PROCEEDINGS OF SCIENCE

Exotic Higgs searches

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Exotic Higgs searches cover a wide range of signatures, thus leading to indications to new physics beyond Standard Model. We report a review on exotic Higgs searches for lepton flavour violating Higgs decays, for "mono-Higgs" searches, for Higgs decays to invisible and for high mass Higgs searches. Both ATLAS and CMS results will be shown, for Run-1 data statistics collected at the energy of $\sqrt{s} = 7,8$ TeV and for the first data collected during Run-2 phase at the energy of $\sqrt{s} = 13$ TeV.

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1. Introduction

Since the discovery of the Higgs boson with a mass of $m_h = 125$ GeV/c^2 by the ATLAS and CMS collaborations [1]-[2], an intense physics program to better characterize the Higgs sector of the Standard Model (SM) has been conducted at LHC. Precise measurements of the properties of the newly discovered boson have so far not shown any deviation from the behavior of a Higgs boson within the SM scenario.

The focus has also been directed into two complementary lines of investigation. Firstly, the search for decays of the 125 GeV/c^2 boson non compatible with SM topologies lead to several studies (see Sections 2-3). Secondly, the search for additional scalar, pseudoscalar and charged Higgs bosons (compatible with an extended Higgs sector with respect to the SM configuration) have been performed (see Section 5).

2. Lepton Flavour Violation

Direct evidence for physics beyond the SM could be indicated via lepton flavour violating (LFV) Higgs boson decays. While in SM such decays are forbidden, they can occur naturally in models like one Higgs doublet, composite Higgs models, models with flavour symmetries, Randall–Sundrum models. LFV decays allow $\tau \to \mu$, $\tau \to e$ and $\mu \to e$ transitions via a virtual Higgs boson. Indirect constraints on Higgs decaying branching ratios come from $\mu \to e\gamma$ and $\tau \to \mu\gamma, e\gamma$ searches, setting limits repectively on Br($H \to e\mu$)$< O(10^{-8})$, Br($H \to \tau\mu$)$< O(10\%)$ and Br($H \to \tau e$)$< O(10\%)$.
Both ATLAS and CMS have performed searches for lepton flavour violating Higgs boson. The analyses are based on the data samples of pp collisions at LHC at a center of mass energy of 8 TeV corresponding to an integrated luminosity of $\sim 20 fb^{-1}$.
The CMS collaboration uses a similar strategy for $H \to \tau\mu$ and $H \to \tau e$ searches both for hadronic and leptonic τ decays [3], [4]. The event selection is subvided in three steps. First, a loose selection defining the basic signature is applied. The sample is then divided into categories, according to the number of jets in the event. The zero jet category contains signal events mostly produced by gluon-gluon fusion. The one-jet category contains signal events predominantly produced by gluon-gluon fusion and a negligibly small number of events produced in association with a W or Z boson decaying hadronically. The two jet category is enriched with signal events produced by vector boson fusion.Finally, requirements are placed on a set of kinematic variables designed to suppress the backgrounds ($Z \to \tau\tau$ is the main background in this analysis). The CMS collaboration also searched for $H \to e\mu$ decay [4].
ATLAS searches for lepton flavour violating Higgs decays have different approaches depending on the τ decay. In the analyses with τ hadronically decays [5] [6], two signal regions are defined, using the transverse mass m_T, built using the $\ell - E_T^{miss}$ and $\tau_h - E_T^{miss}$ kinematics. For τ's decaying leptonically [5] two signal regions with and without jets have been defined, and a new background technique estimate has been introduced, based on the premise that the kinematic properties of the SM background are, to a good approximation, symmetric under the exchange $e \leftrightarrow \mu$.

Higgs decay	ATLAS		CMS	
	Exp.	Obs.	Exp.	Obs.
$H \to \tau\mu$ [5],[3]	1.01%	1.43%	0.75%	1.51%
$H \to \tau e$ [5],[4]	1.21%	1.04%	0.75%	0.69%
$H \to e\mu$ [4]	-	-	0.0048%	0.0036%

Table 1: Expected and observed 95% C.L. branching ratios of lepton flavour violating Higgs searches for ATLAS and CMS collaborations.

