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Search for additional Higgs bosons at CMS

Elisabetta Gallo for the CMS Collaboration

Abstract

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Search for additional Higgs bosons at CMS

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Several extensions of the standard model predict the existence of an additional Higgs doublet and therefore the existence of additional Higgs bosons. Here three searches are presented for heavy Higgs bosons decaying either into ZZ and subsequently into four leptons, or into $b\bar{b}$ or $t\bar{t}$. The results are based on pp collisions collected by the CMS experiment in Run 2 and corresponding to 138 fb^{-1} of integrated luminosity. In absence of a signal, these searches constrain a large part of parameter space in Two-Higgs-Doublets models.

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1. Introduction

The standard model (SM) has been very successful in describing strong and electroweak interactions among elementary particles, culminating with the discovery of the 125 GeV Higgs boson in 2012 by the ATLAS and CMS Collaborations at the CERN LHC. However, the SM still presents many shortcomings and many beyond the SM (BSM) models predict additional scalar or pseudoscalar resonances. Among these, the Two-Higgs-Doublets-Model (2HDM) [1] predicts two Higgs doublets, giving five particles, three neutral (the CP-even states h and H, and the CP-odd state A) and two charged ($H^{\pm}$) bosons.

In 2HDM with CP-conserving couplings and no flavour-changing neutral currents, 4 types of models can be defined, according to which flavour interacts with each Higgs doublet. In *Type I*, every charged fermion interacts with the same Higgs doublet. In *Type II*, up-type quarks interact with one Higgs doublet, down-type quarks and leptons with the other doublet. In *Lepton specific*, all leptons interact with one doublet and all quarks with the other one. In the *Flipped* model, charged leptons and up quarks interact with one doublet and down-type quarks with the other doublet. The branching ratios to different type of fermions or bosons vary according to the mass and model and for this reason it is important to search for these heavy Higgs bosons in different decay modes.

Here three searches for heavy neutral states are presented, where a heavy scalar or pseudoscalar resonance $X = A, H$ decays either into two Z bosons, and subsequently into 4 leptons (e or μ), or into a $b\bar{b}$ or $t\bar{t}$ pair. The analyses are based on pp collision data collected during Run 2 by the CMS detector [2] at $\sqrt{s} = 13$ TeV and corresponding to 138 fb^{-1} of integrated luminosity.

2. Search for $X \to ZZ \to 4$ leptons

The search for a heavy Higgs boson decaying into two Z bosons and subsequently into four leptons is one of the golden channels, due to the high signal-to-background ratio. Here the search covers a wide mass range, from 130 GeV to 3 TeV and the final states $4\mu, 4e, 2\mu 2e$ are considered [3]. A resonance X with spin 0 is assumed and produced either via gluon fusion (ggX) or vector-boson-fusion (VBF). The search is done both in the narrow-width-approximation (NWA), but also assuming a variable width Γ_X, up to 30% of the resonance mass M_X. In the case of non-zero width, the interference among the ggX, the gluon-fusion-SM Higgs production (ggH) and the production of two Z bosons from two gluons (ggZZ) has to be considered, which is one of the challenges of this analysis.

Figure 1 shows the invariant mass distribution of the four selected leptons, where the data are superimposed to the SM background, which includes: the reducible $Z + X$ background, which is estimated with a data-driven method; the irreducible ZZ background which is evaluated with the Monte Carlo (MC); the SM H(125) resonance, shown in red in the plot. The shapes of possible BSM Higgs bosons in both the ggX or VBF channels are also superimposed. The signal is extracted from a 2-dimensional fit in the $M_{4\ell}^{\mathrm{reco}}$ variable and in a kinematic MELA discriminant [4], which exploits the different matrix elements for the signal and main ZZ background. For the VBF category, an additional discriminant based on variables that separate VBF from ggX is used. No excess of data is observed over the expected background and limits on the cross section $\sigma(pp \to X \to ZZ)$ are extracted for exclusive ggX or VBF productions and in the combined channel with a floating VBF fraction. The latter limit is shown in Fig. 1 in the NWA approximation. The highest excess of data over prediction is at a mass M_X of 137.8 GeV with a 3.02 σ (1.85 σ) local (global) significance. A previous excess observed by the ATLAS experiment around 680 GeV [5] is not confirmed by these data. Limits were also extracted for the first time over the full mass range [130-3000] GeV with variable Γ_X/M_X (up to 30%) without any significant excess observed anywhere.

