Heavy Higgs signal-background interference in
$gg \to VV$ in the Standard Model plus real singlet

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Abstract: For the Standard Model extended with a real scalar singlet field, the modification of the heavy Higgs signal due to interference with the continuum background and the off-shell light Higgs contribution is studied for $gg \to ZZ, WW \to 4$ lepton processes at the Large Hadron Collider. A public program that allows to simulate the full interference is presented.

Keywords: Higgs Physics, Hadron-Hadron Scattering
1 Introduction

In 2012, the ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC) announced the discovery of a new scalar resonance with a mass of approximately 125 GeV [1]. The discovered particle is so far consistent with the Higgs boson predicted by the Standard Model (SM) Higgs mechanism [2], but many extensions to the SM preserve the minimal assumptions of an SU(2) doublet which acquires a vacuum expectation value (VEV) thus inducing a physical Higgs boson that couples to fermions and vector bosons in proportion to their mass, while also allowing for an expanded Higgs sector with additional, heavier (or lighter) Higgs-like scalar particles. The search for high mass Higgs-like particles in the $gg \rightarrow H \rightarrow ZZ$ and $gg \rightarrow H \rightarrow WW$ channels at the LHC is ongoing [3–9].

With inclusive NNLO signal uncertainties of $O(10\%)$ in gluon-fusion Higgs production at the LHC, which can be further reduced by experimental selection cuts, it is important to study signal-background interference in the $H \rightarrow VV$ decay modes ($V = Z, W$), because it can be of similar size or larger for Higgs invariant masses above the weak-boson pair threshold. For Higgs invariant masses much larger than $2M_V$, the occurring sizeable Higgs-continuum interference is linked to the preservation of unitarity. In the SM, interference between the Higgs signal and continuum background in $gg \rightarrow H \rightarrow VV$ has been studied in refs. [10–22].$^1$ Higgs-continuum interference results for a heavy SM Higgs boson with a $\Gamma_H/M_H$ ratio of $O(10\%)$ or more have been presented in refs. [13–15, 17]. We note that all Higgs-continuum interference calculations are at leading order (LO), except for Ref. [17], where approximate higher-order corrections have been calculated.

Since a Higgs boson with $M_H \approx 125$ GeV has been discovered, a theoretically consistent search for an additional Higgs boson has to be based on a model that is beyond the SM. The simplest extension of the Higgs sector of the SM introduces an additional real scalar

$^1$We note that the interfering $gg \rightarrow VV$ continuum background at LO is formally part of the NNLO corrections to $pp \rightarrow VV$ [23, 24]. SM Higgs-continuum interference in the $H \rightarrow VV$ decay modes at a $e^+e^-$ collider has been studied in ref. [25]. Predictions for $gg \rightarrow \ell\ell\nu\nu + 0, 1 \text{ jets}$ have been presented in ref. [26].
singlet field which is neutral under the SM gauge groups. The remaining viable parameter space of this 1-Higgs-Singlet extension of the SM (abbreviated by 1HSM) after LHC Run 1 has been studied in refs. [27, 28]. Here, we focus on the case where the additional Higgs boson is heavier than the discovered Higgs boson. In this case, the heavy Higgs signal is affected not only by sizeable interference with the continuum background, but also by a non-negligible interference with the off-shell tail of the light Higgs boson [16]. Heavy Higgs-light Higgs interference in the 1HSM with an additional \(Z_2\) symmetry has been calculated in ref. [29].\(^2\) Heavy Higgs-light Higgs interference in a type-II 2-Higgs-Doublet model for Higgs production in vector boson fusion at an \(e^+e^-\) collider and Higgs to \(ZZ\) decay has been studied in ref. [25].

In this paper, we extend the analysis of ref. [29] by taking into account the full signal-background interference which includes the heavy Higgs-continuum interference. Furthermore, in addition to \(gg \to h_2 \to ZZ \to 4\) leptons, where \(h_2\) is the heavy Higgs boson, we also calculate results for \(gg \to h_2 \to WW \to 4\) leptons. Our calculations are carried out with a parton-level integrator and event generator, which we have made publicly available [30]. In section 2, we discuss the 1HSM and specify the used benchmark points. Calculational details are discussed in section 3. Integrated cross sections and differential distributions in \(M_{VV}\) for the heavy Higgs signal and its interference with the continuum background and off-shell light Higgs contribution are presented in section 4 for \(gg \to h_2 \to ZZ \to \ell\bar{\ell}\ell\bar{\ell}^\prime\) and \(gg \to h_2 \to W^-W^+ \to \ell\bar{\nu}\ell^\prime\bar{\nu}'\). Conclusions are given in section 5.

