PROCEEDINGS OF SCIENCE

Search for 2HDM neutral Higgs bosons through the process $\mathrm{H} \to \mathrm{ZA} \to \ell^+\ell^-\mathrm{b\bar{b}}$ with the CMS detector

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The inability of the standard model (SM) to explain some observed phenomena motivates theoretical models featuring an extension of the SM scalar sector that predict additional Higgs bosons. The Two-Higgs-doublet model (2HDM) is one of these. This note reports on a search for an extended scalar sector, where a new CP-even (odd) boson decays to a Z boson and a lighter CP-odd (even) boson, which further decays to $\mathrm{b\bar{b}}$. The Z boson is reconstructed via its decays to leptons. The analysed data were recorded in proton-proton collisions at $\sqrt{s} = 13$ TeV, collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1}. Data and predictions from the SM are in agreement within uncertainties. Upper limits at 95% confidence level are set on the signal production cross section times branching fraction, with masses of the resonances ranging up to 1000 GeV. The results are interpreted in the context of the Type-II 2HDM.

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1. Introduction

The CMS [1] and ATLAS [2] experimental programmes are focusing efforts on the measurement of the properties of the newly discovered Higgs boson [3, 4, 5], which has a mass of $\sim$ 125 GeV. Although all measurements, to date, are consistent with the standard model (SM) within the experimental uncertainties, additional Higgs bosons are predicted in several extensions of the SM. The Two-Higgs-doublet model (2HDM) [6] is one of these, and its phenomenology is based on the presence of an additional scalar Higgs doublet. It predicts the existence of five new physical Higgs bosons, among which are a CP-even neutral H and a CP-odd neutral A. Important free parameters are the masses of the two bosons, m_H and m_A; the ratio of the vacuum expectation values of the two doublets, $\tan\beta$; and the mixing angle α between the two CP-even eigenstates of the 2HDM, H and h.

A search for H and A is performed through the cascade decay H $\rightarrow$ ZA, where the Z decays into $\ell^+\ell^-$ (electrons or muons) and the A into b$\bar{\text{b}}$. These channels have the highest branching ratio in the alignment limit ($\cos(\beta-\alpha) = 0$) and over a large region of $\tan\beta$, as shown in Fig. 1. The results are interpreted in the context of the Type-II 2HDM, where the masses of the two particles are also interchanged to allow for theoretical interpretation of the results in the A $\rightarrow$ ZH channel. The probed mass range is $m_H = 120 \div 1000$ GeV and $m_A = 30 \div 1000$ GeV. The search is based on LHC proton-proton collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment, corresponding to an integrated luminosity of 35.9 fb^{-1} [7].

