Non-resonant HH production and Higgs self-coupling at CMS

Saswati Nandan

On behalf of the CMS collaboration
Introduction

- Since Higgs boson discovery, many of its properties have been measured very precisely.
- So far, the measurements agree with Standard Model predictions.
- The Higgs potential $V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$.
- The Higgs self-coupling, $\lambda$, has not been measured yet. Only upper limits have been set.
  \[ \lambda = \frac{m_H^2}{2v^2} \approx 0.13 \] (where $m_H$, $v$ are measured precisely).
- $\lambda$ is difficult to measure, because the cross section for HH production, which provides sensitivity to this coupling, is very small.
- $\lambda$ can also be constrained indirectly through single Higgs production.

References:

Physics Letters B (2014) 142-149
Introduction

- HH pair can be produced in different ways:
  - **GGF**
    
    \[ \sigma_{HH}^{GGF}(13\text{TeV}) = 31.05 \pm 3(PDF + \alpha_S)_{+6\%}^{+23\%}(scale + m_{top}) \text{ fb} \]

  - **VBF**
    
    \[ \sigma_{HH}^{VBF}(13\text{TeV}) = 1.71 \pm 2.1%(PDF + \alpha_S)_{+0.03\%}^{-0.04\%}(scale) \text{ fb} \]

- **VHH** (New in CMS)
  \[ \sigma_{HH} \sim 0.86 \text{ fb} \]

- **ttHH** (No result today)
  \[ \sigma_{HH} \sim 0.76 \text{ fb} \]

- Not easy to probe!!!
Introduction

- Anomalous coupling can modify the cross section of HH pair production as well as kinematic properties of HH pair

Coupling modifiers $\kappa$, defined as deviation from SM value
- $\kappa_\lambda = \lambda / \lambda_{\text{SM}}$
- $\kappa_V = C_V / C_{V,\text{SM}}$
- $\kappa_{2V} = C_{2V} / C_{2V,\text{SM}}$
- Deviation from 1 indicates BSM physics

*JHEP(2019)066*
How to probe HH production

- Depends on decay products of Higgs boson:
  - HH→bbZZ \(^{\text{arXiv:2206.10657}}\) (submitted to JHEP)
  - HH→WW*WW*/WW*ττ/ττττ \(^{\text{arXiv:2206.10268}}\) (submitted to JHEP)
  - HH→bbγγ \(^{\text{JHEP 03 (2021) 257}}\)
  - HH→bbττ \(^{\text{arXiv:2206.09401}}\) (submitted to PLB)
  - HH→bbbb \(^{\text{Phys. Rev. Lett. 129 (2022) 081802}}\)

<table>
<thead>
<tr>
<th>H→XX</th>
<th>bb</th>
<th>WW</th>
<th>γγ</th>
<th>ZZ</th>
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</table>

- Shown last year
- Will be shown today

H→bb highest BR,
  large hadronic background
H→WW* second highest BR,
  large hadronic background
H→γγ low BR,
  good mass resolution
H→ZZ low BR,
  clean signature in leptonic decay
H→ττ low BR,
  low background

- No golden channel!!!
Combined limit based on previous results

- Combined upper limit on ggF+VBF production

\[ \sigma_{HH} < 3.4 \ (2.5) \sigma_{HH}^{(SM)} \] based on previous result
Analysis Strategy

- Targeting both GGF and VBF production mode
- 2 channels, based on W decay:
  - Double lepton (DL): $WW^* \rightarrow l\nu l\nu$
  - Single lepton (SL): $WW^* \rightarrow l\nu qq$
- All channels are further splitted:
  - Resolved: 2 small radius jet coming from 2 b quarks
  - Boosted: 2 jets coming from 2 b quarks merged in a single large radius jet
- Resolved: Jets are identified by Deep Neural network (DeepJet)
  - 1b, 2b: 1 or 2 jets passing medium working point of Deepjet

Event Selection

Lepton:
- 2 (1) good lepton in DL(SL)
- Veto extra lepton
- Veto $81 < m_{ll} < 101$ GeV in DL
Jet:
- Resolved: $\geq 2$ ($\geq 3$) small radius jet in DL(SL)
- Boosted: 1 large radius jet in DL, SL, $\geq 1$ small radius jet in SL

