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Search for a very light Higgs boson in Z decays.

The ALEPH Collaboration*)

Abstract

A search has been made for a very light Higgs boson in the processes $e^+e^- \to e^+e^-H$ and $e^+e^- \to \mu^+\mu^-H$ using data collected by ALEPH at the LEP e^+e^- collider at centre of mass energies close to the Z peak. The mass range between 0 and 57 MeV is unambiguously excluded at the 95% confidence level. If we combine this with our previously published analysis, the complete range from 0 to 24 GeV is excluded at 95% C.L. The search is extended to light Higgs bosons of the minimal supersymmetric standard model, with the result that all possibilities of couplings are excluded for Higgs masses below 3 GeV.

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1.- Introduction.

Recently, the first significant searches for the Higgs boson of the Standard Model have been reported at LEP, excluding its existence over a large mass range in a completely unambiguous way. Such a standard Higgs particle is excluded if its mass lies between 32 MeV and 24 GeV by ALEPH,[1,2] between 3 GeV and 19 GeV by OPAL,[3] and between 210 MeV and 14 GeV by DELPHI.[4] In the framework of the mimimal supersymmetric extension of the Standard Model, more Higgs bosons are expected because of the necessary two doublets of scalar fields. However, ALEPH has been able to restrict considerably this possibility,[5,2] excluding a large domain in the plane defined by the mass of the lightest Higgs boson and the ratio v_2/v_1 of the vacuum expectation values of the two Higgs fields. In particular, for masses less than 3 GeV, all values for v_2/v_1 are rejected, except for a small domain below a mass of 50 MeV and v_2/v_1 between 0.35 and 2.5.

Previous experimental results of Higgs searches can be invoked to close this last possibility for a light Higgs particle in a standard scenario. However, except for one experiment[6] which is limited to masses above 1.2 MeV, all the analyses rely on processes which are not governed solely by the fundamental couplings of the theory, but have to take into account large and uncertain corrections from hadronic physics. This is the case for quarkonia radiative decays,[7] nuclear transitions and scattering,[8] and hadron decays.[9] The latter cases suffer from even larger uncertainties in long-distance hadronic effects.

In this letter, we complete our search in the low mass region continuing to use the process

$$Z^0 \rightarrow H^0 Z^{0*}, \qquad (1)$$

where Z^{0*} is a virtual Z^0 decaying into a fermion pair. A Higgs particle with a mass less than a few tens of MeV would be essentially stable: for example, a 10-MeV Higgs produced with the energy distribution of process (1) would travel on average a distance of 100 meters before decaying. In addition, since its coupling to ordinary matter is small, such a light Higgs would be invisible. Fortunately, it can be detected indirectly through the channels

$$Z^0 \rightarrow (H^0) l^+ l^-, \qquad (2)$$

where l^- is an electron or a muon. Therefore the experimental signature we are looking for is an acoplanar lepton pair where the missing energy and momentum are carried away by an undetected particle.

2.- The ALEPH detector and the data sample.

A detailed description of ALEPH can be found in Ref.10. The parts of the detector relevant to the present analysis are:

- the inner tracking chamber (ITC), providing up to 8 coordinates in azimuth and in radius from 13 to 29 cm of the beam axis,
- the large time projection chamber (TPC), extending to a radius of 180 cm, and providing up to 21 three-dimensional coordinates,
- the electromagnetic calorimeter (ECAL), made of sandwiches of lead plates and layers of proportional tubes, the barrel part of which is located between the TPC and the solenoidal superconducting coil which delivers a 1.5 T magnetic field, and providing measurements of the shower energy independently on the wire planes of a whole module and on individual towers constructed from cathode pads,
- the luminosity monitor (LCAL), an extension of the ECAL down to a polar angle of 50 mr,
- the hadronic calorimeter (HCAL), made of streamer tubes inserted in the iron return yoke of the magnet used as an absorber, and equipped with strip and tower read-out.

