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Search for additional Higgs bosons

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Summary. — The discovery of the Higgs boson with the mass of about 125 GeV completed the particle content predicted by the Standard Model. Even though this model is well established and consistent with many measurements, it is not capable to solely explain some observations. Many extensions addressing this fact introduce additional Higgs-like bosons which can be either neutral, singly-charged or even doubly-charged. The current status of searches based on data of the ATLAS and CMS experiments at the LHC are presented. No evidence for such particles was however found.

1. – Introduction

Phenomena like dark matter or neutrino masses are not accounted for by the very successful Standard Model (SM) of particle physics. Furthermore this model has academic shortcomings like the hierarchy problem, or the fact that the gravitational force is not embedded. These flaws are addressed and possibly solved by extensions like electroweak singlet models, left-right symmetric models, little Higgs models or two Higgs doublet models (2HDM). The nowadays popular supersymmetric extensions of the SM are special cases of the 2HDM. In all these models the Higgs sector is extended by additional Higgs bosons and some of them can also carry electric charge.

To search for such Higgs bosons the ATLAS [1] and CMS [2] Collaborations are following a similar approach: Invariant-mass distributions of potential final decay products —like charged leptons or jets— of these new particles are examined for peaks and excesses over the SM prediction. Quantities in the transverse plane —like the transverse mass— are studied in case of undetectable decay products, *e.g.* neutrinos. The observables are scanned for hypotheses of new particles with various mass values. The assumed resonances could be either fairly model-independent or be predicted by a specific model for which derived limits may not only constrain the resonance mass, but additionally other phase space parameters. Section **2** presents the results for searches in final states with neutral particles, sect. **3** summarizes studies for singly-charged resonances and sect. **4** gives the conclusions of analyses targeting doubly-charged Higgs-like particles.

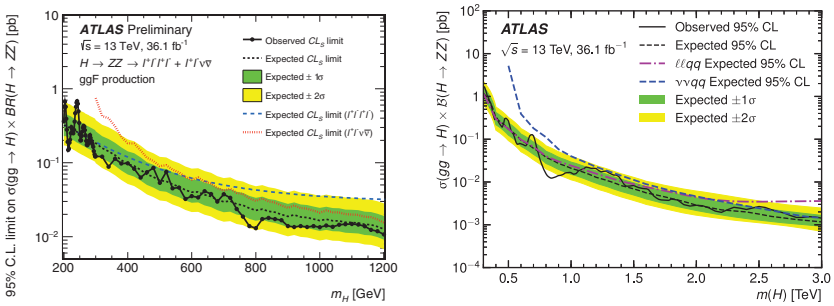

Fig. 1. – Limits on the production cross-section of neutral Higgs-like particles times the branching fraction into Z boson pairs for the gluon fusion production mode. The left plot shows constraints based on the ATLAS analysis of 4ℓ and $2\ell 2\nu$ final states [5]. On the right results for studies of final states with leptons and jets are shown [7].

2. – Searches for neutral Higgs bosons

Neutral Higgs-like bosons decay in most models into gauge boson pairs, or into two quarks or leptons of opposite charge. The following sections highlight results of studies in these channels.

2˙1. *Leptonic final states from resonant decay into ZZ.* – The experimentally cleanest final state of neutral Higgs-like particle decays are four charged leptons produced via intermediate Z boson pairs. The statistics of this channel is however very limited due to the low branching fraction of Z bosons into charged leptons. The situation improves if one Z boson decays into neutrinos. While in the first case the invariant mass of the leptons can be fully reconstructed, only the transverse mass can be constructed in the latter case. Moreover, the backgrounds are higher if the full event kinematics are not accessible. On the other hand, the channel with an invisibly decaying Z boson is more sensitive to high mass resonances as the Z boson can be highly boosted. In both decay channels the major background is Z-boson pair-production within the SM which therefore needs to be precisely modeled. The CMS Collaboration analyzed $2.3\,\mathrm{fb}^{-1}$ and $12.9\,\mathrm{fb}^{-1}$ of proton-proton collision at 13 TeV center-of-mass energy for the $2\ell 2\nu$ [3] and 4ℓ [4] channel, respectively. The ATLAS Collaboration studied the combination of both channels [5] in $36.1\,\mathrm{fb}^{-1}$. As the amount of analyzed data is bigger for ATLAS, the corresponding limits are tighter than for CMS. In fig. 1 (left) the ATLAS results for a narrow-width resonance are presented. Besides, both collaborations studied the impact of the width and production mode, and constrained multiple parameters in for example the 2HDM.