2 Model

As minimal theoretically consistent model with two physical Higgs bosons, we consider the SM with an added real singlet field which is neutral under all SM gauge groups. This 1-Higgs-Singlet extension of the SM has been extensively explored in the literature [31–50]. Higgs Singlet models with an additional \(Z_2\) symmetry have generated some interest recently because of the possibility of the additional Higgs boson being a dark matter candidate, but here we consider the most general extension, allowing cubic terms. The model is described in detail in refs. [50, 51]. In the following, we give a brief summary.

The SM Higgs sector is extended by the addition of a new real scalar field \(s\), which is a singlet under all the gauge groups of the SM and which also gets a VEV under electroweak symmetry breaking. This field is allowed to mix with the \(SU(2)\) Higgs doublet. Without the \(Z_2\) symmetry, shifting the singlet field simply corresponds to a redefinition of the parameter coefficients, so we may perform this shift and take the VEV of the singlet field to zero. After electroweak symmetry breaking, in the unitary gauge, one obtains the potential

\[
V = \frac{\lambda}{4} \phi^4 + \lambda v^2 \phi^2 + \lambda v \phi^3 + \frac{1}{2} M^2 s^2 + \lambda_1 s^4 + \frac{\lambda_2}{2} \phi^2 s^2 + \lambda_2 v \phi s^2 + \mu_1 s^3 + \frac{\mu_2}{2} \phi^2 s + \mu_2 v \phi s .
\]  

(2.1)

\(M^2\) must be positive, and to avoid vacuum instability the quartic couplings must satisfy \(\lambda, \lambda_1 > 0\) and \(\lambda_2 > -2\sqrt{\lambda \lambda_1}\). The mass eigenstates can be parametrised in terms of a

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\(^2\)The heavy Higgs-light Higgs interference results presented in section 4 are in qualitative agreement with ref. [29].
mixing angle $\theta$ as

\begin{align}
    h_1 &= \phi \cos \theta - s \sin \theta \\
    h_2 &= \phi \sin \theta + s \cos \theta,
\end{align}

where $h_1$ is assumed to be the lighter Higgs boson with a mass of approximately 125 GeV, and

$$\tan 2\theta = \frac{-\mu_2 v}{\lambda v^2 - \frac{1}{2}M^2}$$

with

$$-\frac{\pi}{4} < \theta < \frac{\pi}{4}.$$ 

Since in this work we are interested in the leading order di-boson decays of $h_1$ and $h_2$, we neglect all Higgs-self/Higgs couplings, i.e. $\mu_1, \lambda_1, \lambda_2 \simeq 0$, where $\lambda_1$ must be positive to prevent the potential from being unbounded from below. The consideration of non-negligible self-coupling parameters would only affect our study through a change in the calculation of the Higgs widths. But, since there are currently no limits on these couplings, we believe that zero is an appropriate choice.

The model has six independent parameters, which we choose to be $M_{h1}, M_{h2}, \theta, \mu_1, \lambda_1$ and $\lambda_2$. Since we neglect the latter three and fix the first parameter at 125 GeV in accordance with the mass of the observed resonance, we are left with $M_{h2}$ and $\theta$. We study three values for the mass of the heavy Higgs resonance: $M_{h2} = 300$ GeV, $M_{h2} = 600$ GeV and $M_{h2} = 900$ GeV. Finally, we choose $\theta$ so as not to alter the predicted light Higgs cross section too much. It is a convenient feature of this model that the mixing is such that for the processes considered here all relevant light (heavy) Higgs couplings are scaled by $\cos \theta$ ($\sin \theta$) relative to the corresponding SM Higgs couplings. We choose $\theta = \pi/8$, which is consistent with current limits on the Higgs signal strength and does not appear to be in conflict with limits given in ref. [28], but strictly speaking these apply to the model with the additional $Z_2$ symmetry and are not directly applicable here. Ref. [50] gives bounds on the $\lambda_1$ and $\mu_1$ parameters for $M_{h2} \lesssim 500$ GeV and a similar $\theta$, which are in agreement with our choice of zero for these values.

