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

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Work done with Stephen P. Martin, arXiv:1404.0996

Presentation Outline

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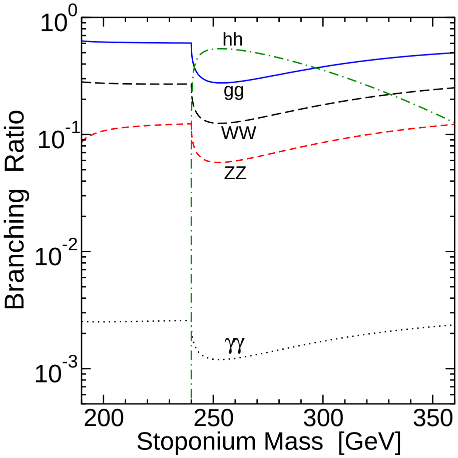
- Can look for invariant mass peaks! (very rare for SUSY)

$pp \to \eta_{\tilde{t}} \to hh$

- Light stop models motivated by weak-scale baryogenesis.
- If $m_{\eta_{\tilde{t}}}$ is not too far above the threshold $2m_h$, $\text{BR}(\eta_{\tilde{t}} \to hh) > 0.7$ is possible.

Arxiv:0801.0327,S.P.Martin



Light Stop Search

Several holes remain,

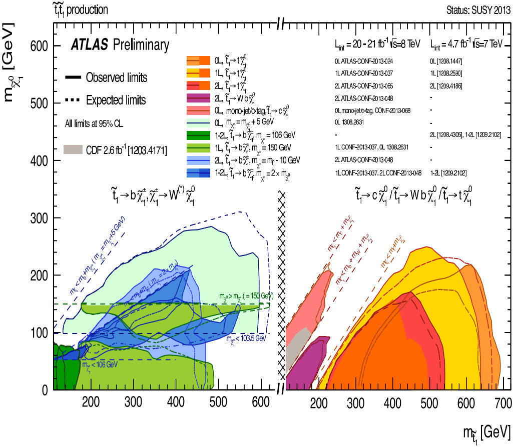
$$m_{\tilde{t}_1} - m_{\tilde{N}_1} \approx m_W + m_b$$

$$m_{\tilde{t}_1} - m_{\tilde{N}_1} \approx m_t$$

$$m_{\tilde{t}_1} \approx m_{\tilde{N}_1}$$

R parity violating

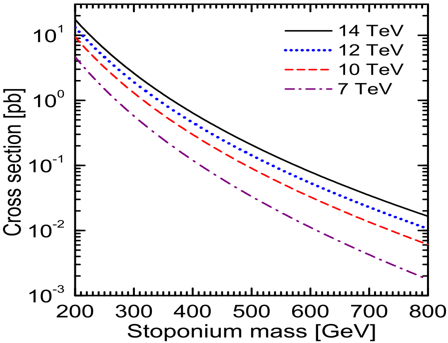
$$\tilde{t}_1 \to jj \ (?)$$



CMS is similar.

Stoponium Production Cross section: $pp \to \eta_{\tilde{t}}$

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



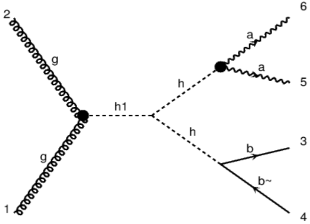
- Calculation is NLO, 1S+2S stoponium production.
- Significant uncertainty from stoponium wavefunction at origin $R(0)$.
- Higher excited states may also contribute, depending on decay modes.

Search for stoponium in di-Higgs mode

Originally proposed by Barger and Keung PLB211, 355, 1988.

A good di-Higgs signal:

$$pp \to \eta_{\tilde{t}} \to hh \to b\bar{b}\gamma\gamma$$



- Results applicable to any di-Higgs resonance, including $H \to hh$ 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 $\eta \to hh \to b\bar{b}b\bar{b}$, ATLAS-CONF-2014-005.
- CMS search for resonant $\eta \to hh \to b\bar{b}\gamma\gamma$, CMS PAS HIG-13-032.

