hep-ph 9312278
FTUV/93-50 IFIC/93-31
IFT-P.072/93 IFUSP-P 1084
MAD/PH/810

Searching for an Invisibly Decaying Higgs Boson in e^+e^-, $e\gamma$, and $\gamma\gamma$ Collisions

O. J. P. Éboli[1] and **M. C. Gonzalez-Garcia**[2]
Physics Dept., University of Wisconsin,
Madison, WI 53706, USA

A. Lopez-Fernandez[3]
PPE Division, CERN, CH-1211 Geneve 23, Switzerland

S. F. Novaes[4]
Instituto de Física Teórica, Universidade Estadual Paulista,
Rua Pamplona, 145 – CEP 01405-900, São Paulo, Brazil

J. W. F. Valle[5]
Instituto de Física Corpuscular - C.S.I.C.
Dept. de Física Teòrica, Universitat de València
46100 Burjassot, València, Spain

ABSTRACT

Higgs bosons can have a substantial "invisible" branching ratio in many extensions of the Standard Model, such as models where the Higgs bosons decay predominantly into light or massless weakly interacting Goldstone bosons. In this work, we examine the production mechanisms and backgrounds for invisibly decaying Higgs bosons at the Next Linear e^+e^- Collider operating in the modes e^+e^-, $e\gamma$, and $\gamma\gamma$. We demonstrate that such machine is much more efficient to survey for invisibly decaying Higgs bosons than the Large Hadron Collider at CERN.

1 Introduction

One of the primary goals of the Next Linear Collider (NLC) is to unravel the nature of the symmetry breaking mechanism of the electroweak interaction. Recently, there has been a great deal of interest in the study of Higgs boson signatures at such a machine [1]. In this work, we analyze the signal and backgrounds at the NLC for the production of Higgs bosons that decay invisibly, *i.e.* into very weakly interacting particles. We study the three possible modes of operation of the NLC, e^+e^-, $e\gamma$, and $\gamma\gamma$, assuming that the it will operate with a center-of-mass energy of $\sqrt{s} = 500$ GeV and a luminosity $\mathcal{L}_{ee} = 10^4$ pb^{-1}/year. Our results show that the best mode of operation to search for invisibly decaying Higgs bosons is the e^+e^- one, where Higgs bosons with masses up to 200 GeV can be observed provided their coupling to the Z is larger than 1/3 of its value in the Standard Model. Fully coupled Higgs bosons can be detected up to masses of 300 GeV. Therefore, the mass range of "invisible" Higgs boson that can be probed at NLC is larger than the corresponding one for LEPII [2, 3] and even for the Large Hadron Collider at CERN (LHC) [4].

There are many reasons to speculate that there exist additional Higgs bosons in nature, besides the one predicted by the Standard Model. For instance, the extension of the minimal Standard Model provided by supersymmetry and the desire to tackle the hierarchy problem [5] predicts a larger physical Higgs spectrum. Another interesting motivation for the enlargement of the Higgs sector is to generate the observed baryon excess by electroweak physics [6]. Although there is not yet a consensus on this matter, there are claims that suggest that a successful electroweak baryogenesis imposes, in the Standard Model, a stringent limit on the higgs mass, namely $m_h \lesssim 40$ GeV [7]. However, this bound is in conflict with the constraint placed by the direct search of the standard model Higgs boson at the LEP experiments around the Z peak [8], *i.e.* $m_{H_{SM}} \gtrsim 60$ GeV. A way to reconcile the LEP data and baryogenesis is to consider models with new Higgs bosons [9]. Moreover, such additional Higgs bosons could be intimately related to the question of neutrino masses [10]. In fact, one specially attractive motivation for extending the Higgs sector is the generation of neutrino masses [11], whose existence is hinted by present data on solar and atmospheric neutrinos, as well as cosmological observations related to the large scale structure of the universe and the possible need for hot dark matter.

Amongst the extensions of the Standard Model, which have been suggested to generate neutrino masses, the so-called majoron models are particularly interesting and have been widely discussed [11]. The majoron is the Goldstone boson associated with the spontaneous breaking of lepton number. Astrophysical arguments based on stellar cooling rates constrain its couplings to charged fermions [12], while the LEP measurements of the invisible Z width substantially restrict the majoron couplings to gauge bosons. In particular, models where the majoron is not a singlet under the $SU(2)_L \times U_Y(1)$ symmetry [13] are now excluded if lepton number is violated only spontaneously [8]. There is, however, a wide class of models motivated by neutrino physics [14] which is characterized by the spontaneous violation of a global $U(1)$ lepton-number symmetry by a singlet vacuum expectation value. Unlike the original model of this type [15], this new class of models may naturally explain the neutrino masses required by astrophysical and cosmological observations without introducing any high mass scale. Another example of this type is provided by supersymmetric extensions of the Standard Model where R parity is spontaneously violated [16].

