TIFR-TH-93-26
PRL-TH-93/9
May 1993

Mass Limits of Invisibly Decaying Higgs Particles from the LEP Data

Biswajoy Brahmachari, Anjan S. Joshipura, Saurabh D. Rindani

Theory Group, Physical Research Laboratory
Navrangpura, Ahmedabad 380 009, India

D.P. Roy

Theory Group, Tata Institute of Fundamental Research
Homi Bhabha Road, Bombay 400 005, India

Sridhar K.

Theory Division, CERN, CH 1211 Geneva 23, Switzerland

Abstract

In the Majoron models the $SU(2)$ doublet Higgs can decay invisibly into a Majoron pair via its mixing with a singlet. An analysis of the LEP data shows the invisible decay mode to be more visible than the SM decay. For these models, the dominantly doublet Higgs H is shown to have a mass limit within ± 6 GeV of the SM limit irrespective of the model parameters. But the dominantly singlet one S can be arbitrarily light for sufficiently small mixing angle.

The e^+e^- collider LEP at CERN has helped in establishing many of the crucial aspects of the standard model (SM). It has however not yet found the Higgs boson which plays a key role in the breaking of the $SU(2) \times U(1)$ invariance of SM. The latest limit [1] on its mass M_H coming from the recent LEP data is nearly 60 GeV.

The published ALEPH data from LEP have also been used to constrain parameters of extensions of SM [2]. Many extensions such as multi-Higgs or supersymmetric models [3] contain additional Higgs doublets which change the couplings of the SM Higgs to the Z and fermions through mixing. This results in somewhat relaxed limits on the Higgs mass [2] compared to SM. There exists some extensions which are however qualitatively different. These extensions, to be generically called Majoron models [4], are characterized by the presence of a Goldstone boson. The couplings of this Goldstone boson to the Higgs are not required in these models to be small on any theoretical or phenomenological grounds. As a consequence, the physical Higgs could decay into an invisible channel containing a Majoron pair [5-8]. Although the importance of extending the Higgs search at LEP to the invisible decay channel has been repeatedly emphasised over the past decade [5-8], there has been no quantitative effort in this direction so far. The present work is devoted to this exercise. We analyse the published ALEPH data [2] for the invisible as well as the SM decay modes of a Higgs particle using a parton level MC event generator. The missing energy channels with 1 or 2 jets which are the most viable channels for the SM Higgs search, are seen to be even more viable for the invisibly decaying Higgs particle. Thus the data gives even stronger Higgs mass limits in the latter case compared to the former, as we shall see below.

The key features shared by all the Majoron models MM [4-11] is a spontaneously broken global $U(1)$ symmetry and a complex $SU(2) \times U(1)$ singlet scalar field η transforming non-trivially under the global $U(1)$ [14]. This $U(1)$ could have different physical meanings in different models, e.g., total lepton number [4], combination of lepton numbers [9], or a more general family symmetry [10]. Moreover, the model may contain more than one Higgs doublet [11], Higgs triplets [6,13], or more singlets as in the supersymmetric model with spontaneous R parity breaking [8]. But irrespective of these details, all models will contain at least one more real scalar ($\eta_R \equiv \mathrm{Re}\ \eta/\sqrt{2}$) mixing with the neutral component ϕ_R of the conventional Higgs doublet. In the simplest case of only one doublet and one singlet, the physical states are given by

$$H = \cos\theta \phi_R + \sin\theta \eta_R \tag{1}$$

$$S = -\sin\theta\phi_R + \cos\theta\eta_R, \tag{2}$$

where θ is a mixing angle. Without any loss of generality θ can be chosen to lie in the range $0 - 45°$. With this choice H and S have dominant doublet and singlet components respectively. We shall follow this choice.

The spontaneous breaking of the global $U(1)$ generates a Majoron $J \equiv \mathrm{Im}\ \eta/\sqrt{2}$ in all the above models. This gets coupled to massive Higgs through a quartic term $\delta\ \phi^\dagger\phi\ \eta^\dagger\eta$ in the scalar potential. Such a coupling cannot be easily forbidden by any symmetry [15] and leads to the decays $H \to JJ$ and $S \to JJ$ which dominate over the conventional $H \to b\bar{b}$ and $S \to b\bar{b}$ decays for a large range in the relevant parameters [5]. Thus the Higgs bosons in these models are expected to decay dominantly into an invisible channel and the experimental search should take this channel into account [16].

