PROCEEDINGS OF SCIENCE

Rare and BSM Higgs Searches

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Recent searches for rare and BSM Higgs boson decays with the ATLAS and CMS experiments on data collected at $\sqrt{s} = 13$ TeV between 2016 and 2018 are presented. These represent previously inaccessible probes of the Higgs properties, enabled by advanced analysis and machine learning methods, as well as the large amount of data collected during the Run2 of the LHC. Topics covered include standard model Higgs decays with a branching fraction magnitude equal to that into charm quarks or lower along with searches for decays into yet unobserved particles or decays of Higgs-like and extended Higgs sector particles.

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1. Introduction

Particle physics has had ten very productive years of Higgs physics, since the first observations of the Higgs boson (H) [1–3] at the LHC. The mass of the H has been measured down to a per-mille precision [4] and 90% of its standard model (SM) couplings (in terms of branching fraction) have been observed. Having recorded millions of Higgs bosons, the ATLAS [5] and CMS [6] experiments have now been able to push the envelope further and search for even rarer decays. Moreover, the Higgs sector can be exploited to probe for physics beyond the standard model (BSM), either by measuring the differences between the expected and predicted couplings or via direct searches for exotic signatures. The most recent analyses in these topics by the ATLAS and CMS Collaborations are presented here.

2. Rare Decays

2.1 $H \rightarrow c\bar{c}$

Establishing couplings to second generation of fermions is a key test of the standard model. During the LHC Run2 the ATLAS and CMS Collaborations have published their first results in $H \rightarrow c\bar{c}$ searches with partial datasets targeting the Higgs-strahlung production mode [7, 8]. Recently both collaborations published results with full LHC Run2 datasets, reporting an observed limit, at the 95% confidence level, of 31 and 7.6 $\times$ the SM expectation with ATLAS [9] and CMS [10] experiment respectively. These limits are shown in Fig. 1.

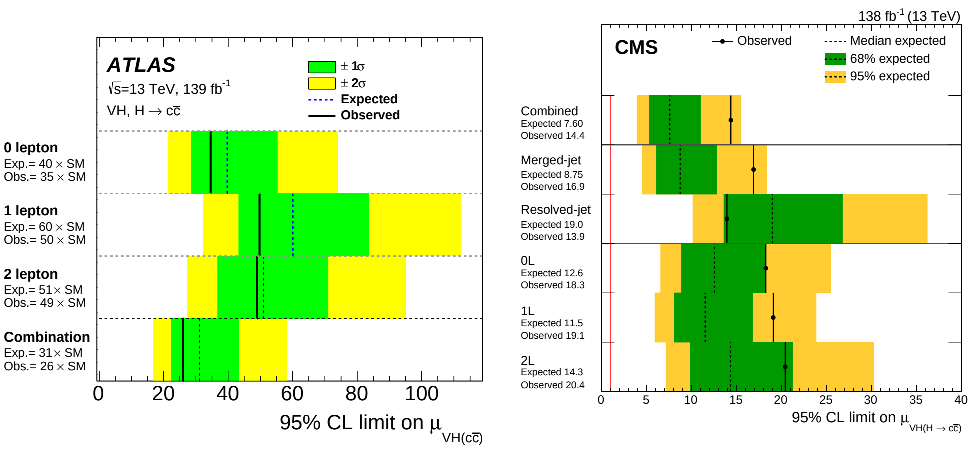

Figure 1: Exclusion limit for $H \rightarrow c\bar{c}$ decays in the VH production mode reported by the ATLAS [9] (left) and CMS [10] (right) Collaborations.

Crossing the threshold of approximately 30 $\times$ the SM expectation on the process rate makes extracting the limits directly on the charm coupling possible. The ATLAS Collaboration was the first to report a symmetric limit of $|\kappa_c| < 8.5$, as well as the first to report the simultaneous constraint on the coupling ratio to charm and bottom quarks of $|\frac{\kappa_c}{\kappa_b}| < 4.5$, showing a direct experimental proof that the coupling to charm quarks is in fact weaker than that to bottom quarks. The CMS Collaboration reported a stronger constraint of $1.1 < \kappa_c < 5.5$. Both experiments extrapolate these limits to estimate achievable sensitivity with the full HL-LHC dataset as shown in Fig. 2.

