Composite Higgs confronts LHC

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Implications of the 125 GeV Higgs Boson

Grenoble – 21 March 2013

Outline

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1. Introduction
2. The structure of the composite Higgs
   - EW precision observables
   - Higgs potential, tuning and light states
3. Collider phenomenology
   - Higgs couplings
   - Direct searches of resonances
   - Late LHC searches
4. Summary

Introduction

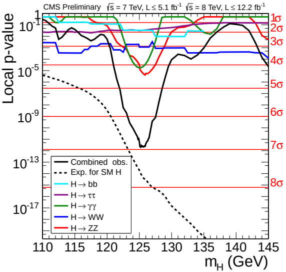
Main goal of the LHC:

Unveil the **nature of the EWSB mechanism**

First step in 2012

discovery of an Higgs-like particle

$m_h \simeq 125$ GeV



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 well 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

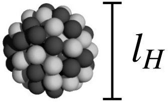
- known example: low-energy Supersymmetry

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]

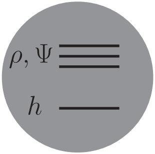


The Hierarchy Problem is **solved**

- 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: $v \ll f$

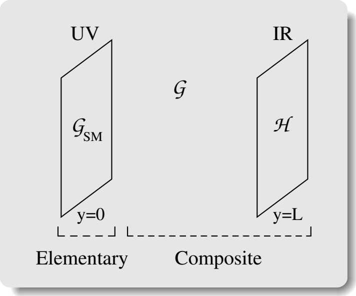
Introduction: Realizations of the Composite-Higgs Idea

Extra dimensions implement the Composite Higgs idea through **Holography** ($MCHM_{4,5,10}$) [Contino, Nomura, Pomarol, Agashe, ...]

Elementary sector ⇔ UV

Composite sector ⇔ Bulk + IR

Global symm. ⇔ Local symm.



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

Introduction: Realizations of the Composite-Higgs Idea

More general realizations can be obtained using **4d effective descriptions** (*DCHM*) [G. P., Wulzer]

- 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)

Implementations similar to deconstructed extra-dimensional models

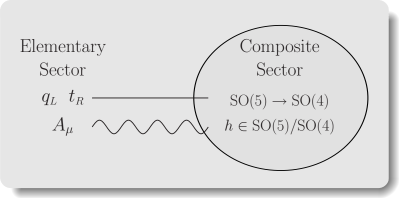
Useful to capture the general properties of composite Higgs for **collider phenomenology**

Outline

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 corrections to the SM observables

[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**

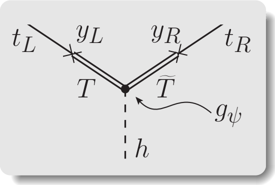
$$\mathcal{L}_{mix} = y_L \overline{q}_L \mathcal{O}_L + y_R \overline{t}_R \mathcal{O}_R + \mathrm{h.c.}$$

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

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



Consequences of partial compositeness

The mixing of the elementary states
induces a **small breaking** of the global symmetry
$\Downarrow$
the Higgs becomes a pseudo Goldstone boson

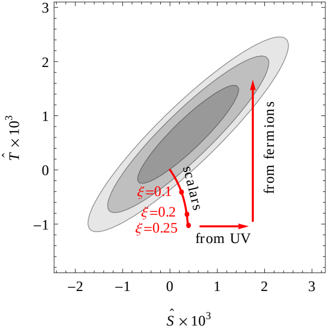
- A **Higgs potential** is induced at the radiative level
- The **custodial symmetry** and P_{LR} **symmetry** are broken and the new resonances contribute to the EW observables
  - Tree-level contributions to S
  - Loop corrections to T and to the $Z\bar{b}_L b_L$ vertex

EW precision observables

The legacy from LEP

The modification of the gauge and Higgs sector generates **sizable corrections** to the EW observables

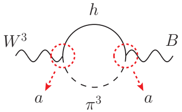
- The non-linear Higgs dynamics gives a correlated shift in S and T ($\Delta S > 0$, $\Delta T < 0$)
- The presence of heavy gauge resonances contributes to S
- Loops of fermion resonances can give a positive contribution to T



