Can the 125 GeV Higgs be the Little Higgs

Jürgen Reuter

DESY

JRR/Tonini, JHEP **1302** (2013) 077; Kilian/JRR **PRD 70** (2004), 015004

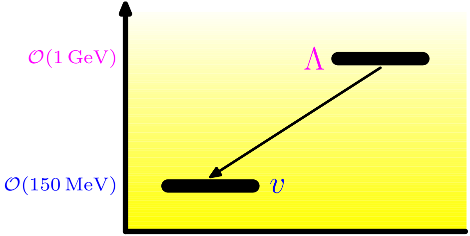
LHC Physics Discussion, DESY, 10.6.2013

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, . . .

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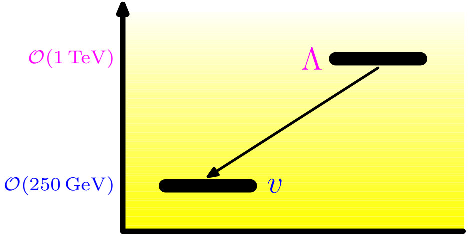


Scale Λ: global symmetry breaking, new particles, new (gauge) IA

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

Without Fine-Tuning: experimentally excluded

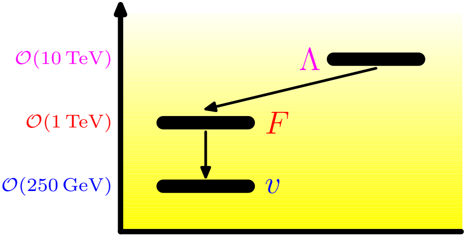
Collective symmetry breaking and 3-scale models

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

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

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

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

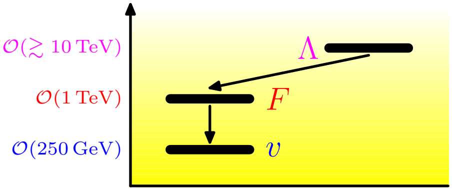


Scale Λ: global SB, new IA

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

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

Characteristics and Spectra

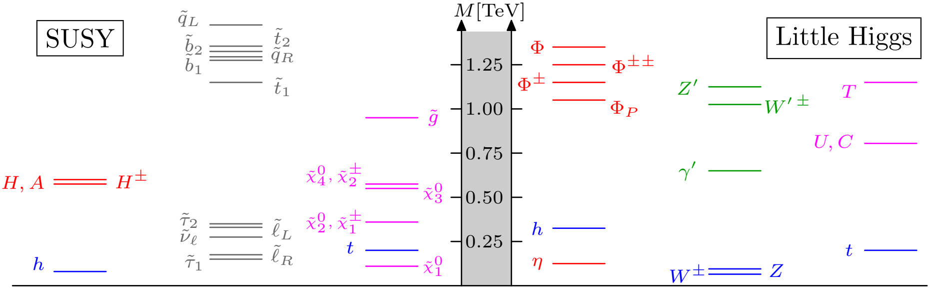


Scale Λ: "hidden sector", symmetry breaking

Scale F: new particles

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

Terascale: new particles to stabilize the hierarchy

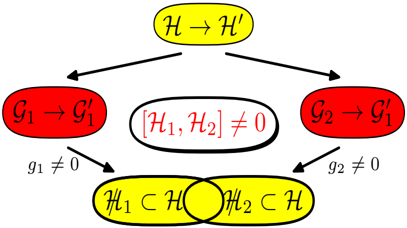


Generic properties of Little-Higgs models

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

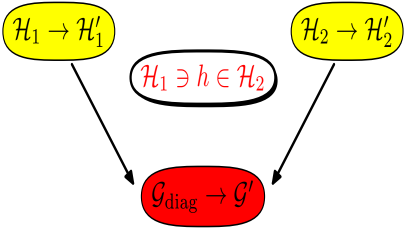
Product Group Models

(e.g. Littlest Higgs)



Simple Group Models

(e.g. Simplest Little Higgs)