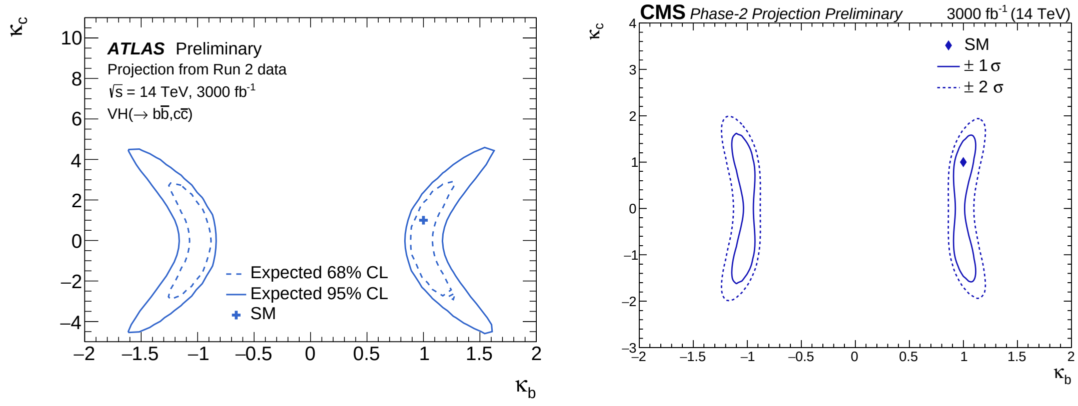

Figure 2: Projected sensitivity at HL-LHC to the H coupling to charm and bottom quarks with the ATLAS [11] (left) and CMS [10] (right) experiments.

The CMS Collaboration reported on a new search for the $H \to c\bar{c}$ process in a yet unprobed production mode, gluon fusion (ggH), in Lorentz-boosted topologies [12]. A limit of 45 × the SM expectation is derived in this orthogonal measurement. The fitted signal region distribution, as well as the limits, are shown in Fig. 3. Both new CMS results report observing the $Z \to c\bar{c}$ process for the first time at the LHC in their respective channels.

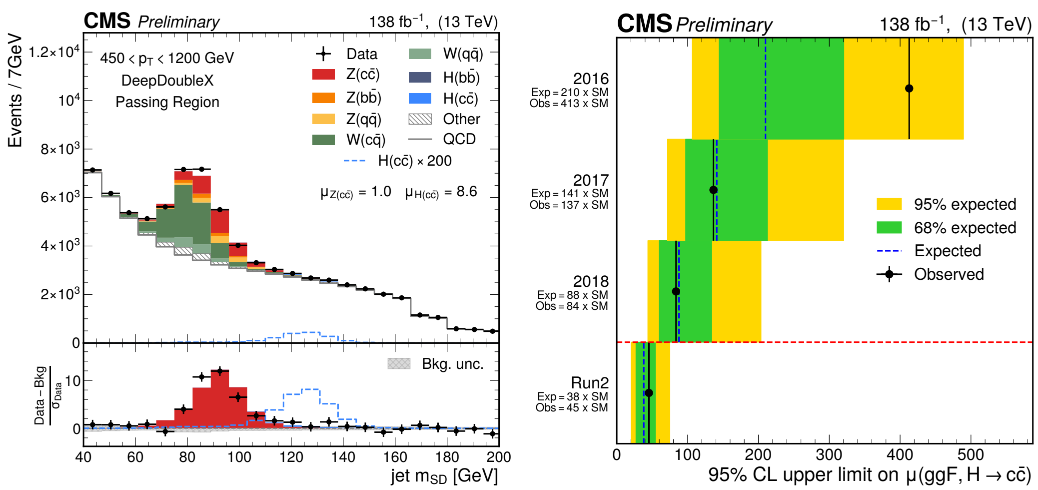

Figure 3: The H candidate jet soft-drop mass distribution in the signal region (left) and a corresponding exclusion limit for the $H \to c\bar{c}$ decay (right) [12]. The $Z \to c\bar{c}$ peak in the mass distribution is clearly visible in red, while the magnified $H \to c\bar{c}$ signal is visualized in dashed blue.

