Little Higgs at the LHC: Status and Prospects

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based on:

Reuter/MT, JHEP **1302**, 077 (2013)

Reuter/MT/de Vries, hep-ph/1307.5010

Reuter/MT/de Vries, DESY-13-123 (in prep.)

SUSY 2013

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Motivation

How to constrain a generic model in *HEP*?

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

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

Two paradigms for *EWSB*

hierarchy problem as guideline to answer the following question:

what is the dynamical origin of *EWSB*?

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

Strongly coupled answer

Original idea: pions of low-energy QCD

E

QCD

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

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

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

low-energy QCD

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

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

Composite/Little Higgs Ansatz

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

Strongly coupled answer

Original idea: pions of low-energy QCD

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QCD

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- perturbative th. for E>Λ

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

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Summary

The Little Higgs paradigm:

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

Outline of the work

purpose: constraining the parameter space of the three most popular Little Higgs models

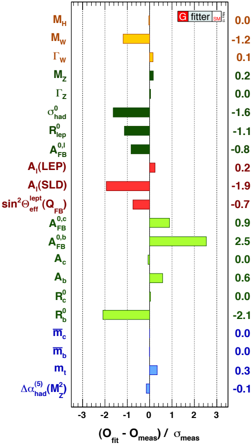
- Simplest Little Higgs (*SLH*) [Schmaltz, 2004]
- Littlest Higgs (L^2H) [Arkani-Hamed et al., 2002]
- Littlest Higgs with T parity (*LHT*) [Low et al., 2003]

scrutinizing the available public data from the 7-8 TeV LHC runs

- Electroweak Precision Tests (EWPT)
- Higgs Searches
- Direct Searches for BSM states

EWPT & Higgs: Data used

Precision constraints of the EW sector:



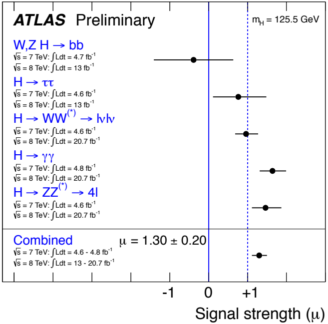
[GFitter Collaboration]

Higgs results expressed in terms of

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

$\Rightarrow$ best fit for each decay of the Higgs

[ATLAS-CONF-2013-034]



up to 25 fb^{-1} at $7 + 8$ TeV!

Little evidence

Where do Little Higgs corrections to *SM* quantities come from?

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

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

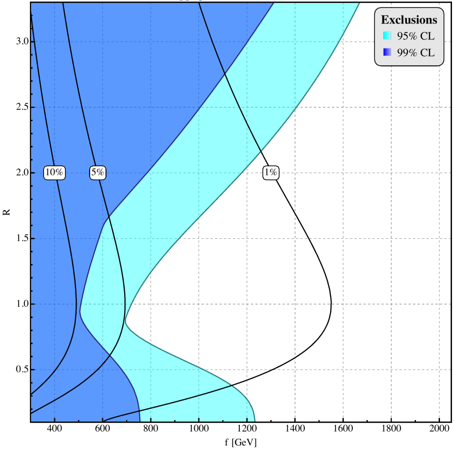
- new Higgs interactions with heavy resonances

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

- modified neutral- and charged-currents

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

EWPT & Higgs: Results



- parameters: f *SSB* scale, R ratio of Yukawa couplings in top sector
- $f \gtrsim$ 694 GeV at 95% CL
  $\Rightarrow$ lower bounds on heavy partners, e.g.

$$m_{W'} \gtrsim 453 \text{ GeV}$$
$$m_T \gtrsim 984 \text{ GeV}$$

- minimum required fine tuning: $\sim 5\%$
- results mainly driven by *EWPT* (ev. see backup)