In any of these models with the spontaneous violation of a global $U(1)$ symmetry around or below the weak scale, the corresponding Goldstone boson can have significant couplings to the Higgs bosons, even though its couplings to matter are suppressed. This implies that the Higgs boson can decay, with a substantial branching ratio, into the invisible mode, $h \to J + J$, where J denotes the majoron [14, 17, 18].

An invisible decay of the Higgs boson leads to events with large missing energy. However, in order to have an observable signature, it must be produced in association with another particle, such as Z, W, or t, which is used to tag the event. The production of an invisibly decaying Higgs boson was previously considered at LEP in association with a Z [3] and at hadron colliders in association with a Z or a $t\bar{t}$ pair [4]. In this paper we concentrate on the possibility of identifying an invisibly decaying Higgs boson at the three different modes of the NLC.

An important feature of this next generation of linear e^+e^- colliders is that they should also be able to operate in the $e\gamma$ or $\gamma\gamma$ modes. The conversion of electrons into photons can occur via the laser backscattering mechanism [19], which leads to a photon beam with almost the same energy and luminosity of the parent electron beam. This makes the NLC a very versatile machine that could employ energetic electrons and/or photons as initial states.

The outline of the paper is as follows. In Sec. 2 we briefly review the features of a simple model exhibiting invisibly decaying Higgs bosons. Section 3 is devoted to the study of the e^+e^- mode of the collider, whereas the modes $e\gamma$ and $\gamma\gamma$ are discussed in Sec. 4. We summarize our conclusions in Sec. 5.

2 The Simplest Model

In order to illustrate the main features of invisibly decaying Higgs bosons, let us analyze a simple model that contains the Standard Model scalar Higgs doublet plus an additional complex singlet σ, which exhibits a nonzero vacuum expectation value $\langle\sigma\rangle$ responsible for breaking a global $U(1)$ symmetry. The scalar potential of this model is [14, 17]

$$V = \mu_\phi^2 \phi^\dagger\phi + \mu_\sigma^2 \sigma^\dagger\sigma + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\sigma^\dagger\sigma)^2 + \delta(\phi^\dagger\phi)(\sigma^\dagger\sigma) \; . \tag{1}$$

Terms like σ^2 were omitted in Eq. (1) since we required this model to exhibit a $U(1)$ invariance under which σ transforms nontrivially and ϕ trivially. Let

$$\sigma \equiv \frac{w}{\sqrt{2}} + \frac{(R_2 + iI_2)}{\sqrt{2}} \quad \text{and} \quad \phi \equiv \frac{v}{\sqrt{2}} + \frac{(R_1 + iI_1)}{\sqrt{2}} \; ,$$

where we have set $\langle\sigma\rangle = w/\sqrt{2}$ and $\langle\phi\rangle = v/\sqrt{2}$. The potential (1) leads to a physical massless Goldstone boson, namely the majoron $J \equiv Im\ \sigma$, and two neutral CP even mass eigenstates H_i (i= 1,2)

$$H_i = \hat{O}_{ij}\ R_j \; , \tag{2}$$

where $\hat{O}_{ij}$ is an orthogonal mixing matrix with mixing angle θ given, in terms of the potential parameters and the vacuum expectation values, by

$$\tan 2\theta = \frac{\delta v w}{\lambda_1 v^2 - \lambda_2 w^2} \; . \tag{3}$$

In this simple model only the doublet Higgs boson ϕ couples to Z, W, and charged fermions in the weak basis. As a result, the CP even states H_i interact with these particles only through their R_1 component. After diagonalizing the scalar boson mass matrix, one finds that the two CP even mass eigenstates H_i possess the following couplings:

$$\begin{aligned} \mathcal{L}_{H_i ZZ} &= (\sqrt{2}G_F)^{1/2}\ M_Z^2\ \hat{O}_{i1}\ Z_\mu Z^\mu H_i \; , \\ \mathcal{L}_{H_i WW} &= 2(\sqrt{2}G_F)^{1/2}\ M_W^2\ \hat{O}_{i1}\ W_\mu^+ W^{-\mu} H_i \; , \\ \mathcal{L}_{H_i f\bar{f}} &= (\sqrt{2}G_F)^{1/2}\ m_f\ \hat{O}_{i1}\ \bar{f} f H_i \; . \end{aligned} \tag{4}$$

As we can see, the strength of the $H_i$couplings are reduced, in relation to the Standard Model, by a factor $\epsilon_i = \hat{O}_{i1}$. Therefore, as long as the mixing appearing in Eq. (4) is $\mathcal{O}(1)$, all CP even Higgs bosons can have significant production rates, similar to the ones of the Standard Model. In general, the $SU(2)$ custodial symmetry implies that the Higgs couplings to Z and W bosons are suppressed by the same factor, which can, in principle, be different from the suppression factor of the couplings to fermions.

