HH non-resonant and self-coupling at ATLAS+CMS

Laura Pereira Sánchez
On behalf of the ATLAS and CMS collaborations

LHCP
June 8th 2021
• Measuring $HH$ production will give us access to the triple Higgs coupling (self coupling) $\lambda_3$, which gives information of the shape of the Higgs potential $V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 \nu H^3 + \frac{1}{4} \lambda_4 \nu H^4 + O(H^5)$.

• The leading $HH$ production mode is gluon gluon fusion ($ggF$):

• The coupling modifier $\kappa_\lambda$ controls the strength of the Higgs self coupling with respect to SM: $\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$

• Destructive interference between the two diagrams results in a very small SM cross section of $\sigma_{ggF}^{HH} = 31.05$ fb at $\sqrt{s} = 13$ TeV.
**VBF HH production**

- *HH* production through *VBF* is the sub-leading *HH* production mode with a SM cross section of $\sigma_{VBF}^{HH} = 1.73 \text{ fb}$ at $\sqrt{s} = 13 \text{ TeV}$ (calculated at N3LO)

- The coupling modifiers $\kappa_\lambda$, $\kappa_V$ and $\kappa_{2V}$ control the strength of the $g_{HHH} = \frac{3m_H}{v^2}$, $g_{V VH} = \frac{2m_V^2}{v}$ and $g_{V V HH} = \frac{2m_V^2}{v^2}$ couplings with respect to the SM value.

- Given the larger cross section, searches for $ggF \ HH$ production provide better sensitivity to $\kappa_\lambda$ but the VBF topology has a unique sensitivity to $\kappa_{2V}$. 
\textbf{HH decay modes}

- Due to the large branching ratio (BR), most searches require at least one $H \rightarrow b\bar{b}$. Different decay modes of the second Higgs are considered.

<table>
<thead>
<tr>
<th>Targeted HH decays shown today</th>
<th>bb</th>
<th>WW</th>
<th>$\tau\tau$</th>
<th>ZZ</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>33%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td>25%</td>
<td>4.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>7.4%</td>
<td>2.5%</td>
<td>0.39%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>3.1%</td>
<td>1.2%</td>
<td>0.34%</td>
<td>0.076%</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.26%</td>
<td>0.10%</td>
<td>0.029%</td>
<td>0.013%</td>
<td>0.0005%</td>
</tr>
</tbody>
</table>

- ATLAS and CMS searches with full run 2 data for the following decay modes are presented:
  - $b\bar{b}b\bar{b}$ has the largest BR but large backgrounds arising from multijet production are challenging.
  - $b\bar{b}WW$, $b\bar{b}ZZ$ and $b\bar{b}\tau\tau$ have smaller BRs and can benefit from using leptons for triggering (hadronic $b\bar{b}\tau\tau$ searches won’t be presented).
  - $b\bar{b}\gamma\gamma$ has the smallest BR but it’s a very sensitive analysis thanks to the clean $m_{\gamma\gamma}$ resolution.

- Other final states without any $H \rightarrow b\bar{b}$ are also included in the combinations with partial run 2 data.
CMS $HH \rightarrow bb\gamma\gamma$ (137 fb$^{-1}$)

- A $ggF$ and $VBF$ BDT are used to discriminate the $HH$ signals against background + a DNN is also used to further discriminate against $t\bar{t}H$.

- Multiple regions optimised for $ggF$ $HH$ (12 regions) or $VBF$ $HH$ (2 regions) are defined from the MVA scores and $\tilde{M}_X = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 2m_h$.

- A 2D fit to $m_{\gamma\gamma}$ and $m_{jj}$ side bands is performed in all regions to estimate the non-resonant backgrounds with data.

