Discovering a Higgs decaying to 4 jets in SUSY
Cascade decays

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Based on arXiv: 1012.1316
in collaboration with Bellazzini, Csaki and Hubisz

SUSY 2011, Aug 28, 2011
Outline

• Why is Higgs still missing?

• How to deal with Higgs decaying to jets?

• How can new physics help?

• Case study

• Conclusions
Summarize the result

- Higgs can decay 4 light jets -- suffer from large SM Bkg
- jet substructure + new physics channels can enhance the discovery
- 14TeV LHC -- 10-30fb^-1
Why is Higgs still missing?

- **LEP**
  - \( m_h > 115 \) GeV
  - \( h \rightarrow 4c, 4g \) or other light jets

- **Tevatron & LHC**
  - no evidence yet
  - for SM Higgs, 115-145 GeV

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h \rightarrow bb ) or ( \tau \bar{\tau} )</td>
<td>115 GeV</td>
</tr>
<tr>
<td>( h \rightarrow jj )</td>
<td>113 GeV</td>
</tr>
<tr>
<td>( h \rightarrow WW^* ) or ( ZZ^* )</td>
<td>110 GeV</td>
</tr>
<tr>
<td>( h \rightarrow \gamma\gamma )</td>
<td>117 GeV</td>
</tr>
<tr>
<td>( h \rightarrow \bar{E}E )</td>
<td>114 GeV</td>
</tr>
<tr>
<td>( h \rightarrow AA \rightarrow 4b )</td>
<td>110 GeV</td>
</tr>
<tr>
<td>( h \rightarrow AA \rightarrow 4\tau, 4c, 4g )</td>
<td>86 GeV</td>
</tr>
<tr>
<td>( h \rightarrow ) anything</td>
<td>82 GeV</td>
</tr>
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</table>
Nonstandard Higgs decay

- H decay to light jets: H -> 4jets
- New scalars couple to Higgs
  - Extended Higgs sector: NMSSM, ...
  - Buried/Charming Higgs: SU(3) -> SU(2), PGB: h, η

<table>
<thead>
<tr>
<th>( \mathcal{H}_u, \Phi_u )</th>
<th>( SU(3)_C )</th>
<th>( SU(3)_W )</th>
<th>( U(1)_X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{H}_d, \Phi_d )</td>
<td>1</td>
<td>3</td>
<td>1/3</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>-1/3</td>
<td></td>
</tr>
</tbody>
</table>

\[
\mathcal{H}_u^T = f_{sb} \begin{pmatrix}
\sin(\tilde{h}/\sqrt{2}f) & 0 \\
0 & e^{i\eta/\sqrt{2}f} \cos(\tilde{h}/\sqrt{2}f)
\end{pmatrix}, \quad \mathcal{H}_d = f_{cb} \begin{pmatrix}
\sin(\tilde{h}/\sqrt{2}f) & 0 \\
0 & e^{-i\eta/\sqrt{2}f} \cos(\tilde{h}/\sqrt{2}f)
\end{pmatrix}.
\]
How should we do?

• Normally form jets and combine them --> invariant mass

• Cluster a “fat” jet, then check the cluster sequence

  • mimic the physical process of showering

  • kinematic cuts iteratively, determine whether from decay or QCD radiation

  • jet mass/kinematics/jet shape

sequential clustering:

\[ d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta \phi^2}{R^2} \]

Kt(p=1), anti-Kt(p=-1), C/A(p=0)
Implementations

• Many ways developed
  BDRS, “Y-splitter”, “Top-tagging”
  Jet grooming : Pruning, Trimming
  Jet shapes

• Butterworth, Davison, Rubin and Salam (BDRS) 0802.2470
  Search SM Higgs to bb

  • mass drop: \( m(\text{subj}) < m(\text{jet}) \); decay kinematics: \( K_t \text{ dist} > y \ m(\text{jet}) \)

  • Filtering: recluster with smaller R, keep hardest 3 subjets

• Modified procedure Higgs -> 4g , need 100fb^{-1} @14TeV LHC

  Chen, Nojiri, Sreethawong (2010)
Reduction of Bkg with new physics signals

- Nonstandard Higgs decay implies new physics

- New colored exotics (> TeV) pair produced, e.g. gluino-gluino, squark-gluino, et al

