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Electroweak symmetry breaking beyond the SM

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What kind of New Physics, if any, we expect to discover at the LHC? I will try to address this formidable question by re-formulating it as follows: is the breaking of the electroweak symmetry weak or strong ?

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1. The need for an Electroweak Symmetry Breaking sector

The huge amount of data collected so far in high-energy experiments can be explained and compactly summarized by the Lagrangian

$$\begin{aligned}
&\mathscr{L} = \mathscr{L}_0 + \mathscr{L}_{mass} \\
&\mathscr{L}_0 = -\frac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \sum_{j=1}^{3} \left(\bar{\Psi}^{(j)} i \not{D} \Psi^{(j)} \right) \\
&\mathscr{L}_{mass} = M_W^2 W^+_\mu W^{-\,\mu} + \frac{1}{2} M_Z^2 Z^\mu Z_\mu \\
&\qquad - \sum_{i,j} \left(\bar{u}_L^{(i)} M^u_{ij} u_R^{(j)} + \bar{d}_L^{(i)} M^d_{ij} d_R^{(j)} + \bar{e}_L^{(i)} M^e_{ij} e_R^{(j)} + \bar{\nu}_L^{(i)} M^\nu_{ij} \nu_R^{(j)} \right) + h.c.\,,
\end{aligned} \tag{1.1}$$

where Ψ is a collective index for the Standard Model (SM) fermions and i, j are generation indices. A remarkable property of $\mathscr{L}$ is that while all the fundamental interactions among the particles (determined by $\mathscr{L}_0$) are symmetric under a local $SU(2)_L \times U(1)_Y$ invariance, the observed mass spectrum (determined by $\mathscr{L}_{mass}$) is not. In other words, the electroweak symmetry is hidden, i.e. spontaneously broken by the vacuum. In mathematical terms, the spontaneous breaking can be made more explicit by introducing as propagating degrees of freedom the Nambu-Goldstone bosons χ^a that correspond to the longitudinal polarizations of the W and Z bosons (for simplicity, from here on I will omit the lepton terms and concentrate on the quark sector):

$$\begin{aligned}
&\Sigma(x) = \exp(i\sigma^a \chi^a(x)/v), \qquad D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W^a_\mu \Sigma + i g_1 \Sigma \frac{\sigma^3}{2} B_\mu \\
&\mathscr{L}_{mass} = \frac{v^2}{4} \mathrm{Tr}\left[\left(D_\mu \Sigma\right)^\dagger \left(D_\mu \Sigma\right) \right] - \frac{v}{\sqrt{2}} \sum_{i,j} \left(\bar{u}_L^{(i)} \bar{d}_L^{(i)} \right) \Sigma \begin{pmatrix} \lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)} \end{pmatrix} + h.c.
\end{aligned} \tag{1.2}$$

The local $SU(2)_L \times U(1)_Y$ invariance is now manifest in the Lagrangian (1.2) with Σ transforming as

$$\Sigma \to U_L(x)\, \Sigma\, U_Y^\dagger(x)\,, \qquad U_L(x) = \exp\left(i\alpha_L^a(x)\sigma^a/2\right) \quad U_Y(x) = \exp\left(i\alpha_Y(x)\sigma^3/2\right). \tag{1.3}$$

In the unitary gauge $\langle \Sigma \rangle = 1$, the chiral Lagrangian (1.2) reproduces the mass term of Eq.(1.1) with

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1\,, \tag{1.4}$$

which is consistent with the experimentally measured value to quite good accuracy. The above relation follows as the consequence of a larger global $SU(2)_L \times SU(2)_R$ approximate invariance of (1.2), $\Sigma \to U_L \Sigma U_R^\dagger$, which is spontaneously broken to the diagonal subgroup $SU(2)_c$ by $\langle \Sigma \rangle = 1$, and explicitly broken by $g_1 \neq 0$ and $\lambda^u_{ij} \neq \lambda^d_{ij}$. In the limit of vanishing g_1 the fields χ^a transform as a triplet under the "custodial" $SU(2)_c$, so that $M_W = M_Z$. This equality is replaced by Eq.(1.4) at tree level for arbitrary values of g_1. Further corrections proportional to g_1 and $\lambda^u - \lambda^d$ arise at the one-loop level and are small. In fact, the success of the tree-level prediction $\rho = 1$ a posteriori justifies the omission in the chiral Lagrangian (1.2) of the additional term

$$v^2\, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma T^3\right]^2 \tag{1.5}$$

that is invariant under the local $SU(2)_L \times U(1)_Y$ but explicitly breaks the global $SU(2)_L \times SU(2)_R$. In other terms, the coefficient of such extra operator is experimentally constrained to be very small.

