Fermiophobic and other non–minimal neutral Higgs bosons at the LHC

A.G. Akeroyd
Dept. de Fisica Teorica, IFIC/CSIC
Univ. de Valencia, 46100 Burjassot, Valencia, Spain

Abstract
The phenomenology of neutral Higgs bosons from non–SUSY, extended Higgs sectors is studied in the context of the LHC, with particular attention given to the case of a fermiophobic Higgs. It is found that enhanced branching ratios to $\gamma\gamma$ and $\tau^+\tau^-$ are possible and can provide clear signatures, while detection of a fermiophobic Higgs will be problematic beyond a mass of 130 GeV.
1 Introduction

It is well known that the Standard Model (SM) [1] requires the breaking of the $SU(2) \times U(1)$ symmetry. Introducing a complex scalar doublet with a non-zero vacuum expectation value (VEV) is an elegant way of achieving this, and predicts one neutral scalar - the Higgs boson ($\phi^0$) [2]. Models with $N$ doublets, which we shall call ‘multi-Higgs-doublet models’ (MHDM) are possible [3], and in particular two doublets are required for the minimal Supersymmetric Standard Model (MSSM) [4]. One of the main goals at future colliders will be to search for the above Higgs bosons, with previous null searches at LEP having produced the bounds of $M_{\phi^0} \geq 70.7$ GeV [5] for the minimal SM, and $M_{h^0} \geq 65.2$ GeV [6] for the lightest CP–even neutral Higgs boson ($h^0$) of the MSSM.

Although there are many theoretically sound extended Higgs models, most attention is given to the minimal SM and the MSSM. We shall be considering a non–SUSY, non–minimal SM in which only the Higgs sector is enlarged and any new physics is assumed to enter at a higher energy scale. Thus the low energy structure resembles the SM with an extended Higgs sector. In an earlier publication [7] we considered the phenomenology of these models at LEP2, assuming that the lightest CP–even neutral scalar ($h_1$) was the only Higgs boson in range at this collider. It was shown that detection is possible and parameter spaces exist for distinctive signatures. We recall that distinguishing among the many possible Higgs representations is a key issue at future colliders, and for the purpose of this paper we shall assume that $\phi^0$ and $h^0$ possess a very similar phenomenology - distinguishing between these two particles provides a challenge for future colliders and is discussed elsewhere [8]. In this paper we study the phenomenology of $h_1$ at the LHC in order to find out whether discovery/distinctive signatures are again possible, assuming that $h_1$ escaped detection at LEP2 and therefore its mass is constrained, $M_{h_1} \geq 100$ GeV. A caveat here is that this bound is for $h_1$ with couplings to vector bosons of $\phi^0$ strength, but if the vector boson ($h_1VV$) coupling is very suppressed a relatively light $h_1$ may escape detection at LEP1 and LEP2 [9], [10].

Throughout the paper we highlight the existence of a fermiophobic Higgs ($H_F$) [11] → [14] which is possible in the models we consider. Such a particle has been searched for recently at both the Tevatron [15] and LEP [16], and is currently bounded to be heavier than 81 GeV (95%). We note that these bounds are for an $H_F$ with $\phi^0$ strength coupling to vector bosons, although in general this is not the case. Our work is organized as follows. In Section 2 we introduce the relevant non–minimal Higgs models and investigate their couplings to the fermions and gauge bosons. Section 3 examines their phenomenology at the LHC in four separate decay channels, and finds parameter spaces which exhibit signals not possible for $\phi^0$ or $h^0$. Finally, Section 4 contains our conclusions.
2 Extended Higgs Sectors

The minimal SM consists of one Higgs doublet \( (T = 1/2, Y = 1) \), although extended models can be considered and have received substantial attention in the literature. For a general review see Ref. [4].

The theoretical structure of the two–Higgs–doublet model (2HDM) is well known, while the general multi–Higgs–doublet model (MHDM) [3], [17] has received substantially less attention, and usually only in the context of the charged Higgs sector. In this paper we shall be considering the models of our earlier work i.e. we shall again focus on the four distinct versions of the 2HDM (denoted Models I, I’, II and II’ with mention given to the MHDM when appropriate. The Higgs sector of the MSSM requires Model II type couplings and thus the phenomenology of Model II has received the most attention in the literature. Models I’ and II’ are rarely mentioned, while Model I has received limited attention. We shall be considering the lightest CP–even Higgs scalar \( (h_1) \) of the above models, and for the 2HDM its couplings to the fermions are given in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Model I</th>
<th>Model I’</th>
<th>Model II</th>
<th>Model II’</th>
</tr>
</thead>
<tbody>
<tr>
<td>( hu\bar{u} )</td>
<td>( \cos \alpha/\sin \beta )</td>
<td>( \cos \alpha/\sin \beta )</td>
<td>( \cos \alpha/\sin \beta )</td>
<td>( \cos \alpha/\sin \beta )</td>
</tr>
<tr>
<td>( h\bar{d}d )</td>
<td>( \cos \alpha/\sin \beta )</td>
<td>( \cos \alpha/\sin \beta )</td>
<td>( -\sin \alpha/\cos \beta )</td>
<td>( -\sin \alpha/\cos \beta )</td>
</tr>
<tr>
<td>( he\bar{e} )</td>
<td>( \cos \alpha/\sin \beta )</td>
<td>( -\sin \alpha/\cos \beta )</td>
<td>( -\sin \alpha/\cos \beta )</td>
<td>( \cos \alpha/\sin \beta )</td>
</tr>
</tbody>
</table>

