

INTRODUCTION TO CH SCENARIOS

Three lectures on CH models, given at Next PhD school
SUSSEX UN. 20-23 June 2016

Plan of the lectures:

I) Introduction

- The SM as an EFT and Naturalness
- The CH solution to the Naturalness Problem
- general structure of a CH model

II) The Higgs as a Goldstone boson

- Vacuum misalignment
- The COWE construction
- The SM gauge fields
- Corrections to the Higgs couplings to gauge fields
- Partial fermion compositeness
- The fermion Yukawa's
- The Higgs potential, top partners and tuning

III) Collider phenomenology

- Top partners
- Vector resonances

Reviews on composite Higgs scenarios:

most of the material of these lectures is based on

• E. Paltco, A. Wulzer, "The Composite Nambu-Goldstone Higgs", Lect. Notes Phys. 813 (2015) pp. 1-316 [arXiv: 1506.01861]

other reviews

• R. Contino, "The Higgs as a Composite Nambu-Goldstone Boson", arXiv: 1005.4269

• B. Bellosozzi, C. Csaki, S. Sora, "Composite Higgses", Eur. Phys. J. C74 (2014) n.5, 2766
arXiv: 1401.2457

(I) INTRODUCTION

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The SM as an EFT and Naturalness

There is plenty of evidence that the Standard Model (SM) is not a full description of Nature, but should be rather seen as a "low energy" description of particle physics. For instance the origin of neutrino masses is not explained by the SM, moreover a complete description of gravity, valid also at the Planck scale, is missing.

Being more precise, the SM can be interpreted as an effective field theory (EFT) valid up to an UV cut-off Λ_{SM} , where new phenomena not described by the SM are present. To be more quantitative, in EFT's it is useful to organize the Lagrangian by classifying its operators in an expansion in energy dimension, $[O] \equiv d_O$. If the new physics (NP) at the Λ_{SM} scale is generic, we expect the EFT Lagrangian to be of the form

$$\mathcal{L} = \sum_d \frac{1}{\Lambda_{\text{SM}}^{d-4}} \mathcal{L}_d , \quad (1.1)$$

where \mathcal{L}_d contains all the operators of dimension $d_0 = d$ which respect the symmetries of the theory, namely

$$\mathcal{L}_d = \sum_{O \text{ with } d_0=d} c_O O , \quad (1.2)$$

where c_O are dimensionless coefficients.

From the expansion (1.1) we can draw an interesting result. If Λ_{SM} is "large", all the operators with $d > 4$ are suppressed at low energy, namely their effects are small at energy scales $E \ll \Lambda_{\text{SM}}$. The operators with $d \leq 4$, instead, are the ones that control the low-energy dynamics.

The SM Lagrangian coincides with all the operators in the effective Lagrangian with $d \leq 4$ that respect the $SU(3)_c \times SO(8)_v \times U(1)_Y$ gauge symmetry. All operators with $d \geq 5$ are instead not included. This kind of structure can be easily understood if $\Lambda_{\text{SM}} \gg T_{\text{EW}}$, in such a way that higher-dimensional operators lead to very suppressed effects at past and present experiments.

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The presence of only operators with $d \leq 4$ is the key of the success of the SM in describing (almost) all the experimental results with very high accuracy. The field content of the SM and its gauge symmetries, in fact, imply that several accidental symmetries^(*) are present in the SM Lagrangian. The "protection" due to these symmetries is essential in allowing the SM to be compatible with many high-precision measurements.

The accidental symmetries of the SM include some exact symmetries, baryon number and lepton family number conservation, as well as approximate ones, custodial symmetry and flavor symmetry.

All these accidental symmetries are broken by operators with $d > 5$. Thus, for the success of the SM, it is essential that these operators are highly suppressed. Lepton flavor conservation, for instance, is broken already at $d=5$ by the Weinberg operator

$$\frac{c}{\Lambda_{SM}} (\bar{\ell}_L H^c)(\ell_L^c H^c) \quad (H^c = i\sigma^2 H^*)$$

which induces, after electroweak (EW) symmetry breaking, a Majorana mass term for the neutrinos, $m_\nu \sim c v^2 / \Lambda_{SM}$ with $v = \langle h \rangle \approx 246 \text{ GeV}$. This term is actually welcome, since neutrino masses are there in Nature. Reasonable values of m_ν ($m_\nu \sim 0.1 \text{ eV}$) can be obtained for $c \sim 1$ and $\Lambda_{SM} \sim 10^{14} \text{ GeV}$, which means that the SM cut-off can be naturally quite high, well above the energy scales we can test at present.

