PROCEEDINGS OF SCIENCE

Searches for exotic Higgs boson decays with the CMS experiment

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Searches for exotic decays of the 125 GeV Higgs boson with the CMS experiment are presented. Three classes of searches are discussed: 1) the Higgs boson decays to a Z boson and a light pseudoscalar, 2) the Higgs boson decays to a pair of light pseudoscalars, and 3) invisible decays of the Higgs boson. These searches are based on proton-proton collision data at $\sqrt{s}$ = 13 TeV collected in Run 2 of the LHC.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
20-25 August 2023
Hamburg, Germany

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https://pos.sissa.it/

PoS(EPS-HEP2023)402

1. Introduction

In 2012, the ATLAS [1] and CMS [2] Collaborations at the CERN Large Hadron Collider (LHC) announced the observation of a Higgs boson (H) at a mass of around 125 GeV [3–5]. For the past decade, the production of 30 times more Higgs bosons has enabled us to gain a greater understanding of its characteristics. Despite good compatibility of the observed boson with the Higgs boson predicted by the Standard Model (SM), there is still room for exotic Higgs boson decays predicted by various theories beyond the SM (BSM), which are yet to be ruled out by all the LHC measurements published so far. The ATLAS and CMS experiments set 12% and 16% respectively on the upper bounds on the branching fraction of the Higgs boson to new particles at 95% confidence level (CL) based on the LHC data in Run 2 [6, 7]. Given these bounds, it is essential to continue to analyze the data for direct evidence of new particles coupling to the Higgs boson and to test possible extensions of the SM of particle physics. In the following sections, various searches for the exotic decays of the Higgs boson performed by analyzing proton-proton collision data at $\sqrt{s}$ = 13 TeV collected by the CMS experiment during Run 2 of the LHC are presented.

2. The Higgs boson decays to a Z boson and a light pseudoscalar

Motivated by models of axion-like particles (ALPs) formulated as an effective field theory of ALPs coupled to SM particles, a search $\mathrm{H} \to \mathrm{Z}a \to ll\gamma\gamma$ (where $l = \mathrm{e}, \mu$) is performed for the pseudoscalar, a, with masses between 1 and 30 GeV [8], assuming the Z boson is on-shell. The two photons decaying from the pseudoscalar will become merged instrumentally if its mass is below 1 GeV, which will require a dedicated reconstruction technique and is thus not considered in this analysis. The final state provides a clean experimental signature that has a low cross section from the SM processes, and is also the first search of this type at the LHC. The background of this search is modeled entirely from data, which is predominantly the Drell-Yan production of Z+jets where the jets are misidentified as photons. A boosted decision tree (BDT), parameterized in the hypothesized pseudoscalar mass, is trained to separate the signal from the background. The most discriminating input features to the BDT include the compatibility of the invariant mass of the pseudoscalar candidate with the hypothesized signal and the energy deposit pattern of the two photons in the electromagnetic calorimeter (ECAL). The results are extracted from simultaneous unbinned maximum likelihood fits of the invariant mass of the four objects $m_{ll\gamma\gamma}$ distribution categorized by the BDT output. As shown in Fig. 1, no significant deviation from the background-only hypothesis is observed and upper limits are set at 95% CL on the signal strength.

3. The Higgs boson decays to a pair of light pseudoscalars

The generic Two-Higgs-Doublet Models augmented by an additional scalar singlet (2HDM+S) predict seven physical scalar and pseudoscalar particles, where one of the scalars can be identified as the discovered Higgs boson with a mass of 125 GeV. Four types of coupling scenarios in 2HDM+S can avoid flavor-changing neutral currents at tree level, including the next-to-minimal supersymmetric extension of the SM as a particular case. These models predict the Higgs boson decaying to a pair of light pseudoscalar bosons when kinematically possible, which has not yet been excluded.

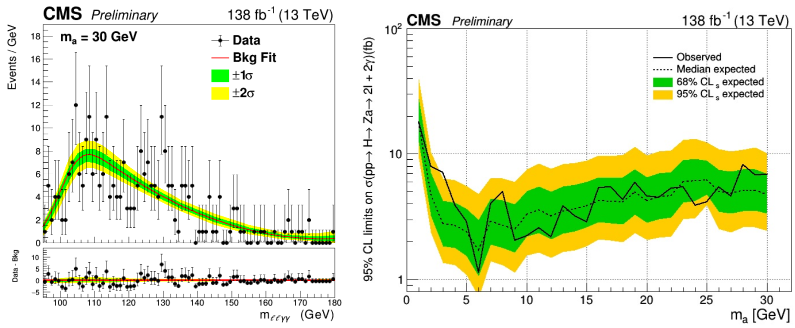

Figure 1: Left: Invariant mass $m_{ll\gamma\gamma}$ distribution for the category of pseudoscalar mass at 30 GeV. Right: Expected and observed 95% CL limits on $\sigma(pp \to \mathrm{H}) \times B(\mathrm{H} \to Za \to ll\gamma\gamma)$. Both figures are taken from Ref. [8].

