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Searches for Beyond SM Higgs Bosons

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The measured Higgs boson, with a mass near 125 GeV, has properties consistent with the Standard Model. Besides the Standard Model interpretation, various possibilities for extended Higgs sectors are being considered. Such options include the minimal and next-to-minimal supersymmetric extensions of the Standard Model. More generic two-Higgs doublet models, as well as truly exotic Higgs bosons decaying e.g. into totally invisible final states are also considered. Recent results on searches for beyond Standard Model production of Higgs bosons at the LHC by the ATLAS and CMS collaborations are presented.

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1. Introduction

The discovery of a Higgs boson with a mass of around 125 GeV by the ATLAS and CMS experiments [1, 2] opens the question of whether it is the Standard Model (SM) Higgs boson or one of typically many Higgs bosons predicted by extensions of the SM.

There are several theoretical models with an extended Higgs sector. Among the most popular and generic ones are the so-called two-Higgs doublet models (2HDM) [3]. Having two complex scalar SU(2) doublets, they are an effective extension of the SM. In total, five different Higgs bosons are predicted: two CP even and one CP odd electrically neutral Higgs bosons, denoted by h, H, and A, respectively, and two charged Higgs bosons, $H^{\pm}$. The parameters used to describe a 2HDM are the Higgs boson masses, m_i, the mixing angle of the two Higgs doublets, α, and the ratios of their vacuum expectation values, $\tan\beta$. There are several classes of 2HDMs, the most relevant ones for this review are the so-called type I, where one SU(2) doublet gives masses to all leptons and quarks and the other doublet essentially decouples from fermions, and the so-called type II, where one doublet gives mass to up-like quarks and the down-type quarks and leptons receive mass from the other doublet. Another theoretical model is supersymmetry (SUSY), which brings along super-partners of the SM particles. The minimal supersymmetric extension of the SM (MSSM), whose Higgs sector is equivalent to the one of a constrained 2HDM of type II and the next-to MSSM (NMSSM) are among the best tested models.

2. Heavy Higgs bosons

The observation of a Higgs boson with a mass of 125 GeV is also consistent with the unitarity constraints on diboson scattering at high energies. Nevertheless, there is a possibility that the newly discovered particle is part of a larger Higgs boson sector and thus only partially responsible for EW symmetry breaking. This can be realized in several scenarios, such as 2HDM, or models in which the SM Higgs boson mixes with a heavy EW singlet, which predict the existence of additional resonances at high mass, with couplings similar to those of the SM Higgs boson.

The ATLAS Collaboration has searched for a heavy neutral scalar H decaying into two SM Z bosons [4], encompassing the decay modes $ZZ \to llll$, $ZZ \to ll\nu\nu$, $ZZ \to llqq$, $ZZ \to \nu\nu qq$. Throughout the text, the symbol l refers to an electron or a muon. It is assumed that additional Higgs bosons would be produced predominantly via the gluon fusion (ggF) and vector-boson fusion (VBF) processes but that the ratio of the two production mechanisms is unknown in the absence of a specific model. For this reason, results are interpreted separately for ggF and VBF production modes. Limits on the cross-section times branching ratio from the combination of all of the searches are shown in Fig. 1 (left).

Also results of a search for a heavy neutral scalar decaying into two W bosons [5] are reported by the ATLAS Collaboration. Two final states are used: $H \to WW \to l\nu l\nu$ and $H \to WW \to l\nu qq$. The search uses proton-proton collision data at 8 TeV corresponding to an integrated luminosity of 20.3 fb^{-1}. No excess of events beyond the SM background prediction is found. Upper limits are set on the product of the production cross section and the $H \to WW$ branching ratio in three different scenarios: a high-mass Higgs boson with a complex-pole scheme (CPS) line-shape and the width predicted for a SM Higgs boson, one with narrow width (shown in Fig. 1 (right)), and one with an intermediate width.

The CMS analysis [6] uses proton-proton collision data recorded with the CMS detector, corresponding to integrated luminosities of up to 5.1 fb^{-1} at $\sqrt{s}$ = 7 TeV and up to 19.7 fb^{-1} at $\sqrt{s}$ = 8 TeV. The analysis is performed in a mass range 145 < m$_H$ < 1000 GeV exploiting both the $H \to WW$ and $H \to ZZ$ decay channels, with the lower boundary being chosen to reduce contamination from h(125) in the WW channels. In the case of a Higgs boson decaying into a pair of W bosons, the fully leptonic ($H \to WW \to l\nu l\nu$) and semileptonic ($H \to WW \to l\nu qq$) final states are considered in the analysis. For a Higgs boson decaying into two Z bosons, final states containing four charged leptons ($H \to ZZ \to 2l2l'$), two charged leptons and two quarks ($H \to ZZ \to 2l2q$), and two charged leptons and two neutrinos ($H \to ZZ \to 2l2\nu$) are considered, where $l' = e, \mu$ or τ.

The combined results obtained for a heavy Higgs boson with SM-like couplings for all the different contributing final states are displayed in Fig. 2. On the left, the observed 95% CL limit is shown for each final state. The expected combined 95% CL limit of the six channels is plotted as a dashed black line, while the yellow shaded region is the $\pm 2\sigma$ uncertainty in the expected limit. On the right, the expected and observed limits are displayed for each of the individual channels as well as the combined result. The top right panel shows the WW final states, while the ZZ final states are displayed in the bottom right panel.