2.2 $H \to Z\gamma$

Both collaborations report on searches for $H \to Z\gamma$ decays facilitated by intermediate top quark and W boson loops, where the Z boson decays leptonically. The reconstructed H mass is shown in Fig. 4 for both searches. The ATLAS and CMS Collaborations extract an observed (expected) upper limit, at the 95% confidence level of 3.6 (1.7) [13] and 4.1 (1.8) [14] with respect to the SM expectation, respectively. Both analyses are statistically limited and as such will directly improve when revisited with Run3 data.

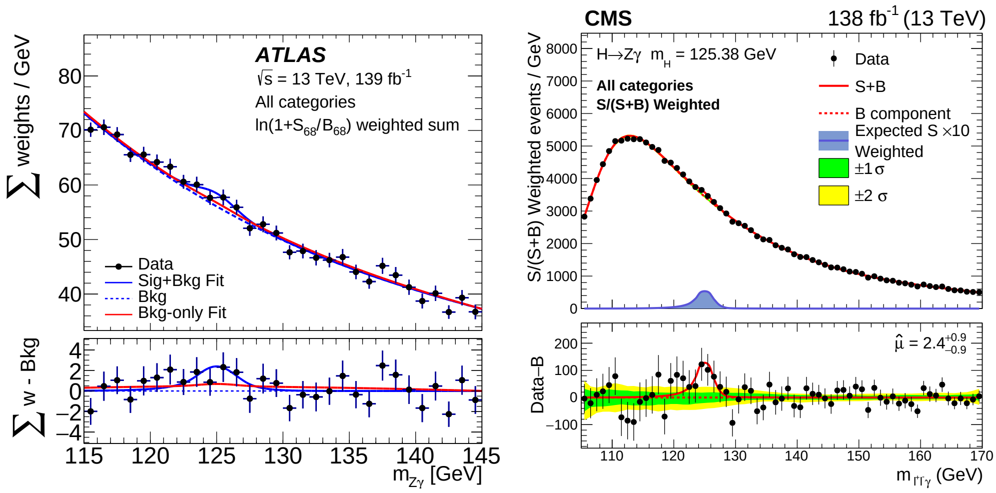

Figure 4: The reconstructed H candidate mass of the $H \to Z\gamma$ process with the Z boson decaying leptonically as recorded by the ATLAS [13] and CMS [14] experiments.

2.3 $H \to \mu\mu/ee$

The H coupling to muons has been studied, with the ATLAS and CMS experiments reporting best fit values of signal strength $\mu(H \to \mu\mu) = 1.2\pm0.6$ [15] and 1.2 ± 0.4 [16] of the SM expectation respectively. With a significance of 3σ the CMS result qualifies as the first evidence for this process and for H couplings to the second generation of fermions more broadly. More recently, searches for the $H \to ee$ decays have also been conducted. While the branching fraction of the Higgs boson to electrons is expected to be far too small (40 000 times smaller than that to muons) to be accessible at the LHC, deviations from the background only hypothesis could be an indication of new physics. However, neither ATLAS nor CMS experiments have observed any such deviations and in turn have derived 95% confidence level upper observed (expected) limits on the branching fraction of $3.6(3.5) \times 10^{-4}$ [17] and $3.0(3.0) \times 10^{-4}$ [18] respectively.

3. Beyond the Standard Model

Due to the near universal coupling of the Higgs boson, Higgs portal models and extended Higgs sector, such as MSSM remain active areas for searches.

