PROCEEDINGS OF SCIENCE

Searches for Higgs boson pair production at 13 TeV with the CMS detector

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The production of a pair of Higgs bosons provides a direct handle on the structure of the Higgs field potential. While the Higgs boson pair production within the Standard Model is very small and essentially out of experimental reach in the LHC Run II, several Standard Model extensions foresee an enhancement that can be already probed with the available data. The latest searches for resonant and non-resonant Higgs pair production made using CMS Run II data are presented considering different decay modes of the Higgs boson.

EPS-HEP 2017, European Physical Society conference on High Energy Physics
5-12 July 2017
Venice, Italy

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[†]On behalf of the CMS Collaboration; M.D. is supported by University of Padova grant CPDR155582.

PoS(EPS-HEP2017)269

The Higgs boson pair production is the most direct way to study the Standard Model (SM) Higgs potential and to access the Higgs boson self-coupling. According to the SM, Higgs boson pairs (HH) are produced in proton-proton (pp) collisions mainly through gluon-gluon fusion via an internal fermion loop. The two interactions involved in the production process are the Higgs boson self-coupling (tri-linear) and the coupling with the top-quark (Yukawa coupling). The SM HH production cross section for 13 TeV pp collisions amounts to $33.53^{+4.3\%}_{-6.0\%}$ fb [1]. Given the small value of the cross-section, the SM Higgs pair-production process cannot be measured with the amount of data collected so far and the extraction of an upper limit is the search target. Nevertheless, alterations of the couplings with respect to the SM expectations will lead to non standard cross-sections and kinematics for this process. These effects can be parametrised within an effective field theory (EFT) approach, as described in [2], which allows to take into account all non standard diagrams possibly contributing to this process.

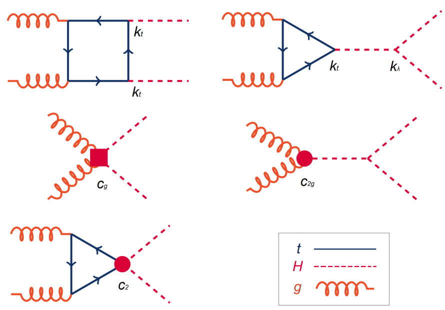

Figure 1: Feynman diagrams that contribute to Higgs boson pair production by gluon-gluon fusion at leading order.

The Lagrangian contains the following five parameters linked to Higgs couplings: $\kappa_\lambda = \lambda/\lambda^{SM}$, $\kappa_t = y_t/y_t^{SM}$, c_g, c_{2g}, and c_2. The resulting Feynman diagrams are shown in Fig. 1. The parameter space for the BSM HH production has thus five dimensions. A statistical approach has been developed in order to identify regions of the parameter space which present similar final state kinematics. The procedure, described in [2], leads to twelve benchmarks which best represent, within a limited uncertainty, the phenomenology of the whole five-dimensional space. The HH searches performed by the CMS collaboration are focused on these twelve benchmarks and extended to the bi-dimensional κ_λ-κ_t plane. The aim is to get a possible discovery of excesses with respect to the SM parameters combination (1,1,0,0,0) and to get constraints of the allowed range for these parameters. Concerning BSM effects, several theories also suggest the existence of heavy particles that can couple to a pair of Higgs bosons. These particles could appear as a resonant contribution to the invariant mass of the HH system and are for example predicted by models with extra dimensions, in particular warped extra dimensions (WED) that describe both spin-0 (radions) and spin-2 (gravitons [3]). A specific realization of the WED models in which both the radion and graviton fields, and the SM fields can propagate in the extra dimension (bulk RS model [4]), is chosen as a benchmark scenario.

This contribution reports the results obtained from the search for HH production on data collected by the CMS experiment from pp collisions at energy in the centre of mass ($\sqrt{s}$) = 13 TeV. The CMS detector is a multi-purpose apparatus designed to reconstruct the high-energy interactions produced by the LHC. Its central feature is a superconducting solenoid with an internal diameter of 6 m. The solenoid generates a magnetic field of 3.8 T inside a volume occupied by four main sub-detectors. The innermost detector is the pixel tracker which provides an impact parameter resolution for charged tracks of about 15 μm. This allows for a precise reconstruction of secondary vertices from B hadron decay, crucially used for the b-jet identification. A detailed description of the CMS detector can be found in [5]. The data collected by the CMS detector from pp collisions at LHC correspond to an integrated luminosity (L_{int}) of 19.1 fb^{-1} at $\sqrt{s}$ = 8 TeV and to a L_{int} of 2.3+35.9 fb^{-1} at $\sqrt{s}$ = 13 TeV.

