PROCEEDINGS OF SCIENCE

Searches for additional Higgs bosons at CMS

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The discovery of a Higgs boson with a mass of about 125 GeV by the ATLAS and CMS experiments at the LHC in 2012 validated the standard model (SM) mechanism in which the particles acquire mass through the spontaneous breaking of the electroweak symmetry. The measurements of the Higgs boson properties are, so far, consistent with the expectations of the standard model. However, beyond the SM theories such as the Two Higgs Doublet Models (2HDM), can also predict a Higgs boson with properties compatible with the observed 125 GeV boson and generate a rich and exciting phenomenology, including the presence of additional Higgs bosons. The results of recent searches for these additional Higgs bosons based on the full LHC Run 2 dataset of the CMS experiment at 13 TeV are presented.

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1. Introduction

Many beyond the standard model theories predict extended Higgs sectors with additional Higgs, e.g., Supersymmetry [1], Two-Higgs-Doublet models (2HDM) [2] and variations, Three-Higgs-Doublet models (3HDM) [3], etc. The simplest extension with two Higgs doublets predicts five Higgs bosons: two charged scalars, $H^{\pm}$, two neutral scalars, H and h, and one neutral pseudoscalar, A. In some analyses, the additional neutral (pseudo)scalar bosons are generically referred to as ϕ. It is crucial to have searches covering a broad mass range for additional Higgs bosons to maximize the sensitivity to different models. Recent searches for additional Neutral Higgs bosons at masses above 60 GeV with the CMS experiment [4] are presented.

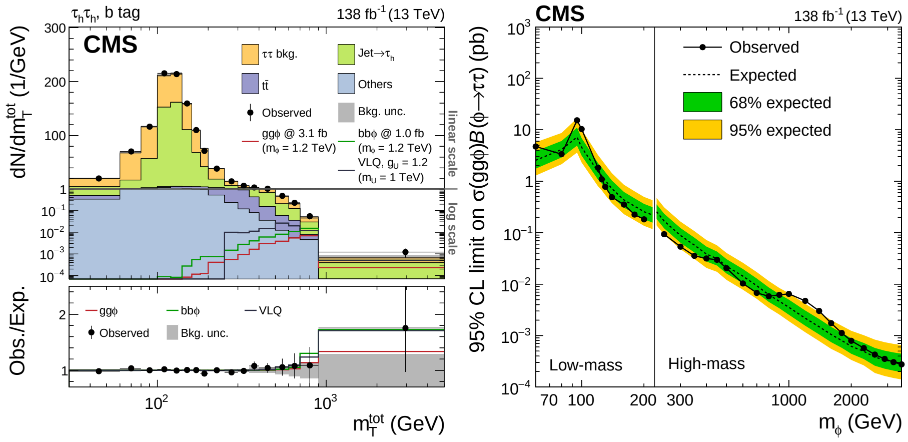
2. $\phi \to \tau\tau$

Searches for resonant $\tau\tau$ final state are very important in the context of searches for additional heavy neutral Higgs bosons, as τ leptons can be identified with higher purity than b quarks and backgrounds from genuine $\tau\tau$ events can be estimated with higher accuracy. The search presented was carried out for this topology using the proton-proton collision dataset collected by the CMS in 2016 - 2018 with an integrated luminosity of L= 138 fb^{-1} and a center of mass energy of $\sqrt{s}$ = 13 TeV [5]. The search was performed in four $\tau\tau$ final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$. Events are further split into several categories based on the number of b-jets and kinematic cuts. The main backgrounds are processes with two genuine τ leptons and processes where jets are misidentified as τ_h. The signal is extracted from distributions of $m_{\mathrm{T}}^{\mathrm{tot}}$, $m_{\tau\tau}$, and y_l depending on the category, using a binned profile likelihood fit. Figure 1a shows an example of the $m_{\mathrm{T}}^{\mathrm{tot}}$ distribution in one of the categories.

In the interpretation of a narrow spin-0 resonance, ϕ, considering the production via the $gg\phi$ and $bb\phi$ processes in a range of $60 \le m_\phi \le 3500$ GeV, two excesses for $gg\phi$ production were observed with local p-values equivalent to about three standard deviations at $m_\phi = 0.1$ and 1.2 TeV, Figure 1b. In the MSSM [1] interpretation, additional Higgs bosons with masses below 350 GeV are excluded at 95% CL for the $M_{\mathrm{h,EFT}}^{125}$ benchmark.

