

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

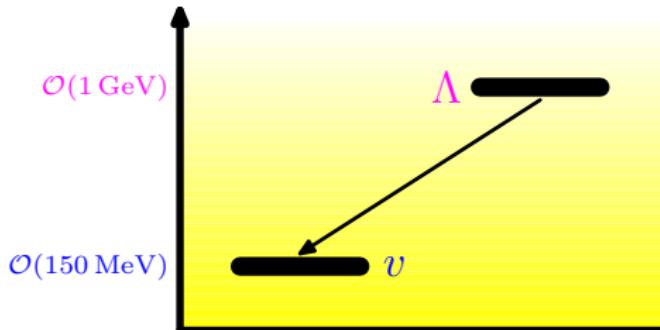
Snowmass Meeting, U. of Washington, Seattle, 2.7.2013

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, $SU(3)_c$

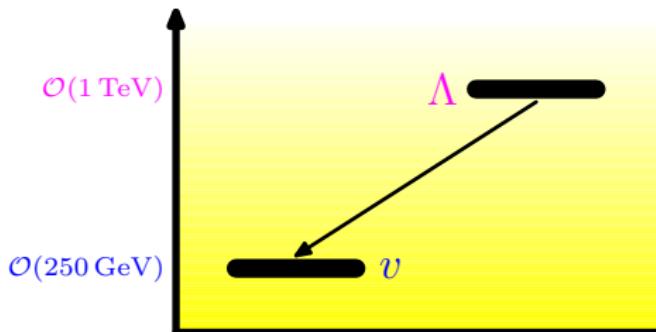
Scale v : pions, kaons, ...

Higgs as Pseudo-Goldstone boson

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



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

Scale v : Higgs, W/Z , ℓ^\pm , ...

Without Fine-Tuning: experimentally excluded

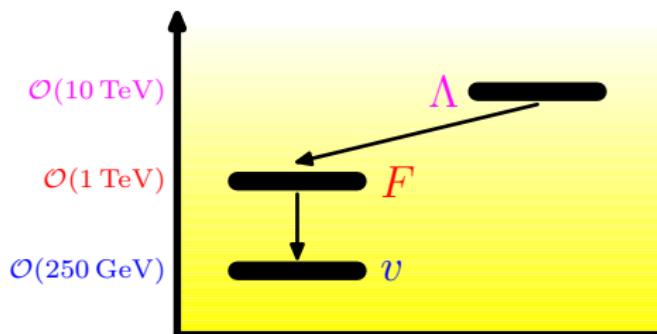
Collective symmetry breaking and 3-scale models

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

2 different global symmetries; one of them unbroken \Rightarrow Higgs exact Goldstone boson

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

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

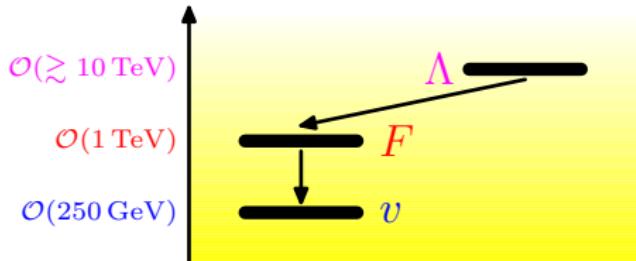


Scale Λ : global SB, new IA

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

Scale v : Higgs, W/Z , ℓ^\pm , ...

Characteristics and Spectra

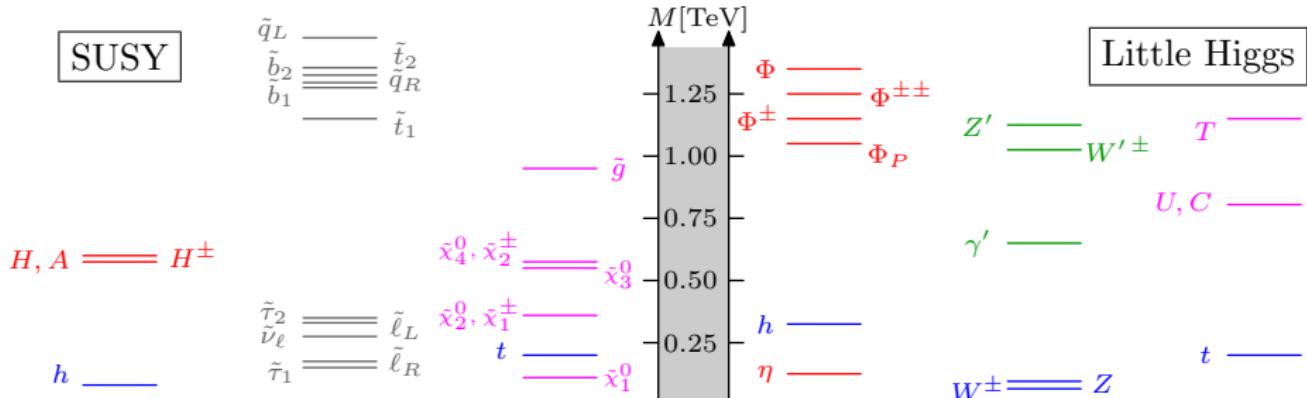


Scale Λ : “hidden sector”, symmetry breaking

Scale F : new particles

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

Terascale: new particles to stabilize the hierarchy

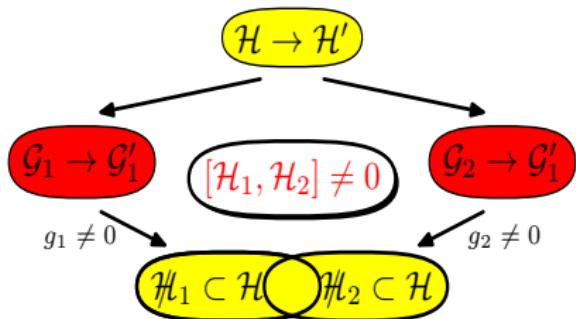


Generic properties of Little-Higgs models

- 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, \dots

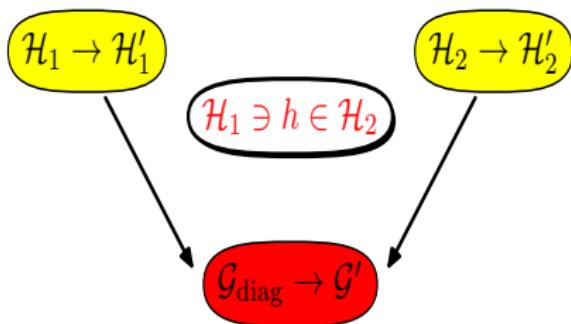
Product Group Models

(e.g. Littlest Higgs)



