Status of Little Higgs Models in 2013

Jürgen Reuter

DESY

JRR/Tonini/de Vries, 2013 (in prep.); JRR/Tonini, JHEP **1302** (2013) 077; Kilian/JRR **PRD 70** (2004), 015004

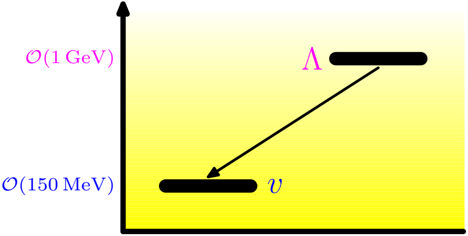
Snowmass Meeting, U. of Washington, Seattle, 2.7.2013

Higgs as Pseudo-Goldstone boson

Nambu-Goldstone Theorem: For each *spontaneously broken global symmetry generator* there is a massless boson in the spectrum.

Old idea: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

Light Higgs as (Pseudo)-Goldstone boson of a spontaneously broken global symmetry



Analogous: QCD

Scale Λ: chiral symmetry breaking, quarks, $SU(3)_c$

Scale v: pions, kaons, …

Higgs as Pseudo-Goldstone boson

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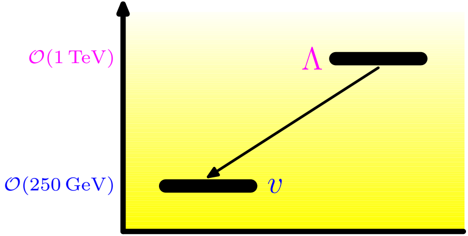


Scale Λ: global symmetry breaking, new particles, new (gauge) IA

Scale v: Higgs, W/Z, $\ell^{\pm}$, $\ldots$

Without Fine-Tuning: experimentally excluded

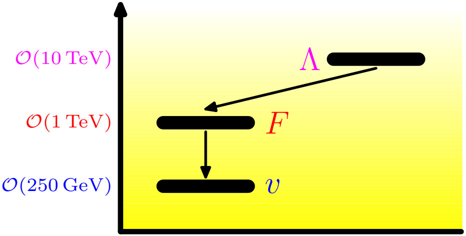
Collective symmetry breaking and 3-scale models

Collective symmetry breaking: Arkani-Hamed/Cohen/Georgi/Nelson/. . . , 2001

2 different global symmetries; one of them unbroken ⇒ Higgs *exact* Goldstone boson

Coleman-Weinberg: boson masses by radiative corrections, but: m_H only at 2-loop level

$$\boxed{m_H \sim \frac{g_1}{4\pi}\frac{g_2}{4\pi}\Lambda}$$

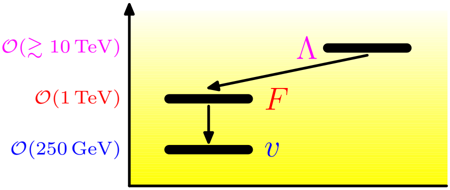


Scale Λ: global SB, new IA

Scale F: Pseudo-Goldstone bosons, new vectors/fermions

Scale v: Higgs, W/Z, $\ell^\pm$, . . .

Characteristics and Spectra

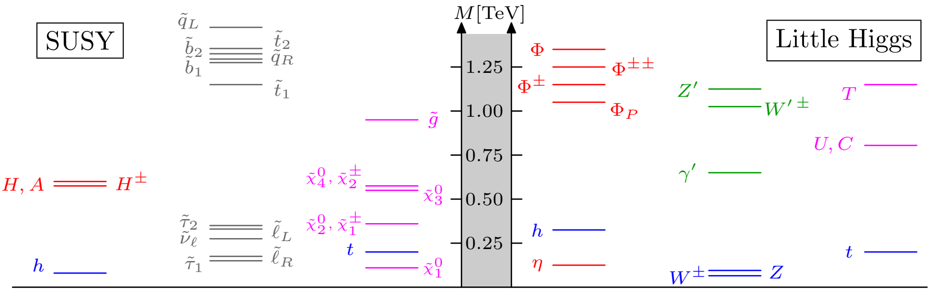


Scale Λ: “hidden sector”, symmetry breaking

Scale F: new particles

Scale v: h, W/Z, $\ell^\pm$, . . .

