We discuss the importance of being able to detect Higgs-to-Higgs-pair decays in the context of the Next-to-Minimal Supersymmetric Model (NMSSM) and demonstrate the excellent capabilities of a photon collider for this purpose.

1 Introduction

The Minimal Supersymmetric Model (MSSM) has been the canonical benchmark for SUSY studies for many years. However, LEP constraints demand parameter choices for which the fine-tuning and little hierarchy problems have become quite an issue. And, of course, there is still no truly attractive explanation of the $\mu$ parameter of the MSSM. The NMSSM relaxes the fine-tuning and hierarchy problems and provides a simple explanation for an electroweak-scale value for $\mu$. As such, it deserves at least as much attention as the MSSM.

It has been demonstrated\(^1\) that it may be very difficult to guarantee discovery of even one of the NMSSM Higgs bosons at the LHC (for parameter choices not already ruled out by LEP) because of the possibility of Higgs-to-Higgs decays. In particular, there are many choices for NMSSM parameters for which all the standard LHC production/decay channels used for guaranteeing discovery of at least one MSSM Higgs boson [these include: 1) $gg \to h/a \to \gamma\gamma$; 2) associated $Wh/a$ or $th/a$ production with $\gamma\gamma\ell\ell^\pm$ in the final state; 3) associated $th/a$ production with $h/a \to bb$; 4) associated $bhh/a$ production with $h/a \to \tau^+\tau^-$; 5) $gg \to h \to ZZ^{(*)} \to 4$ leptons; 6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$; 7) $WW \to h \to \tau^+\tau^-$; 8) $WW \to h \to WW^{(*)}$] fail by virtue of the fact that the only strongly produced relatively light Higgs boson (denoted $h_H$) decays with branching fraction near one to two Higgs bosons, $h_Lh_L$ (most frequently $h_L = a$, the lightest pseudoscalar). For $m_{h_L} > 2m_b$, each $h_L$ decays to $b\bar{b}$ and $\tau^+\tau^-$ (in roughly 0.9:0.1 ratio). For $2m_{\tau} < m_{h_L} < 2m_b$, the $\tau^+\tau^-$ mode is dominant, with $jj = c\bar{c} + s\bar{s} + gg$ making up the rest. In all such cases, the $h_H$ has relatively SM-like couplings, in particular to $WW$, and mass in the [75 GeV, 150 GeV] range (with $m_{h_H} \in [100 \text{ GeV}, 120 \text{ GeV}]$ being particularly probable).

The LHC detection channel $WW \to h_H \to h_Lh_L \to jj\tau^+\tau^-$ (where $j = b$ when $m_{h_L} > 2m_b$) was explored in\(^1\), with the conclusion that (after appropri-\(^a\)}
ate cuts) a signal could be seen above the (dominant after cuts) $t\bar{t}$ background as a broad-bump excess in the $M_{jj\tau^+\tau^-}$ mass distribution at low $M_{jj\tau^+\tau^-}$ above a rapidly falling (as $M_{jj\tau^+\tau^-}$ decreases) $t\bar{t}$ continuum. While nominally large statistics are obtained for this signal, it will be the only signal (other than the perturbativity of $WW \rightarrow WW$ scattering) for the presence of any of the NMSSM Higgs bosons in these cases. If this kind of scenario is nature’s choice, a proper study of the NMSSM Higgs bosons will probably only be possible at a linear $e^+e^-$ collider, or as discussed here, a $\gamma\gamma$ collider.

At a $\sqrt{s} > 350$ GeV $e^+e^-$ collider, one would simply use $e^+e^- \rightarrow ZX$ to detect the $h_H$ Higgs bump in the missing mass $M_X$. Once detected, it is an easy task to explore the $h_H$ decays. In particular, if $h_L h_L$ is the dominant decay mode, one could look also at the branching fractions of the $h_L$ to different modes ($b\bar{b}$, vs. $\tau^+\tau^-$ vs. $gg + c\bar{c} + s\bar{s}$) and check that they are in the ratio expected for a light Higgs boson (with no or suppressed $WW$ coupling) with the observed $m_{h_L}$.