The SM Higgs is assumed to be produced at LEP through the Bjorken process $e^+e^- \to Z^*H \to f\overline{f}H$ [3] and is searched for [1,2] by means of the signals (A) l^+l^- + one or two jets, and (B) one or two jets + missing energy. The signal in (A) would be produced by $Z^* \to l\bar{l}, H \to b\bar{b}$, while (B) is generated when $Z^* \to \nu\overline{\nu}$ and $H \to b\bar{b}$. In Majoron models, the signal in (A) is expected to get diluted [5,11] due to a considerable reduction in the branching ratio for $H \to f\overline{f}$. A similar dilution would also occur in (B), but in this case a new mode namely $Z^* \to q\overline{q}$ and $H \to JJ$ also contribute to the same signal. Indeed this new mode more than compensates for the loss of the SM decay signals, thanks to the larger branching fraction of $Z^\star \to q\overline{q}$ relative to $\nu\overline{\nu}$ and $\ell\overline{\ell}$. In the following, we derive general limits on the Higgs masses including both the contributions (A) and (B).

The spin averaged matrix element square for the Bjorken process in the SM is

$$|\overline{M}|^2_{e^+e^-\to Z^\star H\to f\overline{f}H} = \frac{2(4\pi\alpha)^3 M_Z^2 C_f}{\sin^6\theta_W \cos^6\theta_W} \left[\frac{C_1(p_+\cdot q_-)(p_-\cdot q_+) + C_2(p_+\cdot q_+)(p_-\cdot q_-)}{\{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2\}\{(s_1-M_Z^2) + M_Z^2\Gamma_Z^2\}}\right] \tag{3}$$

with

$$C_{1,2} = (C_V^{e^2} + C_A^{e^2})(C_V^{f^2} + C_A^{f^2}) \pm 4C_V^e C_A^e C_V^f C_A^f, \tag{4}$$

where $p_\pm$ and $q_\pm$ are the $e^\pm$ and $\overline{f}, f$ momenta; and s_1 stands for the virtual $Z^\star$ mass. The colour factor C_f is 3(1) for quarks (leptons); and the vector and axial-vector couplings are defined in terms of the weak isospin T_3 and electric charge Q as

$$C_V^f = T_3^f - 2Q^f \sin^2\theta_W, \quad C_A^f = T_3^f. \tag{5}$$

For the massive b quark there is an additional term in the numerator of the square bracket of (3), i.e.

$$m_b^2(C_V^{e^2} + C_A^{e^2})\Big\{(C_V^{b^2} - C_A^{b^2})\tfrac{s}{2} + C_A^{b^2}\tfrac{(s_1-2M_Z^2)}{M_Z^4}\cdot \\ \cdot(2p_+\cdot(q_+ + q_-)p_-\cdot(q_+ + q_-) - ss_1/2)\Big\} \tag{3a}$$

Due to mixing, eqs.(1-2), the production of $H(S)$ will be reduced by $\cos^2\theta$ ($\sin^2\theta$) compared to eq.(3). Eq.(3) can be used to obtain the expected number of events consistent with the experimental cuts imposed to reduce the background.

We shall work with the published ALEPH data [2], because this is the only LEP data we could find which explicitly describes all the experimental cuts. This will be required for our quantitative MC analysis. The data sample corresponds to a little over 185000 hadronic Z events, spread over a CM energy range of 88.2 – 94.2 GeV at intervals of 1 GeV. The expected number of events for the Bjorken process (3) at each energy is obtained by multiplying the corresponding number of hadronic Z events by the ratio of the two cross-sections. Thus the effect of initial state radiation factors out from the normalisation [17]. What remains unaccounted for is a slight reduction of the final state particle ($Hf\overline{f}$) momenta due to the ISR. This is negligible for our purpose, however, since only 2% of the LEP events have an ISR photon energy exceeding 2 GeV [18].

