Composite Higgs Models at the LHC

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Outline

1. Introduction

2. General Properties of a Composite Higgs

3. Composite Higgs at the LHC

4. Conclusions

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Introduction: WW Scattering

The experiments tell us that the high-energy data are well parametrized by a **massive** $SU(2)_L \times U(1)_Y$ **gauge theory**

The longitudinal modes of the gauge fields can be described as the Goldstones of a non-linear σ-model $SU(2)_L \times SU(2)_R/SU(2)_V$.

However at energies $E \gg m_W$ the W_L scattering amplitude **grows**

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

perturbativity is **lost** at a scale $\Lambda \sim 3\ \mathrm{TeV}$.

$\Downarrow$

need of a **UV completion** which generates **EW breaking**

Introduction: the SM

The **simplest** possibility is to add one scalar d.o.f.

The Goldstones are part of a **linear σ-model**

The scattering amplitude is **regulated**

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

... **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: 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

- EW symmetry broken **directly** by the strong dynamics (*e.g.* **Technicolor**, **Higgsless**)
  - tension with the EW precision data (S parameter and FCNC)
- Presence of an **Higgs-like state** coming from the strong sector
  - ‘interpolates’ between technicolor and SM
  - improves compatibility with experiments

Introduction: New Strongly Coupled Sectors

Which is the nature of the Higgs-like state?

It could be a **scalar** coming from the strong sector
(e.g. RS models with a scalar Higgs on the IR brane)

- **But** its natural mass would be $m_h \sim m_\rho \sim \mathrm{TeV}$

Introduction: New Strongly Coupled Sectors

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The Composite-Higgs Paradigm

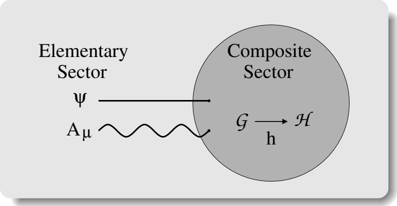
The Higgs is a **Goldstone** from the strong sector

[Georgi, Kaplan]

- The strong sector has a spontaneously broken global invariance $\mathcal{G} \to \mathcal{H}$
- The Higgs is naturally lighter than the other resonances
- The corrections to the EW observables are suppressed by $\xi = (v/f_\pi)^2$

Introduction: General Structure of the Composite-Higgs

Strong Sector with a **global symmetry** $\mathcal{G}$ spontaneously broken to $\mathcal{H}$



Elementary sector mixing induces a small (explicit) breaking of $\mathcal{G}$

- Weak gauging: $\mathcal{G}_{SM} = SU(2)_L \times U(1)_Y \subset \mathcal{H}$
- Linear fermion mixing: $\mathcal{L}_{mix} \sim \lambda_L \, \psi_L \mathcal{O}_R + \lambda_R \, \psi_R \mathcal{O}_L$

Higgs is a **pseudo-Goldstone**

$\Downarrow$

EW symmetry breaking is **radiatively induced**

- The strong sector gives rise to <u>**towers of resonances**</u>

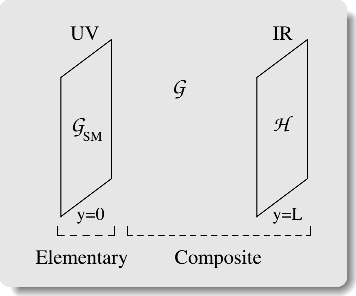
Introduction: Realizations of the Composite-Higgs Idea

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

Elementary sector $\Leftrightarrow$ UV

Composite sector $\Leftrightarrow$ Bulk + IR

Global symm. $\Leftrightarrow$ 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**

- 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**

Note: analogous to Little-Higgs models

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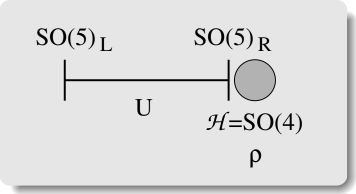
A Simple Effective Realization: the Higgs Sector

We consider an effective description with only one level of resonances [G. P. and Wulzer (2011)]

The **minimal** symmetry pattern which gives rise to an Higgs doublet and has a **custodial symmetry** is $SO(5) \to SO(4)$

Realized as a non-linear σ-model $SO(5)_L \times SO(5)_R \to SO(5)_V$

$$U \to g_L U g_R^\dagger$$

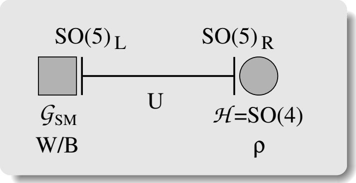


Extra Goldstones removed by gauging of $\mathcal{H} = SO(4) \subset SO(5)_R$, which gives one level of **composite resonances** (ρ_μ)

