The fate of Little Higgs models with LHC Run 2 data

Jürgen R. Reuter, DESY

based on work with
D. Dercks, G. Moortgat-Pick, S. Y. Shim, M. Tonini, M. de Vries


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LTP model and LHC Run 2 data

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The Little Big Higgs boson

- Discovery of a light Higgs boson leaves still open questions:
  1. **Nature of Electroweak Symmetry Breaking**
  2. Higgs boson potential, all the way like the Standard Model!?
  3. Does it fulfill the US-fermion/Europe-boson rule?
  4. Is there something related to the Little Hierarchy problem (strong or weak)
Old Idea: Light Higgs as a (pseudo-) Nambu-Goldstone boson of a spontaneously broken symmetry

[Georgi/Pais, ’75; Georgi/Kaplan, ’84]

Analogy: chiral symmetry breaking in QCD
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Upscale: Technicolor (ruled out by EWPO/LHC)
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Collective Symmetry Breaking: 3-scale model

Arkani-Hamed/Cohen/Georgi, ’01
Arkani-Hamed/Cohen/Grigore/Wacker, ’02
The Littlest Higgs Model

Based on SU(5)/SO(5) coset:

$$
\Sigma(x) = e^{2i\Pi^a(x)X^a/f \langle \Sigma \rangle}
$$

$$
Q^a_1 = \frac{1}{2} \begin{pmatrix}
\sigma^a \\
\end{pmatrix}
$$

$$
Q^a_2 = \frac{1}{2} \begin{pmatrix}
\sigma^a \\
-\sigma^{a*} \\
\end{pmatrix}
$$

$$
Y_1 = \frac{1}{10} \text{diag}(3, 3, -2, -2, -2)
$$

$$
Y_2 = \frac{1}{10} \text{diag}(2, 2, 2, -3, -3)
$$

Broken generators (24-10=14): $X^a$

Collective Symmetry Breaking

$$
M_{W_H} \sim g \cdot f
$$

$$
M_{Z_H} \sim g \cdot f
$$

$$
M_{A_H} \sim g \cdot f
$$

$$
M_{\Phi} \sim f
$$

$$
m_h \sim \frac{f}{16\pi^2}
$$

Local symmetry: $SU(2)_I \otimes U(1)_I \otimes SU(2)_2 \otimes U(1)_2 \rightarrow SU(2)_L \otimes U(1)_Y$

eats up 4 Nambu-Goldstones

Goldstone bosons:

$$
\Pi^a X^a = \frac{1}{\sqrt{2}} \begin{pmatrix}
h & h^T \\
h^T & h^* \\
\end{pmatrix} + \frac{1}{2} \begin{pmatrix}
\Phi & \Phi^* \\
\Phi^T & \Phi \\
\end{pmatrix}
$$

Large contributions to EWPO

Hewett/Petriello/Rizzo, '02; Csáki/Hubisz/Kribs/Meade/Terning, '03; Kilian/JRR, '03

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T-parity: a discrete symmetry for EWPO

Discrete symmetry: $T$ (TeV)-Parity

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

$T^a \rightarrow T^a \quad X^a \rightarrow -X^a$

- (Almost) all new heavy particles $T$-odd
- Tree-level contributions to EWPO eliminated [also triplet $\Phi$ vev]
- Bounds on $f$ relaxed from ca. 4-5 TeV to 500-600 GeV
- Only pair production of new particles at colliders
- Typical cascade decays
- Lightest $T$-odd particle (LTP) is stable $\rightarrow$ Dark Matter candidate

$M_{\Phi} = 1 \text{ TeV}$

$M_{W_H} = M_{Z_H} = g f$
$= 400 - 700 \text{ GeV}$

$M_{A_H} = \frac{g' f}{\sqrt{5}}$
$= 50 - 200 \text{ GeV}$
T-parity: a discrete symmetry for EWPO

Discrete symmetry: \( T \ (\text{TeV}) \)-Parity

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Assume \( T \)-parity violation: \( A_H \) heavily constrained as DM candidate

DM candidate axion-like particle in mesonic sector of UV completion (+ QCD axion)

\( T \)-parity violation: Wess/Zumino/Witten anomaly in UV sector \( \text{Hill/Hill, '07} \)

