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MODEL INDEPENDENT HIGGS BOSON MASS LIMITS AT LEP

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ABSTRACT

We derive model-independent constraints on Higgs mass and couplings from the present LEP1 data samples and discuss the prospects for detecting the associated signals for higher masses, accessible at LEP2. This work is motivated by the fact that, in many extensions of the standard model, the Higgs boson can have substantial "invisible" decay modes, for example, into light or massless weakly interacting Goldstone bosons associated to the spontaneous violation of lepton number below the weak scale.

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1 Introduction

The problem of mass generation remains one of the main puzzles in particle physics today. In the standard model all masses arise as a result of the spontaneous breaking of $SU(2) \otimes U(1)$ the gauge symmetry. This implies the existence of an elementary Higgs boson [1], not yet found. Recently the LEP experiments on e^+e^- collisions around the Z peak have placed important restrictions on the Higgs boson mass

$$m_{H_{SM}} \gtrsim 60\text{GeV}. \tag{1}$$

This limit holds in the standard model.

There are many reasons to think that there may exist additional Higgs bosons in nature. One such extension of the minimal standard model is provided by supersymmetry and the desire to tackle the hierarchy problem [2]. There are, however, many other motivations. One is the question of neutrino masses, whose existence is presently suggested by astrophysical 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 [3]. Most extensions of the minimal standard model to induce neutrino masses require an enlargement in the Higgs sector [4]. Another motivation to extend the Higgs sector is to generate the observed baryon excess by electroweak physics [5]. Indeed, the latter requires $m_{H_{SM}} \lesssim 40$ GeV [6] in conflict with eq. (1). This limit can be avoided in models with new Higgs bosons [7, 8].

Amongst the extensions of the standard model which have been suggested to generate neutrino masses, the majoron models are particularly interesting and have been widely discussed [4]. The majoron is a Goldstone boson associated with the spontaneous breaking of the lepton number. Astrophysical arguments based from stellar cooling rates constrain its couplings to the charged fermions [9], while the LEP measurements of the invisible Z width restrict the majoron couplings to the gauge bosons in an important way. In particular, models where the majoron is not a singlet [10] under the $SU(2) \otimes U(1)$ symmetry are now excluded [11].

There is, however, a wide class of models [12], motivated by neutrino physics, which are characterized by the spontaneous violation of a global $U(1)$ lepton number symmetry by an $SU(2) \otimes U(1)$ singlet vacuum expectation value $\langle\sigma\rangle$ [13]. These models may naturally explain the neutrino masses required by astrophysical and cosmological observations. Another example is provided by supersymmetric extensions of the standard model where R parity is spontaneously violated [14].

In all these extensions of the minimal standard model the global $U(1)$ lepton number symmetry is spontaneously violated close to the electroweak scale. Such a low scale for the lepton number violation is preferred since, in these models, $m_\nu \to 0$ as $\langle\sigma\rangle \to 0$. As a result, a relatively low value of $\langle\sigma\rangle$ is required in order to obtain naturally small neutrino masses. These may arise either at the tree level or radiatively [12].

An alternative argument for why the violation of a global symmetry should happen at a relatively low scale has recently been given. It states that, in the presence of nonperturbative gravitational effects, global symmetries are generally broken explicitly, so that any related Goldstone boson, such as the majoron, is expected to acquire a small mass by gravitational effects. While the corresponding majoron mass is lower than a keV or so, it could affect the evolution of the universe. As a result, the majoron must be unstable, to avoid conflict with cosmology. This leads to an upper bound on the lepton breaking scale $\langle\sigma\rangle \lesssim \mathcal{O}$ (10) TeV [15].

In any model with a spontaneous violation of a global $U(1)$ symmetry around the weak scale (or below) the corresponding Goldstone boson has significant couplings to the Higgs bosons, even if its other couplings are suppressed. This implies that the Higgs boson can decay with a substantial branching ratio into the invisible mode [12, 16, 17]

$$h \to J \ + \ J \tag{2}$$

where J denotes the majoron.

