ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN PPE/91-111
10 July 1991

Search for the Neutral Higgs Bosons of the MSSM and other Two-doublet Models

The ALEPH Collaboration*)

Abstract

Large radiative corrections modify the predictions of the Minimal Supersymmetric extension of the Standard model (MSSM) sufficiently for the constraints on this model, formerly derived from the searches for the CP-even h and for the CP-odd A neutral Higgs bosons, to be invalidated. In particular, the new $h \to AA$ decay mode has to be considered. The results presented here have been obtained from a data sample corresponding to about 185 000 hadronic Z decays collected by the ALEPH experiment at LEP. No indication for any signal of the reactions $e^+e^- \to hZ^*$ or $e^+e^- \to hA$ was found. A domain in the (m_h, m_A) plane is thus excluded at 95% CL in a large class of two-Higgs-doublet models. More restrictive results are derived in the MSSM, with one loop radiative corrections to the Higgs potential taken into account. It is found that $m_h > 41$ GeV/c^2 and $m_A > 20$ GeV/c^2 at 95% CL when the other parameters of the model are varied in their allowed ranges.

(Submitted to Physics Letters B)

*) See next pages for the list of authors.

The ALEPH Collaboration

D. Decamp, B. Deschizeaux, C. Goy, J.-P. Lees, M.-N. Minard

Laboratoire de Physique des Particules (LAPP), IN^2P^3-CNRS, 74019 Annecy-le-Vieux Cedex, France

R. Alemany, J.M. Crespo, M. Delfino, E. Fernandez, V. Gaitan, Ll. Garrido, Ll.M. Mir, A. Pacheco

Laboratorio de Fisica de Altas Energias, Universidad Autonoma de Barcelona, 08193 Bellaterra (Barcelona), Spain[8]

M.G. Catanesi, D. Creanza, M. de Palma, A. Farilla, G. Iaselli,[1] G. Maggi, M. Maggi, S. Natali, S. Nuzzo, M. Quattromini, A. Ranieri, G. Raso, F. Romano, F. Ruggieri, G. Selvaggi, L. Silvestris, P. Tempesta, G. Zito

INFN Sezione di Bari e Dipartimento di Fisica dell' Università, 70126 Bari, Italy

Y. Gao, H. Hu,[21] D. Huang, X. Huang, J. Lin, J. Lou, C. Qiao,[21] T. Ruan,[21] T. Wang, Y. Xie, D. Xu, R. Xu, J. Zhang, W. Zhao

Institute of High-Energy Physics, Academia Sinica, Beijing, The People's Republic of China[9]

W.B. Atwood,[2] L.A.T. Bauerdick, F. Bird, E. Blucher, G. Bonvicini, F. Bossi, J. Boudreau, D. Brown, T.H. Burnett,[3] H. Drevermann, R.W. Forty, C. Grab, R. Hagelberg, S. Haywood, J. Hilgart, B. Jost, M. Kasemann, J. Knobloch, A. Lacourt, E. Lançon, I. Lehraus, T. Lohse, A. Lusiani, A. Marchioro, M. Martinez, P. Mato, S. Menary, A. Minten, A. Miotto, R. Miquel, H.-G. Moser, J. Nash, P. Palazzi, F. Ranjard, G. Redlinger, A. Roth, J. Rothberg,[3] H. Rotscheidt, M. Saich, R. St.Denis, D. Schlatter, M. Takashima, M. Talby,[4] W. Tejessy, H. Wachsmuth, S. Wasserbaech, S. Wheeler, W. Wiedenmann, W. Witzeling, J. Wotschack

European Laboratory for Particle Physics (CERN), 1211 Geneva 23, Switzerland

Z. Ajaltouni, M. Bardadin-Otwinowska, R. El Fellous, A. Falvard, P. Gay, J. Harvey, P. Henrard, J. Jousset, B. Michel, J-C. Montret, D. Pallin, P. Perret, J. Proriol, F. Prulhière, G. Stimpfl

Laboratoire de Physique Corpusculaire, Université Blaise Pascal, IN^2P^3-CNRS, Clermont-Ferrand, 63177 Aubière, France

J.D. Hansen, J.R. Hansen, P.H. Hansen, R. Møllerud, B.S. Nilsson

Niels Bohr Institute, 2100 Copenhagen, Denmark[10]

I. Efthymiopoulos, E. Simopoulou, A. Vayaki

Nuclear Research Center Demokritos (NRCD), Athens, Greece

J. Badier, A. Blondel, G. Bonneaud, J. Bourotte, F. Braems, J.C. Brient, G. Fouque, A. Gamess, R. Guirlet, S. Orteu, A. Rosowsky, A. Rougé, M. Rumpf, R. Tanaka, H. Videau

Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN^2P^3-CNRS, 91128 Palaiseau Cedex, France

D.J. Candlin, E. Veitch

Department of Physics, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom[11]

G. Parrini

Dipartimento di Fisica, Università di Firenze, INFN Sezione di Firenze, 50125 Firenze, Italy

M. Corden, C. Georgiopoulos, M. Ikeda, J. Lannutti, D. Levinthal,[16] M. Mermikides, L. Sawyer

Supercomputer Computations Research Institute and Dept. of Physics, Florida State University, Tallahassee, FL 32306, USA [13,14,15]

A. Antonelli, R. Baldini, G. Bencivenni, G. Bologna,[5] P. Campana, G. Capon, F. Cerutti, V. Chiarella, B. D'Ettorre-Piazzoli,[6] G. Felici, P. Laurelli, G. Mannocchi,[6] F. Murtas, G.P. Murtas, G. Nicoletti, L. Passalacqua, M. Pepe-Altarelli, P. Picchi,[5] P. Zografou

Laboratori Nazionali dell'INFN (LNF-INFN), 00044 Frascati, Italy

B. Altoon, O. Boyle, A.W. Halley, I. ten Have, J.L. Hearns, J.G. Lynch, W.T. Morton, C. Raine, J.M. Scarr, K. Smith, A.S. Thompson, R.M. Turnbull

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom[11]

B. Brandl, O. Braun, R. Geiges, C. Geweniger, P. Hanke, V. Hepp, E.E. Kluge, Y. Maumary, A. Putzer, B. Rensch, A. Stahl, K. Tittel, M. Wunsch

Institut für Hochenergiephysik, Universität Heidelberg, 6900 Heidelberg, Fed. Rep. of Germany[17]

A.T. Belk, R. Beuselinck, D.M. Binnie, W. Cameron, M. Cattaneo, P.J. Dornan,[1] S. Dugeay, A.M. Greene, J.F. Hassard, N.M. Lieske, S.J. Patton, D.G. Payne, M.J. Phillips, J.K. Sedgbeer, G. Taylor, I.R. Tomalin, A.G. Wright

Department of Physics, Imperial College, London SW7 2BZ, United Kingdom[11]

P. Girtler, D. Kuhn, G. Rudolph

Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria[19]

C.K. Bowdery,[1] T.J. Brodbeck, A.J. Finch, F. Foster, G. Hughes, N.R. Keemer, M. Nuttall, A. Patel, B.S. Rowlingson, T. Sloan, S.W. Snow, E.P. Whelan

Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom[11]

T. Barczewski, K. Kleinknecht, J. Raab, B. Renk, S. Roehn, H.-G. Sander, M. Schmelling, H. Schmidt, F. Steeg, S.M. Walther, B. Wolf

Institut für Physik, Universität Mainz, 6500 Mainz, Fed. Rep. of Germany[17]

J-P. Albanese, J-J. Aubert, C. Benchouk, V. Bernard, A. Bonissent, D. Courvoisier, F. Etienne, S. Papalexiou, P. Payre, B. Pietrzyk, Z. Qian

Centre de Physique des Particules, Faculté des Sciences de Luminy, IN^2P^3-CNRS, 13288 Marseille, France

H. Becker, W. Blum, P. Cattaneo, G. Cowan, B. Dehning, H. Dietl, F. Dydak[26], M. Fernandez-Bosman, T. Hansl-Kozanecka,[22] A. Jahn, W. Kozanecki,[2,23] E. Lange, J. Lauber, G. Lütjens, G. Lutz, W. Männer, Y. Pan, R. Richter, J. Schröder, A.S. Schwarz, R. Settles, U. Stierlin, J. Thomas, G. Wolf

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, 8000 München, Fed. Rep. of Germany[17]

V. Bertin, J. Boucrot, O. Callot, X. Chen, A. Cordier, M. Davier, G. Ganis, J.-F. Grivaz, Ph. Heusse, P. Janot, D.W. Kim,[20] F. Le Diberder, J. Lefrançois,[1] A.-M. Lutz, J.-J. Veillet, I. Videau, Z. Zhang, F. Zomer

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, IN^2P^3-CNRS, 91405 Orsay Cedex, France

D. Abbaneo, S.R. Amendolia, G. Bagliesi, G. Batignani, L. Bosisio, U. Bottigli, C. Bradaschia, M. Carpinelli, M.A. Ciocci, R. Dell'Orso, I. Ferrante, F. Fidecaro, L. Foà, E. Focardi, F. Forti, C. Gatto, A. Giassi, M.A. Giorgi, F. Ligabue, E.B. Mannelli, P.S. Marrocchesi, A. Messineo, L. Moneta, F. Palla, G. Sanguinetti, J. Steinberger, R. Tenchini, G. Tonelli, G. Triggiani, C. Vannini, A. Venturi, P.G. Verdini, J. Walsh