In analogy to pion decays \( \pi \to \gamma \gamma \) leads to \( A_H \to WW, ZZ \)
**T-parity: a discrete symmetry for EWPO**

Discrete symmetry: $T$ (TeV)-Parity  

\[
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  Hill/Hill, '07
- In analogy to pion decays $\pi \rightarrow \gamma\gamma$ leads to $A_H \rightarrow WW, ZZ$

**Consequences:**  DM bounds gone, collider phenomenology may change

- Decays to $WW, ZZ$ (1-loop induced); to $ff$ (2-loop induced)  
  Freitas/Schwaller/Wyler, '08

\[
M_\Phi = 1 \text{ TeV}
\]

\[
M_{W_H} = M_{Z_H} = g f = 400 - 700 \text{ GeV}
\]

\[
M_{A_H} = \frac{g' f}{\sqrt{5}} = 50 - 200 \text{ GeV}
\]

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Signatures and constraints on the LHT model

\[ m_t = \frac{\lambda_1 \lambda_2}{\lambda_1^2 + \lambda_2^2} v = \frac{\lambda_2 R}{\sqrt{1 + R^2}} v \]
\[ M_{T^+} = \frac{m_t}{v} f(1 + R^2) \frac{f(1 + R^2)}{R} = M_{T^-} \sqrt{1 + R^2} \]
\[ M_{u,-} = \sqrt{2} \kappa_q f \left( 1 - \frac{1}{8} \frac{v^2}{f^2} \right) \]
\[ M_{d,-} = \sqrt{2} \kappa_q f \]
\[ M_{\ell/\nu,-} = \sqrt{2} \kappa_{\ell} f \]

- New heavy particles: vector-like $T$-odd/even quarks, $T$-odd vectors, LTP ($A_H$)
- SUSY-like search signatures: mono-jets + MET, multi-jets (+MET), jets+leptons (+MET)
- Deviations in coupling constants at level of $\approx 5\%$ ($v^2/f^2$)

Modified HVV couplings:

\[ 2 \frac{m_V^2}{v} \left( 1 + \mathcal{O}(v^2/f^2) \right) h V \cdot V \]

Modified $ttH$ couplings:

\[ \frac{m_t^2}{v} \left[ (1 + \mathcal{O}(v^2/f^2)) h t \bar{t} \right. \]
\[ + \mathcal{O}(v^2/f^2) h t \gamma^5 t \]

Modified $Vff$ couplings:

\[ \frac{g}{c_W} \sum_f \bar{f} \gamma^\mu \left[ (1 + \mathcal{O}(v^2/f^2)) g_L^{SM} P_L \right. \]
\[ + (1 + \mathcal{O}(v^2/f^2)) g_R^{SM} P_R \left. \right] f Z_\mu \]

$\kappa_q$, $\kappa_\ell$, $f$, $R = \frac{\lambda_1}{\lambda_2}$
Electroweak Precision Observables

- $M_H$
- $M_W$
- $\Gamma_W$
- $M_Z$
- $\Gamma_Z$
- $O_\text{had}^0$
- $R_\text{lep}^0$
- $A_{FB}^{0,l}$
- $A_{\ell}(\text{LEP})$
- $A_{\ell}(\text{SLD})$
- $\sin^2(\phi)^{\text{lept}}_{\text{eff}}(Q^2_{FB})$
- $A_{FB}^{0,c}$
- $A_{FB}^{0,b}$
- $A_{c}$
- $A_{b}$
- $R_{\ell}^0$
- $R_b^0$
- $m_c$
- $m_b$
- $m_t$

$\Delta \alpha_{\text{had}}^{(5)}(M_Z^2)$

$\frac{(O_{\text{fit}} - O_{\text{meas}})}{\sigma_{\text{meas}}}$
Electroweak Precision Observables

- $M_H$, $M_W$, $\Gamma_W$, $M_Z$, $\Gamma_Z$
- $O^0_{\text{had}}$
- $R^0_{\text{lep}}$
- $A^0_{\text{FB}}$
- $A_f (\text{LEP})$
- $A_f (\text{SLD})$
- $\sin^2(\phi)_{\text{eff}}^{\text{lept}} (Q_{\text{FB}})$
- $A^0_{\text{c}}$
- $A^0_{\text{b}}$
- $A_{\text{b}}$
- $R^0_{\text{c}}$
- $R^0_{\text{b}}$
- $m_c$
- $m_b$
- $m_t$
- $\Delta \alpha^{(5)}_{\text{had}} (M^2_Z)$