3.1 $H \to$ invisible

The SM prediction for invisible H decays via ZZ* is extremely low at 0.1% of the branching fraction. However, a number of dark matter models could enhance it, making it a prime search channel despite the experimental difficulty of reconstructing invisible decays from missing energy. Separate analyses were carried out by the ATLAS and CMS Collaborations targeting H produced via vector boson fusion (VBF) [19, 20] and produced in association with a Z boson [21, 22]. The VBF channel is the more sensitive of the two, due to a combination of higher production rate and experimental handles on isolating the signal. The ATLAS and CMS Collaborations report a limit on the branching fraction of 0.15 [19] and 0.18 [20] in the VBF channel and 0.19 [21] and 0.29 [22] in the ZH channel respectively. The interpretation of these results as limits on dark matter models is shown in Fig. 5. The LHC searches drive the limits on light dark matter.

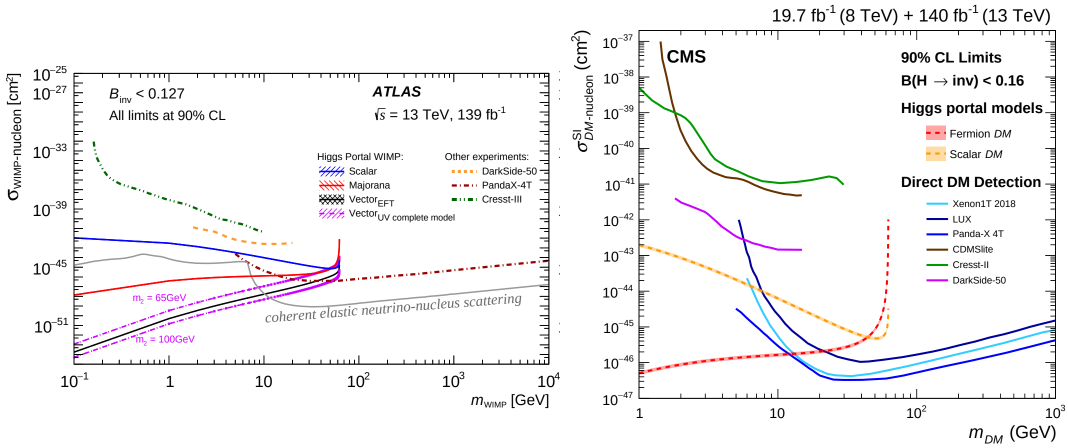

Figure 5: Exclusion limits on potential masses of dark matter particles from various benchmark measurements as well as the new results derived by the ATLAS [19] and CMS [20] Collaborations.

3.2 H → $\gamma\gamma$

Photonic final states offer some of the cleanest experimental signatures available. In a recent search [?] the ATLAS Collaboration probed the di-photon spectrum to unprecedentedly low masses as low as 10 GeV. The obtained limit is shown in Fig 6 (left) and can be interpreted in terms of searches for axion-like-particles. The CMS Collaboration has pursued a search [23] for H decaying to extremely low-mass intermediaries that subsequently decay to photon pairs. As a result, the photons would be highly boosted, so much so that their energy deposits could be found in a single calorimeter cell. A dedicated neural network algorithm has been developed to reconstruct the mass of these collimated photon pairs in an end-to-end fashion and limits were derived over the intermediary particle mass range from 0.1 to 1.2 GeV, shown in Fig. 6 (right).

4. Extended Higgs Sector

Various models and channels are probed in the extended Higgs sector searches. Because of the relationship between H couplings and particle mass, these searches typically target final states with heavier particles, namely top quarks, bottom quarks, W bosons, or taus.

4.1 Top or bottom quark final states

A search for flavour changing neutral current top quark decays into an up-type quark and a light scalar [24] has been performed by the ATLAS Collaboration. No excess over the SM background