However, it is not clear when such an $e^+e^-$ collider will be built. It is possible that a low-energy $\gamma\gamma$ collider based on the use of a pair of CLIC modules\(^2\) might be the first collider able to produce the $h_H$ in a sufficiently clean experimental environment that detection of $h_H \rightarrow h_L h_L$ in a variety of the $h_L$ decay channels would be possible. In what follows, we show that this potential is fully realized. Thus, if SUSY signals consistent with a model like the NMSSM are seen at the LHC, but there is no or only a very weak signal for any of the Higgs bosons, then a low-energy $\gamma\gamma$ collider will become a priority, especially if it can be built before (but also even if only as a facility at) a full-scale $e^+e^-$ collider.

### 2 The $\gamma\gamma$ Collider

We review results for the $h_H = h$, $h_L = a$ cases that would be typical of the NMSSM. For most parameter choices, $m_a > 2m_h$ and the $b\bar{b}$ and $\tau^+\tau^-$ branching ratios would be of order $0.85 - 0.9$ and $0.06$ to $0.1$, respectively. Results presented assume that the primary $h$ has SM-like $\gamma\gamma$ production rate. This is typical of the NMSSM cases that would escape LHC detection in traditional modes. Sensitivity at a $\gamma\gamma$ collider for a Higgs boson that decays primarily to $aa$ but does not have SM-like $\gamma\gamma$ coupling can be obtained by rescaling. The most important signal channels are

1. $\gamma\gamma \rightarrow h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$, \(\leftarrow\) done
2. $\gamma\gamma \rightarrow h \rightarrow aa \rightarrow b\bar{b}\tau^+\tau^-$, \(\leftarrow\) done
3. $\gamma\gamma \rightarrow h \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$. \(\leftarrow\) not yet done

\(^2\) The $\gamma\gamma$ Collider

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2
The important backgrounds are: $\gamma\gamma \rightarrow b\bar{b}b\bar{b}$, $c\bar{c}c\bar{c}$; $\gamma\gamma \rightarrow b\bar{b}\tau^+\tau^-$, $c\bar{c}\tau^+\tau^-$; and $\gamma\gamma \rightarrow \tau^+\tau^-\tau^+\tau^-$, depending upon the final state above.

For the signal, we employed an appropriately kluged version of Pythia 6.158 interfaced with CAIN 4 for correct $\gamma\gamma$ luminosity spectra. For the background, we employed WHIZARD 1.24. The cross sections for 4-fermion processes were cross checked with theoretical computations for $\gamma\gamma \rightarrow e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$, $e^+e^-\mu^+\mu^-$. The cross sections for $\gamma\gamma \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow c\bar{c}$ we obtain are consistent with Pythia, including beam polarization effects. We find that it is easy to develop tagging and cut procedures that effectively eliminate the backgrounds listed above.

If there is very weak knowledge of the Higgs mass from the LHC, one would wish to explore the largest possible range of masses at the $\gamma\gamma$ collider. For nominal CLIC single module, single beam energy of $E_e = 75$ GeV, one can adjust the laser polarizations so that the back-scattered photons have an $E_{\gamma\gamma}$ spectrum which covers a broad range up to $m_h \leq 115$ GeV. By increasing $E_e$ to 82 GeV (as is apparently technically feasible) Higgs discovery in the broad spectrum mode of operation would be possible up to $m_h \leq 125$ GeV. To go still higher in $m_h$ (or to cover the $m_h \in [115$ GeV, 125 GeV] region at $E_e = 75$ GeV) would require using the laser polarization configuration that gives a $E_{\gamma\gamma}$ spectrum that is strongly peaked at $E_{\gamma\gamma}$ values just below the upper limit (for example, the peak is close to $E_{\gamma\gamma} \sim 115$ GeV for $E_e = 75$ GeV). Once the Higgs is detected in $\gamma\gamma$ collisions, its mass will be determined rather precisely; one would then employ the peaked spectrum configuration and an $E_e$ such that the $E_{\gamma\gamma}$ peak is centered at $m_h$.

