Measurement of Higgs self-coupling from non-resonant Higgs pair production and decay to $bb\gamma\gamma$ final state in the CMS experiment at the CERN-LHC.

Soumya Mukherjee, TIFR, Mumbai, India.

On behalf of the CMS collaboration
Higgs pair production in Standard Model

Higgs potential:

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4$$

Expanding about Minimum:

$$V(\phi) = -V(\nu + h)$$

$$V = V_0 + \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2 \nu^2} \nu h^3 + \frac{1}{4} \frac{m_h^2}{\nu^2} h^4$$

- Shape of potential gives relationship between $\lambda_{HHH}$ and $m_H, \nu$
- Measuring $\lambda_{HHH}$ important because it probes the shape of the Higgs potential
- HH production interesting because it measures $\lambda_{HHH}$

In SM:

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{m_H^2}{2 \nu^2} = 0.13$$
Higgs pair production in LHC

Gluon-gluon fusion (ggHH): the largest production mode of HH at the LHC, cross section with $N^2$LO QCD accuracy, $\sigma_{ggHH} = 31.05 \text{ fb} @13 \text{ TeV}$ [1].

Vector Boson fusion (VBFHH): the sub-lead mode, at $N^3$LO, $\sigma_{VBFHH} = 1.73 \text{ fb}$ [2].

VBFHH: unique process for accessing the coupling of Higgs pair with a pair of weak gauge bosons (VVHH, $V = W/Z$)

Coupling modifier: $\kappa_a = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}, C_{2V} = \frac{HHVV}{HHVV^{SM}}, C_V = \frac{HVV}{HVV^{SM}}$
HH search in CMS

- HH decay modes being explored using **full Run2** (137 fb⁻¹) data: HH→ 4b, bbττ, bbγγ, bbWW, bbZZ, 4W, WWττ, 4τ, WWγγ

→ bb (58%) and WW*(21%) have the large BR

- Emphasis of this talk is the latest result using full RunII data on bbγγ

[CMS-HIG-19-018](#)

- Using **2016 (36 fb⁻¹)** data other published results from CMS (atleast one H decays to bb)
  - HH→ 4b
  - HH→ bbττ
  - HH→ bbVV (V = W/Z)
  - HH→ bbγγ

& combined
CMS combined HH result with 2016 data

PRL 122 (2019)

95% CL Upper Limit on (cross section*BR) :

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Expected</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>22.2</td>
<td>12.8</td>
</tr>
</tbody>
</table>

 Allowed range @ 95% CL

- Observed: $-11.8 < \kappa_\lambda < 18.8$
- Expected: $-7.1 < \kappa_\lambda < 13.6$
bbγγ: key features & analysis strategy

- Small branching ratio (0.26%) but highly sensitive
  (i) excellent ECAL resolution for $H \rightarrow \gamma\gamma$ in CMS
  (ii) large branching ratio for $H \rightarrow bb$

Strategy for recent analysis:

- $M_X (M_{HH}) = M_{\gamma\gamma} - M_{bb} + 250 \text{ GeV}$: sensitive for probing BSM
- BDT method to enhance signal vs. background discrimination

Selection:
- $\gamma$, b-jets, VBF jets

- Total 14 categories based on $M_X$ & MVA
- Simultaneous 2D fit to $m_{\gamma\gamma}$ x $m_{jj}$ distributions
- Assuming no $m_{\gamma\gamma}$ - $m_{jj}$ correlation
Backgrounds:
→ QCD induced non-resonant $\gamma\gamma$ + jets, $\gamma$ + jets
→ single Higgs production with $H \rightarrow \gamma\gamma$ (ttH most dominant)

For each category, ggHH and VBFHH signal and single Higgs backgrounds modelling:

○ $m_{\gamma\gamma}$ → multi-Gaussian
○ $m_{jj}$ → Double-sided Crystal Ball

Shape of non-resonant background in each category determined directly from data using discrete profile method [3].