Simple Group Models

(e.g. Simplest Little Higgs)



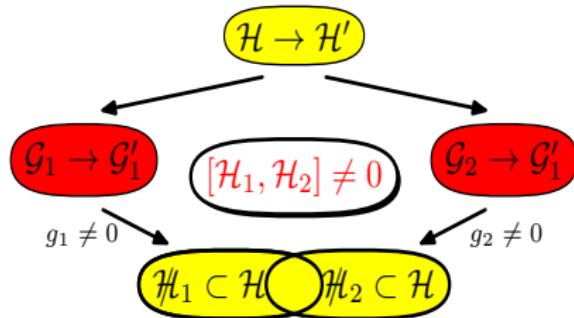
- discrete $T(\text{TeV})$ parity: pair production, cascades, DM

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, \dots

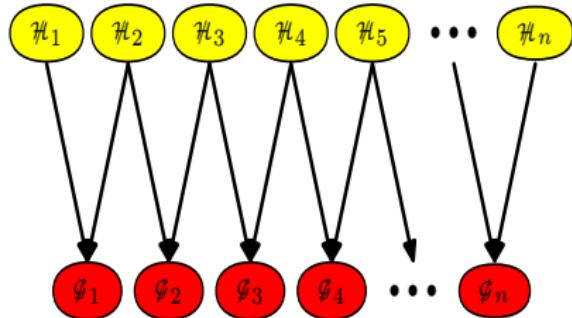
Product Group Models

(e.g. Littlest Higgs)



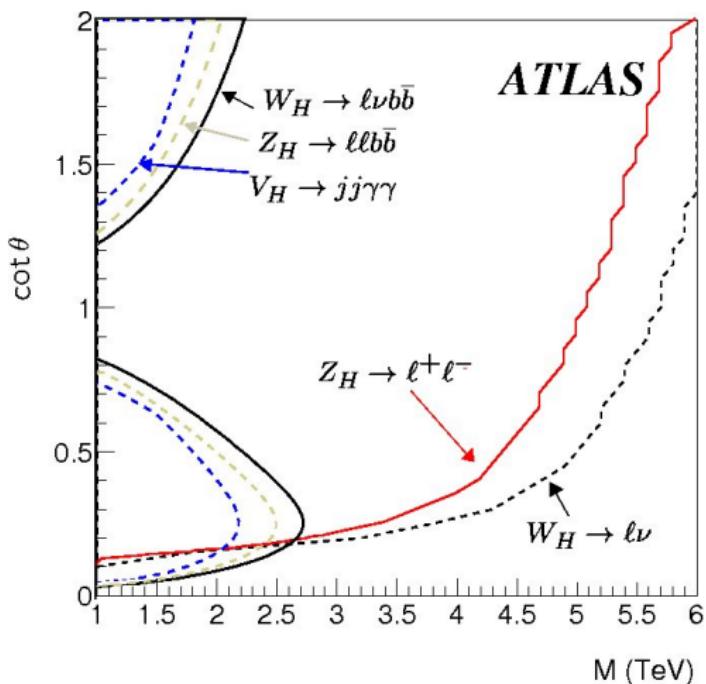
Moose Models

(e.g. Minimal Moose Model)



- discrete $T(\text{TeV})$ 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*:

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

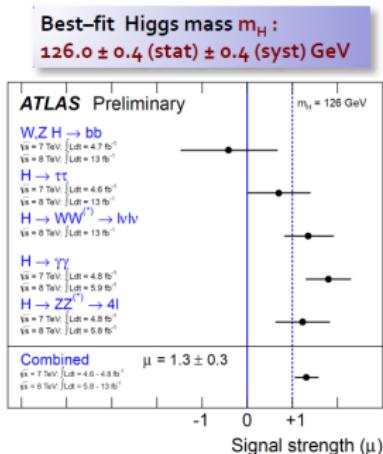
where \mathcal{O}_i depends on the free parameters of the model considered.

Data used: Higgs sector

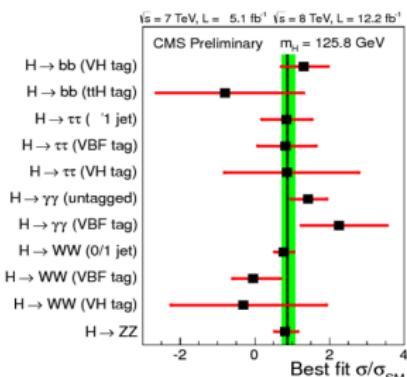
the Higgs results are expressed in terms of a *signal strength modifier*

$$\mu_i = \frac{\sum_p \epsilon_i^p \sigma_p}{\sum_p \epsilon_i^p \sigma_p^{SM}} \cdot \frac{BR(h \rightarrow X_i X_i)}{BR(h \rightarrow X_i X_i)_{SM}}$$

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 :



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



$$\sigma/\sigma_{SM} = 0.88 \pm 0.21$$

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...

Parameter	$(O_{\text{fit}} - O_{\text{meas}}) / \sigma_{\text{meas}}$
M_H	~0.2
M_W	~-1.2
Γ_W	~0.2
M_Z	~0.2
Γ_Z	~-1.7
σ_{had}^0	~-0.8
R_{lep}^0	~-1.1
$A_{\text{FB}}^{0,1}$	~-0.1
$A_t(\text{LEP})$	~0.2
$A_t(\text{SLD})$	~-1.9
$\sin^2 \Theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}})$	~-0.7
A_c	~0.0
A_b	~0.6
$A_{\text{FB}}^{0,c}$	~0.9
$A_{\text{FB}}^{0,b}$	~2.5
R_c^0	~0.0
R_b^0	~-2.4
\bar{m}_c	~0.0
\bar{m}_b	~0.0
m_t	~0.4
$\Delta \alpha_{\text{had}}^{(5)}(M_Z^2)$	~-0.1

LH Smoking guns

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

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

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

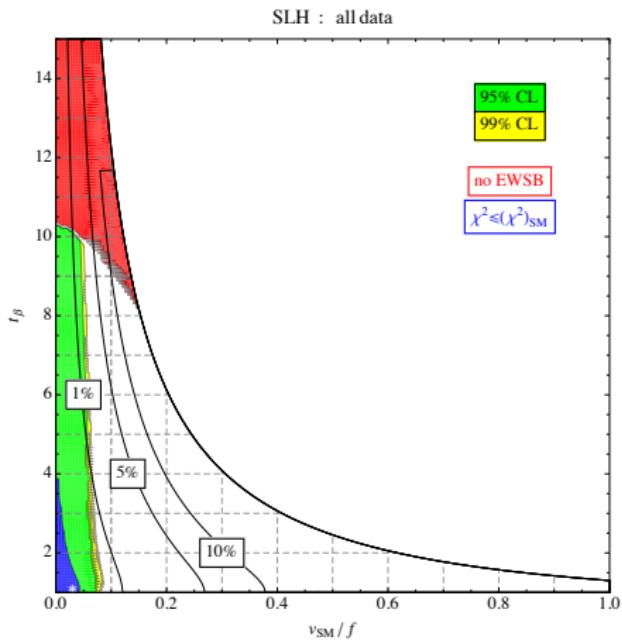
- ▶ interaction terms of Higgs with new fermions/vector bosons

