LC-PHSM-2000-053
November 2000

Measuring the Higgs Branching Fraction into two Photons at Future Linear e^+e^- Colliders

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Abstract

We examine the prospects for measuring the $\gamma\gamma$ branching fraction of a Standard Model-like Higgs boson with a mass of 120 GeV at the future TESLA linear e^+e^- collider, assuming an integrated luminosity of 1 ab^{-1} and center-of-mass energies of 350 GeV and 500 GeV. The Higgs boson is produced in association with a fermion pair via the Higgsstrahlung process $e^+e^- \to ZH$, with $Z \to q\,\bar{q}$ or $\nu\bar{\nu}$, or the WW fusion reaction $e^+e^- \to \nu_e\bar{\nu}_e H$. A relative uncertainty on BF($H \to \gamma\gamma$) of 16% can be achieved in unpolarized e^+e^- collisions at $\sqrt{s}$= 500 GeV, while for $\sqrt{s}$= 350 GeV the expected precision is slightly poorer. With appropriate initial state polarizations ΔBF($H \to \gamma\gamma$)/BF($H \to \gamma\gamma$) can be improved to 10%. If this measurement is combined with the expected error for the total Higgs width, a precision of 10% on the $\gamma\gamma$ Higgs boson partial width appears feasible.

1 Introduction

Following the discovery of the Higgs boson, one of the main tasks of a future linear e^+e^-collider will be precise model-independent measurements of its fundamental couplings to fermions and bosons and its total width [1]. The branching fraction of the Higgs boson into two photons, BF($H \rightarrow \gamma\gamma$), is of special interest since deviations of BF($H \rightarrow \gamma\gamma$) (or the diphoton Higgs partial width $\Gamma(H \rightarrow \gamma\gamma$)) from the Standard Model (SM) value provide sensitivity to new physics. In particular, by virtue of the fact that the $H \rightarrow \gamma\gamma$ coupling can have contributions from loops containing new charged particles, significant differences from the SM value are possible. Thus, a measurement of BF($H \rightarrow \gamma\gamma$) at the next linear collider will be an important contribution to understanding the nature of the Higgs boson and may possibly provide hints for new physics, regardless of the size of the deviation from the SM prediction. The precision of the $H \rightarrow \gamma\gamma$ branching fraction measurements within reach in e^+e^- collisions is the subject of this paper.

The ultimate goal of this measurement is to derive the diphoton Higgs boson partial width. However this needs knowledge of the total Higgs width. The total width of a light SM Higgs boson is too small to be observed directly [2]. The procedure for obtaining this quantity requires measurements of the product $\Gamma(H \rightarrow \gamma\gamma) \cdot BF(H \rightarrow b\bar{b})$ in the $\gamma\gamma$ collider option of a linear collider and $BF(H \rightarrow b\bar{b})$, a quantity easily accessible with high precision in e^+e^- collisions [3]. As both these measurements can be achieved with an accuracy of few percent, the error of the total Higgs width will be dominated by the error of $BF(H \rightarrow \gamma\gamma)$.

However, it has recently been demonstrated that a measurement of the branching fraction BF($H \rightarrow WW^*$) [4] at a high-luminosity linear e^+e^- collider, combined with a precise value for the rate of the WW fusion process $e^+e^- \rightarrow \nu_e\bar{\nu}_e H$ (or for the Higgsstrahlung production rate $\sigma(HZ)$ and assuming W,Z-universality), would permit an accurate measurement of the total width of the Higgs boson.

Precise electroweak data indicate the existence of a light Higgs boson [5] with a mass below about 200 GeV, with a preference for M_H close to 120 GeV. High-luminosity linear e^+e^- colliders in the energy range 300 to 500 GeV [6] are ideal machines for performing precise measurements of the properties of such a particle. In this paper we investigate the prospects of measuring the branching fraction BF($H \rightarrow \gamma\gamma$) from events of the reactions

$$e^+e^- \rightarrow q\bar{q}\gamma\gamma \tag{1}$$

and

$$e^+e^- \to \nu\bar{\nu}\gamma\gamma \tag{2}$$

assuming a Higgs boson mass $M_H = 120$ GeV, at $\sqrt{s} = 350$ and 500 GeV and an integrated luminosity of 1 ab^{-1} at each energy.

The statistical precision for BF($H \to \gamma\gamma$) is mainly determined by $\sqrt{S+B}/S$, where S and B are respectively the number of signal and background events within a small interval of the two-photon invariant mass $\Delta M_{\gamma\gamma}$, centered around M_H. Hence, evaluation of all relevant signal and background processes and optimization of selection procedures are mandatory, taking into account acceptances and resolutions of a linear collider detector.

