The Mass and the Tuning of the Composite Higgs

Andrea Wulzer
New boson **discovered** by ATLAS and CMS !!

\[ m_H \simeq 125 \text{ GeV} \]

Is it really the **SM** Higgs boson ?
Rephrasing the question:

“Is there an Hierarchy Problem?”

We only know a poor way to answer, searching for alternative natural scenarios:
Introduction

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**SUSY:**
- Huge effort from th and ex
- Nothing found
- All confident anyhow

**Composite Higgs:**
Is there an Hierarchy Problem?

Introduction

We only know a poor way to answer, searching for alternative natural scenarios:

**SUSY:**
- Huge effort from th and ex
- Nothing found
- All confident anyhow

**Composite Higgs:**
- Little work done
- Nothing found
- All skeptical anyhow

Rephrasing the question:

“Is there an Hierarchy Problem?”
Imagine the Higgs is **Composite** (Georgi, Kaplan et al. 1984; Agashe, Contino, Pomarol 2004)

Hierarchy Problem is solved:
Corrections to $m_H$ screened above $1/l_H$

$m_H$ is **IR-saturated**
Imagine the Higgs is **Composite** (Georgi, Kaplan et al. 1984; Agashe, Contino, Pomarol 2004)

\[ l_H \]

**Hierarchy Problem is solved:**

Corrections to \( m_H \) screened above \( 1/l_H \)

\( m_H \) is **IR-saturated**

Higgs lighter than resonances because it is a **Goldstone**

Higgs decay constant: \( f \)

EWPT suggest \( \xi = \frac{v^2}{f^2} \simeq 0.2, 0.1 \)
Composite Higgs

Describing a **New Strong Sector**

**SILH Paradigm** (or Prejudice) :
(Giudice, Grojean, Pomarol, Rattazzi)

- One **mass** scale  \( m_\rho \)
- One **coupling**  \( g_\rho = m_\rho / f \leq 4\pi \)

\[ \rho \quad \square \]

\[ H \quad \square \]
Composite Higgs

Describing a **New Strong Sector**

**SILH Paradigm (or Prejudice):**
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- One **mass** scale: $m_\rho$
- One **coupling**: $g_\rho = m_\rho / f \leq 4\pi$

**Generalized SILH:**

- Two **masses**: $m_\rho$, $m_\Psi$
- Two **couplings**: $g_\rho$, $g_\Psi = m_\Psi / f$

\[ \rho \rightarrow H \]

\[ \rho \rightarrow \Psi \rightarrow H \]
Composite Higgs

$g_\rho$ is preferentially large

\[ \rho \rightarrow m_\rho > 3 \text{ TeV} \rightarrow g_\rho \gtrsim 4 \text{ if } \xi = \left(\frac{v}{f}\right)^2 \gtrsim 0.1 \]

Getting a light Higgs will be easier for $g_\rho > g_\Psi \approx 1$
Let us focus on the **minimal coset**

**Composite Sector**

\[ \text{SO}(5) \to \text{SO}(4) \]

\[ H \in \text{SO}(5)/\text{SO}(4) \]

gauge couplings:

fermion couplings:

Linear interaction is **partial compositeness**

**Elementary Sector**

\[ \mathcal{L}_{\text{int}} = g J_{\mu} W_{\mu} \]

\[ \mathcal{L}_{\text{int}} = y_{L} q_{L} O_{L} + y_{R} q_{R} O_{R} \]

\[ W_{\mu}^{1,2,3}, B_{\mu}, f_{L}, f_{R} \]
In the **top sector**: \[ \mathcal{L}_{\text{int}} = y_{L} q_{L} O_{L} + y_{R} t_{R} O_{R} \]

Different \( O_{L,R} \) representations define different models

**Standard choices**

\[
\begin{align*}
\text{MCHM}_{5} & \quad \leftrightarrow \quad O_{L,R} \in 5 \\
\text{MCHM}_{10} & \quad \leftrightarrow \quad O_{L,R} \in 10 \\
\end{align*}
\]

**Other possibilities**

\[
\begin{align*}
O_{L,R} \in 14 \\
\text{OR, with totally composite } t_{R} \quad (\mathcal{L}_{\text{int}} = y_{L} q_{L} O_{L}) \\
O_{L} \in 14 \\
\end{align*}
\]

each choice has a peculiar top-Higgs coupling deviation
Composite Higgs

But why this is called “Partial compositeness”?

