Search for di-Higgs final states and rare or exotic decays of the Higgs boson by the ATLAS collaboration

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Topics

1. Searches for (Non-)Resonant Higgs Production

- \((X \rightarrow) hh \rightarrow \gamma\gamma bb\): non-resonant and resonant production
  Narrow Higgs, \(m_X: 275-400\) GeV
  (ATLAS-CONF-2016-004)

- \(X \rightarrow hh \rightarrow bbbb\): resonant production
  Narrow Higgs and Kaluza-Klein graviton, \(m_X: 600-3000\) GeV
  (ATLAS-CONF-2016-017)

2. Exotic/Rare Higgs Decays

- \(H \rightarrow e\tau\) and \(H \rightarrow \mu\tau\) (LFV)
  (arXiv:1508.03372)

Dataset

- Di-Higgs analyses use 3.2 fb\(^{-1}\) of pp data collected in 2015, w/ \(\sqrt{s} = 13\) TeV
- LFV analysis uses 20.3 fb\(^{-1}\) of pp data collected in 2012, w/ \(\sqrt{s} = 8\) TeV
Search for non-resonant and resonant ($X \rightarrow \gamma\gamma$) $hh$ production

- **Overview**
  - Signal region (SR) with 2 photons and 2 b-tagged jets
  - Control region (CR) with 2 photons and 0 b-tagged jets
  - $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$, $95 \text{ GeV} < m_{bb} < 135 \text{ GeV}$
  - $|m_{\gamma\gamma} - m_{H}| < 2 \cdot \sigma_{m_{\gamma\gamma}} = 3.1 \text{ GeV}$ (res. only)
  - $m_X$ dependent cut on $m_{bb\gamma\gamma}$ (res. only), based on 95% eff. for sim. samples
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- **The \( h \rightarrow bb \) Hypothesis**
  - 4-momentum of \( b\bar{b} \) system scaled by \( m_h/m_{bb} \)
  - 60% improvement, for sim. samples, in \( m_{bb\gamma\gamma} \) res. (top)
  - No significant impact on background (bottom)
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- **Statistical Method**
  - **Non-Res.** Unbinned $m_{\gamma\gamma}$ spectrum fit to background (exponential) and signal (double-sided Crystal Ball) models
  - **Res.** “Cut-and-count” in signal region

- Background is extrapolated from $m_{\gamma\gamma}$ sidebands and CR
**hh → γγbb: Results**

- 0 events observed in signal region
$hh \rightarrow \gamma\gamma bb$: Results

- 0 events observed in signal region
- Upper limit of 3.9 pb on non-resonant $hh$ production set at the 95% C.L.
- Upper limits set vs. $m_X$ on $\sigma_X \times BR_{X\rightarrow hh}$ (left) and converted to the event yield from $X \rightarrow hh$ (right)

Limits based on an effective field theory (EFT) model implemented in MadGraph5_aMC@NLO v2.2.2
Analysis divided into ‘resolved’ and ‘merged’ regimes:

- **Resolved Overview**
  - \(m_{G^*}\) is ‘small’ (below 1.1 TeV) \(\Rightarrow 4\) b-tagged jets
  - Di-jet (\(jj\)) systems are formed, such that \(\Delta R_{jj} < 1.5\)
  - 2 \(jj\)’s are required to be consistent with \(m_h\) (inner circle)
  - Dominant multi-jet background determined in 2-tag data, corrected with ‘outer area’ and validated in ‘annulus’

- **Merged Overview**
  - \(m_{G^*}\) is ‘large’ \(\Rightarrow h\) is ‘boosted’ \(\Rightarrow b\)-jets are collimated
  - Select 2 jets with \(R=1.0\) (\(J\)), and \(|\Delta \eta_{JJ}| < 1.7\)
  - Divide events by number of b-tagged track jets
  - 2 \(J\)’s are required to be consistent with \(m_h\) (inner circle)
  - Two signal regions: ‘3-tag’ and ‘4-tag’
  - Again, multi-jet background determined in 2-tag data, corrected with ‘outer area’ and validated in ‘annulus’

