Higgs boson search significance deformations due to mixed-in scalars

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The existence of exotic scalars that mix with the Standard Model (SM) Higgs boson can affect Higgs boson phenomenology in a multitude of ways. We consider two light Higgs bosons with shared couplings to SM fields and with masses close to each other, in the range where the $h \rightarrow WW \rightarrow l\nu l\nu$ is an important search channel. In this channel, we do not find the dilution of significance of the ‘SM-like’ Higgs boson that is naively expected because of the mixing. This is because of leakage of events from the other scalar into its signal region. Nevertheless, we show that the broadening of the $h \rightarrow WW \rightarrow l\nu l\nu$ significance plots of Standard Model Higgs boson searches could indicate the first evidence of the the extra scalar state.

New mixed-in scalars. We want to consider cases where the Standard Model (SM) Higgs mixes with scalar states leading to multiple Higgs bosons with “shared” couplings to SM fields. The most natural choice for the extra scalar is a singlet but doublets and triplets that do not get a vacuum expectation value (VEV) are also possible candidates. There are many reasons to consider extra scalar particles that are singlets under the SM gauge groups. The existence of these exotic new particles, perhaps from a hidden sector, are of particular phenomenological significance. This is because a relevant, gauge-invariant and Lorentz invariant operator,

$$\mathcal{L}_{\text{eff}} = \frac{g^2}{4} \rho \Phi \cdot \Phi,$$

can be formed by them, thereby enabling a simple renormalizable coupling with the SM Higgs boson: $|H_{SM}|^2 |\Phi|^2$, where $H_{SM}$ is the SM Higgs boson and $\Phi$ are exotic scalar states. If $\Phi$ gets a VEV the SM Higgs boson mixes with $\Phi$, and Higgs phenomenology is no longer SM Higgs phenomenology, but one of multiple scalar states sharing couplings to SM fields according to the strength of the wave-function overlap with the SM Higgs boson. A more complete discussion of the theory can be found in [1]. While complex scalars charged under new hidden gauge groups are of more interest to us, our analysis holds also for a real scalar, $\phi$. In this case the interaction term $|H_{SM}|^2 \phi$ will also contribute to the mixing between the scalars.

Such sharing of couplings can also arise from the mixing of the SM neutral Higgs component with the neutral components of an exotic doublet, $H'$, or a triplet with no hypercharge, $\Sigma$, provided $H'$ or $\Sigma$ get a vanishing or small VEV. A triplet is, of course, required to have no hypercharge, $\Sigma$, provided

$$\Sigma = \left(\begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right),$$

or a triplet with

$$\Sigma = \left(\begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right),$$

leading to multiple Higgs bosons with “shared” couplings to SM fields. The most natural choice for the extra scalar is the SM Higgs boson, $H_{SM}$, where

$$H_{SM} = \left(\begin{array}{c} 0 \\ H_{SM} \end{array} \right),$$

or $H_{SM} = \left(\begin{array}{c} 0 \\ H_{SM} \end{array} \right)$, where $H_{SM}$ is a singlet but doublets and triplets that do not get a small VEV. A triplet is, of course, required to have no hypercharge, $\Sigma$, provided

$$\Sigma = \left(\begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right),$$

or $\Sigma = \left(\begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right)$, or a triplet with

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The existence of exotic doublets too [12].

In this letter we wish to show how the standard significance searches for the SM Higgs boson are affected by the existence of these mixed-in states. Careful inspection of the $h \rightarrow WW \rightarrow l\nu l\nu$ “significance plots” could reveal the existence of two more Higgs bosons, even before the resonance of the second Higgs boson has been found in another search channel with better mass resolution.

We will first describe the method of making significance projections for the SM Higgs boson. For illustration we will proceed along the lines of the ATLAS analysis which has a similar sensitivity to the CMS study but is much easier to reproduce. We will comment on the CMS study at the end. We will then describe how the existence of an extra mixed-in scalar state would alter the significance plots, showing that new physics could be revealed through that shape first. And finally we will make some concluding comments.