Dipartimento di Fisica dell'Università, INFN Sezione di Pisa, e Scuola Normale Superiore, 56010 Pisa, Italy

J.M. Carter, M.G. Green,[1] P.V. March, T. Medcalf, I.S. Quazi, J.A. Strong, R.M. Thomas, L.R. West, T. Wildish

Department of Physics, Royal Holloway & Bedford New College, University of London, Surrey TW20 OEX, United Kingdom[11]

D.R. Botterill, R.W. Clifft, T.R. Edgecock, M. Edwards, S.M. Fisher, T.J. Jones, P.R. Norton, D.P. Salmon, J.C. Thompson

Particle Physics Dept., Rutherford Appleton Laboratory, Chilton, Didcot, OXON OX11 OQX, United Kingdom[11]

B. Bloch-Devaux, P. Colas, C. Klopfenstein, E. Locci, S. Loucatos, E. Monnier, P. Perez, J.A. Perlas, F. Perrier, J. Rander, J.-F. Renardy, A. Roussarie, J.-P. Schuller, J. Schwindling, B. Vallage

Département de Physique des Particules Elémentaires, CEN-Saclay, 91191 Gif-sur-Yvette Cedex, France[18]

J.G. Ashman, C.N. Booth, C. Buttar, R. Carney, S. Cartwright, F. Combley, M. Dinsdale, M. Dogru, F. Hatfield, J. Martin, D. Parker, P. Reeves, L.F. Thompson

Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom[11]

E. Barberio, S. Brandt, H. Burkhardt,[1] C. Grupen, H. Meinhard, L. Mirabito, U. Schäfer, H. Seywerd

Fachbereich Physik, Universität Siegen, 5900 Siegen, Fed. Rep. of Germany[17]

G. Apollinari, G. Giannini, B. Gobbo, F. Liello, F. Ragusa,[25] L. Rolandi, U. Stiegler

Dipartimento di Fisica, Università di Trieste e INFN Sezione di Trieste, 34127 Trieste, Italy

L. Bellantoni, X. Chen, D. Cinabro, J.S. Conway, D.F. Cowen,[24] Z. Feng, D.P.S. Ferguson, Y.S. Gao, J. Grahl, J.L. Harton, J.E. Jacobsen, R.C. Jared,[7] R.P. Johnson, B.W. LeClaire, Y.B. Pan, J.R. Pater, Y. Saadi, V. Sharma, Z.H. Shi, Y.H. Tang, A.M. Walsh, J.A. Wear,[27] F.V. Weber, M.H. Whitney, Sau Lan Wu, G. Zobernig

Department of Physics, University of Wisconsin, Madison, WI 53706, USA[12]

(Submitted to Physics Letters B)

---

[1] Now at CERN.
[2] Permanent adddress: SLAC, Stanford, CA 94309, USA.
[3] Permanent address: University of Washington, Seattle, WA 98195, USA.
[4] Also Centre de Physique des Particules, Faculté des Sciences, Marseille, France
[5] Also Istituto di Fisica Generale, Università di Torino, Torino, Italy.
[6] Also Istituto di Cosmo-Geofisica del C.N.R., Torino, Italy.
[7] Permanent address: LBL, Berkeley, CA 94720, USA.
[8] Supported by CAICYT, Spain.
[9] Supported by the National Science Foundation of China.
[10] Supported by the Danish Natural Science Research Council.
[11] Supported by the UK Science and Engineering Research Council.
[12] Supported by the US Department of Energy, contract DE-AC02-76ER00881.
[13] Supported by the US Department of Energy, contract DE-FG05-87ER40319.
[14] Supported by the NSF, contract PHY-8451274.
[15] Supported by the US Department of Energy, contract DE-FC0S-85ER250000.
[16] Supported by SLOAN fellowship, contract BR 2703.
[17] Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. of Germany.
[18] Supported by the Institut de Recherche Fondamentale du C.E.A..
[19] Supported by Fonds zur Förderung der wissenschaftlichen Forschung, Austria.
[20] Supported by the Korean Science and Engineering Foundation and Ministry of Education.
[21] Supported by the World Laboratory.
[22] On leave of absence from MIT, Cambridge, MA 02139, USA.
[23] Supported by Alexander von Humboldt Fellowship, Germany.
[24] Now at California Institute of Technology, Pasadena, CA 91125, USA.
[25] Now at Dipartimento di Fisica, Università di Milano, Milano, Italy.
[26] Also at CERN, PPE Division, 1211 Geneva 23, Switzerland.
[27] Now at University of California, Santa Cruz, CA 95064, USA.

1. Introduction

With the data collected in 1989 and corresponding to $\sim$ 25000 hadronic Z decays, a search for the neutral Higgs bosons of the Minimal Supersymmetric Extension of the Standard Model (MSSM) had been performed by ALEPH,[1] leading to the exclusion of a large fraction of the domain kinematically accessible in Z decays. Similar results were subsequently reported by the other LEP experiments.[2]

In the derivation of these limits, it was assumed that the tree-level approximation to the full Higgs potential was adequate. Recently, however, it has been realized that substantial radiative corrections occur at the one-loop level if the *top* quark mass is large,[3] thus making a reassessment of these results necessary. In addition, new features arise in the phenomenology of the Higgs bosons of the MSSM, among which a prominent one is the possibility that the CP-odd A boson be less massive than h, the lighter of the two CP-even neutral Higgs bosons. It is therefore necessary to consider, for a complete investigation, a new h decay mode: $h \to AA$.

The analyses presented here were applied to the full data sample, corresponding to $\sim$ 185 000 hadronic Z decays, collected by ALEPH in 1989 and 1990. The results obtained are valid in a large class of two-Higgs-doublet models and are further interpreted in the framework of the MSSM, with one-loop radiative corrections taken into account.

1.1. The class of two-Higgs-doublet models considered

The only class of two-Higgs-doublet models[4] considered here is that in which the *up*-type quarks couple to one of the Higgs doublets, H_2, and thus receive masses proportional to v_2, while the *down*-type quarks and the charged leptons couple to the other doublet, H_1, and receive masses proportional to v_1; here v_2 and v_1 are the vacuum expectation values developed by the neutral components of the two Higgs doublets. The large *top* quark mass value leads to the expectation that $v_2/v_1 > 1$. However, this will not be systematically assumed in the following.

The physical spectrum consists of three neutral bosons, the CP-even h and H and the CP-odd A, and of a pair of charged bosons $H^{\pm}$. If no further specification of the model is made, six parameters are needed to describe the Higgs sector: four Higgs-boson masses, the ratio $\tan\beta = v_2/v_1$, and α, the mixing angle in the CP-even sector.

1.2. Production and decay of neutral Higgs bosons

The phenomenology of the neutral Higgs bosons of two-doublet models in e^+e^- collisions near the Z peak can be easily inferred from their couplings to the Z and to the matter fermions.[4,5] The ZZA coupling vanishes if CP is conserved while the Zhh and ZAA couplings are forbidden by Bose statistics. The ZZh coupling is the same as the minimal Standard Model ZZH_{SM} coupling, except that it is reduced by a factor $\sin(\beta - \alpha)$. The

CP-even h can therefore be searched for just like the minimal Standard Model H_{SM} in the process $e^+e^- \to H_{SM}Z^*$, but with reduced sensitivity:

$$\frac{\Gamma(Z \to hZ^*)}{\Gamma(Z \to H_{SM}Z^*)} = \sin^2(\beta - \alpha).$$

However, when this reduction is strong, the ZhA coupling, proportional to $\cos(\beta - \alpha)$, becomes substantial. This makes a search for the $Z \to hA$ decay promising since the partial width is large:

$$\Gamma(Z \to hA) = \frac{1}{2}\cos^2(\beta - \alpha) \cdot \Gamma_{\nu\bar{\nu}} \cdot \lambda^{\frac{3}{2}} \left(1, \frac{m_h^2}{m_Z^2}, \frac{m_A^2}{m_Z^2}\right)$$

where $\lambda(x, y, z) = (x^2 + y^2 + z^2 - 2xy - 2yz - 2zx)$. Therefore, the searches for $Z \to hZ^*$ and for $Z \to hA$ are to be considered as complementary.

The h decay widths into fermion pairs are deduced from the corresponding ones for H_{SM} by applying factors $f_d = \sin^2\alpha/\cos^2\beta$ for *down*-type quarks and charged leptons, and $f_u = \cos^2\alpha/\sin^2\beta$ for *up*-type quarks. The A decay widths are obtained similarly, but with $f_d = \tan^2\beta$ and $f_u = \cot^2\beta$. For masses well above the $b\bar{b}$ threshold, the A decays mainly to $c\bar{c}$ pairs if $\tan\beta \ll 1$, and to $b\bar{b}$ pairs (but also to $\tau^+\tau^-$ in $\sim 6\%$ of the cases) if $\tan\beta \gtrsim 1$. Model building, particularly within the supersymmetric framework, suggests that the same holds for h decays in spite of the additional dependence on α,[4] and this will be assumed in the following. For very light h and A, below the $\mu^+\mu^-$ threshold, the main decay to e^+e^- remains dominant if $\tan\beta > 1$, but the h lifetime is reduced compared to the H_{SM} lifetime; if $\tan\beta < 1$, the $\gamma\gamma$ decay mode is reinforced, and the lifetime is also modified.