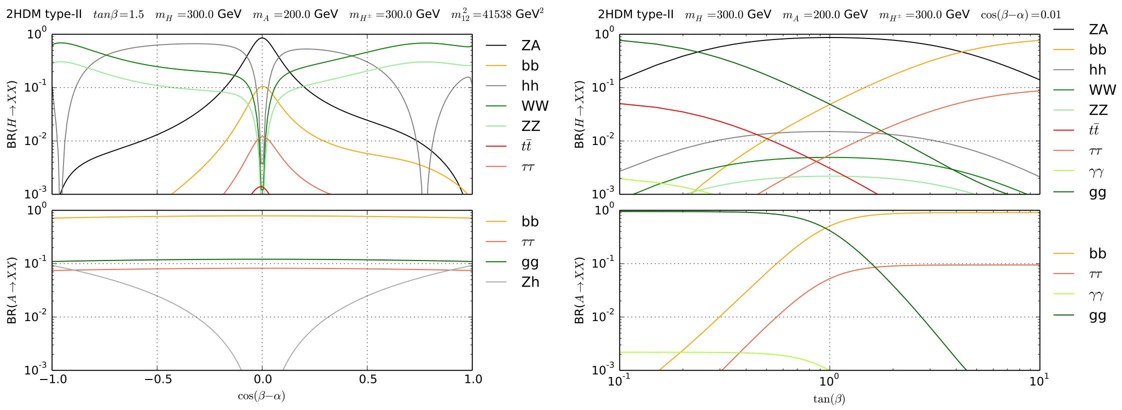

Figure 1: H and A branching fractions as a function of $\cos(\beta-\alpha)$ for the following set of parameters: $\tan\beta = 1.5$, $m_H = 300$ GeV, $m_A = 200$ GeV (right). H and A branching fractions as a function of $\tan\beta$ for the following set of parameters: $\cos(\beta-\alpha) = 0.01$, $m_H = 300$ GeV and $m_A = 200$ GeV (left) [7].

2. Signal extraction

The most dominant backgrounds entering this search are Drell-Yan (DY) in association with heavy-flavor jets and fully-leptonic top quark pair production (t$\bar{\text{t}}$). Diboson and triboson, single top quark, SM Higgs and W + jets production are a minor contribution.
Events with two isolated oppositely charged leptons and two isolated b tagged jets are selected. In

particular, events with same-flavor leptons (e^+e^-, $\mu^+\mu^-$) are used to define the signal region, while events with different-flavor leptons define a control region rich in $\mathrm{t\bar{t}}$ that is used in the maximum likelihood fit to better constrain this background.
The requirement 70 GeV $< \mathrm{m}_{\ell\ell} <$ 110 GeV is then applied in order to enhance the presence of $Z \to \ell\ell$ events, where $\mathrm{m}_{\ell\ell}$ is the invariant mass of the two leptons. In addition, the events are required to have a missing transverse energy ($\mathrm{p}_{\mathrm{T}}^{miss}$) content below 80 GeV in order to reduce the contribution from processes with real $\mathrm{p}_{\mathrm{T}}^{miss}$, such as $\mathrm{t\bar{t}}$ production. Two categories are defined based on the lepton flavors considered: e^+e^- and $\mu^+\mu^-$.

The A boson can be reconstructed by measuring the invariant mass of the two b jets (m_{jj}), while for the H boson the invariant mass of the two b jets and leptons ($\mathrm{m}_{\ell\ell jj}$) is used. For each signal hypothesis, the signal m_{jj} and $\mathrm{m}_{\ell\ell jj}$ distributions are therefore positively correlated in the plane defined by the two reconstructed masses. This can be seen in Fig. 2 (left) for three representative mass hypotheses. An elliptical signal region appears like a sensible choice to enhance the sensitivity of the search, since it would be tailored to nicely enclose the signal while leaving out regions of the phase space where the signal contribution is null or very low and background events are present. Since the shape of the signal is driven by the energy resolution of the final-state objects, ellipses take different sizes and tilt angles, depending on the masses being considered. The ellipses are parametrized as a continuous function of the mass hypotheses in the plane.
The size of each ellipse is defined by a parameter called ρ such that ellipses with $\rho = 1$ contain 1 standard deviation of the signal events. To increase the signal acceptance, ρ is varied in steps of 0.5, from 0 to 3, defining six elliptical bins as shown in Fig. 2 (right). This leads to the definition of a six-bin template, used to perform the statistical analysis. The template corresponding to the $(m_H, m_A) = (261, 150)$ GeV mass hypothesis is shown in Fig. 3 for e^+e^- and $\mu^+\mu^-$ events, separately.