Note: \(O(5-10\%)\) background from \(t\bar{t}\) discussed in backup
No deviation from SM seen in signal regions
$X \rightarrow hh \rightarrow bbbb$: Results

- No deviation from SM seen in signal regions
- 95% C.L. upper limits are placed vs. the mass of $X$
- Results interpreted for a narrow $H \rightarrow hh$ as well as for $G_{KK}^*$
- A non-resonant interpretation yields a 95% C.L. upper limit on $\sigma(pp \rightarrow hh \rightarrow b\bar{b}b\bar{b}) = 1.22$ pb

\[
G_{KK}^* \left( \frac{k}{\bar{M}_{Pl}} = 1 \right):
\]

The transition mass was chosen such that the expected limits intersect.
LFV Higgs Decays (arXiv:1508.03372)

- **Overview**
  - Combines 4 channels: \((e\tau, \mu\tau) \otimes (\tau_{lep}, \tau_{had})\)
  - \(\mu\tau_{had}\) channel taken from JHEP11(2015)211

- **\(\tau_{had}\) Channels**
  - Exactly 1 \(e\) or \(\mu\) and 1, OS \(\tau_{had}\) candidate
  - \(m_{\ell}, E_T\) used as primary discriminants
  - Missing Mass Calculator (MMC) used to reproduce \(m_h\)
    - The MMC uses a likelihood fit, using the \(m_{\tau_{had}} = m_{\tau_{had}}\) hypothesis
  - \(t\bar{t}\) background estimated using events w/ 2 b-tagged jets
  - Multi-jet events estimated using SS leptons

- **\(\tau_{lep}\) Channels**
  - Exactly 1 \(e\) and 1 OS \(\mu\)
  - \(\Delta\phi\) between leptons and \(E_T\) used to increase sensitivity
  - Signal regions defined w/ and w/out jets
  - Primary discriminant is collinear mass:
    \[m_{coll} = \sqrt{2p_T^\ell_1 \left( p_T^\ell_2 + E_T \right)} (\cosh \Delta\eta - \cos \Delta\phi)\]
  - Bkg. estimation uses the symmetry of the \(e\mu\) final state:
    - \(e\mu\) is background for \(\mu e\) and \(\leftrightarrow\)
**LFV Higgs Decays: Results**

- Observed 95% C.L. upper limits on LFV Higgs decays $O(1-2\%)$
- $1\sigma$ excess in $\mu\tau$ (bottom right) driven by $1.3\sigma$ excess in $\mu\tau_{\text{had}}$ (3rd right)
  - Best fit $BR(H \rightarrow \mu\tau) = (0.53 \pm 0.51)\%$
Concluding Thoughts

- We have had a very successful BSM physics program in the first year of Run 2
  - Some interesting Run1 results still appearing

- The next year promises to be very exciting
  - The projected 25 fb$^{-1}$ for 2016 opens up sensitivity to many more avenues for discovery
Stay Tuned!
\( \gamma\gamma bb \) Background Extrapolation

Figure 3: The search for the resonant di-Higgs production requires additional selection on the \( m_{\gamma\gamma} \) and \( m_{bb\gamma\gamma} \) distributions. Two counting categories are defined - a background-dominated category from the \( m_{\gamma\gamma} \) sidebands, and a signal region, inside the \( m_{\gamma\gamma} \) and \( m_{bb\gamma\gamma} \) windows. One factor is required in each dimension to extrapolate the background rate from the sideband to the signal region. Here, \( N_{SB} \) refers to the observed number of sideband events from the continuum background, and \( N^B_{SR} \) refers to the expected number of continuum background events in the signal region. The two \( \varepsilon \) values are the efficiencies to pass the cuts on \( m_{\gamma\gamma} \) and \( m_{bb\gamma\gamma} \).
## $\gamma\gamma bb$ Systematics

