Searches for exotic Higgs boson decays with the ATLAS and CMS experiments

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The observed Higgs boson offers an excellent opportunity to look for new physics at the LHC. Selected searches for exotic Higgs boson decays with the ATLAS and CMS experiments are presented. The Higgs boson decays to dark sector vector bosons, the Lepton Flavor Violating decays, the Flavor Changing Neutral Current decays, the decays to a light pseudo-scalar neutral Higgs boson of the NMSSM and the exotic Higgs boson decays to photon and missing transverse momentum signatures are described, and their Run-I results are given from both experiments. All the above searches for exotic Higgs boson decays present an alternative path to discovery of beyond Standard Model physics.

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1. Introduction

The Higgs boson (indicated with H o r h in the following) studied in various Standard Model (SM) channels by the ATLAS [1-2] and CMS [3-4] experiments at the LHC at CERN gives an excellent opportunity to look for new physics. The observed data was fitted to obtain Higgs boson coupling constants to SM fermions and gauge bosons. These fits constrain the branching fraction (B) of the Higgs boson to beyond the Standard Model (BSM) particles. Depending on the Higgs boson production cross section, the branching fraction B($h \rightarrow$ BSM) could be up to $\approx O(50\%)$ [5]. Even a small BSM coupling can translate into a detectable signature since the predicted total width of the SM Higgs boson is small ($\approx$ 4 MeV). Therefore, the current precision of measurements of couplings to SM particles leaves ample room for BSM physics. An explicit search for (BSM) exotic Higgs boson decays presents an alternative opportunity for discovery of BSM physics and can provide the best window on dark matter.

Selected Run-I searches for exotic Higgs boson decays with the ATLAS and CMS experiments at the LHC are presented: the ATLAS analyses of Higgs boson decays to dark sector vector bosons [6], the analyses from ATLAS and CMS of the Lepton Flavor Violating (LFV) decays [7-8], the Flavor Changing Neutral Current (FCNC) decays [9-11], the decays to a light pseudo-scalar neutral Higgs boson of the NMSSM [12-14], and finally the exotic Higgs boson decays to photon and missing transverse momentum signatures are described [15-16] and their results are summarized. Finally, the conclusions of these searches are given at the end of this document.

All data referred to in this document was taken using *pp* collisions at the LHC at a centre-of-mass energy of $\sqrt{s}$ =8 TeV with an integrated luminosity of about 20 fb^{-1} and for a mass of the Higgs boson of 125 GeV, in some cases also data of $\sqrt{s}$ =7 TeV were included.

2. Search for new light gauge bosons in Higgs boson decays to four-lepton final states

A search for Higgs bosons decaying to four leptons, either electrons or muons, via one or two light exotic gauge bosons Z_d, $H \rightarrow ZZ_d \rightarrow 4l$ or $H \rightarrow Z_dZ_d \rightarrow 4l$ was performed with the ATLAS detector. Model-independent searches for dark sector states were performed [6].

For the $H \rightarrow ZZ_d \rightarrow 4l$ search, in the absence of a significant signal, upper bounds were set on the relative branching ratio R_B = BR($H \rightarrow ZZ_d \rightarrow 4l$)/BR($H \rightarrow 4l$) as function of the mass of the dark vector boson m_{Z_d}. The R_B limit at the 95% confidence level (CL) as a function of m_{Z_d} is shown in Fig. 1 (a). Observed and expected exclusion limits were estimated for the combination of all the four final states (4μ, 4e, 2μ2e, 2e2μ). For relative branching ratios above 0.4 (observed) and 0.2 (expected), the entire mass range of 15 < m_{Z_d} < 55 GeV was excluded at the 95% CL.
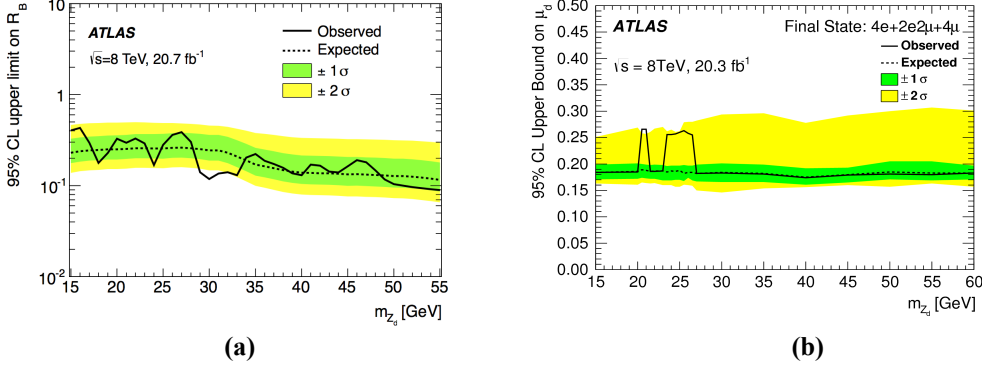
(a)   **(b)**

