Using the Higgs as a portal to the "hidden sector"

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Abstract. The ATLAS and CMS experiments at the Large Hadron Collider at CERN provide an opportunity for studying the physics of the Standard Model (SM) and beyond. In particular, one may search the so called "hidden sector" for a possible new neutral boson which could be revealed by the study of the decay of the recently discovered Higgs-like boson or alternatively any other as yet undiscovered Higgs boson. After the LHC successfully concluded a three years running period, the ATLAS and CMS experiments presented their recent results in Moriond conference with 25 fb^{-1} of integrated luminosity recorded. We present a phenomenology study on $H \to Z'Z' \to 4l$ using the recent results from the ATLAS and CMS experiments. The aim of this work is interpreting the experimental results using the HAHM as a benchmark model and presenting the compatibility of the model with these results with the SM.

1. Introduction

In the summer of the 2012, the ATLAS and CMS collaborations announced the discovery of a new particle, compatible with Higgs boson [1, 2]. However, we lack strong evidence for the Higgs decaying into fermions ($H \to \tau\tau$ and $H \to bb$) which is important to probe the SM Higgs boson hypothesis (see the latest published results from ATLAS and CMS in the $H \to \tau\tau$ search [3, 4] and in the $H \to bb$ search [5, 6]). Furthermore a precise measurement of the properties of this "new boson" is needed: spin, CP-states, mass, signal strength.

The signal strength is the first quantity which has been measured experimentally. It is defined as the ratio between the observed rate and the SM predicted rate ($\mu = \sigma_{obs}/\sigma_{SM}$). This quantity is the one leading to the observation claim. The current experimental results show that μ is close to 1 [7, 8], but an interesting case would be if μ becomes significantly different to 1, as then it would require an extention of the SM.

For these reasons the theories describing physics beyond the Standard Model (BSM) attempt to re-interpret the experimental results. One of these BSM theories is the "Hidden Abelian Higgs Model" (HAHM) [9, 10].

The HAHM model introduces two extra physical states which serve as the main routes to find evidence for the HAHM at the LHC:

- the existence of a new gauge boson Z' (lighter than the Z boson) that couples to SM states according to the strength of the kinematic mixing parameter;
- the existence of two CP-even Higgs boson mass eigenstates, both of which couple to SM states by virtue of the mixing of the HAHM Higgs boson with the SM Higgs boson.

The search for $H \to Z'Z' \to 4l$ is an interesting decay channel which is compatible with one of the main decay channels ($H \to ZZ^{(*)} \to 4l$) used in the discovery of the Higgs and is also motivated by the HAHM model.

The present study investigates how the rate of the observed $4l-$events is changed assuming Wells *et al.* model (HAHM) instead of the SM.

2. Hidden Abelian Higgs Model (HAHM)

The HAHM is one of the representative cases of a Hidden World, where "hidden" means a collection of particles that are not from the SM, that are not charged under the SM gauge groups, and that do not couple via gauge interactions to SM particles.

To explore this "hidden sector", two SM operators that are gauge-invariant can be exploited: the hypercharged field strength tensor $B_{\mu\nu}$ and the Higgs modulus squared $|H_{SM}|^2$. These two operators can couple to the "hidden sector" in a relevant way (dimension≤ 4).

Then, with both SM operators ($B_{\mu\nu}$ and $|H_{SM}|^2$) and extra $U(1)_X$ factor in addition to the SM gauge group with a complex Higgs boson Φ_H that breaks the symmetry upon condensation, the HAHM is defined.

2.1. Model parameters

The description of the parameters of the model are presented in references [9, 10]. Three of these parameters are considered to be free: the mass of the Higgs boson (M_H), the mass of the new gauge boson ($M_{Z'}$) and the mixing angle between the SM and the Hidden Higgs sectors (θ_h). For convenience, we will use the sine-square of the mixing angle ($\sin^2\theta_h \equiv s_h^2$) and then also define the cosine-square of the mixing angle ($\cos^2\theta_h \equiv c_h^2$). The SM limit is when there is no mixing (i.e. $\theta = 0$, which is equivalent to $\chi^2 = 1$ [10]).

2.2. Couplings

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

- it introduces an extra new gauge boson in the allowed decays ($H \to Z'Z'$ and $H \to ZZ'$);
- the $H \to ZZ^*$ couplings are non-trivially modified with respect to SM;
- the Higgs production by gluon fusion is supressed by a factor c_h^2.

Here we consider only $H \to ZZ^*$ and $H \to Z'Z'$ decays. The $H \to ZZ'$ decay is suppressed to first order.

2.2.2. Coupling to SM fermions The gauge bosons Z and Z' are coupled to SM fermions. To the first order, the $Z \to l^+l^-$ coupling in the HAHM is the same as in the SM, and we consider that the new gauge boson Z' decays only to leptons with a very small width, however with a 100% branching fraction.

