Roles of Higgs decay into two pseudoscalar bosons in the search of intermediate-mass Higgs Boson

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Abstract. The dominance of $h \to \eta\eta$ decay mode for the intermediate mass Higgs boson is highly motivated to solve the little hierarchy problem and to ease the tension with the precision data. However, the discovery modes for $m_h \lesssim 150$ GeV, $h \to \gamma\gamma$ and $W/Zh \to (\ell\nu/\ell\ell)(b\bar{b})$, will be substantially affected. We show that $h \to \eta\eta \to 4b$ is complementary and we can use this decay mode to detect the intermediate Higgs boson at the LHC, via $Wh$ and $Zh$ production. Requiring at least one charged lepton and 4 $B$-tags in the final state, we can identify a clean Higgs boson signal for $m_h \lesssim 150$ GeV with a high significance and with a full Higgs mass reconstruction. We use the next-to-minimal supersymmetric standard model and the simplest little Higgs model for illustration.

PACS. 12.60.Fr Extensions of electroweak Higgs sector – 13.85.Rm Limits on production of particles

1 Introduction

The standard model (SM) has been successful in explaining all the data, except for a few observations. One of them is the controversy between the precision data and the direct search for the SM Higgs boson. The precision measurements from LEP and SLD collaborations strongly prefer a light Higgs boson with a mass around 100 GeV \textsuperscript{1}. However, the direct search has put a lower bound of $114.4$ GeV \textsuperscript{2}. Such a high Higgs mass bound also induces the so-called little hierarchy problem in supersymmetric framework. It is urgent to relieve the tension arisen from the Higgs mass bound. A phenomenological approach to lower the Higgs mass bound is to reduce either the coupling $g_{ZZh}$ or $B(h \to b\bar{b})$. One possibility is to add a singlet field to the Higgs sector such that the Higgs doublet and the singlet mix. The SM-like Higgs boson will have a smaller effective coupling $g_{ZZh}$ to the $Z$ boson. More important is that there are additional decay modes for the Higgs boson. In supersymmetric framework, the most popular approach is the next-to-minimal supersymmetric standard model (NMSSM). It has been shown \textsuperscript{3} that, in most parameter space that is natural, the SM-like Higgs boson can decay into a pair of light pseudoscalar bosons with a branching ratio larger than 0.7. The Higgs mass bound can be as low as around 100 GeV. In little Higgs framework, it has been shown \textsuperscript{4} that in the simplest little Higgs model with the $\mu$ parameter (SLH$\mu$) \textsuperscript{5}, the Higgs boson can dominantly decay into a pair of pseudoscalar bosons $\eta$. Together with the reduction of the $g_{ZZh}$ coupling, the Higgs mass bound can be lowered. In these models, the Higgs boson dominantly decays into lighter Higgs bosons (we shall denote the lighter Higgs boson as pseudoscalar boson $\eta$ without loss of generality.) The dominance of $h \to \eta\eta$ mode for the intermediate Higgs boson has significant impacts on the Higgs search strategies. The most useful channel for intermediate Higgs boson, $h \to \gamma\gamma$, will be substantially affected because $B(h \to \gamma\gamma)$ lowers by a factor of a few. So is the $h \to b\bar{b}$ in $Wh$, $Zh$ production. It is therefore utmost important to show the complementarity of the $h \to \eta\eta$ mode, and timely to establish the feasibility of the $h \to \eta\eta$ mode. We have shown in Ref. \textsuperscript{6} that using $h \to \eta\eta \to 4b$ for $m_\eta > 2m_b$ the Higgs signal can be identified at the LHC, via $Wh$, $Zh$ production. With at least one charged lepton and 4$B$-tags in the final state, one can obtain a clean signal of high significance and a full Higgs mass reconstruction.

2 Production and decay

The pseudoscalar boson decays into the heaviest fermion pair that is kinematically allowed, either $b\bar{b}$ or $\tau^+\tau^-$. If $m_\eta > 2m_b$, the SM-like Higgs boson will decay like $h \to \eta\eta \to (4b, 2\tau\tau, 4\tau)$. Feasibility studies focusing on Higgs production at the Tevatron have been performed in extended supersymmetric models. The $gg \to h \to \eta\eta \to 4b$ signal at the Tevatron has been shown overwhelmed by large QCD background \textsuperscript{7}. Similar
conclusions can be drawn for the LHC. Another study using $(2\eta, 2\tau)$ mode for the associated Higgs production with a $W/Z$ at the Tevatron was performed, but a full Higgs mass reconstruction is difficult \cite{8}. The $4\tau$ mode was also studied at the Tevatron for $2m_{\tau} < m_{h} < 2m_{\eta}$ \cite{9}. If $m_{h} < 2m_{\eta}$, on the other hand, the modes $\eta \rightarrow e^{+}e^{-}, \gamma \gamma$ become dominant \cite{10} but the photon pair for each pseudoscalar decay is very collimated, which reduces the detectability. One can also have the pseudoscalar boson produced directly, e.g., in the associated production with a gaugino pair \cite{11}.

