PROCEEDINGS OF SCIENCE

Searches for rare Higgs boson processes with the CMS detector

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The full set of data collected by CMS experiment at a center of mass energy of 13 TeV allows searches for rare production modes of the Higgs boson, subdominant with respect the ones already observed at the LHC, by using a variety of decay modes profiting of the ones with largest expected branching fractions. Rare Higgs boson decay channel searches with the CMS experiment are also discussed. Searches of decays into quarkonia final states can help constrain Yukawa couplings to light and charm quarks. While the expected rate is still limited with the collected data, these modes become enhanced in several BSM theories and can be used to constrain such models. Other rare Higgs boson decay channels, such as $H \to \mu\mu$ or $H \to Z\gamma$, will also be discussed.

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1. Introduction

The discovery of the Higgs boson at the LHC has opened the possibility to explore in detail the structure of the electroweak sector of the Standard Model (SM). The couplings of the Higgs boson to massive vector bosons and to third-generation quarks and charged leptons have been established with good precision. Rare Higgs processes, however, provide unique sensitivity to couplings that are otherwise difficult to probe. In particular, the trilinear Higgs self-coupling (c_λ) and the couplings to second- and first-generation fermions represent the next targets at the LHC and Future Colliders. Loop-induced processes such as $H \to Z\gamma$ also constitute an important benchmark for the SM, because quantum loops may receive contributions from hypothetical particles not included in the SM; those contributions can significantly alter the kinematics, and the production and decay rates.

Rare processes, which are particulary sensitive to these effects, are expected to become more visible with the increasingly larger datasets that LHC is providing in these years. In order to quantify the deviation from the SM expected values of the Higgs boson couplings, a k multiplicative factor is introduced to parametrize the measured coupling to the fermions f and SM vector bosons V: $y_{f,V} = k_{f,V} y_{f,V}^{SM}$. In the SM, all k factors correspond to unity.

2. Rare Higgs boson production modes

2.1 Higgs boson production through vector boson scattering

The production of a Higgs boson in association with two vector bosons via vector boson scattering (VVH) [2] is rare but theoretically and experimentally clean, sensitive to both the Higgs self-coupling (c_λ) and quartic gauge couplings (c_{2W} and c_{2Z}, collectively called c_{2V}). The SM predicts a cross section of about 1.77 fb at leading order [2]. Any deviation from this expectation could affect this process in two ways: by increasing the production cross section by a factor proportional to k_{2V}^2, and by modifying the kinematics of the event. Increasing values of k_{2V} imply that the Lorentz boost of the W and Z bosons become increasingly larger, making this channel competitive with the double Higgs searches in terms of sensitivity to c_λ.

The CMS experiment [1] has searched for this process in final states where the Higgs decays to $b\bar{b}$, with two additional vector bosons (W or Z) decaying hadronically or leptonically [2]. Events are categorized according to lepton multiplicity (0, 1, or 2 leptons) and jet topology. In the all-hadronic channel, the analysis relies on advanced jet tagging algorithms such as ParticleNet [3], which exploit substructure to discriminate boosted boson decays from QCD backgrounds, to define two categories depending on the presence of a boosted or resolved $H \to b\bar{b}$ boson candidate. In cases with two same-flavour, opposite-sign leptons, events are further divided based on their invariant mass, indicating whether they originate from a Z or two W bosons.

Background estimation is performed with a fully data-driven ABCD method using both a VBS-sensitive variable ($|\Delta\eta_{jj}|$, or a dedicated Boosted Decision Tree depending on the channel) and a deep neural network (DNN) discriminant, which is trained specifically to be uncorrelated from the first variable. The data is consistent with the SM expectation (Fig. 1), and limits on anomalous couplings are set either assuming $k_{2W} = k_{2Z} = k_{2V}$ ($0.40 < \kappa_{2V} < 1.60$ at 95% CL), or performing a two-dimensional scan on κ_W and κ_Z independently, as shown in Fig. 1.

