UV Completions of Composite Higgs Models with Partial Compositeness

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Plan

Introduction on Bottom-up Composite Higgs Models

Construction of UV Models

General Set-up and Two Specific Models

Connection with Bottom-up Approaches

Conclusions and Open Questions

Introduction on bottom-up Composite Higgs Models

Is the 125 GeV particle the SM Higgs or not ?

Naturalness arguments disfavour a SM Higgs, but non-SM Higgs, in a way or another, should come together with new physics particles, yet to be seen

Broadly speaking, there are two ways to go for naturally motivated new physics:

Weakly coupled (Supersymmetry)

Strongly coupled (technicolor, little Higgs, composite Higgs)

Technicolor, already in trouble for tensions with LEP electroweak bounds, has problems in accommodating a 125 GeV Higgs (techni-dilaton tends to be heavier)

Little Higgs are also Composite Higgs Models (CHM)

Little Higgs: thanks to an ingenious symmetry breaking mechanism, the Higgs mass is radiatively generated, while the quartic is not

Composite Higgs: the entire Higgs potential is radiatively generated

In principle little-Higgs models are better, because allow for a natural separation of scales between the Higgs VEV and the Higgs compositeness scale

In practice they are not, because the above ingenious mechanism becomes very cumbersome when fermions are included

Fundamental difference between Technicolor and CHM:

- Technicolor: the EW group is **broken** by the strongly coupled sector (techni-quark condensates), no Higgs at all is necessary

- Composite Higgs: the EW group is **unbroken** by the strongly coupled sector, but a Higgs-like particle appears in the spectrum and breaks the EW group via its VEV, as in the SM

Thanks to this difference, LEP bounds can be successfully passed by CHM

In CHM quadratic divergence naturally cut-off by compositeness scale

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

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

$$G_f \supset SU(2)_L \times U(1)_Y \times SU(3)_c$$

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

Implementations in concrete models hard (calculability, flavour problems)

... but CHM are **holographically** related to theories in extra dimensions!

Extra-dimensional models have allowed a tremendous progress

Higgs becomes the fifth component of a gauge field, leading to Gauge-Higgs-Unification models (Holographic CHM)

Key points how to go in model building have been established in higher dimensions

Main lesson learned from extra dimensions and 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

SM fields get mass by mixing with composite fields: the more they mix the heavier they are

Partial Compositeness

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

Light generations are automatically screened by new physics effects

There are roughly two different bottom-up approaches in model building of composite pNGB Higgs models with partial compositeness:

1. Constructions in terms of Gauge-Higgs Unification 5D theories where the Higgs is a Wilson line phase

2. Purely 4D constructions, where the composite sector is assumed to admit a relatively weakly coupled description in terms of free fields

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Where do these mixing come from ?

Models in 1. require a UV completion in a full theory of gravity, such as string theory. Finding, even at a rough qualitative level, non-supersymmetric string vacuum with the desired properties is currently a formidable task.

Models in 2. might admit instead a purely 4D UV completions in terms of some UV theory.

Our aim

Construct 4D UV completions of pNGB composite Higgs models with partial compositeness

Focus on minimal choice with custodial symmetry:

$$G_f \supset SO(5) \times SU(3)_c \times U(1)_X$$

Construction of UV Models

It is hard to follow the RG flow of a 4D strongly interacting gauge theory, so we look for UV completions where the strongly coupled sector is approximately SUSY

In this way we can use the powerful results of SUSY, such as Seiberg dualities, to make some progress

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Notice:

Construction of UV Models

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Notice:

- SUSY is also motivated by the presence of light spin 1/2 resonances. If not baryons, these states should be meson-like bound states of a scalar and a fermion
- The hierarchy problem is solved by the compositeness of the Higgs, not SUSY. In particular, we can decouple SM partners and make them very heavy

(Very brief) Review of Seiberg Duality in N=1 SUSY Theories and ISS

Electric-Magnetic (strong/weak) duality among
N=1 SUSY SQCD Theories

[Seiberg,1994]
[Intriligator,Seiberg,Shih,2006]

$SU(N)$ story

N_f Quarks Q and $\widetilde{Q}$ in the fundamental and anti-fundamental of $SU(N)$

$$N + 1 \leq N_f < \frac{3}{2}N$$

At low energies theory is strongly coupled but there is a dual description in terms of an IR-free $SU(N_f - N)$ theory with

