CMS SEARCHES FOR NEW PHYSICS IN THE HIGGS SECTOR*

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Received 29 March 2025, accepted 12 April 2025, published online 26 June 2025

A summary of CMS searches for new neutral resonances with the main focus on scalars and pseudoscalars, based on data collected during Run 2 of the LHC is presented. Special emphasis is given to the most recent results.

DOI:10.5506/APhysPolBSupp.18.5-A31

1. Introduction

The Standard Model (SM) Higgs sector consists of a doublet of complex scalar fields. After electroweak symmetry breaking, this gives rise to a single physical particle — the SM Higgs boson. However, there is no guarantee that the Higgs sector is minimal. Many extensions of the SM predict extended Higgs sectors which result in additional particles yet to be found. These extensions can have the form of:

— additional Higgs singlets, like in the Two Real Singlet Model (TRSM) [1],

— additional Higgs doublets, like in the general Two Higgs Doublet Model (2HDM) [2] and the Minimal Supersymmetry model (MSSM) [3], which assume the existence of one additional doublet,

— combinations of doublets and singlets, the most commonly known in this category being the Next-to-Minimal Supersymmetry model (NMSSM) [4], which assumes one additional doublet and one additional complex singlet,

— Higgs triplets and various combinations of all the above.

* Presented at the 31$^{\text{st}}$ Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

Inclusion of additional singlets leads to the prediction of extra Higgs scalars. In the 2HDM and MSSM, the Higgs sector is expected to contain five physical Higgs bosons, including two scalars, H and X (the former being identified with the 125 GeV SM Higgs boson), one pseudoscalar, A, and a pair of charged Higgs bosons, $H^{\pm}$. In the NMSSM, there are seven physical Higgs particles: three scalars H, X, and Y (by convention, X is here always assumed to be heavier than Y), pseudoscalars A and a (by convention, a being the lighter of the two), and the charged pair $H^{\pm}$. These additional particles can be detected via their decays involving the SM Higgs boson as well as other SM particles. In particular, depending on the masses of the hypothetical new resonances, the following decays may be of interest at the LHC: $X \to HH$, $X \to YH$, $A \to ZH$, $H \to aa$, and $X, A \to f\bar{f}$, where f denotes a generic fermion.

Similar phenomenology can be also expected in different physics models. Models with Warped Extra Dimenions (WED) lead to the prediction of spin-0 radions, R, spin-2 graviton excitations, G, and their respective decays into a pair of SM Higgs bosons, $R, G \to HH$ [5]. Searches for such scenarios are directly relevant to searches for extended Higgs sectors and will be treated jointly in what follows.

There is complementarity between searches for extended Higgs sectors and searches motivated by models with heavy W' and Z' particles, like in Heavy Vector Triplet (HVT) models. Both classes of models lead to the prediction of new heavy resonances decaying into an SM Higgs boson, H, plus an electroweak gauge boson, W or Z, albeit typically in different mass ranges. In the following, searches for the decay $A \to ZH$ will be discussed together with searches for $V' \to VH$ ($V = W, Z$) carried out within the framework of HVT models.

In this note, we report on searches for such processes with the CMS experiment. The CMS detector is described in detail in Ref. [6].

2. CMS searches for $A, V' \to VH$

Searches for heavy resonances decaying into an SM Higgs boson and an electroweak gauge boson are of interest in the context of both extended Higgs sectors and models with heavy W's and Z's. Searches for $A \to ZH$ focus on the relatively low-mass range, *i.e.*, typically below or up to 1 TeV, while searches for $V' \to VH$ are optimized for high masses, up to several TeV. In most of these analyses the Higgs boson is identified via its decay into a pair of b quarks to profit from the large $H \to b\bar{b}$ branching fraction, which leads to two distinct event topologies. For high-mass resonances, the $b\bar{b}$ pair is produced in the highly-boosted regime and reconstructed in the merged topology, *i.e.*, as a single large radius ($R = 0.8$) jet. Conversely, in the low-mass region, the $b\bar{b}$ pair is reconstructed in the resolved topology, *i.e.*, as two separate standard jets ($R = 0.4$). A summary of searches based on Run 2 data is presented in Table 1.