- Cascade decay

  multi-jets + Large MET + Hτ

(assume lightest exotic is stable or long-lived)
Higgs from SUSY Cascade

- Boosted Higgs is generic

Gori, Schwaller and Wagner (2011)

Gunion et al. (1987); Baer, Bisset, Tata & Woodside (1992); Denegri, Majerotto and Rurua, CMS-NOTE-1997-094; S. Abdullin et al. (CMS Collaboration) (2002); I. Hinchliffe et al. (ATLAS Collaboration) (1997); Datta, Djouadi, Guchait and Moortgat (2004); Kribs, Martin, Roy and Spannowsky (2009, 2010)
Test our approach

- Two MSSM spectra: large mu/ small mu
- Force $h\rightarrow 2\eta\rightarrow 4j$
- Higgs signal 0.8pb 0.1pb
- $\text{Pt}>300\text{GeV}$ 40% 50%

\[\begin{align*}
\text{model 1} & & \text{model 2} \\
& & \\
\tilde{g}, \tilde{q} & \sim 1\text{TeV} & \tilde{g}, \tilde{q} & 2\text{TeV} \\
\tilde{\chi}_3, \tilde{\chi}_4 & 500 & \tilde{\chi}_4 & 625 \\
\tilde{\chi}_2 & 306 & \tilde{\chi}_3 & 306 \\
\tilde{\chi}_1 & 163 & \tilde{\chi}_1 \tilde{\chi}_2 & \sim 150
\end{align*}\]
Analysis path

- Inclusive productions: gluinos/squarks -> cascade decay
  - Signals: h + jets + MET
  - Generic from cascade decays: multi-bosons(w/z/h) + jets + MET
- SUSY cuts: at least 3 jets, leading two jets $P_T > (180, 110) \text{GeV}$, $(H_T, \text{MET}) > (500, 200) \text{GeV}$
- Jet analysis --> identify Higgs jets (BDRS + additional cuts)
- Consider $m_\eta \in [5 - 30] \text{ GeV}$, $m_h \in [90 - 120] \text{ GeV}$
Light $\eta$ ($\sim$10GeV)

- $\eta$ reconstructed automatically from the clustering
- Higgs jet selected and reconstructed from BDRS
- Additional kinematical cut -- $\eta$ is scalar
  - cut on extra subjet
    $$\beta_{\text{flow}} \equiv \frac{p_{T,j3}}{p_{T,j1} + p_{T,j2}}, \quad \text{if} \quad p_{T,j3} > p_T^{\text{min}}.$$  
  - cut on the subjet mass
    $$\alpha_{\text{MD}} \equiv \frac{\min(m_{j1}, m_{j2})}{\max(m_{j1}, m_{j2})}.$$
Result

- Jet mass distribution of all reconstructed jets --> Two resonances: W & Higgs

- BDRS + other kinematical cuts (cut 75% on W/Z, but 30% on Higgs)

- Estimate of discovery with 10/fb. Caveats: SUSY background model dependent

**model 1**

![Jet Mass Distribution](image1)

\( m_h = 120, m_\eta = 10 \text{ GeV} \)

**model 2 similar**

![Jet Mass Distribution](image2)

\( m_h = 100 \text{ GeV} \)

\( m_\eta = 10 \text{ GeV} \)
Heavier $\eta$ (~30GeV)

- Larger angle for the partons from $\eta$ decay --> four final partons more equally distributed
- Four-prong final state is itself hard to mimic
- Require 3 or 4 subjets after reclustering --> enough to reduce QCD jets as well as W/Z jets
- We take $R(\text{subjet}) = 0.25$, $N(\text{subjet}) > 3$ with $p_t > 15$GeV
Result

- Clean resonance!

