The tuning and the mass of the composite Higgs

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based on G. P., M. Redi, A. Tesi and A. Wulzer 1210.7114 [hep-ph]

Outline

1. Introduction
2. The general structure of Composite-Higgs Models
3. The “Minimal” Models
   - Double tuning
   - Light partners for a light Higgs
4. Beyond the “Minimal” Models
   - Multiple invariants
   - Totally composite t_R
5. Minimal tuning, light states and the LHC
6. Conclusions

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Introduction

Main **goal** of the LHC:

Unveil the **nature of the EWSB mechanism**

Need for **theoretical framework** to interpret the data:

- look for a **motivated** scenario
- develop and test hypothetical **models**

Introduction: The Hierarchy Problem

The **Standard Model** solution

- Higgs as an **elementary** scalar
- **Minimal** realization
- Excellent **agreement** with EW data

... **but** the **Higgs mass** is **unstable** under radiative corrections

$$\delta m_h^2\big|_{1-loop} \sim -\frac{\lambda_{top}^2}{8\pi^2}\Lambda_{UV}^2$$

this is known as the **Hierarchy problem**

Introduction: The role of New Physics

New physics can solve the Hierarchy problem by **cancelling** the quadratic **divergence**.

The **cut-off** is set by the scale of the new dynamics:

$$\delta m_h^2\big|_{1-loop} \sim -\frac{\lambda_{top}^2}{8\pi^2}\Lambda_{NP}^2$$

Some **tuning** is **unavoidable** if the new physics is at **high scale**

$$\Delta \gtrsim \frac{\delta m_h^2}{m_h^2} \simeq \left(\frac{\Lambda_{NP}}{400\ \mathrm{GeV}}\right)^2 \left(\frac{125\ \mathrm{GeV}}{m_h}\right)^2$$

Introduction: Solutions to the Hierarchy Problem

The **solutions** to the **Hierarchy Problem** belong to two broad classes

Weakly coupled UV physics

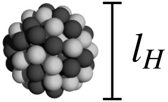
- known example: low-energy **Supersymmetry**

Strongly coupled UV physics

- Presence of an **Higgs-like state** coming from the strong sector

Introduction: The Composite Higgs

Higgs as a **composite state** from a strong dynamics [Georgi, Kaplan]

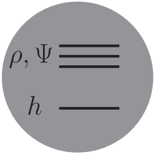


The Hierarchy Problem is **solved**

- Corrections to m_h **screened** at $1/l_H$
- Higgs mass is **IR-saturated**

Introduction: The Composite Higgs

Postulate a **new strong sector**



Modified SILH paradigm

[Giudice, Grojean, Pomarol, Rattazzi; G. P., Redi, Tesi, Wulzer]

- **mass** scales: $m_\rho\ ,\ m_\psi$
- **couplings**: $g_\rho\ ,\ g_\psi \lesssim 4\pi$

Higgs naturally **light** ($m_h \ll m_\rho, m_\psi$) if it is a **Goldstone**

- Underlying **symmetry structure**: $f \simeq m_\rho/g_\rho \simeq m_\psi/g_\psi$
- Separation of scales for EW precision data: $v \ll f$

Introduction: Realizations of the Composite-Higgs Idea

Extra dimensions implement the Composite Higgs idea through **Holography** (*eg.* MCHM) [Contino, Nomura, Pomarol, Agashe, ...]

- Extra-dimensional **gauge theory**
- Higgs comes from the 5th component of gauge fields (Gauge-Higgs Unification)

More general realizations can be obtained using **4d effective descriptions** (*eg.* DCHM) [G. P., Wulzer; De Curtis, Redi, Tesi]

- The Higgs is described by a **non-linear σ-model** [Giudice et al. (2007), Barbieri et al. (2007)]
- Resonances can be described by an **"hidden local symmetry" Lagrangian** (analogous to mesons in QCD)

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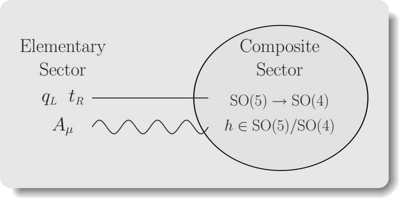
The structure of Composite-Higgs models

