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

E. Boos[1], J.-C. Brient[2], D.W. Reid[3], H.J. Schreiber[4,6], R.Shanidze[5]

[1] *Institute of Nuclear Physics, Moscow State University, 119 899 Moscow, Russia*
[2] *Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN²P³-CNRS, F-91128 Palaiseau Cedex, France*
[3] *NIKHEF, Postbus 41882, 1009 DB Amsterdam, The Netherlands*
[4] *DESY Zeuthen, 15735 Zeuthen, FRG*
[5] *High Energy Physics Institute, Tbilisi State University, 380086 Tbilisi, Georgia; now at Physikalisches Institut, Universität Erlangen-Nürnberg, 91058 Erlangen, FRG*

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%.

I 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($H \to \gamma\gamma$), is of special interest since deviations of BF($H \to \gamma\gamma$) (or the diphoton Higgs partial width $\Gamma(H \to \gamma\gamma)$) from the Standard Model (SM) value provide sensitivity to new physics. The precision of the $H \to \gamma\gamma$ branching fraction measurements within reach in e^+e^- collisions is the subject of this paper. In particular, we consider the reactions $e^+e^- \to q\bar{q}\gamma\gamma$ (1) and $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ (2) at $\sqrt{s} = 350$ and 500 GeV, and assume a Higgs boson mass $M_H = 120$ GeV and an integrated luminosity of 1 ab^{-1} at each energy.

[6)] presented by H.J. Schreiber.

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, 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 [2].

Preliminary results of this study can be found in ref. [3].

II SIGNAL AND BACKGROUND REACTIONS

In e^+e^- collisions the Higgs boson is produced by the Higgsstrahlung process $e^+e^- \to ZH$ and the weak boson (WW and ZZ) fusion reactions, $e^+e^- \to \nu_e\bar{\nu}_e H$ and $e^+e^- \to e^+e^- H$. Since the ZZ fusion reaction is strongly suppressed only the Higgsstrahlung and WW fusion reactions 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 $\to q\bar{q}$ and $\nu\bar{\nu}$ decays and the $H \to \gamma\gamma$ decay are accounted for. Thus, to be most general in our analysis, events of reactions (1) and (2) were generated by means of the program package CompHEP [4], including initial state bremsstrahlung and beamstrahlung for the TESLA linear collider option [5]. 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 [6].

The Higgsstrahlung reaction is characterized by two hadronic jets originating from the Z, together with two energetic photons with an invariant mass equal to M_H. The irreducible background expected in reaction (1) comes mostly 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 [7] 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, we expect a signature of two photons, producing two large electromagnetic neutral showers in the detector with no other activities, and large missing energy due to the two undetected neutrinos. The irreducible background accounted for at the same level as the signal events was also found to arise dominantly from the double bremsstrahlung process.

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.

For details on principal and preselection cuts applied we refer to [8]. The detector

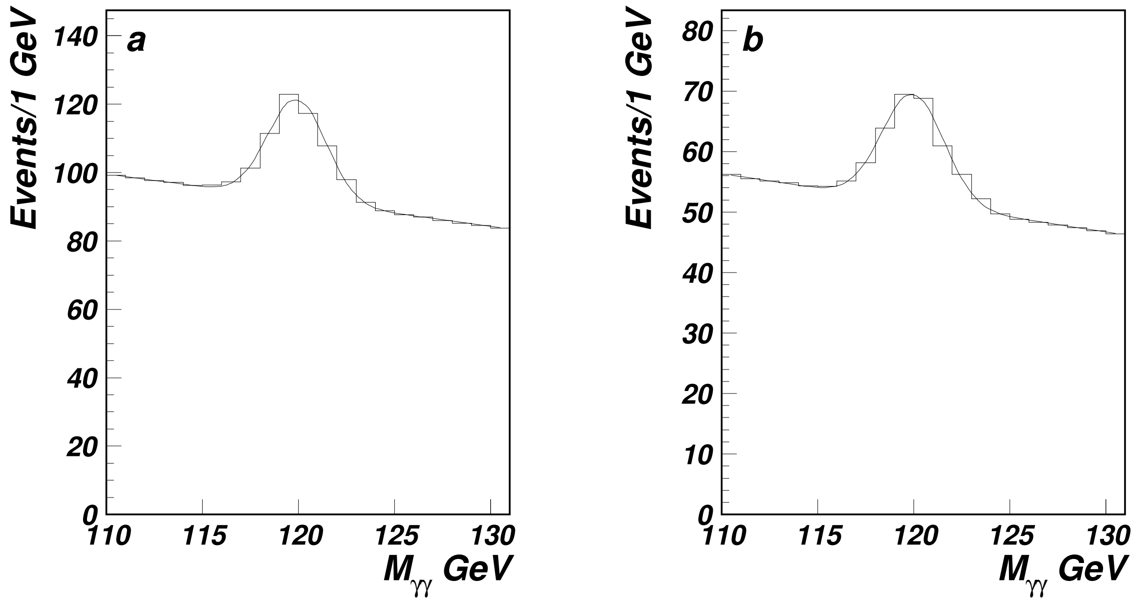

FIGURE 1. $M_{\gamma\gamma}$ invariant mass distributions for 350 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events. The background in the histograms has been averaged to avoid accidental fluctuations.

response for all remaining events was simulated with the parametrized detector simulation package SIMDET [9].