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- Pythia for parton showering, Delphes 3 for detector simulation.
- ***b*-tagging efficiency for *b*-jets = 0.6**
  charm $= 0.1$ and $u, d, s = 0.001$

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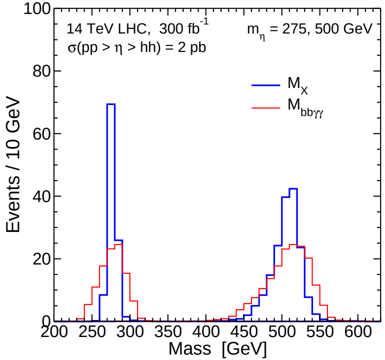
Event Selection

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_η.



Modified invariant mass,

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

It mitigates the effects of b-jet momentum mismeasurements.

Event Selection

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_η 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 $q = u, d, s$)
- $\gamma\gamma q\bar{q}$
- $\gamma\gamma t\bar{t}$
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- $t\bar{t}h$
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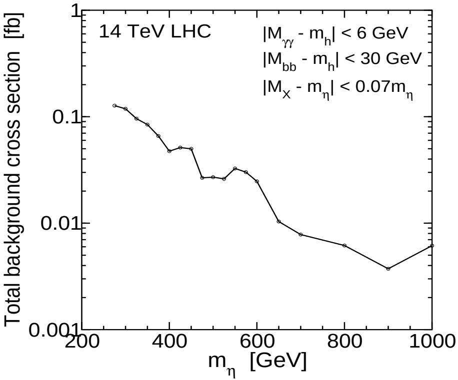
- Generator-level cut on the diphoton pair ($106 < M_{\gamma\gamma} < 146$) in Backgrounds that include $\gamma\gamma$.
- Some of our samples have low statistics, but real data should give better estimates using sidebands away from the signal regions in $M_{\gamma\gamma}$, M_{bb}, and M_X.

Most significant backgrounds after sequential cuts, for $m_\eta = 275$ GeV:

Background	N_{gen}	σ_{pass} (fb)			
		$bb\gamma\gamma$	$M_{\gamma\gamma}$	M_{bb}	M_X
$pp \to \gamma\gamma b\bar{b}$	200000	1.344	0.398	0.120	0.0475
$pp \to \gamma\gamma bq/\bar{b}q$	200000	1.050	0.313	0.104	0.0270
$pp \to \gamma\gamma c\bar{c}$	440000	0.406	0.122	0.0398	0.0170
$pp \to \gamma\gamma qc/q\bar{c}$	600000	0.500	0.145	0.0415	0.0120
$pp \to \gamma\gamma q\bar{q}$	1200000	0.735	0.244	0.0940	0.0096
$pp \to \gamma\gamma t\bar{t}$	200000	0.152	0.0771	0.0211	0.0053
$pp \to t\bar{t}h$	100000	0.0752	0.0647	0.0176	0.0043
Total		4.353	1.430	0.661	0.127

Other backgrounds are smaller, but still included.
Only the σ_{pass} after the last cut depends on M_X.

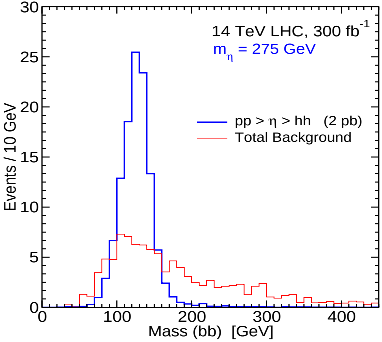
Total Background



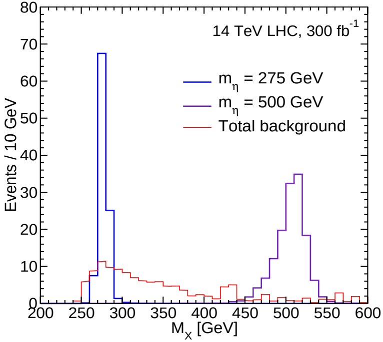
- For larger m_η, the more important backgrounds become: $\gamma\gamma q\bar{q}$ and $\gamma\gamma bq/\bar{b}q$ and $\gamma\gamma qc/q\bar{c}$ with $q = u, d, s$.
- Backgrounds are also more uncertain in our analysis due to statistics of our event samples; determination from data-driven methods will be more reliable.