Direct Searches: Data used

ATLAS and CMS published results of many SUSY & Exotica searches for BSM states, using up to 20 fb^{-1} data of 8 TeV LHC runs

final state topology	ATLAS	CMS
monojet + $\not{E}_T$	CONF-2012-147 ✓	PAS EXO-12-048 ✓
jets + $\not{E}_T$	CONF-2013-047 ✓ CONF-2013-024 ✓	PAS SUS-12-028 ✓
lepton(s) + jets + $\not{E}_T$	CONF-2012-104 ✓ CONF-2013-037 ✓ CONF-2013-007 ✓	

mostly interesting for BSM theorists: 95% CL upper bounds on the visible cross section of a generic BSM signal over the SM background

$$\sigma_{\text{vis}} = \underbrace{\sigma_{\text{prod}}^{\text{BSM}} \cdot \text{BR}}_{\text{th. pred.}} \cdot \underbrace{\epsilon \cdot A}_{\text{cuts efficiency}}$$

Direct Searches: Recasting Analysis

our work:

$\Rightarrow$ recasting of available analyses assuming a Little Higgs signal[1]

- generate samples of LH signal events matching the final state topologies, and evaluate relative cross-sections
- evaluate $\epsilon \cdot A$ of the event samples applying the selection cuts of the different analyses
- if $\sigma_{\mathsf{vis}}^{\mathsf{LH}} > \sigma_{\mathsf{vis}}^{95\%}$: parameter space point is excluded at 95% CL

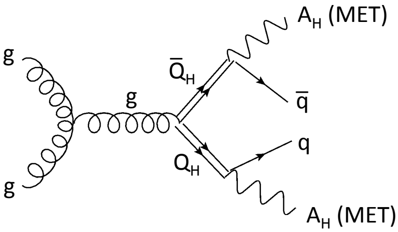
[1] only for the Littlest Higgs model with T parity

An example

example: monojet + $\not{E}_T$ final state topology

possible LHT signal:

$$p\,p \to Q_H\,\bar{Q}_H \to (q A_H)\;(\bar{q} A_H)$$



ATLAS-CONF-2012-147 selection cuts:

- $n_{\mathrm{j}} \leqslant 2$ w/ $p_T > 30$ GeV
- $p_T(j_1) > 120$ GeV, $\eta(j_1) < 2.0$
- $n_{\mathrm{L}} = 0$ w/ $p_T(e) > 20$ GeV, $p_T(\mu) > 7$ GeV
- $\not{E}_T > 120$ GeV
- $\Delta\phi(\not{E}_T, j_2) > 0.5$

$\sigma_{\mathrm{vis}}^{\mathrm{LHT}}\,(f = 400\,\mathrm{GeV}, \kappa = 0.5) = 21.5\,\mathrm{pb}$

$\sigma_{\mathrm{vis}}^{95\%} = 2.8\,\mathrm{pb}$

$\Rightarrow$ exclusion at 95% CL!!

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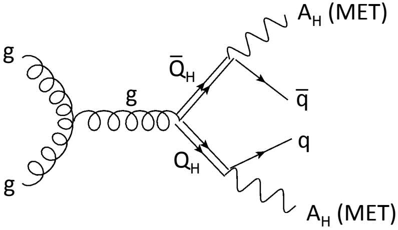

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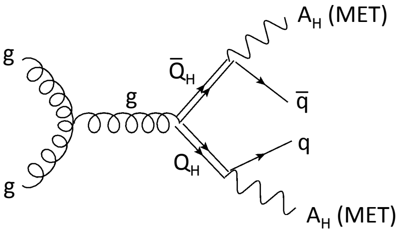

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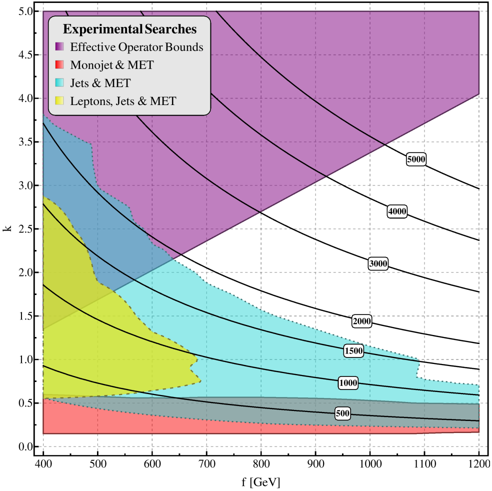
$\Rightarrow$ exclusion at 95% CL!! ⚰

