Search for non-resonant Higgs boson pair production in $b\bar{b}γγ$ final states in p-p collisions at $\sqrt{E} = 13$ TeV

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Introduction

• Higgs potential takes the form: \( V(\phi) = \mu^2 |\phi|^2 + \lambda (|\phi|^2)^2 \)

• To expand around one of the minima, we first explicitly break electroweak symmetry. Result:

\[
V(h) = \frac{1}{2}m_H^2 + \sqrt{\frac{\lambda}{2}}m_H h^3 + \frac{\lambda}{4} h^4
\]

• To probe the structure of the potential we require information on the three Higgs coupling \( \lambda_{HHH} \).

• \( \kappa_{\lambda} \) also confirms if symmetry breaking is SM-like.

• This and other couplings can only be directly studied in di-Higgs channel at LHC.

• Possibility of studying BSM interactions that might contribute to production
Di-Higgs production: SM

- **GGF**: as for single Higgs the main production mode in p-p collisions ($\sigma \approx 30$ fb).

- **VBF**: second most dominant HH production mode ($\sigma \approx 2$ fb). Quarks scatter via the exchange of a virtual vector boson.

- Despite significantly lower $\sigma$ the unique kinematics of the deflected quarks make this channel appealing → competitive sensitivity to trilinear coupling and unique handle on $c_{2V}$.

- $c_{2V}$ is also controlled by vector boson production of single Higgs and the decay of H to boson pairs.
Di-Higgs production: Beyond SM

• Small HH cross section → current measurements have no sensitivity to SM production but we might discover/exclude enhancements by correct null + test statistics:

1. Discovery: $H_0 = b - only$, downward fluctuations of b are not evidence against it.

2. Exclusion: $H_0 = b + s$, upper limit → exclude by p-value.

• Enhancements can be resonant (new resonance couples to t quark or vector boson) or non-resonant:

1. Variation of SM parameters

2. Inclusion of couplings non-SM couplings through effective Lagrangian
Di-Higgs production: Beyond SM

- $\kappa_\lambda$ deviations:

  1. enhancement to $\sigma_{ggF}$ by ↓ destructive interference among box and triangle diagrams (maximal at 2.45 SM);

  2. enhancement to $\sigma_{VBF} \approx$ same % with min closer to SM value and $<<$ absolute ↓.

- $\kappa_{C_{2V}}$ deviations: any deviation from SM significantly↑ $\sigma_{VBF} \rightarrow$ high sensitivity.

- EFT for VBF: only consider variations ($c_\nu$ as well).

- EFT for ggF: operators up to 6D $\rightarrow$ 3 new contact interactions + variations on $\kappa_\lambda$ and $\kappa_f$.

- 12 benchmark H (≠ comb of parameters) shown to represent main kinematical observables dist over phase space.
Di-Higgs Decay: Why $b\bar{b}\gamma\gamma$ channel?

- Properties of both Higgs need to be considered.
- The small $\sigma_{HH}$ cross section motivates searches targeting higher branching ratio modes. However, event purity is also important.

1. $b\bar{b}b\bar{b}$: multiple triggers for 4 jets, high QCD multi-jet background;
2. $b\bar{b}WW^*$: large irreducible $t\bar{t} \rightarrow b\bar{b}WW^*$ background;
3. $b\bar{b}\tau\tau$: moderate $t\bar{t}$ decay + multi-jet background;
4. $b\bar{b}\gamma\gamma$: low background (as $b\bar{b}ZZ^*$) + $H \rightarrow \gamma\gamma$ good mass resolution and clean di-photon trigger.
Events: Data Sample, Reconstruction + selection

- **CMS identifies** collisions vertices + particles by: track-finding, $e/\mu$ ID and reconstruction and jet clustering. **CMS records** interesting events (e.g. heavy jets, clean $\mu$ signals) after a 2 level trigger. It measures $E$, momentum and charge for participating particles.

- Analysed data comprises 2016 2017 2018 runs. To select ggF events:
  
  1. Identify photons: reconstructed $E$ clusters not linked to charged tracks and use BDT to distinguish from jets (trained on isolation and shower shape criteria in $Z \rightarrow ee$ events)
  
  2. Require two photons for triggering with $100 < m_{\gamma\gamma} < 180$ GeV, $p_T^{\gamma_1} > m_{\gamma\gamma}/3$ and $p_T^{\gamma_2} > m_{\gamma\gamma}/4$ + geometry. For more than 2 $\gamma$ choose pair of highest $p_T$.
  
  3. From photon candidates: identify primary pp vertex with BDT (trained on simulated ggF events for track recoiling against di-photon criteria). Double jet requirement allows 99.9% efficiency.
  
  4. Require your 2 jets to have $p_T > 25$ GeV, $\Delta R_{jj} > 0.4$, geometry, not to be from calorimeter noise (associated b-tagging score from other vertex algorithm -DNN) and $70 < m_{jj} < 190$ GeV. For more than 2: b score.

- For VBF there are 2 additions jets from the scatter quarks → additional criteria based on well separated (from each other and photon + b candidates) and energetic “VBF-tagged” jets.
Events: Simulation

- For H testing we need a signal model → need signal simulation.

- **ggF events** are simulated at NLO, for samples with ≠ values of \( \kappa_j \). Samples for any point in \((\kappa_j, \kappa_t)\) from the LC of 3 simulations with ≠ \( \kappa_j \). Full top quark mass dependence also modelled.

- Signal samples simulations are also performed for the benchmark H described by \((\kappa_\lambda, \kappa_t, c_2, c_g, c_{2g})\). These represent the distribution of kinematic variables over the hole parameter space → Add them (↑ N) and recover any point in the 5D space. Can only be done at LO.