- The non-linear σ-mod. $SO(5)/SO(4)$ is recovered for $g_\rho \to \infty$

A Simple Effective Realization: the Higgs Sector

The **elementary fields** (W, B) gauge a $\mathcal{G}_{SM} = SU(2)_L \times U(1)_Y$ subgroup of $SO(5)_L$



The leading order Lagrangian is

$$\mathcal{L} = \frac{f_\pi^2}{4} \mathrm{Tr}\left[(D_\mu U)^\dagger D^\mu U \right]$$

where the covariant derivative is

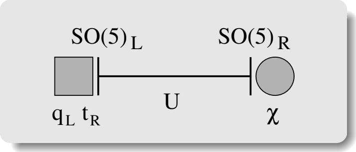
$$D_\mu U = \partial_\mu U - i g_w A_\mu U + i g_\rho U \rho_\mu$$

Before the EW breaking $U = \mathbb{1}$ and the resonance masses are

$$m_\rho \simeq \frac{g_\rho}{2} f_\pi$$

A Simple Effective Realization: the Fermions

The **elementary fermions** q_L, t_R transform under $SO(5)_L$



We want **linear mixing** with the composite fermions χ, so we need an appropriate representation for the composite fields:

$$\chi \in \mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1}) = \begin{pmatrix} T & X_{5/3} \\ B & T_{2/3} \end{pmatrix} \oplus (\widetilde{T})$$

The mixing terms are

$$\mathcal{L}_{mix} = \Delta_L \overline{q}_L (U\chi_R)_{(2,2)} + \Delta_R \overline{t}_R (U\chi_L)_{(1)} + \mathrm{h.c.}$$

Notice that **only** $SO(4)$ **survives** at the second site

$$\mathcal{L}_{mass} = M_{(2,2)}\overline{\chi}_{(2,2)}\chi_{(2,2)} + M_{(1)}\overline{\chi}_{(1)}\chi_{(1)}$$

A Simple Effective Realization: the Fermions

The effective theory implements the **partial compositeness** idea

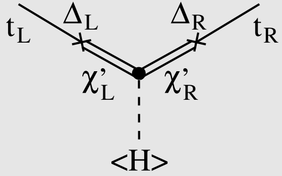
[Kaplan (1991), Contino, Kramer, Son and Sundrum (2006)]

This can be better appreciated in an equivalent basis $\chi' \equiv U\chi$ which move the Higgs to the composite sector

$$\mathcal{L} \supset \Delta_L \overline{q}_L (\chi'_R)_{(2,2)} + \Delta_L \overline{t}_R (\chi'_L)_{(1)} \\ + M_{(2,2)} (\overline{\chi} U^\dagger)_{(2,2)} (U\chi)_{(2,2)} + M_{(1)} (\overline{\chi} U^\dagger)_{(1)} (U\chi)_{(1)}$$

The SM fermions become partially composite states

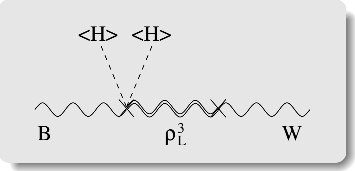
$$m_t \sim \frac{\Delta_L}{M_{(2,2)}} \frac{\Delta_R}{M_{(1)}} g_\rho v$$



EW Precision Tests: the S Parameter

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

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



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

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

The constraint on $\widehat{S}$ require a scale separation between v and f_π

$\Downarrow$

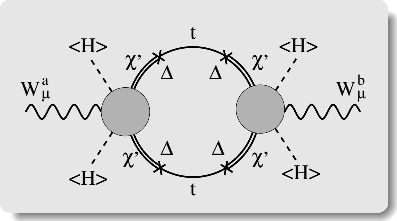
a <u>**fine-tuning**</u> of $\mathcal{O}(\xi)$ is needed