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Impact in % on the search for di-Higgs production in non-resonant mode</th>
<th>Impact in % on the search for di-Higgs production in resonant mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$hh$ signal</td>
<td>Single-$h$ bkg</td>
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<tr>
<td><strong>Luminosity</strong></td>
<td>$\pm 5.0$</td>
<td>$\pm 5.0$</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>$\pm 0.4$</td>
<td>$\pm 0.4$</td>
</tr>
<tr>
<td><strong>Pileup reweighting</strong></td>
<td>$\pm 1.6$</td>
<td>$+2.4 / -0.4$</td>
</tr>
<tr>
<td><strong>Generated event statistics</strong></td>
<td>$\pm 1.3$</td>
<td>$\pm 16.8$</td>
</tr>
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<td></td>
</tr>
<tr>
<td>energy resolution</td>
<td>$+30 / -15$</td>
<td>$+30 / -15$</td>
</tr>
<tr>
<td>energy scale</td>
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<td>$\pm 0.5$</td>
</tr>
<tr>
<td>identification</td>
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<td>$\pm 2.5$</td>
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<td>$\pm 3.4$</td>
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<tr>
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<tr>
<td>energy scale</td>
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<td>$+12$</td>
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</tr>
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<td>$b$-jets</td>
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<td>$\pm 10.0$</td>
</tr>
<tr>
<td>$c$-jets</td>
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<td>$\pm 4.1$</td>
</tr>
<tr>
<td>light-jets</td>
<td>$\pm 0.5$</td>
<td>$+3.9 / -4.6$</td>
</tr>
<tr>
<td>extrapolation</td>
<td>$\pm 5.1$</td>
<td>$\pm 2.8$</td>
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<tr>
<td><strong>Shape</strong></td>
<td>$m_{\gamma\gamma}$ modelling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$m_{b\bar{b}\gamma\gamma}$ modelling</td>
<td></td>
</tr>
<tr>
<td>Theory</td>
<td>PDF+$\alpha_s$</td>
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<tr>
<td></td>
<td>Scale</td>
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<tr>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td>$+34 / -22$</td>
<td>$+43 / -35$</td>
</tr>
</tbody>
</table>

Table 2: Summary of systematic uncertainties, in percent, for 2-tag events in the signal region. Entries marked ‘-’ indicate that the systematic is not applicable in this category. The luminosity uncertainty is fully correlated across all samples. The jet energy scale uncertainty includes components from various sources, including uncertainties on jets arising from $b$-quarks. The $b$-tagging uncertainties include those from the efficiencies to correctly tag jets arising from $b$-quarks as well as mistagging jets from $c$-quarks and light-flavour quarks. There are two extrapolation uncertainties in $b$-tagging: one is from the extrapolation to high-$p_T$ ($p_T > 300$ GeV) jets and one is from extrapolating $c$-jets to $\tau$-jets. In the table these are combined, although they are treated as independent nuisance parameters in the fit. In the search for $X\rightarrow hh$, the jet energy resolution and $m_{b\bar{b}\gamma\gamma}$ modelling uncertainties are parametrised in terms of the mass of the resonance, hence the full range of values is quoted.
The Double Sided Crystal Ball

Figure: Description of the double-sided Crystal Ball function parameters:
\[ \Delta m_X = m_X - \mu_{CB}, \] where \( \mu_{CB} \) is the peak of the Gaussian distribution, \( \sigma_{CB} \) represents the width of the Gaussian part of the function, \( \alpha_{Low} (\alpha_{High}) \) is the point where the Gaussian becomes a power law on the low (high) mass side, \( n_{Low} (n_{High}) \) is the exponent of this power law. (ATLAS-CONF-2014-031)
Resolved Jet Selection

\[ P_T^{\text{lead}} > \begin{cases} 
400 \text{ GeV} & \text{if } m_{4j} > 910 \text{ GeV}, \\
200 \text{ GeV} & \text{if } m_{4j} < 600 \text{ GeV}, \\
0.65m_{4j} - 190 \text{ GeV} & \text{otherwise},
\end{cases} \]

\[ P_T^{\text{subl}} > \begin{cases} 
260 \text{ GeV} & \text{if } m_{4j} > 990 \text{ GeV}, \\
150 \text{ GeV} & \text{if } m_{4j} < 520 \text{ GeV}, \\
0.23m_{4j} + 30 \text{ GeV} & \text{otherwise},
\end{cases} \]

\[ |\Delta \eta_{\text{dijets}}| < \begin{cases} 
1.0 & \text{if } m_{4j} < 820 \text{ GeV}, \\
1.6 \times 10^{-3}m_{4j} - 0.28 & \text{otherwise}.
\end{cases} \]
**Resolved**