$(O_{\text{fit}} - O_{\text{meas}}) / \sigma_{\text{meas}}$

Exclusions
- 95% CL
- 99% CL

LHT EWPT exclusion contours

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Electroweak Precision Observables

- Accidental cancellation to EWPO for $R \approx 1$
- Bounds from 4-fermion contact interactions (later)
- Exclusion limits at 95% CL:
  \[
  f \gtrsim 405 \text{ GeV}
  \]
  \[
  M_W \gtrsim 270 \text{ GeV}
  \]
  \[
  M_T \gtrsim 554 \text{ GeV}
  \]
**Constraints from Higgs measurements**

- Main driver of constraints from Higgs data: **invisible decay channel** $H \rightarrow A_H A_H$
- **Modifications of gluon fusion, vector boson fusion, top-associated production**
- **Minor effect: modifications in branching ratios** (LHC cannot disentangle these!)

Signal strength modifier in channel $i$  

$$
\mu^i = \frac{n^i_S}{n^i_{SM,i}} = \sum_{prod.} \frac{n^i_{S,p} \sigma^i_{p}}{\sigma^i_{SM} \text{BR}^i_{SM}} \rightarrow [c_g \zeta_g^i + c_V \zeta_V^i + c_t \zeta_t^i] \frac{\text{BR}_i}{\text{BR}^i_{SM}}
$$

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$m_H = 125.36$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$\mu = 1.17^{+0.28}_{-0.26}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>$\mu = 1.46^{+0.40}_{-0.34}$</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>$\mu = 1.18^{+0.24}_{-0.21}$</td>
</tr>
<tr>
<td>$H \rightarrow \tau \tau$</td>
<td>$\mu = 1.44^{+0.42}_{-0.37}$</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>$\mu = 0.63^{+0.39}_{-0.37}$</td>
</tr>
<tr>
<td>$H \rightarrow \mu \mu$</td>
<td>$\mu = -0.7^{+3.7}_{-3.7}$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\mu = 2.7^{+4.6}_{-4.5}$</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>$\mu = 1.18^{+0.15}_{-0.14}$</td>
</tr>
</tbody>
</table>

|$\sigma = 7$ TeV, 4.5-4.7 fb$^{-1}$

|$\sigma = 8$ TeV, 20.3 fb$^{-1}$

The diagram illustrates the signal strength modifier $\mu$ for various Higgs decay channels, with total uncertainty indicated for each case.
Constraints from Higgs measurements

- Main driver of constraints from Higgs data: invisible decay channel $H \rightarrow A_H A_H$
- Modifications of gluon fusion, vector boson fusion, top-associated production
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Signal strength modifier in channel $i$

$$
\mu^i = \frac{n^i_S}{n^{SM,i}_S} = \sum_{prod.} \frac{n^i_{S,p} \sigma^{SM}_{p} BR_{SM}^{i}}{\sigma^{SM}_{p} BR_{SM}^{i}} \rightarrow \left[c_g \zeta^i_g + c_V^2 \zeta^i_V + c_t \zeta^i_t\right] \frac{BR_i}{BR_{SM}^i}
$$

- Independent of $R$
- Collective symmetry breaking

\[\begin{array}{c|c|c|c|c}
\text{ATLAS} & \text{Total uncertainty} & \text{Theory} & \text{Stat.}\ \\
\hline
m_H & 125.36 \text{ GeV} & \rightarrow & \rightarrow & \rightarrow \\
\hline
H \rightarrow \gamma\gamma & & & & \\
\mu = 1.17 & 0.28 & -0.28 & 0.26 & \\
\hline
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\hline
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\mu = 1.44 & -0.30 & 0.29 & 0.29 & 0.27 & \\
\hline
H \rightarrow bb & & & & \\
\mu = 0.63 & -0.29 & -0.39 & -0.37 & \\
\hline
H \rightarrow \mu\mu & & & & \\
\mu = -0.7 & -0.37 & 0.08 & -0.07 & \\
\hline
H \rightarrow Z\gamma & & & & \\
\mu = 2.7 & 4.6 & 3.7 & \\
\hline
\text{Combined} & & & & \\
\mu = 1.18 & -0.15 & -0.14 & \\
\end{array}\]
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Signal strength modifier in channel $i$

$$\mu^i = \frac{n^i_S}{n^i_{SM}} = \frac{1}{\prod \sigma^i_{p} \frac{BR^i_{SM}}{BR^i_{SM}}} \left[ c_g \zeta_g^i + c_V \zeta_V^i + c_t \zeta_t^i \right] \frac{BR^i_{SM}}{BR^i_{SM}}$$