Table 1. Summary of CMS searches for $A, V' \to VH$ based on Run 2 data.

Channel	Ref.	Dataset	Mass range
$A \to Z(ll, \nu\nu)H(bb_{\text{resolved}})$	[7]	36 fb^{-1}	225–1000 GeV
$A \to Z(ll)H(\tau\tau)$	[8]	138 fb^{-1}	225–1000 GeV
$W' \to W(l\nu)H(bb_{\text{merged}})$	[9]	137 fb^{-1}	1000–4500 GeV
$V' \to V(jj_{\text{merged}})H(bb_{\text{merged}})$	[10]	138 fb^{-1}	1300–600 GeV
$Z' \to Z(ll, \nu\nu)H(bb_{\text{merged}})$	[11]	137 fb^{-1}	800–4600 GeV
$Z' \to Z(ll, \nu\nu)H(jj_{\text{merged}})$	[12]	138 fb^{-1}	1400–5000 GeV

The two most recent results in this category are: *(i)* the search for $A \to ZH$ with the Z decaying into a pair of light leptons (electrons or muons) and the Higgs decaying into a pair of τ leptons [8], and *(ii)* the search for $Z' \to ZH$, where the Z decays into either a pair of electrons, muons or neutrinos, and the Higgs decays into a pair of merged jets [12]. The $A \to Z(ll)H(\tau\tau)$ search is an update of a previous analysis performed on data collected in 2016 only, with significant improvements. With an improved state of the art τ-lepton identification [13] and an improved b-jet identification [14], as well as increased statistics, the covered A mass range was extended up to 1000 GeV (*cf.* 400 GeV in Ref. [15]). The resulting 95% C.L. upper limits on the cross section times branching fraction, $\sigma(pp \to A \to ZH)$, were improved by nearly an order of magnitude and range from below 1 pb at $m_A = 225$ GeV to about 0.05 pb at $m_A = 1000$ GeV, thus becoming fully competitive with the ones from Ref. [7].

In the $Z' \to Z(ll, \nu\nu)H(jj_{\text{merged}})$ analysis, new state-of-the-art Machine Learning techniques were applied to tag jet flavors and discriminate against QCD background [16]. Subsequently, the selected sample consisted of events with at most one b-tag in order to minimize the overlap with a previously published analysis [11]. The sample was thus composed mainly of events involving $H \to c\bar{c}$ and $H \to VV^* \to 4q$ decays. This enhances the sensitivity of the search at the highest masses ($m_A > 4$ TeV). The observed 95% C.L. upper limit on $\sigma(pp \to Z' \to ZH)$ ranges from 10 fb at 1.5 TeV to 0.3 fb at 5 TeV.

3. CMS searches for $X \to HH$

$X \to HH$ decays have been searched for in a variety of Higgs decay modes, including combinations of $b\bar{b}$, $\gamma\gamma$, WW, and $\tau\tau$ channels. Spin-0 and spin-2 resonances were both considered. A summary of searches based on the full Run 2 data is presented in Table 2.

Table 2. Summary of CMS searches for $X \to HH$ based on Run 2 data.

Channel	Ref.	Dataset	Mass range
$X \to H(WW \to l\nu l\nu, l\nu qq)H(bb_{\rm merged})$	[17]	138 fb^{-1}	800–4500 GeV
$X \to H(WW, \tau\tau)H(WW, \tau\tau)$	[18]	138 fb^{-1}	250–1000 GeV
$X \to H(\gamma\gamma)H(bb_{\rm resolved})$	[19]	138 fb^{-1}	260–1000 GeV
$X \to H(WW \to l\nu l\nu, l\nu qq)H(bb)$	[20]	138 fb^{-1}	250–900 GeV
$X \to H(bb_{\rm merged})H(bb)$	[21]	138 fb^{-1}	1000–3000 GeV
$X \to H(\gamma\gamma)H(\tau\tau)$	[22]	138 fb^{-1}	260–1000 GeV