Our analysis is superior in some respects to the study of ref.[7]. It includes the complete irreducible background in reactions (1) and (2) and demonstrates for the first time the gain in the precision of BF($H \to \gamma\gamma$) when beam polarization is accounted for in signal and background events.

The paper is organized as follows. In Section 2 we discuss simulation of the Higgs signal and background events and their detector response. In Sections 3 and 4 we present our results for unpolarized BF($H \to \gamma\gamma$) measurements at $\sqrt{s} = 350$ and 500 GeV, respectively. In Section 5 we discuss improvements to the $H \to \gamma\gamma$ branching fraction measurement with beam polarization. Section 6 summarizes the conclusions.

2 Signal and Background Reactions

In e^+e^- collisions the Higgs boson is produced by two different processes, the Higgsstrahlung process

$$e^+e^- \to ZH \tag{3}$$

and the weak boson (WW and ZZ) fusion reactions

$$e^+e^- \to \nu_e\bar{\nu}_e H \tag{4}$$

$$e^+e^- \to e^+e^- H \tag{5}$$

The ZZ fusion process (5) is strongly suppressed with respect to reaction (4) (by about a factor of 10 relatively independent of $\sqrt{s}$). Therefore, only the Higgsstrahlung and WW fusion reactions (3) and (4) are considered in this study. These processes are part of the 2-to-4 body reactions (1) and (2) if only the most important Z $\to q\bar{q}$ (of ~70%) and $\nu\bar{\nu}$ (of ~20%) decays and the $H \to \gamma\gamma$ decay are accounted for. Thus, to be most general in our analysis,

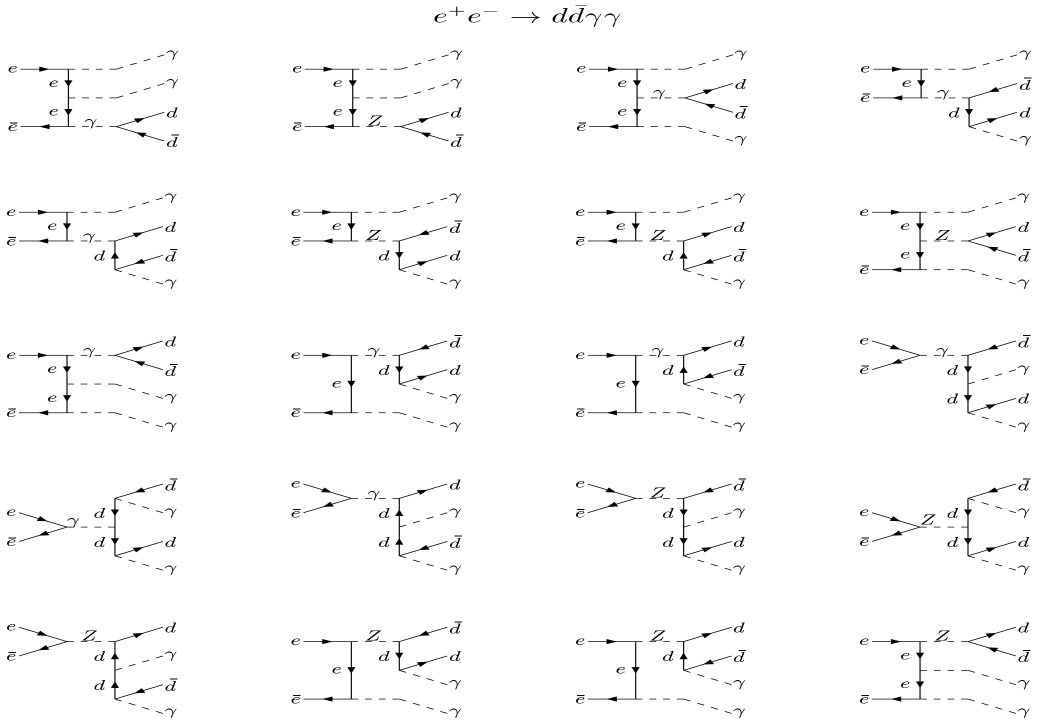

Figure 1: Background diagrams for the reaction $e^+e^- \to d\bar{d}\gamma\gamma$.

events of reactions (1) and (2) were generated by means of the program package CompHEP [8], including initial state bremsstrahlung and beamstrahlung for the TESLA linear collider option [9]. In this way, Higgs boson production and the complete irreducible background as well as possible interferences are taken into account. The branching fraction for $H \to \gamma\gamma$ was imported from the program package HDECAY [10]. It depends on the Higgs mass and is largest near $M_H =$ 120 GeV. In this study we used BF($H \to \gamma\gamma$)= 2.2×10^{-3}.

