LHC search for di-Higgs decays of stoponium and other scalar resonances in events with two photons and two bottom jets

Nilanjana Kumar
Northern Illinois University

Phenomenology 2014 Symposium
University of Pittsburgh
Pittsburgh, May 6, 2014

Presentation Outline

Motivations

Event Generation and Simulation

Event Selection

Discovery Prospects
Motivations
Motivations

• Discovery of SM Higgs, Study of BSM by looking for new heavy particles($\eta$) decay into $h$. 

Motivations

- Discovery of SM Higgs, Study of BSM by looking for new heavy particles (η) decay into $h$.

- A light stop ($\tilde{t}_1$) scenario,
  “stop” = lightest top squark = spin-0 superpartner of top quark.
Motivations

• Discovery of SM Higgs, Study of BSM by looking for new heavy particles($\eta$) decay into $h$.

• A light stop($\tilde{t}_1$) scenario,
  "stop" = lightest top squark = spin-0 superpartner of top quark.

• Motivated by weak-scale baryogenesis, naturalness and abundance of thermal relic density.
Motivations

• Discovery of SM Higgs, Study of BSM by looking for new heavy particles ($\eta$) decay into $h$.

• A light stop ($\tilde{t}_1$) scenario, “stop” = lightest top squark = spin-0 superpartner of top quark.

• Motivated by weak-scale baryogenesis, naturalness and abundance of thermal relic density.

• Stoponium ($\eta\tilde{t}$), a bound state of stop-antistop.
Stoponium
Stoponium

- Stoponium ($\eta_{\tilde{t}}$), a bound state of stop-antistop, possible if

\[ m_{\tilde{t}_1} < m_{\tilde{N}_1} + m_t \quad , \quad m_{\tilde{t}_1} < m_{\tilde{C}_1} + 5 \text{ GeV} \]
Stoponium

- Stoponium (\(\eta_{\tilde{t}}\)), a bound state of stop-antistop possible if

\[ m_{\tilde{t}_1} < m_{\tilde{N}_1} + m_t \quad , \quad m_{\tilde{t}_1} < m_{\tilde{C}_1} + 5 \text{ GeV} \]

- Binding energy of order few GeV.
Stoponium

- Stoponium ($\eta_{\tilde{t}}$), a bound state of stop-antistop possible if
  
  $$m_{\tilde{t}_1} < m_{\tilde{N}_1} + m_t , \quad m_{\tilde{t}_1} < m_{\tilde{C}_1} + 5 \text{ GeV}$$

- Binding energy of order few GeV.

- Decays dominantly by stop-antistop annihilation:
  $$\eta_{\tilde{t}} \rightarrow gg, \; WW, \; ZZ, \; hh, \; \gamma\gamma, \; t\bar{t}, \ldots$$
Stoponium

- Stoponium ($\eta\tilde{t}$), a bound state of stop-antistop possible if
  
  $$m_{\tilde{t}_1} < m_{\tilde{N}_1} + m_t \quad , \quad m_{\tilde{t}_1} < m_{\tilde{C}_1} + 5 \text{ GeV}$$

- Binding energy of order few GeV.

- Decays dominantly by stop-antistop annihilation:
  $$\eta\tilde{t} \rightarrow gg, \, WW, \, ZZ, \, hh, \, \gamma\gamma, \, t\bar{t}, \ldots$$

- Very narrow decay width ($\approx$ few MeV), potentially observable.
Stoponium

- Stoponium ($\eta_{\tilde{t}}$), a bound state of stop-antistop possible if
  
  \[ m_{\tilde{t}_1} < m_{\tilde{N}_1} + m_t \quad , \quad m_{\tilde{t}_1} < m_{\tilde{C}_1} + 5 \text{ GeV} \]

- Binding energy of order few GeV.

- Decays dominantly by stop-antistop annihilation:
  
  \[ \eta_{\tilde{t}} \rightarrow gg, \; WW, \; ZZ, \; hh, \; \gamma\gamma, \; t\bar{t}, \ldots \]

- Very narrow decay width ($\approx$ few MeV), potentially observable.