N_f dual quarks q and $\widetilde{q}$ in fund. and anti-fund. of $SU(N_f - N)$ and neutral mesons $M = Q\widetilde{Q}$ and superpotential

$$W = qM\widetilde{q}$$

$SO(N)$ story

N_f Quarks Q in the fundamental of $SO(N)$

$$N-2 \leq N_f < \frac{3}{2}(N-2)$$

Low energy IR-free dual is $SO(N_f - N + 4)$ theory with

N_f dual quarks q in fund. of $SO(N_f - N + 4)$

and neutral mesons $M = QQ$ and superpotential

$$W = qMq$$

Add superpotential mass deformation in UV theory $\delta W = m\, Q_I^n Q_I^n$

Unbroken flavour symmetry is $G_f = SU(N_f) \to SO(N_f)$

In the IR $\delta W \to m \Lambda M_{II} \equiv -\mu^2 M_{II}$

Drastic consequences in IR theory due to mass deformation: magnetic quarks get a VEV

- SUSY is spontaneously broken

- Global and gauge symmetries spontaneously broken

$$SO(N_f - N + 4) \times SO(N_f) \rightarrow SO(N_f - N + 4)_D \times SO(N - 4)$$

Non-SUSY vacuum metastable

General Set-up

Consider $SO(N)$ SQCD with $N_f = N$ and superpotential

$$W_{el} = mQ^aQ^a + \lambda_{IJK}Q^IQ^J\xi^K$$

ξ^K are $SO(N)$ singlets fields, to be identified with MSSM chiral multiplets

$I = (i, a)$, $a = 1, \ldots, 5$, $i = 1, \ldots, N-5$ When $\lambda_{IJK} = 0$

$$G_f = SO(5)_a \times SU(N-5)_i$$

We assume an external source of SUSY breaking in the visible sector that gives large masses to SM gaugini and sfermions

In the IR $W_{mag} = q_I M^{IJ} q_J - \mu^2 M_{aa} + \epsilon_{IJK} M^{IJ} \xi^K$

Further decompose $a = (m, 5)$, $m = 1, 2, 3, 4$. ISS-like vacuum

$$\langle q^n_m \rangle = \delta^n_m \mu$$

SUSY is spontaneously broken by $F_M \sim \mu^2$

Global and gauge symmetries spontaneously broken

$$SO(4)_m \times SO(5)_a \times SU(N-5)_i \to SO(4)_D \times SU(N-5)_i = H_f$$

Estimate life-time of non-SUSY metastable vacuum

10 NGB's arise from the breaking

$\mathrm{Re}\,(q_n^m - q_m^n)$: along the broken $SO(4)_m \times SO(4)_a$ directions

$\sqrt{2}\,\mathrm{Re}\,q_5^n$: along the broken $SO(5)_a/SO(4)_D$ directions

$\mathrm{Re}\,(q_n^m - q_m^n)$ are eaten by the gauge fields

$\mathrm{Re}\,q_5^n$ are identified as the 4 Higgs components

SM vector fields are introduced by gauging $H_f \supseteq SU(3)_c \times SU(2)_L \times U(1)_Y$

$$SU(2)_L \subset SO(4)_a \cong SU(2)_L \times SU(2)_R \subset SO(5)_a$$

VEV mixes $SO(4)_m$ magnetic and elementary gauge fields

Partial compositeness in the gauge sector

$M_{IJ}\xi^K$ term mix composite and elementary fermions

Partial compositeness in the fermion sector

Yet incomplete, unwanted massless particles around, etc.