Direct Searches: Results

- parameters: f *SSB* scale, κ mirror fermions' coupling (assumed to be flavour blind)
- $f \gtrsim 638$ GeV at 95% CL (Higgs & EWPT: $f \gtrsim 694$ GeV)
- mirror fermions mass $\gtrsim 1$ TeV
- hadronic final states searches still the most sensitive ones
- four-fermion operator bounds necessary to constrain f
- possible optimization with the assumption of LHT signal instead of SUSY signal
  $\Rightarrow$ backup slide

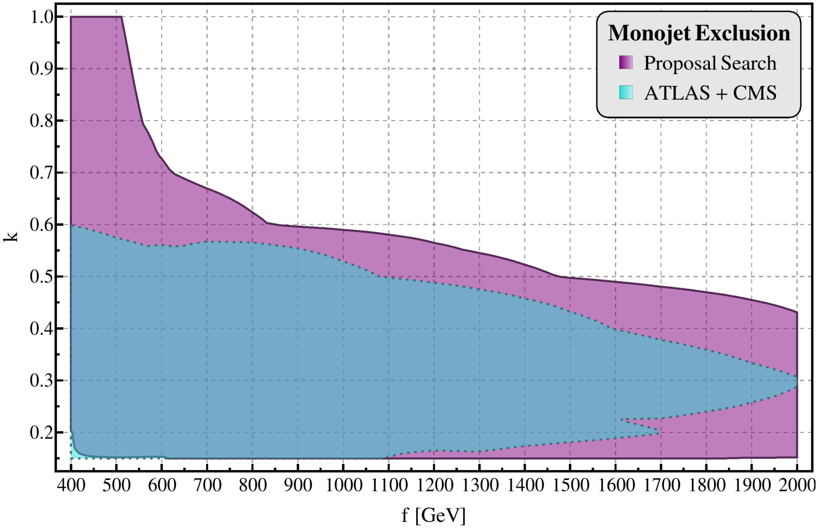


Conclusions

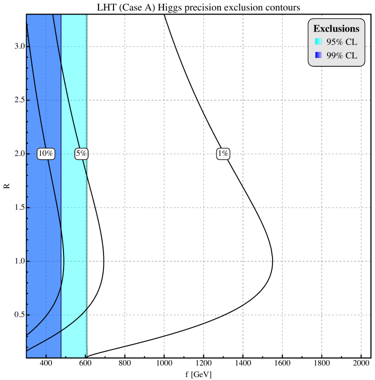
- Little Higgs are a viable alternative to weakly coupled solutions like *SUSY*, where fine tuning is a guideline to understand the naturalness of a model
- Little Higgs models without T parity are already "forced" into the TeV range by Electroweak Precision Data
- for models with T parity, sub-TeV life is still possible: in LHT $f \gtrsim 650\ \mathrm{GeV}$ at 95% CL
- Electroweak Precision Data still represent the most severe constraints, but Higgs- and Direct Searches are getting quickly competitive (especially for T parity models)
- a comprehensive method to constrain the LHT model has been explored, as well as an optimization proposal for SUSY and Exotica searches to increase the exclusion potential
- increasing luminosity will improve the visible cross section upper bounds and reduce the uncertainties of the Higgs results

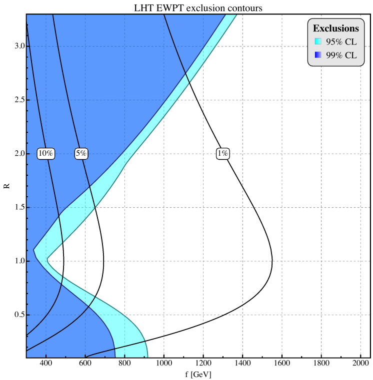
Thank you for your attention!