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

- ▶ modified neutral- and charged-currents

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

SLH results



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

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

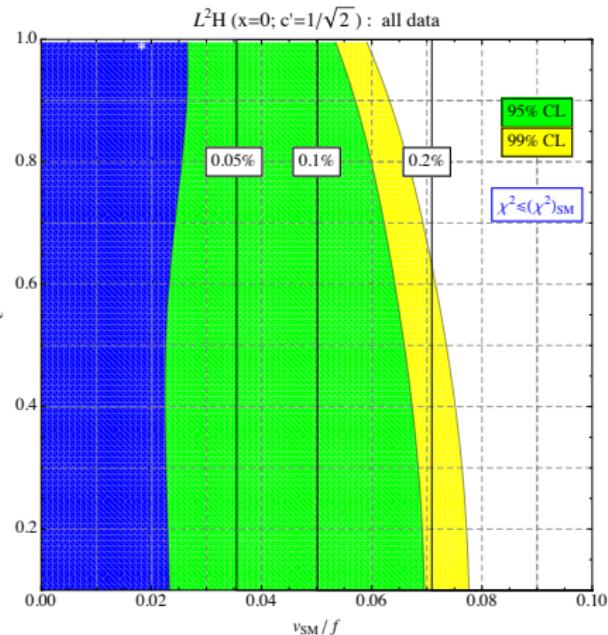
$$\begin{aligned}m_{W'} &\gtrsim 1.35 \text{ TeV} \\ m_T &\gtrsim 2.81 \text{ TeV}\end{aligned}$$

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

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

- results mainly driven by EWPD

L^2H results



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

- free parameters: f SSB scale, c mixing angle in gauge sector
- $f_{\min}^{99\%} = 3.20$ TeV, translates into lower bounds on new states' masses, e.g.
- min. required fine tuning: $\sim 0.1\%$, defined as

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

- results mainly driven by EWPD

Partial decay widths in LH

- ▶ 1-loop decays

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

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

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

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

- ▶ tree-level decays

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

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

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:

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

- Discrete T parity:

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

$$\begin{aligned} V_{CW} = & \lambda_{\phi^2} f^2 \text{Tr}(\phi^\dagger \phi) + i\lambda_{h\phi h} f \left(H\phi^\dagger H^t - H^* \phi H^\dagger \right) - \mu^2 H H^\dagger + \lambda_{h^4} (H H^\dagger)^2 + \\ & + \lambda_{h\phi\phi h} H\phi^\dagger \phi H^\dagger + \lambda_{h^2\phi^2} H H^\dagger \text{Tr}(\phi^\dagger \phi) + \lambda_{\phi^2\phi^2} \left[\text{Tr}(\phi^\dagger \phi) \right]^2 + \lambda_{\phi^4} \text{Tr}(\phi^\dagger \phi \phi^\dagger \phi). \end{aligned}$$

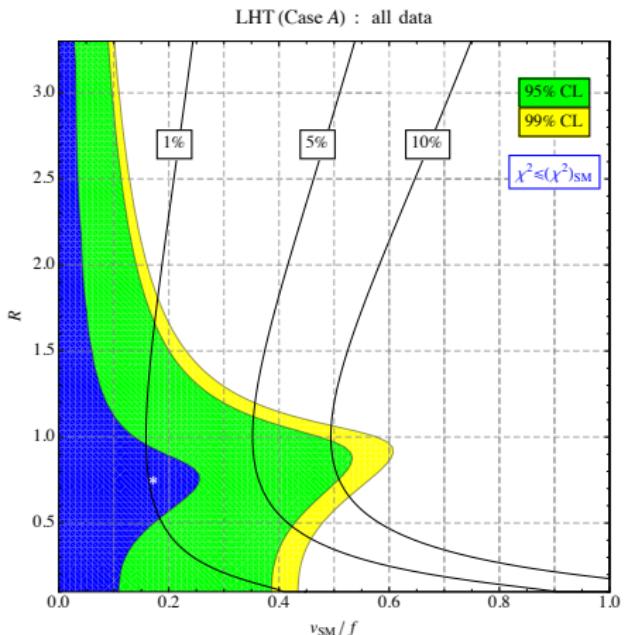
$$\begin{aligned} \lambda_{\phi^2} &= 2(g^2 + g'^2) + 8\lambda_1^2 & \lambda_{h^4} &= \frac{1}{4}\lambda_{\phi^2} \\ \lambda_{h^2\phi^2} &= -16\lambda_1^2 & \lambda_{\phi^4} &= -\frac{8}{3}(g^2 + g'^2) + \frac{16}{3}\lambda_1^2 \end{aligned}$$

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

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

$$\mathcal{L}_t = -\frac{\lambda_1 f}{2\sqrt{2}} \epsilon_{ijk} \epsilon_{xy} \left[(\bar{\Psi}_{1,t})_i \Sigma_{jx} \Sigma_{ky} - (\bar{\Psi}_{2,t} \langle \Sigma \rangle)_i \Sigma'_{jx} \Sigma'_{ky} \right] t'_R - \lambda_2 f (\bar{T}_{L1} T_{R1} + \bar{T}_{L2} T_{R2})$$