Table 1: The fermion couplings of \( h_1 \) in the 2HDM relative to those for the minimal SM Higgs boson \( (\phi^0) \).

Here \( \alpha \) is a mixing angle in the neutral Higgs sector and \( \beta \) is defined by \( \tan \beta = v_2/v_1 \) \((v_i \) is the VEV of the \( i^{th} \) doublet and \( v^2 = \sum_{i=1}^{N} v_i^2 = (246 \text{ GeV})^2 \)). In the MSSM, which is a constrained version of the 2HDM (Model II), the angles \( \alpha \) and \( \beta \) are correlated. For the models that we shall consider \( \alpha \) and \( \beta \) are independent. In all the models there exists a bound on \( \tan \beta \) from considering the effects of the charged Higgs on the \( Z\bar{b}b \) vertex [18]. Although the full \( H^\pm tb \) coupling depends on the model there is a piece \( m_t \cot \beta \) which is common to all models and dominates unless \( \tan \beta \) is very large. From this vertex \( \tan \beta \) may be constrained from current experimental data to be (for \( M_H = M_Z \), where \( M_H \) is the mass of \( H^\pm \)):

\[
\tan \beta \geq 1.54 \ (95\% \ c.l) \tag{1}
\]

This improves the bound \( \tan \beta \geq 2 \) which was found in Ref. [19], with the 1995 value for \( R_b \). We have used the graphs in Ref. [18] to obtain the bound in Eq. (1). In our previous work we used \( \tan \beta \geq 1.25 \). For heavier \( M_H \) smaller values of \( \tan \beta \) are allowed. Note that we have used \( M_H = M_Z \) which is permissible in Model I and I’, and in the MHDM [17]. In Model II and II’ \( M_H \) is constrained by \( b \to s\gamma \) to be
greater than $244 + 63/(\tan \beta)^{1.3}$ GeV [20]. Throughout the paper we shall be varying $\beta$ from $\pi/4 \rightarrow \pi/2$, that is, we shall use a lower bound of $\tan \beta = 1$. The angle $\alpha$ may be varied from $-\pi/2 \rightarrow \pi/2$, although in our analysis it is sufficient to vary $\alpha$ from $0 \rightarrow \pi/2$.

From Table 1 one can vary the angles $\alpha$ and $\beta$ independently in order to find parameter spaces for extreme branching ratios (BRs). There are differences here from the LEP2 scenario [7] due to the rapid strengthening of the $VV^*$ channel for $M_{h_1} \geq 100$ GeV, these decays being negligible at LEP2. In addition the LHC allows different production mechanisms which will be scaled by mixing angle factors. We note that the $h_1VV$ coupling in all 4 models is scaled relative to that of $\phi^0VV$ by a factor $\sin(\beta - \alpha)$.

3 Phenomenology at the LHC

At the LHC the dominant production process for $\phi^0$ is that of $gg$ fusion, which proceeds via a top quark loop [21], [22], [23]. Other production mechanisms are considerably smaller, with the next largest being $WW$ fusion. Vector boson fusion [24] is always suppressed in a 2HDM by a factor $\sin^2(\beta - \alpha)$, while $gg$ fusion can be enhanced by up to a factor of two. If the $gg$ fusion process is absent then the cross-section $\sigma(pp \rightarrow h_1X)$ is heavily diminished, and this happens in the case of a fermiophobic Higgs. The Higgs bremsstrahlung off a $b$ quark is small for $\phi^0$ but in Model II and II' it can be boosted for large values of $\tan \beta$ and may become the dominant production process.

The most studied channels in the literature for detecting $\phi^0$ are [22], [25]:

(i) $\phi^0 \rightarrow \gamma\gamma$ for $80$ GeV $\leq M_{\phi^0} \leq 130$ GeV.

(ii) $\phi^0 \rightarrow ZZ^{(*)} \rightarrow llll$ for $130$ GeV $\leq M_{\phi^0} \leq 800$ GeV.