The chiral formulation (1.2) makes the limit of our current mathematical description most transparent: There is a violation of perturbative unitarity in the scattering $\chi\chi \to \chi\chi$ at energies $E \gg M_W$, which is ultimately linked to the non-renormalizability of the chiral Lagrangian. More specifically, the scattering amplitude grows with E^2,

$$\begin{aligned} &\mathscr{A}(\chi^a\chi^b \to \chi^c\chi^d) = A(s)\,\delta^{ab}\delta^{cd} + A(t)\,\delta^{ac}\delta^{bd} + A(u)\,\delta^{ad}\delta^{bc}\,, \\ &A(s) = \frac{s}{v^2}\left[1 + O\left(\frac{M_W^2}{s}\right)\right] \end{aligned} \tag{1.6}$$

due to the derivative interaction among four Goldstones that comes from expanding the kinetic term of Σ in eq.(1.2). Intuitively, the χ's are the degrees of freedom that are eaten in the unitary gauge to form the longitudinal polarizations of W and Z. The scattering of four Goldstones thus corresponds to the physical scattering of four longitudinal vector bosons: $V_LV_L \to V_LV_L$, with $V_L = W_L, Z_L$. Such correspondence is made rigorous by the Equivalence Theorem, which states that the amplitude for the emission or absorption of a Goldstone field χ becomes equal at large energies to the amplitude for the emission or absorption of a longitudinally-polarized vector boson. As a consequence, the physical scattering $V_LV_L \to V_LV_L$ violates perturbative unitarity at large energies $E \gg M_W$, and the leading energy behavior of its cross section is captured by that of the easier process $\chi\chi \to \chi\chi$. The merit of the chiral formulation is that of isolating the problem to the sector of the Lagrangian responsible for the mass terms for the vector bosons and the fermions.

There are thus two possibilities: *i)* either some new particles with new dynamics come in to restore unitarity before perturbativity is lost, or *ii)* the $\chi\chi$ scattering grows strong until the interaction among four χs becomes non-perturbative. This latter possibility must also be seen as the emergence of new physics, as the theory at the strong scale starts to be described by new, more fundamental, degrees of freedom. Whatever mechanism Nature has chosen, it is generally true that

There has to be some new symmetry breaking dynamics that acts as an ultraviolet completion of the electroweak chiral Lagrangian (1.2).

As required by the experimental evidence, such new dynamics must be (approximately) custodially symmetric, so as to prevent large corrections to the ρ parameter. The most important question then is the following: is this dynamics weak or strong ?

2. Strong vs Weak symmetry breaking

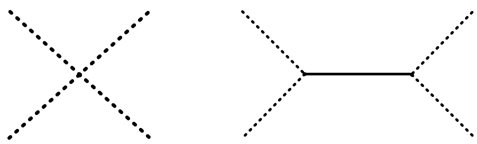
The most economical example of electroweak symmetry breaking (EWSB) sector is that of just one new scalar field $h(x)$, singlet under $SU(2)_L \times SU(2)_R$, in addition to the Goldstones χ. Assuming that h is coupled to the SM gauge fields and fermions only via weak gauging and (proto)-Yukawa couplings, the most general EWSB Lagrangian has three free parameters a, b, c [1] at the

[1] In general c can be a matrix in flavor space, but in the following we will assume it is proportional to unity, so that no flavor-changing neutral current effects originate from the tree-level exchange of h.

quadratic order in h [1]

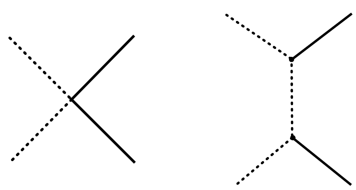
$$\begin{aligned}\mathscr{L}_H =& \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma\right)^\dagger\left(D_\mu\Sigma\right)\right]\left(1+2a\,\frac{h}{v}+b\,\frac{h^2}{v^2}+\dots\right)\\ &-\frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)}\,d_L^{(i)}\right)\Sigma\left(1+c\,\frac{h}{v}+\cdots\right)\begin{pmatrix}\lambda_{ij}^u\,u_R^{(j)}\\ \lambda_{ij}^d\,d_R^{(j)}\end{pmatrix}+h.c.\end{aligned} \tag{2.1}$$

