Partially Supersymmetric Composite Higgs

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Planck 2010

Higgs as GB

An old and still attractive idea is that the Higgs is a pseudo GB emerging from some strongly coupled dynamics.

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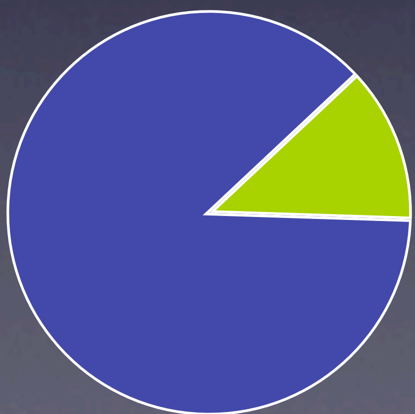
The Higgs quadratic divergences are cut-off by compositeness,

$$m_\rho = g_\rho\, f \qquad\qquad g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

Higgs is an angular variable,



$$\frac{H}{f}$$

Fine tuning:

$$\xi \approx \frac{v^2}{f^2}$$

Partial Compositeness (D. B. Kaplan '80s)

Two sectors:

Strong sector:
Higgs + (top)

Elementary:
SM Fermions
+ Gauge Fields

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$\lambda_{L,R}\,, \quad g$

↔

Elementary:
SM Fermions
+ Gauge Fields

Gauging SU(3)xSU(2)xU(1)
mixing to fermionic operators

$$\mathcal{L}_{mix} = \lambda_L\, \bar{q}_L O_R + \lambda_R\, q_R \bar{O}_L$$

$$\mathcal{L}_{gauge} = g A_\mu J^\mu$$

(Giudice, Grojean, Pomarol, Rattazzi '07)

potential at 1-loop:

$$V(H) \propto \frac{m_\rho^4}{g_\rho^2}\frac{\lambda_{L,R}^2}{16\pi^2}\hat{V}\left(\frac{H}{f}\right)\,.$$

Yukawa's:

$$y_f \sim \frac{\lambda_L \, \lambda_R}{g_\rho}$$

Small couplings are obtained from small mixings

- Light generations mostly elementary
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Automatic flavor protection:

$$FCNC_{ij} \propto \frac{\sqrt{m_i m_j}}{v}$$

Non universal flavor transitions suppressed by the mixings!

MCHM

(Agashe,Contino,
Pomarol '04)

Concrete model:

$$\frac{SO(5)}{SO(4)} \longrightarrow H = (2,2)$$

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If the strong sector is a CFT (-> RS dual) elegant generation of flavor structure

$$\mathcal{L} = \frac{\lambda}{\Lambda^{d-\frac{5}{2}}} \bar{q} O_d$$

(Contino, Pomarol)

- d>5/2 irrelevant, small in IR (light generations)
- d<5/2 relevant, large in IR (top)

Yukawa hierarchies are generated by the running.

Short-comings:

- S-parameter:

$$\hat{S} \sim \frac{m_w^2}{m_\rho^2} \qquad \rightarrow \qquad m_\rho > 3\, TeV$$

- Modified SM couplings:

$$\frac{\delta g_{Z\to b\bar{b}}}{g_{Z\to b\bar{b}}} \sim y_L^2 \frac{v^2}{m_\rho^2}$$

(Agashe et al. '06)

- Flavor protection insufficient:

Flavor bounds from resonance exchange point to even higher scales

(Csaki et al. '08)

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SUSY COMPOSITE HIGGS

(see also Gherghetta-Pomarol '03, Sundrum '09)

Setup:

Strong sector:
G-sym, SUSY

↔

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Strong sector:
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Elementary:
G & SUSY badly broken

Spontaneous breaking G -> H produces SUSY GBs.

Partial compositeness -> partial supersymmetry:
states which belong mostly to the strong sector feel SUSY breaking weakly.

Stops can be light even if SUSY is broken at high scale.
Hierarchical spectrum!

The largest quadratic divergence due to the top is cancelled by the stop and similarly for the self coupling. Divergences from the light fermions are cut by compositeness.

