In the SM Higgs decays most readily to the pair of the heaviest kinematically available particles.

In the presence of new physics this can be dramatically altered.

MSSM and its extensions contain a lot of new particles that could mess with the Higgs sector.

Many possibilities: enhanced decays to $2\tau$, invisible decays etc.

One new dramatic possibility: cascade decays to many-body final states via new intermediate particles.
A selection (far from complete!) of SUSY models with cascade Higgs decay

- $H \to 4b, 4\tau$ in NMSSM, Dermisek, Gunion [hep-ph/0502105, hep-ph/0611142]
- $H \to 6j$ in R-parity violating MSSM Carpenter, Kaplan, Rhee [hep-ph/0607204]
- $H \to 4g$ (Buried Higgs) in SUSY Little Higgs Bellazzini, Csaki, AA, Weiler [0906.3026]
- $H \to 4c$ (Charming Higgs) in SUSY Little Higgs Bellazzini, Csaki, AA, Weiler [0910.0345]
- $H \to \text{lepton jets}$ in MSSM+light hidden sector AA, Ruderman, Volansky, Zupan [1002.2952]
### Experimental searches

#### Decay Channel

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Exp.</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h \rightarrow AA \rightarrow 4b$</td>
<td>LEP, hep-ex/0602042</td>
<td>110 GeV</td>
</tr>
<tr>
<td>$h \rightarrow AA \rightarrow 4\tau$</td>
<td>ALEPH, 1003.0705</td>
<td>$\sim$ 110 GeV</td>
</tr>
<tr>
<td>$h \rightarrow AA \rightarrow 4\mu, 2\mu 2\tau$</td>
<td>D0, 0905.3381</td>
<td>-</td>
</tr>
<tr>
<td>$h \rightarrow AA \rightarrow 4\mu, 4e$</td>
<td>RECAST, 1010.2506</td>
<td>$\sim$ 115 GeV</td>
</tr>
<tr>
<td>$h \rightarrow AA \rightarrow 4c, 4g$</td>
<td>OPAL, hep-ex/0209068</td>
<td>86 GeV</td>
</tr>
<tr>
<td>$h \rightarrow$ anything</td>
<td>OPAL, hep-ex/0206022</td>
<td>82 GeV</td>
</tr>
</tbody>
</table>

see Chang, Dermisek, Gunion, Weiner [0801.4554] for review

- Most searches for Higgs cascade decays are pretty recent
- In some case mass limits are weak because the channel did not receive enough attention
Case study: $H \rightarrow 4g$, Bellazzini, Csaki, AA, Weiler [0906.3026]

- Higgs dominantly decays to a pair of pseudoscalars $A$ with $m_A < 10$ GeV
- $A$ has sizable Yukawa couplings to the third generation quarks and tiny coupling to light quarks and to leptons
- For $m_A > 10$ GeV it dominantly decays to 2 b-quarks (not considered here)
- For $m_A < 10$ GeV it dominantly decays via loop of off-shell bottom quark to 2 gluons
- In effect, the leading Higgs decay is the cascade $h \rightarrow AA \rightarrow 4g$

In this model the branching into standard LHC discovery final states like $h \rightarrow \gamma\gamma$, $h \rightarrow bb$ or $h \rightarrow \tau\tau$ is strongly suppressed
Buried Forever?

- Because \( m_A \ll m_h \), A is boosted, and the 2 gluons from its decay will merge into 1 jet
- The signature of buried Higgs is 2 jets of low invariant mass \( \sim m_A \lesssim 10 \text{ GeV} \)
- At the LHC, it seems hopeless at first sight:
  - Gluon fusion \( gg \rightarrow h \) completely swamped by dijet background
  - VBF channels suffers because of the central jet veto
  - The associated production \( Vh \) or \( tth \) more promising, but the backgrounds from \( V + jets \) and \( tt + jets \) are many orders of magnitude larger than the signal
- Nevertheless...

jet substructure may save the day! Chen et al [1006.1151], AA,Krohn,Shelton,Thallapillil,Wang [1006.1650]
How to dig him out

AA,Krohn,Shelton,Thallapillil,Wang [1006.1650] looks at the following 2 channels

- **Higgstrahlung**: $W + h$
  - At LHC 14 TeV, $\sigma_{Wh} \sim 3$ pb for $m_h \sim 100$ GeV
  - Look at leptonic W boson decays
  - Main background: $W$+jets, $\sigma_W \sim 200$ nb

- **Associated production with top quarks**: $t\bar{t}h$
  - At LHC 14 TeV, $\sigma_{tth} \sim 1$ pb, for $m_h \sim 100$ GeV.
  - Look at dileptonic tops
  - Final state: 2 leptons (e or $\mu$), 2 tagged b-jets, and at least 2 ordinary jets
  - Main background: $tt$+jets, $\sigma_{tt+jets} \sim 1000$ pb, $S/B \sim 1/1000$
  - Note: contrary to the SM case no pesky combinatorics!
  - Other backgrounds like $ttZ$, $Zbb$ are by far subdominant

Assume SM production cross section and 100 percent branching fraction into 4 gluons (caution: both can be suppressed in specific models). Assume $m_A < 10$ GeV so the two gluons to which A decays merge into 1 jet, see Kaplan,McEvoy [1102.0704] for the large $m_A$ case
LHC is a very jetty place, and brute force kinematic cuts are not enough.

