EXOTIC DECAYS OF THE 125 GEV HIGGS

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The discovery of the Higgs-like particle at the LHC announced that a new era of particle physics, the Higgs era, has begun.
If new physics (NP) manifests itself as SM singlet operators, the 125 GeV Higgs is one of the two fields in the SM which may couple with it via renormalizable couplings [Patt and Wilczek, arXiv:hep-ph/0605188]

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

Lorentz invariant gauge singlet

If NP serves as a solution to the hierarchy problem (e.g., SUSY), the 125 GeV Higgs must couple with the NP directly

Both types of couplings can modify the Higgs productions and decays at colliders.

So the 125 GeV Higgs can be a leading window into NP and we should study everything about it within the next years or decades!
Several Ways to Do That

LHC (+ future colliders ...)

Measure the SM Higgs couplings
Several Ways to Do That

LHC (+ future colliders ...)

Measure the SM Higgs couplings

Search for non-standard production
Several Ways to Do That

- LHC (+ future colliders ...)
- Measure the SM Higgs couplings
- Search for exotic decays (absent in the SM)
- Search for non-standard production
Several Ways to Do That

LHC (+ future colliders ...)

Measure the SM Higgs couplings

Search for non-standard production

Exotic decays
Higgs Decay Width in the SM

- The SM Higgs width is tiny for $m_h \sim 125$ GeV
- Its decays into gauge bosons are either off-shell ($WW^*$, $ZZ^*$), or at loop level (di-photon, di-gluon)
- Its decays into fermions tend to be suppressed because of small Yukawa couplings (except $t\bar{t}$)
- 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. 

e.g., $\Delta \mathcal{L} = \lambda S^2 |H|^2$ (common building block in extended Higgs sectors)

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

So exotic Higgs decays are a natural and very efficient way for probing new physics
### 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>SM decays</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>-</td>
<td></td>
</tr>
<tr>
<td>invisible</td>
<td>(20.00 \pm 0.06) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>hadrons</td>
<td>(69.91 \pm 0.06) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>((u\bar{u}+c\bar{c})/2)</td>
<td>(11.6 \pm 0.6) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>((d\bar{d}+s\bar{s}+b\bar{b})/3)</td>
<td>(15.6 \pm 0.4) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(cc)</td>
<td>(12.03 \pm 0.21) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(bb)</td>
<td>(15.12 \pm 0.05) %</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(b\bar{b}\bar{b}\bar{b})</td>
<td>(3.6 \pm 1.3) x 10^{-4}</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

#### Rare and non-standard decays

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Fraction ((\Gamma_i/\Gamma))</th>
<th>Scale Factor/Confidence Level</th>
<th>SM decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J/\psi(1S)X)</td>
<td>(3.51 \pm 0.23) x 10^{-3}</td>
<td>S=1.1</td>
<td></td>
</tr>
<tr>
<td>(\psi(2S)X)</td>
<td>(1.60 \pm 0.29) x 10^{-3}</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(\chi_c(1P)X)</td>
<td>(2.9 \pm 0.7) x 10^{-3}</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(\chi_c(2P)X)</td>
<td>&lt; 3.2 x 10^{-3} CL=90%</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

**Additional Decays:**

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

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Scale Factor/Confidence Level</th>
<th>SM decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau(1S)X + \tau(2S)X + \tau(3S)X)</td>
<td>(1.0 \pm 0.5) x 10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>(\tau(1S)X)</td>
<td>4.4 x 10^{-5} CL=95%</td>
<td>-</td>
</tr>
<tr>
<td>(\tau(2S)X)</td>
<td>1.39 x 10^{-4} CL=95%</td>
<td>-</td>
</tr>
<tr>
<td>(\tau(3S)X)</td>
<td>9.4 x 10^{-5} CL=95%</td>
<td>-</td>
</tr>
<tr>
<td>((D^0 / D^0) X)</td>
<td>(20.7 \pm 2.0) %</td>
<td>-</td>
</tr>
<tr>
<td>(D^\pm X)</td>
<td>12.2 \pm 1.7 %</td>
<td>-</td>
</tr>
<tr>
<td>(D^*(2010)^\pm X)</td>
<td>(11.4 \pm 1.3) %</td>
<td>-</td>
</tr>
<tr>
<td>(D_{s1}(2536)^\pm X)</td>
<td>(3.6 \pm 0.8) x 10^{-3}</td>
<td>-</td>
</tr>
<tr>
<td>(D_{sJ}(2573)^\pm X)</td>
<td>(5.8 \pm 2.2) x 10^{-3}</td>
<td>-</td>
</tr>
<tr>
<td>searched for</td>
<td>(B^+ X)</td>
<td>(6.08 \pm 0.13) %</td>
</tr>
<tr>
<td>searched for</td>
<td>(B^0 X)</td>
<td>(1.59 \pm 0.13) %</td>
</tr>
<tr>
<td>searched for</td>
<td>(A^+_X)</td>
<td>(1.54 \pm 0.33) %</td>
</tr>
</tbody>
</table>

