Search for a generic heavy Higgs at the LHC

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Abstract

A generic heavy Higgs has both dim-4 and effective dim-6 interactions with the Standard Model (SM) particles. The former has been the focus of LHC searches in all major Higgs production modes, just as the SM one, but with negative results so far. If the heavy Higgs is connected with Beyond Standard Model (BSM) physics at a few TeV scale, its dim-6 operators will play a very important role - they significantly enhance the Higgs momentum, and reduce the SM background in a special phase space corner to a level such that a heavy Higgs emerges, which is not possible with dim-4 operators only. We focus on the associated VH production, where the effect of dim-6 operators is the largest and the SM background is the lowest. Main search regions for this type of signal are identified, and substructure variables of boosted jets are employed to enhance the signal from backgrounds. The parameter space of these operators are scanned over, and expected exclusion regions with 300 fb\textsuperscript{-1} LHC data are shown, if no BSM is present. The strategy given in this paper will shed light on a heavy Higgs which may be otherwise hiding in the present and future LHC data.

Keywords: Generic Heavy Higgs, LHC

1. Effective couplings of a heavy Higgs

It is not very natural that the SM has only one fundamental scalar field - the Higgs field. If Nature really chooses this way, there must be something else unknown to us as yet. An alternative, and natural, way is that the 125 GeV Higgs boson discovered at the LHC\textsuperscript{[1]-[2]} may be the lightest Higgs scalar field, among many that have yet to be found. Heavy Higgs particles are predicted in many BSM theories, such as the two-Higgs-doublet models, the minimal supersymmetric extension of the SM, and the left-right symmetric models. In a multiple Higgs field theory, the original Higgs fields are $\Phi_1, \Phi_2, \ldots$. The multi-Higgs potential will cause mixing among them to form the mass eigenstates. Let $\Phi_h$ and $\Phi_H$ be the two doublets containing the lightest ($h$) and next to lightest ($H$) neutral Higgs respectively. The couplings to the SM gauge bosons will be scaled due to the mixing compared with SM gauge coupling. At leading order, the dim-4 operators can be written as

\begin{equation}
L_{WW}^{(4)} = \rho_h g m_w h W^\mu W_\mu, \\
L_{ZZ}^{(4)} = \rho_h \frac{g m_w}{2 \cos^2 \theta_w} h Z^\mu Z_\mu, \\
L_{WW}^{(4)} = \rho_H g m_w h W^\mu W_\mu, \\
L_{ZZ}^{(4)} = \rho_H \frac{g m_w}{2 \cos^2 \theta_w} h Z^\mu Z_\mu,
\end{equation}

where $\theta_w$ is the weak mixing angle, $m_w$ the W boson mass, $\rho_h$ and $\rho_H$ are the scaling factors. In the simplest 2HDM example, we will have $\rho_h = \cos(\beta - \alpha)$, $\rho_H = \sin(\beta - \alpha)$.

For a SM-like light Higgs, $\rho_h$ is not far away from 1. Generally, for a heavy Higgs $H$, there could also be dim-6 effective operators which is related to an even higher energy scale BSM physics\textsuperscript{[3]}:

\begin{equation}
L_{hVV}^{(6)} = \sum_n \frac{f_n}{\Lambda^2} O_n, \quad \text{with} \quad f_n \approx 1,
\end{equation}

where $\Lambda$ is the scale below which the effective Lagrangian holds. It is set to 5 TeV in this work, since BSM at this scale is hard to be probed directly in general. Similar operators also exist for the SM Higgs $h$. As mentioned in\textsuperscript{[3]}, the dim-6 operators that are not constrained by precision electroweak (EW) data and relevant for the heavy Higgs are

\begin{equation}
O_{WW} = \Phi_H^\dagger \tilde{W}_\mu \tilde{W}^{\mu*} \Phi_H, \\
O_{BB} = \Phi_H^\dagger \tilde{B}_\mu \tilde{B}^{\mu*} \Phi_H, \\
O_V = \left(D_\mu \Phi_H^\dagger \right)^\dagger \tilde{W}^{\mu*} \left(D_\mu \Phi_H \right), \\
O_B = \left(D_\mu \Phi_H^\dagger \right)^\dagger \tilde{B}^{\mu*} \left(D_\mu \Phi_H \right), \quad \text{with} \quad f_n \approx 1,
\end{equation}

where $\tilde{B}_\mu = i \sigma^\mu B_\mu$, and $\tilde{W}_\mu = i \sigma^\mu W^{\mu*}_\mu$. After the EW symmetry breaking, the effective Lagrangian terms involving the heavy

