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Searches for additional Higgs bosons at the LHC

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Some latest results of the direct searches for additional Higgs bosons at ATLAS and CMS are presented. The searches for heavy neutral Higgs bosons, light neutral Higgs bosons, singly and doubly charged Higgs bosons are performed using proton-proton collision data at $\sqrt{s} = 13$ TeV collected by the ATLAS and CMS detectors. No significant sign of any beyond standard model Higgs boson is observed. For each search the upper limit on the Higgs boson production cross section times branching ratio is set.

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1. Introduction

In 2012, both the ATLAS [1] and CMS [2, 3] Collaborations observed a new boson with a mass of approximately 125 GeV whose properties are at present compatible with those of the Higgs boson in the standard model (SM) of particle physics. However, many important questions dealing with the nature and origin of the Higgs boson observed at the LHC remain unanswered. Physics beyond the SM (BSM) can also provide a Higgs boson that is compatible with the observed 125 GeV boson. The extended parameter space of several BSM models, such as generalized models containing two Higgs doublets (2HDM) [4] and the next-to-minimal supersymmetric model (NMSSM) [5, 6], give rise to a rich and interesting phenomenology, including the presence of additional Higgs bosons. Searching for additional Higgs bosons is therefore an important way to probe BSM physics and address the naturalness problem in the SM. This paper summarizes some selected results of the latest searches for additional Higgs Bosons in a wide mass range at both ATLAS and CMS. The data set is the proton-proton collisions collected with the ATLAS and CMS detectors at the LHC [7, 8], at a center-of-mass energy of 13 TeV.

2. Heavy neutral Higgs boson searches

Searches for a new hypothetical scalar particle (X) decaying into SM Higgs boson pairs, or the SM Higgs boson and another scalar particle, are performed by ATLAS and CMS.

A search for $X \to HH \to b\bar{b}\gamma\gamma$ is performed by ATLAS with a data set corresponding to an integrated luminosity of 139 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV [9]. Using the TMVA toolkit [10], two boosted decision trees (BDTs) are trained to better separate the signal from the $\gamma\gamma$ plus the $t\bar{t}\gamma\gamma$ backgrounds and the single Higgs boson background, where ZH and $t\bar{t}H$ production modes are the dominant resonant backgrounds. The combined BDT score of an event, obtained by combining the two BDT scores in quadrature, is used to select events. The signal and backgrounds are extracted by fitting analytic functions to the di-photon invariant mass distribution in the range 105 GeV $\leq m_{\gamma\gamma} \leq$ 160 GeV. No excess with respect to background expectations is found. The observed (expected) limits on the cross section $pp \to X \to HH$ range from 610 fb to 47 fb (360-43 fb) over the considered mass range, 251 GeV $\leq m_X \leq$ 1000 GeV, as shown in the left plot of Figure 1. The expected limit on the cross section improves by a factor of two to three depending on the m_X value, compared to the previous ATLAS result based on 36 fb^{-1} of 13 TeV collisions.

CMS performed the first such search with a heavy neutral Higgs boson H decaying into an SM Higgs boson h and another neutral Higgs boson h_S with a mass of $m_{h_S} < m_H - m_h$, using 137 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV [11]. A promising signature for the search is thus given by the decay of the h into a pair of tau leptons and the decay of the h_S into a pair of b quarks, $h(\tau_h\tau_h)h_S(b\bar{b})$. For the τ pair, the $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ final states are used. A mass range of 240-3000 GeV for m_H and 60-2800 GeV for m_{h_S} is covered. A neural network (NN) multi-classification is used for event categorization and also extracting the signal. No signal has been observed. Model independent 95% confidence level upper limits on the product of the production cross section and the branching fractions of the signal process are set ranging from 125 fb (for m_H=240 GeV) to 2.7 fb (for m_H=3000 GeV), as shown in the middle plot of Figure 1.

