PROCEEDINGS OF SCIENCE

Searches for rare Higgs boson production processes with the CMS detector

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The full set of data collected by the CMS experiment at a center of mass energy of 13 TeV allows searches for rare production modes of the Higgs boson, subdominant with respect to the ones already observed at the LHC, by using a variety of decay modes profiting from the ones with largest expected branching fractions. They include associate production of the Higgs boson with two b-quarks, with a c-quark, or vector boson scattering production with two associated W bosons. Double Higgs boson production associated with a pair of top quarks is also considered. While the expected rate is still limited by the collected data, these modes become enhanced in several beyond standard model theories and can be used to constrain such models.

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1. Introduction

The discovery of the 125 GeV Higgs boson [1–3] by the ATLAS and CMS Collaborations [4, 5] opened a new chapter for physics studies at proton colliders. The LHC Run 2 data-taking expanded our knowledge of the Higgs boson properties and its production mechanisms at the LHC [6, 7].

The Higgs boson can be produced at the LHC via several mechanisms [8], the leading ones being the gluon fusion (ggH), the vector boson fusion (VBF), the Higgs-strahlung (VH) and the top-associated production (ttH and tH).

With the exception of tH, all of the above production mechanisms have been observed at the LHC [6, 7], opening a new focus on the Higgs physics sector in the CMS experiment: the search for rare Higgs production mechanisms. These yet unobserved processes are of particular interest as a test for the theoretical predictions in the standard model of particle physics, as their cross-sections are at most of a few pb. They are particularly challenging to tackle as other Higgs production mechanisms can act as a background for their study.

These proceedings offer a review of the latest searches for rare Higgs production mechanisms performed using the LHC Run 2 data and shown by the CMS experiment during the ICHEP2024 conference. More specifically the bottom-associated production [9], the charm-associated production [10], and the production in association with two same-sign W bosons via vector boson scattering [11]. A brief mention is also made regarding the new result on the top-associated production [12], but this was the subject of a separate contribution to the conference. The same applies to results concerning the search for the simultaneous production of two Higgs bosons.

2. The bottom-associated production

The bottom-associated production of the Higgs boson (bbH) is a probe for the Higgs-bottom Yukawa coupling (y_b) complementary with $H \to$ bb decays.

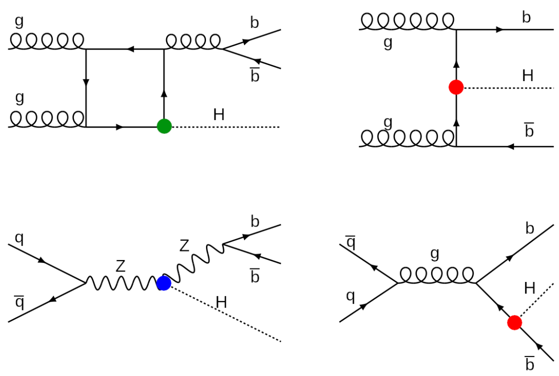

Figure 1: Leading Feynman diagrams contributing to the bottom-associated production of the SM Higgs boson [9]. The couplings are highlighted in red (green) for the Yukawa coupling to bottom (top) quarks, and in blue for the Higgs coupling to Z bosons.

As shown in Fig. 1 there are multiple diagrams contributing to the bbH process, depending on both the bottom (y_b) and top (y_t) Yukawa coupling, and on the Higgs coupling to vector bosons. The ZH process (Fig. 1 bottom left) is considered a background for this search due to the different coupling structure, while the diagram contributing via y_t coupling is considered part of the signal due to its interference with the diagram with the y_b coupling. The theoretical prediction for the bbH cross-section from contributions depending on the Higgs Yukawa couplings is $\sigma(\text{bbH}(y_b, y_t)) = 1.489\,\text{pb}^{-1}$ [8, 13, 14].

This search is performed on Higgs boson decays to τ leptons decaying to hadrons or other leptons and W bosons decaying to an electron-muon pair. Due to the high background from top-pair production, Drell-Yan, and QCD multijet production, Boosted Decision Tree (BDT) models were used to identify signal events. A model was trained for each separate decay channel and for each year of data-taking. Categories were optimized to account for the different background compositions of each channel.