Optimization Proposal: monojet + $\not{E}_T$



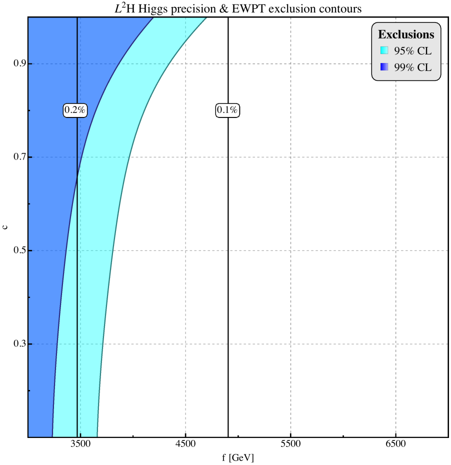
Higgs Searches vs. *EWPT*





- the shape of the combined result is driven by the *EWPT* constraints (much smaller uncertainties)
- Higgs Searches: for $f \gtrsim 600\ \mathrm{GeV}$ invisible decay $h \to A_H A_H$ open and dominant
- Higgs Searches: subdominant dependence on R w.r.t. f is a well-known result in the context of the Higgs Low-Energy Theorem

L^2H results

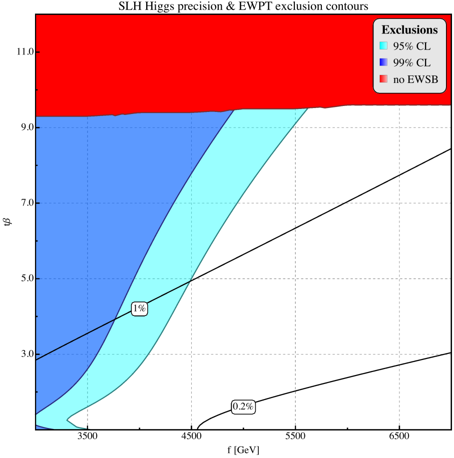


- parameters: f *SSB* scale, c mixing angle in gauge sector
- $f \gtrsim$ 3.6 TeV at 95% CL
  $\Rightarrow$ lower bounds on heavy partners, e.g.

$$m_{W'} \gtrsim 2.4 \text{ TeV}$$
$$m_T \gtrsim 5.1 \text{ TeV}$$

- minimum required fine tuning: $\sim 0.1\%$
- results driven by *EWPT*

SLH results



- parameters: f *SSB* scale, t_β ratio of vevs of scalar fields $\phi_{1,2}$
- $f \gtrsim$ 3.3 TeV at 95% CL
  $\Rightarrow$ lower bounds on heavy partners, e.g.

