Multiple $b$-jets reveal natural SUSY and the 125 GeV Higgs

Erik Perkins

University of California, Santa Barbara

KITP Higgs Identification Miniprogram
21 December 2012

D. Berenstein, T. Liu, EP - 1211.4288
Overview

- Natural SUSY
- Simplified models
- Related work on $h \rightarrow b\bar{b}$
- Analysis
- Results
- Future directions
Want to know the full details of mass generation for fermions

$h \rightarrow b\bar{b}$ seems obvious, but usually considered challenging

Challenge can be overcome in SM using boosted higgs with jet substructure methods

With well-motivated new physics, this search can be carried out in less-boosted region, without the need for jet substructure

Consider simplified models in a natural SUSY context
In the MSSM at tree level,

\[- \frac{m_Z^2}{2} \sim |\mu|^2 + m_{H_u}^2\]

To avoid fine-tuning, we need weak-scale SUSY.

Tolerances of fine-tuning place upper bound on $\mu$

\[|\mu| \lesssim 200 \text{GeV} \left( \frac{m_h}{120 \text{GeV}} \right) \sqrt{0.2\Delta}\]
\[
\delta m_{H_u}^2 \mid \tilde{t} = -\frac{3}{8\pi^2} y_t^2 (m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2) \log \left( \frac{\Lambda}{\text{TeV}} \right)
\]

\[
\delta m_{H_u}^2 \mid \tilde{g} = -\frac{2}{\pi} y_t^2 \left( \frac{\alpha_s}{\pi} \right) |M_3|^2 \log^2 \left( \frac{\Lambda}{\text{TeV}} \right)
\]

- Really, we only need \( m_{\tilde{t}}, m_{\tilde{g}}, m_{\tilde{h}} \) not too heavy, since these contribute most
- \( \implies \) first two sgenerations can decouple
Stop production guarantees lots of $b$-jets

Case 1

Case 2

Case 1 is textbook
(e.g Baer & Tata, Weak-Scale Supersymmetry)
Simplified models

<table>
<thead>
<tr>
<th>Benchmarks</th>
<th>I (GeV)</th>
<th>II (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tilde{g}}$</td>
<td>1281</td>
<td>1264</td>
</tr>
<tr>
<td>$m_{\tilde{t}_1}$</td>
<td>568</td>
<td>260</td>
</tr>
<tr>
<td>$m_{\tilde{t}_2}$</td>
<td>682</td>
<td>586</td>
</tr>
<tr>
<td>$m_{\tilde{b}_1}$</td>
<td>567</td>
<td>555</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_1^0}$</td>
<td>87</td>
<td>84</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_2^0}$</td>
<td>325</td>
<td>415</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_3^0}$</td>
<td>336</td>
<td>433</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}_1^{\pm}}$</td>
<td>321</td>
<td>413</td>
</tr>
<tr>
<td>$m_h$</td>
<td>125</td>
<td>125</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benchmarks</th>
<th>I (%)</th>
<th>II (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(\tilde{t}_2 \rightarrow \tilde{t}_1 h)$</td>
<td>0</td>
<td>47</td>
</tr>
<tr>
<td>$\text{Br}(\tilde{t}_1 \rightarrow \tilde{\chi}_1 h t)$</td>
<td>52</td>
<td>0</td>
</tr>
<tr>
<td>$\text{Br}(h \rightarrow b\bar{b})$</td>
<td>61</td>
<td>61</td>
</tr>
</tbody>
</table>
Finding $h \rightarrow b\bar{b}$ in $VH$, $t\bar{t}h$ possible in SM with jet substructure (0802.2470, 0910.5472)

- Multiple $b$ tagging has been considered before for higgs searches in new physics (hep-ph/0603200, 0912.4731, 1006.1656, 1103.4138, 1108.6329, 1204.2317)

- New physics studies require $\geq 3b$-jets in the final state
- Most also use jet substructure to reconstruct the hadronic higgs