The apparatus was triggered independently by several conditions, of which the ones relevant here are:

- an energy deposit of at least 6.5 GeV in the barrel part of the ECAL, or at least 3.8 GeV in one of the ECAL end caps, or at least 1.6 GeV in both of these end caps,
- an ITC track in coincidence in azimuth with an energy deposition of at least 1.3 GeV in the ECAL,
- an ITC track in coincidence in azimuth with a signal of penetration of at least 40 cm of iron in the HCAL.

The data were processed through a chain of reconstruction programs, the output of which is a set of charged tracks with a momentum resolution $\Delta p/p^2 = 1.1\ 10^{-3}$ GeV^{-1} for $p > 4$ GeV, and of calorimeter clusters with an energy resolution $\Delta E/E = 0.017 + 0.19/\sqrt{E}$ with E in GeV.[10]

This analysis has been performed using data collected in 1989 at the Z^0 peak and in a region within ±3 GeV of it. Selecting runs in which all the detectors are working satisfactorily yields a total of 22486 Z^0 decays to hadrons which are detected and identified as such in ALEPH.

3.- Backgrounds and the photon veto.

The background for process (2) comes mostly from radiative lepton pair production and tau pair production

$$e^+e^- \to l^+l^-\gamma, \tag{3}$$

$$e^+e^- \to \tau^+\tau^- \to 2 \text{ charged particles } (+\gamma\text{'s}) + \nu\text{'s}, \tag{4}$$

when the photons remain undetected. The design of an efficient photon veto is therefore essential to this search.

The raw energy clusters from the reconstruction program are not quite adequate for this purpose, because they still contain fake showers generated by electronic noise. Only clusters with a rough electromagnetic longitudinal profile, as obtained from the threefold segmentation of the ECAL, and consistency between tower and wire energy measurements are kept. For this analysis, the LCAL information is treated identically and is added to that of the ECAL, thereby enabling a photon veto down to very small angles. As far as the HCAL is concerned, only clusters where the pad and strip informations support each other are retained.

In this way it is possible to reduce the photon veto energy down to 1 GeV for the entire calorimeter. The loss from accidental veto caused by fake clusters has been continuously monitored throughout the experiment using random triggers and it is measured to be 3.1%.

4.- The selection procedure.

Candidates for process (2) are defined by the clear signature of 2 charged tracks and no additional isolated photon. The 2 tracks should have a minimum acoplanarity angle to eliminate most lepton pairs and to avoid cases where the photon from reaction (3) is too close to one of the tracks and could not be unambiguously tagged. This problem would be particularly severe in the case of electron pairs because of their energetic showers and the effect of radiation in the detector before they reach the calorimeter. We define the acoplanarity angle as the complement to π of the angle between the components of the momenta transverse to the beam. Initial state radiation does not contribute in practice to the distribution of acoplanarity. To avoid a large contamination from tau pairs, a minimum momentum for the tracks is required. In all cases, conservative cuts are applied to avoid having to deal with difficult veto conditions.

The selection method is therefore based on the following requirements:

(1) two tracks with momenta larger than 30 GeV and satisfying the basic quality criteria: at least 4 space-point coordinates, minimal approach of the track to the interaction point (< 2 cm in the plane transverse to the beam, < 10 cm along the beam),

(2) acoplanarity angle larger than 30 mr,

(3) energy sum of isolated (neutral) clusters in the ECAL less than 1 GeV,

(4) energy sum measured using the wire planes of the ECAL modules not hit by the tracks less than 1 GeV,

(5) energy sum of isolated (neutral) clusters in the HCAL of less than 1 GeV. This is restricted to clusters whose centroids are aligned in a band of ±2 cm behind cracks of the ECAL modules.

Fig.1 shows the acoplanarity distributions from the data and from Monte-Carlo simulations of the $l^+l^-(\gamma)$, $\tau^+\tau^-H^0$ and $l^+l^-H^0$ processes, both after the momentum cut and before any photon veto. As explained above, the acoplanarity cut at 30 mr is conservatively chosen to avoid dealing with photon and electron showers close together. This requirement is the major source of the inefficiency for the Higgs search.