- Can look for invariant mass peaks! (very rare for SUSY)
Motivations

Event Generation and Simulation

Event Selection

Discovery Prospects

\[ pp \rightarrow \tilde{\eta}_t \rightarrow hh \]

- Light stop models motivated by weak-scale baryogenesis.

- If \( m_{\eta_t} \) is not too far above the threshold \( 2m_h \), 
  \( \text{BR}(\eta_t \rightarrow hh) > 0.7 \) is possible.

Arxiv:0801.0327, S.P. Martin

![Graph showing branching ratio vs stoponium mass](image-url)
Several holes remain,

\[ m_{\tilde{t}_1} - m_{\tilde{N}_1} \approx m_W + m_b \]

\[ m_{\tilde{t}_1} - m_{\tilde{N}_1} \approx m_t \]

\[ m_{\tilde{t}_1} \approx m_{\tilde{N}_1} \]

R parity violating

\[ \tilde{t}_1 \rightarrow jj (?) \]

CMS is similar.
Stoponium Production Cross section:  \( pp \rightarrow \eta_{t} \)

arxiv 0912.4813 J.E. Younkin, S.P. Martin, arxiv 1401.1284 Kim, Idlibi, Mehen, Yoon, Hagiwara et al 1990

- Calculation is NLO, 1S+2S stoponium production.
- Significant uncertainty from stoponium wavefunction at origin \( R(0) \).
- Higher excited states may also contribute, depending on decay modes.
Search for stoponium in di-Higgs mode


A good di-Higgs signal:

\[ pp \rightarrow \eta_{\tilde{t}} \rightarrow hh \rightarrow b\bar{b}\gamma\gamma \]

- Results applicable to any di-Higgs resonance, including \( H \rightarrow hh \) in SUSY with low \( \tan \beta \). (Baur, Plehn, Rainwater 0310056; Liu, Wang, Zhu 1310.3634; Chen, Du, Fang, Lu 1312.7212).
- ATLAS search for resonant \( \eta \rightarrow hh \rightarrow b\bar{b}b\bar{b} \), ATLAS-CONF-2014-005.
- CMS search for resonant \( \eta \rightarrow hh \rightarrow b\bar{b}\gamma\gamma \), CMS PAS HIG-13-032.
Presentation Outline

Motivations

Event Generation and Simulation

Event Selection

Discovery Prospects
Event Generation and Simulation
Event Generation and Simulation

• **Madgraph 5** to generate events, in p-p collisions at $\sqrt{s} = 14$ TeV.
Event Generation and Simulation

- **Madgraph 5** to generate events, in p-p collisions at $\sqrt{s} = 14$ TeV.
- Modified **HEFT** to include a small $\eta hh$ coupling to allow the decay.
Event Generation and Simulation

- **Madgraph 5** to generate events, in p-p collisions at $\sqrt{s} = 14$ TeV.
- Modified **HEFT** to include a small $\eta hh$ coupling to allow the decay.
- $m_h = 126$ GeV, $\text{BR}(h \rightarrow b\bar{b}) = 0.57$, $\text{BR}(h \rightarrow \gamma\gamma) = 0.0022$. 
Event Generation and Simulation

- **Madgraph 5** to generate events, in p-p collisions at $\sqrt{s} = 14$ TeV.
- Modified **HEFT** to include a small $\eta hh$ coupling to allow the decay.
- $m_h = 126$ GeV, $\text{BR}(h \rightarrow b\bar{b}) = 0.57$, $\text{BR}(h \rightarrow \gamma\gamma) = 0.0022$.
- Generated $10^5$ events for each of 19 values of $m_\eta$, ranging from 275 GeV to 1000 GeV.
**Event Generation and Simulation**