Terascale: new particles to stabilize the hierarchy

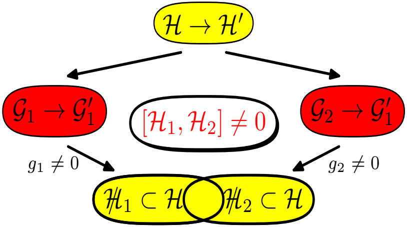


Generic properties of Little-Higgs models

- Extended global symmetry (extended scalar sector)
- Specific functional form of the potential
- Extended gauge symmetry: $\gamma' \equiv A_H, Z' \equiv Z_H, W'^{\pm} \equiv W_H$
- New heavy fermions: T, but also $U, C, \ldots$

Product Group Models

(e.g. Littlest Higgs)



$\mathcal{H} \to \mathcal{H}'$

$\mathcal{G}_1 \to \mathcal{G}_1'$

$[\mathcal{H}_1, \mathcal{H}_2] \neq 0$

$\mathcal{G}_2 \to \mathcal{G}_1'$

$g_1 \neq 0$

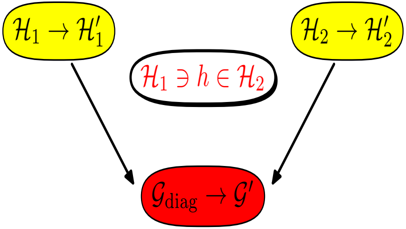
$g_2 \neq 0$

$\mathcal{H}_1 \subset \mathcal{H}$

$\mathcal{H}_2 \subset \mathcal{H}$

Simple Group Models

(e.g. Simplest Little Higgs)



$\mathcal{H}_1 \to \mathcal{H}_1'$

$\mathcal{H}_1 \ni h \in \mathcal{H}_2$

$\mathcal{H}_2 \to \mathcal{H}_2'$

$\mathcal{G}_{\text{diag}} \to \mathcal{G}'$

- discrete T(TeV) parity: pair production, cascades, DM

Generic properties of Little-Higgs models

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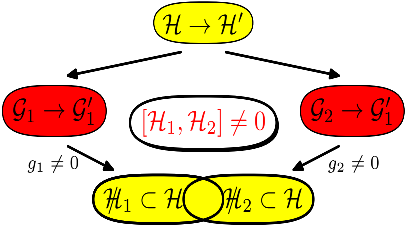
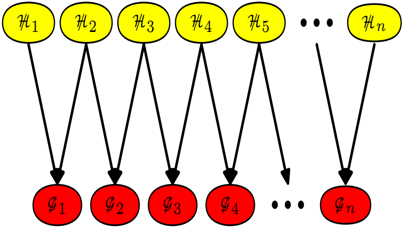


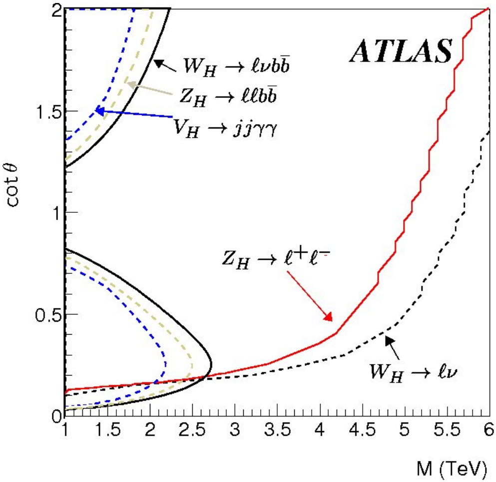
Moose Models

(e.g. Minimal Moose Model)



- discrete T(TeV) parity: pair production, cascades, DM

Direct searches: Drell-Yan mainly



Reach in the gauge boson sector: depends on mixing angle

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?)

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:

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

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

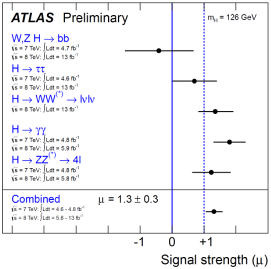
Data used: Higgs sector

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

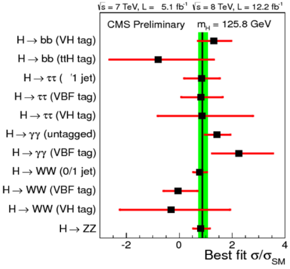
$$\mu_i = \frac{\sum_p {\epsilon^p}_i \, \sigma_p}{\sum_p {\epsilon^p}_i \, \sigma_p^{SM}} \cdot \frac{BR(h \to X_i X_i)}{BR(h \to X_i X_i)_{SM}}$$