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\textsuperscript{1}In general, they can be in any allowed SU(2)\textsubscript{L} representations. For simplicity, we will just illustrate the case where all fields are doublet.
Higgs and W/Z bosons are

\[ \mathcal{L}^{(6)}_{HHW} = g_{WW} \frac{f_W}{2\Lambda^2} \left( W_{\mu\nu} W^{\mu\nu} H + h.c. \right) - g_{WW} \frac{f_{WW}}{2\Lambda^2} W_{\mu\nu} W^{\mu\nu} H, \]

\[ \mathcal{L}^{(6)}_{HZZ} = g_{ZZ} \frac{c^2 f_W + s^2 f_\mu}{2c^2 \Lambda^2} Z_{\mu\nu} Z^{\mu\nu} H - g_{ZZ} \frac{c f_{WW} + s f_{BB}}{2c^2 \Lambda^2} Z_{\mu\nu} Z^{\mu\nu} H, \tag{4} \]

where \( s = \sin \theta_W \) and \( c = \cos \theta_W \). Similar terms exist for \( H\gamma \gamma \) and \( HZ\gamma \) vertices, but relatively suppressed by \( s \) and \( s^2 \). In addition, to simplify the parameter space, we also neglect terms of \( O(s^2) \) and \( O(s^3) \) in Eq. (4) which involve coefficients \( f_B \) and \( f_{BB} \), as done in Ref. [3].

2. Search for a generic heavy Higgs at the LHC

2.1. Main search channels

Heavy Higgs have been intensively searched for at the LHC in the \( H \to ZZ \to 4\ell \) decay \([4,5]\) and in the diboson final state \([6,7]\), with negative results so far. The main production channel is gluon-gluon fusion (ggF). It is reasonable to assume that the Yukawa coupling between the heavy Higgs and fermions is small, or the Higgs is even fermi-phobic, so that it can escape the direct detection in the ggF channel. The remaining production channels are associated VH (V=W/Z) and Vector Boson Fusion (VBF), which only involve the interactions between heavy Higgs and W/Z bosons.

Different from \([3,8]\) where final states with just one lepton and multiple jets are used, we start with at least two leptons. Specifically, the following channels are investigated in this work:

- **VH \to \ell^+ \ell^- jjj**, where the two leptons (\( \ell \)) are of opposite sign (OS) charge and same flavor (e or \( \mu \)), which originate from a Z boson decay, and a number of jets denoted by \( j \). This is called the 2\( \ell \) OS channel.

- **VH \to \ell \ell^\ast \ell^- jj**, where one pair of lepton originate from a Z boson decay. This is called the 3\( \ell \) channel.

- **VH \to \ell \ell^\ast \ell^\ast jj**, where the two leptons are of same sign (SS) charge. This final state originates from the \( WH \to W^+W^\pm W^\mp \) decay mode. This is called the 2\( \ell \) SS channel.

In the 2\( \ell \) SS and 3\( \ell \) channel, the heavy Higgs mass can be reconstructed. It is not possible in the 2\( \ell \) SS channel, but the signal sensitivity is the highest in this channel due to the low background. In principle, the channel \( WH \to W^+W^\pm W^\mp \to 3\ell 3\nu \) can be also used, and we can additionally require no pair of leptons with OS charge and same flavors to suppress the Z+X background. However, the signal yield of this channel is only about 10% of that in the 2\( \ell \) SS channel. Therefore, we do not consider this channel here. We also checked the \( VH \to \ell \ell jjjj \) channel as used in \([3,8]\). Although the signal yield is about a factor 10 larger than in the 2\( \ell \) OS, the W+jets background is also about ten times larger than Z+jets, and the \( t\bar{t} \to W(\tau)\bar{b}+jets \) can be another major background even after the b-jet veto. Therefore, the sensitivity of \( VH \to \ell \ell jjjj \) is not expected to be much higher than 2\( \ell \) OS, which is the least sensitive in the three channels considered in this work.

