Status of Little Higgs Models in 2015

Jürgen R. Reuter

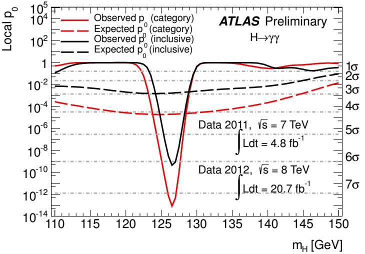
DESY

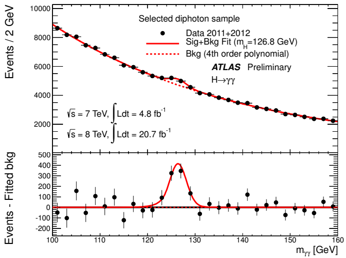
JRR/Tonini/de Vries, **JHEP 1402** (2014) 053; arXiv:1307.5010; JRR/Tonini, **JHEP 1302** (2013) 077; Kilian/JRR/Rainwater **PRD 74** (2006), 095003; **PRD 71** (2005), 015008; Kilian/JRR **PRD 70** (2004), 015004

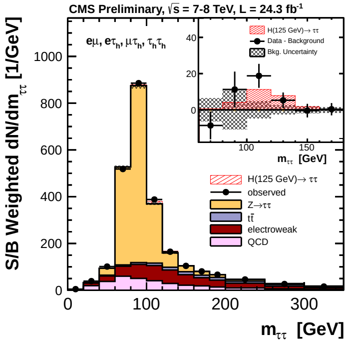
Seminar, LAPTh, Annecy-le-Vieux, 26.03.2015

Standard Model Triumph:

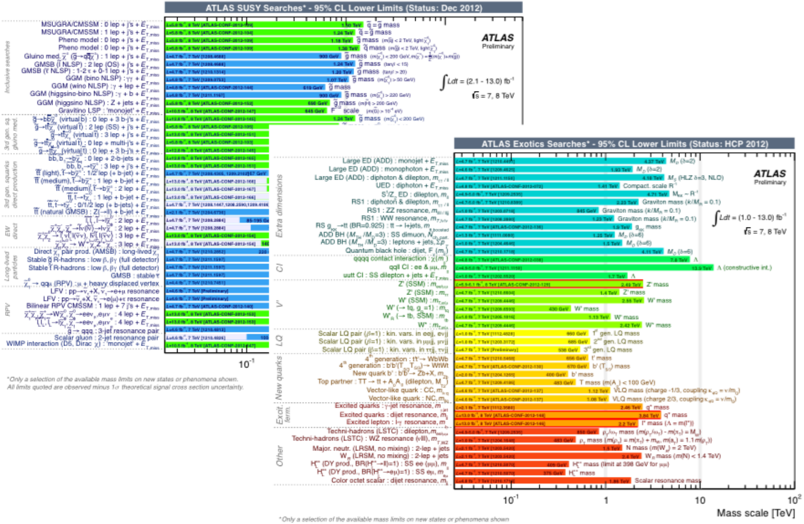
- 2012: Discovery of a Higgs boson







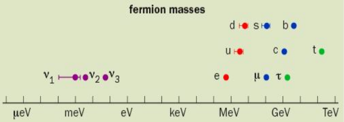
No evidence beyond SM ... and what now?



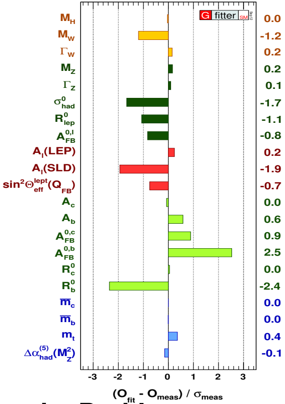
Doubts on the Standardmodel

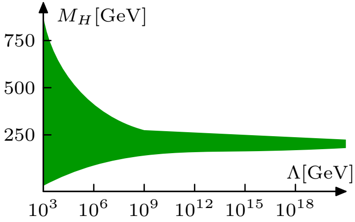
– describes microcosm (too good?)

– 28 free parameters



– Higgs ?, form of Higgs potential ?





Hierarchy Problem

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry for quantum corrections to Higgs mass

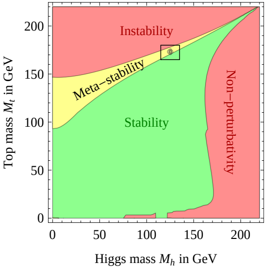
$$\boxed{\delta M_H^2 \propto \Lambda^2 \sim M^2_{\text{Planck}} = (10^{19})^2\ \text{GeV}^2}$$

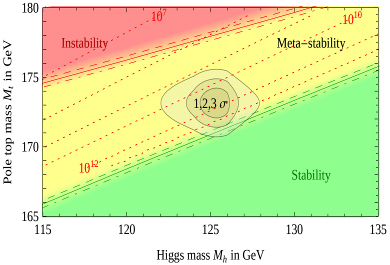
$(125\ \text{GeV})^2$ = (100000000000000000000000000000000020000 –

1000000000000000000000000000000000000) GeV^2

Electroweak vacuum stability

- Recent analysis: Metastable vacuum with lifetime longer than the age of the universe Degrassi et al., arXiv:1205.6497





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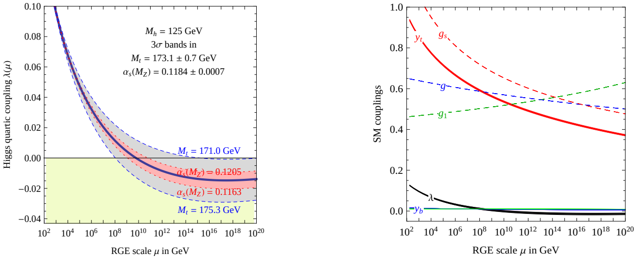

- Could the Higgs field ever have fallen in the correct vacuum? Hertzberg, arXiv:1210.3624

- Importance of higher terms in Higgs potential (gravity etc.) ?

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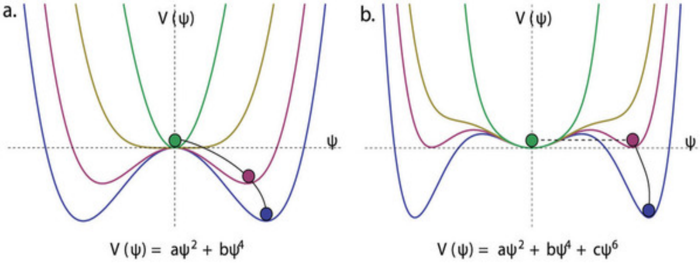

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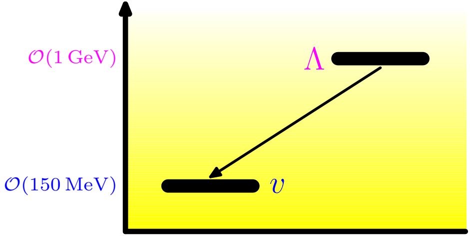
Higgs as Pseudo-Goldstone boson

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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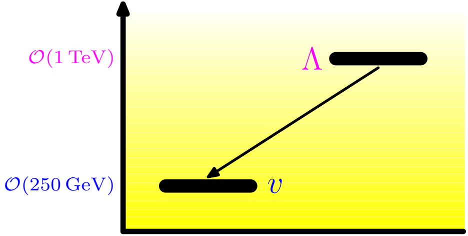


Scale Λ: global symmetry breaking, new particles, new (gauge) IA

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

Without Fine-Tuning: experimentally excluded

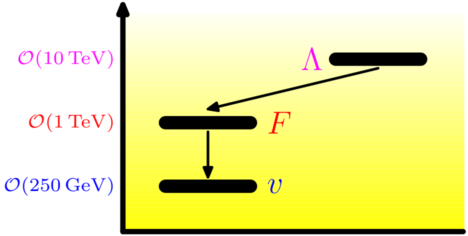
Collective symmetry breaking and 3-scale models

