Higgs bosons in non-minimal Models

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On behalf of ATLAS and CMS
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   → Doubly charged Higgs searches

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Summary
Introduction

Despite its longstanding huge predictive power, the Standard Model is affected by a few flaws. One of them is the famous Hierarchy Problem.

Assuming that SM is an effective low-energy theory with an Ultraviolet cut-off $\Lambda$

The most important radiative corrections to the Higgs boson mass arise from loops involving top, gauge bosons and the Higgs itself.

\[ \delta m_h = \frac{3}{8\pi^2} \lambda \Lambda \]  
from top

\[ \delta m_h^2 \propto a_w \Lambda^2 \]  
from gauge bosons

\[ \delta m_h^2 \approx \frac{\lambda}{16\pi^2} \Lambda^4 \]  
from higgs

Example: if $\Lambda = 10$ TeV the lowest order corrections are:

\[ \sim (2 \text{ TeV})^2 \]  
top loops
\[ \sim -(750 \text{ GeV})^2 \]  
$W/Z$ loops
\[ \sim -(1.25 \text{ m}_H)^2 \]  
Higgs loops

Higgs mass would explode unless extremely un-natural fine tuning is applied at all orders so to keep $m_H \sim O(200 \text{ GeV})$
Aside from just passively accepting that Mother Nature might be so fine-tuned ....
Try other viable theoretical solutions, e.g.

- Stabilize the Higgs mass through additional symmetries
  - Supersymmetry (Plenty of coverage in other talks)
  - Little Higgs models
  - LRSM

- Shift the cut-off to lower energies
  - Extra Dimensions, e.g. Randall-Sundrum
The (SM) Higgs boson remains light thanks to a global symmetry which breaks at the TeV scale.

**New particles:**

- $W_H^\pm, Z_H, \gamma_H : \lesssim 1$ TeV
- $T : \lesssim 1$ TeV
- $\phi^{\pm \pm}, \phi^\pm, \phi^0 : \lesssim 10$ TeV

New heavy gauge bosons $M_W < 6 \text{TeV} \left( \frac{m_h}{200 \text{GeV}} \right)^2$

Heavy Top quark $M_T < 2 \text{TeV} \left( \frac{m_h}{200 \text{GeV}} \right)^2$

Triplet of heavy Higgs bosons

Are required to provide cancellation of the one-loop quadratic divergences to the SM Higgs mass

New Higgses appear: lose mass constraints

SM Higgs is still there: usual searches
Two (left and right) Higgs triplets provide a parity conserving Lagrangian

All fermions are treated symmetrically as LH and RH doublets

Symmetry based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$\rightarrow$ New neutrinos, bosons, Higgses

Yukawa couplings of the triplet Higgs allow for Majorana mass terms of the RH neutrinos ($\sim 10^{11}$ GeV)

See-saw mechanism possible

Natural explanation of the low, non-zero mass of left-handed neutrinos
Search for doubly charged Higgs (Littlest Higgs)

Production: VBF mechanism

$\phi^{++} \rightarrow W^+W^+ \rightarrow \ell^+\ell'^+\nu\nu$

Sensitivity up to 2 TeV
Requires VEV large enough in conflict with bounds from electro-weak fits

- Two positive leptons with $p_T > 150, 20$ GeV and $|\eta| < 2.5$
- $|p_{T1} - p_{T2}| > 200$ GeV
- $|\eta_1 - \eta_2| < 2.0$
- $E_T^{miss} > 50$ GeV
- Two “tag jets”, $p_T > 15$, $E > 200, 100$ GeV, $|\eta_1 - \eta_2| > 5$

Search for RH doubly charged Higgs (LRSM)

Same-sign di-leptons

Di-leptons from $\tau$ pairs

Doubly-charged RH Higgs pair production via new ZR

Discovery reach (>10 events, low background, after selection) for a) 100 fb$^{-1}$ and b) 300 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta^{++}$ 300 GeV</th>
<th>$\Delta^{++}$ 800 GeV</th>
<th>$W+W^+ qq$</th>
<th>$W tt$</th>
<th>$WZ qq$</th>
<th>$tt$</th>
<th>total backg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated leptons</td>
<td>278 (327)</td>
<td>63 (95)</td>
<td>109/19</td>
<td>7.6/0.6</td>
<td>0/0.8</td>
<td>17/0</td>
<td>133/13</td>
</tr>
<tr>
<td>Lepton $P_T$</td>
<td>256 (301)</td>
<td>63 (94)</td>
<td>63/11</td>
<td>5.9/0.5</td>
<td>0/0.8</td>
<td>1.1/0</td>
<td>70/12</td>
</tr>
<tr>
<td>$2.4(P_T^1 + P_T^2) - M_H &gt; 480$</td>
<td>191(227)</td>
<td>59(85)</td>
<td>10/2.1</td>
<td>1.3/0.3</td>
<td>0/0</td>
<td>0</td>
<td>12/2.4</td>
</tr>
<tr>
<td>Fwd Jet tagging</td>
<td>156(186)</td>
<td>56(74)</td>
<td>6.0/1.3</td>
<td>0/1.3</td>
<td>0/0</td>
<td>0</td>
<td>6/1.3</td>
</tr>
<tr>
<td>ptmiss</td>
<td>154(181)</td>
<td>56(68)</td>
<td>3.0/0.3</td>
<td>0/0</td>
<td>0/0</td>
<td>3.1/0.3</td>
<td></td>
</tr>
</tbody>
</table>