**ATLAS**

$m_H = 125.36$ GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mu$</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$1.17+0.28$</td>
<td>+0.20</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>$1.46+0.40$</td>
<td>+0.19</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>$1.18+0.24$</td>
<td>+0.21</td>
</tr>
<tr>
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<td>$1.44+0.42$</td>
<td>+0.29</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>$0.63+0.39$</td>
<td>+0.01</td>
</tr>
<tr>
<td>$H \rightarrow jj$</td>
<td>$0.71+0.37$</td>
<td>+0.01</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$2.7+4.6$</td>
<td>+0.82</td>
</tr>
<tr>
<td>Combined</td>
<td>$1.18+0.15$</td>
<td>+0.00</td>
</tr>
</tbody>
</table>

**Signal strength modifier in channel $i$**

$$\mu^i = \frac{n^i_S}{n^i_{SM,i}} = \sum \frac{n^i_{S,p} \sigma^i_{p} \frac{BR^i_{SM}}{BR^i_{SM}}}{\prod \sigma^i_{p} \frac{BR^i_{SM}}{BR^i_{SM}}} = \left[ c_g \zeta_g^i + c_V \zeta_V^i + c_t \zeta_t^i \right] \frac{BR^i_{SM}}{BR^i_{SM}}$$
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Signal strength modifier in channel $i$

$$\mu^i = \frac{n_S^i}{n_{SM}^i} = \sum_{\text{prod.}} \frac{n_S^i p \sigma_p^{SM \text{BR}^i_{SM}}}{\sigma_p^{SM \text{BR}^i_{SM}}} \left[ c_g \zeta_g^i + c_V^2 \zeta_V^i + c_t^2 \zeta_t^i \right] \frac{\text{BR}^i_{SM}}{\text{BR}^i_{SM}}$$

EWPT/Higgs data:

$$f \gtrsim 694 \text{ GeV}$$
Direct searches: Topologies & Benchmarks

**Notation:**

\[ q_H := \{d_H, u_H, s_H, c_H, b_H, t_H\} \]
\[ \ell_H := \{e_H, \mu_H, \tau_H, \nu_{eH}, \nu_{\mu H} \nu_{\tau H}\} \]
\[ V_H := \{W_H, Z_H, A_H\} \]
\[ T^\pm := T\text{-even/odd top partners} \]

**Production processes:**

1. \( pp \rightarrow q_H q_H, q_H \bar{q}_H, \bar{q}_H q_H \)
2. \( pp \rightarrow q_H V_H \)
3. \( pp \rightarrow \ell_H \bar{\ell}_H \)
4. \( pp \rightarrow V_H V_H \)
5. \( pp \rightarrow T^+ \bar{T}^+, T^- \bar{T}^- \)
6. \( pp \rightarrow T^+ q, \bar{T}^+_q, T^+_W, \bar{T}^- W^\pm \)

**2 \times 2 \times 3 different benchmark scenarios:**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Model</th>
<th>Constraint</th>
<th>Phenomenology</th>
<th>Considered Topology</th>
</tr>
</thead>
</table>
| \( f_H \) | Fermion Universality | \( \kappa_\ell = \kappa_q \) | • mass degeneracy of \( q_H, \ell_H \)  
• \( \ell_H \) production negligible | Exclude process 3 |
| \( f_H \) | Heavy \( q_H \) | \( \kappa_q = 3.0 \) | • \( q_H \) decoupled  
• \( \ell_H \) production relevant | Exclude processes 1, 2 |
| \( f_H \) | Light \( \ell_H \) | \( \kappa_\ell = 0.2 \) | • \( \ell_H \) very light  
• \( V_H \) branching ratios change | Exclude process 3 |
| \( T^\pm \) | Light \( T^\pm \) | \( R = 1.0 \) | • \( T^\pm \) are light/accessible | Include process 4, 5 |
| \( T^\pm \) | Heavy \( T^\pm \) | \( R = 0.2 \) | • \( T^\pm \) are heavy/inaccessible | Exclude process 4, 5 |
| \( A_H \) | TPC | No TPV | • \( A_H \) is stable and invisible | \( A_H \) stable |
| \( A_H \) | TPV | With TPV | • \( A_H \) is unstable | \( A_H \rightarrow VV \) decays |
Toolchain for event simulation and recasting