- Low mass candidates suppressed and no W/Z peaks

- Efficiency is lower and the more data is needed --> ~10-30/fb

combinatorics large, veto evts with N(jet)>7

model 2 similar
Conclusions

• Search the light jet final states maybe the right way to find Higgs

• It’s difficult in the conventional way and with SM productions

• Maybe the presence of BSM new particles are the cure

• A new resonance give a hint of Higgs, but confirm it require other channels

• Discovery the light pseudo-scalar also very important, measure the decay branching ratio of Higgs?

• More work needs to be done before Higgs is being discovered
### Backup Slides

<table>
<thead>
<tr>
<th>Model</th>
<th>1</th>
<th>2</th>
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<tr>
<td>$m_{\tilde{q}_L,R}$</td>
<td>940, 910</td>
<td>1000</td>
</tr>
<tr>
<td>$m_{\tilde{\ell}}$</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$m_{\tilde{g}}$</td>
<td>949</td>
<td>2036</td>
</tr>
<tr>
<td>$m_{\chi_1^0}$</td>
<td>163</td>
<td>138</td>
</tr>
<tr>
<td>$m_{\chi_2^0}$</td>
<td>306</td>
<td>−158</td>
</tr>
<tr>
<td>$m_{\chi_3^0}$</td>
<td>−518</td>
<td>306</td>
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<td>$m_{\chi_4^0}$</td>
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<td>$m_{\chi_1^\pm}$</td>
<td>305</td>
<td>148</td>
</tr>
<tr>
<td>$m_{\chi_2^\pm}$</td>
<td>534</td>
<td>625</td>
</tr>
<tr>
<td>tan $\beta$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\mu$</td>
<td>512</td>
<td>150</td>
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<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>$\sigma(\tilde{g}, \tilde{q})$</td>
<td>2.5 pb</td>
<td>0.41 pb</td>
</tr>
<tr>
<td>BR($\tilde{q}_L \rightarrow h$)</td>
<td>30%</td>
<td>22%</td>
</tr>
<tr>
<td>BR($\tilde{q}_L \rightarrow Z$)</td>
<td>3%</td>
<td>25%</td>
</tr>
<tr>
<td>BR($\tilde{q}_L \rightarrow W$)</td>
<td>64%</td>
<td>48%</td>
</tr>
<tr>
<td>$\sigma \cdot$ BR($h$)</td>
<td>0.29 pb</td>
<td>0.04 pb</td>
</tr>
<tr>
<td>$\sigma \cdot$ BR($h + W/Z$)</td>
<td>0.47 pb</td>
<td>0.1 pb</td>
</tr>
<tr>
<td>$\sigma \cdot$ BR($W/Z$)</td>
<td>1.04 pb</td>
<td>0.23 pb</td>
</tr>
</tbody>
</table>
Simulation details

- Event generation (Pythia 6.4) with ISR/FSR, MPI
- Normal jet -- use C/A with R=0.5 (fastjet)
- SUSY signal cut (similar to CMS)
  - \( N(\text{jet}) > 2 \), \( pt(j1,j2) > 180,110 \text{GeV} \)
  - \( HT > 500 \text{ GeV}, \text{MET} > 200 \text{ GeV} \)

<table>
<thead>
<tr>
<th>( m_h, m_\eta )</th>
<th>(120, 10)</th>
<th>(100, 10)</th>
<th>(120, 30)</th>
<th>(100, 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R )</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.667</td>
<td>0.667</td>
<td>0.667</td>
<td>0.5</td>
</tr>
<tr>
<td>( \alpha_{MD} )</td>
<td>&gt; 0.7</td>
<td>&gt; 0.8</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>( \beta_{flow} )</td>
<td>&lt; 2%</td>
<td>&lt; 0.5%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( p_T^{\text{min}} )</td>
<td>2.0</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( R_{\text{sub}} )</td>
<td>-</td>
<td>-</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>( n_{\text{subj}} )</td>
<td>-</td>
<td>-</td>
<td>( \geq 4 )</td>
<td>( \geq 4 )</td>
</tr>
<tr>
<td>( p_T^{\text{min}}_{\text{sub}} )</td>
<td>-</td>
<td>-</td>
<td>15</td>
<td>17</td>
</tr>
</tbody>
</table>