Search for pair production of doubly charged Higgs

Drell-Yan production of $\Delta^{++}\Delta^{--}$
NLO $\sigma$ (Spira, Muhlleitner, 2003)

Same-sign lepton final state
SM bkg very small

$\Delta^{++}$ decays:
$\mu^+\mu^+, \mu^+\tau^+, \tau^+\tau^+$
were studied
$4\mu$
$1\mu3\tau, 2\mu2\tau, 3\mu1\tau$
with $\tau$->hadrons

Rommerskirchen et al, CMS Note 2006/081
## Δ++/-- discovery and exclusion

4μ final state

Exclusion Limit = \((760^{+0.5}_{-2} \text{ (bkg)} \pm 10 \text{ (signal) } \pm 4 \text{ (lumi)}) \text{ GeV}/c^2\)

Discovery Limit = \((650^{+0.4}_{-0.3} \text{ (bkg)} \pm 3 \text{ (signal)} \pm 0.2 \text{ (lumi)}) \text{ GeV}/c^2\)

With τ in the final state. No background left!

<table>
<thead>
<tr>
<th>(m_\Delta^{\pm \pm} \text{ (GeV)})</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{\text{ev}} \text{ expected at } 10 \text{ fb}^{-1})</td>
<td>26</td>
<td>10</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>(\sigma_{\text{NLO}} \pm \text{stat } \pm \text{syst } \text{(fb)})</td>
<td>(93.9^{+19.3}_{-17.5} \pm 12.2)</td>
<td>(19.6^{+6.8}_{-5.6} \pm 2.5)</td>
<td>(5.9^{+3.4}_{-2.5} \pm 0.8)</td>
<td>(2.2^{+1.9}_{-1.5} \pm 0.3)</td>
</tr>
<tr>
<td>Luminosity for 95% CL exclusion, fb(^{-1})</td>
<td>1.3</td>
<td>3.0</td>
<td>7.7</td>
<td>16.8</td>
</tr>
</tbody>
</table>
Randall, Sundrum, PRL 83, 3370 (1999)  

Only one extra dimension

\[ ds^2 = e^{-2kyl} \eta_{\mu\nu} \, dx^\mu \, dx^\nu - dy^2 \]

Planck brane

\[ y = 0 \]

anti - de Sitter space

\[ y = \pi r_c \]

TeV/SM brane

\[ k \sim \text{curvature} \]

Gravity scale: \[ \Lambda_\pi = M_{Pl} e^{-kr_c \pi}, \quad r_c = \text{compactification radius} \]

The hierarchy between Planck and EW scale is removed by the exponential warp factor if \( kr_c \sim 12 \rightarrow r_c \sim 10^{-32} \text{ m} \rightarrow \text{no deviations from Newton’s law} \]
Radion, $\phi$, scalar field representing the fluctuation of the distance between the two branes

Introduced in the model to stabilize the size of extra dimension ($k r_c \sim 12$)

*Goldberger and Wise, PRL 83 (1999) 4922*

Free parameters of 5D Randall-Sundrum model:

$m_\phi, m_h, \Lambda_\phi (\phi \text{ vev}), \xi (\phi-h \text{ mixing})$

Very important phenomenological side: without any fine tuning of parameters $\Lambda_\phi \sim 1 \text{ TeV}$ and $m_\phi < \text{ TeV}$

Radion couples to gauge bosons and fermions similarly to SM Higgs mixes with the Higgs
Branching Ratios of Radion and Higgs

Tri-linear terms in the Higgs radion sector
open $\phi \rightarrow hh$

e.g. $\text{BR}(\phi \rightarrow hh) \sim 20-30\%$
for $m_h = 120$ GeV
$m_\phi \sim 250-350$ GeV
$\Lambda_\phi = 5$ TeV
Higgs in radion decays

Channels:
\( \phi \rightarrow \gamma \gamma \rightarrow \gamma \gamma \)bb
2 high-\( P_T \) isolated photons + 2 b-jets
Di-photon trigger
Low backgrounds from:
\( \gamma \gamma \)bb (irred.), \( \gamma \gamma bj \), \( \gamma \gamma jj \), \( \gamma \gamma cj \), \( \gamma \gamma cc \)

\( \phi \rightarrow \tau \tau \)bb
1 isolated lepton + 2 b-jet + 1 \( \tau \)-jet

Backgrounds:

\( \phi \rightarrow hh \rightarrow \tau \tau bb \)
Largest signal rate but
HUGE multi-jet background
Hopeless

\( \phi \rightarrow hh \rightarrow \gamma \gamma bb \)
2 high-\( P_T \) isolated photons + 2 b-jets
Di-photon trigger
Low backgrounds from:
\( \gamma \gamma \)bb (irred.), \( \gamma \gamma bj \), \( \gamma \gamma jj \), \( \gamma \gamma cj \), \( \gamma \gamma cc \)

\( \phi \rightarrow hh \rightarrow \tau \tau bb \)
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Analysis assumes $h$ already been discovered

Fast detector simulation

PYTHIA for signal/bkg
$m_h=125 \text{ GeV}$
$m_\phi=300\text{GeV}$
$\Lambda_\phi = 1 \text{ TeV}$

Event Selection:
- Two isolated photons with $P_T > 20 \text{ GeV}$, $|\eta|<2.4$
- Two jets of $E_T > 15 \text{ GeV}$, $|\eta| < 2.5$, at least one b-tagged jet
- $m_{\gamma\gamma} = m_h \pm 2 \text{ GeV}$, $m_{bj} = m_h \pm 20 \text{ GeV}$, $m_{\gamma bj}$ mass cuts

For $m_\phi = 300\ (600) \text{ GeV and } \xi=0$
$\Rightarrow$ Reach in $\Lambda_\phi = 2.2\ (0.6) \text{ TeV}$

Full simulation for the signal (corrected Pythia)
Fast simulation for the background
MadGraph for $\gamma\gamma$, $\gamma\gamma$, $\gamma\gamma$, CompHep for Zbb
Fix $M_\phi=300$ GeV $M_h=125$ GeV $\Rightarrow$ scan the $(\zeta, \Lambda_\phi)$ plane
Designed to discover Higgs + Radion

Event Selection:
- Two isolated photons with $P_{T1} > 40$ GeV, $P_{T2} > 25$, $|\eta|<2.4$
- Two jets of $E_T > 15$ GeV, $|\eta| < 2.5$, at least one b-tagged jet
- $m_{\gamma\gamma}, m_{\gamma bj}, m_{\gamma bj}$ mass cuts
- 3.7% efficiency

Selected $\gamma bj$ sample

Presence of one Higgs

SUSY07 - Karlsruhe - Germany
N. Marinelli
Univ. of Notre Dame
Then look at $m_{\gamma bj}$ for those events with
$m_{\gamma} = \gamma\gamma$ observed peak $\pm$ 4 GeV
$m_{bj} = \gamma\gamma$ observed peak $\pm$ 30 GeV
Radion is found from the excess of events

D. Dominici et al. CMS Note 2005/007

Presence of one Higgs
Scan in ($\Lambda_\phi, \xi$) plane for $m_\phi=300$ GeV/c$^2$, $m_h=125$ GeV/c$^2$

5σ discovery contours for 30 fb$^{-1}$

Effects due to Background + systematic errors are included

Reach in $\Lambda_\phi$ up to 2.5 TeV
$M_h = 125$ GeV

Reach in $\Lambda_\phi \sim 1$ TeV
$\phi \rightarrow hh \rightarrow bbbb$

In order to confirm a signal in this channel the background needs to be known to 0.1\% (e.g. via extrapolation from non-signal region)
Summary

Non-minimal models (Randall-Sundrum extra dim, Little Higgs) have become popular, aside from Supersymmetry, as alternative solutions to the Hierarchy Problem in the SM.

First studies have been performed by both ATLAS and CMS oriented to discovering the new particles/testing the models.

Radions (RS): Overall a reach in $\Lambda_\phi$ up to 2.5 TeV should be possible.

CMS attempts a simultaneous discovery of the SM-like Higgs and the radion (RS) in the $\phi \rightarrow hh \rightarrow \gamma\gamma bb$ channel.

Littlest Higgs:

Search of new heavy doubly charged Higgs bosons investigated both in VBF and Drell-Yan production.

Sensitivity at large masses ($>\sim 1$ TeV) seems to be rather poor however discovery can be achieved up to ~650 GeV or exclusion up to ~750 GeV.
Summary

Non-minimal models (Randall-Sundrum extra dim, Little Higgs) have become popular, aside from Supersymmetry, as alternative solutions to the Hierarchy Problem in the SM.

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Left-Right Symmetric Model

The existence of RH doubly charged Higgs can be probed in the purely leptonic channel up to ~1.7 TeV (100 fb\(^{-1}\)).

Whatever it is waiting for us round the corner ............ it will be fun!