Other channels are considered to give a lesser chance of detection, e.g. those which make use of $\phi^0 \rightarrow b\bar{b}$ decays are swamped by backgrounds. For the models that we shall consider there are four possible channels which could distinguish $h_1$ from $\phi^0$:

(i) An enhanced signal in channels which exploit the decay $h_1 \rightarrow \gamma\gamma$.

(ii) An enhanced signal in the channel $h_1 \rightarrow \tau^+\tau^-$. 

(iii) An enhanced signal in the channel $h_1 \rightarrow t\bar{t}$ or $b\bar{b}$ in the heavy Higgs mass region.

(iv) An enhanced or suppressed signal in the channel $h_1 \rightarrow ZZ^{(*)} \rightarrow llll$.

In the subsections that follow we shall see that some of the above signatures are exclusive to a particular 2HDM model, while others only suggest that a detected neutral Higgs boson would be of a non–minimal nature. Each of the above signatures...
will be examined in the context of $pp$ collisions at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 30$ or 100 fb$^{-1}$. We shall focus on the four distinct versions of the 2HDM, remembering that $h_1$ from the MHDM can mimic any $h_1$ from the 2HDM. However, there are possible differences in the phenomenology of the 2HDM and MHDM. To illustrate this, we note here that once $\alpha$ and $\beta$ have been chosen to obtain a distinctive BR, the production cross-section is constrained and often suppressed compared to $\phi^0$. This is due to the fact that if (say) large $\cos \alpha \rightarrow 1$ is required to enhance a particular partial width, any coupling proportional to $\sin \alpha$ will be automatically reduced (see Table 1). In the MHDM this correlation among the couplings is relaxed, as explained in Ref. [7], due to the more complicated mixing matrices and the presence of more VEVs. Hence it is possible to have the same enhanced BRs in the MHDM along with a larger production cross-section, resulting in more signal events overall.

### 3.1 $h_1 \rightarrow \gamma \gamma$

For $\phi^0$, the decay to $\gamma \gamma$ proceeds via charged particle loops (see Fig. 1), i.e. fermions and $W$ bosons. We thus concentrate on the decay $\phi^0 \rightarrow \gamma \gamma$ and look for ways of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{phi0_gammagamma}
\caption{Decays of $\phi^0 \rightarrow \gamma \gamma$.}
\end{figure}

enhancing $h_1 \rightarrow \gamma \gamma$. For $\phi^0$ the vector boson loops dominate and contribute with opposite sign to the fermion loops. One–loop corrections are small [23], and the tree–level width can be written as [4]:

$$\Gamma(\phi^0 \rightarrow \gamma \gamma) = \frac{G_F \alpha^2 M_{\phi^0}^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2,$$

(2)

where $N_c$ is the colour factor, $Q_f$ is the electric charge of the fermion, and the $\tau$ variables are defined by

$$\tau_f = \frac{M_{\phi^0}^2}{4m_f^2} \quad \text{and} \quad \tau_W = \frac{M_{\phi^0}^2}{4M_W^2}.$$  

(3)

The above equations show that the dominant fermion loop is that of the $t$ quark (i.e. $f = t$). The amplitudes $(A)$ are real and vary from $A_W = -7(-12)$ for $\tau = 0(1)$,
\( A_f = 4/3(2) \) for \( \tau = 0(1) \). Hence the \( W \) loops are dominant. For the minimal SM Higgs, \( \text{BR} (\phi^0 \rightarrow \gamma\gamma) \approx 0.1\% \rightarrow 0.2\% \) for \( 80 \text{ GeV} \leq M_{\phi^0} \leq 130 \text{ GeV} \). To increase this BR for \( h_1 \) one would naively wish to enhance the width \( \Gamma(h_1 \rightarrow \gamma\gamma) \) significantly, but this is not an option since:

(i) The \( W \) loop contributes the most, and the \( h_1WW \) vertex is suppressed relative to \( \phi^0WW \) by a factor \( \sin^2(\beta - \alpha) \).

(ii) Although it is possible to reduce the strength of the \( tt \) vertex and thus cause less destructive interference, this does not increase the width much, and the corresponding reduction in \( \sigma(gg \rightarrow h_1) \) is disastrous from the point of view of the total cross-section.