Furthermore, if $m_h > 2m_A$, the CP-even h may decay into a pair of CP-odd A bosons. Indeed, except for some fortuitous choices of parameters such as $\tan\beta = 1$, this decay mode even tends to be dominant.

1.3. Higgs bosons in the MSSM

More detailed predictions can only be made in specific models, of which the most popular is the Minimal Supersymmetric extension of the Standard Model (MSSM).[6] In this model, the number of parameters is greatly reduced with respect to a general two-doublet model: only one Higgs boson mass, say m_A, and $\tan\beta$ (or alternatively another mass, say m_h) suffice. The other Higgs boson masses and the mixing angle α are then all determined.

When the Higgs potential is considered at the tree-level, interesting mass relations arise in the MSSM.[4] In particular, the charged Higgs bosons are always heavier than the W. One of the neutral CP-even states, h, is always lighter than the Z, while the other, H, is heavier than the Z. The mass of the CP-odd state, m_A, is bound to lie between m_h and m_H.

However, this simple picture is modified when the radiative corrections, which are substantial at the one-loop level if the *top* quark mass is large, are taken into account. The main corrections,[3] typically of order

$$\frac{3g^2}{8\pi^2 \sin^2\beta} \frac{m_t^4}{m_W^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right),$$

affect principally the CP-even squared mass matrix (and thus m_h, m_H and α), whereas the charged Higgs boson and the A masses are much less affected[7,8] and the couplings very little,[8] except through the modification of α. In the above expression, $m_{\tilde{t}}$ is the mass of the supersymmetric partners of the *top* quark, assumed to be mass degenerate. As a consequence of these corrections, the tree-level mass relations are deeply modified. In particular, the lighter CP-even state h can even become heavier than the CP-odd A.

1.4. Experimental framework

The results of the searches for neutral Higgs bosons of two-doublet models reported here have been obtained using a sample of $\sim$ 185 000 hadronic Z decays, collected by ALEPH in 1989 and 1990 during a scan of the Z peak and corresponding to an integrated luminosity of 8.6 pb^{-1}. In this sample, all major components of the detector[9] were required to be simultaneously operational and all major trigger logics enabled.

The backgrounds to the searches presented here have been studied using a sample of 265 000 fully simulated $Z \to hadrons$ Monte-Carlo events. In this simulation and in those performed for the Higgs-boson production and decay processes, the Lund Parton Shower algorithm[10] has been used for the fragmentation of the $q\bar{q}$ systems. In addition, Monte-Carlo samples corresponding to at least three times the recorded integrated luminosity have been used to study the backgrounds from $e^+e^- \to l^+l^-$, $e^+e^- \to (e^+e^-)l^+l^-$ ($l = e$, μ or τ) and $e^+e^- \to (e^+e^-)hadrons$. The signal processes have been simulated with due account taken of the luminosities accumulated at the various energies of the scan and of the effect of initial state radiation. This is particularly relevant when the mass domain studied is close to the kinematic limit.

In all the analyses performed to derive the results presented here, a standard ALEPH algorithm[11] has been used to reconstruct the energy flow. The algorithm classifies the components of the final state as charged particles, photons and neutral hadrons, and the energy resolution obtained for well contained hadronic events is $\sim 9\%$.

2. Searches for $e^+e^- \to hZ^*$

The ALEPH searches for the minimal Standard Model Higgs boson H_{SM} in the reaction $e^+e^- \to H_{SM}Z^*$ have been described previously.[12] The final state topologies which have been investigated are:

- acoplanar lepton pairs,
- four leptons,
- monojets,
- acoplanar jets,
- energetic lepton pairs in hadronic events,
- isolated charged particle pairs in hadronic events,
- isolated charged particles in hadronic events.

No candidate events were found in any of these analyses, which excludes at 95% CL a Standard Model Higgs boson with a mass smaller than 48 GeV/c^2. These searches, hereafter called "standard searches," have been optimized for the detection of a Higgs boson with mass $\sim$ 50 GeV/c^2, either decaying into a *tau* pair and produced in association with a $\nu\bar{\nu}$, l^+l^- or $q\bar{q}$ pair, or decaying hadronically and produced in association with a $\nu\bar{\nu}$ or l^+l^- pair ($l = e$, μ or τ). For the last four of the topologies in the above list, the charged multiplicities are required to exceed 5, 7, 7 and 6, respectively, corresponding to a minimum detected charged multiplicity of 5 in the Higgs boson decay.

The standard searches for $e^+e^- \to H_{SM}Z^*$ can be reinterpreted in the context of two-Higgs-doublet models as searches for h in $e^+e^- \to hZ^*$. Assuming the selection efficiencies to be similar for the two processes, the only difference comes from the cross-section reduction by the factor $\sin^2(\beta-\alpha)$. Then, if N_{exp}^{SM} is the number of events expected to be observed in the Standard Model case for a Higgs boson with mass $m_{H_{SM}}$, a 95% CL upper limit on $\sin^2(\beta-\alpha)$ can be set at the value $3.0/N_{exp}^{SM}$ for $m_h = m_{H_{SM}}$ (3.0 is the 95% CL upper limit on any signal when no events were observed). Indeed, the detection efficiencies are in general the same for h and H_{SM} because the standard searches are sufficiently inclusive not to be affected, for instance, by the proportion of Higgs boson decays into $c\bar{c}$ or $b\bar{b}$. This is not the case, however, when $m_h < 2m_\mu$ since the results of the H_{SM} searches performed in this mass range are affected by the H_{SM} lifetime. Therefore, no general limit on $\sin^2(\beta-\alpha)$ can be derived when $m_h < 2m_\mu$.

In addition, if the decay $h \to AA$ can take place, the standard searches have to be reexamined according to the A decay modes. When $m_A > 2m_b$, their efficiencies are at least as large as if the $h \to AA$ channel were closed. On the other hand, for lighter A bosons, some of those searches, developed for a high mass H_{SM}, which is expected to decay to large multiplicity final states, may not apply efficiently since a substantial fraction of the Higgs boson decay final states then contains only four charged particles.[13] This is particularly true for $2m_\tau < m_A < 2m_b$ and $\tan\beta \gg 1$, a case where the decay mode $A \to \tau^+\tau^-$ dominates. These searches have therefore been slightly modified in order to cope with this specific configuration:

For the $Z^* \to \nu\bar{\nu}$ final state, the event is required to contain exactly four charged particle tracks originating from the beam crossing point, each making an angle θ with the beam axis such that $|\cos\theta| < 0.95$. In order to avoid energy losses in the beam pipe region, the total energy measured within 12° of the beam axis should not exceed 1 GeV. The event is then divided into two hemispheres by a plane perpendicular to the thrust axis. Each hemisphere has to contain a total energy of at least 2 GeV and exactly two charged particle tracks, with total electric charge zero. To remove low charged multiplicity hadronic Z decays, the acoplanarity angle between the directions of the total momenta of the two hemispheres is required to be smaller than 175°. Finally, to remove events from $\gamma\gamma$ interactions, the total momentum transverse to the beam axis should exceed 5% of the centre-of-mass energy unless the total mass of the event is larger than 25 GeV/c^2.

For the $Z^* \to l^+l^-$ final state, with $l = e$ or μ, the search for energetic lepton pairs in hadronic events has been repeated, but now requiring a multiplicity of exactly six charged particle tracks.

No events were found in either of these searches, while 0.3 are expected from the background processes. When combined with the standard searches, these analyses provide a 21% efficiency for the detection of a 48 GeV/c^2 h boson produced in the reaction $e^+e^- \to hZ^*$ and decaying into a pair of 6 GeV/c^2 A bosons.

The upper limit on $\sin^2(\beta - \alpha)$ as a function of m_h obtained when combining all these searches is presented in Fig. 1.

3. Results inferred from the Z partial width measurements

The cases not excluded by the searches for $e^+e^- \to hZ^*$ correspond to m_h too large or to $\sin^2(\beta - \alpha)$ much smaller than unity. In the latter instance, however, it is expected that $Z \to hA$ occurs at a substantial rate if kinematically allowed. Hence the Z width measurements provide constraints on this process.

ALEPH has measured[14] $B_l = \Gamma_{ll}/\Gamma_Z = (3.34 \pm 0.02)\%$, where Γ_{ll} is the Z leptonic width and Γ_Z the Z total width, from which it can be inferred that any contribution to the Z width from non-standard processes is limited to less than 0.26 $\Gamma_{\nu\bar{\nu}}$ at 95% CL, with $\Gamma_{\nu\bar{\nu}}$ the Z decay width into a neutrino pair. To obtain this limit, *(i)* it has been assumed that no non-standard processes contaminate the selection of lepton pairs; *(ii)* the Standard Model expectation for B_l has been conservatively decreased by its theoretical uncertainty (which is dominated by the uncertainty in α_s); and *(iii)* the probability distribution for B_l has been conservatively restricted to the physically acceptable domain (bounded from above by the Standard Model expectation) and normalized to unity therein.[15]

A 95% CL upper limit on $\cos^2(\beta - \alpha)$ can thus be derived for any (m_h, m_A). Taking into account the upper limit on $\sin^2(\beta - \alpha)$ obtained for the same m_h from the searches for $Z \to hZ^*$ reported above, this (m_h, m_A) is excluded if the sum of these limits is less than unity. The resultant excluded region in the (m_h, m_A) plane is shown by curve (A) in Fig. 5.