- Steering program and Recasting tool: CheckMate2
  [Dercks/Desai/Kim/Rolbiecki/Tattersall/Weber, ’16]
- Model file for LHT model via UFO format
  [Degrande et al., ’12]
- Partonic events: MG5_aMC@NLO
  [Alwall et al., ’10] and
  WHIZARD v2.5
  [Kilian/Ohl/JRR, ’10]
- Clustering, jet selection: FastJet v3.3
  [Cacciari/Salam/Soyez, ’11]
- Parton shower and hadronization: Pythia v8.2
  [Sjöstrand/Mrenna/Skands, ’08]
- Fast detector simulation: Delphes v3.2
  [de Favereau et al., ’14]
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All used searches that have been recasted here:

<table>
<thead>
<tr>
<th>CM identifier</th>
<th>Final State</th>
<th>Designed for</th>
<th>Lum.</th>
<th>SR</th>
<th>Ref.</th>
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</thead>
<tbody>
<tr>
<td>atlas_conf_2016_096</td>
<td>( \not{E}_T + 2-3 \ell )</td>
<td>( \tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell} )</td>
<td>13.3</td>
<td>8</td>
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</tr>
<tr>
<td>atlas_conf_2016_054</td>
<td>( \not{E}_T + 1 \ell + (b)-j )</td>
<td>( \tilde{q}, \tilde{g} )</td>
<td>14.8</td>
<td>10</td>
<td>ATLAS-CONF-2016-054</td>
</tr>
<tr>
<td>atlas_conf_2017_022</td>
<td>( \not{E}_T + 0 \ell + 2-6 j )</td>
<td>( \tilde{q}, \tilde{g} )</td>
<td>36.1</td>
<td>24</td>
<td>ATLAS-CONF-2017-022</td>
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<tr>
<td>atlas_conf_2017_039</td>
<td>( \not{E}_T + 2-3 \ell )</td>
<td>( \tilde{\chi}^\pm, \tilde{\chi}^0, \tilde{\ell} )</td>
<td>36.1</td>
<td>37</td>
<td>ATLAS-CONF-2017-039</td>
</tr>
</tbody>
</table>
13 TeV recasting results: Fermion Universality

\[
\begin{align*}
\kappa_q = & \frac{m(q_H)}{m(q)} = 1 \text{ TeV} \\
\kappa_q = & \frac{m(q_H)}{m(q)} = 2 \text{ TeV} \\
\kappa_q = & \frac{m(q_H)}{m(q)} = 3 \text{ TeV} \\
\kappa_q = & \frac{m(Z_H)}{m(q_H)} = 0 \text{ TeV} \\
\kappa_q = & \frac{m(Z_H)}{m(q_H)} = 1 \text{ TeV} \\
\kappa_q = & \frac{m(Z_H)}{m(q_H)} = 5 \text{ TeV} \\
\end{align*}
\]

\((\text{Fermion Universality}) \oplus (\text{Heavy } T^\pm) \oplus (\text{TPC})\)
13 TeV recasting results: Fermion Universality

(Fermion Universality) \( \oplus \) (Light \( T^\pm \)) \( \oplus \) (TPC)