A better way of increasing \( \text{BR} (h_1 \rightarrow \gamma\gamma) \) is to suppress other decay channels such as \( bb \) (which dominates in the relevant mass region). This suppression can be achieved in Models II and II' for small \( \sin \alpha \) although in Model II the above parameter choice suppresses \( bb \) and \( \tau^+\tau^- \) decays simultaneously, thus further enhancing \( \text{BR} (h_1 \rightarrow \gamma\gamma) \). In the extreme case of \( \text{BR} (h_1 \rightarrow b\bar{b}) \rightarrow 0 \) (\( \sin \alpha \rightarrow 0 \)), one finds that enhancements of a factor two (relative to \( \phi^0 \)) are possible for \( \text{BR} (h_1 \rightarrow \gamma\gamma) \). Choices of \( \tan \beta \) close to 1 would cause a factor 2 increase for the the main production mechanism \( gg \rightarrow h_1 \) relative to that for \( \phi^0 \). Table 2 (from Ref. [26]) shows the expected signal for \( \phi^0 \) for \( \mathcal{L}=30 \text{ fb}^{-1} \) with the significance being rather low in the range \( 80 \text{ GeV} \leq M_{\phi^0} \leq 100 \text{ GeV} \). For \( h_1 \) the enhancement of \( \gamma\gamma \) events by a factor up to 4 would provide a clear signature, and Table 3 shows the signal numbers for Model II with \( \alpha = 0 \) and \( \beta = \pi/4 \).

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
\( M_{\phi^0} \) (GeV) & 80 & 100 & 120 \\
\hline
\( \text{BR} (\phi^0 \rightarrow \gamma\gamma) \) & 0.09\% & 0.15\% & 0.23\% \\
\hline
\( S/\sqrt{B} \) & 1.5 & 2.7 & 4.1 \\
\hline
\end{tabular}
\end{center}

Table 2: Signals for process \( pp \rightarrow \phi^0X, \phi^0 \rightarrow \gamma\gamma \), for \( \mathcal{L}=30 \text{ fb}^{-1} \) (from Ref. [26]).

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
\( M_{h_1} \) (GeV) & 80 & 100 & 120 \\
\hline
\( \text{BR} (h_1 \rightarrow \gamma\gamma) \) & 0.22\% & 0.37\% & 0.40\% \\
\hline
\( S/\sqrt{B} \) & 6.1 & 10.9 & 11.5 \\
\hline
\end{tabular}
\end{center}

Table 3: Signals for process \( pp \rightarrow h_1X, h_1 \rightarrow \gamma\gamma \), with maximum enhancement, for \( \mathcal{L}=30 \text{ fb}^{-1} \).

In Model I' it is not possible to simultaneously suppress the \( h_1b\bar{b} \) coupling and keep the \( h_1tt \) coupling near \( \phi^0 \) strength. A consequence of this is that although similar enhancements of \( \text{BR} (h_1 \rightarrow \gamma\gamma) \) are again possible, the production mechanism \( (gg \rightarrow ... \)
$h_1$) would be heavily suppressed. However, a chance of detection remains in the associated production channel $q\bar{q} \rightarrow Wh_1$ with subsequent decays $W \rightarrow l\nu_l$ and $h_1 \rightarrow \gamma\gamma$. Enhancing $h_1 \rightarrow \gamma\gamma$ would require $\alpha \rightarrow \pi/2$, $\beta \approx \pi/4$ (i.e. $\beta$ at its smallest value), and hence $\sin^2(\beta - \alpha) \approx 0.5$; thus the associated production cross-section would be suppressed relative to $\phi^0$ by a factor 0.5. However, with the higher $\text{BR}(h_1 \rightarrow \gamma\gamma)$ one would expect a comparable number of events, and since a reasonable statistical signal in the associated production channel is possible for $\phi^0$ with high luminosity, then an analogous signal for $h_1$ may be obtainable. Table 4 uses the results of the simulation done in Ref. [29].

<table>
<thead>
<tr>
<th>$M_{\phi^0}$ (GeV)</th>
<th>Signal (S)</th>
<th>Background (B)</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>13.5</td>
<td>10.5</td>
<td>4.2</td>
</tr>
<tr>
<td>110</td>
<td>18.3</td>
<td>7.0</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Table 4: Signals for process $pp \rightarrow \phi^0 lX$, $\phi^0 \rightarrow \gamma\gamma$, for $\mathcal{L} = 100$ fb$^{-1}$ (from Ref. [29]).

![Figure 2: Statistical signal as a function of $\tan\beta$ for the three $H_F$ considered, with $M_F = 80$ GeV.](image)
The event numbers for $\phi^0$ include contributions from the associated process $pp \rightarrow t\bar{t}\phi^0$, $\phi^0 \rightarrow \gamma\gamma$, with the lepton trigger originating from $t \rightarrow Wb \rightarrow l\nu b$. This contributes about 60% of the signal in Table 4. For the above mentioned case of $h_1$, the contribution in this channel would be negligible (since the parameter choice for a larger BR ($h_1 \rightarrow \gamma\gamma$) requires suppression of the $h_1b\bar{b}$ and $h_1t\bar{t}$ coupling). Therefore we would expect around half the number of events shown in Table 4, giving a small signal between $2.5\sigma$ and $3.5\sigma$. Hence a null search in the $gg \rightarrow h_1 \rightarrow \gamma\gamma$ channel but a signal in the associated channel would then be evidence for Model I$'$.