Figure 1: (a) The 95% CL upper limits on the relative branching ratio, $R_B = \text{BR}(H \to ZZ_d \to 4l)/\text{BR}(H \to 4l)$ as a function of m_{Z_d} [6]. (b) The 95% confidence level upper bound on the signal strength $\mu_d = \sigma \times \text{BR}(H \to Z_d Z_d \to 4l)]/[\sigma \times \text{BR}(H \to ZZ^* \to 4l)]_{\text{SM}}$ of $H \to Z_d Z_d \to 4l$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV [6]. In both (a) and (b) the $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

The upper limits on R_B led to upper limits on branching ratio of $H \to ZZ_d \to 4l$ assuming the SM branching ratio of $H \to ZZ^* \to 4l$ of 1.25×10^{-4} [17-18]. They were found to be in the range $(1–9) \times 10^{-5}$ for $15 < m_{Z_d} < 55$ GeV.

For the $H \to Z_d Z_d \to 4l$ search, in the absence of a significant excess of events, upper bounds on the signal strength $\mu_d = \sigma \times \text{BR}(H \to Z_d Z_d \to 4l)/[\sigma \times \text{BR}(H \to ZZ^* \to 4l)]_{\text{SM}}$ were set for the mass range of $15 < m_{Z_d} < 60$ GeV using the combined $4e$, $2e2\mu$, 4μ final states. The 95% CL upper bounds on μ_d are shown in Fig. 1 (b) as a function of the hypothesized m_{Z_d} for the combination of the three final states $4e$, $2e2\mu$ and 4μ. Assuming the SM Higgs boson production cross section and using $\text{BR}(H \to ZZ^* \to 4l)_{\text{SM}} = 1.25 \times 10^{-4}$, upper bounds on the branching ratio of $H \to Z_d Z_d \to 4l$ were obtained. They were set in the range $(2–3) \times 10^{-5}$ at the 95% CL, for $15 < m_{Z_d} < 60$ GeV.

3. Search for Lepton-Flavour-Violating decays of the Higgs boson

The presence of non–SM Higgs boson decays, like lepton–flavour–violating (LFV) decays, would serve as direct evidence for physics beyond the SM. The observation of the Higgs boson offers the possibility of sensitive direct searches for LFV Higgs boson decays.

A direct search for lepton-flavour-violating decays of a Higgs boson to a μ-τ pair ($H \to \mu\tau$), was performed by CMS. The search was done in two channels, $H \to \mu\tau_e$ and $H \to \mu\tau_h$, where τ_e and τ_h are tau leptons reconstructed in the electronic and hadronic decay channels, respectively [7].