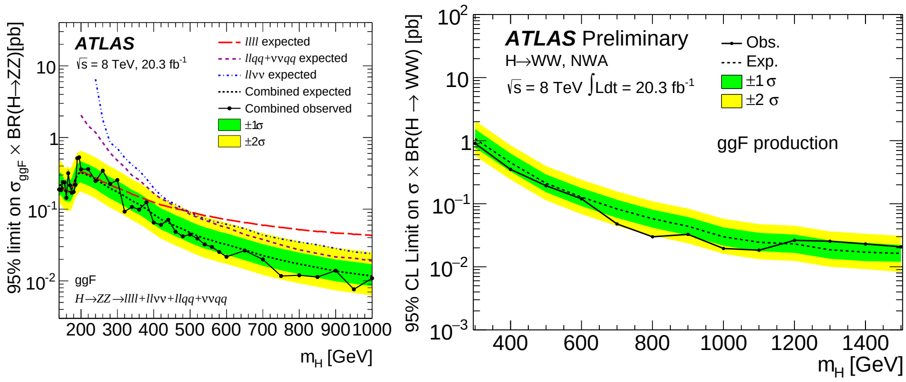

Figure 1: Left: ATLAS 95% CL upper limits on $\sigma\times$ BR($H \to ZZ$) as a function of m$_H$, resulting from the combination of all of the searches in the ggF channel. Right: ATLAS CL upper limits on $\sigma\times$ BR($H \to WW$) for a signal with a narrow width from the combination of the $H \to WW \to l\nu l\nu$ and $H \to WW \to l\nu qq$ final states. The solid black line and points indicate the observed limit. The dashed black line indicates the expected limit and the bands the 1-σ and 2-σ uncertainty ranges around the expected limit.

3. LFV decays

This section describes a search for a lepton flavour violation (LFV) decay of a Higgs boson with m_H = 125 GeV at the CMS experiment [7]. The 2012 dataset collected at a centre-of-mass energy of $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb^{-1} is used. The search is performed 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. The μ comes promptly from the LFV H decay and tends to have a larger momentum than in case of $H \to \tau\tau$ decays. In addition, since the

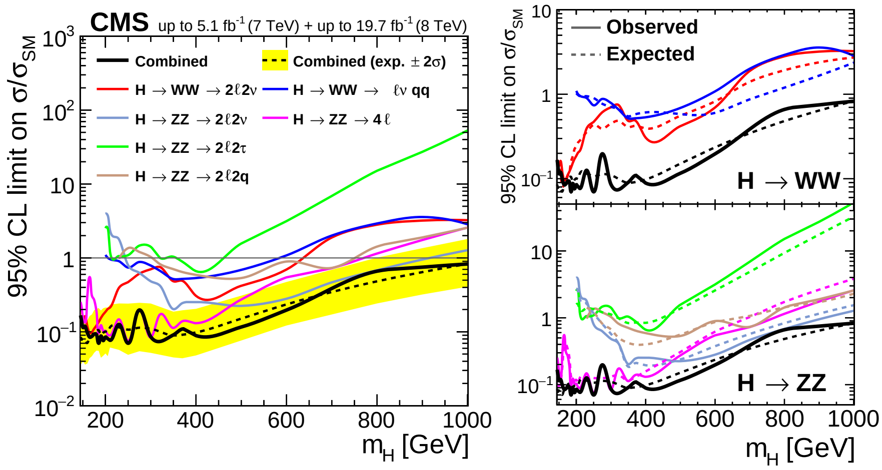

Figure 2: CMS upper limits at the 95% CL for each of the contributing final states and their combination. The observed and expected limits of the six individual channels are compared with each other and with the combined results (left), for $H \to WW$ channels (top right panel) and $H \to ZZ$ channels (bottom right panel) separately.

neutrinos in the decay arise from one τ which is highly Lorentz boosted, they tend to be collinear with the visible τ decay products.

The two channels are divided into categories based on the number of jets in order to separate the different H production mechanisms. The dominant production mechanism is gluon-gluon fusion but there is also a significant contribution from vector boson fusion which is enhanced by requiring jets to be present in the event. The dominant background in the $H \to \mu\tau_e$ channel is $Z \to \tau\tau$. Other smaller backgrounds come from misidentified leptons in W+jets, QCD multijets and $t\bar{t}$ events. In the $H \to \mu\tau_h$ channel the dominant background arises from misidentified τ leptons in W+jets, QCD multijets and $t\bar{t}$ events. Less significant backgrounds come from $Z \to \tau\tau$ and Z+jets. The principal backgrounds are estimated using data. There is also a small background from SM H decays which is estimated with simulation. The presence or absence of a signal is established by fitting a mass distribution for signal and background. The observed and expected collinear mass distribution, M_{col}, which provides an estimator of the reconstructed H mass using the observed decay products, is shown in Fig. 3 (left) combined for all channels and categories. Exclusion limits are derived using the asymptotic CLs criterion.

A slight excess of events with a significance of 2.4 σ is observed, corresponding to a p-value of 0.010. The best fit branching ratio is $BR(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint of $B(H \to \mu\tau) <$ 1.51% at 95% confidence level (CL) is set. The limit is used to constrain the Yukawa couplings $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$. Fig. 3 (right) compares this result to the constraints from previous indirect measurements.

Recent results in the $H \to \mu\tau_h$ channel [8] from the ATLAS collaboration set a constraint of $BR(H \to \mu\tau) < 1.85\%$ at 95% CL.