**Baryons:**

- \(b\)-baryon X

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Scale Factor/Confidence Level</th>
<th>SM decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\psi(1S)X + \psi(2S)X + \chi_c(1P)X + \chi_c(2P)X)</td>
<td>(3.8 \pm 0.22) x 10^{-3} CL=95%</td>
<td>-</td>
</tr>
</tbody>
</table>
``Invisible’’ Higgs Width

As a comparison (for mh=125GeV)

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

There exists a lot of room for exotic Higgs decays: > 50% BR is allowed!
(exotic and invisible decays are not distinguished here)

see also Belanger, Dumont, Ellwanger, Gunion, Kraml; Espinosa, Muhlleitner, Grojean, Trott; Ellis; Strumia
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]

\[ \frac{g(hAA)}{g(hAA)}_{SM} - 1 \] LHC (14TeV, 300/fb, 1 sigma CL)

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

assume BR(h→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(ν)+h</td>
<td>280</td>
</tr>
<tr>
<td>Z(τ)+h</td>
<td>55</td>
</tr>
<tr>
<td>ttH</td>
<td>260</td>
</tr>
</tbody>
</table>

Associated Production (AP)

Searching for them are not so easy:

- Many events in ggF/VBF, but suitability depends on the Higgs decays
- Can always trigger w/ AP... but not many events
- Usually specific signature => dedicated search strategies are required
What is the discovery potential for exotic Higgs decays at LHC8? At LHC14? And even at a future Higgs factory?
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
- Eventually, assemble comprehensive summary document & construct website to inform experimental analyses (timescale ~ O(few weeks))
The "Exotic Higgs Decay Working Group"

Exotic Higgs Decays

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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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Motivation for Studying Non-Standard-Model $h$ Decays

1. The decays of any newly discovered particle need to be thoroughly characterized, and this is especially true of the $h$, for several reasons. For any new particle, including most recently the $b$ and $t$ quarks, the $W$ boson and especially the $Z$ boson, the study of its decays represents a powerful strategy for seeking and constraining BSM physics. Specifically, searches for decays that are expected to be small or absent in the SM (e.g. $b \rightarrow s \gamma$, $B_s \rightarrow \mu \mu$, $t \rightarrow cZ$, $Z \rightarrow 4\tau$) --- in short, null experiments --- are especially sensitive, because often these decays are suppressed by exact or approximate symmetries of the SM that are absent in many BSM contexts. Since the $h$ interacts with all SM particles proportional to their masses, but often interacts differently with BSM particles, which often do not get any or all of their mass from the Higgs field, many of its decays that are allowed by symmetries, but are highly suppressed in the SM, are greatly enhanced in BSM contexts. (The same is true of its production modes, though this lies beyond our scope.)
### 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)
     - \((b\bar{b})(b\bar{b})\)
     - \((b\bar{b})(\tau^+\tau^-)\)
     - \((b\bar{b})(\mu^+\mu^-)\)
     - \((\tau^+\tau^-)(\mu^+\mu^-)\)
     - \((b\bar{b})(\gamma\gamma)\)
     - \((\tau^+\tau^-)(\gamma\gamma)\)
     - \((\gamma\gamma)(\gamma\gamma)\)
     - \((\gamma\gamma)(g\bar{g})\)
   - via Spin-1 Bosons (Z')
     - \((\ell^+\ell^-)(\ell^+\ell^-)\)
     - \((\ell^+\ell^-)(q\bar{q})\)
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. \( h \rightarrow 2 \rightarrow 1 + 0 \)
   - \( \gamma + \text{MET} \)
3. \( h \rightarrow 2 \rightarrow 2 + 0 \)
   - via Spin-0 Bosons (S)
     - \((b\bar{b}) + \text{MET}\)
     - \((\tau^+\tau^-) + \text{MET}\)
     - \((\mu^+\mu^-) + \text{MET}\)
     - \((\gamma\gamma) + \text{MET}\)
   - via Spin-1 Bosons (Z')
     - \((\ell^+\ell^-) + \text{MET}\)
   - via Spin-1/2 Fermions
     - \(\gamma\gamma + \text{MET}\)
     - \([\gamma\gamma] + \text{MET}\)
     - \([\ell^+\ell^-] + \text{MET}\)
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')
     - \((l^-\bar{l}^+)(l^-\bar{l}^+)(q\bar{q})\)