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

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

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

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

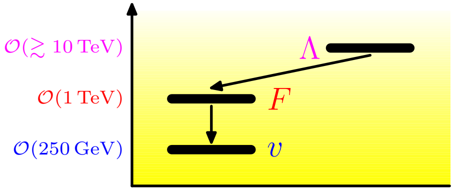


Scale Λ: global SB, new IA

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

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

Characteristics and Spectra

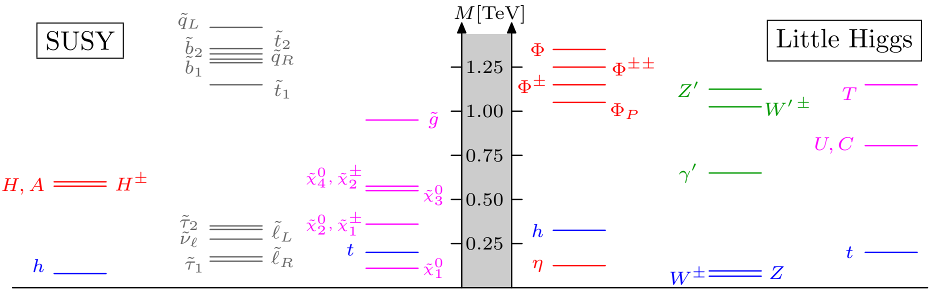


Scale Λ: "hidden sector", symmetry breaking

Scale F: new particles

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

Terascale: new particles to stabilize the hierarchy

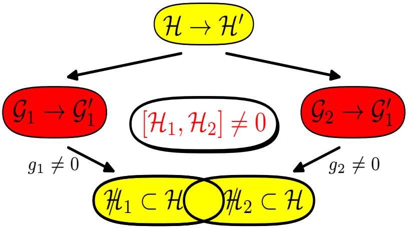


Generic properties of Little-Higgs models

- 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 $U, C, \ldots$

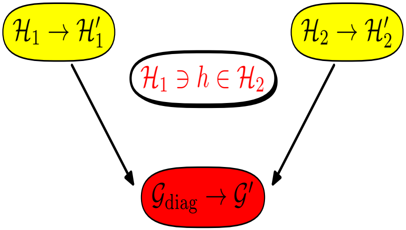
Product Group Models

(e.g. Littlest Higgs)



Simple Group Models

(e.g. Simplest Little Higgs)



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

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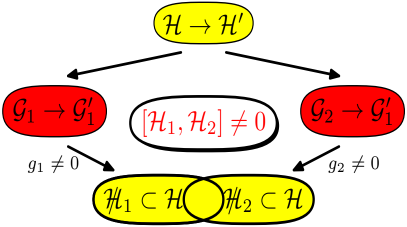
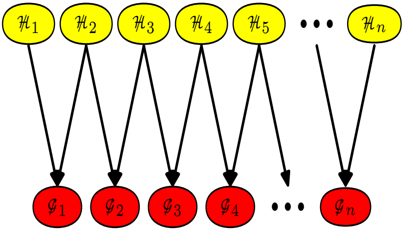


Quiver [Moose] Models

(e.g. Minimal Moose Model)



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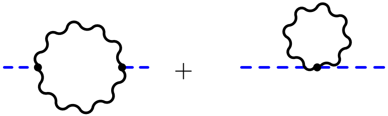
Prime Example: Simple Group Model

- enlarged gauge group: $SU(3) \times U(1)$; globally $U(3) \to U(2)$
- **Two** nonlinear Φ representations $\boxed{\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2}$

$$\Phi_{1/2} = \exp\left[\pm i \frac{f_{2/1}}{f_{1/2}} \Theta\right] \begin{pmatrix} 0 \\ 0 \\ f_{1/2} \end{pmatrix} \qquad \Theta = \frac{1}{\sqrt{f_1^2 + f_2^2}} \begin{pmatrix} \eta & 0 & \\ 0 & \eta & h^* \\ \multicolumn{2}{c}{h^T} & \eta \end{pmatrix}$$

Coleman-Weinberg mechanism: Radiative generation of potential



$$= \frac{g^2}{16\pi^2} \Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2\right) \sim \frac{g^2}{16\pi^2} f^2$$

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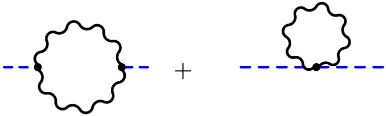
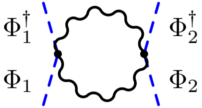


$$= \frac{g^2}{16\pi^2} \Lambda^2 \left(|\Phi_1|^2 + |\Phi_2|^2\right) \sim \frac{g^2}{16\pi^2} f^2$$

but: 

$$= \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2 \Rightarrow \frac{g^4}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) f^2 (h^\dagger h)$$

Indirect constraints: Higgs/EW precision

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.

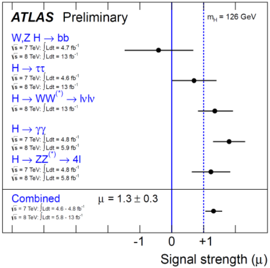
Data used: Higgs sector

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

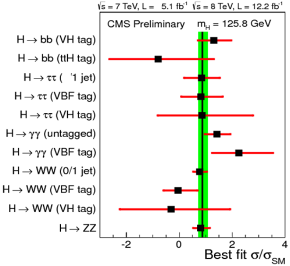
$$\mu_i = \frac{\sum_p {\epsilon^p}_i \, \sigma_p}{\sum_p {\epsilon^p}_i \, \sigma_p^{SM}} \cdot \frac{BR(h \to X_i X_i)}{BR(h \to X_i X_i)_{SM}}$$

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*

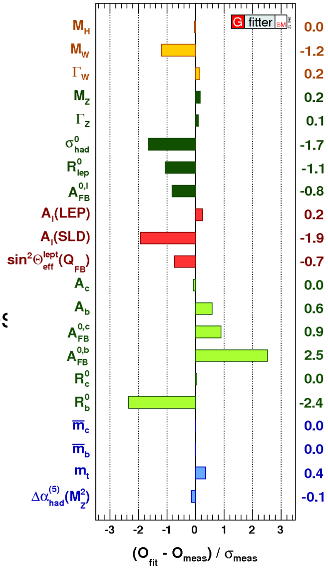
every extension of *SM* has to satisfy at least the precision constraints of the electroweak sector:

- 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

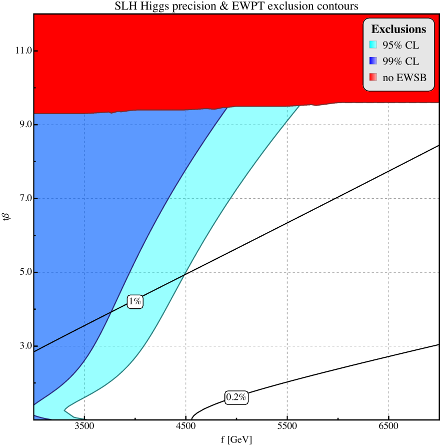
$$\text{e.g.} \quad \frac{m_T}{v} y_T \, h \, \bar{T} \, T \qquad m_T \sim f, \; y_T \sim \mathcal{O}\left(v^2/f^2\right)$$

- 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

JRR/Tonini, JHEP 1302 (2013) 077; JRR/Tonini/de Vries, JHEP 1402 (2014) 053



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

- 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.

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

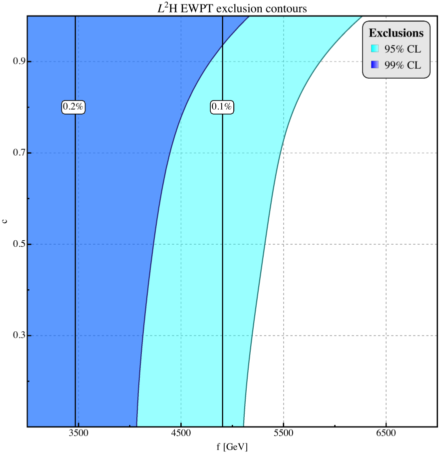
- min. required fine tuning: $\sim 1\%$, defined as

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

- results mainly driven by *EWPD*
- includes data from Moriond 2013

L^2H results

JRR/Tonini, JHEP 1302 (2013) 077; JRR/Tonini/de Vries, JHEP 1402 (2014) 053



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- free parameters: f *SSB* scale, c mixing angle in gauge sector
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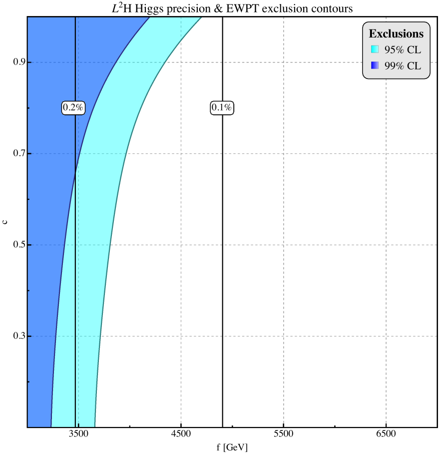

