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PRELIMINARY

Searches for Higgs bosons in e^+e^- collisions at centre-of-mass energies up to 209 GeV

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Abstract

Using preliminary data collected in the year 2000 at centre-of-mass energies ranging from 200 to 209 GeV, a search for Higgs bosons is performed by ALEPH. No evidence for signal is found in the search for the Standard Model Higgs boson, the neutral Higgs bosons of the MSSM, the charged Higgs bosons, the invisibly decaying Higgs boson, and the fermiophobic Higgs boson. Combined with lower energy ALEPH data, 95% confidence level lower limits are set on the masses of all of these Higgs bosons.

ALEPH contribution to the 2000 Summer Conferences

1 Introduction

This note reports on the search for various types of Higgs bosons in the preliminary data collected by the ALEPH detector at LEP in the year 2000 with centre-of-mass energies ranging from 200 to 209 GeV. The types of Higgs bosons included in this search are the Standard Model Higgs boson, the neutral Higgs bosons of the MSSM, the charged Higgs bosons, the invisible Higgs boson, and the fermiophobic Higgs boson. The results of this search are combined with the results of the search in lower energy ALEPH data.

2 The Standard Model Higgs boson

The search for the Standard Model Higgs boson follows closely the analysis designed for the data collected in 1999 [1] with the following improvements.

- The two neural network analyses used for the missing energy final state ($h\nu\bar{\nu}$) in the NN stream have been replaced by a single neural network analysis which has attempted to include the best features from both analyses.
- The missing energy analysis ($h\nu\bar{\nu}$) for the cut stream has an improved rejection of $q\bar{q}\gamma$ events. Events with three hadronic jets are removed by cutting on y_{23} and the minimum angle between the three jets. Events originating from $q\bar{q}\gamma\gamma$ with a photon in the detector are removed by requiring that the energy of the third jet is not predominately electromagnetic.
- The analysis for the leptonic final state ($h\ell^+\ell^-$ where ℓ denotes an electron or muon) has three improvements: 1) an increased efficiency in the selection of events where the Higgs boson decays to τ leptons, 2) reduced expected background for events with isolated photons, and 3) an increased sensitivity above the kinematic threshold by relaxing requirements on the reconstructed Z boson mass for events with a large Higgs boson mass.

The expected number of background events and the number of candidates for each analysis are summarized in Table 1 for $99.8\,\mathrm{pb}^{-1}$ of data collected at centre-of-mass energies ranging from 200 to 209 GeV.

The mass distribution of the selected candidates is shown for both the NN and cut streams in Figure 1. No evidence for a signal is seen. Figure 2 shows the confidence level distribution as a function of the Standard Model Higgs boson mass. The NN stream excludes masses below $111.1\,\mathrm{GeV}/c^2$ with 95% confidence level (CL) while the expected exclusion is $112.3\,\mathrm{GeV}/c^2$. The cut stream excludes masses below $109.9\,\mathrm{GeV}/c^2$ with an expected exclusion of $111.5\,\mathrm{GeV}/c^2$. These exclusion limits do not include the effects from the systematic uncertainties. Since the expected limit of the NN stream is better, the ALEPH result and figures use the NN stream.

Figure 2 shows the the expected and observed background hypothesis confidence levels. The peak in the observed distribution near a Higgs boson mass of $115\,\mathrm{GeV}/c^2$ is caused almost entirely by a single candidate shown in Figure 3. This candidate is selected by both the NN and cut stream four jet analyses. The reconstructed Higgs boson mass is $114.3\,\mathrm{GeV}/c^2$ and both Higgs boson jets are well b-tagged with displaced vertices. Also the 14 GeV of missing energy in the event is in the direction of the b-tagged jet with an identified muon, consistent

Table 1: The number of expected and observed events for each channel used in the search for the Standard Model Higgs boson and neutral Higgs bosons of the MSSM.

Neutral Higgs Analysis		Background Expected	Events Observed
$hq\bar{q}$ NN	2b	19.0	16
	4b	2.5	4
$hq\bar{q}$ Cut	hZ Only	7.8	10
	hZ & hA	2.7	3
	hA Only	3.7	5
$h\nu\bar{\nu}$ NN		18.0	20
$h\nu\bar{\nu}$ Cut		9.0	9
$h\ell^+\ell^-$		13.7	10
$\tau^+\tau^- q\bar{q}$		6.3	7

with a single missing energetic neutrino in a semi-leptonic b decay. A Higgs boson with a mass of $114\,\mathrm{GeV}/c^2$ is just beyond the sensitivity of this search, where only 3.7 signal events would be expected in the data.

3 Neutral Higgs bosons of the MSSM

The same selection analyses used in the search for the Standard Model Higgs boson are used to search for the lightest CP-even h and the CP-odd A neutral Higgs bosons of the MSSM. These results are based upon $94.2\,\mathrm{pb}^{-1}$ of data collected with centre-of-mass energies ranging from 200 to 209 GeV. The selection results are summarized in Table 1 and interpreted using the same techniques described in Ref. [1].

The mass limit on the h boson mass of the MSSM is shown as a function of $\tan\beta$ for the $m_{\mathrm{h}}^{\mathrm{max}}$ benchmark parameter set [2] in Figure 4. The 95% CL lower limit on the mass of the lighter CP-even Higgs boson h, with these benchmark parameters, is $91.2\,\mathrm{GeV}/c^2$ for $\tan\beta > 0.5$ with an expected limit of $90.6\,\mathrm{GeV}/c^2$. For the CP-odd Higgs boson A, the 95% CL lower limit on the mass is $91.6\,\mathrm{GeV}/c^2$ with an expected limit of $91.0\,\mathrm{GeV}/c^2$. In the $m_{\mathrm{h}}^{\mathrm{max}}$ parameter set, $\tan\beta$ values within [0.7,2.1] are excluded at the 95% confidence level. These exclusion limits do not include the effects from the systematic uncertainties.