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. \( h \rightarrow 2 \rightarrow 1+0 \)
   - \( \gamma + \text{MET} \)

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

Decays into purely visible or purely MET are familiar to us
Decays into MET + visible are less studied in the past
Decays to Standard Objects Without Missing Energy

1. \( h \rightarrow 2 \rightarrow (2)+(1) \)
   - \( \gamma + Z \)
   - \( \gamma + Z' \)
2. \( h \rightarrow 2 \rightarrow (2)+(2) \)
   - 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')
     - \((l^+l^-)(l^+l^-)\)
     - \((l^+l^-)(\gamma\gamma)\)
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
     - \([\gamma\gamma] + \) MET
     - \([l^+l^-] + \) MET

Can be found in many NP scenarios: SUSY, little Higgs, SM+X, .... we build up benchmarks in the Next-Minimal-Supersymmetric-SM (NMSSM)
NMSSM: R-symm limit vs. PQ-symm Limit

\[ W_{\text{NMSSM}} = Y_U Q H_u U^c - Y_D Q H_d D^c - Y_E L H_d E^c + \lambda N H_u H_d + \frac{1}{3} \kappa N^3 \]

\[ V_{\text{soft}} = m^2_{H_d} |H_d|^2 + m^2_{H_u} |H_u|^2 + m^2_N |N|^2 - (\lambda A \lambda H_u H_d N + \text{h.c.}) + \left( \frac{\kappa}{3} A \kappa N^3 + \text{h.c.} \right) \]

\begin{itemize}
  \item R-symmetry: Al, Ak -> 0, k is not small
  \item a1 is singlet-like and light: R-axion.
  \item Singlet-like CP-even Higgs and singlino-like neutralino are typically not light
  \begin{align*}
    M^2_{H33} & \sim \kappa (A \kappa + 4 \kappa s) \\
    M^2_{A22} & \sim -3 \kappa A \kappa s \\
    M_{\chi^055} & \sim 2 \kappa s
  \end{align*}
\end{itemize}

\begin{itemize}
  \item PQ-symmetry: k -> 0, Ak -> 0, Al is not small
  \item a_1, h_1 (singlet-like) and \chi_1 (singlino-like) tend to be simultaneously light
\end{itemize}

NMSSM: R-symmetry limit vs. PQ-symmetry 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
- $h \rightarrow \chi_1 \chi_2$ becomes significant, if kinematically allowed!


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

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

\[
y_{h_2 h_1 h_1} = -\sqrt{2}\lambda\varepsilon \frac{m_Z v}{\mu} + 2\sqrt{2}v\varepsilon^2 + \sum_{i=0}^{4} \mathcal{O} \left( \frac{\lambda^{4-i}}{\tan^i\beta} \right)
\]

\[
\varepsilon \propto \left( \frac{A_\lambda}{\mu \tan \beta} - 1 \right)
\]
**NMSSM: R-symm limit vs. PQ-symm Limit**

**R-symmetry**
- $h \rightarrow a_1a_1$ is typically significant


**PQ-symmetry**
- $h \rightarrow a_1a_1, h_1h_1$ are generically suppressed
- $h \rightarrow \chi_1\chi_2$ becomes significant, if kinematically allowed!

**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
- $h \rightarrow \chi_1 \chi_2$ becomes significant, if kinematically allowed!


$\chi_2 \rightarrow \chi_1 h_1, \chi_1 a_1$ are typically dominant
**NMSSM: R-symmetry limit vs. PQ-symmetry Limit**

**R-symmetry**

- $h \to a_1 a_1$ is typically significant
  

**PQ-symmetry**

- $h \to a_1 a_1$, $h_1 h_1$ are generically suppressed
- $h \to \chi_1 \chi_2$ becomes significant, if kinematically allowed!
  

---

<table>
<thead>
<tr>
<th>$a_1$</th>
<th>$\mu^-, \tau^-, b$</th>
</tr>
</thead>
</table>

| $h_2$ | $\chi_1, \chi_2$, $\chi_1 h_1, \chi_1 a_1$ become off-shell and $\text{Br}(\chi_2 \to \text{photon} + \chi_1)$ can be enhanced to $O(1\%)$ level |