Composite sector with a spontaneously broken **global symmetry**

$$\mathrm{SO}(5) \to \mathrm{SO}(4)$$



Higgs described by a **non-linear σ-model**

$$\mathcal{L} = \frac{f^2}{2} \sum_i D_\mu U_{i5} D^\mu U_{i5}$$

$$U = \exp[i h_{\hat{a}} T^{\hat{a}}]$$

$$D_\mu U = \partial_\mu U - i g A_\mu U$$

The **non-linearities** induce interesting experimental signatures

[Giudice et al., Barbieri et al., ...]

$$\lambda \simeq \lambda_{SM}(1 + c\xi) \qquad \xi = (v/f)^2$$

Partial compositeness

SM fields obey **partial compositeness**

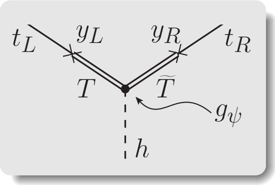
$$\mathcal{L}_{mix} = y_L f \overline{q}_L \mathcal{O}_L + y_R f \overline{t}_R \mathcal{O}_R + \mathrm{h.c.}$$

In a low-energy effective description this translates into a mixing with **fermionic resonances**

$$\mathcal{L}_{mix} = y_L f \; \overline{q}_L \Psi_R + y_R f \; \overline{t}_R \Psi_L + \mathrm{h.c.}$$

The SM fields are an **admixture** of elementary and composite states

$$|SM_n\rangle = \cos\varphi_n |elem_n\rangle + \sin\varphi_n |comp_n\rangle$$



Generation of the Higgs potential

The mixing gives a **small breaking** of the global symmetry

- Higgs potential **radiatively induced** (mostly by top partners)

The **quantum numbers** of the $\mathcal{O}_{L,R}$ operators fix the **structure of the potential** in a $y_{L,R}/g_\psi$ expansion. [Mrazek, Pomarol et al.]

$$V^{(2)} \sim \frac{N_c}{16\pi^2} m_\psi^4 \sum_i \left[\frac{y_L^2}{g_\psi^2} I_L^{(i)}(h/f) + \frac{y_R^2}{g_\psi^2} I_R^{(i)}(h/f) \right]$$

$$V^{(4)} \sim \frac{N_c}{16\pi^2} m_\psi^4 \sum_i \left[\frac{y_L^2 y_R^2}{g_\psi^4} I_{LR}^{(i)}(h/f) + \frac{y_L^4}{g_\psi^4} I_{LL}^{(i)}(h/f) + \frac{y_R^4}{g_\psi^4} I_{RR}^{(i)}(h/f) \right]$$

	I_L, I_R	I_{LL}, I_{RR}, I_{LR}
$\mathbf{r_L = r_R = 5}$	$\sin^2(h/f)$	$\sin^{2n}(h/f) \quad n = 1, 2$
$\mathbf{r_L = r_R = 10}$	$\sin^2(h/f)$	$\sin^{2n}(h/f) \quad n = 1, 2$
$\mathbf{r_L = r_R = 14}$	$\sin^2(h/f)$, $\sin^4(h/f)$	$\sin^{2n}(h/f) \quad n = 1, 2, 3, 4$
$\mathbf{r_L = r_R = 4}$	$\sin^2(h/2f)$	$\sin^{2n}(h/2f) \quad n = 1, 2$

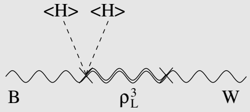
EW Precision Tests

The new dynamics gives **deviations** in the **EW observables**

- $\widehat{S}$ from **heavy gauge resonances**

$$\widehat{S} \simeq \frac{g_w^2}{g_\rho^2}\xi \simeq \frac{m_W^2}{m_\rho^2}$$

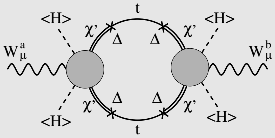
bound on $m_\rho \gtrsim 2\ \mathrm{TeV}$