*HEFT shape benchmarks are included in the optimisation of the $ggF$ regions*
**CMS** $HH \rightarrow bb\gamma\gamma$ (137 fb$^{-1}$)

- This search is limited by statistics

Observed (expected) limits are presented for different observables at 95% CL:

- $\sigma^{HH}_{ggF+VBF} < 7.7 \ (5.2) \times \sigma^{HH \ SM}_{ggF}$
- $-3.3 \ (-2.5) < \kappa_\lambda < 8.5 \ (8.2)$

- Fixing $\sigma^{ggF \ HH}_{VBF}$ to SM:
  - $\sigma^{HH}_{VBF} < 225 \ (208) \times \sigma^{HH \ SM}_{VBF}$
  - $-1.3 \ (-0.9) < \kappa_{2V} < 3.5 \ (3.1)$

- Fixing $\sigma^{HH \ BSM}_{ggF}$ to SM:
  - $\sigma^{HH \ BSM}_{ggF}$ on 12 BSM Higgs EFT shape benchmarks

- 2D scans to the $\kappa_1$ vs $\kappa_\lambda$ and $\kappa_{2V}$ vs $\kappa_2$ planes
  - A $t\bar{t}H$ cat is added to improve sensitivity to $\kappa_1$
**ATLAS** \( HH \rightarrow bb\gamma\gamma \) (139 fb\(^{-1} \))

- Two different BDTs are used for events with high/low \( \tilde{M}_X \) masses to discriminate \( \kappa_\gamma = 1 \) or \( \kappa_\gamma = 10 \) \( ggF \) \( HH \) against background. A total of 4 regions are defined from cuts on the score of the BDTs.

- The analysis is optimised for \( ggF \) \( HH \), however \( VBF \) \( HH \) events are also considered as signal.

- The \( m_{\gamma\gamma} \) SB are fit to estimate the non-resonant background with data.

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**Observed (expected) limits:**

- \( \sigma_{ggF+VBF}^{HH} < 4.1 \) (5.5) \( \times \sigma_{ggF+VBF}^{HH \text{ SM}} \)

- \( -1.5 \) \((-2.4) \) \( < \kappa_\lambda < 6.7 \) \((7.7) \)

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- The sensitivity of the analysis is limited by the statistical precision

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*Check out Alex Zeng Wang’s poster for details*
**CMS** $HH \rightarrow bbbb$ (138 fb$^{-1}$)

- $HH$ candidates are reconstructed from the 4 jets and $\chi = \sqrt{(m_{H_1} - 125)^2 + (m_{H_2} - 120)^2}$ is used to divide events in SR and CR.

- $VBF$ candidates are selected by requiring 2 additional non-$b$-jets and a $VBF$-vs-$ggF$ BDT is used to reduce mis-classification of $ggF$ events.

- $m_{HH} + VBF$-vs-$ggF$ BDT or a dedicated $ggF$ BDT are used to enhance sensitivity to both SM and BSM scenarios, resulting in a total of 4 SRs.

- The large multijet background is estimated from data and a maximum likelihood binned fit is simultaneously performed in all SRs.

\[
\sigma_{ggF+VBF}^{HH} < 3.6 \times (7.3) \times \sigma_{ggF+VBF}^{HH \ SM}
\]

\[
-2.3 (-5.0) < \kappa_\lambda < 9.4 (12.0)
\]

\[
-0.1 (-0.4) < \kappa_{2V} < 2.2 (2.5)
\]

- Dominated by background modelling uncertainties.
**ATLAS VBF HH → bbbb (126 fb⁻¹)**

- Set limits on $\sigma_{VBF}^{HH}$ and $\kappa_2$.

- Targets $VBF \ HH → bbbb$ as signal while $ggF \ HH$ events are considered background.

- Concentric signal, validation and side-band regions (SR, VR, and SB) are defined from the 2D (sub-)leading $m_{2b}$ to fit the multijet and all-hadronic $t\bar{t}$ backgrounds to data.

- The sensitivity of the analysis is limited by the statistical precision, followed by systematics on the multi jet background.

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**Observed (expected) limits at 95% CL:**

- $\sigma_{VBF}^{HH} < 1000 \ (540) \times \sigma_{VBF}^{HH \ SM}$
- $-0.43 \ (-0.55) < \kappa_2 < 2.56 \ (2.72)$
ATLAS $HH \rightarrow bbl\nu\nu$ (139 fb$^{-1}$)

- Targets $ggF HH \rightarrow bbWW^*$, $bbZZ^*$ and $bb\tau\tau$ in a final state with two $b$-jets, two leptons ($l = e, \mu$) and missing transverse energy.

- A multi-class classification Neural Network is used to differentiate the $HH \rightarrow bbWW^*$ signal (due to its larger branching fraction) from the SM backgrounds.

- The main discriminant is defined as
  \[ d_{HH} = \ln(p_{HH}/p_{top} + p_{Zll} + p_{Z\tau\tau}) \]
  where $p_i$ are the NN outputs that represent the probability of an event to belong to a class $i$.