The dominant channels for the Higgs signal in the SM ($HZ^\star \to b\overline{b}\nu\overline{\nu}$) as well as the Majoron models MM ($HZ^\star \to JJq\overline{q}$) are the missing energy channels containing 1 or 2 jets. Therefore we shall concentrate on the experimental data and cuts of ALEPH [2] in these channels. The two channels are separated by defining two hemispheres with respect to the thrust axis. Events with total energy deposit < 2 GeV in one of the hemispheres constitute the 1) monojet channel while the remainder constitute the 2) acoplanar jets channel.

Since the 2nd channel dominates the signal for most of the Higgs mass range, let us discuss it in some detail. In our parton level MC simulation it corresponds to events, where the angle between the two quarks $\theta_{jj} > 90^\circ$ and the softer quark has an energy > 2 GeV. Table I summarises the effects of the ALEPH cuts on a 50 GeV Higgs signal for the SM and MM decays. The corresponding results for the ALEPH simulation of a 50 GeV SM Higgs signal are also shown along with their data. To start with, the missing energy $\not{E}$ cut is implimented through a visible mass cut $M_{jj} < 70$ GeV. The low angle cut requires the energy coming out within 12° of the beam axis to be < 3 GeV and that beyond 30° of the beam axis to be $> 60\%$ of the visible energy. It removes events with jets close to the beam pipe, where measurement errors can simulate a $\not{E}$. The acollinearity cut removes the $Z \rightarrow q\overline{q}$ and $\tau^+\tau^-$ background where the $\not{E}$ can be due to fluctuation (including escaping ν) of one or both the jets. The $\tan\alpha > 4$ cut for the missing momentum $\vec{\not{p}}$, making an angle α with the beam axis, removes the $\not{E}$ background from ISR and $e^+e^- \rightarrow (e^+e^-)\gamma\gamma$ processes. The isolation cut removes $\not{E}$ background from the fluctuation of any one of the jets. The acoplanarity cut for a 3-jet like events removes that due to fluctuation of one or more of these jets. This is analogous to the acollinearity cut for the 2-jet events. The acoplanarity cut for the 2-jet events removes the $\not{E}$ background arising from ISR along with the fluctuation of one or both the jets. The remaining few events are the residual $\gamma\gamma$ events, which are removed by the total p_T cut. The last line shows that the original visible mass cut is dispensible, since all the events are removed even without it.

The cuts are seen to have no strong effect on the Higgs signal for either the SM or the MM, since they naturally simulate a large missing energy which is neither tied up to the beam nor the jet directions. Comparing our parton level MC simulation for the SM Higgs signal with the full MC simulation of ALEPH one sees an agreement to within 10% for any combination of the cuts. Since a 10% variation in the signal corresponds to a < 1 GeV charge in M_H, we expect the M_H limit from the parton level MC to be reliable to within 1 GeV. The overall efficiency factor in the two cases of course agree at the level of $\sim 2\%$. We have checked that the agreement continues to be good to $\sim 10\%$ for $M_H \geq 20$ GeV [19]. For $M_H < 20$ GeV, the $H \rightarrow \tau^+\tau^-, D\overline{D}$ decay modes become important; so that there is an appreciable loss of efficiency due to the ALEPH requirement of at least 5 good tracks. Although one could incorporate this into the parton level MC, we felt it unnecessary to extend our SM Higgs analysis to this region. Comparing the Higgs signals for the SM and MM decays one again sees that the effect of the cuts are very similar in the two cases. This is to some extent accidential; $M_H = 50$ GeV corresponds to a peak value of $M_{Z^\star} \simeq 40$ GeV, so that the decay quark jets have very similar kinematics for the two cases. At lower M_H, the efficiency factor for the MM decay is somewhat lower than the SM decay (Fig. 1). This is partly due to the 70 GeV mass cut which affects the MM decay signal as $M_{Z^\star}$ increases with decreasing M_H. For the same reason, however, the decay quark jets are expected to be hard and hence satisfy the requirement of ≥ 5 good tracks automatically. Consequently our parton level MC result should hold even at low Higgs mass for the MM decay.