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*

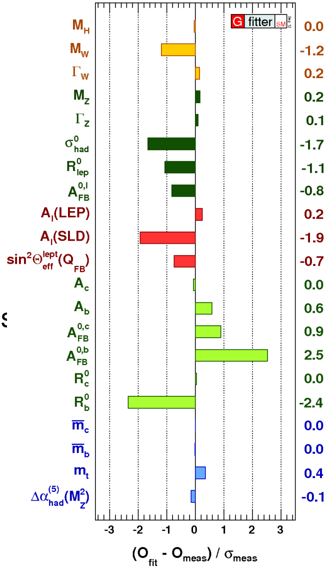
every extension of *SM* has to satisfy at least the precision constraints of the electroweak sector:

- 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

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

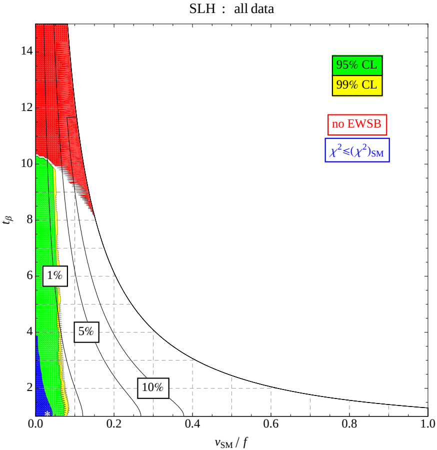
- interaction terms of Higgs with new fermions/vector bosons

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

- modified neutral- and charged-currents

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

SLH results



$$\chi^2_{\text{min}}/\text{d.o.f.} = 1.043$$
$$\chi^2_{\text{SM}}/\text{d.o.f.} = 1.048$$

- free parameters: f *SSB* scale, t_β ratio of *vevs* of scalar fields $\phi_{1,2}$
- $f^{99\%}_{\text{min}} = 2.88$ TeV, translates into lower bounds on new states' masses, e.g.

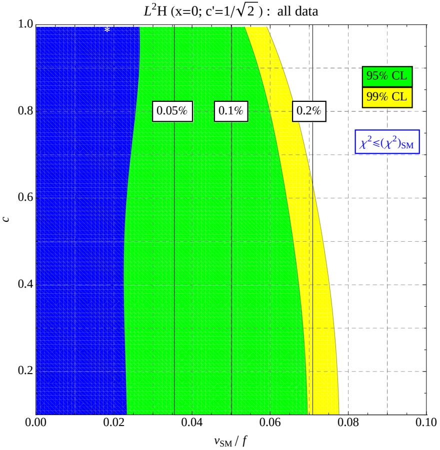
$$m_{W'} \gtrsim 1.35\ \text{TeV}$$
$$m_T \gtrsim 2.81\ \text{TeV}$$

- min. required fine tuning: $\sim 1\%$, defined as

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

- results mainly driven by *EWPD*

L^2H results



$$\chi^2_{\text{min}}/\text{d.o.f.} = 1.048$$
$$\chi^2_{\text{SM}}/\text{d.o.f.} = 1.049$$

- free parameters: f *SSB* scale, c mixing angle in gauge sector
- $f^{99\%}_{\text{min}} = 3.20$ TeV, translates into lower bounds on new states' masses, e.g.

$$\begin{aligned} m_{W'} &\gtrsim 2.13 \text{ TeV} \\ m_T &\gtrsim 4.50 \text{ TeV} \end{aligned}$$

- min. required fine tuning: $\sim 0.1\%$, defined as

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

- results mainly driven by *EWPD*

Partial decay widths in *LH*

- 1-loop decays

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

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

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

$\Rightarrow$ 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 $g_{hff} = \frac{m_f}{v} y_f$

LHT: Littlest Higgs with T parity

- Goldstone boson matrix:

$$\Sigma = e^{2\,i\,\Pi/f} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & H & \sqrt{2}\Phi \\ H^\dagger & 0 & H^t \\ \sqrt{2}\Phi^\dagger & H* & 0 \end{pmatrix} \qquad \Phi \propto \begin{pmatrix} \sqrt{2}\phi^{++} & \phi^+ \\ \phi^+ & \phi^0 + i\,\phi^P \end{pmatrix}$$

