must be accompanied by positive contributions to T which can only arise in the presence of new physics around the TeV scale(²).

The correction to T is even more necessary in CHM for two reasons. First with $m_\rho \sim 3\,\text{TeV}$ we expect (positive) contributions to the S parameter of the order of the experimental uncertainty. Moreover the modified couplings of the Higgs to W bosons gives an extra-negative contributions to the T parameter [7]. Depending on the mass of the Higgs a positive contribution to T in the range 0.2–.04 is typically necessary to agree with precision electro-weak tests.

(²) Yet, this new physics might be beyond the experimental reach of LHC.

Sizable contributions to T can certainly arise from the next states of theory around the scale m_ρ. In particular the mixing of quark doublets with singlets of the strong sector can give a large positive contribution if it dominates. Whether the required contribution to T is obtained remains model dependent but it is conceivable.

To summarize, our point of view is that a heavy Higgs does not worsen significantly the status of electro-weak precision tests in CHM while it is suggested by naturalness of the electro-weak scale, improving the little hierarchy problem between m_ρ and v. Finding a heavy Higgs at the LHC would immediately rule out the SM and provide a significant hint for compositeness. This an exciting possibility because LHC should be able to discover a Higgs up to 500 GeV in the near future. Moreover the decay into longitudinal W and Z, which is the main decay channel of a heavy SM Higgs, would be modified (reduced), so that measuring mass and width could allow to see deviations from the SM. If a light Higgs is found distinguishing the SM from CHMs will require much more refined tests or production of resonances at LHC14 with high luminosity.

5. – Conclusions

Finding something like the Higgs in the present LHC run is quite likely. Distinguishing the SM Higgs from a composite Higgs will take energy (14 TeV) and time (hundreds of fb^{-1} of luminosity). Unless it is heavy. In this case the SM will be ruled out with 7 TeV center-of-mass energy by 2012 and differences with SM predictions could be seen even with relatively low luminosity. We have emphasized that in CHM the Higgs can be naturally heavy. If this is realized, the discovery of CHM might be around the corner.

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