The Higgsstrahlung reaction (3) is characterized by two hadronic jets originating from the Z, together with two energetic photons with an invariant mass equal to M_H. The background expected in reaction (1) comes from the 100 lowest-order diagrams with $q = d, u, s, c, b$, which are shown, for the d-quark as an example, in Fig. 1. The most serious background arises from the double bremsstrahlung process $e^+e^- \to Z\gamma\gamma \to q\bar{q}\gamma\gamma$. Because of its importance, $Z\gamma\gamma$ events estimated with CompHEP have been cross-checked at the generator level with KORALZ 4.2 [11] and found to be in good agreement in the $\gamma\gamma$ invariant mass range relevant for this study.

For the signal events in reaction (2), with contributions from WW fusion and Higgsstrahlung processes (and small interferences between them), we expect a signature of two photons, producing two large electromagnetic neutral showers

$e^-e^+ \to \nu\bar{\nu}\gamma\gamma$

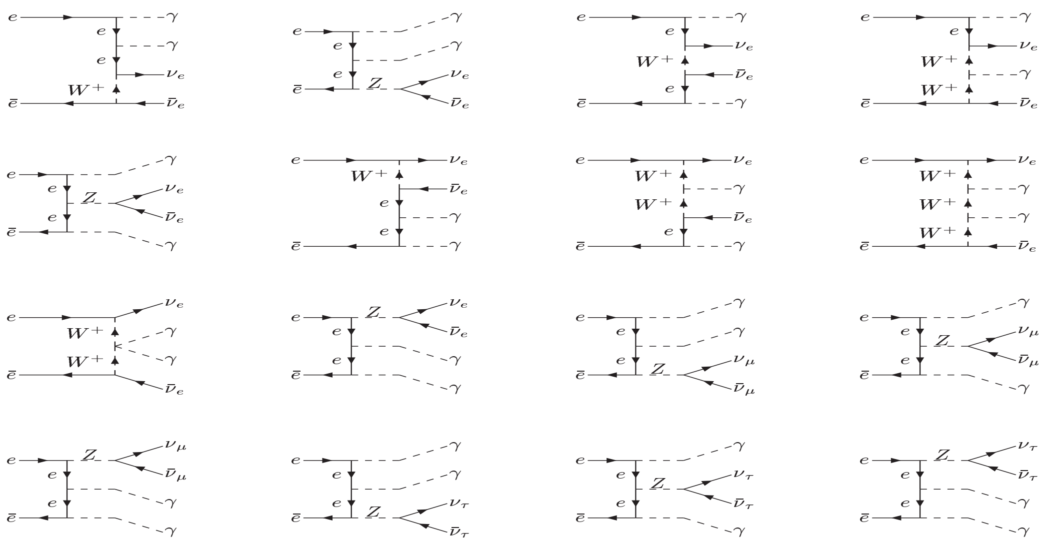

Figure 2: Background diagrams for the reaction $e^+e^- \to \nu\bar{\nu}\gamma\gamma$.

in the detector with no other activities, and large missing energy due to the two undetected neutrinos. The background diagrams contributing to reaction (2) are shown in Fig. 2. They were accounted for at the same level as the signal events. Again, the most serious, irreducible background was found to arise from the double bremsstrahlung process $e^+e^- \to Z\gamma\gamma \to \nu\bar{\nu}\gamma\gamma$.

Possible reducible backgrounds to $e^+e^- \to HZ$ events which might mimic the signal, such as the reactions $e^+e^- \to ZZ$ and $e^+e^- \to WW$ with large cross sections, were found to be very small after application of selection criteria.

Processes like $e^+e^- \to \gamma\gamma(\gamma)$ or $e^+e^- \to (e^+e^-\ )\ \gamma\gamma$, when both electrons are undetected, might constitute a significant background to $e^+e^- \to ZH$, $\nu\bar{\nu}H$ $\to \nu\bar{\nu}\gamma\gamma$ events. However, after kinematical cuts their rates were also found to be small or negligible.