Here $V(h)$ denotes the potential, including a mass term, for h. Each of these parameters controls the unitarization of a different sector of the theory: For $a=1$ the exchange of the scalar unitarizes the $\chi\chi\to\chi\chi$ scattering (equivalent to $V_LV_L\to V_LV_L$ at high energy) [2]



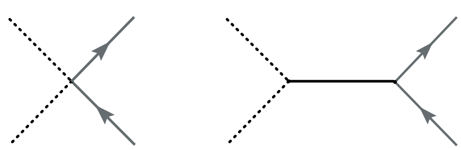
$$A(s)\simeq\frac{s}{v^2}\left(1-a^2\right)\,.$$

Since we have introduced a new particle in the theory, we have to check that also the inelastic channels involving h are unitarized. The $\chi\chi\to hh$ scattering (equivalent to $V_LV_L\to hh$ at high energy), is perturbatively unitarized for $b=a^2$:



$$\mathscr{A}(\chi^a\chi^b\to hh)\simeq\delta^{ab}\,\frac{s}{v^2}\left(b-a^2\right)\,.$$

Finally, for $ac=1$ the $\chi\chi\to\psi\bar{\psi}$ (equivalent to $V_LV_L\to\psi\bar{\psi}$ at high energy) scattering is unitarized



$$\mathscr{A}(\chi^a\chi^b\to\psi\bar{\psi})\simeq\delta^{ab}\,\frac{m_\psi\sqrt{s}}{v^2}\,(1-ac)\,.$$

Only for $a=b=c=1$ the EWSB sector is weakly interacting (provided the scalar h is light), as for example $a\neq1$ implies a strong $VV\to VV$ scattering with violation of perturbative unitarity at energies $\sqrt{s}\approx4\pi v/\sqrt{1-a^2}$, and similarly for the other channels. The point $a=b=c=1$ in fact defines what I would call the "Higgs model": $\mathscr{L}_H$ (with vanishing higher-order terms in h) can be rewritten in terms of the $SU(2)_L$ doublet

$$H(x)=\frac{1}{\sqrt{2}}\,e^{i\sigma^a\chi^a(x)/v}\begin{pmatrix}0\\ v+h(x)\end{pmatrix} \tag{2.2}$$

and gets the usual form of the Standard Model Higgs Lagrangian. In other words, χ^a and h together form a linear representation of $SU(2)_L\times SU(2)_R$. In terms of the Higgs doublet $H(x)$, the custodial

[2] In the following, dashed and solid lines denote respectively the fields χ and h, whereas solid lines with an arrow denote fermions.

invariance of the Lagrangian appears like an accidental symmetry: at the renormalizable level, all the $(SU(2)_L \times U(1)_Y)$-invariant operators are functions of $H^\dagger H = \sum_i \omega_i^2$, where ω_i are the four real components parametrizing the complex doublet H. This implies that the theory is invariant under an $SO(4) \sim SU(2)_L \times SU(2)_R$ invariance, broken down to $SO(3) \sim SU(2)_c$ in the vacuum $\langle H^\dagger H \rangle = v^2$, under which the ω_i components are rotated. The unitarity of the Higgs model can be traced back to its renormalizability, which is now evident from the Lagrangian written in terms of H.

The weakly-interacting Higgs model has two main virtues: it is theoretically attractive because of its calculability, and it is insofar phenomenologically successful, passing in particular all the LEP and SLD electroweak precision tests. Both calculability (which stems from perturbativity) and the success in passing the precision tests follow from the Higgs boson h being light. It is however well known that an elementary light scalar, such as h, is unstable under radiative corrections, hence highly unnatural in absence of some symmetry protection. It is quite possible, on the other hand, that a light Higgs-like scalar arises as a bound state of a new strong dynamics: its being composite would solve the SM Higgs hierarchy problem, while its being light would still be required to pass the electroweak tests. The Lagrangian (2.1) with generic a, b, c gives a general parametrization of such composite Higgs theories where all the other resonances have been integrated out. Away from the unitary point $a = b = c = 1$ the exchange of the light composite Higgs h fails to completely unitarize the theory, which eventually becomes strongly interacting at high energies. Similarly to pion-pion scattering in QCD, unitarity is ultimately reinforced at the strong dynamics scale through the exchange of the other (spin-1) resonances.