- Discrete T parity:

$$T: \quad \Pi \to -\Omega\,\Pi\,\Omega \qquad \Omega = \text{diag}(1,1,-1,1,1)$$

$$V_{CW} = \lambda_{\phi^2} f^2\,\text{Tr}(\phi^\dagger\phi) + i\lambda_{h\phi h} f \left(H\phi^\dagger H^t - H^*\phi H^\dagger\right) - \mu^2 H H^\dagger + \lambda_{h^4}(HH^\dagger)^2 +$$

$$+ \lambda_{h\phi\phi h}\, H\phi^\dagger\phi H^\dagger + \lambda_{h^2\phi^2}\, HH^\dagger \text{Tr}(\phi^\dagger\phi) + \lambda_{\phi^2\phi^2}\left[\text{Tr}(\phi^\dagger\phi)\right]^2 + \lambda_{\phi^4}\,\text{Tr}(\phi^\dagger\phi\phi^\dagger\phi).$$

$$\lambda_{\phi^2} = 2(g^2 + g'^2) + 8\lambda_1^2 \qquad \lambda_{h^4} = \tfrac{1}{4}\lambda_{\phi^2} \qquad \lambda_{h\phi\phi h} = -\tfrac{4}{3}\lambda_{\phi^2}$$

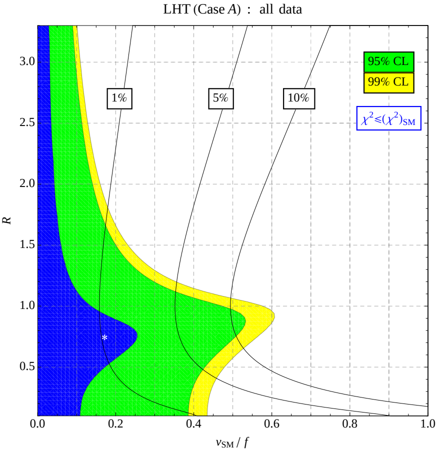
$$\lambda_{h^2\phi^2} = -16\,\lambda_1^2 \qquad \lambda_{\phi^4} = -\tfrac{8}{3}(g^2 + g'^2) + \tfrac{16}{3}\lambda_1^2$$

- Yukawa couplings $\qquad k, R \equiv \lambda_1/\lambda_2$

$$\mathcal{L}_k = -\,kf\left(\bar{\Psi}_2\xi\Psi_c + \bar{\Psi}_1\langle\Sigma\rangle\Omega\xi^\dagger\Omega\Psi_c\right) - m_q\,\bar{u}'_c\,u_c - m_q\,\bar{d}'_c\,d_c - m_\chi\,\bar{\chi}'_c\,\chi_c + \text{h.c.}$$

$$\mathcal{L}_t = -\,\frac{\lambda_1 f}{2\sqrt{2}}\,\epsilon_{ijk}\,\epsilon_{xy}\left[\left(\bar{\Psi}_{1,t}\right)_i \Sigma_{jx}\,\Sigma_{ky} - \left(\bar{\Psi}_{2,t}\langle\Sigma\rangle\right)_i \Sigma'_{jx}\,\Sigma'_{ky}\right] t'_R - \lambda_2 f\left(\bar{T}_{L_1}T_{R_1} + \bar{T}_{L_2}T_{R_2}\right)$$

LHT results



$$\chi^2_{\text{min}}/\text{d.o.f.} = 1.048$$
$$\chi^2_{\text{SM}}/\text{d.o.f.} = 1.053$$

- free parameters: f *SSB* scale, R ratio of Yukawa couplings in top sector
- $f^{99\%}_{\text{min}} = 405.9$ GeV, translates into lower bounds on new states' masses, e.g.

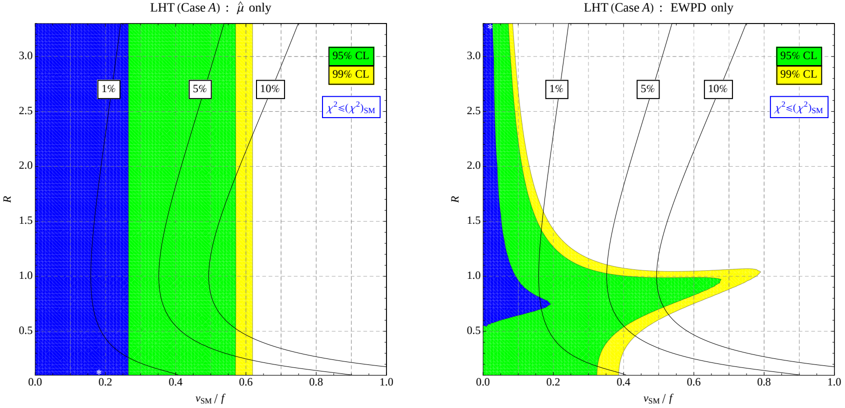
$$\begin{aligned} m_{W'} &\gtrsim 269.6 \text{ GeV} \\ m_T &\gtrsim 553.6 \text{ GeV} \end{aligned}$$