Fig. 1 shows the expected number of signal events as a function of the Higgs mass for the SM and MM decays. The normalisation corresponds to the production cross-section from (3) – i.e. it corresponds to the limit $\theta \to 0$ when H becomes essentially a doublet. The event rates are shown both before and after the experimental cuts. The contributions of the two channels to the latter rate are also shown separately. As expected the SM signal is dominated by the monojet and acoplanar jets contributions at small and large M_H respectively. The MM signal is dominated by the acoplanar jets throughout the M_H range of interest; but the importance of the monojet contribution increases with increasing M_H (i.e. decreasing $M_{Z^\star}$). Comparing the SM and MM decay signals we see that the latter is larger by a factor of $2 \to 3$ for $m_H = 20 \to 50$ GeV. This is due to the larger branching fraction of $Z^\star \to q\overline{q}$ relative to $\nu\overline{\nu}$, which remains largely unaffected by the cuts. The SM decay signal can be increased a little by including contributions from other channels, notably $Z^\star \to \ell^+\ell^-$. The crosses denote the resulting signal taken from [2]. Still the size of the SM decay signal remains small relative to the MM decay. This clearly demonstrates that an invisible decay mode of a Higgs particle would be more visible at LEP compared to the SM decay. The 95% CL limits on M_H, corresponding to 3 signal events, are 48 and 54 GeV for the SM and MM decays respectively. It may be noted here that the latest M_H limit of ~ 60 GeV for the SM decay [1] would roughly correspond to a 65 GeV limit for the MM decay.

In general one expects both the SM and MM decays to occur with a relative branching ratio r say. Moreover, the physical Higgs particles H and S are expected to be combinations of the doublet and singlet fields. Thus the expected size of the Higgs signal is in general

$$\begin{aligned} N_{\rm exp} = \cos^2\theta & \left\{ N_{SM}(M_H)\tfrac{r_H}{1+r_H} + N_{MM}(M_H)\tfrac{1}{1+r_H} \right\} \\ & + \sin^2\theta \left\{ N_{SM}(M_S)\tfrac{r_S}{1+r_S} + N_{MM}(M_S)\tfrac{1}{1+r_S} \right\}, \end{aligned} \tag{6}$$

where N_{SM} and N_{MM} correspond to the crosses of Fig. 1a and the solid line of Fig. 1b respectively. One can get independent limits on M_H and M_S by assuming that only one of them contributes to the signal. These will be somewhat weaker than the joint limit of course. Fig. 2 shows the independent limits on M_H and M_S for the extreme values of $r_{H,S} = 0$ and

∞ as a functions of the mixing angle θ. Thus the 2 bands represent the lower limits of M_H and M_S over the entire parameter space. Note that the limit of M_H, representing the physical Higgs particle with larger doublet component, is remarkably stable vis a vis the SM limit. For small θ, where H is dominated by the doublet component, the limit increases from 48 to 54 GeV as the branching fraction for the MM decay increases from 0 to 1 as expected from Fig. 1. Increasing the mixing angle θ to its maximal value of 45° decreases the production rate by a factor of 2 and correspondingly the M_H limit by ~ 6 GeV. Thus

$$M_H^{\text{lim.}} = M_{SM}^{\text{lim.}} \pm 6 \text{ GeV} \tag{7}$$

for the entire parameter space. Again this correlation should hold for the recent LEP data [1] as well. The M_S limits coincide with M_H at $\theta = 45°$ as expected from (6); but goes down steadily with θ (i.e. the SZZ coupling). Thus the M_S limit goes down to ~ 10 GeV for $\theta \sim 10°$, below which there is no M_S limit from the published ALEPH data [2]. It is easy to translate this into a M_S mass limit of ~ 10 GeV for $\theta \sim 5°$ for the recent data [1]. Recently some of the above points have been discussed at a qualitative level in [20].

Finally, Fig. 3 shows the joint limit on M_H and M_S from (6) for $r_{H,S} = 0$, where the invisible decay mode dominates for both the Higgs particles. The limits are shown for 3 representative values of the mixing angle. The corresponding limits for $r_{H,S} = \infty$ are essentially given by parallel curves shifted to the left by ~ 6 GeV.