More stringent limits can be obtained when the hA final state has a topology such that it cannot contribute to the hadronic standard selection[14] which requires, in particular, at least five charged particle tracks. From the ALEPH measurement[14] $\sigma^0_{had} = (41.44 \pm 0.36)$ nb, where σ^0_{had} is the peak hadronic cross-section, one infers[16] that the contribution of such final states is limited to less than 0.13 $\Gamma_{\nu\bar{\nu}}$ at 95% CL. The corresponding upper limit on $\cos^2(\beta - \alpha)$ is 0.27 for m_h and $m_A \ll m_Z$. Within the MSSM, this excludes the delicate region $m_h < 2m_\mu$ since, for such small values of m_h, A is predicted to be lighter than h and $\cos^2(\beta - \alpha)$ close to unity when one-loop radiative corrections are taken into account.

4. Searches for $Z \rightarrow hA$

Even for $\sin^2(\beta - \alpha)$ substantially smaller than unity, it is not possible to obtain any limitation from the Z width measurements when m_h or m_A are sufficiently large. Direct searches for $Z \rightarrow hA$ must therefore be performed.

4.1. Search in four-jet final states

For sufficiently massive Higgs bosons, a search in the 4-jet topology is relevant, the final state being predominantly $c\bar{c}c\bar{c}$ when $\tan\beta \ll 1$, or $b\bar{b}b\bar{b}$ when $\tan\beta \gtrsim 1$. A search for a localized excess in the jet-jet mass distribution in 4-jet events therefore has been performed. This was optimized to differentiate the signal from high mass ($\gtrsim$ 35 GeV/c^2) Higgs bosons from standard hadronic Z decays.

Events with at least five charged particle tracks originating from the beam crossing point and carrying more than 10% of the centre-of-mass energy are clustered into jets using the JADE algorithm,[17] with a y_{cut} value of 0.03 corresponding to a maximum jet mass of about 16 GeV/c^2. Only events with at least four jets are kept, and those with five jets or more are further reduced by merging into a single jet the jet pair with the smallest invariant mass until only four jets are left. To ensure that the four jets are well separated, it is required in addition that no jet-jet angle be less than 50°. To improve the jet energy resolution, the energies of the four jets are recalculated from their directions, imposing energy-momentum conservation and keeping fixed the jet velocities.[18] It is then required that all jet energies be greater than $0.25E_{beam}$ and smaller than $0.70E_{beam}$.

For each of the three possible pairings in the four-jet system, the following angles are defined:

(i) the production angle θ^p formed by the common direction of the pairs with the beam axis,

(ii) the decay angles θ_i^d (with $i = 1$ or 2 labelling the jet pairs) between the direction of one of the jets of pair i and the direction of the pair itself, measured in the pair rest frame.

An accepted pairing has to fulfil the following conditions:

(i) $50° < \theta^p < 130°$, which takes advantage of the $\sin^2\theta^p$ distribution expected for the signal, in contrast to the $1 + \cos^2\theta^p$ distribution of the standard hadronic Z decays,

(ii) $50° < \theta_i^d < 130°$ for at least one of the pairs, which takes advantage of the isotropic angular distribution of the decay of spin-0 particles, in contrast to the QCD background

in which daughter jets tend to be emitted at small angles with respect to their parent jets.

At this point, 1495 events are selected in the data while 1443 are expected from standard hadronic Z decays.

For each of the retained pairings, the sum $M = m_1 + m_2$ and the difference $m = |m_1 - m_2|$ of the two pair masses are calculated. Because of the overall energy-momentum conservation constraint imposed in the determination of the jet energies, these variables are much less correlated than m_1 and m_2, and the resolution is substantially better for M than for m. The (M, m) plane is divided into overlapping bins of size 4×10 (GeV/c^2)^2, corresponding to about twice the resolution, and scanned in steps of 250 MeV/c^2 in M and 625 MeV/c^2 in m. The probability for a $c\bar{c}c\bar{c}$ event induced by the pair production of Higgs bosons with masses $m_h = m_A = 41$ GeV/c^2 to lead to at least one combination in the bin ($|M - 2 \times 41 \text{ GeV}/c^2| < 2$ GeV/c^2, $m < 10$ GeV/c^2) is 19%.

A polynomial fit to the distibution in M and m expected from standard hadronic Z decays is performed in order to smooth out the fluctuations induced by the limited Monte-Carlo statistics. A local excess is then sought in the data by comparing in each bin the number of events observed to the expectation from the polynomial. The result of this comparison, measured in each bin as a signed number of standard deviations, is shown in Fig. 2. The distribution is well described by a normalized Gaussian, showing that data and simulation are in good agreement. In particular, no excess, which would be signalled by large positive fluctuations, is observed in the data.

For a given pair of values for the Higgs boson masses, the content N_{obs} of the appropriate bin is compared to the expectation μ_{exp} from standard hadronic Z decays. A 95% CL upper limit for the expectation value of any contribution additional to μ_{exp} is then derived,[15] giving an upper limit on $\cos^2(\beta - \alpha)$ for that pair of mass values. In order to obtain a conservative upper limit, N_{obs} has been used in the calculation instead of μ_{exp} whenever N_{obs} had fluctuated below μ_{exp}. In addition, a systematic error of 10% has been subtracted from the expected number of signal events to account for the limited Monte-Carlo statistics and for uncertainties in the modelling of quark hadronization.

The 95% CL upper limit on $\cos^2(\beta - \alpha)$ resulting from this search is shown in Figs. 3a and 4 as a function of m_h and m_A for $\tan\beta \ll 1$, the case in which the $c\bar{c}c\bar{c}$ final state is dominant. The results for $\tan\beta \gtrsim 1$ are not shown because, in that case, more stringent limits can be obtained from the search in the $\tau^+\tau^- b\bar{b}$ final state.

4.2. Search in the $\tau^+\tau^-$ – hadrons final state

Some of the standard searches for $e^+e^- \to H_{SM}Z^*$ had been developed to be particularly sensitive to the $\tau^+\tau^-$*hadrons* final state. The standard searches can therefore be efficiently applied to the $\tau^+\tau^- b\bar{b}$ final state resulting from $e^+e^- \to hA$ which contributes $\sim 12\%$ when $\tan\beta \gtrsim 1$, at least when $m_A > m_h/2$. For $m_h = m_A = 42$ GeV/c^2, the resulting efficiency is 25%. The 95% CL upper limit on $\cos^2(\beta - \alpha)$ thus obtained for $\tan\beta \gtrsim 1$ is shown in Figs. 3b and 4 as a function of m_h and m_A.

However, if either h or A becomes light enough to decay predominantly to ≤ 4 charged particles, the latter search becomes less efficient (with an efficiency of 15% for $m_h = 48$ GeV/c^2 and $m_A = 6$ GeV/c^2). Therefore a specific analysis has been developed for this case:

The events are required to contain four or six charged particle tracks originating from the beam crossing point, with total electric charge zero, each making an angle θ with the beam axis such that $|\cos\theta| < 0.95$. The total energy measured within 12° of the beam axis should not exceed 1 GeV. The JADE algorithm[17] is then used to form jets, with a y_{cut} value of 0.01 corresponding to a maximum jet mass of about 9 GeV/c^2. Events are selected with exactly three such jets, one of which should contain a single positively charged particle and another a single negatively charged particle. Each of these two "*tau*-jets" is required to have a mass smaller than 1.8 GeV/c^2. To remove the background from low multiplicity hadronic Z decays which tend to exhibit a back-to-back topology, the maximum angle between two jet directions should not exceed 165°. To take advantage of the missing energy carried away by the neutrinos in *tau* decays, the total energy has to be less than 85% of the centre-of-mass energy. Only two events survived at this stage, both identified as $\tau^+\tau^-\gamma$ final states with the photon converting into an e^+e^- pair in the detector material. Both of these events are eliminated using an algorithm designed to identify such converted pairs. No candidate event was found in any of the background Monte-Carlo samples.

With this analysis taken into account, the overall efficiency becomes 30% for $m_h = 48$ GeV/c^2 and $m_A = 6$ GeV/c^2 (or *vice versa*), when h (or A) decays to a *tau* pair.

4.3. Search in the AAA final state

If $m_A < m_h/2$, the decay $h \to AA$ can take place, leading to a final state consisting of three A bosons. The ultimate topology then depends on m_A. If $\tan\beta \gtrsim 1$, the search for $\tau^+\tau^-$*hadrons* final states is applicable without any modification as long as $m_A > 2m_b$, but a new search had to be developed specifically for topologies consisting of three low multiplicity jets in order to cope with lower mass A bosons: if $2m_b > m_A > 2m_\tau$, each jet contains two *taus*, and thus two (four) charged particles in 72% (26%) of the cases; if $m_A < 2m_\tau$, the A-decay charged particle multiplicity is two (two or four) in $\gtrsim 20\%$ ($\gtrsim 70\%$) of the cases.[13]

The events are required to contain six or eight charged particle tracks originating from the beam crossing point, with total electric charge zero, each making an angle θ with the beam axis such that $|\cos\theta| < 0.95$. The total energy measured within 12° of the beam axis should not exceed 1 GeV. The JADE algorithm is again used to form jets, with $y_{cut} = 0.01$. Exactly three such jets are required, each electrically neutral and containing two or four charged particles. The maximum angle between two jet directions should not exceed 165°. Finally, the total energy has to be smaller than 85% of the centre-of-mass energy. However, in order to retain efficiency if $m_A \lesssim 2m_\tau$, this last criterion is not applied if the three jet masses are smaller than 4.5 GeV/c^2.