Since no excess is observed in data, upper limits were placed on the bbH signal strength, i.e. the ratio between its measured cross-section and the expected one, via a combined fit in all categories and are shown in Fig. 2 (left). These limits were obtained by varying coherently all contributions to the bbH process and estimating the maximum cross-section of the process that is still compatible with the observed data at 95% confidence level (CL). By varying separately the reduced coupling modifiers for the top (κ_t) and bottom (κ_b) Yukawa couplings, leaving the one to tau leptons freely floating, and fixing the other couplings to their SM value, contours at 68% and 95% CL on the couplings are obtained, as shown in Fig. 2 (right).

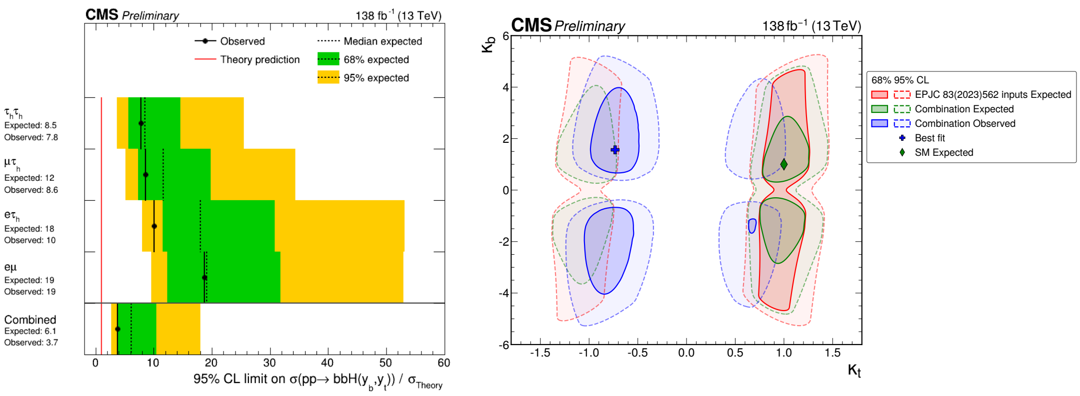

Figure 2: Observed and expected upper limits at 95% confidence level on the bbH production shown on the left for the inclusive signal strength and on the right as limits on the coupling modifiers to the top and bottom Yukawa coupligs [9].

3. The charm-associated production

The charm-associated production (cH) has an estimated cross-section of ~90 fb due to the small size of the charm Yukawa coupling. The main challenge in cH searches is the identification of charm jets (c-jets) from other jet types, such as light quark and gluon jets, or bottom-initiated jets (b-jets). This challenge is partially contained by limiting the search [10] to the Higgs production in association with a single c-jet. As shown in the diagram in Fig. 3, Higgs boson decays to photons ($H \to \gamma\gamma$) were studied in this search.

Separate BDT models are trained to distinguish the cH signal from the ggH production process and the continuous background of di-photon or photon plus jet production. Based on the output

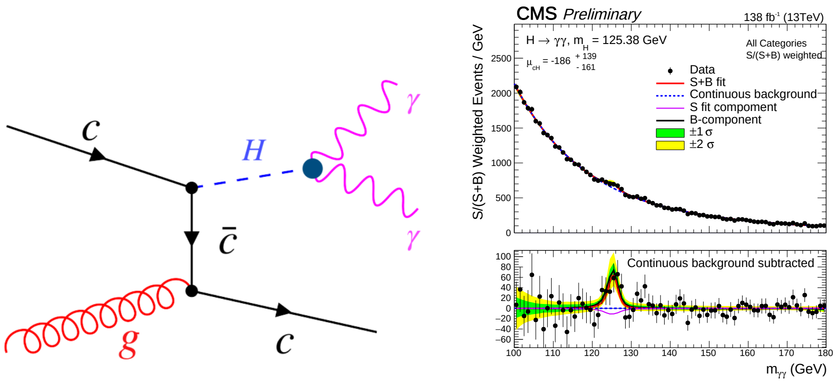

Figure 3: Left: Example of a Feynman diagram contributing to the charm-associated Higgs production (cH) with the Higgs boson decaying to photons. Right: distribution of the di-photon invariant mass in one of the categories used to place upper limits on the cH signal strength [10].

scores of these two BDT models, nine event categories are defined for each of the 3 data-taking years. Upper limits on the cH signal strength are extracted from a parametric fit of the diphoton invariant mass distribution as shown in Fig. 3. The observed (expected) upper limit on the signal strength is $\mu_{\mathrm{cH}} < 243(355)$ at 95% CL, corresponding to an upper limit on the coupling modifier $|\kappa_c| < 38.1(72.5)$.