- Is there another way?
Simulation framework

- SUSY-HIT $\rightarrow$ MadGraph+Pythia
- no detector simulation, but smearing and detector-level cuts
- no pileup - this will impact b-tagging and $E_T$ measurement
- parametrized b-tagging $\varepsilon \rightarrow 60\%$
Backgrounds

- $t\bar{t}b\bar{b}$ is important - always 4 b jets
- $t\bar{t}$+jets is less important - low $\not{E}_T$ in hadronic top decays
- $b\bar{b}b\bar{b}$+jets is less important because of low $H_T$ and low $\not{E}_T$
- SUSY backgrounds from events without Higgs are less important - fewer jets & b tags
- COMBINATORICS! This is the dominant background after event-level cuts
Production cross sections

- $\tilde{t}$ cross sections are $\mathcal{O}(1\text{pb}-0.1\text{pb})$ at 14 TeV

- LO $t\bar{t}b\bar{b}$ cross section normalized to 8.9 pb; include K factor of 2.3
**$t\bar{t}b\bar{b}$ distribution**

- multiple b-tagging requirement kills $ttbb$ efficiently
- non-top b’s come from gluon splitting, so softer, more collinear

- extra b’s fail the jet $p_T$ cut, or are reconstructed as a single b-jet
Event level kinematic distributions I

Case 1
Jet multiplicity

Case 2
Jet multiplicity

B jet multiplicity

B jet multiplicity
Event level kinematic distributions II

Case 1

Case 2
Event-level cuts

Case 1

- \( n_j \geq 6 \)
- \( n_b \geq 4, \ p_T > 30 \text{ GeV} \) for \( \geq 1 \)
- \( \not{\vec{E}}_T > 150 \text{ GeV} \)
- \( H_T > 500 \text{ GeV} \)

Case 2

- \( n_j \geq 6 \)
- \( n_b \geq 4, \ p_T > 30 \text{ GeV} \) for \( \geq 1 \)
- \( \not{\vec{E}}_T > 120 \text{ GeV} \)
- \( H_T > 650 \text{ GeV} \)
Event level cut flow

- 40/fb of 14 TeV data

<table>
<thead>
<tr>
<th>$\sqrt{s} = 14$ TeV</th>
<th>$t\bar{t}$+jets</th>
<th>$t\bar{t}bb$</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>$5.2 \times 10^7$</td>
<td>$8.2 \times 10^5$</td>
<td>26176</td>
<td>822275</td>
</tr>
<tr>
<td>Cut 1</td>
<td>$3.5 \times 10^7$</td>
<td>474234</td>
<td>20600</td>
<td>406331</td>
</tr>
<tr>
<td>Cut 2</td>
<td>88700</td>
<td>12077</td>
<td>961</td>
<td>824</td>
</tr>
<tr>
<td>Cut 3</td>
<td>51 / 79</td>
<td>442 / 796</td>
<td>567</td>
<td>436</td>
</tr>
<tr>
<td>Cut 4</td>
<td>29 / 23</td>
<td>351 / 366</td>
<td>547</td>
<td>389</td>
</tr>
</tbody>
</table>

- Natural SUSY revealed (at $\lesssim 20\sigma$ for $\sim 40$/fb)
- Or, relatively easy to kill this scenario
Busy events | 
Want clean events...
Busy events II

... but get messy events

$\phi$ vs $y$
The combinatorial problem

- At least 6 pairs to choose - if only 1 higgs, only 1 correct pair
- If we naively look at all pairs in the event, combinatorial background dominates (note: jet pairs are correlated here)

- How to choose the pair?
Pair $p_T$ distribution and ranking

- jet pair $p_T$ can discriminate the correct pair
- Ranking pairs by $p_T$ is most effective