Such an invisible Higgs decay would lead to events with large missing energy that could be observable at LEP and affect the corresponding Higgs mass bounds.

It is the purpose of this letter to derive *in a model independent way* the limits on the Higgs boson mass that can be deduced from the present LEP samples. For simplicity we focus on the simplest model, sketched in section 2. We obtain limits that must hold *irrespective of whether the Higgs decays visibly or invisibly*. In order to do this we first determine the lightest Higgs boson production rates. These are, generically, somewhat suppressed with respect to the standard model prediction. We call this suppression factor ϵ^2. Then we combine three final-state search methods:

1. $Z \to HZ^*$, $H \to q\bar{q}$, $Z \to \nu\nu$ or ll where we directly use the SM Higgs search results
2. $Z \to HZ^*$, $H \to$invisible, $Z \to ll$, where we combine the results of acoplanar lepton pair searches. This gives good limits for low Higgs masses
3. $Z \to HZ^*$, $H \to$ invisible, $Z \to q\bar{q}$ where we reinterpret the results SM Higgs search in the $H\nu\nu$ channel. This allows better limits for high values of the Higgs mass.

Our results are summarized in figures 1 and 2. Finally, we have also determined the additional range of parameters that can be covered by LEPII for a total integrated luminosity of 500 pb^{-1} and centre-of-mass energies of 175 GeV and 190 GeV.

2 The Simplest Example

There are many models of interest for neutrino physics, astrophysics and cosmology where the Higgs boson will have important invisible decay rates. Some examples have been considered previously [12, 16]. For our present purposes they do not need to be specified beyond the structure of their neutral scalar potential responsible for the breaking of the $SU(2) \otimes U(1)$ and the global symmetries.

The simplest model contains, in addition to the scalar Higgs doublet of the standard model an additional complex singlet σ which also acquires a nonzero vacuum expectation value $\langle\sigma\rangle$ which breaks the global symmetry. The scalar potential is given by [12, 16]

$$V = \mu_\phi^2 \phi^\dagger\phi + \mu_\sigma^2 \sigma^\dagger\sigma + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\sigma^\dagger\sigma)^2 + \delta(\phi^\dagger\phi)(\sigma^\dagger\sigma) \tag{3}$$

Terms like σ^2 are omitted above in view of the imposed $U(1)$ invariance under which we require σ to transform nontrivially and ϕ to be trivial. Let $\sigma \equiv \frac{w}{\sqrt{2}} + \frac{R_2+iI_2}{\sqrt{2}}$,

$\phi^0 \equiv \frac{v}{\sqrt{2}} + \frac{R_1+iI_1}{\sqrt{2}}$, where we have set $\langle\sigma\rangle = \frac{w}{\sqrt{2}}$ and $\langle\phi^0\rangle = \frac{v}{\sqrt{2}}$. The above potential then leads to a physical massless Goldstone boson, namely the majoron $J \equiv \mathrm{Im}\ \sigma$ and two massive neutral scalars H_i (i= 1,2)

$$H_i = \hat{O}_{ij}\ R_j \tag{4}$$

The mixing $\hat{O}$ can be parametrized as

$$\hat{O} = \begin{pmatrix} cos\theta & sin\theta \\ \\ -sin\theta & cos\theta \end{pmatrix} \tag{5}$$

mixing angle θ as well as the Higgs masses M_i^2 are related to the parameters of the potential in the following way:

$$\begin{aligned} 2\delta v w &= (M_2^2 - M_1^2)\sin 2\theta \\ 2\lambda_1 v^2 &= M_1^2 \cos^2\theta + M_2^2 \sin^2\theta \\ 2\lambda_2 w^2 &= M_2^2 \cos^2\theta + M_1^2 \sin^2\theta. \\ tan2\theta &= -\frac{\delta v\omega}{\lambda_1 v^2 - \lambda_2 \omega^2} \end{aligned} \tag{6}$$

We can take the physical masses $M_{1,2}^2$, the mixing angle θ, and the ratio of two vacuum expectation values characterizing the violation of the $SU(2) \otimes U(1)$ and global symmetries,

$$\tan\beta = \frac{v}{w} \tag{7}$$

as our four independent parameters. In terms of these all the relevant couplings, Higgs boson production cross sections and decay rates can be fixed.

