**EXOTIC HIGGS DECAYS - AN OVERVIEW**

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A Potential Leading Window into New Physics

- Solving hierarchy problem requires Higgs to couple with new physics directly.

- Higgs is one of the two SM fields that can have renormalizable couplings to SM singlet operators [Patt and Wilczek, arXiv:[hep-ph/0605188]]

\[ \mathcal{L} \supset \lambda H^\dagger H \mathcal{O}_{\text{NP}} \]

Lorentz invariant gauge singlet

- Both couplings can modify the Higgs productions and decays at LHC.
- So we should study everything about it!
Many Possible Higgs Measurements

LHC (+ future colliders ...)

Measure the SM Higgs decays

Search for exotic Higgs decays (absent in the SM)

Search for non-standard Higgs production
Higgs Decay Width in the SM

- The SM Higgs width is tiny for $m_H \sim 125$ GeV

- Decays into gauge bosons are either off-shell ($WW^*$, $ZZ^*$), or at loop level (di-photon, di-gluon)

- Decays into fermions tend to be suppressed because of small Yukawa couplings (except $tt^*$)

- About three orders smaller than the Z or W widths ($\sim 4$MeV only)
A small non-standard Higgs coupling may lead to sizable effect.

\[ \Delta \mathcal{L} = \lambda S^2 |H|^2 \] (common building block in extended Higgs sectors)

\[ \lambda \sim 0.005 \] and \[ m_S < \frac{m_H}{2} \] can give \( \text{Br}(H \rightarrow SS) \sim 10\% \)

So exotic Higgs decays are a natural and very efficient way for probing BSM physics.
``Invisible’’ Higgs Width

- The currently allowed branching ratio for exotic Higgs decays is big

\[ \text{BR}_{\text{exotic}} < 0.3 \text{ at 95\% C.L.} \]

- As a comparison (for \( m_{h}=125\text{GeV} \))

\[
\begin{align*}
\text{Br}(h_{\text{SM}} \to ZZ^*) & \sim 0.03 \\
\text{Br}(h_{\text{SM}} \to WW^*) & \sim 0.15 \\
\text{Br}(h_{\text{SM}} \to \tau\tau) & \sim 0.06
\end{align*}
\]

There exists a lot of room! (in a more general context, > 0.5 BR is allowed!)

Giardinoa, Kannike, Masina, Raidal, Strumia, 1303.3570

see e.g. Belanger, Dumont, Ellwanger, Gunion, Kraml; Espinosa, Muhlleitner, Grojean, Trott; Ellis
There Will Always Be Room for Exotic Decays

$O(10\%)$ BR into exotic decay modes are not only allowed by existing data, but will remain reasonable targets for the duration of the LHC program [M. Peskin, 2013]

$g(h\bar{A}A)/g(h\bar{A}A)_{\text{SM}} - 1$ LHC (14TeV, 300/fb, 1 sigma CL)

Allowed Br for exotic Higgs decays
How Many Exotic Decay Events Possible Right Now?

assume $\text{BR}(h \rightarrow \text{new}) = 10\%$, LHC8, 20/fb

<table>
<thead>
<tr>
<th>channel</th>
<th># events (raw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>39000</td>
</tr>
<tr>
<td>VBF</td>
<td>3150</td>
</tr>
<tr>
<td>$W(\ell \nu)+h$</td>
<td>280</td>
</tr>
<tr>
<td>$Z(\ell\ell)+h$</td>
<td>55</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>260</td>
</tr>
</tbody>
</table>

Searching for them are not easy:

- Many events in ggF/VBF, but suitability depends on the Higgs decays
- Can always trigger w/ AP... but not many events
- Specific signature => dedicated search strategies are usually required

=> What is the discovery potential for exotic Higgs decays at LHC8? And at LHC14? And even at a future collider?
The "Exotic Higgs Decay Working Group"


Self-formed group of theorists. Our aims are:

- Survey, systematize, prioritize exotic Higgs decays
- Develop search strategies, assess discovery potential, provide viable benchmark models/points
- Inform trigger selection for LHC14 + future collider
- Assemble comprehensive summary document & website to inform experimental analyses (timescale of vol I ~ O(few weeks))
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Non-Standard-Model $h$ Decays

Much work has been done over the past twenty years on non-SM Higgs decays in different contexts. The purpose of this document is to assemble the motivations, models, and signatures of non-SM decays of $h$ bosons that appear in the literature, and provide the necessary information for contextualizing, systematizing, and prioritizing LHC searches for such decays.

