General Composite Higgs Models

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Plan

Introduction on Composite Higgs Models

General Set-Up

Generalized Weinberg Sum Rules and Higgs Mass

A Possible Issue for Partial Compositeness

Conclusions

Introduction on Composite Higgs Models (CHM)

A composite Higgs coming from some strongly coupled theory can solve the hierarchy problem. At some scale the Higgs compositeness appears and the quadratic divergence is naturally cut-off

The Higgs field might or might not be a pseudo Nambu-Goldstone boson (pNGb) of a spontaneously broken global symmetry.
Models where the **Higgs is a pNGB are** the most promising

The spontaneously broken global symmetry has also to be explicitly broken (by SM gauge and Yukawa couplings), otherwise the Higgs remains massless

Whole Higgs potential is radiatively generated

The symmetry breaking pattern is closely related to the QCD case

The $SU(2)_L \times SU(2)_R$ global symmetry is replaced by

$$G_f \supset SU(2)_L \times U(1)_Y$$

The SM gauge group arises as a weak gauging of G_f

The SM gauge fields are the analogue of the photon.
The Higgs field is the analogue of the pions

Important difference: fermion fields must now be added (no QCD analogue)

Implementations in concrete models hard (calculability, flavour problems)

Recent breakthrough: the composite Higgs paradigm is **holographically** related to theories in extra dimensions!

Extra-dimensional models have allowed a tremendous progress

The Higgs becomes the fifth component of a gauge field, leading to

Gauge-Higgs-Unification (GHU) models also known as Holographic Composite Higgs models

Not only relatively weakly coupled description of CHM, Higgs potential fully calculable, but the key points of how to go in model building have been established in higher dimensions

Main lesson learned from extra dimensions reinterpreted in 4D

$$\mathcal{L}_{tot} = \mathcal{L}_{el} + \mathcal{L}_{comp} + \mathcal{L}_{mix}$$

Elementary sector: SM particles but Higgs (and possibly top quark)

Composite sector: unspecified strongly coupled theory with unbroken global symmetry $G \supset G_{SM}$

Mixing sector: **mass mixing** between SM fermion and gauge fields and spin 1 or 1/2 bound states of the composite sector

Crucial ingredient in such constructions is the notion of

Partial Compositeness

SM fields get mass by mixing with composite fields:
the more they mix the heavier they are
(4D counterpart of 5D wave function overlap)

$$m \propto \epsilon_L \epsilon_R v_H$$

Light generations are automatically screened by new physics effects

Natural mechanism to suppress dangerous FCNC

Independently of the nature of composite sector, the pNGB Higgs dynamics can be parametrized by using the Callan-Coleman-Wess-Zumino (CCWZ) construction [Giudice,Grojean,Pomarol,Rattazzi,2007]

The composite sector might be intrinsically strongly coupled, with no small expansion parameter (e.g. some CFT), or admit some weakly coupled description in terms of free fields (e.g. mesons in large N)

We assume the second case, where simple parametrizations are possible

[Barbieri,Bellazzini,Rychkov,Varagnolo,2007;Anastasiou,Furlan,Santiago, 2009;Gripaios,Pomarol,Riva,Serra,2009;Mrazek et al,2011;Panico,Wulzer, 2011;Curtis,Redi,Tesi,2012; ...]

The Higgs potential is generally incalculable in these models

One can impose a collective symmetry breaking mechanism on moose-type models, deconstructed versions of 5D models

Considerable progress, but models still too close to their 5D parents

Is it possible to build more general CHM, not directly related to the 5D holographic models and yet with a calculable Higgs potential ?

This requires a symmetry principle, alternative to collective symmetry breaking, to protect the Higgs potential

or

we might look for the generic constraints a model should have

Our aim

Construct 4D pNGB CHM where the Higgs mass is calculable thanks to the imposition of generalized Weinberg sum rules

Weinberg sum rules

In QCD, for $SU(2)_V \times SU(2)_A \to SU(2)_V$

$$\langle V^a_\mu(q) V^b_\nu(-q)\rangle \equiv P^t_{\mu\nu}\delta^{ab}\Pi_{VV}(q^2)$$

$$\langle A^a_\mu(q) A^b_\nu(-q)\rangle \equiv P^t_{\mu\nu}\delta^{ab}\Pi_{AA}(q^2)$$

$\Pi_{LR} = \Pi_{VV} - \Pi_{AA}$ is such that

$$\lim_{p_E^2\to\infty} \Pi_{LR}(-p_E^2) = 0$$ First sum rule (I)

$$\lim_{p_E^2\to\infty} p_E^2\Pi_{LR}(-p_E^2) = 0$$ Second sum rule (II)

(I) consequence of symmetry restoration
(II) assumes UV asymptotically free theory

[S. Weinberg, 1967]

At leading order in $1/N_c$

$$\Pi_{VV}(p_E^2) = p_E^2 \sum_n \frac{f_{\rho_n}^2}{p_E^2 + m_{\rho_n}^2}$$

$$\Pi_{AA}(p_E^2) = f_\pi^2 + p_E^2 \sum_n \frac{f_{a_n}^2}{p_E^2 + m_{a_n}^2}$$

$SU(2)_L \times SU(2)_R$ is explicitly broken by electromagnetic interactions

mass splittings among charged and neutral pions expected

If one assumes that only first vector and axial resonance contribute to the form factors and impose rules I and II, the pion potential becomes calculable