In the IR, operators correspond to particles:

$$\langle 0 | \mathcal{O} | Q \rangle \neq 0 \quad \mathcal{O}_{L,R} \leftrightarrow Q_{L,R}$$

Important Remark:

$\mathcal{O}$ and $Q$ carry color!

$Q =$“vector-like colored fermions”

Top Partners
Composite Higgs

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**Important Remark:**

- $O$ and $Q$ **carry color**!
- $Q$ = “vector-like colored fermions”
- Top Partners

**SM Quantum Numbers:**

$$\begin{pmatrix}
T \\
B
\end{pmatrix}
\begin{pmatrix}
X_{5/3} \\
X_{2/3}
\end{pmatrix}
\otimes \tilde{T}$$

- $y_L$
- $q_L$
- $y_R$
- $t_R$
Composite Higgs

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In the IR, operators correspond to particles:

\[ \langle 0|\mathcal{O}|Q\rangle \neq 0 \quad \mathcal{O}_{L,R} \leftrightarrow Q_{L,R} \]

\[ \mathcal{L}_{\text{int}} = y_L q_L \mathcal{O}_L + y_R t_R \mathcal{O}_R \] gives a **mass-mixing** in the IR:

\[ \mathcal{L}_{\text{mass}} = m_T^* \overline{T}T + y f \overline{t}T \]

physical particles are **partially composite**: \[ \sin \phi = \frac{y f}{m_T} \]

\[ |SM_t\rangle = \cos \phi |t\rangle + \sin \phi |T\rangle \]

\[ |BSM_T\rangle = \cos \phi |T\rangle - \sin \phi |t\rangle \]

phys. partner’s mass

\[ m_T = \sqrt{m_T^* 2 + y^2 f^2} \]
Composite Higgs

\[ y_t = \begin{cases} \frac{y_{LYR}}{g_{\Psi}} & \text{if } m_T \sim m_{\Psi} \\
\text{normal spectrum} \\
\text{OR} \\
\frac{y_{LYR} f}{m_T} & \text{if } m_T \ll m_{\Psi} \\
\text{anomalously light partner} \end{cases} \]
\( y_t = \begin{cases} \frac{y_{LYR}}{g_\Psi} & \text{if } m_T \sim m_\Psi \\ \text{normal spectrum} \\ \text{OR} \\ \frac{y_{LYR} f}{m_T} & \text{if } m_T \ll m_\Psi \\ \text{anomalously light partner} \end{cases} \)

For \( y_L \approx y_R \) \begin{cases} y = \sqrt{y_t g_\Psi} \\ \text{OR} \\ y = \sqrt{y_t \frac{m_T}{f}} \end{cases}

be careful with saturation
\[ m_T = \sqrt{m_T^2 + y^2 f^2} \geq y f \]
\[ y \geq y_t \]
Higgs potential is radiatively generated

\[ V(h/f) = V^{(2)} + V^{(4)} + \ldots \]

The SO(5) symmetry constrains \( V \) at each order

\[ V^{(2)} = \frac{N_c}{16\pi^2} m_\Psi^4 \sum_i \left[ \frac{y_{L,R}^2}{g_\Psi^2} I_{L}^i(h/f) + \frac{y_{L,R}^2}{g_\Psi^2} I_{R}^i(h/f) \right] \]

\[ V^{(4)} = \frac{N_c}{16\pi^2} m_\Psi^4 \sum_i \left[ \frac{y_{L,R}^4}{g_\Psi^4} I_{LL}^i(h/f) + \frac{y_{L,R}^4}{g_\Psi^4} I_{RR}^i(h/f) + \frac{y_{L,R}^2 y_{L,R}^2}{g_\Psi^4} I_{LR}^i(h/f) \right] \]
**Mass and Tuning**