We recall that a fermiophobic Higgs ($H_F$) may have a sizeable BR ($H_F \rightarrow \gamma\gamma$) [13]. It too has no production channel $gg \rightarrow H_F$, but would give a clear, distinct signal in the associated production channel for $H_F \rightarrow \gamma\gamma$ decays. It has a larger BR ($H_F \rightarrow \gamma\gamma$) than is possible in Model I$'$, varying from 20% for $M_F = 100$ GeV to $\approx 1\%$ for $M_F = 130$ GeV. The current bound on $M_F$ from the Tevatron ($\geq 81$ GeV) assumes $\phi^0$ strength couplings to vector bosons, which in general is not the case. Hence an $H_F$ with a mass considerably less than 81 GeV is not ruled out. Figs. 2 and 3 show the statistical significance (defined by $N = S/\sqrt{B}$) for two different values of $M_F$ as a function of $\tan\beta$($\cot\theta_H$) for the three $H_F$ considered in Ref. [14]. For the Higgs triplet model one must make the replacement $\cot\theta_H \rightarrow \tan\beta$ in the figures.
horizontal line at \( N = 5 \) marks the 5\( \sigma \) discovery limit. The \( H_F \) of the 2HDM (Model I), which requires \( \cos \alpha \rightarrow 0 \), is labelled as \( h_1^F \) and its cross-section is proportional to \( \cos^2 \beta \). For \( h_1^F \) one registers a 5\( \sigma \) signal if \( \tan \beta \leq 16 \) (5) for \( M_F = 80 \) GeV (110). For values of \( \tan \beta \) close to 1 the signal is of order 500\( \sigma \) in Fig. 2 and 70\( \sigma \) in Fig. 3. For \( H_0^{1'} \) the coverage is better due to its cross-section being enhanced by a factor 8/3 relative to that of \( h_1^F \). When \( \text{BR} \left( H_F \rightarrow \gamma \gamma \right) \leq 1\% \) (for \( M_F \geq 130 \) GeV) there will little difference between the signal for \( \phi^0 \) and the signal for \( H_F \). To our knowledge there has not been a rigorous simulation for the associated production process for heavier Higgs masses, but we may conclude that detection of \( H_F \) will be very difficult in this channel for \( M_F \geq 130 \) GeV.

3.2 \( h_1 \rightarrow \tau^+ \tau^- \)

The next channel we wish to consider is \( h_1 \rightarrow \tau^+ \tau^- \). For the SM Higgs in the mass region \( 100 \text{ GeV} \leq M_{\phi^0} \leq 170 \) GeV this decay varies from \( \text{BR}=8\% \) to 0.1\%. One can see from Table 1 that choosing large \( \tan \beta \) (thus \( 1/\cos \beta \) large) enhances the \( h_{1ll} \) vertex.

![Figure 4: Statistical signal in the \( \tau \tau \) channel as a function of \( \tan \beta \) for \( M_{h_1} = 120 \) GeV and four different values of \( \alpha \).](image)
Figure 5: Same as for Fig. 4 but fixing $\alpha = \pi/4$ and for three different values of $M_{h_1}$.

In Fig. 4 we plot the statistical signal as a function of $\tan \beta$ for $M_{h_1} = 120$ GeV, for four different values of $\alpha$. The choice of $\alpha = \pi/4$ allows the best coverage, giving a $5\sigma$ signal for $\tan \beta \geq 12$. As one moves away from this value the signal can still be strong, although larger values of $\tan \beta$ are required. As $\tan \beta$ becomes very large one can obtain $\text{BR}(h_1 \rightarrow \tau\tau) \rightarrow 100\%$ for all the displayed values of $\alpha$, and thus all four curves will asymptote to a fixed value of $N$. Smaller $\alpha$ is favourable from the point of view of the cross–section and this is why the curves with $\alpha \leq \pi/4$ asymptote to larger values of $N$ than is possible for $\alpha = \pi/4$; they take longer to reach the $5\sigma$ signal because the BR to $\tau\tau$ for smaller $\tan \beta$ is inferior to the corresponding BR with $\alpha = \pi/4$. Since setting $\alpha = \pi/4$ gives the best coverage we use this value in Fig. 5, which shows the expected signal for $M_{h_1}$ up to 300 GeV. It is clear from the graphs that a good signal in this channel is possible even for relatively large values of $M_{h_1}$.

