CMS di-Higgs searches in final states with two photons

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Introduction

The Higgs field potential:

\[ V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4 = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4 \]

\[ \text{plus effect of cov. derivative on } \phi \text{ in } \mathcal{L}_\text{H} \]

Mass-term \( \lambda_3 \), trilinear self-coupling \( \lambda_4 \), quartic self-coupling \( C_{2v} \), \( \phi \) coupling

- Measurement of self-couplings \( \lambda_3(\lambda_4) \) is crucial for understanding the field potential:
  - Mediates our understanding of how EWSB is realized.
- There are 2 production modes:

Gluon Gluon Fusion (~31 fb)

Vector Boson Fusion (~1.7 fb)

Could measure self-coupling of Higgs boson

Could measure self-coupling of Higgs boson, and the coupling between 2 Higgs and 2 vector boson (\( C_{2v} \))
Effective Field Theory Parameterised BSM Lagrangian:

\[ \mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^S v H^3 - \frac{m_t}{v} (\kappa_t H + \frac{c_2}{v} H^2)(t_1 t_R + h.c.) + \frac{12\pi}{5} (c_8 H - \frac{c_{2g}}{2v} H^2) C_{\mu\nu} C_{a,\mu\nu} \]

\[ \kappa_\lambda = \frac{\lambda_{HHH}^S}{\lambda_{HHH}^S}, \quad \lambda_{HHH}^S, \quad \kappa_t = \frac{y_t}{y_t^{SM}}, \quad y_t^{SM} = \sqrt{2m_t^2} / v \]

SM \((k_\lambda=1, \ k_t=1, \ c_{2g} = c_g = c_3=0)\)  \quad BSM

There are 5 parameters in the Lagrangian: \(K_\lambda, \ K_t, \ C_{2g}, \ C_2, \ C_g\).

Points in the parameter phase space could be clustered in different benchmarks.
The HH production has a very small cross-section in SM.
• The cross-section of ggHH is 1000X smaller than ggH.
• The cross-section of VBFHH is 2000X smaller than VBFH.

It is a difficult work to distinguish HH signal from background.
• The Higgs decays to two photons can provide help.
  – It has a clean final state in CMS, and a narrow di-photon mass spectrum.
  – The small branching ratio (~0.26%).
• Combines higher rate of bb/WW with low backgrounds & excellent mass resolution of γγ would be a good choice.

CMS has performed the search for non-resonant HH in the two decay channels with the top two largest branching ratios (bbγγ and WWγγ).
**HH → WWγγ search: Overview**

- This analysis only investigated ggHH production.
- It used Full-RunII Data.
- There are 3 final states depending on the W bosons decays:
  - Fully-hadronic (FH) : $4q + \gamma\gamma$
  - Semi-leptonic (SL) : $2q + l + \nu + \gamma\gamma$
  - Fully-leptonic (FL) : $2l + 2\nu + \gamma\gamma$
- For these 3 final states, chosen different strategies.
- 1D fit of $M_{\gamma\gamma}$ for signal extraction.
- This search (HIG-21-014) has been approved by CMS recently:
  - First time to be presented!
HH $\rightarrow$ WW\gamma\gamma$ search: Strategy

For SM analysis:
Multiclass DNN
(Signal, SH, Other bkg)

For EFT benchmark:
Binary DNN
(Signal, Other bkg)

4 Categories

Limit using combined
Run-2 Data

Semi-Leptonic

* Exactly 1 lepton
* $\geq 1$ diPhoton Candidate with standard diPhoton pre-selection

Full-Hadronic

* Exactly 0 leptons
* $\geq 4$ jets
* $\geq 1$ diPhoton Candidate with standard diPhoton pre-selection

Binary DNN
(WWgg vs bkg)

3 Categories

Limit using combined
Run-2 Data

Binary DNN
(bbgg vs bkg)

Fully-Leptonic

* Exactly 2 leptons
* $\text{MET} > 20$
* $\geq 1$ diPhoton Candidate with standard diPhoton pre-selection

Cut Based

Limit using combined
Run-2 Data

Combine all channel
Events categorisation in SL channel:

- Trained multi-class DNN to separate HH, single-Higgs and backgrounds
- Then used HH score to do the categorisation:
  - Simultaneous optimisation of number of categories and boundaries based on total significance

SL DNN score Data/MC distribution
The dashed lines indicate the DNN boundaries
**Events categorisation in FH channel:**
- Trained binary DNN to separate HH from backgrounds
- An dedicated bbγγ DNN was trained to reduce the overlaps.
- Then used HH score to do the categorisation

**Events categorisation in FL channel:**
- The raw events of MC samples are not enough to train MVA.
- Only cut based method was used in this channel.
- Several optimised selections were used in this channel

**FH DNN score Data/MC distribution**
The dashed lines indicate the DNN boundaries

**FL Data/MC comparison of dilepton invariant mass.**
The main NR background is DY, the main resonant background is VH.
Inclusive $S+B$ Fitting:

Inclusive $S+B$ fits for full-run2 data, all categories summed.

The observed diphoton mass distributions:
- The signal plus background fit (red)
- The Single-Higgs + continuum background fit (blue)
- Continuum background (black dashed line), with bands covering the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties
- All analysis categories are combined and weighted by $S$ over $S+B$
Obs.(exp.) upper limit on HH signal strength: \(97(52)\times\text{SM at 95\% C.L.}\)

- No deviations from SM observed.

Obs.(exp.) upper limit on HH signal for 20 EFT benchmarks:

- \(1.7 - 6.2\ (1.0 - 3.9)\ \text{pb.}\)
HH $\rightarrow$ WWγγ search: Results

$\kappa_\lambda$ (Higgs self-coupling) and $C_2$ (coupling of 2 top and 2 Higgs) scan:

\[
\begin{align*}
\text{Obs. (Exp.) } \kappa_\lambda &\in [-25.8 (-14.4), 24.1 (18.3)] \\
\text{Obs. (Exp.) } C_2 &\in [-2.4 (-1.7), 2.9 (2.2)]
\end{align*}
\]
This analysis investigated both ggHH and VBFHH productions.

It used Full-RunII Data.

The main backgrounds:
- Non-resonant (NR) backgrounds primarily from QCD
- Secondary, peaking background from SM single Higgs (Mainly ttH).

MVA strategy used to separate signal and backgrounds.
- BDT was used in ggF and VBF to separate HH from $\gamma(\gamma) +$ Jets events.
- Dedicated DNN was used to reject ttH($H \rightarrow \gamma\gamma$) events.

Simultaneous fit of $m_{\gamma\gamma}$ and $m_{bb}$ was performed for signal extraction.

Results has been published in JHEP03(2021)257.
Analysis strategy

- **Object Selection:** Photons, b-jets, light quark jet ...

- **VBF HH Phase-space**
  - MVA Training and Categorization - 2 cats (MVA & MX)
  - Total 14 categories
  - Simultaneous fit to $M_{gg} \times M(jj)$

- **ggHH Phase-space**
  - MVA Training and Categorization - 12 cats (MVA & MX)

- **ttH Phase-space:**
  - 4 leptonic & 4 hadronic cats
  - *for HH+H combination

**Equation:**

- $MX = M_{\gamma\gamma ij} - M_{jj} - M_{\gamma\gamma} + 250$, Effective 4-body invariant mass of $bb\gamma\gamma$. 
Event categorisation based on MVA score & $\tilde{M}_X$

- In final, there are 3 MVA categories × 4 $\tilde{M}_X$ categories in ggF mode.
- And 2 MVA categories for low and high $\tilde{M}_X$ categories in VBF mode.

MVA score distributions, the grey regions are removed, the blue dashed lines indicate the boundaries.
**HH → bbγγ search: Results**

- **Obs.(exp.) upper limit on HH signal strength:** 7.7(5.2)×SM at 95% C.L.
  - No deviations from SM observed.