We now turn to the Higgs boson decay rates, which are sensitive to the details of the mass spectrum and thus to the Higgs potential. For definiteness, we focus on the model given in Eq. (1) in which case the invisible width of the H_i is

$$\Gamma(H_i \to JJ) = \frac{\sqrt{2}G_F}{32\pi} M_{H_i}^3 g_{H_i JJ}^2 \ , \tag{5}$$

where the corresponding couplings are $g_{H_i JJ} = \tan\beta\ \hat{O}_{i2}$, with $\tan\beta = v/w$. The width for $H_i \to b\bar{b}$ gets diluted compared to the Standard Model one, because of mixing effects. Explicitly one has

$$\Gamma(H_i \to b\bar{b}) = \frac{3\sqrt{2}G_F}{8\pi} M_H m_b^2 \left(1 - 4\frac{m_b^2}{M_H^2}\right)^{3/2} g_{H_i b\bar{b}}^2 \ , \tag{6}$$

which is smaller than the Standard Model prediction by the factor $g_{H_i b\bar{b}}^2$, where $g_{H_i b\bar{b}} = \hat{O}_{i1}$. Heavy Higgs bosons can also decay into ZZ or W^+W^- pairs, however, the partial widths into these modes are diminished by the same factor appearing in the $b\bar{b}$ mode, as can be seen from Eq. (4).

In summary, the branching ratio of the Higgs decay into the invisible mode JJ depends upon the mixing angles β and θ and for a large fraction of the parameter space the invisible Higgs decay mode is expected to have quite large branching ratio [2]. This is characteristic of models where there exists a global symmetry that is broken around the weak scale.

From the existing Z sample at LEP [2] it is possible to obtain limits on invisibly decaying Higgs bosons. Moreover, it is possible to set Higgs boson mass limits that are not vitiated by detailed assumptions on its mode of decay. In this paper we stress that this invisible decay can be used as a useful signature for Higgs bosons at linear e^+e^- colliders.

3 Invisible Higgs Bosons at the NLC: the e^+e^- Mode

At the NLC, the main production mechanisms for H_i involve their couplings to heavy particles such as Z and W bosons and top quarks, depending on the collider mode chosen. For the NLC operating in the e^+e^- mode, the most important reactions for Higgs production [20] are the Higgs bremsstrahlung off a Z boson

$$e^+e^- \to Z^* \to ZH \tag{7}$$

and the WW fusion process

$$e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}H \ . \tag{8}$$

For Higgs bosons decaying invisibly, this second mechanism becomes irrelevant since it leads to an undetectable final state. In Fig. 1 we plot the cross section for the Higgs bremsstrahlung process as a function of the Higgs mass for $\sqrt{s} = 500$ GeV, assuming that the coupling of the Higgs boson to the Z is the one predicted by the Standard Model.

The main sources of background for invisibly decaying Higgs bosons are

$$\begin{array}{llll} e^+e^- \to \nu\bar{\nu}Z & (\sigma = 0.48 \text{ pb}) & & [A] \\ e^+e^- \to W^+W^- & (\sigma = 7.8 \text{ pb}) & \to (q\bar{q}')\,[\ell]\,\nu & [B] \\ & & \to (\ell\bar{\ell})\,\nu & [C] \\ e^+e^- \to e\nu_e W & (\sigma = 6.0 \text{ pb}) & \to (q\bar{q}')\,[e]\,\nu_e & [D] \\ & & \to (e^+e^-)\,\nu_e & [E] \end{array}$$

where the particles in square brackets escape undetected and the fermion pairs in parentheses have an invariant mass close to the Z mass. The equations above show the total cross sections for each process without taking into account any kinematical cut or branching ratio.

The Higgs bremsstrahlung mechanism (7) with the Z decaying into hadronic modes possesses large backgrounds due to the processes $[B]$ and $[D]$, even when we demand the Z invariant mass reconstruction. For this reason we will consider in our study only the leptonic decay modes $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$. In this case, the signature for an invisibly decaying Higgs boson will be two charged leptons with invariant mass compatible with the Z mass, plus missing transverse momentum. The requirement of missing transverse momentum eliminates further backgrounds like $\gamma\gamma$ and $\ell\bar{\ell}(\gamma)$ events, and makes the background coming from the process $[E]$ to be irrelevant. Finally, the most dangerous background that we are left with is process $[A]$ [21]. In order to suppress this contribution, we impose a further cut on the reconstruction of the Z energy

$$E_Z(m_H) = \frac{s + m_Z^2 - m_H^2}{2\sqrt{s}} \;\pm\; \Delta E \,. \tag{9}$$

where ΔE is the size of the uncertainties expected for the energy measurement at NLC, which we assume to be $\Delta E = 10$ GeV. This cut relies upon the fact that the energy of the Z is fixed when it is produced in association with the Higgs boson.

Further suppression of this background can be attained using the fact that the Z's in the signal are produced at larger polar angles than the ones in the background, as can be seen in Fig. 2. Therefore, we impose an additional angular cut $|\cos\theta_Z| < 0.7$. After all these cuts, the background $[C]$ becomes very small as shown in Fig. 3. This figure also shows the number of events we are left with for the signal and backgrounds $[A]$ and $[C]$

for $\epsilon^2\times$ BR$_{\rm invis}=1$, where BR$_{\rm invis}$ is the invisible branching ratio of the Higgs boson, and an integrated luminosity of 10^4 pb^{-1}.