The searches for Higgs boson pair production have been performed by the CMS collaboration on the data collected from pp at $\sqrt{s}$ = 8 TeV. The combination of the results obtained with different decay channels have been recently published in [6], leading to a limit on production cross section for the non-resonant HH that is 43 times the SM rate. The limit on resonant HH production obtained from the combination ranges from 1.13 (1.09) pb at m_X = 300 GeV, to 21 (18) fb at m_X = 1000 GeV for spin-0 (spin-2) resonances. The search for both non-resonant and resonant HH production has been performed on the data collected from pp collisions at $\sqrt{s}$ = 13 TeV during 2015-2016, in the following decay channels: $b\bar{b}b\bar{b}$, $b\bar{b}l\nu l\nu$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$. One of the two Higgs boson is always searched for in the $b\bar{b}$ decay channel in order to exploit its higher branching ratio. The results are here reported.

1. HH to $b\bar{b}b\bar{b}$

This full hadronic decay channel provides the highest branching ratio together with an high rate of irreducible background events coming from multi-jet QCD interactions.

The events of interest are collected by an hadronic multijet trigger and selected asking for 4 b-tagged jets. A data-driven method is developed in order to describe the background events. Two searches are performed on the data collected in 2015: a model-independent search for a narrow-width resonance in a [260-1200] GeV mass range [8] and a search for non-resonant HH production [9]. The first excludes at a 95% confidence level RS1 KK-Graviton (kL = 35, k/M_{Pl}=0.1) in the mass ranges of [350-725] GeV and [775-850] GeV. The latter sets an observed (expected) upper limit on production cross section equal to 3880 (3490) fb. The four b-quark channel is also exploited for the search of resonances in a higher mass range (800-3000 TeV). The search [7] is performed on data collected in 2016 and it is the sole that looks in the TeV regime. The mass of the original particle is such that the Higgs bosons receive enough Lorentz boost to merge the two produced b-quarks into one *fat* jet, identified with dedicated sub-structure techniques. The signal is extracted from the four body invariant mass spectrum (Fig. 2). No excesses are observed and a [970-1450] GeV mass range is excluded for radion of mass scale Λ_R = 3 TeV.

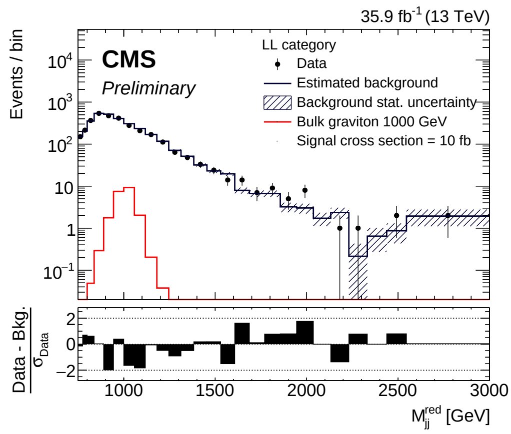

Figure 2: Comparison between the data, predicted background and the bulk graviton signal (assuming cross section of 10 fb) [7].

2. HH to $b\bar{b}l\nu l\nu$

The search for resonant and non-resonant HH is performed in the $H \to b\bar{b}$, $H \to VV \to l\nu l\nu$ channel (with l equal e or μ) on data collected in 2016 [10]. Multivariate techniques are used for signal extraction, exploiting a deep neural network specifically developed for each one of the production modes. A parametrized machine learning technique is used in order to ensure optimal sensitivity on a wide signal range with one single training of the network. Resonances are searched in a [260-900] GeV mass range. The production cross-section times branching ratio is excluded within the [434-17] fb range for narrow-width spin-0 particles and within the [448-14] fb range for narrow-width spin-2 particles. For the SM HH hypothesis, a production cross section times branching ratio of 72 fb is excluded (81 fb expected).