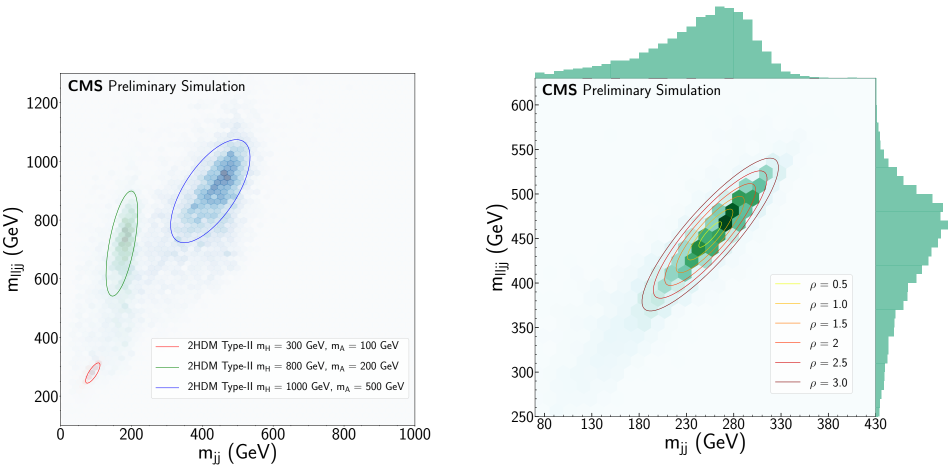

Figure 2: The m_{jj} vs. $\mathrm{m}_{\ell\ell jj}$ plane for signal samples under three different mass hypotheses, on which the parametrised ellipse is shown (left). A signal hypothesis with $m_H = 500$ GeV and $m_A = 300$ GeV is shown in the $\mathrm{m}_{\ell\ell jj}$-m_{jj} plane (right). The different ellipses show the variation of the ρ parameter in steps of 0.5, from 0 to 3 [7].

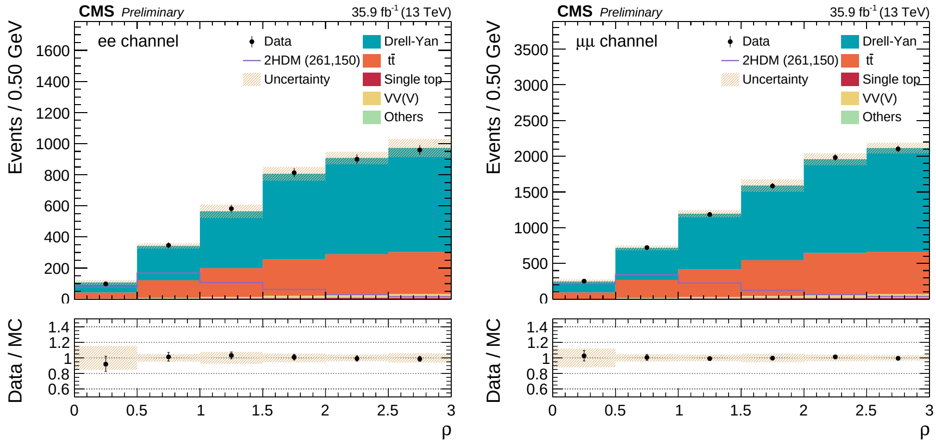

Figure 3: Distribution of the parameter ρ corresponding to the mass hypothesis $(m_H, m_A) = (261, 150)$ GeV for e^+e^- (left) and $\mu^+\mu^-$ (right) events [7].

3. Results

A binned maximum likelihood fit is performed in order to extract the best-fit signal cross sections using the six binned templates mentioned in Section 2. Another bin is included in the fit containing the different-flavor lepton events to further constrain the $\mathrm{t\bar{t}}$ background.
Upper limits at 95% confidence level (CL) are set on the product of the signal production cross section and branching fraction as a function of the A and H mass hypotheses and are shown in Fig. 4 (top). Figure 4 also shows expected and observed (with ±1, ±2 standard deviation bands) 95% CL exclusion limits under the 2HDM benchmarks $\tan\beta = 1.5$ and $\cos(\beta-\alpha) = 0.01$ as a function of m_A and m_H (bottom left), and $m_H = 379$ GeV and $m_A = 172$ GeV as a function of $\cos(\beta-\alpha)$ and $\tan\beta$ (bottom right).