3 Calculational details

In section 4, we present results calculated with an extended version of gg2VV [14, 16, 18], which is publicly available [30]. Representative Feynman graphs for the light and heavy Higgs and interfering continuum background processes are shown in figure 1. The heavy Higgs ($h_2$) graphs define the signal process. They interfere with the light Higgs ($h_1$) graphs and with the gluon-induced continuum background graphs. The amplitudes are calculated using a modified (for compatibility only) output of FeynArts/FormCalc [52, 53], using a custom coded UFO [54] model file generated by FeynRules [55]. The widths are calculated using FeynRules for consistency. The used width values are given in table 1. As discussed in section 2, a negligible contribution from the $h_2 \rightarrow h_1 h_1$ decay is assumed. The PDF set MSTW2008LO [56] with default $\alpha_s$ is used and the CKM matrix is approximated.
Figure 1. Representative Feynman graphs for $gg \rightarrow \{h_1, h_2\} \rightarrow ZZ, WW \rightarrow 4$ leptons. The heavy Higgs ($h_2$) graphs define the signal process, which interferes with the light Higgs ($h_1$) graphs (a,b). They also interfere with the gluon-induced continuum background graphs (c,d).

|       | $h_1$   | $h_2$   |
|-------|---------|---------|
| $M$ [GeV] | 125     | 300     | 600     | 900     |
| $\Gamma$ [GeV] | 0.0042577 | 1.70204 | 20.7236 | 69.1805 |

Table 1. Widths of the physical Higgs bosons $h_1$ and $h_2$ in the 1HSM with mixing angle $\theta = \pi/8$. 

by the unit matrix, which causes a negligible error [14]. As input parameters, we use the specification of the LHC Higgs Cross Section Working Group in App. A of ref. [57] with $G_\mu$ scheme and LO weak boson widths for consistency. More specifically, $M_W = 80.398$ GeV, $M_Z = 91.1876$ GeV, $\Gamma_W = 2.141$ GeV, $\Gamma_Z = 2.4952$ GeV, $M_t = 172.5$ GeV, $M_b = 4.75$ GeV, $G_F = 1.16637 \times 10^{-5}$ GeV$^{-2}$ are used. Finite top and bottom quark mass effects are included. Lepton masses are neglected. The fixed-width prescription is used for weak boson propagators. The Higgs amplitudes are implemented using the complex-pole scheme [58]. The box graphs shown in figure 1(c,d) are affected by numerical instabilities when Gram determinants approach zero. In these critical phase space regions the amplitude is evaluated in quadruple precision. Residual instabilities are eliminated by requiring that $p_{T,W}$ and $p_{T,Z}$ are larger than 1 GeV. This criterion is also applied to the Higgs amplitudes, which are not affected by numerical instabilities, to obtain consistent cross section-level results. The numerical effect of this technical cut has been shown to be small [14, 19]. Furthermore, minimal selection cuts are applied: $M_{ll} > 4$ GeV and $M_{lll} > 4$ GeV cuts are applied for the $gg \rightarrow Z(\gamma^*)Z(\gamma^*) \rightarrow \ell\ell\ell\ell\bar{\ell}\bar{\ell}$ process to eliminate the soft photon singularities. The renormalisation and factorisation scales are set to $M_{VV}/2$ and the $pp$ collision energy is $\sqrt{s} = 8$ TeV.

The phase space integration is carried out using the multi-channel Monte Carlo integration technique [59], in which every kinematic structure has its own mapping from random variables to the phase space configuration such that singularities or peaks in the amplitude are compensated, and the inverse Jacobi determinants of all mappings are summed.
to give the inverse weight at each phase space point. This approach has the advantage of being easy to extend from the SM to two-Higgs models: one simply adds an extra channel with a mapping for the heavy Higgs resonance. The multi-channel technique has been implemented in $gg2VV$, and has been tested thoroughly. Each mapping was phase space integrated individually to check that the result matches the analytically known phase space volume for massless final state particles. Cross sections for the continuum background and $h_1$ only contributions\(^3\) to the processes considered here were found to be in agreement with the results of ref. [18], which were calculated using $gg2VV$ with a different phase space implementation. Furthermore, results for similar processes calculated using the same code show excellent agreement with a fully independent implementation [60].

