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Search for the Neutral Higgs Boson from Z^o Decay in the Higgs Mass Range between 11 and 24 GeV

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The ALEPH Collaboration

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

Laboratoire de Physique des Particules (LAPP), IN²P³-CNRS, 74019 Annecy-le-Vieux Cedex, France

J.M. Crespo, M. Delfino, E. Fernandez[1], M. Martinez, R. Miquel, Ll.M. Mir, S. Orteu, A. Pacheco, J.A. Perlas, E. Tubau

Laboratorio de Fisica de Altas Energias, Universidad Autonoma de Barcelona, 08193 Bellaterra (Barcelona), Spain[10]

M.G. Catanesi, M. de Palma, A. Farilla, G. Iaselli, G. Maggi, S. Natali, S. Nuzzo, 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, D. Huang, S. Jin, J. Lin, T. Ruan, T. Wang, W. Wu, Y. Xie, D. Xu, R. Xu, J. Zhang, Z. Zhang, W. Zhao

Institute of High-Energy Physics, Academia Sinica, Beijing, The People's Republic of China[11]

H. Albrecht[2], W.B. Atwood[3], F. Bird, E. Blucher, T.H. Burnett[4], T. Charity, H. Drevermann, Ll. Garrido, C. Grab, R. Hagelberg, S. Haywood, B. Jost, M. Kasemann, G. Kellner, J. Knobloch, A. Lacourt, I. Lehraus, T. Lohse, D. Lüke[2], A. Marchioro, P. Mato, J. May, A. Minten, A. Miotto, P. Palazzi, M. Pepe-Altarelli, F. Ranjard, A. Roth, J. Rothberg[4], H. Rotscheidt, W. von Rüden, R. St.Denis, D. Schlatter, M. Takashima, M. Talby[5], H. Taureg, W. Tejessy, H. Wachsmuth, S. Wheeler, W. Wiedenmann, W. Witzeling, J. Wotschack

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

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

Laboratoire de Physique Corpusculaire, Université Blaise Pascal, IN²P³-CNRS, Clermont-Ferrand, 63177 Aubière, France

J.D. Hansen, J.R. Hansen, P.H. Hansen, R. Mø llerud, G. Petersen

Niels Bohr Institute, 2100 Copenhagen, Danmark[12]

E. Simopoulou, A. Vayaki

Nuclear Research Center Demokritos (NRCD), Athens, Greece

J. Badier, A. Blondel, G. Bonneaud, J. Bourotte, F. Braems, J.C. Brient, M.A. Ciocci, G. Fouque, R. Guirlet, A. Rougé, M. Rumpf, R. Tanaka, H. Videau, I. Videau[1]

Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN²P³-CNRS, 91128 Palaiseau Cedex, France

(Submitted to Phys. Lett. B)

D.J. Candlin

Department of Physics, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom[13]

A. Conti, G. Parrini

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

M. Corden, C. Georgiopoulos, J.H. Goldman, M. Ikeda, J. Lannutti, D. Levinthal[18], M. Mermikides, L. Sawyer, G. Stimpfl

Supercomputer Computations Research Institute and Dept. of Physics, Florida State University, Tallahassee FL 32306, USA[15,16,17]

A. Antonelli, R. Baldini, G. Bencivenni, G. Bologna[6], F. Bossi, P. Campana, G. Capon, V. Chiarella, G. De Ninno, B. D'Ettorre-Piazzoli[7], G. Felici, P. Laurelli, G. Mannocchi[7], F. Murtas, G.P. Murtas, G. Nicoletti, P. Picchi[6], P. Zografou

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

B. Altoon, O. Boyle, A.W. Halley, I. ten Have, J.L. Hearns, I.S. Hughes, J.G. Lynch, W.T. Morton, C. Raine, J.M. Scarr, K. Smith[1], A.S. Thompson

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom[13]

B. Brandl, O. Braun, R. Geiges, C. Geweniger[1], P. Hanke, V. Hepp, E.E. Kluge, Y. Maumary, M. Panter, A. Putzer, B. Rensch, A. Stahl, K. Tittel, M. Wunsch

Institut für Hochenergiephysik, Universität Heidelberg, 6900 Heidelberg, Fed. Rep. of Germany[19]

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

Department of Physics, Imperial College, London SW7 2BZ, United Kingdom[13]

P. Girtler, D. Kuhn, G. Rudolph

Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria[21]

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

Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom[13]

T. Barczewski, L.A.T. Bauerdick, K. Kleinknecht[1], B. Renk, S. Roehn, H.-G. Sander, M. Schmelling, F. Steeg

Institut für Physik, Universität Mainz, 6500 Mainz, Fed. Rep. of Germany [19]

J-P. Albanese, J-J. Aubert, C. Benchouk, A. Bonissent, D. Courvoisier, F. Etienne, E. Matsinos, S. Papalexiou, P. Payre, B. Pietrzyk[1], Z. Qian

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

W. Blum, P. Cattaneo, G. Cowan, B. Dehning, H. Dietl, M. Fernandez-Bosman, D. Hauff, A. Jahn, E. Lange, G. Lütjens, G. Lutz, W. Männer, H-G. Moser, Y. Pan, R. Richter, A.S. Schwarz, R. Settles, U. Stiegler, U. Stierlin, J. Thomas, G. Waltermann

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, 8000 München, Fed. Rep. of Germany[19]

V. Bertin, G. de Bouard, J. Boucrot, O. Callot, X. Chen, A. Cordier, M. Davier, G. Ganis, J.-F. Grivaz, Ph. Heusse, P. Janot, V. Journé, D.W. Kim, J. Lefrançois, A.-M. Lutz, J.-J. Veillet, F. Zomer

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

S.R. Amendolia, G. Bagliesi, G. Batignani, L. Bosisio, U. Bottigli, C. Bradaschia, I. Ferrante, F. Fidecaro, L. Foà[1], E. Focardi, F. Forti, A. Giassi, M.A. Giorgi, F. Ligabue, A. Lusiani, E.B. Mannelli, P.S. Marrocchesi, A. Messineo, F. Palla, G. Sanguinetti, S. Scapellato, J. Steinberger, R. Tenchini, G. Tonelli, G. Triggiani

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

J.M. Carter, M.G. Green, P.V. March, T. Medcalf, M.R. Saich, J.A. Strong[1], R.M. Thomas, T. Wildish
Department of Physics, Royal Holloway & Bedford New College, University of London, Surrey TW20 OEX, United Kingdom[13]