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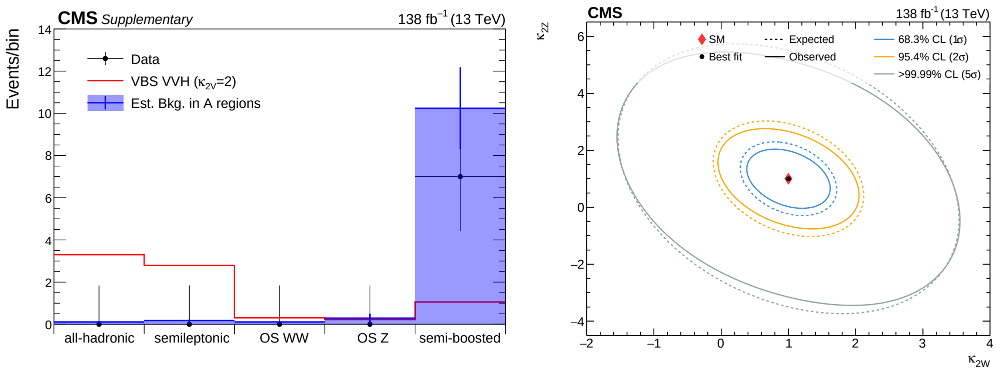

Figure 1: Left: number of events in the signal region (A region) of the 5 categories. Right: 2D scan of the κ_W and κ_Z coupling modifiers, showing the excluded region [2].

2.2 Higgs boson produced in association with a charm quark or a photon

The couplings of the Higgs boson to light quarks can be constrained by searching for its production in association with an additional quark or a photon. Final states consisting of a Higgs boson (decaying to a pair of W bosons) and a charm quark (reconstructed as charm-tagged hadronic jet) are explored by CMS [4]. An upper limit on the cross section of this process is set at 1065 (506 expected) times the SM expectation at 95% CL. This process allows to set an upper limit on the charm-Higgs boson coupling, and values of $|k_c|$ larger than 211 (85 expected) are excluded.

The production of a Higgs boson in association with a high-p_T photon [5] provides sensitivity to effective $H\gamma\gamma$ and $HZ\gamma$ couplings, as well as light-quark Yukawa couplings. The experimental signature consists of a boosted $H \to b\bar{b}$ or $H \to ZZ^* \to 4\ell$ recoiling against a photon. Constraints are set on the coupling of the Higgs boson to each light quark, under the assumption that all other couplings have the SM predicted value. The $|k_u|$ factor is found to be $(0.0 \pm 1.5) \times 10^3$, $|k_d|$ is bound in the $(0.0 \pm 7.1) \times 10^2$ range, and $|k_s|$ in the $(-33, +34)$ interval at 95% CL.

3. Rare Higgs boson decays

A viable alternative for probing the couplings to the light quarks is to search for rare decays where the Higgs boson decays through a light quark loop to a meson and a photon. However, interference between these diagrams and those with other SM particles in the loops limits the sensitivity, even though these processes are experimentally clean with small SM background.

3.1 Decays to a light meson and a photon

The decays $H \to M\gamma$, where M denotes a light vector meson (ρ^0, ϕ, K^*), probe Yukawa couplings to the u, d, and s quarks respectively, and the latter process is possible only through flavor-changing neutral currents [6]. The meson decays to a pair of charged pions or kaons, or a pion and a kaon. CMS employs specialized triggers combining a high-p_T photon with the addition of two tracks to select these events. The events reconstruction is based on the identification of meson candidates from track pairs with invariant masses consistent with the target meson. A further categorization that aims at different Higgs production modes further increases the sensitivity to VBF and Higgs associated production processes. Multivariate classifiers trained on di-track invariant mass sidebands are used to isolate the signal from QCD background. In the meson signal regions, shown in Figure 2, parametric fits of the invariant mass spectra are performed. Upper limits on branching fractions are set to $B(H \to \rho^0\gamma) < 3.7 \times 10^{-4}$, $B(H \to \phi\gamma) < 3.0 \times 10^{-4}$, and $B(H \to K^{*0}\gamma) < 1.7 \times 10^{-4}$ at 95% CL.

3.2 Decays to a charmed meson and a photon

The decay of the Higgs boson to a J/Ψ or a Ψ' meson (collectively referred to as $\Psi(nS)$) and a photon represents a probe to the charm Yukawa coupling, because the decay may occur through a loop of charm quarks [7]. Unfortunately, non-direct diagrams interfere destructively and are approximately 18 times larger in magnitude. The final state consists only of a photon and the two muons from the $\Psi(nS)$ decay, allowing to reject most of the multijet background. This analysis exploits the spin correlations in the signal to perform an angular analysis of the decay, and uses a categorization and a signal extraction strategy similar to that used in the previous analysis.