The breaking of baryon number, which would involve proton decay, is instead present only at $d=6$, thus it is further suppressed by $1/\Lambda_{SM}^2$. The current limits on the proton lifetime imply $\Lambda_{SM} \gtrsim 10^{16} \text{ GeV}$ (for an operator with $c \sim 1$).

Flavor symmetries are also broken at $d=6$, however the present bounds are not very severe. The strongest ones come from CP-violation in the Kaons, and imply $\Lambda_{SM} \gtrsim 10^8 \text{ GeV}$ (for $c \sim 1$).

Constraints from EW precision measurements are even milder and require $\Lambda_{SM} \gtrsim \text{few. } 10^3 \text{ GeV}$.

(*) An accidental symmetry is a symmetry that is automatically present at a given order in the operator-dimension expansion even if it is not explicitly imposed.

The above discussion shows that the SM, seen as an EFT, does not require additional symmetries in order to be compatible with the data, it only needs to have a high enough cut-off Λ_{SM} .

The picture we described so far, however, has some shortcomings. A first limitation comes from the fact that in a completely generic theory we would expect the dimensionless parameters (i.e. the couplings in the $d=4$ operators) to be of $\mathcal{O}(1)$, whereas in the SM some hierarchies are present in the quark and lepton Yukawa couplings. This means that the UV completion of the SM can not be completely generic, instead it must give rise to these hierarchies. This however is not a huge deal, since, once the hierarchies are generated at $E \sim \Lambda_{\text{SM}}$, they remain unchanged also at low energy^(*).

There is however another operator in the SM Lagrangian which gives some trouble if Λ_{SM} is large, namely the Higgs mass term

$$\frac{1}{2} m_H^2 |\mathbf{H}|^2.$$

This is the only operator in the SM Lagrangian with $d < 4$. Following the usual estimate of the EFT operator coefficients we would expect

$$m_H^2 \sim \Lambda_{\text{SM}}^2.$$

But, on the other hand, we know nowadays that

$$m_H \approx 125 \text{ GeV}.$$

If the cut-off Λ_{SM} is high, so that the corrections from $d \geq 5$ operators are below the bounds, then it is hard to justify the huge hierarchy between m_H and Λ_{SM} . For instance if $\Lambda_{\text{SM}} \sim 10^{16}$ GeV, comparable with a possible GUT scale, an hierarchy of $\gtrsim 28$ orders of magnitude would be present between m_H^2 and Λ_{SM}^2 . To make the problem worse, a small Higgs mass is not "technically Natural", since it receives quadratically divergent radiative corrections (the largest contribution coming from top-quark loops).

This is the essence of the well-known "Hierarchy Problem" (also called "Naturalness Problem").

(*) This is a consequence of the fact that the coupling constant of $d=4$ operators only change logarithmically with the energy scale. Thus hierarchies among different parameters are relatively stable (they are called "technically" Natural).

The Composite Higgs solution to the Naturalness Problem

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So far we saw that the clash between the high Λ_{IR} required to suppress the $d \geq 5$ operators and the small Λ_{IR} needed to explain the value of m_H gives origin to the Naturalness Problem. In our analysis, however, we assumed that the NP at the Λ_{IR} scale was rather "generic", which translated into the assumption that $c_i \approx 1$ for all $d \geq 5$ operators.

Non-generic NP, instead, can help in solving the Naturalness Problem. Since we want to avoid the hierarchy in the Higgs mass we can assume that $\Lambda_{\text{IR}} \sim \text{TeV}$, so that the radiative corrections to m_H are small. In this case higher-dimensional operators are only suppressed by powers of $\frac{1}{\text{TeV}}$, so for generic $c_i \approx \mathcal{O}(1)$ they would spoil the agreement with the experimental data. We can however assume that NP has particular symmetries and/or selection rules in such a way that the dangerous $d \geq 5$ operators are generated with $c_i \ll 1$, thus leading to a large enough suppression.