D.R. Botterill, R.W. Clifft, T.R. Edgecock, M. Edwards, S.M. Fisher, J. Harvey, 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[13]

B. Bloch-Devaux, P. Colas, C. Klopfenstein, E. Lançon, E. Locci, S. Loucatos, L. Mirabito, E. Monnier, P. Perez, F. Perrier, J. Rander, J.-F. Renardy, A. Roussarie, J.-P. Schuller
Département de Physique des Particules Élémentaires, CEN-Saclay, 91191 Gif-sur-Yvette Cedex, France[20]

J.G. Ashman, C.N. Booth, F. Combley, M. Dinsdale, J. Martin, D. Parker, L.F. Thompson
Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom[13]

S. Brandt, H. Burkhardt, C. Grupen, H. Meinhard, E. Neugebauer, U. Schäfer, H. Seywerd
Fachbereich Physik, Universität Siegen, 5900 Siegen, Fed. Rep. of Germany[19]

B. Gobbo, F. Liello, E. Milotti, F. Ragusa[8], L. Rolandi[1]
Dipartimento di Fisica, Università di Trieste e INFN Sezione di Trieste, 34127 Trieste, Italy

L. Bellantoni, J.F. Boudreau, D. Cinabro, J.S. Conway, D.F. Cowen, Z. Feng, J.L. Harton, J. Hilgart, R.C. Jared[9], R.P. Johnson, B.W. LeClaire, Y.B. Pan, T. Parker, J.R. Pater, Y. Saadi, V. Sharma, J.A. Wear, F.V. Weber, Sau Lan Wu, S.T. Xue, G. Zobernig
Department of Physics, University of Wisconsin, Madison, WI 53706, USA [14]

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[1] Now at CERN.
[2] Permanent address: DESY, Hamburg, Fed. Rep. of Germany.
[3] On leave of absence from SLAC, Stanford, CA 94309, USA.
[4] On leave of absence from University of Washington, Seattle, WA 98195, USA.
[5] Also Centre de Physique des Particules, Faculté des Sciences, Marseille, France
[6] Also Istituto di Fisica Generale, Università di Torino, Torino, Italy.
[7] Also Istituto di Cosmo-Geofisica del C.N.R., Torino, Italy.
[8] Now at INFN Milano.
[9] Permanent address: LBL, Berkeley, CA 94720, USA.
[10] Supported by CAICYT, Spain.
[11] Supported by the National Science Foundation of China.
[12] Supported by the Danish Natural Science Research Council.
[13] Supported by the UK Science and Engineering Research Council.
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Search for the Neutral Higgs Boson from Z° Decay in the Higgs mass range between 11 and 24 GeV

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ABSTRACT

A search for the neutral Higgs boson in the mass range above 10 GeV (above the $H^\circ \to b\bar{b}$ threshold), using the processes $Z^\circ \to H^\circ e^+e^-$, $Z^\circ \to H^\circ \mu^+\mu^-$ and $Z^\circ \to H^\circ \nu\bar{\nu}$, is performed on data collected by the ALEPH detector corresponding to about 25,000 events of $Z^\circ \to$ hadrons. Combining all these processes, the mass range excluded is 11 GeV to 24 GeV at 95% C.L. Together with a previously published result from ALEPH, the mass range excluded is 32 MeV to 24 GeV at 95% C.L. This result also extends the excluded mass region for neutral Higgs bosons from supersymmetry.

1. INTRODUCTION

The proposed neutral Higgs boson [1] of the Electroweak Theory of Glashow, Weinberg and Salam [2] so far remains undetected experimentally. Recently limits on its mass have been reported at LEP, excluding the range from 32 MeV to 15 GeV by the ALEPH Collaboration [3], and from 3 GeV to 19.3 GeV by the OPAL Collaboration [4], thereby significantly extending the mass range of those limits previously reported [5]. It is the purpose of this paper to extend the search of Ref. [3] to a mass range up to about 24 GeV for the neutral Higgs boson resulting from doubling the event statistics and a modified analysis procedure. We use the data collected during the early running of LEP, from September 19 to December 19, 1989, which correspond to about 25,000 $Z^\circ \to$ hadrons. These data were taken over a range of the center-of-mass energies from 88.3 GeV to 95.0 GeV, corresponding to a total integrated luminosity of 1.2 pb^{-1}. The decay modes of $Z^\circ \to H^\circ \nu\bar{\nu}$ and $Z^\circ \to H^\circ \ell\ell$ (ℓ = e and μ) are used. Event selection criteria are similar to those given in Ref. [3] but are modified to optimize the detection efficiency of a Higgs with mass in the range between 11 GeV and 24 GeV. In this paper, we also extend the search for neutral Higgs bosons from supersymmetry.

2. THE ALEPH DETECTOR

The ALEPH detector is described in detail elsewhere [6]. The parts of the detector relevant to this analysis are the inner tracking chamber (ITC), the large time-projection chamber (TPC), the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). A 1.5 T solenoidal magnetic field is provided by the superconducting coil surrounding the TPC and ECAL. The luminosity calorimeter (LCAL) provides energy and position measurements of the showers produced by the small angle Bhabha scattering $e^+e^- \to e^+e^-$. The trigger conditions are the same as described in Ref. [3].

3. SEARCH FOR $Z^\circ \to H^\circ Z^*$ ($Z^* \to e^+e^-$, $\mu^+\mu^-$, $\nu\bar{\nu}$)

We present here the method of a search for a Higgs boson from 11 GeV (above $H^\circ \to b\bar{b}$ threshold) to about 24 GeV by using the processes $Z^\circ \to H^\circ Z^*$. A description of the simulation of $Z^\circ \to H^\circ Z^*$ ($Z^* \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\bar{\nu}$) is given in Ref. [3]. For the Higgs mass region above 10 GeV, $H^\circ \to b\bar{b}(g)$ dominates. Sections 3.1 to 3.2 give the descriptions of how to identify events of the type $Z^\circ \to H^\circ Z^*$ and to reject background events from photon-photon interactions, beam-gas interactions and Z° decays. At least 3 pb^{-1} of simulated data have been produced for the background processes $Z^\circ \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ as well as the two-photon interactions ($\gamma\gamma \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$ and hadrons) and 10 pb^{-1} for $Z^\circ \to q\bar{q}(g)$, using the full detector simulation. They are used as an important guide to devise the event selection criteria as listed below.