<table>
<thead>
<tr>
<th>“Invariant” polynomials:</th>
<th>$I_L(s_h^2)$</th>
<th>$I_R(s_h^2)$</th>
<th>$I_{LL}, I_{RR}, I_{LR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_L = r_R = 5$</td>
<td>$\sin^2(h/f)$</td>
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<td>$\sin^{2n}(h/f)$ for $n = 1, 2$</td>
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<tr>
<td>$r_L = r_R = 10$</td>
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</tr>
<tr>
<td>$r_L = r_R = 14$</td>
<td>$\sin^2(h/f), \sin^4(h/f)$</td>
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\[
V(h/f) = V^{(2)} + V^{(4)} + \ldots
\]

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V^{(2)} = \frac{N_c}{16\pi^2} m^4_\Psi \sum_i \left[ \frac{y_L^2}{g^2_\Psi} I^i_L(h/f) + \frac{y_R^2}{g^2_\Psi} I^i_R(h/f) \right]
\]

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\]
Mass and Tuning

“Invariant” polynomials with composite $t_R$:

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<td></td>
</tr>
</tbody>
</table>

| $r_L = 14$ | $\sin^2(h/f), \sin^4(h/f)$ | $\sin^{2n}(h/f)$ with $n = 1, 2, 3, 4$ |

$$V(h/f) = V^{(2)} + V^{(4)} + \ldots$$

The $SO(5)$ symmetry constrains $V$ at each order

$$V^{(2)} = \frac{N_c}{16\pi^2} m^4 \sum_i \left[ \frac{y^2_L}{g^2_{\Psi}} I^i_L(h/f) \right]$$

$$V^{(4)} = \frac{N_c}{16\pi^2} m^4 \sum_i \left[ \frac{y^4_L}{g^4_{\Psi}} I^{i}_{LL}(h/f) \right]$$
Mass and Tuning

Need **two** or more terms for realistic EWSB

In the MCHM$_{5,10}$(4):

$$ V = V^{(2)} + V^{(4)} = \frac{N_c}{16\pi^2} m_\Psi^4 \epsilon^2 \left[ (a_L + a_R) s_h^2 + (b_L \epsilon^2 + b_R \epsilon^2) s_h^4 \right] $$

**Minimization condition:**

$$ \left| \frac{a_L + a_R}{b_L \epsilon^2 + b_R \epsilon^2} \right| = 2 \sin^2 \frac{\langle h \rangle}{f} = 2 \xi $$

**Fine tuning:**

$$ \Delta^{5+5} = \frac{\max(|a_L|, |a_R|)}{|a_L + a_R|} \approx \frac{1}{2 \xi} \frac{\max(|a_L|, |a_R|)}{|b_L \epsilon^2 + b_R \epsilon^2|} \approx \frac{1}{\xi \epsilon^2} $$

**Higgs mass:**

$$ m_H^2 \approx \frac{N_c}{2\pi^2} y^4 v^2 $$

$$ \epsilon = \frac{y}{g_\Psi} $$

$$ s_h = \sin \frac{h}{f} $$
Mass and Tuning

Higgs mass:

\[ m_H^2 \simeq \frac{N_c}{2\pi^2} y^4 \langle \nu \rangle^2 \]

**normal** spectrum:

\[ y = \sqrt{y_t g \Psi} \]

\[ m_H \simeq \sqrt{\frac{N_c}{2\pi^2}} m_t g \Psi = 500 \text{ GeV} \left( \frac{g \Psi}{5} \right) \]

\[ m_t > g \rho f \]

\[ m_H \simeq 125 \text{ GeV} \]

**anomalously light** top partners:

\[ y = \sqrt{y_t \frac{m_T}{f}} \]

Panico, AW (2011)
Higgs mass:

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**anomalously light** top partners:

\[ y = \sqrt{y_t \frac{m_T}{f}} \]

\[ m_H \simeq \sqrt{\frac{N_c}{2\pi^2} m_t \frac{m_T}{f}} = 100 \text{ GeV} \left( \frac{y_t m_T}{f} \right) \]

\[ m_H \simeq 125 \text{ GeV} \]