There are a few ways of achieving such structure, among which supersymmetry and composite Higgs (CH) scenarios offer the best motivated and more fruitful options. In this course I will focus on the CH option.

It is important to stress that several implementations of the CH paradigm exist. For instance extra-dimensional scenarios a la Randall-Sundrum, Little Higgs models and Twin-Higgs models in the CH framework are all deviations/extensions of the basic CH idea.

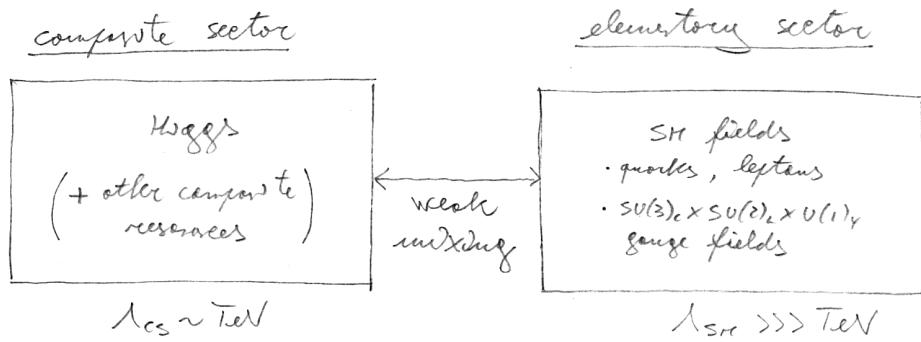
The general idea underlying CH models is the assumption that the Higgs is not an elementary state (as it is in the SM) but instead it is a composite object arising from a new strongly-coupled dynamics. The strong-coupling scale Λ_{CS} of the new dynamics should be around the TeV, in such a way that the Higgs mass $m_H \approx 125 \text{ GeV}$ can be naturally generated.

The other SM fields, instead, are assumed to be external with respect to the composite dynamics^(*), as suggested by the experimental data which show no deviations in their behavior. The sector describing the SM fields, usually called "elementary sector", is characterized by a high cut-off $\Lambda_{\text{SM}} \gg \text{TeV}$, which naturally suppresses $d \geq 5$ operators involving the elementary fields.

(*) A possible exception is the top quark, which in some CH models is interpreted as a fully composite state.

The overall structure of a CH model can be shown pictorially as

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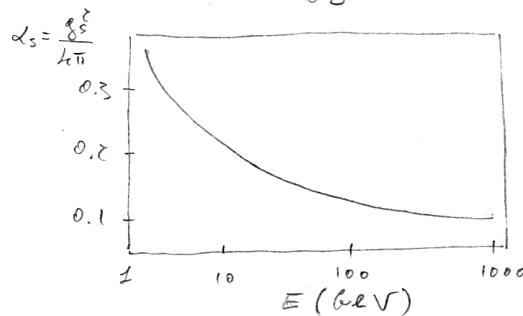
Obviously the elementary and the composite sectors should be connected, in such a way that EW symmetry breaking induced by the Higgs can be communicated to the SM fields. This is achieved through a weak mixing between the two sectors. The smallness of this mixing explains why dangerous corrections to the SM observables coming from the composite dynamics are suppressed. In fact they correspond to higher-dimensional operators with coefficients of order

$$\frac{c}{\lambda_{cS}^{d-4}} \quad \text{with} \quad c \ll 1,$$

since the size of c is controlled by the weak mixing.

At this point it is natural to ask how the hierarchy $\lambda_{cS} \ll \lambda_{Se}$ is generated. This is not a difficult thing to do, since we can use a general property of strongly-coupled sectors: dimensional transmutation. To understand this it is useful to recall what happens in the usual QCD.

QCD, neglecting the quark masses which arise only through EW symmetry breaking, is fully characterized by only the strong coupling constant g_s . Due to the RG running g_s changes as a function of the energy scale, in particular it grows when we go towards smaller energy scales.



This implies the presence of a Landen pole at low energy λ_{cS} , at which the theory becomes fully strongly coupled. The

$$\lambda_{cS} \sim \lambda_{Se} e^{-8\pi^2/9g_{sw}^2} \approx 300 \text{ MeV} \ll \lambda_{Se}.$$

The position of the Larden pole is exponentially sensitive to the value of the strong coupling constant at the UV scale $g_{\text{UV}} = g_S(\text{UV})$, thus a huge hierarchy $\Lambda_{\text{CS}} \ll \Lambda_{\text{UV}}$ can be naturally generated.