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LHT: Littlest Higgs with T parity

- 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:

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

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

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

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

T parity/Dark Matter Cheng/Low, 2003; Hubisz/Meade, 2005; Wang/Yang/Zhu, 2013

- 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, $F \sim 0.5 - 1$ 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

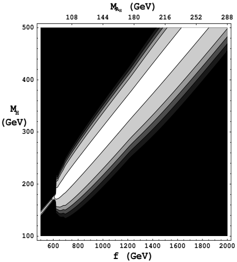
$W', Z' \sim$ 650 GeV, $\Phi \sim$ 1 TeV

$T, T' \sim$ 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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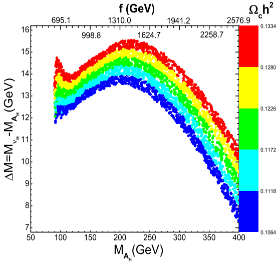
Wang/Yang/Zhu, 2013

Relic density/SI cross section



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  Wang/Yang/Zhu, 2013

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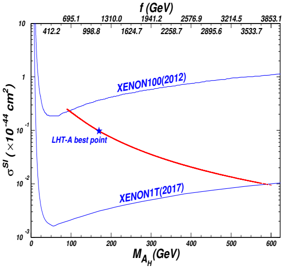
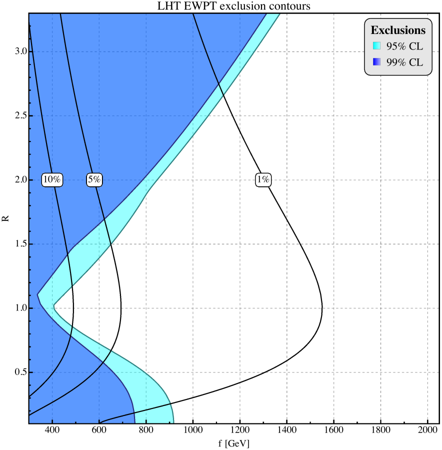


- T parity Simplest LH: Pseudo-Axion η LTP
  Z' remains odd: good or bad (?) Martin, 2006
- T parity might be anomalous (???) Hill/Hill, 2007

LHT results

JRR/Tonini, JHEP 1302 (2013) 077; JRR/Tonini/de Vries, JHEP 1402 (2014) 053



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

- 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.

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

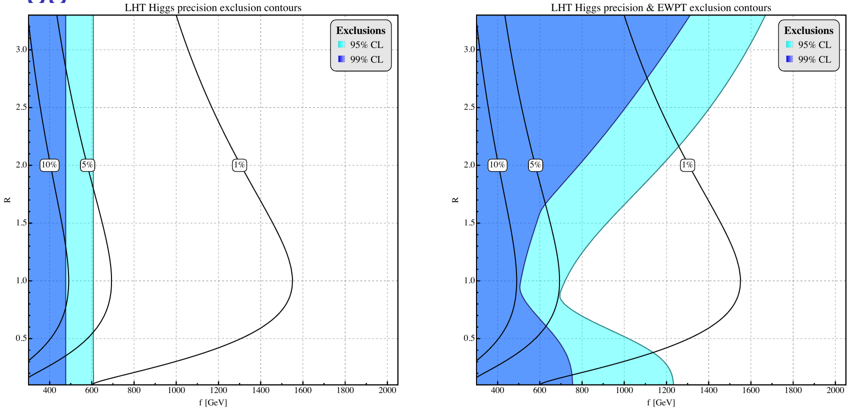
- min. required fine tuning: $\sim 10\%$, defined as

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

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

EWPT $\Rightarrow$ $\boxed{f \gtrsim 405 \text{ GeV}}$

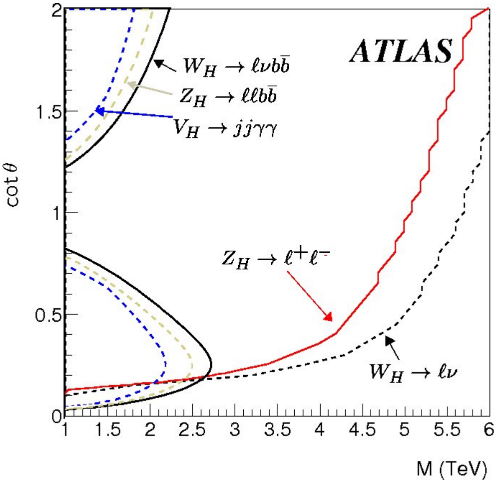
Higgs data vs. *EWPD*



- the shape of result driven by *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

EWPT and Higgs data $\Rightarrow$ $\boxed{f \gtrsim 694 \text{ GeV}}$

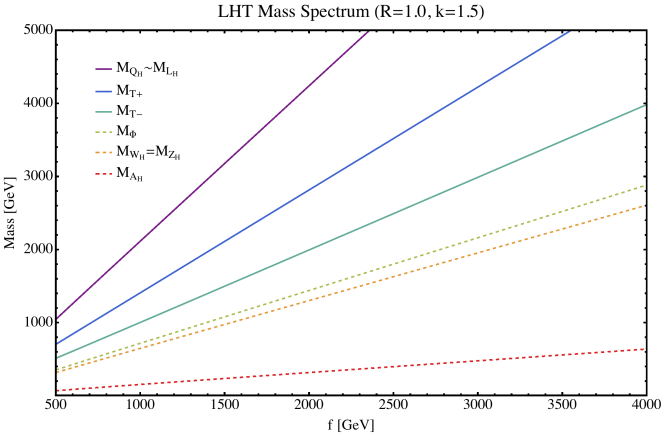
Direct searches: Drell-Yan mainly



Reach in the gauge boson sector: depends on mixing angle

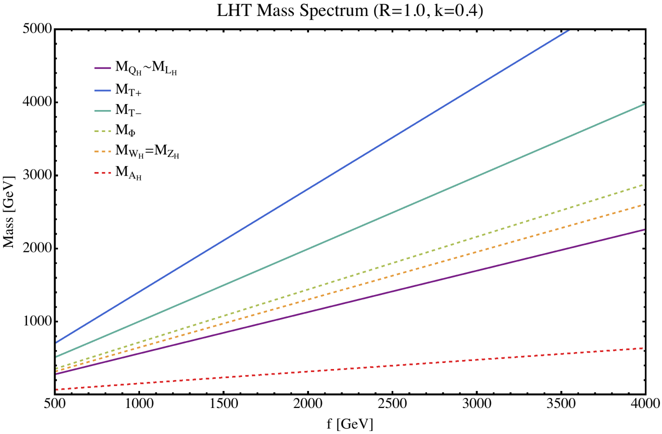
Direct Searches: Focus on LHT

- Defining two benchmark scenarios: 1. heavy quarks



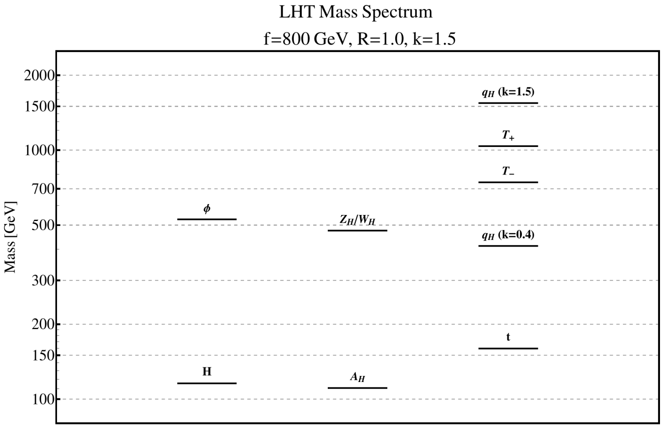
Direct Searches: Focus on LHT

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



Direct Searches: Focus on LHT

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



Branching Ratios

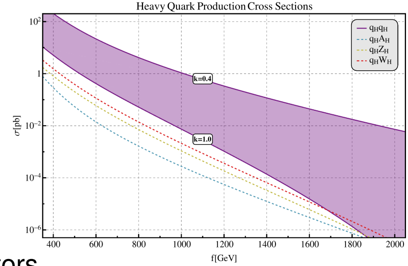
- Decay patterns:

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%

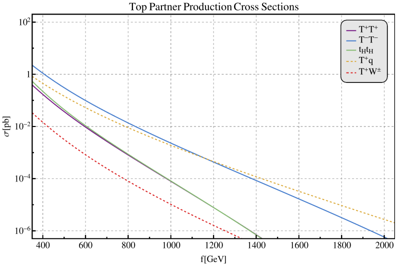
Particle	Decay	$\mathrm{BR}_{k=1.0}$	$\mathrm{BR}_{k=0.4}$
d_H	$W_H^-\ u$	62%	0%
	$Z_H\, d$	30%	0%
	$A_H\, d$	6%	100%
u_H	$W_H^+\ d$	58%	0%
	$Z_H\, u$	30%	0%
	$A_H\, u$	9%	100%
T_H^-	$A_H\ t$	100%	100%
	$Z_H\ t$	0%	0%
$\Phi^{0/P}$	$A_H\ H$	100%	100%
$\Phi^\pm$	$A_H\, W^\pm$	100%	100%
$\Phi^{\pm\pm}$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

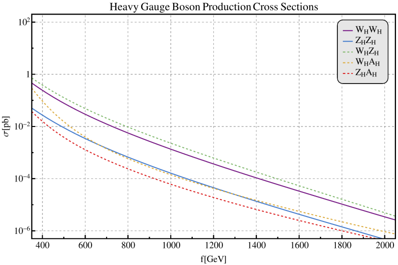
Cross Sections (I)

- Heavy Quarks



- Heavy Top and Vectors





Channels and signatures: Parameters

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

Channels and signatures (I)

final state			production	$\sigma_{8\,\mathrm{TeV}} \times \mathrm{Br}$ (fb)		$\sigma_{14\,\mathrm{TeV}} \times \mathrm{Br}$ (fb)	
$\# l^{\pm}$	# jets	$\not{E}_T$	modes	$k = 1.0$	$k = 0.4$	$k = 1.0$	$k = 0.4$
0	1	✓	$q_H A_H$	0.24	1.1×10^2	2.1	4.5×10^2
0	2	✓	$q_H q_H$	0.56	5.6×10^3	5.2	3.2×10^4
0	3	✓	$q_H W_H^{\pm}$ $q_H Z_H$	0.73 0.76	14 8.6	8.0 8.0	77 49
0	4	✓	$q_H q_H$ $W_H^{\pm} W_H^{\mp}$ $W_H^{\pm} Z_H$ $Z_H Z_H$	4.0 1.9 4.8 0.56	9.1×10^2 low low low	35 9.1 23 3.0	5.6×10^3 low low low
0	4	✗	$T^+ q$	2.0	2.0	17	17
0	5	✓	$q_H W_H^{\pm}$ $q_H Z_H$	5.1 4.1	✗ ✗	54 44	✗ ✗
0	6	✓	$q_H q_H$ $T^- T^-$	1.6 2.5	9.7×10^2 2.5	1.7×10^2 25	6.0×10^3 25

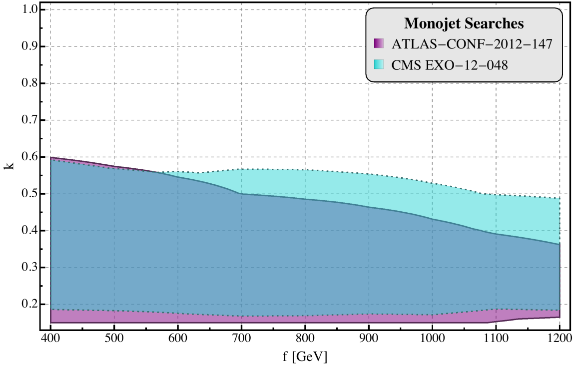
Channels and signatures (II)

final state			production	$\sigma_{8\text{ TeV}} \times \mathrm{Br}$ (fb)		$\sigma_{14\text{ TeV}} \times \mathrm{Br}$ (fb)	
$\# l^\pm$	# jets	$\not{E}_T$	modes	$k = 1.0$	$k = 0.4$	$k = 1.0$	$k = 0.4$
$l^\pm$	2	✓	$q_H q_H$ $W_H^\pm W_H^\mp$ $W_H^\pm Z_H$ $T^+ q$	0.058 0.77 2.1 1.3	9.0×10^2 low low 1.2	1.1 3.9 10 10	5.6×10^3 low low 10
$l^\pm$	3	✓	$q_H W_H^\pm$ $q_H Z_H$	3.5 0.99	✗ ✗	37 11	✗ ✗
$l^\pm$	4	✓	$q_H q_H$ $T^- T^-$	7.4 2.2	9.7×10^2 2.2	82 21	6.0×10^3 21
$l^+ l^-$	0	✓	$W_H^\pm W_H^\mp$	0.32	low	1.7	low
$l^+ l^-$	1	✓	$q_H W_H^\pm$	0.54	✗	5.8	✗
$l^+ l^-$	2	✓	$q_H q_H$ $T^- T^-$	1.1 0.47	✗ 0.47	11 4.6	✗ 4.6
$l^\pm l^\pm$	2	✓	$q_H q_H$	0.37	✗	2.7	✗

Recasting results

JRR/Tonini/deVries,2013

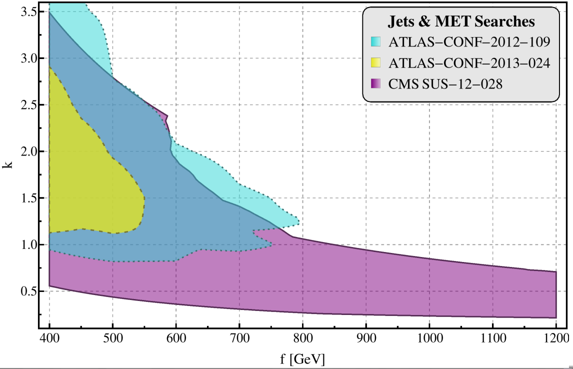
- 95% CL from Monojets + $\not{E}_T$ from LHC8
- 1 hard jet, $\not{E}_T$, no leptons, 2nd jet w. $p_T > 30$ GeV
  signal regions: ATLAS $(p_T, \not{E}_T) >$ 120/220/350/500 GeV, CMS: $\not{E}_T >$ 250/300/350/400/450/500/550 GeV
- Dijet suppression: ATLAS $\Delta\phi(\not{E}_T, j_2) > 0.5$, CMS $\Delta\phi(j_1, j_2) < 2.5$
- $pp \to q_H q_H$, $pp \to q_H A_H$



Recasting results

JRR/Tonini/deVries,2013

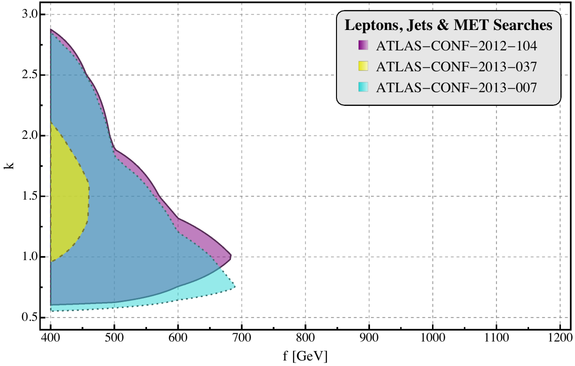
- 95% CL from Jets + $\not{E}_T$ from LHC8
- $\geqslant 2$ hard jets, $\not{E}_T$, no leptons
- signal regions: ATLAS $\not{E}_T > 200/300/350$ GeV, CMS: $(N_j, N_b) = (2-3, 0); (2-3, 1-2); (\geqslant 4, 1-2); (\geqslant 4, 0); (\geqslant 4, \geqslant 2)$
- QCD suppression: ATLAS $\Delta\phi(\not{E}_T, j_2) > 0.5$, $\not{E}_T/m_{eff}$, CMS $\Delta\phi(j_1, j_2) < 2.5$
- $pp \to q_H q_H \to (jA_H)(jA_H)$