4 Results

In this section, we present integrated and differential cross section-level results for the $h_2$ signal ($S$) and its interference ($I$) at the LHC for the processes

$$gg \rightarrow \{h_1, h_2\} \rightarrow Z(\gamma^*) Z(\gamma^*) \rightarrow \ell\ell\bar{\ell}\bar{\ell}$$ (4.1)

and

$$gg \rightarrow \{h_1, h_2\} \rightarrow W^-W^+ \rightarrow \ell\bar{\nu}\nu'\bar{\ell}'$$ (4.2)

with input parameters, settings and cuts as described in section 3. The following notation is used:

$$S \sim |M_{h_2}|^2$$ (4.3)

$$I_{h_1} \sim 2 \text{Re}(M_{h_2}^* M_{h_1})$$ (4.4)

$$I_{bkg} \sim 2 \text{Re}(M_{h_2}^* M_{bkg})$$ (4.5)

$$I_{full} = I_{h_1} + I_{bkg}$$ (4.6)

$$R_i = \frac{S + I_i}{S}.$$ (4.7)

The interference of the heavy Higgs signal with the light Higgs and continuum background is given separately. We also give the combined interference to illustrate the overall effect. The ratios $R_{h_1}$, $R_{bkg}$ and $R_{full}$ illustrate the relative change of the heavy Higgs signal due to interference with the light Higgs and continuum background amplitude contributions. Integrated results for processes 4.1 and 4.2 are shown in tables 2 and 3, respectively. As illustrated by the differential distributions shown below, a $|M_{VV} - M_{h_2}| < \Gamma_{h_2}$ window cut is an effective means to eliminate or mitigate the interference.\(^4\) Therefore, integrated results with window cut are presented in tables 4 and 5.

Corresponding $M_{VV}$ distributions for $M_{h_2} = 300, 600, 900$ GeV are shown in figures 2–5 and 6–9 for processes 4.1 and 4.2, respectively. Results for the heavy Higgs signal

\(^3\)without mixing, i.e. $\theta = 0$

\(^4\)For process 4.2, an invariant $M_{WW}$ cut cannot be applied experimentally. However, a transverse mass cut is feasible.
Table 2. Cross sections for $gg \to \{h_1, h_2\} \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ in $pp$ collisions at $\sqrt{s} = 8$ TeV at loop-induced leading order in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 300, 600, 900$ GeV and mixing angle $\theta = \pi/8$. Results for the heavy Higgs signal $(S)$ and its interference with the light Higgs ($I_{h_1}$) and the continuum background ($I_{bkg}$) and the full interference ($I_{full}$) are given. The ratio $R_i = (S + I_i)/S$ illustrates the relative change of the heavy Higgs signal due to interference with the light Higgs and continuum background amplitude contributions. Minimal cuts are applied (see main text). Cross sections are given for a single lepton flavour combination. The integration error is displayed in brackets.

| $M_{h_2}$ [GeV] | $S$     | $I_{h_1}$  | $I_{bkg}$  | $I_{full}$  | $R_{h_1}$ | $R_{bkg}$ | $R_{full}$ |
|------------------|---------|------------|------------|------------|-----------|----------|----------|
| 300              | 0.12609(9) | 0.01187(5) | 0.00358(7) | 0.01545(9) | 1.094(2)  | 1.028(2) | 1.123(2) |
| 600              | 0.01820(2) | -0.00506(3) | 0.00571(3) | 0.00664(4) | 0.722(2)  | 1.314(2) | 1.035(3) |
| 900              | 0.001775(2) | -0.003296(8) | 0.003403(6) | 0.00011(1) | -0.857(5) | 2.918(4) | 1.060(6) |

Table 3. Cross sections for $gg \to \{h_1, h_2\} \to W^-W^+ \to \ell^+\ell^-\nu'\bar{\nu}'$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 300, 600, 900$ GeV and mixing angle $\theta = \pi/8$. Other details as in table 2.

| $M_{h_2}$ [GeV] | $S$     | $I_{h_1}$  | $I_{bkg}$  | $I_{full}$  | $R_{h_1}$ | $R_{bkg}$ | $R_{full}$ |
|------------------|---------|------------|------------|------------|-----------|----------|----------|
| 300              | 1.414(2) | 0.1173(6)  | -0.045(1)  | 0.072(2)   | 1.083(2)  | 0.968(2) | 1.051(2) |
| 600              | 0.1874(2) | -0.0558(3) | 0.0942(3)  | 0.0385(4)  | 0.702(2)  | 1.503(2) | 1.205(3) |
| 900              | 0.01799(2) | -0.03500(6) | 0.04957(7) | 0.01458(9) | -0.945(4) | 3.755(5) | 1.810(6) |

Table 4. Cross sections for $gg \to \{h_1, h_2\} \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 300, 600, 900$ GeV and mixing angle $\theta = \pi/8$. An additional window cut $|M_{ZZ} - M_{h_2}| < \Gamma_{h_2}$ is applied. Other details as in table 2.