4 Charged Higgs bosons

The search for the charged Higgs bosons has been extended by including $90.6\,\mathrm{pb}^{-1}$ of data collected at centre-of-mass energies ranging from 200 to 209 GeV. The selection analyses follow closely the analyses described in Ref. [3] with the following improvements.

- The linear discriminant used in the four jet selection $c\bar{s}s\bar{c}$ includes two additional variables. The first one is $\log_{10}(y_{34})$, where y_{34} is the Y_{cut} value at which the transition from three

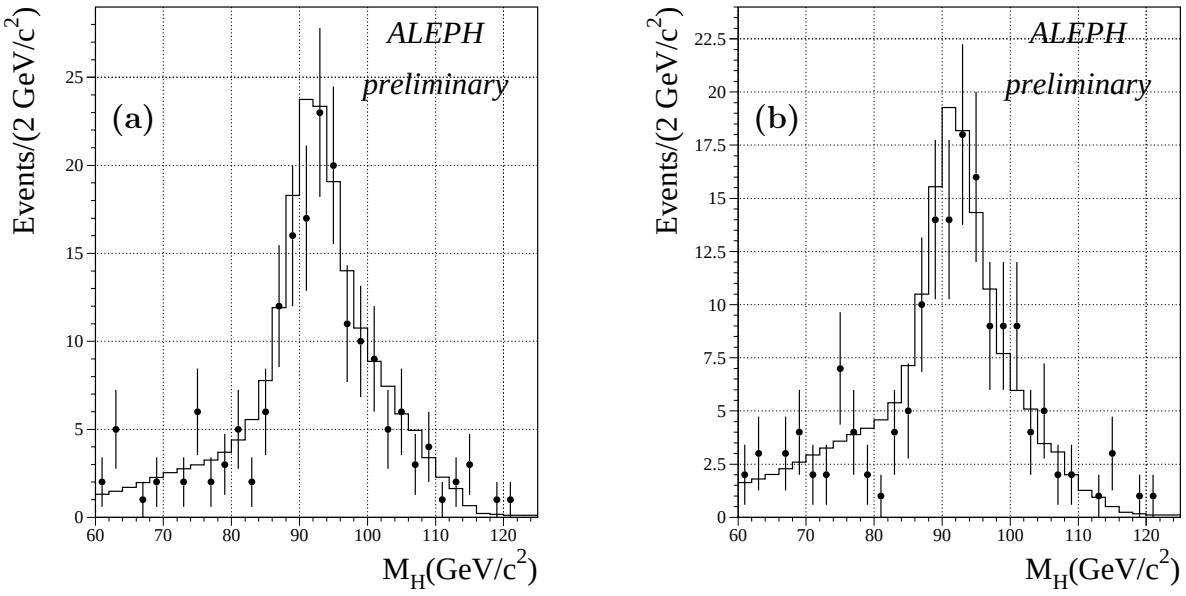

Figure 1: Distributions of the reconstructed Higgs boson mass for the data (dots with error bars) selected in the hZ searches by the NN stream (a), and the cut stream (b). The histograms show the Standard Model background expectation.

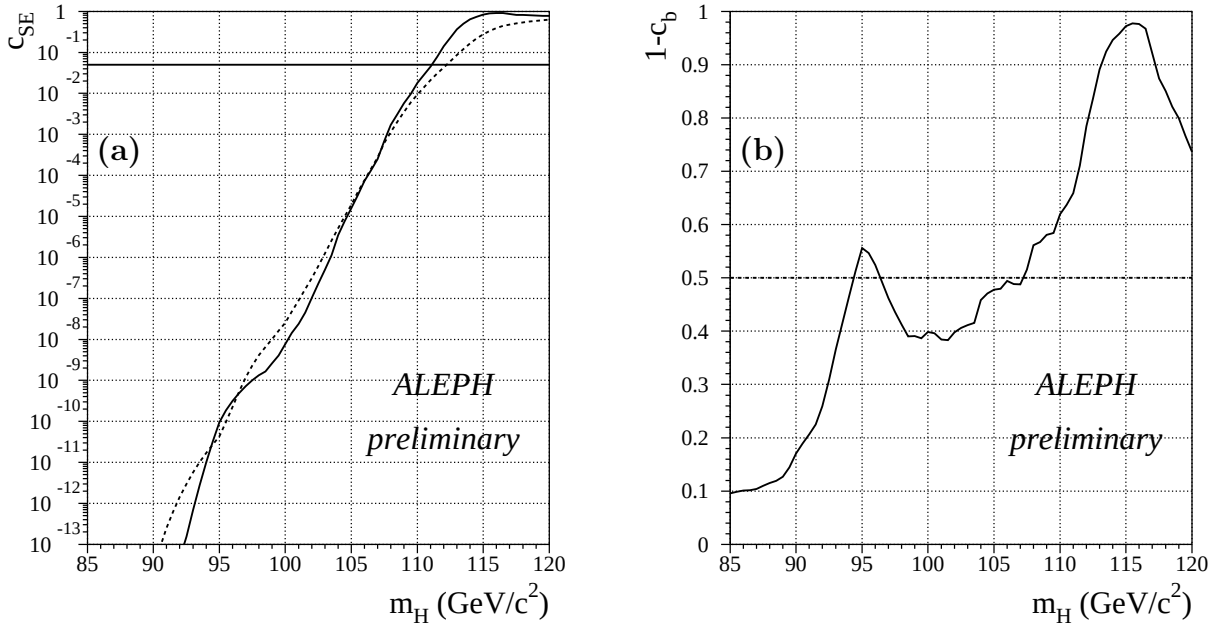

Figure 2: Observed (solid) and expected (dashed) CL curves for (a) the signal hypothesis and (b) the background hypothesis as a function of the hypothesized Standard Model Higgs boson mass for the NN stream. For the signal hypothesis (a), the intersection of the horizontal line at 5% with the curves define the observed and expected 95% CL lower limits on the Standard Model Higgs boson mass.

