Little Higgs at the LHC: Status and Prospects

Marco Tonini

DESY Theory Group (Hamburg)

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
30 August 2013
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 \textit{EWSB}

hierarchy problem as guideline to answer the following question:

\textbf{what is the dynamical origin of \textit{EWSB}?}

- weakly coupled answer \rightarrow \text{Supersymmetry}
- strongly coupled answer \rightarrow \text{Composite Higgs, Little Higgs...}
**Motivation**

**Strongly coupled answer**

**Original idea:** pions of low-energy QCD

- **QCD**
  - quarks as d.o.f.
  - perturbative th. for $E > \Lambda$

- **low-energy QCD**
  - pions: pNGB of SSB (new d.o.f.)
  - eff. theory valid up to $E < \Lambda$

$\Lambda \sim 1 \text{ GeV}$: SSB of QCD-flavour symmetry $SU(2) \times SU(2) \rightarrow SU(2)$

$$L_{QCD} = -\frac{1}{4} G_{\mu \nu}^a G^{\mu \nu \alpha} + \sum_{q=u,d} \bar{q} i \not{D} q$$

$$L_{2\theta} = \frac{f^2}{4} \text{tr} |\partial_{\mu} \Sigma|^2, \quad \Sigma = \exp \frac{i}{f} \left( \begin{array}{cc} \pi^0 & \pi^+ \\ \pi^- & -\pi^0 \end{array} \right)$$

**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

<table>
<thead>
<tr>
<th><strong>QCD</strong></th>
<th>( L_{QCD} = -\frac{1}{4} G_{\mu\nu}^a G^{\mu\nu}<em>a + \sum</em>{q=u,d} \bar{q} i D q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>- quarks as d.o.f.</td>
<td>( \Lambda \sim 1 \ \text{GeV} )</td>
</tr>
<tr>
<td>- perturbative th. for ( E&gt;\Lambda )</td>
<td>SSB of QCD-flavour symmetry ( \text{SU}(2)x\text{SU}(2) \to \text{SU}(2) )</td>
</tr>
</tbody>
</table>

**low-energy QCD**
- pions: pNGB of SSB (new d.o.f.)
- eff. theory valid up to \( E<\Lambda \)

\( \Sigma = \exp \left( \frac{i}{f} \begin{pmatrix} \pi^0 & \pi^+ \\ \pi^- & -\pi^0 \end{pmatrix} \right) \)

Composite/Little Higgs Ansatz

*Higgs as pNGB of a new (approximate) global symmetry which is spontaneously broken at a scale \( \Lambda \sim 4\pi f \)*
The Little Higgs paradigm:

- it is an effective theory valid up to the cut-off $\Lambda$: 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. $v \sim O(100 \text{ GeV})$ for $f \sim 1 \text{ TeV}$ with only log-sensitivity to $\Lambda$
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
Motivation

EWPT & Higgs Searches

Direct Searches

EWPT & Higgs: Data used

Precision constraints of the EW sector:

\[
\mu_i = \frac{\sum_p \epsilon^p_i \sigma^p_i}{\sum_p \epsilon^p_i \sigma_i^{SM}} \cdot \frac{BR(h \rightarrow X_i X_i)}{BR(h \rightarrow X_i X_i)_SM}
\]

⇒ best fit for each decay of the Higgs

\[\mu = 1.30 \pm 0.20\]

Higgs results expressed in terms of

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 $h \rightarrow A_H A_H$ in LHT
- modified Higgs couplings with SM fermions and vector bosons

\[ 2 \frac{m_W^2}{v} y_W h W^+ W^-, \quad y_W = \begin{cases} 1 \\ 1 + \mathcal{O} \left( \frac{v^2}{f^2} \right) \end{cases} \]

- new Higgs interactions with heavy resonances

\[ \frac{m_T}{v} y_T h \bar{T} T \quad m_T \sim f, \quad y_T \sim \mathcal{O} \left( \frac{v^2}{f^2} \right) \]

- modified neutral- and charged-currents

\[ \frac{g}{c_W} \sum_f \bar{f} \gamma^\mu \left( (g_L^{SM} + \delta g_L) P_L + (g_R^{SM} + \delta g_R) P_R \right) f Z_\mu \]
**EWPT & Higgs: Results**

- **parameters**: \( f \) \( SSB \) scale, \( R \) ratio of Yukawa couplings in top sector

- \( f \gtrsim 694 \text{ GeV} \) at 95\% CL
  \[ \Rightarrow \text{lower bounds on heavy partners, e.g.} \]
  \[ m_{W'} \gtrsim 453 \text{ GeV} \]
  \[ m_T \gtrsim 984 \text{ GeV} \]

- minimum required fine tuning: \( \sim 5\% \)

- results mainly driven by \textit{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.

<table>
<thead>
<tr>
<th>final state topology</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>monojet + (E_T)</td>
<td>CONF-2012-147</td>
<td>PAS EXO-12-048</td>
</tr>
<tr>
<td>jets + (E_T)</td>
<td>CONF-2013-047</td>
<td>PAS SUS-12-028</td>
</tr>
<tr>
<td></td>
<td>CONF-2013-024</td>
<td></td>
</tr>
<tr>
<td>lepton(s) + jets + (E_T)</td>
<td>CONF-2012-104</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CONF-2013-037</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CONF-2013-007</td>
<td></td>
</tr>
</tbody>
</table>

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

\[
\sigma_{\text{vis}} = \sigma_{\text{prod}}^{\text{BSM}} \cdot \text{BR} \cdot \epsilon \cdot A
\]
Direct Searches: Recasting Analysis

our work:

⇒ recasting of available analyses assuming a Little Higgs signal

- 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 $\sigma_{\text{vis}}^{\text{LH}} > \sigma_{\text{vis}}^{95\%}$: 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:

$$pp \rightarrow Q_H \bar{Q}_H \rightarrow (qA_H) (\bar{q}A_H)$$

ATLAS-CONF-2012-147 selection cuts:

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

$$\sigma^{\text{LHT}}_{\text{vis}} (f = 400 \text{ GeV}, \kappa = 0.5) = 21.5 \text{ pb}$$

$$\sigma^{95\%}_{\text{vis}} = 2.8 \text{ pb}$$

$\Rightarrow$ exclusion at 95% CL!!
An example

example: monojet + $E_T$ final state topology

possible LHT signal:

$$p p \rightarrow Q_H \bar{Q}_H \rightarrow (q A_H) (\bar{q} A_H)$$

ATLAS-CONF-2012-147 selection cuts:

- $n_j \leq 2$ w/ $p_T > 30$ GeV
- $p_T(j_1) > 120$ GeV, $\eta(j_1) < 2.0$
- $n_L = 0$ w/ $p_T(e) > 20$ GeV, $p_T(\mu) > 7$ GeV
- $E_T > 120$ GeV
- $\Delta \phi(E_T, j_2) > 0.5$

$$\sigma^{\text{LHT}}_{\text{vis}} (f = 400 \text{ GeV}, \kappa = 0.5) = 21.5 \text{ pb}$$

$$\sigma^{95\%}_{\text{vis}} = 2.8 \text{ pb}$$

⇒ exclusion at 95% CL!!
An example

example: monojet + \( E_T \) final state topology

possible LHT signal:

\[
p p \rightarrow Q_H \bar{Q}_H \rightarrow (qA_H) (\bar{q}A_H)
\]

ATLAS-CONF-2012-147 selection cuts:

- \( n_j \leq 2 \) w/ \( p_T > 30 \text{ GeV} \)
- \( p_T(j_1) > 120 \text{ GeV}, \eta(j_1) < 2.0 \)
- \( n_L = 0 \) w/ \( p_T(e) > 20 \text{ GeV}, \)
  \( p_T(\mu) > 7 \text{ GeV} \)
- \( E_T > 120 \text{ GeV} \)
- \( \Delta \phi(\vec{E}_T, j_2) > 0.5 \)

\[
\sigma_{\text{LHT}}^{\text{vis}} (f = 400 \text{ GeV}, \kappa = 0.5) = 21.5 \text{ pb}
\]

\[
\sigma_{\text{vis}}^{95\%} = 2.8 \text{ pb}
\]

\[\Rightarrow \text{ exclusion at } 95\% \text{ CL}!! \pm \]
Direct Searches: Results

- parameters: $f$ SSB scale, $\kappa$ 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 $f \gtrsim 650$ 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 + $E_T$
the shape of the combined result is driven by the *EWPT* constraints (much smaller uncertainties)

- **Higgs Searches:** for $f \gtrsim 600$ GeV invisible decay $h \rightarrow A_H A_H$ 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.
  
  $m_{W'} \gtrsim 2.4$ TeV  
  $m_T \gtrsim 5.1$ TeV

- minimum required fine tuning: $\sim 0.1\%$

- results driven by $EWPT$
parameters: $f$ SSB scale, $t_\beta$ 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**

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

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

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

\[
\Rightarrow \quad \text{narrow-width approximation: } \sigma_{LH}^{ggh} = \sigma_{SM}^{ggh} \cdot \frac{\Gamma(h \rightarrow gg)_{LH}}{\Gamma(h \rightarrow gg)_{SM}}
\]

- **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 $g_{hff} = \frac{m_f^2}{v} y_f$
LHT Mass Spectrum

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

- $q_H$ (k=1.5)
- $T_+$
- $T_-$
- $\phi$
- $Z_{H}/W_H$
- $q_H$ (k=0.4)
- $t$
- $H$
- $A_H$
## LHT typical Branching Ratios

<table>
<thead>
<tr>
<th>Particle</th>
<th>Decay</th>
<th>BR_{k=1.0}</th>
<th>BR_{k=0.4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_H )</td>
<td>( W_H^+ d )</td>
<td>61%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>( Z_H u )</td>
<td>30%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>( A_H u )</td>
<td>9%</td>
<td>100%</td>
</tr>
<tr>
<td>( A_H )</td>
<td>stable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( W_H^\pm )</td>
<td>( A_H W_H^\pm )</td>
<td>100%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>( u_H d )</td>
<td>0%</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>( d_H u )</td>
<td>0%</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>( l_H^\pm \nu )</td>
<td>0%</td>
<td>13.5%</td>
</tr>
<tr>
<td></td>
<td>( \nu_H l_H^\pm )</td>
<td>0%</td>
<td>13.5%</td>
</tr>
<tr>
<td>( Z_H )</td>
<td>( A_H H )</td>
<td>100%</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>( d_H d )</td>
<td>0%</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>( u_H u )</td>
<td>0%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>( l_H^\pm l_H^{\mp} )</td>
<td>0%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>( \nu_H \nu )</td>
<td>0%</td>
<td>14%</td>
</tr>
</tbody>
</table>
Heavy Quark Production Cross Sections

- $q_H q_H$
- $q_H A_H$
- $q_H Z_H$
- $q_H W_H$

$k=0.4$

$k=1.0$
LHT 8 TeV Production Cross Sections (2)

Top Partner Production Cross Sections

σ [pb] vs. f [GeV]

- $T^+T^+$
- $T^-T^-$
- $t_Ht_H$
- $T^+q$
- $T^+W^\pm$

Cross sections are shown on a logarithmic scale.