The signal variable studied was the collinear mass, M_{col}, in the $100 < M_{col} < 150$ GeV region. The signal strength was set according to the SM H production cross section at $M_H = 125$ GeV with B($H \rightarrow \mu\tau$) = 10%. A slight excess of events with a significance of 2.4 σ was observed. The best fit branching fraction is B($H \rightarrow \mu\tau$) = (0.84 $^{+0.39}_{-0.37}$)%. A constraint of B($H \rightarrow \mu\tau$) < 1.51% at the 95% CL was set. The limit was used to constrain the Yukawa couplings, $|Y_{\mu\tau}| + |Y_{\tau\mu}| < 3.6 \times 10^{-3}$ and it is shown in Fig. 2 (a). It improves the previous bound by an order of magnitude.
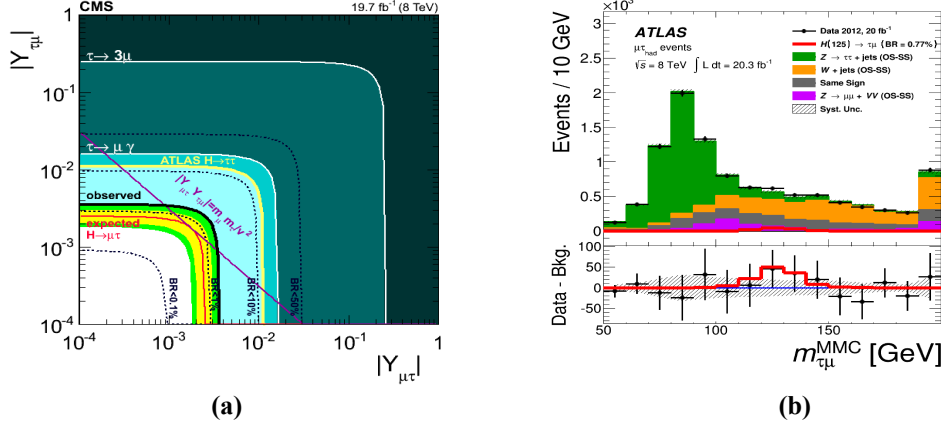

(a)	**(b)**

Figure 2: (a) Constraints on the flavour-violating Yukawa couplings, $|Y_{\mu\tau}|$ and $|Y_{\tau\mu}|$ [7]. The black dashed lines are contours of B($H \rightarrow \mu\tau$) for reference. The expected limit (red solid line) with one sigma (yellow) and two sigma (green) bands, and observed limit (black solid line) are derived from the limit on B($H \rightarrow \mu\tau$) from the present analysis. The shaded regions are derived constraints from null searches for $\tau \rightarrow 3\mu$ (dark green) and $\tau \rightarrow \mu\gamma$ (lighter green). The yellow line is the limit from a theoretical reinterpretation of an ATLAS $H \rightarrow \tau\tau$ search [19]. The light blue region indicates the additional parameter space excluded by ATLAS result. The purple diagonal line is the theoretical naturalness limit $Y_{ij}Y_{ji} \leq m_i m_j / v^2$. (b) Post–fit combined $m_{\mu\tau}^{MMC}$ distribution obtained by adding individual distributions in SR1 and SR2 [8]. The grey band in the bottom panel plot illustrates the post–fit systematic uncertainties on the background prediction. The signal is shown assuming Br($H \rightarrow \mu\tau$) = 0.77%, the central value of the best fit to Br($H \rightarrow \mu\tau$). The last bin of the distribution contains overflow events.

A direct search for LFV $H \rightarrow \mu\tau$ decays was also performed with the ATLAS detector [8]. The analysis was performed in the $H \rightarrow \mu\tau_{had}$ channel, where τ_{had} is a hadronically decaying τ–lepton. The presence of signal was inferred from an excess of data over the predicted background using the mass, $m_{\mu\tau}^{MMC}$ (MMC [20]). The post–fit $m_{\mu\tau}^{MMC}$ distributions in the combined distribution for signal regions (SR1 and SR2) is shown in Fig. 2 (b). A small excess of the data over the predicted background was found in the 120 GeV< $m_{\mu\tau}^{MMC}$ <140 GeV region in SR2, having a local significance of 2.2 standard deviations and a combined significance for both signal regions of 1.3 standard deviations. This corresponds to a best fit value for the branching fraction of Br($H \rightarrow \mu\tau$)=(0.77 ± 0.62)%. Due to the low significance of the observed excess of events, an upper limit on the LFV branching ratio Br($H \rightarrow \mu\tau$) for a Higgs boson with $m_H = 125$ GeV was set. The observed and the median expected upper limits at

the 95% CL were found to be 1.85% and (1.24 $^{+0.50}_{-0.35}$)%, respectively. This search places significantly more stringent constraints on Br($H \rightarrow \mu\tau$) compared to earlier indirect estimates. The result of this analysis was found to be consistent with the one published by the one performed by the CMS Collaboration and described above.

4. Search for Flavour-Changing-Neutral-Current decays

The decay of a top quark to a Higgs boson plus an up-type (*c,u*) quark would proceed via a flavour-changing neutral current (FCNC). According to the SM, FCNC processes are forbidden at tree level and very much suppressed at higher orders due to the Glashow-Iliopoulos-Maiani mechanism [21]. Observations of FCNC decays of the top quark would therefore provide a clear signal of new physics.