2.1 Results

Since no consistent excesses were found, upper limits on branching ratios are set at 95 % C.L. The results of the searches are listed in table 1. In the $H \to \tau\mu$ channel a slight excess has been observed in both ATLAS and CMS experiments, corresponding respectevely to 1.3 σ and 2.4 σ. CMS collaboration recently published [7] the results of $H \to \tau\mu$ analysis with data at $\sqrt{s} = 13$ TeV, corresponding to 2.3 fb^{-1} . No excess was found as in the previous analysis, but more data are needed before any definitive conclusion.

3. Invisible Higgs

There are a different proposed extension of the Standard Model for the Higgs boson sector. Some scenarios provide invisible decays of the Higgs boson. For example, the Higgs boson can decay to neutralinos in supersymmetric models, or graviscalars in models with extra dimensions. In general, interactions of the Higgs boson with the unknown dark matter (DM) sector may introduce invisible decay modes, and bounds on these decays can constrain DM models.
The identification of an invisible decaying Higgs boson is performed by searching events where Higgs boson is produced together with other particles. The searches cover different production modes of the Higgs boson and use events with a large missing transverse momentum, E_T^{miss} . The processes studied in the analyses are:

- Higgs boson production via vector boson fusion (VBF) process: the signature consists in two jets with a large separation in pseudorapidity, forming a large invariant dijet mass, together with large E_T^{miss} .
- Higgs boson production in association with a Z boson, with Z decaying to two leptons, and the Higgs boson decays to invisible particles. A search for final states with two opposite-sign and same-flavour leptons (electrons or muons) with large E_T^{miss} has been performed.
- Higgs boson production in association with a vector boson V (W or Z), where $V \to jj$ and the Higgs boson decays to invisible particles. The signature is two jets with an invariant mass consistent with the V mass and large E_T^{miss} .

The analysis with the best sensitivity is the VBF one, which benefits from a large SM cross section, but also suffers from large backgrounds due to its two jets plus missing transverse energy E_T^{miss} final state. The associated production mode has a smaller SM cross section, but the presence of the

V boson provides a variety of identifiable final states with relatively low backgrounds. Dedicated control regions have been defined in order to estimate the background contribution.
The ATLAS collaboration performed searches in VBF [8] channel, and in VH channels [9], where V=W,Z, in $V \to jj$ and $Z \to \ell\ell$ final states. CMS collaboration searched for invisible Higgs decays in VBF channel [11] and in ZH cahnnel [12], where $Z \to bb$ or $Z \to \ell\ell$.

3.1 Results

In these searches, no excess of events was found and upper limits at 95% C.L. were set on the Higgs boson production cross section times the branching ratio. The Run-1 results for ATLAS and CMS collaborations are reported in table 2.

	Channels	$\sqrt{s}$[TeV]	Exp.	Obs.
ATLAS	$(Z \to \ell\ell)h$ [9]	8	0.62	0.75
	$(V \to qq)h$[9]	8	0.86	0.78
	VBF [8]	8	0.28	0.31
	Invisible comb. [10]	7+8	0.27	0.25
	Invisible and visible comb. [10]	7+8	0.24	0.23
CMS	Vh [12]	7+8	0.83	0.81
	VBF [11]	8	0.40	0.57
	Invisible comb. [13]	7+8	0.30	0.36

Table 2: Upper bounds on BR(h →invisible) at the 95% CL from the individual searches and their combination for ATLAS and CMS collaboration.

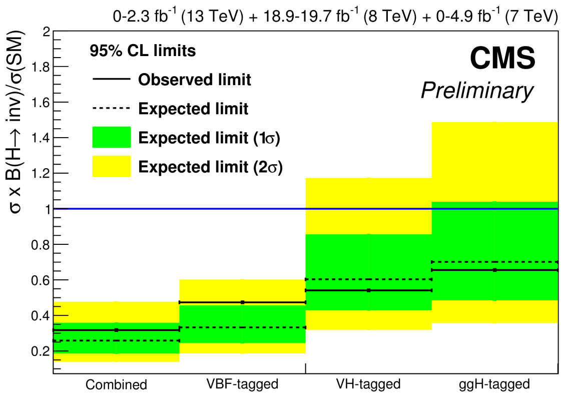


Figure 1: Upper bounds on BR(h →invisible) at the 95% CL from the individual searches and their combination for Run-1 and Run-2 data for CMS collaboration.

The ATLAS collaboration also provides an upper limit obtained from the combination of all channels [10], visible and invisible. These results are dominated by the direct searches for invisible decays and improve the expected limit of 11% in sensitivity compared to the invisible decay channels alone.
The CMS collaboration has also published results [14], [15] for early Run-2 data for VBF and VH analyses. The observed and expected 95% limits for Run-1 and Run-2 combination are showed in Fig. 1.