Table 2: The number of expected and observed events for each channel used in the search for the charged Higgs bosons.

Charged Higgs Analysis	Background Expected	Events Observed
$c\bar{s}s\bar{c}$	452.8 ± 14.5	438
$\bar{c}s\tau^+\nu_\tau$	49.2 ± 2.1	50
$\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$	9.6 ± 0.3	4

to four jets occurs. The second one is the product of the smallest jet energy E_{min} and the minimum jet-jet angle $\theta_{q\bar{q}'}$.

- The $c\bar{s}s\bar{c}$ selection also has an improved jet pairing method which selects the jet combination which has the lowest χ^2 of the fit to the event.

- The $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ analysis is the same as described in Ref. [4] except that a better rejection of the $\gamma\gamma \to \ell^+\ell^-$ backgrounds is obtained by requiring that there is no energy within 12° of the beamline.

The expected and observed number of events are shown in Table 2 for each selection analysis. The mass distribution of the selected candidates for the $c\bar{s}s\bar{c}$ and $\bar{c}s\tau^+\nu_\tau$ analyses are shown in Figure 5. No evidence for signal is found, and limits are derived in the (m_{H^+}, Br($H^+ \to \tau^+\nu_\tau$)) plane, shown in Figure 6.

For Br($H^+ \to \tau^+\nu_\tau$) = 1, the 95% CL limit on the charged Higgs boson mass is $82.8\,\mathrm{GeV}/c^2$ with an expected limit of $86.4\,\mathrm{GeV}/c^2$. For Br($H^+ \to \tau^+\nu_\tau$) = 0, the 95% CL limit is $80.9\,\mathrm{GeV}/c^2$ with an expected limit of $78.4\,\mathrm{GeV}/c^2$. The 95% CL lower limit on the charged Higgs boson mass, independent of the branching ratio, is $76.4\,\mathrm{GeV}/c^2$ with an expected limit of $77.0\,\mathrm{GeV}/c^2$.

5 The invisible Higgs boson

The acoplanar jet analysis designed to search for an invisibly decaying Higgs boson in the 1999 data [5] has been applied to the data sample comprising $94.2\,\mathrm{pb}^{-1}$ at centre-of-mass energies ranging from 200 to 209 GeV.

A total of 14 candidates were selected by the acoplanar jet search with 22.0 background events expected. The probability of such a deficit of events is only 2%. Although no problems have been found to explain this deficit, the source of this deficit is still under investigation. The effect of this deficit can be seen in Figure 7 which shows the distribution of the confidence level in the background only hypothesis. Although there is an overall deficit of events, there is a slight excess of events at higher Higgs boson masses.

Since there is no evidence of a signal, a 95% CL limit on the lower Higgs boson mass is shown as a function of ξ^2 in Figure 8. The parameter ξ^2 is a Standard Model cross section correction factor which is the product of the branching ratio to invisible decays and a model-dependent factor which reduces the cross section with respect to the Standard Model. For a production

Table 3: The expected and observed lower Higgs boson mass limits.

Higgs Boson Type	Expected Limit	Observed Limit
Standard Model H	112.3	111.1
MSSM h	90.6	91.2
MSSM A	91.0	91.6
Charged	77.0	76.4
Invisible	109.5	107.2
Fermiophobic	102.2	101.7

cross section equal to that of the Standard Model ($\xi^2 = 1$), invisibly decaying Higgs bosons with masses below $107.2\,\mathrm{GeV}/c^2$ are excluded at 95% CL with an expected limit of $109.5\,\mathrm{GeV}/c^2$.

6 The fermiophobic Higgs boson

The search for Higgs bosons decaying into photon pairs is investigated using the same analysis applied to the 1999 data [6]. This analysis is sensitive to all topologies arising from a Higgs boson, with a mass between 0 and $125\,\mathrm{GeV}/c^2$, produced in association with a fermion pair via the Higgsstrahlung process.

In $94.2\,\mathrm{pb}^{-1}$ of data collected with centre-of-mass energies ranging from 200 to 209 GeV, 2 candidates were selected while 2.2 background events were expected. The highest mass candidate, shown in Figure 9, has a photon pair invariant mass of $108.3\,\mathrm{GeV}/c^2$.

The 95% CL lower mass limit on the Higgs boson decaying into photon pairs is shown in Figure 10 as a function of the ratio of the photon pair cross section to the Standard Model cross section. For a fermiophobic Higgs boson, the 95% CL lower mass limit is $101.7\,\mathrm{GeV}/c^2$ with an expected limit of $102.2\,\mathrm{GeV}/c^2$. For a Standard Model Higgs cross section, i.e. $\mathrm{Br}(\mathrm{H} \to \gamma\gamma) = 1$, the lower Higgs boson mass limit is $109.5\,\mathrm{GeV}/c^2$ with an expected limit of $110.4\,\mathrm{GeV}/c^2$.