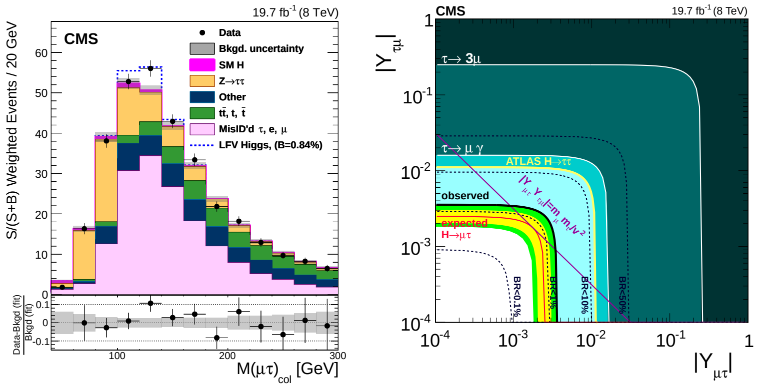

Figure 3: Left: CMS distribution of M_{col} for all categories combined, with each category weighted by significance (S/(S + B)), where the signal (S) and the background (B) are computed as the integral of the bins in the range $100 < M_{col} < 150$ GeV using BR($H \to \mu\tau$) = 0.84%. The MC Higgs signal shown is for BR($H \to \mu\tau$) = 0.84%. The bottom panel shows the fractional difference between the observed data and the fitted background. Right: CMS constraints on the flavour-violating Yukawa couplings, $|Y_{\mu\tau}|$ and $|Y_{\tau\mu}|$. The black dashed lines are contours of BR($H \to \mu\tau$) 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 BR($H \to \mu\tau$) from the presented analysis. The shaded regions are derived constraints from null searches for $\tau \to 3\mu$ (dark green) and $\tau \to \mu\gamma$ (lighter green). The yellow line is the limit from a theoretical reinterpretation of an ATLAS $H \to \tau\tau$ search [9]. The light blue region indicates the additional parameter space excluded by the CMS result. The purple diagonal line is the theoretical naturalness limit $Y_{ij}Y_{ji} \leq m_i m_j / v_2$.

4. Invisible and quasi-invisible Higgs boson decays

Astrophysical observations provide strong evidence for dark matter that could be explained by the existence of weakly interacting massive particles. The recently observed Higgs boson at 125 GeV might decay to a component of the dark matter (DM) or long-lived unstable particles which do not interact with the detector, provided this decay is kinematically allowed. This is referred to as an invisible decay of the Higgs boson. The search for invisible decays of Higgs bosons has been extensively studied at the LHC with the full 7 and 8 TeV datasets, by both the ATLAS and CMS collaborations.

CMS has performed a search for VBF-produced Higgs bosons decaying to invisible final states [10]. The 95% C.L. limit on the cross section times $BR(H \to inv.)$ as a function of the Higgs boson mass, assuming SM Higgs boson production cross sections and acceptances, is shown in Fig. 4 (right). The observed (median expected) limit on $BR(H \to inv.)$ of a SM Higgs boson with $m_H = 125$ GeV is 57 (40)%. When combined with searches at CMS in the channel where the Higgs boson is produced in association with a Z the observed (median expected) limit on $BR(H \to inv.)$ of a SM Higgs boson with $m_H = 125$ GeV is 47(35)%.

In ATLAS, Higgs boson decays to particles that are invisible to the detector are searched for in the final states of two or three jets and large missing transverse momentum [11] in a pp collision dataset corresponding to an integrated luminosity of 20.3 fb^{-1} at a centre-of-mass energy of 8 TeV. No excess of events over the expected backgrounds is observed. The results are used to constrain the cross section for Higgs boson production in association with vectors bosons (VH), followed by the decay $H \to inv.$ for $115 < m_H < 300$ GeV. The observed 95% CL upper limit on $\sigma_{VH} \times BR(H \to inv.)$ varies from 1.6 pb at 115 GeV to 0.13 pb at 300 GeV, as shown in Fig. 4 (left). Assuming SM production and including the $gg \to H$ contribution, an observed (expected) upper limit of 78% (86%) on $BR(H \to inv.)$ is derived for the discovered Higgs boson with m_H = 125 GeV.

In the search for VBF-produced Higgs bosons decaying to invisible at ATLAS [12], no excess is observed in the data with respect to the expected background processes, and the resulting limit on the number of signal events is used to set an upper limit on the $H \to inv.$ branching ratio assuming the SM Higgs boson production cross section. The resulting expected upper limit on $BR(H \to inv.)$ is 35% at 95% CL with a $\pm 1\sigma$ range on the expectation of 25% to 49%. The observed yield of 539 events in the signal region data gives a 95% CL observed upper bound of 29% on $BR(H \to inv.)$.

Several BSM models predict Higgs boson decays to undetectable particles and photons. In certain low-scale SUSY models, the Higgs bosons are allowed to decay into a gravitino ($\tilde{G}$) and a neutralino ($\tilde{\chi}_1$) or a pair of $\tilde{\chi}_1$. The neutralino then decays into a photon and a $\tilde{G}$, the lightest supersymmetric particle (LSP) and dark matter candidate.