These limits have been compared to maximally allowed products of the production cross section and the branching fractions of the signal process in the next-to-minimal supersymmetric extension of the standard model, as shown in the right plot of Figure 1.

ATLAS performed the search for a heavy neutral Higgs boson, A, decaying into a Z boson and another heavy Higgs boson, H, using a data sample corresponding to an integrated luminosity of 139 fb^{-1} [12]. Two final states were considered, where the H boson decays into a pair of b-quarks or W bosons, and in both cases the Z boson decays into a pair of electrons or muons. The analysis requires exactly two oppositely charged muons or electrons. In order to improve the mass resolution of the heavy Higgs boson A, the mass of two b-jets from H or 4 jets from H to WW is constrained to agree with the Higgs mass. For the $\ell\ell bb$ final states, 3 event categories according to production modes and the number of b-jets, are employed. The data are in good agreement with the background predicted by SM. For $\ell\ell bb$, upper limits are set in the range 6.2-380 fb for gluon-gluon fusion and 6.8-210 fb for b-associated production of a narrow A boson in the mass range 230-800 GeV, assuming the H boson is in the mass range 130-700 GeV. For $\ell\ell WW$, the observed upper limits are in the range 0.023-8.9 pb for gluon-gluon fusion production of a narrow A boson in the mass range 300-800 GeV, assuming the H boson is in the mass range 200-700 GeV.

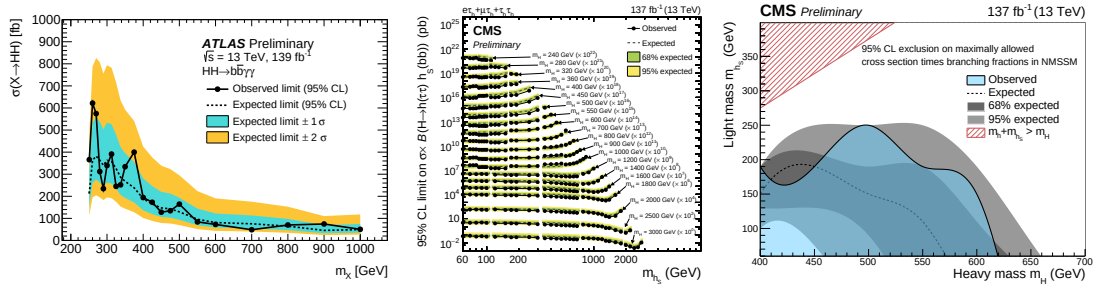

Figure 1: (Left) Observed and expected limits at 95% confidence level (CL) on the production cross section of a narrow width scalar resonance X as a function of the mass m_X of the hypothetical scalar particle, performed by ATLAS with $X \to HH \to b\bar{b}\gamma\gamma$ [9]. (Middle) Expected and observed 95% CL upper limits on $\sigma \times B(H \to h(\tau_h\tau_h)h_S(b\bar{b}))$ for all tested values of m_H and m_{h_S} [11]. The limits for each corresponding mass value have been scaled by orders of ten as indicated in the annotations. (Right) Mass range in mH and mhS for which the maximally allowed $\sigma \times B(H \to h(\tau_h\tau_h)h_S(b\bar{b}))$ within the NMSSM can be excluded at 95% CL by this CMS search [11].

3. Light neutral Higgs boson searches

Searches for light pseudoscalar a_1 bosons, produced from decays of the 125 GeV Higgs boson (H), in different decay channels are performed at the LHC using the 2016 data set [13, 14, 15, 16, 17, 18, 19, 20, 21]. Based on 139 fb^{-1} of 13 TeV collisions, ATLAS performed the search for decays of the observed Higgs boson to a pair of light neutral Higgs bosons, with one a-boson decays to a b-quark pair and the other to a muon pair [22]. After some basic selections on the dimuon pair, two b-tagged jets and missing transverse energy (E_T), a BDT is employed to reduce the SM mainly $t\bar{t}$ and DY backgrounds. A kinematic likelihood fitis performed to improve the