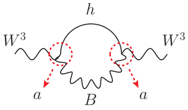
The scalar contribution

The **deviations** from the SM Higgs couplings ($a = \sqrt{1-\xi}$) are fixed by the low-energy σ-model structure

$$\Delta \widehat{S} = \frac{g^2}{192\pi^2 sin^2\theta_w} \xi \log\left(\frac{m_\rho^2}{m_h^2}\right)$$



$$\Delta \widehat{T} = -\frac{3g^2}{64\pi^2 \cos^2\theta_W} \xi \log\left(\frac{m_\rho^2}{m_h^2}\right)$$



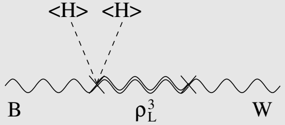
- The logarithmic divergence cancels only for the SM ($a = 1$)
- For $a \neq 1$ **logarithmic sensitivity** to **new physics** scale m_ρ

[Barbieri, Bellazzini, Rychkov, Varagnolo 2007]

The tree-level contribution to S

The $\widehat{S}$ **parameter** is induced a **tree-level** by the mixing of the elementary gauge boson with the composite resonances.

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



A rather **strong bound** is found on the gauge resonance masses

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

The constraint on $\widehat{S}$ favors a scale separation between v and f

$\Downarrow$

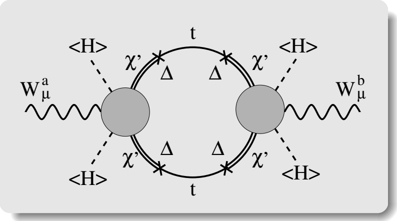
a minimal <u>**fine-tuning**</u> of $\mathcal{O}(\xi)$ is needed

The fermion contribution to T

The $SO(4) \simeq SU(2)_L \times SU(2)_R$ **custodial symmetry** forbids a contribution to T at tree-level

Sizable 1-loop contributions come from fermion loops

$$\Delta \widehat{T} \sim \frac{N_c}{16\pi^2} \frac{y^4}{g_\psi^2} \xi$$



For $y_L \sim y_R \sim \sqrt{y_t g_\psi}$ one gets the estimate

$$\Delta \widehat{T} \sim \frac{N_c}{16\pi^2} y_t^2 \xi \simeq 2 \cdot 10^{-2} \xi$$

- Bound on the compositeness scale $\xi \lesssim 0.2$

Higgs potential, tuning and light states

Generation of the Higgs potential

The dominant contribution to the Higgs potential comes from top partner loops

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.]

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

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

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

The "Minimal" Models

The "minimal" models ($\mathcal{O}_{LR} \in \mathbf{4}, \mathbf{5}, \mathbf{10}$) share the same structure of the Higgs potential

- only **one invariant** at leading order

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

$$\alpha, \beta \sim \mathcal{O}(1)$$

- all the minimal holographic models ($MCHM_{4,5,10}$) belong to this class

To satisfy the constraint $\xi \ll 1$ the **leading** term must be tuned with the **subleading** one

- a "preliminary" tuning is needed in the α coefficient
- the y^4 term controls the Higgs mass

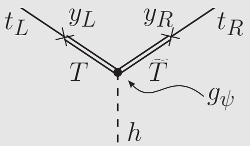
Light partners for a light Higgs

[Matsedonskyi, G. P., Wulzer]

$y_{L,R}$ are related to the generation of the top mass

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

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



The Higgs mass is related to the mass of the lightest top partner

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

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

Light partners for a light Higgs

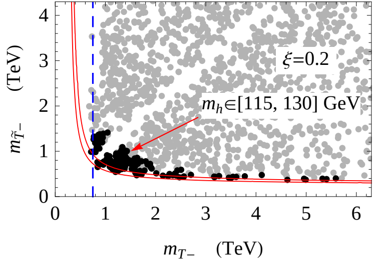
[Matsedonskyi, G. P., Wulzer]