A combination of all CMS searches for new resonances decaying into a pair of SM Higgs bosons was recently published [23]. No deviation larger than 2 standard deviations (s.d.) from SM predictions was observed. The combination of upper limits on $\sigma(pp \to X \to HH)$ is shown in Fig. 1. As can

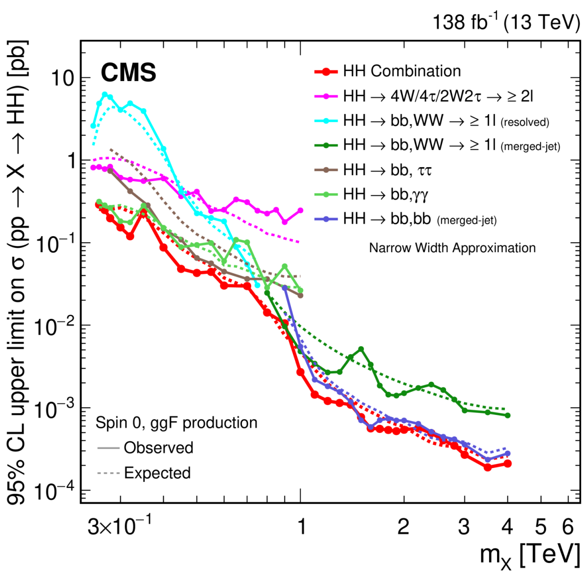

Fig. 1. Combination of upper limits on $\sigma(pp \to X \to HH)$ for a spin-0 resonance X, as a function of its mass, based on available CMS results from Run 2 [23].

be seen, in the high-X mass region ($m_X > 1$ TeV), Higgs decays into $b\bar{b}$ pairs in the merged topology offer the best sensitivity, while below 1 TeV, many channels contribute in a competitive way. This combination does not include the most recent result, namely the search for $X \to H(\gamma\gamma)H(\tau\tau)$ [22]. In this analysis, a parametric neural network (pNN) was used, trained to identify the signal under two different spin hypotheses and a grid of X mass values. The pNN scores were used for event categorization. Ultimately, the signal was extracted for each mass and spin hypothesis from maximum likelihood fits to the $m_{\gamma\gamma}$ distribution in intervals of the pNN score. Results were given in the form of upper limits on $\sigma(pp \to X \to HH)$ that go from about 1 pb at $m_X = 250$ GeV to 0.2 pb at $m_X = 1000$ GeV.

It is worth noting that searches for $X \to HH$ provide unique direct sensitivity to the region of $m_A = 400$–600 GeV and $\tan\beta < 4$ in the hMSSM parameter space. They also lead to the most stringent limits to date in parts of the parameter space of WED models.

4. CMS searches for $X \to YH$

A summary of searches based on Run 2 data is presented in Table 3. Note that all the searches in this section are also relevant to $X \to HH$ (some are explicitly mentioned twice). New results in this category include the search for $X \to Y(bb)H(bb)$ in the resolved topology [24] and for Y and H decaying into pairs of $\tau\tau$ and $\gamma\gamma$ [22]. The $Y(bb)H(bb)$ analysis is based on a collected sample of events with 4 b-tagged jets. The SM background was evaluated using a 3 b-tags sample with event weights applied. These weights were calculated in a dedicated control region to reproduce the kinematics of the 4 b-tags sample using the 3 b-tags sample as input. They were then validated

Table 3. Summary of CMS searches for $X \to YH$ based on Run 2 data.