Still want another variable, relatively independent of kinematics
Pull is designed to find dijets from color singlet decays

\[ \vec{t} = \sum_{i \in \text{jet}} \frac{p_T^i |r_i|}{p_T^{\text{jet}}} \vec{r}_i \]

For color singlets, \( \theta_t \) is less
Jet superstructure II

- Standard deviation of pull angles for each pair exhibit a slight $p_T$ dependence

- Use all pull information available for each pair
- Construct a $\chi^2$ variable as an effective pull angle

$$\theta_{\text{eff}} = \sqrt{\frac{\theta^2_{t,1}}{\sigma_{\theta_t}(p_T,1)} + \frac{\theta^2_{t,2}}{\sigma_{\theta_t}(p_T,2)}}$$
Effective pull angle distribution could be helpful

As with $p_T$, rank jet pairs by $\theta_{eff}$
Choosing the right pair

- Plot the pairs in the $p_T$-rank vs. $\theta_{\text{eff}}$-rank plane.
- In the higgs mass window, a noticeable difference!

- Now we can cut!
- Take triangular region with $p_T$-rank + $\theta_{\text{eff}}$-rank < 5
- Want to use multiple pairs per event (higgs pair may not be highest ranked)
- Pairs need to be uncorrelated
- Effective bin (mass window) is 40 GeV wide
- Choose multiple pairs per event if invariant masses differ by $\geq 40$ GeV
- Select pairs from rank triangle, starting with highest $p_T$ pair
- Admit additional pair $i$ if $|m_i - m_j| > 40$ GeV for $j > i$
Invariant mass distributions

- Higgs revealed

- No assumption of $m_h$
<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}$+jets</th>
<th>$t\bar{t}bb$</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>$5.2 \times 10^7$</td>
<td>$8.2 \times 10^5$</td>
<td>26176</td>
<td>822275</td>
</tr>
<tr>
<td>Cut 1</td>
<td>$3.5 \times 10^7$</td>
<td>474234</td>
<td>20600</td>
<td>406331</td>
</tr>
<tr>
<td>Cut 2</td>
<td>88700</td>
<td>12077</td>
<td>961</td>
<td>824</td>
</tr>
<tr>
<td>Cut 3</td>
<td>51 / 79</td>
<td>442 / 796</td>
<td>567</td>
<td>436</td>
</tr>
<tr>
<td>Cut 4</td>
<td>29 / 23</td>
<td>351 / 366</td>
<td>547</td>
<td>389</td>
</tr>
<tr>
<td>$\theta_{\text{eff}}$ rank</td>
<td>20 / 11</td>
<td>5+157 / 4+157</td>
<td>99+215</td>
<td>65+135</td>
</tr>
<tr>
<td>$p_T$ rank</td>
<td>20 / 12</td>
<td>4+166 / 4+159</td>
<td>91+219</td>
<td>86+108</td>
</tr>
<tr>
<td>$p_T - \theta_{\text{eff}}$ plane</td>
<td>13 / 13</td>
<td>5+104 / 3+104</td>
<td>78+147</td>
<td>65+62</td>
</tr>
</tbody>
</table>
Sensitivity comparison

- Higgs revealed

Case 1

Best $S/B$ is given by ranking plane method in both cases.
Important features:

- something like SM higgs $\leftrightarrow h \rightarrow b\bar{b}$ dominates
- light top partner $\leftrightarrow$ additional jets, b-jets
- long lived neutral particle $\leftrightarrow E_T$

Shared by:

- Randall-Sundrum with KK-parity
- little higgs with T-parity
Future directions

- Unfold events in detail to measure branching fractions
- Explicitly apply techniques to RS, LH models
Summary

- What is fermion mass generation mechanism? Need \( \text{BR}(h \rightarrow b\bar{b}) \)
- New physics cascades can help via b-jet multiplicity, \( \not{E}_T \)
- Combinatorics can be overcome with kinematics and color flow
- (Re)discovery potential for 14 TeV LHC with < 1 year of data