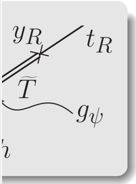
$y_{L,R}$ are related to t

The presence of l
enhances the

$y_t \simeq y_L$

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





The Higgs mass is r … partner

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

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

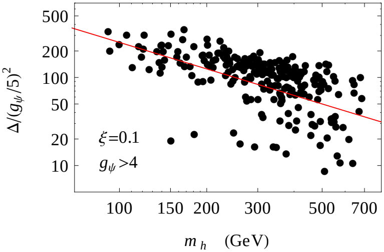
The degree of tuning

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

We can also estimate the amount of tuning

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

- A **large** fermion scale $m_\psi \simeq g_\psi f$ implies **tuning**
- The tuning **does not** improve if **only one** state becomes light



- for the numerical analysis we use $\Delta \equiv d\log(v/f)/d\log i$

[Barbieri, Giudice]

Minimal tuning

In general a **low amount of tuning** requires the presence of **light fermionic resonances**

A simple reason is the quadratic divergence in the Higgs mass

- the top partners regulate the divergence
- Λ_{NP} is related to the fermion mass scale $\Lambda_{NP} \simeq m_\psi = g_\psi f$

The **minimal** amount of tuning is

$$\Delta \gtrsim \left(\frac{\Lambda_{NP}}{400\ GeV}\right)^2 \simeq \left(\frac{m_\psi}{400\ GeV}\right)^2$$

A bound on the partners implies a bound on the tuning

Natural SUSY: light stops	$\Leftrightarrow$	**Natural CH**: light top partners

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Higgs couplings

Modification of the Higgs couplings

The non-linear dynamics generates a **distortion of the Higgs couplings**

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left(1+2a\frac{h}{f}\right) - m_t\,\overline{q}_L\Sigma t_R\left(1+c\frac{h}{f}\right) + h.c.$$

In the SM the parameters are fixed $a = c = 1$

The size of the corrections are determined by $\xi = (v/f)^2$

$$MCHM_4 \quad (\mathcal{O}_{L,R} \in \mathbf{4}) \qquad a = c = \sqrt{1-\xi}$$

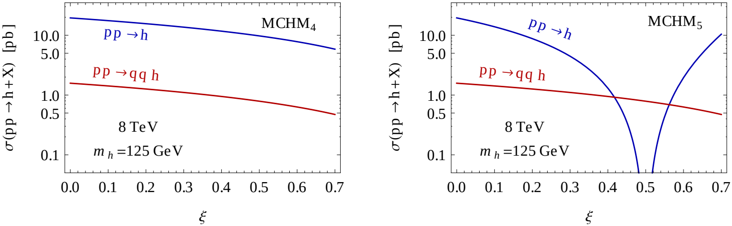
$$MCHM_5 \quad (\mathcal{O}_{L,R} \in \mathbf{5}) \qquad a = \sqrt{1-\xi},\ c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Higgs production cross section

The Higgs production cross section is modified

$$\sigma(gg \to h) = c^2 \sigma_{SM}(gg \to h) \qquad \sigma(VBF) = a^2 \sigma_{SM}(VBF)$$

- In the $MCHM_4$ all channels are rescaled by a common factor
- In the $MCHM_5$ the relative importance of the channels is modified

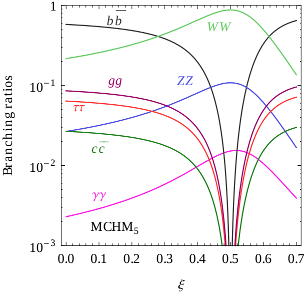


Higgs decays

The modification of the Higgs couplings can also change the **Higgs branching ratios**

In the $MCHM_5$

- suppression of the fermionic channels and the decay into gluons
- enhancement of the bosonic channels

