

# Higgs to four leptons searches at the LHC : constraints on Abelian Hidden sector models

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**Abstract.** Recent results on Higgs searches at the LHC by the ATLAS and CMS collaborations claim the observation of a new boson with properties compatible with the Standard Model (SM) Higgs boson, at a mass of about 126 GeV. The production rate of the new particle seems compatible with the SM prediction. In some models beyond the SM, an Abelian Hidden sector is coupled to the SM, and the resulting exotic Higgs and new gauge ( $Z'$ ) fields are allowed to mix with the corresponding SM fields. This admits new processes such as the decay of the lightest Higgs boson (after mixing) to a pair of new gauge bosons, and the decay of the new gauge bosons to pairs of leptons :  $H \rightarrow Z'Z' \rightarrow 4\ell$ . This modifies the rate of 4-lepton events sought for in the usual SM  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  search. Assuming the observed particle is a Higgs boson of a mass of 126 GeV, we investigate the consequences of the addition of this new process to the search for a SM Higgs boson decaying to 4 leptons, and the resulting constraints on the Abelian Hidden sector model parameters. The constraints are drawn in terms of Higgs mixing angle and new gauge boson mass.

## 1. Introduction

The observation of a new particle consistent with the Standard Model (SM) Higgs ( $H$ ) boson [1, 2] opens a new era for the LHC experiments, which are switching from the discovery mode to measuring the properties of the new particle. Several quantities are of particular interest: spin, CP state, mass. A precise measurement of these quantities will require refined analyses. Another quantity, which is in fact the first to be measured experimentally because it is the one leading to the discovery (or observation) claim, is the production rate. This number is predicted in the SM, as a function of the  $H$  mass  $M_H$ , and experiments usually quote the signal strength  $\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}}$ , the ratio between the observed rate and the SM predicted rate. Current experimental results show that  $\mu$  is consistent with 1, although still with large uncertainties, which shall shrink as experiments analyze more data and refine their analyses.

A particularly interesting scenario is if  $\mu$  becomes significantly different from 1, because it then requires extensions of the SM. An example of such extensions is the existence of a Hidden sector connected to the SM, and in particular a case where the Higgs domains of the two sectors are mixing. This is a general concept, that can be applied in several models [3, 4, 5, 6], and it has been studied in general in [7, 8]. Applications to a specific model will require measurements of precise numbers such as the Higgs couplings, observation of new gauge bosons, etc. In this article, we focus on a particular model, the Hidden Abelian Higgs Model (HAHM) proposed by Wells *et al.* [3, 4]. It is a particularly interesting model since it allows processes such as  $H \rightarrow Z'Z' \rightarrow 4\ell$  and  $H \rightarrow ZZ' \rightarrow 4\ell$ . These processes can be sought for directly, using



minimal changes in the standard  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  searches carried on by ATLAS or CMS. Another interesting aspect is that for a light  $Z'$  boson (around 50 or 60 GeV) and a light Higgs boson (around 125 GeV), a  $H \rightarrow Z'Z' \rightarrow 4\ell$  event would pass the usual cuts applied for the  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  analyses, so that we may have direct access to the “hidden” part of the Higgs width. This provides two interesting observables for the new model :

- (i) a modified rate of  $4\ell$ -events compared to the SM prediction; and
- (ii) a narrow resonance in the “secondary” dilepton invariant mass distribution (the one containing the off-shell  $Z$ ).

It has to be noted that for lighter  $Z'$  (typically below 50 GeV),  $H \rightarrow Z'Z'$  events would be mostly cut out by analysis cuts on the invariant mass, but  $H \rightarrow ZZ'$  events may survive. This of course depends strongly on the analysis cuts that are applied and may be different between the various experiments.

The present study focuses on the first item (i) and investigates how the rate of observed  $4\ell$ -events is changed assuming Wells *et al.* model (HAHM) instead of the SM.

## 2. Hidden Abelian Higgs Model (HAHM)

### 2.1. Model parameters

The model is presented in [3, 4], where its parameters are defined. Three of the parameters can be considered as free: the Higgs boson mass  $M_H$ , the new gauge boson mass  $M_{Z'}$ , and the mixing angle between the SM and Hidden Higgs sectors  $\theta_h$ . For convenience, we will use the sine-square of the mixing angle,  $\sin^2 \theta_h$ , which we will denote  $s_h^2$ , and similarly, the cosine-square of this angle will be denoted  $c_h^2$ .