Background Estimation

QCD multijet, Fake lepton: data driven
DY: data driven in DL
Other: Estimated from simulation
Signal Extraction

- Multi-classifier training:
  Separate GGF signal, VBF signal and other dominant backgrounds using Deep Neural Network (DNN)

- Signal distribution is flat in signal nodes
- Total background distribution is flat in background nodes

- Use DNN score to extract signal
Exclusion limit on HH production cross section:

- Observed (expected): $\sigma_{HH} < 14\, (18)\, \sigma_{HH}^{(SM)}$

Constraint on Higgs self coupling modifier:

- Observed (expected): $-7.2(-8.7) < \kappa_\lambda < 13.8(15.2)$
**Analysis Strategy**

- Targeting GGF production mode
- 3 channels, based on W decay:
  - **Fully hadronic (FH):** $WW^* \rightarrow 4q$
  - **Di-lepton (DL):** $WW^* \rightarrow l\nu l\nu$
  - **Single lepton (SL):** $WW^* \rightarrow l\nu qq$

**Signal and Background Modelling**

- Signal: Modelled by an analytic fit of a sum of up to five Gaussians to a binned $m_{\gamma\gamma}$ distribution
- Single Higgs: Same as signal
- Continuum background: Modelled from data

**Event Selection**

- **Photon:**
  - 1 good di-photon candidate
  - $100 < m_{\gamma\gamma} < 180$ GeV
- **Lepton:**
  - 0, 1, 2 lepton in FH, SL, DL
  - Veto extra lepton
- **Jet:**
  - $\geq 4$ small radius jet in FH

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Non-resonant HH production and Higgs self-coupling at CMS  LHCP2023
Signal Extraction

- **FH:**
  - **bb\(\gamma\gamma\) rejection:** BDT classifier to separate bb\(\gamma\gamma\) and WW\(\gamma\gamma\)
  - Signal: bb\(\gamma\gamma\), Background: WW\(\gamma\gamma\), \(\gamma\gamma\)+jets, \(\gamma\)+jets, QCD multijet

- **WW\(\gamma\gamma\) classifier:** BDT classifier to separate WW\(\gamma\gamma\) signal and \(\gamma\gamma\)+jets, \(\gamma\)+jets, QCD multijet backgrounds

- **DL:** Cut based

- **SL:**
  - **Multi-classifier:** Separate signal, single Higgs, and continuum background

- 4 categories are defined for each classifier output to maximize signal sensitivity

- Combined fit of \(m_{\gamma\gamma}\) is performed in all classifier categories to extract signal
Exclusion limit on HH production cross section:

- Observed (expected): $\sigma_{HH} < 52 \ (97) \ \sigma_{HH}^{(SM)}$

Constraint on Higgs self coupling modifier:

- Observed (expected): $-25.8 \ (-14.4) < k_\lambda < 24.1 \ (18.3)$
Analysis Strategy

- 4 channels, based on W/Z decay:
  - SL(W→lν), MET(Z→νν), DL(Z→ll), FH(W/Z→qq)

- BDT training to separate $\kappa_\lambda$ and $\kappa_v$ coupling enriched regions

- Resolved (All channels):
  - Jets are identified by Deep Neural network (DeepJet) training
  - 3b, 4b: 3 or 4 jets passing medium working point of DeepJet

- Boosted (Single lepton, MET):
  - Jets are identified by ParticleNet training
  - Low, High purity: Classified based on ParticleNet score

Event Selection

Jet:
- $\geq$2 large radius jet (boosted) or $\geq$3 small radius jet (resolved)

Lepton:
- 1 (SL), 2 (DL) good lepton

MET:
- Missing transverse energy $>$150 (resolved), $>$250 (boosted) GeV
**Background Estimation**

- **BDT reweighting:**
  - Used in statistics depleted region
  - Train between nominal region and other region with some cuts inverted
- **QCD multijet in FH:**
  - Data driven
- **Other:** From simulation

**Signal Extraction**

- **BDT or Neural network training to separate signal and background**
- **Separate training for each** $\kappa_\chi$ **and** $\kappa_{VV}$ **enhanced regions**
- **Use classifier output to extract signal**
Exclusion limit on HH production cross section:
- Observed (expected): $\sigma_{HH} < 294 \ (124) \ \sigma_{HH}^{(SM)}$