A fit to the three-body invariant mass spectrum with parametric functions (Figure 2) is used to set limits on the branching fraction of these decays: $B(H \to J/\Psi\gamma) < 2.6 \times 10^{-4}$ and $B(H \to \Psi(2S)\gamma) < 9.9 \times 10^{-4}$ at 95% CL. By assuming that all other couplings are fixed at the SM value, the boundary on the coupling is found to be $-166 < k_c < +208$. An upper limit of approximately 7 times the SM is placed on the similar $Z \to J/\Psi\gamma$ decay.

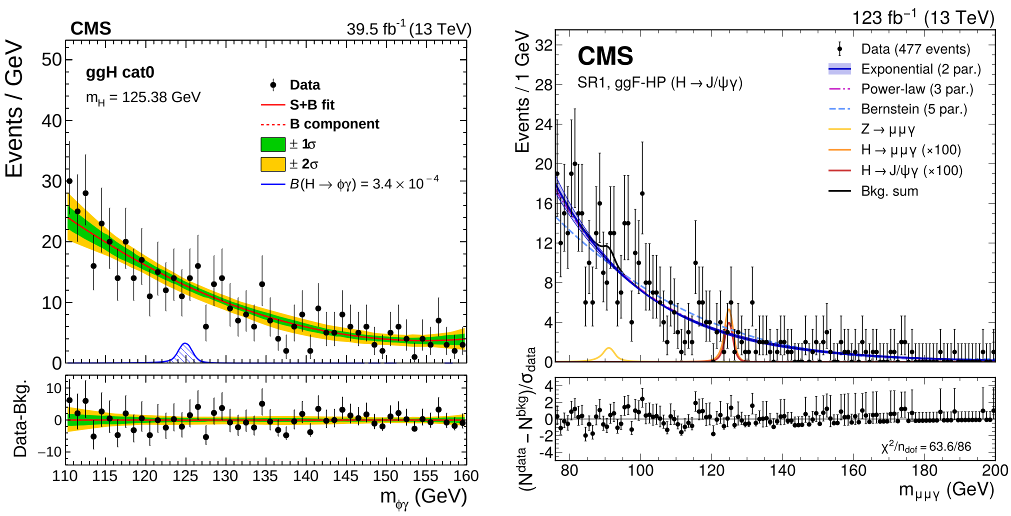

Figure 2: Invariant mass distributions for the $H \to \rho\gamma$ (left) [6] and $H \to J/\Psi\gamma$ (right) [7] searches.

4. Higgs boson decays to a Z boson and a photon

The loop-induced decay $H \to Z\gamma$ is predicted in the SM with a branching ratio of $(1.57 \pm 0.09) \times 10^{-3}$. The CMS experiment performs a search of this process in the $Z \to \ell\ell$ final state [8], where the Z decays to a pair of electrons and muons, thus reducing the total branching fraction by another order of magnitude. The irreducible SM background consists of Drell-Yan processes with an initial state radiation genuine photon or jet misidentified as photon. Events are split into

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categories: one category for events with an additional lepton (from WH or ZH production), 3 categories according to the score of a multivariate discriminant that targets the VBF topology, and 4 categories targeting gluon-fusion produced Higgs bosons.

The CMS analysis measures a mild excess above the SM expectation, as shown in Fig. 3, with a best-fit signal strength $\mu = 2.4 \pm 0.9$. A combined fit with the equivalent ATLAS result [8] yields $\mu = 2.2 \pm 0.7$, corresponding to a branching fraction of $(3.4 \pm 1.1) \times 10^{-3}$ and a statistical significance of 1.9σ.