7 Conclusions

The search for Higgs bosons has been extended to include data collected up to July 16, 2000 with centre-of-mass energies ranging from 200 to 209 GeV. No evidence for a signal was found. The 95% confidence level limits on the Standard Model Higgs boson, the neutral Higgs bosons of the MSSM, the charged Higgs bosons, the invisibly decaying Higgs boson, and the fermiophobic Higgs boson have been updated and are summarized in Table 3.

References

[1] ALEPH Collaboration, *Search for the neutral Higgs bosons of the Standard Model and the MSSM in e^+e^- collisions at centre-of-mass energies from 192 to 202 GeV*, ALEPH

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[2] M. Carena, S. Heinemeyer, C.E.M. Wagner, and G. Weiglein, *Suggestions for improved benchmark scenarios for Higgs-boson searches at LEP 2*, CERN-TH/99-374 (1999).

[3] ALEPH Collaboration, *Search for charged Higgs bosons in e^+e^- collisions at $\sqrt{s}$ = 192-202 GeV*, contributed paper to this conference, Abstract 324.

[4] ALEPH Collaboration, *Search for charged Higgs bosons in e^+e^- collisions at centre-of-mass energies up to $\sqrt{s} = 189$ GeV*, CERN-EP/2000-086, submitted to Phys. Lett. B.

[5] ALEPH Collaboration, *Search for an invisibly decaying Higgs boson in e^+e^- collisions at 189 GeV*, CERN-EP/99-125 (1999) submitted to Phys. Lett. B.

[6] ALEPH Collaboration, *Search for gamma-gamma decays of a Higgs boson produced in association with a fermion pair in e+e- collisions at LEP*, CERN EP/2000-083 (2000) submitted to Phys. Lett. B.

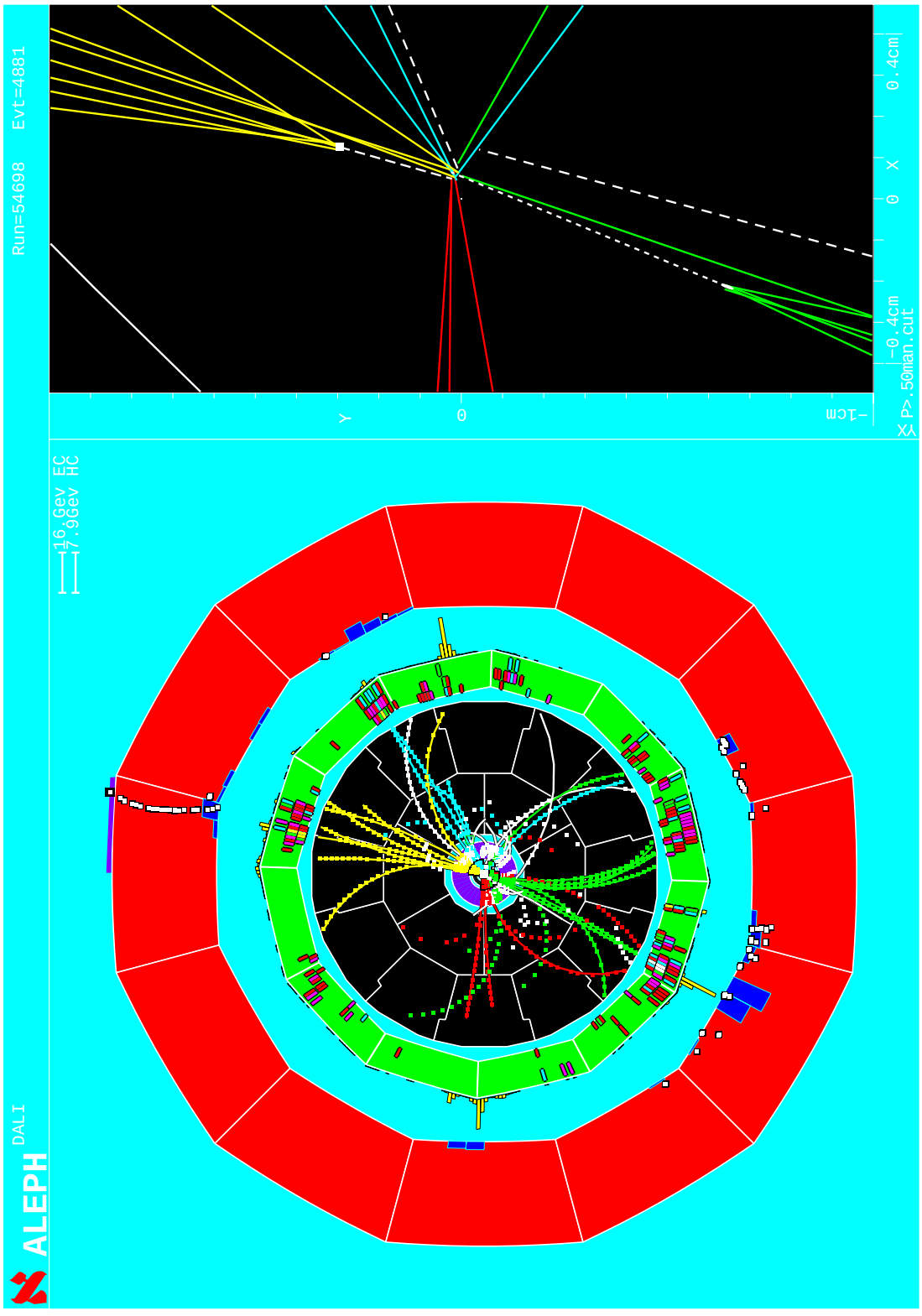

Figure 3: Standard Model Higgs boson candidate selected by the four jet (2b) analysis. The reconstructed Higgs boson mass is 114.3 GeV/c^2 and two of the jets are well b tagged with displaced vertices.