As the cross sections for the background discussed are orders of magnitude larger than the signal cross sections, we first applied the following principal cuts at the generation level, to both the signal and background events:

- the transverse energy, E_T, for each photon exceeds 20 GeV;
- the two-photon invariant mass, $M_{\gamma\gamma}$, is required to be larger than 100 GeV;
- the $q\bar{q}$ invariant mass, $M_{q\bar{q}}$, is within $M_Z \pm 20$GeV.

After these criteria, practically all Higgs events survive, while background contributions are substantially reduced.

The detector response for all signal and the remaining background events was simulated with the parametrized detector simulation package SIMDET [12] using parameters as presented in the Conceptual Design Report [6].

3 BF($H \to \gamma\gamma$) measurement at 350 GeV

Different Higgs event rates are expected from processes (3) and (4) at our two energies, $\sqrt{s} = 350$ and 500 GeV. The Higgsstrahlung cross section scales, after a maximum close its threshold, with $1/s$, while the fusion cross section rises logarithmically with $\sqrt{s}$. At 350 GeV, the Higgsstrahlung cross section is approximately 140 fb for $M_H = 120$ GeV, which is about four times larger than the WW fusion cross section. Since the Z boson hadronic decay is by far dominant, $q\bar{q}\gamma\gamma$ events constitute the main source of the Higgs signal at 350 GeV. The Z invisible $\nu\bar{\nu}$ decay in the Higgsstrahlung and the fusion channels lead to identical event topologies - two isolated high energy photons and a large missing energy due to the two undetected neutrinos - are treated together in our study.

Considering only Z branching fractions into $q\bar{q}$ and $\nu\bar{\nu}$ and the Higgs decay into two photons, we expect about 220 respectively 130 Higgs events in reactions (1) and (2) at 350 GeV for an integrated luminosity of 1 ab^{-1}. Different event selection procedures were applied to the $q\bar{q}\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ event samples in order to account for their distinct properties in the final state.

In order to avoid large not useful event samples the following preselection procedure was applied to the 2-jet 2-photon candidates:

- at least two isolated neutral clusters compatible with photons exist, with transverse energy $E_T > 20$ GeV for each;
- no particle exists in a half cone of 10^o around the isolated photon directions;
- the number of charged tracks per event exceeds 5;
- the visible event energy, E_{vis}, exceeds $0.8 \times \sqrt{s}$ GeV;
- the total momentum along the beam direction is within $\pm$ 100 GeV;
- all particles, excluding the two selected photons, were forced into two hadronic jets with an invariant mass compatible with the Z boson, $70 < M_{jj} < 110$ GeV.

After all cuts the background to the Higgsstrahlung events close to M_H was significantly reduced, but still one order of magnitude larger than the signal, so further and more stringent selection criteria were necessary to improve the signal-to-background ratio.

In a first trial, we applied the conventional method of using consecutive cuts on kinematical variables. In particular, we demanded

- the energy of the two-photon system is between $140 < E_{\gamma\gamma} < 200$ GeV;
- the transverse energy of the two-photon system is larger than 50 GeV;
- each photon polar angle is restricted to $|cos\theta_{\gamma}| < 0.9$;
- the polar angle of the two-photon system is required to be $|cos\theta_{\gamma\gamma}| < 0.8$.

These cuts gave a selection efficiency of 56% for Higgs signal events.

Secondly, we applied a more sophisticated selection procedure. Kinematical variables of the final state photons and of the $\gamma\gamma$ subsystem were combined into a global discriminant variable P_H[1]. This quantity can be considered as a measurement of the "Higgs-likeness" of an event, with $0 \leq P_H \leq 1$. Background events are preferably distributed at low P_H values while for Higgs signal events P_H is close to 1. The distribution of P_H is shown in Fig. 3, and a cut of $P_H > 0.85$ was applied to select the Higgs candidates. This method results to a signal selection efficiency of 42% and 2.3 times less background, so that a significant better signal-to-background ratio exists compared to the application of consecutive cuts. Therefore, only results using the discriminant variable procedure are discussed in the following. The $\gamma\gamma$ invariant mass spectrum for $q\bar{q}\gamma\gamma$ signal and surviving background events is shown in Fig. 4a. The superimposed curve is the result of a fit to the sum of a Gaussian, used to describe the signal, and a second order polynomial function, which was found to describe the background in very good approximation between 110 and 130 GeV.

From the normalizations of the signal and background, which were allowed to vary, the number of signal and background events in an optimal $M_{\gamma\gamma}$ window width of 2.5 GeV around M_H is obtained[2]. These numbers are collected in Table 1 and suggest a statistical error of 27% for $\sigma(HZ) \cdot BF(H \to \gamma\gamma)$ in the reaction $e^+e^- \to ZH \to q\bar{q}\gamma\gamma$.