3. Experimental results from ATLAS and CMS in the $H \to ZZ^{(*)} \to 4l$

For this study, we assume that the new boson observed by the ATLAS and CMS experiments [1, 2] is a Higgs boson. Here we used the recent experiment results given by ATLAS and CMS [7, 8].

3.1. Higgs boson mass and signal strength

Although the ATLAS and CMS experiments measure a different mass for the new boson (difference of 2 GeV) [7, 8], in this study we assume that the Higgs boson has a mass of 126 GeV.

Table 1 shows the signal strength μ which is the ratio of the cross-section observed with respect to the SM expectation and its uncertainty σ_μ, these values correspond to the $4l$ channel only.

Table 1. The recent experimental results by ATLAS [7] and CMS [8] experiments.

Experiment	μ	σ_μ
ATLAS	1.66	$^{0.45}_{-0.38}$
CMS	0.93	$^{0.26}_{-0.23}$

3.2. Experimental selection criteria

The selection criteria for the analyses of both the ATLAS and the CMS experiments are based on selecting events with 4 leptons and forming leptons pairs. The invariant mass of one of the leptons-pairs (m_{12}) is close to the mass of the SM Z boson and the another leptons-pair (m_{34}) is considered for the off-shell Z boson. The selection criteria on these quantities considered by the ATLAS and CMS experiments is shown in Table 2.

Table 2. Selection criteria over m_{12} and m_{34} by ATLAS [7] and CMS [8] experiments for m_{4l} about 126 GeV.

Experiment	m_{12}	m_{34}
ATLAS	$>$ 50 GeV	$>$ 17.5 GeV
CMS	$>$ 40 GeV	$>$ 12.0 GeV

Since the kinematics of the leptons from $H \to Z'Z' \to 4l$ events are similar to the ones from $H \to ZZ^* \to 4l$, we will assume that all the efficiencies and acceptance are unchanged.

In order to have a consistent approach with both experiments and avoid boundary effects, we will consider two cases:

- in the case of the $H \to Z'Z'$ events with 20 GeV $< M_{Z'} <$ 35 GeV the H can not be detected by the experiment, because the applied cuts exclude this case;
- in the case of the $H \to Z'Z'$ events with 55 GeV $< M_{Z'} <$ 80 GeV the H can be detected by the experiment, because this case is compatible with the applied cuts.

Because of the cuts on m_{12} and on m_{34}, the cases with $M_{Z'} <$ 20 GeV and 35 GeV $< M_{Z'} <$ 55 GeV are not considered. We also don't consider the case where the Z' boson is havier than the Z boson.

4. Constraints on HAHM parameters

We obtain limits on the hidden sector parameters by calculating the event rate predicted by HAHM, compared to the SM, and by checking the compatibility with the experimental results. According to the HAHM, the hidden width depends on the three free parameters: M_H, $M_{Z'}$ and s_h^2. We will present the results in the $(M_{Z'}, s_h^2)$ plane where the mass of the Higgs boson is fixed to 126 GeV.

4.1. Method

Considering only gluon fusion, which is a dominant production mode at the LHC, we compute the expected production rate of the $H \to 4l$ events using Equation 1:

$$\frac{\sigma_{HAHM}}{\sigma_{SM}} = \frac{\sigma_{HAHM}(gg \to H) \times BR_{HAHM}(H \to 4l)}{\sigma_{SM}(gg \to H) \times BR_{SM}(H \to 4l)} \tag{1}$$

where the denominator is given by the SM values which depends only on the SM Higgs mass. The term $BR_{SM}(H \to 4l)$ involves only the $H \to ZZ^* \to 4l$ events, and therefore is a constant of the SM (since the mass of the Z boson is known). In the numerator, the values comes from the HAHM model and depends 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.

The term $BR_{HAHM}(H \to 4l)$ can be decomposed into three components:

$$\begin{aligned} BR_{HAHM}(H \to 4l) &= BR_{HAHM}(H \to ZZ^* \to 4l) + BR_{HAHM}(H \to Z'Z' \to 4l) \\ &+ BR_{HAHM}(H \to ZZ' \to 4l) \end{aligned}$$

We also assume the universal suppression in Equation 1:

$$\frac{\sigma_{HAHM}}{\sigma_{SM}} = c_h^2 = (1 - s_h^2) \tag{2}$$

We compare the quantity obtained by Equation 1 in the $(M_{Z'}, s_h^2)$ plane, with the measured value of the production rate divided by the SM prediction (μ), this approach was used in reference [11]. The reason we chose to look specifically at the Z' mass, is because we want to place ourselves in the case of Hidden particles decaying into SM fermions which can be detectable by the experiments.