- Extra jets in the event are used to reconstruct $W$ and $t$ candidates

$$X_t = \sqrt{\left(\frac{m_W - 80.4 \text{ GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5 \text{ GeV}}{0.1 m_t}\right)^2},$$

- The $t\bar{t}$ CR has $X_{t\bar{t}} < 3.2$, and the SR has the inverse

**Merged**

- Strict cuts on the leading $J$ $p_T$ significantly reduces $t\bar{t}$ background

- Remaining background estimated from MC simulation
**bbbb Systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>Background</th>
<th>SM $bb$</th>
<th>$G_{kk}^*$ (500 GeV)</th>
<th>$G_{kk}^*$ (800 GeV)</th>
<th>$H$</th>
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<tbody>
<tr>
<td>Luminosity</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>JER</td>
<td>–</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>JES</td>
<td>–</td>
<td>12</td>
<td>14</td>
<td>5</td>
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<tr>
<td>$b$-tagging</td>
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<tr>
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<td>2</td>
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<tr>
<td>Multijet</td>
<td>5</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$t\bar{t}$</td>
<td>6</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>Total</td>
<td>8</td>
<td>26</td>
<td>21</td>
<td>28</td>
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Table 2: Summary of systematic uncertainties (expressed in percentage yield) in the total background and signal event yields in the signal region of the resolved analysis. Signal yield uncertainties are provided for non-resonant SM Higgs pair production, for the $G_{kk}^*$ with $k/M_{Pl} = 1$ and $m = 500$ GeV, and for three resonances with $m = 800$ GeV, a $G_{kk}^*$ with $k/M_{Pl} = 1$, a $G_{kk}^*$ with $k/M_{Pl} = 2$, and a spin-0 narrow-width $H$ boson.

<table>
<thead>
<tr>
<th>Source</th>
<th>Background</th>
<th>$k/M_{Pl} = 1$</th>
<th>$k/M_{Pl} = 2$</th>
<th>$H$</th>
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3-tag

<table>
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<th>Source</th>
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<th>$k/M_{Pl} = 2$</th>
<th>$H$</th>
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<tbody>
<tr>
<td>JER</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
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<td>&lt; 1</td>
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<td>JMR</td>
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<tr>
<td>Statistical</td>
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4-tag

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<th>$H$</th>
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<td>Total</td>
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Table 5: Summary of systematic uncertainties (expressed in percentage yield) in the total background and signal event yields in the 3-tag and 4-tag signal regions in the boosted analysis. Uncertainties are provided for a resonance mass of 1.5 TeV in the context of the bulk RS model with $k/M_{Pl} = 1$ or 2, as well as for a spin-0 narrow-width $H$ boson. The statistical uncertainties on the background include the fitted $\mu$ normalization uncertainties and the statistical uncertainty associated with the data yield in the 2-tag sample.
LFV $\tau_{\text{lep}}$ Fits

**ATLAS**

$\sqrt{s} = 8$ TeV $\int L \, dt = 20.3$ fb$^{-1}$

- Data $e\mu$ SR$_{\text{H}}$Jets
- Symm. background
- Tot. background
- Post-fit uncertainty

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- Symm. background
- Tot. background
- Post-fit uncertainty
- $H \rightarrow \mu \tau$ (BR=1%)

**ATLAS**

$\sqrt{s} = 8$ TeV $\int L \, dt = 20.3$ fb$^{-1}$

- Data $e\mu$ withJets
- Symm. background
- Tot. background
- Post-fit uncertainty

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$\sqrt{s} = 8$ TeV $\int L \, dt = 20.3$ fb$^{-1}$

- Data $e\mu$ withJets
- Symm. background
- Tot. background
- Post-fit uncertainty
- $H \rightarrow \mu \tau$ (BR=1%)
LFV ‘excess’