EW Precision Tests: the T Parameter

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

The relevant 1-loop contribution comes from fermion loops

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



For $\Delta_L \sim \Delta_R \sim \sqrt{y_t g_\rho} f_\pi$ one gets the estimate

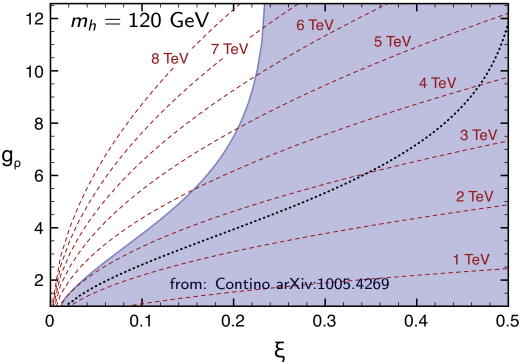
$$\widehat{T} \sim \frac{N_c}{16\pi^2} y_t^2 \xi \simeq 2 \cdot 10^{-2} \xi$$

- Bound comparable with the one from $\widehat{S}$

EW Precision Tests: Bounds in Explicit Models

In explicit models we typically get an exclusion

$$\xi \lesssim 0.2 \qquad m_\rho \gtrsim 3 \text{ TeV}$$



dotted line: exclusion region with an extra contribution $\Delta \widehat{T} = +2 \cdot 10^{-3}$

EW Precision Tests: the $Zb_L\overline{b}_L$ Coupling

Large tree-level corrections to the $Zb\overline{b}$ vertex are canceled by an automatic **LR-symmetry** of the composite sector [Agashe et al. (2006)]

$$T^a_L \leftrightarrow T^a_R$$

The mixing of the b_L with the top partners leaves the symmetry unbroken (the B is invariant)

Corrections arise from

- mixing with the bottom partners (suppressed by the small b mass)
- 1-loop effects

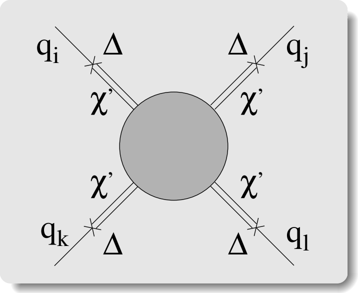
The constraint is comparable with the one from the S parameter

EW Precision Tests: FCNC

FCNC among light quarks are naturally **suppressed** thanks to partial compositeness

Four-fermions operators among elementary states generated at the scale Λ are proportional to

$$\frac{\Delta_i \Delta_j \Delta_k \Delta_l}{f_\pi^4 \Lambda^2} \sim \frac{\sqrt{y_i y_j y_k y_l}}{\Lambda^2}$$



Sizable effects can come from the 3rd generation

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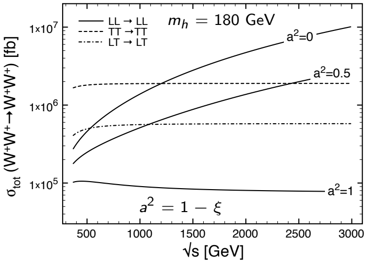
WW scattering

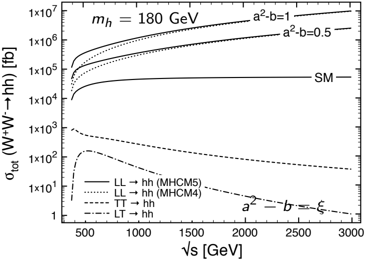
The Higgs has modified couplings with the Gauge bosons

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

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

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





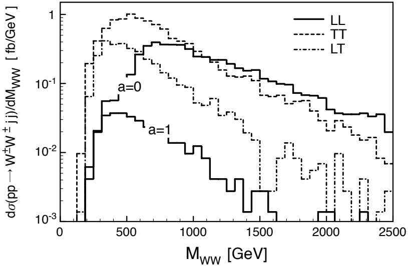
[Contino et al. arXiv:1002.1011]

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]

Single Higgs Production

The Yukawa coupling are **modified**

$$\mathcal{L}_{Yuk} = -m_i \overline{\psi}_{Li} \psi_{Ri} \left(1 + c\frac{h}{v}\right) + \mathrm{h.c.}$$

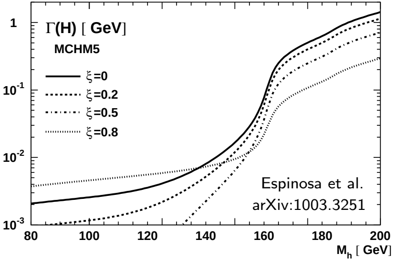
In the model with fermions in the fundamental representation

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Significant **reduction** of the $gg \to h$ cross section

