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Exotic Higgs decays, including new scalars (ATLAS+CMS)

Giuseppe Carratta[a,b,*], **on behalf of the ATLAS and CMS Collaborations**

[a] *Dipartimento di Fisica e Astronomia "Augusto Righi", Alma Mater Studiorum Università di Bologna, Via Irnerio 46, 40126, Bologna, Italy*

[b] *INFN - Sezione di Bologna, Viale Carlo Berti Pichat 6/2, 40127, Bologna, Italy*

E-mail: carratta@bo.infn.it

Searches for exotic decays of the Standard Model (SM) Higgs boson and for evidence of additional beyond the SM Higgs-like particles provide fundamental tests of the SM theory, leading to possible indications of new physics mechanisms. The latest results from the ATLAS and CMS Collaborations are presented. The analyses are performed in a wide range of topologies, using proton-proton collision data collected with the two multi-purpose detectors at the LHC at a centre-of-mass energy $\sqrt{s} = 13$ TeV, with an integrated luminosity up to 139 fb^{-1}. No evidence for new physics processes is found, thus setting exclusion limits on the various models.

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*Speaker

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Since the announcement of the Higgs boson discovery in 2012 by the ATLAS [1] and CMS [2] Collaborations, several measurements to test the agreement between its properties and the SM expectations have been conducted at the LHC. Even if any deviations are found, there are still open questions where the Higgs boson can play a crucial role as a portal to Beyond the Standard Model (BSM) physics.

There are different ways to access New Physics, this note will focus on models which predict non-standard (the so-called *exotic*) decay of the SM 125 GeV Higgs boson and on the production of additional BSM Higgs-like particles. The analyses presented here cover a wide range of signatures using the data collected by the ATLAS [3] and CMS [4] detectors at a centre-of-mass energy $\sqrt{s}$ = 13 TeV, with an integrated luminosity up to 139 fb^{-1}.

1. $H \to AA \to 4\gamma$

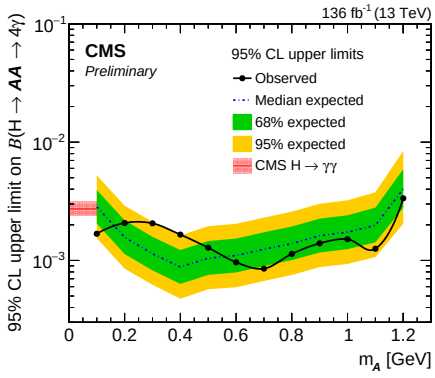

Figure 1: Observed (black solid curve) and median expected (blue dashed curve) 95% CL upper limits on $\mathcal{B}$ as a function of m_A, with the corresponding one (green) and two (yellow) standard deviation bands (Taken from Ref [5]).

CMS performed a direct search for exotic decays of a SM Higgs boson into a pair of hypothetical new scalar particles, each decaying to a pair of SM photons [5]. These kind of decays are candidates in various BSM mechanisms such as the 2-Higgs-doublet-like models (2HDM) and are of particular interest in searches for axion-like particles (ALP). An innovative deep learning technique is used to estimate the $\gamma\gamma$ mass in the electromagnetic calorimeter to distinguish signal from background events. No excess is found, then upper limits (UL) (Figure 1) on the branching fraction ($\mathcal{B}$ or $\mathcal{BR}$) of 0.9-3.3 $\times 10^{-3}$ are set at the 95% confidence level (CL) for masses of A in the range 0.1 < m_A < 1.2 GeV.

2. $H \to aa \to bb\mu\mu$

The SM Higgs boson decay into a pair of pseudoscalar particles, one decaying into a b-quark pair and the other into a muon pair, has been searched by ATLAS [6]. This channel provides a clean signature with also a large $\mathcal{B}$, and its resolution is improved by using a kinematic likelihood constraining $m_{bb} \simeq m_{\mu\mu}$ in H $\to aa$ decays.
A narrow $\mu\mu$ resonance is searched for in the invariant mass spectrum between 16 GeV and 62 GeV. A BDT is trained on 7 kinematic variables to separate signal from backgrounds events. A model-independent fit is performed to test the compatibility of the data with the background-only hypothesis, showing a large discrepancy for $m_{\mu\mu}$ = 52 GeV, corresponding to a local (global) significance of 3.3 σ (1.7 σ). ULs on the $\mathcal{B}$ ($H \to aa \to bb\mu\mu$) are set at 95% CL in the range 0.2-4.0 $\times 10^{-4}$ (Figure 2).