A sample of our $E_e = 75$ GeV broad-spectrum results appears in fig. 1, where we show the signal in the $4b$ final state invariant mass spectrum (after cuts and $b$-tagging) for a grid of choices: $m_h = 80, 90, 100,$ and 110 GeV and $m_a = 20, 35,$ and 50 GeV, yielding 9 cases for which $h \rightarrow aa$ is kinematically allowed. In all these cases, the $a$ mass could be determined quite precisely from the 26 mass spectra. A sample of our $E_e = 75$ GeV peaked-spectrum results for the $2\tau$ final state (where the $\tau$'s decay to a low-multiplicity “jet” + neutrinos and the $2\tau$ mass is reconstructed by using $p_T$ balancing and the assumption of collinearity between visible and invisible momentum for each $\tau$ decay) appears in fig. 2. There we display the “$4j$” mass spectra in the cases $(m_h, m_a) = (115, 56), (123, 35), (118, 41)$ and $(124, 59)$ GeV; the signal peaks contain 78, 20, 92 and 4.5 events, respectively. The small numbers in the 2nd and 4th cases are simply a result of the fact that $m_h$ is significantly beyond the $E_{\gamma\gamma} \sim 115$ GeV peak (at $E_e = 75$ GeV); the $E_{\gamma\gamma}$ spectrum runs out just above $E_{\gamma\gamma} = 125$ GeV. (Better event rates would be obtained by running the CLIC modules at $E_e = 82$ GeV, as possible.) In general, so long as one is
4-JET INV. MASS - SIGNAL on top of BACKGROUND

Figure 1: Signal (big red peak) vs. backgrounds (4b – green; 2b2c – blue; 4c – yellow) for \( \gamma\gamma \to h \to aa \to 4b \) for various \( m_h \) and \( m_a \) choices. \( E_\gamma = 75 \text{ GeV} \) broad-spectrum results.

Not severely event-rate limited, a rather accurate determination of \( \frac{B(a \to b b)}{B(a \to \tau^+ \tau^-)} \) would be possible from the ratio of the 4b to 2b2\( \tau \) event rates.

Besides \( h \to aa \) decay cases, we have also explored cases in which \( h \to a_1a_2 \) with \( m_{a_1} \neq m_{a_2} \) (not relevant for the difficult NMSSM cases, but possibly relevant in the context of other models, including the CPX MSSM \(^7\) where \( a_1 \) and \( a_2 \) would actually be CP-mixed states). There, one must repeat the analysis for various choices of \( m_{a_1} \) and \( m_{a_2} \) and look for that choice which
maximizes the signal rate. In fact, we find that by doing so not only is an excellent signal obtained, but also it is possible to determine the two masses with reasonable accuracy.

3 Conclusion
Because of increasing constraints on the Higgs sector, the MSSM can no longer be regarded as the most attractive and simple supersymmetric model. This
Honor belongs to the NMSSM, where the addition of just one extra singlet superfield solves the \( \mu \)-problem and greatly ameliorates the now-apparent fine-tuning and little-hierarchy problems of the MSSM. The price is the possible difficulty of detecting any of the NMSSM Higgs bosons at the LHC. For a large part of NMSSM parameter space the Higgs-to-Higgs-pair \( h_H \rightarrow h_L h_L \) decays are important or dominant for the most SM-like Higgs boson. When dominant, the only Higgs signal at the LHC will be a broad-bump in the \( jj\tau^+\tau^- \) signal. If not dominant, other LHC signals may be present, but understanding the NMSSM Higgs sector will still require direct observation of the \( h_L h_L \) final state. An \( e^+e^- \) linear collider is certainly capable of exploring such decays using \( e^+e^- \rightarrow Zh_H \) production. Here, we have summarized the very excellent ability of a two-CLIC-module based (or other low-energy) \( \gamma\gamma \) collider to provide a detailed survey of \( \gamma\gamma \rightarrow h_H \rightarrow h_L h_L \) production/decay in the most important \( h_L h_L \) final state decay modes. In general, the \( \gamma\gamma \) collider will be an excellent facility and complement to the LHC for studying any \( h_H \) with SM-like properties, regardless of its dominant decay mode(s) (cf. 8).

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**References**

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