3. HH to $b\bar{b}\tau\tau$

The search for resonant and non-resonant HH production is performed in the $b\bar{b}\tau\tau$ channel on data collected in 2016 [11]. The three most sensitive decay channels of the τ lepton pair are used, namely $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, where μ stands for muonic, e for electronic and h for hadronic decay channel. The analysis is performed in different event categories based on the number of b-tagged jets. The fat jets are also considered but the resonant HH are searched up to a maximum mass of 900 GeV. A Boosted Decision Tree is trained against $t\bar{t}$ processes and the signal is extracted from variables related to the four body mass. Model independent limits are set on resonant HH production and are interpreted in the context of MSSM scenarios where the HH production cross section is parametrized as a function of the m_A and $\tan_\beta$ parameters of the model. As for the non-resonant production, the 95% CL observed upper limit corresponds to approximately 28 times the SM cross section. Exclusion limits are derived also as a function of κ_λ and κ_t.

4. HH to $b\bar{b}\gamma\gamma$

The search for resonant and non-resonant HH production is performed in the $b\bar{b}\gamma\gamma$ channel on the data collected in 2016 [12]. The analysis technique has been significantly improved with respect to Run I, leading to a significant increase of sensitivity beyond the increase in statistics. Events are categorized depending on system invariant mass and output of a multivariate discriminator. The signal is extracted from the $m_{\gamma\gamma}$-m_{jj} plane. The HH resonances are searched for in the [250-900] GeV range, under spin-0 and spin-2 hypotheses. No statistically significant deviation from the background only hypothesis is found. The observed limits exclude the radion signal hypothesis, assuming $\Lambda_R = 3$ TeV, for all mass points below $m_X = 550$ GeV, and exclude the graviton hypothesis (k/M_{Pl}=0.1) in the [280-900] GeV mass range. The 95% CL upper limit on the non-resonant HH production is set at 1.67 fb. Exclusions are set for $\kappa_\lambda <$ -8.82 and $\kappa_\lambda >$ 15.04, assuming all other Higgs couplings to be SM-like and for $\kappa_t >= 2$ assuming $\kappa_\lambda = 1$. Exclusion limits are also derived as a function of κ_λ and κ_t, as shown in Fig. 3.

5. Summary

The sensitivity of the CMS experiment to HH production experiences an impressive growth with respect to the one of Run 1 thanks to the increased statistics and to the improvements on the analysis techniques. The results are compatible within the uncertainties to the expected SM background contribution. The upper confidence limits set on the resonant and non-resonant HH production cross sections are shown in Tab. 1 and Fig. 4. Among these the tighter upper limit on the SM non-resonant HH production is equivalent to about 20 times the SM rate, obtained with the search on the $b\bar{b}\gamma\gamma$ channel. Further improvements are expected from the update of the searches on the four b-quark decay channel, the searches on new decay channels and a combination of them. The increase of statistics will allow to further improve the sensitivity of these analyses, which will play a key role in the upcoming LHC runs.

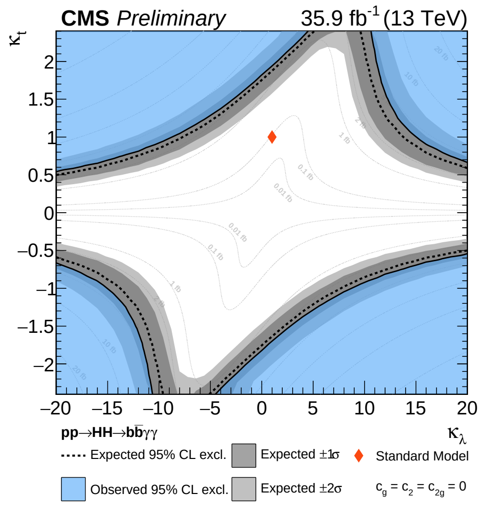

Figure 3: Exclusion limits for the non-resonant HH production as a function of κ_λ and κ_t [12].