In the CH scenario we assume that a similar mechanism is at work in the composite sector, so that $\Lambda_{\text{CS}} \ll \Lambda_{\text{SM}}$ is naturally obtained.

The analogy with QCD can also be used to derive some general properties of the phenomenology of the composite dynamics. Indeed a strongly coupled sector generally gives rise to many resonances with masses of order Λ_{CS} . In QCD these resonances correspond to the mesons (e.g. the ρ , $m_\rho \approx 770 \text{ MeV}$) and the baryons (proton and neutron, $m_{p,n} \approx 940 \text{ MeV}$).

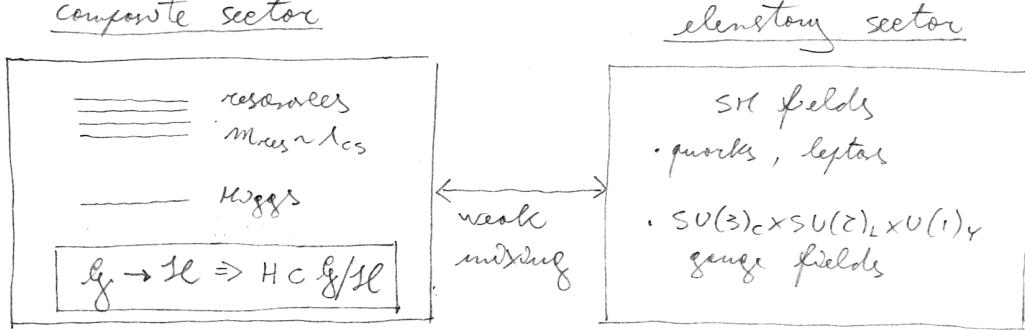
This kind of phenomenology is not exactly what we would like for a sector giving rise the Higgs. If the Higgs is a grave resonance we would expect it to have a mass $m_H \sim \Lambda_{\text{CS}} \sim \text{TeV}$, moreover we would expect additional resonances with a comparable mass. However the collider experiments tell us that such additional states close in mass to the Higgs are not there, moreover $m_H \approx 125 \text{ GeV} < \Lambda_{\text{CS}} \sim \text{TeV}$. Although it is possible to live with these issues and solve them by some tuning (for instance this is the case in the RS models with an Higgs coming from a 5D scalar), there exists a more elegant and natural possibility.

The possibility is to assume that the Higgs is not a grave composite state, but instead it is a (pseudo-) Goldstone boson coming from a spontaneously broken global symmetry of the composite sector. Going back to our analogy with QCD, the Higgs is the analog of the pions, which are naturally lighter than the other QCD resonances.

Of course if the global symmetry $U(1)$ of the composite sector is exact, the Goldstone Higgs would be exactly massless. We thus also need to assume that the $U(1)$ invariance is spontaneously broken. This breaking naturally fits in the CH picture since it comes from the mixing of the elementary sector with the composite dynamics. Again this is analogous to QCD, where the breaking of chiral symmetry (and thus the pion mass) is due to the Higgs mechanism that generates the quark masses.

The structure of a CH models with a Goldstone Higgs is a very compelling scenario, moreover it provides a very predictive framework. (8)

The general structure of such models can be pictorially summarized as



Since the Higgs must be charged under $SU(2)_L \times U(1)_Y$, we also need to require that the SM EW group is a subgroup of L_g (or better of S_L)
 $L_g \subset S_L \subset SU(2)_L \times U(1)_Y$.

Actually, as we will see, in many models^(*) also the QCD group $SU(3)_C$ is part of the structure of the composite sector.

Another advantage of the Goldstone Higgs scenario is the fact that the Higgs couplings in this scenario are close to the SM ones, as preferred by the present data. This property follows from the "vacuum misalignment" mechanism, which we will discuss later on. Notice, instead, that the Higgs as a generic non-Goldstone composite state would instead generally suffer from large corrections to its couplings.

(*) Noteworthy, this is the case in scenarios implementing the "partial compositeness" idea for the SM fermions.