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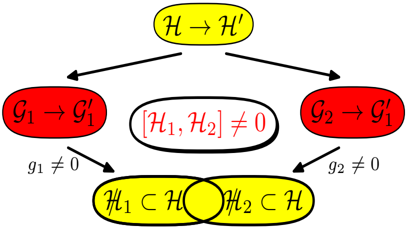
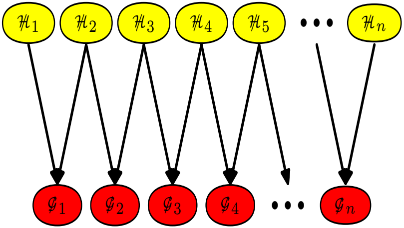


Moose Models

(e.g. Minimal Moose Model)



Little Higgs Models

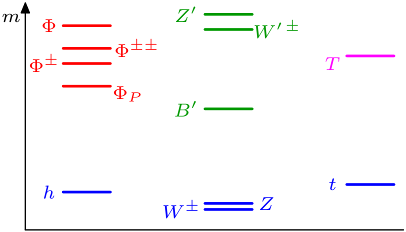
Plethora of "Little Higgs Models" in 3 categories:

- **Moose Models**
  - Orig. Moose (Arkani-Hamed/Cohen/Georgi, 0105239)
  - Simple Moose (Arkani-Hamed/Cohen/Katz/Nelson/Gregoire/Wacker, 0206020)
  - Linear Moose (Casalbuoni/De Curtis/Dominici, 0405188)
- **Simple (Goldstone) Representation Models**
  - Littlest Higgs (Arkani-Hamed/Cohen/Katz/Nelson, 0206021)
  - Antisymmetric Little Higgs (Low/Skiba/Smith, 0207243)
  - Custodial $SU(2)$ Little Higgs (Chang/Wacker, 0303001)
  - Littlest Custodial Higgs (Chang, 0306034)
  - Little SUSY (Birkedal/Chacko/Gaillard, 0404197)
- **Simple (Gauge) Group Models**
  - Orig. Simple Group Model (Kaplan/Schmaltz, 0302049)
  - Holographic Little Higgs (Contino/Nomura/Pomarol, 0306259)
  - Simplest Little Higgs (Schmaltz, 0407143)
  - Simplest Little SUSY (Roy/Schmaltz, 0509357)
  - Simplest T parity (Butenuth/JRR, 2010)

Varieties of Particle spectra

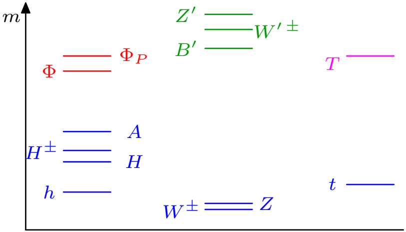
$$\mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2)\times U(1)]^2}{SU(2)\times U(1)}$$

Arkani-Hamed/Cohen/Katz/Nelson, 2002



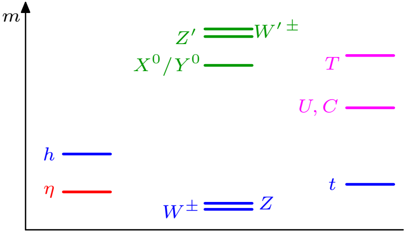
$$\mathcal{H} = \frac{SO(6)}{Sp(6)}, \mathcal{G} = \frac{[SU(2)\times U(1)]^2}{SU(2)\times U(1)}$$

Low/Skiba/Smith, 2002



$$\mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2}, \mathcal{G} = \frac{SU(3)\times U(1)}{SU(2)\times U(1)} \Longrightarrow$$