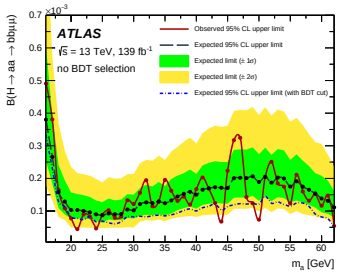

Figure 2: Observed (red solid line) and expected (black dashed line) ULs on $\mathcal{B}$ ($H \to aa \to bb\mu\mu$) at 95% CLs as a function of the signal mass hypothesis (Taken from Ref [6]).

3. $H^{\pm} \to W^{\pm}Z \to \ell\nu\ell'\ell'$

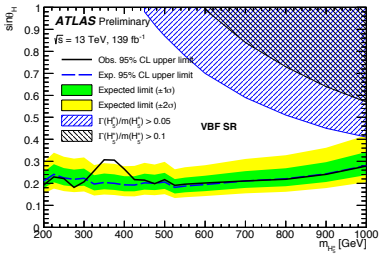

Figure 3: Observed and expected 95% CL ULs on the parameter $\sin\theta_H$ of the GM model as a function of $m_{H_5^{\pm}}$ in the VBF scenario (Taken from Ref [7]).

ATLAS searched for WZ resonances of a BSM charged Higgs boson produced via Vector Boson Fusion (VBF) in a fully leptonic final states, considering only light leptons (i.e. electrons and muons). The Georgi-Machacek (GM) model focusing on the singly-charged Higgs boson $H_5^{\pm}$ was used as a benchmark [7]. The analysis exploits an artificial neural network to define the VBF signal regions, finding a local excess at a resonance mass of around 375 GeV (Figure 3).

4. $H^{\pm\pm} \to \ell^+\ell^+$

ATLAS presents a search for a doubly charged Higgs (DCH) boson $H^{\pm\pm}$ focusing on the benchmark scenario of the Left-Right Symmetric Model [8], which allows lepton flavour violation. Due to the vacuum expectation value considered by this analysis, only leptonic decays of DCH are relevant. Then, multileptonic final states are considered, targeting topologies with two, three and four light-leptons with high values of both transverse momentum and invariant mass of the leading lepton pair. The observed lower mass limit excludes DCH bosons with masses below 1080 GeV (Figure 4).

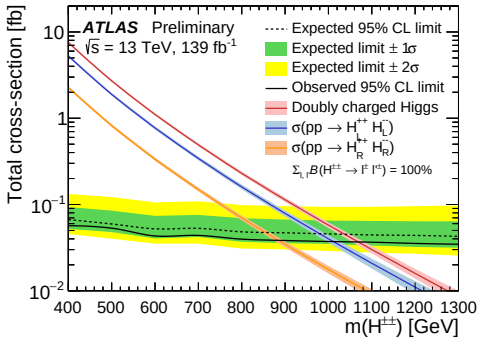

Figure 4: Observed (black solid curve) and expected (black dashed curve) 95% CL ULs on the $H^{\pm\pm}$ pair production cross-section as a function of $m_{H^{\pm\pm}}$ (Taken from Ref [8]).

5. $ttH/A \to t\bar{t}t\bar{t}$

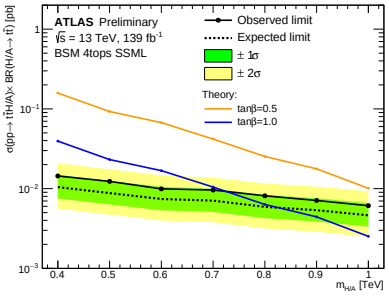

Figure 5: Observed (black solid) and expected (black dashed) 95% CL ULs on the ttH/A cross section times $\mathcal{BR}$ ($H/A \to t\bar{t}$) as function of $m_{H/A}$ (Taken from Ref [9]).