In general, the cross section of VBF is about an order of magnitude higher than VH in the high mass region, so it seems that VBF is the best channel to look for a heavy Higgs, and to suppress backgrounds by the presence of leptons in the final state, the decay modes of \( H \to ZZ \to (\ell\ell)jj \) and \( H \to ZZ \to 4\ell \) can be used. However, the former is accompanied by large SM backgrounds, and the yield of the latter is too small to be detected in the high momentum region. Therefore, we focus on the VH production mode, with the heavy Higgs decaying into two W/Z bosons, and final states with at least two leptons from the three bosons’ decays, as listed above. Figure 1 shows the leading order (LO) cross section of signal with different parameters as a function of the heavy Higgs mass. It is evident that when dim-6 operators are present, both VH and VBF production cross sections increase significantly, and VH increases much more than the VBF process. In addition, some traditional VBF variables such as \( \Delta p_T \) may stop working for dim-6 operators. A comparison of two benchmark signals in the VBF \( H \to ZZ \to 4\ell \) channel is made in Fig. 3, one with and another without the dim-6 operators. The presence of these operators enhances the Higgs \( p_T \), but also makes \( \Delta p_T \) background-like. Both signals have a yield of no more than 0.5 event at 300 fb\(^{-1}\) after object selection cuts, since their cross sections are already at \( O(10^{-3} - 10^{-2}) \) fb level before any detector level cuts, as indicated in the caption of Fig. 1(b). As a result, the 4\( \ell \) channel significances are much lower than 2\( \ell \) and 3\( \ell \), and we do not included it in the final result.

The extra derivatives in Eq. (4) will not only increase the heavy Higgs process cross section substantially, but also make the heavy Higgs and associated boson have higher momenta. Combined with the large Higgs mass, this means that all three bosons present in the process are boosted, which leads to boosted boson jets in the final state. We can use both the high \( p_T \) and substructure features of these jets to suppress the backgrounds. For large \( p_T \), the contribution from off-shell VH production can be also sizable.

The dilepton and leading jet (with 70 GeV < \( m_j < 150 \) GeV) \( p_T \) for VH production in the 2\( \ell \) channel are shown in Fig. 5. Indeed, the bosons in signals with dim-6 operators have higher \( p_T \)’s.

2.2. Simulation of signal and background events

The effective interactions in Eq. (4) are modeled by FeynRules \([9]\) and passed to MadGraph5 \([10]\) for the heavy Higgs production and decay, and the partons are showered and hadronized by

\(^3\)On the other hand, the \( t\bar{t} \) background is severely suppressed by the Z mass window cut in the 2\( \ell \) OS channel.
The tracking range is defined to be within $|\eta| < 2.5$, where $\eta$ is the pseudorapidity. The electron tracking and identification is worthwhile to note that ATLAS sees evidence of the SM triboson process with partial 13 TeV data.\textsuperscript{[13]}
efficiencies are 90 – 94% (71 – 77%) in the region $|\eta| \leq 1.5$ (1.5 < $|\eta|$ < 2.5), and those for muons is 94% (83%) in $|\eta| \leq 1.5$ (1.5 < $|\eta|$ < 2.5). The jet and missing transverse energy ($E_T^{\text{miss}}$) are based on calorimeter measurements. The electromagnetic calorimeter resolutions are parametrized as 10.1% $\sqrt{E} \oplus 0.17% E$ (28.5% $\sqrt{E} \oplus 3.50% E$) for $|\eta| \leq 3.2$ (3.2 < $|\eta|$ < 4.9), while those for the hadronic calorimeter are 1.59 GeV @ 52.05% $\sqrt{E} \oplus 3.02% E$, 70.6% $\sqrt{E} \oplus 5.00% E$ and 100.0% $\sqrt{E} \oplus 9.42% E$ for $|\eta| \leq 1.7$, 1.7 < $|\eta|$ < 3.2 and 3.2 < $|\eta|$ < 4.9, respectively. The energy $E$ is all in GeV.

The minimum $p_T$ for an electron (muon) is 15 GeV (10 GeV). The normal jets are clustered with the anti-$k_t$ algorithm with a cone parameter 0.4. To account for the boosted bosons and the Higgs, anti-$k_t$ fat jets with a cone parameter 1.0 are also used. If any jet (fat jet) overlaps with a lepton within $\Delta R < 0.4$ ($\Delta R < 1.0$), this jet (fat jet) is removed in the event from consideration. A jet and a fat jet should also have $\Delta R > 1.4$ to be considered as non-overlapping. The normal (fat) jets are required have $p_T > 30$ GeV ($p_T > 50$ GeV), and with $|\eta| < 4.0$.