In Fig. 4 we show the 95% confidence level discovery contours in the $\epsilon^2\times$ BR$_{\rm invis}$ versus M_H plane that can be explored at the NLC in the e^+e^- mode. From this figure, we can learn that invisibly decaying Higgs bosons with masses below 200 GeV can be detected provided their coupling to the Z is higher than 1/3 of its value in the Standard Model, while fully coupled Higgs bosons can be discovered up to masses of almost 300 GeV.

4 Invisible Higgs Bosons at NLC: the $\gamma\gamma$ and $e\gamma$ Modes

In a linear collider, it is possible to transform an electron beam into a photon one through the process of laser backscattering [19]. This mechanism relies on the fact that Compton scattering of energetic electrons by soft laser photons gives rise to high energy photons, that are collimated in the direction of the incident electron. For unpolarized initial electrons and laser, the spectrum of backscattered photons is [22]

$$F_L(x) \equiv \frac{1}{\sigma_c}\frac{d\sigma_c}{dx} = \frac{1}{D(\xi)}\left[1-x+\frac{1}{1-x}-\frac{4x}{\xi(1-x)}+\frac{4x^2}{\xi^2(1-x)^2}\right] , \qquad (10)$$

with

$$D(\xi) = \left(1-\frac{4}{\xi}-\frac{8}{\xi^2}\right)\ln(1+\xi)+\frac{1}{2}+\frac{8}{\xi}-\frac{1}{2(1+\xi)^2} , \qquad (11)$$

where ω_0 is the laser energy, σ_c is the Compton cross section and $\xi \simeq 4\omega_0 E/m^2$, with m and E being the electron mass and energy respectively. In contrast to the bremsstrahlung spectrum, the backscattered photon distribution (10) peaks close to the maximum allowed value for the photon energy, which occurs at $x_{\rm max}=\xi/(1+\xi)$. Moreover, the luminosity of the backscattered photon beam can be very close to the one of the parent electron beam provided that there is no e^+e^- pair creation by the interaction of the backscattered photons with the laser. In our calculation we have chosen ω_0 such that it maximizes the backscattered photon energy without spoiling the luminosity through e^+e^- pair creation. This choice leads to $\xi = 2(1+\sqrt{2})$ and the maximum of the spectrum is located at $x_{\rm max}\simeq 0.83$.

The laser backscattering mechanism transforms the NLC into a very versatile machine that can operate in two additional modes which are $e\gamma$ and $\gamma\gamma$. The differential luminosities for these modes can be easily obtained from Eq. (10) and are given by

$$\frac{d\mathcal{L}_{e\gamma}}{dz} = \mathcal{L}_{ee}\; 2zF_L(z^2) , \qquad (12)$$

$$\frac{d\mathcal{L}_{\gamma\gamma}}{dz} = \mathcal{L}_{ee}\, 2z \int_{z^2/x_{max}}^{x_{max}} \frac{dx}{x} F_L(x) F_L(z^2/x) \;, \tag{13}$$

where $\mathcal{L}_{ee}$ is the luminosity of the NLC operating in the e^+e^- mode. The total cross section for any process in these modes is obtained by folding the elementary cross section with the corresponding photon luminosity

$$\sigma(s) = \int_{z_{min}}^{z_{max}} dz\, \frac{d\mathcal{L}_{ij}}{dz}\, \hat{\sigma}_{ij}(\hat{s} = z^2 s) \tag{14}$$

where i,j is either $e\gamma$ or $\gamma\gamma$. Here $z^2 = \tau = \hat{s}/s$, where s is the total e^+e^- center-of-mass energy squared and $\hat{s}$ the ij pair center-of-mass energy squared.

4.1 The $\gamma\gamma$ Mode

Since neutral Higgs bosons do not couple directly to photons, their production in a $\gamma\gamma$ collider must proceed through either higher order processes or in association with heavy particles. The main production mechanism for neutral Higgs bosons at such colliders is via one-loop triangle diagrams [23]. However, this mechanism becomes useless for an invisibly decaying Higgs boson since it would lead to an undetectable signature. Therefore, the most promising processes are those in which the Higgs boson is produced in association with a W^+W^- or a $t\bar{t}$ pair, where the heavy particles can be used to tag the events.

$$\begin{array}{ll} \gamma\gamma \to W^+W^-H & [WWH] \\ \gamma\gamma \to t\bar{t}H & [TTH] \end{array}$$

In the case of a standard Higgs boson, the process $[WWH]$ has been already considered in the literature [24] and $[TTH]$ was previously analyzed in Ref. [25, 26]. However, for the sake of completeness, we show in Fig. 5 the total cross section for these processes as a function of the Higgs mass for $\epsilon^2\times$ BR$_{\rm invis} = 1$ and $m_{\rm top} = 140$ GeV.