These issues are addressed in a model-dependent way

Explicit Model: I (elementary RH top)

$N = 11$ flavours and two singlet fields

S_{ij}: $(\mathbf{1}, \overline{\mathbf{20}})$
S_{ia}: $(\mathbf{5}, \overline{\mathbf{6}})$ of $SO(5)_a \times SO(6)_i$.

$$W_{el} = mQ^a Q^a + \frac{1}{2} m_{1S} S_{ij}^2 + \lambda_1 Q^i Q^j S_{ij} + \frac{1}{2} m_{2S} S_{ia}^2 + \lambda_2 Q^i Q^a S_{ia}$$

Integrate out S_{ij} and S_{ia}:

$$W_{el}^{eff} = m_{ab} Q^a Q^b - \frac{\lambda_1^2}{2m_{1S}} (Q^i Q^j)^2 - \frac{\lambda_2^2}{2m_{2S}} (Q^i Q^a)^2$$

Gauge $SU(3)_c \times U(1)_X \subset SO(6)_i$,

$SU(2)_L \times U(1)_Y \subset SO(4)_a$

Let us now add SM matter: focus on top quark only

$$\delta W_{el} = \lambda_L (\xi_L)_{ia} Q^i Q^a + \lambda_R (\xi_R)^{ia} Q^i Q^a \qquad \text{flows to}$$

$$\delta W_{mag} = \epsilon_L (\xi_L)^{ia} M_{ia} + \epsilon_R (\xi_R)^{ia} M_{ia} \qquad \epsilon_{L,R} = \Lambda \lambda_{L,R}$$

$\xi_{L,R}$ spurion fields. Dynamical components are $Q = (t,b)^t$ and t^c

Vacuum Decay

Like in ISS, there are SUSY vacua at large meson VEV's

Bounce action estimate gives $S_b \gtrsim \epsilon^{-\frac{10}{3}}$ $\qquad \epsilon = \dfrac{\mu}{\Lambda}$

$$\alpha_m(\mu) = \frac{2\pi}{5 \log\left(\frac{\Lambda}{\mu}\right)}$$

The 3 SM gauge couplings develop **Landau poles**

but at scales larger than the highest mass scale of the theory, so UV theory has a well defined range of validity

Explicit Model: II (composite RH top)

$N = 9$ flavours and one singlet field
S_{ij}: $(\mathbf{1}, \overline{\mathbf{10}})$ of $SO(5)_a \times SU(4)_i$.

$$W_{el} = mQ^aQ^a + \lambda Q^iQ^jS_{ij}$$

Integrate out S_{ij}: $\Longrightarrow S_{ij} = 0 \quad M_{ij} = 0$

Gauge $SU(3)_c \times U(1)_X \subset SU(4)_i$,

$SU(2)_L \times U(1)_Y \subset SO(4)_a$

Multiplets M_{i5} are massless.

We identify t_R as the fermion component of M_{i5}

Get rid of unwanted extra massless fermion from M_{45} by adding elementary conjugate chiral field ϕ that mix with it, as M_{ia} is going to mix with t_L.

Lifting RH stop requires extra source of SUSY breaking

Introduce it in terms of spurions in UV theory

$$\mathcal{L}_{el} = \int d^4\theta \sum_{I=1}^{N_f} Z_I(\mu) Q_I^\dagger e^{V_{el}} Q_I + \left(\int d^2\theta S(\mu) W_{el}^\alpha W_{el,\alpha} + h.c. \right)$$

$$Z_I(\mu) = Z_I^0(\mu)(1 - \theta^2 B_I(\mu) - \bar\theta^2 B_I^\dagger(\mu) - \theta^2\bar\theta^2(\widetilde{m}_I^2(\mu) - |B_I(\mu)|^2))$$

$$S(\mu) = \frac{1}{g^2(\mu)} - \frac{i\Theta}{8\pi^2} + \theta^2 \frac{m_\lambda(\mu)}{g^2(\mu)}$$

IR soft terms induced by the UV ones can be computed

[Arkani-Hamed, Rattazzi 1999 + ...]

$$\widetilde{m}^2_{M_{IJ}} = \widetilde{m}_I^2 + \widetilde{m}_J^2 - \frac{2}{b} \sum_{K=1}^{N_f} \widetilde{m}_K^2 \,,$$

$$\widetilde{m}^2_{q_I} = -\widetilde{m}_I^2 + \frac{1}{b} \sum_{K=1}^{N_f} \widetilde{m}_K^2 \,.$$

Sum rule:

$$\sum_{I,J=1}^{N_f} \widetilde{m}^2_{M_{IJ}} + 2N_f \sum_{I=1}^{N_f} \widetilde{m}^2_{q_I} = 0$$