LHT results



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

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

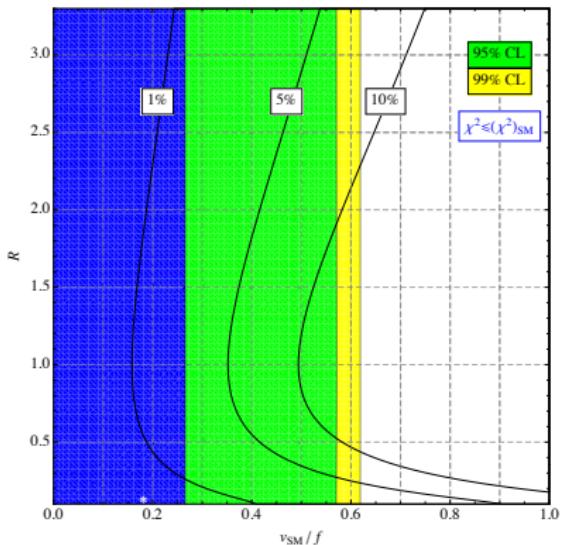
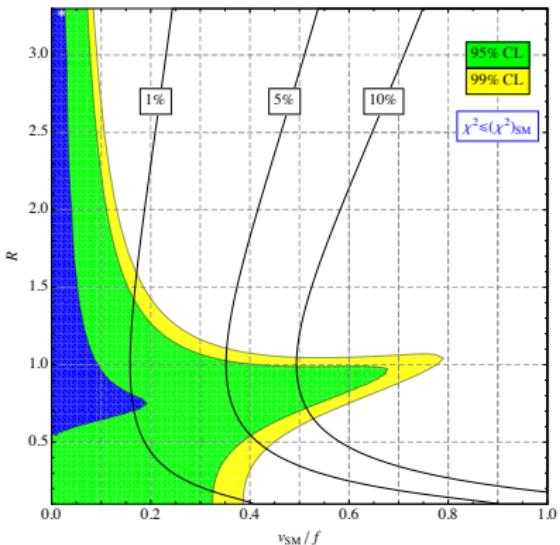
$$\begin{aligned}m_{W'} &\gtrsim 269.6 \text{ GeV} \\ m_T &\gtrsim 553.6 \text{ GeV}\end{aligned}$$

- min. required fine tuning: $\sim 10\%$, defined as

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

- results mainly driven by EWPD (see next slide)

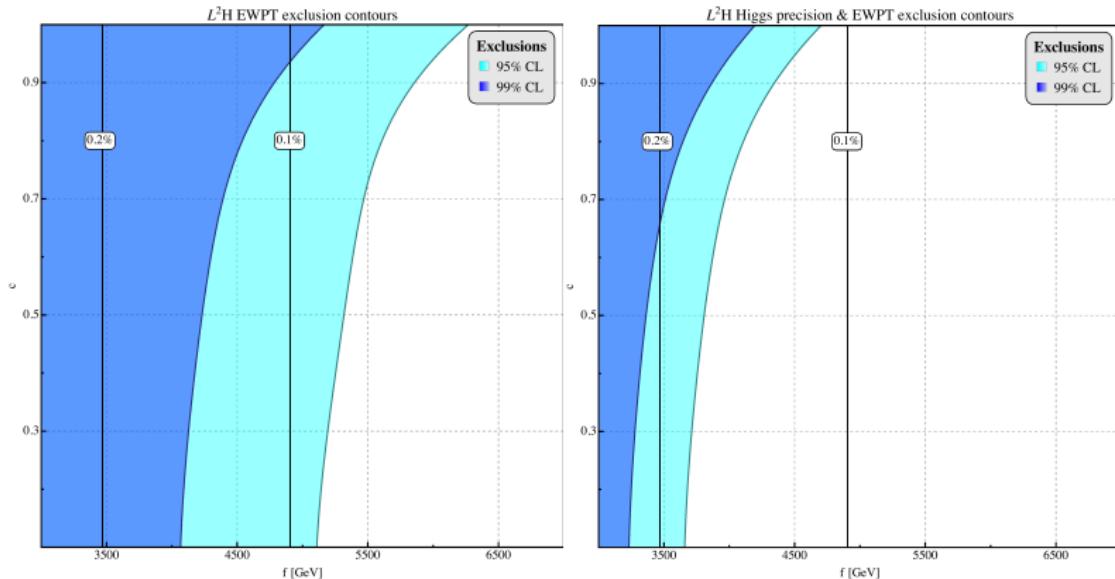
Higgs data vs. EWP^D

LHT (Case A) : $\hat{\mu}$ onlyLHT (Case A) : EWP^D only

- 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 $h \rightarrow A_H A_H$ open and dominant
- Higgs data only: subdominant dependence on R w.r.t. f is a consequence of the Collective Symmetry Breaking mechanism

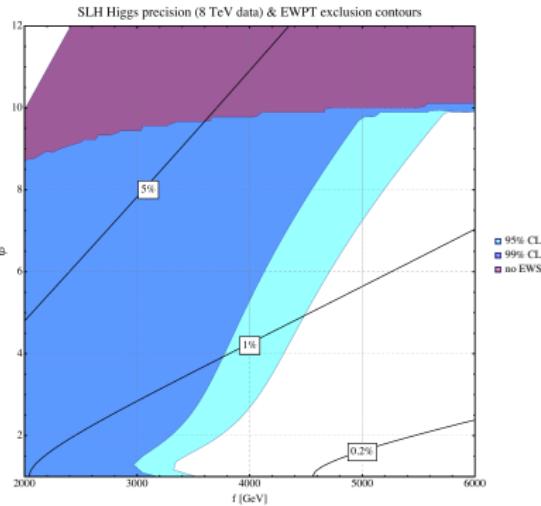
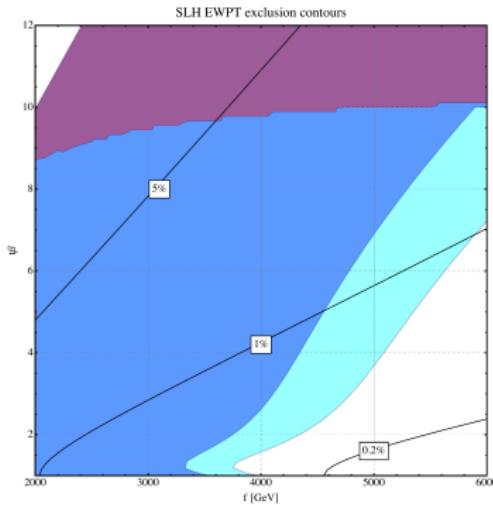
New Results (incl. Moriond 2013)

Littlest Higgs Model



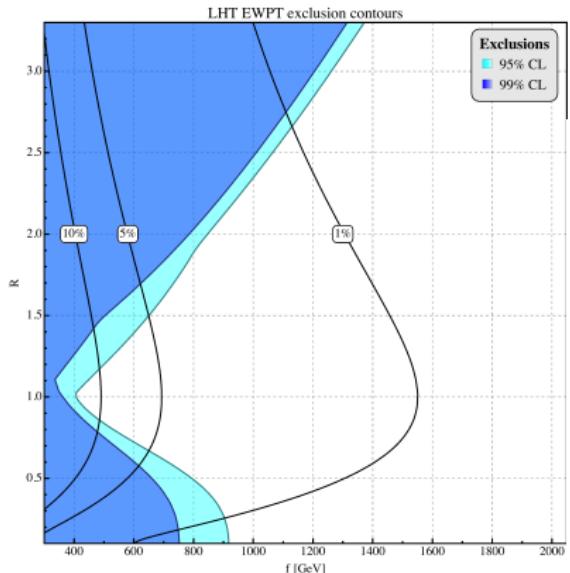
New Results (incl. Moriond 2013)