Final signal extraction performed by simultaneous fit to all categories.
**bbγγ (ggHH + VBFHH): results on \( \sigma \times BR \)**

**Observed**:
- \(-3.3 < \kappa_\lambda < 8.5\)
- \(-1.3 < C_{2V} < 3.5\)

**Expected**:
- \(-2.5 < \kappa_\lambda < 8.2\)
- \(-0.9 < C_{2V} < 3.0\)

**First from CMS**

**Inclusive HH (* SM)**

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<thead>
<tr>
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<th>Observed</th>
<th>Expected</th>
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<tbody>
<tr>
<td>Observed</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Expected</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>

**Allowed range @ 95% CL**

*Best-to-date!*
Constraining BSM, results for $C_2$

- EFT approach includes three new additional couplings for $ggHH$ compared to SM.

- Parameters of interest: $\kappa_\lambda, \kappa_t$ from SM + $c_2, c_g, c_{2g}$ from BSM

- Hence, $ggHH$ cross section and kinematics of final state particles depend on the above 5 coupling parameters.

- $C_2$ is not present in SM

**Observed:** $-0.6 < C_2 < 1.0$

**Expected:** $-0.4 < C_2 < 0.9$
1D Likelihood scans

→ ttH process considered for better constraint on $\kappa_\lambda$ and $\kappa_t$
→ ttH categories are mutually exclusive to the all HH categories [4]

→ Inclusion of ttH makes positive $\kappa_\lambda$ preferable
rules out negative $\kappa_t$ at 95% CL
2D Likelihood scan for BSM search

Validity region for using $\kappa_t$ dependence of $ttH$ at LO & $\kappa_\lambda$ dependence at NLO [5]

VBFHH involves $\kappa_\lambda$ and $C_{2V}$ but not $\kappa_t$
Summary

1. Measurement of the Higgs boson self-coupling is of high priority for the LHC physics programme.

2. Several analyses with different HH decay channels are being considered with \( bb\gamma\gamma \) mode having the best sensitivity.

3. Highlights of results obtained by CMS collaboration from Run2 data using inclusive \( bbgg \) final state.
   i) Improvement in the allowed range of trilinear Higgs coupling
   ii) The VBFHH production mode considered along with the \( ggHH \) mode for the first time.
   iii) first results on the VVHH coupling parameter
   iv) 95% confidence level upper limit on (cross section * BR) for inclusive diHiggs production

4. Other final state analyses with full Run2 data and final combined results are on the way.
   
   Stay tuned!

5. More interesting results are expected in Run3 and HL-LHC era.

   Thank you very much for kind attention
Backups and additional Materials
HH: EFT Lagrangian for ggHH process \[6\]

\[
\mathcal{L}_{HH} = \kappa \lambda_{HHH}^{\text{SM}} v H^3 - \frac{m_t}{v} \left( \frac{\kappa_t}{v} \frac{c_2}{2} \right) (t_L t_R + \text{h.c.}) + \frac{1}{4} \frac{\alpha_s}{3\pi v} \left( c_{2g} \frac{H}{2v} H^2 \right) G^\mu\nu G_{\mu\nu}. \]

- **SM couplings**
- **BSM couplings**
HH: EFT BSM Benchmark [7]

- The different values of coupling parameters leads different kinematics and cross-sections
- In CMS HH analysis 12 benchmark points have been explored to get the EFT sensitivity
- Each benchmark points have been defined by a set of 5 coupling parameters
- The generator level $m_{HH}$ distributions is hugely different in each benchmark scheme

Benchmark points:

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<th>2</th>
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<th>5</th>
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<th>7</th>
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<th>10</th>
<th>11</th>
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<td>$\kappa_\lambda$</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>$\kappa_t$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
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<td>1.0</td>
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<tr>
<td>$c_2$</td>
<td>-1.0</td>
<td>0.5</td>
<td>-1.5</td>
<td>-3.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<td>-1.0</td>
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<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$c_g$</td>
<td>0.0</td>
<td>-0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.8</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>
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<td>0.0</td>
</tr>
<tr>
<td>$c_{2g}$</td>
<td>0.0</td>
<td>0.6</td>
<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>
<td>0.0</td>
</tr>
</tbody>
</table>
**bbγγ : Event selection**

**Photon selection:**
- Hgg MVA γ ID > -0.9
- Pixel-safe electron veto is applied
- $p_T(\gamma_1)/M(\gamma\gamma) > \frac{1}{3}$, $p_T(\gamma_2)/M(\gamma\gamma) > \frac{1}{4}$
- $100 < M(\gamma\gamma) < 180$ GeV