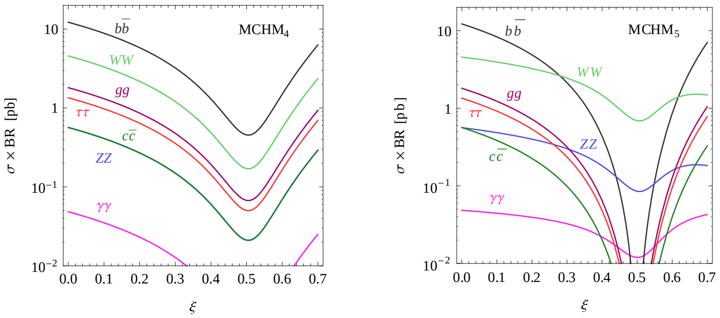


In the $MCHM_4$ the branching ratios are not modified

The relevance of the various channels

The signal in all the channels is typically reduced

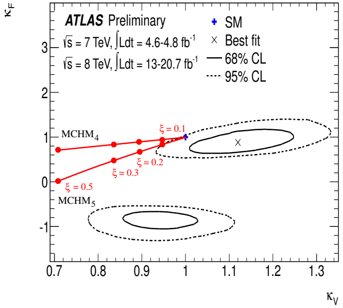
- in the $MCHM_5$ the enhancement in the BR partially compensates the reduction in the bosonic channels

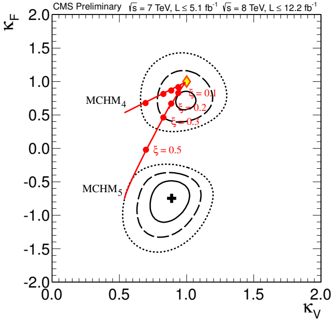


Comparison with the experimental results

The experimental sensitivity is not enough to put strong bounds on the scale of new physics

Small values for the Higgs compositeness seem preferred $\xi \lesssim 0.2$





Direct searches of resonances

Composite resonances

The strong dynamics gives rise to many resonances which can be accessible at the LHC

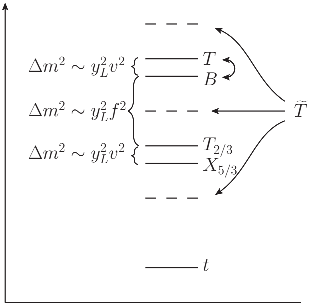
- **Heavy vectors**
  - EW neutral and charged
  - direct bound from EWPT: $m_\rho \gtrsim 2$ TeV
  - reach: ~ 2 TeV for 100 fb^{-1} at 14 TeV
- **Gluon resonances**
  - Color octets
  - no direct bound from EWPT
  - reach: ~ 4 TeV for 100 fb^{-1} at 14 TeV
- **Fermion resonances**
  - light top partners are expected
  - easily produced at the LHC: already some bounds

The spectrum of top partners

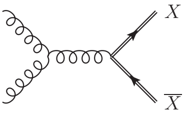
Costodial invariance $\mathrm{SO}(4) \simeq \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ implies the presence of **extended multiplets** of top partners

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

- New colored fermions strongly coupled to the top
- Exotic resonances
- The lightest states can be the singlet $\widetilde{T}$ or the exotic doublet $(X_{5/3}, T_{2/3})$

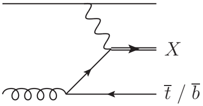


Production mechanisms



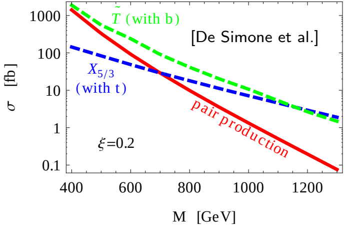
QCD **pair production**

- model independent
- relevant at low mass



Single production with t or b

- model dependent
- potentially relevant at high masses
- production with b dominant when allowed



The exotic state $X_{5/3}$

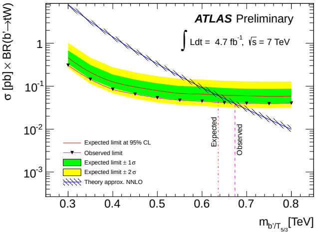
Production mechanisms:

- QCD pair production
- single production with t

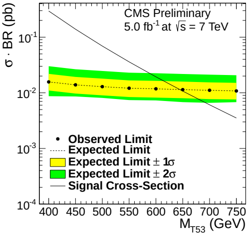
Decay:

- $BR(X_{5/3} \to Wt) = 1$

Limits from same sign dilepton processes: $m_{X_{5/3}} \gtrsim 670$ GeV



[ATLAS-CONF-2012-130]



[CMS-PAS-B2G-12-003]

The exotic state $X_{5/3}$

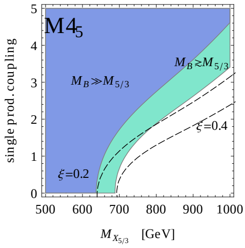
Production mechanisms:

- QCD pair production
- single production with t

Decay:

- $BR(X_{5/3} \to Wt) = 1$

Taking into account **single production** the bound can be significantly improved



[De Simone et al.]