4. Production in association to two same-sign W bosons

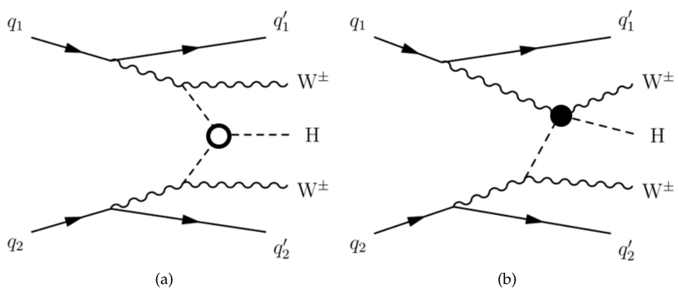

Figure 4: Feynman diagram for the VBS production of a Higgs boson in association with two same-sign W bosons [11]. The Higgs boson is produced on the left via Higgs boson self-coupling and on the right via the quartic WWHH coupling.

The vector boson scattering (VBS) production of the Higgs boson in association with two same-sign W bosons takes place via the Higgs self-coupling (λ_{HHH}) and the WWHH coupling (λ_{WW}), as shown in Fig. 4. The final state chosen for this search comprises two same-sign leptons (electrons, muons, or hadronically decaying tau leptons), two forward jets, and a Higgs boson decaying into a pair of b-jets. The complex final state helps identifying the process against its dominant backgrounds: top quark pair production and multi-boson production. A BDT classifier is used to further improve the signal identification. The signal region is defined by a high dijet invariant mass ($m_{jj} > 100$ GeV) and large pseudorapidity separation ($\Delta\eta_{jj} > 3$) between the jets.

The analysis region is further categorized based on the presence of either 0 or 1 hadronically decaying tau leptons. Backgrounds are then constrained in a region defined by inverting the requirement for a jet to be identified as coming from a b-quark. The search placed observed (expected) upper limits on the coupling modifier $\kappa_{WW} \in [-3.33, 5.33]([-2.39, 4.39])$ at 95% CL as shown in Fig. 5.

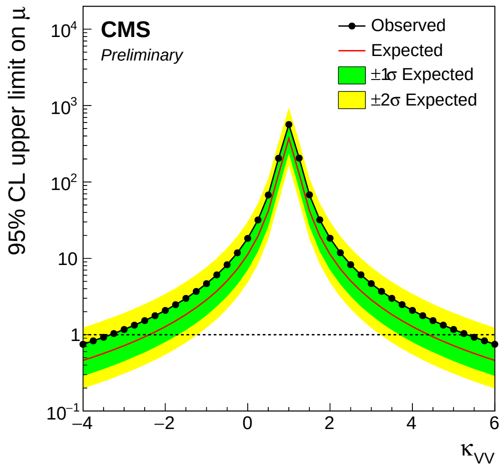

Figure 5: Upper limits at 95% CL level on the signal strength for the VBS production of the Higgs boson in association with two same-sign W bosons as a function of the coupling modifier $\kappa_{\rm WW}$ [11].

5. Summary

The CMS Collaboration has set stringent limits on several rare Higgs boson production mechanisms using the full Run 2 dataset as shown in Table 1. These results, including searches for bbH, cH, tH, and WWH production via VBS, are consistent with the standard model and help constrain Higgs boson couplings. With the addition of Run 3 data and further improvements in analysis techniques, more stringent limits are expected, opening the doors to more precise tests of the standard model and the possibility of discovering new physics.

Table 1: Latest upper limits on the signal strength of rare Higgs production mechanisms placed by the CMS experiment via the analysis of the LHC Run 2 data [9, 10, 12].

	Limits at 95% CL	
Parameter	Observed	Expected
$\mu_{\rm tH}$	14.6	19.3
$\mu_{\rm bbH}$	3.7	6.1
$\mu_{\rm cH}$	243	355

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