Little Higgs models in light of the 126 GeV discovery at the LHC

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work in collaboration with J. Reuter

6th Annual Workshop of the Helmholtz Alliance "Physics at the Terascale"

04 December 2012

Motivation

How to constrain a generic model in *HEP*?

- direct searches of resonances
- electroweak precision tests
- flavour constraints
- nowadays: Higgs sector

Higgs sector is the key to understand EW-scale physics (and beyond?)

Quicksand of the Standard Model

a new resonance at 126 GeV has just been discovered, but...
radiative corrections to *SM* Higgs mass are quadratically divergent

$$\frac{3}{4}\frac{m_h^2}{v^2}\frac{\Lambda^2}{32\pi^2} \qquad -6\,y_t^2\,\frac{\Lambda^2}{32\pi^2} \qquad \left(\frac{9}{4}\,g^2+\frac{1}{2}\,g'^2\right)\frac{\Lambda^2}{32\pi^2}$$

$$m_h^2 \simeq m_0^2 + \Lambda^2 \times (\text{loop factors}) = (126 \text{ GeV})^2$$

Big Hierarchy Problem

highly unnatural for $\Lambda \gg$ *TeV*

Quicksand of the Standard Model

need new physics to prevent *fine-tuning*!
in particular (for 10% fine-tuning), new physics should appear at

$$\Lambda_{\text{top}} \lesssim 2 \text{ TeV}, \quad \Lambda_{\text{gauge}} \lesssim 5 \text{ TeV}, \quad \Lambda_{\text{quartic}} \lesssim 10 \text{ TeV}$$

but... severe constraints on the low-energy effects of new-physics:

broken symmetry	operators	scale Λ
B, L	$(QQQL)/\Lambda^2$	10^{13} TeV
flavor (1,2$^{\text{nd}}$ family), CP	$(\bar{d}s\bar{d}s)/\Lambda^2$	1000 TeV
flavor (2,3$^{\text{rd}}$ family)	$m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV
custodial $SU(2)$	$(h^\dagger D_\mu h)^2/\Lambda^2$	5 TeV
none (S-parameter)	$(D^2 h^\dagger D^2 h)/\Lambda^2$	5 TeV

Little Hierarchy Problem

no fine-tuning implies $\Lambda \lesssim 1\,TeV$
vs.
no dangerous corrections implies $\Lambda \gtrsim 10\,TeV$

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Two paradigms for *EWSB*

hierarchy problem as guideline to answer the following question:

what is the dynamical origin of *EWSB*?

- weakly coupled answer → Supersymmetry
- strongly coupled answer → Composite Higgs, Little Higgs...

Strongly coupled answer

Original idea: pions of low-energy QCD

E

QCD

- quarks as d.o.f.
- perturbative th. for E>Λ

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \sum_{q=u,d} \bar{q}\, i \not{D}\, q$$

Λ ~ 1 GeV:
SSB of QCD-flavour symmetry
SU(2)xSU(2)→SU(2)

low-energy QCD

- pions: pNGB of SSB (new d.o.f.)
- eff. theory valid up to E<Λ

$$\mathcal{L}_{2\partial} = \frac{f^2}{4} \text{tr}\left|\partial_\mu \Sigma\right|^2, \quad \Sigma = \exp \frac{i}{f} \begin{pmatrix} \pi^0 & \pi^+ \\ \pi^- & -\pi^0 \end{pmatrix}$$

Composite/Little Higgs Ansatz

Higgs as pNGB of a new (approximate) global symmetry which is spontaneously broken at a scale $\Lambda \sim 4\pi f$

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Summary

The Little Higgs paradigm:

- Higgs as a pNGB of a global SSB at $\Lambda \sim 4\pi f$ (like pions!)
- new fermionic/vector states with masses $\sim f$ besides *SM*-ones
- *EWSB* is triggered *naturally* (Collective Symmetry Breaking), i.e. $v \sim \mathcal{O}(100$ GeV$)$ for $f \sim 1$ TeV with only logarithmic sensitivity to the cut-off $\Lambda \Rightarrow$ Big Hierarchy solved!
- $\Lambda \sim 10$ TeV for $f \sim 1$ TeV $\Rightarrow$ Little Hierarchy solved!
- it is an effective theory valid up to Λ: no *UV*-completion of the strongly coupled regime $E > \Lambda$