The FCNC $t \rightarrow qH$ decay, followed by $H \rightarrow \gamma\gamma$, has been searched for in a data set of proton-proton collisions recorded by the ATLAS experiment, consisting of 4.7fb^{-1} at $\sqrt{s}$ =7 TeV and 20.3 fb^{-1} at $\sqrt{s}$=8 TeV [9].

The remaining top quark in the event was searched for in two final states: a bottom quark and either a hadronically decaying W boson or a leptonically decaying W boson. In the hadronic selection, which combined the 7 and 8 TeV data, the diphoton mass distribution $m_{\gamma\gamma}$ was used as discriminating variable in the fit. The analysis in the leptonic selection was based on event counting.

The fitted branching ratio was found to be B = (0.22 $^{+0.31}_{-0.26}$)%. As no significant signal was found, limits on the $t \rightarrow cH$ and $t \rightarrow uH$, branching ratios were derived. The evolution of the signal confidence level CLs as a function of the branching fraction B for $t \rightarrow qH$ is shown in Fig. 3. The observed (expected) limit on B is 0.79 (0.51)% at the 95% CL.
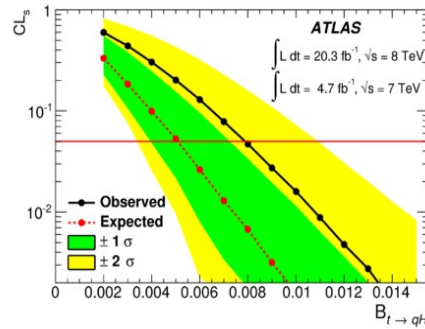

Figure 3: Evolution of CLs as a function of the branching fraction B of the $t \rightarrow qH$ decay for the observation of a signal at 125.5 GeV (solid line) and the expectation in the absence of signal (dashed line) [9]. The 1 and 2 σ uncertainty bands around the expected curve are also shown.

An upper limit on the λ_{tcH} coupling of 0.17 was obtained, with an expected value of 0.14. As the analysis was equally sensitive to the $t \rightarrow uH$ and $t \rightarrow cH$ modes, the limit obtained on the couplings can be written as $\sqrt{(\lambda^2_{tcH} + \lambda^2_{tuH})} < 0.17$ with an expectation of 0.14.

A similar search for top quark decays via a flavor-changing neutral current was performed in CMS [10]. No significant excess of events was observed in the number of diphoton events in the hadronic and leptonic channels. An upper limit was set on the branching fraction for the

signal production. Fig. 4 (a) shows the signal strength (r) at the 95% CL as a function of the branching fraction B for $t \rightarrow cH$ by combining the hadronic and leptonic channels. An observed (expected) limit on the branching fraction B for $t \rightarrow cH$ was found 0.47% (0.71%) at the 95% CL. Similar results were presented for $t \rightarrow uH$ samples. Fig. 4 (b) shows the result by combining the hadronic and leptonic channels. An observed (expected) limit on the branching fraction B for $t \rightarrow uH$ was found to be 0.42% (0.65%) at 95% CL.
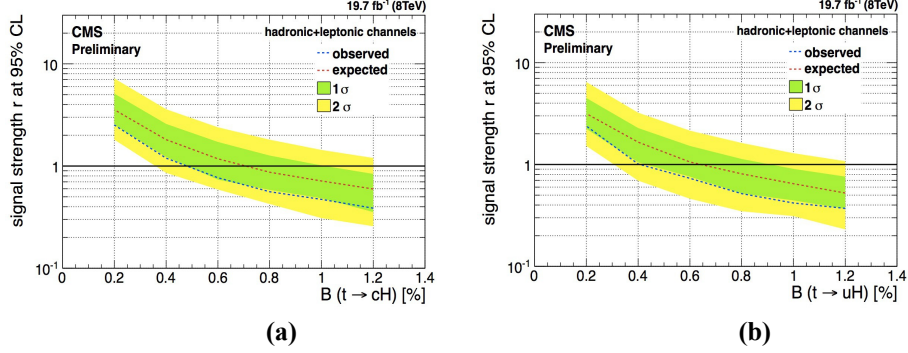

(a)   **(b)**

Figure 4: (a) Signal strength at the 95% CL as a function of the branching fraction B for $t \rightarrow cH$ of the combined hadronic and leptonic channels [10]. (b) Signal strength at the 95% CL as a function of the branching fraction B for $t \rightarrow uH$ of the hadronic and leptonic channels combined [10].