This completes the discussion on the Higgs boson spectrum and couplings in this simplest scheme. Note that there are no physical charged Higgs bosons in this case. In more complicated models, e.g. supersymmetric ones [14], there may exist also massive CP-odd scalar bosons, as well as electrically charged bosons. For simplicity we will not consider this case in what follows.

3 Higgs Production and Decay

The Higgs boson can be produced at the e^+e^- collider through its couplings to Z. In the simplest prototype model sketched above only the doublet Higgs boson ϕ has a coupling to the Z in the weak basis, not the $SU(2) \otimes U(1)$ singlet field σ. After diagonalizing the scalar boson mass matrix one finds that the two CP even mass eigenstates H_i (i=1,2) have couplings to the Z, involving the mixing angle θ. These couplings may be given as follows

$$\mathcal{L}_{HZZ} = (\sqrt{2}G_F)^{1/2} M_Z^2 Z_\mu Z^\mu \hat{O}_{i1} H_i \tag{8}$$

Through these couplings both CP even Higgs bosons may be produced through the Bjorken process. As long as the mixing appearing in eq. (8) is $\mathcal{O}$ (1), all Higgs bosons can have significant production rates, but always smaller than in the standard model. For example, if only the light field H_1 is below the Z boson mass, only this one will be produced, with a rate $cos^2\theta$ smaller than in the standard model .

We now turn to the Higgs boson decay rates, which are sensitive to the details of the mass spectrum and Higgs potential. For definiteness we focus on the simplest potential, given in eq. (3). In this case the coupling of H_i to the majoron J can be written in the following way:

$$\mathcal{L}_J = \frac{(\sqrt{2}G_F)^{1/2}}{2} \tan\beta [M_2^2 cos\theta H_2 - M_1^2 sin\theta H_1] J^2 \tag{9}$$

The width for the invisible H_i decay can be parametrized by

$$\Gamma(H \to JJ) = \frac{\sqrt{2}G_F}{32\pi} M_{H_i}^3 g_{H_iJJ}^2 \tag{10}$$

where the corresponding couplings are given by

$$g_{H_iJJ} = tan\beta \quad \hat{O}_{i2} \tag{11}$$

The rate for $H \to b\bar{b}$ also gets diluted compared to the standard model prediction, because of the mixing effects. Explicitly one has,

$$\Gamma(H \to b\bar{b}) = \frac{3\sqrt{2}G_F}{8\pi} M_H m_b^2 (1 - 4m_b^2/M_H^2)^{3/2} g_{Hb\bar{b}}^2 \tag{12}$$

which is smaller than th standard model prediction by the factor $g_{H_ib\bar{b}}$, where

$$g_{H_ib\bar{b}} = \hat{O}_{i1} \tag{13}$$

The width of the Higgs decay to the JJ relative to the conventional $b\bar{b}$ mode depends upon the mixing angles. There are, in principle, three cases to consider: (i)

$\omega \approx v$, (ii) $\omega \gg v$ and (iii) $\omega \ll v$. In the first case, one can see from eq. (6) that the mixing among the doublet and singlet field can be substantial if the parameters of the quartic terms in the Higgs potential are of comparable magnitude. As a result, the production as well as the invisible decay of both physical Higgs bosons H_i can be important. In this case we have

$$\begin{aligned}\frac{\Gamma(H_1 \to JJ)}{\Gamma(H_1 \to b\bar{b})} &= \frac{1}{12}\left(\frac{M_1}{m_b}\right)^2 (1 - 4m_b^2/M_1^2)^{-3/2}(tan\beta\, tan\theta)^2 \\ &\approx 8\left(\frac{M_1}{50GeV}\right)^2 (tan\beta\, tan\theta)^2 \qquad (14)\end{aligned}$$

A similar expression with $\tan\theta$ replaced by $\cot\theta$ holds in case of H_2. It is clear that a Higgs boson with $M_H > 50$ GeV decays mostly invisibly if $\tan\beta$ and $\tan\theta$ are $\mathcal{O}$ (1). The production of $H_1(H_2)$ gets diluted compared to the standard model prediction by $cos^2\theta$ ($\sin^2\theta$).