2˙2. *Final states with jets from resonant decay into ZZ.* – At the cost of resolution and high signal-over-background ratios, it is possible to further increase the statistics by requiring one of the Z bosons originating from the neutral resonance decay to subsequently decay into quarks reconstructed as jets. If the two jets are identified as separate objects, the acceptance drops rapidly with the mass of the resonance as the Z bosons get boosted. For so-called "merged selections" in which just one large-radius jet is consistent with a Z-boson decay, the acceptance remains at about 50% up to masses of 3 TeV for the resonance. Both the CMS and ATLAS Collaborations analyzed $12.9\,\mathrm{fb}^{-1}$ [6] and $36.1\,\mathrm{fb}^{-1}$ [7] of proton-proton collision data at 13 TeV for resonant events with the other Z boson decaying into opposite-charged same-flavor leptons. For the study done by ATLAS, decays of the other Z boson into neutrinos were considered too. The limits

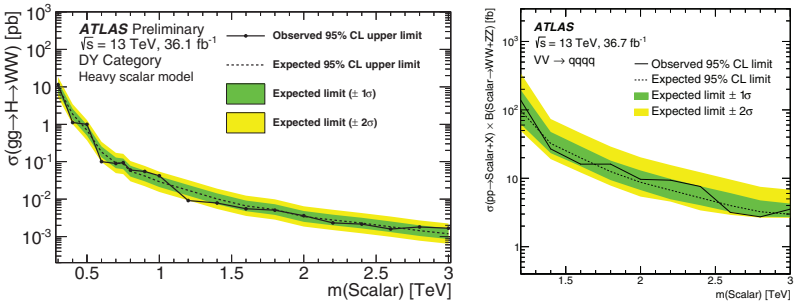

Fig. 2. – Limits on production rates of high-mass Higgs-like resonances are shown for the WW intermediate state [8] on the left and for the combined $WW + ZZ$ intermediate state [9] on the right. For both analyses the final state features jets produced by electroweak gauge-boson decays.

on high-mass resonances from ATLAS are presented in fig. 1 (right) for the gluon fusion production mode while those for vector-boson production are not shown. Corresponding constraints by CMS are less stringent because less data was included.

2˙3. *Final states with jets from resonant decay into WW.* – An analysis similar to the one reported in the previous section was carried out by ATLAS [8]. Events with candidates for W boson pairs is studied in $36.1\,\text{fb}^{-1}$ of 13 TeV data. A W boson is required to be reconstructed from its leptonic decay products while the other one needs to be matched to two jets or one merged jet with a big radius. The expected and observed limits for the purely gluon initiated production of a Higgs-like particle are shown in fig. 2 (left).

2˙4. *Final states with jets from resonant decay into $WW + ZZ$.* – Events with two jets of big radius, a rapidity gap in-between and an combined invariant mass above 1 TeV are examined by ATLAS [9] in $36.7\,\text{fb}^{-1}$ of 13 TeV data. The jets are required to be consistent with either a pair of W bosons or Z bosons. Figure 2 (right) displays the corresponding results.