No events satisfied these criteria, either in the data or in any of the background Monte-Carlo samples, while the efficiency of this selection is 16% for $m_h = 48$ GeV/c^2 and $m_A = 6$ GeV/c^2, when h decays to an A pair and $\tan\beta \gtrsim 1$. Except for $m_A < 2m_c$, this analysis does not apply for $\tan\beta < 1$ because the typical A-decay multiplicity is too large when $A \to c\bar{c}$.

5. Results and conclusions

5.1. Results valid in general two-Higgs-doublet models

In any two-Higgs-doublet model of the class considered here, the 95% CL upper limit on $\cos^2(\beta-\alpha)$, obtained as a function of m_h and m_A from the Z width measurements and from the direct searches for $Z \to hA$, can be combined with the 95% CL upper limit on $\sin^2(\beta-\alpha)$ obtained for the same m_h from the searches for $e^+e^- \to hZ^*$: a given (m_h, m_A) pair is excluded at the 95% confidence level if the sum of these two upper limits is smaller than unity.

The domain thus excluded for $\tan\beta \gtrsim 1$ is limited by curve (B) in Fig. 5. In particular, $m_h = m_A < 43.4$ GeV/c^2 is excluded at 95% CL.

For $\tan\beta \ll 1$, the excluded domain is limited by a curve similar to (B) in Fig. 5, but extending only to $m_h = m_A = 42.9$ GeV/c^2. In addition, as explained in Section 4.3, the limit obtained using the Z width measurements, indicated by curve (A) in Fig. 5, is the only one appropriate when $m_A < m_h/2$.

5.2. Results valid in the framework of the MSSM

Within the MSSM, larger excluded domains can be inferred. For instance, $m_h = m_A < 44.4$ GeV/c^2 (< 44.2 GeV/c^2) would be excluded at 95% C.L for $\tan\beta \gg 1$ ($\ll 1$) if the tree-level relations were valid. When one-loop radiative corrections are taken into account, the situation is more complicated as the prediction depends on a number of unknown parameters, with a particularly large sensitivity to the *top* quark mass.[3,7] As an example, the domain excluded for $\tan\beta > 1$, the only case considered in the literature,[3] is shown in Fig. 5 for $m_t = 140$ GeV/c^2, for $m_{\tilde{t}} = 1$ TeV/c^2 and for negligible mixing among the supersymmetric partners of the *top* quark. The same result is shown in Fig. 6 as an excluded domain in the ($\tan\beta$ *vs* m_A) plane. This presentation has the advantage that the occasional twofold ambiguity in the values of $\tan\beta$ corresponding to a given (m_h, m_A) couple is removed.

For the above choice of parameters, $m_h < 41$ GeV/c^2 and $m_A < 31$ GeV/c^2 are excluded at 95% CL. It can also be seen that $\tan\beta = 1$ remains allowed when $m_A > 31$ GeV/c^2. Similarly constraining limits are obtained when the *top* quark mass is varied. For instance, still with $m_{\tilde{t}} = 1$ TeV/c^2, m_h and m_A have to exceed 41 and 44 GeV/c^2, respectively, when $m_t = 90$ GeV/c^2, or 44 and 25 GeV/c^2, respectively, when $m_t = 190$ GeV/c^2. If $m_{\tilde{t}}$ is further allowed to vary from m_t to a few TeV/c^2 and m_t up to a few hundred GeV/c^2, 95% CL lower limits of 41 GeV/c^2 on m_h and of 20 GeV/c^2 on m_A remain valid.

In conclusion, lower mass limits for the CP-even h and for the CP-odd A neutral Higgs bosons of the MSSM have been established taking into account the one-loop radiative corrections to the Higgs potential.

Acknowledgements

We wish to congratulate and thank our colleagues in the LEP Division for the remarkable performance of the LEP accelerator. We also thank the engineers and technicians in all our institutions for their support in constructing and operating ALEPH. Those of us from non-member countries thank CERN for its hospitality.

References

1. D. Decamp *et al.*, ALEPH Coll., Phys. Lett. 237B (1990) 291;
   D. Decamp *et al.*, ALEPH Coll., Phys. Lett. 241B (1990) 141.
2. P. Abreu *et al.*, DELPHI Coll., Phys. Lett. 245B (1990) 276;
   B. Adeva *et al.*, L3 Coll., Phys. Lett. 251B (1990) 311;
   M.Z. Akrawy *et al.*, OPAL Coll., Z. Phys. C49 (1991) 1.
3. Y. Okada, M. Yamaguchi and T. Yanagida, Progr. Theor. Phys. Lett. 85 (1991) 1, and preprint TU-363 (1990);
   J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. 257B (1991) 83;
   H.E. Haber and R. Hempfling, Phys. Rev. Lett. 66 (1991) 1815;
   R. Barbieri, M. Frigeni and F. Caravaglios, Phys. Lett. 258B (1991) 167;
   R. Barbieri and M. Frigeni, Phys. Lett. 258B (1991) 395.
4. J.F. Gunion, H.E. Haber, G. L. Kane and S. Dawson, "The Higgs Hunter's Guide" (Addison Wesley, 1990).
5. P.J. Franzini, P. Taxil *et al.*, *in* "Z Physics at LEP", CERN-89-08, eds. G. Altarelli, R. Kleiss and C. Verzegnassi, Vol.II, p.59.
6. H.-P. Nilles, Phys. Rep. C110 (1984) 1;
   H.E. Haber and G.L. Kane, Phys. Rep. C117 (1985) 75;
   R. Barbieri, Riv. Nuovo Cimento 11 (1988) 1.
7. J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. 262B (1991) 477.
8. F. Zwirner, private communication.
9. D. Decamp *et al.*, ALEPH Coll., Nucl. Inst. and Methods A294 (1990) 121.
10. T. Sjöstrand *et al.*, *in* "Z Physics at LEP", *op. cit.*, Vol.III, p.143.
11. D. Decamp *et al.*, ALEPH Coll.,Phys. Lett. 246B (1990) 306.
12. D. Decamp *et al.*, ALEPH Coll., Searches for the Standard Higgs Boson produced in the reaction $e^+e^- \to H^0Z^*$, CERN-PPE/91-19, January 1991.
13. P. Janot, Update and improvements of the ALEPH Higgs decay simulation, H0SDECAY, LAL 89-45 (1989).
14. D. Decamp *et al.*, ALEPH Coll., Improved Measurements of Electrowak Parameters from Z Decays into Fermion Pairs, CERN-PPE/91-105, July 1991.
15. Particle Data Group, Phys. Lett. 239B (1990), p.III-35,III-36.
16. D. Decamp *et al.*, ALEPH Coll.,Phys. Lett. 236B (1990) 511.
17. S. Bethke *et al.*, JADE Coll., Phys. Lett. 213B (1988) 235.
18. S.L. Wu, Z. Phys. C9 (1981) 329.

Figure Captions

1. 95% CL upper limit on $\sin^2(\beta-\alpha)$, as a function of m_h, inferred from the searches for $e^+e^- \to hZ^*$.

2. In the analysis of four-jet final states, distribution of the normalized fluctuation $(N_{obs}-\mu_{exp})/\sqrt{\mu_{exp}}$, where N_{obs} and μ_{exp} are the numbers of events observed in the data and expected from standard hadronic Z decays, respectively, in $4\times10(\mathrm{GeV}/c^2)^2$ bins in the (M,m) plane. There are 6336 entries. A Gaussian fit yields a mean of 0.04 and a σ of 0.99.

3. In the (m_A *vs* m_h) plane, equal value contours for the 95% CL upper limit on $\cos^2(\beta-\alpha)$, inferred from the direct searches for $Z\to hA$.

   In (a), $\tan\beta \ll 1$ and the limits were obtained from the search in four-jet final states.

   In (b), $\tan\beta \gtrsim 1$ and the limits were obtained from the search in $\tau^+\tau^-$ *hadrons* final states.

   In both cases, the innermost contour corresponds to a value of 0.2, and this value is to be increased by 0.2 for each new contour encountered when moving outwards. The heavy line is the kinematic limit in Z decays.

4. 95% CL upper limit on $\cos^2(\beta-\alpha)$ when $m_h = m_A$ for $\tan\beta \gtrsim 1$ (heavy line) and for $\tan\beta \ll 1$ (light line).

5. In the (m_A *vs* m_h) plane and for $\tan\beta > 1$, domains excluded by the searches for $e^+e^- \to hZ^*$ combined with the Z width measurements (A) and with the direct searches for $Z\to hA$ (B). The region theoretically forbidden in the MSSM when one-loop radiative corrections are taken into account is shown in light grey. The following choice of unknown parameters has been made: m_t=140 GeV/c^2 and $m_{\tilde{t}}$=1 TeV/c^2; negligible mixing among the supersymmetric partners of the *top* quark has been assumed. Under these assumptions, the dark region is also excluded by the searches reported here, and the hatched area is excluded for the lower of the two possible values of $\tan\beta$ allowed therein.

