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Composite Higgs models

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Presentation plan

The renormalization group

Every QFT is an effective theory with an UV cut-off:

$$\mathcal{L}(\Lambda) \equiv \mathcal{L}(g_i(\Lambda)),\ \Lambda$$

RG transformation $\Lambda \to \Lambda'$

$$\mathcal{L}(\Lambda) \to \mathcal{L}(\Lambda')$$
$$g_i(\Lambda) \to g_i(\Lambda')$$

$\frac{dg_i}{d\ln\Lambda} = \beta_i$

The coupling constants are NOT constants!
Their values depend on the energy at which they are measured!
If the value of a coupling at low energy (IR) strongly depends on its value at high energy (UV), the coupling is *UV-sensitive*.

The hierarchy problem

Operator $O(\Lambda)$ with canonical dimension $[O] < 4$ ("*Relevant*")
$\rightarrow$ Lagrangian coupling $g(\Lambda)$

$$\lambda(\Lambda) = \frac{g(\Lambda)}{\Lambda^{4-[O]}}$$

RG flow of the coupling from the UV towards the IR

$$\lambda(\Lambda_{IR}) = \left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right)^{4-[O]} [\lambda(\Lambda_{UV}) + \delta\lambda]$$

Hierarchy between physical scales

$$\Lambda_{UV} \gg \Lambda_{IR}$$

- Strong UV-sensitivity
  $\left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right)^{4-[O]} \gg 1$

- We need to *fine-tune* the UV value to fit the IR one
- This is the Hierarchy Problem (HP)

Scalar masses

$$\mathcal{L}_M = m_\phi^2 \phi^\dagger \phi + m_\psi \bar{\psi}\psi + M_W^2 W_\mu^\dagger W_\mu$$

- Fermions→ protected by custodial chiral symmetry: $\delta m_\psi \propto m_\psi \rightarrow$ no HP
- Massive gauge vectors→ protected by gauge symmetry→ $\delta M_W \propto M_W \rightarrow$ no HP
- Scalars are not protected by any symmetry→ $\delta m^2 \propto \Lambda_{UV}^2 \rightarrow$ HP!

The Higgs boson

In the SM we have one elementar scalar: the Higgs field $\mathcal{H}$

- The electroweak gauge group is spontaneously broken by the Higgs potential at a scale v (called *weak scale*)
- The spectrum contains the Higgs boson with a mass: $m_h^2 \sim v^2$

The Lagrangian contains a relevant operator:

$$\mathcal{L}_{SM} \subset \mathcal{H}^\dagger \mathcal{H}$$

which provides the mass to Higgs boson

$\Rightarrow$ strong UV-sensitivity of the Higgs mass m_h^2

This is the HP in the Standard Model!

QCD analogy

In QCD we have scalar particles: the *pions* π

- They are *composite* states
- They arise as the Nambu-Golstone bosons (NGB) of a (spontaneously broken) global symmetry $\mathcal{G}_\chi$ (chiral symmetry)
- They are exactly massless $m_\pi = 0$ if $\mathcal{G}_\chi$ is exact
- The explicit breaking of $\mathcal{G}_\chi$ generates a mass term δm_π

Do we have a hierarchy problem for pions?

Electromagnetic interactions break $\mathcal{G}_\chi \Rightarrow \delta m_\pi$ at 1 loop

They could be dangerous in principle

Pion potential

We can compute the pion potential generated by e.m. interactions

$$V(\pi) \propto \frac{\alpha_{em}}{(4\pi)^2} \sin^2(\frac{\pi}{f_\pi})$$

A detailed computation gives:

$$\delta m_\pi^2 \simeq \frac{3\alpha_{em} \log 2}{2\pi} m_\rho^2$$

The ρ meson is the first *resonance* generated by strong dynamics
$m_\rho^2 \sim \Lambda_{QCD}^2 \rightarrow$ *compositness scale*
The pion mass is sensitive to the compositness scale and not to the UV cutoff of the theory$\rightarrow$ no HP

Composite Higgs models (CHMs)

Idea: the Higgs as a NGB!

Some new strong dynamics at high energies characterized by a global symmetry $\mathcal{G}$ spontaneously broken to a subgroup $\mathcal{G}'$

- The symmetry breaking occurs at energy scale $f \gg v$
- $\mathcal{G}'$ must contain the electroweak gauge group $\mathcal{G}_{SM}$
- the Higgs field is a NGB (a composite state)$\rightarrow$ massless Higgs boson!

SM couplings are invariant under $\mathcal{G}_{SM}$ but not under the whole $\mathcal{G} \Rightarrow$ explicit breaking of $\mathcal{G} \Rightarrow$ they generate a mass term for the Higgs boson!

Higgs potential

Analogously to pions, we can compute the potential for the higgs boson h

- main contributions: electroweak gauge bosons (W,Z) couplings and top quark coupling

$$V(h) \simeq \alpha \cos \frac{h}{f} - \beta \sin^2 \frac{h}{f}$$

Under some assumptions on $\mathcal{G}$: the higgs mass is sensitive to the compositness scale $\sim f$ rather than to the UV cutoff

NO hierarchy problem!

Problem: $f \gg v$! How to generate a *light* Higgs boson, $m_h \sim v$?

Weak scale

There is a difference with QCD!

From $\frac{\partial V}{\partial h} = 0$ we get a vev for the higgs:

$$f \sin \frac{\langle h \rangle}{f} = f \sin \theta \equiv v$$

θ is a free parameter called *misalignment angle*

The assumption is $\theta \ll 1$

Inserting into the potential we find a light mass for the Higgs boson:

$$m_h^2 \sim v^2$$

This is called *dynamical generation* of the weak scale!

We have a separation of scales parametrized by

$\xi = \sin^2 \theta = \left(\frac{v}{f}\right)^2 \ll 1$

Explicit models

The minimal model: $SO(5) \to SO(4)$

- $\mathcal{G}_{SM} \subset SO(4)$
- There are 4 Goldstone bosons in the fundamental of $SO(4) \Rightarrow$ this is exactly the Higgs field $\mathcal{H}$!
- No additional degrees of freedom

A "non-minimal" model: $SO(6) \to SO(5)$

- There are 5 Goldstone bosons: the higgs field $\mathcal{H}$ + a SM singlet η
- Additional degrees of freedom (η) to the SM ones

There are several models, each of them with its phenomenology...

Phenomenology

There are several phenomenological consequences of CHMs:

- Corrections to the SM couplings between the higgs boson and massive vectors V=W,Z

$$g_{VVh} = g^{SM}_{VVh}\sqrt{1-\xi} \qquad g_{VVhh} = g^{SM}_{VVhh}(1-2\xi)$$

- Corrections to the electroweak precision parameters S and T
- new resonances in the new strong sector $\mathcal{G}$ (in analogy with the ρ meson in QCD)
- new particles in non-minimal models

In general CHMs are compatible with experimental data for a small enough value of ξ, corresponding to a large separation of scales ($f \gg v$)$\Rightarrow$ it is required a tuning on ξ ($\geq$10%)

Conclusions

- The hierarchy problem is a matter of UV-sensitivity of the parameters of a theory
- The higgs mass in the Standard Model is strongly UV-sensitive
- CHMs try to solve the hierarchy problem by assuming a composite higgs boson, generated as a NGB by some new strong dynamics
- The weak scale is dynamically generated, providing a light higgs boson
- CHMs are still compatible with experimental data, even though it is required a tuning on their parameters

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Thank you for the attention!

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