- A counting experiment is performed, fitting simultaneously the Top CR, the Z+HF CR, the same flavour (SF) and different flavour (DF) SRs with all three $HH$ decays as signal.

- Leading uncertainties arise from MC modelling in the Top and Z+HF background estimates.

<table>
<thead>
<tr>
<th>$\sigma(gg \rightarrow HH)$ [pb]</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>Expected</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma(gg \rightarrow HH)/\sigma^{SM}(gg \rightarrow HH)$</td>
<td>0.5</td>
<td>0.6</td>
<td>0.9</td>
<td>1.3</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>$\sigma(gg \rightarrow HH)$</td>
<td>14</td>
<td>20</td>
<td>29</td>
<td>43</td>
<td>62</td>
<td>40</td>
</tr>
</tbody>
</table>

Observed (expected) limit:
- $\sigma_{ggF}^{HH} < 40 \ (29) \times \sigma_{ggF}^{HH \ SM}$
CMS $HH \rightarrow bbllll$ (137 fb$^{-1}$)

- Targets $ggF \ HH \rightarrow bbZZ^*$ in a final state with two $b$-jets and four leptons ($l = e, \mu$).

- The $m(4l)$ is used to define a CR for the $Z+X$ background and a SR with $m(4l) \sim m_H$. The irreducible single Higgs background is estimated from simulation.

- For further discrimination, a total of 9 BDTs are trained (for each data taking year and leptonic final state e.g. $4\mu$, $4e$ or $2e2\mu$) using events in the SR.

- A multi-dimensional binned fit to the BDT distribution in data is performed.

- The JES uncertainties, together with the statistical uncertainties of the last bin of the BDT, have the highest impact on the analysis.

Observed (expected) limits at 95% CL:

- $\sigma_{ggF}^{HH} < 30\ (37) \times \sigma_{ggF}^{SM}$
- $-9\ (-10.5) < \kappa_\lambda < 14\ (15.5)$
**HH combination (25-36.1 fb⁻¹)**

- Searches for $ggF \, HH$ in different decay channels within each experiment are combined.

**Observed (expected) limits at 95% CL:**

- **ATLAS:** $\sigma^{HH}_{ggF} < 6.9 \, (10) \times \sigma^{HH \, SM}_{ggF}$
- **CMS:** $\sigma^{HH}_{ggF} < 12.8 \, (22.2) \times \sigma^{HH \, SM}_{ggF}$
- **ATLAS:** $-5 \, (-5.8) < \kappa_\lambda < 12 \, (12.0)$
- **CMS:** $-11.8 \, (-7.1) < \kappa_\lambda < 18.8 \, (13.6)$

- Looser limits than the $HH \rightarrow b\bar{b}\gamma\gamma$ and $HH \rightarrow b\bar{b}b\bar{b}$ searches with full run 2 data.

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Partial run 2 data
ATLAS H+HH combination (27.5-79.8 fb⁻¹)

- \(\kappa_\lambda\) enters at tree (loop level) for HH (H) production affecting \(\sigma\)

- Single Higgs and HH analyses with multiple decay and production modes are combined:
  - \(H \rightarrow \gamma\gamma, H \rightarrow ZZ^*, H \rightarrow WW^*, H \rightarrow \tau\tau, H \rightarrow b\bar{b}, VH\) with \(H \rightarrow b\bar{b}\), \(t\bar{t}H\) with \(H \rightarrow b\bar{b}\) and \(H \rightarrow\) leptons.
  - \(HH \rightarrow b\bar{b}b\bar{b}, HH \rightarrow b\bar{b}\tau\tau\) and \(HH \rightarrow b\bar{b}\gamma\gamma\)

- Observed (expected) limits to the Higgs self coupling are set for different coupling assumptions:
  - ATLAS HH+H combination: \(-2.3 (-5.1) < \kappa_\lambda < 10.3 (11.2)\)

→ The CMS single Higgs combination (HIG-19-005-pas) results in slightly looser limits: \(-3.5 (-5.1) < \kappa_\lambda < 14.5 (13.5)\)
Conclusions

