HIGGS BOSON SEARCH AT e^+e^- AND PHOTON LINEAR COLLIDERS*

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The various search modes for the Higgs bosons of the Standard Model (SM) and its Minimal Supersymmetric Extension (MSSM) at the International Linear Collider (ILC) will be summarized briefly. In particular, as a unique discovery mode the production of heavy neutral MSSM Higgs bosons for medium values of $\tan\beta$ in photon collisions will be presented. Furthermore, $\tau^+\tau^-$ fusion into MSSM Higgs bosons in the photon mode will be shown to give access to the mixing parameter $\tan\beta$ with a precision of better than 10% for large values of this parameter.

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1. Introduction

One of the major endeavors of high energy physics at future colliders is the experimental test of the Higgs mechanism which allows to introduce standard particle masses without violating gauge symmetries. Four steps have to be taken [1]: First of all the Higgs boson(s) must be discovered. Next, the spin zero nature of the Higgs field can be verified through the determination of the Higgs boson quantum numbers. In the third step, by measuring its couplings to gauge bosons and fermions the proportionality to the masses of the respective particles as predicted by the Higgs mechanism can be checked. Finally, the triple and quartic Higgs self-couplings have to be determined in order to reconstruct the Higgs potential itself, responsible for the non-zero vacuum expectation value due to its specific form. In the following, the first step in this program will be summarized briefly. The discovery modes at the ILC and the Photon Linear Collider (PLC) will be discussed, complemented by a brief note on the extraction of $\tan\beta$ in $\tau^+\tau^-$ fusion at the PLC.

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2. Higgs boson search at the ILC

2.1. The SM Higgs boson

The main SM Higgs boson production mechanisms are Higgs-strahlung, $e^+e^- \to ZH$ [2] at lower energies and WW fusion, $e^+e^- \to H\bar{\nu}\nu$ [3] at higher energies, *cf.* Fig. 1. The full electroweak (EW) corrections at one loop have been calculated for both the Higgs-strahlung [4, 5] and the fusion process [5, 6]. They are of $\mathcal{O}(10\%)$. Since the recoiling Z boson in Higgs-strahlung is monoenergetic at leading order the Higgs mass can be reconstructed independent of the Higgs boson decay. Combining recoil mass techniques and reconstruction of the Higgs decay products, the expected accuracy on M_H is 40–80 MeV for intermediate mass Higgs bosons [7].

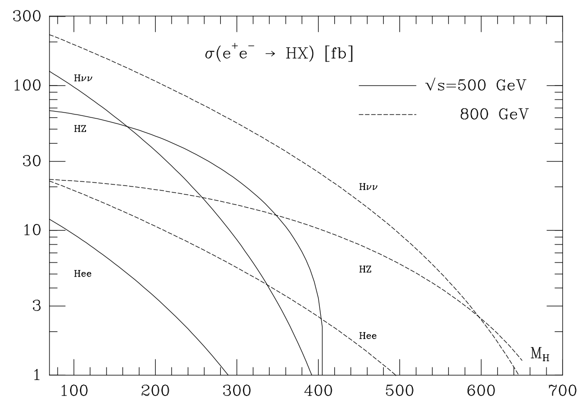

Fig. 1. SM Higgs boson production processes as a function of the Higgs boson mass for two typical collider energies, $\sqrt{s} = 500$, 800 GeV [8].

2.2. The MSSM Higgs bosons

Supersymmetry and the requirement of an anomaly free theory require the introduction of two complex Higgs doublets in the MSSM, leading after EW symmetry breaking to 5 physical Higgs particles, 2 neutral CP-even h, H, one CP-odd A and two charged bosons $H^\pm$. The neutral Higgs boson production mechanisms [9] are Higgs-strahlung, $e^+e^- \to Z + h/H$, gauge boson fusion, $e^+e^- \to \bar{\nu}\nu/e^+e^- + h/H$, and associated production, $e^+e^- \to A + h/H$. Charged Higgs bosons are produced in pairs $e^+e^- \to H^+H^-$ or, if kinematically allowed, in top decays, $t \to H^+b$. The production processes for h, H as well as the Higgs-strahlung and associated production process are mutually complementary to each other *cf.* Fig. 2, coming either with $\sin^2(\beta-\alpha)$ or $\cos^2(\beta-\alpha)$ so that the lightest Higgs boson can always be discovered, its production cross section being large enough. All Higgs particles can be discovered at $\sqrt{s} = 500$ GeV for masses below about 230 GeV. If the

Higgs decay modes are complicated or invisible, missing mass techniques allow their detection. Experimental studies have shown, that the H, A masses can be measured with several hundred MeV accuracy in Higgs pair production far above the kinematical threshold [10]. The expected accuracy of $M_{H^\pm}$ is of order 1% for $M_{H^\pm} = 300\,\mathrm{GeV}$ [11].