Based on the CMS inclusive multilepton analysis and a CMS 2HDM search involving lepton and photon final states, a limit at the 95% CL on the branching ratio of the flavor-changing decay $t \rightarrow cH$ was published [11]. Given the good agreement between data and background, an upper limit was placed of 0.56% on $B(t \rightarrow cH)$, consistent with the expected limit of $(0.65 ^{+0.29} _{-0.19})$%. The observed limit corresponds to a bound on the left- and right-handed top-charm flavor violating Higgs Yukawa couplings of $\sqrt{(|\lambda^h_{tc}|^2 + |\lambda^h_{ct}|^2)} < 0.14$.

5. Higgs boson decays to light pseudo-scalar neutral Higgs boson in NMSSM

A search for the pair production of new light bosons (denoted as "a_1" or "a"), each decaying into a pair of isolated muons, was performed with the CMS experiment at the LHC [12].

A range of new physics scenarios predict this decay topology, including the next-to-minimal supersymmetric standard model (NMSSM) [22] and models with hidden (or dark) sectors [23–25]. The a_1 boson can have a substantial branching fraction $B(a_1 \rightarrow \mu^+\mu^-)$ if its mass is within $2m_\mu < m_{a1} < 2m_\tau$ [26-27]. A search for final states containing muon pairs provides sensitivity to models of this form.

One event was observed in the signal region, with 2.2 ± 0.7 events expected from the SM backgrounds. The 95% CL upper limits from this search for the NMSSM scenarios are shown in Fig. 5.
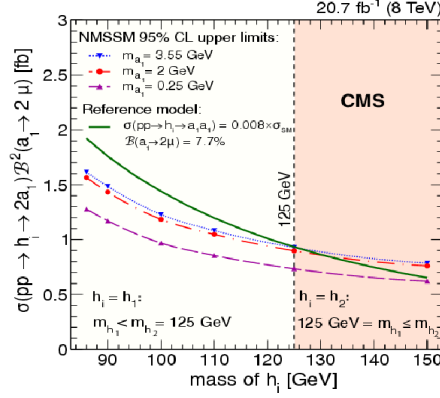
Figure 5: 95% CL upper limits from the search for the NMSSM scenarios with m_{a1} = 0.25 GeV (dashed curve), m_{a1} = 2 GeV (dash-dotted curve) and m_{a1} = 3.55 GeV (dotted curve) on $\sigma(pp \to h_{1/2} \to 2a_1)$ B^2($a_1 \to 2\mu$) as a function of m_{h1} in the range $86 < m_{h1} < 125$ GeV and of m_{h2} for $m_{h2} > 125$ GeV [12]. As an illustration, the limits are compared to the predicted rate (solid curve) obtained using a simplified scenario with $\sigma(pp \to h_i \to 2a_1)$ = 0.008 σ_{SM}, which yields predictions for the rates of dimuon pair events comparable to the obtained experimental limits, and B($a_1 \to 2\mu$) = 7.7%. The chosen B($a_1 \to 2\mu$) is taken from [27] for m_{a1} = 2 GeV and $\tan\beta$ = 20.

A search for the decay of a scalar Higgs boson to two pseudo-scalar "a" Higgs bosons ($H \to$ aa) in the $\mu\mu\tau\tau$ final state, in the context of the NMSSM was performed by the ATLAS experiment [13].

