UV Completions of Composite Higgs Models with Partial Compositeness

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Based on 1211.7290, in collaboration with Francesco Caracciolo and Alberto Parolini and work in progress with David Marzocca and A. Parolini

This talk is dedicated to the memory of Francesco

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Plan

Introduction on Bottom-up Composite Higgs Models

Construction of UV Models

Higgs Potential

Conclusions and Open Questions

Introduction on Bottom-Up Composite Higgs Models (CHM)

What Composite Higgs Models am I talking about ?

Technicolor, already in trouble for tensions with LEP electroweak bounds, is essentially ruled out by a 125 GeV Higgs (techni-dilaton too heavy)

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

CHM I consider: 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

In absence of a better name I will generically refer to CHM

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

Weakly coupled gauge interactions in strongly coupled theories are best seen as coming from a weak gauging of a subgroup of an unbroken global symmetry

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)

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 description in terms of relatively weakly coupled 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.

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Focus on this in the following

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

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 also solved by the compositeness of the Higgs, no need of SUSY.

(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

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

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 mass 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

$$\langle q_m^n \rangle = \delta_m^n \mu$$

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

Explicit Model with semi-elementary RH top

$SO(11)$ gauge theory with $N = 11$ flavours (Q^a, Q^i)

$$\begin{array}{l} Q^i\colon\ (\mathbf{1},\mathbf{6}) \\ Q^a\colon\ (\mathbf{5},\mathbf{1}) \end{array} \quad \text{of } SO(5)_a \times SO(6)_i.$$

Lagrangian renormalized at scale E is

$$\mathcal{L}_{el} = \int d^4\theta \Big(\sum_{I=1}^{N_f} Z_I(E)|Q_I|^2 + \tilde{Z}_I(E)|\xi|^2 \Big) + \int d^2\theta \Big(S_{el}(E) W_{el}^2 + S_{SM}(E) W_{SM}^2 + W_{el} \Big) + h.c.$$

ξ are SM chiral fields, neutral under $SO(11)$

$$\begin{aligned} Z_I(E) &= Z_I^0(E)(1 - \theta^4 \widetilde{m}_I^2(E)) \\ S(E) &= \frac{1}{g^2(E)} - \frac{i\Theta}{8\pi^2} + \theta^2 \frac{\widetilde{m}_\lambda(E)}{g^2(E)} \end{aligned}$$

$$W_{el} = m_{ab}Q^aQ^b - \frac{\lambda_1}{\Lambda_{UV}}(Q^iQ^j)^2 - \frac{\lambda_2}{\Lambda_{UV}}(Q^iQ^a)^2$$
$$+\lambda_L(\xi_L)_{ia}Q^iQ^a + \lambda_R(\xi_R)^{ia}Q^iQ^a$$

For simplicity set to zero soft terms in the composite sector

$$Z_I(E) = 1 \qquad\qquad S(E)_{el} = \frac{1}{g_{el}^2(E)}$$

Gauge $SU(3)_c \times U(1)_X \subset SO(6)_i, \quad SU(2)_L \times U(1)_Y \subset SO(4)_a$

The SM gauge couplings hit a Landau pole at Λ_{UV}

Vacuum stability and TeV new physics fix $\Lambda_{UV} \sim 10^2 \div 10^3$ TeV

In the IR we have

$$W_{mag} = hQ_IM^{IJ}Q_J - \mu^2 M_{aa} - m_1 M_{ij}^2 - m_2 M_{ia}^2$$
$$+\epsilon_L(\xi_L)_{ia}M_{ia} + \epsilon_R(\xi_R)^{ia}M_{ia}$$

$$\epsilon = \lambda\Lambda, \qquad \mu^2 = -m\Lambda.$$

Higgs Potential and EWSB

At the linear level, Higgs components are given by $\mathrm{Re}\, q_5^n$

Better to use a non-linear realization where its NGB nature is manifest

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

Look for the NGB's first

$$q_b^n = \exp\left(\frac{i\sqrt{2}}{f} h^{\hat{a}} T_{\hat{a}} + \frac{i}{2f}\pi^a T_a\right)_{bc} \tilde{q}_c^m \exp\left(\frac{i}{2f}\pi^a T_a\right)_{mn}$$

