PROCEEDINGS OF SCIENCE

Searches for additional Higgs bosons (high and low mass) at CMS

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We present a summary of recent CMS searches for additional Higgs bosons predicted in extended scalar-sector models. The analyses target a wide range of signatures, including low-mass diphoton resonances, exotic decays of the 125 GeV Higgs boson into pairs of light pseudoscalars, heavy Higgs bosons produced in association with bottom quarks and decaying to $b\bar{b}$, and the cascade process $A \to ZH \to \ell\ell t\bar{t}$. The searches use up to 138 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13$ TeV. In all channels, the observed data are consistent with Standard Model expectations, and upper limits are set on the relevant production cross sections and branching fractions. The results provide stringent constraints on Two-Higgs-Doublet Models, supersymmetric scenarios, and other extensions of the Higgs sector, and significantly enhance the sensitivity of previous CMS searches.

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1. Introduction

Many extensions of the Standard Model (SM) predict the existence of additional Higgs bosons beyond the 125 GeV scalar discovered in 2012 [1],[2]. Examples include Two-Higgs-Doublet Models (2HDM) [3], the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [4], and composite Higgs scenarios [5]. In these frameworks, additional CP-even and CP-odd neutral bosons (H, A) and charged states ($H^{\pm}$) appear naturally. The simplest 2HDM introduces five physical Higgs bosons (h, H, A, $H^{\pm}$); extending the model by a singlet field leads to a 2HDM+S structure with up to seven states. Such extended Higgs sectors can address questions of baryogenesis, dark matter interactions, and the naturalness of electroweak symmetry breaking.

The CMS experiment [6] at the CERN Large Hadron Collider (LHC) performs a broad program of searches for these new scalars across a wide range of final states and masses. This contribution summarises recent Run 2 results based on up to 138 fb^{-1} of proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV.

2. Overview of the CMS search program

The CMS experiment has performed numerous analyses targeting different production and decay modes of additional Higgs bosons. These include searches for decays into photon pairs ($A/H \to \gamma\gamma$), τ lepton pairs ($A/H \to \tau\tau$), top quark pairs ($A/H \to t\bar{t}$), and b quark pairs ($A/H \to b\bar{b}$), as well as associated or cascade decays such as $A \to ZH$, $h_{125} \to aa$, and $H \to hh$. Together, these analyses probe both the low-mass region below the SM Higgs boson and the multi-TeV regime. No significant deviations from the SM predictions have been observed so far.

3. Selected new analyses

Low-mass diphoton resonance search

The analysis in Ref. [7] searches for narrow resonances in the diphoton invariant-mass spectrum between 10 and 70 GeV using 54.4 fb^{-1} of integrated luminosity recoded in 2018 by CMS. This low-mass region is particularly challenging because of the overwhelming SM prompt diphoton and photon-jet backgrounds. Despite these experimental difficulties, the diphoton channel remains one of the cleanest final states at the LHC, providing sensitivity to a broad class of models predicting light scalar or pseudoscalar states, such as axion-like particles or singlet-extended Higgs sectors. Since the analysis assumes only a minimal set of model-dependent assumptions, it offers a very generic probe of new physics.

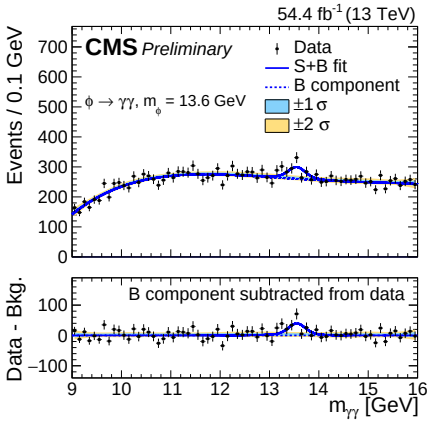


Figure 1: Signal plus background fits (dark blue) are shown for the most significant excess in the SR at a mass hypothesis of 13.6 GeV, with signal yield freely floating. In the ratio pad, the background model is subtracted from the data. Taken from [7].