The Higgs signal selection from the $\gamma\gamma\nu\bar{\nu}$ final state relies on events without charged tracks in the detector. For the neutral clusters, compatible with photons, the following criteria were required:

[1] In particular, the quantities used are: energies, transverse energies and polar angles of both photons, the angle between the photons and the energy, the transverse energy and the polar angle of the $\gamma\gamma$ system

[2] In order to estimate the optimized number of signal to background events for a narrow Gaussian resonance whose observed width is dominated by instrumental effects, the mass window chosen should be 1.2 Γ_{exp}, centered on the actual Higgs mass.

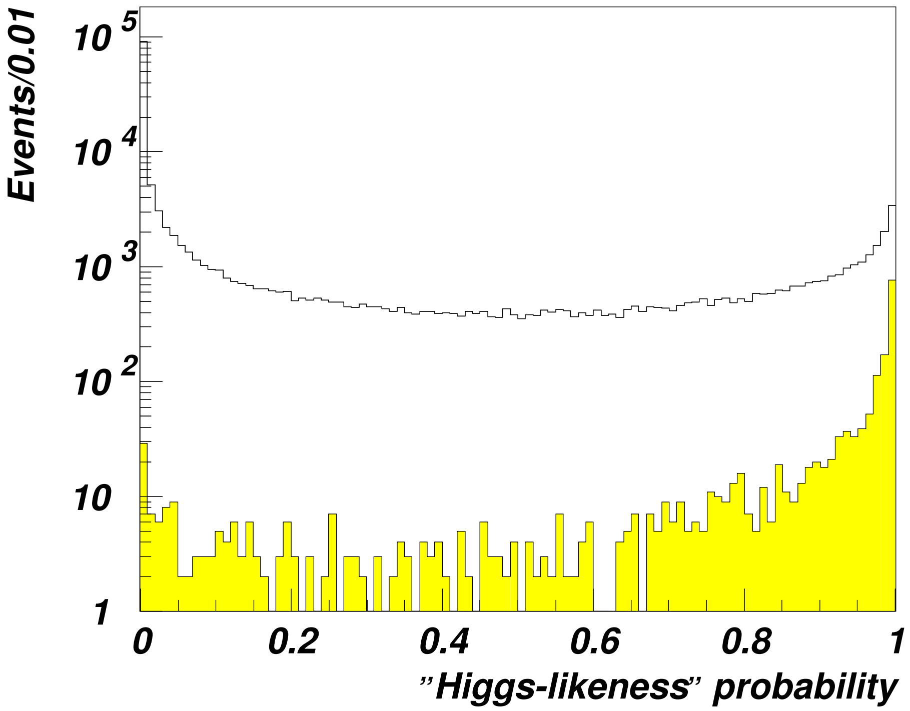

Figure 3: "Higgs-likeness" probability for $e^+e^- \to HZ \to q\bar{q}\gamma\gamma$ events (shaded) and the background considered.

- at least two electromagnetic clusters have transverse energies larger than 20 GeV;
- their polar angles are within $|cos\Theta_\gamma| < 0.9$;
- the polar angle of the two-photon system is restricted to $|cos\Theta_{\gamma\gamma}| < 0.8$.

These cuts gave a Higgs selection efficiency of 45% and removed possible backgrounds to a large extent. The resulting $M_{\gamma\gamma}$ mass distribution is shown in Fig. 4b. The number of signal and background events, obtained from an analogous fit procedure, are also shown in Table 1. They allow for $\sqrt{S+B}/S \simeq$ 28.5%. After combining the $q\bar{q}\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ final states and neglecting the presumably small Higgs cross section uncertainties, the H $\to \gamma\gamma$ branching fraction error is estimated to 18% at $\sqrt{s} = 350$ GeV.