We shall conclude by relating the relative branching ratios $r_{H,S}$ to the underlying model parameters. In the simplest case discussed above, the Higgs sector of the model with ϕ and η fields contains [5] one more independent parameter, $\tan\beta \equiv \langle\phi\rangle/\langle\eta\rangle$, in addition to M_H, M_S and θ. The relative branching ratios are given by

$$r_H \approx \frac{1}{12}\left(\frac{m_b}{M_H}\right)^2 \cot^2\theta \cot^2\beta \left(1 - 4\frac{m_b^2}{M_H^2}\right)^{3/2} \tag{8}$$

$$r_S \approx \frac{1}{12}\left(\frac{m_b}{M_S}\right)^2 \tan^2\theta \cot^2\beta \left(1 - 4\frac{m_b^2}{M_S^2}\right)^{3/2} . \tag{9}$$

The actual value of θ as well as $\tan\beta$ is detemined by the scale of the global $U(1)$ breaking relative to the $SU(2) \times U(1)$ breaking scale, as well as by the quartic couplings in the Higgs potential. Typical expectations would thus be $\tan\beta \approx O(1)$ and $\cos\theta \approx O(1)$, if the two scales coincide. In the event of $\langle \eta \rangle >> \langle \phi \rangle$, $\tan \beta$ is very small and the Higgs decay to a Majoron pair is supressed. In the converse limit of $\langle \eta \rangle << \langle \phi \rangle$, the Higgs mainly decay [11] to Majoron pairs if the coefficient of the quartic term $\phi^\dagger \phi \ \eta^\dagger \eta$ in the potential is $O(1)$.

In the foregoing discussions, we have assumed that the Higgs sector of the Majoron model contains a doublet and a singlet. Some models [8,11] do require additional scalar fields either as doublets or singlets. The Higgs fields in these models will not be given by simple expressions like eqs.(1) and (2) containing only one mixing angle. The limits on the various Higgs masses would be different in these models, since the production cross sections would now be suppressed by different amounts and N_{exp} would change accordingly. But generically, one should be able to derive strong constraints in these models as well. Specifically, in the absence of large mixing angles, the limit of $M_H > 54$ would be applicable to these models as well, if Higgs decays mainly into the invisible channel.

In summary, we have considered here limits on the Higgs mass in Majoron models which contain the interesting possibility of the decay of Higgs bosons to an invisible channel. A minimal models of this type contains two Higgs scalars H and S which are predominantly $SU(2) \times U(1)$ doublet and singlet, respectively. We have shown that the LEP data imply a stringent limit on the mass of the H. Specifically, the limit on M_H could be better than in SM; and in any case it should lie within ± 6 GeV of the SM limit. In contrast, the predominantly singlet Higgs S could be even lighter than 10 GeV. We have used in this work only the published ALEPH data [2]. A similar analysis of the more recent data [1] would evidently strengthen these results [21].

B.B would like to acknowledge the hospitality and financial support of Tata Institute of Fundamental Research during the course of this work. D.P.R acknowledges discussion with T. Aziz, A. Gurtu and K. Sudhakar on the LEP data.

References

[1] J.F. Grivaz, Orsay report no. LAL 92-59 (1992).

[2] D. Decamp et al., ALEPH Collaboration, Phys. Rep. **216**, 253 (1992); CERN report CERN-PPE-91-19 (1991).

[3] J. Gunion et al., *The Higgs Hunter's Guide*, (Addison Wesley, Menlo Park, 1991)

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

[5] A.S. Joshipura and S.D. Rindani, Phys. Rev. Lett. **69**, 3269 (1992).

[6] R.E. Schrock and M. Suzuki, Phys. Lett. **10B**, 250 (1982); L.F. Li, Y. Liu and L. Wolfenstein, Phys. Lett. **159B**, 45 (1985).

[7] E.D. Carlson and L.B. Hall, Phys. Rev. **D 40** 3187 (1985); G. Jungman and M.A. Luty, Nucl. Phys. **B361**, 24 (1991).

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

[9] A.S. Joshipura and S.D. Rindani, Phys. Rev. **D 46**, 3000 (1992).