LHC Sensitivity Projections. We will first reproduce the ATLAS sensitivity projections for Higgs searches at the LHC for 7 TeV center of mass energy that were made in Ref. 3. We concentrate on the $h \rightarrow WW \rightarrow l\nu l\nu (l = e, \mu)$ channel as this is the most sensitive channel in the range $125 - 190$ GeV. In the range $130 - 180$ GeV this is by far the dominant channel and sensitivity limits obtained from just this channel alone are very close to limits obtained by combining all channels. For $m_h \lesssim 130$ GeV the $h \rightarrow \gamma\gamma$ channel starts to become competitive with the $h \rightarrow WW \rightarrow l\nu l\nu$ channel and for $m_h \gtrsim 190$ GeV the $h \rightarrow ZZ \rightarrow 4l$ channel becomes important so that considering the $h \rightarrow WW \rightarrow l\nu l\nu$ channel alone for these masses would give us weaker sensitivity estimates compared to estimates evaluated by combining all channels.

For our computations we will use the expected Standard Model (SM) signal ($S_{SM}$) and background ($B$) values for $L = 1$ fb$^{-1}$ integrated luminosity given in Ref. 3. The values for $S_{SM}$ and $B$ for the $h \rightarrow WW \rightarrow l\nu l\nu$ channel have been given in Ref. 3 as a function of the putative mass of the Higgs $m_h$ used for the search. The only $m_h$-dependent cut that has been applied in Ref. 3 is,

$$m_T \leq m_h \quad (1)$$

where the transverse mass $m_T$ is defined by

$$m_T = \sqrt{(E_T^l + E_T^{miss})^2 - (\mathbf{P}_T^l + \mathbf{P}_T^{miss})^2},$$

the transverse momentum of the lepton pair,

$$\mathbf{P}_T^l = \mathbf{P}_T^{l1} + \mathbf{P}_T^{l2}, \quad E_T^l = \sqrt{(E_T^l)^2 - (\mathbf{P}_T^l)^2}$$

and $E_T^{miss}$ is the transverse momentum of the lepton pair.

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Here $\Delta B$ is the systematic error. As far as significance estimates are concerned we use the significance estimator (defined as $S_{12}$ in [6]),

$$Z_0 = 2(\sqrt{S + B} - \sqrt{S}) \sqrt{\frac{B}{B + (\Delta B)^2}}.$$  \hspace{1cm} (3)

Taking $\Delta B/B = 0.15$ we find projections for the 95% upper limit on $S/S_{SM}$ that can be put with $\mathcal{L} = 1 \text{ fb}^{-1}$. As values of the signal and background have been given only for a discrete set of masses in Ref. [3], for intermediate masses we have linearly interpolated. The results, shown in Fig. 1, agree very well with ATLAS projections for the reach of the $h \rightarrow WW \rightarrow l\nu l\nu$ channel (red dots in Fig. 1). We also show in Fig. 1 the projected ATLAS limits obtained in Ref. [3] after combining all the channels. The numerical value $\Delta B/B = 0.15$ has been chosen to get maximum agreement with the ATLAS projections in Ref. [3]. As mentioned earlier after combining all the channels stronger limits can be obtained although the limits from the $h \rightarrow WW \rightarrow l\nu l\nu$ channel alone are close to the combined limits for 130 GeV $< m_h < 190$ GeV.

Significance with mixed-in Higgs bosons. As can be seen from Fig. 1 even if the SM Higgs is excluded at a certain mass it is still possible to have a Higgs boson at that mass if the production cross-section times branching ratio is suppressed by $\xi$ compared to the SM. We want to consider the scenario where there are two Higgs scalars, $h$ and $H$, and the production cross-section times branching ratio of these Higgs bosons is suppressed as follows,

$$\sigma_h = \xi \sigma_{SM}(m_h),$$

$$\sigma_H = (1 - \xi) \sigma_{SM}(m_H),$$ \hspace{1cm} (4)

where $\xi \leq 1$. For a sufficiently large $\xi$ it would be hard to detect the scalar $H$. In a situation where only $h$ is detected, deviations from SM can still be detected if the cross-section for production of $h$, which would be smaller than the SM expectation, can be measured. As we will see, however, it may not always be easy to detect such a deviation in the cross-section.