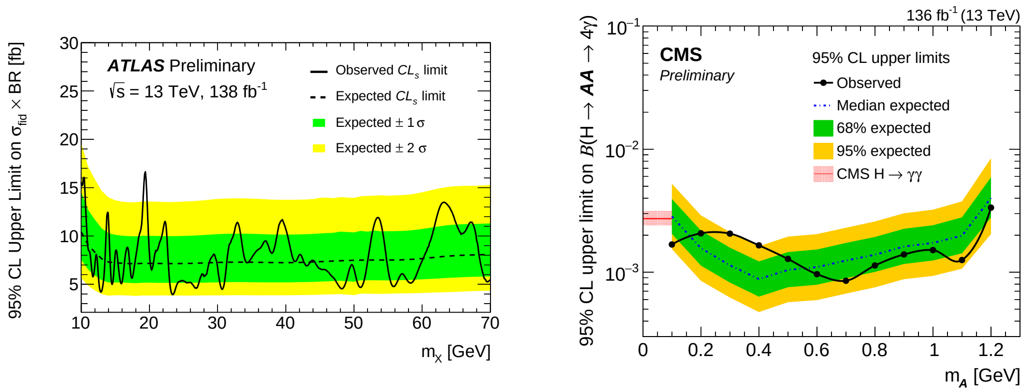

Figure 6: Exclusion limits on a light (pseudo) scalar resonance decaying to a di-photon pair from the ATLAS [**?**] (left) and CMS [23] (right) Collaborations. Note that the probed mass ranges are different.

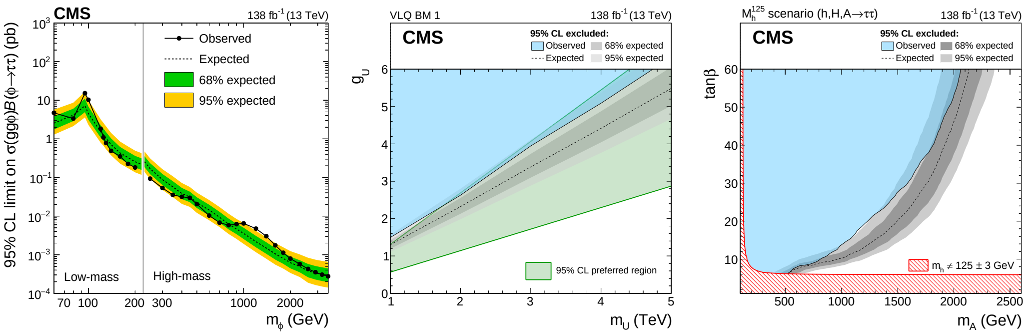

Figure 7: The exclusion limit of a di-τ resonance (left) along with a reinterpretation in terms of a VLQ (centre) and MSSM (left) models [26].

expectation has been observed. On the opposite end of the mass spectrum is a search for a heavy (pseudo) scalar in a ttH production mode in a final state with four top quarks [25]. Despite a factor of four improvement in sensitivity over the previous result, no deviations from the SM model were observed.

4.2 τ final states

Di-τ resonance searches are a promising channel to explore because of the combination of the strong coupling and good background rejection from τ identification. The CMS Collaboration has published an analysis [26] that performs three searches in this final state; model independent search, t-channel vector leptoquark (VLQ) search, and an MSSM search. Two local excesses were observed in the model independent searches at 100 GeV and 1.2 TeV with local significances of 3.1σ and 2.8σ respectively. The exclusion limit along with the local excesses is shown in Fig 7 (left) along with model dependent limits for two possible VLQ and MSSM scenarios.

The CMS Collaboration has also reported on search for a heavy charged H decaying to a neutral H and a W boson [27]. Despite covering 43% of the expected branching ratio, no deviations from the SM were found.

4.3 W boson (leptonic) final states

The CMS Collaboration presented a comprehensive search for resonances of masses between 115 GeV and 5 TeV decaying to pairs of leptonically decaying W bosons [28]. The search covers VBF and ggF production modes and was also interpreted under various model hypotheses. An excess at 650 GeV has been reported in the VBF production mode with a global (local) signifiance of 2.6 (3.8)σ, shown in Fig 8 (left). The analysis is statistically limited and as such will be of interest to follow in Run3 and beyond.