Simplest Little Higgs



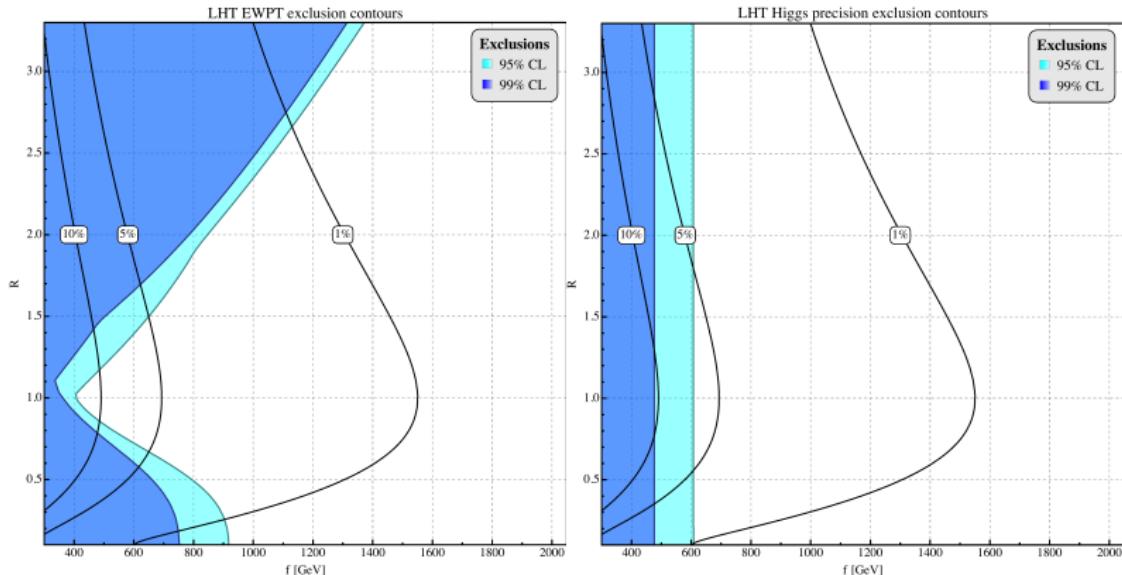
New Results (incl. Moriond 2013)

Littlest Higgs with T Parity



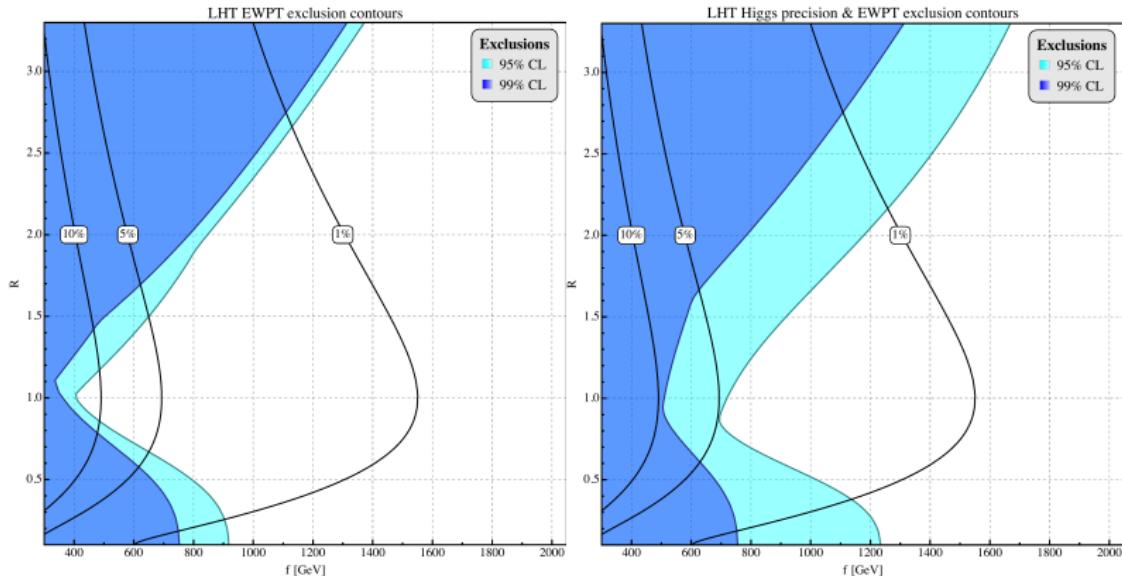
New Results (incl. Moriond 2013)

Littlest Higgs with T Parity



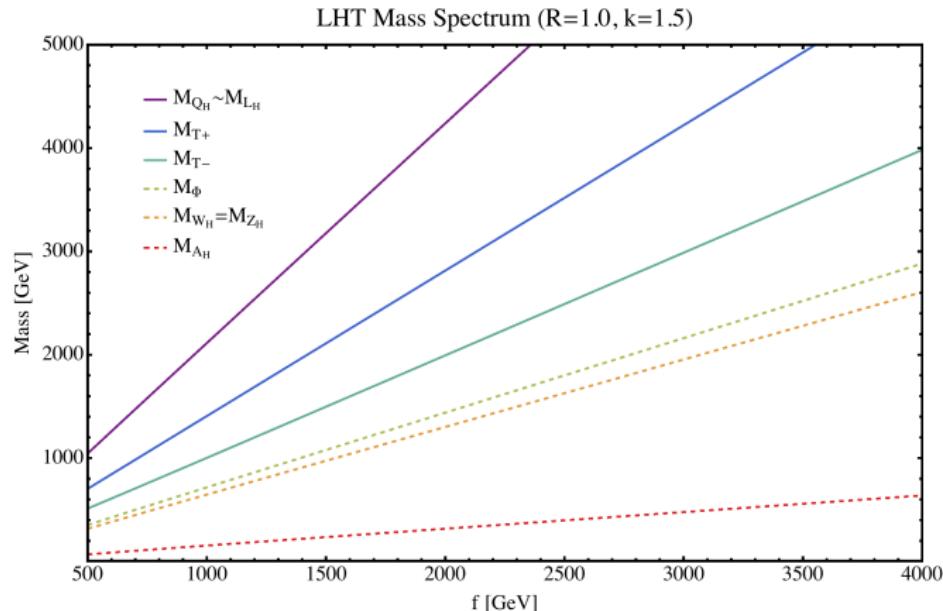
New Results (incl. Moriond 2013)