The possible backgrounds for these processes come from the reactions

$$\begin{array}{lll} \gamma\gamma \to W^+W^- & (\sigma = 48 \text{ pb}) & [WW] \\ \gamma\gamma \to W^+W^-[\gamma] & (\sigma = 1 \text{ pb},\ p_T^\gamma > 20 \text{ GeV}) & [WWG] \\ \gamma\gamma \to W^+W^-Z \to W^+W^-\nu\bar{\nu} & (\sigma = 4 \text{ fb}) & [WWZ] \\ \gamma\gamma \to t\bar{t} & (\sigma = 0.4 \text{ pb}) & [TT] \\ \gamma\gamma \to t\bar{t}[\gamma] & (\sigma = 0.2 \text{ fb},\ p_T^\gamma > 20 \text{ GeV}) & [TTG] \\ \gamma\gamma \to t\bar{t}Z \to t\bar{t}\nu\bar{\nu} & (\sigma = 0.2\times 10^{-3} \text{ fb}) & [TTZ] \end{array}$$

where the $[\gamma]$ in the $[WWG]$ and $[TTG]$ backgrounds escapes undetected, going into the beam pipe. Several of these reactions have been analyzed previously in Ref. [26, 27]. In order to ensure the reconstruction of the W^+W^- and $t\bar{t}$ pairs, we restrict ourselves to hadronic decay modes of the W's and we impose that none of the charged particles in the final state goes down the beam pipe, that we assume to have an an angular size of 20°, corresponding to the cut $|\cos\theta_{W,t}| < 0.94$. The potentially larger backgrounds ($[WW]$ and $[TT]$) can be eliminated by requiring the existence of missing p_T in the event, thus, we adopted the cut $\not{p}_T > 40$ GeV. This requirement also discards the $[TTG]$ and $[TTZ]$ backgrounds and reduces considerably the $[WWG]$ one, as can be seen in Fig. 6.

Unlike the e^+e^- mode, it is impossible to reconstruct the invisible invariant mass due to the unknown center-of-mass energy of the $\gamma\gamma$ system. This constitutes an unavoidable drawback for both the $\gamma\gamma$ and $e\gamma$ modes that might only be circumvented by using polarized photons whose energy distribution is narrower.

In Fig. 6 we show, for $\epsilon^2\times$ BR$_{\text{invis}} = 1$, the expected number of events for the signals and backgrounds, taking into account the hadronic branching ratio of the W and the above cuts. As can be seen from this figure, a fully coupled Higgs boson produced in association with a W pair would lead to a 2σ signature if its mass is lighter than 80 GeV. Nevertheless, this mass range would have been almost fully explored by LEP200 [2] assuming that the Higgs couplings to Z and W are related, as required by the $SU(2)$ custodial symmetry. For the associated production with a $t\bar{t}$ pair the cross section is very small and would lead to more than 1 event only if the Higgs boson is lighter than 50 GeV. For the simple model we discussed in Sec. 2, this range is already ruled out by LEP data since the mixing angle appearing in the Higgs coupling to fermions and to gauge bosons are the same. However, in a general model, containing more fermions or an additional scalar doublet, the couplings of the Higgs to gauge bosons and to fermions are independent and the $[TTH]$ process would not be directly constrained by LEP data.

4.2 The $e\gamma$ Mode

The main production mechanisms of Higgs bosons in a linear collider operating in the $e\gamma$ mode are

$$\begin{array}{ll} e\gamma \to e\gamma\gamma \to eH & [EH]\,, \\ e\gamma \to \nu WH & [NWH]\,, \\ e\gamma \to eZH & [EZH]\,. \end{array}$$

The reaction $[EH]$ was analyzed in Ref. [28] and it takes place through the one-loop process $\gamma\gamma \to H$, where one of the photons is generated via bremsstrahlung off the electron. For an invisibly decaying Higgs this process is irrelevant since the final electron goes down the beam pipe and there is no detectable particle in the final state. On the other hand, the $[NWH]$ reaction [29] leads to a W^- plus missing p_T signature. However, this signal will be buried in a huge background due to the process $e\gamma \to W^-\nu$, which overcomes the signal by more than 3 orders of magnitude. Therefore, we must restrict the search for an invisibly decaying Higgs boson to the process $[EZH]$ [30]. In Fig. 7 we show the total cross section for this process as a function of the Higgs mass, assuming $\epsilon^2\times$ BR$_{\text{invis}} = 1$ without applying any cut.