4. Mono-h

The discovery of the Higgs boson provides a new opportunity to search for DM production via the h + E_T^{miss} signature. This final state allows to probe information about the structure of DM-SM coupling. This signature is known as "mono-h".
The modelization of such process follows typically two approaches: one use effective field theory (EFT), which are described by contact operators since the mediator particles of the interaction are

too heavy to be produced directly in the experiment; the second approach use simplified models, a less generic description which rely on few parameters.
Only ATLAS collaboration has published results both with Run-1 and Run-2 available datasets. The ATLAS results have been interpreted in terms of the following simplified models:

- A model where a vector or scalar mediator is exchanged in the s-channel, radiates a Higgs boson, and decays into two DM particles.
- A heavy scalar Higgs (H) decays into a Higgs boson and DM candidates.
- In the Z′-2HDM model a vector mediator Z' decays in $Z' \to hA$, where A is a pseudoscalar which subsequently decays into two DM particles.

ATLAS searches were performed in final states with E_T^{miss} and a Higgs boson decaying into a pair of bottom quarks $h \to b\bar{b}$ [16], a pair of photons $h \to \gamma\gamma$ [17] or in four leptons $h \to ZZ^* \to 4\ell$ [18].

4.1 Results

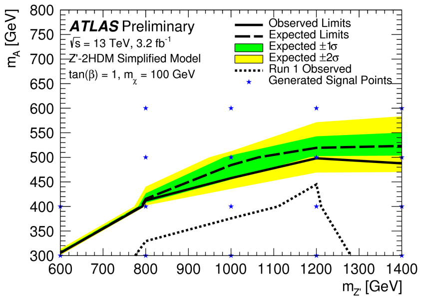
No excesses were found in the analyses, and upper limits on the production cross section for the process times branching ratio of the Higgs boson were set at 95% C.L., interpreted as lower limits on the mass parameters of interest in the specific model. Figure 2 shows the results for the three ATLAS analyses for a specific model, with Run-2 dataset corresponding to 3.2 fb^{-1} . For $h \to b\bar{b}$ analysis figure 2 shows the constraints on the (m'_Z, m_A) space for the Z′-2HDM model, and exclude masses of the pseudoscalar A up to 500 GeV. In the model involving heavy scalar production, $h \to \gamma\gamma$ search set a 95% CL upper limit of 29.6 fb. Finally in the $h \to ZZ^* \to 4\ell$ analysis the theoretical expectation ranges between 0.3 fb and 1.0 fb for the scalar model.

5. High mass Higgs searches

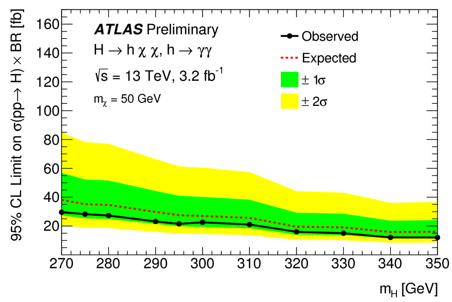
Aside from the studies of the properties and decays of the 125 GeV/c^2 Higgs boson, both ATLAS and CMS have conducted a rich program of searches for additional Higgs bosons. Most of these results have been performed using the Run-1 data collected at LHC, though a few new results based on the 2015 dataset are publicly available.

Many of these results have been intepreted in the context of a *Two-Higgs-Doublet-Model* (2HDM) scenario, where an additional electroweak doublet participates to the ElectroWeak Symmetry Breaking Mechanism of the SM. Such configuration for the Higgs sector is typical of several extensions of the SM, including, but not limited to, SUSY or Composite Higgs scenarios. Moreover, an extended Higgs sector is possible also within a non-minimal SM description, in that no additional first principles are required besides the existence of the new electroweak doublet. Assuming this structure for the Higgs sector leads to the presence of two scalar, one pseudoscalar and two charged Higgs bosons. In the vast majority of the interpretations, the lower mass scalar boson is interpreted to be the already discovered Higgs boson with a mass of 125 GeV/c^2.