Concentrate on the kinematic regime where Higgs is boosted, $p_T(h) \gtrsim 150$ GeV, so that 2 jets from Higgs decay are approximately collimated and appear as one fat jet in the detector.

Then study the jet substructure, to identify the characteristic kinematics and color flow of buried Higgs. It turns out for QCD it is not easy to fake that substructure.

Jet substructure tools successfully earlier applied for the SM Higgs in the $W(H \rightarrow b\bar{b})$ channel Butterworth et al [0802.2470] and $t\bar{t}h$ channel, Plehn et al [0910.5472].
Signal and background are generated with MadGraph pipelined to Pythia 6.4 and Slowjet

- ISR, showering, pile-up and underlying event included
- 3 signal samples: $m_h = 80, 100, 120$, and $m_A = 8$ GeV
- The $t\bar{t}$+jets background is matched using MadGraphs native kT-MLM procedure
- Jet clustering is done in FastJet and SlowJet using the anti-kT scheme (similar results with C/A)
- Results robust under changing model of parton shower (Pythia virtuality-ordered) and choice of matching scheme (shower-kT)
This talk: ttH channel only (similar techniques and final signal significance in Wh channel). For each generated signal and background event

- Cluster all particles into jets of size $R = 0.4$ using the anti-kT algorithm
- Preselection of the dileptonic top sample: events with 2 identified opposite sign leptons + 2 identified b-jets
- Drop leptons and identified b-jets and further cluster remaining untagged jets into fat jets of size $R = 1.5$.
- Trim the fat jets to remove contamination from unrelated soft activity
- Select the hardest fat jet with at least 2 subjets and cut $p_T \gtrsim 130$ GeV
- Find 2 hardest subjets, and cut on their $p_T \gtrsim 40$ GeV
Substructure variables

- Signal has 2 subjets with the same and low invariant mass
- QCD radiation favors mass hierarchy and slightly larger jet masses (after pT cuts)

Mean invariant mass:

\[ \bar{m} = \frac{m(j_1) + m(j_2)}{2} \]

Mass democracy:

\[ \alpha_{sub} = \min \left( \frac{m(j_1)}{m(j_2)}, \frac{m(j_2)}{m(j_1)} \right) \]

Background (Blue) × 1, Signal (Red) × 100
Color flow variables

- Signal is color singlet until pseudoscalar decay at $\sim 10$ GeV: expect less radiation between jets

$$\beta_{sub} = \frac{p_T(j_3)}{p_T(j_1) + p_T(j_2)}$$

$$NJ(j, p_{th}) = \text{Number of subjets with } p_T > p_{th} \text{ inside the hardest fat jet}$$

Background (Blue) x 1, Signal(Red) x 100
- Cut on mass democracy $\alpha_{sub} \gtrsim 0.7$ on color flow $\beta_{sub} \lesssim 0.03$,
- After all cuts, signal displays a clear peak in the invariant mass of the fat jet, while background sharply drops at high masses

Background (black)
Signal + Background (purple $m_h = 80$ GeV, red $m_h = 100$ GeV, orange $m_h = 120$ GeV)
Bump Hunting

Similar significance in the $W+h$ channel, with a larger cross section after cuts but worse $S/B$

![Graph 1](image1.png)

![Graph 2](image2.png)

Significance, assuming 100 fb-1 as $\sqrt{s} = 14$ TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$m_h = 80$ GeV</th>
<th>$m_h = 100$ GeV</th>
<th>$m_h = 120$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow hW$</td>
<td>$S/\sqrt{B}$</td>
<td>6.6</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>$S/B$</td>
<td>0.34</td>
<td>0.90</td>
</tr>
<tr>
<td>$pp \rightarrow ht\bar{t}$</td>
<td>$S/\sqrt{B}$</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>$S/B$</td>
<td>1.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Conclusions

- Higgs may turn out to be standard and boring, but it may well be a vicious beast.
- Each case study usually leads to developing new collider tools and tightens our nets.
- With the help from methods of jet substructure a light Higgs boson decaying via a cascade $h \rightarrow AA \rightarrow 4g$ into 2 light jets can be discovered at the LHC with sufficiently large integrated luminosity.