| $M_{h_2}$ [GeV] | $S$     | $I_{h_1}$  | $I_{bkg}$  | $I_{full}$  | $R_{h_1}$ | $R_{bkg}$ | $R_{full}$ |
|------------------|---------|------------|------------|------------|-----------|----------|----------|
| 300              | 0.0879(3) | 4.0(7)e-05 | 0.00547(4) | 0.00551(4) | 1.000(4)  | 1.062(4) | 1.063(4) |
| 600              | 0.01318(4) | -0.00020(3) | 0.00104(2) | 0.00084(3) | 0.985(5)  | 1.079(5) | 1.064(5) |
| 900              | 0.001273(4) | -0.000130(4) | 0.000373(4) | 0.000243(5) | 0.898(5)  | 1.293(6) | 1.191(6) |

and including interference with the light Higgs and the continuum background are displayed. Vertical dashed lines at $M_{VV} = M_{h_2} \pm \Gamma_{h_2}$ are used to visualize the effect of a $|M_{VV} - M_{h_2}| < \Gamma_{h_2}$ window cut. For invariant $VV$ masses with negative signal plus
$gg \rightarrow h_2 \rightarrow W^- W^+ \rightarrow \ell \bar{\nu} \ell' \nu'$

min. cuts & $|M_{VV} - M_{h_2}| < \Gamma_{h_2}$

$\sigma$ [fb], $pp, \sqrt{s} = 8$ TeV

| $M_{h_2}$ [GeV] | $S$ | $I_{h_1}$ | $I_{bkg}$ | $I_{falt}$ | $R_{h_1}$ | $R_{bkg}$ | $R_{falt}$ |
|-----------------|-----|---------|---------|---------|---------|---------|---------|
| 300             | 0.990(1) | 0.00033(8) | 0.0343(2) | 0.0346(2) | 1.000(2) | 1.035(2) | 1.035(2) |
| 600             | 0.1360(2) | -0.00183(5) | 0.01584(7) | 0.01401(8) | 0.987(2) | 1.116(2) | 1.103(2) |
| 900             | 0.01292(2) | -0.00134(1) | 0.00432(5) | 0.00298(5) | 0.896(2) | 1.334(4) | 1.230(4) |

Table 5. Cross sections for $gg (\rightarrow \{h_1, h_2\}) \rightarrow W^- W^+ \rightarrow \ell \bar{\nu} \ell' \nu'$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 300, 600, 900$ GeV and mixing angle $\theta = \pi/8$. An additional window cut $|M_{WW} - M_{h_2}| < \Gamma_{h_2}$ is applied. Other details as in table 2.

interference, the distributions are shown in figures 4 and 8.

As seen in the tables and figures, interference effects increase significantly with increasing heavy Higgs mass. They can range from $O(10\%)$ to $O(1)$ effects for integrated cross sections. With window cut we find that interference effects are mitigated to $O(10\%)$ or less. We note that the heavy Higgs-continuum background interference is negative above $M_{h_2}$ and positive below $M_{h_2}$, while the heavy Higgs-light Higgs interference has the opposite behaviour. Consequently, in the heavy Higgs resonance region a strong cancellation occurs when both interference contributions are added. It is therefore essential to take both contributions into account in phenomenological and experimental studies. Despite the occurring cancellation, the full interference is clearly non-negligible and modifies the heavy Higgs line shape. We find overall $O(10\%)$ effects for integrated cross sections, even if a window cut is applied.

We note that our results for heavy Higgs-light Higgs interference are qualitatively in agreement with those given in ref. [29], where this interference is considered for $gg \rightarrow \{h_1, h_2\} \rightarrow ZZ \rightarrow 4\ell$, but in the 1HSM model with an extra $Z_2$ symmetry, so that a direct comparison is not possible. In the model considered there, $\mu_1$ and $\mu_2$ are 0, but the $h_2 \rightarrow h_1 h_1$ decay is still present when kinematically accessible. The main difference between this and our model is that the VEV of the singlet cannot be rotated away, and one is left with the additional parameter of $\tan \beta = v/\text{VEV}(s)$. If VEV$(s)$ were taken to be 0 (corresponding to the $Z_2$ symmetry being unbroken), there would be no mixing between the singlet and the doublet.
Figure 2. Invariant $ZZ$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ in $pp$ collisions at $\sqrt{s} = 8$ TeV at loop-induced leading order in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 300$ GeV and mixing angle $\theta = \pi/8$. Results for the heavy Higgs ($h_2$) signal ($S$) and including interference with the light Higgs ($S + I_{h_1}$) and the continuum background ($S + I_{h_1} + I_{bkg}$) are shown. Minimal cuts are applied (see main text). Vertical dashed lines are shown at $M_{VV} = M_{h_2} \pm \Gamma_{h_2}$. Other details as in table 2.