Distribution of signals and Background

M_{bb} after M_X cut:



M_X after M_{bb} cut:



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

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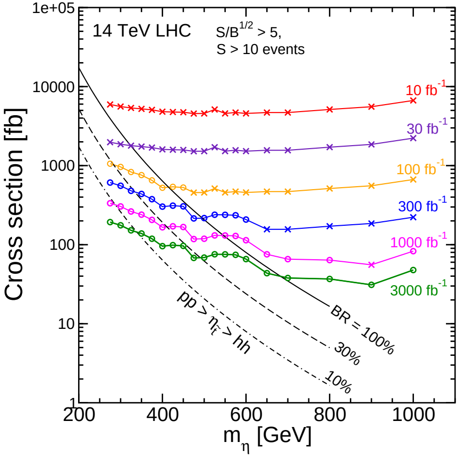
- Also require a minimum of $S > 10$ signal events for a discovery, which becomes important when the signal and background cross-sections are both low.

Discovery prospects of $\sigma(pp \to \eta \to hh)$

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

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

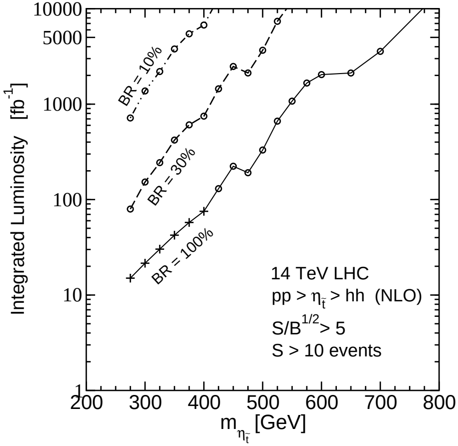


- Discovery for $\sigma = 1$ pb easily possible with less than ≤ 100 fb^{-1} if $m_\eta \geq 275$ GeV.
- Discovery for $\sigma =$ 150-200 fb may be possible with 300 fb^{-1}.

Luminosity required for discovery of Stoponium

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

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



- With **15 fb**$^{-1}$ LHC would be able to discover the di-Higgs decay of stoponium with $m_{\eta_{\tilde{t}}} = 275$ GeV, if the BR $\approx 100\%$.
- For lower branching ratios, the required integrated luminosity is clearly much higher.

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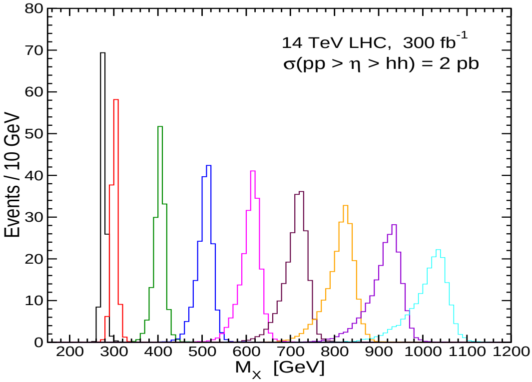
- A di-Higgs resonance of any heavy scalar with a cross-section of 1 pb can be easily discovered with less than 100 fb^{-1} of integrated luminosity, as long as $m_\eta \geq 275$ GeV.
- If heavy stops and/or small BR, then prospects are grim for the di-Higgs channel.
- Searches for di-Higgs resonances should be performed anyway, on general grounds.

M_X Distribution



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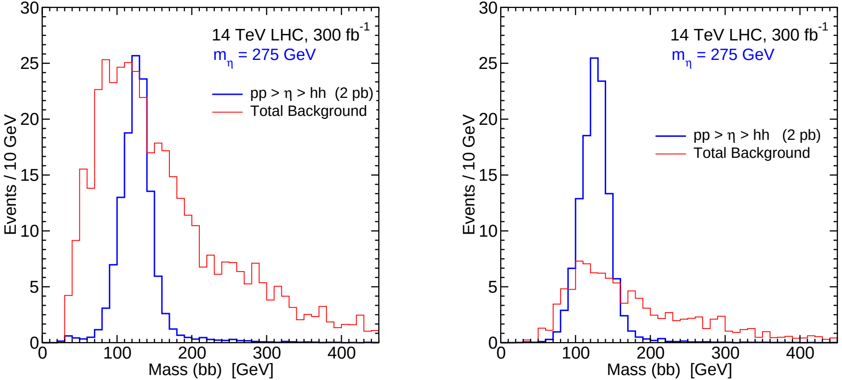
M_{bb} distribution



The M_{bb} distributions of the total background is reduced after including cut on M_X.