In Ref. \cite{6}, we focus on $W h$ and $Z h$ production at the LHC, followed by the leptonic decay of the $W$ and $Z$, and $h \rightarrow \eta \eta \rightarrow b b b b$. In the final state, we require a charged lepton and 4 $b$-tagged jets. The advantage of having a charged lepton in the final state is to suppress the QCD background. We require 4 $b$-tagged jets to avoid the huge $t \bar{t}$ background. We are still left with some irreducible backgrounds from $W + n b$ and $Z + n b$ production with $n \geq 4$, $t \bar{t} b b$ and $t t t t$ production ($t t t t$ is much smaller than $t \bar{t} b b$ and so we ignore it in the rest of the paper.) We study the feasibility of searching for the Higgs boson using $W h, Z h \rightarrow \ell \nu (\ell = e, \mu) + 4 b + X$ at the LHC. A naive signal analysis at the Tevatron already tells us that the signal rate is too small for realistic detection. At the LHC, we found a sufficiently large signal rate with a relatively small background for $m_{h} \lesssim 160 \text{GeV}$. Reconstructing the invariant mass of the 4 $b$-tagged jets is shown to play a crucial role: The signal will peak at $m_{h}$ while the serious background begins at $M_{b} \gtrsim 160 \text{GeV}$.

Details of the Higgs sector of NMSSM and SLH$\mu$ model are referred to Refs. \cite{12} and \cite{3}, respectively. The dominant production for an intermediate Higgs boson at the LHC is the gluon fusion. However, as mentioned above the decay $h \rightarrow \eta \eta$ followed by $\eta \rightarrow b b$ is overwhelmed by QCD backgrounds.\cite{7}. The next production mechanism, the WW fusion, has the final state consisting of only hadronic jets. Therefore, we consider the associated production with a $W$ or $Z$ boson. The cross section is proportional to the square of the coupling $g_{Vh}$. In the NMSSM, the deviation of $g_{Vh}$ from the SM value depends on the nature of the $h_1$. For the bench-mark points \#2 and \#3 of Ref. \cite{13} the size of $g_{Vh}$ is very close to the SM value, though the sign may be opposite. We consider 2 bench-mark points A and B, which are very similar to the bench-mark points \#2 and \#3 of Ref. \cite{13}, by scanning the parameter space using NMHDECAY \cite{14}. In the SLH$\mu$, $g_{Vh}$ deviates from the SM value as

\[
\begin{align*}
\frac{g_{SVW}}{g_{SWh}} &= 1 - \frac{v^2}{3 f^2} \left( s_{\beta}^4 + c_{\beta}^4 \right) + O \left( \frac{v^4}{f^4} \right) \\
\frac{g_{SVZH}}{g_{ZZh}} &= 1 - \frac{v^2}{3 f^2} \left( s_{\beta}^4 + c_{\beta}^4 \right) - \frac{v^2}{f^2} (1 - t_W^2) \frac{4}{3} \left( \frac{h_1}{h_1} \right) + O \left( \frac{v^4}{f^4} \right),
\end{align*}
\]

where $t_W$ is tangent of the Weinberg angle, $f$ is the symmetry breaking scale at TeV, $c_{\beta} = \cos \beta$, $s_{\beta} = \sin \beta$, and $\tan \beta$ is the ratio of the VEV of the two pseudo-Nambu–Goldstone multiplets of the SLH$\mu$ model \cite{5,4}.

We employ full helicity decays of the gauge bosons, $W \rightarrow \ell \nu$ or $Z \rightarrow \ell \ell$, and the phase decays of the Higgs boson and the pseudoscalar in $h \rightarrow \eta \eta \rightarrow b b b b$. The detection requirements on the charged lepton and $b$ jets in the final state are

\[
\begin{align*}
& p_{T}(\ell) > 15 \text{ GeV}, \quad |\eta(\ell)| < 2.5, \\
& p_{T}(b) > 15 \text{ GeV}, \quad |\eta(b)| < 2.5, \quad \Delta R(b \bar{b}, b \bar{b}) > 0.4,
\end{align*}
\]

where $p_{T}$ denotes the transverse momentum, $\eta$ denotes the pseudorapidity, and $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ denotes the angular separation of the $b$-jets and the lepton. The smearing for the $b$ jets is $\frac{\Delta E_{T}}{E} = \frac{5.6}{5} + 0.03$, where $E$ is in GeV. In order to minimize the reducible backgrounds, we require to see at least one charged lepton and 4 $b$-tagged jets in the final state. We employ a $B$-tagging efficiency of 70$\%$ for each $B$ tag, and a probability of 5$\%$ for a light-quark jet faking a $B$ tag.