- $\widehat{T}$ from **fermion loops**

$$\widehat{T} \sim \frac{N_c}{16\pi^2}\frac{y^4}{g_\rho^2}\xi \sim \frac{N_c}{16\pi^2}y_t^2\xi \simeq 2{\cdot}10^{-2}\xi$$

bound on $\xi \lesssim 0.2$



The constraints require a **scale separation** between v and f

$\Rightarrow$ a **fine-tuning** of $\mathcal{O}(1/\xi)$ is needed

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The "Minimal" Models: Double tuning [G. P., Redi, Tesi, Wulzer]

All "minimal" models ($\mathcal{O}_{L,R} \in \mathbf{4}, \mathbf{5}, \mathbf{10}$) are in the **same class**:

- Only **one invariant** at leading order

$$V \simeq \frac{N_c}{16\pi^2} g_\psi^2 f^4 y^2 \left[(\alpha_L + \alpha_R) \sin^2\left(\frac{h}{f}\right) + \beta \frac{y^2}{g_\psi^2} \sin^4\left(\frac{h}{f}\right) \right]$$

$$\alpha_{L,R}, \beta \sim \mathcal{O}(1)$$

To satisfy the constraint $\xi \ll 1$ we need to **tune** the **leading** terms with the **subleading** ones

An **additional cancellation** of $\alpha = \alpha_L + \alpha_R$ is needed

$\Rightarrow$ **"Double" tuning** $\Delta = \dfrac{\max(\alpha_L, \alpha_R)}{\alpha} \simeq \dfrac{1}{\xi} \dfrac{g_\psi^2}{y^2}$

The top mass

To get some quantitative estimates we need to connect the mixings $y_{L,R}$ to physical observables:

- Generation of the **SM fermion masses**

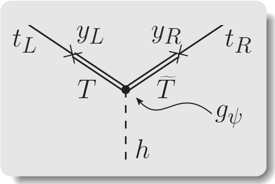
The top mass

To get some quantitative estimates we need to connect the mixings $y_{L,R}$ to physical observables:

- Generation of the **SM fermion masses**

The top mass is generated through **partial compositeness**

$$y_t \simeq \frac{y_L y_R}{g_\psi}$$



- We set a **common mass scale** for the resonances $m_\psi \simeq g_\psi f$
- We choose $y_L \sim y_R$, realized in **explicit models** and needed to **minimize the tuning**.

The Higgs mass

From the potential we extract the Higgs mass

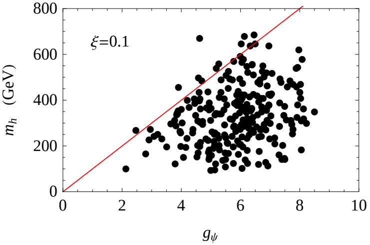
$$m_h^2 \simeq \frac{N_c}{2\pi^2} y^4 v^2$$

We **expect** a rather **heavy Higgs**

$$m_h \simeq \sqrt{\frac{N_c}{2\pi^2}} y_t g_\psi v \simeq 500 \text{ GeV} \left(\frac{g_\psi}{5}\right)$$

The estimate reproduces the **upper bound**

... **but** in many configurations the Higgs mass is **smaller**

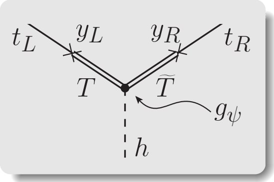


Light partners for a light Higgs

[Matsedonskyi, G. P., Wulzer]

When **anomalously light** resonances are present

$$y_t \simeq y_L y_R \frac{f}{m_{light}}$$



- The presence of **light** top partners **enhances** the top Yukawa

Using the expression for the top mass we get

$$m_h \simeq \sqrt{\frac{N_c}{2\pi^2}} \frac{y_t m_{light}}{f} \simeq 100 \text{ GeV} \left(\frac{m_{light}}{f}\right)$$