3. $H \to \gamma\gamma$

This analysis checks the existence of an additional "SM-like" Higgs boson with a mass below 125 GeV, which has a possible realization in models containing two Higgs doublets such as the 2HDM and NMSSM [6]. The analysis uses the dataset collected with the CMS experiment in proton-proton collisions corresponding to, respectively, 36.3 fb^{-1}, 41.5 fb^{-1} and 54.4 fb^{-1}, during the 2016, 2017 and 2018 LHC running periods, at $\sqrt{s}$ = 13 TeV. Multivariate analysis (MVA) techniques are used in photon identification and event classification. The signal is extracted from the background using a parametric fit to the $m_{\gamma\gamma}$ distribution in all event classes. The signal is modeled empirically by a sum of a few Gaussian functions and the background is modeled by fitting analytic functions using the discrete profiling method [7]. The means, widths, and relative fractions of the Gaussian functions are determined by the fits. A simultaneous fit of signal samples is performed for each production process, event class, and primary vertex identification correctness



(a) (b)

Figure 1: **(a)** Distribution of $m_{\mathrm{T}}^{\mathrm{tot}}$ in the global "b tag" categorie in $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ final states. The solid histograms show the stacked background predictions after a background-only fit to the data. The best fit $gg\phi$ signal for $m_\phi = 1.2$ TeV is shown by the red line. The bin contents show the event yields divided by the bin widths. **(b)** Expected and observed 95% CL upper limits on the product of the cross sections and branching fraction for the decay into τ leptons for $gg\phi$ production in a mass range of $60 \leq m_\phi \leq 3500$ GeV, in addition to $H(125)$. Plots taken from [5].

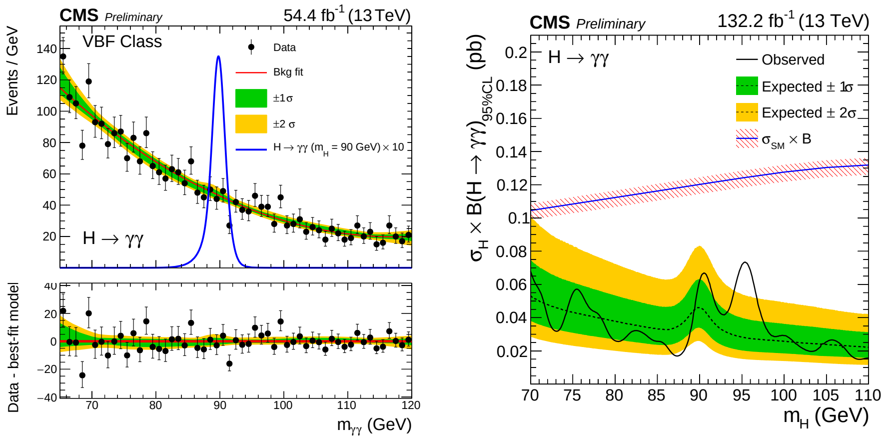
scenario, an example of the VBF event class is shown in Figure 2a. The dominant backgrounds are direct diphoton production and processes with jets misidentified as photons.

For the combined dataset, one excess with approximately 2.9σ local (1.3σ global) significance is observed for a mass hypothesis of 95.4 GeV, Figure 2b.

4. $H \to e\mu$

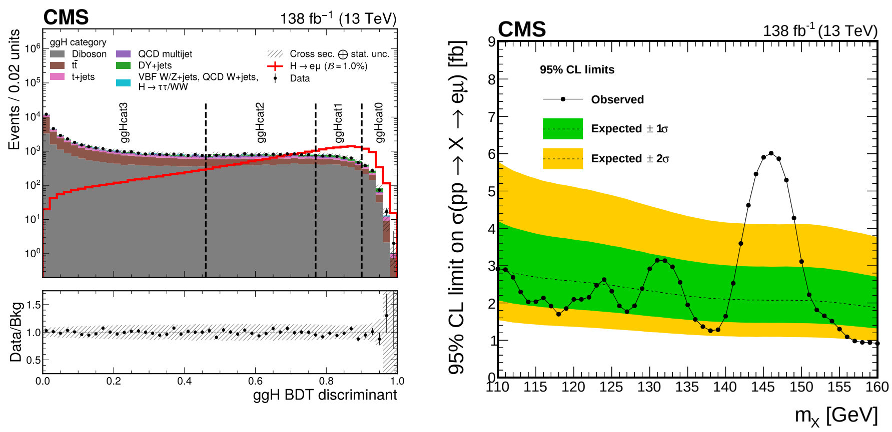
The lepton-flavor violating (LFV) decays are forbidden in the SM but may arise in beyond the SM theories with more than one Higgs boson doublet. Additional Higgs bosons with a mass below $2m_W$ in the LFV decay channels are important to constrain the Type-III 2HDM model. This search is performed with a proton-proton collision dataset at a center-of-mass energy of 13 TeV collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. The signals considered are produced in the ggH and VBF modes, and its topology consists of an oppositely charged electron-muon pair and possible additional jets (with no bjets). The events are split into production modes, and then into categories using the output of BDTs. Figure 3a shows the BDT categories for the ggH production mode. The signal is extracted from the background using a parametric fit to the $m_{e\mu}$ distribution. The $m_{e\mu}$ distributions of signal events are fit with a sum of Gaussian distributions and the background is modeled with a Bernstein polynomial.