$\mu\mu bb$ mass resolution, varying the b-jet energies within their resolution. The left plot in Figure 2 shows the upper limits on $B(H \to aa \to bb\mu\mu)$ as a function of the signal mass m_a. The upper limits on the branching fraction range between 0.22 to $4\times\ 10^{-4}$ depending on the a mass. The limit is improved by a factor of 2-5 over the full $m_{\mu\mu}$ range compared to the previous result with 36 fb^{-1} data, with a factor of $\sim$2 from the larger data set and a further factor $\sim$2 from the BDT for the discrimination of the signal against the SM backgrounds. The largest excess is observed at $m_{\mu\mu}$ = 52 GeV with a local significance of 3.3σ and a global significance of 1.7σ.

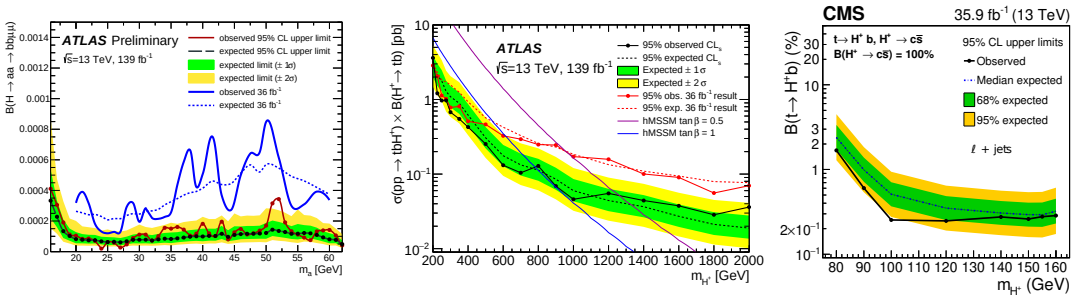

Figure 2: (Left) Upper limits on $B(H \to aa \to bb\mu\mu)$ as a function of the signal mass [22]. (Middle) Observed and expected upper limits for the production of $H^+ \to tb$ in association with a top quark and a bottom quark [23]. (Right) The expected and observed upper limit in % on $B(t \to H^+b)$ as a function of m_{H^+} using m_{jj} after the individual charm tagging categories have been combined, for the combination of muon+jets and electron+jets channels [24].

4. Charged Higgs boson searches

For singly charged Higgs boson decaying into fermions, ATLAS performed the search for charged Higgs decaying into a top quark and a bottom quark using 139 fb^{-1} data [23]. In this search, 1 lepton plus jets events are categorized according to numbers of jets and b-jets. A Neural Network is used to discriminate between signal and background events. The main background is $t\bar{t}$ which was estimated from MC but corrected in data control regions. As shown in the middle plot of Figure 2 the observed upper limits on the cross section times the branching ratio range from 3.6 pb at 200 GeV to 36 fb at 2000 GeV at 95% confidence level, which improved by 5% to 70%, depending on the H^+ mass, compared to the previous ATLAS search with 36 fb^{-1}.

CMS performed the search of singly charged Higgs bosons produced in the process of top quark pair production, where one top quark decays to a bottom quark and a charged Higgs boson and the other to a bottom quark and a W boson, using 35.9 fb^{-1} data set [24]. With the W boson decaying to a charged lepton (electron or muon) and a neutrino, the final state comprises an isolated lepton, missing transverse momentum, and at least four jets, of which two are tagged as b jets. To enhance the search sensitivity, one of the jets originating from the charged Higgs boson is required to satisfy a charm tagging selection. An upper limit in the range 1.68%-0.25% is set on the branching fraction of the top quark decay to the charged Higgs boson and bottom quark for a charged Higgs boson mass between 80 and 160 GeV, as shown in the right plot of Figure 2.