### 2.2. Couplings

**2.2.1. Higgs couplings** In the model, the Higgs boson is coupled to SM particles in a similar way as in the SM, with the following features :

- (i) decays involving new gauge bosons ( $H \rightarrow ZZ'$ ,  $H \rightarrow Z'Z'$ ) are allowed;
- (ii)  $H \rightarrow ZZ^{(*)}$  couplings are non-trivially modified with respect to SM; and
- (iii) all other couplings are suppressed by a factor  $c_h^2$ , in particular the effective coupling to gluons for the Higgs boson production by gluon fusion.

To the first order, the  $H \rightarrow ZZ'$  process is suppressed compared to the other decays. In the following, we will consider only  $H \rightarrow ZZ^{(*)}$  and  $H \rightarrow Z'Z'$  decays.

**2.2.2. Coupling to SM fermions** The gauge bosons  $Z$  and  $Z'$  are coupled to SM fermions. Couplings depend on many model parameters. To the first order, the  $Z \rightarrow \ell^+\ell^-$  coupling in the HAHM is the same as in the SM, and we will consider that the new gauge boson  $Z'$  decays only to leptons with a 100% branching fraction.

## 3. Experimental results from ATLAS and CMS in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ search

### 3.1. Higgs boson mass and signal strength

In this study, we assume that the new boson observed by the ATLAS and CMS experiments [1, 2] is a Higgs boson of mass 126 GeV. The experimental results on the signal strength  $\mu$  (ratio of the observed cross-section to the SM expectation) are shown in Table 1 with the corresponding uncertainty  $\sigma_\mu$ . These numbers are in the  $4\ell$  channel only.

The approach of this study is to assess how the HAHM parameters are constrained by these experimental results, if we assume that  $H \rightarrow Z'Z'$  events are allowed and may be observed.

	$\mu$	$\sigma_\mu$
ATLAS	1.4	$\pm 0.6$
CMS	0.7	$^{+0.4}_{-0.3}$

**Table 1.** Experimental results from ATLAS [1] and CMS [2] in the  $4\ell$  channel.

### 3.2. Experimental analysis cuts

The ATLAS and CMS experiments have different analysis strategies, but both analyses are cut-based. The kinematics of the leptons from  $H \rightarrow Z'Z' \rightarrow 4\ell$  events is similar to that of the  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ , therefore we will assume that all efficiencies and acceptance are unchanged. Both analyses are based on selecting events with 4 leptons and forming lepton pairs. One pair has a mass  $m_{12}$  close to the SM  $Z$  boson mass, and the other has a mass  $m_{34}$  on which the cut is relaxed to account for off-shell  $Z$  boson. The cuts on these quantities are:

- ATLAS:  $m_{12} > 50$  GeV,  $m_{34} > 17.5$  GeV for a 4-lepton mass of about 126 GeV;
- CMS:  $m_{12} > 40$  GeV,  $m_{34} > 12$  GeV.

In order to have an approach that is consistent with both experiments and avoids boundary effects, we will consider the following cases:

- (i) if  $20 \leq M_{Z'} < 35$  GeV, the  $H \rightarrow Z'Z'$  events cannot be detected by the experiments; and
- (ii) if  $55 \leq M_{Z'} < 80$  GeV, the  $H \rightarrow Z'Z'$  events can be detected by the experiments.

The cases of  $M_{Z'} < 20$  GeV and  $35 \leq M_{Z'} < 55$  GeV are discarded because of the  $m_{34}$  and  $m_{12}$  cuts respectively. We also do not consider the case where the  $Z'$  boson would be heavier than the  $Z$  boson.

## 4. Constraints on HAHM parameters

We draw limits on hidden sector parameters by calculating the event rate predicted by the new model, compared to the SM, and by checking the compatibility with the experimental results.

In the HAHM, the hidden width is known as a function of the three free parameters:  $M_H$ ,  $M_{Z'}$  and  $s_h^2$ . The Higgs boson mass being fixed to 126 GeV, results will be presented in a  $(M_{Z'}, s_h^2)$  plane.