To maximize sensitivity across the full mass range, the search region is divided into four partially overlapping windows, each indivually optimized

for the corresponding mass regime. In each window, a parametric signal-plus-background model is fit to the diphoton invariant mass distribution. The background contribution is modeled directly from data using analytic functions constrained by the sideband regions, thereby reducing reliance on simulation in a phase space where theoretical and detector related uncertainties are large. The signal model is derived from simulation and incorporates the detector resolution and reconstruction effects tailored to the low-energy photon regime.

Across the scanned mass range, no significant excess compatible with a new resonance is observed. The most pronounced deviation occurs at a mass hypothesis of 13.6 GeV, where a local significance of 3.5 standard deviations (SD) is found, corresponding to a global significance of 1.9 SD. Figure 1 illustrates the fitted invariant-mass distribution in the vicinity of this excess. Given the global significance, the deviation is compatible with a statistical fluctuation.

In the absence of a confirmed signal, the analysis sets upper limits at 95% confidence level on the production cross section times branching ratio for a narrow resonance as a function of its mass. These limits range from the sub-picobarn to the several-picobarn level, depending on the mass window with higher limits in the low mass region. The results significantly extend the sensitivity of previous searches in this mass range [8].

$h_{125} \to aa \to 4\tau$

A search for light pseudoscalar bosons in decays of the observed Higgs boson is presented in Ref. [9]. If the SM-like Higgs boson h_{125} decays into a pair of light pseudoscalars a, the final-state kinematics can become highly boosted for pseudoscalar masses below approximately 10–15 GeV. In this regime, the decay products of the two a bosons may merge spatially, producing collimated leptons challenging to reconstruct.

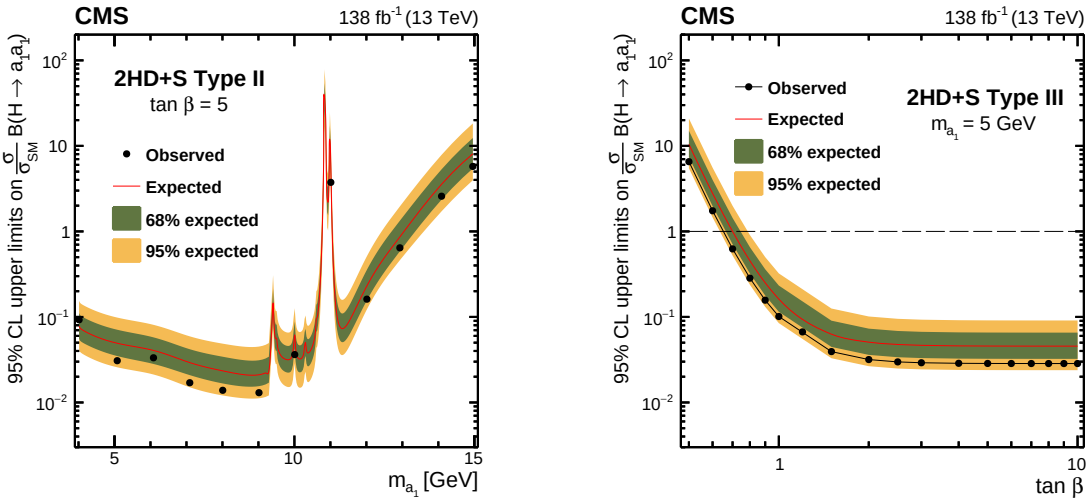


Figure 2: The observed (points) and expected (red line) 95% CL upper limits on $\sigma(pp \to H + X)\,\mathcal{B}(H \to a_1 a_1)$ for different 2HD+S models. Taken from [9].