Recasting results

JRR/Tonini/deVries,2013

- 95% CL from Leptons + Jets + $\not{E}_T$ from LHC8
- single isolated lepton, $\geqslant 2$ hard jets, $\not{E}_T$,
- signal regions: ATLAS $\not{E}_T >$ 200/300/350 GeV
- Cuts: $\not{E}_T > 250\,\mathrm{GeV}$, $m_T(l, \not{E}_T) > 250\,\mathrm{GeV}$, $\not{E}_T/m_{\text{eff}} > 0.2$, $m_{\text{eff}}^{\text{inc}} > 800\,\mathrm{GeV}$
- $pp \to q_H q_H$ with $q_H \to W_H q, Z_H q$, $t_H \to t A_H$, $Z_H \to H A_H$

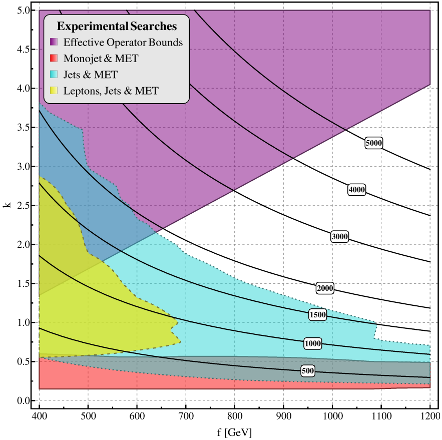


Combined analysis

JRR/Tonini/deVries,2013

- Operator bounds: $\mathcal{O}_{4\text{-f}} = -\frac{k^2}{128\,\pi^2 f^2}\bar{\psi}_L\gamma^\mu\psi_L\bar{\psi}'_L\gamma_\mu\psi'_L + O\left(\frac{g}{k}\right)$

  Hubisz/Meade/Noble/Perelstein, 2005



- Bound from combined analysis: $\boxed{f \gtrsim 638\text{GeV}}$

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

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  4. Direct searches: $\boxed{f \gtrsim 638 \text{ GeV@}95\% \text{ CL}}$
- We need more data!

One Ring to Find them ... One Ring to Rule them Out

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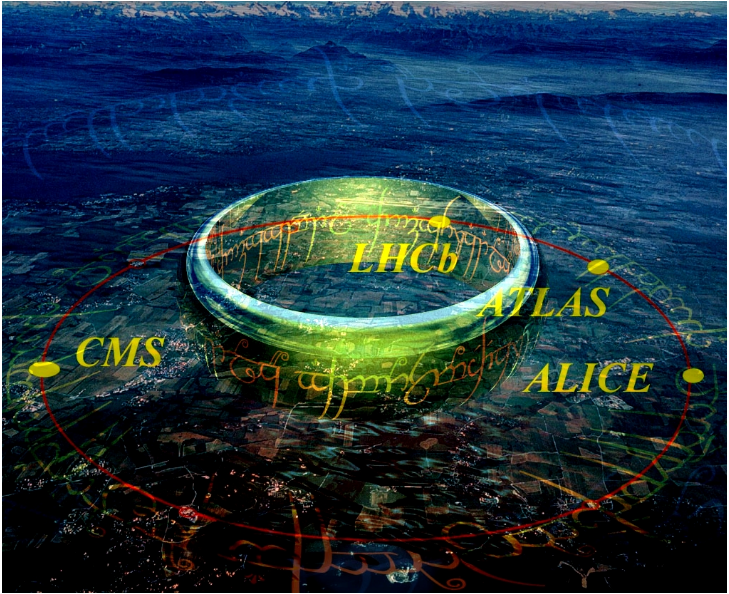
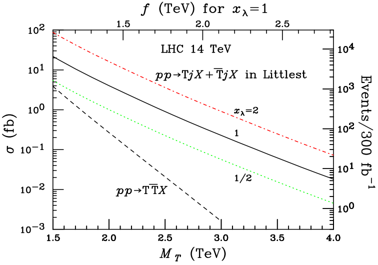


BACKUP SLIDES:

Direct Searches – Heavy Quark States

- EW single dominates QCD pair production: Perelstein/Peskin/Pierce, ’03



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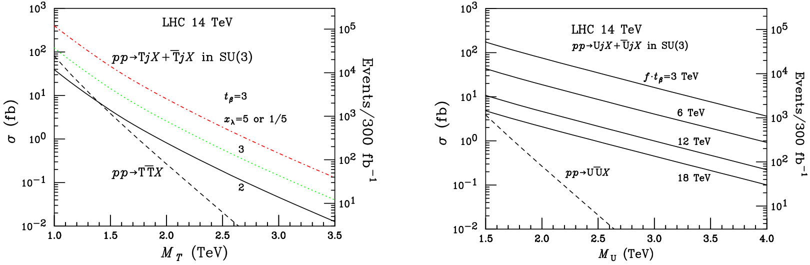


- Characteristic branching ratios :

$$\Gamma(T \to th) \approx \Gamma(T \to tZ) \approx \frac{1}{2}\Gamma(T \to bW^+) \approx \frac{M_T \lambda_T^2}{64\pi}, \qquad \Gamma_T \sim 10\text{–}50\,\text{GeV}$$

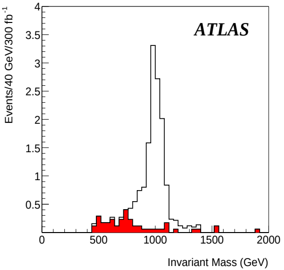
- Proof of T as EW singlet; but: $T \to Z'T, W'b, t\eta$!

AIM: *Determination of* $M_T, \lambda_T, \lambda_{T'}$

$\lambda_{T'}$ indirect ($T\bar{T}h$ impossible)

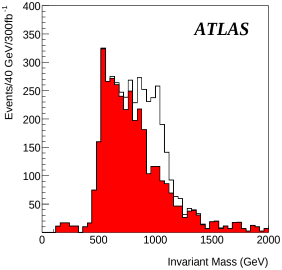
$T \to Zt \to \ell^+\ell^-\ell\nu b$ SN-ATLAS-2004-038

- $\not{E}_T > 100$ GeV, $\ell\ell\ell, p_T > 100/30$ GeV, $b, p_T > 30$ GeV
- Bkgd.: WZ, ZZ, btZ
- Observation for $M_T \lesssim 1.4$ TeV



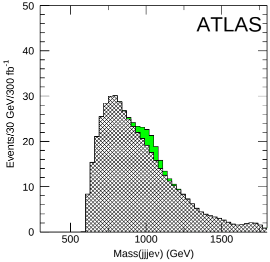
$T \to Wb \to \ell\nu b$ SN-ATLAS-2004-038

- $\not\!\!E_T > 100$ GeV, $\ell, p_T > 100$ GeV, $b, p_T > 200$ GeV, max. $jj, p_T > 30$ GeV
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single t
- Observation for $M_T \lesssim 2.5$ TeV



$T \to th \to \ell\nu bbb$ SN-ATLAS-2004-038

- $\ell, p_T > 100$ GeV, $jjj, p_T > 130$ GeV, at least 1 b-tag
- Bkgd.: $t\bar{t}, Wb\bar{b}$, single t
- Observation for $M_T \lesssim 2.5$ TeV



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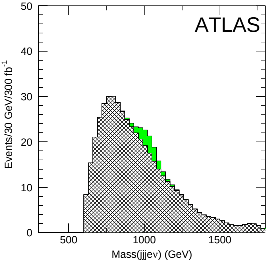

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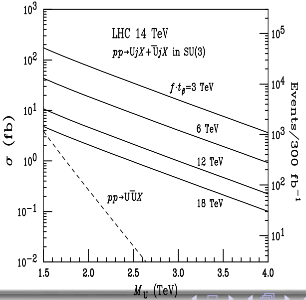
Additional heavy quarks (Simple Group Models): U, C or D, S Han et al., 05

- Large cross section: u or d PDF
- Huge final state ℓ charge asymmetry
- Good mass reconstruction



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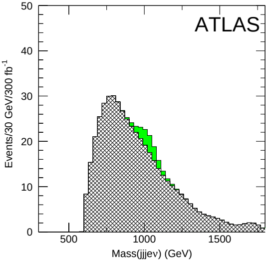

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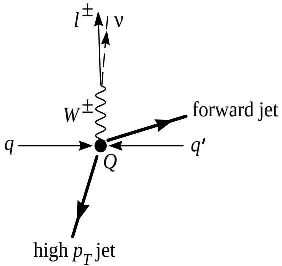