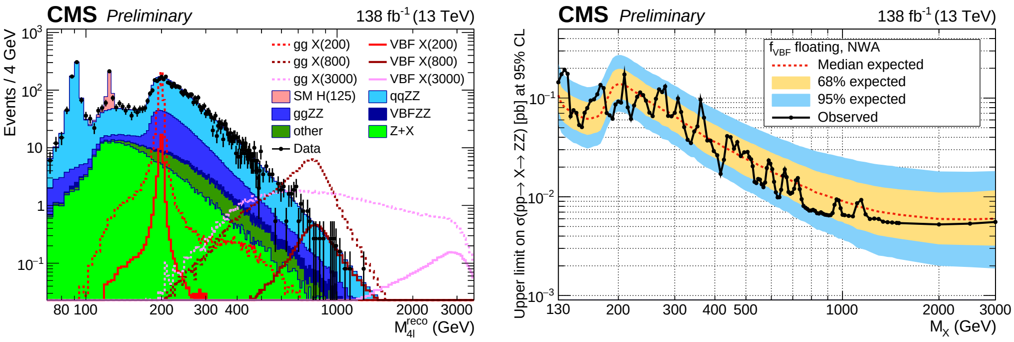

Figure 1: Left: Distribution of the invariant mass of the 4 leptons ($M_{4\ell}^{\text{reco}}$), showing also the possible BSM Higgs boson signals superimposed. The widths and normalizations for the BSM Higgs states are taken for this plot as for a SM-like Higgs boson at higher masses. Right: result on the upper limit on the cross section $\sigma(pp \to X \to ZZ)$, assuming a floating fraction of the VBF component. From [3].

3. Search for $A/H \to b\bar{b}$

The coupling of a BSM Higgs boson to b-quarks is particularly enhanced for the *Type II* and *Flipped* models and at high $\tan\beta$, the latter being the ratio of the vacuum expectation values of the two Higgs doublets. Here a search for a neutral boson in the mass range 125 GeV to 1800 GeV is reported, in the decay into a $b\bar{b}$ pair, and produced in the b-associated mode and therefore accompanied by at least one additional b-jet from the production [6]. The analysis requires then three b-tagged jets in the event and the invariant mass of the highest two b-jets, M_{12}, is used as discriminating variable and to reconstruct the mass of the searched boson, hereafter called $\phi = A/H$.

Two main challenges are present in the analysis. The first one is the lower mass range, down to 125 GeV, as the trigger, which requires at least two high p_T b-tagged jets, sets a relative high p_T threshold in order to contain the rate. For this reason, two categories were triggered and selected, a fully-hadronic one (FH) and a semi-leptonic (SL) category where one of the b-jets could contain a muon, allowing therefore to lower the jet p_T threshold and reach lower mass values of the ϕ resonance. The second challenge is the very high background from QCD multi-b jets, which has a much higher cross-section and it is difficult to model with the MC. For this purpose a data-driven method was employed: events were selected in the data and MC with 3 b-jets (bbb, signal region) and 2 b-jets, while b-vetoing the third jet ($bbnb$, control region). A transfer factor from the $bbnb$ to the bbb, initially determined from the MC and then left floating in data in the final fit, was used to correct the $bbnb$ data, to determine the background shape in the bbb signal region. The background shape was modeled and fitted in different regions, due to the effect of the turn-on of the trigger threshold. An example of the background shape in a high mass region is shown in Fig. 2.

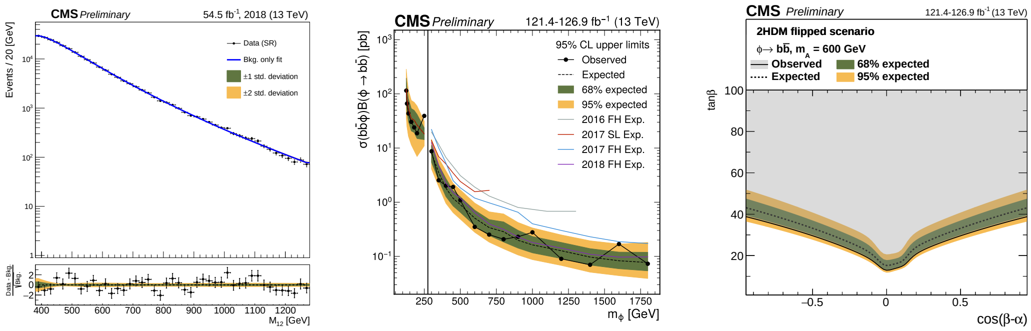

Figure 2: Left: Distribution of the invariant mass of the 2 highest p_T b-jets for a high mass range for the 2018 data. The line shows the fit to the background-only distribution with the ± 1 and ± 2 σ bands. The lower panel shows the pulls. Middle: Observed and expected model-independent limits for the b-associated production of a $\phi = A/H$ decaying into a $b\bar{b}$ pair for the Run 2 data, for the individual SL and FH categories, and for the combination. Right: Interpretation in the *Flipped* scenario. From [6].

The mass M_{12} is modeled in the signal MC with a Double Crystal Ball function and a signal is searched for by a maximum likelihood (ML) fit of the data M_{12} distribution to the signal plus the control regions. In the absence of a significant excess, model-independent limits are set, which are shown in Fig. 2. The limits extend over a wide range of mass, where the lower range is covered by the SL category. A local excess of 3.2 (2.8) σ of local (global) significance was observed at 250 GeV. The limits can be interpreted also in the different 2HDMs, and this analysis particularly excludes a large parameter space in the *Flipped* scenario, as shown in Fig. 2. The limit is here shown in the plane $\tan\beta$ and $\cos(\beta-\alpha)$ at a fixed value of m_A, where α is the mixing angle between the two scalars in 2HDM. These limits were the most stringent at the time of the presentation.

4. Search for $A/H \rightarrow t\bar{t}$

In the case in which the mass of the A/H state is greater than $2m_{\text{top}}$, the decay into $t\bar{t}$ is favored in a large paramater space. The signal manifests itself then as a narrow resonance in the invariant mass of the top pair, $m_{t\bar{t}}$. Due to the short lifetime of the top quark, spin information are preserved in the angular distribution of its decay products. Spin correlations among the final states particles from the decay of the top pair can then be exploited to determine the nature (scalar or pseudoscalar) of the searched boson, and to discriminate the signal from the main SM $t\bar{t}$ background. The challenge of the analysis is the interference with the SM top pair production in the gluon fusion channel, which gives rise to a peak-dip structure in $m_{t\bar{t}}$, which has to be correctly modeled.

Here the CMS analysis of the full Run 2 data is reported [7], in a mass range spanning from about 365 GeV, at threshold, to 1 TeV and widths from 0.5% to 25% of the resonance mass. A moderate excess had been observed in the 2016 data by CMS around 400 GeV [8], further motivating this search.

The data were splitted in three independent categories: two categories coming from the semi-leptonic top pair decays ($\ell + \geq 4$ jets and $\ell + 3$ jets) and a dilepton category. For the semileptonic category, a 2-dimensional ML fit in $m_{t\bar{t}}$ and in an angular variable, to distinguish both from the SM $t\bar{t}$ background and between different CP hypotheses for the new resonance, was performed to search for a possible signal. In the dileptonic category, a 3-dimensional ML fit was done in $m_{t\bar{t}}$ and two helicity angles (c_{han}, c_{hel}), to distinguish the background from a possible scalar or pseudoscalar new resonance.