The CMS collaboration performed a search for exotic decays of a Higgs boson into undetectable particles and one or two isolated photons [13] in pp collisions at a center-of-mass energy of 8 TeV. The data correspond to an integrated luminosity of up to 19.4 fb^{-1} collected with the CMS detector at the LHC. Higgs bosons produced in gluon-gluon fusion or in association with a Z boson are investigated. Models including Higgs boson decays into a $\tilde{G}$ and a $\tilde{\chi}_1$ or a pair of $\tilde{\chi}_1$, followed by the $\tilde{\chi}_1$ decay to a $\tilde{G}$ and a photon, are tested. The measurements for the selected events in data are consistent with the background only hypothesis, and the results are interpreted as limits on the product of cross sections and branching ratios. Assuming a SM Higgs boson production cross-section, a 95% CL upper limit is set on the branching ratio of a 125 GeV Higgs boson decaying into undetectable particles and one or two isolated photons as a function of the neutralino mass. For neutralino masses from 1 to 120 GeV an upper limit in the range of 7 to 13% is obtained. In addition, Fig. 5 (left) shows the observed and expected model-independent 95% CL upper limits for the ggF analysis on the product of cross section, acceptance, and efficiency for $m_T^{llE_T^{miss}} > 100$ GeV, as function of the missing transverse energy (E_T^{miss}) threshold.

The ATLAS collaboration performed a search for Higgs boson decays to neutralinos and gravitinos, using VBF Higgs boson production and a final-state signature of at least one photon, E_T^{miss}, and two VBF jets [14]. The full 2012 8 TeV pp collision dataset from the ATLAS detector at the LHC was studied, corresponding to an integrated luminosity of 20.3 fb^{-1}. The search was optimised for $H \to \tilde{\chi}^0 \tilde{G} \to \gamma \tilde{G} \tilde{G}$ signal leading to a $\gamma + E_T^{miss} + jj$ final state, and also applied to models with $H \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to \gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0$ leading to a $\gamma + E_T^{miss} + jj$ final state, and $H \to \tilde{\chi}_2^0 \tilde{\chi}_2^0 \to \gamma\gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0$ leading to a $\gamma\gamma + E_T^{miss} + jj$ final state. After all selections, the number of events observed agree with the SM backgrounds within uncertainties. The limits obtained are similar to or stronger than indirect limits from the Higgs boson coupling measurements, and are the first direct limits on these Higgs boson decays. Fig. 5 (right) shows the observed limits for different NLSP and LSP masses for the production of NLSP + LSP $\to \gamma$ + LSP + LSP.

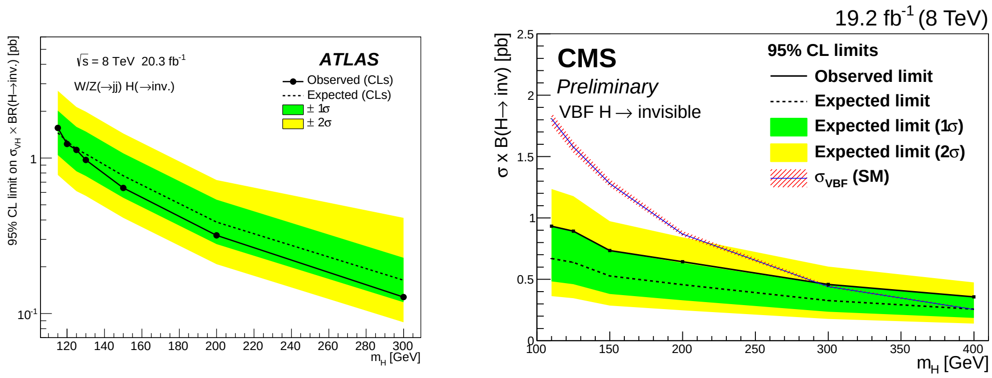

Figure 4: Left: ATLAS upper limits on $\sigma_{VH} \times BR(H \to inv.)$ at 95% CL for a Higgs boson with $115 < m_H < 300$ GeV. The full and dashed lines show the observed and expected limits, respectively. Right: CMS 95% C.L. limit on the cross section times $BR(H \to inv.)$ as a function of the Higgs boson mass, assuming SM Higgs boson production cross sections and acceptances.

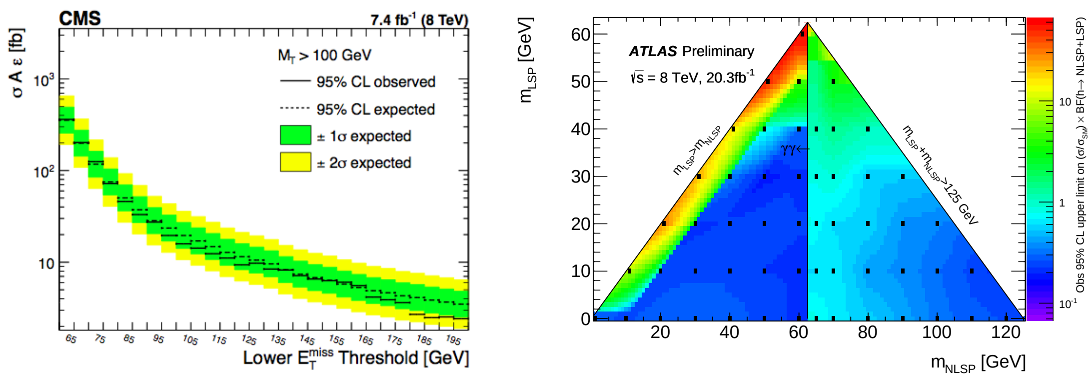

Figure 5: Left: CMS expected and observed 95% CL upper limit on the product of cross section, acceptance, and efficiency ($\sigma(pp \to \gamma + E_T^{miss})A\varepsilon$) for $m_T^{llE_T^{miss}} > 100$ GeV, as function of the E_T^{miss} threshold for the ggF channel. Right: ATLAS observed 95% CL limits on σ/σ_{SM} times $BR(H \to \mathrm{NLSP} + \mathrm{LSP})$ for various NLSP and LSP masses. The black squares indicate the generated signal points that are used for interpolation.