It is possible for the photon in $\gamma + n j$ background to fake an electron in the EM calorimeter. However, we will ignore this since the charged lepton from the $W$ or $Z$ decay is quite energetic and produces a track in the central tracking device, in contrast to that from a photon. The backgrounds from $W + n j$ and $Z + n j$ contribute at a very low level and are reducible as we require 4 $b$-tagged jets in the final state. The background from $WZ \rightarrow \ell \nu b b$ is also reducible by the 4 $b$-tagging requirement. So is QCD production of $t \bar{t}$ pair with one of the top decay hadronically and the other semi-leptonically. Jets from the $W$ decay may fake a $B$-tag. This background is under control after applying our selective cuts. While most of the backgrounds are reducible, there are a few channels that are irreducible. They are (i) $t \bar{t} b b$ production, and (ii) $W/Z + 4 b$ production.

3 Results

As mentioned in the Introduction, we use two popular models for new physics: (i) NMSSM and (ii) SLH$\mu$. In NMSSM, we scan the code NMHDECAY \cite{14} and choose two bench-mark points, A and B, both of which have $B(h \rightarrow a_1 a_1) \approx 1$ and $B(a_1 \rightarrow b b) \approx 0.9$. In a large portion of the parameter space of NMSSM, the mass of $h_1$ is around $100 \text{ GeV}$ and $B(h_1 \rightarrow a_1 a_1) \gtrsim 0.7$ \cite{3}. The bench-mark points that we employ are quite common in the NMSSM. In the SLH$\mu$ model, we employ two points in the parameter space such that the mass of the Higgs boson is $O(100) \text{ GeV}$ and $B(h \rightarrow \eta \eta) \gtrsim 0.7$ \cite{4}.

We show the signal cross sections of $W h$ and $Z h$ for the NMSSM and for SLH$\mu$ in Table \ref{table-1} and various backgrounds in Table \ref{table-2} respectively. The cross sections are under the cuts listed in Eq. (2). We have imposed a $B$-tagging efficiency of 0.7 for each $b$ jet and a mis-tag efficiency of 0.05 for a light-quark jet to fake
For SLH, two NMSSM bench-mark points have been substantially studied. Suppose that the SLH and NMSSM signals can easily understand the relative importance of these with respect to the SM values in Table 1. With these values, we can show the significance of the signal by evaluating the signal and background cross sections and the significance of the background in the SLH model itself. Nevertheless, if we look at combination of the SM and NMSSM signals, shown in Table 3 using the lepton to jet cuts and efficiencies as in Table 1.

A comment on the background rates in Table 1 is in order here. In general, one defines the background in the SM as the background for our search in WH, Zh → ℓ + 4b as those arising from the new physics under consideration. The background in the NMSSM (including NMSSM interactions) is the same as in the SM. In the SLH model, however, especially the tbb̄ from tℓ → bbb̄ increases the background substantially. Suppose that the SLH is the actual model describing our world. If we are searching for the Higgs bosons in extended models, we have

to fight against the tℓ → bbb̄ background in the SLH model itself. Nevertheless, if we look at combination of signal channels, this tbb̄ would be an interesting one for the η boson.

Since we require all 4 b-tagged jets, we can reconstruct the invariant mass M_{4b} of the signal and the background. We show the invariant mass spectrum for the NMSSM point B in Fig. 1. The spectrum for other benchmark points are similar. For m_h ≳ 160 GeV the signal peak will stand out of the continuum, provided that the B(h → ηη) still dominates. We can calculate the significance of the signal by evaluating the signal and background cross sections under the signal peak:

\[ m_h - 15 \text{ GeV} < M_{4b} < m_h + 15 \text{ GeV} , \quad (4) \]

which is a conservative choice for the signal peak resolution. We show the total signal and background cross sections and the significance S/√B in Table 2 using

### Table 1. Signal cross sections for Wh and Zh production for benchmark points NMSSM (A) and NMSSM (B), and for SLHμ (A) and SLHμ (B) at the LHC.