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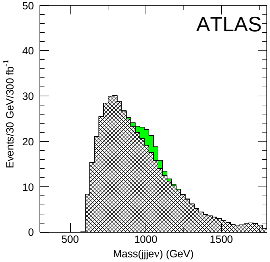

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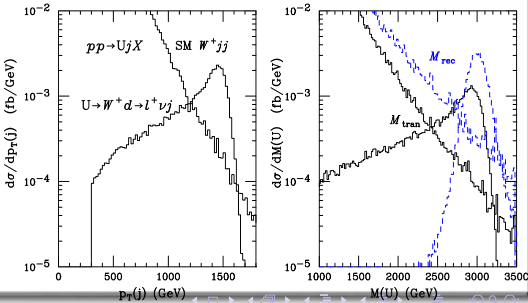
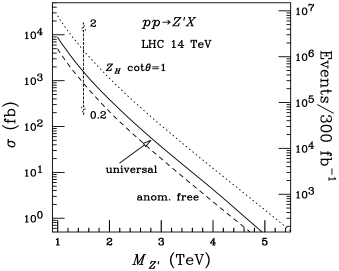


Direct Searches – Heavy Vectors

Drell-Yan Production: Tevatron Limits $\sim 500 - 600$ GeV

- Dominant decays:
  Product group: $Z' \to Zh, WW$,
  $W' \to Wh, WZ$
  Simple group: $Z' \to qq, \quad X \to fF$



Direct Searches – Heavy Vectors

Drell-Yan Production: Tevatron Limits $\sim 500 - 600$ GeV

- Dominant decays:
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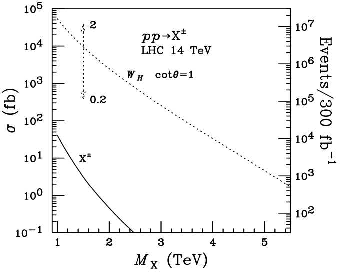

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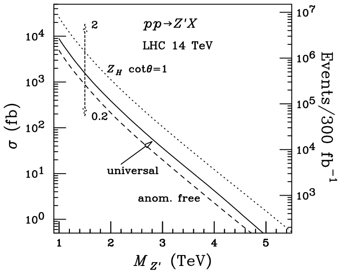

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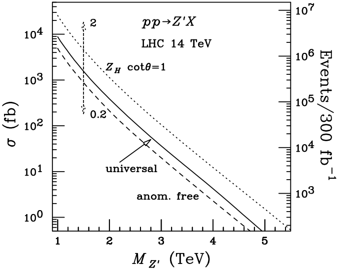
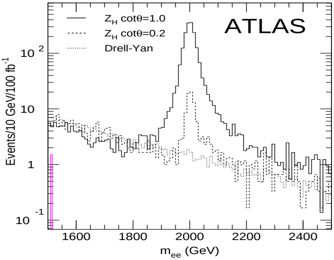
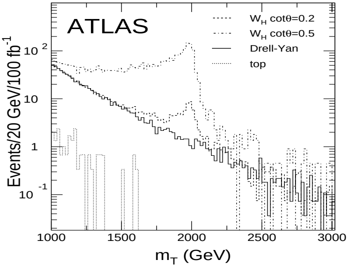




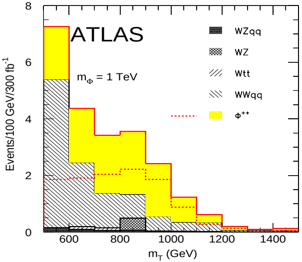


Direct Searches – Heavy Scalars

Generally: **Large model dependence**

no states complex singlet complex triplet

- Littlest Higgs, complex triplet: $\Phi^0, \Phi_P, \Phi^{\pm}, \Phi^{\pm\pm}$
- Cleanest channel: $q\bar{q} \to \Phi^{++}\Phi^{--} \to \ell\ell\ell\ell$: Killer: PS
- WW-Fusion: $dd \to uu\Phi^{++} \to uuW^+W^+$
- 2 hard forward jets, hard close $\ell^+\ell^+$ p_T-unbalanced



Alternative: Model-Independent search in WW fusion:

ILC: Beyer/Kilian/Krstonosic/Mönig/JRR/Schmidt/Schröder, 2006

LHC: Alboteanu/Kilian/JRR, 2008; Kilian/JRR/Sekulla, 2013

Pseudo-Axions in Little Higgs

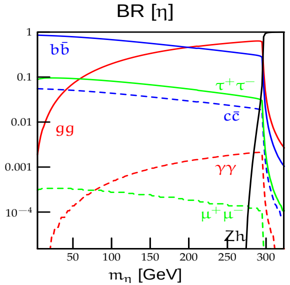
Kilian/Rainwater/JRR, 2004, 2006; JRR, 2007

– gauged $U(1)$ group: Z' $\longleftrightarrow$ ungauged: η

– couples to fermions like a pseudoscalar

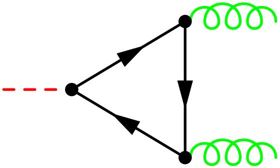
– $m_\eta \lesssim 400$ GeV

– SM singlet, couplings to SM particles v/F suppressed



– η axion-like particle:

Anomalous $U(1)$:



$$\longrightarrow \quad \frac{1}{F}\frac{\alpha_s}{8\pi^2}\eta F_{\mu\nu}F_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$

– $U(1)$ explicitly broken $\Rightarrow$ Axion limits from astroparticle physics not applicable

Classification of Axions in Little Higgs Models

Number of Pseudo-Axions: $n = g - l$
Mismatch between global (g) and local rank reduction (l)

Product Group Models

Arkani-Hamed,...

- Doubling of electroweak gauge group: $SU(2) \times SU(2) \to SU(2)_L$, $U(1) \times U(1) \to U(1)_Y$ (latter not necessary) $\Rightarrow l = 1$
  - Littlest Higgs, g: $SU(5) \to SO(5) \Rightarrow n = (4-2) - 1 = 1$
  - antisymmetric, g: $Sp(6)/SO(6)$, $n = (3-2) - 1 = 0$

Simple Group Models

Kaplan,Schmaltz, ...

- Simple gauge group: $SU(N) \times U(1) \to SU(2) \times U(1) \Rightarrow \; l = N - 2$
- Higgs is distributed over several global symmetry multiplets
- Simplest Little Higgs, g: $[SU(3)]^2/[SU(2)]^2$ $\quad n = g - l = 2 - 1 = 1$
- Original Simple Group Model, g: $[SU(4)]^3/[SU(3)^3 \times SU(2)]$, l: $SU(4) \to SU(2)$ $\quad n = g - l = 4 - 2 = 2$

Moose Models

Arkani-Hamed, ...

- "Minimal" Moose: g $[SU(3)]^4 \to SU(3)$, l $[SU(3) \times SU(2)]/SU(2)$ $n = g - l = 6 - 2 = 4$
- 3-site model: g $[SU(2)]^4/[SU(2)]^2$, l $[SU(2)]^2 \to SU(2)$, $n = 2 - 1 = 1$

$ZH\eta$ coupling as a discriminator

Kilian/Rainwater/JRR, 2006

- pseudo-axion: $\xi = \exp\left[i\eta/F\right]$, $\Sigma = \exp\left[i\Pi/F\right]$ non-linear representation of the remaining Goldstone multiplet Π

$$\mathcal{L}_{\text{kin.}} \sim F^2 \operatorname{Tr}\left[(D^\mu(\xi\Sigma)^\dagger(D_\mu(\xi\Sigma))\right] = \ldots - 2F(\partial_\mu\eta)\,\text{Im}\operatorname{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] + O(\eta^2)$$

- Use special structure of covariant derivatives:

$$D_\mu\Sigma = \partial_\mu\Sigma + A^a_{1,\mu}\left(T^a_1\Sigma + \Sigma(T^a_1)^T\right) + A^a_{2,\mu}\left(T^a_2\Sigma + \Sigma(T^a_2)^T\right),$$

$$\operatorname{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] \sim W^a_\mu \operatorname{Tr}\left[\Sigma^\dagger(T^a_1 + T^a_2)\Sigma + (T^a_1 + T^a_2)^*\right] = 0.$$