We note that the enhancement of the Higgs bremsstrahlung off a $b$ quark at high $\tan \beta$ is possible in Model II, while $\text{BR}(h_1 \rightarrow \tau^+\tau^-)$ would approach 10% in this limit. The combination of an enhanced production cross–section and a $\text{BR}(h_1 \rightarrow \tau^+\tau^-)$ of order 10% would also allow a large signal in the $\tau\tau$ channel. With values of $\tan \beta \geq 50$ one could obtain a signal larger than is obtained for $h_1$ of Model I using the same $\tan \beta$ value. However, the accompanying decays in Model II would be to $bb$ with the process
$h_1 \to ZZ \to llll$ suppressed, and so one would not see a signal in the $llll$ channel. For Model I' the accompanying decays are $h_1 \to WW^{*}, ZZ^{*}$ and so an observable signal in the $llll$ channel is still likely, unless BR $(h_1 \to \tau^{+}\tau^{-})$ is close to 100%. Therefore a positive signal in both channels would be distinctive of Model I'.

3.3 $h_1 \to t\bar{t}, h_1 \to b\bar{b}$

Decays of a Higgs to quark pairs, although usually dominant for the intermediate mass Higgs boson (i.e. $M_{h} \leq 2M_W$), are considered difficult at a hadron collider and other channels give better chances of detection. However, in the 2HDM it is possible that the quark decays ($t\bar{t}$ or $b\bar{b}$) dominate the vector boson channels over a wide range of Higgs masses and therefore it is important to infer whether these quark decays can indeed present a signature, or if $h_1$ would be hidden.

In any 2HDM it is possible for $h_1 \to t\bar{t}$ decays to predominate (for $M_{h_1} \geq 2m_t$) if the $VV$ decays are sufficiently suppressed i.e. $\sin^2(\beta-\alpha) \to 0$. In the extreme case of $\sin^2(\beta-\alpha) = 0$ (i.e. $\beta = \alpha$), $t\bar{t}$ decays would predominate for $\tan\beta \leq 5$ in all models, while for $\tan\beta \geq 5$ decays to $b\bar{b}$ would predominate in Models II and II'.

We present the event numbers for $h_1$ in Table 5 by rescaling the ATLAS numbers, taking $\alpha = \beta$ and BR $(h_1 \to t\bar{t}) = 100\%$.

<table>
<thead>
<tr>
<th>$M_{h_1}$ (GeV)</th>
<th>Signal (S)</th>
<th>Background (B)</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>370</td>
<td>1800</td>
<td>68600</td>
<td>6.9</td>
</tr>
<tr>
<td>400</td>
<td>1980</td>
<td>85700</td>
<td>6.8</td>
</tr>
<tr>
<td>500</td>
<td>1670</td>
<td>127400</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Table 5: Statistical signal in the $h_1 \to t\bar{t}$ channel for $\mathcal{L} = 30$ fb$^{-1}$ (from Ref. [25] with rescaling).

The statistical significance of the signal is large but is only meaningful if the theoretical error on $\sigma(pp \to t\bar{t})$ is less than 1%, which is not the case at the present. If the error is reduced then there would be some chance of detection in this channel.

The other quark decay that could dominate is that of $h_1 \to b\bar{b}$ in Models II and II' for $\tan\beta \geq 5$. For detection in this decay mode one requires a good trigger in order to suppress the huge QCD background. However, producing this $h_1$ in association with a $W$ boson via $q\bar{q} \to W^* \to Wh_1$, with $W \to l\nu_l$ (a lepton trigger) and $h_1 \to b\bar{b}$ only probes $M_{h_1} \leq 120$ GeV [25], [28]. Therefore we conclude that the quark decays ($t\bar{t}$, $b\bar{b}$) of $h_1$ would be difficult to observe at the LHC.

3.4 $h_1 \to ZZ^{(*)}$

The SM Higgs decay to two $Z$ bosons, with the subsequent decay $ZZ \to llll$ is the ‘gold–plated’ channel, since it gives a large signal throughout the range $130 \text{ GeV} \leq$
$M_H \leq 800$ GeV. Below the real $ZZ$ threshold one of the vector bosons must be off-shell. In the 2HDM, $\Gamma(h_1 \rightarrow VV^{(*)})$ is suppressed by $\sin^2(\beta - \alpha)$ although for $M_{h_1} \geq 150$ GeV these decays will usually predominate, unless this suppression is large and/or another channel is greatly boosted. Table 6 shows the expected signal and background ratio for $\phi^0$, which is very large over much of the mass interval $200$ GeV $\leq M_{\phi^0} \leq 800$ GeV, reaching as high as 40 standard deviations.