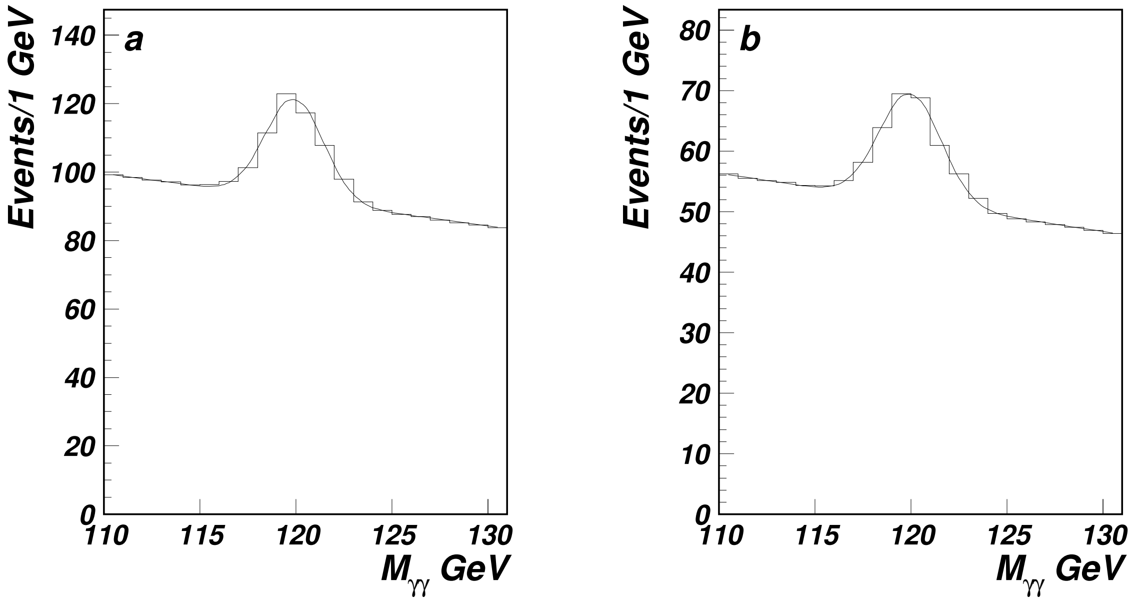

Figure 4: $M_{\gamma\gamma}$ invariant mass distributions for 350 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events. The background in the histograms has been averaged to avoid accidental fluctuations.

Energy	350 GeV			500 GeV	
Process	$q\bar{q}\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$		$q\bar{q}\gamma\gamma$	$\nu\bar{\nu}\gamma\gamma$
Signal(S)	93	57	150	35	99
Bkg (B)	366	206	572	410	163
$S/\sqrt{B}$	4.9	4.0	6.3	1.7	10.2
Precision(%)	23.0	28.5	17.9	60.3	16.4

Table 1: Number of signal and background events estimated from fits to $M_{\gamma\gamma}$ spectra and the precisions expected for the cross section times the H $\to \gamma\gamma$ branching fraction.

4 BF($H \to \gamma\gamma$) measurement at 500 GeV

At $\sqrt{s} = 500$ GeV, the cross sections for the Higgs signal reactions (3) and (4) are about equal, so that most of the Higgs events have the $\nu\bar{\nu}\gamma\gamma$ signature, with the dominant contribution from the WW fusion process.

The Higgs candidate selection procedures applied were similar to that at 350 GeV. For the $q\bar{q}\gamma\gamma$ final state, the "Higgs-likeness" probability P_H was also