- Little Higgs mechanism cancels this coupling
- Simple Group Models: $\Phi = \exp[i\Sigma/F]$, $\zeta = (0, \ldots 0, F)^T$ VEV directing in the N direction

$$\mathcal{L}_{\text{kin.}} \sim F^2 D^\mu(\zeta^\dagger\Phi^\dagger) D_\mu(\Phi\zeta) = \ldots + \frac{i}{F}(\partial_\mu\eta)\zeta^\dagger \left(\Phi^\dagger(D_\mu\Phi) - (D_\mu\Phi^\dagger)\Phi\right)\zeta$$
$$= \ldots + iF(\partial_\mu\eta)\left(\Phi^\dagger(D_\mu\Phi) - (D_\mu\Phi^\dagger)\Phi\right)_{N,N} .$$

$$\Sigma = \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix}, \qquad \mathbb{V}_\mu = \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \text{heavy vector fields}$$

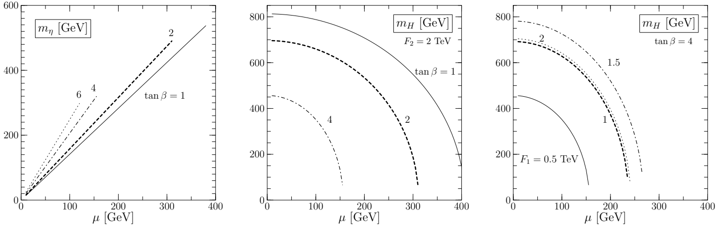
$$\mathbb{V}_\mu + \frac{i}{F}[\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2}[\Sigma,[\Sigma,\mathbb{V}_\mu]] + \ldots$$
$$= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F}\begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger\mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2}\begin{pmatrix} hh^\dagger\mathbb{W} + \mathbb{W}hh^\dagger & 0 \\ 0 & -2h^\dagger\mathbb{W}h \end{pmatrix} + \ldots$$

- 1st term cancels by multiple Goldstone multiplets
- 2st term cancels by EW symmetry
- 3rd term

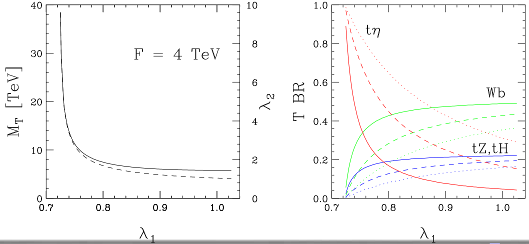
$$(\partial^\mu\eta)h^\dagger\mathbb{W}_\mu h \sim vHZ_\mu\partial^\mu\eta .$$

More properties of Pseudo-Axions

- Take e.g. one specific model: Simplest Little Higgs   Schmaltz, 2004
- Simple Group Model, two Higgs-triplets with a $\tan\beta$-like mixing angle



- $\tan\beta \sim 1$: heavy Higgs, (very) light pseudoscalar
- Heavy top decays: Kilian/Rainwater/JRR, 2006



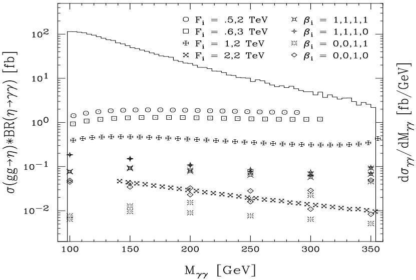
Discovery of Pseudo-axions

Kilian/Rainwater/JRR, 2004, 2006

LHC: Gluon fusion, diphoton signal for $m_\eta \gtrsim 200$ GeV, 7σ possible

LHC: $T \to t\eta$

ILC: $e^+e^- \to t\bar{t}\eta$



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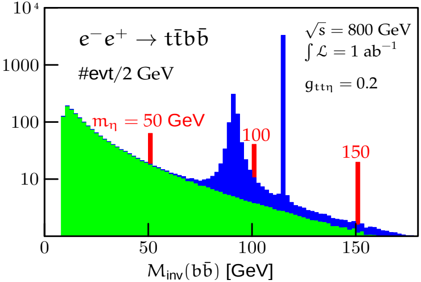

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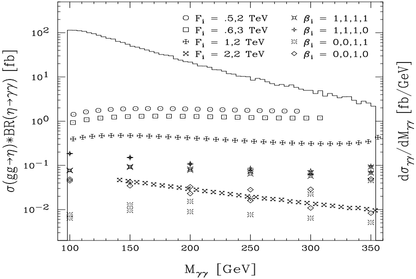

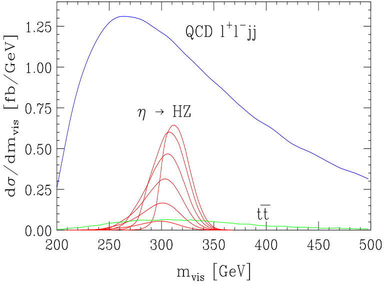

$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \to \left\{ \begin{array}{lll} H \to Z\eta & \to \ell\ell bb \\ \eta \to ZH & \to \ell\ell bb, \ell\ell\ell jj \end{array} \right\}$$

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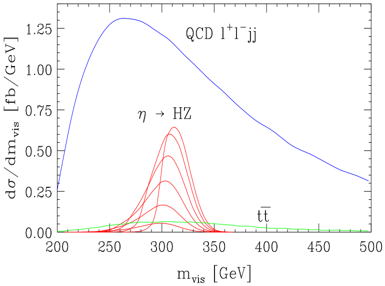

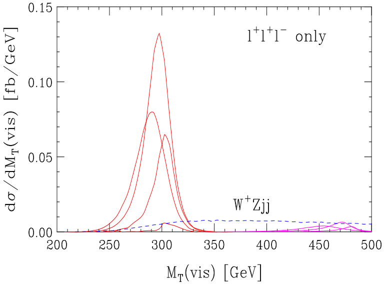

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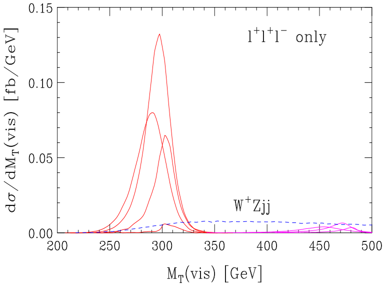

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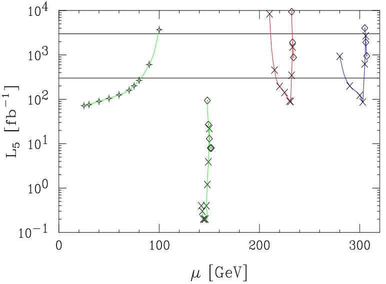

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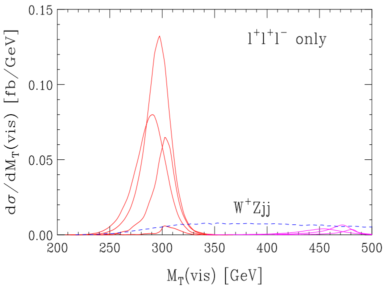

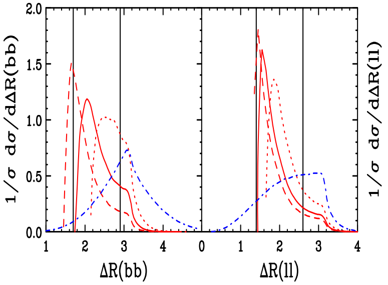

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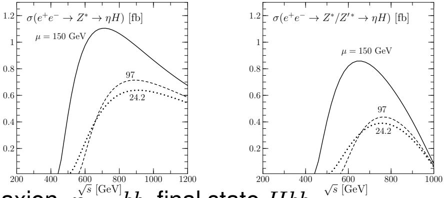
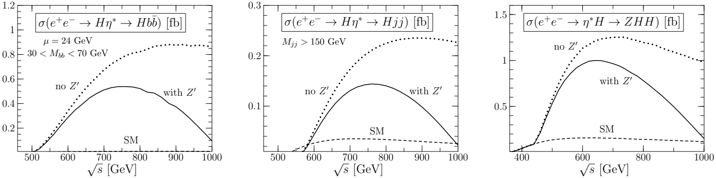
η pheno at ILC

Kilian/Rainwater/JRR, 2006

If $ZH\eta$ coupling present: $H\eta$ production in analogy to HA:



- Light pseudoaxion, $\eta \to bb$, final state Hbb
- Intermediate range, $\eta \to gg$, final state Hjj
- $\eta \to ZH$: ZHH final state