Channel	Ref.	Dataset	Mass range
$X \to Y(bb_{\text{resolved}})H(\tau\tau)$	[25]	137 fb^{-1}	X: 800–4500 GeV Y: 60–2800 GeV
$X \to Y(bb_{\text{merged}})H(bb_{\text{merged}})$	[26]	138 fb^{-1}	X: 900–4000 GeV Y: 60–600 GeV
$X \to Y(bb_{\text{resolved}})H(\gamma\gamma)$	[19]	138 fb^{-1}	X: 300–1000 GeV Y: 90–800 GeV
$X \to Y(bb_{\text{resolved}})H(bb_{\text{resolved}})$	[24]	138 fb^{-1}	X: 400–1600 GeV Y: 60–1400 GeV
$X \to Y(\tau\tau)H(\gamma\gamma), Y(\gamma\gamma)H(\tau\tau)$	[22]	138 fb^{-1}	X: 300–1000 GeV

in a validation region, and finally applied in the signal region. The largest excess with respect to SM predictions was observed for $m_X = 700$ GeV and $m_Y = 400$ GeV, with a local (global) significance of 4.1 (2.8) standard deviations.

In Ref. [23], a combination of upper limits on $\sigma(pp \to X \to YH)$, with Y assumed to decay into $b\bar{b}$, based on all the CMS analyses that were available to date, was presented. The combination is shown in Fig. 2. For large values of m_X and relatively small m_Y, our best sensitivity is driven by $H \to b\bar{b}$ decays in the merged topology, for larger m_Y Higgs decays to $\tau\tau$ take over, and for small m_X $H \to \gamma\gamma$ decays give the most stringent limits. The new $X \to Y(bb)H(bb)$ search in resolved topology produces further significant improvements in the region $m_X < 1000$ GeV.

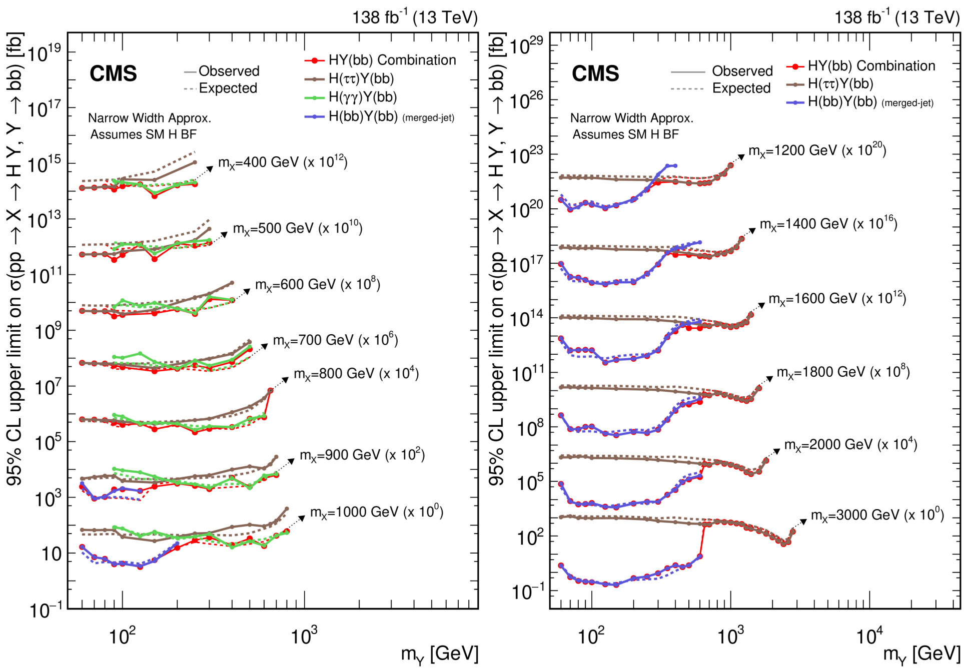

Fig. 2. Combination of upper limits on $\sigma(pp \to X \to YH)$ for a spin-0 resonance X, for X masses below 1 TeV (left) and above 1 TeV (right), as functions of the Y mass, based on available CMS results from Run 2 [23].

The $X \to YH \to \tau\tau\gamma\gamma$ analysis [22] is the same as described in the previous section. Here, the largest deviation from SM predictions was found at $m_X = 320$ GeV and $m_Y = 60$ GeV, where it amounts to 2.6 (2.2) s.d. locally (globally). These results place new non-trivial limits in the available NMSSM parameter space.