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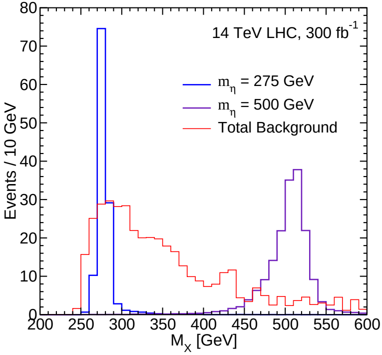

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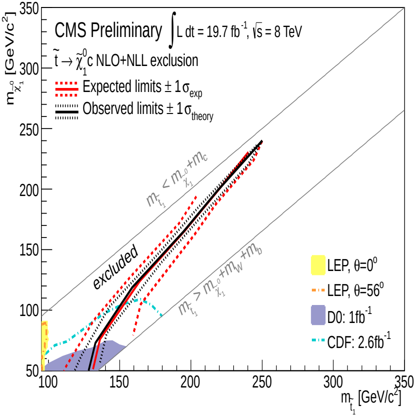
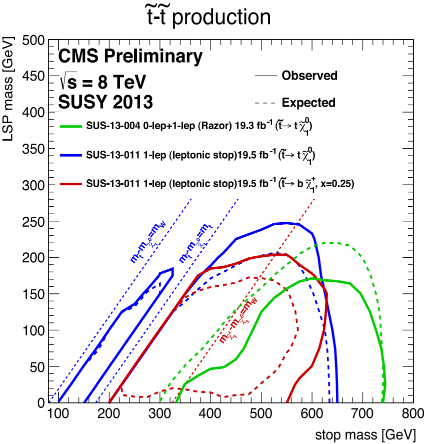
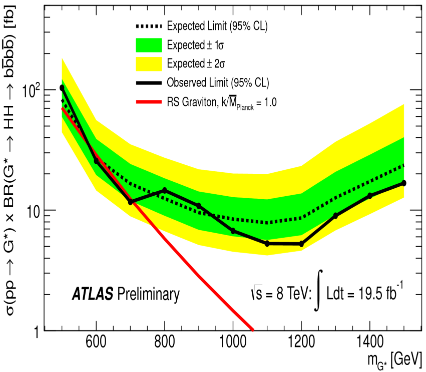
Stop search from CMS:



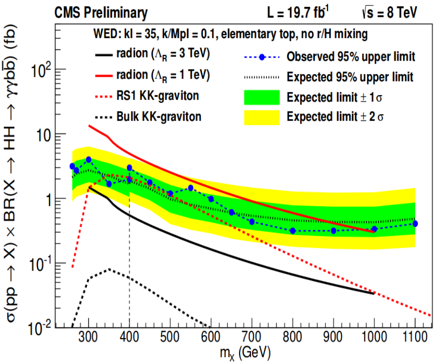


ATLAS and CMS looked for di-higgs resonance

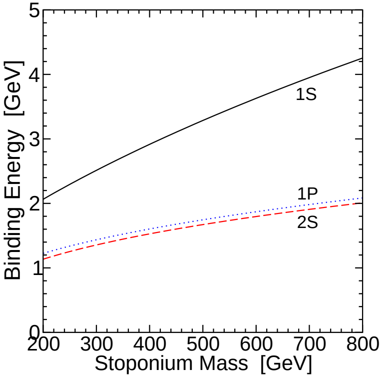
ATLAS $b\bar{b}b\bar{b}$



CMS $\gamma\gamma b\bar{b}$



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



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.

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$pp \to t\bar{t}h$	100000	0.0752	0.0647	0.0176	0.00428
$pp \to Zh$	100000	0.00940	0.00812	0.00338	0.00068
$pp \to b\bar{b}h$	100000	0.0116	0.0102	0.00257	0.00053
$pp \to hh$	100000	0.0103	0.00936	0.00772	0.00263
Total		4.353	1.430	0.661	0.127