[Falkowski (2008), Furlan (2011)]

$$\Gamma(gg \to h) \simeq \frac{(1-2\xi)^2}{1-\xi} \Gamma_{SM}$$



Espinosa et al.
arXiv:1003.3251

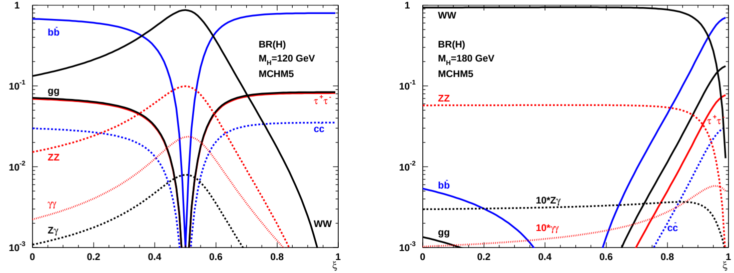
Single Higgs Production

The Higgs couplings to the fermions and to the EW gauge bosons can be modified in different ways

- change in the branching ratios

$$\frac{\Gamma(h \to f\bar{f})}{\Gamma^{SM}(h \to f\bar{f})} = \frac{\Gamma(h \to gg)}{\Gamma^{SM}(h \to gg)} = \frac{(1-2\xi)^2}{1-\xi}$$

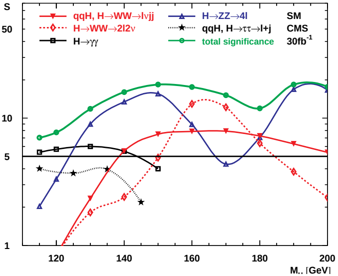
$$\frac{\Gamma(h \to VV)}{\Gamma^{SM}(h \to VV)} = 1-\xi$$

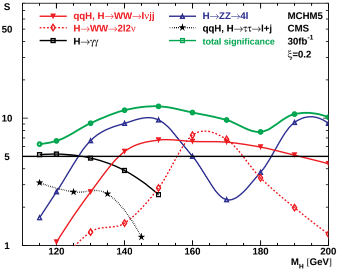


[Espinosa et al. arXiv:1003.3251]

Single Higgs Production

The significance of the channels for Higgs discovery are modified





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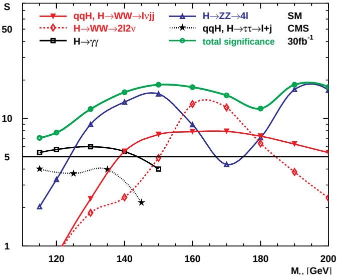
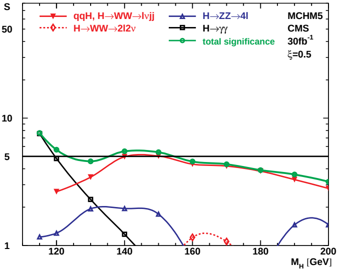


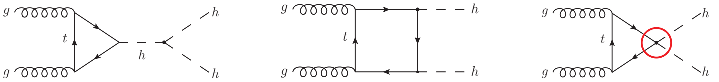


[Espinosa et al. arXiv:1003.3251]

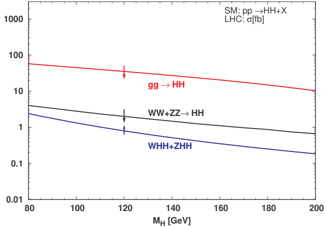
Double Higgs Production

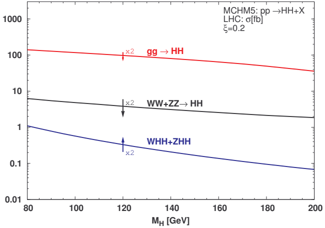
The Goldstone nature of the Higgs induces a **new non-renormal. coupling** with the fermions

$$\mathcal{L} \supset 4\frac{\xi m_f}{v^2} hhf\bar{f}$$



- Double Higgs production is **strongly enhanced**





[Gröber and Mühlleitner arXiv:1012.1562]

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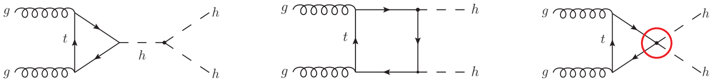

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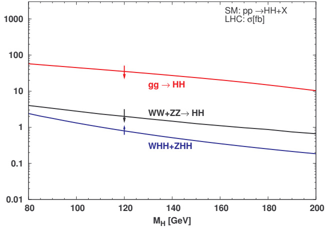

