Searches for pair-production of Higgs bosons using the CMS detector at the LHC

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On behalf of the CMS Collaboration

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HH in the SM

- \( V(\phi) = -\mu^2 \phi^2 + \lambda^2 \phi^4 \)
- \[ = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v^2} \nu h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4 \]

- Destructive interference between the two terms leads to a small cross section
- \( \sigma(gg \to HH)_{SM} = 33.53 \text{ fb} \pm 4.3\% \text{(scale)} \pm 6.0\% \text{(PDF)} \)
- \( \sigma(VBF HH)_{SM} = 1.64 \pm 0.05 \text{ fb} \)
- BSM contribution can modify the Higgs boson coupling parameters and enhance the HH cross section
Di-Higgs non-resonant with BSM contribution

- EFT approach (PRD 91 (2015) 115008) using higher dimension operators

- \( L_{hh} = \frac{1}{2} \partial_\mu \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa \lambda_{SM} v h^3 \)

- \( -\frac{m_t}{v} \left( v + k_t h + \frac{c_2}{v} h h \right) (t_L t_R + \text{h. c.}) \)

- \( \frac{\alpha_S}{12} \left( c_1 g h - \frac{c_2 g}{2v} h h \right) G^A_{\mu\nu} G^{A\mu\nu} \)

\[ \kappa_\lambda = \frac{\lambda}{\lambda_{SM}} \]

\[ \kappa_t = \frac{y_t}{y_{t,SM}} \]
Di-Higgs resonant production

- Resonant production
  - BSMs with new contributions
    - KK graviton, radion, heavy higgs bosons.
    - Overall enhancement of hh production cross section
- Searches look for a narrow resonance X with a mass $m_X$ using the invariant mass spectrum $m_{HH}$. 
Explored final states

- **bbbb:**
  - Resolved
  - Boosted
  - Semi-boosted

- **bbττ**
  - Resolved
  - Boosted

- **bbℓ+ℓνν**

- **bbγγ**

- The bbbb final state has the branching fraction advantage
- Other decay channels give cleaner final states: lower backgrounds, trigger advantage.
- **Combination of all analysis for the best signal sensitivity.**
<table>
<thead>
<tr>
<th>Final state</th>
<th>Targeted search</th>
<th>Documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4b</td>
<td>Low mass resonance</td>
<td>CMS-PAS-HIG-17-009, arXiv:1806.03548</td>
</tr>
<tr>
<td></td>
<td>High mass resonance</td>
<td>CMS-PAS-B2G-16-026, PLB 781 (2018) 244</td>
</tr>
<tr>
<td></td>
<td>Intermediate mass resonance and non-resonant HH</td>
<td>CMS-PAS-B2G-17-019</td>
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<tr>
<td></td>
<td>Non-resonant HH</td>
<td>CMS-PAS-HIG-17-017</td>
</tr>
<tr>
<td>bbττ</td>
<td>Low mass resonance and non-resonant HH</td>
<td>CMS-PAS-HIG-17-002, PLB 788 (2018) 101</td>
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<tr>
<td></td>
<td>High mass resonance</td>
<td>CMS-PAS-B2G-17-006</td>
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<tr>
<td>bbε⁺ε⁻νν</td>
<td>Low mass resonance and non-resonant HH</td>
<td>CMS-PAS-HIG-17-006, JHEP 01 (2018) 054</td>
</tr>
<tr>
<td>bbγγ</td>
<td>Low mass resonance and non-resonant HH</td>
<td>CMS-PAS-HIG-17-008, arXiv:1806.00408</td>
</tr>
<tr>
<td>Combination</td>
<td>Resonant and non-resonant HH</td>
<td>CMS-PAS-HIG-17-030</td>
</tr>
</tbody>
</table>

Low mass resonance searches mostly for $m_X < 1$ TeV (dependent on final state).
HH→4b resonant

- 3 analyses for different resonance mass ranges:
  - Resolved: 4 b jets used to reconstruct the HH-→4b
  - Fully-merged: 2 large-area jets each identifying a boosted H-→bb
  - Semi-resolved: 1 large-area jet and 2 b jets

- Background estimation from sidebands of Higgs boson candidate masses.
- Low and medium mass regions.