| Channels | NMSSM (A) | NMSSM (B) | SLHμ (A) | SLHμ (B) |
|----------|-----------|-----------|-----------|-----------|
| λ = 0.18, κ = -0.43 | λ = 0.26, κ = 0.51 | f = 4 TeV | f = 2 TeV |
| tan β = 29 | tan β = 23 | μ = 20 GeV | μ = 20 GeV |
| A_λ = -437 GeV | A_λ = -222 GeV | x_3 = 5.86 | x_3 = 10 |
| A_κ = -4 GeV | A_κ = -13 GeV | tan β = 17 | tan β = 9.47 |
| μ_eff = -143 GeV | μ_eff = 144 GeV |

| m_h | m_a | m_h | m_a |
|-----|-----|-----|-----|
| 110 GeV | 109 GeV | 146.2 GeV | 135.2 GeV |
| 30 GeV | 39 GeV | 68.6 GeV | 47.9 GeV |

| B(h → a_1a_1) = 0.92 | B(h → a_1a_1) = 0.99 | B(η → g) = 0.65 | B(η → g) = 0.75 |
| B(τ → b_1b_1) = 0.03 | B(η → g) = 0.92 | B(η → g) = 0.85 | B(η → g) = 0.86 |
| gVV/hSM/VV = 0.99 | gVV/hSM/VV = -0.99 | gVV/hSM/VV = 0.57 | gVV/hSM/VV = 0.44 |
| gta/hSM/ta = 0.99 | gta/hSM/ta = -1.2 × 10^-2 | gta/hSM/ta = -0.89 | gta/hSM/ta = -1.38 |

| C^2_{4b} = 0.80 | C^2_{4b} = 0.83 | C^2_{4b} = 0.16 | C^2_{4b} = 0.11 |

### Fig. 1. Invariant mass spectrum M_{4b} of the signal and various backgrounds for the benchmark point B of the NMSSM.

### Table 2. Various background cross sections under the same cuts and efficiencies as in Table 1

| Channels | cross sections (fb) |
|----------|---------------------|
| tt       | 112 (NMSSM & SLHμ)  |
| tbb̄     | 236 (NMSSM), 284 (SLHμ A), 429 (B) |
| W + 4b   | 3.80 (NMSSM), 4.16 (SLHμ A), 4.63 (B) |
| Z + 4b   | 3.85 (NMSSM & SLHμ) |

This is a summary of the results presented in the document.
Table 3. Total signal and background cross sections after applying the cuts in Eq. (2) and the invariant mass cut of $m_h - 15 \text{ GeV} < M_{bb} < m_h + 15 \text{ GeV}$. The significance $S/\sqrt{B}$ is for a luminosity of 30 fb$^{-1}$.

|             | NMSSM | SLHμ |
|-------------|-------|------|
|             | A     | B    | A    | B    |
| signal      | 6.53 fb | 18.85 fb | 2.50 fb | 1.25 fb |
| bkgd        | 4.83 fb | 4.77 fb | 13.83 fb | 22.45 fb |
| $S/\sqrt{B}$| 16.3  | 47.3 | 3.7  | 1.4  |

Table 3. Total signal and background cross sections after applying the cuts in Eq. (2) and the invariant mass cut of $m_h - 15 \text{ GeV} < M_{bb} < m_h + 15 \text{ GeV}$. The significance $S/\sqrt{B}$ is for a luminosity of 30 fb$^{-1}$. The significance of the NMSSM bench-mark points are large because of the smallness of background. On the contrary, the SLHμ bench-mark points have smaller significance but close to 4 for point A, but not for point B. It is due to smaller signal rates and a much larger background from $t\bar{t}\eta$ production.

For $m_h$ below 250 GeV, the $t\bar{t}h$ cross section is sub-dominant relative to the $Zh$ and $W h$ production when the Higgs is SM-like. In other models, however, the top Yukawa coupling can be much enhanced. In this case, the $t\bar{t}h$ production could be dominant. Unfortunately the signal analysis in $t\bar{t}h$ is more complicated because of a total of 6 $b$ jets in the final state, but only 4 of those can be reconstructed at $m_h$. Therefore, efficiency will drop in picking the right $b$ jets.

In conclusion, the dominance of $h \rightarrow \eta\eta$ decay mode is highly motivated because it can relieve the little hierarchy problem and the tension with the precision data. However, the dominance of $h \rightarrow \eta\eta$ in the intermediate mass region worsens significantly the discovery channels of $gg \rightarrow h \rightarrow \gamma\gamma$ and $Wh \rightarrow t\nu b\bar{b}$. In this Letter, we have shown for the first time that $h \rightarrow \eta\eta \rightarrow 4b$ is complementary to make up for the loss of efficiencies in $h \rightarrow \gamma\gamma$ and $h \rightarrow b\bar{b}$ modes. It is made possible by considering the $Wh$ and $Zh$ production with at least one charged lepton and 4 $B$-tags in the final state and we can identify a clean Higgs signal with a full reconstruction of the Higgs boson mass. Our work therefore urges the experimenters to fully establish the feasibility of this mode.

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