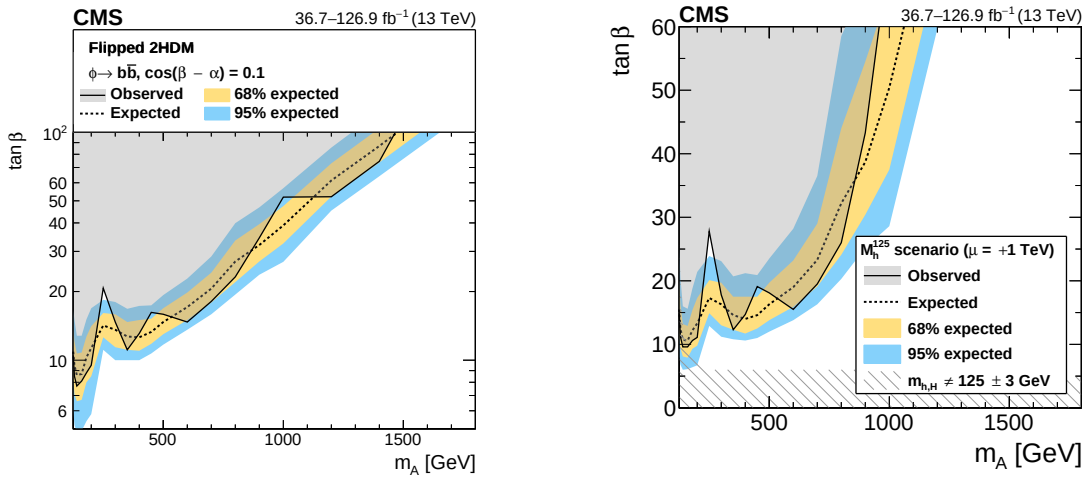
The analysis exploits the distinctive signature in which two same-sign muons originate from different a decays and are accompanied by nearby leptons or hadrons from the remaining τ decays.

The dominant background arises from QCD multijet events followed by electroweak processes, including diboson and $t\bar{t}$ production. To improve the accuracy the background is estimated from data using dedicated control regions modifying the muon isolation criteria.

A binned maximum-likelihood fit is performed across multiple signal categories, each targeting complementary regions of phase space. No deviation from the SM expectation is observed. Upper limits at 95% confidence level are set on the branching fraction $\mathcal{B}(h_{125} \to aa)$ under several 2HDM+S benchmark scenarios as a function of the pseudoscalar mass. Figure 2 shows two examples of the derived limits on the extended Higgs sector. These results improve upon earlier CMS constraints by up to a factor of four, particularly in the region of very light pseudoscalars, and provide some of the most stringent bounds to date on exotic decays of the Higgs boson into light beyond-the-Standard-Model states.

$H \to b\bar{b}$

The search described in Ref. [10] targets heavy neutral Higgs bosons produced in association with b quarks and decaying into a pair of b quarks. In 2HDMs and supersymmetric extensions of the SM, the production of heavy scalar (H) or pseudoscalar (A) bosons in association with a b quark is enhanced at large values of $\tan\beta$. In these scenarios, the associated production mode $pp \to bH/A$ provides competitive sensitivity for masses up to the multi-TeV regime.



(a) Limits as function of m_A in a 2HDM Flipped scenario.

(b) Limits as function of m_A in a M_h^{125} scenario of the MSSM.

Figure 3: Limits as function of m_A in a 2HDM Flipped scenario (left) and a M_h^{125} scenario of the MSSM (right). Taken from [10].

The analysis exploits two complementary event categories. The first category selects events where a soft muon is found inside the b-jet cone, allowing efficient identification of b decays with leptonically decaying W bosons. The second category targets fully hadronic final states without the presence of such a muon, relying instead on b-tagging techniques and optimized jet reconstruction strategies. This two-pronged approach maximises acceptance across the mass range.

The dominant background arises from heavy-flavour multijet production. Because this background is difficult to predict reliably with simulation alone, it is estimated from data using dedicated control regions.