Panico, AW (2011)
Mass and Tuning

As we discussed previously the model with\

\( g_H \) is preferred. A light Higgs can also be obtained

while the bottom partners mass parameters have been chosen in the range [naive estimate. The dashed red lines correspond the estimate given in eq. (1). This can be clearly seen from the scatter plot in fig. 1, where the Higgs mass is plotted as a function of the bottom partners mass parameters. Moreover the amount of tuning is in good agreement with the estimate \( \xi = 0.1 \).
Light Higgs wants Light Partners:

\[ \xi = 0.2 \]
\[ m_H > 130 \]
\[ m_H \in [115, 130] \]

[Matcedonsky, Panico, AW (2012)]
Mass and Tuning

**Figure 3:** Scatter plots of the masses of the lightest exotic state of charge $5/3$ and of the lightest resonance for $\xi = 0.2$ (left panel) and $\xi = 0.1$ (right panel) in the three-site DCHM model. The black dots denote the points for which $115 \text{ GeV} \leq m_H \leq 130 \text{ GeV}$, while the gray dots have $m_H > 130 \text{ GeV}$. The scans have been obtained by varying all the composite sector masses in the range $[-8f, 8f]$ and keeping the top mass fixed at the value $m_t = 150 \text{ GeV}$.

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Of SO(4). Obviously the $X_{5/3}$ cannot mix with any other state even after EWSB, and therefore it remains always lighter than the other particles in the fourplet. In particular (see fig. 9 for a schematic picture of the spectrum), it is significantly lighter than the $t$.

In fig. 3 we show the scatter plots of the masses of the lightest exotic charge $5/3$ state and of the $e_t$. In the parameter space region in which the Higgs is light the $X_{5/3}$ resonance can be much lighter than the other resonances, especially in the configurations in which the $t$ and $e_t$ have comparable masses. In these points the mass of the exotic state can be as low as 300 GeV.

Notice that in the plots in fig. 2 there are no points in which the masses of the $t$ and of the $e_t$ coincide. This is due to a repulsion of the mass levels induced by the mixings due to EWSB. As expected, this effect is more pronounced for larger values of $\xi$.

**3.4 The top mass and a lower bound on the Higgs mass**

As noticed above, the asymptotic region $m_t \sim m_{e_t}$, which could in principle give rise to configurations with realistic Higgs masses, is not accessible in our model. Indeed in the scatter plots of fig. 2 we find a lower bound on $m_t$. We will show below that this bound comes from the requirement of obtaining a realistic top mass and that an analogous bound, which however is not visible in fig. 2, exists for the $e_t$ mass. From these results we will also derive an absolute lower bound on the Higgs mass.

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**Exotic Bidoublet is even lighter:**

[Matsedonsky, Panico, AW (2012)]
Mass and Tuning

LHC has **already probed** part of this plot:

CMS search of B:

\[ M_{X_{5/3}} > 611 \]

CMS search of T>Wb:

\[ M_{\tilde{T}} > 370 \]

\[ m_{5/3} \] (TeV)

\[ m_{\tilde{T}} \] (TeV)

\[ \xi = 0.2 \]

\[ m_H > 130 \]

\[ m_H \in [115, 130] \]

Figure 3: Scatter plots of the masses of the lightest exotic state of charge \( \frac{5}{3} \) and of the lightest \( e_T \) resonance for \( \xi = 0.2 \) (left panel) and \( \xi = 0.1 \) (right panel) in the three-site DCHM model. The black dots denote the points for which \( 115 \text{ GeV} \leq m_H \leq 130 \text{ GeV} \), while the gray dots have \( m_H > 130 \text{ GeV} \). The scans have been obtained by varying all the composite sector masses in the range \([8, 8] \), and keeping the top mass fixed at the value \( m_t = 150 \text{ GeV} \).