- We are not yet sensitive to SM $HH$ production but competitive upper limits to $\sigma^{HH}/\sigma^{SM}$ are set by three analyses:

\[
\frac{\sigma_{ggF+VBF}^{HH}}{\sigma_{ggF+VBF}^{SM}} = \begin{cases} 
4.1 \ (5.5) \times \sigma_{ggF+VBF}^{HH SM} \ & (ATLAS \ HH \rightarrow bb\gamma) \\
< 7.7 \ (5.2) \times \sigma_{ggF+VBF}^{HH SM} \ & (CMS \ HH \rightarrow bb\gamma) \\
< 3.6 \ (7.3) \times \sigma_{ggF+VBF}^{HH SM} \ & (CMS \ HH \rightarrow bbbb)
\end{cases}
\]

- The most stringent limits to $\kappa_\lambda$ at 95% CL correspond to:

\[-1.5 \ (-2.4) < \kappa_\lambda < 6.7 \ (7.7)\] 

- Limits have improved considerably with respect to the partial Run 2 combined limits → Stay tuned for full run 2 combinations!

- HL-LHC prospects: $\sigma_{ggF}^{HH} = 2.6 \times \sigma_{ggF}^{HH SM}$ (CMS - 5 channels) or $\sigma_{ggF}^{HH} = 3.5 \times \sigma_{ggF}^{HH SM}$ (ATLAS - 3 channels)

- First limits on $VBF \ HH$ production are also set in ATLAS and CMS. The current most stringent limits on $\sigma^{VBF \ HH}$ correspond to:

\[\sigma_{VBF}^{HH} = 225 \ (208) \times \sigma_{VBF}^{HH SM}\] 

- The current most stringent limits on $\kappa_{2v}$ correspond to:

\[-0.1 \ (-0.4) < \kappa_{2v} < 2.2 \ (2.5)\] 

Observed (expected) limits at 95% C.L.
Thank you for your time!

Any comments or questions?
Backup
Summary of $\sigma$, $\kappa_\lambda$ and $\kappa_{2V}$ limits with full run 2 data

<table>
<thead>
<tr>
<th>Process</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$ (ATLAS)</td>
<td>$\sigma_{ggF+VBF}^{HH} = 4.1 \ (5.5) \times \sigma_{ggF+VBF}^{HH SM}$</td>
</tr>
<tr>
<td></td>
<td>$-1.5 \ (-2.4) &lt; \kappa_\lambda &lt; 6.7 \ (7.7)$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\nu\nu$ (ATLAS)</td>
<td>$\sigma_{ggF}^{HH} &lt; 40 \ (29) \times \sigma_{ggF}^{HH SM}$</td>
</tr>
<tr>
<td></td>
<td>$-9 \ (-10.5) &lt; \kappa_\lambda &lt; 14 \ (15.5)$</td>
</tr>
<tr>
<td>$VBF \rightarrow b\bar{b}bb$ (ATLAS)</td>
<td>$\sigma_{VBF}^{HH} &lt; 1000 \ (540) \times \sigma_{VBF}^{HH SM}$</td>
</tr>
<tr>
<td></td>
<td>$-0.43 \ (-0.55) &lt; \kappa_{2V} &lt; 2.56 \ (2.72)$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$ (CMS)</td>
<td>$\sigma_{ggF+VBF}^{HH} &lt; 7.7 \ (5.2) \times \sigma_{ggF+VBF}^{HH SM}$</td>
</tr>
<tr>
<td></td>
<td>$-3.3 \ (-2.5) \kappa_\lambda &lt; 8.5 \ (8.2)$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}bb$ (CMS)</td>
<td>$\sigma_{ggF+VBF}^{HH} &lt; 3.6 \ (7.3) \times \sigma_{ggF+VBF}^{HH SM}$</td>
</tr>
<tr>
<td></td>
<td>$-2.3 \ (-5.0) &lt; \kappa_\lambda &lt; 9.4 \ (12.0)$</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}bb$ (CMS)</td>
<td>$\sigma_{ggF+VBF}^{HH} &lt; 30 \ (37) \times \sigma_{ggF+VBF}^{HH SM}$</td>
</tr>
<tr>
<td></td>
<td>$-9 \ (-10.5) &lt; \kappa_\lambda &lt; 14 \ (15.5)$</td>
</tr>
</tbody>
</table>
The $HH$ candidates are reconstructed from the 4 jets and the expected distance between the $m_{H_i}$ peak positions $\chi = \sqrt{(m_{H_1} - 125)^2 + (m_{H_2} - 120)^2}$ is used to divide events in a SR and CR.