Some IR soft terms are negative definite

$$m_{m,\lambda} = m_\lambda \frac{b_m g_m^2}{b g^2}$$

B-terms can induce **tadpoles** for mesons M

They deform the spectrum but leave unaltered the symmetry breaking pattern

We can then lift the stop but we cannot decouple it. Because of negative definite mass terms, these cannot be larger than μ

Notice: UV soft terms are assumed to be **SO(5) invariant** otherwise symmetry protecting Higgs badly broken

Partial compositeness in the gauge and fermion sectors as in the previous model, with obvious difference of tR

We have found **no** SUSY vacua at large meson VEV's, but only runaway

Non-SUSY vacua long-lived, if not absolutely stable

The 3 SM gauge couplings still develop **Landau poles** but again at scales larger than the highest mass scale of the theory, so UV theory has a well defined range of validity

Connection with Bottom-up Approaches

Guideline for 4D bottom-up constructions of pNGB composite Higgs models is given by the CCWZ construction

Symmetry breaking pattern is $SO(5) \times SO(4) \to SO(4)_D$

$$U = \begin{pmatrix} \exp\left(\frac{i\sqrt{2}}{f}\pi^A T^A\right)_{ab} & 0 \\ 0 & \exp\left(-\frac{i}{f}\pi^a \widetilde{T}^a\right)_{mn} \end{pmatrix}$$

$$\frac{i\sqrt{2}}{f}\pi^A T^A = \frac{i\sqrt{2}}{f} h^{\hat{a}} T^{\hat{a}} + \frac{i}{f}\pi^a T^a$$

Gauge $SO(4)$ and $SU(2)_L \times U(1)_R \subset SO(5)$ Unitary Gauge: $\pi^a = 0$

$$D_\mu U = \partial_\mu U - -i\sqrt{2}(g_0 W_\mu^a T_{aL} + g_0' B_\mu T_{3R} + g_\rho \rho_\mu^a \widetilde{T}^a)U$$

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

$$iU^\dagger D_\mu U = d^a_\mu T^a_{G/H} + E^a_\mu T^a_H$$

$$\frac{f^2}{4}\mathrm{Tr}\left(d_\mu d^\mu\right) \supset \frac{1}{2}(\partial_\mu h^{\hat{a}})^2 + \frac{f^2}{4}\mathrm{Tr}\left(g_\rho \rho_\mu - g W_\mu\right)^2$$

Partial compositeness in gauge sector

Spin 1 resonance mass: $m_\rho \simeq \dfrac{f g_\rho}{\sqrt{2}}$

SM fermions are assumed to mix with spin 1/2 resonances

Introduce N_S and N_Q massive singlets and bi-doublets S_i and Q_j of $SO(4)_D$

$$\mathcal{L}_f = \bar{q}_L i\hat{D} q_L + \bar{t}_R i\hat{D} t_R + \sum_{i=1}^{N_S}\bar{S}_i(i\hat{\nabla} - m_{iS})S_i + \sum_{j=1}^{N_Q}\bar{Q}_j(i\hat{\nabla} - m_{iQ})Q_j + \sum_{i=1}^{N_S}\left(\frac{\epsilon^i_{tS}}{\sqrt{2}}\bar{\xi}_R U S_i + \epsilon^i_{qS}\bar{\xi}_L U S_i\right) + \sum_{j=1}^{N_Q}\left(\frac{\epsilon^j_{tQ}}{\sqrt{2}}\bar{\xi}_R U Q_i + \epsilon^j_{qQ}\bar{\xi}_L U Q_i\right) + h.c.,$$

Partial compositeness in fermion sector

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

$$\hat{D} = \gamma^\mu (\partial_\mu - i g_0 \frac{\sigma^a}{2} W^a_\mu - i g'_0 Y_q B_\mu) \, , \quad \hat{\nabla} = \gamma^\mu (\partial_\mu - i E_\mu - i q_X g'_0 B_\mu)$$

$$E_\mu = g_0 W_\mu + g_\rho \rho_\mu + \ldots$$

$$\mathcal{L}_{Tot} = \mathcal{L}_{\sigma_g} + \mathcal{L}_f$$

Let's come back to our models and match
with bottom-up constructions

Look for the NGB's first

$$q^n_a = \exp\left(\frac{i}{\sqrt{2}\mu} (\pi^{\hat{a}} T_{\hat{a}} + \frac{1}{2} \pi^a T_a) \right)_{ab} \widetilde{q}^m_b \, \exp\left(\frac{i}{2\sqrt{2}\mu} \sum_{a=1}^{6} \pi^a T_a \right)_{mn}$$