Obviously the \( X_{5/3} \) cannot mix with any other state even after EWSB, and therefore it remains always lighter than the other particles in the fourplet. In particular (see fig. 9 for a schematic picture of the spectrum), it is significantly lighter than the \( T \) and \( e_T \). In fig. 3 we show the scatter plots of the masses of the lightest exotic charge \( \frac{5}{3} \) state and of the \( e_T \). In the parameter space region in which the Higgs is light the \( X_{5/3} \) resonance can be much lighter than the other resonances, especially in the configurations in which the \( T \) and \( e_T \) have comparable masses. In these points the mass of the exotic state can be as low as 300 GeV.

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Mass and Tuning

Let us consider alternative scenarios

For \( \mathcal{O}_{L,R} \in 14 \):

\[
V = V^{(2)} = \frac{N_c}{16\pi^2} m_\Psi^4 \epsilon^2 \left[ (a_L + a_R) s_h^2 + (b_L + b_R) s_h^4 \right]
\]

Minimization condition:

\[
\left| \frac{a_L + a_R}{b_L + b_R} \right| = 2 \sin^2(\langle h \rangle / f) = 2 \xi
\]

Fine tuning:

\[
\Delta^{14+14} = \max(\frac{|a_L| + |a_R|}{|a_L + a_R|}) = \frac{1}{2\xi} \max(\frac{|a_L| + |a_R|}{|b_L + b_R|}) \sim \frac{1}{\xi}
\]

Higgs mass:

\[
m_H^2 \sim \frac{N_c}{2\pi^2} y^2 g_\Psi^2 v^2
\]
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### Heavy Higgs even with anomalously light partners

saturation: $y \geq y_t \quad \rightarrow \quad m_H \geq \sqrt{\frac{N_c}{2\pi^2}} m_t g \Psi = 650 \text{ GeV} g \Psi \frac{g \Psi}{5}$

we can hope to get 125 only for $g \Psi \sim 1$

Higgs mass:

$$m^2_H \sim \frac{N_c}{2\pi^2} y^2 g^2 \Psi v^2$$
Mass and Tuning

Let us consider alternative scenarios

For $O_L \in 14$ plus composite $t_R$:

$$V = V^{(2)} = \frac{N_c}{16\pi^2} m_{\Psi}^4 \epsilon^2 \left[ a s_h^2 + b s_h^4 \right]$$

Minimization condition:

$$\left| \frac{a}{b} \right| = 2\xi$$

Fine tuning:

$$\Delta^{14} = \frac{1}{\left| a \right|} = \frac{1}{2b\xi}$$

Higgs mass:

$$m_H^2 \simeq \frac{N_c}{2\pi^2} y^2 g_{\Psi}^2 v^2 \times b$$
Mass and Tuning

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For $O_L \in 14$ plus composite $t_R$:

$$V = V^{(2)} = \frac{N_c}{16\pi^2} m_\Psi^4 \epsilon^2 \left[ a s_h^2 + b s_h^4 \right]$$

The Higgs is again typically heavy

$$y = y_L = y_t \rightarrow m_H = \sqrt{\frac{N_c}{2\pi^2}} m_t g_\Psi \times \sqrt{b} = 650 \text{ GeV} \frac{g_\Psi}{5} \times \sqrt{b}$$

either $g_\Psi \approx 1$ or tuning:

$$\Delta^{14} \approx \frac{1}{\xi} \cdot 27 \left( \frac{125 \text{ GeV}}{m_H} \right)^2 \left( \frac{g_\Psi}{5} \right)^2$$

Higgs mass: $$m_H^2 \approx \frac{N_c}{2\pi^2} y^2 g_\Psi^2 v^2 \times b$$
Mass and Tuning

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For $O_L \in 14$ plus composite $t_R$:

$$V = V^{(2)} = \frac{N_c}{16\pi^2} m^4 \epsilon^2 \left[ a s_h^2 + b s_h^4 \right]$$

$$\epsilon = \frac{y}{g\Psi}$$

$$s_h = \sin h/f$$

The Higgs is again typically heavy

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either $g\Psi \simeq 1$ or tuning:

$$\Delta^{14} \simeq \frac{1}{\xi} \cdot 27 \left( \frac{125 \text{ GeV}}{m_H} \right)^2 \left( \frac{g\Psi}{5} \right)^2$$

comparable tuning in the minimal models:

$$\Delta^{5+5} \simeq \frac{1}{\xi} \cdot 20 \left( \frac{125 \text{ GeV}}{m_H} \right)^2 \left( \frac{g\Psi}{5} \right)^2$$
We have studied the impact of the 125 GeV Higgs on CH scenario.