- **High \( f \):** bounds follow \( M(q_H) \) isocontours, \( f \times \kappa < f \kappa_{\text{max}} \), with \( f \kappa_{\text{max}} \sim 1.5/2 \) TeV (Run 1/Run 2)
- **Most effective analysis:** search for 2 Jets + MET from \( pp \rightarrow q_H q_H \rightarrow j j A_H A_H + X \)
- **Low \( f \):** independent of \( \kappa \), large \( \kappa \): \( q_H \) too heavy; \( V_H \) production, \( M(V_H) \gtrsim 600 \) GeV, \( f \gtrsim 900 \) GeV
- **Light \( T^\pm \):** if kinematically accessible improve \( f \)-bound to \( f \gtrsim 1.3 \) TeV
- **TPV:** \( q_H \) isocontours slightly weakened (more \( V \)), \( f \)-bound improved (!) \([\ell \text{ take over } j \text{ analyses}]\)
13 TeV recasting results: Fermion Universality

(Fermion Universality) ⊕ (Heavy $T^\pm$) ⊕ (TPV)

- **High $f$:** bounds follow $M(q_H)$ isocontours, $f \times \kappa < f \kappa_{\text{max}}$, with $f \kappa_{\text{max}} \sim 1.5/2$ TeV (Run 1/Run 2)
- Most effective analysis: search for 2 Jets + MET from $pp \rightarrow q_H q_H \rightarrow j j A_H A_H + X$
- **Low $f$:** independent of $\kappa$, large $\kappa$: $q_H$ too heavy; $V_H$ production, $M(V_H) \gtrsim 600$ GeV, $f \gtrsim 900$ GeV
- **Light $T^\pm$:** if kinematically accessible improve $f$-bound to $f \gtrsim 1.3$ TeV
- **TPV:** $q_H$ isocontours slightly weakened (more $V$), $f$-bound improved (!) [$\ell$ take over $j$ analyses]
Bounds from 4-fermion operators

- Low-energy bounds: flavor observables (kaon, D-, B-physics)  \[ \text{Blanke et al., '06, '15} \]

- Mirror fermions generate 4-fermion operators via box diagrams  \[ \text{Hubisz/Meade/Noble/Perelstein, '06} \]
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Diagram:

- Mirror fermions
- Goldstone bosons of heavy gauge bosons

\[
\begin{align*}
\bar{\psi}_L & \rightarrow \psi'_{L} \\
\psi_{L} & \rightarrow \phi_{VH} \\
\phi_{VH} & \rightarrow \psi_{c} \\
\psi_{c} & \rightarrow \phi_{VH} \\
\phi_{VH} & \rightarrow \bar{\psi}'_{L}
\end{align*}
\]
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[Blanke et al., ’06, ’15]

- Mirror fermions generate 4-fermion operators via box diagrams  
[Hubisz/Meade/Noble/Perelstein, ’06]

\[ O_{4\text{-}\text{ferm.}} = -\frac{\kappa_{q,\ell}^2}{128\pi^2 f^2} \left( \overline{\psi}_L \gamma^\mu \psi_L \right) \left( \overline{\psi}'_L \gamma_\mu \psi'_L \right) \]
Bounds from 4-fermion operators

- Low-energy bounds: flavor observables (kaon, D-, B-physics) [Blanke et al., ’06, ’15]

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\[ \mathcal{O}_{4\text{-ferm.}} = -\frac{k_{q,\ell}^2}{128\pi^2 f^2} (\overline{\psi}_L \gamma^\mu \psi_L) (\overline{\psi}_L' \gamma^\mu \psi_L') \]

Strongest constraints still from LEP: 
\[ \Lambda [\overline{e}e(\overline{q}q)] \gtrsim 26.4 \text{ TeV} \]

LHC Dijet Bounds: 
\[ \Lambda [(\overline{q}q)(\overline{q}q)] \gtrsim 15.7 \text{ TeV} \]

\[ \Rightarrow \text{EWPO} \]
LHC Run 2 and EWPO/Higgs Results
LHC Run 2 and EWPO/Higgs Results

(Light $\ell_H$) $\oplus$ (Light $T^\pm$) $\oplus$ (T-parity conservation)
Conclusions / Summary

✦ Little Higgs models explain light Higgs as (pseudo-)Nambu-Goldstone boson
✦ Solves (little) hierarchy breaking by collective symmetry breaking
✦ EFT description of coset space, most commonly embedded in Composite Model
✦ Inclusion of discrete symmetry ($T$-parity) for EWPO and DM
✦ Constraints on parameter space from EWPO / Higgs data / direct searches
✦ 4-fermion operators give strict bounds (complimentary to direct searches)
✦ With LHC Run 2 scales go up into TeV range: $f \gtrsim 1.3$ TeV
✦ LHC bounds & LUX / Xenon direct detection (almost) rule LHT DM
✦ Prospects for 14 TeV HL-LHC: exclusion 1.5-1.8 TeV [preliminary]
✦ Higgs data (except for $H \rightarrow A_H A_H$) irrelevant $\Rightarrow$ need for a lepton collider
ONE RING TO FIND THEM ...
ONE RING TO RULE THEM OUT ?
BACKUP SLIDES
T-parity: a discrete symmetry for Dark Matter