**b-jet selection:**
- b jets are chosen with the highest sum of DeepJet score
- $p_T(\text{jets}) > 25$ GeV, $|\eta| < 2.4$
- $70 < M_{bb} < 190$ GeV

**Forward (VBF) jet selection:**
- $\Delta R < 0.4$ applied between one jet and one photons and one jet and one selected b-jet
- Identify pair of jets with $|\eta| < 4.7$, lead jet $p_T > 40$ GeV & sublead jet $p_T > 30$ GeV
- VBF jets: pair of highest invariant mass ($M_{jj}$).
BSM scenario

- Typically probed via anomalous coupling parameters in terms of modifiers of SM values ($c_i / \kappa_i$). Anomalous values of the coupling modifiers enhance the cross section typically.

- EFT approach includes three new additional couplings for $ggHH$ compared to SM.

**Parameters of interest:** $\kappa_\lambda$, $\kappa_t$ from SM + $c_2$, $c_g$, $c_{2g}$ from BSM

- Hence, $ggHH$ cross section and kinematics of final state particles depend on the above 5 coupling parameters.

- Similarly for $VBFHH$, relevant coupling modifiers $C_V$, $C_{2V}$ and $\kappa_\lambda$ dictate the kinematics & cross section.

- Recent analyses target $VBFHH$ mode along with $ggHH$. 

![Graph showing the cross section $\sigma_{VBFHH}$ vs $C_{2V}$ and $\kappa_\lambda$ for $C_V = 1$]
ttH and single Higgs parametrization:

- The SM Higgs production and decay rates can be used to constrain on the $k_\lambda$
- Deviation from SM Higgs production and decay rate are parameterized by 3D model ($k_\lambda$, $k_V$, $k_F$)
- The production rates have been modified by this coupling parameter in terms of SM value

$$\mu_i(\kappa_V, \kappa_F, \kappa_\lambda) = Z^{BSM}_H(\kappa_\lambda) \left[ S_i(\kappa_V, \kappa_F) + K_{BSM}(1 - \kappa_\lambda) \right]$$

$$Z^{BSM}_H(\kappa_\lambda) = (1 - (\kappa_\lambda^2 - 1)\delta Z)^{-1}$$

$K_{BSM}$: Constants and process dependant

ttH has the largest value

References:
### bbγγ: Event selection

#### Photon selection:
- Hgg MVA γ ID > -0.9
- Pixel-safe electron veto is applied
- $p_T(\gamma_1)/M(\gamma\gamma) > \frac{1}{3}$, $p_T(\gamma_2)/M(\gamma\gamma) > \frac{1}{4}$
- $100 < M(\gamma\gamma) < 180$ GeV

#### b-jet selection:
- b jets are chosen with the highest sum of DeepJet score
- $p_T(jets) > 25$ GeV, $|\eta| < 2.4$ (2016) & $|\eta| < 2.5$ (2017/2018)
- $70 < M_{bb} < 190$ GeV

#### VBF Jet selection:
- **Tight PU** jet ID for jet $p_T < 50$ GeV for all $\eta$
- $\Delta R < 0.4$ applied between one jet and one photons and one jet and one selected b-jet
- Identify pair of jets with $|\eta| < 4.7$, lead jet $p_T > 40$ GeV & sublead jet $p_T > 30$ GeV
- VBF jets: pair of highest invariant mass ($M_{jj}$).
**bbγγ**: Invariant mass distributions in ggHH
**bb\gamma\gamma: ttHScore (An MVA to separate HH Vs ttH)**

- **A DNN based classifier**
- **Signal:** SM ggHH + 12 BSM Benchmark samples
  **Background:** ttH

- **Input variables:**
  (i) Low level information of individual particle flow (PF) objects
  (ii) High level event kinematics
    - Angular variables: $\cos\theta_{\text{CS}}^\ast$, $\cos\theta_{\text{bb}}$, $\cos\theta_{\gamma\gamma}$
    - Variables for the leptonic decays of W from top
      $\Delta R_{\text{MET, } b_1}$, $\Delta R_{\text{MET, } b_2}$, four vector of Leptons $p_T > 0$
    - Variables for the hadronic decays of W boson

- Hyper parameters are optimized by Bayesian optimization

- Good signal to background separation.