### 4.1. Method

Our approach is to calculate, using only the theoretical (phenomenological) considerations, the expected production rate of  $H \rightarrow 4\ell$  events, compared to the SM prediction. In other words, we can calculate, if we consider only gluon fusion (dominant production mode at the LHC) :

$$\frac{\sigma_{\text{HAHM}}}{\sigma_{\text{SM}}} = \frac{\sigma_{\text{HAHM}}(gg \rightarrow H) \cdot \text{BR}_{\text{HAHM}}(H \rightarrow 4\ell)}{\sigma_{\text{SM}}(gg \rightarrow H) \cdot \text{BR}_{\text{SM}}(H \rightarrow 4\ell)} . \quad (1)$$

We compare the above quantity in a  $(M_{Z'}, s_h^2)$  plane, with the measured value of the production rate divided by the SM prediction ( $\mu$ ). This approach is similar to the one used in [7], although applied to a specific model (HAHM). Of course, in the HAHM model, the Hidden decay width is linked to the  $Z'$  mass. The reason we chose to look specifically at the  $Z'$  mass is that in the usual approach [7, 8], it is considered that the decays to Hidden particles is not accessible (invisible), and therefore not sought for. We want to place ourselves in the case of Hidden particles ( $Z'$ ) decaying to SM fermions, therefore potentially adding signal to the SM search  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ .

In Eq. 1, the denominator is given by the SM values, and depends only on the (SM)  $H$  mass. The term  $\text{BR}_{\text{SM}}(H \rightarrow 4\ell)$  involves only  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  events, and therefore is a constant of

the SM (since the  $Z$  mass is known). In the numerator, however, values come from the HAHM model and depend on the free parameters  $M_H$ ,  $M_{Z'}$  and  $s_h^2$ . The cross-section term depends on the Higgs mass and the mixing angle, and we assume the universal suppression :

$$\frac{\sigma_{\text{HAHM}}(gg \rightarrow H)}{\sigma_{\text{SM}}(gg \rightarrow H)} = c_h^2 = (1 - s_h^2) . \quad (2)$$

The term  $\text{BR}_{\text{HAHM}}(H \rightarrow 4\ell)$  can be decomposed into three components:

$$\text{BR}_{\text{HAHM}}(H \rightarrow 4\ell) = \text{BR}_{\text{HAHM}}(H \rightarrow ZZ^{(*)} \rightarrow 4\ell) + \text{BR}_{\text{HAHM}}(H \rightarrow Z'Z' \rightarrow 4\ell) + \text{BR}_{\text{HAHM}}(H \rightarrow ZZ' \rightarrow 4\ell) \quad (3)$$

As stated before,  $H \rightarrow Z'Z' \rightarrow 4\ell$  events are considered as detected if  $M_{Z'} > 55$  GeV, and as not detected if  $M_{Z'} < 35$  GeV. Besides  $H \rightarrow ZZ' \rightarrow 4\ell$  are not taken into account. Therefore, the formulae that are used to evaluate the rate of events in the HAHM model are :

$$\frac{\sigma_{\text{HAHM}}}{\sigma_{\text{SM}}} = \begin{cases} (1 - s_h^2) \cdot \frac{\text{BR}_{\text{HAHM}}(H \rightarrow ZZ^{(*)})}{\text{BR}_{\text{SM}}(H \rightarrow ZZ^{(*)})} & \text{if } M_{Z'} < 35 \text{ GeV} \\ (1 - s_h^2) \cdot \frac{\text{BR}_{\text{HAHM}}(H \rightarrow ZZ^{(*)}) \cdot [\text{BR}_{\text{SM}}(Z \rightarrow 2\ell)]^2 + \text{BR}_{\text{HAHM}}(H \rightarrow Z'Z')}{\text{BR}_{\text{SM}}(H \rightarrow ZZ^{(*)}) \cdot [\text{BR}_{\text{SM}}(Z \rightarrow 2\ell)]^2} & \text{if } M_{Z'} > 55 \text{ GeV} \end{cases} , \quad (4)$$

where we have used that the branching fraction  $Z' \rightarrow \ell^+ \ell^-$  is 100%. An immediate consequence, is that in the first case ( $M_{Z'} < 35$  GeV), the ratio is always less than 1, since the branching fractions in the HAHM model are lower than in the SM. This means that for a low-mass  $Z'$ , the HAHM model predicts less events than the SM, given the experimental analysis cuts that are used. On the other hand, in the second case ( $M_{Z'} > 55$  GeV), the ratio can be either larger or smaller than 1.