HH to	L_{int} fb^{-1}	SM observed (expected) σ/σ_{SM} 95% CL limits [fb]	BSM (excluded phase space)	
$b\bar{b}b\bar{b}$	2.3	342 (308)	-	[9]
$b\bar{b}l\nu l\nu$	35.9	79 (89)	-	[10]
$b\bar{b}\tau\tau$	35.9	28 (25)	κ_λ (<-18;>26) with $\kappa_t = 1$	[11]
$b\bar{b}\gamma\gamma$	35.9	19 (17)	κ_λ (<-8;>15) with $\kappa_t = 1$ & $\kappa_t >= 2$ if κ_λ=1	[12]

Table 1: Summary of results of searches for non-resonant HH production.

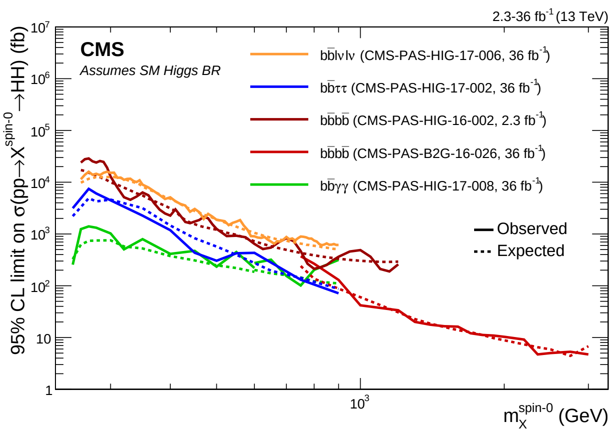

Figure 4: Summary of results of searches for spin-0 resonant HH production [13].

References

[1] LHC Higgs Cross Section Working Group collaboration, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, 1610.07922.

[2] A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, *Higgs pair production: choosing benchmarks with cluster analysis*, *Journal of High Energy Physics* **2016** (Apr, 2016) 126.

[3] H. Davoudiasl, J. L. Hewett and T. G. Rizzo, *Phenomenology of the Randall-Sundrum Gauge Hierarchy Model*, *Phys. Rev. Lett.* **84** (Mar, 2000) 2080–2083.

[4] L. Fitzpatrick, J. Kaplan, L. Randall and L.-T. Wang, *Searching for the Kaluza-Klein graviton in bulk RS models*, *Journal of High Energy Physics* **2007** 013.

[5] The CMS Collaboration, *The CMS experiment at the CERN LHC*, *Journal of Instrumentation* **3** (2008) S08004.

[6] The CMS Collaboration, *A search for Higgs boson pair production in the* $\mathrm{b\bar{b}}\tau\tau$ *final state in proton-proton collisions at* $\sqrt{s} = 8$ TeV, 1707.00350.

[7] The CMS Collaboration, *Search for heavy resonances decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-B2G-16-026. http://cds.cern.ch/record/2264684.

[8] The CMS Collaboration, *Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at* 13 TeV, Tech. Rep. CMS-PAS-HIG-16-002. https://cds.cern.ch/record/2141024.

[9] The CMS Collaboration, *Search for non-resonant pair production of Higgs bosons in the* $\mathrm{b\bar{b}b\bar{b}}$ *final state with* 13 TeV *CMS data*, Tech. Rep. CMS-PAS-HIG-16-026. https://cds.cern.ch/record/2209572.

[10] The CMS Collaboration, *Search for resonant and non-resonant Higgs boson pair production in the* $\mathrm{b\bar{b}l}\nu\mathrm{l}\nu$ *final state at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-HIG-17-006. https://cds.cern.ch/record/2257068.

[11] The CMS Collaboration, *Search for pair production of Higgs bosons in the two tau leptons and two bottom quarks final state using proton-proton collisions at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-HIG-17-002. https://cds.cern.ch/record/2256096.

[12] The CMS Collaboration, *Search for Higgs boson pair production in the final state containing two photons and two bottom quarks in proton-proton collisions at* $\sqrt{s} = 13$ TeV, Tech. Rep. CMS-PAS-HIG-17-008. http://cds.cern.ch/record/2273383.

[13] The CMS Collaboration, *Summary plots from searches for Higgs boson*, tech. rep. https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG.