PROCEEDINGS OF SCIENCE

Searches for additional Higgs bosons at CMS

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Several searches for additional Higgs bosons are presented, performed with data collected by the CMS detector during the LHC Run 2 operation at a center-of-mass-energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. The additional Higgs bosons are assumed to decay to lighter Higgs bosons, two Z bosons, two b quarks, or a Z boson and a Higgs boson. No significant excess is observed in all studies, and upper limits on the production cross section multiplied by the decay branching ratio at 95% confidence level are computed.

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1. Introduction

The discovery [1, 2] of the Higgs boson with a mass of 125 GeV (H) has indicated the great success of the Standard Model (SM). However, the SM has some limitations, and theories beyond the SM (BSM) propose extensions of the Higgs sector, which predict additional Higgs bosons. The additional Higgs boson always has a spin = 0, and can be a neutral, CP-even boson (noted as X), a neutral, CP-odd boson (noted as A), or a charged boson (noted as $H^{\pm}$).

There have been quantities of studies to search for additional Higgs bosons conducted by the CMS experiment [3]. The latest searches are presented, which use the full Run 2 data set at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}.

2. Search for $X \to YH \to 2\gamma 2\tau$

The next-to-minimal supersymmetric SM (NMSSM) [4] extends the SM Higgs sector to a combination of two Higgs doublet and one complex singlet field. This scenario introduces five neutral Higgs bosons, three of which are CP-even. The heaviest neutral Higgs boson X can decay to two lighter Higgs bosons Y and H, with H representing the one with mass close to 125 GeV.

A recent search performed by the CMS experiment [5] targets $X \to YH$, with $Y \to 2\gamma$, $H \to 2\tau$ or $Y \to 2\tau$, $H \to 2\gamma$. A large mass range is considered: M_X from 300 GeV to 1 TeV, and M_Y from 70 GeV to 800 GeV. All Higgs bosons have narrow widths, and X is produced via gluon fusion (ggF). Events are required to have two identified and isolated photons, and at least one τ lepton candidate, which can be an electron, muon, hadronically decayed τ lepton, or an isolated track. Events are further categorized based on a dedicated parameterized neural network (pNN), with M_X and M_Y as the conditional parameters. Three scenarios are studied individually: $Y(2\tau)H(2\gamma)$, $Y(2\gamma)H(2\tau)$ with $M_Y < 125$ GeV, and $Y(2\gamma)H(2\tau)$ with $M_Y > 125$ GeV.

The invariant mass of the two selected photons $M_{\gamma\gamma}$ is fitted to extract the signal yield. The signal process and single H production are described by double crystal ball functions parameterized on simulation; the continuum backgrounds are described by smooth functions fitted on data.

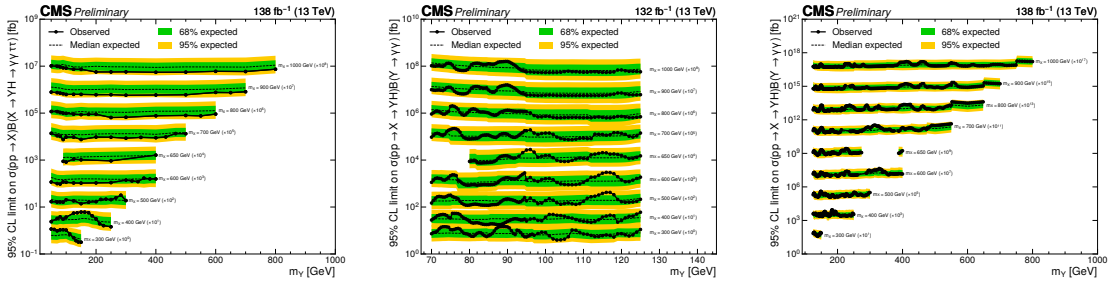

Figure 1: Upper limits on $\sigma(pp \to X) \cdot BR$ at 95% CL as a function of M_X and M_Y, in the three scenarios: $Y(2\tau)H(2\gamma)$ (left), $Y(2\gamma)H(2\tau)$ with $M_Y < 125$ GeV (middle), and $Y(2\gamma)H(2\tau)$ with $M_Y > 125$ GeV (right). The plots are taken from [5].

No significant excess is observed in all examined phase space. Upper limits at 95% confidence level (CL) on the production cross section of X multiplied by the decay branching ratio are computed, as a function of M_X and M_Y, shown in Figure 1. The observed limits are mostly compatible with

the expected ones within ±2 standard deviation. The most significant excess is at $M_X = 450$ GeV, $M_Y = 161$ GeV, in the $Y(2\gamma)H(2\tau)$ scenario, reaching a local (global) significance of 3.2 (0.3) σ.

3. Search for X → ZZ → 4ℓ

A search for an additional scalar Higgs boson X decaying into a pair of Z bosons in the 4-lepton final state [6] is presented. The examined mass range M_X is from 130 GeV to 3 TeV, with various decay width assumptions. The resonance can be produced via ggF or vector boson fusion (VBF).

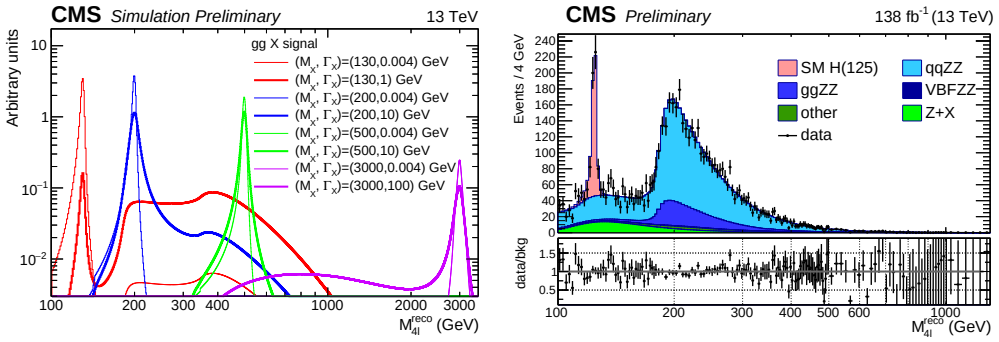

Figure 2: The $M_{4\ell}^{\text{reco}}$ distributions from the statistical model for a few signal processes (left), as well as backgrounds and observed data (right). The plots are taken from [6].

Events are required to have four identified and isolated leptons (electrons or muons), with which the Z boson and ZZ candidates are constructed. The kinematics of VBF jets are used for categorization to improve the sensitivity to VBF signals. Results are computed by performing two-dimensional fits on the 4-lepton mass $M_{4\ell}^{\text{reco}}$ and a kinematic discriminant calculated by the Matrix Element Likelihood Approach [7]. A parametric method is used to build the statistical model for signal, background and interference processes. Figure 2 shows the $M_{4\ell}^{\text{reco}}$ shapes from the signal and background models, as well as observed data.

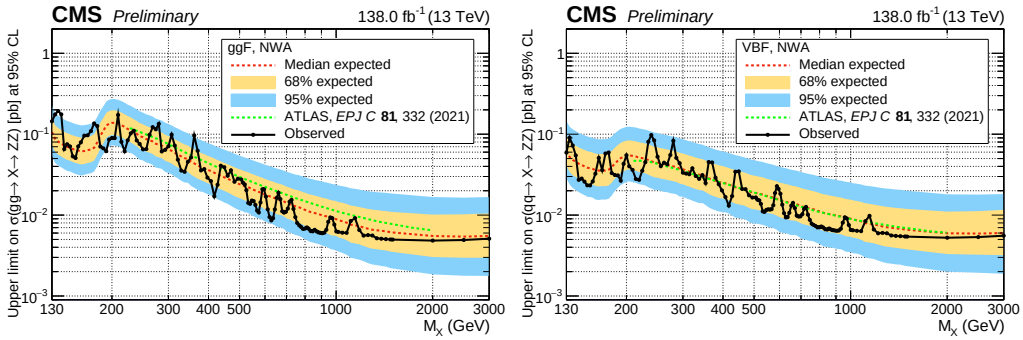

Figure 3: Upper limits on $\sigma(pp \to X \to ZZ)$ at 95% CL as a function of M_X, with narrow width assumption, produced via ggF (left) or VBF (right). The plots are taken from [6].

Upper limits on the production cross section of X multiplied by its decay branching ratio to two Z bosons at 95% CL are computed, as a function of M_X, Γ_X, for the two production mechanisms. Figure 3 shows the results with the narrow width assumption. Compared to the ATLAS experiment

[8], the expected upper limits are more stringent for the ggF production, and comparable for the VBF production. Observed results are in general compatible with the background-only hypothesis. The highest significance is at $M_X = 137.8$ GeV with the ggF production, reaching 3.02 σ locally and 1.85 σ globally. Besides, various width assumptions are tested, up to 30% of M_X, shown in [6]. No additional excess is observed.

4. Search for X/A → bb

The two Higgs doublet models (2HDM) [9] proposes an additional scalar Higgs boson X and a pseudoscalar Higgs boson A. Especially, in the *type-II* scenario which is present in the minimal supersymmetric SM (MSSM) [10] and *flipper* scenario, their coupling strengths with b quarks are enhanced. Based on this, a search for X or A (noted as ϕ together) decaying to two b quarks by the CMS experiment [11] is presented. The additional Higgs boson is produced via ggF or associated with two b quarks, with the mass ranging from 125 GeV to 1.8 TeV.

Two types of data sets are used: events passing the double-b-jet triggers (full hadronic, FH), which have very high transverse momentum (p_T) thresholds to reduce trigger rates; events with a muon decayed from a b hadron (semi-leptonic, SL) to cover more phase space. Events are selected to have at least 3 b jets. The distributions of $M_{j_1 j_2}$, the invariant mass of the two p_T-leading b jets, is fitted to extract the results. Signals are estimated from simulation, fitted with double crystal ball functions; backgrounds are described by smooth functions derived from data.

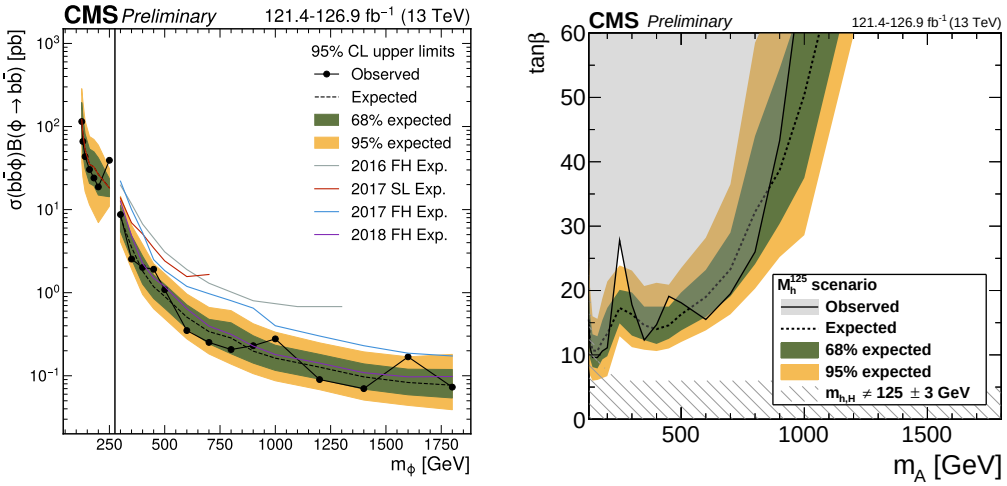

Figure 4: Left: upper limits at 95% CL on the production cross section multiplied by the decay branching ratio of $\phi \to$ bb. Results with different data sets are shown. Right: the exclusion limit on (m_A, tanβ) in the M_h^{125} scenario of MSSM. The plots are taken from [11].

The left plot of Figure 4 shows the upper limits at 95% CL on the production cross section multiplied by the decay branching ratio of $\phi \to$ bb, as a function of M_ϕ. FH data sets cannot be used for $M_\phi \leq 250$ GeV due to the high p_T thresholds of triggers. The observed results are compatible with expected backgrounds, except a small excess at 250 GeV in the SL data set, which

reaches a local (global) significance of 3.2 (2.8) σ. Results are also interpreted with different scenarios in MSSM and 2HDM. One example is shown in the right plot of Figure 4.

5. Search for A → ZH → 2ℓ2τ

Finally, the search for a pseudoscalar Higgs boson A decaying to ZH [12], with the Z → 2ℓ and H → 2τ, is presented. The A is produced via ggF or associated with b quarks (bbA), predicted by MSSM as the dominating production mechanisms. The mass of A ranges from 225 to 800 GeV.

In each event, identified and isolated leptons are selected, which can be electrons, muons or hadronically decayed τ leptons (τ_h). The Z boson candidate is built as two electrons or two muons, and the H candidate is built as eτ_h, $\mu\tau_h$ or $\tau_h\tau_h$, whose 4-momentum is computed with the FastMTT algorithm, a simplified likelihood approach based on visible objects and missing transverse energy. Events are further categorized based on the number of b jets, targeting the two production mechanisms.

The distribution of $M_{2\ell 2\tau}$ is fitted to extract the results. The left plot of Figure 5 shows its distributions in the category with no b jets. All processes are estimated from simulation, except reducible backgrounds, which are estimated with a data-driven method. Upper limits on production cross section of A multiplied by its decay branching ratio to ZH at 95% CL are computed, individually with the two production mechanisms. Results with the ggF production are shown in the right plot of Figure 5. No excess is observed. Besides, results are interpreted in the MSSM, and details are shown in [12].

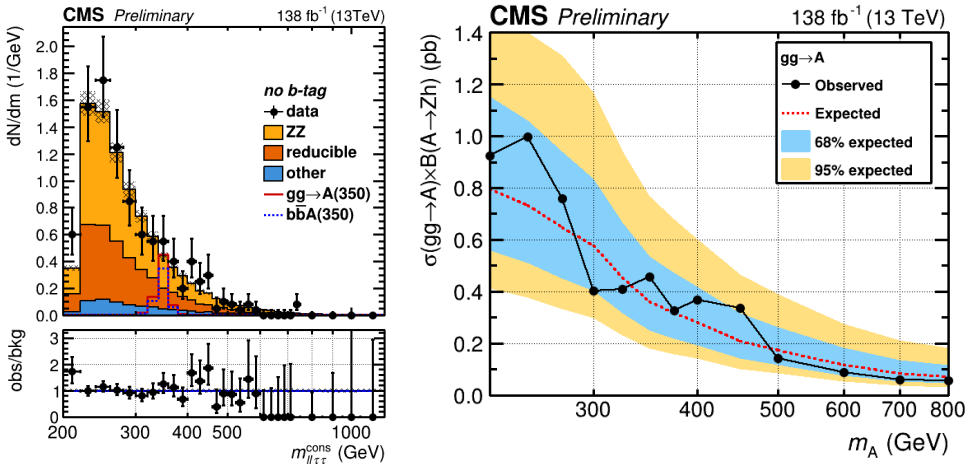

Figure 5: Left: the $M_{2\ell 2\tau}$ distributions of signal, background processes and observed data, in the category without b jets. Right: upper limits on production cross section of A multiplied by its decay branching ratio to ZH at 95% CL as a function of M_A, with the ggF production mechanism. The plots are taken from [12].

6. Summary

In conclusion, several recent results of searching for additional scalar or pseudoscalar Higgs bosons are presented, using the full Run 2 data collected by the CMS detector at $\sqrt{s}$ = 13 TeV.

Upper limits at 95% confidence level on the production cross section of the additional Higgs bosons multiplied by the branching ratio of the examined decay channels are computed. Some excesses are observed, but not significant enough to assert any claim. More decay channels and scenarios are being studied, and the ongoing Run 3 operation is expected to provide more data to further check the existing excesses.

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