Please click here for the motivation for the careful consideration of Non-Standard-Model $h$ decays at the LHC.

Please click here for the list of possible decays, discussion of prioritization, and available studies.

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Decays to Standard Objects Without Missing Energy

1. $h \rightarrow 2 \rightarrow (2)+(1)$
   - $\gamma + Z$
   - $\gamma + Z'$
2. $h \rightarrow 2 \rightarrow (2)+(2)$
   - via Spin-0 Bosons ($S$)
     - $(b\bar{b})(b\bar{b})$
     - $(b\bar{b})(\tau^+\tau^-)$
     - $(b\bar{b})(\mu^+\mu^-)$
     - $(\tau^+\tau^-)(\mu^+\mu^-)$
     - $(b\bar{b})(\gamma\gamma)$
     - $(\tau^+\tau^-)(\gamma\gamma)$
     - $(\gamma\gamma)(\gamma\gamma)$
     - $(\gamma\gamma)(gg)$
   - via Spin-1 Bosons ($Z'$)
     - $(l^+l^-)(l^+l^-)$
     - $(l^+l^-)(q\bar{q})$
3. $h \rightarrow 2 \rightarrow (3)+(3)$ or $(2+1)(2+1)$
   - via Bosons

Decays to Standard Objects With Missing Energy
(except for that from b’s, c’s, tau’s)

1. $h \rightarrow 0$
   - MET (Invisible decay)
2. $h \rightarrow 2 \rightarrow 1+ 0$
   - $\gamma + MET$
3. $h \rightarrow 2 \rightarrow 2 + 0$
   - via Spin-0 Bosons ($S$)
     - $(b\bar{b}) + MET$
     - $(\tau^+\tau^-) + MET$
     - $(\mu^+\mu^-) + MET$
     - $(\gamma\gamma) + MET$
   - via Spin-1 Bosons ($Z'$)
     - $(l^+l^-) + MET$
   - via Spin-1/2 Fermions
     - $\gamma\gamma + MET$
     - $[l^+l^-] + MET$
     - $[l^+l^-] + MET$
purely visible or purely MET: familiar to us
Decays to Standard Objects Without Missing Energy

1. \( h \rightarrow 2 \rightarrow (2) + (1) \)
   - \( \gamma + Z \)
   - \( \gamma + Z' \)
2. \( h \rightarrow 2 \rightarrow (2) + (2) \)
   - via Spin-0 Bosons (S)
     - \((b\bar{b})(b\bar{b})\)
     - \((b\bar{b})(\tau^+\tau^-)\)
     - \((b\bar{b})(\mu^+\mu^-)\)
     - \((\tau^+\tau^-)(\mu^+\mu^-)\)
     - \((b\bar{b})(\gamma\gamma)\)
     - \((\tau^+\tau^-)(\gamma\gamma)\)
     - \((\gamma\gamma)(\gamma\gamma)\)
     - \((\gamma\gamma)(g\bar{g})\)
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     - \((\mu^+\mu^-) + \text{MET}\)
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     - \((l^+l^-) + \text{MET}\)
   - via Spin-1/2 Fermions
     - \(\gamma\gamma + \text{MET}\)
     - \([\gamma\gamma] + \text{MET}\)
     - \([l^+l^-] + \text{MET}\)

**MET + visible : relatively less studied in the past**
Decays to Standard Objects Without Missing Energy

1. $h \rightarrow 2 \rightarrow (2)+(1)$
   - $\gamma + Z$
   - $\gamma + Z'$
2. $h \rightarrow 2 \rightarrow (2)+(2)$
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     - $(b\bar{b})(\mu^+\mu^-)$
     - $(\tau^+\tau^-)(\mu^+\mu^-)$
     - $(b\bar{b})(\gamma\gamma)$
     - $(\tau^+\tau^-)(\gamma\gamma)$
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   - via Spin-1 Bosons (Z')
     - $(l^+l^-) +$ MET
   - via Spin-1/2 Fermions
     - $\gamma\gamma +$ MET
     - $[\gamma\gamma] +$ MET
     - $[l^+l^-] +$ MET