- Optimization for threshold value is chosen by taking 90% of signal efficiency.
**bbγγ: List of input variables used for training**

**Common variables with ggHH analysis**

1. Leading & subleading DeepJet score
2. \( \cos(\theta^*_CS), \cos(\theta_x) \) and \( \cos(\theta_y) \) - Helicity angles
3. \( p_T^{\gamma}/M_{HH}, p_T^{bb}/M_{HH} \)
4. Leading & subleading photon ID MVA
5. \( p_T^{\gamma}/m_{\gamma\gamma} \rightarrow \text{lead and sublead photon} \)
6. \( p_T^{bb}/m_{bb} \rightarrow \text{lead and sublead b-jet} \)
7. \( \min \Delta R_{\gamma b} \) and other \( \Delta R_{\gamma b} \)
8. \( p_T^{HH} \)
9. MX
10. Leading and subleading photon resolution, \( \sigma_E/E \)
11. Diphoton mass resolution, \( \sigma_m/m_{\gamma\gamma} \)
12. Leading ans subleading b-jet resolution \( \sigma_E/E \)
13. Di-bjet mass resolution, \( \sigma_m/m_{bb} \)
14. Median energy density in an event (\( \rho \))

**VBF jet related variables**

1. Leading and subleading VBF jet \( p_T/M_{jj}^{VBF} \)
2. Leading and subleading VBF jet \( \eta \)
3. Product of VBF jet \( \eta \)
4. Difference of VBF jet \( \eta \)
5. Quark Gluon Likelihood (QGL) of two VBF jets
6. Minimum angular distance between one VBF jet and one photon & one VBF jet and one b-jet
   \( \rightarrow \min \Delta R_{j\gamma} \) and \( \min \Delta R_{jb} \)
7. Centrality variables between diphoton and di-bjet system with respect two the two VBF jets, \( C_{\gamma\gamma}, C_{bb} \)

\[
C_{xx} = \exp \left[ -\frac{4}{(\eta_1 - \eta_2)^2} \left( \eta_{xx} - \frac{\eta_1 + \eta_2}{2} \right)^2 \right]
\]
where \( x = \gamma \) or \( b \)

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**QGL: CMS DP -2016/070**
**bbγγ**: MVA distributions for VBFHH

![Graphs showing MVA distributions for VBFHH](image)
bb\gamma\gamma: Systematic uncertainties

-- Statistically dominated analysis
-- Total impact of systematics on signal strengths is around 2% on

**Experimental:**
- Luminosity
- Preselection SF
- Triggers
- Photons ID MVA
- Photon resolution
- Electron Veto SF
- Jet energy scale & resolution
- b-tagging SF
- Pile up jet Id
- Prefiring Issue
- HEM (HCAL Minus)

**Theoretical:**
- Background Modelling
- QCD scale
- PDF systematics
- PS scheme
bbγγ: Expected likelihood scans
bbγγ: Benchmark points [5]
bbZZ(4l) : key features

- (i) Clear signature from 4l (ii) Large BR. H→ bb
- Targets only ggHH production

- Full reconstruction of H→ ZZ* final states.
- H(bb) reconstructed from jets with highest b tag score.
bbZZ(4l) : analysis strategy

- **Backgrounds:**
  - **(i) Irreducible:** determined from Monte Carlo
    - (a) single Higgs production: ggH, VBFH, HW, HZ, ttH, bbH
    - (b) QCD induced nonresonant production: \( qq \rightarrow ZZ^* \), \( gg \rightarrow ZZ^* \)
    - (c) \( ttW, ttZ \)
  - **(ii) Reducible:** \( Z + X \) : where one or two leptons are fakes, mainly from heavy flavour decays, mis-reconstructed jets and converted \( \gamma \)
    - \( \rightarrow \) determined from data by measuring probability of fake \( e, \mu \) in control regions

- Total 9 BDT trainings: 3 separate years (2016, 17, 18) & 3 channels (4e, 4\( \mu \) and 2e2\( \mu \) )

- **Signal extracted using shape analysis:** maximum likelihood fit to merged BDT output distribution of all years and all channels with proper weightage.
bbZZ(4l) : Results