The ATLAS Collaboration has reported on a search for a charged resonance decaying to a W and a Z boson in fully leptonic final state [29]. A local excess has been measured at 375 GeV with a significance of 2.8σ, shown in Fig 8 (right). The search is statistically limited. Interpretations under the Georgi-Machacek and heavy vector triples models have also been performed. In addition the ATLAS Collaboration reported on two other searches, a heavy H decaying to a pair of W bosons in an associated production with another W [30] and a doubly charged H decaying into pairs of same-charged leptons [31]. No deviations from the SM were reported

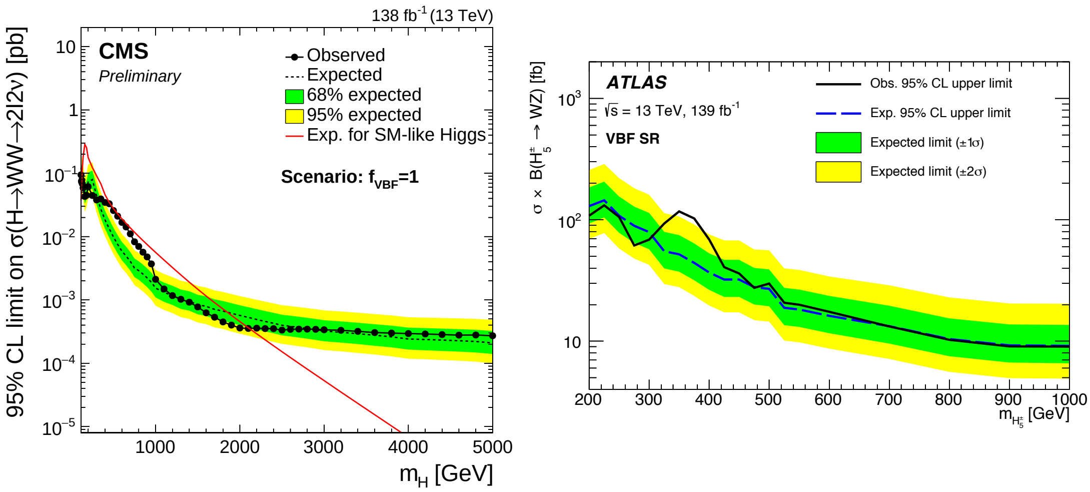

Figure 8: The exclusion limits for a heavy H decaying to pairs of W bosons [28] (left), and a charged resonance decaying to a W and Z boson pair [29] (right). The reported excesses at 650 and 375 GeV are visible.

5. Summary

A number of new searches have been presented by the ATLAS and CMS Collaborations, strongly improving current limits, extending probed ranges through improved analysis techniques or accessing entirely new phase spaces. Despite no clear signs of BSM physics, several analyses reported local excesses with up to 3σ significances, which will be particularly interesting to follow-up in Run3 as they are currently statistically limited.

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References

[1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1–29, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS Experiment at the LHC", *Phys. Lett. B* **716** (2012) 30–61, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[3] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.

[4] CMS Collaboration, "A measurement of the Higgs boson mass in the diphoton decay channel", *Phys. Lett. B* **805** (2020) 135425, doi:10.1016/j.physletb.2020.135425, arXiv:2002.06398.

[5] ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider", *JINST* **3** (2008) S08003, doi:10.1088/1748-0221/3/08/S08003.

[6] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[7] ATLAS Collaboration, "Search for the decay of the Higgs boson to charm quarks with the ATLAS Experiment", *Phys. Rev. Lett.* **120** (2018) 211802, doi:10.1103/PhysRevLett.120.211802, arXiv:1802.04329.

[8] CMS Collaboration, "A search for the standard model Higgs boson decaying to charm quarks", *JHEP* **03** (2020) 131, doi:10.1007/JHEP03(2020)131, arXiv:1912.01662.

[9] ATLAS Collaboration, "Direct constraint on the Higgs-charm coupling from a search for Higgs boson decays into charm quarks with the ATLAS detector", arXiv:2201.11428.

[10] CMS Collaboration, "Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV", arXiv:2205.05550.

[11] ATLAS Collaboration, "Extrapolation of ATLAS sensitivity to $H \to b\bar{b}$ and $H \to c\bar{c}$ decays in VH production at the HL-LHC", ATLAS Note ATL-PHYS-PUB-2021-039, 2021.