Littlest Higgs with T Parity



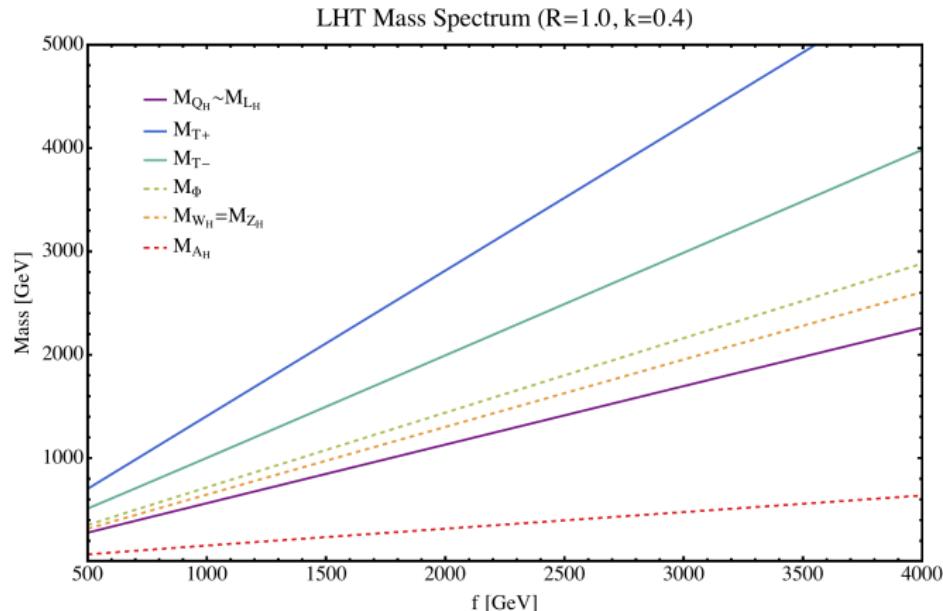
Direct Searches: Focus on LHT

- Defining two benchmark scenarios:
 - 1. heavy quarks



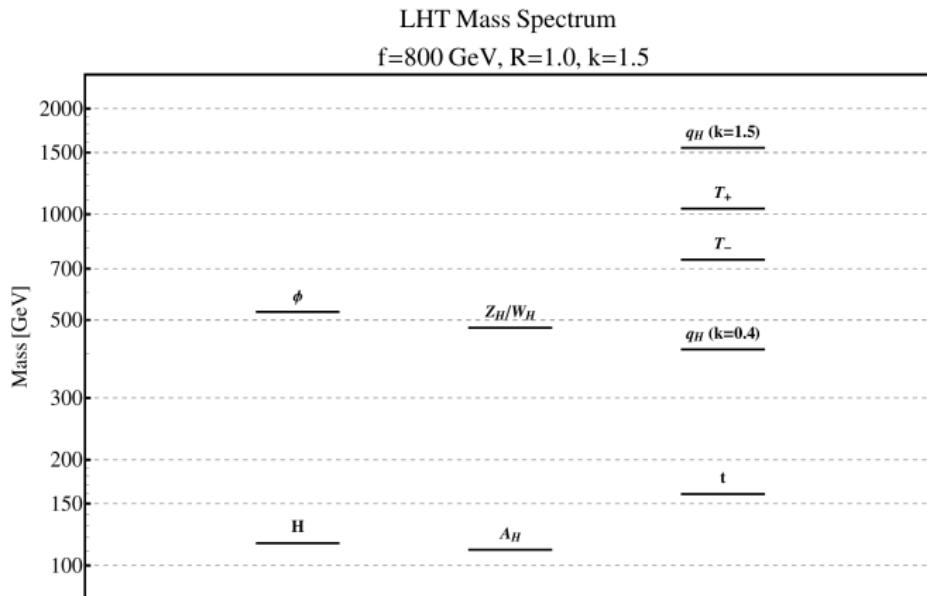
Direct Searches: Focus on LHT

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



Direct Searches: Focus on LHT

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



What about Direct Searches?

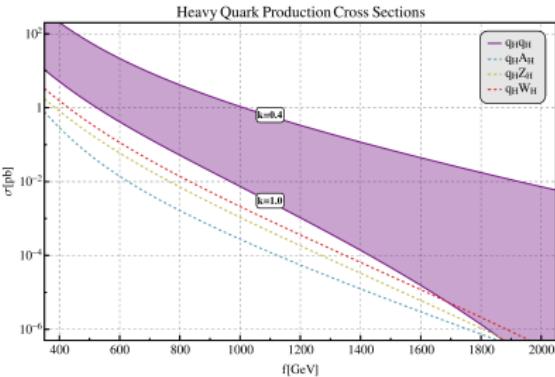
- Decay patterns:

Particle	Decay	$\text{BR}_{k=1.0}$	$\text{BR}_{k=0.4}$
l_H^\pm	$W_H^\pm \nu$	62%	0%
	$Z_H l^\pm$	31%	0%
	$A_H l^\pm$	6%	100%
ν_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%

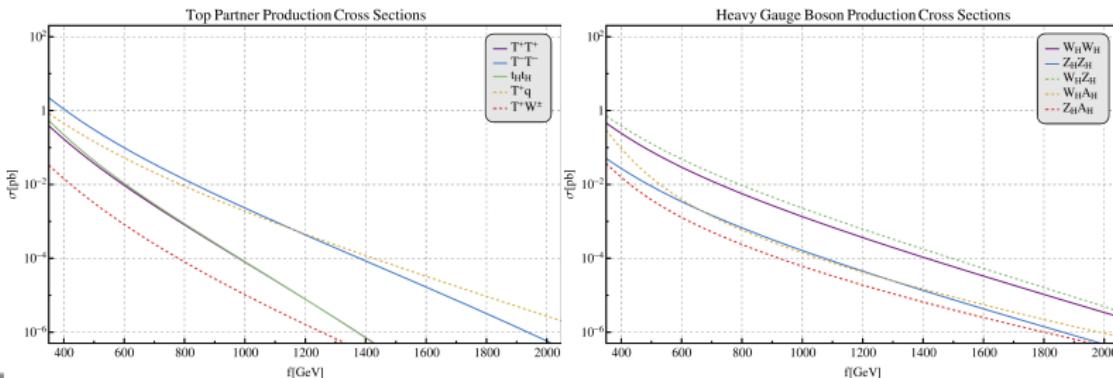
Particle	Decay	$\text{BR}_{k=1.0}$	$\text{BR}_{k=0.4}$
d_H	$W_H^- u$	62%	0%
	$Z_H d$	30%	0%
	$A_H d$	6%	100%
u_H	$W_H^+ d$	58%	0%
	$Z_H u$	30%	0%
	$A_H u$	9%	100%
T_H^-	$A_H t$	100%	100%
	$Z_H t$	0%	0%
$\Phi^{0/P}$	$A_H H$	100%	100%
Φ^\pm	$A_H W^\pm$	100%	100%
$\Phi^{\pm\pm}$	$A_H (W^\pm)^2$	100%	96%
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