Constraint on Higgs self coupling modifier:
- Observed (expected): $-37.7\ ^{-30.1}_{+28.9} < k_{\lambda} < 37.2 \ (28.9)$
Constraint on Higgs self-coupling through single Higgs production

- Higgs self-coupling can be constrained through single Higgs production at NLO corrections

NLO diagrams contributing to Higgs self-coupling

Nature 607 (2022) 60-68
Search for non-resonant HH production has been probed in different final states using the full LHC Run2

Three new channels (HH→bbWW*, HH→WW*γγ, VHH→bbbb) have been added since last year

Many BSM studies have been done (More in back up)

Looking forward to seeing many interesting results with Run3 and full combination

Stay tuned!!!
Constraint on $\kappa_\lambda$ vs $\kappa_{2V}$

Nature 607 (2022) 60-68
(a) SM-like processes

(b) Pure BSM processes
EFT benchmarks  arXiv:1507.02245
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<td>1./6.*(-3.)</td>
<td>-0.5*(-3.)</td>
<td>1./3.*(-3.)</td>
<td>-1./6.*(-3.)</td>
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</tbody>
</table>
Object selection

- Small radius jet:
  - $p_T > 25$ GeV, $|\eta| < 2.4$
  - Medium working point of DeepJet score

- Large radius jet:
  - $p_T > 200$ GeV, $|\eta| < 2.4$, $\tau_2 / \tau_1 < 0.75$
  - $p_T$ of subjet $> 20$ GeV
  - $30 < m_{SD} < 210$
  - $m_{ll} > 12$ GeV

Event category in SL channel:

<table>
<thead>
<tr>
<th>Categories</th>
<th>Sub-Categories</th>
</tr>
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<tbody>
<tr>
<td>HH(GGF)</td>
<td>Resolved 1b</td>
</tr>
<tr>
<td></td>
<td>Resolved 2b</td>
</tr>
<tr>
<td></td>
<td>Boosted</td>
</tr>
<tr>
<td>HH(VBF)</td>
<td>Resolved 1b</td>
</tr>
<tr>
<td></td>
<td>Resolved 2b</td>
</tr>
<tr>
<td></td>
<td>Boosted</td>
</tr>
<tr>
<td>Top + Higgs</td>
<td>Resolved</td>
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<tr>
<td>WJets + Other</td>
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Event category in DL channel:

<table>
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<td>HH(GGF)</td>
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</tr>
<tr>
<td></td>
<td>Resolved 2b</td>
</tr>
<tr>
<td></td>
<td>Boosted</td>
</tr>
<tr>
<td>HH(VBF)</td>
<td>Resolved 1b</td>
</tr>
<tr>
<td></td>
<td>Resolved 2b</td>
</tr>
<tr>
<td></td>
<td>Boosted</td>
</tr>
<tr>
<td>Top + Other</td>
<td>Resolved</td>
</tr>
<tr>
<td>DY + Multi-boson</td>
<td>Inclusive</td>
</tr>
</tbody>
</table>
QCD multijet, Fake lepton estimation:

- SR → Signal region
- AR → Similar to signal region but lepton fails the tight selection
- Prompt → lepton matched with generator level lepton coming from W, Z, τ or Higgs
- FF → fake factor which is the probability to pass the fake to tight cut

\[ w = (-1)^{n+1} \prod_{i=1}^{n} \frac{f_i}{1 - f_i} \]

DY estimation:

- Calculate transfer weight from 0-bjet → 1/2-bjet region in Z-peak region
- Weights are binned in HT (P_T sum of AK4 jets) for resolved and softdrop mass of leading AK8 jet for boosted category.
- Apply transfer weight in Z-veto region
- Non DY backgrounds are subtracted from data in both Z-peak and Z-veto region.
Exclusion limit on HH production cross section in VBF production:
- Observed (expected): $\sigma_{HH} < 277$ (301) $\sigma_{HH}^{(SM)}$

Constraint on $\kappa_{2V}$:
- Observed (expected): $-1.1(-1.4) < \kappa_{2V} < 3.2 (3.5)$
Non-resonant HH production and Higgs self-coupling at CMS LHCP2023
Object selection:

- $p_T > 35$ (25) GeV leading (sub-leading) photon
- $|\eta| < 2.5$
- $p_T/m_{\gamma\gamma} > 1/3$ (1/4) for leading(sub-leading) photon in Fully Hadronic and Di-lepton channel
- Jet $p_T > 25$GeV, $|\eta| < 2.4$
- No jet with medium working point of btag score in Di-leptonic channel
Non-resonant HH production and Higgs self-coupling at CMS LHCP2023
### Object Selection

<table>
<thead>
<tr>
<th>Channel</th>
<th>Vector boson decay products selection</th>
<th>Vector boson reconstruction and selection</th>
<th>Jet selection</th>
</tr>
</thead>
</table>
| MET small-radius | \( \vec{p}_T^Z = \vec{p}_T^{\text{miss}} \)  
\( p_T^Z > 150 \text{ GeV} \) | \( \vec{p}_T^Z = \vec{p}_T^{\text{miss}} \)  
\( p_T^Z > 250 \text{ GeV} \) | \( \geq 4 \) small-radius jets  
with \( p_T > 35 \text{ GeV} \) |
| MET large-radius | \( \vec{p}_T^Z = \vec{p}_T^{\text{miss}} \)  
\( p_T^Z > 250 \text{ GeV} \) | \( \geq 2 \) large-radius jets  
with \( p_T > 200 \text{ GeV} \) |
| 1L              | \( p_T^\ell > 32(28) \text{ GeV} \)  
2018/2017 (2016) | \( \vec{p}_T^W = \vec{p}_T^\ell + \vec{p}_T^{\text{miss}} \)  
\( p_T^W > 125 \text{ GeV} \) | \( \geq 3 \) small-radius jets  
with \( p_T > 25 \text{ GeV} \) and  
\( \geq 4 \) small-radius jets  
with \( p_T > 15 \text{ GeV} \)  
OR  
\( \geq 2 \) large-radius jets  
with \( p_T > 200 \text{ GeV} \) |
|                | OR                                   |                                         | 2L                                                |
|                | \( p_T^\mu_1 > 20 \text{ GeV} \)  
\( p_T^\mu_2 > 20 \text{ GeV} \)  
\( p_T^{e_1} > 25 \text{ GeV} \)  
\( p_T^{e_2} > 20 \text{ GeV} \) | \( \vec{p}_T^Z = \vec{p}_T^{\mu_1} + \vec{p}_T^{\mu_2} \)  
\( p_T^Z > 50 \text{ GeV} \) | \( \geq 4 \) small-radius jets  
with \( p_T > 20 \text{ GeV} \) |
| FH             | \( p_T^h_1 > 20 \text{ GeV} \)  
\( 65 < m_V < 105 \text{ GeV} \) | \( \vec{p}_T^V = \vec{p}_T^{h_1} + \vec{p}_T^{h_2} \) | \( \geq 4 \) small-radius jets  
with \( p_T > 40 \text{ GeV} \) and  
\( \geq 6 \) small-radius jets  
with \( p_T > 20 \text{ GeV} \) |
### Event Categories

<table>
<thead>
<tr>
<th>Coupling enrichment</th>
<th>MET small-radius</th>
<th>MET large-radius</th>
<th>1L small-radius</th>
<th>1L large-radius</th>
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<td>$N_b \geq 3$</td>
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<td>$N_b = 4$</td>
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<td>$D_{b\bar{b},1} \times D_{b\bar{b},2}$</td>
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<td>HP, LP</td>
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<tr>
<td>SB</td>
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<td>HP, LP</td>
<td>$\kappa_\lambda + \kappa_{VV}$</td>
<td>HP, LP</td>
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<td>$N_b = 4$</td>
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<td>Per year</td>
<td>Per year</td>
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<td>Per year</td>
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<td>12</td>
<td>9</td>
<td>12</td>
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</table>
Constraint on $\kappa_{VV}$:
- Observed (expected): $-12.2(-7.2) < \kappa_{VV} < 13.5 (8.9)$

Constraint on $\kappa_V$:
- Observed (expected): $-3.7(-3.1) < \kappa_V < 3.8 (3.1)$