To estimate the contamination from the background processes (3) and (4), Monte-Carlo events are generated with a complete simulation of the detector and run through the selection procedure. As a result, we expect (0.8 ± 0.3) and (0.6 ± 0.4) events for the τ pair and the radiative lepton pair processes, respectively. It should be noted that the τ background could have been reduced by a factor of about 7 by identifying the lepton pair, however this was not necessary.

Starting with 3096 events satisfying cut (1), the acoplanarity cut (2) leaves 84 candidates. Only 2 are left after the ECAL veto corresponding to cuts (3) and (4). In both these events, the photon escaped through the crack between two ECAL modules but was caught in the staggered HCAL segments through cut (5). Thus, no event survived our selection procedure.

5.-A check with an alternative method.

Since no candidate is found after the selection, a check is performed using a somewhat complementary method. In particular, the largest inefficiency in the first method is the acoplanarity cut and this second method serves as a cross check by loosening this criterion. On the other hand, as this creates more problems for the veto, more complex requirements must be used to define photons extending the vetoed energy range down to 200 MeV. The inherent inefficiencies of this harder veto are compensated for by applying it over a restricted portion of the solid angle which can be defined thanks to the planar nature of the events from the background process (3).

The acoplanarity cut (2) used in the first selection procedure is replaced here by an acollinearity cut in events with two charged particles passing cut (1). These acollinear tracks define a plane and photons from background processs (3) must also be in this plane.

Our second selection procedure can be summarized by the following steps after imposing the cut (1):

(2) acollinearity angle larger than 10 mr,

(3) the event plane must be more than 200 mr away from the beam line (the 200 mr is dictated as this is the size of the forward (backward) hole in the ECAL. This cut eliminates events from process (3) where the photon was radiated along the beam line by one of the incoming leptons).

(4) no ECAL cluster of electromagnetic character pointing towards the origin with an energy larger than 200 MeV,

(5) no ECAL cluster of "reduced" quality (only timing information is used, with rough agreement between the wire and the tower energies in modules not hit by the tracks) with energy larger than 200 MeV within 150 mr of the event plane (only that part of the plane in which transverse momentum would be balanced is considered).

(6) no HCAL cluster whose centroid is within ± 2 cm of an ECAL crack in the event plane, as described in (4) above,

Only 3 events survive these cuts, while 2 are expected from a Monte Carlo simulation of processes (3) and (4). This is compatible with the absence of a significant signal, and thereby crosschecks our first procedure. By itself, this method would exclude a Higgs mass range up to 37 MeV. However, since the previous method is simpler, as efficient, more conservative, and leading to a larger excluded Higgs mass range, we prefer to use it in deriving the final result.

6.- The results.

Having observed no events, we now examine how this can constrain the existence of a light Higgs boson. For this, we need to know the production cross section and our experimental efficiency.

The standard model cross section for the process (2) is well established.[11] It is well behaved when the mass M_H of the Higgs particle becomes very small as can be noticed from

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_H} = \frac{4\sqrt{2}G}{\pi}\Gamma_{ll}^2|\vec{q}_H|\frac{M_Z^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\cdot\frac{3s+2M_H^2-6\sqrt{s}E_H+E_H^2}{(s-2\sqrt{s}E_H+M_H^2-M_Z^2)^2+M_Z^2\Gamma_Z^2},$$

where $(E_H, \vec{q}_H)$ is the Higgs 4-momentum, G the Fermi coupling constant, Γ_{ll} the partial width of the Z into a lepton pair and s the square of the center-of-mass energy.

Furthermore, it is possible to take into account electroweak higher order effects through the so-called "improved Born approximation"[12] and initial state radiation through a convolution with the photon spectrum calculated to second order.[13] These effects are included in the Monte-Carlo generator.[14] The Higgs lifetime is calculated[11] taking into account the dominant decay channels expected at low masses, i.e. e^+e^- and $\gamma\gamma$. It is in principle possible that $\nu\bar{\nu}$ channels could contribute. However, it is most likely that the neutrino mass scale forbids such a possibility in practice; furthermore, the existence of such decay channels would not significantly alter the results of our search based on the "invisibility" of the produced Higgs.