Statistical analysis

We considered the three most popular Little Higgs models:

- Simplest Little Higgs (*SLH*) [Schmaltz]
- Littlest Higgs (L^2H) [Arkani-Hamed et al.]
- Littlest Higgs with *T*-parity (*LHT*) [Low et al.]

and realized a χ^2 analysis on their parameter spaces, taking into account the whole set of 7+8 TeV Higgs searches by *ATLAS* and *CMS*, and by fitting 21 different *EW* Precision Observables:

$$\chi^2 = \sum_i \frac{(\mathcal{O}_i - \mathcal{O}_i^{\text{exp}})^2}{\sigma_i^2}$$

where $\mathcal{O}_i$ depends on the free parameters of the model considered.

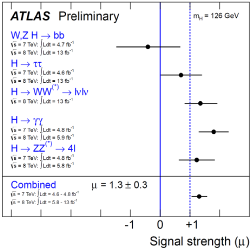
Data used: Higgs sector

the Higgs results are expressed in terms of a *signal strength modifier*

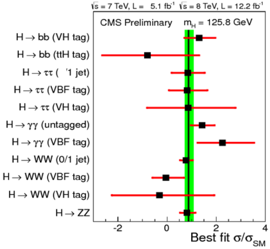
$$\mu_i = \frac{\sum_p \epsilon^p{}_i \, \sigma_p}{\sum_p \epsilon^p{}_i \, \sigma_p^{SM}} \cdot \frac{BR\,(h \to X_i X_i)}{BR\,(h \to X_i X_i)_{SM}}$$

we included in our χ^2 analysis the best-fit values of μ_i reported by the Collaborations for all the different 7+8 TeV channels i:

Best–fit Higgs mass m_H :
126.0 ± 0.4 (stat) ± 0.4 (syst) GeV



- M=125.8 ±0.4 (stat) ± 0.4 (syst) GeV



- σ/σ_{SM}=0.88±0.21

Data used: *EWPD*

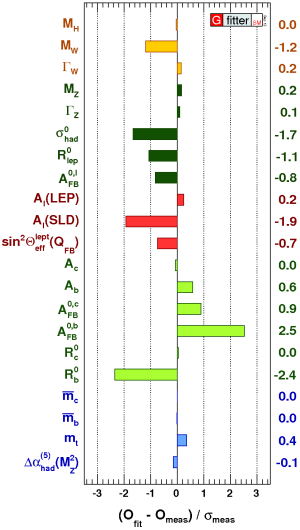
every extension of *SM* has to satisfy at least the precision constraints of the electroweak sector:

- low-energy observables

  e.g. ν-scattering, parity violation observables...

- Z-pole observables

  e.g. m_Z, Γ_Z, Z-pole asymmetries...



LH Smoking guns

Where do the *LH* corrections to the *SM* quantities come from?

- new decay channels of the Higgs, e.g. $h \to A_H A_H$ in *LHT*
- modified Higgs couplings with *SM* fermions and vector bosons

$$\text{e.g.} \quad 2\,\frac{m_W^2}{v} y_W \, h\, W^+ W^-, \quad y_W = \begin{cases} 1 & SM \\ 1 + \mathcal{O}\left(v^2/f^2\right) & LH \end{cases}$$

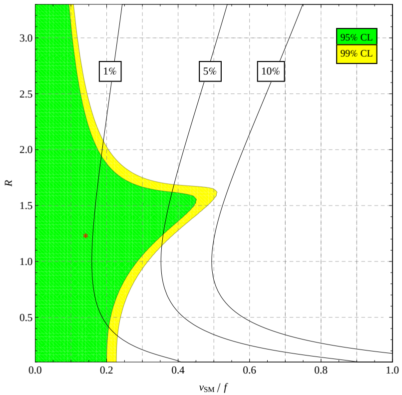
- interaction terms of Higgs with new fermions/vector bosons

$$\text{e.g.} \quad \frac{m_T}{v} y_T \, h\, \bar{T} T \qquad m_T \sim f,\; y_T \sim \mathcal{O}\left(v^2/f^2\right)$$