[12] CMS Collaboration, "Inclusive search for a boosted Higgs boson decaying to a charm quark pairs in proton-proton collisions at sqrt(s) = 13 TeV", CMS Physics Analysis Summary CMS-PAS-HIG-21-012, 2022.

[13] ATLAS Collaboration, "A search for the $Z\gamma$ decay mode of the Higgs boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Phys. Lett. B* **809** (2020) 135754, doi:10.1016/j.physletb.2020.135754, arXiv:2005.05382.

[14] CMS Collaboration, "Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV", arXiv:2204.12945.

[15] ATLAS Collaboration, "A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector", *Phys. Lett. B* **812** (2021) 135980, doi:10.1016/j.physletb.2020.135980, arXiv:2007.07830.

[16] CMS Collaboration, "Evidence for Higgs boson decay to a pair of muons", *JHEP* **01** (2021)

148, doi:10.1007/JHEP01(2021)148, arXiv:2009.04363.

[17] ATLAS Collaboration, "Search for the Higgs boson decays $H \to ee$ and $H \to e\mu$ in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", *Phys. Lett. B* **801** (2020) 135148, doi:10.1016/j.physletb.2019.135148, arXiv:1909.10235.

[18] CMS Collaboration, "Search for the Higgs boson decay to a pair of electrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV", arXiv:2208.00265.

[19] ATLAS Collaboration, "Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb $^{-1}$ of proton-proton data recorded by the ATLAS experiment", *JHEP* **08** (2022) 104, doi:10.1007/JHEP08(2022)104, arXiv:2202.07953.

[20] CMS Collaboration, "Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at $\sqrt{s}$ = 13 TeV", *Phys. Rev. D* **105** (2022) 092007, doi:10.1103/PhysRevD.105.092007, arXiv:2201.11585.

[21] ATLAS Collaboration, "Search for associated production of a Z boson with an invisibly decaying Higgs boson or dark matter candidates at $\sqrt{s}$ =13 TeV with the ATLAS detector", *Phys. Lett. B* **829** (2022) 137066, doi:10.1016/j.physletb.2022.137066, arXiv:2111.08372.

[22] CMS Collaboration, "Search for dark matter produced in association with a leptonically decaying Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV", *Eur. Phys. J. C* **81** (2021) 13, doi:10.1140/epjc/s10052-020-08739-5, arXiv:2008.04735. [Erratum: Eur.Phys.J.C 81, 333 (2021)].

[23] CMS Collaboration, "Search for exotic Higgs boson decays H to AA to 4 photons with events containing two merged photons in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS Physics Analysis Summary CMS-PAS-HIG-21-016, 2022.

[24] ATLAS Collaboration, "Search for a new scalar resonance in flavour-changing neutral-current top-quark decays $t \to qX$ ($q = u, c$), with $X \to b\bar{b}$, in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", ATLAS Note ATLAS-CONF-2022-027, 2022.

[25] ATLAS Collaboration, "Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production in the multilepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", ATLAS Note ATLAS-CONF-2022-008, 2022.

[26] CMS Collaboration, "Searches for additional Higgs bosons and vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS Physics Analysis Summary CMS-PAS-HIG-21-001, 2022.

[27] CMS Collaboration, "Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV", arXiv:2207.01046.

[28] CMS Collaboration, "Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS Physics Analysis Summary CMS-PAS-HIG-20-006, 2020.

[29] ATLAS Collaboration, "Search for resonant $WZ \to \ell\nu\ell'\ell'$ production in proton $-$ proton collisions at $\sqrt{\mathbf{s}}$ = **13** TeV with the ATLAS detector", arXiv:2207.03925.

[30] ATLAS Collaboration, "A search for heavy Higgs bosons decaying into vector bosons in

same-sign two-lepton final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", ATLAS Note ATLAS-CONF-2022-033, 2022.

[31] ATLAS Collaboration, "Search for doubly charged Higgs boson production in multi-lepton final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", ATLAS Note ATLAS-CONF-2022-010, 2022.