No excess of data above the background prediction has been observed in the SM Higgs boson interpretation. Nevertheless, for the additional Higgs bosons hypothesis, a peak with local (global) combined significance of 3.8 (2.8) standard deviations is observed at $m_X \approx 146$ GeV, Figure 3b.



(a) (b)

Figure 2: **(a)** Background model fits using the chosen “best-fit” parametrization to the 2018 data in the VBF event classes. The corresponding signal model for m_H = 90 GeV, multiplied by 10, is also shown. **(b)** Expected and observed exclusion limits (95% CL, in the asymptotic approximation) on the product of the production cross section and branching fraction into two photons for an additional SM-like Higgs boson, from the analysis of the combined data from 2016, 2017, and 2018. Plots taken from [8].



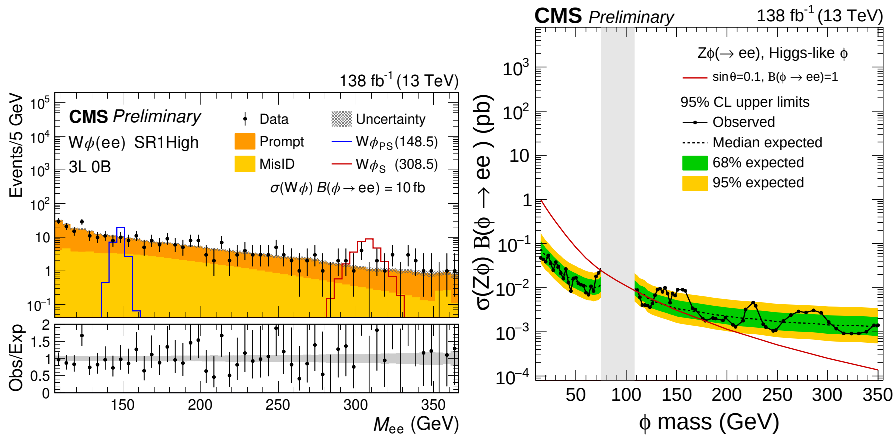
(a) (b)

Figure 3: **(a)** The ggH BDT discriminant distribution of the data, simulated backgrounds, and signals of $H \to e\mu$ for each BDT trained in the ggH category. **(b)** The observed (expected) 95% CL upper limits on $\sigma(pp \to X \to e\mu)$ as a function of the hypothesized m_X assuming the relative SM-like production cross sections of the ggH and VBF production modes. Plots taken from [9].

5. $\phi \rightarrow ll$

First direct search for $(Z\backslash W\backslash t\bar{t})\phi$ that considers decays into all lepton flavors, probing separately 24 $X\phi$ signal scenarios for production mode, coupling, and decay. The analysis uses a proton-proton collision dataset collected by the CMS experiment at the LHC in 2016 - 2018 at a center-of-mass energy of 13 TeV and corresponds to an integrated luminosity of 138 fb^{-1}. Three types of couplings are considered: Scalar (S), Pseudoscalar (PS), and Higgs-like (H). The $W\phi$ and $Z\phi$ production cross sections for scalar and pseudoscalar couplings are proportional to the mass scales Λ_S^{-2} and Λ_{PS}^{-2}, respectively, and the Higgs-like coupling is proportional to $\sin^2\theta$. Similarly, the $tt\phi$ production cross sections for scalar and pseudoscalar couplings are proportional to the Yukawa couplings g_S^2 and g_{PS}^2, respectively. It is considered the ϕ boson mass scenarios between 15 and 350 GeV, excluding those with masses between 75 and 108 GeV for the $\phi \rightarrow ee/\mu\mu$ signal scenarios due to high SM Z boson background contributions. Seven distinct channels are considered based on the number of light leptons (L) and τ_h (T) candidates: 1L2T, 1L3T, 2L1T, 2L2T, 3L, 3L1T, 4L. The signal regions definition results in 37 observed dilepton mass spectra, one of these dilepton mass spectra is shown in Figure 4a. The main backgrounds are prompt (ZZ and WZ) and MisID (DY and $t\bar{t}$). A binned maximum-likelihood fit is performed to discriminate between the potential signal and the SM background processes for each signal model separately

It was observed that there was no statistically significant deviation from the SM expectations in any of the probed mass distributions. The largest deviation is observed in the $Z\phi(\rightarrow ee)$ mass spectrum at 156 GeV, with a local (global) significance corresponding to 2.9 (1.4) standard deviations, Figure 4b.