- Lightest $T$-odd particle $A_H$ (50-200 GeV)
- Dominant decay via s-channel Higgs exchange
  \[ A_H \rightarrow h \rightarrow WW, ZZ, hh \]  
  [Hubisz/Meade, '03]
- Constraints from overclosure of universe
- Heavy lepton/quark coannihilation helps  
  [Yang/Wang/Shu, '13]
T-parity: a discrete symmetry for Dark Matter

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Severe constraints from direct detection
  Yang/Wang/Shu, ’13; Wu/Yang/Zhang, ’16
T-parity violation
**T-parity violation**

\[
\Gamma(A_H \rightarrow ZZ) = \left( \frac{N g'}{80 \sqrt{3} \pi^3} \right)^2 \left( 1 - \frac{4m_Z^2}{M_{A_H}^2} \right)^{\frac{5}{2}} \frac{M_{A_H}^3 m_Z^2}{f^4}
\]

\[
\Gamma(A_H \rightarrow W^+ W^-) = \left( \frac{N g'}{40 \sqrt{3} \pi^3} \right)^2 \left( 1 - \frac{4m_W^2}{M_{A_H}^2} \right)^{\frac{5}{2}} \frac{M_{A_H}^3 m_W^2}{f^4}
\]

\[
\Gamma(A_H \rightarrow f f) = \left( \frac{N_C f M_{A_H}}{48 \pi} \right) \left( 1 - \frac{4m_f^2}{M_{A_H}^2} \right)^{\frac{1}{2}}
\]

\[
\left[ c_-^2 \left( 1 - \frac{4m_f^2}{M_{A_H}^2} \right) + c_+^2 \left( 1 + \frac{2m_f^2}{M_{A_H}^2} \right) \right]
\]
Cross Sections & Branching ratios (I)

(Fermion Universality/Light $\ell H$) $\oplus$ (Light $T^\pm$)

Left: fixed $\kappa$
Full line: $f = 1$ TeV
Dashed: $f = 2$ TeV

Right: fixed $f$
Full line: $\kappa = 1$ TeV
Dashed: $\kappa = 2$ TeV

(Heavy $qH$) $\oplus$ (Light $T^\pm$)

13 TeV
Cross Sections & Branching ratios (I)

(Fermion Universality/Light $\ell_H$) $\oplus$ (Light $T^{\pm}$) 13 TeV

Left: fixed $\kappa$
- Full line: $f = 1$ TeV
- Dashed: $f = 2$ TeV

Right: fixed $f$
- Full line: $\kappa = 1$ TeV
- Dashed: $\kappa = 2$ TeV

destructive $t$-$q_H$-channel interference w./ s-channel
Cross Sections & Branching ratios (II)

Branching ratios have very small $f$ dependence (only small $f$, mass effects)

$\frac{d_H}{u_H}$, very similar: $u_H$  [FU,L$\ell$]

$\frac{\ell_H}{v_H}$, very similar: $v_H$  [FU]

$T^+$  [Light $T^-$]

Light $T^{-}$:

$\text{BR}(T^{-} \rightarrow tA_H) = 1$

Light $\ell_H$:

$\text{BR}(\ell_H/v_H \rightarrow \ell/vA_H) = 1$

$W_H$, very similar: $Z_H$  [FU,H$q$]

$W_H$, very similar: $Z_H$  [L$\ell$]
Cross Sections 8 TeV

(Fermion Universality/Light $\mathcal{L}_H$) $\oplus$ (Light $T^\pm$) 8 TeV

(Fixed $f$)
Full line: $f = 1$ TeV
Dashed: $f = 2$ TeV

Left: fixed $\kappa$

Right: fixed $f$
Full line: $\kappa = 1$ TeV
Dashed: $\kappa = 2$ TeV
Cross Sections 14 TeV