3.1 Final state with four resolved photons

In scenarios of fermiophobic a decays, the branching fraction $B(a \to \gamma\gamma)$ can be close to unity. A search $\mathrm{H} \to aa \to 4\gamma$ with pseudoscalar masses between 15 and 62 GeV is presented [9]. This analysis benefits from the clean signature of four well-isolated and fully reconstructed photons in the final state. Masses below 15 GeV are not considered since most of the events contain at least one merged diphoton pair and the analysis would require a dedicated reconstruction technique. The dominant background processes include SM production of photons+jets and multijet with jets misidentified as isolated photons, and all contributions are estimated entirely from data using the method of event mixing. A BDT, parameterized in the hypothesized pseudoscalar mass, is trained to separate the signal from the background, using input features related to the identification and kinematic information of the photons and pseudoscalar candidates. The results are extracted by performing simultaneous unbinned maximum likelihood fits of the Higgs candidate mass distribution $m_{\gamma\gamma\gamma\gamma}$. No significant deviation from the background-only hypothesis is observed. As shown on the left side of Fig. 2, upper limits are set at 95% CL on the signal strength.

3.2 Final state with four boosted photons

A search for the same final state of four photons $\mathrm{H} \to aa \to 4\gamma$ is presented [10], but with a lower pseudoscalar mass range of 0.1 to 1.2 GeV. Because of the boosted pseudocalars, the main challenge of this search is the reconstruction of the diphoton mass, since the two photons are predominantly reconstructed as a single photon-like object (Γ) so that the measured invariant mass $m_{\Gamma\Gamma}$ peak is degenerate with the SM $H \to \gamma\gamma$ background. This analysis uses a novel machine learning reconstruction algorithm trained on ECAL energy deposit patterns to measure the invariant mass m_Γ of the merged diphoton candidates, which is otherwise impossible with the standard CMS reconstruction algorithm. The invariant masses of the two merged diphoton candidates are used to discriminate signal from background which is composed of the SM $H \to \gamma\gamma$ process and all other nonresonant processes. No excess of events above the estimated background is observed. Upper limits are set at 95% CL on the signal strength, as shown on the right side of Fig. 2.

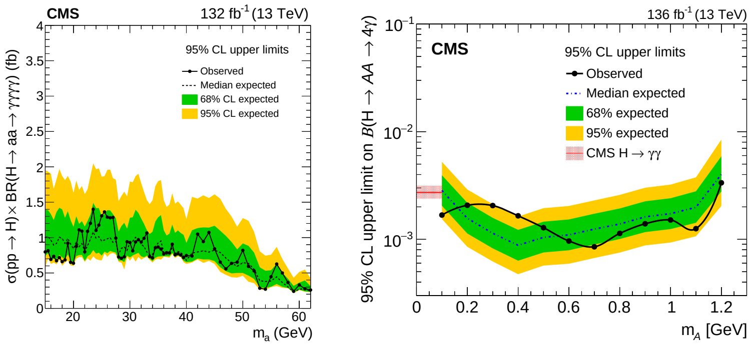

Figure 2: Expected and observed 95% CL limits on the signal strength $\mathrm{H} \to aa \to 4\gamma$ from the resolved (left) [9] and the merged (right) [10] diphoton analyses.

3.3 Final states with two b jets and two muons or two tau leptons

A search for $\mathrm{H} \to aa$ in the two final states $\tau\tau bb$ or $\mu\mu bb$ is performed for the pseudoscalar masses between 15 and 60 GeV [11]. The $\tau\tau bb$ final state benefits from the large branching fractions of the pseudoscalars that decay to heavy quarks and leptons in most models. Three $\tau\tau$ final states are considered: $e\mu$, $e\tau_{\mathrm{h}}$, and $\mu\tau_{\mathrm{h}}$. The $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel is discarded due to the high thresholds in the corresponding triggers despite its largest branching fraction, while the ee and $\mu\mu$ final states have low branching fractions and suffer from large Drell-Yan background. The main backgrounds include $\mathrm{t\bar{t}}$+jets, Drell-Yan $\mathrm{Z}(\tau\tau)$+jets, and reducible processes with jets faking hadronic decaying tau. Event categorization is based on the presence of exactly one b jet or at least two b jets being reconstructed. Deep neural networks are trained per b jet multiplicity bin to discriminate the signal from the background using input features including invariant mass of and angular separation between the tau lepton and b jet candidates, while ensuring its output uncorrelated with the final observable for signal extraction. The results are extracted from simultaneous binned maximum likelihood fits of the $\tau\tau$ invariant mass distribution. In the $\mu\mu bb$ final state, it benefits from the excellent $\mu\mu$ mass resolution and the large branching fractions of the pseudoscalars that decay to heavy quarks. The dominant background comes from the $\mathrm{t\bar{t}}$+jets and Drell-Yan processes, which are estimated fully based on the data. A cut-based event categorization is employed using jet transverse momentum, b jet tagging score, and the invariant masses of the pseudoscalar and Higgs candidates. An unbinned maximum likelihood fit is performed on the $\mu\mu$ invariant mass distribution to extract the results. No excess of events above the background-only expectation is observed in both final states. As shown in Fig. 3, the two final states are combined and the upper limits are set at 95% CL on the branching fractions in the 2HDM+S interpretation.