- **Madgraph 5** to generate events, in p-p collisions at $\sqrt{s} = 14$ TeV.
- Modified **HEFT** to include a small $\eta hh$ coupling to allow the decay.
- $m_h = 126$ GeV, $\text{BR}(h \rightarrow b\bar{b}) = 0.57$, $\text{BR}(h \rightarrow \gamma\gamma) = 0.0022$.
- Generated $10^5$ events for each of 19 values of $m_\eta$, ranging from 275 GeV to 1000 GeV.
- Pythia for parton showering, Delphes 3 for detector simulation.
Event Generation and Simulation

- **Madgraph 5** to generate events, in p-p collisions at $\sqrt{s} = 14$ TeV.
- Modified **HEFT** to include a small $\eta hh$ coupling to allow the decay.
- $m_h = 126$ GeV, $\text{BR}(h \rightarrow b\bar{b}) = 0.57$, $\text{BR}(h \rightarrow \gamma\gamma) = 0.0022$.
- Generated $10^5$ events for each of 19 values of $m_\eta$, ranging from 275 GeV to 1000 GeV.
- Pythia for parton showering, Delphes 3 for detector simulation.
- *b-tagging efficiency for b-jets* = 0.6
  charm = 0.1 and $u, d, s = 0.001$
Presentation Outline

Motivations

Event Generation and Simulation

Event Selection

Discovery Prospects
Event Selection

Event Selection S1:

- $p_T(b_1, b_2) > (40, 30)$ GeV
- $p_T(\gamma_1, \gamma_2) > (20, 15)$ GeV
- $|\eta(b_1, b_2)| < 2.7$
- $|\eta(\gamma_1, \gamma_2)| < 2.5$
- $\Delta R_{ij} > 0.5$, for $i, j = b_1, b_2, \gamma_1, \gamma_2$
A cut on Resonance Invariant Mass

- Distributions of $M_{bb\gamma\gamma}$ and $M_X$ for $m_\eta = 275$ GeV and 500 GeV.

- Most of the events are within about $\pm 7\%$ of $m_\eta$.

Modified invariant mass,

$$M_X \equiv M_{bb\gamma\gamma} - M_{bb} + m_h$$

It mitigates the effects of $b$-jet momentum mismeasurements.
The sequence of event selection cuts we used is:

**S2:** As in S1, with $|M_{\gamma\gamma} - m_h| < 6$ GeV,

**S3:** As in S2, with $|M_{bb} - m_h| < 30$ GeV,

**S4:** As in S3, with $|M_X - m_\eta| < 0.07 m_\eta$, where $m_\eta$ is the position of the putative peak.
Backgrounds

- non-resonant $\gamma\gamma b\bar{b}$ production
- $\gamma\gamma c\bar{c}$
- $\gamma\gamma qc/q\bar{c}$ (where $q = u, d, s$)
- $\gamma\gamma q\bar{q}$
- $\gamma\gamma t\bar{t}$
- $\gamma\gamma bq$
Backgrounds

- non-resonant $\gamma\gamma b\bar{b}$ production
- $\gamma\gamma c\bar{c}$
- $\gamma\gamma q c / q\bar{c}$ (where $q = u, d, s$)
- $\gamma\gamma q\bar{q}$
- $\gamma\gamma t\bar{t}$
- $\gamma\gamma b q$

- 4-jet background ($jjjj$) is not included because efficiencies for jets faking photons is quite low, and distributed at low photon $p_T$ and invariant masses.

- $\gamma\gamma Z$
- $t\bar{t}h$
- $Zh$
- $b\bar{b}h$
- $hh$
Backgrounds

- non-resonant $\gamma\gamma b\bar{b}$ production
- $\gamma\gamma c\bar{c}$
- $\gamma\gamma qc/q\bar{c}$ (where $q = u, d, s$)
- $\gamma\gamma q\bar{q}$
- $\gamma\gamma t\bar{t}$
- $\gamma\gamma bq$

- 4-jet background ($jjjj$) is not included because efficiencies for jets faking photons is quite low, and distributed at low photon $p_T$ and invariant masses.

- Generator-level cut on the diphoton pair ($106 < M_{\gamma\gamma} < 146$) in Backgrounds that include $\gamma\gamma$. 

- $\gamma\gamma Z$
- $t\bar{t}h$
- $Zh$
- $b\bar{b}h$
- $hh$
Backgrounds

- non-resonant $\gamma\gamma b\bar{b}$ production
- $\gamma\gamma c\bar{c}$
- $\gamma\gamma q\bar{c}/q\bar{c}$ (where $q = u, d, s$)
- $\gamma\gamma q\bar{q}$
- $\gamma\gamma t\bar{t}$
- $\gamma\gamma bq$

- 4-jet background ($jjjj$) is not included because efficiencies for jets faking photons is quite low, and distributed at low photon $p_T$ and invariant masses.

- Generator-level cut on the diphoton pair ($106 < M_{\gamma\gamma} < 146$) in Backgrounds that include $\gamma\gamma$.

- Some of our samples have low statistics, but real data should give better estimates using sidebands away from the signal regions in $M_{\gamma\gamma}$, $M_{bb}$, and $M_X$. 

- $\gamma\gamma Z$
- $t\bar{t}h$
- $Zh$
- $b\bar{b}h$
- $hh$
Most significant backgrounds after sequential cuts, for $m_\eta = 275$ GeV:

<table>
<thead>
<tr>
<th>Background</th>
<th>$N_{gen}$</th>
<th>$\sigma_{\text{pass}}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$bb\gamma\gamma$</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma b\bar{b}$</td>
<td>2000000</td>
<td>1.344</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma bq/\bar{b}q$</td>
<td>2000000</td>
<td>1.050</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma c\bar{c}$</td>
<td>440000</td>
<td>0.406</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma qc/q\bar{c}$</td>
<td>600000</td>
<td>0.500</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma q\bar{q}$</td>
<td>1200000</td>
<td>0.735</td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma t\bar{t}$</td>
<td>200000</td>
<td>0.152</td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t}h$</td>
<td>100000</td>
<td>0.0752</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4.353</td>
</tr>
</tbody>
</table>

Other backgrounds are smaller, but still included. Only the $\sigma_{\text{pass}}$ after the last cut depends on $M_X$. 
For larger $m_\eta$, the more important backgrounds become: $\gamma\gamma q\bar{q}$ and $\gamma\gamma bq/\bar{b}q$ and $\gamma\gamma qc/q\bar{c}$ with $q = u, d, s$.

Backgrounds are also more uncertain in our analysis due to statistics of our event samples; determination from data-driven methods will be more reliable.
Distribution of signals and Background

$M_{bb}$ after $M_X$ cut:

![Graph showing $M_{bb}$ distribution after $M_X$ cut.]

$M_X$ after $M_{bb}$ cut:

![Graph showing $M_X$ distribution after $M_{bb}$ cut.]

With a 2 pb signal for $pp \rightarrow \eta \rightarrow hh$, and 300 fb$^{-1}$ at $\sqrt{s} = 14$ TeV, discovery should be very easy.
Presentation Outline

Motivations

Event Generation and Simulation

Event Selection

Discovery Prospects
Discovery Prospects
Set a requirement for a 5-sigma observation of the signal by demanding that $S/\sqrt{B} > 5$, where $S$ and $B$ are the numbers of signal and background events, respectively, that pass the S4 selection.
Discovery Prospects

- Set a requirement for a 5-sigma observation of the signal by demanding that $S/\sqrt{B} > 5$, where $S$ and $B$ are the numbers of signal and background events, respectively, that pass the S4 selection.

- Also require a minimum of $S > 10$ signal events for a discovery, which becomes important when the signal and background cross-sections are both low.
Discovery prospects of $\sigma(pp \rightarrow \eta \rightarrow hh)$

- $S/\sqrt{B} = 5$, $S > 10$
- $S/\sqrt{B} > 5$, $S = 10$

- Discovery for $\sigma = 1$ pb easily possible with less than $\leq 100$ fb$^{-1}$ if $m_\eta \geq 275$ GeV.
- Discovery for $\sigma = 150$-200 fb may be possible with 300 fb$^{-1}$.
Luminosity required for discovery of Stoponium

- $S/\sqrt{B} = 5, S > 10$
- $S/\sqrt{B} > 5, S = 10$

- With 15 fb$^{-1}$ LHC would be able to discover the di-Higgs decay of stoponium with $m_{\eta_t} = 275$ GeV, if the BR $\approx 100\%$.

- For lower branching ratios, the required integrated luminosity is clearly much higher.
<table>
<thead>
<tr>
<th>Motivations</th>
<th>Event Generation and Simulation</th>
<th>Event Selection</th>
<th>Discovery Prospects</th>
</tr>
</thead>
</table>

**Conclusion**
Conclusion

- LHC searches for di-Higgs resonances should be a priority in the future, in order to exploit the Higgs discovery as a possible window to new physics.
Conclusion

- LHC searches for di-Higgs resonances should be a priority in the future, in order to exploit the Higgs discovery as a possible window to new physics.

- A di-Higgs resonance of any heavy scalar with a cross-section of 1 pb can be easily discovered with less than 100 fb$^{-1}$ of integrated luminosity, as long as $m_\eta \geq 275$ GeV.
Conclusion

- LHC searches for di-Higgs resonances should be a priority in the future, in order to exploit the Higgs discovery as a possible window to new physics.

- A di-Higgs resonance of any heavy scalar with a cross-section of 1 pb can be easily discovered with less than 100 fb$^{-1}$ of integrated luminosity, as long as $m_\eta \geq 275$ GeV.

- If heavy stops and/or small BR, then prospects are grim for the di-Higgs channel.
Conclusion

- LHC searches for di-Higgs resonances should be a priority in the future, in order to exploit the Higgs discovery as a possible window to new physics.

- A di-Higgs resonance of any heavy scalar with a cross-section of 1 pb can be easily discovered with less than 100 fb$^{-1}$ of integrated luminosity, as long as $m_\eta \geq 275$ GeV.

- If heavy stops and/or small BR, then prospects are grim for the di-Higgs channel.

- Searches for di-Higgs resonances should be performed anyway, on general grounds.
Most of the events are within about $\pm 7\%$ of $m_\eta$. 
The $M_{bb}$ distributions of the total background is reduced after including cut on $M_X$. 

14 TeV LHC, 300 fb$^{-1}$

$m_\eta = 275$ GeV

$pp > \eta > hh$ (2 pb)

Total Background
The $M_X$ distributions of the total background is reduced after including cut on $M_{bb}$.
Stop search from CMS:

CMS Preliminary $\int L dt = 19.7 \text{ fb}^{-1}$, $\sqrt{s} = 8 \text{ TeV}$

$\tilde{t} \rightarrow \chi_1^0 c$ NLO+NLL exclusion

- Expected limits $\pm 1\sigma_{\text{exp}}$
- Observed limits $\pm 1\sigma_{\text{theory}}$

$\tilde{t} \tilde{t}$ production

CMS Preliminary $\sqrt{s} = 8 \text{ TeV}$

SUSY 2013

- Observed
- Expected

- SUS-13-004 0-lep+1-lep (Razor) 19.3 fb$^{-1}$ ($\tilde{t} \rightarrow t \chi_1^3$)
- SUS-13-011 1-lep (leptonic stop) 19.5 fb$^{-1}$ ($\tilde{t} \rightarrow t \chi_1^3$)
- SUS-13-011 1-lep (leptonic stop) 19.5 fb$^{-1}$ ($\tilde{t} \rightarrow b \chi_1^3$, $x=0.25$)