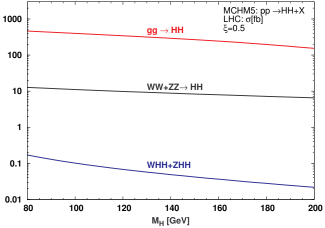

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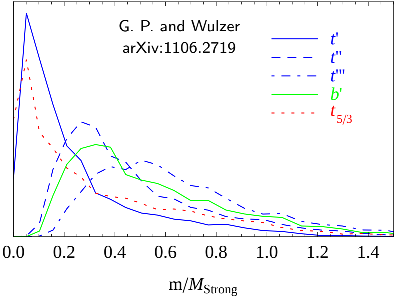
Fermionic Resonances

Custodial invariance $SO(4) \simeq SU(2)_L \times SU(2)_R$ implies the presence of extended multiplets with **exotic states**

$$(2,2) = \left[Q = \begin{pmatrix} T \\ B \end{pmatrix} \quad Q' = \begin{pmatrix} T_{5/3} \\ T_{2/3} \end{pmatrix} \right]$$

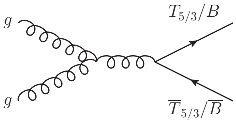
The top resonances and the exotic custodians are **typically light**

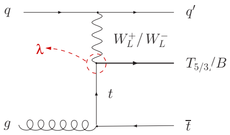


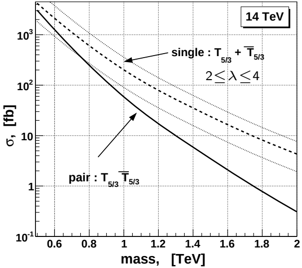
- Light resonances are related to the presence of a light Higgs

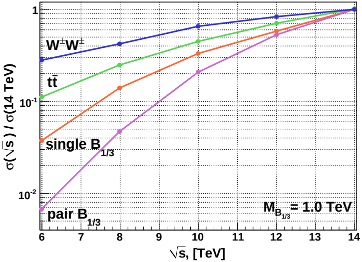
Fermionic Resonances

The $T_{5/3}$ and the B can be pair or singly produced









[Mrazek and Wulzer arXiv:0909.3977]

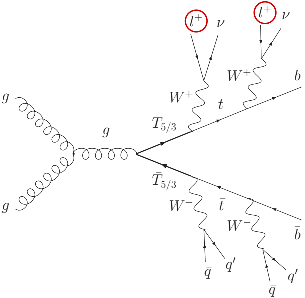
Fermionic Resonances

Best channel: **same-sign dileptons** in final states

[Contino, Servant (2008);

Mrazek, Wulzer (2009);

Dissertori et al. (2010)]



Discovery reach (for $M_{T_{5/3}} = M_B$ and $\lambda = 3$)

Mass [TeV]	L_{disc} @ 10 TeV [fb^{-1}]	L_{disc} @ 14 TeV [fb^{-1}]
0.5	0.072	0.024
1.0	5.5	1.1
1.5	210	26.4
2.0		327

Fermionic Resonances

Current bounds come from pair production at CMS

(from searches for 4th generation quarks)

$T\overline{T} \to WbW\overline{b} \to b\bar{b}\, l^+ l^- \not{E}_T$	$m_T > 422$ GeV	L=1.14 fb^{-1} [PAS-EXO-11-050]
$T\overline{T} \to WbW\overline{b} \to b\, 3j\, l^\pm \not{E}_T$	$m_T > 450$ GeV	L=0.80 fb^{-1} [PAS-EXO-11-051]
$T\overline{T} \to tZ\bar{t}Z \to (l^+ l^-) l^\pm jj$	$m_T > 417$ GeV	L=191 pb^{-1} [PAS-EXO-11-005]
$B\overline{B} \to WtW\bar{t} \to l^\pm l^\pm b\, 3j \not{E}_T$ $\to lll\, b\, j \not{E}_T$	$m_B > 495$ GeV	L=1.14 fb^{-1} [PAS-EXO-11-036]

(all bounds assume 100% BR to the given channel)

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Conclusions

LHC will tell the last word on the mechanism of **EW symmetry breaking** and on the **Hierarchy problem**.

To interpret the experimental data it is important to analyze **motivated scenarios** of BSM physics.

The **Composite-Higgs paradigm** is a **compelling** idea with several interesting signatures

- early signal: **light fermionic resonances**
- for a later stage: - modified properties of the **Higgs sector**
  - **vector resonances** (gluon resonances)

[see: Barcelo, Carmona et al. arXiv:1110.5914;
Bini, Contino and Vignaroli arXiv:1110.6058]