These possibilities can be implemented in many NP scenarios. For benchmark selection, we will mainly focus on the NMSSM.
**R-limit vs. PQ Limit**

### R-symmetry
- $a_1$ is singlet-like and light - pseudo-Goldstone boson of R-symmetry breaking.
- Singlet-like CP-even Higgs and singlino-like neutralino are typically not light

\[
W_{NMSSM} = Y_U Q H_u U^c - Y_D Q H_d D^c - Y_E L H_d E^c + \lambda N H_u H_d + \frac{1}{3} \kappa N^3
\]
\[
V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_N^2 |N|^2 - (\lambda A_{\lambda} H_u H_d N + \text{h.c.}) + \left(\frac{\kappa}{3} A_{\kappa} N^3 + \text{h.c.}\right)
\]

- $M_{H^{33}}^2 \sim \kappa (A_{\kappa} + 4\kappa s)$
- $M_{A^{22}}^2 \sim -3\kappa A_{\kappa} s$
- $M_{\chi_{055}} \sim 2\kappa s$

- R-symmetry: $A_l, A_k \to 0, k$ is not small

### PQ-symmetry
- $a_1, h_1$ (singlet-like) and $\chi_1$ (singlino-like) can be simultaneously light


- PQ-symmetry: $k \to 0, A_k \to 0, A_l$ is not small
R-limit vs. PQ Limit

\textbf{R-symmetry}

- h -> a1a1 is typically significant


\textbf{PQ-symmetry}

- h -> a1a1, h1h1 are generically suppressed
- h2 \to \chi_1\chi_2 can be significant!


\[ m_{h_1}^2 \approx -4v^2\epsilon^2 + \frac{4\lambda^2 v^2}{\tan^2 \beta} \Rightarrow \epsilon^2 < \frac{\lambda^2}{\tan^2 \beta} \]

\[ y_{h_2a_1a_1} = -\sqrt{2}\lambda\epsilon \frac{m_Z v}{\mu} + \sum_{i=0}^{4} O \left( \frac{\lambda^{4-i}}{\tan^i \beta} \right), \]

\[ y_{h_2h_1h_1} = -\sqrt{2}\lambda\epsilon \frac{m_Z v}{\mu} + 2\sqrt{2}v\epsilon^2 + \sum_{i=0}^{4} O \left( \frac{\lambda^{4-i}}{\tan^i \beta} \right) \]
**R-limit vs. PQ Limit**

- **R-symmetry**
  - $h \rightarrow a_1 a_1$ is typically significant

- **PQ-symmetry**
  - $h \rightarrow a_1 a_1, h_1 h_1$ are generically suppressed
  - $h_2 \rightarrow \chi_1 \chi_2$ can be significant!


R-limit vs. PQ Limit

R-symmetry

- $h \rightarrow a_1 a_1$ is typically significant

- $h \rightarrow a_1 a_1, h_1 h_1$ are generically suppressed
- $h_2 \rightarrow \chi_1 \chi_2$ can be significant!


PQ-symmetry

- $\chi_2 \rightarrow \chi_1 h_1, \chi_1 a_1$ are typically dominant

R-limit vs. PQ Limit

R-symmetry

- \( h \rightarrow a_1a_1 \) is typically significant


PQ-symmetry

- \( h \rightarrow a_1a_1, h_1h_1 \) are generically suppressed
- \( h_2 \rightarrow \chi_1\chi_2 \) can be significant!


If mass splitting between \( \chi_2 \) and \( \chi_1 \) is small, \( \chi_2 \rightarrow \chi_1h_1, \chi_1a_1 \) become off-shell, \( \text{Br}(\chi_2 \rightarrow \text{photon} + \chi_1) \) can be enhanced to \( O(0.1\%-1\%) \) level [S. Gori, TL and J. Shelton, arXiv: 13xx.xxxx]
LHC Upgrade Plan

Many possibilities to explore during the whole LHC era. Next I will show some examples (preliminary results)
Example I: di-muon + MET

- Trigger: $W + h_2$
- Main background: $W + \gamma^*/Z$
  (after some specific isolation cut)

- With 13/fb data only at LHC8, \[ \frac{S}{\sqrt{B}} \sim 5\sigma \] can be achieved, with
  \[
  C_{\text{eff}} = \frac{\sigma(h_2)}{\sigma(h_{\text{SM}})} \times \text{Br}(h_2 \rightarrow \chi_1\chi_2) \times \text{Br}(\chi_2 \rightarrow h_1\chi_1) \times \text{Br}(h_1 \rightarrow f\bar{f}) = 0.1
  \]

Example II: $bbb\bar{b}$

- **Trigger**: $Wh + Zh$
- **Strategies**: work in the boost regime, apply jet substructure tool + 2b-tags
- **For 100/fb data at LHC14 and $C_{eff} = 1$**

<table>
<thead>
<tr>
<th>$m_a$ (GeV)</th>
<th>Signal</th>
<th>$s/b$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.9</td>
<td>2%</td>
<td>0.18</td>
</tr>
<tr>
<td>30</td>
<td>37.4</td>
<td>33%</td>
<td>3.49</td>
</tr>
<tr>
<td>40</td>
<td>63.1</td>
<td>55%</td>
<td>5.89</td>
</tr>
<tr>
<td>50</td>
<td>61.0</td>
<td>53%</td>
<td>5.69</td>
</tr>
</tbody>
</table>

Carena, Han, Huang, Wagner (2007)
Cheung, Song, Yan (2007)
Kaplan, McEvoy (2011)
Example III: di-b + MET

- **Trigger:** Z + h2
- **Main background:** Z + gluon and tt + jets
- **Strategies:** Z ID + jet substructure tool
- **With 300/fb data only at LHC14, \( S / \sqrt{B} \sim 5\sigma \) can be achieved (Ceff = 0.5)

Red: Z + gluon, gluon \( \rightarrow \) bb
Blue: tt + jets
Green: signal \( \times 20 \)

**Table:**

<table>
<thead>
<tr>
<th>( m_{h_1} )</th>
<th>( m_{h_2} )</th>
<th>( m_{X_1} )</th>
<th>( m_{X_2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 GeV</td>
<td>125 GeV</td>
<td>10 GeV</td>
<td>80 GeV</td>
</tr>
</tbody>
</table>

Exotic Higgs Decays at a Higgs Machine?

Difficult cases at the LHC:
- Soft light jets in the final state
- The BR of exotic Higgs decay is of $O(\%)$ level

**Question:** can a future Higgs factory play a role as a discovery machine?

**Chris Potter** will try to address this question in the next talk.
Higgs may be leading window to BSM physics => must look explicitly for exotic Higgs decays

There are a large array of models, so we need to survey, systematize, prioritize possibilities, and assess their discovery potential

R symmetry and PQ symmetry limits in the NMSSM provide supersymmetric benchmarks for a series of exotic Higgs decays with and without MET

More results of collider analyses are coming soon ... ...
Thank you!
R-limit vs. PQ Limit

R-symmetry

- $h \to a_1 a_1$ is typically significant
- $h \to a_1 a_1$, $h_1 h_1$ are generically suppressed
- $h_2 \to \chi_1 \chi_2$ can be significant!

PQ-symmetry

[Dobrescu et al., Phys. Rev. D 63 (2001);
Dermisek et al., Phys. Rev. Lett. 95 (2005)]

[Draper, TL, Wagner, Wang and Zhang,

\[ m^2_{h_1} \approx -4v^2 \varepsilon^2 + \frac{4\lambda^2 v^2}{\tan^2 \beta} \Rightarrow \varepsilon^2 < \frac{\lambda^2}{\tan^2 \beta} \]

\[ y_{h_2 a_1 a_1} = -\sqrt{2}\lambda \varepsilon \frac{m_Z v}{\mu} + \sum_{i=0}^{4} \mathcal{O} \left( \frac{\lambda^{4-i}}{\tan^i \beta} \right) , \]

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**Z Boson Measurements (from PDG)**

### Z Decay Modes

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Fraction ( \Gamma_i / \Gamma )</th>
<th>Scale Factor/Confidence Level</th>
<th>( p ) (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^+ e^- )</td>
<td>3.363 ( \pm 0.004 ) %</td>
<td>45594</td>
<td></td>
</tr>
<tr>
<td>( \mu^+ \mu^- )</td>
<td>3.366 ( \pm 0.007 ) %</td>
<td>45594</td>
<td></td>
</tr>
<tr>
<td>( \tau^+ \tau^- )</td>
<td>3.370 ( \pm 0.008 ) %</td>
<td>45559</td>
<td></td>
</tr>
<tr>
<td>( \ell^+ \ell^- )</td>
<td>3.3658 ( \pm 0.0023 ) %</td>
<td>45594</td>
<td></td>
</tr>
<tr>
<td>invisible hadrons</td>
<td>20.00 ( \pm 0.06 ) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>((u\bar{u}+c\bar{c})/2)</td>
<td>69.91 ( \pm 0.06 ) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>((d\bar{d}+s\bar{s}+b\bar{b})/3)</td>
<td>11.6 ( \pm 0.6 ) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(c\bar{c})</td>
<td>15.6 ( \pm 0.4 ) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(b\bar{b})</td>
<td>15.12 ( \pm 0.05 ) %</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**SM decays ...**

**Well measured ...**

| \( \Upsilon(1S) X + \Upsilon(2S) X \) | (1.0 \( \pm 0.5 \) \( \times 10^{-4} \) | - | |
| \( \Upsilon(1S) X \) | < 4.4 \( \times 10^{-5} \) CL=95% | - | |
| \( \Upsilon(2S) X \) | < 1.39 \( \times 10^{-4} \) CL=95% | - | |
| \( \Upsilon(3S) X \) | < 9.4 \( \times 10^{-5} \) CL=95% | - | |
| \( (D^0 / D^0) X \) | (20.7 \( \pm 2.0 \) \% | - | |
| \( D^\pm X \) | (12.2 \( \pm 1.7 \) \% | - | |
| \( D^{*}(2010)^\pm X \) | (11.4 \( \pm 1.3 \) \% | - | |
| \( D_{s1}(2536)^\pm X \) | (3.6 \( \pm 0.8 \) \( \times 10^{-3} \) | - | |
| \( D_{sJ}(2573)^\pm X \) | (5.8 \( \pm 2.2 \) \( \times 10^{-3} \) | - | |
| \( \psi(3770)^\pm X \) | searched for | | |
| \( B^+ X \) | \( i \) \( (6.08 \pm 0.13 \) \% | - | |
| \( B^0 X \) | \( i \) \( (1.59 \pm 0.13 \) \% | - | |
| \( B^0_s X \) | searched for | | |
| \( \Lambda^+_b X \) | (1.54 \( \pm 0.33 \) \% | - | |
| \( \Xi^0_b X \) | searched for | | |
| \( b\text{-baryon} X \) | \( i \) \( (1.38 \pm 0.22 \) \% | - | |

**Rare and non-standard decays ...**

**limits ... but could have something amazing ...**

- \( e^+ e^- \gamma \)
- \( \mu^+ \mu^- \gamma \)
- \( \tau^+ \tau^- \gamma \)
- \( \ell^+ \ell^- \gamma \gamma \)
- \( q\bar{q} \gamma \)
- \( \nu\bar{\nu} \gamma \gamma \)
- \( e^\pm \mu^\mp \)
- \( e^\pm \mu^\mp \)
- \( \mu^\pm \mu^\mp \)
- \( e^\pm \mu^\mp \)
- \( \mu^\pm \mu^\mp \)
- \( p e \)
- \( \rho \mu \)

<table>
<thead>
<tr>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 ( \times 10^{-4} ) CL=95% 45594</td>
</tr>
<tr>
<td>5.6 ( \times 10^{-4} ) CL=95% 45594</td>
</tr>
<tr>
<td>7.3 ( \times 10^{-4} ) CL=95% 45556</td>
</tr>
<tr>
<td>6.8 ( \times 10^{-6} ) CL=95% 45594</td>
</tr>
<tr>
<td>5.5 ( \times 10^{-6} ) CL=95% 45594</td>
</tr>
<tr>
<td>3.1 ( \times 10^{-6} ) CL=95% 45594</td>
</tr>
<tr>
<td>1.7</td>
</tr>
<tr>
<td>9.8</td>
</tr>
<tr>
<td>1.2</td>
</tr>
<tr>
<td>1.8 ( \times 10^{-6} ) CL=95% 45588</td>
</tr>
<tr>
<td>1.8 ( \times 10^{-6} ) CL=95% 45588</td>
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</table>