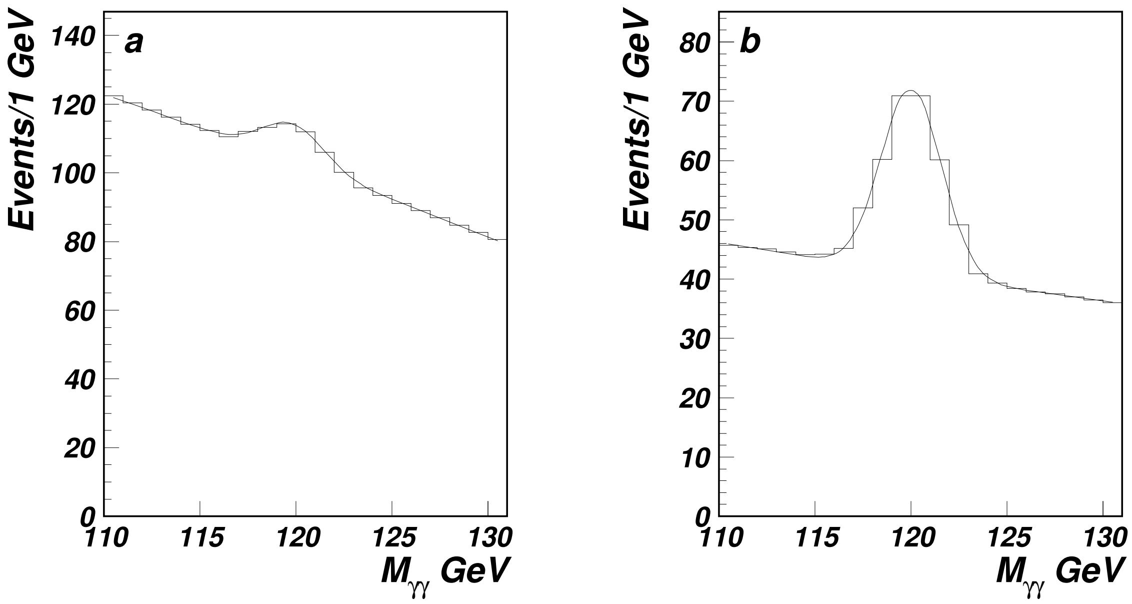

Figure 5: $M_{\gamma\gamma}$ invariant mass distributions for 500 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events. The background in the histograms has been averaged to avoid accidental fluctuations.

demanded to be larger than 0.85, resulting to the $M_{\gamma\gamma}$ distribution as shown in Fig. 5a. Signal and background event numbers obtained from the fit are also presented in Table 1. As can be seen, the signal is statistically insignificant, and we will not consider these events in our analysis.

For the $\nu\bar{\nu}\gamma\gamma$ events we required

- the recoil mass against the two photon system, $M_{rec} = \sqrt{s + M_{\gamma\gamma}{}^2 - 2\sqrt{s}M_{\gamma\gamma}}$, is within 150 to 370 GeV and
- $\mathrm{E}_T^{min}(\gamma) > 20$ GeV and $\mathrm{E}_T^{max}(\gamma) > 50$ GeV.

The first criteria reduces substantially the main background from double bremsstrahlung $\gamma\gamma Z \to \gamma\gamma\nu\bar{\nu}$ events. By this cut also the low rate Higgsstrahlung $e^+e^- \to ZH \to \nu\bar{\nu}\gamma\gamma$ events were eliminated. Surviving background arises mainly from W-exchange diagrams shown in Fig. 2, with two photons radiated from the beam particle(s). The transverse energy cut applied removes part of this background.

The $M_{\gamma\gamma}$ distribution for the $\gamma\gamma\nu\bar{\nu}$ events selected is shown in Fig. 5b. The numbers obtained for the signal and background events as well as the precision for $\sigma \cdot BF(H \to \gamma\gamma) \simeq 16.4\%$ are also given in Table 1.

5 Polarization

Linear e^+e^- colliders offer the possibility for longitudinal polarized electron and positron beams, with varying polarization degrees in right-handed or left-handed modes. Higgs boson production rates in both processes (3) and (4) depends significantly on the polarization degree and the helicity of the incoming particles.

The Higgs cross section for given electron (P_-) and positron (P_+) polarizations normalized to the unpolarized case can be expressed by

$$R_i = 1 + \eta_i(P_- - P_+) - P_-P_+ \quad , \tag{6}$$

where η_i is the asymmetry factor for the cross sections, $\eta_i = (\sigma_i^{+-} - \sigma_i^{-+})/(\sigma_i^{+-} + \sigma_i^{-+})$, with different indices i to indicate the Higgsstrahlung (i=1) and the WW fusion (i=2) reactions. $\sigma_i^{+-}(\sigma_i^{-+})$ denotes the cross section for 100% right-handed (left-handed) polarized electrons in collision with 100% left-handed (right-handed) polarized positrons. The asymmetry factors were calculated with CompHEP to $\eta_1 = -0.21$ and $\eta_2 = -1$. For the WW fusion process the absolute value of the asymmetry η_2 is maximal, as this process occurs only via a selected combination of electron and positron helicities. If only the e$^-$ beam is polarized, $R_i = 1 + \eta_i P_-$. Some R_i values for various left- and right-handed beam particle polarization degrees are shown in Table 2, which illustrates the potential of polarized colliding beams for Higgs boson physics at a linear collider. Obviously, only left-handed e$^-$ which collide with right-handed e$^+$ with largest polarization degrees as possible enhance the Higgs event rates at most.

However, the dominant background in processes (1) and (2), such as $Z\gamma\gamma$ and W-exchange $\nu_e\bar{\nu}_e\gamma\gamma$, scale in approximately the same way with beam polarizations as the signal processes, as was verified by CompHEP simulations. Hence, the $\gamma\gamma$ invariant mass spectra shown in Figs.4 and 5 can be rescaled by the appropriate R_i factor, and the statistical precision of the H $\to \gamma\gamma$ branching fraction is improved by only a factor $\sqrt{R_i}$.