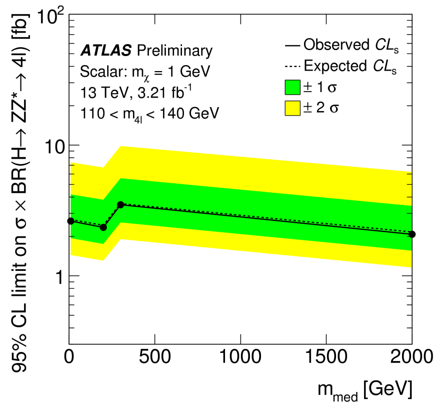
A general 2HDM is characterized by many degrees of freedom, with 14 a priori unconstrained parameters and four special types, depending on how the two SU(2)$_L$ electroweak doublets are coupled to the fermion sector. In their studies, both ATLAS anc CMS have focused on only two



(a) *Exclusion plot on the (m'_Z, m_A) space for the Z'-2HDM in the $h \to b\bar{b}$ analysis.*



(b) *Upper limits at 95% C.L. on the production cross section for the $h \to \gamma\gamma$ channel.*



(c) *Upper limits at 95% C.L. on the production cross section for the $h \to ZZ^* \to 4\ell$ channel.*

Figure 2: Run-2 results of the ATLAS collaboration for mono-h searches.

configurations, generally called type-I and type-II. In 2HDM's of type-I, the two Higgs doublets couple to both up- and down-type fermions equally; in 2HDM's of type-II one doublet couples exclusively to up-type and the other exclusively to down-type fermions. The 14 free parameters can be reduced to six requiring CP conservation in the Higgs sector and other external measurements. The remaining six parameters are the masses of the five physical Higgs bosons m_h, m_H, m_A and $m_{H\pm}$, the mixing angle α between the two scalars and the ratio of the vacuum expectation values of the two doublets $tan\beta$. The two angles α and β can be substituted by $\cos(\beta-\alpha)$ and $\tan\beta$ without loss of generality.

5.1 Indirect constraints to 2HDM

By identifying the lower mass scalar in 2HDM with the discovered 125 GeV/c^2 Higgs boson h, both ATLAS and CMS have been able to give indirect constraints on the model using the properties of h, using the inputs to their combined coupling analysis [19] based on the Run-1 dataset only. The results [20]-[21] are shown in Figure 3 in terms of exclusion plots on the $\cos(\beta-\alpha)$ and $\tan\beta$ parameters.