5. 2HDM, MSSM, and NMSSM Higgs bosons

A charged Higgs boson, $H^\pm$, appears in many models with an extended scalar sector such as the 2HDM, where a second Higgs boson doublet is introduced, and the Higgs Triplet Models, where a triplet is added to the Higgs doublet of the SM. While $H^\pm \to \tau^\pm\nu, cs, tb$ decays dominate in the 2HDM at tree level, $H^\pm \to W^\pm Z$ decays are allowed at loop level and are predicted at tree level in Higgs Triplet Models.

ATLAS has performed a search for the $H^\pm$ boson assuming that it couples to $W^\pm$ and Z bosons. In this case it is produced via vector-boson fusion, $W^\pm Z \to H^\pm$, at the LHC and decays to $W^\pm Z$. The search [15] is performed in the channel with subsequent decays of $W^\pm \to q\bar{q}$ and $Z \to l^+l^-$, over the $H^\pm$ mass range $200 < m_{H^\pm} < 1000$ GeV. The data are compared with the SM expectation in Fig. 6 (left). No significant excess of events is observed in the data compared with the SM expectation. Fig. 6 (right) shows the exclusion limits at the 95% CL on the VBF production cross section times the branching ratio $BR(H^{\pm} \to W^{\pm}Z)$ as a function of $m_{H^{\pm}}$, assuming that the signal has a small intrinsic width, i.e. much smaller than the experimental resolution. The observed limits range from 31 fb at $m_{H^{\pm}} = 650$ GeV to 1020 fb at $m_{H^{\pm}} = 220$ GeV; the corresponding expected limits are 55 fb and 719 fb, respectively.

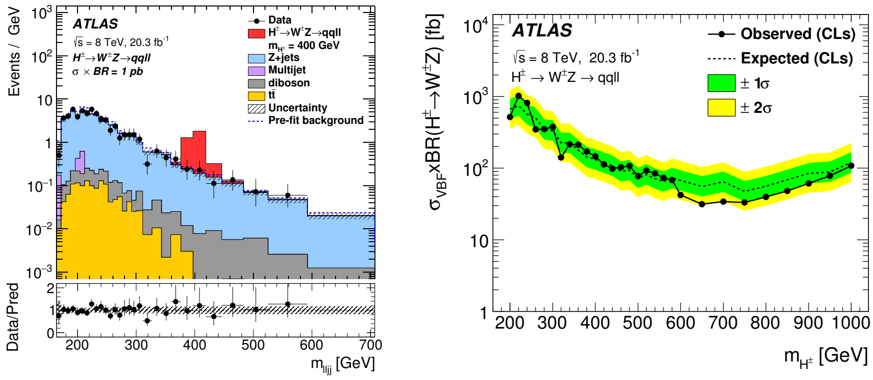

Figure 6: Left: The ATLAS m_{lljj} distribution for data and the expected SM background. The hashed band indicates the post-fit systematic uncertainty. Included in the plot is an example signal sample with $m_{H^{\pm}}$= 400 GeV, which has been plotted with a cross section times branching ratio, $\sigma \times BR(H^{\pm} \to W^{\pm}Z) = 1$ pb for illustration. No data events are observed for values of $m_{lljj} > 600$ GeV. Right: ATLAS exclusion limits in fb at the 95% CL for the vector-boson fusion production cross section of a $H^{\pm}$ boson times its branching ratio to $W^{\pm}Z$ assuming that the signal has a narrow intrinsic width.

In a type-II 2HDM, such as the MSSM, the main H^+ production mode at the LHC would be through top-quark decays $t \to bH^+$, for charged Higgs boson masses, $m_{H^+} < m_t - m_b$. In this mass regime, the charged Higgs boson is produced most frequently in $t\bar{t}$ production and it preferentially decays to a τ lepton and a neutrino, $H^+ \to \tau^+\nu_\tau$, for $\tan\beta > 5$. The ATLAS and CMS experiments have set 95% CL upper limits on the branching ratio $BR(t \to H^+b) \times BR(H^+ \to \tau^+\nu)$.

The CMS experiment performed a search for this production mode with H^+ decaying to $\tau^+\nu$ in a fully hadronic final state [16]. The data sample used in the analysis corresponds to an integrated luminosity of 19.7 ± 0.5 fb^{-1}. The transverse mass spectrum observed in data agrees with the SM expectation. An expected 95% CL model- independent upper limit on $BR(t \to H^+b) \times BR(H^+ \to \tau^+\nu)$ in the range of 1.1-0.22% is obtained for $m_{H^+} =$ 80-160 GeV while for $m_{H^+} =$ 180-600 GeV a model-independent limit on $BR(pp \to \bar{t}(b)H^+) \times BR(H^+ \to \tau^+\nu)$ is set to 0.41-0.030 pb. The corresponding observed 95% CL model-independent upper limit is set to 1.2-0.16% for $m_{H^+} =$ 80-160 GeV and to 0.38-0.026 pb for $m_{H^+} =$ 180-600 GeV. The results are interpreted in different MSSM benchmark scenarios [17] and are used to set exclusion limits in the $m_{H^+} - \tan\beta$ and $m_A - \tan\beta$ parameter spaces, as shown in Fig. 7.