The highest local significance observed corresponds to 3.9σ for the signal hypothesis with $m_H = 627$ GeV and $m_A = 162$ GeV, which globally becomes 1.3σ once accounting for the look-elsewhere effect [8].

4. Summary

The search for a new CP-even (odd) neutral Higgs boson decaying into a Z boson and a lighter CP-odd (even) Higgs boson in the $\ell^+\ell^-\mathrm{b\bar{b}}$ final state is presented. The search is based on LHC proton-proton collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment, corresponding to an integrated luminosity of 35.9 fb^{-1}. No significant deviations from the SM predictions are observed.
Upper limits on the product of the signal production cross section and branching fraction are set. A theoretical interpretation in the context of the Type-II Two-Higgs-doublet model (2HDM) is also performed, where the CP-even (odd) scalar corresponds to the H (A) boson of the 2HDM. The specific benchmark scenario corresponding to $\tan\beta = 1.5$ and $\cos(\beta-\alpha) = 0.01$ is excluded for m_H in the range ∼150–700 GeV and m_A in the range ∼30–295 GeV with $m_H > m_A$, or alterna-

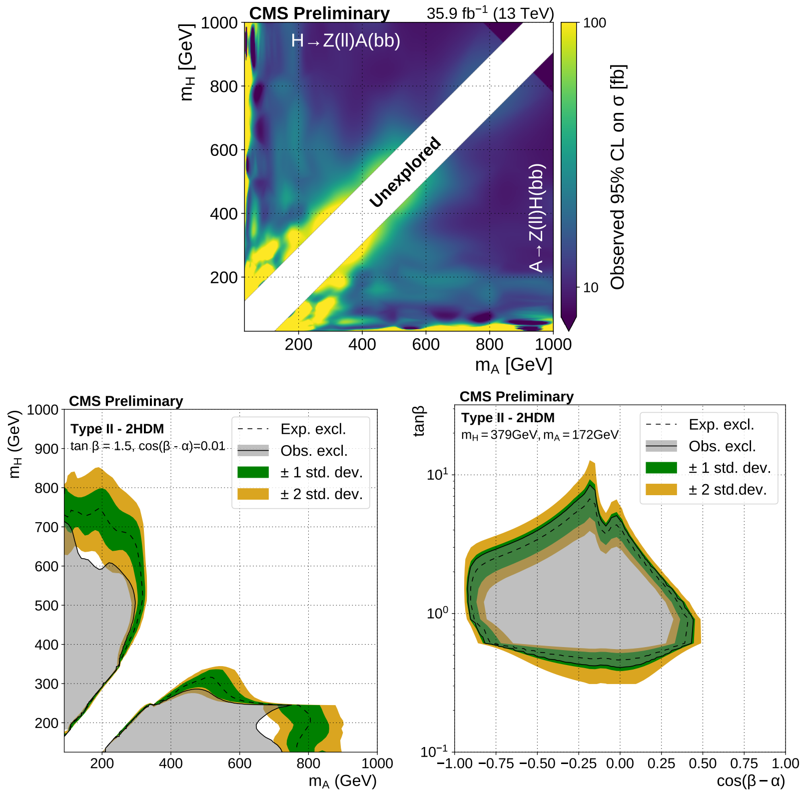

Figure 4: Expected (with ± 1, ± 2 standard deviation bands) and observed 95% CL exclusion limits for $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$ as a function of m_A and m_H (left) and $m_H = 379$ GeV and $m_A = 172$ GeV as a function of $\tan\beta$ and $\cos(\beta - \alpha)$ (right) in the Type-II 2HDM benchmark scenario [7].

tively, for m_H in the range $\sim$125–280 GeV and m_A in the range $\sim$200–700 GeV with $m_H < m_A$. Results are also interpreted in the benchmark scenario where $m_H = 379$ GeV and $m_A = 172$ GeV. In this context, the region with $\cos(\beta - \alpha)$ in the range $\sim$-0.9–0.3 and $\tan\beta$ in the range $\sim$0.5–7 is excluded.

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