2˙5. *Leptonic final states with resonant decay into WW.* – The purely leptonic final state of decays of W boson pairs was searched for the presence of a heavy resonance. The results of ATLAS [10] are based on $36.1\,\text{fb}^{-1}$ of 13 TeV data and $2.3\,\text{fb}^{-1}$ for CMS [11]. As more data was analyzed by ATLAS the resulting limits on heavy resonances are more stringent as the corresponding ones by CMS, and therefore shown in fig. 3 (left). Additional interpretations for example in the context of specific 2HDMs are available as well and provided by both collaborations.

2˙6. *Resonant decay into $Z\gamma$.* – Photons accompanied by either two opposite-charge same-flavor leptons or two jets both consistent with a Z boson decay were studied by ATLAS [12] and CMS [13] in $3.2\,\text{fb}^{-1}$ and $35.9\,\text{fb}^{-1}$ of 13 TeV data. For the leptonic Z boson decay ATLAS performed a separate dedicated analysis using $36.1\,\text{fb}^{-1}$ [14]. The combination of both Z boson decay modes in the larger dataset results in tighter constraints by CMS which are displayed in fig. 3 (right). The impact of the assumed width of the resonance on the limit has also been studied.

2˙7. *Resonant decay into $\gamma\gamma$.* – The steep falling invariant-mass spectra of photon pairs is exploited to search for resonances with masses below 120 GeV. $19.7\,\text{fb}^{-1}$ of proton-

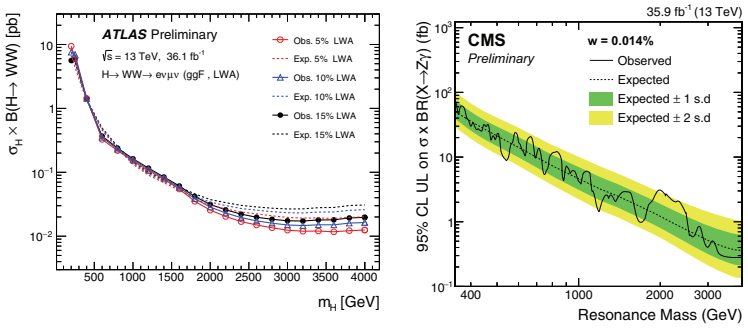

Fig. 3. – The left plot shows constraints on high-mass neutral resonances produced by gluon fusion and based on ATLAS studies of the $e\nu\mu\nu$ final state [10]. Different width hypotheses are studied. Constraints resulting from CMS studies of $Z\gamma$ production [13] are shown on the right for a Γ/m ratio of 0.014% of the Higgs-like resonance combining different Z boson decay modes.

proton collision data at a center-of-mass energy of 8 TeV is analyzed by CMS [15]. For masses above 200 GeV a total of 36.7 fb^{-1} and 12.9 fb^{-1} data recorded at 13 TeV collision energy are analyzed by ATLAS [16] and CMS [17]. The derived limits presented in fig. 4 do not show any significant excess over expectations.

2˙8. *Pseudo-scalars into leptons or bottom quarks.* – Detector signatures with combinations of two pairs of muons, τ leptons or b-quarks are examined by CMS [18] in 19.7 fb^{-1} data recorded at 8 TeV. Light Higgs-like bosons occurring in for example 2HDM plus singlet models could decay via pseudo-scalars and result in such final states. There is no clear indication found for a signal and therefore limits like shown in fig. 5 (left) are set. There are constraints on the mass of the corresponding pseudo-scalars available as well.

2˙9. *Resonant decay into Zh.* – Heavy neutral pseudo-scalar particles could decay into a Z boson and the SM Higgs boson. ATLAS [19] analyzed 36.1 fb^{-1} of 13 TeV data for this process assuming the Higgs particle decays into a pair of $b\bar{b}$ quarks and the Z boson in different final states. Additional b-tagged jets were required when the pseudo-scalar was produced in association with a pair of b-quarks. As there was no excess found, limits derived from this decay channel are shown in fig. 5 (right).