Schmaltz, 2004

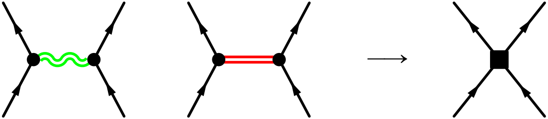


- $[SU(4)]^4 \to [SU(3)]^4$

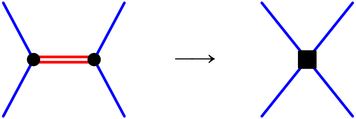
Kaplan/Schmaltz, 2003

2HDM, $h_{1/2}$, $\Phi'_{1,2,3}$, $\Phi'_{P\,1,2,3}$, $Z'_{1,\ldots,8}$, $W'^{\pm}_{1,2}$, q', ℓ'

Effective Dim. 6 Operators

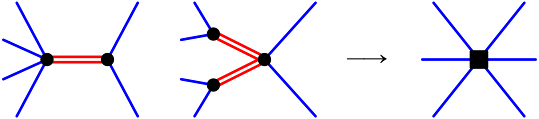


$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{F^2} \operatorname{tr}[J^{(I)} \cdot J^{(I)}]$$

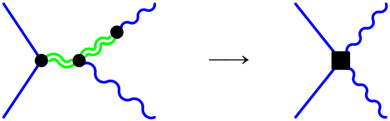


$$\mathcal{O}'_{h,1} = \frac{1}{F^2} \left((Dh)^\dagger h \right) \cdot \left(h^\dagger (D^h) \right) - \frac{v^2}{2} |Dh|^2$$

$$\mathcal{O}'_{hh} = \frac{1}{F^2} (h^\dagger h - v^2/2) \; (Dh)^\dagger \cdot (Dh)$$



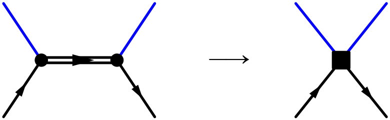
$$\mathcal{O}'_{h,3} = \frac{1}{F^2} \frac{1}{3} (h^\dagger h - v^2/2)^3$$



$$\mathcal{O}'_{WW} = -\frac{1}{F^2}\frac{1}{2}(h^\dagger h - v^2/2)\,\mathrm{tr}\,W_{\mu\nu}W^{\mu\nu}$$

$$\mathcal{O}_B = \frac{1}{F^2}\frac{i}{2}(D_\mu h)^\dagger(D_\nu h)B^{\mu\nu}$$

$$\mathcal{O}'_{BB} = -\frac{1}{F^2}\frac{1}{4}(h^\dagger h - v^2/2)B_{\mu\nu}B^{\mu\nu}$$



$$\mathcal{O}_{Vq} = \frac{1}{F^2}\overline{q}h(\not{D}h)q$$

Constraints on LHM

Constraints from contact IA: ($f_{JJ}^{(3)}$, $f_{JJ}^{(1)}$) $4.5\,\text{TeV} \lesssim F/c^2$ $\quad 10\,\text{TeV} \lesssim F/c'^{\,2}$

◇ **Constraints evaded** $\iff$ $c, c' \ll 1$
$B', Z', W'^{\pm}$ superheavy ($\mathcal{O}(\Lambda)$) *decouple from fermions*

ΔS, ΔT in the Littlest Higgs model, violation of Custodial SU(2): Csáki et al., 2002; Hewett et al., 2002; Han et al., 2003; Chen/Dawson, 2003; Kilian/JRR, 2003

$$\frac{\Delta S}{8\pi} = -\left[\frac{c^2(c^2 - s^2)}{g^2} + 5\frac{c'^{\,2}(c'^{\,2} - s'^{\,2})}{g'^{\,2}}\right]\frac{v^2}{F^2} \to 0 \qquad \alpha\Delta T \to \frac{5}{4}\frac{v^2}{F^2} - \frac{2v^2\lambda_{2\phi}^2}{M_\phi^4} \gtrsim \frac{v^2}{F^2}$$

General models

- Triplet sector: (almost) identical to Littlest Higgs (ΔS only)
- More freedom in $U(1)$ sector: (ΔT)