A **light Higgs** requires **light partners**

Light partners for a light Higgs

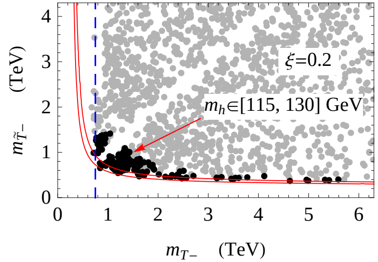
[Matsedonskyi, G. P., Wulzer]

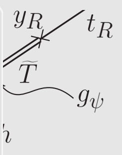
When **anom**

resonances

$y_t \simeq y_L$

Light partners: $m_{light} \lesssim 1$ TeV





- The presence of … p Yukawa

Using the expression

$$m_h \simeq \sqrt{\frac{N_c}{2\pi^2}\frac{y_t\, m_{light}}{f}} \simeq 100 \text{ GeV} \left(\frac{m_{light}}{f}\right)$$

A **light Higgs** requires **light partners**

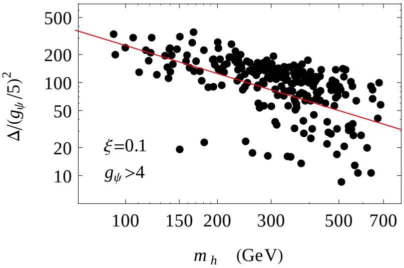
The degree of tuning

[G. P., Redi, Tesi, Wulzer]

The estimate of the **tuning** can be rewritten:

$$\Delta \simeq \frac{1}{\xi}\frac{g_\psi^2}{y_t}\frac{f}{m_{light}} \simeq \frac{1}{\xi}20\left(\frac{125\ \mathrm{GeV}}{m_h}\right)\left(\frac{g_\psi}{5}\right)^2$$

- A **large** fermion scale $m_\psi \simeq g_\psi f$ implies **tuning**



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Beyond the "Minimal" Models

"Minimal" models are characterized by only **one invariant** in the Higgs potential at leading order

- presence of a **"double" tuning**
- necessity of **light top partners**

A **large part** of the models studied in the literature belong to this class (*eg.* $\mathrm{MCHM}_{4,5,10}$)

Can we find **more general set-ups** with different properties?

Consider models with **multiple invariants** at leading order

Can be done with fermions in higher SO(5) reps. (*eg.* $\mathbf{r} = \mathbf{14}$)

Multiple leading-order invariants

The Higgs potential now takes the form

$$V = \frac{N_c}{16\pi^2} g_\psi^2 f^4 y^2 \left[(\alpha_L + \alpha_R) \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right) \right]$$

$$\alpha_{L,R}, \beta \sim \mathcal{O}(1)$$

- We can tune with two terms of the **same order**.

The amount of tuning is **minimal** $\quad \Delta \simeq \frac{1}{\xi}$

The Higgs mass

The absence of “double” tuning makes the potential larger:

- **“minimal”** models: $V \sim \left(\frac{y}{g_\psi}\right)^4$
- **“non-minimal”** models: $V \sim \left(\frac{y}{g_\psi}\right)^2$

Without anomalously light partner $m_\psi \simeq g_\psi f$ the **Higgs mass** is

$$m_h \simeq \sqrt{\frac{N_c}{2\pi^2} y_t g_\psi^3 v^2} = 1\ \mathrm{TeV} \left(\frac{g_\psi}{5}\right)^{3/2}$$

- The Higgs is **too heavy**

The Higgs mass with light partners

If **anomalously light partners** are present $\quad y_t \simeq y_L y_R \dfrac{f}{m_{light}}$

... **but** due to the elementary–composite mixing we always have

$$m_{light} \gtrsim y\, f \quad \Rightarrow \quad y \gtrsim y_t$$

This imples a **lower bound** on the Higgs mass

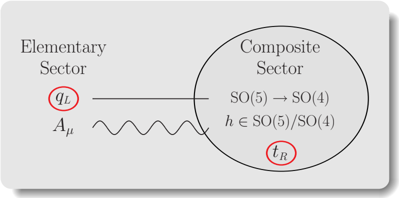
$$m_h \gtrsim \sqrt{\frac{N_c}{2\pi^2}} y_t g_\psi v = 500\ \mathrm{GeV} \left(\frac{g_\psi}{5}\right)$$

A **light Higgs** requires:

- some **additional tuning**
- typical presence of **anomalously light states**

The case of a totally composite t_R

We can assume that the t_R is an $\mathrm{SO}(5)$ **singlet** from the **composite sector**



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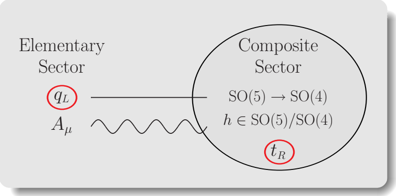


Only the y_L mixing breaks $\mathrm{SO}(5)$ and generate an Higgs **potential**.