The ATLAS experiment performed the same search [18] where the analysis makes use of a total of 19.5 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV, recorded in 2012 with the ATLAS detector at the LHC. The data are found to be in agreement with the SM predictions. Upper limits at the 95% CL are set on the branching ratio $BR(t \to H^+b) \times BR(H^+ \to \tau^+\nu)$ between 0.23% and 1.3% for a mass range of $m_{H^+} =$ 80-160 GeV. For the mass range of $m_{H^+} =$ 180-1000 GeV, upper limits are set for the production cross section times branching ratio, $\sigma(pp \to \bar{t}H^+ + X) \times BR(H^+ \to \tau^+\nu)$

between 0.76 pb and 4.5 fb. Interpreted in the context of the m_h^{max} (shown in Fig. 7), m_h^{mod+} and m_h^{mod-} scenarios of the MSSM [17], the entire parameter space with $\tan\beta > 1$ is excluded for the low-mass range $90 \leq m_{H^+} \leq 140$ GeV, and a large part of the parameter space with $\tan\beta > 1$ is excluded for $140 \leq m_{H^+} \leq 160$ GeV.

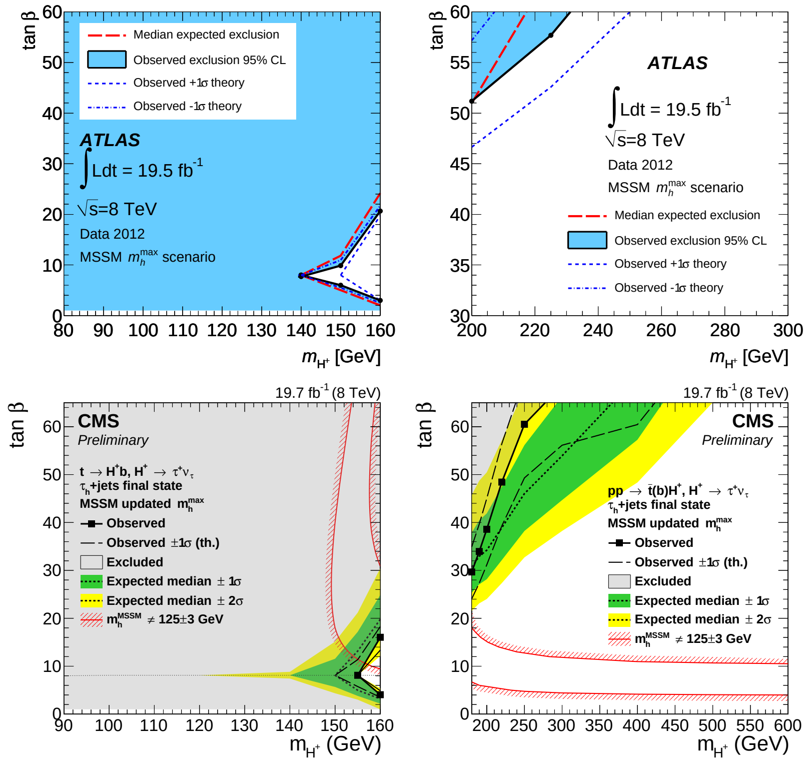

Figure 7: The 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+}. Results from ATLAS (top) and CMS (bottom) experiments are shown in the context of m_h^{max} benchmark scenario of the MSSM for the regions in which reliable theoretical predictions exist.

A CP-odd Higgs boson, A, appears in many models with an extended scalar sector, e.g. in the case of the 2HDM. The lightest scalar h is assumed to be the boson observed at the LHC at a mass of 125 GeV. If the masses of the heavier bosons are at or below the TeV scale, they can be accessible at the LHC. Searches for this extended sector can be performed either by measuring the values of the couplings of the discovered h boson to other SM particles, or via direct searches. A way to probe this kind of new physics is therefore to search for bosons that decay into final states that contain an SM-like Higgs boson.

Data recorded in 2012 by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 20.3 fb^{-1} of proton-proton collisions, are used to search for or a CP-odd Higgs boson, A, decaying to Zh, where h denotes a light CP-even Higgs boson with a 125 GeV mass [19]. No deviations from the SM background predictions are observed in the three final states considered: $Zh \to ll\tau\tau$, $Zh \to llbb$, and $Zh \to \nu\nu bb$. Upper limits are set at the 95% CL for $\sigma(gg \to A) \times BR(A \to Zh) \times BR(h \to ff)$ of 0.098-0.013 pb for $f = \tau$ and 0.57-0.014 pb for $f = b$ in the range of m_A = 220-1000 GeV (shown in Fig. 8 (left)). This Zh resonance search improves significantly the previously published constraints on CP-odd Higgs boson production in the low $\tan\beta$ region of the 2HDM.

CMS performed searches for new physics in signatures expected from decays of a pseudo-scalar Higgs boson A into a Z boson and an SM-like h boson, with the Z boson decaying into l^+l^- and the h boson into $b\bar{b}$ [20]. Different techniques are employed to increase the sensitivity to signal, exploiting the presence of the three resonances A, Z, and h to discriminate against SM backgrounds. Upper limits at a 95% CL are set on the product of a narrow pseudo-scalar boson cross section and branching ratio $\sigma_A \times BR(A \to Zh \to llbb)$ which correspond to 30 to 3 fb at the low and high ends of the 250-600 GeV mass range. Results are also presented as a function of the width of the A boson. Interpretations are given in the context of Type-I and Type-II 2HDM formulations, thereby reducing the parameter space for extensions of the SM.