The detection efficiency has a part which is mass-independent and takes into account the effects of the trigger (0.996 ± 0.001), of the selection procedure (0.43 ± 0.03), and of the accidental veto (0.964 ± 0.002). The finite value of the Higgs lifetime introduces a mass-dependent efficiency, since the analysis requires the Higgs particle to decay outside the detector. As the Higgs mass increases, the mean decay length decreases as M_H^2, where M_H is the Higgs mass, so that we expect the efficiency to drop. This search for a relatively stable Higgs is thus quite complementary to the method we previously used[1] which required the actual observation of the $H^0 \to e^+e^-$ decay inside the detector.

The overall detection efficiency is given in Table 1 for different values of the Higgs mass. The expected rate is shown in Fig.2, together with the results of our earlier method.[1] From the present analysis, taking into account uncertainties in the detection efficiencies, it is now possible to unambiguously exclude a standard Higgs boson with a mass below 57 MeV at 95% C.L. This exclusion applies down to arbitrarily small masses without restriction in the framework of the Standard Model. Furthermore, we can combine these results with our previous ones to rule out at 95% C.L. a continuous mass range from 0 to 24 GeV. If at least 99% C.L. is required, we still exclude the complete range from 0 to 20 GeV.

The present search can be applied to the light neutral Higgs bosons of the minimal supersymmetric Standard Model.[15] In this framework, one expects two neutral scalars: one heavier than the Z^0 and one, h, lighter than the Z^0. The only two parameters needed to completely describe the Higgs sector can conveniently be chosen as M_h and $\tan\beta = v_2/v_1$. In particular, the mixing angle α between the two neutral scalars is then determined. As v_2/v_1 deviates from unity, the Z^0Z^0h coupling is reduced with respect to the standard Z^0Z^0H coupling by a factor $\sin(\alpha - \beta)$ and therefore the rate for $Z^0 \to Z^{0*}h$ decreases from the standard value.

Since the basic couplings of the h boson to fermion pairs depend on the angles α and β, one has to take into account the dependence of the efficiency on M_h and v_2/v_1.[16] The null result of this search can thus be translated into an domain excluded at 95% C.L. in the $(M_h, v_2/v_1)$ plane which is shown in Fig.3. When taken together with our previously published limits[5] , these new results eliminate all possibilities for light Higgs bosons in the framework of the minimal supersymmetric model for all values of the vacuum expectation values of the two Higgs fields.

7.- Conclusion.

A search for a long-lived neutral Higgs boson has been performed based on the processes $Z^0 \rightarrow H^0 e^+ e^-$, $H^0 \mu^+ \mu^-$ using the data collected in 1989 at LEP by the ALEPH detector. Within the Standard Model phenomenology, no signal is found, thereby excluding Higgs boson masses less than 57 MeV. A complete mass range from 0 to 24 GeV is ruled out if this new result is combined with our earlier limits dealing with short-lived Higgs bosons. Extending the framework to the minimal supersymmetric version of the Standard Model, our combined results show no evidence for a light Higgs particle whatever the value of the couplings.

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Figure Captions.

1. Acoplanarity angle distribution after cut (1) (see text)
   (a) for Monte Carlo $l^+l^-(\gamma...)$, $\tau^+\tau^-$ and $l^+l^-H^0$ events with a Higgs mass of 5 MeV, normalized to the luminosity of the experiment.
   (b) for data.

2. Expected number of events in this experiment as a function of the Higgs mass:
   Curves (A),(B),(C) refer respectively to the present analysis (search for an invisible Higgs), our previous analysis[1] (search for a decaying Higgs) and the sum of both yields.

3. Excluded domain in the $(M_h, v_2/v_1)$ plane:
   Curve A refers to the present analysis (inside excluded), whereas the curve B delineates the region still allowed by our previous analysis.[5] The angular shape of curve B results from several complementary analyses, each leading to its own excluded area (dashed lines are used to show in each case the specific region excluded).

Table Captions.