Throughout this section, a charged particle is required to have 4 TPC coordinates, $|d_o|$ smaller than 4 cm and $|z_o|$ smaller than 7 cm, where $|d_o|$ is defined as the distance of closest approach to the interaction point in the plane perpendicular to the beam axis and z_o is defined as the coordinate along the beam with respect to the interaction point.

3.1 *SELECTION OF EVENTS FOR* $Z^\circ \to H^\circ \nu\bar{\nu}$

The decay channel $Z^\circ \to H^\circ \nu\bar{\nu}$ provides the best means to search for a Higgs over a wide range of Higgs masses. For the mass range considered here, where $H^\circ \to b\bar{b}(g)$ dominates, the signal is mostly two-jet events with large missing energy and momentum. The event selection criteria are as follows:

(1) The event is required to have a minimum of six charged particles and no single charged particle with energy greater than 45% of the total charged energy. The total charge of the event should not exceed ± 4. The LUND cluster algorithm [7] is applied to these charged particles and only events with two jets are accepted.

(2) The angle between the beam direction and the sphericity axis of the event, calculated with charged particles only, must be greater than 40°.

(3) The magnitude of the vector sum of the transverse momenta of all charged particles with respect to the beam axis must be greater than 3 GeV.

(4) The total energy from the ECAL wire planes and the total energy of the charged particles are required to be smaller than 25 GeV and 35 GeV respectively.

(5) $\cos\theta_{max} > -0.75$ ($\theta_{max} < 138.6°$).
θ_{max} is the maximum angle between any charged particle with momentum greater than 0.3 GeV/c and the direction of the vector sum of the momenta of all charged particles.

(6) Events are rejected if the total energy in LCAL exceeds 3 GeV. From a study of the randomly triggered events, this requirement on the LCAL energy introduces a 1.6% inefficiency for the acceptance of the Higgs events.

Selection criteria (2) and (3) remove background from two-photon and beam-gas interactions, while (4) to (6) primarily remove the background from $Z^\circ \rightarrow q\bar{q}(g)$. Applying the selection criterion (1) to (6) to the data, no event survives. Fig. 1 shows the distribution of $\cos\theta_{max}$ for (a) data and (b) the Monte Carlo simulation of a 25 GeV Higgs mass after all other selection criteria have been applied. Fig. 2 shows the two-dimensional distribution of the total ECAL energy versus the total charged energy after all other selection criteria have been applied for (a) data and (b) the Monte Carlo simulation of a 25 GeV Higgs mass.

3.2 *SELECTION OF EVENTS FOR* $Z^\circ \rightarrow H^\circ e^+e^-$ *and* $Z^\circ \rightarrow H^\circ \mu^+\mu^-$

The topologies of the decay modes $Z^\circ \rightarrow H^\circ Z^*$ ($Z^* \rightarrow e^+e^-, \mu^+\mu^-$) are simple. However, the production rates of these decay modes are low. The selection criteria are as follows:

(1) The event is required to have a minimum of five charged particles and no charged particles with energy greater than the beam energy.

(2) To form a Z^* candidate, two oppositely-charged particles are required, each with at least 7 GeV momentum; the cosine of the angle θ_{12} between them is required to be smaller than 0.5 ($\theta_{12} > 60°$). If more than one pair of charged particles satisfies this criterion, the pair with the highest energy is chosen. The remaining charged particles are assigned to the Higgs candidate.

(3) For the $H^\circ e^+e^-$ search, a positive electron identification is required on one of the two Z^* particles. Electrons are identified with 85% efficiency using their characteristic shower in the ECAL. For the $H^\circ\mu^+\mu^-$ search, pion rejection is done on the two charged particles forming the Z^* candidates using the ECAL information. For each μ candidate, the associated ECAL cluster, if there is any, is required to have only this charged track associated to it. If each of the two μ candidates has an associated ECAL cluster, then the maximum and minimum energies of these two clusters are required to be less than 7 GeV and 1 GeV respectively. If only one of the two μ candidates is associated to an ECAL cluster, its ECAL energy is required to be less than 1 GeV, consistent with a minimum ionizing particle. The efficiency of this method for identifying muon pairs from $Z^\circ \to H^\circ\mu^+\mu^-$ is 90%.

(4) To reject backgrounds of the types $Z^\circ \to q\bar{q}(g)$ and $Z^\circ \to \tau^+\tau^-$, the cosine of the angle θ between the most energetic charged particle of the Higgs candidate and either of the charged particles of the Z^* candidate is required to be less than 0.9 ($\theta > 25.8°$).

With the above event selection criteria, 19 events survive, two being $H^\circ e^+e^-$ candidates and 17 $H^\circ\mu^+\mu^-$ candidates. The preponderance of $H^\circ\mu^+\mu^-$ candidates in the data is due to the fact that the ECAL is better suited for identifying electrons than for identifying muons. In this analysis, the muon detection system has not yet been used for muon identification. The Higgs candidate mass is estimated from the recoil mass to the Z^*. For the $H^\circ e^+e^-$ candidates the lepton momenta are taken from the ECAL cluster measurements, for the $H^\circ\mu^+\mu^-$ candidates the lepton momenta are taken from the TPC measurement. The recoil mass of these surviving events exceeds 68 GeV amongst the 2 $H^\circ e^+e^-$

candidates and 46 GeV amongst the 17 $H^\circ\mu^+\mu^-$ candidates. Since the resolution of the recoil mass is 5 GeV from Monte Carlo, these events are at least 4 standard deviations from a 25 GeV Higgs mass. From the Monte Carlo simulation, 16±2 events from the background process $Z^\circ \to q\bar{q}(g)$ (2±1 from $H^\circ e^+e^-$ candidates and 14±2 from $H^\circ\mu^+\mu^-$ candidates) are expected. Hence, no event survives in the mass range of this search. Fig.3 shows the distribution of the recoil mass to the Z^* candidates for (a) the data, (b) for the Monte Carlo simulated events from $q\bar{q}(g)$ and (c) for the Monte Carlo simulation of a 25 GeV Higgs mass.

3.3 ESTIMATION OF THE NUMBER OF EVENTS EXPECTED FROM $Z^\circ \to H^\circ Z^*$ AND SYSTEMATIC ERRORS

Events at different Higgs masses have been simulated for this analysis. Table 1 gives the detection efficiencies and the expected event numbers at different Higgs masses. The corrections due to different production cross-sections at different total center-of-mass energies are taken into account. The systematic errors on the expected number of $Z^\circ \to H^\circ Z^*$ events are estimated to be: less than 2% from the integrated luminosity, less than 4% corresponding to uncertainties in the cross section calculation and less than 1% for trigger efficiencies. In addition, by varying the values of variables used in the event selection criteria over a reasonable range, we find that the uncertainty in the efficiency due to the event selection criteria is less than 7%. Combining all errors in quadrature, we find that the maximum systematic error for the expected number of events for the combined processes $Z^\circ \to H^\circ Z^*$ ($Z^* \to e^+e^-, \mu^+\mu^-, \nu\bar{\nu}$) is less than 9%.