As we mentioned before, the $H \to Z'Z' \to 4l$ events are considered as detected if $M_{Z'} > 55$ GeV, and as not detected if $M_{Z'} < 35$ GeV. Therefore, the formulas that are used to evaluate the rate of events in the HAHM model, where the branching fraction from $H \to ZZ' \to 4l$ is neglected, are:

$$\frac{\sigma_{HAHM}}{\sigma_{SM}} = \begin{cases} (1 - s_h^2) \times \frac{BR_{HAHM}(H \to ZZ^*)}{BR_{SM}(H \to ZZ^*)}, & \text{if } M_{Z'} < 35 \text{ GeV.} \\ (1 - s_h^2) \times \frac{BR_{HAHM}(H \to ZZ^*)[BR_{SM}(Z \to 2l)]^2 + BR_{HAHM}(H \to Z'Z')}{BR_{SM}(H \to ZZ^*)[BR_{SM}(Z \to 2l)]^2} & \text{if } M_{Z'} > 55 \text{ GeV.} \end{cases} \tag{3}$$

Here we have used that the branching franction $Z' \to l^+l^-$ is 100%. Given the experimental selection criteria that we used, an immediate consequence in the first case ($M_{Z'} < 35$ GeV), was that the ratio is always less than 1 since the branching fractions in the HAHM model are lower than the SM, this means, the HAHM model, for lower Z' mass predicts less events than the SM. On the other hand, for the second case ($M_{Z'} > 55$ GeV), the ratio can be either larger or smaller than 1.

4.2. Results

The results are presented in two cases: low-mass Z' (20 GeV $< M_{Z'} <$ 35 GeV) and high-mass Z' (55 GeV $< M_{Z'} <$ 80 GeV). We show the distribution of the $\frac{\sigma_{HAHM}}{\sigma_{SM}}$ in the $(M_{Z'}, s_h^2)$ plane, and we superimpose the contour corresponding to the experimental results (ATLAS and/or CMS) for μ, and also the 68% and 95% C.L. The values used are presented in Table 1.

4.2.1. Low-mass Z' case: (20 GeV $< M_{Z'} <$ 35 GeV) This is the region where the $M_{Z'}$ does not pass the experimental cuts, and where we used the first case of Equation 3. Figure 1 shows the distribution of $\frac{\sigma_{HAHM}}{\sigma_{SM}}$ in the $(M_{Z'}, s_h^2)$ plane, with the μ contour is the solid line, with the 68% C.L. (dashed line) and with 95% C.L. (dot-dashed line) contours.

From Figure 1, the left plot shows only the 95% C.L. contours. This is because the value of μ for ATLAS is larger than 1, while the HAHM predicts less events than the SM. Therefore, the yellow region is compatible with ATLAS results at 95% C.L. For the CMS case where μ is lower than 1, we can see that the HAHM results are compatible with CMS results at 68% C.L. (see the green region from the plot on the right from Figure 1).

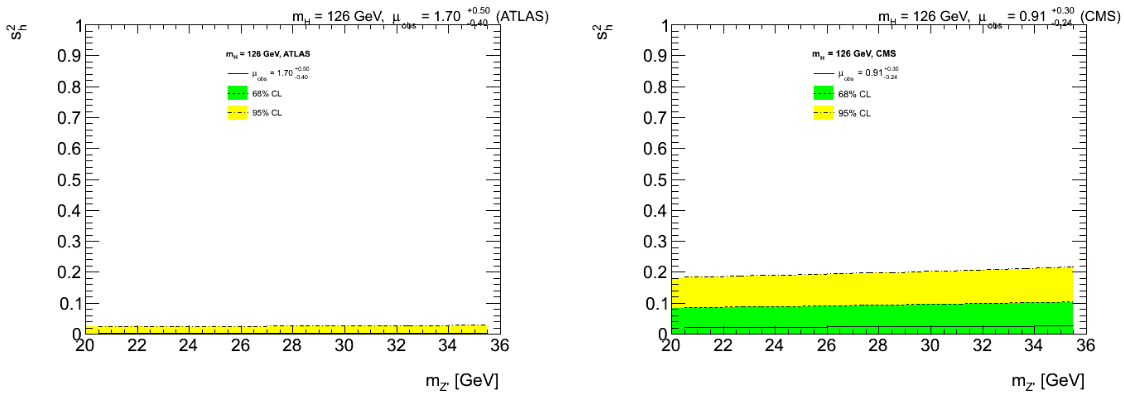

Figure 1. Low-mass Z' case. The plots show the distribution of $\frac{\sigma_{HAHM}}{\sigma_{SM}}$ in the $(M_{Z'}, s_h^2)$ plane and the 68% and 95% C.L. contours for HAHM using the experimental results from (a) ATLAS and from (b) CMS. The HAHM model is almost excluded by ATLAS (a) with $\mu > 1$.