- modified neutral- and charged-currents

$$\text{e.g.} \quad \frac{g}{c_W} \sum_f \bar{f} \gamma^\mu \Big((g_L^{SM} + \delta g_L) P_L + (g_R^{SM} + \delta g_R) P_R \Big) f\, Z_\mu$$

LHT results



$$\chi^2_{\textbf{min}}/\text{d.o.f.} = 1.06$$
$$\chi^2_{\textbf{SM}}/\text{d.o.f.} = 0.97$$

- free parameters: f *SSB* scale, R ratio of Yukawa couplings in top sector
- $f^{99\%}_{\text{min}} = 487.0$ GeV, translates into lower bounds on new states' masses, e.g.

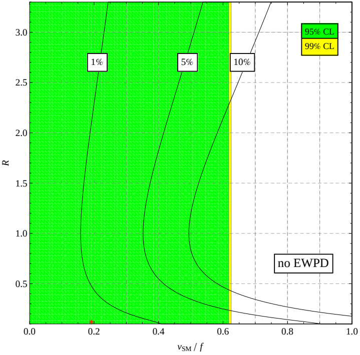
$$m_{W'} \gtrsim 323.5 \text{ GeV}$$
$$m_T \gtrsim 743.1 \text{ GeV}$$

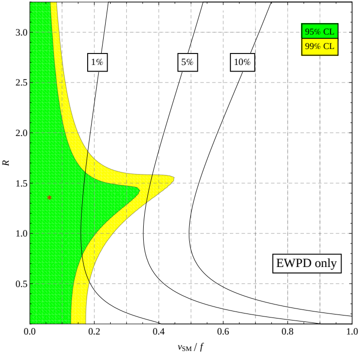
  beyond the current limits from direct searches
- min. required fine tuning: $\sim 10\%$, defined as

$$\Delta = \frac{|\delta\mu^2|}{\mu^2_{\text{obs}}}$$

- results mainly driven by *EWPD* (see next slide)

Higgs data vs. *EWPD*



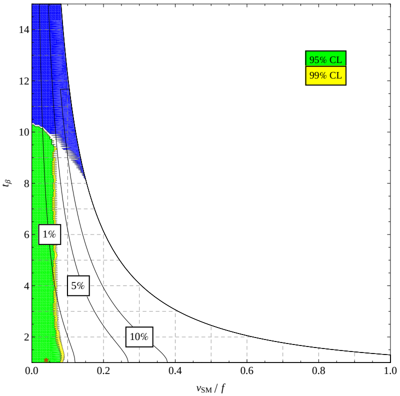


- the shape of the combined result is driven by the *EW* constraints (much smaller uncertainties)
- Higgs data only: for $v/f \gtrsim 0.6$ decay $h \to A_H A_H$ open and dominant
- Higgs data only: subdominant dependence on R w.r.t. f is a consequence of the Collective Symmetry Breaking mechanism
- *EWPD* only: in the central region around $R \sim 1.5$ there is a cancellation among the different contributions to the *T*-parameter (best fit: $T = 0.05 \pm 0.12$)

Conclusions

- *Little Higgs* models are an appealing solution to the hierarchy problem, alternative to weakly coupled solutions like *SUSY*
- most of the parameter space of three popular *Little Higgs* models is still compatible at $\sim 99\%$ *CL* with the early results of the 7+8 TeV Higgs searches
- electroweak precision data represent still the most severe constraints
- fine-tuning as a guideline to understand the naturalness of a model: *Little Higgs* models require a minimum level of $\sim 10\%$ of fine tuning
- new data on the Higgs sector with increasing luminosity will reduce the uncertainties and thus give more precise information

Thank you for your attention!



$$\begin{aligned} \chi^2_{\textbf{min}}/\text{d.o.f.} &= 1.02 \\ \chi^2_{\textbf{SM}}/\text{d.o.f.} &= 0.97 \end{aligned}$$

- free parameters: f *SSB* scale, t_β ratio of *vevs* of scalar fields $\phi_{1,2}$
- $f^{99\%}_{\textbf{min}} = 2.72$ TeV, translates into lower bounds on new states' masses, e.g.