For the idealized case of collisions of perfect left-polarized e$^-$ with perfect right-polarized e$^+$ beams the precision achievable for $\sigma(H) \cdot BF(H \to \gamma\gamma)$ is expected to be 10.3% and 8.2% at 350 and 500 GeV, respectively, after combining reactions (3) and (4) at 350 GeV and considering only reaction (4) at 500 GeV. For the feasible (ambitious) case of collisions of 80% left-handed electrons with 40 (60)% rigth-handed positrons [13] the statistical precision for $\sigma(H) \cdot BF(H \to \gamma\gamma) = 12.8$ (12.1)%, respectively, 10.2 (9.6)% at $\sqrt{s} = 350$ and 500 GeV, for 1 ab^{-1} integrated luminosity. The errors of the diphoton branching fraction of the Higgs boson are then deduced after convolution with the uncertainties for the inclusive Higgs production rates which are expected to be close or better than 2% [14].

e^- beam (P_-)	e^+ beam (P_+)	$e^+e^- \to HZ$	$e^+e^- \to \nu_e\bar{\nu}_e H$
+1	0	0.79	0
-1	0	1.21	2
+0.8	0	0.83	0.2
-0.8	0	1.17	1.8
+1	-1	1.58	0
-1	+1	2.42	4
+0.8	-0.4	1.07	0.12
-0.8	+0.4	1.57	2.52
+0.8	-0.6	1.19	0.08
-0.8	+0.6	1.77	2.88

Table 2: Cross section scaling factors of Higgsstrahlung and WW fusion processes for various left-handed and rigth-handed polarization degrees, normalized to the unpolarized event rates.

6 Conclusions

In this study we examined the prospect at a future linear e^+e^- collider of measuring the branching fraction of a Standard Model-like Higgs boson into two photons, BF($H \to \gamma\gamma$). A Higgs boson mass of 120 GeV and an integrated luminosity of 1 ab^{-1} at either $\sqrt{s}$ = 350 or 500 GeV were assumed. In order to estimate the precision attainable on BF($H \to \gamma\gamma$), all expected backgrounds were included in the analysis, and acceptances and resolutions of a linear collider detector were convoluted. In particular, by simulating the 2-to-4 particle reactions $e^+e^- \to q\bar{q}\gamma\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma\gamma$, in which the signal reactions are embedded, the complete irreducible background has been accounted for.

At 350 GeV, where both the Higgsstrahlung and the WW fusion mechanisms contribute significantly, the statistical error for BF($H \to \gamma\gamma$) is 18%, after combining both Higgs production channels and and convolution with the uncertainty of the more easily measurable inclusive Higgs boson cross sections. It should be noted that the isolation of $e^+e^- \to ZH \to q\bar{q}\gamma\gamma$ signal events required a multidimensional analysis on a likelihood estimator. Otherwise, background from double bremsstrahlung is overwhelming and greatly hinders the BF($H \to \gamma\gamma$) measurement.

At 500 GeV, only the $\nu\bar{\nu}\gamma\gamma$ final state is worth consideration and the application of consecutive cuts on kinematical variables resulted in a reasonable signal-to-noise ratio and a convincing signal. The relative precision expected for the $H \to \gamma\gamma$ branching fraction is found to be 16%.

If 80% left-handed electrons collide with 40 (60)% right-handed positrons the Higgsstrahlung and WW fusion cross sections are significantly enhanced, so improving substantially the precision on BF($H \to \gamma\gamma$), even taking into account that the background scales in the same way. Under such circumstances, the uncertainty for BF($H \to \gamma\gamma$) is lowered to 12.8 (12.1)% and 10.2 (9.6)% at $\sqrt{s}$ = 350 and 500 GeV, respectively. With these uncertainties it should be possible to deduce a relative precision for the diphoton Higgs partial width of $\frac{\Delta\Gamma(H\to\gamma\gamma)}{\Gamma(H\to\gamma\gamma)} \simeq 13.5\%(12.6\%)$ and 11.1%(10.6%) at $\sqrt{s}$ = 350 and 500 GeV, respectively, if an uncertainty of 4.3% for the total Higgs width [14] is accounted for. These uncertainties are about a factor 5 worse than those expected from the reaction $\gamma\gamma \to H \to b\bar{b}$ [15], measurable after conversion of an e^+e^- collider to a Compton collider.

Acknowledgments

E.B. and R.S. would like to thank DESY Zeuthen for the kind hospitality, support and fruitful coorperation. The work of E.B. was partly supported by the RFBR-DFG 99-02-04011, RFBR 00-01-00704, Universities of Russia 990588 and CERN-INTAS 99-0377 grants.

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