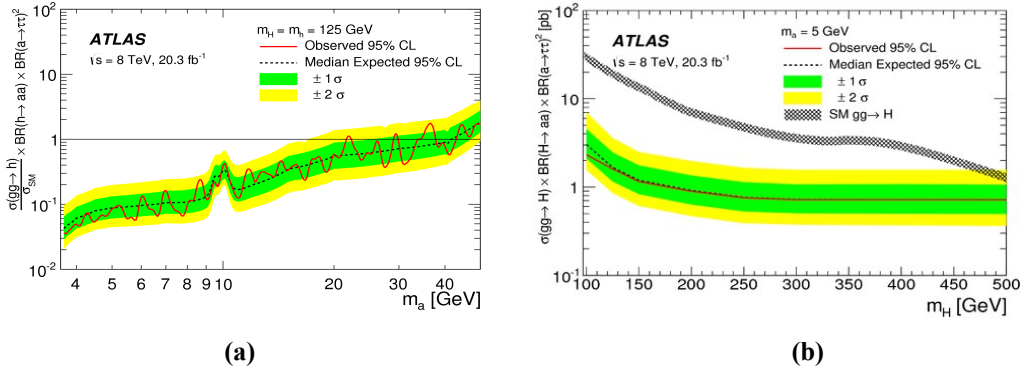**(a)**   **(b)**

Figure 6: Observed (solid red) and expected (dashed black) limits with the expected ±1 and ±2 bands shown in green and yellow respectively. (a) Expected and observed limits on the rate (σ(gg $\to h$) x BR($h \to$ aa)) relative to the SM Higgs boson gluon-gluon fusion production cross section (SM) as a function of m_a with m_H set to 125 GeV [13]. (b) The total rate (σ(gg $\to H$) x BR($H \to$ aa)) as a function of m$_H$ with m$_a$ set to 5 GeV, evaluated at 50 GeV intervals from m_H = 100 GeV to 500 GeV [13]. The width of the black band indicates the theoretical uncertainty in the SM $gg \to H$ cross-section [28]. In both figures, the observed and expected limits have been scaled by an $O(1)$ parameter, BR(a $\to \tau\tau$)^2, to account for the branching ratios assumed in this analysis and facilitate reinterpretation of the results.

For the purposes of this analysis, the assumption of no coupling of the "a" boson to quarks was made. A scan of the dimuon invariant mass distribution from 3.7 GeV to 50 GeV showed

no significant excess of data over SM backgrounds. With no evidence to support the NMSSM hypothesis, a 95% CL limit was set. The Fig. 6 (a) shows the observed and expected limits on the rate $(\sigma(gg \to h) \times BR(h \to aa))$ relative to the SM Higgs boson gluon-gluon fusion production cross section (SM), as a function of m_a from 3.7 GeV to 50 GeV with m_H set to 125 GeV, with the most stringent limit placed at 3.5% for m_a= 3.75 GeV. Also in Fig. 6 (b) the total rate $(\sigma(gg \to H) \times BR(H \to aa))$ is given as a function of m_H with m_a set to 5 GeV, m_H from 100 GeV to 500 GeV and at $m_H = m_h = 125$ GeV. The observed 95% CL upper limits on the production rate were consistent with the expected limit and were determined to be from 2.33 pb to 0.72 pb.

   *S*earches for new phenomena in events with at least three photons in the ATLAS detector were studied [14]. A model-independent search was performed for a Higgs boson decaying to four photons via two intermediate pseudoscalar "a" particles (for both the SM Higgs boson of $m_h = 125$ GeV and for Higgs-like scalars of higher masses).

   For the $H/h \to aa \to 4\gamma$ BSM signal scenario, the resonance search in the diphoton mass spectrum detected no significant excess of events above background. Upper limits (assuming kinematics associated only with gluon-gluon fusion Higgs boson production), were determined to be $\sigma/\sigma_{SM} \times BR(h\to aa) \times BR(a\to\gamma\gamma)^2 < 1\times10^{-3}$, for 10 GeV $< m_a <$ 62 GeV. Additionally, limits were set for Higgs boson-like scalars with masses larger than 125 GeV. The results of these resonance searches are shown in Fig. 7 for the SM Higgs boson (a) and, as an example of a higher scalar mass, for $m_H = 600$ GeV (b). Limits were found to be $\sigma_H \times BR(H\to aa) \times BR(a\to\gamma\gamma)^2 < 0.02$ pb for 10 GeV $< m_a <$ 90 GeV and < 0.001 pb for higher m_a (up to 245 GeV for the resonance search for $m_H = 600$ GeV shown in Fig. 7 (b).