2.3. Search in the 2$\ell$ OS and SS channels

To search for a heavy Higgs with boosted bosons in the 2$\ell$ OS channel, four signal regions are defined as shown in Tab. 1. The event topology is characterized by a high momentum boson recoiling against two other bosons that come from a heavy Higgs decay, as schematically displayed in Fig. 4. In region (1), the associated $Z \rightarrow \ell\ell$ recoils against a high momentum Higgs decaying into four jets ($\ell\ell$ denotes the combined 4-vector of two leptons). The momentum is so high that the four jets form a fat jet (denoted by $J$). A parameterless $k_t$ algorithm is run on the fat jet to exclusively cluster up to two subjets. Exactly two such subjets are required, and each one’s mass should be consistent with a vector boson. To further suppress backgrounds, the $N$-subjettiness variables $\tau_{1,2}$ are used. They are jet substructure variables calculated using exclusive $k_t$ axes, indicative of the subjet multiplicity in a parent jet. Similar topology to (1) exists in region (2), except that one boson from the heavy Higgs forms a boosted boson jet (a single normal jet denoted by $j_1$, which is leading in $p_T$), and the other with a lower $p_T$ splits into two normal jets ($j_2$ and $j_3$). 2nd and 3rd leading in $p_T$, and $j_2$ denotes the combined 4-vector of these two jets. In region (3) and (4), the leading jet is the associated boson. One boson from Higgs decay forms two jets (region 3) or a single jet (region 4), and the other decays into dilepton. The $\Delta R$ cuts are applied to impose correct topologies in different regions. The distributions of $\tau_{2}/\tau_{1}$ for the boson jets $j_{1,2}$ in region (2-4) are shown in Fig. 4.

For signals with $m_H = 300$ GeV, the regions definitions are similar to $m_H = 600$ GeV, but due to the lower Higgs mass, events have less number of boosted jet subjets. A bit tighter mass window cut is applied on the bosons, and region (4) is removed due to poor signal significance. Conversely, in signal with $m_H = 900$ GeV, events have much larger number of boosted boson jets, and the Higgses can hardly form a fat jet. As a result, region (1) and (3) are removed, and a new region similar to (2) but with $j_{2,3}$ replaced by a single normal jet is added.

In the 2$\ell$ SS channel, the $Z$-jets will be severely suppressed, and the main backgrounds consist of $WZ$+jets where one lepton from $Z$ missed the reconstruction or identification, $t\bar{t}V$ and triboson $WWW$. Three signal regions are similarly defined in Tab. 2 and illustrated in Fig. 6. Compared to the 2$\ell$ OS channel, large $E_T^{\text{miss}}$ is required due to neutrinos, and $b$-jet veto is applied to suppress the $t\bar{t}V$ background. The minimum subleading lepton $p_T$ is 50 GeV to suppress fake leptons which typically have lower $p_T$.

5The $\Delta R$ is defined as $\Delta R = \Delta \eta \oplus \Delta \phi$.

6The fake lepton background is not modeled in this work, and is expected to be small with the high lepton $p_T$ cut applied in this work.
Table 2: The signal region definitions for $m_H = 600$ GeV in the 2$\ell$ SS channel.

| Region (1) | Region (2) |
|-------------|-------------|
| $m_{\ell\ell} > 300$ GeV, $p_T^{\ell\ell} > 100$ GeV, $p_T^{\ell_j} > 300$ GeV, $p_T^{\ell_j} > 50$ GeV, $\Delta \phi_{\ell\ell} > 2.0$, $E_T^{miss} > 100$ GeV, no b-tagged jets |
| $p_T^{\ell\ell} > 400$ GeV, $p_T^{\ell_j} > 100$ GeV, $\tau_2^{\ell_j}/\tau_1^{\ell_j} < 0.6$ |

Table 3: The signal region definitions for $m_H = 600$ GeV in the 3$\ell$ channel.

| Region (1) | Region (4) |
|-------------|-------------|
| $p_T^{\ell\ell} > 600$ GeV |
| $p_T^{\ell_j} > 600$ GeV |
| $80$ GeV $< m_{\ell\ell} < 100$ GeV, $60$ GeV $< m_{j_1} < 140$ GeV, $\tau_2^{\ell_j}/\tau_1^{\ell_j} < 0.50$ |

2.4. Search in the 3$\ell$ channel

In the 3$\ell$ channel, six signal regions are defined as shown in Tab. 3 and schematically displayed in Fig. 7. Regions (1-3) are characterized by a $W(\ell\nu)$ boson recoiling against a heavy Higgs ($\ell\nu$ denotes the combined 4-vector of $\ell$ and $\nu$ from $W$), from which a boson decays into dilepton, and the other forms a normal jet, a fat jet or two normal jets ($j_{12}$ denotes the combined 4-vector of $j_1$ and $j_2$). Regions (4-6) are similar to (1-3), except that the roles of $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ are swapped. The three leptons should have a net charge of $\pm 1$. For $3\ell$ and $3\mu$ final states, the opposite-charged lepton pair with a smaller $\Delta R$ is regarded as from $Z \rightarrow \ell\ell$, while for $e\mu\mu$ and $\mu\mu\mu$, the correct combination is obvious. To suppress the fake leptons from jets (not modeled in this work) which generally have low $p_T$, the lepton not coming from $Z \rightarrow \ell\ell$ is required to have $p_T > 50$ GeV.