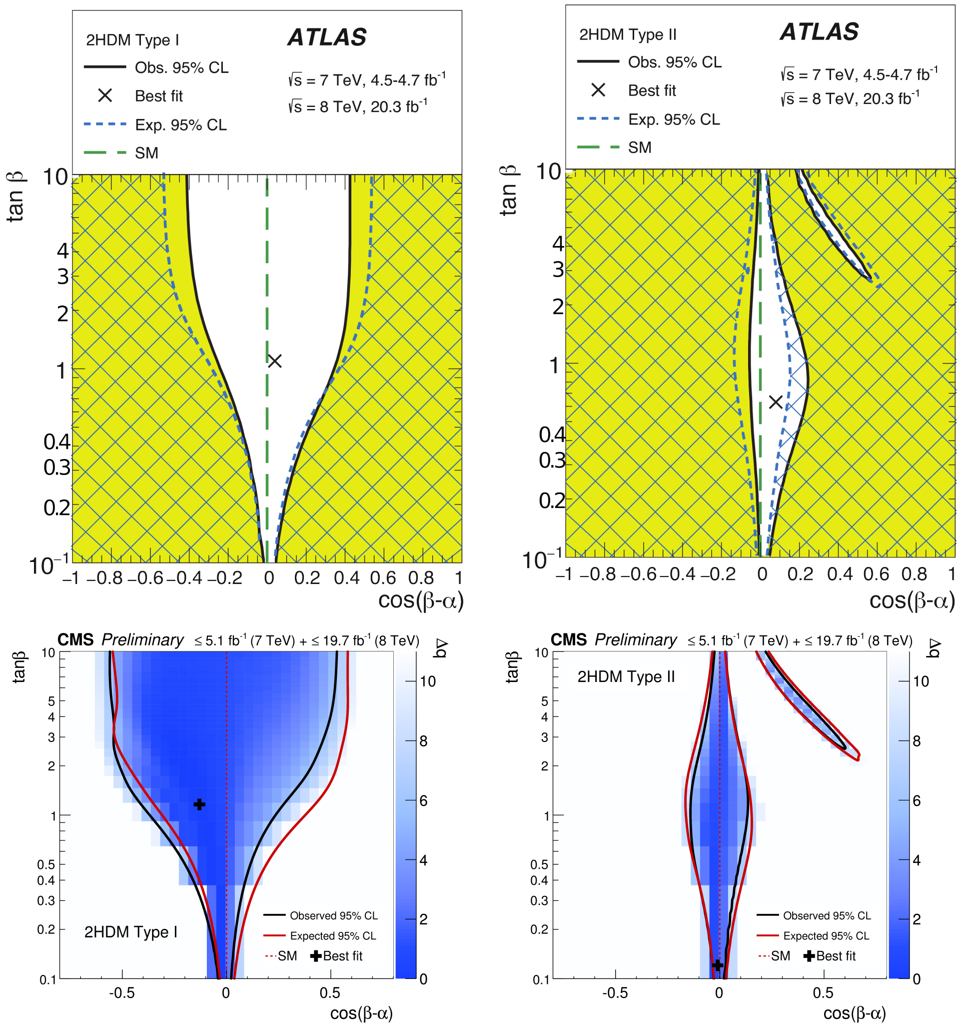


Figure 3: Regions of the $[\cos(\beta-\alpha), \tan\beta]$ plane of two types of 2HDMs excluded by fits to the measured rates of Higgs boson production and decays for ATLAS and CMS. The likelihood contours where -2lnΛ=6.0, corresponding approximately to the 95% CL (2 std. dev.), are indicated for both the data and the expectation for the SM Higgs sector. The cross in each plot marks the observed best-fit value.

5.2 Direct constraints to 2DHM

The CMS collaboration also produced a summary of the direct searches for high mass scalar, pseudoscalar and charged Higgs bosons within a 2HDM interpretation [21] of the Run-1 dataset only. Given that the interpretation of the 125 GeV/c^2 Higgs boson couplings within the 2HDM constrain the $\cos(\beta-\alpha)$ parameter to be small, in this study the CMS collaboration fixed $\cos(\beta-\alpha) = 0.1$. This allowed to show the results in terms of the higher mass Higgs boson parameter and $\tan(\beta)$. This summary is reported in Figure 4.

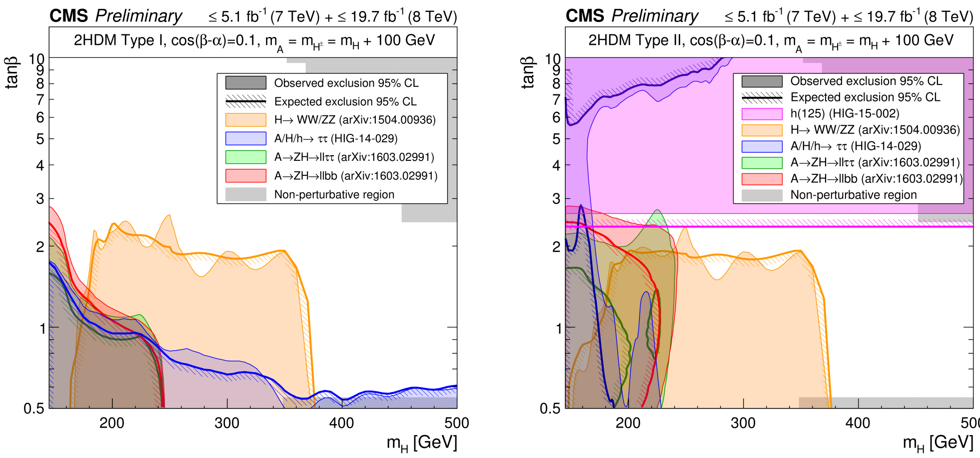


Figure 4: 95% CL exclusion contours, in two 2HDM scenarios of (a) Type-I and (b) Type-II, as obtained by selected CMS analyses that have been performed on the LHC Run-1 dataset, in the $[m_H, \tan\beta]$ plane.

6. Conclusions

While a detailed characterization of the properties of the newly discovered 125 GeV$/c^2$ Higgs boson remains an important part of the LHC physics program, both ATLAS and CMS are deeply focused on the searches for exotic Higgs decays and the presence of an extended Higgs sector. So far, no deviation with respect to the SM expected behavior has been observed using either the Run-1 or the Run-2 LHC collision datasets. Limits have been put on the Lepton-Flavour-Violating and Invisible decays of the Higgs boson, and on the parameter space of general extensions of the Higgs sector.

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