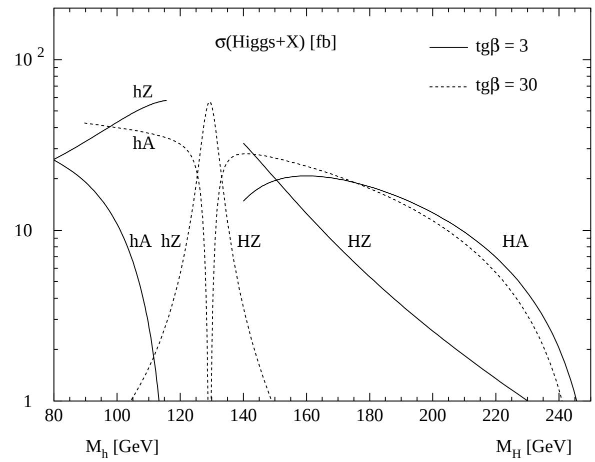

Fig. 2. MSSM Higgs boson production as a function of $M_{h,H}$ for $\tan\beta = 3.30$ [8].

An interesting MSSM parameter scenario is the intense-coupling regime, introduced in Ref. [12]. All Higgs bosons are rather light and similar in mass, $M_h \sim M_H \sim M_A \lesssim 130\,\mathrm{GeV}$, $M_{H^\pm} \lesssim 150\,\mathrm{GeV}$. For large $\tan\beta$ values, one of the CP-even neutral Higgs bosons behaves as A with large couplings to down-type fermions. The other behaves SM-like and couples strongly to W, Z and top. Since the bosons are light, they are in principle all accessible. The masses being rather close, several search channels have to be considered at the same time, further complicated by sizable widths compared with the mass differences. In addition, the couplings can be significantly different from the SM or the MSSM decoupling limit. Experimental studies [13] have shown that in a multichannel analysis the neutral Higgs masses can be extracted with an accuracy of 100–300 MeV.

3. Higgs bosons at the PLC

3.1. Heavy MSSM Higgs boson production in $\gamma\gamma$ collisions

Heavy H, A bosons may escape discovery at the Large Hadron Collider (LHC) for intermediate values of $\tan\beta$ and are not accessible in the e^+e^- mode of the ILC for masses above $\sqrt{s}/2$ [14]. The heavy H, A appear as resonances in $\gamma\gamma$ collisions [15]. Therefore, $\gamma\gamma \to H, A$ offers a unique possibility to search for heavy Higgs bosons not accessible elsewhere. The photons are generated by Compton back-scattering of laser light so that almost the entire energy of the electrons/positrons at a Linear Collider can be transferred to the photons [16], with luminosities of about one third of the e^+e^- luminosity in the high-energy regime [17].

In Ref. [15] the search for H, A in $\gamma\gamma$ collisions with subsequent decay into $b\bar{b}$ was analyzed taking into account the NLO corrections to the signal [18], background [19] and interference process. To enhance the signal to background ratio slim two-jet configurations have been selected in the final state, the incoming $e^{\pm}e^-$ beams have been chosen polarized and a cut on the scattering angle of the b-quark, θ, has been applied. The maximum of the $\gamma\gamma$ luminosity has been tuned to M_A. The $b\bar{b}$ final states have been collected with a resolution in the invariant mass $M_A \pm \Delta$, $\Delta = 3\,\mathrm{GeV}$. (For more details see also [20].) In $\gamma\gamma$ fusion the mass reach can thus be extended to $\sim 80\%$ of the total e^+e^- energy, *i.e.* in the first phase of the ILC H, A bosons can be discovered up to masses of about 400 GeV, and up to 800 GeV in the second phase, for medium values of $\tan\beta$, as can be inferred from Fig. 3. A detailed study taking into account all relevant theoretical and experimental issues has shown that the cross section can be determined with a statistical precision of 10% and better [21].

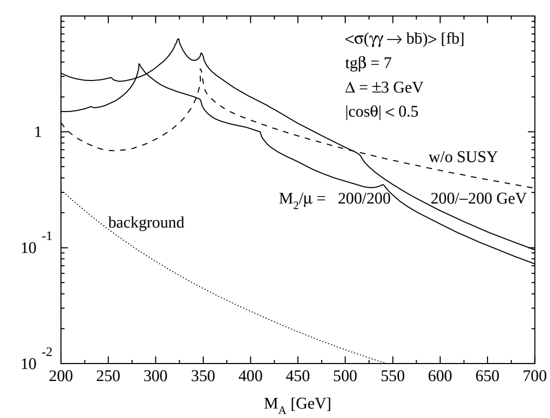

Fig. 3. H, A production cross sections in $\gamma\gamma$ collisions as a function of M_A with final decays into $b\bar{b}$ and the corresponding background cross section. The MSSM parameters have been chosen as $\tan\beta = 7, M_2 = \pm\mu = 200\,\mathrm{GeV}$; the limit of vanishing SUSY-particle contributions is shown for comparison [15].