The singlet $\widetilde{T}$

Production mechanisms:

- QCD pair production
- single production with b

Decay:

- $BR(\widetilde{T} \to Zt) \sim BR(\widetilde{T} \to ht) \sim \frac{1}{2} BR(\widetilde{T} \to Wb)$

Bounds by recasting the searches for 4-th generation t'

- channel $t' \to Zt$
  - weak bounds $m_{\widetilde{T}} \gtrsim 320$ GeV
  - single production with b suppressed by cuts, space for improvement with a different analysis

The singlet $\widetilde{T}$

Production mechanisms:

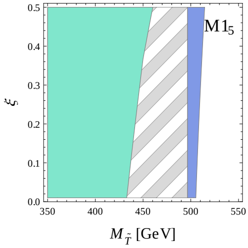
- QCD pair production
- single production with b

Decay:

- $BR(\widetilde{T} \to Zt) \sim BR(\widetilde{T} \to ht) \sim \frac{1}{2} BR(\widetilde{T} \to Wb)$

Bounds by recasting the searches for 4-th generation t'

- ▸ channel $t' \to Wb$
  - main signal from pair production
  - stronger bounds $m_{\widetilde{T}} \gtrsim 450$ GeV

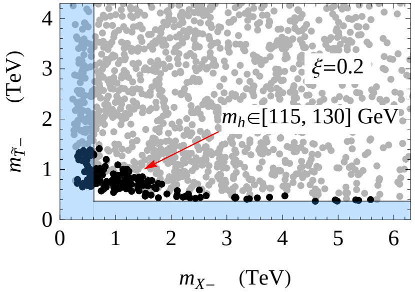


[De Simone et al.]

Bounds on explicit models

Current bounds already give non-trivial exclusions in realistic models

Most of the parameter space is still viable ($m_\psi \simeq 1$ TeV) and will be tested at LHC14



Late LHC searches

WW scattering

The Higgs in the SM has the fundamental role of regulating the **WW scattering amplitude**

An effective theory without the Higgs has a very small range of perturbativity ($\Lambda \sim 3$ TeV)

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) \simeq \frac{g^2}{4m_w^2}(s+t) \propto E^2$$

The Higgs allows **perturbativity at high energy**

$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) \propto \frac{m_h^2}{E^2}$$

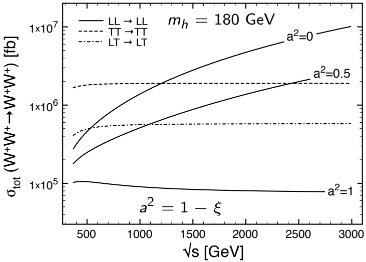
WW scattering

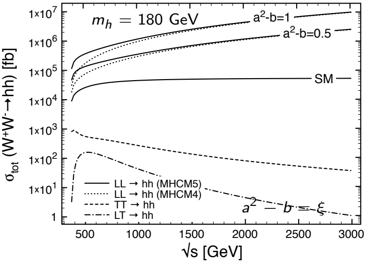
In composite models the couplings of the Higgs are modified

$$\mathcal{L} \supset m_W^2 \left[W_\mu W^\mu + \frac{Z_\mu Z^\mu}{2c_W^2} \right] \left(1 + 2\sqrt{1-\xi}\frac{h}{v} + (1-2\xi)\frac{h^2}{v^2} + \ldots \right)$$

The WW scattering is only **partially** regulated at high energy

$$\mathcal{A}(W_L W_L \to W_L W_L) \sim \mathcal{A}(W_L W_L \to hh) \sim \frac{s}{v^2}\xi$$