- **Anomalously light partners**: $g_\Psi \simeq g_\rho$ and $M_{\text{CHM}_{5,10,4}}$
- **Ad hoc tuning**: $g_\Psi \simeq g_\rho$, $14^+ \text{ composite } t_R, \ldots$

Searching for explicit examples in each category

[Panico, Redi, Tesi, AW, to appear]
We have studied the impact of the 125 GeV Higgs on CH scenario.

- Light top partners are typically required, **essential** for a moderate level of tuning.

- Light partners are easily detectable, best way to search for CH!!

[Barbieri, Bellazzini, Rychkov, Varagnolo (2012)]
Summary and Outlook

NO LHC search devoted to top partners
Waiting for exp. to “wake up”, recast other searches

[De Simone, Matsedonsky, Rattazzi, AW (2012)]

Bound can be strengthened by including the single production process

[De Simone, Matsedonsky, Rattazzi, AW, to appear]
Summary and Outlook

✦ We have studied the impact of the 125 GeV Higgs on CH scenario.

✦ Light top partners are typically required, **essential** for a moderate level of tuning.

✦ Light partners are easily detectable, best way to search for CH !!

✦ Light partners could be in **tension with EWPT**

  is it really so in a concrete model ?

  [Barbieri, Bellazzini, Rychkov, Varagnolo (2007)]
Summary and Outlook

✦ We have studied the impact of the 125 GeV Higgs on CH scenario

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✦ Light partners could be in **tension with EWPT**
  is it really so in a concrete model? [Barbieri, Bellazzini, Rychkov, Varagnolo (2007)]

Stringent CH searches are possible already at 8 TeV

Much more will come at 14 TeV
Figure 3: Left panel: logarithmic sensitivity as a function of $s_h$. Right panel: logarithmic sensitivity with the requirement that the top mass be kept fixed (see text). The green dots correspond to a random scan over parameter space with $c_u > 0$. The subset that satisfies $140$ GeV $< m_t (\mu \sim \mu_{\text{IR}}) < 160$ GeV is indicated by red triangles. The results for the $c_u < 0$ region are similar.

There is a sense in which there is little sensitivity to the details of the new physics beyond the standard model. This also underscores the role that the heavy top plays in driving EWSB. The above situation should be contrasted with supersymmetric (SUSY) scenarios that also present, generically, a sensitivity of order a percent to various fundamental parameters. In the SUSY case, reproducing a large top mass is no more difficult than in the SM (it is enough to choose the top Yukawa coupling, one of the "fundamental" parameters of these theories, to be of order one). However, there is a well-known intrinsic fine-tuning associated with a cancellation between the $\mu$ term and the soft SUSY breaking parameters in the Higgs sector. The latter depend quadratically on the stop soft SUSY breaking masses, which in turn need to be taken somewhat heavy (at least in the simplest SUSY extensions of the standard model) in order to get a large enough Higgs quartic coupling that allows satisfying the LEP bound on the Higgs mass. If, in addition, one takes into account the RG running from a high scale, and quantifies the fine-tuning by the sensitivity to the high-energy parameters of the theory, the situation worsens. In warped scenarios, the RS mechanism eliminates any possible fine-tuning due to running from a high scale. The dynamical generation of the weak scale in gauge-Higgs unification scenarios, allows for a further natural separation between the weak scale and the KK scale $\mu_{\text{ir}}$. In fact, EWSB is generic, except that in most of parameter space it is characterized by $s_h = 1$, which is not phenomenologically acceptable. The sensitivity shown in Fig. 3 is associated with the requirement $0 < s_h < 1$. Our observation is that all of this sensitivity is actually associated with getting the correct top mass (which in these cases...)

[Panico,Ponton,Santiago,Serone (2008)]