A **minimally-tuned** model requires **two leading invariants** (can be obtained with fermions in the **14**)

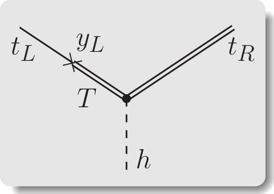
$$V = \frac{N_c}{16\pi^2} g_\psi^2 f^4 y_L^2 \left[\alpha \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right) \right], \qquad \alpha, \beta \sim \mathcal{O}(1)$$

The amount of **tuning** is $\quad \Delta = \dfrac{1}{\alpha} \simeq \dfrac{1}{\beta\,\xi}$

The Higgs mass

The elementary–composite mixing is now **minimal**

$$y_t \simeq y_L$$



The Higgs mass is somewhat **reduced**

$$m_h \simeq \sqrt{\beta}\sqrt{\frac{N_c}{2\pi^2} y_t^2 g_\psi^2 v^2} = \sqrt{\beta}\, 500 \text{ GeV} \left(\frac{g_\psi}{5}\right)$$

We still need some **additional tuning** to get $\beta < 1$:

$$\Delta \simeq \frac{1}{\xi}\frac{N_c}{2\pi^2} y_t^2 g_\psi^2 \frac{v^2}{m_h^2} \simeq \frac{1}{\xi} 16 \left(\frac{125 \text{ GeV}}{m_h}\right)^2 \left(\frac{g_\psi}{5}\right)^2$$

- For $m_h \simeq 125$ GeV **similar tuning** as in "minimal" models

The Higgs mass

t_R

The elementary–compo

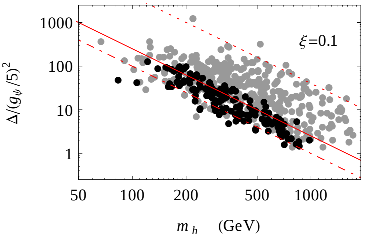
is now **minim**

$y_t \simeq y_L$

The Higgs mass is somewh

$m_h \simeq \sqrt{\beta}\sqrt{\frac{N_c}{2\pi^2}}$

Sizable tuning



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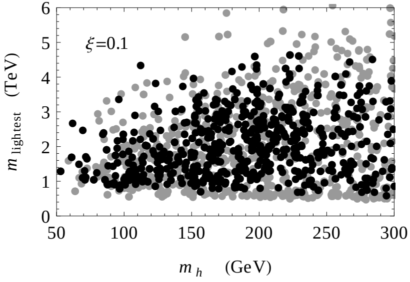
- For $m_h \simeq 125\ \mathrm{GeV}$ **similar tuning** as in “minimal” models

Heavy partners

The elementary–composite mixing is now **structurally minimized**.

A **light Higgs** can be obtained **without** light resonances



... **but** some **tuning** is **necessary**

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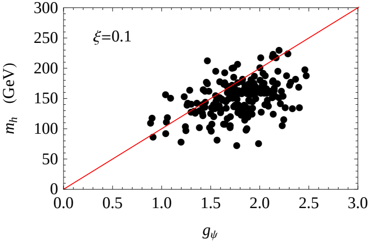
The limit of small fermionic scale

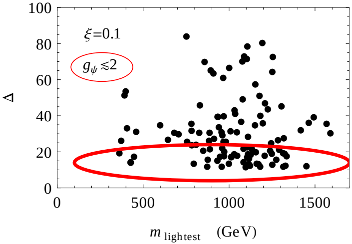
Configuration with **minimal tuning** can be obtained only if the **fermionic scale is small**: $g_\psi \lesssim 2$.