<table>
<thead>
<tr>
<th>$M_{h_1}$ (GeV)</th>
<th>Signal (S)</th>
<th>Background (B)</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5.2</td>
<td>4.7</td>
<td>2.4</td>
</tr>
<tr>
<td>130</td>
<td>24.8</td>
<td>8.2</td>
<td>8.5</td>
</tr>
<tr>
<td>150</td>
<td>68.5</td>
<td>10.0</td>
<td>21.7</td>
</tr>
<tr>
<td>170</td>
<td>19.9</td>
<td>9.5</td>
<td>6.5</td>
</tr>
<tr>
<td>180</td>
<td>51.9</td>
<td>9.0</td>
<td>17.3</td>
</tr>
<tr>
<td>200</td>
<td>189</td>
<td>29</td>
<td>35.3</td>
</tr>
<tr>
<td>300</td>
<td>314</td>
<td>68</td>
<td>38.2</td>
</tr>
<tr>
<td>400</td>
<td>267</td>
<td>56</td>
<td>35.7</td>
</tr>
<tr>
<td>500</td>
<td>137</td>
<td>29</td>
<td>25.6</td>
</tr>
<tr>
<td>600</td>
<td>70</td>
<td>25</td>
<td>14.1</td>
</tr>
<tr>
<td>700</td>
<td>38</td>
<td>21</td>
<td>8.3</td>
</tr>
<tr>
<td>800</td>
<td>22</td>
<td>17</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 6: Statistical signal in the $\phi^0 \rightarrow ZZ^{(*)} \rightarrow llll$ channel for $L = 100$ fb$^{-1}$ (from Ref.[26]).

For the mass region $100$ GeV $\leq M_{\phi^0} \leq 130$ GeV the $ZZ \rightarrow llll$ channel does not provide a strong enough signature since the BR($\phi^0 \rightarrow llll$) is too low. In a 2HDM one can suppress the $b\bar{b}$ channel in this region which may enable the $llll$ signal to be used for lower masses of $h_1$ than is possible for $\phi^0$. An extreme case of this is the fermiophobic Higgs ($H_F$) which has a considerably larger BR to $ZZ^*$ than is possible for $\phi^0$ in this mass region. Enhancements are possible in the other versions of the 2HDM, although one cannot suppress all fermion channels simultaneously – an option only available in Model I. A major problem with detecting $H_F$ is that there is no $gg \rightarrow H_F$ production process, and $VV$ fusion will be suppressed by at least a factor of 0.5 (for $\alpha = \pi/2$, $\beta = \pi/4$). This results in a sizeable drop in the cross-section, $\sigma(pp \rightarrow H_F X)$, by at least a factor of 10 relative to $\phi^0$ in the range $80$ GeV $\leq M_{H_F} \leq 120$ GeV. However, BR ($H_F \rightarrow ZZ^*$) is much larger than that for $\phi^0$, the former varying from 6% $\rightarrow$ 9% ($20\% \rightarrow 29\%$ for $H_F^0$) in the region $80$ GeV $\leq M_{H_F} \leq 120$ GeV. This is in contrast to BR ($\phi^0 \rightarrow ZZ^*$) which varies from 0.01% $\rightarrow$ 1.3%. Therefore the signal event number may be considerably greater (an order of magnitude) for $H_F$ in the region $M_F \leq 100$ GeV than for $\phi^0$. In fact, a signal for $\phi^0$ in this channel is unlikely for $M_{\phi^0} \leq 120$ GeV (see Table 6), but may be possible for $H_F$ with a few events over a
small background. For $M_F \geq 120$ GeV the signal for $H_F$ becomes weaker than that for $\phi^0$ since $\text{BR}(\phi^0 \rightarrow ZZ^*)$ is increasing rapidly, and coupled with the latter’s superior cross-section more events are produced overall.

Other models which may provide an enhanced signal in the $llll$ channel are Models II and II’, although Model II has the possibility of the largest signal since both $b\bar{b}$ and $\tau^+\tau^-$ can be simultaneously suppressed. The choice of $\cos^2 \alpha \rightarrow 1$ and moderate $\sin^2 \beta \equiv 0.5$ would boost the $t\bar{t}$ coupling and so enhance the $gg \rightarrow h_1$ cross-section, and also cause the required suppression of the $b\bar{b}$ and $\tau^+\tau^-$ decays (in Model II’ the $\tau^+\tau^-$ cannot be simultaneously suppressed, and so the BR to $ZZ^*$ would be less). This means that although $c\bar{c}$ and $gg$ decays would dominate, BR ($h_1 \rightarrow ZZ^*) = 1\%$ is possible, and combined with the enhanced cross-section one would find an increase of order 4 for the $llll$ signal. This analysis is for $M_{h_1} = 110$ GeV.

For the heavier Higgs masses, $M_{h_1} \geq 2M_Z$, the decay to two real $Z$ bosons $h_1 \rightarrow ZZ$ is available. Two signatures remain which could suggest a 2HDM in this channel:

(i) An enhanced cross-section. Since $gg \rightarrow \phi^0$ gives the largest rate, if one enhances the $h_1t\bar{t}$ coupling it is possible to have more $llll$ events than for the $\phi^0$ case.