- 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)

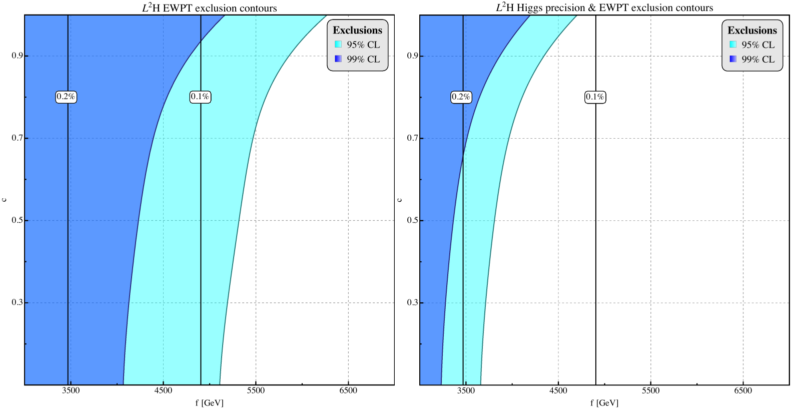
Higgs data vs. *EWPD*



- 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

New Results (incl. Moriond 2013)

Littlest Higgs Model



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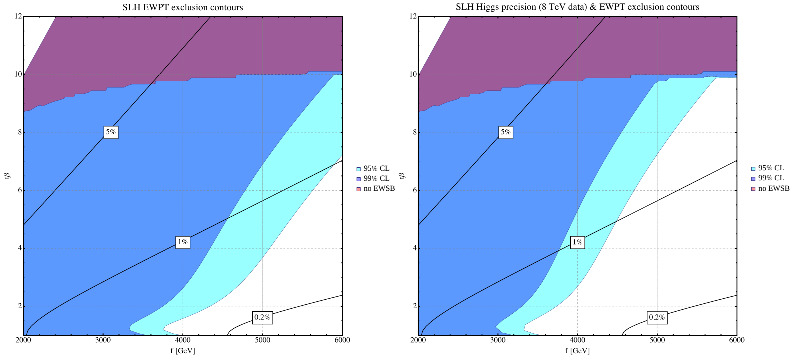
Simplest Little Higgs



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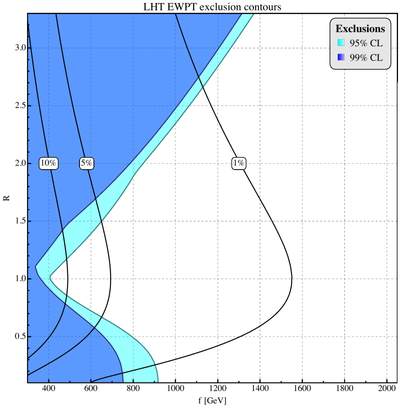
Littlest Higgs with T Parity



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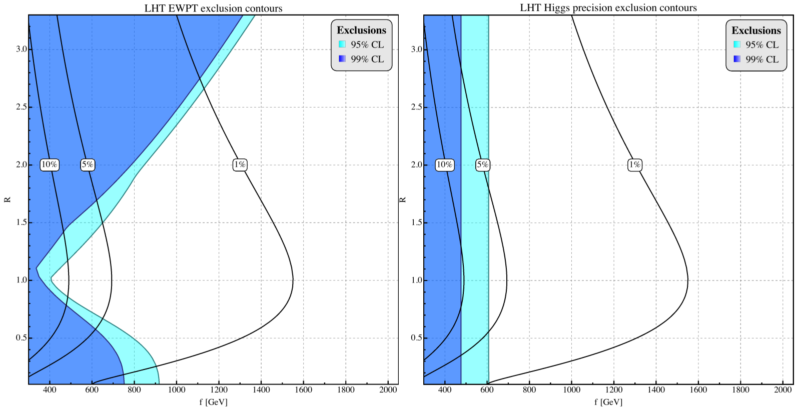