We will now describe how the $h \rightarrow WW \rightarrow l\nu l\nu$ significance plots are distorted for the scenario mentioned above. An important difference from the last section is that instead of using the cut in eq. (1) for the search we use the sliding mass window,

$$0.75 m_h < m_T < m_h.$$ \hspace{1cm} (5)

This is the cut being used by ATLAS in their present searches [7,9]. The background $B$ after applying the above cut can be easily calculated from the background values given in Ref. [3] where the cut in eq. (1) has been applied, by using [13]

$$B(0.75 m_h < m_T < m_h) = B(m_T < m_h) - B(m_T < 0.75 m_h).$$ \hspace{1cm} (6)

We show in Fig. 2 the background obtained by applying the cut in eq. (5). One can similarly reconstruct the background $m_T$-distribution. For a particular $m_h$-bin, we will get a cross-section equal to,

$$B(m_T < m_h) - B(m_T < m_h - 10 \text{GeV}).$$ \hspace{1cm} (7)

There is a subtlety which must be kept in mind if this cut is used for discovery searches and not just for setting exclusion limits. If a Higgs boson does exist at a certain mass $m^{true}_{h/H}$, we will obtain a significance after applying the sliding mass cut above, even for Higgs masses different from $m^{true}_{h/H}$. Thus instead of a sharp peak in significance at $m^{true}_{h/H}$ a broad excess would be seen around $m^{true}_{h/H}$, and the peak significance would not necessarily be obtained at $m^{true}_{h/H}$ if the background after applying the above cut is not flat with respect to $m_h$. As shown in Fig. 2 the background rises for $m_h \lesssim 135$ GeV and falls for $m_h \gtrsim 150$ GeV. Consider the case of a Higgs boson with $m^{true}_h = 125$ GeV. Although the signal is maximum if one takes $m_h = 125$ GeV in the sliding window in eq. (5) the background is smaller for lower values of $m_h$,
as shown in Fig. 2 so that the maximum significance is obtained at a mass lower than the 125 GeV. This can be seen from \( \xi = 1 \) curve in Fig. 4 that shows the significance vs. \( m_h \) curve peaking below 125 GeV. Note, the plot was made for \( \xi = 1 \) but it would have the same shape (i.e., same peak position) for any \( \xi \) value. On the other hand, the significance curve for a 170 GeV Higgs would peak at values higher than 170 GeV because the background falls for \( m_h > 170 \) GeV.

Before discussing an example we mention how the significances scale with integrated luminosity. Because of systematic effects the significances do not scale as \( \mathcal{L}^{0.5} \) but as \( \mathcal{L}^{\alpha} \) where \( \alpha \) varies between 0.3 and 0.6 [3]. In this work we take \( \alpha = 0.4 \) throughout.

**Example with one extra mixed-in Higgs boson.** We want to illustrate the distortions in the significance plots that arise if there are two Higgs bosons with cross-sections given by eq. 4 but the standard single Higgs search strategy is used. In order to better understand the significance profiles we need to look at the underlying \( m_T \)-distributions for the signal and background first.
is due to a mixed-in scalar or a background modeling error, would require more effort in reanalyzing and understanding the different backgrounds. To quantify the significance of this excess we need to look at the significance plots shown in Fig.4 and Fig.5. As can be seen from Fig.4 and Fig.5, there is no noticeable feature at 170 GeV. Also the significance at 125 GeV does not decrease (in fact it marginally increases) when we go from $\xi = 1$ to $\xi = 0.8$. This is again because of the above mentioned extra events from the decay of the scalar $H$ having $m_T < 125$ GeV that leak into the “125 GeV signal”.

The Higgs boson at 125 GeV would also be seen in the $h \rightarrow ZZ \rightarrow 4l$ and $h \rightarrow \gamma\gamma$ channels with much better mass resolution. The cross-section can, however, not be measured accurately with 15 fb$^{-1}$ data because of statistical uncertainties. This is because a 20% reduction in the cross-section would be less than even one sigma downward fluctuation. As far as the 170 GeV Higgs is concerned neither the $h \rightarrow ZZ \rightarrow 4l$ channel nor the $h \rightarrow \gamma\gamma$ channel is sensitive to it with 15 fb data for $(1 - \xi) = 0.2$.