The main backgrounds for this process are

$$
\begin{array}{llll}
e\gamma \to eZ & (\sigma = 13 \text{ pb}) & & [EZ]\,, \\
e\gamma \to eZ\nu\bar{\nu} & (\sigma = 1.3\times 10^{-2} \text{ pb}) & & [EZNN]\,, \\
e\gamma \to eW^+W^- & (\sigma = 3.8 \text{ pb}) & \to [e]\nu e(q\bar{q}') & [EWW]\,, \\
e\gamma \to eZ\gamma & (\sigma = 0.4 \text{ pb},\ p_T^\gamma > 15 \text{ GeV}) & \to eZ[\gamma] & [EZG]\,,
\end{array}
$$

where the $[\gamma]$ in $[EZG]$ escapes undetected, going into the beam pipe, and the $(q\bar{q}')$ pair from the W decays is mistaken as a Z boson. Some of these reactions have been analyzed in references [30, 31]. As before, the $[EZ]$ background is eliminated by demanding the event to contain missing p_T ($\not{p}_T > 20$ GeV). The bulk of the $[EWW]$ events steams from effective photons ($e\gamma \to e\gamma\gamma \to eWW$), so in order to reduce this background we require a large scattering angle for the outgoing electron $\theta_e > 10°$, that corresponds to $|\cos\theta_e| < 0.984$. The $[EWW]$ background could be eliminated if we restricted ourselves to leptonic Z decays. However, this would also reduce dramatically the signal, which is already small. In our analyses, we consider both leptonic and hadronic decays of the W's and Z's. We can further improve the signal over background ratio noticing that in the signal the Z's are more copiously produced in the forward hemisphere, as shown Fig. 8, while in the $[EZNN]$ process, as well as for the W in the $[EWW]$ process, they are symmetrically produced. Therefore, we also demand that $\cos\theta_{Z,W} > 0$.

In Fig. 9 we show the number of leptonic and hadronic events from the signal and backgrounds for $\epsilon^2\times$ BR$_{\text{invis}} = 1$. As can seen in this figure, the $[WWE]$ background is still much larger than the signal for the case of hadronic decays. Therefore, these decays modes could not be used unless an extremely good invariant mass resolution would permit the discrimination between hadronic decaying Z's and W's. On the other hand, the signal for leptonic Z decays is very weak and only observable in a range of Higgs masses which are already ruled out by LEP.

5 Discussion

The Higgs boson can decay to invisible Goldstone bosons in a wide class of models in which a global symmetry, such as lepton number, is broken spontaneously close to the weak scale. These models are attractive from the point of view of neutrino physics and suggest the need to search for Higgs bosons in the invisible mode. We have investigated the reach of a high energy linear e^+e^- collider to discover a Higgs boson decaying invisibly.

An important feature of the next generation of linear e^+e^- colliders is that they should also be able to operate in the $e\gamma$ or $\gamma\gamma$ modes. We have studied the possibilities of the different modes of NLC to observe an invisible Higgs decay signature. According to our results, it would be very difficult to observe such a invisibly decaying Higgs boson in the $\gamma\gamma$ and $e\gamma$ modes of the collider. In these modes, not only the cross sections for the signals are small but also the backgrounds are difficult to be reduced since it is not possible to reconstruct the invisible invariant mass due to the unknown center-of-mass energy of the $\gamma\gamma$ and $e\gamma$ systems.

The best results are obtained in the e^+e^- mode of the collider. Our results in this case are summarized in Fig. 4, where we show the exclusion contours at 95% CL in the $\epsilon^2\times$ BR_{invis} vs. m_H plane that can be explored at the NLC in the e^+e^- mode. Invisibly decaying Higgs bosons with masses below 200 GeV can be detected provided their coupling to the Z is larger than 1/3 of the Standard Model Higgs coupling. A fully coupled Higgs bosons can be detected up to masses of 300 GeV. Therefore, our results indicate that a machine like the NLC will be able to survey a much larger m_H range than the LHC.

ACKNOWLEDGMENTS

O.J.P.E. is very grateful to the Institute of Elementary Particle Physics Research of the Physics Department, University of Wisconsin—Madison for its kind hospitality. This work was supported by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, by the U.S. Department of Energy under contract No. DE-AC02-76ER00881, by the Texas National Research Laboratory Commission under Grant No. RGFY93-221, by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq/Brazil), by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP/Brazil), and by the National Science Foundation under Contract INT 916182.

[1] Permanent address: Inst. de Física, Universidade de São Paulo, Caixa Postal 20516, CEP 01452-990 São Paulo, Brazil; E-mail: EBOLI@USPIF.IF.USP.BR (InterNet) – USPIF::EBOLI (DecNet)

[2] CONCHA@WISCPHEN (BitNet) – 47397::CONCHA (DecNet)

[3] E-mail: ALFON@CERNVM (BitNet)

[4] E-mail: UEIFT1::NOVAES (DecNet)

[5] E-mail: VALLE@EVALUN11 (BitNet) – 16444::VALLE (DecNet)

FIGURE CAPTIONS

Fig. 1: Total cross section for the process $e^+e^- \to HZ$ as a function of Standard Model Higgs-boson mass (m_H) at $\sqrt{s} = 500$ GeV.