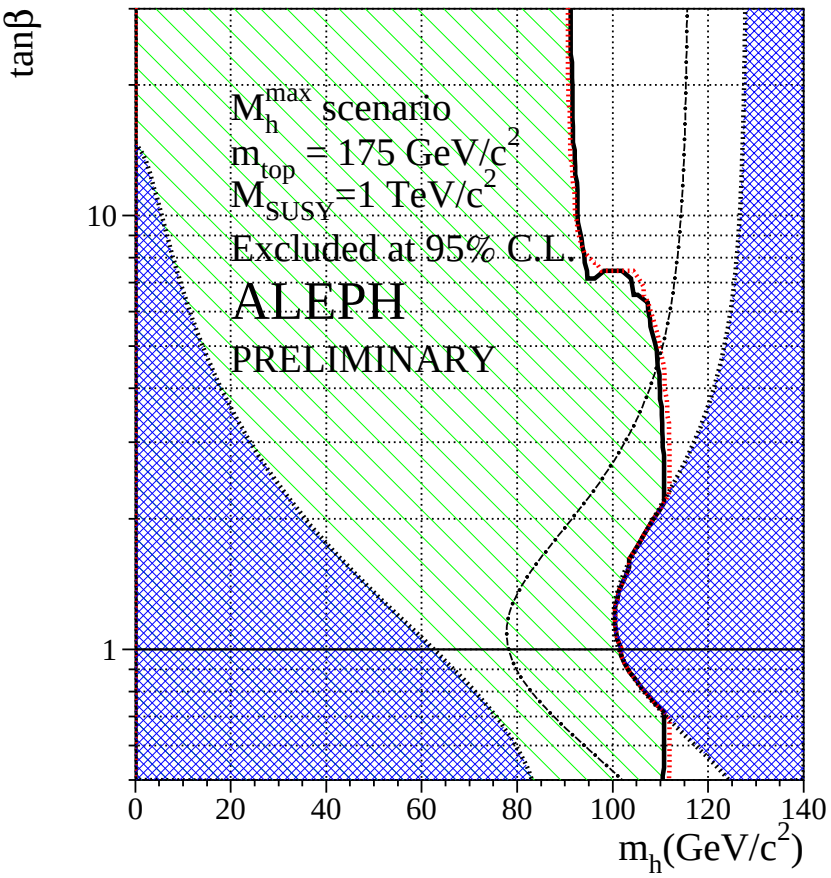

Figure 4: The expected (dashed) and observed (solid) excluded regions at 95% CL in the [$m_{\rm h}$,tan β] plane of the MSSM for the $m_{\rm h}^{\rm max}$ parameter set. The densely hatched regions are not allowed theoretically. The dash-dotted curve represents the theoretically forbidden region in the no stop mixing parameter set.

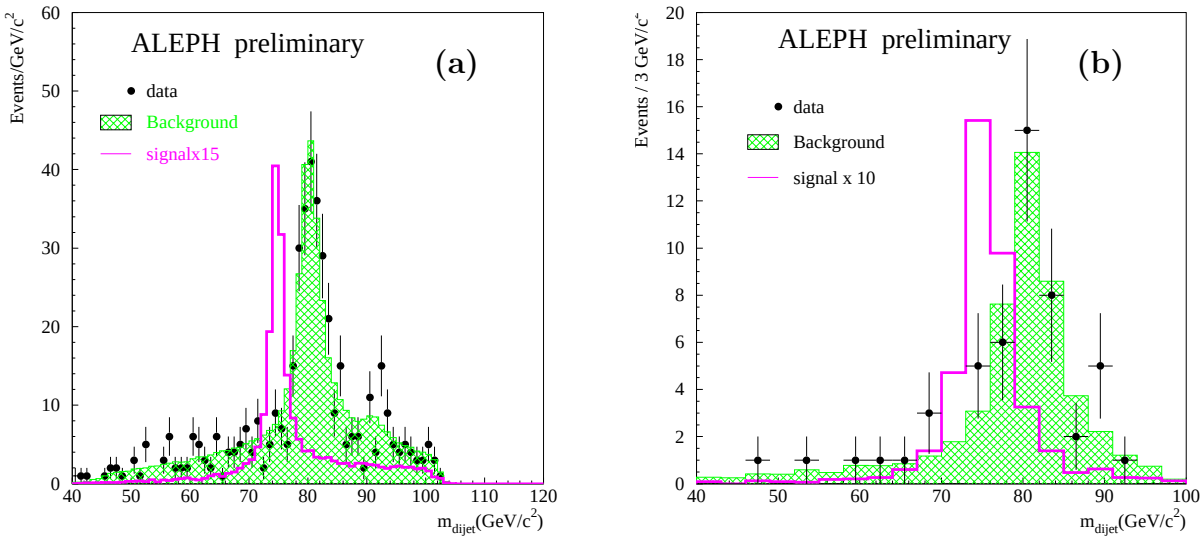

Figure 5: Distributions of the reconstructed Higgs boson mass for the data (dots with error bars) selected in the charged Higgs boson searches by the $c\bar{s}\bar{s}c$ (a), and the $\bar{c}s\tau^+\nu_\tau$ (b) analyses. The hatched histograms show the Standard Model background expectation, and the hollow histograms show the expected signal with arbitrary normalization.