## 4.2. Results

Results are presented first for the low-mass  $Z'$  ( $20 \text{ GeV} < M_{Z'} < 35 \text{ GeV}$ ), and then for the larger-mass  $Z'$  ( $55 \text{ GeV} < M_{Z'} < 80 \text{ GeV}$ ). We show the distribution of  $\sigma_{\text{HAHM}}/\sigma_{\text{SM}}$  in the  $(M_{Z'}, s_h^2)$  plane, and we superimpose the contour corresponding to experimental results (ATLAS, CMS)  $\mu$ , and 68% and 95% C.L.. The values used have already been introduced previously, in Table 1.

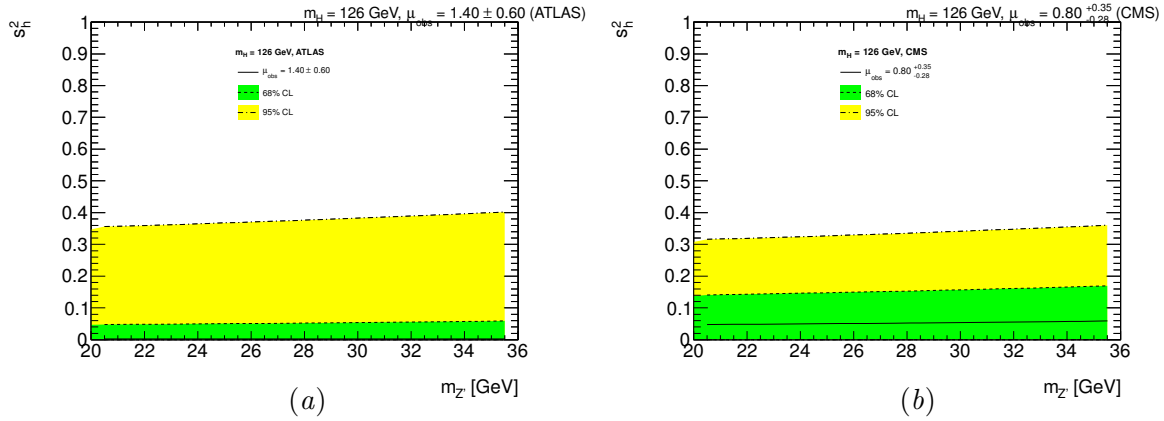
### 4.2.1. Low-mass $Z'$ ( $20 \text{ GeV} < M_{Z'} < 35 \text{ GeV}$ )

In the low-mass region, we assume that the exotic decays do not pass the experimental analysis cuts, and therefore Eq. 4 (top) is used. Figure 1 shows the distribution of  $\sigma_{\text{HAHM}}/\sigma_{\text{SM}}$  in the  $(M_{Z'}, s_h^2)$  plane, with the  $\mu$ , and 68% and 95% C.L. contours.

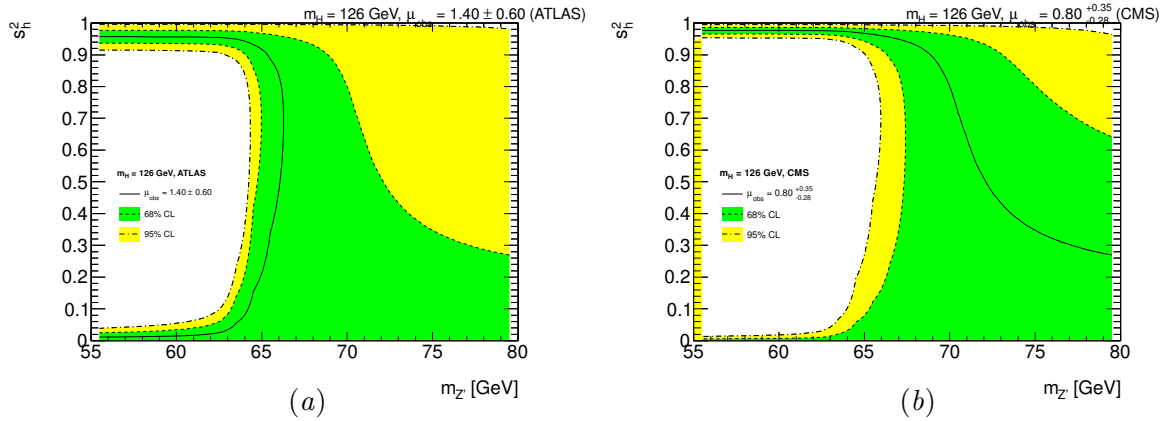
Only the 95% C.L. contour (dot-dashed curve) is visible on the left plot (ATLAS). This is because the ATLAS result  $\mu$  is larger than 1, while the HAHM predicts less events than the SM. The yellow region below the dot-dashed curve is compatible with the ATLAS result at 95% C.L.. On the other hand, CMS result  $\mu$  is smaller than 1, therefore we see the  $\mu$  contour (solid line), and we also see the 68% C.L. contour (dashed line).