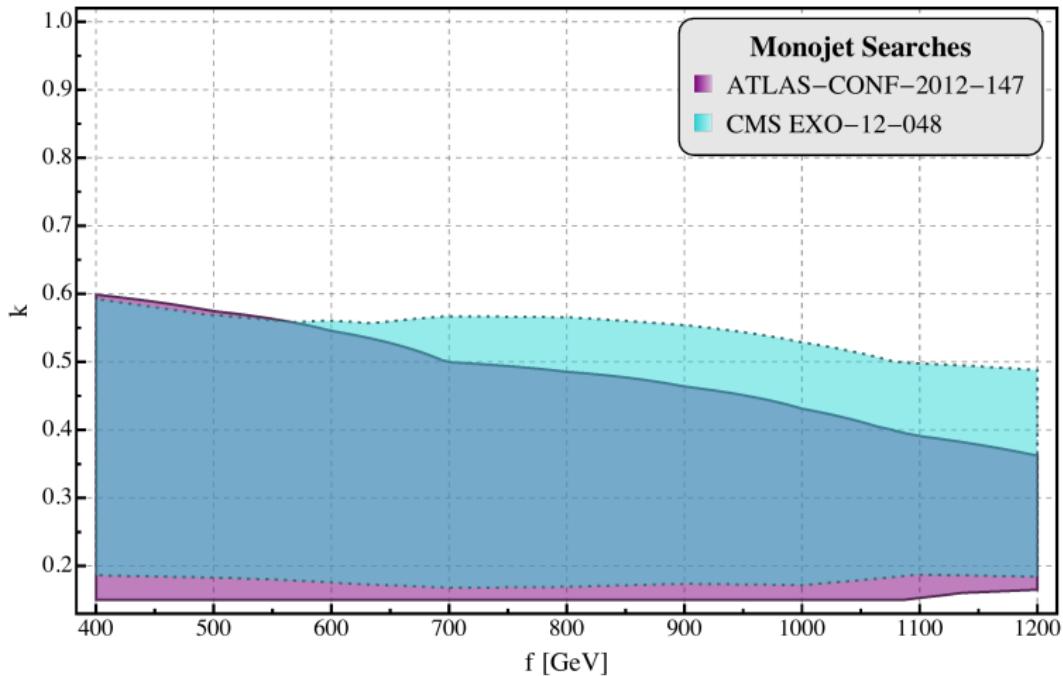


Channels and signatures

final state			modes	params	final state			modes	params
leptons	# jets	\cancel{E}_T			leptons	# jets	\cancel{E}_T		
0	1	✓	$q_H A_H$	f, k	l^\pm	2	✓	$W_H^\pm W_H^\mp$	f, k
0	2	✓	$q_H q_H$	f, k				$W_H^\pm Z_H$	f, k
0	3	✓	$q_H W_H^\pm$	f, k	l^\pm	3	✓	$q_H W_H^\pm$	f, k
0	4	✓	$q_H q_H$	f, k				$T^+ q$	f, k, R
			$W_H^\pm W_H^\mp$	f, k	l^\pm	4	✓	$q_H q_H$	f, k
			$W_H^\pm Z_H$	f, k				$T^- T^-$	f, k, R
			$Z_H Z_H$	f, k	$l^+ l^-$	0	✓	$W_H^\pm W_H^\mp$	f, k
0	4	✗	$T^+ q$	f, k, R	$l^+ l^-$	1	✓	$q_H W_H^\pm$	f, k
0	5	✓	$q_H W_H^\pm$	f, k	$l^+ l^-$	2	✓	$q_H q_H$	f, k
0	6	✓	$q_H q_H$	f, k				$T^- T^-$	f, k, R
			$T^- T^-$	f, k, R	$l^\pm l^\pm$	2	✓	$q_H q_H$	f, k