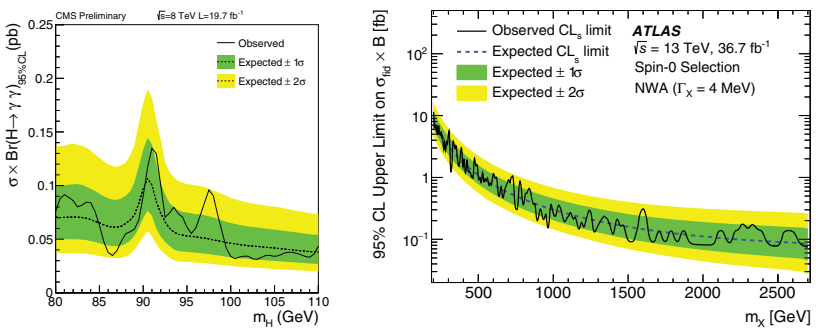

Fig. 4. – Constraints on Higgs-like resonances below 120 GeV obtained by CMS [15] are shown on the left. The search of ATLAS for masses above 200 GeV for potential resonances [16] is based on more data and gives therefore tighter constraints. The limits for a narrow-width assumption are given on the right.

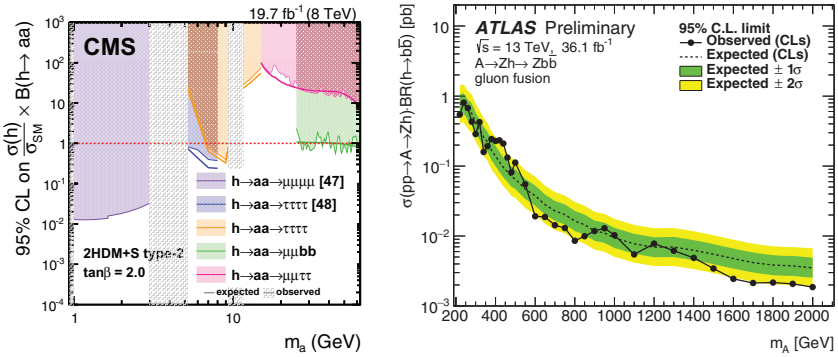

Fig. 5. – The left plot shows results of a CMS search [18] for light Higgs-like resonances decaying via pseudo scalars into various final states. The display is exemplary for one specific phase space point of a specific model while more benchmark scenarios are studied. Constraints on pseudo-scalar production times branching ratio rates based on an ATLAS analysis [19] examining the Zh final state are presented on the right.

2˙10. *Resonant decay into Higgs bosons.* – The statistics available in current data recorded at the LHC is by far not sufficient to measure di-Higgs production as it is predicted by the SM. Therefore an excess would be a signal of new physics *e.g.* due to the existence of an intermediate resonance. There is a variety of analyses based on proton-proton collision at 13 TeV: $HH \to (b\bar{b})(\gamma\gamma)$ was studied by CMS [20] in 35.9 fb^{-1} and by ATLAS [21] in 3.2 fb^{-1}; the decay $HH \to (b\bar{b})(b\bar{b})$ was searched in 35.9 fb^{-1} by CMS [22] and in 13.3 fb^{-1} by ATLAS [23]; for the $HH \to (WW)(\gamma\gamma) \to (\ell\nu jj)(\gamma\gamma)$ final state 13.3 fb^{-1} were analyzed by ATLAS [24]; finally CMS searched in 35.9 fb^{-1} for $HH \to (WW/ZZ)(b\bar{b}) \to (\ell\nu\ell\nu)(b\bar{b})$ [25] and $HH \to (b\bar{b})(\tau\tau)$ [26]. In neither of the studies any excess for resonant di-Higgs production was found, and therefore limits down to 19 times the SM prediction for this process were set.