T parity and Dark Matter

Cheng/Low, 2003; Hubisz/Meade, 2005

- T parity: $T^a \to T^a, \quad X^a \to -X^a$, automorphism of coset space analogous to R parity in SUSY, KK parity in extra dimensions
- Bounds on F MUCH relaxed, $F \sim 1$ TeV
  but: Pair production!, typical cascade decays
- Lightest T-odd particle (LTP) $\Rightarrow$ Candidate for Cold Dark Matter

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Littlest Higgs: A' LTP

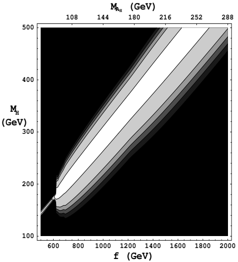
$W', Z' \sim$ 650 GeV, $\Phi \sim$ 1 TeV

$T, T' \sim$ 0.7-1 TeV

Annihilation: $A'A' \to h \to WW, ZZ, hh$

Hubisz/Meade, 2005

0/10/50/70/100



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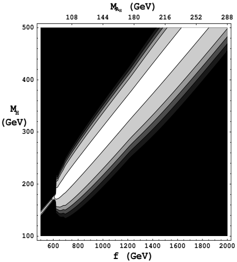
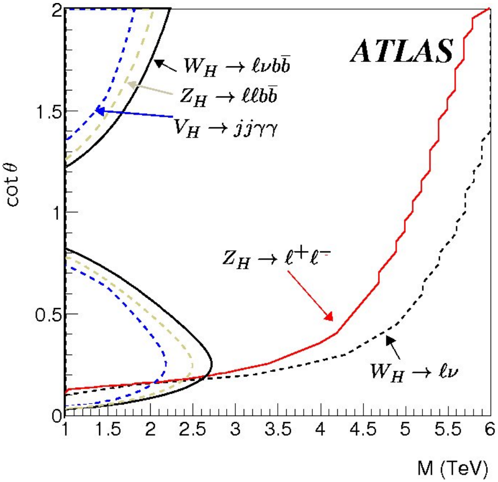


- T parity Simplest LH: Pseudo-Axion η LTP
  Z' remains odd: good or bad (?)

Kilian/Rainwater/JRR/Schmaltz

- T parity might be anomalous (???)

Hill/Hill, 2007



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.

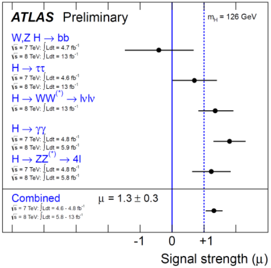
Data used: Higgs sector

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

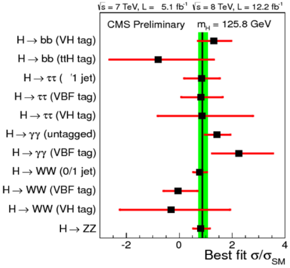
$$\mu_i = \frac{\sum_p \epsilon^p{}_i \, \sigma_p}{\sum_p \epsilon^p{}_i \, \sigma_p^{SM}} \cdot \frac{BR(h \to X_i X_i)}{BR(h \to X_i X_i)_{SM}}$$

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*

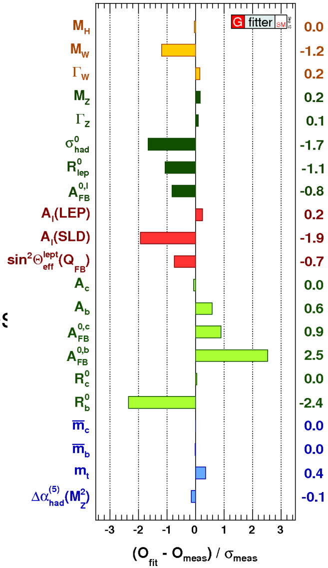
every extension of *SM* has to satisfy at least the precision constraints of the electroweak sector:

- 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

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

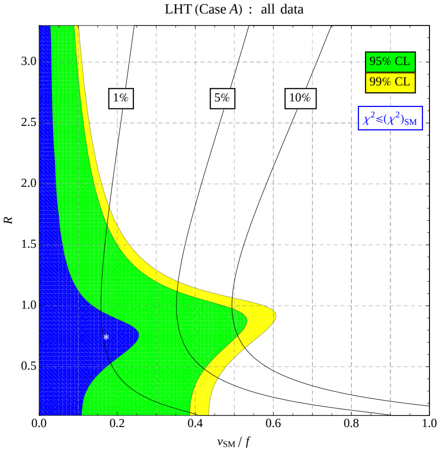
- interaction terms of Higgs with new fermions/vector bosons

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

- modified neutral- and charged-currents

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

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.