ATLAS performed the doubly charged Higgs search in the pair production of doubly charged $H^{\pm\pm}$ bosons, or the associated production of a doubly charged $H^{\pm\pm}$ boson and a singly charged $H^{\pm}$ boson using 139 fb^{-1} data [25]. The search is guided by a type-II seesaw model that extends the scalar sector of SM with a scalar triplet [26]. Three final states including two same-charge leptons, three leptons, and four leptons, are considered. Combining those channels, $H^{\pm\pm}$ bosons are excluded at 95% confidence level up to 350 GeV and 230 GeV for the pair and associated production modes, respectively.

CMS investigated the singly and doubly charged Higgs bosons in a context of Georgi-Machacek (GM) model [27] using 137 fb^{-1} data [28]. Both charged Higgs boson are produced in vector boson fusion processes and decaying into vector bosons. The search was performed in fully leptonic decays of the vector bosons. Events are selected by requiring two or three electrons or muons, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass. The exclusion limits on the product of the charged Higgs boson cross section and branching fraction, as a function of Higgs mass from 200 GeV to 3 TeV, are shown in Figure 3 with the left plot for doubly charged Higgs and the middle plot for singly charged Higgs. The observed 95% confidence level limits exclude GM s_H parameter values greater than 0.20-0.35 for the mass range from 200 to 1500 GeV, as shown in the right plot of Figure 3 .

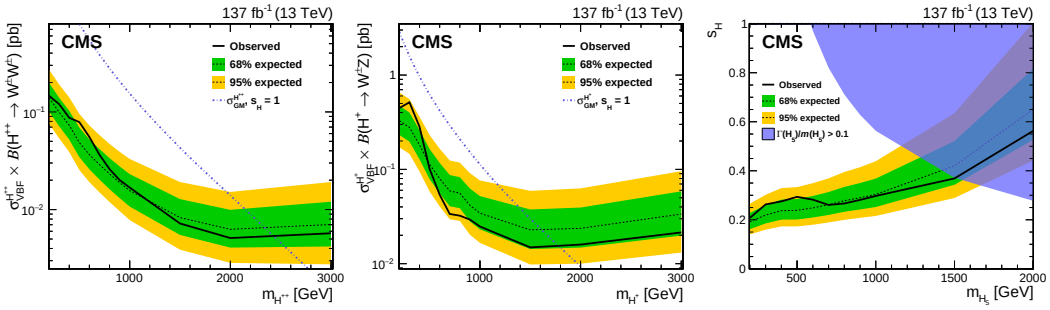

Figure 3: Expected and observed exclusion limits at 95% CL for $\sigma_{\mathrm{VBF}}(H^{\pm\pm})B(H^{\pm\pm}\to WW)$ as functions of $m_{H^{\pm\pm}}$ (left), for $\sigma_{\mathrm{VBF}}(H^{\pm})B(H^{\pm}\to WZ)$ as functions of $m_{H^{\pm}}$ (middle), and for s_H as functions of m_{H_5} in the GM model (right) [28]. The contribution of the $H^{\pm}$ ($H^{\pm\pm}$) boson signal is set to zero for the derivation of the exclusion limits on the $\sigma_{\mathrm{VBF}}(H^{\pm\pm})B(H^{\pm\pm}\to WW)$ ($\sigma_{\mathrm{VBF}}(H^{\pm})B(H^{\pm}\to WZ)$). The exclusion limits for s_H are shown up to $m_{H_5}=2000$GeV, given the low sensitivity in the GM model for values above that mass. Values above the curves are excluded.

5. Summary

Some latest results of the searches for additional Higgs bosons, including heavy neutral Higgs bosons, light neutral Higgs bosons, singly and doubly charged Higgs bosons, in a wide mass range at the LHC are presented. No significant sign of any beyond the standard model Higgs boson is observed. The upper limits on the Higgs boson production cross section times branching ratio are set. For some searches, the results are interpreted in the context of some BSM models.

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