2˙11. *Resonant decay into τ leptons.* – It is important to search observables build from pair-produced τ leptons for deviations from the SM prediction in order to test for models with a SM Higgs-like resonance, and in particular if the couplings to the new Higgs-like particle are proportional to the τ-lepton mass. ATLAS performed a study using 36.1 fb^{-1} of 13 TeV data [27] while CMS [28] analyzed 12.9 fb^{-1}. The decays of the τ leptons are in both analyses allowed to be hadronic or leptonic. With respect to similar earlier analyses the increased statistics of the dataset increased the sensitivity of this signature significantly. However, neither ATLAS nor CMS found any indications for deviations from the SM. The derived constraints are consistent with results shown in previous sections and available for more general models as well as for specific supersymmetric models.

2˙12. *Resonant decay into $t\bar{t}$.* – It is of great importance to search for Higgs-like bosons decaying into a pair of top quarks. In case of mass-dependent couplings the spectra formed from pair-produced top-quarks will show an enhancement in case of new physics phenomena. ATLAS analyzed 20.3 fb^{-1} of 8 TeV data [29] and derived constraints for the masses of a pseudo-scalar and scalar as predicted by 2HDMs. A more generic analysis by ATLAS is based on 13.2 fb^{-1} of 13 TeV data [30]. Various signal regions, characterized by the (b-)jet multiplicity are studied. Exclusion limits are not only given for neutral, but also for singly-charged Higgs-like particles in case of combinations of top quarks and bottom quarks in the studied region.

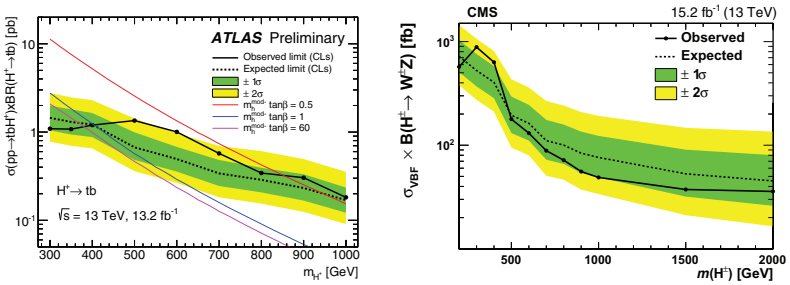

Fig. 6. – Limits for singly-charged Higgs-like particles as obtained from the analysis of signatures with top quarks and bottom quarks performed by ATLAS [31] on the left. The right plots shows constraints derived by the CMS study of WZ production [34].

3. – Searches for singly-charged Higgs bosons

Besides neutral resonances various models (*e.g.* the 2HDM) introduce singly-charged Higgs-like particles. Therefore the ATLAS and CMS Collaborations search for related signatures in LHC data and derive constraints to related models if no indication of new physics was found.

3˙1. *Resonant decay into top and bottom quarks.* – A study like presented in the previous section, however, more refined and particularly targeting at charged Higgs-like particles in the context of minimal supersymmetric extensions of the SM (MSSM) was carried out by ATLAS [31]. The analyzed dataset is the same as previously mentioned and the signatures with bottom and top quarks got examined. The corresponding results are shown in fig. 6 (left).

3˙2. *Resonant decay into τ lepton and neutrino.* – Many models predict a large branching ratio for the charged Higgs boson into τ leptons. For both searches, the CMS analysis [32] of 12.9 fb^{-1} of 13 TeV data and the ATLAS study [33] of 14.7 fb^{-1}, the examined signatures also feature at least one b-jet possibly originating from a top quark decay. The derived exclusion limits of the CMS study for a dedicated MSSM scenario are given in fig. 7 and are consistent with ATLAS results. In particular for low masses the CMS investigations show that most of the parameter space is ruled out.