3.4 RESULTS ON THE SEARCH FOR THE NEUTRAL HIGGS BOSON

After applying the selection criteria given in sections 3.1 and 3.2, we find that no event survives in our data sample in the range of this search. Fig.4 shows the number of events expected from the sum, as well as the individual processes, for $Z^\circ \to H^\circ e^+e^-$, $Z^\circ \to H^\circ\mu^+\mu^-$ and $Z^\circ \to H^\circ\nu\bar{\nu}$ as a function of the Higgs masses. To set a mass limit conservatively, we reduce the number of expected events by 9% to take into account the systematic error. The mass range from 11 GeV to 24 GeV for the neutral Higgs boson is excluded at 95% C.L. from this analysis. Fig.4 also presents the number of events expected from the sum of all processes as a function of the Higgs boson mass from the results in Ref. [3], giving a combined excluded mass range from 32 MeV to 24 GeV at 95% C.L. limit.

4. LIMITS FOR THE NEUTRAL HIGGS BOSON FROM SUPERSYMMETRY.

In the minimal supersymmetric extension of the Standard Model, two doublets of Higgs fields are needed, leading to five physical states: two charged scalar bosons heavier than the W; two neutral scalar bosons, one heavier than the Z°, the other, denoted h, lighter than the Z°; one neutral pseudoscalar boson, denoted A, heavier than h. All masses and couplings depend on only two parameters, here chosen as M_h and either M_A or v_2/v_1, the ratio of the vacuum expectation values of the two Higgs doublets [8].

The scalar h behaves very similarly to the standard Higgs boson H°. Limits on the latter can therefore be used to reduce the allowed domain in the space of parameters (M_h, v_2/v_1) or (M_h, M_A), but the sensitivity of this method is reduced when v_2/v_1 is different from unity. However, in this case, the rate of the process $Z^{\circ} \rightarrow hA$ may become substantial, and a complementary search is to be done [9]. Such an analysis has been reported by the ALEPH Collaboration [10]. Here we use the result of our extended search for the standard Higgs boson H°, and we update the analysis presented in Ref. [10] of the search for associate hA production in Z° decays, using all of the data collected by ALEPH in 1989.

The excluded domains, in the (M_h, v_2/v_1) plane, are presented in Fig.5a with the same notations as for Fig.1b of Ref. [10]: curve (A) limits the domain excluded by our standard Higgs searches; curve (F) limits the domain excluded by the dedicated search for $Z^{\circ} \rightarrow hA$, with at least one of h or A decaying into a τ pair (no candidate is found with the selection described in Section 7 of Ref. [10]). For $v_2/v_1 > 1$, an alternate presentation of the same results in the (M_h, M_A) plane is given in

Fig.5b. If, as theoretically expected [11], v_2/v_1 is substantially greater than unity, the range $M_h \simeq M_A < 39.2$ GeV is excluded.

5. CONCLUSION

A search for the neutral Higgs boson has been performed based on the processes $Z^\circ \rightarrow H^\circ e^+e^-$, $H^\circ \mu^+\mu^-$ and $H^\circ \nu\bar{\nu}$ using 1.2 pb^{-1} of data collected by the ALEPH detector. While the process $Z^\circ \rightarrow H^\circ \nu\bar{\nu}$ provides the most powerful means for this search, the result of combining all the processes, together with the result given in Ref. [3], excludes the neutral Higgs boson over the mass range from 32 MeV to 24 GeV at 95% C.L. This result is obtained within the context of the Standard Model with no further assumption. This result also extends the excluded mass region for neutral Higgs bosons from supersymmetry.

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TABLE 1

Detection Efficiency (Eff.) and Number of Expected Events (N) as a Function of Higgs Mass

M_{H° (GeV)	$H^\circ\nu\bar{\nu}$		$H^\circ\mu+\mu-$		$H^\circ e+e$		Total
	Eff.	N	Eff.	N	Eff.	N	ΣN
11	0.433	6.1	0.625	1.5	0.599	1.4	9.0
12	0.530	6.7	0.640	1.4	0.607	1.3	9.4
13	0.588	6.8	0.653	1.3	0.614	1.2	9.2
14	0.618	6.5	0.664	1.2	0.619	1.1	8.7
15	0.628	6.0	0.674	1.1	0.623	1.0	8.0
16	0.624	5.4	0.682	1.0	0.627	0.9	7.3
17	0.615	4.8	0.689	0.9	0.629	0.8	6.6
18	0.603	4.3	0.693	0.8	0.630	0.8	5.9
19	0.592	3.9	0.696	0.8	0.629	0.7	5.3
20	0.584	3.5	0.697	0.7	0.628	0.6	4.8
21	0.580	3.2	0.696	0.6	0.626	0.6	4.4
22	0.579	2.9	0.694	0.6	0.622	0.5	4.0
23	0.580	2.7	0.690	0.5	0.617	0.5	3.7
24	0.578	2.4	0.684	0.5	0.611	0.4	3.3
25	0.569	2.2	0.676	0.4	0.604	0.4	3.0

FIGURE CAPTIONS

Fig.1 $\cos\theta_{max}$ distribution for (a) data (b) Monte Carlo simulation of $Z^\circ \to H^\circ \nu\bar{\nu}$ for a 25 GeV Higgs mass, both after applying all other selection criteria. The Monte Carlo distribution is normalized to the total number of hadronic events in the data.