4. Invisibly decaying Higgs boson

In SM, the branching fraction $B(H \to \mathrm{inv})$ is predicted to be around 0.1% via the channel $\mathrm{H} \to \mathrm{ZZ}^* \to 4\nu$. However, the rate can be greatly enhanced in BSM scenarios, such as the scalar sector connecting the SM and dark sectors where the Higgs boson can decay to a pair of dark matter

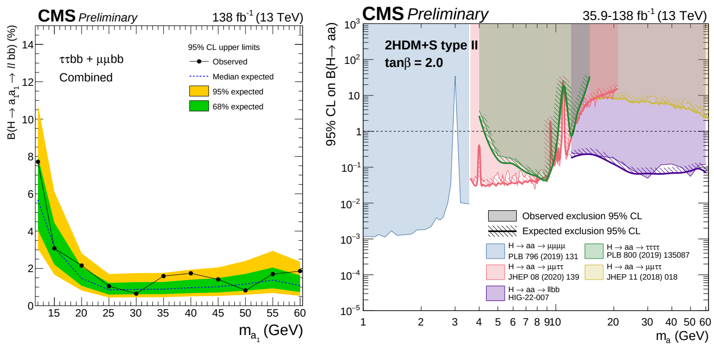

Figure 3: Left: Expected and observed 95% CL limits on $\mathcal{B}(\mathrm{H} \to aa \to llbb)$ under the 2HDM+S scenarios [11]. Right: Summary of expected and observed 95% CL limits on $\mathcal{B}(\mathrm{H} \to aa)$ interpreted in type II of 2HDM+S at $\tan\beta = 2.0$ [12].

particles when kinematically possible. Therefore, direct searches for $\mathrm{H} \to \mathrm{inv}$ are essential and observation of its higher-than-expected rate will be evidence of BSM.

A recent search for invisible decays of the Higgs boson produced in association with a pair of $\mathrm{t\bar{t}}$ quarks or a W/Z boson, which decays to a fully hadronic final state, is presented [13]. The $\mathrm{t\bar{t}H}$ production channel features final states with b jets, or boosted t quarks or W bosons, while the VH production channel features a dijet pair with an invariant mass closes to that of a W or Z boson. The signal is characterized by a large missing transverse momentum from the invisibly decaying Higgs boson, recoiling from its associated hadronic decaying particles. The main background comes from the Drell-Yan production of $\mathrm{Z}(\nu\nu)$+jets and the lost lepton events from $\mathrm{t\bar{t}}$+jets and W+jets processes. No significant excess of events is observed above the SM prediction. Upper limit of 0.47 (0.40 expected) is set at 95% CL on the branching fraction $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, assuming the SM production cross section of the Higgs boson. As shown in Fig. 4, the 95% CL upper limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ of 0.15 (0.08 expected) is set by combining this analysis with previous searches in complementary production modes performed at $\sqrt{s} = 7$, 8, and 13 TeV in Run 1 (2011–2012) and Run 2 (2015–2018) data.

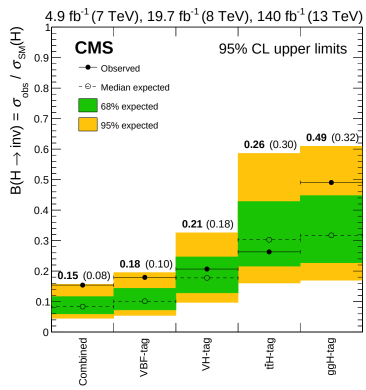

Figure 4: Expected and observed 95% CL limits on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ with sensitivity breakdown in production modes, combining data from Run 1 and Run 2 [13].

5. Summary

Recent CMS searches for exotic decays of the Higgs boson based on data collected in Run 2 of the LHC have been presented. No excess of data over the SM background prediction is reported in these analyses. Upper limits have been set on the production rate of such processes.

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