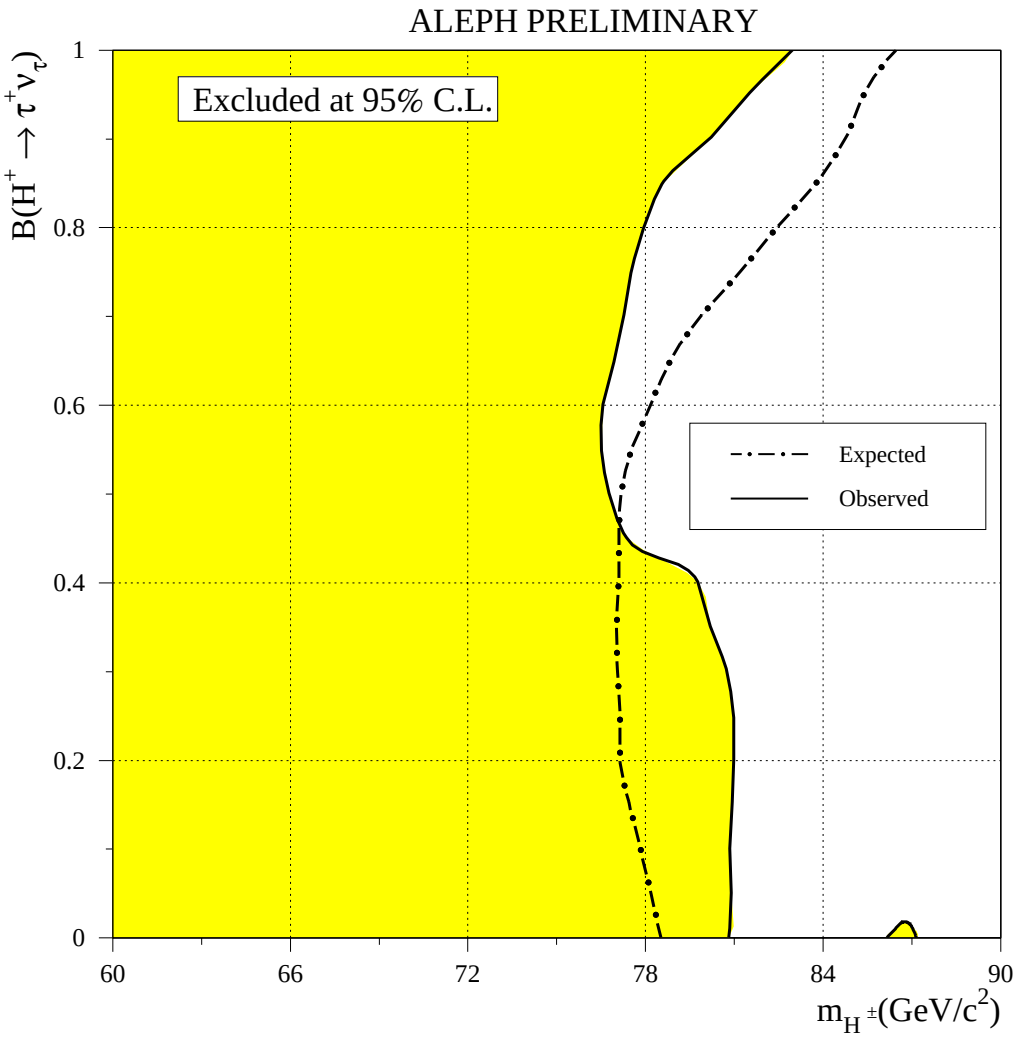

Figure 6: The expected (dash-dotted) and observed (solid) 95% CL exclusion limits for the charged Higgs boson mass as a function of the branching ratio into $\tau^+\nu_\tau$.

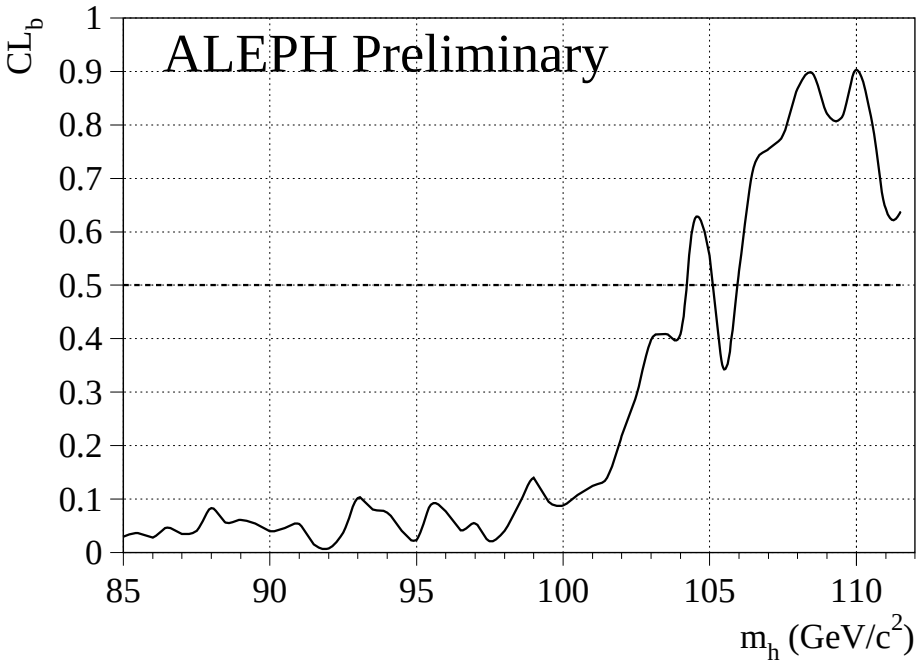

Figure 7: The expected (dashed) and observed (solid) CL curves for the background hypothesis as a function of the invisible Higgs boson mass.

