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LOOKING FOR INVISIBLY DECAYING HIGGS BOSONS THROUGH THE FINAL STATE $b\bar{b} + \not{p}_T$ [1]

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We study the potential of LEP II to unravel the existence of invisibly decaying Higgs bosons through the reaction $e^+e^- \to b\bar{b} + \not{p}_T$. We perform our analyses in a model independent way and our results show that LEP II is capable of discovering such a Higgs for a wide range of masses and couplings.

There are a variety of well motivated extensions of the standard model (SM) with an spontaneously broken global symmetry. This symmetry could be either be lepton number or a combination of family lepton numbers [1, 2]. These models are characterised by a more complex symmetry breaking sector which contain additional Higgs bosons. It is specially interesting for our purposes to consider models where such symmetry is broken at the electroweak scale [3, 4]. In general, these models contain a massless Goldstone boson, called majoron (J), which interacts very weakly with normal matter. In such models, the normal doublet Higgs is expected to have sizeable invisible decay modes to the majoron, due to the strong Higgs majoron coupling. This can have a significant effect on the Higgs phenomenology at LEP II. In particular, the invisible decay could contribute to the signal of two acoplanar jets and missing momentum. This feature of majoron models allows one to strongly constrain the Higgs mass in spite of the occurrence of extra parameters compared to the SM. In particular, the LEP I limit on the predominantly doublet Higgs mass is close to the SM limit irrespective of the decay mode of the Higgs boson [5, 6].

In this work we consider a model containing two Higgs doublets ($\phi_{1,2}$) and a singlet (σ) under the $SU(2)_L \times U(1)_Y$ group. The singlet Higgs field carries a non-vanishing $U(1)_L$ charge,

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which could be lepton number. Here we only need to specify the scalar potential of the model:

$$\begin{aligned} V &= \mu_i^2\phi_i^\dagger\phi_i + \mu_\sigma^2\sigma^\dagger\sigma + \lambda_i(\phi_i^\dagger\phi_i)^2 + \lambda_3(\sigma^\dagger\sigma)^2 + \\ & \lambda_{12}(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_{13}(\phi_1^\dagger\phi_1)(\sigma^\dagger\sigma) + \lambda_{23}(\phi_2^\dagger\phi_2)(\sigma^\dagger\sigma) \\ & +\delta(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\kappa[(\phi_1^\dagger\phi_2)^2 + \ h.\ c.] \end{aligned} \tag{1}$$

where the sum over repeated indices i=1,2 is assumed.

Minimisation of the above potential leads to the spontaneous $SU(2)_L \times U(1)_Y \times U(1)_L$ symmetry breaking and allows us to identify a total of three massive CP even scalars H_i (i=1,2,3), plus a massive pseudoscalar A and the massless majoron J. We assume that at the LEP II energies only three Higgs particles can be produced: the lightest CP-even scalar h, the CP-odd massive scalar A, and the massless majoron J. Notwithstanding, our analyses is also valid for the situation where the Higgs boson A is absent [7], which can be obtained by setting the couplings of this field to zero.

At LEP II, the main production mechanisms of invisible Higgs bosons are the Bjorken process ($e^+e^- \to hZ$) and the associated production of Higgs bosons pairs ($e^+e^- \to Ah$), which rely upon the couplings hZZ and hAZ respectively. The important feature of the above model is that, because of its singlet nature, the majoron is not size-ably coupled to the gauge bosons and cannot be produced directly, therefore, thereby evading strong LEP I constraints. The hZZ and hAZ couplings depend on the model parameters via the appropriate mixing angles, but they can be effectively expressed in terms of the two parameters ϵ_A, ϵ_B:

$$\mathcal{L}_{hZZ} = \epsilon_B \left(\sqrt{2}G_F\right)^{1/2} M_Z^2 Z_\mu Z^\mu h \tag{2}$$

$$\mathcal{L}_{hAZ} = -\epsilon_A \frac{g}{\cos\theta_W} Z^\mu h \overleftrightarrow{\partial_\mu} A \tag{3}$$

The couplings $\epsilon_{A(B)}$ are model dependent. For instance, the SM Higgs sector has $\epsilon_A = 0$ and $\epsilon_B = 1$, while a majoron model with one doublet and one singlet leads to $\epsilon_A = 0$ and $\epsilon_B^2 \leq 1$.

The signatures of the Bjorken process and the associated production depend upon the allowed decay modes of the Higgs bosons h and A. For Higgs boson masses m_h accessible at LEP II energies the main decay modes for the CP-even state h are $b\bar{b}$ and JJ. We treat the branching fraction B for $h \to JJ$ as a free parameter. In most models B is basically unconstrained and can vary from 0 to 1. Moreover, we also assume that, as it happens in the simplest models, the branching fraction for $A \to b\bar{b}$ is nearly one, and the invisible A decay modes $A \to hJ$, $A \to JJJ$ do not exist (although CP-allowed). Therefore our analysis depends finally upon five parameters: M_h, M_A, ϵ_A, ϵ_B, and B. This parameterisation is quite general and very useful from the experimental point of view: limits on M_h, M_A, ϵ_A, ϵ_B, and B can be later translated into bounds on the parameter space of many specific models.

The parameters defining our general parametrisation can be constrained by the LEP I data. In fact, Refs. [5, 8] analyse some signals for invisible decaying Higgs bosons, and conclude that LEP I excludes M_h up to 60 GeV provided that $\epsilon_B > 0.4$.

The $\bar{b}b + \not{p}_T$ topology is our main subject of investigation and we evaluate carefully signals and backgrounds, choosing the cuts that enhance the signal over the backgrounds. Our goal is to evaluate the limits on M_h, M_A, ϵ_A, ϵ_B, and B that can be obtained at LEP II from this final state. There are three sources of signal events with the topology $\not{p}_T$+ 2 b-jets: one due to the associated production and two due to the Bjorken mechanism.

$$e^+e^- \quad \to (Z \to b\bar{b}) \; + \; (h \to JJ) \tag{4}$$
$$e^+e^- \quad \to (Z \to \nu\bar{\nu}) \; + \; (h \to b\bar{b}) \tag{5}$$
$$e^+e^- \quad \to (A \to b\bar{b}) \; + \; (h \to JJ) \, . \tag{6}$$

The signature of this final state is the presence of two jets containing b quarks and missing momentum ($\not{p}_T$). It is interesting to notice that for light M_h and M_A, the associated production dominates over the Bjorken mechanism [8].

There are several sources of background for this topology:

$$e^+e^- \quad \to Z/\gamma \; Z/\gamma \to q\bar{q} \; \nu\bar{\nu} \tag{7}$$
$$e^+e^- \quad \to (e^+e^-)\gamma\gamma \to [e^+e^-]q\bar{q} \tag{8}$$
$$e^+e^- \quad \to Z^*/\gamma^* \; \to q\bar{q}[n\gamma] \tag{9}$$
$$e^+e^- \quad \to W^+W^- \to q\bar{q}' \; [\ell]\nu \tag{10}$$
$$e^+e^- \quad \to W[e]\nu \to q\bar{q}' \; [e]\nu \tag{11}$$
$$e^+e^- \quad \to Z\nu\bar{\nu} \to q\bar{q} \; \nu\bar{\nu} \tag{12}$$

where the particles in square brackets escape undetected and the jet originating from the quark q is identified (misidentified) as being a b-jet.

At this point the simplest and most efficient way to improve the signal-over-background ratio is to use that the Higgs bosons A and h decays lead to jets containing b-quarks. So we require that the events contain two b-tagged jets. Moreover, the background can be further reduced requiring a large $\not{p}_T$. Having these facts in mind we impose the following set of cuts, based on the ones used by the DELPHI collaboration for the SM Higgs boson search [9]:

1. Charged multiplicity cut. We require that the event should contain more than 8 charged particles. With this cut we eliminate potential backgrounds from the production of $\tau^+\tau^-$ pairs.

2. Missing momentum cuts. We require:

   - The z component of the missing momentum to be smaller than $0.15 \times \sqrt{s}$.
   - The absolute value of cosine of the polar angle of the missing momentum to be less than 0.9.
   - The transversal component of missing momentum $\not{p}_T$ should be bigger than 25 GeV for $\sqrt{s} = 175$ and 190 GeV and 30 GeV for $\sqrt{s} = 205$ GeV.

3. Acolinearity cut. The cosine of the angle between the axes of the two most energetic jets is required to be above -0.8. This is equivalent to the requirement that the angle between the axes is smaller than 145°.

4. Scaled acoplanarity cut. The scaled acoplanarity is computed as the complement of the angle in the perpendicular plane to the beam pipe between the total momenta in the two thrust hemispheres, multiplied by min $\{\sin\theta_{jet\ 1}, \sin\theta_{jet\ 2},\}$ in order to remove instability at low polar jet angles [9]. Scaled acoplanarity is required to be greater than $7°$.

5. Thrust/number of jets cut. We require the event thrust to be bigger than 0.8. For the intermediate visibly decaying Higgs boson masses in the range $45 - 80$ GeV this cut gives relatively small signal efficiency. For this mass range instead of the thrust cut we demand that the two most energetic jets should carry more than 85% of the visible energy.

6. Invariant mass cut. We assume that the visible mass should be in the range $M \pm 10$ GeV, where M is the mass of the visibly decaying particle (Z, h, or A).

7. b-tagging cut. We adopt the efficiencies for the b-tagging directly from the DELPHI note [9]: 68% efficiency for the signal and the appropriate values for the backgrounds extracted from Table 5 of ref. [9].

Depending on the h and A mass ranges, including or excluding the invariant mass cut gives better or weaker limits on the ZhA and ZZh couplings. Therefore, for each mass combination four limits are calculated (with or without invariant mass cut, with thrust cut or the cut on the minimal two-jet energy) and the best limit is kept.

We denote the number of signal events for the three production processes (4 – 6), after imposing all cuts, N_{JJ}, N_{SM}, and N_A respectively, assuming that $\epsilon_A = \epsilon_B = 1$. Then the expected number of signal events when we take into account couplings and branching ratios is

$$N_{exp} = \epsilon_B^2 \left[B N_{JJ} + (1 - B) N_{SM} \right] + \epsilon_A^2 B N_A \ . \tag{13}$$

In general, this topology is dominated by the associated production, provided it is not suppressed by small couplings ϵ_A or phase space. The most important background after the cuts is (7). The total numbers of background events summed over all relevant channels are 2.3, 2.8 and 5.9 for $\sqrt{s} = 175$, 190 and 205 GeV respectively.

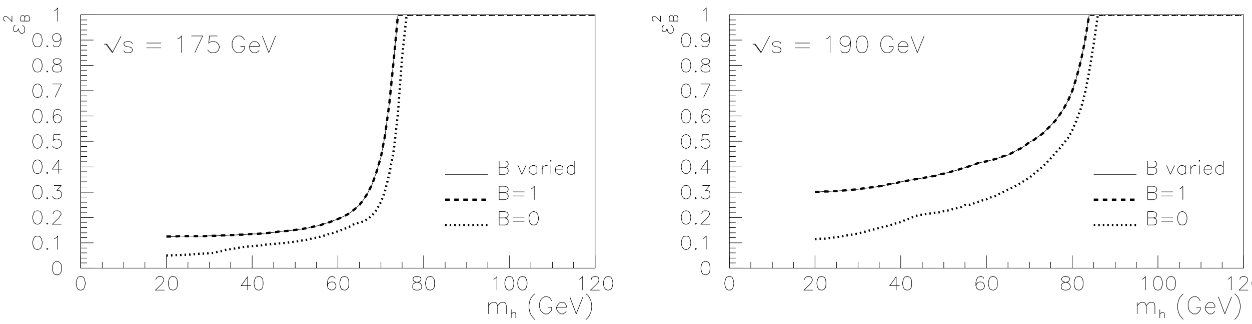

Figure 1: Limits on ϵ_B^2 as a function of M_h for $\sqrt{s} = 175, 190$ GeV and for different values of $B = Br(h \to JJ)$

In order to obtain the limits shown in Figs. 1-2, we assumed that only the background events are observed, and we evaluated the 95 % CL region of the parameter space that can be excluded with this result. By taking the weakest bound, as we vary B, we obtained the absolute bounds on ϵ_A and ϵ_B independent of the h decay mode. The limits on ϵ_A obtained by searches for the $b\bar{b}\ +\ \not{p}_T$ final states are stronger than those given by the $b\bar{b}b\bar{b}$ topology. The bounds on ϵ_B apply directly also for the simplest model of invisibly decaying Higgs bosons, where just one singlet is added to the SM. A more complete presentation of these results will be given in ref. [10].

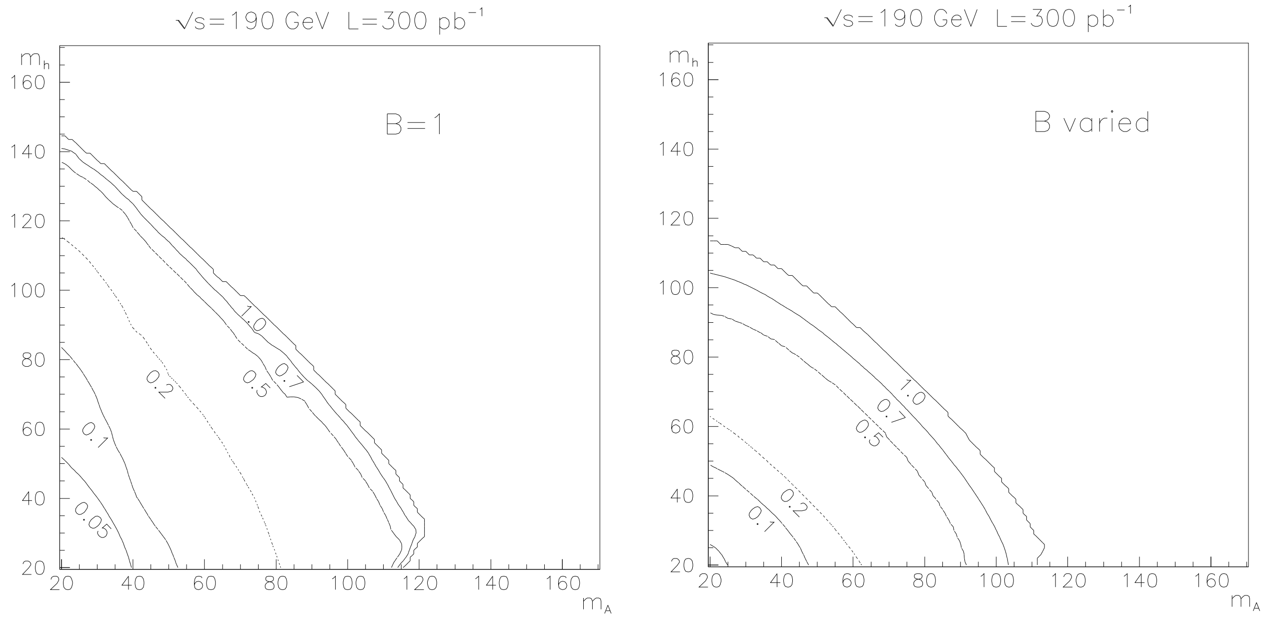

Figure 2: Limits on ϵ_A^2 as a function of M_h, M_A for $\sqrt{s} = 190$ GeV. The left plot shows the limits obtained for $B = Br(h \to JJ) = 1$, in the right plot B is varied from 0 to 1.

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