- **VBF events** are generated at LO for different combinations of \((\kappa_\lambda, c_V, c_{2V})\).

- **Background events**: estimated by data-driven methods but we require simulations for MVA discriminants + optimisation of categories for analysis (later). The possible types are:

  1. \( \gamma \gamma + \text{jets} \) (irreducible) at LO: dominant!

  2. \( \gamma + \text{jets} \) (reducible) where jets are misidentified as isolated photon and b jets.

  3. \( H \rightarrow \gamma \gamma \) (resonant, simulation-driven) at NLO for ggF H, VBF H, \( t\bar{t}H \), V H.

- All simulations use a Parton Shower scheme.
Analysis Strategy

• We expected: low sensitivity due to small BR → goal is to improve sensitivity while keeping a data driven narrative.

• **Strategy:** simulate resonant background and signal events → run them through selection → study \((m_{\gamma\gamma}, m_{jj})\) distribution of simulation vs data candidates → identify distinguishing characteristics for signal vs background.

• **Improvement:** train MVA classifier in MC samples signal + background and apply to actual data. Perform the fit in the mutually exclusive ggF and VBF categories we will obtain (already with less background), simultaneously.

• Background: falling spectrum (non-resonate) + Signal: peak → signal extraction = fit of candidates in \((m_{\gamma\gamma}, m_{jj})\) plane.

• \(M_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)\) particularly sensitive to \(\neq\) values of the couplings.
Background Rejection

- Two types of backgrounds: resonant (similar shape to the signal → simulation driven rejection necessary) and non-resonate (falling spectrum → reduced by simulation rejection before data drive estimation).

- **Resonate rejection:** where signal is purest $ttH$ production is dominant → dedicated classifier ($ttH$ score). Trained on SM HH + 12 H (s) and $ttH$ events (b). Uses low level and kinematic features (angular variables + variables do distinguish decays of W produced by top quark). Implemented with DRNN.

- **Non resonate rejection:** BDT tree to separate ggF events and background. Trained on $\gamma\gamma + jets$ and $\gamma + jets$ events (b) and SM ggF + 12 H (s) Uses kinematic variables (angular, single H and transverse HH), ID variables (photon ID + b tagging) for reducible background and energy resolution variables.

- Remark: BST output transformed for uniform signal.
VBF Background Rejection and Signal Categorisation

• 1/3 of ggF events passing selection criteria also pass dedicated VBF criteria to separate them from resonant background and ggF need another BDT.

• Trained with MC non-resonant backgrounds and SM ggF simulated events (b) and a mix of SM VBF and \( c_{2V} = 0 \) (s). Uses same criteria as before + dedicated VBF-tagged jets criteria (kinematic variables, invariant mass, rapidity difference, quark-gluon likelihood, etc). Two \( \neq \) regions are trained: low \( M_X \) sensible to SM and high \( M_X \) sensible to \( c_{2V} \) anomalous values.

• Events are further subcategorised taking into consideration MVA scores and \( M_X \) ranges and optimising for significance \( S/\sqrt{B} \).

• MVA scores optimised simultaneously. For MVA VBF < 0.52 background contamination to \( \uparrow \) for sensitivity to increase, same for MVA ggF < 0.37. Sub categories are optimised based on \( M_X \) for ggF.

• Events not passing selection for HH categories are tested for \( t\bar{t}H \) for combined analysis of \( \kappa_\lambda \) and \( \kappa_t \).
Models + Systematics

• To extract the signal, in each HH categories, we perform fits in \((m_{\gamma\gamma}, m_{jj}) \rightarrow \) need a shape template \(\rightarrow\) simulation.

• Final 2D signal model is product of \(m_{jj}\) and \(m_{\gamma\gamma}\). Correlations are not significant (by comparing simulated \(m_{jj} - m_{\gamma\gamma}\) in signal samples with the built 2D one).

• Single Higgs background (resonant) shape is constructed from same methodology.

• Non-resonant background model extracted from data. Uses profiling method that considers analytical function choice as nuisance, when profiling.

• Systematics: only affect 1st two models (data-driven method accounts for \(\neq\) function choices). A study of main sources confirms statistical limitation of this search. (impact: 2%)
CL$_S$ + Results

- **Sensitivity problem:** when sensitivity is ↓ we might reject the null when the alternate also deserves it (low power against alternate).

- **Solution:** $p'_{s+b} = \frac{p_{s+b}}{1 - p_b} < 5\%$ for exclusion (prob of falsely rejecting s+b is ↓ + prob of correctly accepting b-only is ↑, protected against downward b fluctuations setting arbitrarily small limits).

- To extract HH signal: fit to all 14 HH categories w/ L defined for each using s and b models + nuisance theoretical and experimental systematics.

- No significant deviation from b-only.

- 95% CL on $\mathcal{B}(HH \to \gamma\gamma b\bar{b}) = 0.67(0.45)$ fb $7.7 (5.2) \times$ SM.
Results: Brasilian-flag plots

- Limits can be set (using all HH categories) as a function of $\kappa_\lambda$, assuming SM-like properties for other processes ($\kappa_t = 1$).

- Taking advantage of categorisation = focusing on one category and constraining yield of mutually exclusive ones to SM signals.

- Upper limits on $\sigma_{VBF HH} \mathcal{B}(HH \rightarrow \gamma\gamma b\bar{b}) = 1.02(0.94)$ fb or $225(208) \times SM$ (most stringent).
Results: Combined Searches

- If we assume a HH signal with SM properties we can constrain $\kappa_\lambda$, $\kappa_t$, $C_2V$

- Combining HH categories with $t\bar{t}H$ one (signal extracted from $m_{\gamma\gamma}$ fit) we can perform further searches → evaluate likelihood on Asimov data set.
Previous best

CMS 2018

CMS NOW

Atlas 2018