(ii) A suppression of the $llll$ signal relative to $\phi^0$ would be very noticeable, since the $\phi^0$ signal can be as large as 40$\sigma$.

Case (i) is possible in all 2HDM, as mentioned earlier for parameter choices such as $\cos^2 \alpha \rightarrow 1$ and moderate $\sin^2 \beta \equiv 0.5$. This would cause an enhancement of 2 for the $gg$ fusion cross-section, and the overall cross-section would be enhanced by roughly the same factor (since $gg$ fusion gives the largest contribution). Case (ii) is also possible in any 2HDM and therefore the above scenarios do not give any information on which particular model would be present. There are two ways for case (ii) to be realized.

(a) The choice of $\beta \approx \alpha$ forces $\sin^2(\beta - \alpha) \approx 0$ and so the $h_1 \rightarrow ZZ$, $WW$ decays are heavily suppressed. Instead the $t\bar{t}$ or $b\bar{b}$ channel predominates for the heavy Higgs mass region, $M_{h_1} \geq 2M_Z$ (see Section 3.3).

(b) The BRs to $ZZ$ and $WW$ may be kept dominant, but with the production cross-section heavily suppressed, i.e. the $h_1t\bar{t}$ coupling is heavily reduced which in turn suppresses the mechanism $gg \rightarrow h_1$.

Case (b) is true for a fermiophobic Higgs whose main production process would be $WW$ and $ZZ$ fusion. Using the ATLAS studies and Table 6 we can evaluate the statistical signal. The cross-section is roughly 10 times less for $h_1^F$ than for $\phi^0$ throughout the range $200$ GeV $\leq M_{H_F} \leq 800$ GeV, and BR ($h_1^F \rightarrow ZZ)$ $\approx$ BR ($\phi^0 \rightarrow ZZ$). We would find that a 4$\sigma$ signal is only possible up to $M_F = 400(600)$ GeV for $h_1^F$ ($H_0^F$). For $H_0^F$ the cross-section is roughly half that of $h_1^F$ throughout the heavy mass region, but this is compensated by the fact that BR($H_0^F \rightarrow ZZ$) is twice that
of $h_F^1$, with the result being that a similar signal is expected. This analysis is for maximum values for production cross-sections. Therefore it turns out that there is a sizeable parameter space ($\cos^2 \beta$, $M_F$) for a hidden $H_F$ at the LHC. We stress that the distinctive signature of a fermiophobic Higgs ($H_F \to \gamma\gamma$) is lost in this heavier mass region, and the suppressed $llll$ signal could be mimicked by another $h_1$ with suppressed $ZZ$ decays and/or production cross-section.

4 Conclusions

We have studied the phenomenology of the lightest CP-even neutral Higgs boson($h_1$) of a non-SUSY, non-minimal Standard Model at the LHC. Emphasis was given to the problem of distinguishing $h_1$ from the SM Higgs boson ($\phi^0$) and to the detection prospects of a fermiophobic Higgs ($H_F$). This is complementary to our earlier work which considered prospects at LEP2. We considered four different decay channels and showed that the following signals are possible:

(i) An enhanced signal in the $pp \to h_1 X$, $h_1 \to \gamma\gamma$ channel would be evidence for Model II or II', although Model II can produce the greater number of events. A signal in the associated production channel $pp \to h_1 W$, $h_1 \to \gamma\gamma$ and $W \to l\nu_l$ but no signal in the above channel would be evidence for Model I' or a fermiophobic Higgs, with the latter capable of more signal events.

(ii) A large signal from $h_1 \to \tau^+\tau^-$ decays is possible in Model I', even for relatively large masses, and would be accompanied by a signature in the $llll$ channel, unless the former has a branching ratio close to 100%. In Model II it is possible to have a comparable enhancement of $\tau^+\tau^-$ events but the accompanying decays would be to hadrons, the latter unlikely to be separated from the backgrounds.

(iii) Enhanced $h_1 \to t\bar{t}, b\bar{b}$ decays in the heavy Higgs region are possible although they are very difficult to detect at the LHC due to the large jet background. Detection may be possible in the $t\bar{t}$ channel if the theoretical error on the background $pp \to t\bar{t}$ cross-section can be reduced to below 1%.

(iv) A suppressed or enhanced signal in the $llll$ channel would indicate a non-minimal Higgs sector, although would not shed light on which model were actually present.

Detection of a fermiophobic Higgs will be difficult for masses greater than 130 GeV, the only chance being a suppressed signal in the $llll$ channel. Such a suppression, however, may be mimicked in all the models considered and so is not indicative of fermiophobia. The unmistakable signature of $H_F$ is available up to $M_F \leq 130$ GeV, and would be a spectacular excess of $\gamma\gamma$ events in the associated production channel provided that the cross-section is not so suppressed.
Acknowledgements

This work has been supported by the UK Royal Society.

References