4.2.2. High-mass Z' case: (55 GeV < $M_{Z'}$ < 80 GeV) The high mass region between (35 GeV, 55 GeV) is excluded as well, because of the experimental analysis cuts applied. Then, we used the second case of Equation 3. Figure 2 shows the the distribution of $\frac{\sigma_{HAHM}}{\sigma_{SM}}$ in the $(M_{Z'}, s_h^2)$ plane for high-mass Z' case.

As we mentioned before, for the high-mass Z' case, the $\frac{\sigma_{HAHM}}{\sigma_{SM}}$ ratio can be smaller or larger than 1, therefore more contours are visible. The green and yellow regions are part of the parameter space that is compatible with the experimental results at 68% C.L. and 95% C.L. respectively. We can see from Figure 2 that a large region is allowed: the region for $M_{Z'}$ below 63 GeV and the s_h^2 between to 0/1. Indeed for $M_{Z'} < 63$ GeV $\sim M_H/2$ and small or large mixing angle, the $H \to Z'Z'$ decay with two on-shell bosons is kinematically allowed whereas the $H \to ZZ^*$ 3-body decay is somewhat suppressed. Accordingly the expected number of $4l-$events will significantly increase. We should consider that the branching fraction of $Z' \to 2l$ has been taken as 100% which overestimated the expected number of evens with the HAHM model.

For $M_{Z'} > 63$ GeV $\sim M_H/2$ the $H \to Z'Z'$ 3-body decay is suppressed compared with the $H \to ZZ^*$ 3-body decay, and so we are in the SM case. Most of the parameter space is compatible with the experimental results at 95% C.L.

5. Conclusions

The HAHM model is not yet excluded experimentally by the ATLAS and the CMS experiments. We have performed a phenomenology study on the $H \to Z'Z' \to 4l$ using the HAHM model as a benchmark model to extract limits on the model in the $(M_{Z'}, s_h^2)$ parameter space from the recent experimental results from these experiments.

In this study we show that the measured event rate is compatible with a large part of the HAHM parameter space (see section 4.2.2 and Figure 2), therefore the model is still compatible with the experimental results and with the SM.

Since the search for $H \to Z'Z' \to 4l$ is compatible with the $H \to ZZ^* \to 4l$, we expect the experimental results soon from this search using the HAHM as a benchmark model to complement this study.

References

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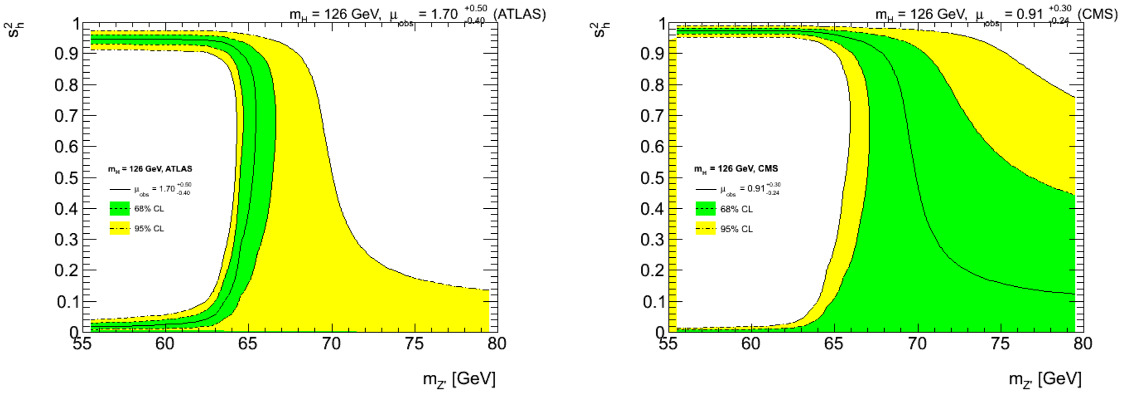

Figure 2. High-mass Z' case. The plots show the distribution of $\frac{\sigma_{HAHM}}{\sigma_{SM}}$ in the $(M_{Z'}, s_h^2)$ plane and the 68% and 95% C.L. contours for HAHM using the experimental results from (a) ATLAS and from (b) CMS. In the $M_{Z'} = 63$ GeV a transition of the s_h^2 it can be seen. For $M_{Z'} < 63$ GeV the $H \to Z'Z'$ is more favored while $M_{Z'} > 63$ GeV, $H \to Z'Z'$ is suppresed conpared with $H \to ZZ^*$, so it is SM-like.

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