More detailed insights from photon collider option

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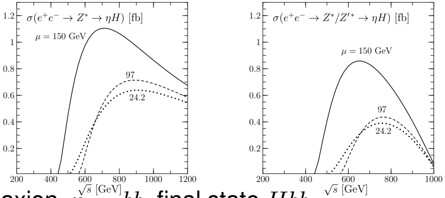

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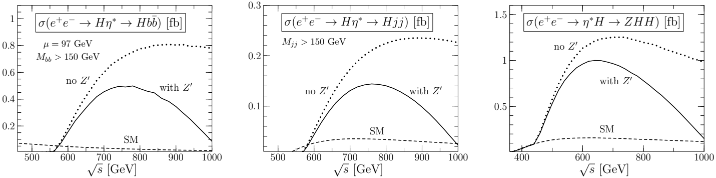
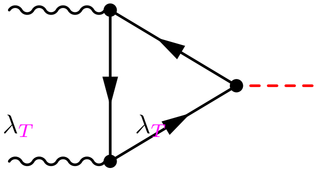


More detailed insights from photon collider option

Pseudo Axions at the Photon Collider

- Photon Collider as precision machine for Higgs physics (s channel resonance, anomaly coupling)



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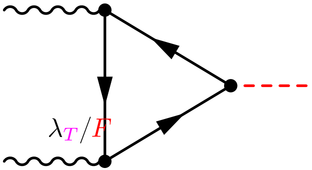

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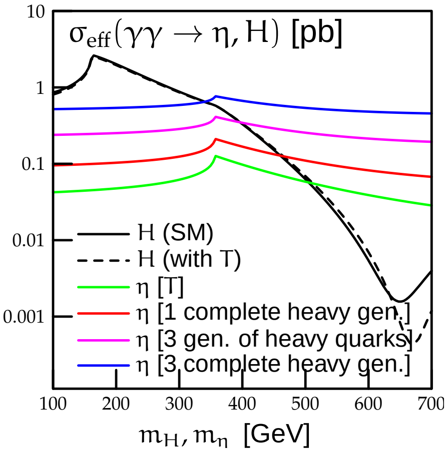
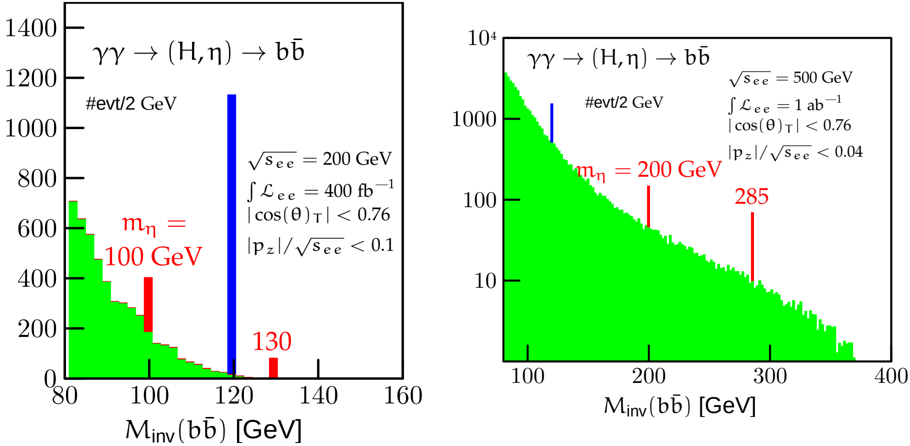


$$g_{bb\eta} = 0.4 \cdot g_{bbh}$$

m_η	100	130	200	285
$\Gamma_{\gamma\gamma}$[keV]	0.15	0.27	1.1	3.6



Simplest Little Higgs (“μ Model”)

Schmaltz ’04, Kilian/Rainwater/JRR ’04

Field content ($SU(3)_c \times SU(3)_w \times U(1)_X$ quantum numbers)

$$\begin{array}{lclclc} \Phi_{1,2} & : & (1,3)_{-\frac{1}{3}} & \Psi_\ell & : & (1,3)_{-\frac{1}{3}} & {u_{1,2}}^c & : & (\bar{3},1)_{-\frac{2}{3}} \\ \Psi_Q & : & (3,3)_{\frac{1}{3}} & d^c & : & (\bar{3},1)_{\frac{1}{3}} & e^c, n^c & : & (1,1)_{1,0} \end{array}$$

Lagrangian $\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{\text{Yuk.}} + \mathcal{L}_{\text{pot.}}$ $\qquad \Psi_{Q,L} = (u,d,U)_L, \Psi_\ell = (\nu,\ell,N)_L$:

$$\mathcal{L}_{\text{Yuk.}} = -\lambda_1^u \overline{u}_{1,R} \Phi_1^\dagger \Psi_{T,L} - \lambda_2^u \overline{u}_{2,R} \Phi_2^\dagger \Psi_{T,L} - \frac{\lambda^d}{\Lambda} \epsilon^{ijk} \overline{d}_R^b \Phi_1^i \Phi_2^j \Psi_{T,L}^k$$
$$- \lambda^n \overline{n}_{1,R} \Phi_1^\dagger \Psi_{Q,L} - \frac{\lambda^e}{\Lambda} \epsilon^{ijk} \overline{e}_R \Phi_1^i \Phi_2^j \Psi_{Q,L}^k + \text{h.c.},$$

$$\mathcal{L}_{\text{pot.}} = \mu^2 {\Phi_1}^\dagger \Phi_2 + \text{h.c.}$$

Hypercharge embedding $\qquad (\mathrm{diag}(1,1,-2)/(2\sqrt{3}))$:

$$Y = X - T^8/\sqrt{3} \qquad\qquad D_\mu \Phi = (\partial_\mu - \frac{1}{3} g_X B_\mu^X \Phi + i g W_\mu^w) \Phi$$

Partial decay widths in LH

- 1-loop decays

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

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

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: $\frac{\sigma_{LH}}{\sigma_{SM}}(gg \to h) = \frac{\Gamma(h \to gg)_{LH}}{\Gamma(h \to gg)_{SM}}$

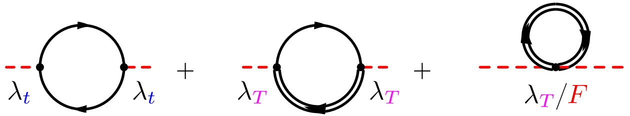
- tree-level decays

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

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

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

Cancellations of Divergencies in Yukawa sector

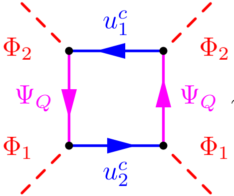


$$\propto \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2(k^2-m_T^2)} \left\{ \lambda_t^2(k^2-m_T^2) + k^2\lambda_T^2 - \frac{m_T}{F}\lambda_T k^2 \right\}$$

Little Higgs global symmetry imposes relation

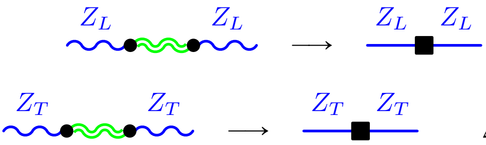
$$\boxed{\frac{m_T}{F} = \frac{\lambda_t^2+\lambda_T^2}{\lambda_T}} \quad \Longrightarrow \quad \text{Quadratic divergence cancels}$$

Collective Symm. breaking: $\lambda_t \propto \lambda_1 \lambda_2$, $\lambda_1 = 0$ *or* $\lambda_2 = 0 \Rightarrow SU(3) \to [SU(3)]^2$



$$\sim \frac{\lambda_1^2\lambda_2^2}{16\pi^2} \log\left(\frac{\Lambda^2}{\mu^2}\right) |\Phi_1^\dagger \Phi_2|^2$$

Constraints from Oblique Corrections: S, T, U



$$\Delta T \sim \Delta\rho \sim \Delta M_Z^2 Z \cdot Z$$

$$\Delta S \sim {W^0}_{\mu\nu} B^{\mu\nu}, \Delta U \sim {W^0}_{\mu\nu} W^{0\,\mu\nu}$$

◇ All low-energy effects order v^2/F^2 (Wilson coefficients)

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

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

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

◇ **Constraints evaded** $\Longleftrightarrow$ $c, c' \ll 1$

$B', Z', W'^{\pm}$ superheavy ($\mathcal{O}(\Lambda)$) *decouple from fermions*