[10] F. Wilczek, Phys. Rev. Lett. **49**, 1549 (1982); D.B. Reiss, Phys. Lett. **115B**. 217 (1982).

[11] A.S. Joshipura and J.W.F. Valle, CERN report CERN-TH. 6652/92, Nucl. Phys. B (to be published).

[12] G. Gelmini and M. Roncadelli, Phys. Lett. **B99**, 411 (1981).

[13] A.S. Joshipura, Int. J. Mod. Phys. **A7**, 2021 (1992); K. Choi and S. Santamaria, Phys. Lett. **B267**, 504 (1991).

[14] The triplet Majoron model [12] is an exception to this. But this by itself is ruled out by the LEP data on invisible Z width unless an additional singlet [13] is added.

[15] This is not true in the supersymmetric extension of the singlet Majoron model where this coupling is forbidden by the combined requirement of supersymmetry and lepton number conservation.

[16] The same considerations hold even if the global symmetry is larger than $U(1)$, as e.g. the dark Higgs model of Bjorken. J.D. Bjorken, Invited talk at the Symp. on the SSC Laboratory, Corpus Chrisli, Texas, 13-17 Oct. 1991, SLAC-PUB-5673 (1991).

[17] F.A. Berends and R. Kleiss, Nucl. Phys. **B260**, 32 (1985).

[18] A more detailed MC analysis including ISR along with jet fragmentation and covering the recent L3 data is in progress. A. Gurtu, K. Sudhakar and D.P. Roy (work in progress).

[19] One can easily check this by comparing the solid line of Fig. 1a) with the corresponding curve of ref. [2].

[20] A. Lopez-Fernandez et al., Valencia Preprint FTUV/93-19, April 1993.

[21] On completion of this work came to learn that the ALEPH group is finalising the analysis of the full data sample in terms of an invisibly decaying Higgs signal. A part of their preliminary result has been reported in "Searches for Signals of Supersymmetry", by J.F. Grivaz, Invited talk at the XXVIIIth Recontre de Moriond, 13-20 March 1993, Orsay preprint LAL 93-11, April 1993. We are grateful to Prof. Grivaz for this information.

Table I. Effect of ALEPH cuts in the acoplanar jets channel on the parton level MC simulation of a 50 GeV Higgs signal for the Standard Model and Majoron Model (Invisible Decay). The corresponding results for the ALEPH simulation of a 50 GeV SM Higgs signal are also shown along with their Data.

Cut	Data No. of Events	Efficiency (%) SM (ALEPH)	of a 50 GeV SM	Higgs signal MM
Mass Cut $M_{\text{vis.}} < 70$ GeV	11,865	99.4	100	100
Low Angle Cut $E_{12} < 3$ GeV, $E^{30} < .6E_{\text{vis.}}$	5,018	90.4	81	77
Acollinearity $\theta_{jj} < 165°$	305	83.2	72	71
Low Angle Cut for $\vec{\not{p}}$ Tan $\alpha > .4$	155	78.8	70	69.5
Isolation of $\vec{\not{p}}$ $E_{\text{cone}} < 3$ GeV	73	75.1	70	68.6
Acoplanarity for 3 jet events $S = \sum_{i=1}^{3} \theta_i < 350°$ if $\theta_i^{\min} > 40°$	19	71.2	70	68.6
Acoplanarity $\phi_{jj} < 175°$	7	67.7	66.5	66.4
$\gamma\gamma$ Bg. Cut $\lvert \sum \vec{p_T} \rvert > .05E_{CM}$ if $M_{\text{vis}} < 25$ GeV	0	67.7	66.5	66.4
Without Mass Cut	0	67.8	66.5	66.4

Figure Captions

Fig. 1. The expected Higgs signals for the SM and MM (invisible) decay modes corresponding to the published ALEPH data [2].

Fig. 2. Mass limits for H and S shown as functions of the mixing angle for the two limits corresponding to predominant MM ($r = 0$) and SM ($r = \infty$) decays.

Fig. 3. Joint mass limit for H and S shown for $r_{H,S} = 0$ and 3 representative values of the mixing angle θ. The region to the right of the curves are allowed.