5. CMS searches for $H \to aa$

Decays of the SM Higgs boson into a pair of light pseudoscalars, $H \to aa$, are possible in the NMSSM scenario. Searches have been conducted in various combinations of the theoretically predicted dominant a decay modes into b quarks, muons, and τ leptons. A summary of recent CMS searches is presented in Table 4.

Table 4. Summary of CMS searches for $H \to aa$ based on Run 2 data.

Channel	Ref.	Dataset	Mass range
$H \to aa \to bbbb$	[27]	138 fb^{-1}	15–60 GeV
$H \to aa \to \mu\mu bb, \tau\tau bb$	[28]	138 fb^{-1}	12–60 GeV
$X, H \to aa \to \mu\mu\mu\mu$	[29]	137 fb^{-1}	0.21–60 GeV
$H \to aa \to \mu\mu\tau\tau, \tau\tau\tau\tau$	[30]	138 fb^{-1}	4–15 GeV

In addition to searches motivated directly by the NMSSM, with $aa \to bbbb$ [27], $aa \to \mu\mu bb, \tau\tau bb$ [28], and $aa \to \mu\mu\tau\tau, \tau\tau\tau\tau$ [30], a model-independent search was carried out for pair production of low-mass new bosons decaying into a four-muon final state, where the parent particle is not explicitly assumed to be a Higgs boson [29]. Using data taken with special trigger conditions, this search extended the covered a mass range down to as low as 0.21 GeV. No significant excess over background was observed, hence upper limits were calculated on the cross section $\sigma(pp \to H \to aa)$ times the respective model-dependent a branching fractions.

6. Search for $X, A \to t\bar{t}$

A search for new heavy resonances, including scalars and pseudoscalars, decaying directly into a $t\bar{t}$ pair was performed based on the entire Run 2 dataset [31]. Both purely leptonic ($llbb$) and semileptonic ($ljbb$) final states were considered. The SM $t\bar{t}$ production background was calculated in terms of perturbative QCD (pQCD) only, to a final accuracy of NNLO QCD with corrections from soft-gluon resummation at NNLL and NLO EW. The signal was extracted based on 2-dimensional (for $ljbb$) or 3-dimensional (for $llbb$) distributions of the reconstructed $t\bar{t}$ invariant mass and spin correlation variables chosen to maximize the sensitivity to the parity of the hypothetical resonance. A clear excess of events, amounting to over 5 s.d. after combining the final states, was observed at the $t\bar{t}$ production threshold of 343 GeV. This is shown in Fig. 3. While angular analysis clearly disfavors the scalar hypothesis, the observed excess is consistent with a pseudoscalar A with a mass around 365 GeV. However, a $t\bar{t}$ ${}^1S_0^{[1]}$ bound state η_{t} at precisely the $t\bar{t}$ production threshold was in fact predicted in a simplified model