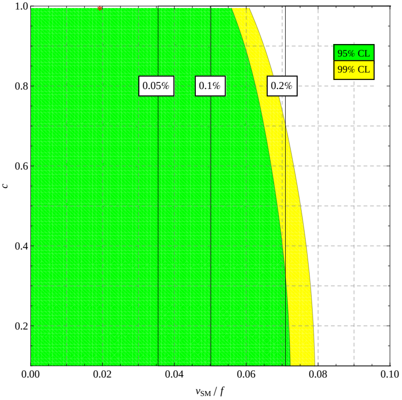
$$\begin{aligned} m_{W'} &\gtrsim 1.23 \text{ TeV} \\ m_T &\gtrsim 2.68 \text{ TeV} \end{aligned}$$

  beyond the current limits from direct searches
- min. required fine tuning: $\sim 1\%$, defined as

$$\Delta = \frac{|\delta\mu^2|}{\mu^2_{\textbf{obs}}}$$

- results mainly driven by *EWPD*

L^2H results



$$\chi^2_{\textsf{min}}/\text{d.o.f.} = 0.99$$
$$\chi^2_{\textsf{SM}}/\text{d.o.f.} = 0.97$$

- free parameters: f *SSB* scale, c mixing angle in gauge sector
- $f_{\textsf{min}}^{99\%} = 3.12$ TeV, translates into lower bounds on new states' masses, e.g.

$$m_{W'} \gtrsim 2.07 \text{ TeV}$$
$$m_T \gtrsim 4.38 \text{ TeV}$$

  beyond the current limits from direct searches
- min. required fine tuning: $\sim 0.1\%$, defined as

$$\Delta = \frac{|\delta\mu^2|}{\mu^2_{\textsf{obs}}}$$

- results mainly driven by *EWPD*

Partial decay widths in LH

- 1-loop decays

$$\Gamma(h \to gg)_{LH} \sim \frac{\alpha_s^2 m_h^3}{32\pi^3 v^2} \Big| \sum_{\text{f,col}} -\frac{1}{2} F_{\frac{1}{2}}(x_f)\, y_f \Big|^2$$

$$\Gamma(h \to \gamma\gamma)_{LH} \sim \frac{\alpha^2 m_h^2}{256\pi^3 v^2} \Big| \sum_{\text{f,ch}} \frac{4}{2} F_{\frac{1}{2}}(x_f)\, y_f + \sum_{\text{v,ch}} F_1(x_v)\, y_v + \sum_{\text{s,ch}} F_0(x_s)\, y_s \Big|^2$$

where $x_i = \frac{4m_i^2}{m_h^2}$, $F_i(x_i)$ are loop functions, y_i the modified Yuk. couplings

$\Rightarrow$ narrow-width approximation: $\frac{\sigma_{LH}}{\sigma_{SM}}(gg \to h) = \frac{\Gamma(h \to gg)_{LH}}{\Gamma(h \to gg)_{SM}}$

- tree-level decays

$$\Gamma(h \to VV)_{LH} \sim \Gamma(h \to VV)_{SM} \left(\frac{g_{hVV}}{g_{hVV}^{SM}} \right)^2$$

$$\Gamma(h \to f\bar{f})_{LH} \sim \Gamma(h \to f\bar{f})_{SM} \left(\frac{g_{hff}}{g_{hff}^{SM}} \right)^2$$

where $g_{hVV} = \frac{m_V^2}{v}\, y_V$ and $g_{hff} = \frac{m_f}{v}\, y_f$