- $m_{\tilde{t}_1} < m_{\tilde{c}_1} + m_c$
- $m_{\tilde{t}_1} > m_{\tilde{c}_1} + m_W + m_b$
- $m_{\tilde{t}_1} > m_{\tilde{c}_1} + m_W + m_h$
- $m_{\tilde{t}_1} < m_{\tilde{c}_1} + m_h$
- $m_{\tilde{t}_1} > m_{\tilde{c}_1} + m_h$
- $m_{\tilde{t}_1} < m_{\tilde{c}_1} + m_h$
- $m_{\tilde{t}_1} > m_{\tilde{c}_1} + m_h$

LEP, $\theta=0^{\circ}$
LEP, $\theta=56^{\circ}$
D0: 1fb$^{-1}$
CDF: 2.6fb$^{-1}$

Expected limits $\pm 1\sigma_{\text{theory}}$

Observed limits $\pm 1\sigma_{\text{theory}}$
ATLAS and CMS looked for di-higgs resonance

ATLAS $bar{b}bar{b}$

CMS $\gamma\gamma b\bar{b}$
Stoponium binding energy $2m_{\tilde{t}} - m_{\eta_{\tilde{t}}}$ as a function of stoponium mass $m_{\eta_{\tilde{t}}}$:

![Graph showing binding energy as a function of stoponium mass.](Image)

SPM 0801.0237, using Hagiwara et al 1990 potential model, extrapolated from charmonium and bottomonium data.

In contrast, stoponium decay width due to annihilation is typically of order few MeV. Since $E_{\text{binding}} \gg \Gamma_{\text{decay}}$, stoponium will form, unless 2-body stop decay modes are kinematically open.
# Backgrounds

<table>
<thead>
<tr>
<th>Background</th>
<th>$N_{gen}$</th>
<th>$\sigma_{pass}$ (fb)</th>
<th>$M_{bb\gamma\gamma}$</th>
<th>$M_{\gamma\gamma}$</th>
<th>$M_{bb}$</th>
<th>$M_X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \gamma\gamma bb$</td>
<td>2000000</td>
<td>$1.344$</td>
<td>$0.398$</td>
<td>$0.120$</td>
<td>$0.0475$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma cc$</td>
<td>4400000</td>
<td>$0.406$</td>
<td>$0.122$</td>
<td>$0.0398$</td>
<td>$0.0170$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma tt$</td>
<td>2000000</td>
<td>$0.152$</td>
<td>$0.0771$</td>
<td>$0.0211$</td>
<td>$0.00533$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma bq/bq$</td>
<td>2000000</td>
<td>$1.050$</td>
<td>$0.313$</td>
<td>$0.104$</td>
<td>$0.0270$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma qc/q\bar{c}$</td>
<td>6000000</td>
<td>$0.500$</td>
<td>$0.145$</td>
<td>$0.0415$</td>
<td>$0.0120$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma q\bar{q}$</td>
<td>1200000</td>
<td>$0.735$</td>
<td>$0.244$</td>
<td>$0.0940$</td>
<td>$0.0096$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow \gamma\gamma ZZ$</td>
<td>2000000</td>
<td>$0.0660$</td>
<td>$0.0232$</td>
<td>$0.00276$</td>
<td>$0.00072$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow ttth$</td>
<td>1000000</td>
<td>$0.0752$</td>
<td>$0.0647$</td>
<td>$0.0176$</td>
<td>$0.00428$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow Zh$</td>
<td>1000000</td>
<td>$0.00940$</td>
<td>$0.00812$</td>
<td>$0.00338$</td>
<td>$0.00068$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow b\bar{b}hh$</td>
<td>1000000</td>
<td>$0.0116$</td>
<td>$0.0102$</td>
<td>$0.00257$</td>
<td>$0.00053$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow hh$</td>
<td>1000000</td>
<td>$0.0103$</td>
<td>$0.00936$</td>
<td>$0.00772$</td>
<td>$0.00263$</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.353</strong></td>
<td><strong>1.430</strong></td>
<td><strong>0.661</strong></td>
<td><strong>0.127</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>