(a) (b)

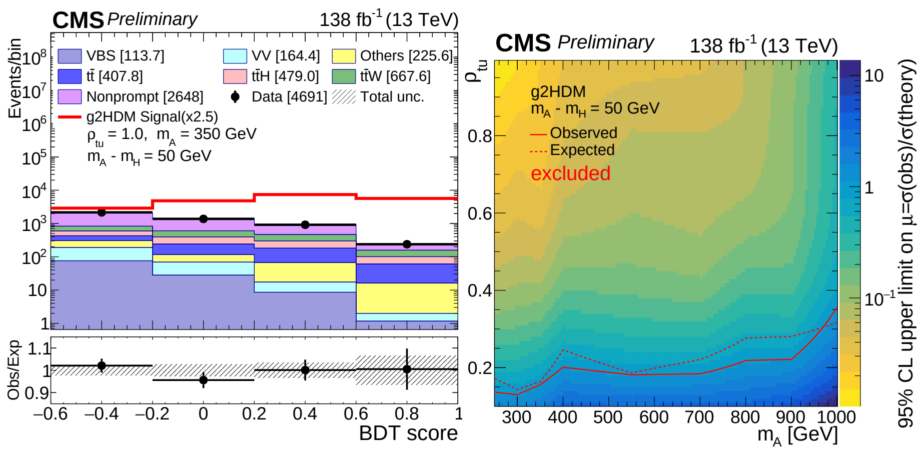
Figure 4: **(a)** Dilepton mass spectra for the $W\phi(ee)$ SR1 event selection for the combined 2016–2018 data set. The expected background distributions and the uncertainties are shown after fitting the data under the background-only hypothesis. **(b)** The 95% confidence level upper limits on the product of the signal production cross section and branching fraction of the $Z\phi$ signal model with Higgs-like couplings in the dielectron decay scenarios. Plots taken from [10].

6. $H/A \rightarrow t\bar{q}$

This analysis provides a possible explanation for the electroweak baryogenesis [11] and muon anomalous magnetic moment [12] in the context of the g2HDM model with new Yukawa couplings

[2, 13, 14]. It was performed a search for the existence of two new couplings: ρ_{tu} and ρ_{tc}, through the $pp \to t(H/A) \to tt\bar{q}(q = u, c)$ processes, using proton-proton collision data collected at a center-of-mass energy of 13 TeV with the CMS detector at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. The signal topology has two same-sign leptons, at least 3 jets (2 b jets plus 1 u or c jet), and the presence of missing transverse momentum. New Higgs bosons in the 200-1000 GeV mass range are targeted in the search. The search is performed in three same-sign dilepton categories: $e \pm e\pm$, $\mu \pm \mu\pm$, and $e \pm \mu\pm$, and a BDT discriminant is used to separate signal and background events. The nonprompt lepton background is estimated from a data-driven method. A post-fit distribution of the BDT discriminant for all channels combined with A–H interference is shown in Figure 5a. The signal strength parameter μ, is obtained using a simultaneous maximum likelihood fit, performed for all categories.

No significant excess over the expected SM background has been observed, and exclusion limits are derived in the context of the g2HDM model. Observed 95% CL upper limit on the signal strength with A-H interference for the combination of all decay channels as functions of m_A and ρ_{tu} is shown in Figure 5b.



(a) (b)

Figure 5: **(a)** Post-fit distributions of the BDT discriminants combining the categories $e \pm e\pm$, $\mu \pm \mu\pm$, and $e \pm \mu\pm$ using the full Run 2 data set, for m_A = 350 GeV with ρ_{tu} = 1.0 with $A - H$ interference. **(b)** Observed 95% CL upper limit on the signal strength as functions of m_A and ρ_{tu} for the g2HDM signal model with $A - H$ interference, using the full Run 2 data set for the combination of $e \pm e\pm$, $\mu \pm \mu\pm$, and $e \pm \mu\pm$ categories. Plots taken from [15].

7. Summary

It has been presented new searches for additional Neutral Higgs bosons with the proton-proton collision dataset collected by the CMS experiment between 2016 and 2018, Run 2, in a wide mass range. So far, a good agreement between measurements with predictions from standard model assumptions. Nevertheless, some excesses were observed, in which more data is necessary to clarify their nature. In this scenario, searches for additional Higgs bosons above and below 125 GeV using Run 3 are highly expected.

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