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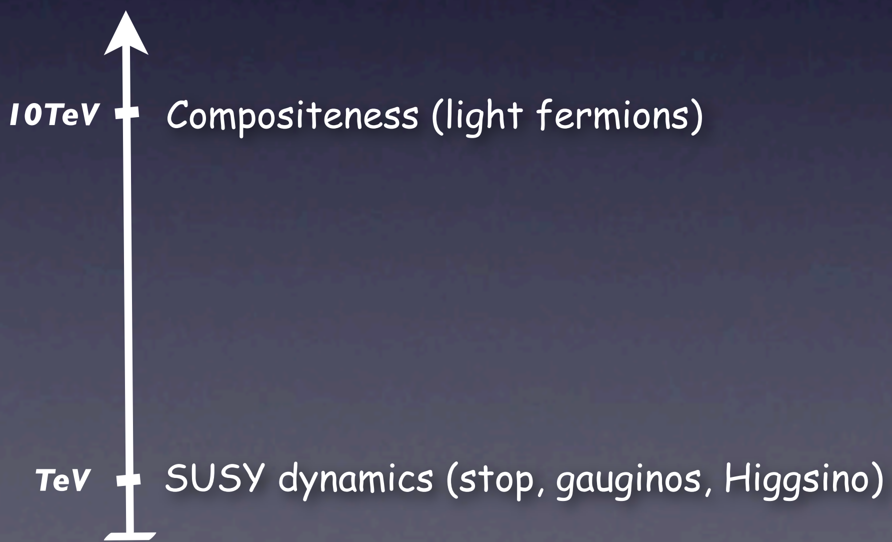
IFF gauginos remain light the compositeness scale could be around 10-20 TeV naturally.



SMCHM

The breaking SO(5)/SO(4) produces 4 chiral fields,

$$\Sigma = f\,\frac{\sin h/f}{h}\,(h_1,\; h_2,\; h_3,\; h_4,\; h\;\cot h/f)\,, \qquad h = \sqrt{\sum h_i^2}$$

$$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix} h_2 - ih_1 \\ h_4 + ih_3 \end{pmatrix} \qquad H_d = \frac{1}{\sqrt{2}}\begin{pmatrix} -h_4 + ih_3 \\ h_2 + ih_1 \end{pmatrix}\,,$$

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4 of the 8 scalars are partners of GBs which are massless by supersymmetry.

Kahler,

$$K = \sum_{i=1}^{5} \Sigma_i(h)\Sigma_i(\bar{h})$$
$$= \bar{H}_u H_u + \bar{H}_d H_d - \frac{1}{3f^2}[H_u H_d + \bar{H}_u \bar{H}_d](\bar{H}_u H_u + \bar{H}_d H_d) + \frac{1}{f^2}(H_u H_d)(\bar{H}_u \bar{H}_d) + \ldots$$

To couple the elementary sector we introduce linear couplings to operators of the strong sector,

$J_i \qquad\qquad O_i$

In the supersymmetric limit,

$$
\begin{aligned}
\mathcal{L}_{gauge} &= \int d^2\theta W^a_\alpha W^\alpha_a + h.c. + g \int d^4\theta V_i J_i + \ldots \\
J &= j_0 + i\theta j_{1/2} - i\bar{\theta}\bar{j}_{1/2} - \theta\sigma^\mu\bar{\theta} j_\mu + \ldots
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quartic potential is generated at tree level,

$$V_D = \frac{g^2 + g'^2}{8}(|H_u|^2 - |H_d|^2)^2 + \frac{g^2}{2}|H_u^\dagger H_d|^2 + \dots$$

No μ-term.

Mixing to the chiral operators is given by superpotential couplings,

$$\mathcal{L}_{chiral} = \int d^2\theta \lambda_i \Phi_i O_i^c + \lambda_i^c \Phi_i^c O_i .$$
$$O = O_0 + \theta O_{\frac{1}{2}} + \theta^2 O_F$$

The mixing breaks the GB symmetry and generates SUSY Yukawa couplings

$$y_i \sim \frac{\lambda_i \lambda_i^c}{g_\rho}$$

For CFTs, as in MCHM, the running allows to generate hierarchical Yukawa structures.

SUSY is broken at a high scale in the elementary sector mostly simply softly,

$$X = \theta^2 m_0$$

In the mass base SUSY breaking is felt differently depending on the degree of compositeness. For scalars,

$$m \sim m_0 \cos\alpha$$

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$$m \sim m_0 \cos\alpha \quad \xrightarrow{\text{CFT}} \quad m_0 \left(\frac{\mu_{IR}}{\Lambda}\right)^{\frac{5}{2}-\Delta}$$

States which are mostly part of the strong sector feel weakly SUSY breaking. Stops automatically protected.

Zero tree level mass for the GBs, highly suppressed for the scalar partners.

We assume,

$$m_0 >> m_\rho \sim 10\, TeV$$

The light generations are practically non supersymmetric. Their quadratic divergences are not dangerous,

$$\delta m_H^2 \sim \frac{3y_i^2}{16\pi^2} m_\rho^2 \qquad y_i << 1$$

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For the top since it is strongly composite the supersymmetric partners are naturally light,

$$\delta m_H^2 \sim \frac{3\, y_t^2}{4\pi^2}\, m_{\tilde{t}}^2 \log \frac{m_\rho}{m_{\tilde{t}}}$$

Small fine tuning!

Gaugino

(Sundrum '09)

An important flaw is that the gaugino is part of the elementary sector and could be heavy,

$$\delta m_H^2 \approx \frac{g^2}{16\pi^2} m_\rho^2$$

Severe fine tuning.

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Severe fine tuning.

The gaugino can be light because of chiral symmetry. This can be realized if R-symmetry is approximately preserved.

Similar to Split Supersymmetry.

(Arkani-Hamed, Dimopoulos '04)

RS Model

The action contains an SO(5) SUSY gauge theory in a slice of AdS5,

$$A_M\,, \qquad \Psi_D, \qquad \phi$$

The breaking to SO(4) can be realized by boundary conditions. GBs arise from Dirichlet b.c. for A.

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By N=1 SUSY the scalar delivers dim[G-H] zero modes which make up a chiral field,

$$\Sigma^{\hat{a}} = \phi^{\hat{a}} + i A_5^{\hat{a}}$$

The covariant derivatives in the bulk generate the SUSY quartic.

Matter fields arise from hypermultiplets,

$$\Psi_D\,, \qquad \phi\,, \qquad \phi^c$$

With SUSY b.c. 1 chiral zero mode,

$$\phi = f(c)\,\frac{z_{IR}}{L^2}\left(\frac{z}{z_{IR}}\right)^{\frac{3}{2}-c}\,,$$

$$\chi = f(c)\,\frac{z_{IR}^{\frac{3}{2}}}{L^2}\left(\frac{z}{z_{IR}}\right)^{2-c}\,,$$

$$\Delta = \frac{3}{2} + \left|c + \frac{1}{2}\right|\,.$$

Adding non supersymmetric masses on the UV brane,

$$m_\phi \approx m_0\left(\frac{z_{IR}}{z_{UV}}\right)^{c-\frac{1}{2}}$$

Potential

In MCHM the full potential is generated at one loop leading naturally,

$$H \sim f$$

In SMCHM SUSY quartic at tree level,

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Mass term not allowed by SUSY + Goldstone.

$$W = \frac{\lambda_u \lambda_u^c}{g_\rho} \int d^2\theta\, Q H_u u^c F\left(\frac{H_u H_d}{f^2}\right) + \frac{\lambda_d \lambda_d^c}{g_\rho} \int d^2\theta\, Q H_d d^c F\left(\frac{H_u H_d}{f^2}\right),$$

$$\frac{\lambda_i^2}{g_\rho^2} \int d^4\theta\, \bar{\Phi}_i \Phi_i \left[G\left(\frac{H_u H_d}{f^2}\right) + h.c.\right] - \frac{\lambda_i^{c\,2}}{g_\rho^2} \int d^4\theta\, \bar{\Phi}_i^c \Phi_i^c \left[G\left(\frac{H_u H_d}{f^2}\right) + h.c.\right],$$

After SUSY breaking mass terms are generated

$$V_{Yukawa} \sim N_c \frac{y_{u,d}^2}{16\pi^2} \times m_s^2 \, |H_{u,d}|^2 \times \hat{V}\left(\frac{H_u H_d}{f^2}\right) \; ,$$

$$V_{kinetic} \sim N_c \frac{m_s^4}{g_\rho^2} \times \frac{y_{L,R}^2}{16\pi^2} \times \hat{V}\left(\frac{H_u H_d}{f^2}\right) \; ,$$

$$V_{Higgs} \sim \frac{m_s^4}{16\pi^2} V\left(\frac{H_u}{f}, \frac{H_d}{f}\right) \; ,$$

Peccei-Quinn symmetry is broken,

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Not easy to obtain the appropriate potential:
Coupling to the MSSM fields insufficient and other breaking effects likely needed.

Bounds

Contributions to S well within experimental bounds.

Corrections to the Z-coupling would not require special mechanisms.

T-parameter more delicate,

$$\delta T \approx \frac{g_\rho^2}{16\pi^2}\left(\frac{v}{f}\right)^2$$

requires f to be a few TeV.

Flavor bounds from compositeness much more relaxed.

SUSY flavor problem: Solved

A distinctive feature are hierarchical soft terms,

$$, \left(m^2_{\tilde{q}}\right)_{ij} = \left(m^2_{0\,\tilde{q}}\right)_{ij} \cos\varphi_{\tilde{q}_i} \cos\varphi_{\tilde{q}_j}$$

This spectrum suppresses FCNC,

$$\delta\mathcal{M}_{K\bar{K}} \sim \frac{g^4}{16\pi^2}\frac{(\Delta m^2_{sd})^2}{m^6_{\tilde{q}}}$$

(Cohen, Kaplan, Nelson '96)

Thanks to compositeness the superpartners of the light generations could be very heavy without reintroducing fine tuning. This removes the SUSY flavor (and also CP) problem.

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- Partial compositeness naturally realizes a hierarchical spectrum. Huge benefits for flavor. Only the states most closely related to the hierarchy will be produced at LHC.

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- An amusing twist is that the strong sector could be supersymmetric. The compositeness scale could be larger avoiding experimental bounds with mild fine tuning.
- Partial compositeness naturally realizes a hierarchical spectrum. Huge benefits for flavor. Only the states most closely related to the hierarchy will be produced at LHC.
- Interesting to build an explicit model. Extensions such us the NMSSM are naturally obtained and should be explored.

T in SMCHM

There are 2 Higgs doublets so in general contributions to T. Their VEVs preserve SO(3) when

$$\tan\beta = 1$$

Luckily the T-violating operator

$$(\bar{H}_{u,d} H_{u,d})^2$$

does not appear in the leading Kahler potential.

It will be generated producing,

$$\delta T \approx \frac{g_\rho^2}{16\pi^2}\left(\frac{v}{f}\right)^2$$

SUSY GBs

Start from linear sigma-model,

$$\mathcal{L} = \sum_{i=1}^{5} \left\{ \int d^4\theta \, \bar{\Sigma}_i \Sigma_i + \int d^2\theta \left[m \, \Sigma_i \Sigma_i - \frac{m}{2f^2} \left(\Sigma_i \Sigma_i \right)^2 \right] + h.c. \right\} ,$$

Action is invariant under SO(5). Broken vacuum can be parameterized,

$$\Sigma = f \, \frac{\sin h/f}{h} \left(h_1 , \; h_2 , \; h_3 , \; h_4 , \; h \; \cot h/f \right) , \qquad h = \sqrt{\sum h_i^2}$$

Kahler is obtained plugging. Note that any power is also invariant and will be generated,

$$K = \left(\bar{\Sigma}_i \Sigma_i + \frac{g_\rho^2}{16\pi^2} (\bar{\Sigma}_i \Sigma_i)^2 + \dots \right) .$$

Minimally below 10 TeV the d.o.f. are SM fields, gauginos, stops and the SUSY Higgs doublets.