In this case all the terms in the y expansion are of the **same order**

$$\frac{y_L}{g_\psi} \sim \frac{y_R}{g_\psi} \sim 1$$

- **all** models share **similar properties**



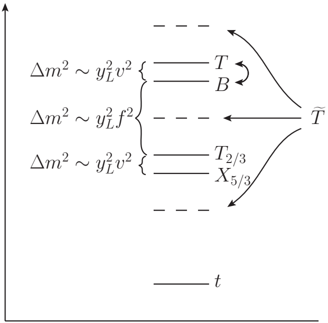


The spectrum of the resonances

Costodial invariance $\mathrm{SO}(4) \simeq \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ implies the presence of **extended multiplets** of top partners

$$Q = (\mathbf{2}, \mathbf{2})_{2/3} = \begin{bmatrix} T & X_{5/3} \\ B & T_{2/3} \end{bmatrix}, \qquad \widetilde{T} = (\mathbf{1}, \mathbf{1})_{2/3}$$

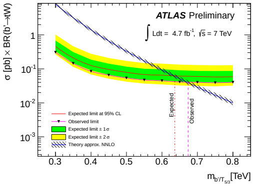
- **New colored fermions** strongly coupled to the top
- **Exotic** resonances

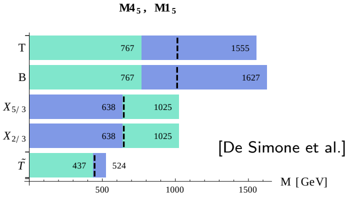


The experimental searches

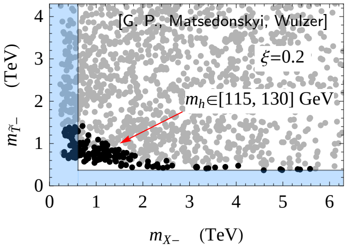
The light states are **easily accessible** at the LHC

Available data already give significant **bounds**





- Already probing part of the parameter space



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Conclusions

We analyzed **quantitatively** the issue of **fine-tuning** in composite-Higgs models:

- "minimal" models suffer from a **"double" tuning**
- "non-minimal" constructions lead to a **large Higgs mass**

Minimal tuning $\Delta \simeq 1/\xi$ can be obtained

only for a **small** fermionic mass scale $g_\psi = m_\psi/f \sim 1$.

A **separation** of the **fermionic** ($m_\psi \lesssim 1\ \mathrm{TeV}$) and **bosonic** mass scale ($m_\rho \gtrsim 2\ \mathrm{TeV}$) is needed

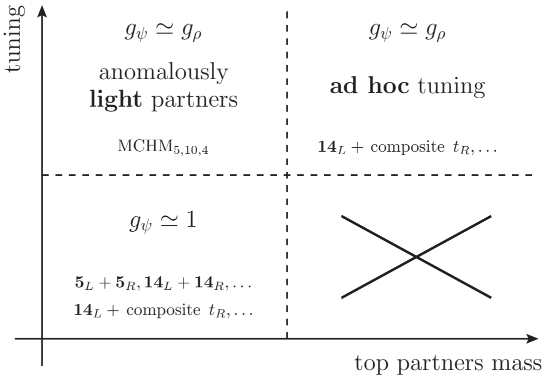
Light states are predicted which are **easily accessible** at the LHC

- available data already put some **constraint**

Conclusions

The general classification is a **key** to identify interesting **alternative scenarios** [Pomarol, Riva; G. P., Redi, Tesi, Wulzer]

- "Non-minimal" models
- Totally composite t_R
- ...



Backup slides

Light partners for a light Higgs

A more refined formula for the Higgs mass

$$m_h^2 \simeq \frac{N_c}{\pi^2} \frac{m_t^2}{f^2} \frac{m_T^2 m_{\widetilde{T}}^2}{m_T^2 - m_{\widetilde{T}}^2} \log \frac{m_T^2}{m_{\widetilde{T}}^2}$$

- Good agreement with the numerical results