6. In the ($\tan\beta$ *vs* m_A) plane, domains excluded by the searches for $e^+e^- \to hZ^*$ and by the direct searches for $Z\to hA$. Here the MSSM is assumed, and one-loop radiative corrections are taken into account with the same choice of parameters as in Fig. 5.

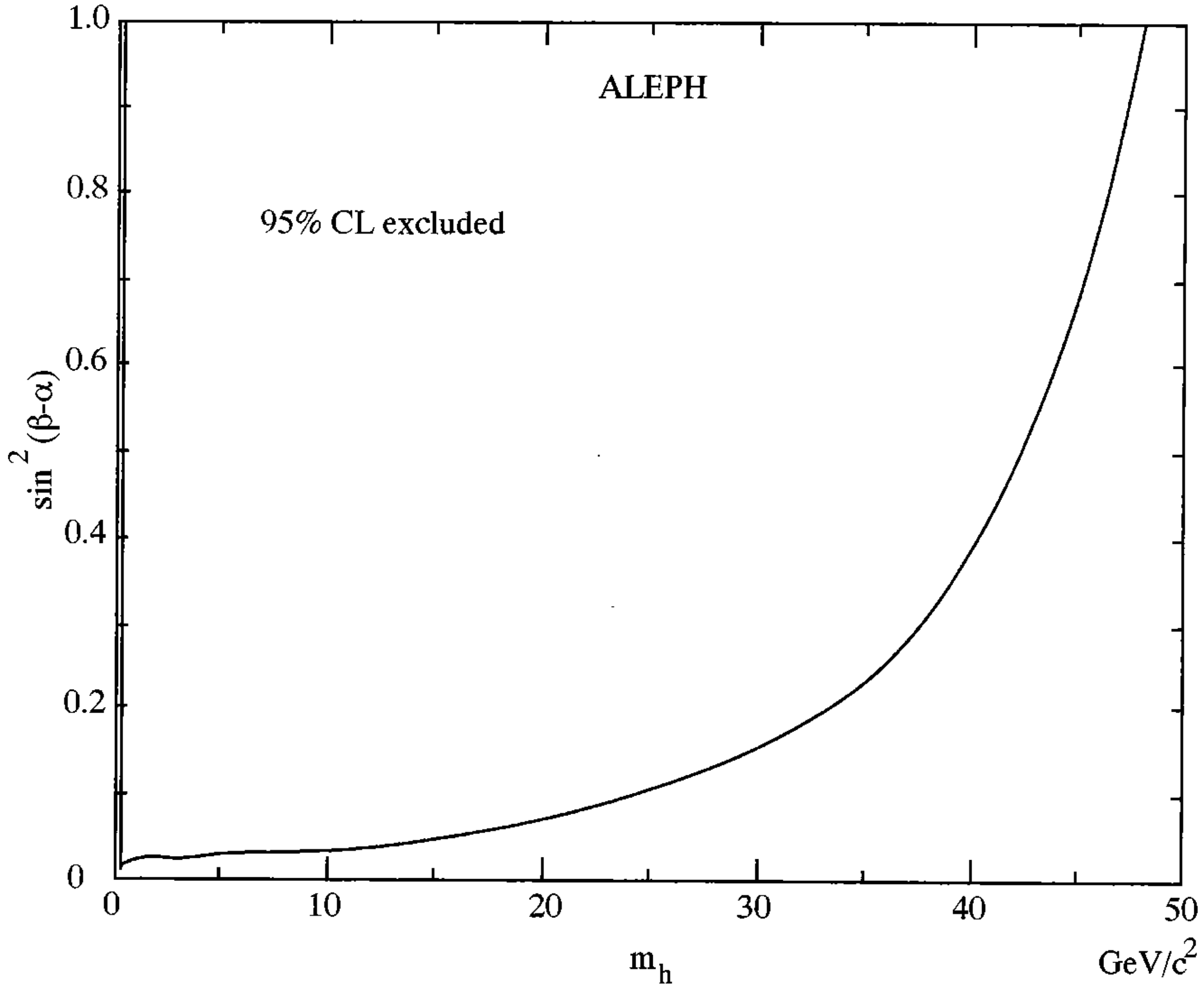

ALEPH
95% CL excluded
sin²(β-α)
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
m_h
GeV/c²

