Production of MSSM Higgs Bosons in $\gamma\gamma$ Collisions

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**Abstract**

The heavy Higgs bosons $H, A$ of the minimal supersymmetric extension of the Standard Model can be produced as resonances in high-energy $\gamma\gamma$ colliders. Prospects of the search for these particles in $b\bar{b}$ and neutralino-pair final states are studied in this report. Heavy Higgs bosons can be found with masses up to about 70-80% of the initial $e^+e^-$ collider energy for moderate values of $\tan\beta$, i.e. in areas of the parameter space not accessible at other colliders.

**Key words:** Higgs bosons; Supersymmetry; Photon collider

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**1 Introduction**

The search for Higgs bosons is one of the most important endeavors of present and future experiments. The minimal supersymmetric extension of the Standard Model [MSSM] contains two isospin doublets of Higgs fields which materialize, after electroweak symmetry breaking, in five elementary Higgs particles [1]: two neutral CP-even ($h, H$), one neutral CP-odd ($A$) and two charged ($H^\pm$) Higgs bosons. The MSSM Higgs sector can be described, in leading order, by two independent parameters which are in general chosen as the pseudoscalar mass $M_A$ and $\tan\beta = v_2/v_1$, i.e. the ratio of the two vacuum expectation values of the scalar Higgs fields. While the mass of the lightest CP-even Higgs boson $h$ is bounded to $M_h \lesssim 130$ GeV [2], the masses of the heavy Higgs bosons $H, A, H^\pm$ are expected to be of the order of the electroweak scale up to about 1 TeV. The heavy Higgs bosons are nearly mass degenerate. An important property of the SUSY couplings is the enhancement of the bottom Yukawa couplings with increasing $\tan\beta$. The negative direct search for the
MSSM Higgs particles at LEP2 yields lower limits $M_{h,H,A} \gtrsim 90$ GeV for the neutral Higgs masses [3].

Extensive studies have demonstrated that, while the light Higgs boson $h$ of the MSSM can be found at the LHC, the heavy Higgs bosons $H,A$ may escape discovery for intermediate values of $\tan \beta$ [4]. At $e^+e^-$ linear colliders heavy MSSM Higgs bosons can only be found in associated production $e^+e^- \rightarrow HA$ [5] according to the decoupling theorem. In the first phase of the TESLA collider with a total $e^+e^-$ energy of 500 GeV the heavy Higgs bosons can thus be discovered with masses up to about 250 GeV. To extend the mass reach, the $\gamma \gamma$ option of TESLA can be used in which high-energy photon beams are generated by Compton backscattering of laser light [6]. Higgs particles can be formed as resonances in $\gamma \gamma$ collisions [7]: $\gamma \gamma \rightarrow h,H,A$. Center-of-mass energies of about 80% of the $e^+e^-$ collider energy and a high degree of longitudinal photon polarization can be reached at the $\gamma \gamma$ collider. Integrated luminosities $\int L = 300$ fb$^{-1}$ are expected per annum [8]. Photon colliders therefore provide a useful instrument for the search of heavy Higgs bosons not accessible elsewhere [9].

2 Analysis

Branching ratios. As promising examples for MSSM Higgs production in $\gamma \gamma$ collisions the two decay modes $H,A \rightarrow b\bar{b}$ and $\tilde{\chi}_0^0\tilde{\chi}_0^0$ have been investigated for $\tan \beta = 7$ and pseudoscalar masses $200$ GeV $\leq M_A \leq 800$ GeV, i.e. the blind region at LHC. The additional MSSM parameters for the gaugino sector have been chosen as $M_2 = -\mu = 200$ GeV assuming a universal gaugino mass at the GUT scale. They correspond to neutralino masses $m_{\tilde{\chi}_1^{\pm,0}} = 93, 161, 214, 256$ GeV and to chargino masses $m_{\tilde{\chi}_1^\pm} = 162, 258$ GeV. The branching ratios [10–12] (excluding invisible decays into $\tilde{\chi}_1^0\tilde{\chi}_1^0$ pairs) are presented in Fig. 1. For moderate Higgs masses the $b\bar{b}$ decay modes turn out to be dominant, while for large Higgs masses the dominant role is played by the chargino and neutralino decay modes. The decays to $\tau^+\tau^-$ and $t\bar{t}$ pairs are suppressed with respect to $b\bar{b}$ decays by nearly an order of magnitude.

Fig. 1. Branching ratios of the heavy Higgs bosons $H,A$ as a function of the corresponding Higgs mass. The MSSM parameters have been chosen as $\tan \beta = 7$, $M_2 = -\mu = 200$ GeV.
**Signal.** At LO, the Higgs boson production in $\gamma\gamma$ collisions with equal helicities is mediated by loop contributions of all charged particles [13]. Sfermions, however, are assumed to be very heavy and effectively decoupled in the present analysis. The NLO QCD corrections consist of the two-loop corrections to the quark triangle loops of the photonic Higgs couplings and the NLO corrections to the final Higgs decays into quark-antiquark pairs ($b\bar{b}$). The two-loop corrections to the Higgs couplings to photons are of moderate size, if the quark mass inside the triangle loop is chosen as the running quark mass at a typical scale fixed by the c.m. energy of the process [14]. The NLO QCD corrections to the final Higgs decays into bottom quarks generate large logarithms, which however can be absorbed in the running Yukawa coupling at the scale of the c.m. energy [11,15]. After inserting the running quark masses, the total QCD corrections increase the signal cross section by about 20–40%.