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \simeq \frac{3\alpha_{em}}{4\pi} \frac{m_\rho^2 m_a^2}{m_a^2 - m_\rho^2} \log\left(\frac{m_a^2}{m_\rho^2}\right)$$

Good theoretical prediction of pion mass difference

General Set-Up

Assume composite sector with global symmetry

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X$$

Gauge $\quad SU(2)_L \times U(1)_Y \subset SO(4) \times U(1)_X \qquad Y = T_{3R} + X$

NGB matrix: $\quad U = \exp\left(i\sqrt{2}\frac{h}{f}\right)$

$$\mathcal{L}_{\sigma_g} = -\frac{1}{4} W^{aL}_{\mu\nu} W^{aL\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{f^2}{4} \mathrm{Tr}\left(\hat{d}_\mu \hat{d}^\mu\right)$$

$$iU^\dagger D_\mu U = \hat{d}_\mu + \hat{E}_\mu \qquad \begin{cases} \hat{d}_\mu = & -\frac{\sqrt{2}}{f}(D_\mu h) + \dots \\ \hat{E}_\mu = & g_0 A_\mu + \frac{i}{f^2}(h \overleftrightarrow{D}_\mu h) + \dots \end{cases}$$

[CCWZ notation]

$$m_W = \frac{gf}{2} \sin\frac{\langle h \rangle}{f} \equiv \frac{gv}{2}\,. \qquad s_h = \sin\frac{\langle h \rangle}{f}, \qquad \xi \equiv s_h^2$$

Include Spin 1 resonances

It is known how to add spin 1 resonances in a chiral Lagrangian [Ecker et al,1989]

Consider fields in the $SU(2)_L \times SU(2)_R$ representations

ρ_L: $(\mathbf{3},\mathbf{1})$ ρ_R: $(\mathbf{1},\mathbf{3})$ a: $(\mathbf{2},\mathbf{2})$

``Vector Resonances'' ``Axial Resonances''

$$\mathcal{L}_g = \mathcal{L}^v + \mathcal{L}^a$$

$$\begin{aligned}
\mathcal{L}^v &= \sum_{i=1}^{N_{\rho_L}} \Big(-\frac{1}{4}\rho_{\mu\nu}^{i,2} + \frac{f_\rho^2}{2}\left(g_\rho \rho^i - \hat{E}\right)^2 + \sum_{j<i} \frac{f_{\mathrm{mix}_{ij}}^2}{2} g_\rho^2 \left(\rho^i - \rho^j\right)^2 \Big), \\
\mathcal{L}^a &= \sum_{i=1}^{N_a} \Big(-\frac{1}{4} a_{\mu\nu}^{i,2} + \frac{f_a^2}{2\Delta_i^2}\left(g_a a^i - \Delta_i \hat{d}\right)^2 \Big).
\end{aligned}$$

$$\rho^i_{\mu\nu} = \partial_\mu \rho^i_\nu - \partial_\nu \rho^i_\mu - i g_{\rho^i}[\rho^i_\mu, \rho^i_\nu], \quad a_{\mu\nu} = \nabla_\mu a_\nu - \nabla_\nu a_\mu, \quad \nabla = \partial - i\hat{E}$$

$$m^2_{\rho^i} = f^2_{\rho^i} g^2_{\rho^i} \qquad\qquad m^2_{a_i} = \frac{f^2_{a_i} g^2_{a_i}}{\Delta_i^2}$$

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ρ-SM gauge mass mixing terms

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Spin 1/2 resonances

Fermion resonances S and Q in singlet and fundamental SO(4) representations

Let us introduce explicit breaking terms, transforming in SO(5) representations

$$\mathcal{L} \;= \bar{q}_L i\hat{D} q_L + \bar{t}_R i\hat{D} t_R + \sum_{i=1}^{N_S} \bar{S}_i (i\hat{\nabla} - m_{iS}) S_i + \sum_{j=1}^{N_Q} \bar{Q}_j (i\hat{\nabla} - m_{iQ}) Q_j +$$

$$\sum_{i=1}^{N_S} \left(\frac{\epsilon^i_{tS}}{\sqrt{2}} \bar{\xi}_R P_L U S_i + \epsilon^i_{qS} \bar{\xi}_L P_R U S_i \right) + \sum_{j=1}^{N_Q} \left(\frac{\epsilon^j_{tQ}}{\sqrt{2}} \bar{\xi}_R P_L U Q_i + \epsilon^j_{qQ} \bar{\xi}_L P_R U Q_i \right) + h.c.,$$

$$\xi_L = \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix}, \qquad \xi_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}$$

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Spin 1/2 resonance -SM fermion mass mixing terms

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Generalized Weinberg sum rules in our context