Figure 1

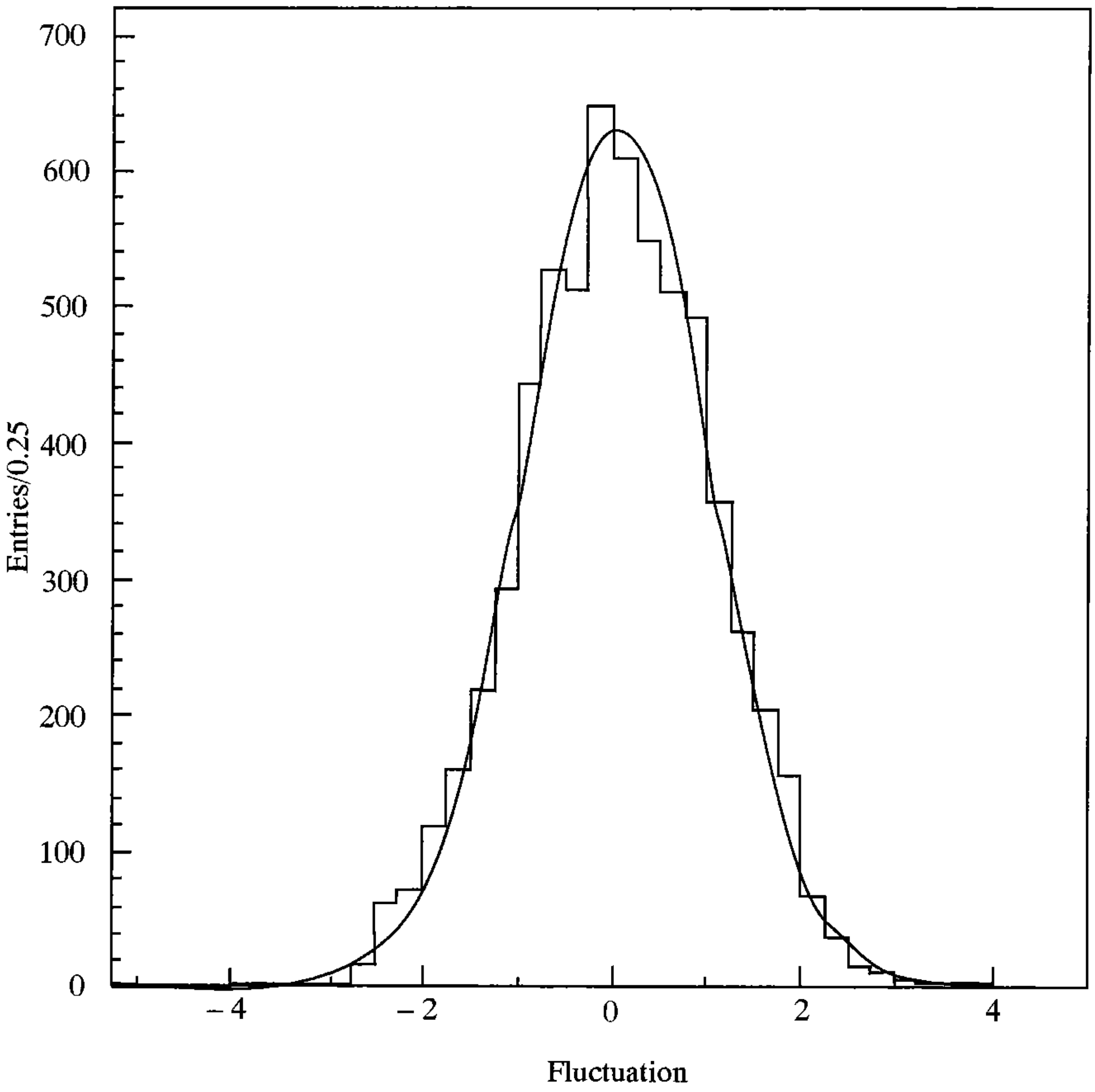


Figure 2

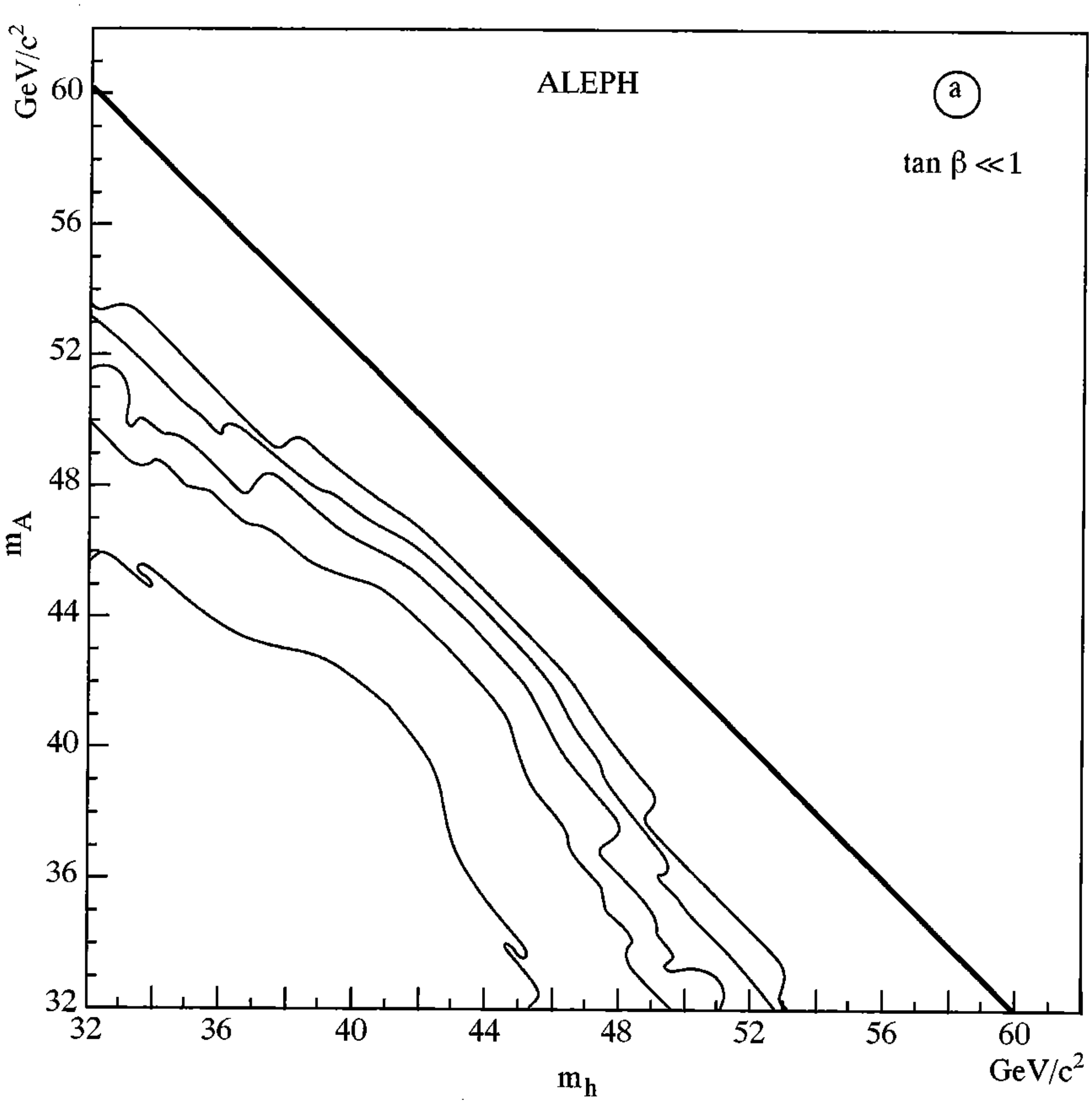
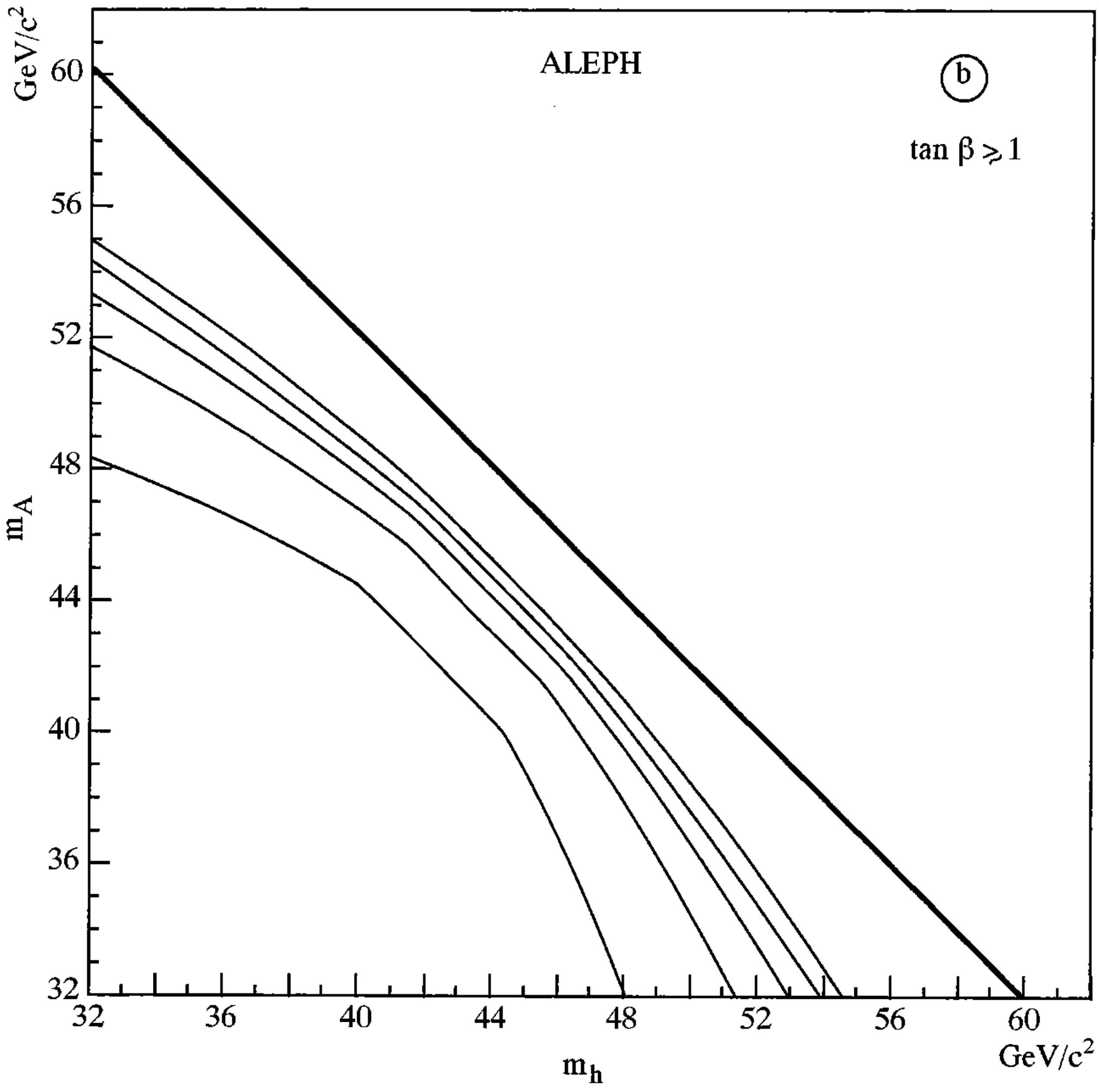

ALEPH
a
tan β ≪1
GeV/c²
60
56
52
48
44
40
36
32
m_A
32
36
40
44
48
52
56
60
GeV/c²
m_h

Figure 3a



ALEPH
b
tan β ≳ 1
GeV/c²
60
56
52
48
44
40
36
32
m_A
32
36
40
44
48
52
56
60
GeV/c²
m_h