**Backgrounds.** The main background processes $\gamma\gamma \rightarrow b\bar{b}$ and $\tilde{\chi}^+\tilde{\chi}^-$ are pure QED reactions in lowest order. Since the signals are generated for equal photon helicities, this configuration can be enhanced by choosing opposite helicities for the incoming laser photons and electrons/positrons in the initial state [6,16]. The NLO QCD corrections for polarized photon beams have been calculated in Ref. [17]. For $b\bar{b}$ production they turn out to be moderate for photons of opposite helicities but large for photons of equal helicity. The differential cross section for photons of equal helicity is suppressed by a factor $m_b^2/s$ at LO due to a helicity flip of the bottom quark line. This suppression, however, is removed by gluon radiation and the size of the cross section increases to order $\alpha_s$. Moreover, there are large Sudakov and non-Sudakov logarithms due to soft gluon radiation and soft gluon and bottom exchange in the virtual corrections [18] which must be resummed. In order to suppress the gluon radiation we have selected slim two-jet configurations in the final state, defined within the Sterman–Weinberg criterion. If the radiated gluon energy is larger than 10% of the total $\gamma\gamma$ energy and if the opening angle between all three partons in the final state is more than 20°, the event is classified as three-jet event and rejected. The contamination of $b\bar{b}$ final states by the processes $\gamma\gamma \rightarrow c\bar{c}$ can be kept under experimental control by $b$ tagging.

**Interference.** The interference between the signal and background processes has been taken into account properly. This part receives contributions only from configurations with equal photon helicities in the initial state. We have determined the NLO QCD corrections to quark final states [9] including the resummation of the large (non-)Sudakov logarithms. The QCD corrections to the interference term are large.

**3 Results and Conclusions**

**$b\bar{b}$ channel.** We assume that a rough scan in the $e^+e^-$ energy will first be performed which will provide preliminary evidence for the observation of a Higgs boson in the $\gamma\gamma$ resonance channel. Since the luminosity spectrum for photons
of equal helicity is strongly peaked at about 80% of the $e^+e^-$ c.m. energy [6,16], the maximum of the spectrum will be tuned in the second step to the value of the pseudoscalar Higgs mass $M_A$ at which the signal peak in the energy scan appeared. The experimental analysis will be optimized subsequently for the heavy Higgs boson search. A cut in the scattering angle of the final bottom quark ($|\cos \theta| < 0.5$) strongly reduces the background while it affects the signal process only moderately. By collecting $\bar{b}b$ final states with a resolution in the invariant mass $M_A \pm 3\text{ GeV}$, which is expected to be achieved at the photon collider [19], the sensitivity to the combined $H$ and $A$ resonance peaks above the background is strongly increased.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Cross section for resonant heavy Higgs boson $H,A$ production as a function of the pseudoscalar Higgs mass $M_A$ with final decay into $\bar{b}b$ pairs and the corresponding background cross section. The maximum of the photon luminosity in the $J_z = 0$ configuration has been tuned to coincide with $M_A$. The cross sections are defined in $\bar{b}b$ mass bins of $M_A \pm 3\text{ GeV}$ around the $A$ resonance. An angular cut on the bottom production angle $\theta$ has been imposed: $|\cos \theta| < 0.5$. The MSSM parameters have been chosen as $\tan \beta = 7, M_2 = -\mu = 200\text{ GeV}$.}
\end{figure}

The result for the peak cross section is shown in Fig. 2 as a function of the pseudoscalar mass $M_A$. It can be inferred from the figure that the background is strongly suppressed against the signal. Significances of the heavy Higgs boson signals sufficient for a discovery of the Higgs particles up to about 70–80% of the $e^+e^-$ c.m. energy can be reached. At a 500 GeV $e^+e^-$ linear collider the $H,A$ bosons with masses up to about 400 GeV can be discovered in the $\bar{b}b$ channel at the photon collider, while for $\sqrt{s_{ee}}$ above 800 GeV the range can be extended to about 600 GeV [9]. For heavier Higgs masses the signal rate becomes too small for detection.

$\tilde{\chi}^0\tilde{\chi}^0$ channels. For the MSSM parameters introduced above, the heavy Higgs bosons have significant decay branching ratios to pairs of charginos and neutralinos, cf. Figs. 1. However, due to the integer chargino charge, the chargino background from continuum production is in general more than an order of magnitude larger than the signal. Pairs of neutralinos cannot be produced
in $\gamma\gamma$ collisions at leading order so that neutralino decays open a potential discovery channel for the heavy Higgs bosons $H, A$, see also Ref. [20]. This is obvious for moderate Higgs masses below the chargino decay threshold. Detailed analyses of the topologies in the final state are needed, however, to separate the neutralinos from the background charginos above the threshold. For example, the signal channel $\gamma\gamma \rightarrow H, A \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0$ leads, if the sfermions are heavy, in the $\tilde{\chi}_2^0$ cascade decay predominantly to the hadronic final states $jj + E_T$ whereas the continuum process $\gamma\gamma \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$ generates the distinct final state $W^+W^+ + E_T$ with $jjjj + E_T$ jet topologies. Thus, the neutralino decays are expected to provide novel discovery channels of the heavy Higgs bosons at a photon-photon collider.

![Graph](image.png)

**Fig. 3.** Same as in Fig. 2 but for chargino and neutralino final states.

**Summary.** It has been shown in this report that the heavy Higgs bosons $H$ and $A$ of the minimal supersymmetric extension of the Standard Model MSSM can be discovered for intermediate values of $\tan\beta$ up to masses of about 400 GeV at a photon-photon collider in the first phase of the linear collider project. The mass reach can be extended beyond 600 GeV at a TeV collider. The discovery potential in this region of the supersymmetric parameter space is unique since neither at the LHC nor in the respective $e^+e^-$ phase of the linear collider this region is accessible.

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