### 4.2.2. High-mass $Z'$ ( $55 \text{ GeV} < M_{Z'} < 80 \text{ GeV}$ )

In the high-mass region, we assume that the exotic decays pass the experimental analysis cuts, and therefore Eq. 4 (bottom) is used. Making this assumption also implies that we assume that the kinematics of the leptons (which are the objects reconstructed experimentally) is the same as for standard  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  events. This assumption has been checked using events generated with MadGraph. Figure 2 shows the distribution of  $\sigma_{\text{HAHM}}/\sigma_{\text{SM}}$  in the  $(M_{Z'}, s_h^2)$  plane, with the  $\mu$ , and 68% and 95% C.L. contours.



**Figure 1.** (a)  $\text{BR}_{\text{SM}}(H \rightarrow ZZ)$  in the  $(M_{Z'}, s_h^2)$  plane, (b)  $\text{BR}_{\text{SM}}(H \rightarrow Z'Z')$  in the  $(M_{Z'}, s_h^2)$  plane.



**Figure 2.** (a)  $\text{BR}_{\text{SM}}(H \rightarrow ZZ)$  in the  $(M_{Z'}, s_h^2)$  plane, (b)  $\text{BR}_{\text{SM}}(H \rightarrow Z'Z')$  in the  $(M_{Z'}, s_h^2)$  plane.

The same colors and styles are used for the contours: the solid line is the  $\mu$  contour, the dashed line is the 68% C.L. contour, and the dot-dashed line the 95% C.L. contour. As already stated,  $\sigma_{\text{HAHM}}/\sigma_{\text{SM}}$  in this case can be smaller or larger than 1, therefore more contours are visible. The green [yellow] region between the two dashed [dot-dashed] lines is the part of the parameter space that is compatible with the experimental results at 68% C.L. [95% C.L.]. We see that in both cases, a large region of the parameter space is excluded (not compatible at 95% C.L.), below  $M_{Z'} \sim 63$  GeV, and between  $s_h^2 \in [0.02, 0.94]$  approximately. Indeed, for  $M_{Z'} < M_H/2$ , the  $H \rightarrow Z'Z'$  decay with two on-shell bosons is kinematically allowed, and will significantly increase the number of expected  $4\ell$ -events. It should be reminded here that the branching fraction of  $Z' \rightarrow 2\ell$  has been taken as 100%, which overestimates the number of expected events with the HAHM model. Lower branching fraction would lead to a larger region compatible at 68 or 95% C.L. .

For  $M_{Z'} > M_H/2$ , since both  $H \rightarrow ZZ^{(*)}$  and  $H \rightarrow Z'Z'$  are suppressed ( $H \rightarrow Z'Z'$  is suppressed, and  $H \rightarrow ZZ^{(*)}$  gets the SM value, so we are almost in the SM case), most of the parameter space is compatible at least at 95% C.L., with the experimental results.

## 5. Conclusion

Assuming that the newly-observed particle is a Higgs boson of mass 126 GeV, we show that the measured event rate is compatible with a large part of the HAHM parameter space. Refined analyses from the ATLAS and CMS experiments, with larger statistics and improved systematic uncertainties treatment, are expected soon and will improve the limits set on the Higgs mixing angle and new gauge boson mass. A direct search for  $H \rightarrow Z'Z' \rightarrow 4\ell$  events by the experiments would complement this study.

## References

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