Search for non-resonant Higgs boson pair production in final states with two bottom quarks and two photons in proton-proton collisions at $\sqrt{s} = 13$ TeV

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LHC physics course workshop

25/01/2022
Introduction:

- Discovery of the Higgs boson has been significant interest to understand the Brout–Englert–Higgs mechanism.
- Measuring the Higgs boson’s trilinear self-coupling is of particular importance because it provides valuable information for reconstructing the shape of the scalar potential.
- Higgs boson’s trilinear self-coupling is directly accessible via Higgs boson pair (HH) production.

I) gluon-gluon fusion (ggF)

II) vector-boson fusion (VBF)

- Present analysis was achieved by improving the b jet energy resolution with a dedicated energy regression, introducing new multivariate methods for background rejection, optimizing the event categorization, and adding dedicated VBF categories.
Higgs Production:

\[ \mathcal{L}_{HH} = \kappa_\lambda \lambda_{H H H} v H^3 - \frac{m_t}{v} \left( \kappa_t H + \frac{c_2}{v} H^2 \right) (\bar{t}_L t_R + h.c.) + \frac{\alpha_s}{4 \pi v} \left( c_g H - \frac{c_2}{2v} H^2 \right) G^{\mu \nu} G_{\mu \nu}, \]

**ggF**

**VBF**
CMS detector & data obtained:

Features:
- CMS apparatus is a superconducting solenoid of 6 m internal diameter.
- Providing a magnetic field of 3.8 T.
- Inside the solenoid a lead tungstate crystal electromagnetic calorimeter (ECAL) and brass and scintillator hadron calorimeter (HCAL) are there etc.

Event selection:
- Events of interest are selected using a two-tiered trigger system.
  1) The first level (L1).
  2) The second level, known as the high-level trigger.
- The energy of photons is obtained from the ECAL measurement.
- Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation.
- For each event, hadronic jets are clustered from reconstructed particles using the infrared and collinear safe anti-kT algorithm.
Event reconstruction and selection:

- Photons are identified using a boosted decision tree (BDT)-based multivariate analysis (MVA) technique trained to separate photons from jets (photon ID).

- Events have two identified photon candidates that are within the ECAL and tracker fiducial region ($\eta < 2.5$), excluding the ECAL barrel-endcap transition region ($1.44 < \eta < 1.57$).

- Jet candidates are required to have $p_T > 25$ GeV and $\eta < 2.4$ ($2.5$) for 2016 (2017–2018).

- The energy correction and resolution estimator are computed for each of the Higgs boson candidate jets through a regression implemented in a DNN and trained on jet properties.

- In events with more than two jets, the Higgs boson candidate is reconstructed from the two jets with the highest b tagging scores and dijet invariant mass is required to be $70 < m_{jj} < 190$ GeV.
Analysis strategy:

➢ To improve the sensitivity of the search, MVA techniques are used to distinguish the ggF and VBF HH signal from the dominant nonresonant background.
➢ The properties of the HH system was studied from the reconstructed diphoton and dijet candidates, to identify observables that can help us distinguish between the signal and background.
Signal model:

Parametrized signal shape for $m_{\gamma\gamma}$ (left) and $m_{jj}$ (right) in the best resolution ggF (upper) and VBF (lower) categories. The open squares represent simulated events and the blue lines are the corresponding models.
Systematic uncertainties :

- The systematic uncertainties only affect the signal model and the resonant single H background.
- The dominant experimental uncertainties are as follows:
  - Photon identification BDT score
  - Photon energy scale and resolution
  - Per-photon energy resolution estimate
  - Jet energy scale and resolution corrections
  - Jet b tagging
  - Pileup jet identification
  - Integrated luminosity
Results:

Invariant mass distributions $m_{\gamma\gamma}$ (upper) and $m_{jj}$ (lower) for the selected events in data (black points) in the best resolution ggF (CAT0) and VBF (CAT0) categories.
Results:

Expected and observed 95% CL upper limits on the product of the ggF HH production cross section obtained for different nonresonant benchmark models (upper) and BSM coupling $c_2$ (lower).

Expected and observed 95% CL upper limits on the product of the VBF HH production cross section.
Nonresonant Higgs boson pair production (HH) has been presented, where one of the Higgs bosons decays to a pair of bottom quarks and the other to a pair of photons. This search uses proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC.

Upper limits at 95% confidence level (CL) on the product of the HH production cross section and the branching fraction into $\gamma\gamma b\bar{b}$ are extracted for production in the standard model (SM) and in several scenarios beyond the SM.

The expected upper limit at 95% CL on $s_{HHB}(HH \rightarrow \gamma\gamma b\bar{b})$ is 0.45 fb, corresponding to about 5.2 times the SM prediction, while the observed upper limit is 0.67 fb, corresponding to 7.7 times the expected value for the SM process. The presented search has the highest sensitivity to the SM HH production to date.

The most stringent limit to date is set on the product of the HH VBF production cross-section and the branching fraction into $\gamma\gamma b\bar{b}$. The observed (expected) upper limit at 95% CL amounts to 1.02 (0.94) fb, corresponding to 225 (208) times the SM prediction.
Backup slides
Background reduction in the ggF HH signal region

The distribution of the ttHScore (left) and MVA output (right) in data and simulated events
Background reduction in the VBF HH signal region

The distribution of the two MVA outputs is shown in data and simulated events in the two VBF
Background model:

Single Higgs background model:

➢ The SM single H background shape is constructed from the simulation following the same methodology as used for the signal model described.
➢ The $m_{jj}$ modeling in the HH categories depends on the production mechanism, and a parametrisation is obtained from the simulated distributions: for the ggH and VBF H processes.

Nonresonant background model:

➢ The model used to describe the nonresonant background is extracted from data using the discrete profiling method.
➢ The method treats the choice of the background function as a discrete nuisance parameter in the likelihood fit to the data.
➢ A set of MC pseudo-experiments was generated with positive and negative correlations between $m_{yy}$ and $m_{jj}$ injected and then fitted with the factorized 2D model.
More Results:

Negative log-likelihood, as a function of $\kappa_\lambda$, evaluated with an Asimov data set assuming the SM hypothesis (left) and the observed data (right)
Negative log-likelihood scan, as a function of $\kappa_t$, evaluated with an Asimov data set assuming the SM hypothesis (left) and the observed data (right).
Negative log-likelihood contours at 68 and 95% CL in the \((k_\lambda, c_{2v})\) plane evaluated with an Asimov data set assuming the SM hypothesis (left) and with the observed data (right).