(Fermion Universality/Light $\ell^H$) $\oplus$ (Light $T^\pm$)  

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Full line: $f = 1$ TeV
Dashed: $f = 2$ TeV

Right: fixed $f$
Full line: $\kappa = 1$ TeV
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13 TeV recasting results: Heavy $q_H$

\[(\text{Heavy } q_H) \oplus (\text{Heavy } T^\pm) \oplus \text{(TPC)}\]
13 TeV recasting results: Heavy $q_H$

\[ (\text{Heavy } q_H) \oplus (\text{Light } T^\pm) \oplus (\text{TPC}) \]

- $q_H \rightarrow q V_H \rightarrow \ell H \rightarrow \ell V_H$; multijets $\rightarrow$ multileptons

- $\sigma(pp \rightarrow q_H q_H)$ 2-3 orders of magnitudes larger than $\sigma(pp \rightarrow \ell_H \ell_H)$

- Limits for large $f$ similar to FU: exclusions $f \gtrsim 950$ GeV ($1350$ GeV with $T^\pm$)

- $\kappa \lesssim 0.5$: $V_H \rightarrow \ell_H \ell$ now open; covered by multilepton analysis; $f \gtrsim 1.9$ TeV

- Only very tiny changes for TPV
(Heavy $q_H$) $\oplus$ (Heavy $T^\pm$) $\oplus$ (TPV)

- $q_H \to qV_H \Longrightarrow \ell_H \to \ell V_H$; multijets $\Longrightarrow$ multileptons
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13 TeV recasting results: Light $\ell_H$

(Light $\ell_H$) \oplus (Light $T^\pm$) \oplus (TPC)

- 2 main exclusion regions, intersect at $f \approx 1.6$ TeV and $\kappa_q \approx 1.2$
- $\kappa_q > 0.5$: 3$\ell$ search, $pp \rightarrow q_H q_H \rightarrow jjV_HV_H \rightarrow jj\ell\ell\ell\ell A_H A_H$
- $\kappa_q < 0.5$: $V_H$ have hadronic decays, multi-jet analyses dominate
- Large-$\kappa$ bound stronger due to leptons compared to Fermion Universality
- Presence of $T^\pm$ leads only to marginal changes
- TPV: bounds slightly weakened due to smaller MET cut efficiency
13 TeV recasting results: Light $\ell_H$

\[(\text{Light } \ell_H) \oplus (\text{Heavy } T^\pm) \oplus (\text{TPV})\]

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Prospects for 14 TeV HL-LHC

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(Fermion Universality) $\oplus$ (Heavy $T^\pm$) $\oplus$ (TPC)

$q_H$ mass bounds improves by 1.0-1.5 TeV: $M(q_H) \gtrsim 3$-4 TeV

14 TeV $\quad$ 3,000 / fb
Prospects for 14 TeV HL-LHC

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(Heavy $q_H$) $\oplus$ (Heavy $T^\pm$) $\oplus$ (TPC)  

14 TeV  3,000 / fb

Relatively moderate improvements for $\ell_H$ mass bounds
### Prospects for 14 TeV HL-LHC

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(Light $\ell_H$) $\oplus$ (Heavy $T^\pm$) $\oplus$ (TPC)  

Little improvement compared to 13 TeV
LHC Run 2 and EWPO/Higgs Results

(Fermion Universality) \( \oplus \) (Heavy \( T\pm \)) \( \oplus \) (\( T\)-parity conservation)
LHC Run 2 and EWPO/Higgs Results

(Fermion Universality) $\oplus$ (Light $T^\pm$) $\oplus$ ($T$-parity conservation)
LHC Run 2 and EWPO/Higgs Results

(Heavy $q_H$) $\oplus$ (Heavy $T^{\pm}$) $\oplus$ ($T$-parity conservation)
LHC Run 2 and EWPO/Higgs Results

(Heavy $q_H$) $\oplus$ (Light $T^\pm$) $\oplus$ ($T$-parity conservation)
LHC Run 2 and EWPO/Higgs Results

\[(\text{Light } \ell_H) \oplus (\text{Heavy } T^\pm) \oplus (T\text{-parity conservation})\]
LHC Run 2 and EWPO/Higgs Results

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