Figure 5: The four signal regions defined in the 2$\ell$ channel. The green (red) arrow denotes a normal (fat) jet.

Figure 6: The three signal regions defined in the 2$\ell$ SS channel. The green (red) arrow denotes a normal (fat) jet.

2.5. Event yields and mass spectrum

The event yields in the three channels are given in Tab. 4. The mass distributions with all signal regions combined in each

The transverse mass of a $W$ boson is calculated as $m_T = \sqrt{2p_T^{E_T^{miss}}[1 - \cos \Delta \phi_\ell]}$. 

5
channel are shown in Fig. 8 with the benchmark signal B as in Fig. 23. Good heavy Higgs candidate mass can be reconstructed in the 2ℓ OS and 3ℓ channels, while in the 2ℓ SS channel, only the hadronic V boson mass can be shown. The right tail in the signal in the bottom plot of Fig. 8 is due to the mis-matched jets illustrated in Fig. 5-3, and a small W boson mass peak is also visible in the “other” component (dominated by t/tV) of the background. As evident from Tab. 4 the 2ℓ SS channel provides the best sensitivity among all channels.

| 2ℓ OS chan. | Signal | Z+QCD jets | Other |
|-------------|--------|------------|-------|
|             | 4.0    | 41.6       | 3.5   |

| 3ℓ chan.    | Signal | WZ+QCD jets | Other |
|-------------|--------|-------------|-------|
|             | 3.6    | 7.2         | 1.3   |

| 2ℓ SS chan. | Signal | WZ+QCD jets | Other |
|-------------|--------|-------------|-------|
|             | 11.4   | 4.1         | 3.1   |

Table 4: The signal and background event yields expected with 300 fb−1 of LHC data, with all signal regions combined in each channel. In the 2ℓ channels, “other” includes VV+jets, triboson, t/tV and t/tV backgrounds. The signal shown has the following parameters: \( m_H = 600 \text{ GeV} \), \( \rho_H = 0.05 \), \( f_w = f_{WW} = 50 \).

3. Sensitivity in the model parameter space

To extract the signal sensitivity, mass window cuts are applied to the distributions shown in Fig. 8 and number counting is performed. The sensitivity is based on ratios of Poisson likelihoods, and toy distributions are obtained for background-only and signal+background hypotheses. In this work, three mass parameters: \( m_H = 300, 600, 900 \text{ GeV} \), are investigated. Since \( \rho_b \approx 1 \) from current Higgs measurement, it is expected that \( \rho_H \) is not very large. Hence \( \rho_H = 0.05 \) is taken as a benchmark value, and the two dimensional parameter space of \( f_w \) and \( f_{WW} \) is scanned. Since the Higgs width is proportional to \( \rho_H m_H^4 \), the small \( \rho_H \) also makes the Higgs width small. With \( \rho_H = 0.05 \) and \( f_w = f_{WW} = 50 \), a Higgs of mass 900 GeV has a width of only 0.571 GeV. Therefore, the interference between the signal and the SM triboson background (since they have the same final state) can be safely neglected.

Suppose there is no heavy Higgs signal with large dim-6 operator coefficients, the 95% Confidence Level (CL) exclusion regions for three different Higgs masses are shown in Fig. 24 for two integrated data luminosities: 300 fb−1 and 3 ab−1.
just 300 fb

the parameter space allowed by unitarity can be excluded, with

are also shown in these figures. It is evident that a large part of

large values of

will shift the area enclosed by the unitarity

comparing the 2ℓ and 3ℓ channels. The bounds based on the

consideration of gauge boson scattering amplitude unitarity are also shown in these figures. It is evident that a large part of

the parameter space allowed by unitarity can be excluded, with

just 300 fb−1 of data. It is worthwhile to note that with ρH = 1

large values of ρH will shift the area enclosed by the unitarity

bounds away from the origin, making these signals much easier

to be excluded.

4. Conclusion

In summary, a search strategy for a heavy Higgs with generic dim-6 couplings to SM gauge boson is presented in this work. We go beyond the final state studied in Ref. [3] to focus on the
two and three lepton final states, where the SM background can be substantially suppressed by means of boosted boson jets and jet substructure moments. The signal we are looking at can be sparse in ggF and VBF productions (thus escaped detection so far), but can be found in the VH production with proper sets of cuts. This is a phase space corner not touched upon by LHC up to date, and searching for such a generic heavy Higgs may shed light on something new toward BSM.

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