Thus we see that in the scenario mentioned none of the measurements discussed so far would give any clear indication of the presence of the 170 GeV scalar. The only difference between the $\xi = 1$ and $\xi = 0.8$ case would be in the shape of the significance vs $m_h$ curve, which is due to a difference in the underlying $m_T$-distribution. As can be seen from Fig.4 and Fig.5, the significance falls off much more sharply in the $\xi = 1$ case. The $\xi = 0.8$ curve lies within the two-sigma bands around the median $\xi = 1$ expectation for low luminosities (see Fig.4) and the difference in shape becomes significant only at higher luminosities (see Fig.5).

To disentangle the signal for $H$ one can treat signal due to a supposed SM Higgs at 125 GeV as part of the background. The mass of the lighter Higgs can be inferred from excesses that would exist in other channels like $h \rightarrow ZZ \rightarrow 4l$ and $h \rightarrow \gamma\gamma$. This leads to a curve (Fig.6) which peaks in the high mass region. For 10 fb$^{-1}$ luminosity we get almost a three-sigma excess which indicates the presence of a heavier Higgs boson in addition to the Higgs at 125 GeV. Note that we are subtracting the SM contribution for a 125 GeV Higgs whereas in reality the Higgs boson $h$ at 125 GeV has a reduced cross-section with $\xi = 0.8$, and so the subtraction is unwittingly too large. The dashed curve in Fig.6 shows the significance curve if the correct light Higgs contribution with $\xi = 0.8$ is subtracted from the signal and included in the background. Note that the peak position, even for the dashed curve is somewhat displaced to masses higher than 170 GeV. This is because of the falling background at 170 GeV as discussed below eq. 7.

Finally let us comment on the CMS Higgs search analysis. Although both the ATLAS and CMS analyses have similar sensitivities, the CMS analysis is more involved as the cuts have been optimized individually for each Higgs boson mass $m_H$. The basic qualitative features that we have highlighted here, however, should still be true for the CMS analysis. Even in the CMS study Higgs bosons would show up as broad resonances in the $h/H \rightarrow WW \rightarrow 2\ell 2\nu$ channel, in most of the mass region considered here, before they are discovered in other channels with better mass resolution. Thus even in the CMS study the shape of the significance plots would be crucial for distinguishing an SM Higgs scenario from the case where there is an additional mixed-in scalar state. For the specific example we have considered even in the CMS study one expects that a heavier Higgs at 170 GeV, even with smaller couplings, would have substantial leakage of events to the signal window of a Higgs with lower mass and that the significance plot would have a longer tail if there is an additional heavier Higgs. To see how our results still hold for the CMS study as far as the details are concerned, however, a thorough analysis needs to be done with the CMS cuts.

Conclusions. In this letter we have considered two mixed-in scalars having masses in the range where $h/H \rightarrow WW \rightarrow 2\ell 2\nu$ channel is sensitive. We find no dilution of significance of the ‘SM-like’ Higgs boson expected because of the mixing, because of leakage of events from the other scalar into its signal region. Nevertheless, with one extra mixed-in exotic Higgs boson, the shape of the significance plot for Higgs boson discovery in the $WW \rightarrow 2\ell 2\nu$ channel—even while performing search for one SM Higgs— gets altered in a way that might reveal the existence of this other Higgs boson. The presence of the other scalar leads to a broadening of the excess over a larger mass range relative to the minimal SM Higgs case. In such a situation we propose that the second scalar can be more clearly identified by subtracting the contribution due to the ‘SM-like’ Higgs.

Of course, the total production rate for the ‘SM-like’ Higgs, which could be measured in other channels like $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ \rightarrow 4l$, would be off compared to the SM in the event that the Higgs boson is mixed-in with a scalar. The QCD uncertainties of production rate, and
the statistical uncertainties that would be present in the initial phase of discovery would, however, be large enough that distortions in the $h \to WW \to 2\ell\nu$ significance plot may be more revealing than simple accounting for the total rate.