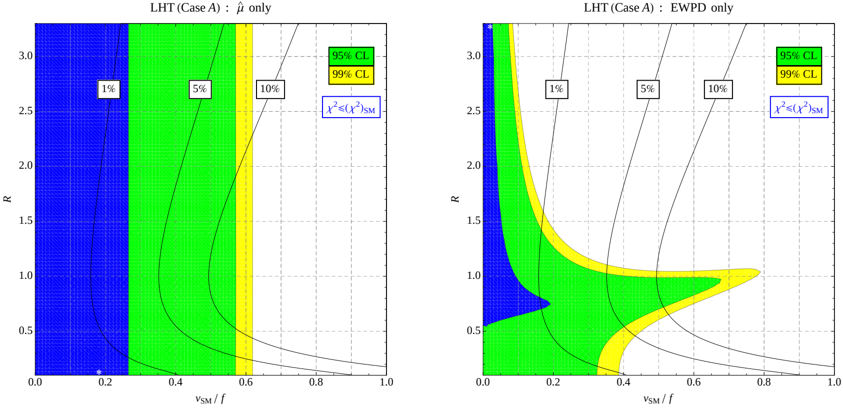
$$m_{W'} \gtrsim 269.6 \text{ GeV}$$
$$m_T \gtrsim 553.6 \text{ GeV}$$

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

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

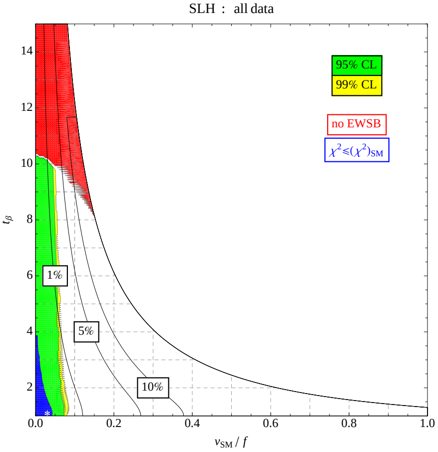
- results mainly driven by *EWPD* (see next slide)

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

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.

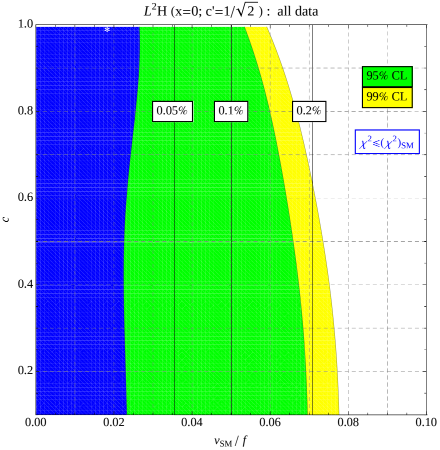
$$m_{W'} \gtrsim 1.35 \text{ TeV}$$
$$m_T \gtrsim 2.81 \text{ TeV}$$

- 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.

$$m_{W'} \gtrsim 2.13 \text{ TeV}$$
$$m_T \gtrsim 4.50 \text{ TeV}$$

- 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. 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