A similar search is performed in CMS, $A \to Zh$, with the Z boson decaying into l^+l^- and the h boson into $\tau\tau$ [21]. Model independent expected and observed cross section times branching ratio limits for the $A \to Zh \to ll\tau\tau$ process are shown in Fig. 8 (right).

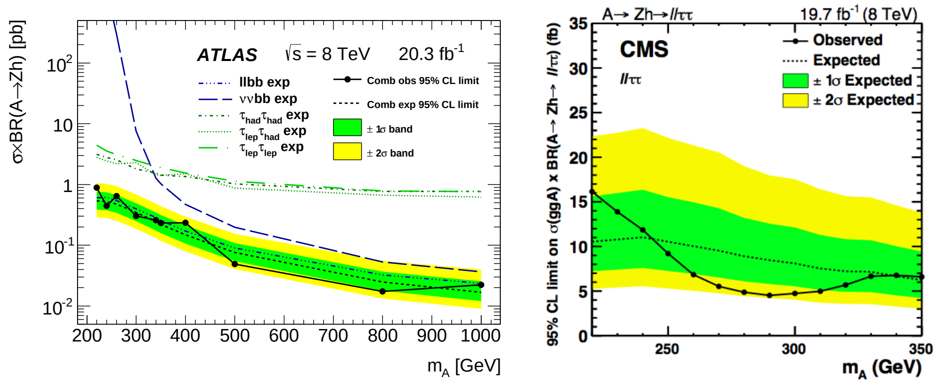

Figure 8: Left: ATLAS combined observed and expected upper limits at the 95% CL for the production cross section of a gluon-fusion-produced A boson times its branching ratio to Zh and branching ratio of h to bb. The expected upper limits for sub-channels are also shown. Right: CMS upper limits at 95% CL on cross section times branching ratio on $A \to Zh \to ll\tau\tau$ for all $ll\tau\tau$ final states combined.

A CMS search for a new resonance decaying to a Z boson and a lighter resonance is also performed [22]. Two different searches are carried out, targeting the decay of the lighter resonance in either a pair of τ leptons or a pair of b-quarks. In both cases the Z boson is identified via its decay into either a pair or electrons or a pair of muons. Since the analysis strategy adopted is independent from the assumed model and spin, the results can be also interpreted in the specular topology $H \to ZA$, where the expected 2HDM mass hierarchy is inverted and the pseudo-scalar A is predicted to be light. Concerning the $ll\tau\tau$ channel, the following leptonic and hadronic di-τ final states are considered: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$, where τ_h indicates a hadronically-decaying τ. The choice of bb and $\tau\tau$ final states is motivated by the large branching ratios predicted in most of the 2HDM phase space.

No significant deviations from the expectations of the SM are observed and upper limits on the cross section times branching ratio are set using a dataset corresponding to an integrated luminosity of 19.8 fb^{-1} at $\sqrt{8}$ TeV of proton-proton collisions. The search excludes cross sections times branching ratios as low as 1 fb (5 fb) for the ll$\tau\tau$ (llbb) final state, depending on the light and heavy resonance masses. Limits have also been set on type II 2HDM models (see Fig. 9), which predict the process $H/A \to ZA/H$, where H and A are CP-even and CP-odd scalar bosons, respectively. In particular the model considered corresponds to the parameters $\cos(\beta-\alpha) = 0.01$ and $\tan\beta = 1.5$.

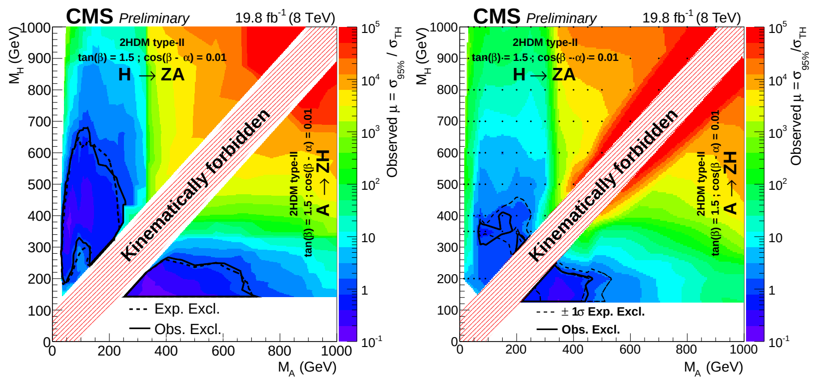

Figure 9: CMS observed 95% limits on the ratio of the cross section to the one predicted by the theory for the $llbb$ (left) and $ll\tau\tau$ (right) final states as function of the A and H boson masses. The black dots on the right plot refer to the full simulated signal samples. $\pm1\sigma$ expected exclusion contours are drawn (dashed lines), together with the actual excluded regions delimited with solid lines.

In the context of the MSSM and nMSSM different searches were performed by the CMS and ATLAS collaborations [23, 24, 25, 26, 27, 28].

6. Di-Higgs searches

While the production of Higgs bosons pairs is very small within the SM, roughly 10 fb at 8 TeV, several BSM theories foresee an enhancement that can be already probed with the available data. The CMS and ATLAS collaborations performed dedicated analyses to search for new resonances in the $X \to HH \to b\bar{b}\gamma\gamma$ and $X \to HH \to b\bar{b}b\bar{b}$ processes, which are fully reconstructible final states. Here H indicates the discovered SM-like 125 GeV Higgs boson.

Models inspired by warped extra dimensions [30] predict the existence of new heavy particles X (with $m_X > 2m_H$), that can decay to a pair of Higgs bosons. Examples of such particles are radion (spin-0) [31, 32, 33] or the first Kaluza-Klein excitation of the graviton (spin- 2) [34, 35].