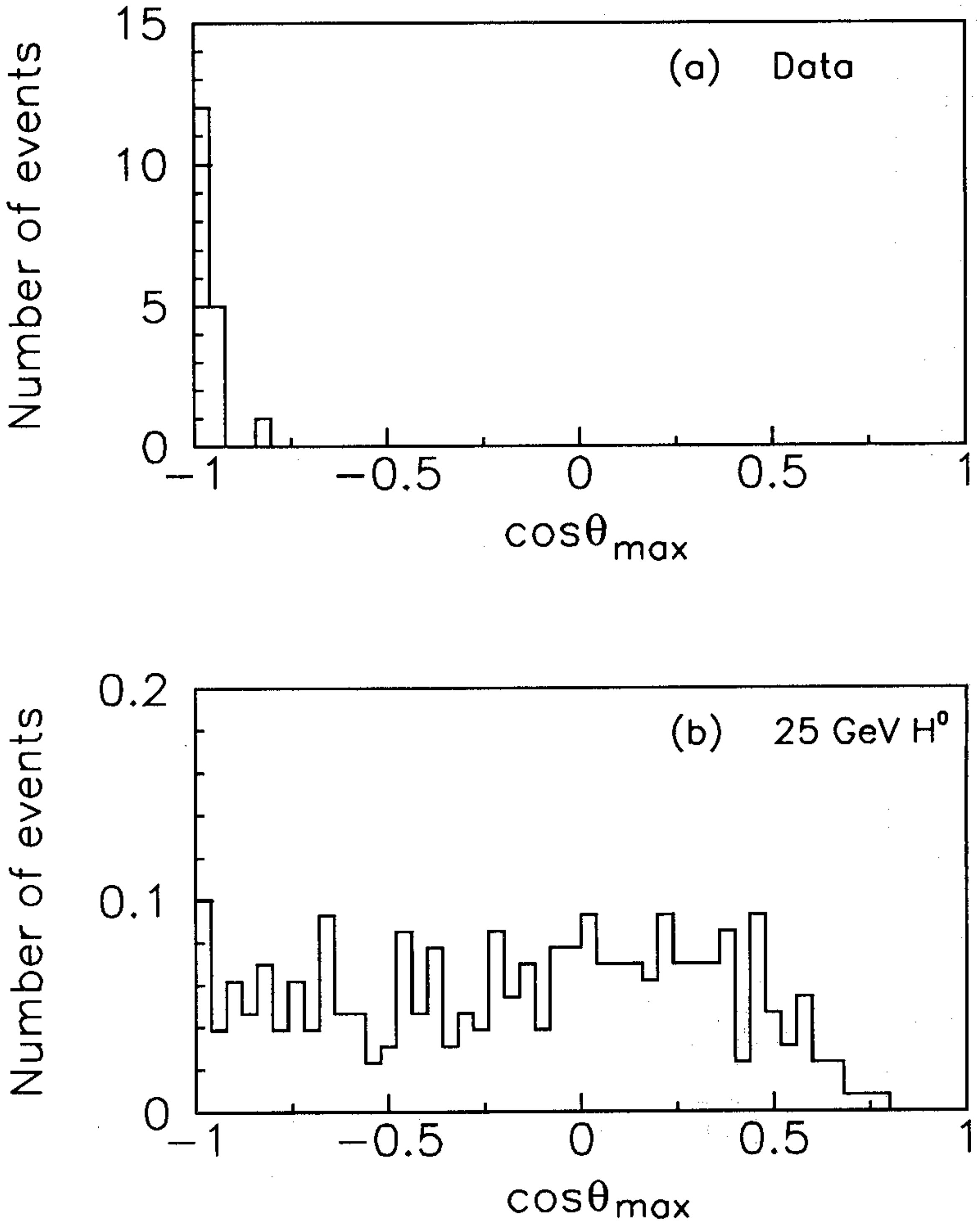
Fig.2 Total ECAL energy versus total charged energy after all other selection criteria have been applied for (a) data and (b) the Monte Carlo simulation of a 25 GeV Higgs mass (not normalized).

Fig.3 Distribution of recoil mass to the Z* for (a) data, (b) $Z^\circ \to q\bar{q}(g)$ Monte Carlo simulation and (c) the Monte Carlo simulation of $Z^\circ \to H^\circ \mu^+\mu^-$ and $Z^\circ \to H^\circ e^+e^-$ for a 25 GeV Higgs mass. The shaded area of (a)-(c) is the $H^\circ e^+e^-$ candidates, while the non-shaded area is the $H^\circ \mu^+\mu^-$ candidates. The Monte Carlo distributions are normalized to the total number of hadronic events in the data.

Fig.4 The number of events expected for $Z^\circ \to H^\circ \ell^+\ell^-$ (ℓ = e, μ), $Z^\circ \to H^\circ \nu\bar{\nu}$ and the sum of all the above channels as a function of the Higgs mass for $M_{H^\circ} > 10$ GeV. The 95% C.L. limit at 3 expected events is indicated, corresponding to zero observed candidates. Below 15 GeV the sum of $Z^\circ \to H^\circ \ell^+\ell^-$ (ℓ = e, μ or τ), $Z^\circ \to H^\circ \nu\bar{\nu}$, and $Z^\circ \to H^\circ q\bar{q}$ is shown for the results of the search in Ref. [3].

Fig.5 Excluded domains (a) in the (M_h, v_2/v_1) plane, (b) in the (M_h, M_A) plane for $v_2/v_1 > 1$, from:

(A) : the search for H° (see section 4 of this paper)
(E) : low multiplicity final states in $Z^\circ \to$ hA (see section 6 of Ref. [8])
(F) : $\tau^+\tau^-$ jet-jet final states in $Z^\circ \to$ hA (updated from section 7 of Ref. [8])
(G) : 4 -jet final states in $Z^\circ \to$ hA (see section 8 of Ref. [8]).



15
10
5
0
Number of events
(a) Data
−1
−0.5
0
0.5
1
cosθmax
0.2
0.1
0
Number of events
(b) 25 GeV H⁰
−1
−0.5
0
0.5
1
cosθmax