If ω and v are very different from each other then the mixing angle in eq. (6) is very small. Hence in cases (ii) and (iii), only the predominantly doublet component (H_1) will be produced. Using eq. (6) in the basic majoron coupling, eq. (9), one finds that if $\omega \gg v$ then mostly the singlet Higgs boson which decays to two majorons. But its production rate is, of course, negligible. In contrast, for the other case, $\omega \ll v$, the doublet Higgs field mainly decays to majorons and is produced without any substantial suppression relative to the standard model predictions.

In summary, the invisible Higgs decay mode is expected to have quite important implications if there exists, as suggested by neutrino physics, a global symmetry that gets broken around or below the weak scale, not too much above. From this point of view it is therefore desirable to obtain limits on Higgs bosons that are not vitiated by detailed assumptions on its mode of decay.

4 LEP I Limits

The production and subsequent decay of any Higgs boson which may decay visibly or invisibly involves three independent paramenters: the Higgs boson mass M_H, its coupling strength to the Z, normalized by that of the standard model , we call this factor ϵ^2, and the invisible Higgs boson decay branching ratio.

We have used the results published by the LEP experiments on the searches for various exotic channels in order to deduce the regions in the parameter space of the model that can be ruled out already. The procedure was the following. For each value of the Higgs mass, we calculated the lower bound on ϵ^2, as a function of the branching ratio $BR(H \rightarrow \text{visible})$. By taking the highest such bound for $BR(H \rightarrow \text{visible})$ in the range between 0 and 1, we obtained the absolute bound on ϵ^2 as a function of M_H.

For a Higgs of low mass (below 30 GeV) decaying to invisible particles we considered the process $Z \rightarrow HZ^*$, with $Z^* \rightarrow e^+e^-$ or $Z^* \rightarrow \mu^+\mu^-$ and combined the results of the LEP experiments on the search for acoplanar lepton pairs [18, 19, 20] which found no candidates in a total sample corresponding to 780.000 hadronic Z decays. The efficiencies for the detection of the signal range from 20% at very low Higgs masses to almost 50% for $M_H = 25$ GeV.

For higher Higgs masses the rate of the process used above is too small, and we considered instead the channel $Z \rightarrow HZ^*$, $Z^* \rightarrow q\bar{q}$. Here we translated the results of the searches for the Standard Model Higgs in the channel $Z \rightarrow Z^* H_{SM}$, with $H_{SM} \rightarrow q\bar{q}$ and $Z \rightarrow \nu\bar{\nu}$, following ref. [21]. The efficiency of these searches for an invisible Higgs increases from 25% at $M_H = 30$ GeV to about 50% at $M_H = 50$ GeV.

For visible decays of the Higgs boson its signature is the same as that of the Standard Model one, and the searches for this particle can be applied directly. For masses below 12 GeV we have taken the results of a model independent analysis made by the L3 collaboration (ref. [22]). For masses between 12 and 35 GeV we combined the results from references [18, 21, 22]; finally for masses up to 60 GeV we used the combined result of all the four LEP experiments given in reference [21]. In all cases the bound on the ratio $BR(Z \rightarrow ZH)/BR(Z \rightarrow ZH_{SM})$ was calculated from the quoted sensitivity, taking into account the background events where they existed.