III BF($H \to \gamma\gamma$) MEASUREMENT AT 350 GEV

Different Higgs event rates are expected from the Higgsstrahlung and WW fusion processes at $\sqrt{s} = 350$ and 500 GeV. At 350 GeV, the Higgsstrahlung cross section 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 and are treated together in our study. Different event selection procedures were however 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.

For the $q\bar{q}\gamma\gamma$ events a global discriminant variable P_H, the "Higgs-likeness", with $0 \leq P_H \leq 1$ was invoked [8]. A cut of $P_H > 0.85$ was applied to select the Higgs candidates. The $\gamma\gamma$ invariant mass spectrum for the surviving $q\bar{q}\gamma\gamma$ events is shown in Fig. 1a. 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 good approximation. 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 around M_H is obtained. These numbers 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 two electromagnetic clusters, we required transverse energies larger than 20 GeV, polar angles within $|cos\Theta_\gamma| < 0.9$ and the polar angle of the two-photon system $|cos\theta_{\gamma\gamma}| < 0.8$. The resulting $M_{\gamma\gamma}$ mass distribution is shown in Fig. 1b, and an analogous fit procedure yields for $\sqrt{S+B}/S \simeq 28.5\%$. After combining both 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.

IV BF($H \to \gamma\gamma$) MEASUREMENT AT 500 GEV

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

For the $q\bar{q}\gamma\gamma$ final state, the "Higgs-likeness" probability was also demanded to be larger than 0.85, resulting to the $M_{\gamma\gamma}$ distribution as shown in Fig. 2a, with a statistically insignificant signal.

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 $M_{\gamma\gamma}$ distribution for the surviving $\gamma\gamma\nu\bar{\nu}$ events is shown in Fig. 2b, from which we estimate an error of $\sigma \cdot BF(H \to \gamma\gamma) \simeq 16.4\%$.

V 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 depend significantly on the polarization degree and the helicity of the incoming particles. As discussed in ref. [8], 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 surviving 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.1 and 2 can be rescaled by appropriate cross section scaling factors [8], and the statistical precision of the H $\to \gamma\gamma$ branching fraction improves by only the square root of the scaling factor.

For the feasible (ambitious) case of collisions of 80% left-handed electrons with 40 (60)% rigth-handed positrons [10] 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.

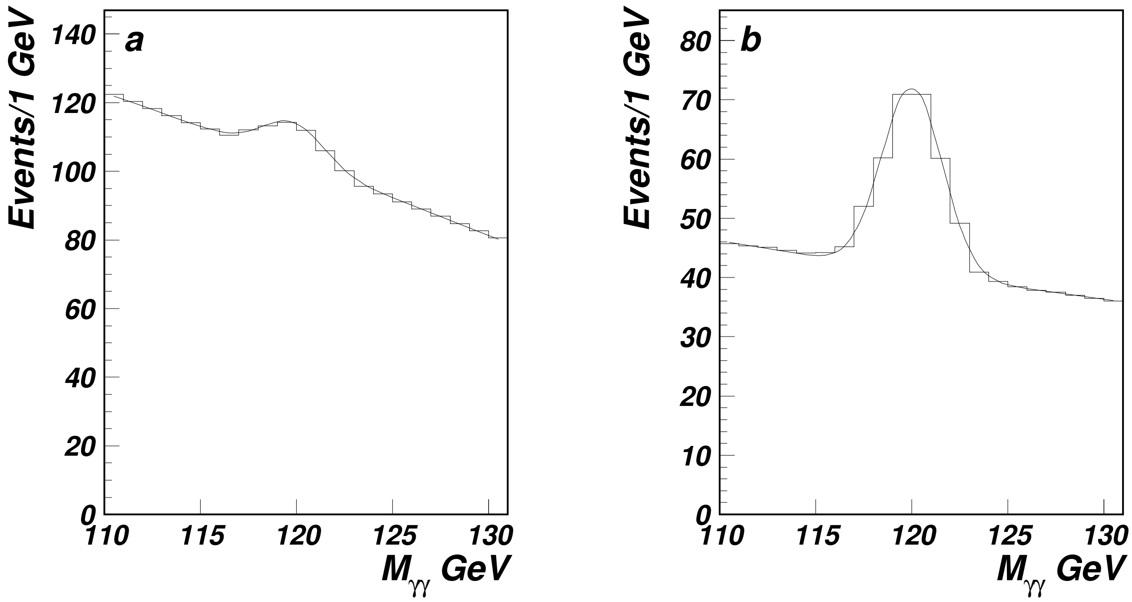

FIGURE 2. $M_{\gamma\gamma}$ invariant mass distributions for 500 GeV: a) $q\bar{q}\gamma\gamma$ and b) $\nu\bar{\nu}\gamma\gamma$ events. The background in the histograms has been averaged to avoid accidental fluctuations.

VI CONCLUSIONS

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$(H \to \gamma\gamma)$, is examined. 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.

At 350 GeV, 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 inclusive Higgs boson cross sections [11].

At 500 GeV, only the $\nu\bar{\nu}\gamma\gamma$ final state is worth to consider and 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$(H \to \gamma\gamma\ )$ 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 $\frac{\Delta\Gamma(H\to\gamma\gamma)}{\Gamma(H\to\gamma\gamma)} \simeq 10.6\%$ at best, if an uncertainty of 4.3% for the total Higgs width [11] is accounted for.

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