The analogous analysis [22] for the SM Higgs boson production in $\gamma\gamma$ fusion [23] concludes that the partial width $\Gamma(H \to \gamma\gamma)$ can be extracted with 2% accuracy for $M_H = 120\,\mathrm{GeV}$. This provides a sensitivity to new charged particles running in the loop-induced $H\gamma\gamma$ coupling.

3.2. Determination of $\tan\beta$ *in* $\tau^+\tau^-$ *fusion*

Since the measurement of the important mixing parameter $\tan\beta$ is a difficult task and expected accuracies at the LHC and the ILC are at the order of 10%, any additional method for its determination is valuable. The $\tau\tau$ fusion to h, H, A at a PLC [24], provides a promising channel and is based on the two-step process, *cf.* Fig. 4(a),

$$\gamma\gamma \to (\tau^+\tau^-) + (\tau^+\tau^-) \to \tau^+\tau^- + h/H/A\,. \tag{1}$$

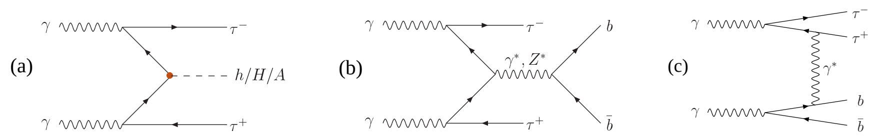

Fig. 4. (a) The signal process $\tau\tau$ fusion into h, H, A. (b) The annihilation and (c) the diffractive background process.

For the large $\tan\beta$ case studied in [24], 80 to 90% of the Higgs bosons decay into a b quark pair so that the final state consists of a pair of τ's and resonant b quark jets. The couplings of h, H, A to τ pairs being of the order of $\tan\beta$ (if M_A is sufficiently light in the h case) [25], the signal process is enhanced for large $\tan\beta$ values. The main background channels are $\tau^+\tau^-$ annihilation into a b-quark pair mediated by virtual γ/Z exchanges (Fig. 4(b)) and thus suppressed by the electroweak coupling, and diffractive $\gamma\gamma \to (\tau^+\tau^-)(b\bar{b})$ events (Fig. 4(c)), which is suppressed by choosing proper cuts. The results of the numerical analysis taking into account the full set of signal and background diagrams are shown in Fig. 5. Assuming standard design parameters of a PLC an error $\Delta\tan\beta \sim 1$, uniformly for $\tan\beta \gtrsim 10$,

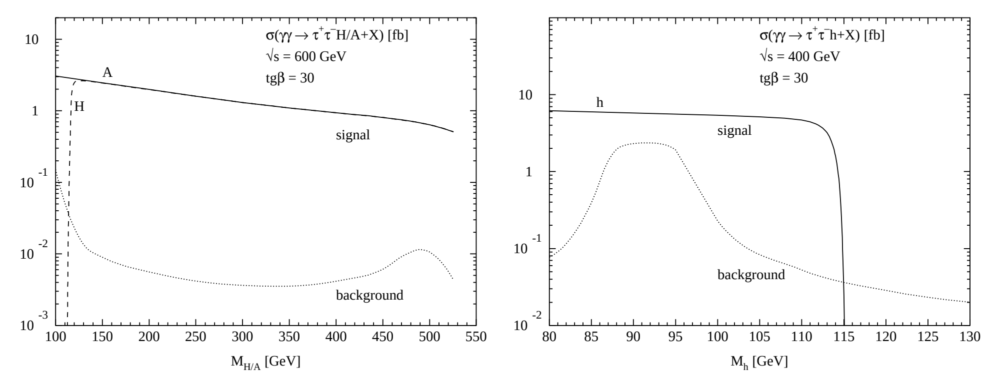

Fig. 5. The $\tau\tau$ fusion into H/A (left) and h (right) for $\tan\beta = 30$ compared to the background process. Cuts as specified in [24]. $\sqrt{s}$ denotes the $\gamma\gamma$ collider c.m. energy, *i.e.* 80% of the $e^\pm e^-$ LC energy.

may be expected, improving on complementary measurements at the LHC and ILC.

4. Summary

At a future ILC the SM and MSSM Higgs bosons are accessible up to the kinematical limit independent of their decay properties. The precision on the masses is $\mathcal{O}(1\%)$ and better. The PLC provides the unique possibility to discover heavy MSSM H, A bosons in a wedge centered around medium $\tan\beta$ values, not accessible elsewhere, and complements the Higgs boson search at the ILC. Furthermore, the important mixing parameter $\tan\beta$ can be extracted in photon collisions with a statistical accuracy of 10% and better for large values of this parameter. The PLC can thus be considered a valuable complement to the $e^{\pm}e^{-}$ mode of a future ILC.

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