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Search for a Light Higgs Boson in the Yukawa Process

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Abstract

The Yukawa process $e^+e^- \to f\bar{f}$ h/A, where f is a tau lepton or a b quark, is used to search for light scalar or pseudoscalar Higgs bosons in the framework of general two-Higgs-doublet models. The analysis is based on the data sample collected by the ALEPH experiment at LEP at centre-of-mass energies at and around the Z peak. Since no deviation from the standard model expectations has been observed in the data, this search results in a new 95% C.L. excluded region of the $(m_A, \tan\beta)$ plane in any two-Higgs-doublet model.

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1 Introduction

In any two-Higgs-doublet model, the Higgs boson spectrum consists of two CP-even Higgs bosons h and H, a CP-odd A and a pair of charged scalars H^+H^-. Three reactions can in principle contribute to the Higgs boson production:

- the Higgs-strahlung process $e^+e^- \to hZ^*$, with a cross section proportional to $\sin^2(\beta-\alpha)$;
- the pair production $e^+e^- \to hA$, with a cross section proportional to $\cos^2(\beta-\alpha)$;
- the Yukawa process $e^+e^- \to f\bar{f}h$ or $f\bar{f}A$, with a cross section proportional to $m_f{}^2$ and, for down-type quarks and for leptons, to $\sin^2\alpha/\cos^2\beta$ and $\tan^2\beta$, respectively. (The cross section is suppressed for up-type quarks for $\tan\beta$ larger than 1.)

where α is the mixing angle in the CP-even Higgs sector, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. The Feynman diagrams for these three processes are displayed in Fig. 1

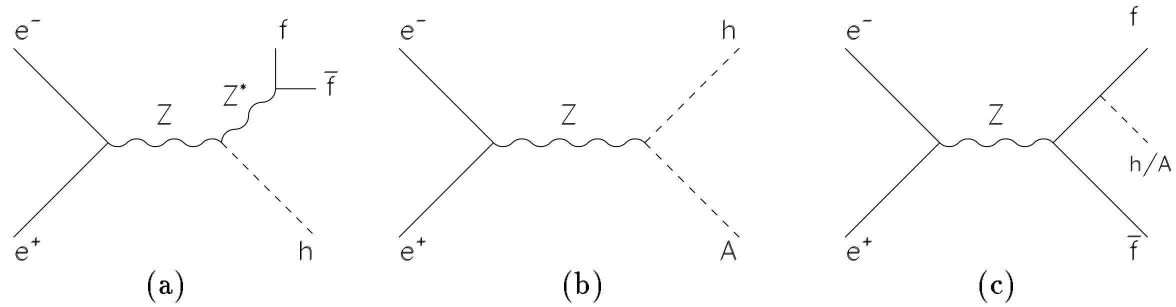

Figure 1: Feynman diagrams for (a) the Higgs-strahlung process, (b) the associated pair production and (c) the Yukawa process.

In the Minimal Supersymmetric extension of the Standard Model (MSSM), the most popular of the two-Higgs-doublet models, only two parameters are needed at tree level to determine the couplings and the masses of the Higgs bosons, which are therefore related to each other. As a consequence of these relations, it turns out that a combination of searches for $e^+e^- \to hZ^*$ and hA is sufficient to exclude a light scalar or pseudoscalar Higgs boson below ~ 45 GeV/c^2 at the 95% confidence level [1].

However, Higgs boson masses and couplings are generally unrelated in other two-Higgs-doublet models. A light scalar Higgs boson h would be missed if $\sin^2(\beta-\alpha)$ were too small for the Higgs-strahlung process to contribute significantly and A too heavy for the pair production to be kinematically allowed. Similarly, a light pseudoscalar Higgs boson would escape detection either for large $\sin^2(\beta-\alpha)$ and m_h values. In both instances, the Yukawa process may therefore become the dominant Higgs production mechanism at LEP I.

Since, in addition, the high value of R_b measured by the LEP experiments [2] could be at least partially accounted for by a light pseudoscalar A associated to a very large value of $\tan\beta$ [3] where $\mathrm{e^+e^-} \to \mathrm{f\bar{f}A}$ has the largest cross section, a study of this process becomes particularly relevant. Finally, it has been argued several times [4, 5] that the Yukawa process should allow a region of the MSSM parameter space to be explored, yet uncovered by the two other Higgs production mechanisms ($\tan\beta$ in excess of 60, m_A above 55 GeV/c^2).

The purpose of this note is to set 95% C.L. limits on the $\mathrm{e^+e^-} \to \mathrm{f\bar{f}A}$ cross section (and similarly on the $\mathrm{e^+e^-} \to \mathrm{f\bar{f}h}$ cross section), and to interpret it as an excluded region in the (m_A,$\tan\beta$) plane independent of the two-Higgs-doublet model. This cross section, proportional to the square of the fermion f mass, is sizeable only when f is a tau lepton or a b quark. The final states to be studied are therefore *(i)* $\mathrm{b\bar{b}b\bar{b}}$ and $\tau^+\tau^-\mathrm{b\bar{b}}$ for m_A in excess of $2m_\mathrm{b}$; *(ii)* $\tau^+\tau^-\tau^+\tau^-$ between $2m_\tau$ and $2m_\mathrm{b}$; *(iii)* and a $\tau^+\tau^-$ pair accompanied by a low charged multiplicity system down to $2m_\mathrm{e}$.

All these topologies correspond to already existing ALEPH analyses. In the last two cases, the relevant topology is the so-called llV topology, studied in detail in Ref. [6] with the ALEPH data collected from 1989 to 1993. The result of the analysis updated with the 1994-1995 ALEPH data, altogether corresponding to about 4.5 million hadronic Z decays, is reported in Section 2. The four-b and the $\tau^+\tau^-\mathrm{q\bar{q}}$ topologies were studied in Refs. [7, 8] with the ALEPH data collected until 1994 and are not updated here with the modest additional integrated luminosity recorded in 1995. The interpretation of the three analyses in the context of Higgs boson production via the Yukawa process is presented in Section 3.

2 Update of the analysis in the llV topology

The llV topology corresponds to a four- or six-charged particle final state which mainly arises, in the Standard Model, from electroweak four-lepton production $\mathrm{e^+e^-} \to \ell^+\ell^-\ell^+\ell^-$ (with $\ell = \mathrm{e}, \mu$ or τ) and from $\mathrm{e^+e^-} \to \ell^+\ell^-\mathrm{q\bar{q}}$ when the mass of the quark-antiquark pair does not exceed a few GeV/c^2.

The selection of this topology has been applied to the 1994-1995 ALEPH data with no modifications with respect to the analysis presented in Ref. [6]. The numbers of events expected in the data in the fifteen llV classes is shown in Table 1, including systematic uncertainties.

The total number of events expected, 533.5 ± 10.8, is to be compared to the 530 events selected in the data, the details of which are shown in Table 2. The agreement is satisfactory in all classes with a χ^2 of 8.5 for 12 degrees of freedom. Particularly relevant for the present analysis are the 121 $\tau^+\tau^-\mathrm{V}$ events observed with 105.1 ± 2.8 events expected. Also shown in Fig. 2 are the distributions of the $\mathrm{x^+x^-}$ mass in $\mathrm{e^+e^-} \to \ell^+\ell^-\mathrm{x^+x^-}$ for $\mathrm{x} = \pi$, and $\mathrm{x} = \mathrm{e}$ or μ, well reproduced by the Monte Carlo prediction.

Table 1: Number of events expected in the data in the fifteen different llV classes

	$e^+e^-x^+x^-$	$\mu^+\mu^-x^+x^-$	$\tau^+\tau^-x^+x^-$	Total
$x = e$	86.8 ± 2.8	59.7 ± 1.8	33.7 ± 1.2	180.2 ± 4.6
$x = \mu$	66.4 ± 2.1	46.2 ± 1.4	30.1 ± 0.9	142.7 ± 3.5
$x = \pi$	70.2 ± 3.7	50.2 ± 2.5	30.2 ± 1.6	150.6 ± 7.1
$x = \mu$ *or* π	25.3 ± 0.9	19.0 ± 0.7	10.3 ± 0.4	54.6 ± 1.8
$x = K$	2.8 ± 0.1	1.8 ± 0.1	0.8 ± 0.1	5.4 ± 0.2
Total	251.5 ± 6.4	176.9 ± 4.4	105.1 ± 2.8	533.5 ± 10.8

Table 2: Number of events observed in the fifteen different llV classes

	$e^+e^-x^+x^-$	$\mu^+\mu^-x^+x^-$	$\tau^+\tau^-x^+x^-$	Total
$x = e$	80	63	37	180
$x = \mu$	73	42	34	149
$x = \pi$	59	47	40	146
$x = \mu$ *or* π	20	21	9	50
$x = K$	3	1	1	5
Total	235	174	121	530

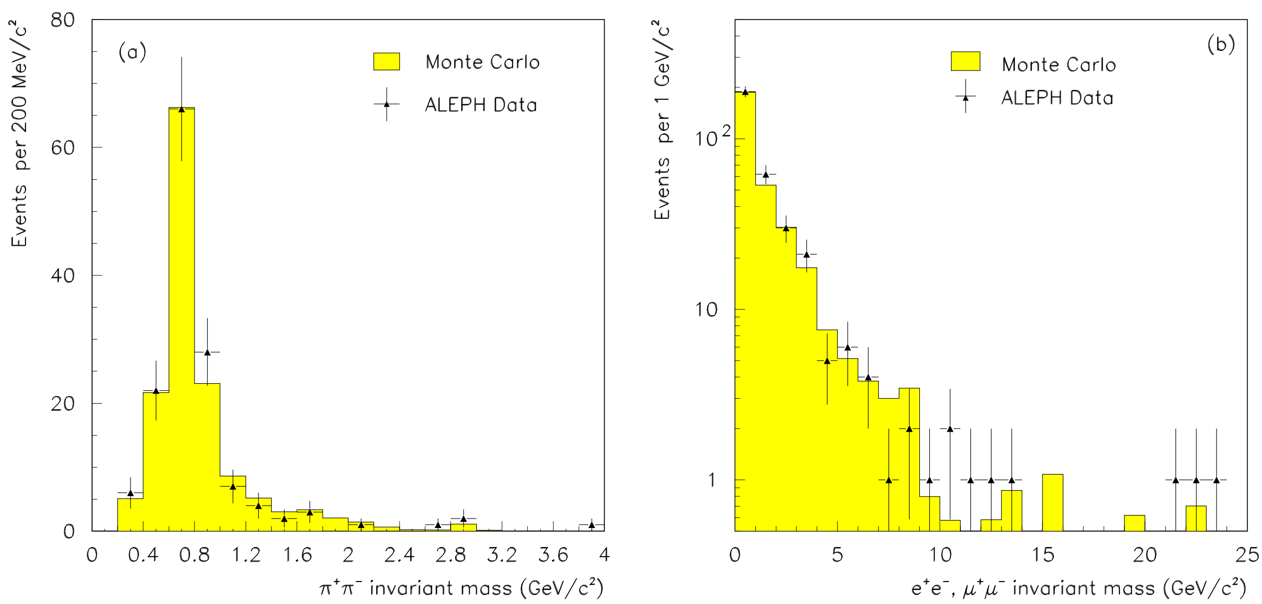

Figure 2: Distributions of the x^+x^-mass when (a) $x = \pi$ and (b) $x = e$ *or* μ, for the data (triangles with error bars) and for the Monte Carlo expectation (shaded histogram) with an absolute normalization.

3 Results

Events from the Yukawa process $e^+e^- \to f\bar{f}A$ where $f = \tau$ or b were simulated for several A masses between 100 MeV/c^2 and 40 GeV/c^2 with a Monte Carlo generator based on the matrix element squared of Ref. [5]. The decays of the A particle were simulated with the HZHA [9] and H0SDECAY [10] programs, above and below the $A \to \tau^+\tau^-$ threshold, respectively. These events were then processed through the ALEPH simulation and reconstruction programs, and used to determine the selection efficiencies. To derive all the limits presented below, the efficiencies were conservatively reduced (and the numbers of background events expected were conservatively increased) by their systematic uncertainty.

Below the $b\bar{b}$ threshold, the topology of interest is the llV topology. (The $\tau^+\tau^- q\bar{q}$ analysis of Ref. [8] has there a vanishing efficiency due to the low mass of the $\tau^+\tau^-$ pair.) When applied to the simulated $e^+e^- \to \tau^+\tau^- A$ events, the analysis of Section 2 has a typical efficiency of 30% above the $\mu^+\mu^-$ threshold. Below the $\mu^+\mu^-$ threshold, the A boson decays principally into an e^+e^- pair, and the efficiency is noticeably reduced by severe photon conversion rejection criteria [6]. For $m_A = 5$ GeV/c^2 and $\tan\beta = 30$, for example, the number of signal events expected is 40.5, to be compared to a background expectation of 105.1 ± 2.8 and 121 events observed. For this mass, $\tan\beta$ in excess of 27.5 is excluded at the 95% confidence level.

However, as can be seen from Fig. 2, the background V mass distribution is strongly peaked at low masses while the corresponding distribution for the signal is expected, for substantial values of m_A, to be shifted to larger masses. A second analysis was therefore optimized for A masses above 5 GeV/c^2 by adding to the selection algorithm a cut on the measured V mass. This cut was set to 1.25 GeV/c^2 to minimize the average 95% C.L. limit on the $e^+e^- \to \tau^+\tau^- A$ production cross-section, as determined from a large number of toy Monte Carlo experiments. The signal efficiency is reduced to typically 20% and a total of 32 $\tau^+\tau^- V$ events remain in the data, in agreement with the standard model expectation of 30.0 ± 0.8 events. For $m_A = 5$ GeV/c^2 and $\tan\beta = 30$, the number of signal events expected becomes 18.9, allowing $\tan\beta$ in excess of 23.3 to be excluded at the 95% confidence level. The 95% C.L. limit set on $\tan\beta$ with these two analyses is shown in Fig. 3 as the function of m_A, as curves A and B.

Above the $b\bar{b}$ threshold, the four-b quark and the $\tau^+\tau^- q\bar{q}$ topologies [7, 8] become more appropriate. With the data collected by ALEPH by the end of 1994, 664 events were found in the four-b quark channel, in agreement with the standard model expectation of 594 ± 45 events (mainly from $b\bar{b}gg$ events), and six events were selected in the $\tau^+\tau^- q\bar{q}$ topology. (In this topology, the background from $e^+e^- \to q\bar{q}$ is affected by a large systematic uncertainty, and no background subtraction was therefore performed.) Typical signal efficiencies of 10% are achieved in both topologies. The 95% C.L. limit set on $\tan\beta$ with these two analyses is shown in Fig. 3 as the function of m_A, as curves D and C, respectively.

It can be seen that the high background in the four-b-quark channel, associated to an efficiency twice smaller than that obtained for the hA pair production [7], prevents this final state from providing with an useful limit in the present context. The projections made in Refs. [4, 5] where it was assumed that the $b\bar{b}gg$ background could be totally rejected while keeping a selection efficiency for the signal as high as 30% are therefore unrealistic.

When combined, these analyses turn into an excluded region in the (m_A, $\tan\beta$) plane, also displayed in Fig. 3. A similar curve is obtained in the ($m_h, \sin\alpha/\cos\beta$) via the $e^+e^- \to f\bar{f}h$ production. The sharp variations in the shape of the curve are essentially driven by the opening of new decay channels for the Higgs boson when increasing its mass, inducing important modifications to the selection efficiency. For instance, the branching fraction of the Higgs boson into two charged particles is much larger just above than just below the $\tau^+\tau^-$ threshold, where the hadronic decay dominates. This sudden change is responsible for the sharp peak around $2m_\tau$. Above the $b\bar{b}$ threshold, the $\tau^+\tau^- q\bar{q}$ analysis has the largest efficiency, but still much lower than the llV search below this threshold. This accounts for the degradation of the limit around $2m_b$.

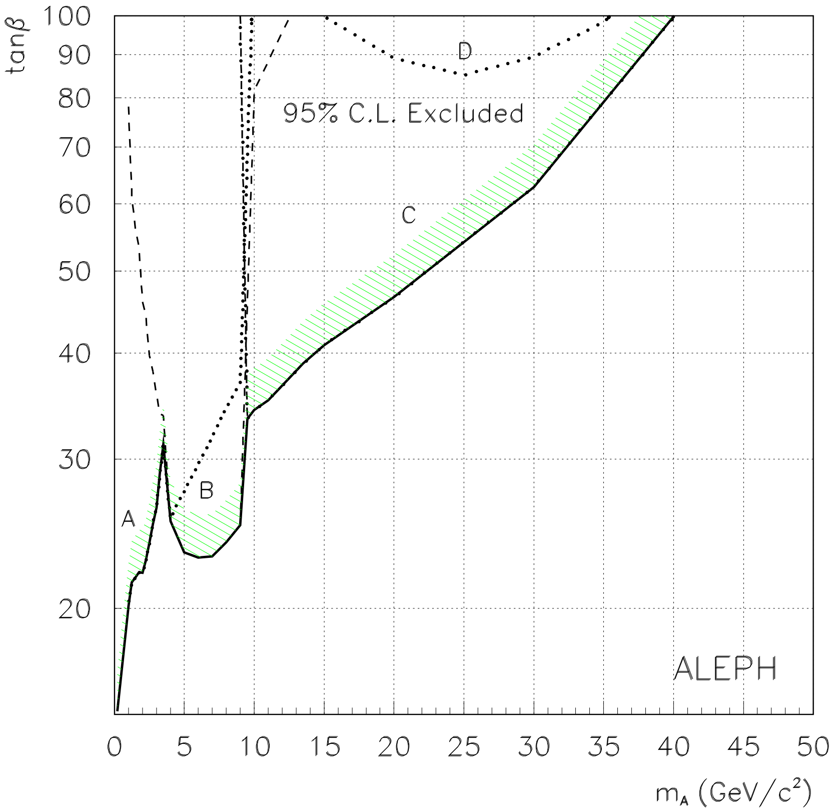

Figure 3: 95% C.L. excluded region in the (m_A, $\tan\beta$) plane, when the four analyses, A (llV topology, dotted curve), B (llV topology with a mass cut at 1.25 GeV/c^2, dashed curve), C ($\tau^+\tau^- q\bar{q}$ final state, dash-dotted curve) and D (four-b-jet final state, upper dotted curve), are combined. The 95% C.L. excluded region is above the hatched full curve.

As can be seen from Fig. 3, any m_A value between $\sim$ 100 MeV/c^2 and 28 GeV/c^2 is excluded at 95% C.L. in any two-Higgs-doublet model, if $\tan\beta$ is in excess of 60. Masses larger than $\sim$ 40 GeV/c^2 cannot be ruled out, which could still partially account for the large measured value of R_b. When this study is restricted to the MSSM, the Yukawa process cannot compete with the pair production $e^+e^- \to hA$ (which is sensitive to masses as large as 55 GeV/c^2 for $\tan\beta = 60$ [7]) in contrast to what was expected in Refs. [4, 5].

4 Conclusion

The interpretation of the ALEPH analyses in the llV, $\tau^+\tau^-\mathrm{q\bar{q}}$ and $\mathrm{b\bar{b}b\bar{b}}$ final states in the context of Higgs boson production via the Yukawa process $\mathrm{e^+e^-} \to \mathrm{f\bar{f}A}$ allows the large $\tan\beta$ region to be excluded, in any two-Higgs-doublet model, for a light pseudoscalar A ($m_\mathrm{A} \lesssim 30$ GeV/c^2). A similar limit is obtain on $\sin\alpha/\cos\beta$ for a light scalar h via the $\mathrm{e^+e^-} \to \mathrm{f\bar{f}h}$ production. This, however, cannot rule out the scenario in which the high value of R_b would be caused by loops of h and A with a light A ($m_\mathrm{A} \lesssim$ 50-60 GeV/c^2) for large $\tan\beta$ values (in excess of 50). In the context of the MSSM, this study does not extend the region already excluded by the analysis of the Higgs-strahlung process $\mathrm{e^+e^-} \to \mathrm{hZ^*}$ and the pair production $\mathrm{e^+e^-} \to \mathrm{hA}$.

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