A new BSM heavy scalar or pseudoscalar Higgs boson (H/A) produced in association with $t\bar{t}$ is searched for by ATLAS [9]. The 2HDM signal benchmark with a large $\mathcal{BR}$ of the $H/A \to t\bar{t}$ process and a small width is considered. This analysis targets final states with three or two opposite sign light leptons, vetoing the ones coming from a Z boson and a large jet multiplicity. A mass parametrized BDT is applied to discriminate signals from background events, leading to the observation of ULs in the range 14-6 fb^{-1} for a heavy Higgs boson mass between 400 GeV and 1000 GeV, respectively (Figure 5).

6. $A/H \to \tau\tau$

CMS searches for a heavy neutral boson in resonant and non-resonant $\tau\tau$ signatures providing interpretations in the vector leptoquarks and MSSM scenarios [10]. Four $\tau\tau$ final states are considered: $\tau_{had}\tau_{had}$, $\tau_{had}e$, $\tau_{had}\mu$ and $e\mu$, where e, μ and τ_{had} are referred to the electronic, muonic and hadronic τ decays, respectively. Analysis regions are defined depending on the heavy neutral boson mass: $m_A > 250$ GeV and $m_A < 250$ GeV, thus showing limits with a separation into low-mass and high-mass regions (Figure 6). Two excesses for gluon fusion (ggF) production with a local p-value of 3.1σ and 2.8σ at $m_\phi = 0.1$ TeV and $m_\phi = 1.2$ TeV respectively, are found.

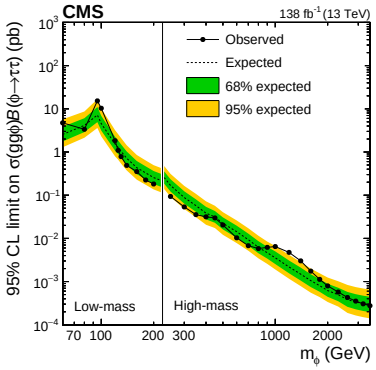

Figure 6: Observed (black solid curve) and expected (black dashed curve) 95% CL ULs on the production of the cross sections and $\mathcal{B}$ for the decay into τ leptons via gluon fusion (Taken from Ref [10]).

7. $H^\pm \to HW^\pm$

A BSM heavy single-charged Higgs boson ($H^\pm$) decaying to a heavy neutral Higgs boson ($m_H = 200$ GeV, $H \to \tau\tau$) and a W boson, with associated production of a top quark, is searched for by the CMS Collaboration [11]. The 2HDM scenario is considered, thus suppressing the $H^\pm \to hW^\pm$ processes, where h is the SM Higgs boson. The analysis is looking for four topologies with the presence of at least one hadronic τ and a light lepton. An innovative resolved top quark tagger is used to guarantee a high signal versus background ratio, which is further increased by the application of a MVA classifier. The observed ULs range from 0.085 pb to 0.019 pb for a $H^\pm$ mass of 300 GeV and 700 GeV, respectively.

8. $H \to WW$

ATLAS [12] and CMS [13] performed two similar analyses looking for a heavy Higgs boson decaying into a pair of W bosons, looking for ggF and VBF production (CMS) or associated production via WH vector bosons (ATLAS). CMS provided interpretation for the 2HDM and the minimal supersymmetric SM (MSSM) models targeting leptonic decay of the W bosons, while ATLAS interprets its results as an Effective Field Theory using higher dimensional operators. An excess of 2.6σ for a resonance mass of 650 GeV in the VBF-only scenario is found by CMS, and ATLAS sets limits in the mass region 300 to 1500 GeV depending upon the assumed couplings.

9. Conclusions

This note summarised the most recent results searching for exotic decays of the SM Higgs boson and for evidence of additional BSM Higgs-like particles, carried out by the ATLAS and CMS Collaborations. These analyses are performed using data from LHC proton-proton collisions at $\sqrt{s} = 13$ TeV looking into several kinds of signatures. No significant global excesses with respect to the SM predictions have yet been observed. Limits on several mechanisms of New Physics are set, which provide the starting points for Run-3 data-taking.

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