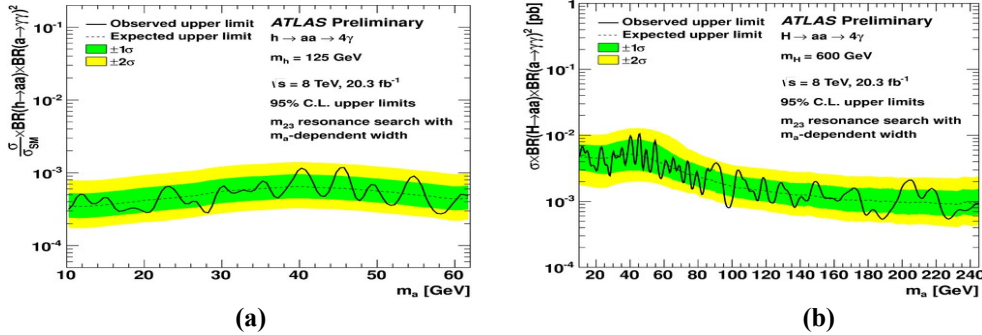| (a) | (b) |

Figure 7: Upper lmits at the 95% CL, on (a) $\sigma/\sigma_{SM} \times BR(h\to aa) \times BR(a\to\gamma\gamma)^2$ [14] and

(b) $\sigma_H \times BR(H\to aa) \times BR(a\to\gamma\gamma)^2$ [14]. Also shown are the $\pm1\sigma$ and 2σ uncertainty bands resulting from the resonance search hypothesis tests, taking into account the statistical and systematic uncertainties from simulated signal samples which are used to determine signal efficiency and Gaussian resonance width due to detector resolution for each mass hypothesis.

6. Searches for exotic Higgs boson decays into undetectable particles and photons

A search was performed in ATLAS for exotic Higgs boson decays to neutralinos and/or gravitinos in events with at least one photon, missing transverse momentum and two forward jets, a topology where vector boson fusion production was enhanced [15].

A cut-and-count experiment was performed and the total number of expected background and signal events in the control and signal regions were used to set limits on (σ/σ_{SM}) x BF($h \rightarrow$ NLSP + LSP). After all selections, the number of events observed agree with the expected SM backgrounds within uncertainties. The limits obtained were similar to or stronger than indirect limits from the Higgs boson coupling measurements, and were the first direct limits on these Higgs boson decays. The best-fit value of the signal yield corresponds to a BF of (11.6 ± 10.9)%. The significance of the excess of observed data over the expected SM backgrounds was 1.1.

Fig. 8 shows the expected and observed limits on the (σ/σ_{SM}) x BF($h \rightarrow$ NLSP + LSP) at the 95% CL for the monophoton (a) and and diphoton (b) signal samples, obtained using the *CLs* method [29] with an Asimov approximation.

(a)   **(b)**
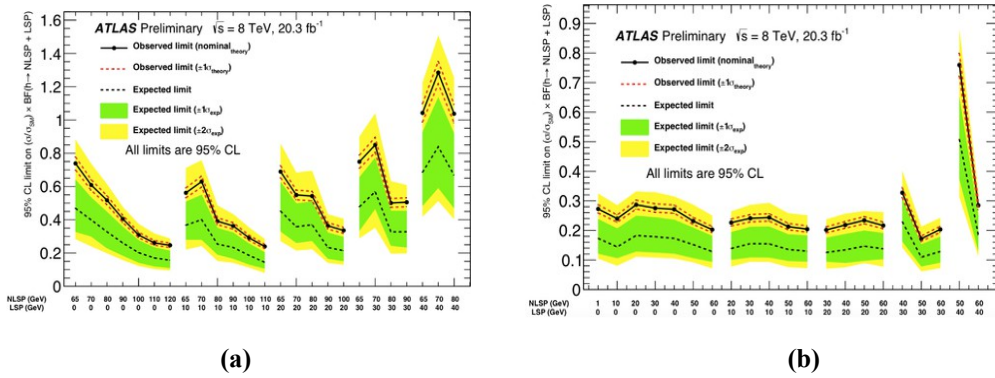
Figure 8: Observed and expected limits for various NLSP and LSP masses for (a) monophoton signals [15] and (b) diphoton signals [15]. The green and yellow bands show the ±1 and ±2 excursions of the expected limits respectively.

A similar search was also performed in CMS for exotic decays of a Higgs boson into undetectable particles and one or two isolated photons [16].