$VBF$ candidates are selected by requiring 2 additional non $b$-jets. Additionally, a BDT is used to separate SM $ggF$ from $\kappa_{2V} = 2$ $VBF$ signal and correctly classify the $ggF$ $HH$ events that are misclassified as $VBF$.

To enhance sensitivity to both SM and BSM, the $ggF$ category is divided in high/low $m_{HH}$ regions and the BDT score is used divide the $VBF$ category in SM/anomalous $\kappa_{2V}$. A BDT is then trained in the two $ggF$ categories to further discriminate signal from bkg.

The large multi jet background is estimated from data in a SR with 3 $b$-jets and extrapolated to the 4 $b$-jet SR using a transfer factor from the CR with 3/4 $b$-jets. Differences in the distributions of the 3$b$ and 4$b$ categories are addressed with a BDT based reweighting.

A maximum likelihood fit binned to the BDT score ($ggF$, $m_H$ ($VBF$ SM) or unbinned (anomalous $VBF$) is simultaneously performed in the four categories.

The dominant uncertainties arise from the background modelling.
CMS Higgs combination (35.9-137 fb⁻¹)

- Results from $H \rightarrow \gamma\gamma, H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow ll\nu\nu$, $H \rightarrow \tau\tau, H \rightarrow \mu\mu$ and $t\bar{t}H$ with $H$ decaying to leptons are combined considering both their decays and production modes.

- The signal strength modifier is calculated for production ($\mu^i = \sigma/\sigma^{SM}$), decay ($\mu^f = B/B^{SM}$) and production times decay $\mu_i^f = \mu_i\mu^f$

- Limits on multiple coupling modifiers $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$ or $\kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$ are performed e.g. $\kappa_Z, \kappa_W, \kappa_t, \kappa_\tau, \kappa_g, \kappa_\gamma, \kappa_\mu$

- Limits to $\kappa_\lambda, \kappa_\lambda^V(\kappa_V)$ and $\kappa_\lambda^F(\kappa_F)$ are set, where $\kappa_\lambda$ is the Higgs boson production self coupling $\kappa_\lambda$ and $\kappa_F, \kappa_V$ are the LO coupling modifiers for Higgs boson coupling to fermions and vector bosons.

- Observed (expected) limits at 95% CL (assuming $\kappa_F = \kappa_V = 1$):
  
  $-3.5 (-5.1) < \kappa_\lambda < 14.5 (13.5)$
$\sigma(\kappa_\lambda)$: LO (solid), NLO (dashed)

Results presented today

Independent analyses

\[ VBF + ggF \; HH \rightarrow bb\gamma\gamma \]  
ATLAS

\[ HH \rightarrow bb\nu\nu \]  
CMS

\[ VBF + ggF \; HH \rightarrow bb\gamma\gamma \]  
CMS

\[ HH \rightarrow bb\nu\nu \]  
ATLAS

\[ VBF \; HH \rightarrow bbbb^* \]  
ATLAS

Full Run 2

Combinations

\[ ggF \; HH \; combination \]  
ATLAS

\[ ggF \; HH \; combination \]  
CMS

\[ HH + H \; combination \]  
ATLAS

\[ H \; combination \]  
CMS

Partial Run 2

* 2015 data not included
Extra: CMS $HH \rightarrow bb\gamma\gamma$ (137 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Category</th>
<th>MVA</th>
<th>$\tilde{M}_X$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF CAT 0</td>
<td>0.52–1.00</td>
<td>&gt;500</td>
</tr>
<tr>
<td>VBF CAT 1</td>
<td>0.86–1.00</td>
<td>250–500</td>
</tr>
<tr>
<td>ggF CAT 0</td>
<td>0.78–1.00</td>
<td>&gt;600</td>
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<tr>
<td>ggF CAT 1</td>
<td></td>
<td>510–600</td>
</tr>
<tr>
<td>ggF CAT 2</td>
<td></td>
<td>385–510</td>
</tr>
<tr>
<td>ggF CAT 3</td>
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<td>250–385</td>
</tr>
<tr>
<td>ggF CAT 4</td>
<td>0.62–0.78</td>
<td>&gt;540</td>
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<td>ggF CAT 5</td>
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<td>360–540</td>
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<td>ggF CAT 6</td>
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<td>ggF CAT 8</td>
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<td>&gt;585</td>
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<td>ggF CAT 9</td>
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<td>375–585</td>
</tr>
<tr>
<td>ggF CAT 10</td>
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<td>330–375</td>
</tr>
<tr>
<td>ggF CAT 11</td>
<td></td>
<td>250–330</td>
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</tbody>
</table>
Extra: CMS $HH \rightarrow bb\gamma\gamma$ (137 fb$^{-1}$)

1D limits to $\kappa_t$ and $\kappa_\lambda$ with/out the $t\bar{t}H$ category

**ggF $HH$ HEFT shape benchmarks**

<table>
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<tr>
<th>$\kappa_\lambda$</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>SM</th>
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<tbody>
<tr>
<td>$\kappa_t$</td>
<td>7.5</td>
<td>1.0</td>
<td>1.0</td>
<td>-3.5</td>
<td>1.0</td>
<td>2.4</td>
<td>5.0</td>
<td>15.0</td>
<td>1.0</td>
<td>10.0</td>
<td>2.4</td>
<td>15.0</td>
<td>1.0</td>
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<tr>
<td>$c_2$</td>
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<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
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<tr>
<td>$c_{2g}$</td>
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<td>-0.8</td>
<td>0.0</td>
<td>-1.0</td>
<td>-0.2</td>
<td>-0.2</td>
<td>1.0</td>
<td>0.6</td>
<td>0.0</td>
<td>-1.0</td>
<td>0.0</td>
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</tbody>
</table>

**Table 1:** Benchmark parameters for ggF $HH$ HEFT shape benchmarks.
**Extra: CMS $HH \rightarrow bb\gamma\gamma$ (137 fb$^{-1}$)**

A 2D fit to $m_\gamma\gamma$ and $m_\gamma\gamma$ is performed to estimate the non-resonant background with data.
Extra: ATLAS $HH \rightarrow bb\gamma\gamma$ (139 fb$^{-1}$)
**ATLAS VBF $HH \rightarrow bbbb$ (126 fb$^{-1}$)**

- Set limits on $\sigma_{VBF}^{HH}$ and $\kappa_{2V}$
- Targets $VBF \ HH \rightarrow bbbb$ as signal while $ggF \ HH$, $t\bar{t}$ and multi-jet events are considered backgrounds.

### Table: Observed and Expected Limits

<table>
<thead>
<tr>
<th>$\sigma_{VBF}$ [fb]</th>
<th>Observed</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>Expected</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1450</td>
<td>500</td>
<td>660</td>
<td>920</td>
<td>1280</td>
<td>1720</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{VBF}/\sigma_{VBF}^{SM}$</td>
<td>840</td>
<td>290</td>
<td>390</td>
<td>540</td>
<td>750</td>
<td>1000</td>
</tr>
</tbody>
</table>

### Diagram: ATLAS $VBF \ HH \rightarrow bbbb$ Event Rates vs. Signal Region

The observed (excluded) region corresponds to $-0.43 < \kappa_{2V} < 2.56$ ($-0.55 < \kappa_{2V} < 2.72$) are excluded at the 95% CL.
### Region Definitions

<table>
<thead>
<tr>
<th>Observable</th>
<th>CR-Top</th>
<th>VR-1</th>
<th>CR-Z+HF</th>
<th>VR-2</th>
<th>SR-SF</th>
<th>SR-DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton Flavour</td>
<td>DF</td>
<td>SF</td>
<td>DF or SF</td>
<td>SF</td>
<td>SF</td>
<td>DF</td>
</tr>
<tr>
<td>$m_{\ell\ell}$ [GeV]</td>
<td>(20, 60)</td>
<td>(20, 60)</td>
<td>(81.2, 101.2)</td>
<td>(71.2, 81.2)</td>
<td>(20, 60)</td>
<td>(20, 60)</td>
</tr>
<tr>
<td>$m_{bb}$ [GeV]</td>
<td>$\leq (100, 140)$</td>
<td>&gt; 140</td>
<td>(100, 140)</td>
<td>(100, 140)</td>
<td>(110, 140)</td>
<td>(110, 140)</td>
</tr>
<tr>
<td>$d_{HH}$</td>
<td>&gt; 4.5</td>
<td>&gt; 4.5</td>
<td>&gt; 0</td>
<td>&gt; 0</td>
<td>&gt; 5.45</td>
<td>&gt; 5.55</td>
</tr>
</tbody>
</table>

### Event Yields

<table>
<thead>
<tr>
<th>Data</th>
<th>108</th>
<th>171</th>
<th>852</th>
<th>157</th>
<th>16</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Bkg.</td>
<td>$108 \pm 10$</td>
<td>$162 \pm 10$</td>
<td>$852 \pm 29$</td>
<td>$147 \pm 11$</td>
<td>$14.9 \pm 2.1$</td>
<td>$4.9 \pm 1.2$</td>
</tr>
<tr>
<td>Top</td>
<td>$92 \pm 11$</td>
<td>$77 \pm 10$</td>
<td>$55 \pm 7$</td>
<td>$71 \pm 10$</td>
<td>$4.8 \pm 1.4$</td>
<td>$3.8 \pm 1.1$</td>
</tr>
<tr>
<td>$Z/\gamma^* +$ HF</td>
<td>$3.2 \pm 0.5$</td>
<td>$70 \pm 4$</td>
<td>$686 \pm 33$</td>
<td>$60 \pm 4$</td>
<td>$7.8 \pm 1.4$</td>
<td>$0.21 \pm 0.05$</td>
</tr>
<tr>
<td>Other</td>
<td>$13.1 \pm 3.4$</td>
<td>$14.2 \pm 1.9$</td>
<td>$110 \pm 13$</td>
<td>$15.8 \pm 1.2$</td>
<td>$2.3 \pm 0.5$</td>
<td>$0.9 \pm 0.4$</td>
</tr>
<tr>
<td>$HH$ ($\times 20$)</td>
<td>$2.70 \pm 0.25$</td>
<td>$1.03 \pm 0.22$</td>
<td>$1.97 \pm 0.11$</td>
<td>$1.22 \pm 0.05$</td>
<td>$5.0 \pm 0.6$</td>
<td>$4.8 \pm 0.8$</td>
</tr>
</tbody>
</table>

### Post-fit Normalisation

\[ \mu_{\text{Top}} = 0.79 \pm 0.10 \quad \mu_{Z/\gamma^* + \text{HF}} = 1.36 \pm 0.07 \]
## ATLAS HH Combination

<table>
<thead>
<tr>
<th>Final state</th>
<th>Obs.</th>
<th>Exp.</th>
<th>Exp. stat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>$-10.9 - 20.1$</td>
<td>$-11.6 - 18.8$</td>
<td>$-9.8 - 16.3$</td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>$-7.4 - 15.7$</td>
<td>$-8.9 - 16.8$</td>
<td>$-7.8 - 15.5$</td>
</tr>
<tr>
<td>Combination</td>
<td>$-5.0 - 12.0$</td>
<td>$-5.8 - 12.0$</td>
<td>$-5.3 - 11.5$</td>
</tr>
</tbody>
</table>
ATLAS H+HH combination (27.5-79.8 fb⁻¹)

- Results from single Higgs and Higgs pair production analyses with multiple decay and production modes are combined:
  - $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$, $H \to \tau\tau$, $H \to b\bar{b}$, $VH$ with $H \to b\bar{b}$, $t\bar{t}H$ with $H \to b\bar{b}$ and $H \to$ leptons.
  - $HH \to b\bar{b}b\bar{b}$, $HH \to b\bar{b}\tau\tau$ and $HH \to b\bar{b}\gamma\gamma$

- $\kappa_\lambda$ enters at tree (loop level) for $HH$ ($H$) production affecting $\sigma$

- Observed (expected) limits to the Higgs self coupling are set for the combinations under two different assumptions:
  
  A. New physics affects only the Higgs self coupling: $-2.3 (-5.1) < \kappa_\lambda < 10.3 (11.2)$
  
  B. Including the couplings $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$ and $\kappa_l$ (more relaxed limits): $-3.7 (-6.2) < \kappa_\lambda < 11.5 (11.6)$

- CMS uses single Higgs combination to set limits to $\kappa_\lambda$ (assuming $\kappa_F = \kappa_V = 1$):
  $-3.5 (-5.1) < \kappa_\lambda < 14.5 (13.5)$