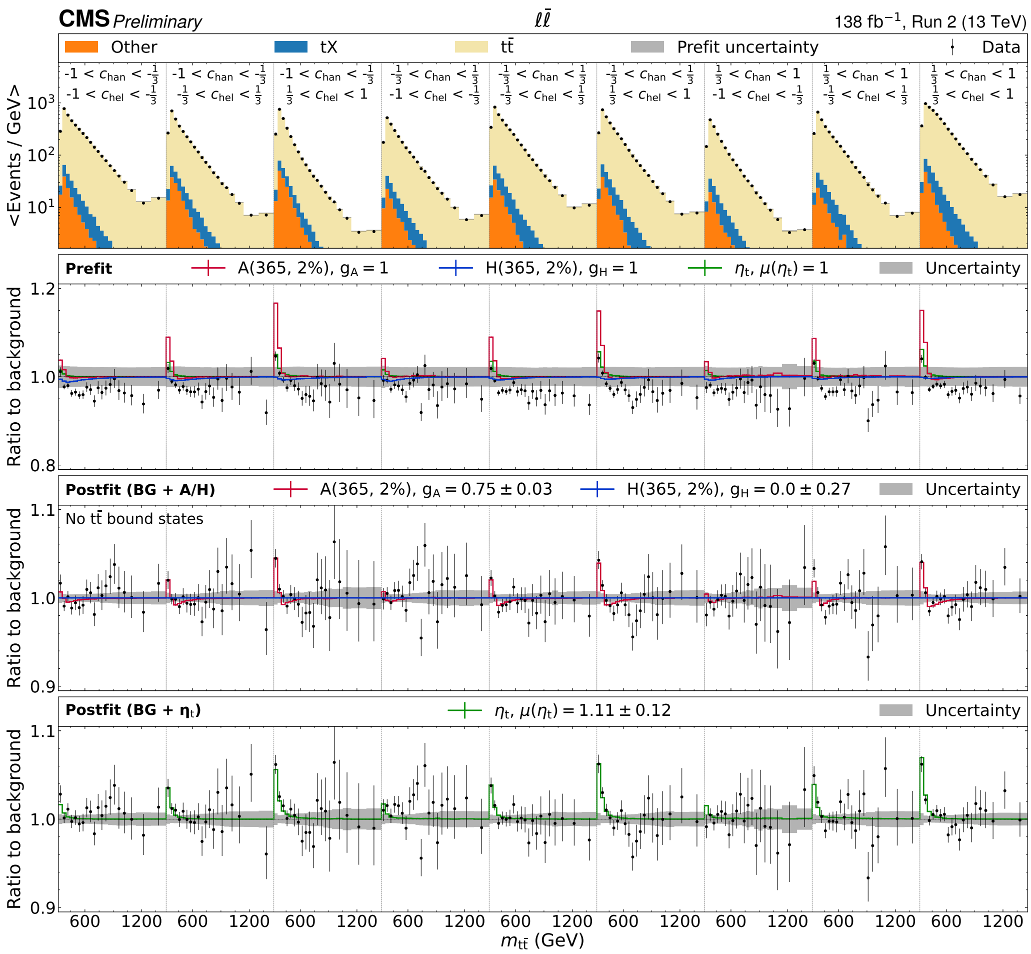

Figure 3: Observed and expected $m_{t\bar{t}}$ distributions, in bins of c_{han}, c_{hel}, in the dilepton channel. From [7].

An example of the observed distributions is shown in Fig. 3. The data are shown in the first panel on top of the main $t\bar{t}$ background contribution, shown in yellow. In the second panel, the prefit distribution shows a significant excess of the data over the background close to the threshold. An A pseudoscalar resonance (third panel), with a mass of 365 GeV and a width of 2% its mass would describe this excess in all bins and all categories (the other two categories are not shown here). The overall excess is above 5 σ.

An independent explanation of the observed excess was introduced postulating the formation of a *toponium* state at threshold [9], which is shown in the 4th panel of Fig. 3, as green histogram. The cross section of this color singlet η_t state was calculated in [10] in NRQCD, predicting a cross section around 6.43 pb, however without uncertainties and contributions from the the color-octet states. In spite of this, this prediction is very much in agreement with an extracted cross section of 7.1 pb ±11% from these data.

5. Summary

Three searches for a heavy Higgs boson are reported here, in three independent channels. The search for $X \to ZZ \to 4$ leptons covers a wide range, until 3 TeV and for the first time assumes widths ranging from the NWA up to 30% of the mass M_X. The search for $A/H \to b\bar{b}$ is particularly competitive in the 2HD *Flipped* model. The search for $A/H \to t\bar{t}$ confirms with the whole Run 2 the excess seen at threshold with the 2016 data and points to either a pseudoscalar state or the formation of a toponium. The years 2022-2024 were very successful in data-taking and Run 3 will be very promising for these searches as well.

6. Acknowledgements

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