Unitary Gauge: $\pi^a = 0$ Coset is effectively $SO(5)/SO(4)$

$$U = \exp\left(i\frac{\sqrt{2}}{f} h^{\hat{a}} T_{\hat{a}}\right) \qquad f \equiv \mu\sqrt{\frac{2}{h}}$$

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

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

SO(5) is broken by SM couplings. At tree-level we can have SO(5) explicit breaking of soft terms for the Higgs (analogue of bare quark masses in QCD)

$$V^{(0)}(h) = m_1^2|q_5^n|^2 + m_2^2|q_m^n|^2 \supset \frac{m_H^2}{2} f^2 s_h^2$$

$$m_H^2 = m_1^2 - m_2^2, \quad s_h \equiv \sin\frac{h}{f}$$

m_H can naturally be taken small, $m_H \sim g/(4\pi)f$

$$\begin{aligned} V^{(1)}(h) &= \frac{1}{64\pi^2}\mathrm{STr}\left[M^4\left(\log\frac{M^2}{Q^2} - \frac{3}{2}\right)\right] \\ &= -\gamma\, s_h^2 + \beta\, s_h^4 + \ldots \end{aligned}$$

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

$$M_{Higgs}^2 = \frac{8\beta}{f^2}\xi(1 = \xi)$$

independent of soft terms!

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QCD analogue with Weinberg sum rules

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only mass scale in the composite sector

$$m_H \sim \quad ?$$

with partial compositeness additional states and scales complicate the analysis

The top is the key player. It must necessarily be semi-composite

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

$$\beta \simeq \beta_f \propto \frac{\epsilon^4 N_c}{16\pi^2} \qquad m_H^2 \sim \frac{\epsilon^4 N_c}{2\pi^2 f^2}\xi \simeq \frac{N_c}{2\pi^2}\frac{m_t^2 M_f^2 f^2}{v^2 f^2}\frac{v^2}{f^2}$$

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

a light Higgs implies light fermion resonances

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

Easy to accommodate a 125 GeV Higgs. SUSY helps in lowering the Higgs mass because the composite sector contribution partially cancels

Light fermion resonances are again present together, of course, with light scalar partner resonances

Explicit Model with fully composite RH top

SO(9) gauge theory with $N = 9$ flavours (Q^a, Q^i)

Q^i: $(\mathbf{1}, \mathbf{4})$
Q^a: $(\mathbf{4}, \mathbf{1})$ of $SO(5)_a \times SU(4)_i$.

$$\mathcal{L}_{el} = \int d^4\theta \Big(\sum_{I=1}^{N_f} Z_I(E)|Q_I|^2 + \tilde{Z}_I(E)|\xi|^2 \Big) + \int d^2\theta \Big(S_{el}(E) W_{el}^2 + S_{SM}(E) W_{SM}^2 + W_{el} \Big) + h.c.$$

$$W_{el} = m_{ab} Q^a Q^b - \frac{\lambda_2}{\Lambda_{UV}} (Q^i Q^a)^2 + \lambda_L (\xi_L)_{ia} Q^i Q^a$$

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 a SUSY breaking in the composite sector

IR soft terms induced by the UV ones can be computed

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

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

Some IR soft terms are negative definite

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

They deform the spectrum but leave unaltered
the symmetry breaking pattern

Conclusions

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

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

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

The mysterious fermion mass mixing come from ordinary Yukawa couplings in the UV theory

Several assumptions made in bottom-up considerations (coset structure, choice of representations, etc.) are derived, of course in a SUSY set-up!

Phenomenology drastically different from usual MSSM. 125 GeV Higgs no problem at all

Extending our 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

Alternatively, one can give-up partial compositeness for light fermions and rely on irrelevant deformations

Anyway, the SUSY partners of ordinary SM fermions (approximately elementary) may reintroduce a SUSY flavour problem and spoil the flavour protection of partial compositeness

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Of course, the real goal is constructing UV completions of **non-SUSY** CHM but given that **no UV** realization is known this can be seen as a proof of existence for the special case of an approximately SUSY composite sector

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 (work in progress)

Thank You