- **$\kappa_\lambda$ (Higgs self-coupling) and $C_{2v}$ (coupling of 2 Vector boson and 2 Higgs) scan:**


![Graph 1](image1.png)

*Obs. (Exp.) $\kappa_\lambda \in [-3.3 (-2.5), 8.5 (8.2)]*

![Graph 2](image2.png)

*Obs. (Exp.) $C_{2v} \in [-1.3 (-0.9), 3.5 (3.1)]*
$\HH \rightarrow bb\gamma\gamma$ search: Results

- $C_2$ (coupling of 2 top and 2 Higgs) scan and limits for 12 EFT benchmarks

- Obs. (Exp.) $C_2 \in [-0.6 (-0.4), 1.1 (0.9)]$

- Obs. (Exp.) limits for 12 benchmarks: 0.3-1.0 (0.2 - 1.0)fb
Summary

The Di-Photon final state has special features in HH analyses.

- Presented HH analyses with one Higgs decays to two photons and the other Higgs decays to the final states with the top 2 largest branching ratio (bb/WW).

- **HH → WWγγ 2022 new results:**
  - This is the first HH → WWγγ search with full RunII dataset in LHC!
  - Obs.(Exp.) SM limit: $97 (52) \times SM$
  - Obs.(Exp.) coupling constraints:
    - $\kappa_\lambda \in [-25.8 (-14.4), 24.1 (18.3)]$, $C_2 \in [-2.4 (-1.7), 2.9 (2.2)]$
  - Obs.(Exp.) EFT limits on HH: $1.7 - 6.2$ (1.0 - 3.9) pb.

- **HH → bbγγ results:**
  - Obs.(Exp.) SM limit: $7.7 (5.2) \times SM$
  - Obs.(Exp.) coupling constraints:
    - $\kappa_\lambda \in [-3.3 (-2.5), 8.5 (8.2)]$, $C_2 \in [-0.6 (-0.4), 1.1 (0.9)]$, $C_{2v} \in [-1.3 (-0.9), 3.5 (3.1)]$
  - Obs.(Exp.) EFT limits on HH → bbγγ: $0.3 - 1.0$ (0.2 - 1.0)fb
Thanks for your attention!
HH $\rightarrow$ WW$\gamma\gamma$ search: Strategy

- Event classification in exclusive categories based on the number of good leptons:
  - Semi-Leptonic: Exactly 1 lepton
  - Fully-Leptonic: Exactly 2 leptons
  - Fully-Hadronic: Exactly 0 lepton

- Because of the different statistics and characteristics in different channels, we chosen different strategies for 3 final states
  - Semi-Leptonic: Multi-Class DNN
    - Trained a multi-classed DNN to separate HH, H and continuum background.
  - Fully-Leptonic: Cut-based
    - Because of the clean final state and low stats, we chosen cut-based method.
  - Fully-Hadronic: 2 Binary DNN (WW$\gamma\gamma$ DNN + bb$\gamma\gamma$ killer DNN)
    - We trained a WW$\gamma\gamma$ DNN to separate HH from all backgrounds(H + continuum background)
    - Then trained an additional bb$\gamma\gamma$ DNN to reject HH$\rightarrow$bb$\gamma\gamma$ events
HH $\rightarrow$ WW$\gamma\gamma$ per-channels fit

**SL channel**

**CMS Preliminary**

$138 \text{ fb}^{-1}$ (13 TeV)

$H\rightarrow WW\gamma\gamma$

$m_{\gamma\gamma} = 125.0 \text{ GeV}$

$S/(S+B)$ weighted

- $H + H + B$ fit
- $H + B$ component
- $B$ component
- $\pm 1 \sigma$
- $\pm 2 \sigma$

$H + B$ component subtracted

**FH channel**

**CMS Preliminary**

$138 \text{ fb}^{-1}$ (13 TeV)

$H\rightarrow WW\gamma\gamma$

$m_{\gamma\gamma} = 125.0 \text{ GeV}$

$S/(S+B)$ weighted

- $H + H + B$ fit
- $H + B$ component
- $B$ component
- $\pm 1 \sigma$
- $\pm 2 \sigma$

$H + B$ component subtracted

**FL channel**

**CMS Preliminary**

$138 \text{ fb}^{-1}$ (13 TeV)

$H\rightarrow WW\gamma\gamma$

$m_{\gamma\gamma} = 125.0 \text{ GeV}$

$S/(S+B)$ weighted

- $H + H + B$ fit
- $H + B$ component
- $B$ component
- $\pm 1 \sigma$
- $\pm 2 \sigma$

$H + B$ component subtracted