$$m_{W'} \gtrsim 1.5 \text{ TeV}$$
$$m_T \gtrsim 3.2 \text{ TeV}$$

- minimum required fine tuning: $\sim 0.5\%$
- results driven by *EWPT*

Partial Decay Widths in *LH*

- 1-loop decays

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

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

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

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

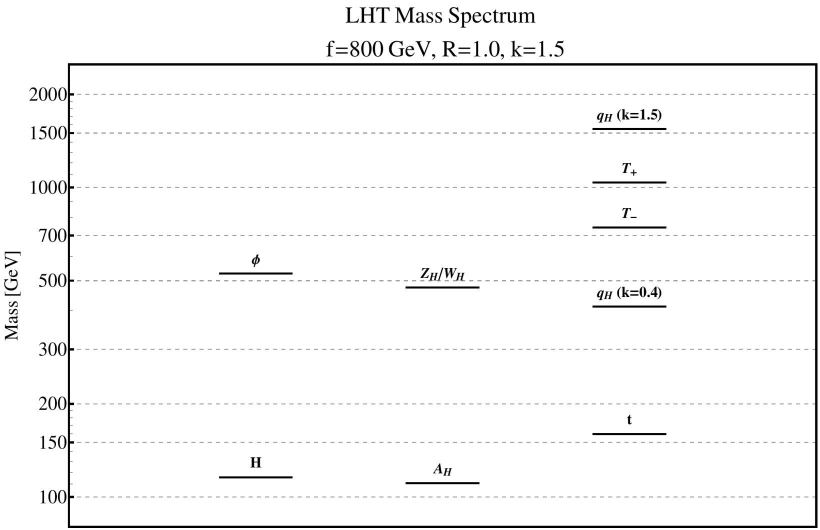
- tree-level decays

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

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

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

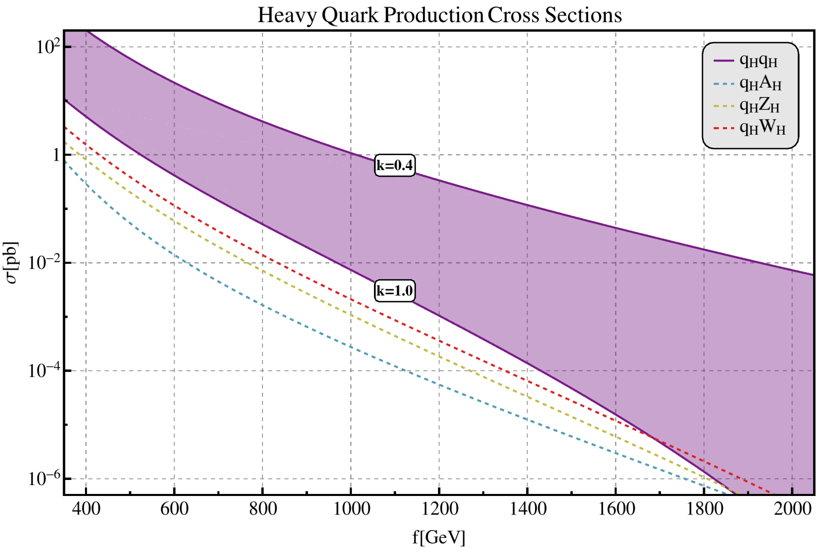
LHT typical Mass Spectrum



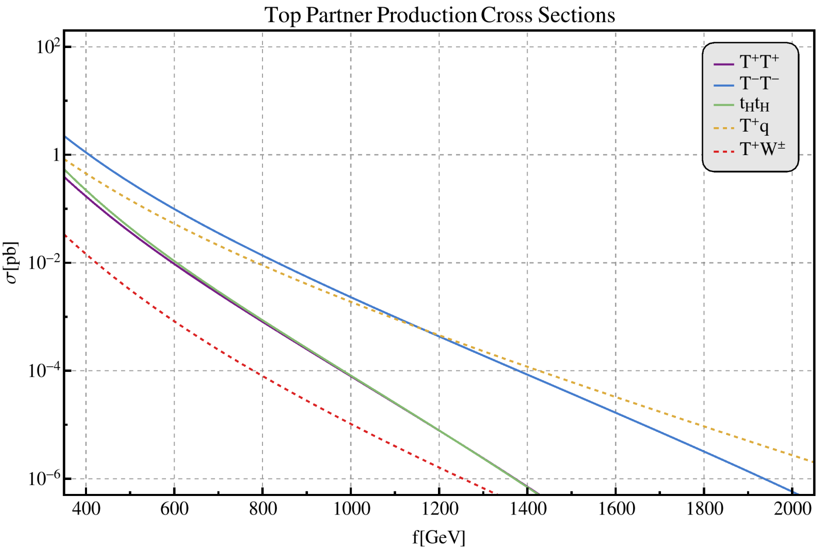
LHT typical Branching Ratios

Particle	Decay	$\mathrm{BR}_{k=1.0}$	$\mathrm{BR}_{k=0.4}$
u_H	$W_H^+\,d$	61%	0%
	$Z_H\,u$	30%	0%
	$A_H\,u$	9%	100%
A_H	stable		
$W_H^\pm$	$A_H\,W^\pm$	100%	2%
	$u_H\,d$	0%	44%
	$d_H\,u$	0%	27%
	$l_H^\pm\,\nu$	0%	13.5%
	$\nu_H\,l^\pm$	0%	13.5%
Z_H	$A_H\,H$	100%	2%
	$d_H\,d$	0%	40%
	$u_H\,u$	0%	30%
	$l_H^\pm\,l^\mp$	0%	14%
	$\nu_H\,\nu$	0%	14%

LHT 8 TeV Production Cross Sections (1)



LHT 8 TeV Production Cross Sections (2)



LHT 8 TeV Production Cross Sections (3)