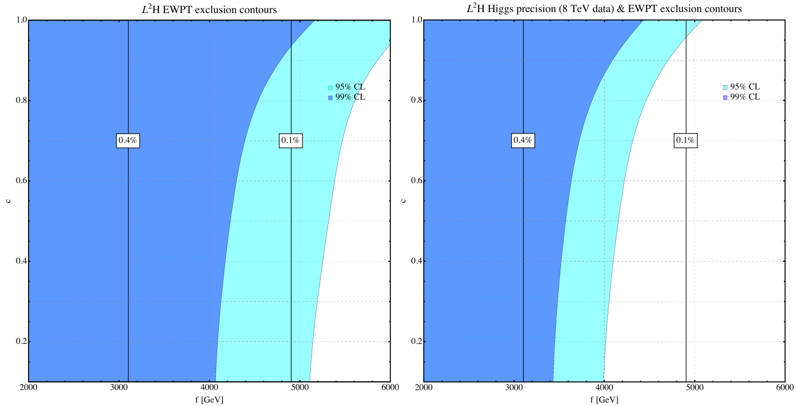
$$\Gamma(h \to VV)_{LH} \sim \Gamma(h \to VV)_{SM} \left(\frac{g_{hVV}}{g_{hVV}^{SM}} \right)^2$$

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

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

New Results (incl. Moriond 2013)

Littlest Higgs Model



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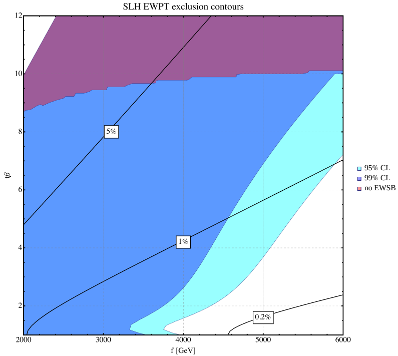
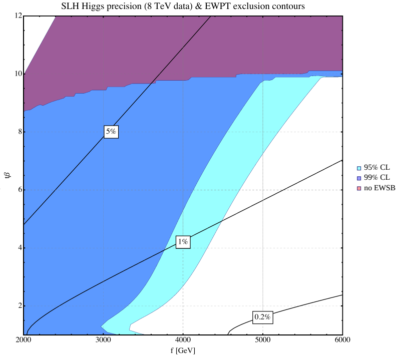
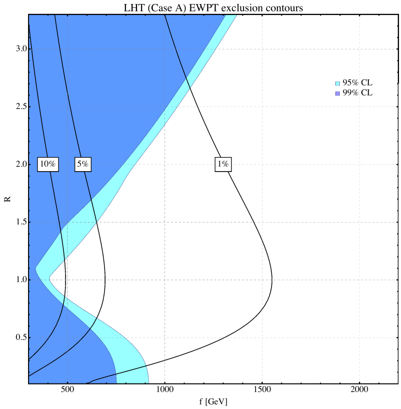




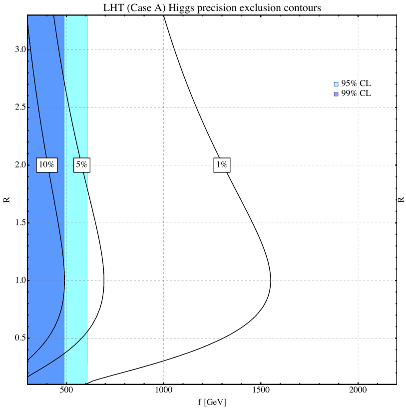
New Results (incl. Moriond 2013)

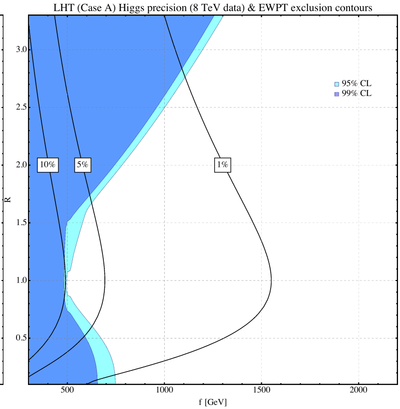
Littlest Higgs with T Parity



New Results (incl. Moriond 2013)

Littlest Higgs with T Parity





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
- To do list: recast also direct searches $\Longrightarrow$ JRR/Tonini/de Vries