Analogue of Π_{LR} in gauge sector

$$\Pi_1(p^2) = g_0^2 f^2 + 2g_0^2 p^2 \left[\sum_{i=1}^{N_a} \frac{f_{a_i}^2}{(p^2 - m_{a_i}^2)} - \sum_{j=1}^{N_\rho} \frac{f_{\rho^j}^2}{(p^2 - m_{\rho^j}^2)} \right]$$

$$\lim_{p_E^2 \to \infty} g_0^{-2} \Pi_1(-p_E^2) = f^2 + 2\sum_{i=1}^{N_a} f_{a_i}^2 - 2\sum_{j=1}^{N_\rho} f_{\rho^j}^2 \equiv 0\,. \quad \text{(I)}$$

$$\lim_{p_E^2 \to \infty} g_0^{-2} p_E^2 \Pi_1(-p_E^2) = 2\sum_{i=1}^{N_a} f_{a_i}^2 m_{a_i}^2 - 2\sum_{j=1}^{N_\rho} f_{\rho^j}^2 m_{\rho^j}^2 \equiv 0. \quad \text{(II)}$$

Sum rule (I) requires at least one vector resonance.

Sum rule (II) requires at least one axial resonance.

Similar sum rules in fermion sector

Higgs Mass

The Higgs boson is finally a reality

Basic question: what is its expected mass in CHM ?

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$$m_H \sim \quad ?$$ with partial compositeness additional states and scales complicate the analysis

Higgs Potential

Calculable Higgs potential is a crucial portal for new physics.

Let first consider the top quark.

The top must be semi-composite

$$m_t \sim \frac{\epsilon^2}{M_f}\frac{v}{f} \sim v \quad \Longrightarrow \quad \epsilon^2 \sim M_f f$$

The top mixing largest explicit symmetry breaking terms

The Higgs mass is related to new resonances masses

For $s_h \ll 1$ $\qquad V(h) = V_g(h) + V_f(h)$

$$V_g(h) = -\gamma_g s_h^2 + \beta_g s_h^4 \qquad V_f(h) = -\gamma_f s_h^2 + \beta_f s_h^4$$

Non-trivial minimum at $s_h^2 = \xi = \dfrac{\gamma}{2\beta}$

$$m_h^2 = \frac{8\beta}{f^2}\xi\,(1-\xi)\,. \qquad \beta \simeq \beta_f \propto \frac{\epsilon^4 N_c}{16\pi^2}$$

$$m_H^2 \sim \frac{\epsilon^4 N_c}{2\pi^2 f^2}\xi \simeq \frac{N_c}{2\pi^2}\frac{m_t^2 M_f^2 f^2}{v^2 f^2}\frac{v^2}{f^2}$$

$$\boxed{m_H \simeq \sqrt{\frac{N_c}{2\pi^2}}\,\frac{m_t M_f}{f}}$$

Direct relation between Higgs and resonance masses and

a light Higgs implies light fermion resonances

[Matsedonskyi, Panico and Wulzer; Redi and Tesi; Marzocca, MS, Shu; Pomarol and Riva]

We can relax the second sum rule. In this way **EWSB no longer calculable, but Higgs mass still predicted**

Collider Signatures

The deviations to SM couplings might be
too small to be detected at the LHC

On the other hand, the light sub-TeV fermion resonances, necessary to explain a 125 GeV Higgs, seem a generic and clear prediction for CHM

LHC already puts significant constraints on the parameter space of CHM, particularly when the lightest fermion resonance has Q=5/3

[Matsedonskyi, Panico and Wulzer, 1204.6333; De Simone,Matsedonskyi,Rattazzi,Wulzer,1211.5663]

Roughly one has

$$m_{2/3} \gtrsim 400 \quad \text{GeV}$$

$$m_{5/3} \gtrsim 600 \quad \text{GeV}$$

Partial Compositeness for Light Fermions

Partial compositeness for light flavours is a nice and efficient mechanism to suppress dangerous FCNC

It requires one exotic fermion excitation for each SM fermion
Many flavours and one should worry about possible **Landau poles**

Minimal case (bottom-up): $G_f = SO(5)$

Composite fermions in the fundamental of SO(5)

In total we have

$$N_f = (1+5) \times 6 = 36$$

active flavours above the fermion mass scale f

In this case α_3 blows up at the scale $\Lambda_{LP} \sim 300\Lambda$

$\Lambda = 4\pi f$ is cut-off of the effective field theory

Anyhow, where do these fermions come from ?

In vector-like gauge theories with fermion constituents
fermion bound states are typically baryon-like

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Scalar is unnatural ⇒ Assume composite sector is supersymmetric

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SM gauge couplings develop unacceptably low Landau poles
if one assumes partial compositeness for **all** SM fermions

Conclusions

Generically a 125 GeV Composite Higgs seems to imply the presence of light, sub TeV, colored fermion resonances

Light fermion states are also welcome from EWPT considerations, because of possible sizable and positive contributions to the T parameter

There are obvious generalizations to our approach, other SO(4) representations, more general cosets, ...

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Some more time will be needed to understand whether the Higgs is an elementary or a composite particle

Searches for heavy colored fermions might play a crucial role