Figure 3. Invariant $ZZ$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 600$ GeV and mixing angle $\theta = \pi/8$. Other details as in figure 2.
Figure 4. Invariant $ZZ$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ in $pp$ collisions at $\sqrt{s} = 8 \text{ TeV}$ in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125 \text{ GeV}$, $M_{h_2} = 600 \text{ GeV}$ and mixing angle $\theta = \pi/8$. As figure 3, but with linear $d\sigma/dM_{ZZ}$ scale, to illustrate negative $S + I_{h_1}$.

Figure 5. Invariant $ZZ$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ in $pp$ collisions at $\sqrt{s} = 8 \text{ TeV}$ in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125 \text{ GeV}$, $M_{h_2} = 900 \text{ GeV}$ and mixing angle $\theta = \pi/8$. Other details as in figure 2.
Figure 6. Invariant $WW$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow W^- W^+ \rightarrow \ell \bar{\nu} \ell' \bar{\nu}'$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 300$ GeV and mixing angle $\theta = \pi/8$. Other details as in figure 2.

Figure 7. Invariant $WW$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow W^- W^+ \rightarrow \ell \bar{\nu} \ell' \bar{\nu}'$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 600$ GeV and mixing angle $\theta = \pi/8$. Other details as in figure 2.
Figure 8. Invariant $WW$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow W^- W^+ \rightarrow \ell \bar{\nu} \ell' \nu'$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 600$ GeV and mixing angle $\theta = \pi/8$. As figure 7, but with linear $d\sigma/dM_{WW}$ scale, to illustrate negative $S + I_{h_1}$.

Figure 9. Invariant $WW$ mass distributions for $gg \rightarrow \{h_1, h_2\} \rightarrow W^- W^+ \rightarrow \ell \bar{\nu} \ell' \nu'$ in $pp$ collisions at $\sqrt{s} = 8$ TeV in the 1-Higgs-Singlet extension of the SM with $M_{h_1} = 125$ GeV, $M_{h_2} = 900$ GeV and mixing angle $\theta = \pi/8$. Other details as in figure 2.
5 Conclusions

In the 1-Higgs-Singlet extension of the SM, the modification of the heavy Higgs ($h_2$) signal due to interference with the continuum background and the off-shell light Higgs ($h_1$) contribution has been studied for the $gg \rightarrow \{h_1, h_2\} \rightarrow Z(\gamma^*)Z(\gamma^*) \rightarrow \ell\ell\ell\ell^\prime$ and $gg \rightarrow \{h_1, h_2\} \rightarrow W^-W^+ \rightarrow \ell\nu\ell^\prime\nu^\prime$ processes at the LHC. Interference effects increase significantly with increasing heavy Higgs mass. They can range from $\mathcal{O}(10\%)$ to $\mathcal{O}(1)$ effects for integrated cross sections. With a $|M_{VV} - M_{h_2}| < \Gamma_{h_2}$ window cut, we find that interference effects are mitigated to $\mathcal{O}(10\%)$ or less. We find that the heavy Higgs-continuum background interference is negative above $M_{h_2}$ and positive below $M_{h_2}$, while the heavy Higgs-light Higgs interference has the opposite behaviour. Consequently, in the heavy Higgs resonance region a strong cancellation occurs when both interference contributions are added. It is therefore essential to take both contributions into account in phenomenological and experimental studies. Despite the occurring cancellation, the full interference is clearly non-negligible and modifies the heavy Higgs line shape. We find overall $\mathcal{O}(10\%)$ effects for integrated cross sections, even if a window cut is applied to mitigate the interference effects. Our calculations have been carried out with a parton-level integrator and event generator, which we have made publicly available.

Acknowledgments

The authors would like to thank A. Hadef for a comparison of preliminary results during the initial stages of the project and S. Liebler for providing a preprint. N.K. would like to thank the Galileo Galilei Institute for Theoretical Physics for hospitality and the INFN for partial support during the preparation of this paper. C.O. would like to thank the Department of Physics, Royal Holloway, University of London for supplementary financial support. This work was supported by STFC grants ST/J000485/1, ST/J005010/1 and ST/L000512/1.

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