Fig. 1

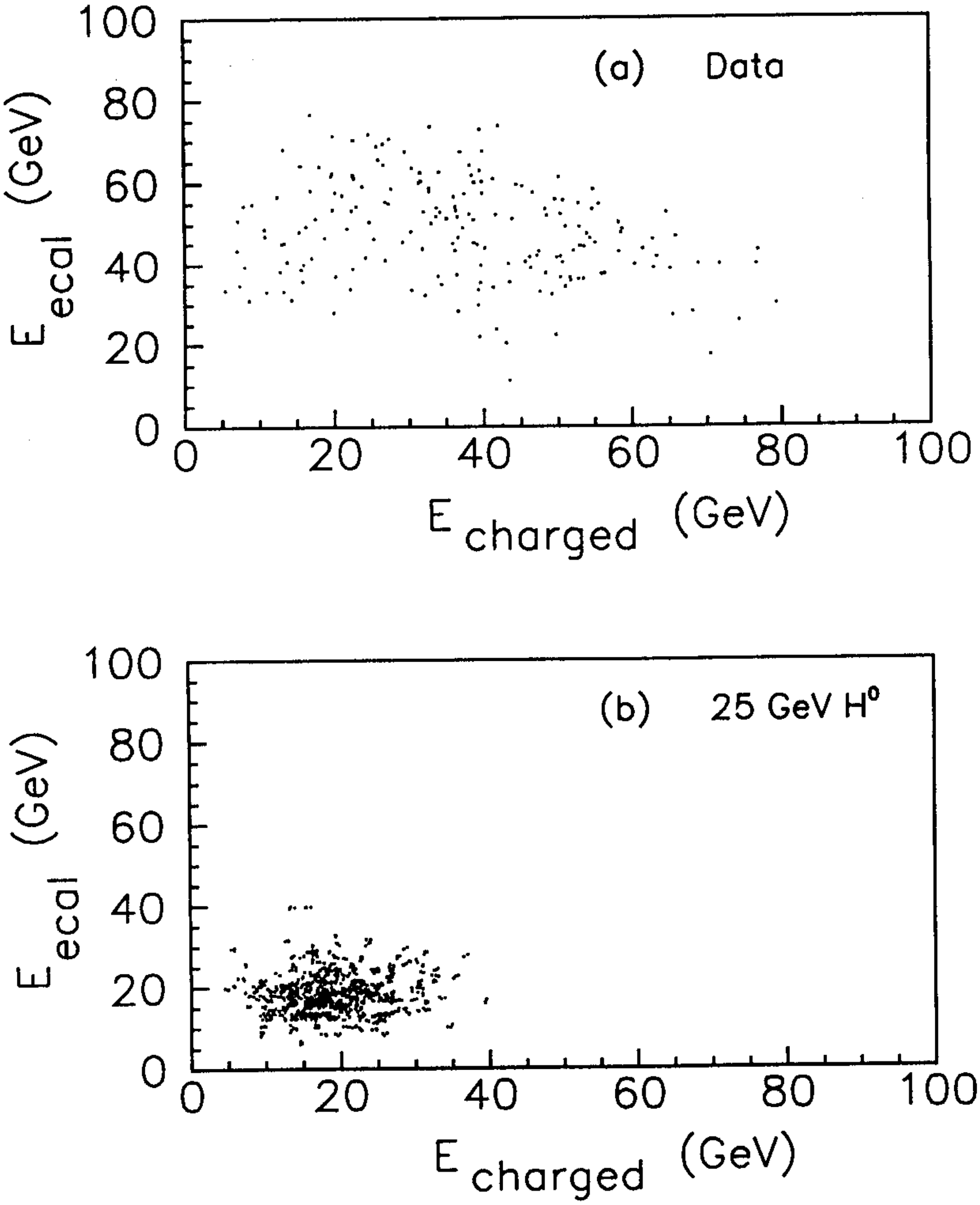

(a) Data
E_{ecal} (GeV)
$E_{charged}$ (GeV)
(b) 25 GeV H^0
E_{ecal} (GeV)
$E_{charged}$ (GeV)
0
20
40
60
80
100