Figure 3b

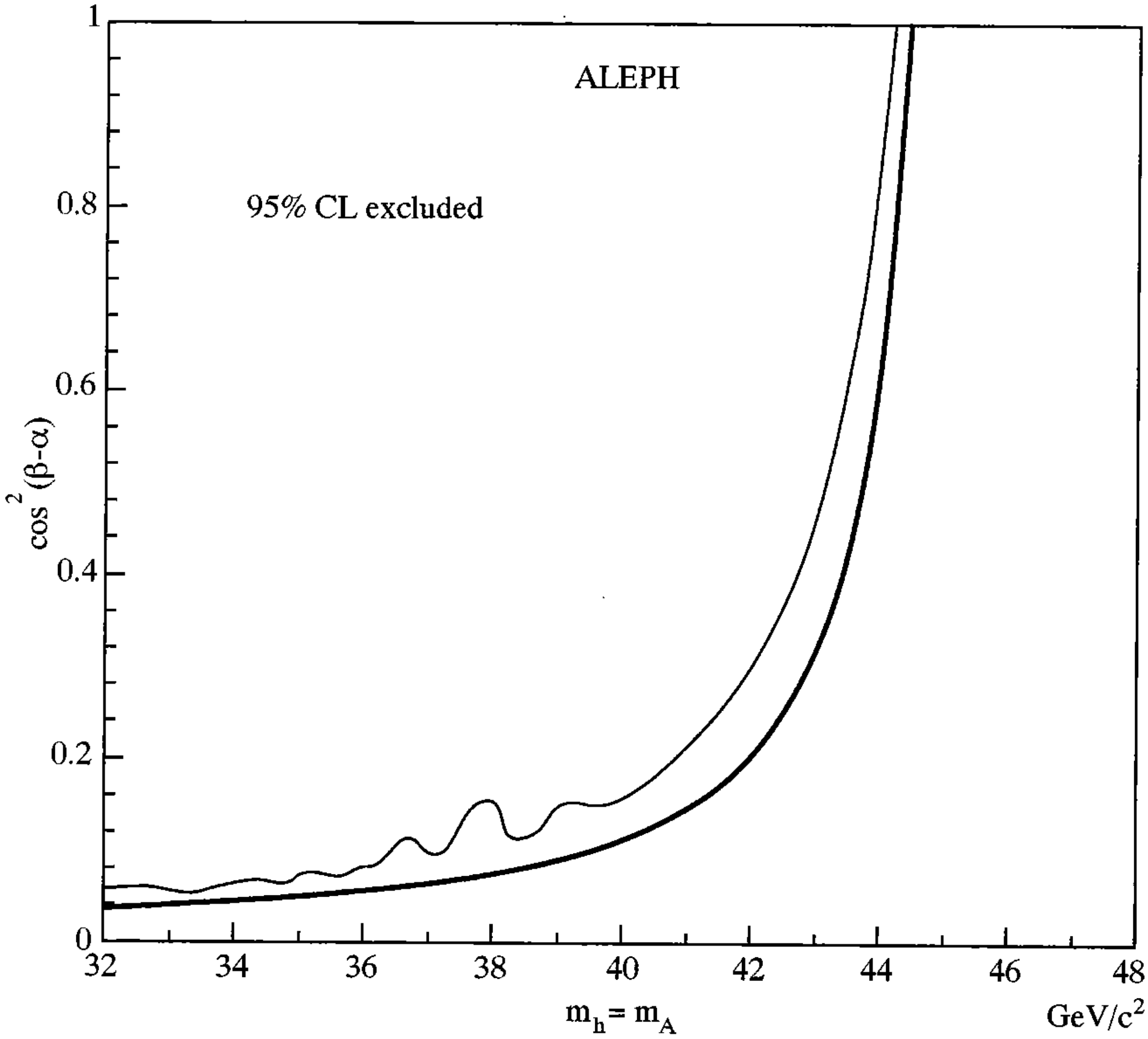
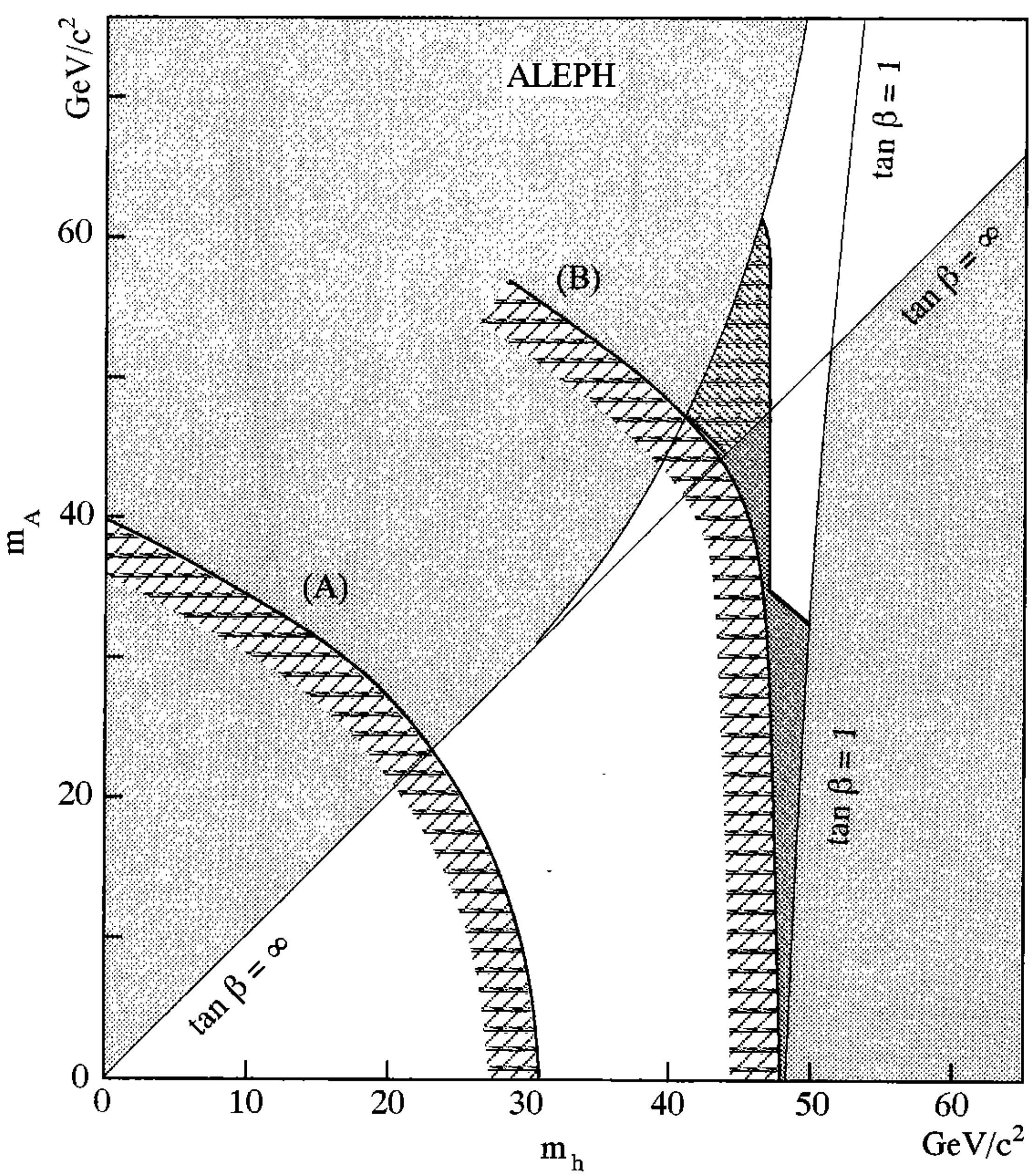

ALEPH
95% CL excluded
cos²(β-α)
1
0.8
0.6
0.4
0.2
0
32
34
36
38
40
42
44
46
48
m_h = m_A
GeV/c²

Figure 4



ALEPH
GeV/c²
60
40
20
0
10
20
30
40
50
60
m_A
m_h
GeV/c²
(A)
(B)
tan β = 1
tan β = ∞
tan β = ∞
tan β = 1

Figure 5

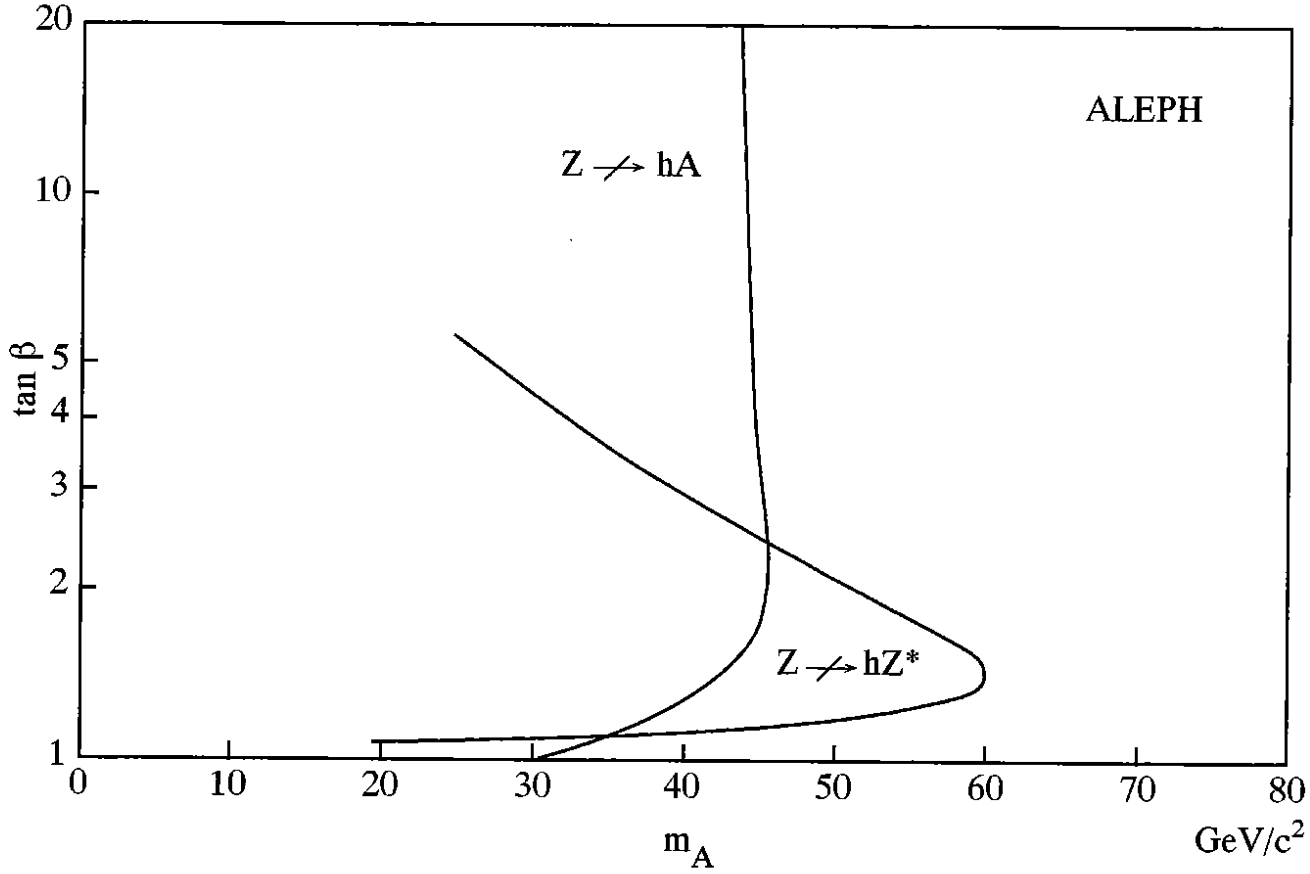


Figure 6