Fig. 2: Angular distribution of Z in the background process $e^+e^- \to \nu\bar{\nu}Z$ (dotted line) and in the Standard Model signal $e^+e^- \to HZ$ (solid lines). The signal distributions are shown for $m_H = 20$, 200, and 300 GeV from the upper to lower solid lines.

Fig. 3: Number of events for the signal ZH (solid line), assuming $\epsilon^2\times$ $\text{BR}_{\text{invis}} = 1$, and backgrounds $e^+e^- \to \nu\bar{\nu}Z$ (dashed line) and W^+W^- (dotted line). We imposed the cut $|\cos\theta_Z| < 0.7$ and assumed an uncertainty in the Z energy of 10 GeV.

Fig. 4: Accessible region in the plane ($\epsilon^2\times$ BR_{invis}, M_H) at 95 % CL. We assumed a center-of-mass energy of 500 GeV and an integrated luminosity of 10^4 pb^{-1}.

Fig. 5: Total cross section for the processes $\gamma\gamma \to W^+W^-H$ (solid line) and $\gamma\gamma \to t\bar{t}H$ (dashed line) as a function of the Higgs mass, for $\sqrt{s} = 500$ GeV and $m_{\text{top}} = 140$ GeV.

Fig. 6: Total number of $[WWH]$, $[WWZ]$, $[WWG]$, and $[TTH]$ events in the $\gamma\gamma$ mode for $m_{\text{top}} = 140$ GeV, after considering the relevant branching ratios. We imposed the cuts $|\cos\theta_{W,t,\bar{t}}| < 0.94$, $\not{p}_T > 40$ GeV, and $|\cos\theta_\gamma| > 0.94$.

Fig. 7: Total cross section for the process $e\gamma \to eZH$ at $\sqrt{s} = 500$ GeV. We assumed $\epsilon^2\times$ $\text{BR}_{\text{invis}} = 1$ and did not apply any cut.

Fig. 8: Angular distribution of the Z in the background process $e\gamma \to eZ\nu\bar{\nu}$ (dotted line) and in the signal $e\gamma \to eZH$ (solid lines). The signal distribution is shown for $m_H = 60$ GeV.

Fig. 9: Final number of events for signal and backgrounds in the $e\gamma$ mode. The solid lines correspond to hadronic Z events while the dashed lines correspond to the leptonic ones.

References

[1] A. Djouadi, D. Haidt, B. Kniehl. B. Mele and P. M. Zerwas, Proceedings of the workshop e^+e^- collisions at 500 GeV, the physics potential' DESY-Report 92-123, ed. P. Zerwas and references therein; V. Barger *et al.*, Phys. Rev. **D46** (1992) 3725.

[2] A. Lopez-Fernandez, J. C. Romão, F. de Campos, and J. W. F. Valle, *Phys. Lett.* **B312** (1993) 240.

[3] O. J. P. Éboli, M. C. Gonzalez Garcia, S. F. Novaes, J. C. Romão, A. Lopez-Fernandez, F. de Campos and J. W. F. Valle, to be published in the Proceedings of the "Workshop on e^+e^- collisions at 500 GeV: The Physics Potential", edited by P. Zerwas et al.; B. Brahmachari, A. S. Joshipura, S. D. Rindani, D. P. Roy and Sridhar K., *Phys. Rev.* **D48** (1993) 4224.

[4] J. C. Romao, J. L. Diaz-Cruz, F. Campos and J. W. F. Valle, FTUV/92-39 (1992); S. G. Frederiksen *et al.,* SSCL-Preprint-577 (1992); J. F. Gunion, Preprint UCD-93-28.

[5] H. P. Nilles, *Phys. Rep.* **110** (1984) 1; H. Haber and G. Kane, *Phys. Rep.* **117** (1985) 75.

[6] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, *Phys. Lett.* **B155** (1985) 36.

[7] M. Dine, R. L. Leigh, P. Huet, A. Linde, and D. Linde, *Phys. Lett.* **B283** (1992) 319; M. E. Carrington, *Phys. Rev.* **D45** (1992) 2933.

[8] L. Rolandi in *Proceedings of the XXVI International Conference on High Energy Physics*, ed. J. R. Sanford (1992) pg. 56.

[9] A. I. Bocharev, S. V. Kuzmin, and M. E. Shaposnikov, *Phys. Lett.* **B244** (1990) 275; *Phys. Rev.* **D43** (1991) 369; N. Turok and J. Zadrozny, *Nucl. Phys.* **B358** (1991) 471; B. Kastening, R. D. Peccei and X. Zhang, *Phys. Lett.* **B266** (1991) 413; L. McLerran *et al.,* *Phys. Lett.* **B256** (1991) 451; A. G. Cohen, D. B. Kaplan, and A. E. Nelson, *Phys. Lett.* **B245** (1990) 561; *Nucl. Phys.* **B349** (1991) 727; Y. Kondo et al. *Phys. Lett.* **B263** (1991) 93; N. Sei et al., NEAP-49 (1992) G. W. Anderson and L. J. Hall, *Phys. Rev.* **D45** (1992) 2685.