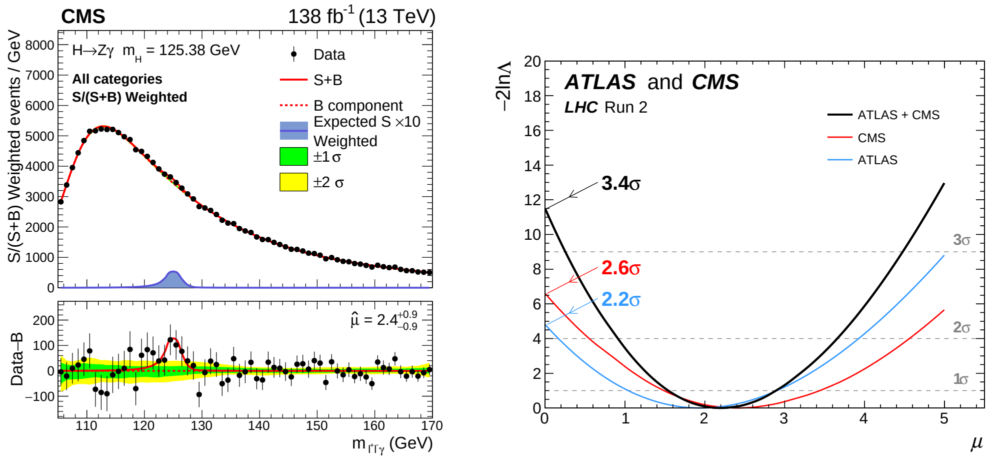

Figure 3: Left: Weighted sum over all categories of the data points and signal-plus-background model after the simultaneous fit to the $m_{\ell\ell\gamma}$ distributions. Right: Negative profile log-likelihood scan of the signal strength for the combination of the CMS and ATLAS searches [8].

5. Higgs boson decays to a pair of muons

The rare decay $H \to \mu\mu$ ($2.18 \cdot 10^{-4}$ in the SM) provides direct access to the Yukawa coupling of the Higgs boson to the muons. Thanks to the excellent resolution in the measurement of the dimuon mass (up to $\approx 1\%$, as shown in Fig. 4), and recovering the photons emitted as final state radiation, CMS observes evidence for this decay with a 3.0σ significance [9]. The measured signal strength is $\mu = 1.19^{+0.44}_{-0.42}$, which is fully consistent with the SM prediction. The measurement also constrains the coupling of the Higgs boson to muons in the $0.85 < \kappa_\mu < 1.29$ interval at 95% CL.

6. Summary

The presented searches cover a broad range of rare Higgs production and decay modes. Most results remain statistically limited, but they represent significant progress toward probing previously inaccessible couplings. The $H \to Z\gamma$ measurement suggests a mild tension with the SM that requires further confirmation, while the evidence for $H \to \mu\mu$ secures the first step in measuring second-generation Yukawa couplings. Searches for $H \to M\gamma$ and cH production are still far from the sensitivity required for the SM, but are sensitive to physics beyond the SM that may alter the couplings or enter in the quantum loops in these decays, providing powerful tests of the SM and

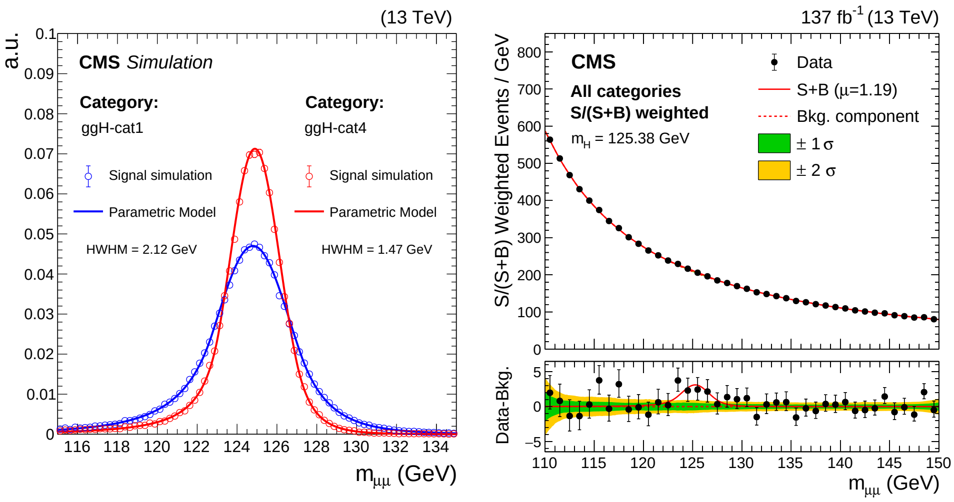

Figure 4: $m_{\mu\mu}$ resolution (left) and distribution for the weighted combination of all categories (right) [9].

unique sensitivity to potential new physics. With 138 fb^{-1} of Run-2 data, CMS has significantly extended the reach of these searches. The ongoing Run-3 data taking, with over 200 fb^{-1} of new data already recorded, is expected to deliver decisive measurements of several rare processes, including those sensitive to second-generation Yukawa couplings.

References

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