Efficiencies: resolved analysis

Efficiencies: fully-merged analysis

Mass distribution: semi-resolved events

- Fully-merged and semi-resolved: Background estimated from sideband regions using misidentification rate of Higgs jets in QCD background.
- The two analyses are combined.

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HH→4b resonant

Low mass: Resolved analysis

- Upper limits set on the cross section of bulk gravitons and radions in the warped extradimensional models
- Including semi-resolved events improve limits between 55–8% for the radion in the mass range 750–1600 GeV.
- Non-resonant HH production also probed with boosted final states.

High mass: Fully-merged analysis

Fully-merged + semi-resolved

- Observed upper limit
- Expected upper limit
- 68% Expected limit
- 95% Expected limit
- Expected limit ± 1 std. deviation
- Expected limit ± 2 std. deviation

Spin 0

CMS

35.9 fb⁻¹ (13 TeV)

σ(pp→X)×Br(X→b̄b)σ(pp→X)×Br(X→b̄b)

m_X (GeV)

Spin 0

CMS

35.9 fb⁻¹ (13 TeV)

σ(pp→X)×Br(X→b̄b)σ(pp→X)×Br(X→b̄b)

m_X [GeV]

Spin 0

CMS

35.9 fb⁻¹ (13 TeV)

σ(pp→X)×Br(X→b̄b)σ(pp→X)×Br(X→b̄b)

m_X [TeV]
HH→4b non-resonant

- Analysis optimized to be sensitive to the SM gg→HH→4b process.
- Main background: QCD multijets. Reduced requiring 4 b jets and a BDT classifier.
- A hemisphere mixing technique is used to provide samples for BDT training and for predicting the background BDT shape.

- BDT modelling checked using data sidebands which exclude m(bb) around the Higgs boson mass.
- Background BDT shape corrections extracted by comparing the training on the original sample with 200 replicas of same sample size.
- Shape correction validated in data sideband regions.
BDT discriminator $> 0.2$ is used only to take advantage of the better data-background compatibility.

- Sensitivity loss $\approx 1.5\%$.

- Minor backgrounds from ttH, VH, bbH and gg$\rightarrow$H

- Limits set on different shape benchmarks:
  - SM, 12 BSM benchmarks, $\kappa_\lambda = 0$

- Sensitivity varies depending on the kinematic distributions, mainly $m_{HH}$.

- Limits set also as a function of $\kappa_\lambda$ assuming $\kappa_t = 1$. 
HH → bbγγ

- Small BR (0.26%) but clean signature
- 2 photons+2 b-tagged jets (triggering using 2 photons)
- Resonant mass
  \[ \widetilde{M}_X = M(jj\gamma\gamma) - M(jj) - M(\gamma\gamma) + 250 \]
- MVA categorization
- Signal searched for using a parametric fit to M(jj) and M(\gamma\gamma)

CMS Simulation

CMS

Grav. m_X = 300 GeV
Rad. m_X = 600 GeV
gg → HH (x10^6)
VBF HH (x10^6)

Events/(0.04)

Classification MVA

35.9 fb^{-1} (13 TeV)

Data
- Limits computed on the cross section of bulk gravitons and radions in the warped extradimensional models.

- Limit on SM cross section of $gg\rightarrow HH\rightarrow bb\gamma\gamma$: 2 fb (obs) 1.6 fb (exp)
  - Corresponds to 24 (obs) 19 (exp) times the SM expectations.
  - Including VBF HH production improves sensitivity by 1.3%.

- Constraint on $\kappa_\lambda$ between -11 and 17.
Final state with 2 b jets and >= 1 hadronically decaying tau lepton.

- Taus decaying to leptons (e/ \( \mu \)) included.

- Low mass and high mass resonance analyses.

- Non-resonant HH search also sets limits in NMSSM parameter space in the low \( \tan \beta \) region.

NMSSM Interpretation

<table>
<thead>
<tr>
<th>( m_A ) (GeV)</th>
<th>Observed 95% CL excl.</th>
<th>Expected ±1( \sigma )</th>
<th>Expected 95% CL excl.</th>
<th>Expected ±2( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>3.5</td>
<td>3</td>
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<tr>
<td>500</td>
<td>3.5</td>
<td>3</td>
<td>2.5</td>
<td>2</td>
</tr>
</tbody>
</table>

Spin 0

- Assumes SM BRs all channels, 1 and 2-btags combined

95% CL upper limits
- Observed
- Median expected
- 68% expected
- 95% expected
- Bulk Radion (\( \Lambda_n=1 \))

<table>
<thead>
<tr>
<th>( m_X ) (GeV)</th>
<th>( \sigma \times BR(X \rightarrow HH) ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>10^-3</td>
</tr>
<tr>
<td>1500</td>
<td>10^-2</td>
</tr>
<tr>
<td>2000</td>
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<tr>
<td>3500</td>
<td>10^3</td>
</tr>
<tr>
<td>4000</td>
<td>10^4</td>
</tr>
</tbody>
</table>
- Event categories: $e^+e^-$, $\mu^+\mu^-$, $e^\pm\mu$.
- Neural network training used to improve signal-background separation.
  - Parametric training as function of mass (resonance) or $\kappa_t$ (non-resonant) signals.
Combination of several HH decay channels.

Interpretation in terms of spin-0 (radion) and spin-2 (bulk graviton) production cross section times the branching fraction to HH.

Narrow width approximation used.
Non-resonant search summary

- Limits set on 12 BSM shape benchmarks, SM, and $\kappa_\lambda=0$.
- **Limit on $f \kappa_\lambda$ for $\kappa_t = 1$:**
  - Observed: $-11.8\text{–}18.8$
  - Expected: $-7.1\text{–}13.6$
- Sensitivity to benchmarks with higher $m_{HH}$ improved by including boosted topologies.

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\frac{\sigma}{\sigma_{SM}}$ Obs (Exp)</th>
<th>Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb\gamma\gamma$</td>
<td>24 (19)</td>
<td></td>
</tr>
<tr>
<td>$bb\tau\tau$</td>
<td>31 (25)</td>
<td></td>
</tr>
<tr>
<td>$bb\ell^+\ell^-\nu\nu$</td>
<td>79 (89)</td>
<td>35.9 fb$^{-1}$</td>
</tr>
<tr>
<td>$bbbb$</td>
<td>75 (37)</td>
<td></td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>22.2 (12.8)</strong></td>
<td></td>
</tr>
</tbody>
</table>
Summary

- CMS searches for HH production presented
- Several analyses depending on
  - Decay channels: $bb\tau\tau$, $bb\gamma\gamma$, $bbVV$, $bbbb$
  - HH mass range: Low mass, high mass
- All results consistent with SM backgrounds so far
  - Upper limits on resonance cross sections, anomalous couplings
- Combination of searches performed.
  - Observed upper limit of 22.2 and expected upper limit of 12.8 times the SM prediction.
  - Improved sensitivity to non-SM couplings using boosted topologies.
- Limits also set on the resonant production of HH from the decay of spin-0 radions and spin-2 bulk gravitons in warped extradimensional models.
Interpreting non-resonant results

- Connecting $L_{hh}$ to observables at the experiments
- Clusters in parameter space with similar Higgs boson kinematics (JHEP 04 (2016) 126)

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$\kappa_A$</th>
<th>$\kappa_t$</th>
<th>$c_2$</th>
<th>$c_g$</th>
<th>$c_{2g}$</th>
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<td>0.6</td>
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<td>0.0</td>
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<tr>
<td>11</td>
<td>2.4</td>
<td>1.0</td>
<td>0.0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>12</td>
<td>15.0</td>
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<td>SM</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

- Kinematic vary widely for the different shape benchmarks.
- Searches in different final states provide good sensitivity for the different kinematic variations
HH combination $\kappa_\lambda$ scan

\[ \text{Observed} \quad 22.2 \quad \text{SM} \]

\[ \text{Combined} \quad 23.6 \quad \text{SM} \]

\[ \text{Expected} \quad 12.8 \quad \text{SM} \]

\[ \text{Expected} \quad 18.8 \quad \text{SM} \]

\[ \text{Expected} \quad 25.1 \quad \text{SM} \]

\[ \text{Expected} \quad 36.9 \quad \text{SM} \]

\[ \text{Expected} \quad 88.8 \quad \text{SM} \]

\[ 35.9 \text{ fb}^{-1} (13 \text{ TeV}) \]

CMS preliminary $gg \rightarrow HH$
HH-4b resonant

- Signal modelled using a sum of two Gaussians or Gaussian+exponential tails using MC simulations
- Background uses parametric fits derived from sideband regions in the $m_H$ mass spectrum.
HH->4b resonant

Events / 20 GeV

 Arbitrary units

Bulk graviton: LL category (signal region)

CMS

Simulation

Arbitrary units

1000 1500 2000 2500 3000

m_{jj, red} [GeV]

10^{-1} 10^{-2} 10^{-3} 10^{0} 10^{1} 10^{2} 10^{3}

Events / 20 GeV

Data

Background pre-fit

Background post-fit

Bulk graviton 1600 GeV

Bulk graviton 2500 GeV

Signal cross section = 10 fb

Data - Fit

[-1, 2]

CMS

Simulation

35.9 fb^{-1} (13 TeV)

TT category: Signal region

Data

Background pre-fit

Background post-fit

Bulk graviton 1600 GeV

Bulk graviton 2500 GeV

Signal cross section = 10 fb

Arbitrary units

0

0.05

0.1

0.15

0.2

0.25

0.3

1500 2000 2500 3000

m_{jj, red} [GeV]
HH→4b boosted non-resonant

In the SM the $m_{HH}$ peaks at ~400 GeV.

BSM couplings can boosted Higgs bosons and result in higher $m_{HH}$ distributions.

Using boosted topologies gives good sensitivity to those shape benchmarks which have high $m_{HH}$ distributions.

Highest sensitivity to the benchmarks 2 and 5.

Also good sensitivity to the benchmarks 8, 9, and 11.
HH→bbγγ

CMS Simulation (13 TeV)

- pp→X→HH→γγb¯b (spin-2): selection steps
- Online
- Diphoton
- Dijet
- MPC+HPC (LM)
- MPC+HPC (HM)

Acceptance x Efficiency

m_X [GeV]

CMS

Simulation (13 TeV)

35.9 fb^{-1} (13 TeV)

pp→HH→γγb¯b

95% CL upper limits
- Observed
- Expected
- Expected ± 1 std. deviation
- Expected ± 2 std. deviation

Shape benchmark hypothesis

σ(pp→HH) × B(H→γγb¯b) [fb]
Non-resonant HH cross section limit at 30 times SM.

Cross section limits also set for different benchmarks for the Higgs boson coupling.
- >= 1 hadronic tau decay $\tau_h$
- Resolved H decay: 1 or 2 b jet
- Boosted H decay: Fat jet (AK8) with subjets matched to AK4 jets
- MVA discriminator for $\tau_\mu \tau_h / \tau_e \tau_h$ to reject ttjets

$m_{HH}$ for resonant search

**Resolved**

**Boosted**

**Low mass spin 0**

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Dilepton triggers

Event categories: $e^+e^-$, $\mu^+\mu^-$, $e^\pm\mu^\mp$

$12 < m_{ll} < 15$ GeV: Reject quarkonia and $Z \rightarrow ll$

2 $b$-tagged jets

DY background estimated from the data using a BDT to classify events according to jet flavours: $ll+bb$, $ll+cc$, and $ll+light$ flavour jets.

3 $m_{jj}$ categories

Neural network training is used to improve signal-background separation. Training parametrized as a function of the mass (resonant search) and $\kappa_\lambda$ and $\kappa_t$ (non-resonant search).
HH->bbℓ⁺ℓ⁻νν interpretation

- Limits set on spin-0 radion and spin-2 bulk graviton.
- Non-resonant HH cross section limit at 79 times SM.
- Limit for different $\kappa_\lambda/\kappa_t$ values.
- Limit also set over $\kappa_\lambda$ and $\kappa_t$ parameter space.
Summary of resonant searches

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

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