Fig. 2

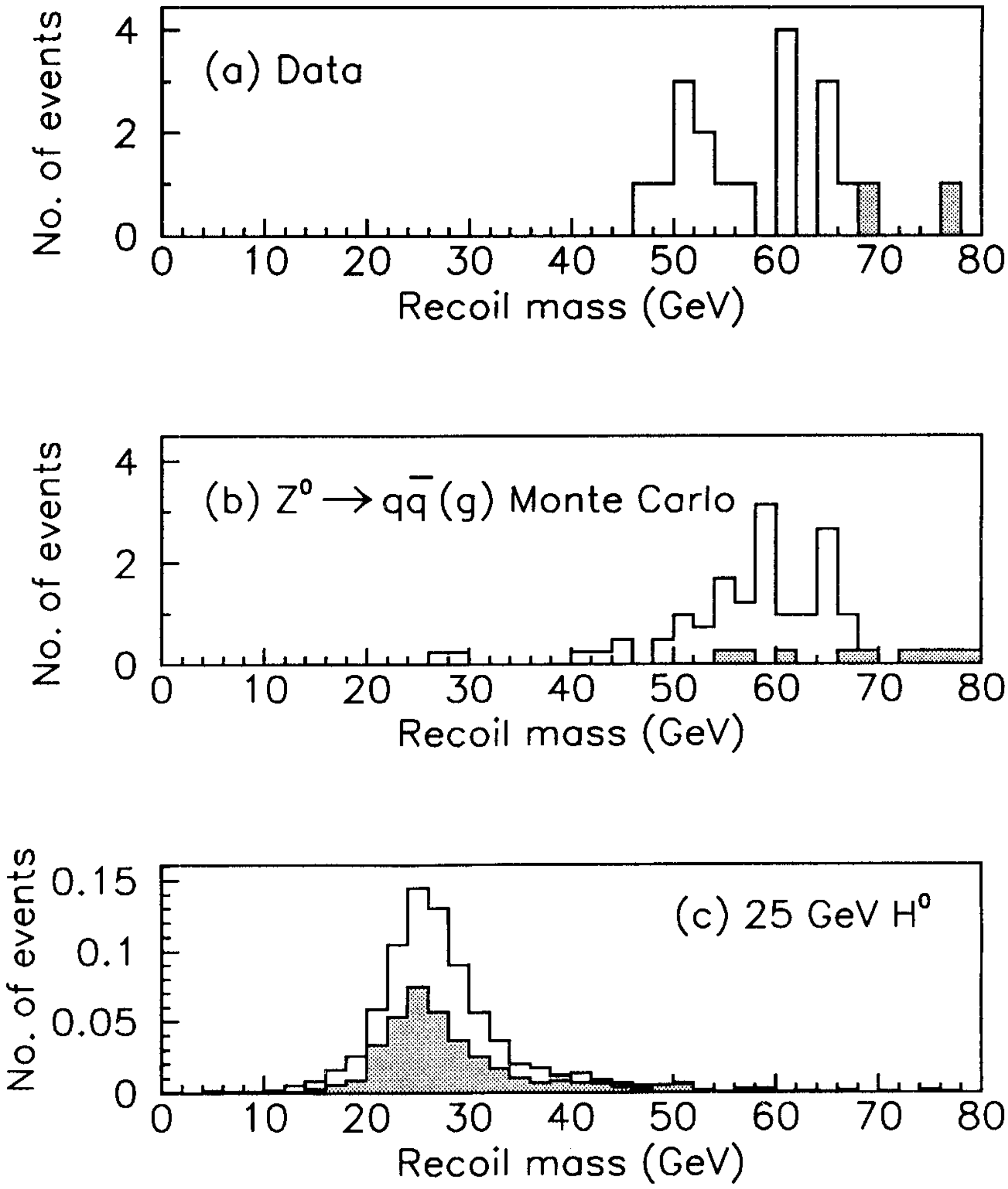
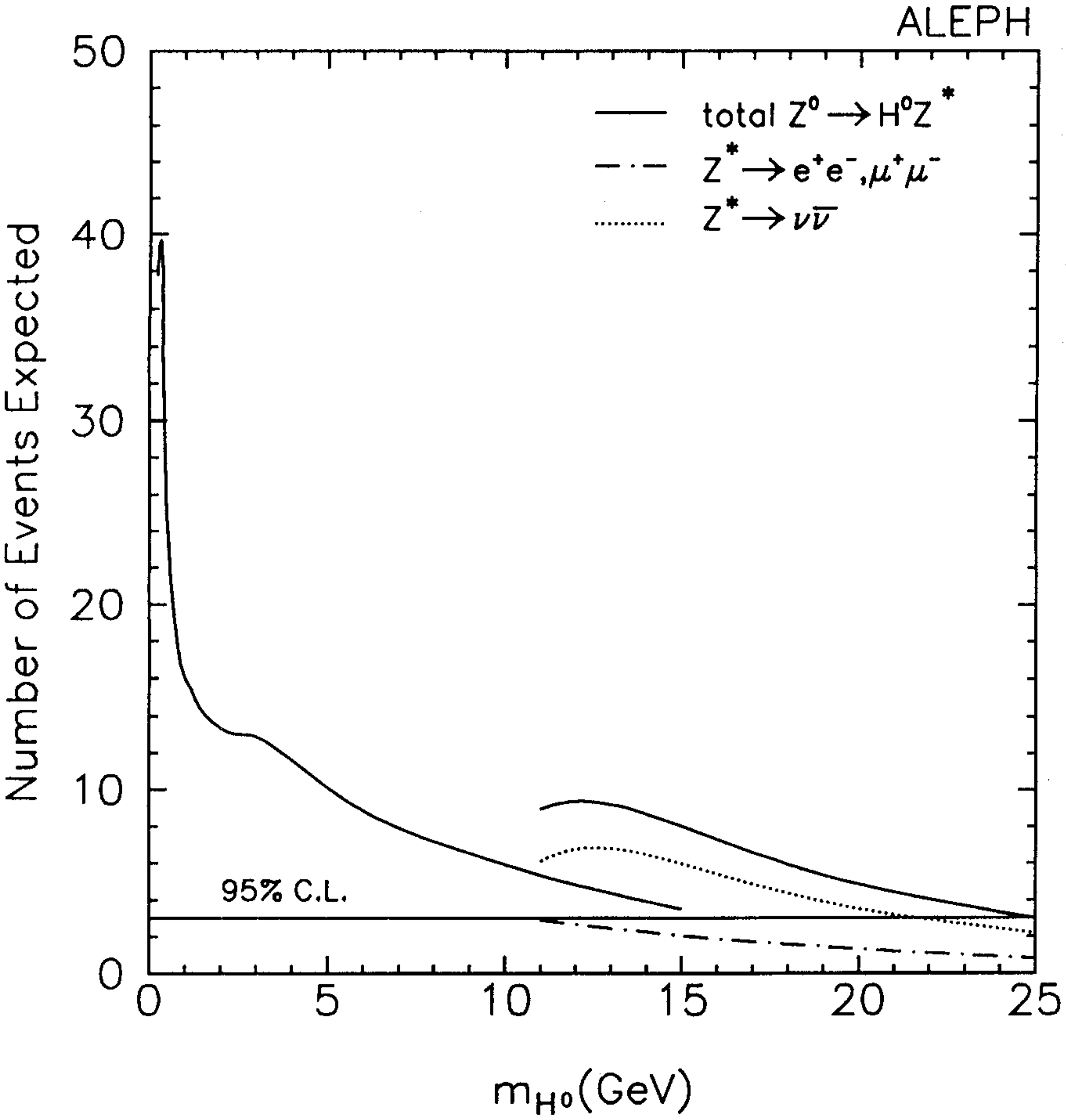

(a) Data
No. of events
Recoil mass (GeV)
(b) $Z^0 \rightarrow q\bar{q}$ (g) Monte Carlo
No. of events
Recoil mass (GeV)
(c) 25 GeV H^0
No. of events
Recoil mass (GeV)

Fig. 3



ALEPH
total $Z^0 \rightarrow H^0 Z^*$
$Z^* \rightarrow e^+e^-, \mu^+\mu^-$
$Z^* \rightarrow \nu\bar{\nu}$
95% C.L.
Number of Events Expected
m_{H^0}(GeV)
0
10
20
30
40
50
0
5
10
15
20
25