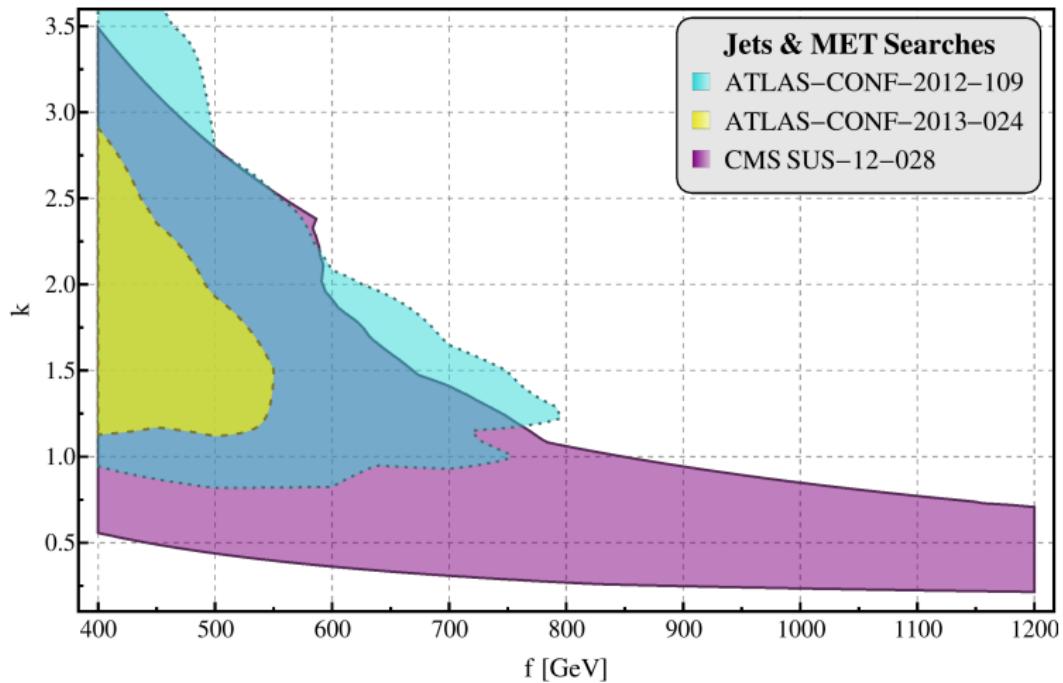
Recasting results

- 95% CL from Monojets + \cancel{E}_T from LHC8



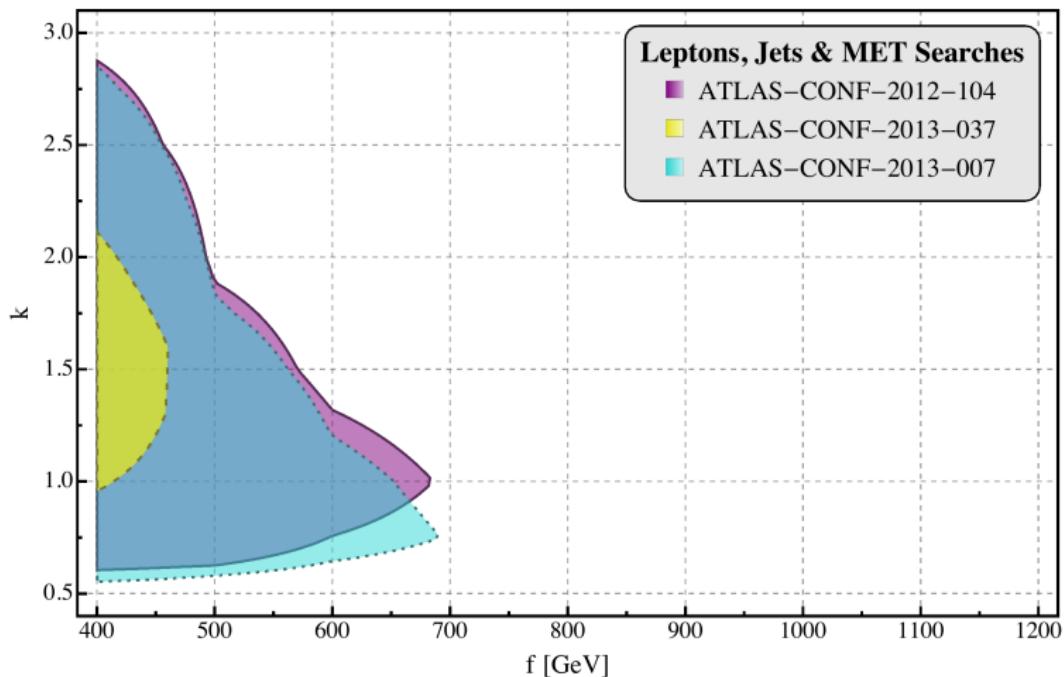
Recasting results

- 95% CL from Jets + \cancel{E}_T from LHC8

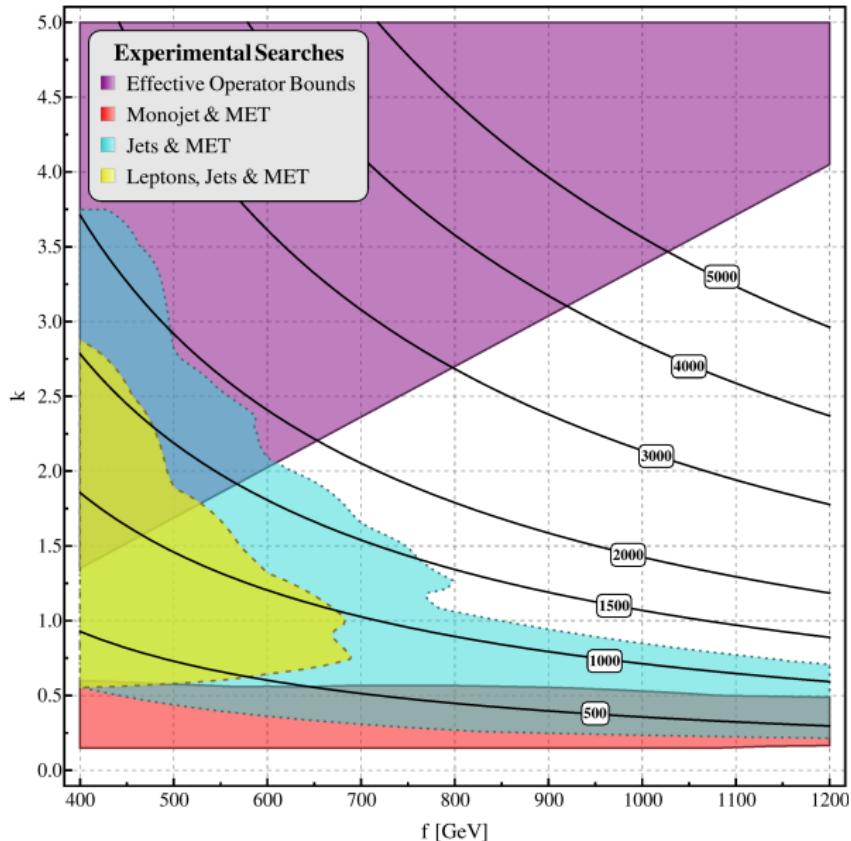


Recasting results

- 95% CL from Leptons + Jets + \cancel{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:
 1. EWPO:

$$f \gtrsim 405 \text{ GeV@95\% CL}$$

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:
 1. EWPO: $f \gtrsim 405 \text{ GeV@95\% CL}$
 2. Higgs: $f \gtrsim 607 \text{ GeV@95\% CL}$

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:
 1. EWPO: $f \gtrsim 405 \text{ GeV@95\% CL}$
 2. Higgs: $f \gtrsim 607 \text{ GeV@95\% CL}$
 3. Higgs+EWPO: $f \gtrsim 694 \text{ GeV@95\% CL}$

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:
 1. EWPO: $f \gtrsim 405 \text{ GeV@95\% CL}$
 2. Higgs: $f \gtrsim 607 \text{ GeV@95\% CL}$
 3. Higgs+EWPO: $f \gtrsim 694 \text{ GeV@95\% CL}$
 4. Direct searches: $f \gtrsim 650 \text{ GeV@95\% CL}$

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:
 1. EWPO: $f \gtrsim 405 \text{ GeV@95\% CL}$
 2. Higgs: $f \gtrsim 607 \text{ GeV@95\% CL}$
 3. Higgs+EWPO: $f \gtrsim 694 \text{ GeV@95\% CL}$
 4. Direct searches: $f \gtrsim 650 \text{ GeV@95\% CL}$
- ▶ We need more data!

Lessons from Lepton Photon last week ...

There are either colored exotics ...



Lessons from Lepton Photon last week ...

... or the world is fine tuned