The CMS experiment reported the results of a model-independent search for the resonant pair production of Higgs bosons [36]. The search for a narrow width resonance, denoted by X, is performed in the 270-1100 GeV mass range. Data from proton-proton collisions at the LHC and recorded by the CMS experiment corresponding to an integrated luminosity of 17.9 ± 0.5 fb^{-1} at $\sqrt{s}$ = 8 TeV are used. This search is performed for the case where both Higgs bosons decay into $b\bar{b}$. The main challenge of this search is to distinguish the signal of four bottom quarks in the final state, that hadronize into jets (b jets), from the copious multijet background described by quantum chromodynamics (QCD) in pp collisions. This challenge is addressed by suitable event selection criteria that include dedicated b-jet identification techniques and a model of the multijet background that is validated in data control regions.

No evidence for a signal is observed. Upper limits at a 95% CL on the production cross section for such spin-0 (shown in Fig. 10 (left)) and spin-2 resonances, in the mass range from 270 to 1100 GeV, are reported. Using these results, a radion with decay constant of Λ_R = 1 TeV and mass from 300 to 1100 GeV, and a Kaluza-Klein graviton with mass from 380 to 830 GeV are excluded at a 95% CL.

A CMS analysis is dedicated to the search for new resonances in the $X \to HH \to \gamma\gamma b\bar{b}$ process [37], which is a fully reconstructible final state. It combines the large branching fraction of the $H \to b\bar{b}$ decay, with the comparatively low background and good mass resolution of the $H \to \gamma\gamma$. The search is performed in the mass range 260-1100 GeV and the data sample corresponds to an integrated luminosity of 19.7 fb^{-1}, collected by the CMS detector at $\sqrt{s} = 8$ TeV.

The observations are compatible with expectations from SM processes. Upper limits at 95% CL are extracted on the cross-section of new particles production. The limits are compared to the predictions from theories beyond the SM, based on the assumption of the existence of warped extra dimensions. The radion, under the assumptions described and with Λ_R = 1 TeV is observed (expected) to be excluded with masses below 0.97 TeV (0.88 TeV) as well as the RS1 KK-graviton with masses between 340 and 400 GeV.

Searches for non-SM physics with events consistent with either resonant $(X \to hh)$ or non-resonant pair production of Higgs bosons in the $hh \to \gamma\gamma b\bar{b}$ channel [38] were performed by the ATLAS collaboration using 20.3 fb^{-1} of proton-proton collision data at $\sqrt{s} = 8$ TeV. This channel is particularly important in the search for resonances with mass m_X in the range $260 < m_X < 500$ GeV, where backgrounds and combinatorics make other channels such as $b\bar{b}b\bar{b}$ or $b\bar{b}\tau^+\tau^-$ challenging. A 95% CL upper limit is placed on the non-resonant production cross section at 2.2 pb, while the expected limit is $1.0^{+0.5}_{-0.2}$ pb. The difference derives from a small excess of events, corresponding to 2.4σ. In the search for a narrow resonance decaying to a pair of Higgs bosons, the expected exclusion on the production cross section falls from 1.7 pb for a resonance at 260 GeV to 0.7 pb at 500 GeV. The observed exclusion ranges from 0.7-3.5 pb. It is weaker than expected for resonances below 350 GeV, as shown in Fig. 10 (right).

7. Summary

A large number of models have been tested, searching for extended Higgs sectors, against the LHC Run 1 data. No evidence for BSM Higgs bosons is observed and cross-section limits and exclusion regions for the parameter space of several models have been obtained. With the LHC Run 2 data, at $\sqrt{s} = 13$ TeV centre-of-mass energy, the reach of these analyses will be extended.

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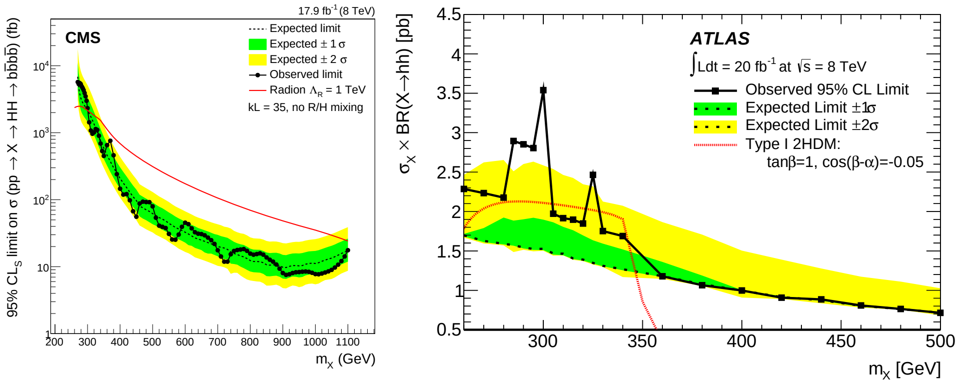

Figure 10: Left: The CMS observed and expected upper limits on the cross section for $pp \to X \to H(b\bar{b})H(b\bar{b})$ at a 95% CL, where the resonance X has spin-0. The theoretical cross section for the RS1 radion, with $\Lambda_R = 1$ TeV , $kL = 35$, and no radion Higgs boson mixing, decaying to four b jets via Higgs bosons is overlaid. Right: ATLAS 95% CL upper limit on the cross section times branching ratio of a narrow resonance decaying to pairs of Higgs bosons as a function of m_X.

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