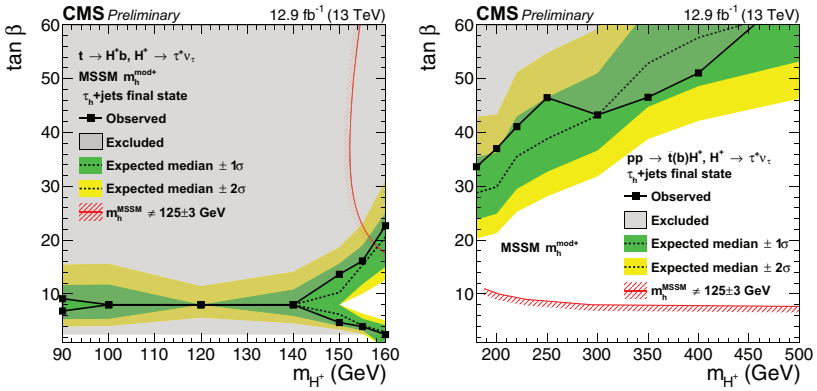

Fig. 7. – Constraints on $\tan\beta$ in dependence of the mass of a singly-charged MSSM Higgs particle as derived by CMS [32].

3˙3. *Resonant decay into WZ.* – A singly-charged Higgs-like boson can also be searched for in the WZ final state. This signature was studied by CMS in $15.2\,\text{fb}^{-1}$ of 13 TeV [34] to search for indications of general fermiphobic Higgs boson. In fig. 6 (right) the corresponding general exclusion limits are shown.

4. – Searches for doubly-charged Higgs bosons

Higgs-like bosons with double electric charge are part of type-II seesaw models or left-right symmetric models. The branching ratio of these new particles are commonly free parameters of the models and therefore limits are derived for specific values or benchmark points.

4˙1. *Same-charge lepton pair from resonant decay.* – The two multi-purpose LHC experiments studied signatures with pairs of same-charge same-flavor leptons pairs in events with lepton multiplicities ranging from two to four. The ATLAS analysis [35] of $36.1\,\text{fb}^{-1}$ of 13 TeV data is optimized for Drell-Yan production of the doubly-charged resonance while the CMS analysis [36] of $12.9\,\text{fb}^{-1}$ also considers the doubly-charged resonance being produced with a singly-charged resonance. Some dedicated exclusion limits are presented in fig. 8.

5. – Summary

All presented studies show good agreement with the SM expectations and yet there are no indications for the presence of new physics in the form of additional Higgs-like particles or resonances. The derived constraints on the cross section times branching fraction range from several picobarn for resonances with masses of about 200–400 GeV to several femtobarn for resonances of up to 4 TeV of mass. The limits are consistent throughout all channels and do not only address neutral resonances, but also singly-charged ones. As constraints on doubly-charged Higgs-like particles are quite model dependent it is not possible to shortly summarize the results. However, also for these particles there was no evidence found.

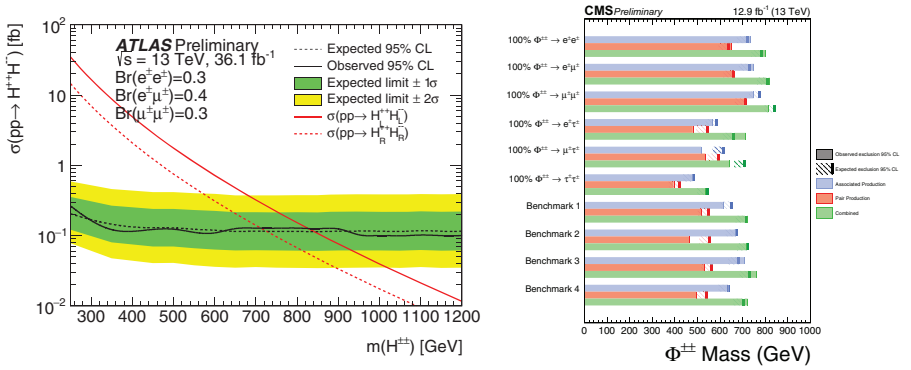

Fig. 8. – The left plot displays constraints on doubly-charged Higgs-like resonances resulting from analysis by ATLAS [35]. On the right there is a summary of results based on CMS studies [36].

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