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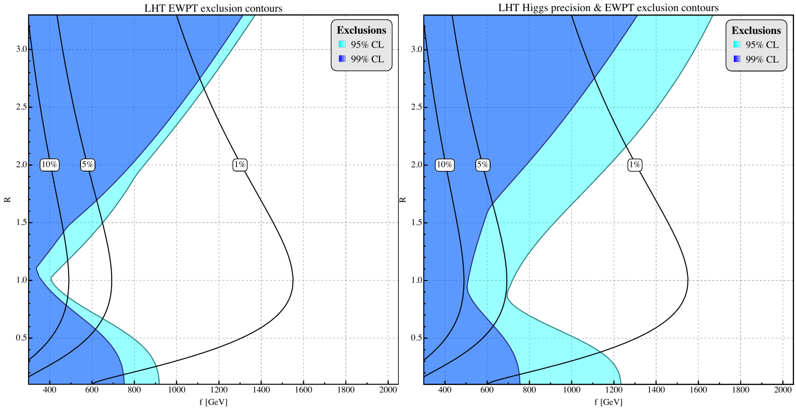
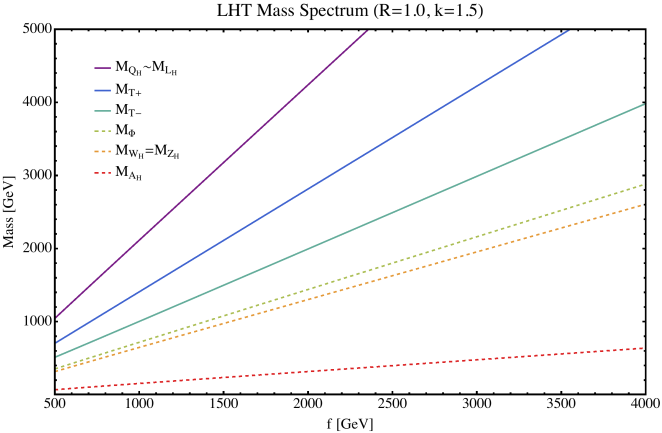


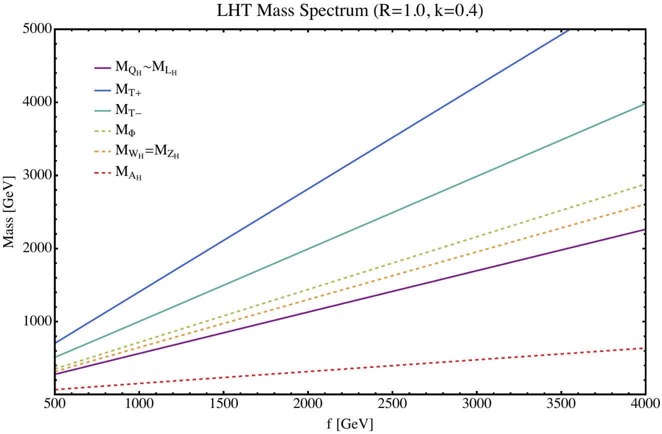
Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 1. heavy quarks



Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 2. heavy top/vectors

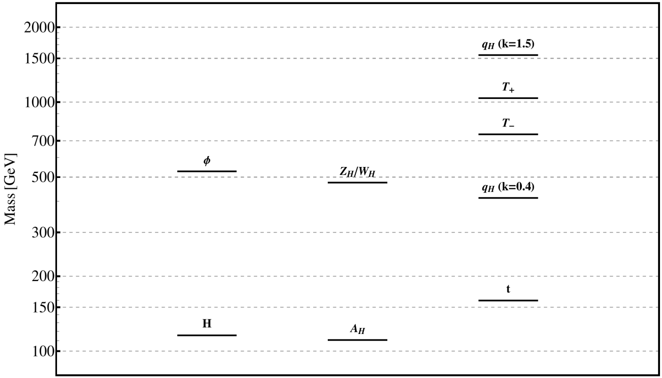


Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 1. $k = 1.5$, 2. $k = 0.4$

LHT Mass Spectrum

f=800 GeV, R=1.0, k=1.5



What about Direct Searches?

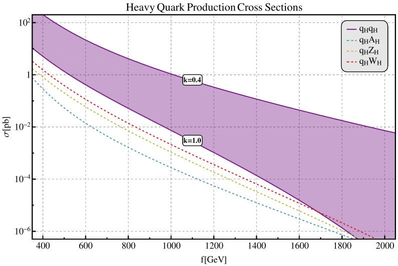
- Decay patterns:

Particle	Decay	$\mathrm{BR}_{k=1.0}$	$\mathrm{BR}_{k=0.4}$
$l_H^\pm$	$W_H^\pm\ \nu$	62%	0%
	$Z_H\, l^\pm$	31%	0%
	$A_H\, l^\pm$	6%	100%
$\nu_H^\pm$	$W_H^\pm\ l^\mp$	61%	0%
	$Z_H\, \nu$	30%	0%
	$A_H\, \nu$	9%	100%
T_H^+	$W^+\ b$	46%	45%
	$Z\ t$	22%	22%
	$H\ t$	21%	21%
	$T_H^-\ A_H$	11%	11%
A_H	stable		
Z_H	$A_H\, H$	100%	2%
	$d_H\, d$	0%	41%
	$u_H\, u$	0%	30%
	$l_H^\pm\ l^\mp$	0%	14%
	$\nu_H\, \nu$	0%	14%