Kinetic term $|D_\mu q_a^n|^2$ gives chiral Lagrangian and SM gauge mixing

Unitary Gauge: $\pi^a = 0 \longrightarrow q_a^n = U_{ab}\,\tilde{q}_b^n$

$$\pi_{\hat{a}} = h_{\hat{a}} \qquad\qquad f = 2\mu$$

The Higgs can be removed by non-derivative Lagrangian terms by field redefinition of all bosons and fermions with SO(5) flavour indices

$$M_{ab} \to (UMU^t)_{ab}, \qquad \psi_{M_{ab}} \to (U\psi_M U^t)_{ab}\,, \qquad \ldots$$

$$\bar{\psi}_{M_{ia}} i\gamma^\mu D_\mu \psi_{M_{ia}} \to \bar{\psi}_{M_{ia}} U^t i\gamma^\mu D_\mu (U\psi_{M_{ia}}) = \bar{\psi}_{M_{ia}} i\gamma^\mu \Big(\nabla_\mu - i(d_\mu)\Big)\psi_{M_{ia}}$$

Model I: $\psi_{M_{in}}$ mix with $\psi_{q_i^n}$: ω angle of mixing

Effectively we have $N_Q = 2\ (\psi_{M_{in}},\, \psi_{q_i^n})$, $N_S = 1\ (\psi_{M_{i5}})$

$$\begin{aligned}
\frac{\epsilon_{tS}}{\sqrt{2}} &= \epsilon_R\,, \quad \frac{\epsilon_{tQ}^1}{\sqrt{2}} = \epsilon_R \cos\omega\,, \quad \frac{\epsilon_{tQ}^2}{\sqrt{2}} = \epsilon_R \sin\omega\,, \\
\epsilon_{qS} &= \epsilon_L\,, \quad \epsilon_{qQ}^1 = \epsilon_L \cos\omega\,, \quad \epsilon_{qQ}^2 = \epsilon_L \sin\omega\,.
\end{aligned}$$

CHM of the general form recently introduced

[Marzocca,M.S.,Shu,2012]

The cut-off of the magnetic theory is given by

$$\Lambda = \mu \exp\left(\frac{2\pi(N_f - 6)}{\alpha_m(\mu)}\right)$$

parametrically higher than EFT estimate $\Lambda \leq 4\pi f$

Spin 1/2 and spin 1 resonances governed by different coupling constants

$$m_\rho \sim g_m \mu \qquad\qquad m_\psi \sim h \mu$$

Magnetic gauge coupling

Yukawa coupling in the superpotential
(set to 1 before)

In general vector and fermion masses expected to be different

Important, because recently CHM with light fermion resonances have been shown to be favored to give a 125 GeV Higgs

[Redi, Tesi; Matsedonskyi, Panico, Wulzer; Marzocca,M.S.,Shu; Pomarol,Riva]

Key difference between our UV completed models and bottom-up constructions in the literature: composite sectors in our models are almost SUSY

Summary

Introduced a framework to construct UV completions of bottom-up CHM with a pNGB Higgs and partial compositeness

Construction based on N=1 SO(N) SUSY theories and Seiberg dualitites

Constructed two models: I RH top (semi)elementary
II RH top fully composite

Completions based on simple theories such as SO(N) SUSY gauge theory

Future directions

Concrete sources of extra SUSY breaking that lift SM partners and produces flavour invariant and/or small soft terms in composite sector

Generalizations to our cosets, fermion representations, etc. should not be hard

More accurate study of phenomenology, in particular Higgs properties

Open problem

Extending results to other SM fermions **not** straightforward

One can naively enlarge the flavour group and accommodate more resonances coupling to all SM fermions, but this lead to **unacceptably low Landau poles** for SM couplings

One can give-up partial compositeness for light fermions and rely on irrelevant deformations

This Landau pole problem seems generic, pretty much like in models of direct gauge mediation of SUSY breaking