Upper Limit on signal strength

95% CL Upper Limit on (cross section*BR)

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only ggHH (* SM)</td>
<td>30</td>
<td>37</td>
</tr>
</tbody>
</table>

Allowed range @ 95% CL

- Observed: \(-9 < \kappa_4 < 14\)
- Expected: \(-10.5 < \kappa_4 < 15.5\)
**bbZZ(4l): Event selection**

- **H → ZZ**
  - 4 leptons
  - Z candidates
    - Lepton pairs:
      - Opposite charge
      - Same flavour
      - $12 < m_{h(\ell)} < 120$ GeV
  - ZZ candidates
  - Events in signal region: $115 \leq m_{4l} \leq 135$ GeV
  - Non overlapping Z cand pairs:
    - $m_{Z_1} > 40$ GeV (Z1 is Zcand with closest mass to nominal Z mass)
    - $p_T(11) > 20$ GeV, $p_T(12) > 10$ GeV
    - $\Delta R > 0.02$ for each of the 4 leptons
    - $m_{ll} > 4$ GeV for the opposite charge lepton pairs
    - $4e$ and $4\mu$ candidates discarded if the alternative combination $Z_a Z_b$ satisfies $|m(Z_a) - m(Z)| < |m(Z_1) - m(Z)|$ and $m(Z_b) < 12$ GeV
    - $m_{4l} > 70$ GeV
    - If more than one ZZ candidate survives the selection, the one with the highest value of the scalar sum of transverse momentum of leptons is chosen

- **H → bb**
  - If $< 2$ jets, events are not considered
  - If only 2 jets, the bb candidate is built with the 2 jets
  - If $\geq 2$ jets, bb candidate is built from the 2 highest b tagger score jets in the event
### bbZZ(4l): Systematic uncertainties

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<th>Theory uncertainties</th>
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<td><strong>PDF and $\alpha_s$</strong></td>
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<td>$m_{top}$ unc HH</td>
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<td>$\alpha_s$ ggH</td>
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<td>ggZZ</td>
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### Experimental uncertainties

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<th>source</th>
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<tr>
<td>Luminosity</td>
<td>2.6%</td>
<td>2.3%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Leptons ID and reco eff</td>
<td>1.6 – 15.5%</td>
<td>1.1 – 12.1%</td>
<td>1.0 – 11%</td>
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<td>$b$ tagging SF</td>
<td>shape</td>
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<tr>
<td>$Z$+$X$ uncertainties</td>
<td>30 – 41%</td>
<td>30 – 38%</td>
<td>30 – 37%</td>
</tr>
</tbody>
</table>
bbZZ(4l): BDT Variables

- $p_T$ of the four leptons
- $\Delta R$ between two reconstructed $H$
- B-tag score of two $b$-jets
- $p_T$ and invariant mass of the two jets
- The highest value of the b-tagging score.
### CMS HH analyses results with 2016 data (36 $\text{fb}^{-1}$)

<table>
<thead>
<tr>
<th>Channels</th>
<th>95% CL UL on cross section<em>BR (</em> SM)</th>
<th>Constraints on $\kappa_\lambda$</th>
</tr>
</thead>
</table>
| HH→ $b\bar{b}\gamma\gamma$  
**PLB 778 (2019) 7** | Obs.: 9  
Exp.: 24 | Obs.: $-11 < \kappa_\lambda < 17$  
Exp.: $-8 < \kappa_\lambda < 14$ |
| HH→ $b\bar{b}\tau\tau$  
**PLB 778 (2018) 101** | Obs.: 30  
Exp.: 25 | Obs.: $-18 < \kappa_\lambda < 26$  
Exp.: $-14 < \kappa_\lambda < 22$ |
| HH→ $b\bar{b}b\bar{b}$  
**JHEP 04 (2019) 112** | Obs.: 75  
Exp.: 37 | Obs.: $-23 < \kappa_\lambda < 30$  
Exp.: $-15 < \kappa_\lambda < 23$ |
| HH→ $b\bar{b}VV$ ($V = W/Z$)  
**JHEP 01 (2018) 054** | Obs.: 79  
Exp.: 89 | Obs.: $-11 < \kappa_\lambda < 17$  
Exp.: $-8 < \kappa_\lambda < 14$ |

All consider only ggHH production mode