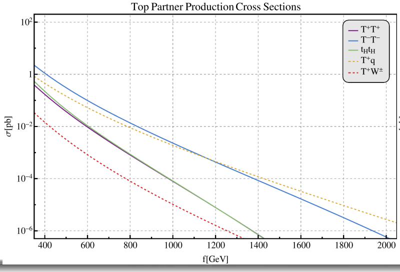
Particle	Decay	$\mathrm{BR}_{k=1.0}$	$\mathrm{BR}_{k=0.4}$
d_H	$W_H^-\ u$	62%	0%
	$Z_H\ d$	30%	0%
	$A_H\ d$	6%	100%
u_H	$W_H^+\ d$	58%	0%
	$Z_H\ u$	30%	0%
	$A_H\ u$	9%	100%
T_H^-	$A_H\ t$	100%	100%
	$Z_H\ t$	0%	0%
$\Phi^{0/P}$	$A_H\ H$	100%	100%
$\Phi^\pm$	$A_H\, W^\pm$	100%	100%
$\Phi^{\pm\pm}$	$A_H\ (W^\pm)^2$	100%	96%
$W_H^\pm$	$A_H\, W^\pm$	100%	2%
	$u_H\ d$	0%	44%
	$d_H\ u$	0%	27%
	$l_H^\pm\ \nu$	0%	16.5%
	$\nu_H\, l^\pm$	0%	16.5%

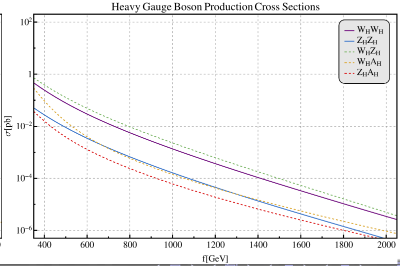
Cross Sections

- Heavy Quarks



- Heavy Top and Vectors





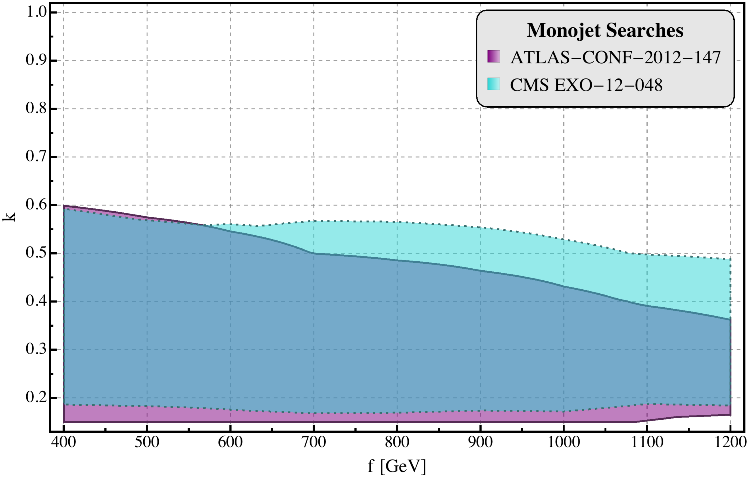
Channels and signatures

final state			modes	params
leptons	# jets	$\not{E}_T$		
0	1	✓	$q_H A_H$	f, k
0	2	✓	$q_H q_H$	f, k
0	3	✓	$q_H W_H^\pm$	f, k
0	4	✓	$q_H q_H$ $W_H^\pm W_H^\mp$ $W_H^\pm Z_H$ $Z_H Z_H$	f, k f, k f, k f, k
0	4	✗	$T^+ q$	f, k, R
0	5	✓	$q_H W_H^\pm$	f, k
0	6	✓	$q_H q_H$ $T^- T^-$	f, k f, k, R

final state			modes	params
leptons	# jets	$\not{E}_T$		
$l^\pm$	2	✓	$W_H^\pm W_H^\mp$ $W_H^\pm Z_H$ $q_H q_H$	f, k f, k f, k
$l^\pm$	3	✓	$q_H W_H^\pm$ $T^+ q$	f, k f, k, R
$l^\pm$	4	✓	$q_H q_H$ $T^- T^-$	f, k f, k, R
$l^+ l^-$	0	✓	$W_H^\pm W_H^\mp$	f, k
$l^+ l^-$	1	✓	$q_H W_H^\pm$	f, k
$l^+ l^-$	2	✓	$q_H q_H$ $T^- T^-$	f, k f, k, R
$l^\pm l^\pm$	2	✓	$q_H q_H$	f, k