Fig. 4

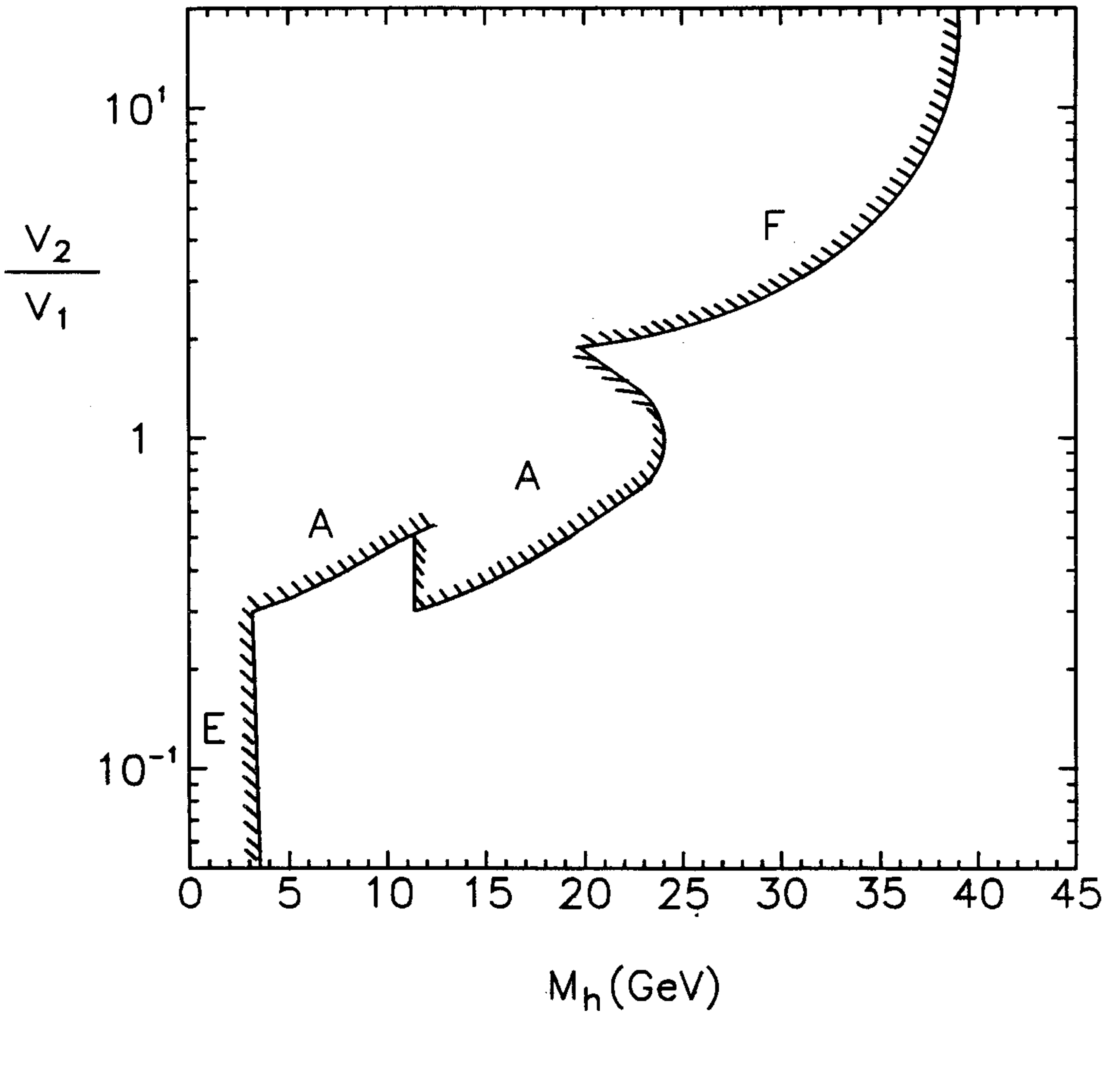
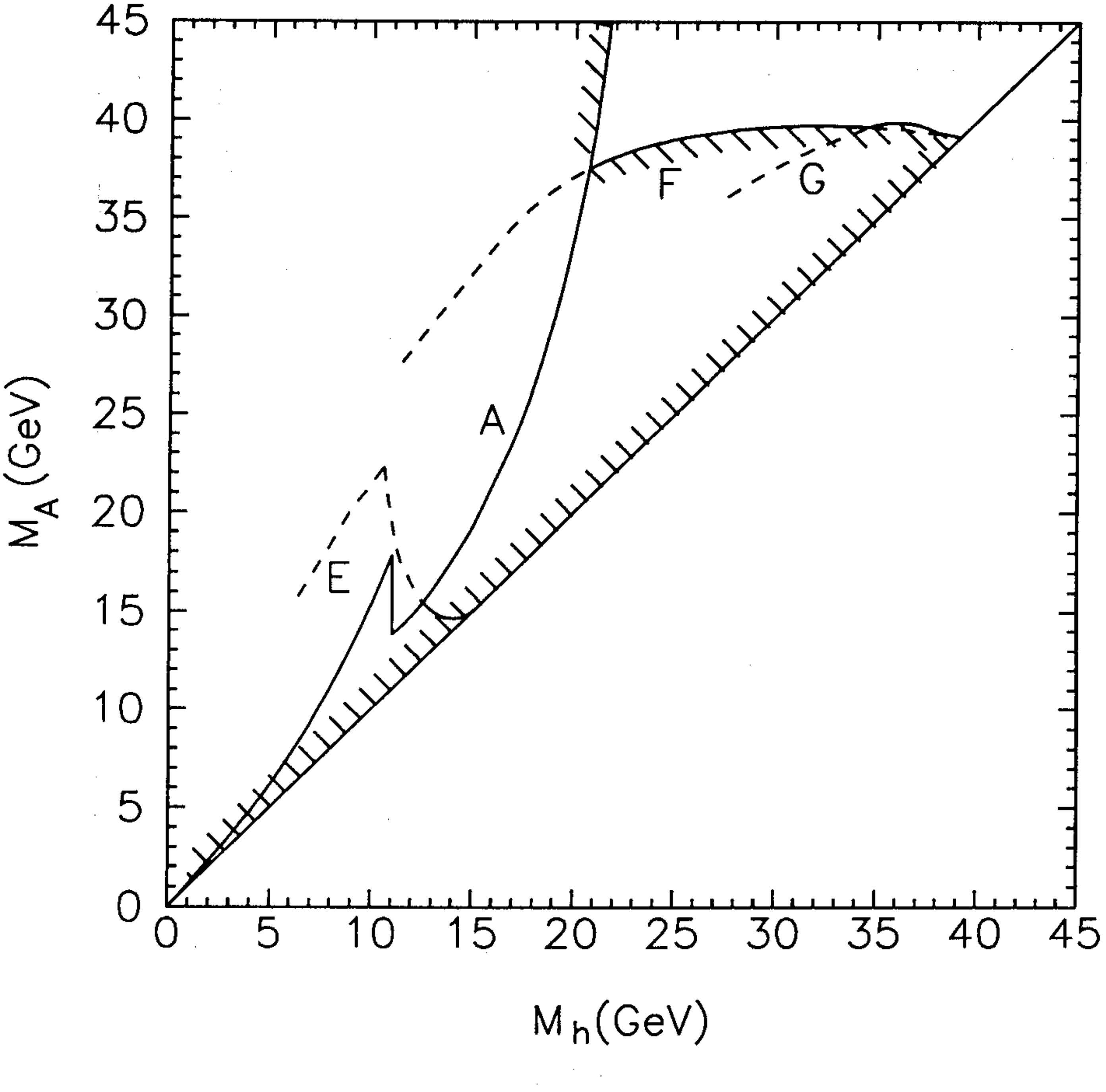


Fig.5 (a)



45
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
M_A (GeV)
M_h(GeV)
A
E
F
G

Fig.5 (b)