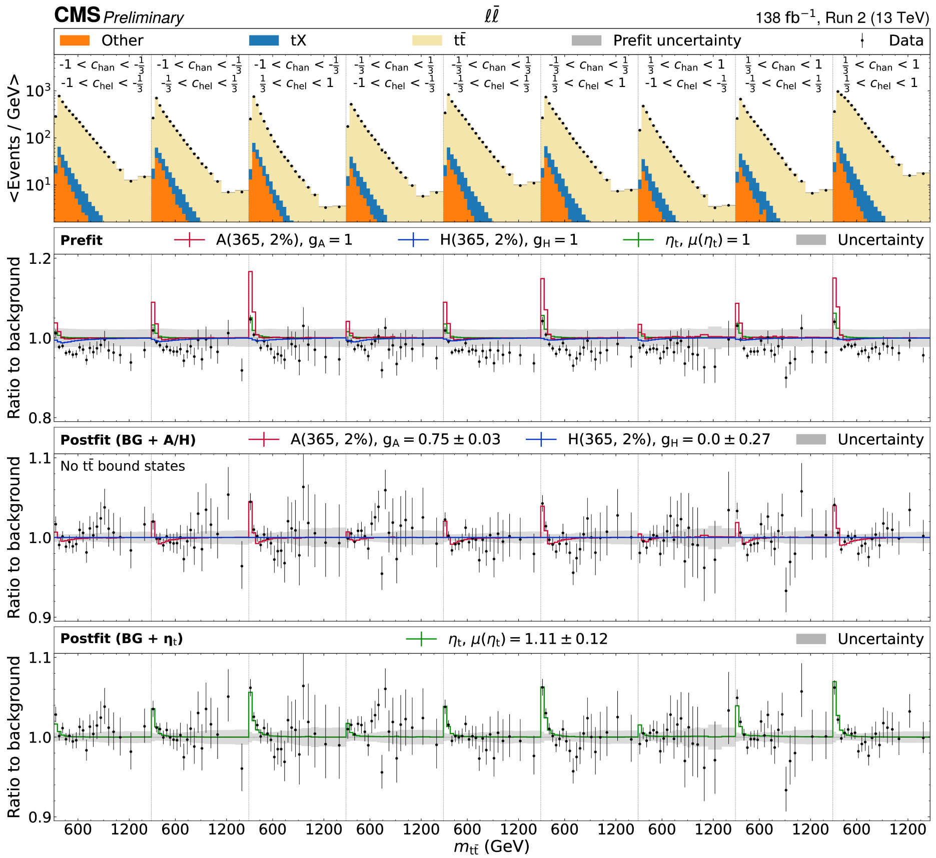

Fig. 3. Distributions of the reconstructed $t\bar{t}$ mass of events in the purely leptonic decay mode, in intervals of angular variables $c_{\rm hel}$ and $c_{\rm han}$. From top to bottom: data and pQCD background predictions, their prefit ratio, the postfit ratio in the A and scalar signal hypotheses, the postfit ratio in the $\eta_{\rm t}$ hypothesis [31].

of non-relativistic QCD [32]. Predictions of this model provide a good fit to the observed data in the entire kinematic range (see Fig. 3, bottom). In particular, lack of evidence of interference between the signal and the pQCD background slightly favors the $t\bar{t}$ bound state hypothesis over the pseudoscalar A hypothesis, the difference in likelihood with respect to the background-only hypothesis being 86.2 and 72.6, respectively (*cf.* 10.4 for the scalar hypothesis). The cross section of this contribution is found to be $\sigma(\eta_{\rm t}) = 7.1$ pb $\pm\, 11\%$, in consistency with non-relativistic QCD predictions. Assuming the $\eta_{\rm t}$ hypothesis, no other excesses were found in data in the rest of the spectrum, thus new upper limits were derived on the production of heavy scalar and pseudoscalar resonances decaying to $t\bar{t}$, in a mass range of 365–1000 GeV and relative widths of 0.5–25%.

7. Summary and outlook

A lot of new results were published over the course of 2024. These included searches for new heavy resonances decaying into a Higgs boson and an electroweak gauge boson, $A, V' \to HV$, a pair of Higgs bosons, $X, G \to HH$, and a Higgs boson and another new boson, $X \to HY$, as well as searches for the SM Higgs boson decaying into lighter Higgs bosons.

Searches for such resonances using Run 2 data are almost completely finalized, with few pending exceptions. Many of the new analyses are followups and extensions of previously published results based on data collected in 2016 only. In addition to a significant increase in statistical power, a lot of improvement has been made in the analysis techniques, in particular in what concerns the usage of advanced Machine Learning techniques for jet flavor tagging, τ lepton identification, *etc.*

A few interesting excesses over SM predictions were observed, with global significances between 2–3 s.d., otherwise no sign of New Physics was found.

The highlight of the season was the first significant observation, at more than 5 s.d., of a resonant pseudoscalar structure at the $t\bar{t}$ production threshold, consistent with a toponium bound state.

We are now turning the focus to Run 3 data, with even more statistics and further improvements in the analysis.

This research was partially funded by a grant from the National Science Center (NCN), Poland, contract No. 2021/41/B/ST2/01369.

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