Insofar we have tacitly assumed that these latter are heavier than the composite Higgs. This is in fact required (unless some non-trivial symmetry protection mechanism is at work) to avoid large corrections to the precision observables, for example to the Peskin-Takeuchi S parameter. As first pointed out by Georgi and Kaplan in the eighties [2], the composite Higgs boson can be naturally lighter than the other resonances if it emerges as the (pseudo-)Goldstone boson of an enlarged global symmetry of the strong dynamics. For example, if the strong sector has an $SO(5)$ global symmetry spontaneously broken down to $SO(4) \sim SU(2)_L \times SU(2)_R$, this implies four real Goldstones transforming as a fundamental of $SO(4)$, or equivalently as a complex doublet H of $SU(2)_L$ [3]. The couplings of the SM fermion and gauge fields to the strong sector will in general break explicitly its global symmetry, thus generating a Higgs potential at the one-loop level. By naive dimensional analysis, the expected mass scale of the other resonances is $m_\rho \sim 4\pi f$, where f is the σ-model scale associated with the composite Higgs. This latter gets instead a much lighter mass $m_h \sim g_{SM} v$ at one-loop, with g_{SM} being some SM coupling, thus implying a parametric hierarchy $m_h \ll m_\rho$. In this context, the electroweak scale v is dynamically determined and will not in general coincide with f, differently from Technicolor theories where no separation of scales exists. The ratio $\xi = v^2/f^2$ sets the size of the parametric suppression in all corrections to the precision observables, as $f \to \infty$ ($\xi \to 0$) with fixed v is a decoupling limit where the Higgs stays light and all the other resonances become infinitely heavy. As a matter of fact, $v \lesssim 0.3 f$ is enough to largely suppress any correction from the heavy resonances.

3. The Higgs boson: elementary or composite?

It is at this point clear that the discovery of a light Higgs boson alone will not be sufficient to rule out the possibility of a strong electroweak symmetry breaking. Experimentally, one should measure the parameters a, b, c as precisely as possible and look for deviations from the unitary point $a = b = c = 1$. In general these parameters are independent from each other, although they will be related in specific composite Higgs models as functions of ξ. Ref. [4] also showed that the behavior of a and b at small ξ is universal whenever the light Higgs boson is part of a composite $SU(2)_L$ doublet.

A first determination of a and c will come from a precise measurement of the couplings of the Higgs to the SM fermions and vectors. This will require disentangling possible modifications of both the Higgs production cross sections and decay rates. Preliminary studies have shown that the LHC should be eventually able to extract the individual Higgs couplings with a $\sim 20\%$ precision [5], though much will depend on the value of its mass. This would imply a sensitivity on $(1-a^2)$ up to $0.1-0.2$ [4]. As stressed by the authors of ref. [6], the parameter a is already constrained by the LEP precision data: modifying the Higgs coupling to the SM vectors changes the infrared one-loop contribution to $\varepsilon_{1,3}$ ($\varepsilon_1 = \varepsilon_1^{SM} + \alpha T$, $\varepsilon_3 = \varepsilon_3^{SM} + \alpha/(4\sin^2\theta_W)S$) by an amount $\Delta\varepsilon_{1,3} = -c_{1,3}(1-a^2)\log(\Lambda^2/m_h^2)$, where $c_{1,3}$ are one-loop numerical coefficients and Λ denotes the scale at which the other resonances set on and unitarity is ultimately restored in VV scattering. For example, assuming no additional corrections to the precision observables and setting $m_h = 120\,\mathrm{GeV}$, $\Lambda = 2.5\,\mathrm{TeV}$, one obtains $0.8 \lesssim a^2 \lesssim 1.5$ at 99% CL.

Measuring the Higgs couplings will give important clues on its nature and on the role it plays in the EWSB mechanism. A "direct" probe of the strength of the symmetry breaking dynamics will however come only from a precise study of the VV scattering. A smoking gun of strong electroweak symmetry breaking would be discovering a light Higgs and at the same time finding an excess of events in $VV \to VV$ scattering compared to the SM expectation: this would be the sign that the energy-growing behavior of the scattering cross section of longitudinal W and Z's is not saturated at a low scale by the Higgs exchange.

Another smoking gun of composite Higgs models and strong symmetry breaking would be the observation of the $VV \to hh$ scattering [4], which in the SM has an extremely small cross section. The importance of this channel comes from the fact that it is the only process giving information on the parameter b, which is not constrained by the scattering $VV \to VV$ or the precision tests and cannot be determined by measuring the single Higgs couplings. An exploratory analysis [1] has shown that the three-lepton channel with the Higgs decaying to W^+W^-, $pp \to hhjj \to 4Wjj \to l^+l^-l^\pm \not{E}_T\, jjjj$, seem to give the best chances of discovery. A fully realistic study with detector simulation is however needed to confirm these results and establish the ultimate LHC sensitivity on the parameter b.

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