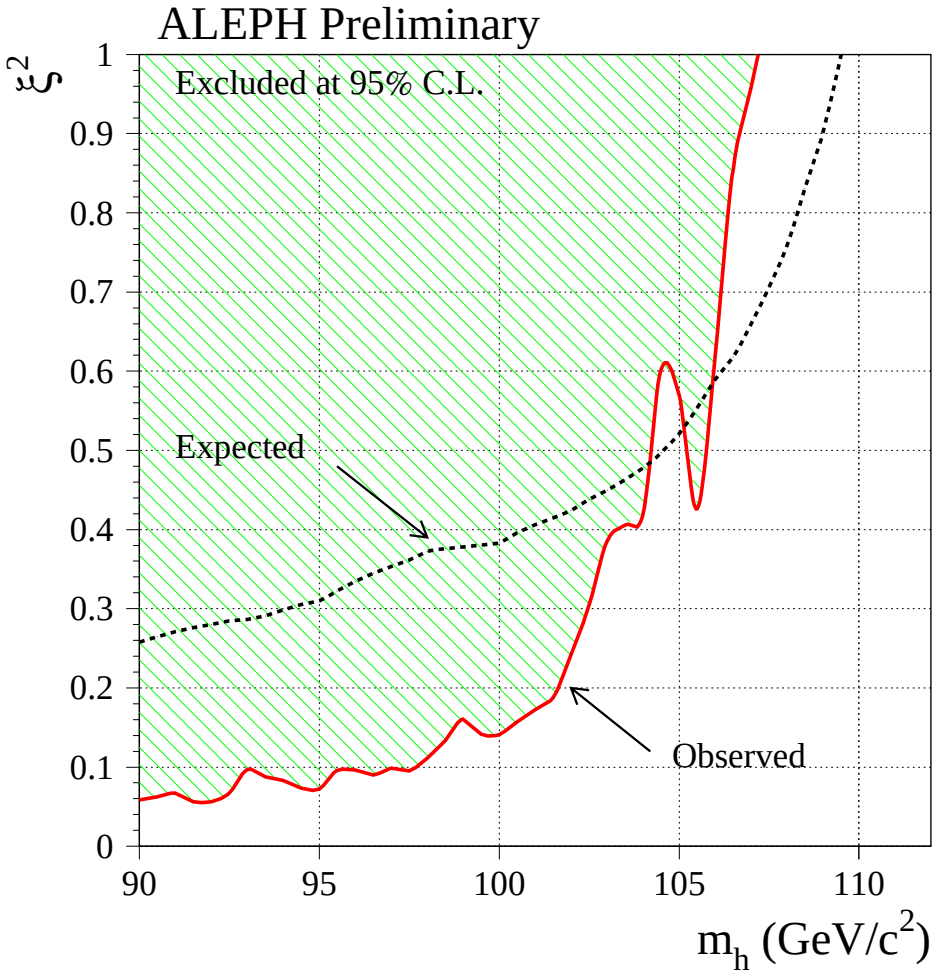

Figure 8: The expected (dashed) and observed (solid) 95% CL exclusion limits for the invisible Higgs boson mass as a function of ξ^2, the invisible Higgs production cross section correction factor to the Standard Model cross section.