As an illustration we show in Figure 1 the exclusion contours in the plane ϵ^2 vs. $BR(H \rightarrow \text{visible})$ for the particular choice for the Higgs mass $M_H = 50$ GeV. The two curves corresponding to the searches for visible and invisible decays are combined to give the final bound; values of ϵ^2 above 0.2 are ruled out independently of the value of $BR(H \to \text{visible})$. The solid line in Figure 2 shows the region in the ϵ^2 vs. M_H that can be excluded by the present LEP analyses, independent of the mode of Higgs decay, visible or invisible.

5 Prospects for LEPII

We have also estimated the additional range of parameters that can be covered by LEPII. We assumed that the total luminosity collected will be 500 pb^{-1}, and give the results for two values of the centre-of-mass energy: 175 GeV and 190 GeV.

Our results on the visible decays of the Higgs are based on the study of efficiencies and backgrounds in the search for the Standard Model Higgs described in reference [24]. For the invisible decays of the Higgs we considered only the channel HZ with $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$, giving a signature of two leptons plus missing transverse momentum. The requirement that the invariant mass of the two leptons must be close to the Z mass can kill most of the background from WW and $\gamma\gamma$ events; the background from ZZ events with one of the Z decaying to neutrinos is small and the measurement of the mass recoiling against the two leptons allows to further reduce it, at least for M_H not too close to M_Z. Hadronic decays of the Z were not considered, since the background from WW and $We\nu$ events is very large, and b-tagging is much less useful than in the search for ZH_{SM} with $Z \to \nu\bar{\nu}$, since the $Zb\bar{b}$ branching ratio is much smaller than $Hb\bar{b}$ in the standard model.

The dashed and dotted curves on figure 2 show the exclusion contours in the ϵ^2 vs. M_H plane that can be explored at LEPII, for the given centre-of-mass energies. Again, these contours are valid irrespective of whether the Higgs decays visibly, as in the standard model , or invisibly.

6 Discussion

The Higgs can decay to a pair of invisible massless Goldstone bosons in a wide class of models in which a global symmetry, such as lepton number, is broken spontaneously around or below the weak scale. These models are attractive from the point of view of neutrino physics and suggest the need to search for the Higgs boson in the invisible mode.

We have presented *model independent limits* on the Higgs boson mass and HZZ coupling strength that can be deduced from the present LEP samples. Our limits combine three final-state searches and are summarized in figures 1 and 2. These limits do not depend on the mode of Higgs boson decay. They are probably conservative and could still be somewhat improved with more data and/or more refined analysis. They apply to a very wide class of extensions of the standard model , including many models where neutrinos acquire mass as a result of the spontaneous violation of lepton number around or below the weak scale. Other global symmetries, such as the Peccei-Quinn symmetry, are not relevant in this context. Moreover, we mention that there are other ways to engender invisible Higgs decays, e.g. in the minimal supersymmetric standard model , in which the Higgs boson may decay as $H \to \chi\chi$ where χ is the lightest neutralino. This would require $2m_\chi < M_H$.

Apart from the invisible Higgs boson decay, the possible validity of these majoron schemes may have important consequences for the physics of neutrinos and weak interactions [4, 25].

The possibility of invisible Higgs decay is also very interesting from the point of view of a linear e^+e^- collider at higher energy [26]. Heavier, intermediate-mass, Higgs bosons can also be searched at high energy hadron supercolliders such as LHC/SSC [27, 28]. The limits from LEP derived in this paper should serve as useful guidance for such future searches.

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Figure Captions

Figure 1

Figure 1 gives shows the exclusion contours in the plane ϵ^2 vs. $BR(H \rightarrow \text{visible})$ for the particular choice $m_H = 50$ GeV. The two curves corresponding to the searches for visible (curve A) and invisible (curve B) decays are combined to give the final bound, which holds irrespective of the value of $BR(H \rightarrow \text{visible})$.

Figure 2

The solid curve shows the region in the ϵ^2 vs. m_H that can be excluded by the present LEP analyses, independent of the mode of Higgs decay, visible or invisible. The dashed and dotted curves on figure 2 show the exclusion contours in the ϵ^2 vs m_H plane that can be explored at LEPII, for the given centre-of-mass energies.

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