[10] J. Peltoniemi and J. W. F. Valle, *Phys. Lett.* **B304** (1993) 147.

[11] J. W. F. Valle, *Prog. Part. Nucl. Phys.* **26** (1991) 91 and references therein.

[12] J. E. Kim, *Phys. Rep.* **150** (1987) 1, and references therein.

[13] G. Gelmini and M. Roncadelli, *Phys. Lett.* **B99** (1981) 411; R. E. Schrock and M. Suzuki, *Phys. Lett.* **B110** (1982) 250; L. F. Li, Y. Liu, and L. Wolfenstein, *Phys. Lett.* **B159** (1985) 45; See also D. Chang and W. Keung, *Phys. Lett.* **B217** (1989) 238.

[14] A. Joshipura and J. W. F. Valle, *Nucl. Phys.* **B397** (1993) 105.

[15] Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, *Phys. Lett.* **98B** (1980) 265.

[16] A. Masiero and J. W. F. Valle, *Phys. Lett.* **B251** (1990) 273; P. Nogueira, J. C. Romão, and J. W. F. Valle, *Phys. Lett.* **B251** (1990) 142; J. C. Romão, N. Rius, and J. W. F. Valle, *Nucl. Phys.* **B363** (1991) 369; J. C. Romão and J. W. F. Valle, *Nucl. Phys.* **B381** (1992) 87; J. C. Romão, C. A. Santos, and J. W. F. Valle, *Phys. Lett.* **B288** (1992) 311; M. C. Gonzalez-Garcia, J. C. Romão, and J. W. F. Valle, *Nucl. Phys.* **B391** (1993) 100; G. Giudice etal, *Nucl. Phys.* **B396** (1993) 243; M. Shiraishi, I. Umemura, K. Yamamoto, *Phys. Lett.* **B313** (1993) 89.

[17] A. S. Joshipura and S. Rindani, *Phys. Rev. Lett.* **69** (1992) 3269; R. Barbieri and L. Hall, *Nucl. Phys.* **B364** (1991) 27; G. Jungman and M. Luty, *Nucl. Phys.* **B361** (1991) 24. E. D. Carlson and L. B. Hall, *Phys. Rev.* **D40** (1989) 3187.

[18] J. C. Romão, F. de Campos, and J. W. F. Valle, *Phys. Lett.* **B292** (1992) 329.

[19] F. R. Arutyunian and V. A. Tumanian, Phys. Lett. **4** (1963) 176; R. H. Milburn, Phys. Rev. Lett. **10** (1963) 75.

[20] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, *The Higgs Hunter's Guide*, (Addison-Wesley, 1990) and references therein.

[21] The cross section for the process $e^+e^- \to \nu\bar{\nu}Z$ was first evaluated by B. Mele and S. Ambrosiano *Nucl. Phys.* **B374** (1992) 3.

[22] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo and V. I. Telnov, Nucl. Instrum. & Methods **205** (1983) 47; idem **219** (1984) 5; V. I. Telnov, Nucl. Instrum. & Methods **A294** (1990) 72.

[23] J. F. Gunion and H. E. Haber, *Phys. Rev.* **D48** (1993) 5109; R. Richard, in Proceedings of e^+e^- Collisions at 500 GeV: The Physics Potential, DESY 92-123B (pg 883); O. J. P. Éboli. M. C. Gonzalez-Garcia, F. Halzen and D. Zeppenfeld, *Phys. Rev.* **D48** (1993) 1430.

[24] M. Baillargeon and F. Boudjema, *Phys. Lett.* **B317** (1993) 371.

[25] E. Boos, I. Ginzburg, K. Melnikov, T. Sack, and S. Shichanin, Z. Phys. **C56** (1992) 487.

[26] K. Cheung, Phys. Rev. D**47** (1993) 3750.

[27] M. Baillargeon, and F. Boudjema, Proceedings of the *Beyond the Standard Model III*, Ottawa (June 1992); F. T. Brandt, O. J. P. Éboli, E. M. Gregores, M. B. Magro, P. G. Mercadante, and S. F. Novaes, Preprint IFT-P.053/93 and IFUSP-P 1065 (submitted for publication).

[28] O. J. P. Éboli, M. C. Gonzalez-Garcia, and S. F. Novaes U.W. Madison preprint MAD/PH/753 (1993) (to appear in Phys. Rev. D).

[29] E. Boos, et al., Phys. Lett. **B273** (1991) 173; K. Hagiwara, I. Watanabe, and P. M. Zerwas, Phys. Lett. **B278** (1993) 187. K. Cheung, Phys. Rev. **48** (1993) 1035.

[30] K. Cheung, *Nucl. Phys.* **B403** (1993) 572.

[31] O. J. P. Éboli, M. C. Gonzalez-Garcia, and S. F. Novaes U.W. Madison preprint MAD/PH/764 (1993) (to appear in Nucl. Phys. B).