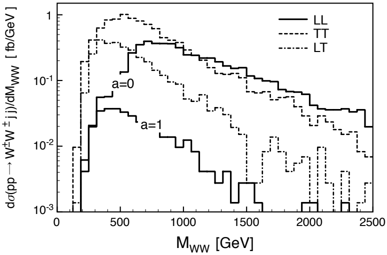
[Contino et al. arXiv:1002.1011]

WW scattering

The $LL \to LL$ scattering is accidentally **suppressed** with respect to the $TT \to TT$

$$\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt} \simeq \frac{\xi^2}{2304}\frac{s^2}{m_W^4}$$

- **Very difficult** at LHC



The $WW \to hh$ process has a rather small cross section

- Only for **late LHC**

$\sigma(pp\to hhjj)$[fb] (m_h=180 GeV)	MCHM4	MCHM5
ξ=1	9.3	14.0
ξ=0.8	6.3	9.5
ξ=0.5	2.9	4.2
ξ=0 (SM)	0.5	0.5

[Contino et al. arXiv:1002.1011]

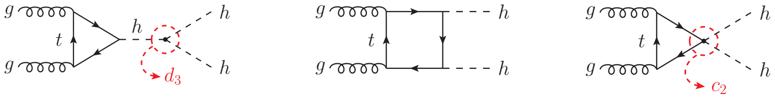
Double Higgs production

The non-linear structure of the composite Higgs theory gives rise to **new non-renormalizable interactions**

$$\mathcal{L} = -m_t \, \overline{q}_L \Sigma t_R \left(1 + c\frac{h}{v} + c_2 \frac{h^2}{v^2} + \cdots \right) + h.c.$$

$gg \to hh$ is a one of the most promising channels to test the **non-linear Higgs couplings**

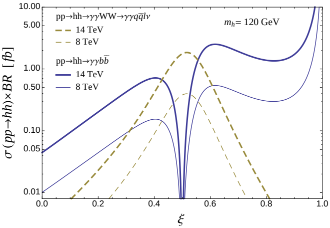
[Dib, Rosenfeld, Zerwekh 2006; Grober, Muhlleitner 2011]



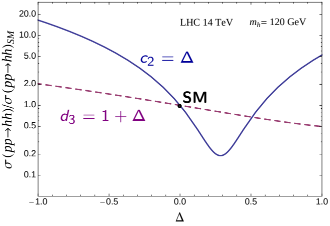
Double Higgs production

[Contino, Ghezzi, Moretti, G. P., Piccinini, Wulzer]

The new interaction gives a large **enhancement** of the cross section



- large dependence on non-SM coupling c_2
- poor sensitivity on Higgs trilinear d_3



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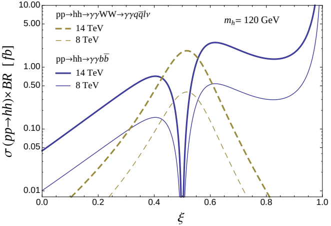
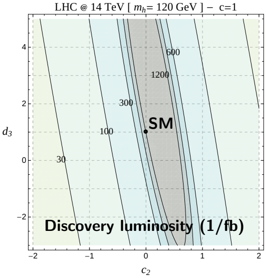


- large dependence on non-SM coupling c_2
- poor sensitivity on Higgs trilinear d_3
- High luminosity required ($\gtrsim$ 600 fb^{-1} at 14 TeV for the SM)



Outline

Summary

Composite Higgs models offer a **simple** and **motivated** solution to the Hierarchy problem

In many "minimal" models the presence of a **light Higgs** ($m_h \simeq 125$ GeV) is tightly connected with the presence of **light top partners**

A **light fermionic mass scale** is also preferred to minimize the amount of **tuning**

Summary

Interesting **phenomenological features**:

- **Modified couplings** in the Higgs sector
  - change in the Higgs production and BR's
  - modification of *WW* scattering
  - new non-linear interactions

- **Resonances** from the strong sector
  - light partners already constrained by current data
  - LHC14 can test the most natural part of the parameter space ($m_\psi \sim 1$ TeV)