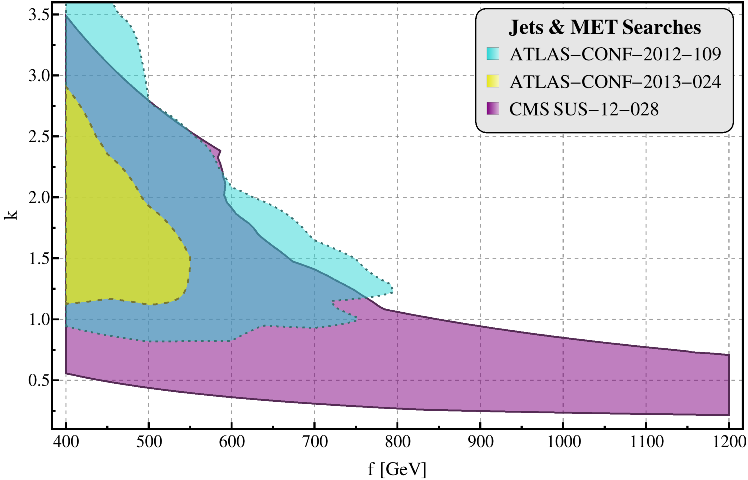
Recasting results

- 95% CL from Monojets + $\not{E}_T$ from LHC8



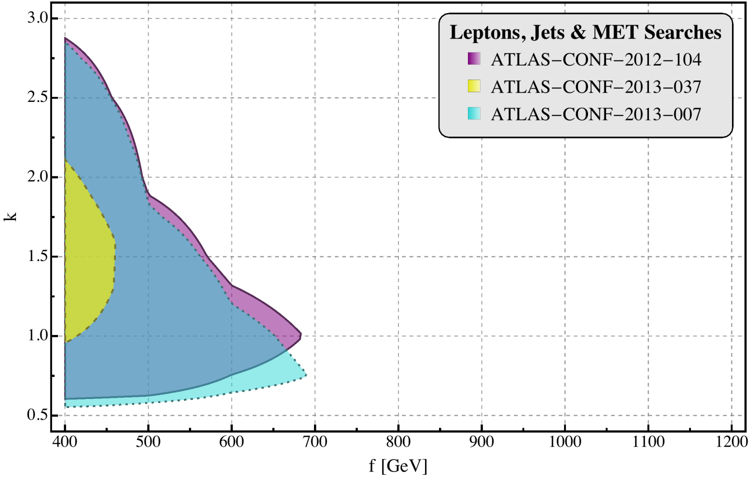
Recasting results

- 95% CL from Jets + $\not{E}_T$ from LHC8

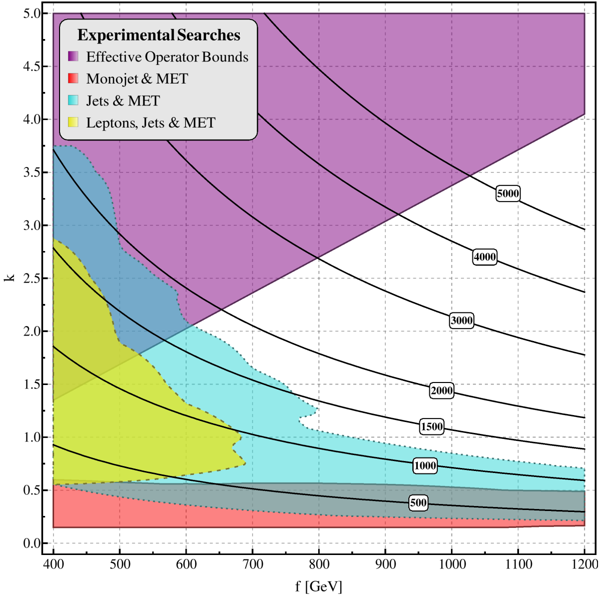


Recasting results

- 95% CL from Leptons + Jets + $\not{E}_T$ from LHC8



Combination



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
- Limits on the LHT:
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- We need more data!

Lessons from Lepton Photon last week ...

There are either colored exotics ...

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... or the world is fine tuned