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APPENDIX

In this appendix we review the procedure for evaluating exclusion confidence levels and discovery significances assuming a Gaussian distribution for the expected number of events. For exclusion of a particular value of the mean expected signal $S$, the hypothesis being tested is the signal plus background hypothesis so that expected number of events, $N_{\text{exp}}$, has the mean value $N_{\text{exp}} = S + B$. We assume a Poisson distribution for $N_{\text{exp}}$ with mean value $S + B$ and standard deviation $\sqrt{S + B}$. If the number of events finally observed in the experiment is $N_{\text{obs}} < S + B$ the signal plus background hypothesis is said to be excluded at 95% confidence level if the probability that $N_{\text{exp}}$ can fluctuate downward form its mean value $S + B$ to a value less than or equal to $N_{\text{obs}}$ is less than 5%. For $S + B \gg 1$ the Poisson distribution we have assumed for $N_{\text{exp}}$ tends to a Gaussian distribution and the statement above implies that signal values $S$, still allowed after setting the 95% CL [14] bound would satisfy,

$$\frac{S + B - N_{\text{obs}}}{\sqrt{S + B}} \leq 1.64.$$  \hspace{1cm} (8)

To find the median 95 % exclusion potential we take $N_{\text{obs}} = B$ to obtain,

$$\frac{S}{\sqrt{S + B}} \leq 1.64.$$  \hspace{1cm} (9)

The upper limit on the allowed signal is the maximum value of $S$ for which this condition holds.

The significance of a discovery, on the other hand, is defined as the significance for rejecting the background-only hypothesis if an excess is seen over the background. We assume a Poisson distribution with mean $B$ and standard deviation $\sqrt{B}$ for the background. The median discovery significance, $Z_0$ is then the number of standard deviations by which the background must fluctuate upward from its mean value to give an excess equal to the mean expected signal $S$, that is,

$$Z_0 = \frac{S}{\sqrt{B}}.$$  \hspace{1cm} (10)

For a 5$\sigma$ discovery, for instance, we would have $Z_0 = 5$. The above expression, however, overestimates the significance if the statistics is low. A better approximation for the significance is given by the expression (defined as $S_{c12}$ in [3]).

$$Z_0 = 2(\sqrt{S + B} - \sqrt{B}).$$  \hspace{1cm} (11)

This is the definition of significance we will use here.

Systematic uncertainties also play a very important role especially in the $h \to WW \to 4l$ channel. The standard way to incorporate systematic effects is by convoluting the Poisson distribution for $N_{\text{exp}}$ (which is a Gaussian distribution in the large statistics limit) with the probability density function for the systematic uncertainty. Numerical convolution of the Poisson distribution with a systematic uncertainty having a Gaussian shape with standard deviation $\Delta B$ leads to the modification of eq. 9 and eq. 11 to [8].

$$\frac{S}{\sqrt{S + B + (\Delta B)^2}} \leq 1.64 \text{ and } Z_0 = 2(\sqrt{S + B} - \sqrt{B}) \sqrt{\frac{B}{B + (\Delta B)^2}}.$$  \hspace{1cm} (12)

respectively.

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the mixing angle, \( \alpha \), between the mass eigenstates \( h \) and \( H \), which is proportional to \( \beta \) in this limit, also vanishes, i.e. \( \alpha = e\beta \to 0 \). However, depending on the parameters of the potential, we can still have \( \alpha/\beta \) relatively large (for the case of the doublets, see for eg., eq. 88 in Ref. [2]) so that we can have a non-negligible mixing angle \( \alpha \) even if \( \beta \) is much smaller.

[13] In Ref. [3] background values for \( B(m_T < m_h) \) for \( m_h < 120 \) GeV have not been provided; for \( m_h < 120 \) GeV we use the shape of the \( m_T \)-distribution curves for the background provided in [7] keeping the normalization of Ref. [3]. Note that [7] considers the signal and background only for the \( H + 0 \) jet and \( H + 1 \) jet analyses whereas Ref. [3] also consider the subdominant \( H + 2 \) jet contribution.

[14] Note that 95\% CL corresponds to 1.96 standard deviations if both upward and downward fluctuations are considered and 1.64 standard deviations if only downward fluctuations are considered as is the case here.