The invariant mass of the two leading b-tagged jets is used as the primary discriminant, and a binned maximum-likelihood fit is performed simultaneously in both categories. Across the entire search range from a few hundred GeV up to almost 2 TeV, the data are found to be consistent with the SM prediction, and model-independent upper limits at 95% confidence level are set on the product of the production cross section and branching fraction $\sigma(pp \to bH/A)\,\mathcal{B}(H/A \to b\bar{b})$. Two of those limits can be found in Fig. 3. These limits combine the current result with previous searches in the same state. In total heavy Higgs bosons with masses up to about 1.5 TeV are excluded.

$A \to ZH \to \ell\ell t\bar{t}$

A search for heavy Higgs bosons decaying into a Z boson and another heavy scalar is presented in Ref. [11]. Such signatures arise naturally in extended Higgs-sector models, including Type II 2HDM, where the spectrum contains both a pseudoscalar boson A and a heavier scalar H. For mass hierarchies in which $m_A > m_H + m_Z$, the decay $A \to ZH$ becomes kinematically allowed and can dominate depending on the model parameters. This analysis targets this scenario and represents the first dedicated CMS search for the $A \to ZH$ decay with a hadronic $H \to t\bar{t}$ final state.

The Z boson is reconstructed in the dilepton final state, $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$, which provides good mass resolution and efficient background suppression.

The dominant backgrounds originate from inclusive $t\bar{t}$ production and from Drell-Yan events in association with jets. To mitigate the background uncertainties, control regions are used to constrain the background normalisation and to validate the modelling of the background.

A simultaneous profile likelihood fit is performed in two dimensional bins of the reconstructed invariant mass difference Δm and p_T^Z using categories defined by the number of jets, b-tagged jets and invariant dilepton mass. Over the full mass range considered the data are found to be consistent with the SM prediction, and no significant excess is observed.

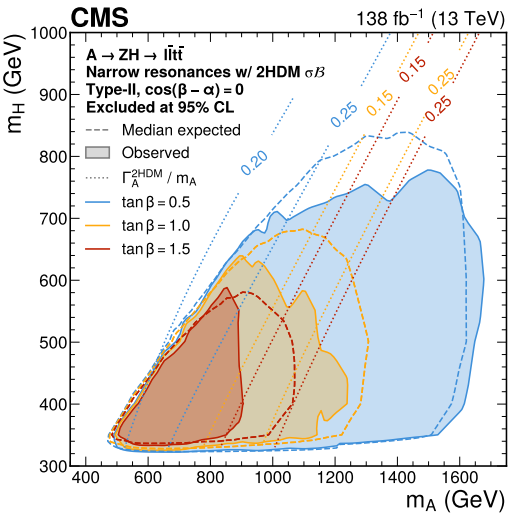


Figure 4: Median expected (dashed lines) and observed (filled contours) 95% CL exclusion regions in the (m_H, m_A) parameter space of the type-II 2HDM derived assuming narrow resonances. The enclosed regions are excluded. The dotted lines indicate points of constant total decay width Γ_A of the A boson relative to its mass in the 2HDM, for the $\tan\beta$ value of the corresponding colour. Taken from [11].

Upper limits at 95% confidence level are derived for $\sigma(pp \to A)\,\mathcal{B}(A \to ZH)\,\mathcal{B}(H \to t\bar{t})$ as a function of the masses m_A and m_H.The results are also interpreted in the context of a Type II 2HDM scenario (Figure 4). In this model, A boson masses up to approximately 1.6 TeV are excluded, depending on the mass splitting between A and H and the value of $\tan\beta$. The probed parameter space is highly relevant for scenarios of electroweak baryogenesis attempting to explain the observed matter-antimatter asymmetry in the universe [12].

4. Summary and outlook

CMS has conducted a comprehensive program of searches for additional Higgs bosons across a wide range of final states and mass hypotheses. No significant deviations from the SM have been observed so far, but the analyses set stringent limits on the parameter space of extended Higgs sectors, including the 2HDM, NMSSM, and 2HDM+S models. With the ongoing Run 3 data taking at $\sqrt{s} = 13.6\,\text{TeV}$, the sensitivity to such signatures is expected to increase substantially, providing exciting opportunities to further probe the structure of the scalar sector in the years to come.

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