NMSSM: R-symm limit vs. PQ-symm Limit

**R-symmetry**

- $h \rightarrow a_1a_1$ is typically significant


**PQ-symmetry**

<table>
<thead>
<tr>
<th>Benchmarks</th>
<th>$h \rightarrow \chi_1\chi_2$</th>
<th>$h \rightarrow \chi_1\chi_2$</th>
<th>$h \rightarrow \chi_2\chi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>0.18</td>
<td>0.064</td>
<td>0.02</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$3.4 \times 10^{-3}$</td>
<td>$9.0 \times 10^{-3}$</td>
<td>$1.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>9.0</td>
<td>12.5</td>
<td>10</td>
</tr>
<tr>
<td>$\mu (\text{GeV})$</td>
<td>326</td>
<td>138</td>
<td>160</td>
</tr>
<tr>
<td>$A_\lambda (\text{GeV})$</td>
<td>2960</td>
<td>1700</td>
<td>1800</td>
</tr>
<tr>
<td>$A_\kappa (\text{GeV})$</td>
<td>-43.5</td>
<td>-17</td>
<td>-7</td>
</tr>
<tr>
<td>$M_1 (\text{GeV})$</td>
<td>85</td>
<td>80</td>
<td>55</td>
</tr>
<tr>
<td>$m_{h_1} (\text{GeV})$</td>
<td>23.0</td>
<td>34.6</td>
<td>17.4</td>
</tr>
<tr>
<td>$m_{h_2} (\text{GeV})$</td>
<td>124.7</td>
<td>125.3</td>
<td>124.9</td>
</tr>
<tr>
<td>$m_{a_1} (\text{GeV})$</td>
<td>28.7</td>
<td>31.6</td>
<td>14.2</td>
</tr>
<tr>
<td>$m_{\chi_1} (\text{GeV})$</td>
<td>12.7</td>
<td>39.1</td>
<td>19.7</td>
</tr>
<tr>
<td>$m_{\chi_2} (\text{GeV})$</td>
<td>80.8</td>
<td>66.4</td>
<td>47.3</td>
</tr>
<tr>
<td>BR($h_2 \rightarrow a_1a_1$)</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>BR($h_2 \rightarrow \chi_1\chi_1$)</td>
<td>$&lt; 0.01$</td>
<td>0.04</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>BR($h_2 \rightarrow \chi_1\chi_2$)</td>
<td>0.28</td>
<td>0.27</td>
<td>0.05</td>
</tr>
<tr>
<td>BR($h_2 \rightarrow \chi_2\chi_2$)</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>0.31</td>
</tr>
<tr>
<td>BR($\chi_2 \rightarrow \chi_1h_1 + \chi_1a_1$)</td>
<td>0.92$\pm$0.08</td>
<td>$&lt; 0.01$</td>
<td>0.09 $\pm$ 0.60</td>
</tr>
<tr>
<td>BR($\chi_2 \rightarrow \chi_2 X^*$)</td>
<td>$&lt; 0.01$</td>
<td>0.96</td>
<td>0.30</td>
</tr>
<tr>
<td>BR($\chi_2 \rightarrow \chi_1\gamma$)</td>
<td>$&lt; 0.01$</td>
<td>0.04</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Tuesday, August 13, 2013
Many things 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
\[
C_{\text{eff}} = \frac{\sigma(h_2)}{\sigma(h_{\text{SM}})} \times \text{Br}(h_2 \rightarrow \chi_1\chi_2) \times \text{Br}(\chi_2 \rightarrow h_1\chi_1) \times \text{Br}(h_1 \rightarrow f\bar{f}) = 0.1
\]

[Huang, TL, Wang et. al., arXiv: 13xx.xxxx]
Example II: bbbb

- **Trigger:** Wh + Zh
- **Strategies:** work in the boost regime, apply jet substructure tool + 2b-tags
- **For 100/fb data at LHC14 and Ceff = 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, $\frac{S}{\sqrt{B}} \sim 5\sigma$ can be achieved (Ceff = 0.5)

[Red: Z + glu, gluon -> bb]
[Blue: tt + jets]
[Green: signal X 20]

- $m_{h_1} = 45$ GeV 
- $m_{h_2} = 125$ GeV 
- $m_{X_1} = 10$ GeV 
- $m_{X_2} = 80$ GeV

[Huang, TL, Wang et. al., arXiv: 13xx.xxxx]
The final state is purely MET or soft jets (with or without MET), given the BR for the exotic Higgs decay below 10%.

Question: can a Higgs factory play a role in discovering exotic decays which are challenging at the LHC?

The 125 GeV Higgs can be a leading window into BSM physics => must look explicitly for its exotic decays

There exist many possibilities for its exotic decays, so we need to survey, systematize, prioritize them, and assess their discovery potential

R- and PQ-symmetry limits in the NMSSM provide supersymmetric benchmarks for various exotic Higgs decays with and without MET

The LHC and a future Higgs factory can play a crucial role in searching for them ... ...
Thank you!