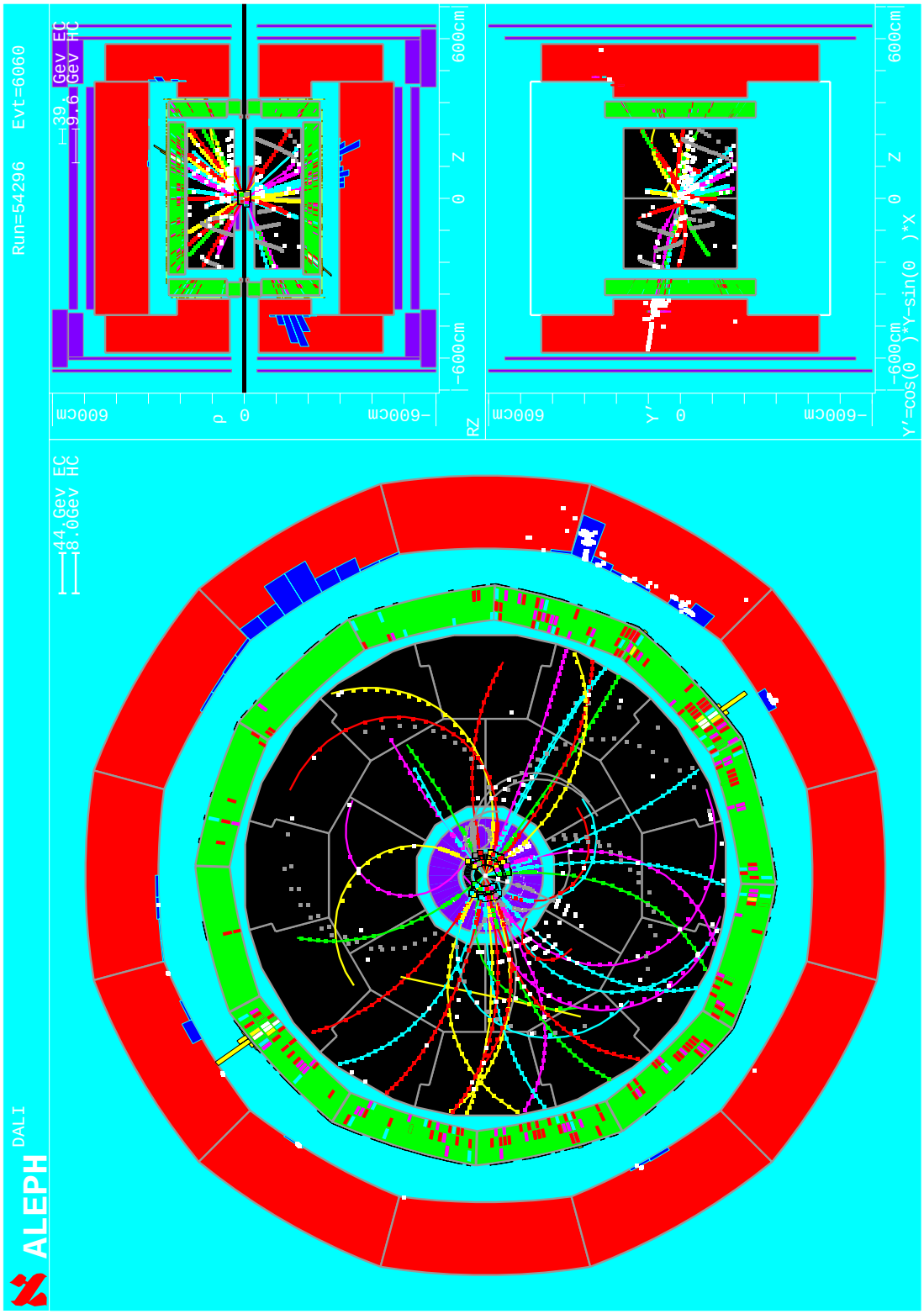

Figure 9: Fermiophobic Higgs boson candidate with a photon pair invariant mass of 108.3 GeV/c^2.

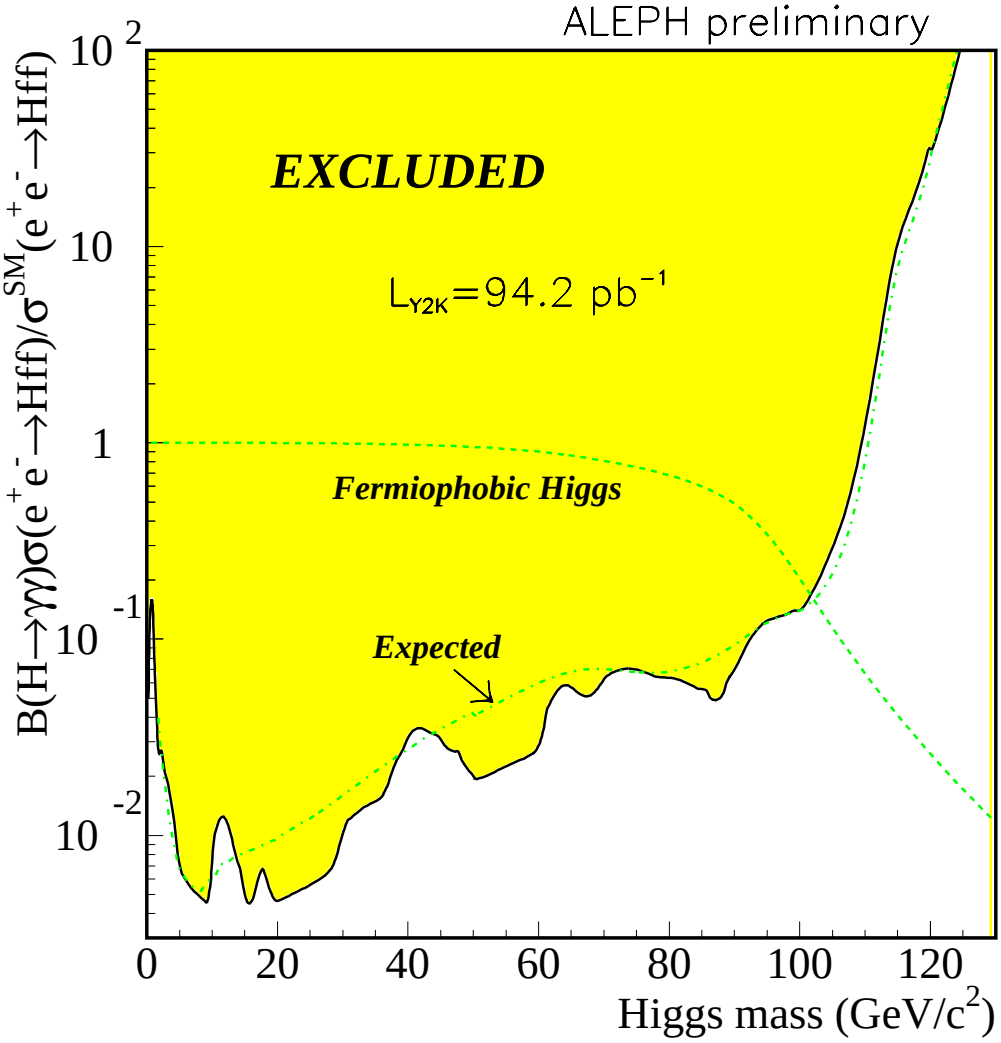

Figure 10: The expected (dash-dotted) and observed (solid) 95% CL mass limit on the Higgs boson as a function of the ratio of the photon pair cross section to the Standard Model cross section. The dashed curve is the predicted branching ratio for a fermiophobic Higgs boson.