Higgs bosons produced in gluon-gluon fusion and in association with a Z boson were investigated, using models in which the Higgs boson decays into a gravitino and a neutralino or a pair of neutralinos, followed by the decay of the neutralino to a gravitino and a photon. The selected events were consistent with the background-only hypothesis, and limits were placed on the product of cross sections and branching fractions.

The 95% CL upper limits on $(\sigma B)/\sigma_{SM}$, where σ_{SM} is the production cross section for the SM Higgs boson, were evaluated for different neutralino (χ_1^0) mass values ranging from 1 GeV to 120 GeV for the individual searches and their combination and are shown in Fig. 9. An upper limit in the range of 7 to 13% was obtained. A 95% CL upper limit on the branching fraction of 10% is set for a neutralino mass of 95 GeV.
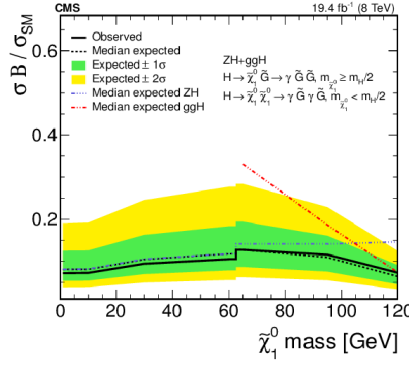
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Figure 9: Expected and observed 95% CL upper limits on σ/σ_{SM} for m_H= 125 GeV as a function of $m\tilde{\chi}_1^0$ assuming the SM Higgs boson cross sections, for the *ZH* and *ggH* channels and their combination, with $B \equiv B(H\rightarrow\tilde{\chi}_1^0\tilde{\chi}_1^0) \, B(\tilde{\chi}_1^0\rightarrow\tilde{G}+\gamma)^2$ for $m\tilde{\chi}_1^0 < m_H/2$ and $B \equiv B(H\rightarrow\tilde{\chi}_1^0\tilde{G}) \, B(\tilde{\chi}_1^0\rightarrow\tilde{G}+\gamma)$ for $m\tilde{\chi}_1^0 \geq m_H/2$ [16].

Expected and observed limits are also shown for the decay of possible heavier scalar Higgs bosons as a function of the Higgs boson mass in Fig. 10.
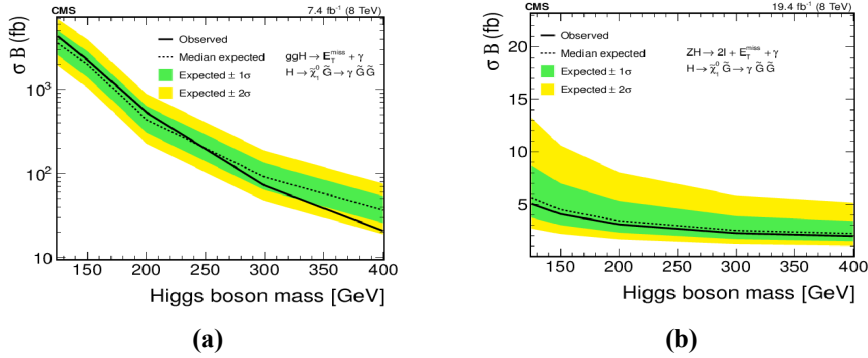

(a)   (b)

Figure 10: Expected and observed 95% CL upper limits on $\sigma_{gg\rightarrow H}$ as a function of the Higgs boson mass with $m\tilde{\chi}_1^0 = m_H - 30$ GeV in the (a) *ggH* channel [16] and (b) *ZH* channel [16].

7. Conclusions

Searches for exotic Higgs bosons decays performed in various channels and with different strategies in the ATLAS and CMS experiments at the LHC were presented. No evidence of BSM physics has been found so far. The observation of the SM-like Higgs boson has already excluded large regions of the parameter phase space. However, there is still space left for BSM models to be compatible with the observed Higgs boson. Many exotic Higgs boson analyses with Run-I data from pp collisions at √s=8 TeV are still ongoing and are going to be published soon. The Run-II data from *pp* collisions at √s=13 TeV will enhance the discovery potential of exotic Higgs boson decay searches and new challenges for the corresponding analyses have to be faced.

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