1. Detection efficiency and expected number of events as a function of the Higgs mass M_H (with lifetime τ_H).

M_H (MeV)	τ_H (ps)	Efficiency	Events
0	∞	.415	9.0
20	210	.353	7.7
40	105	.234	5.1
60	70	.139	3.0
80	52.5	.082	1.8

Table 1.

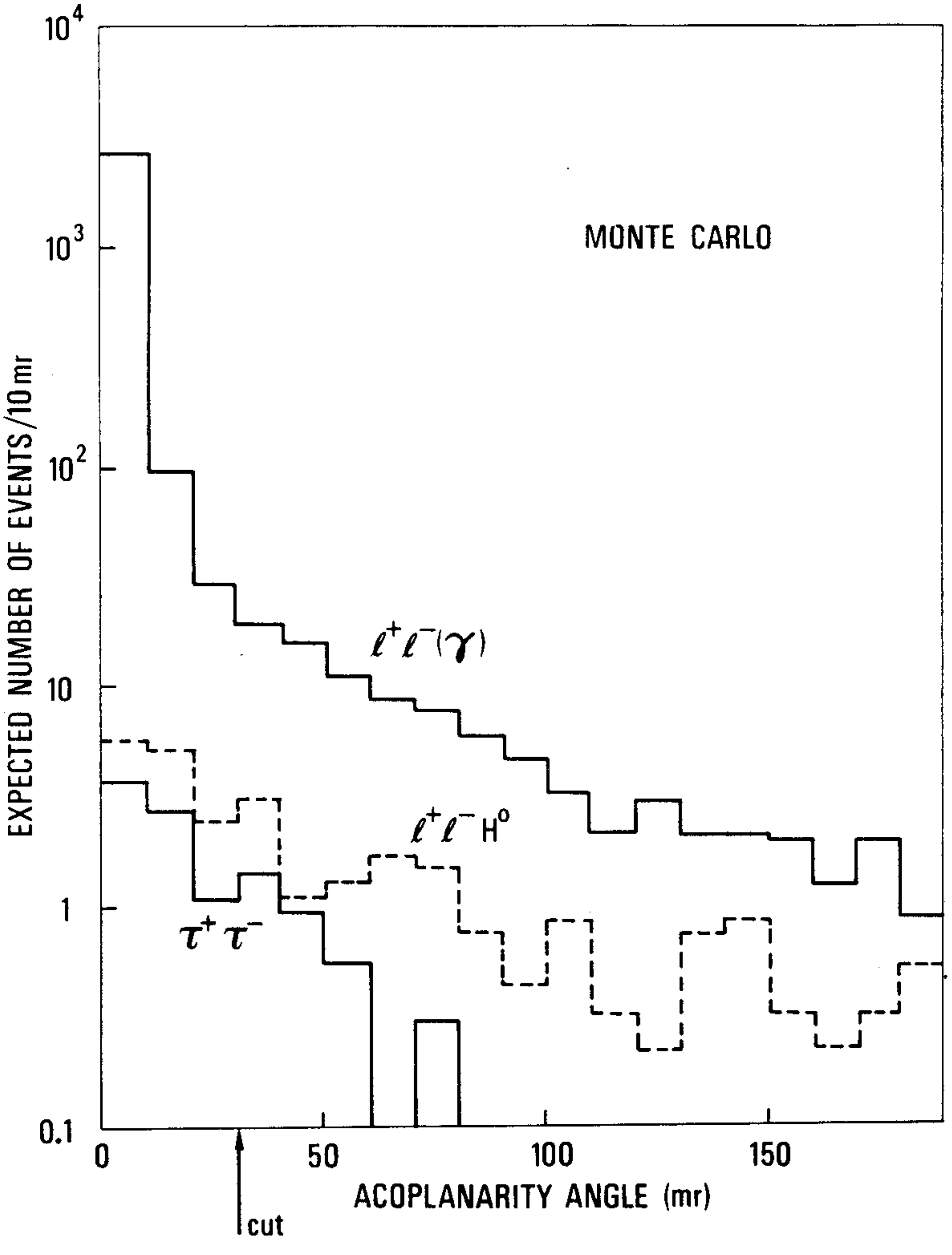
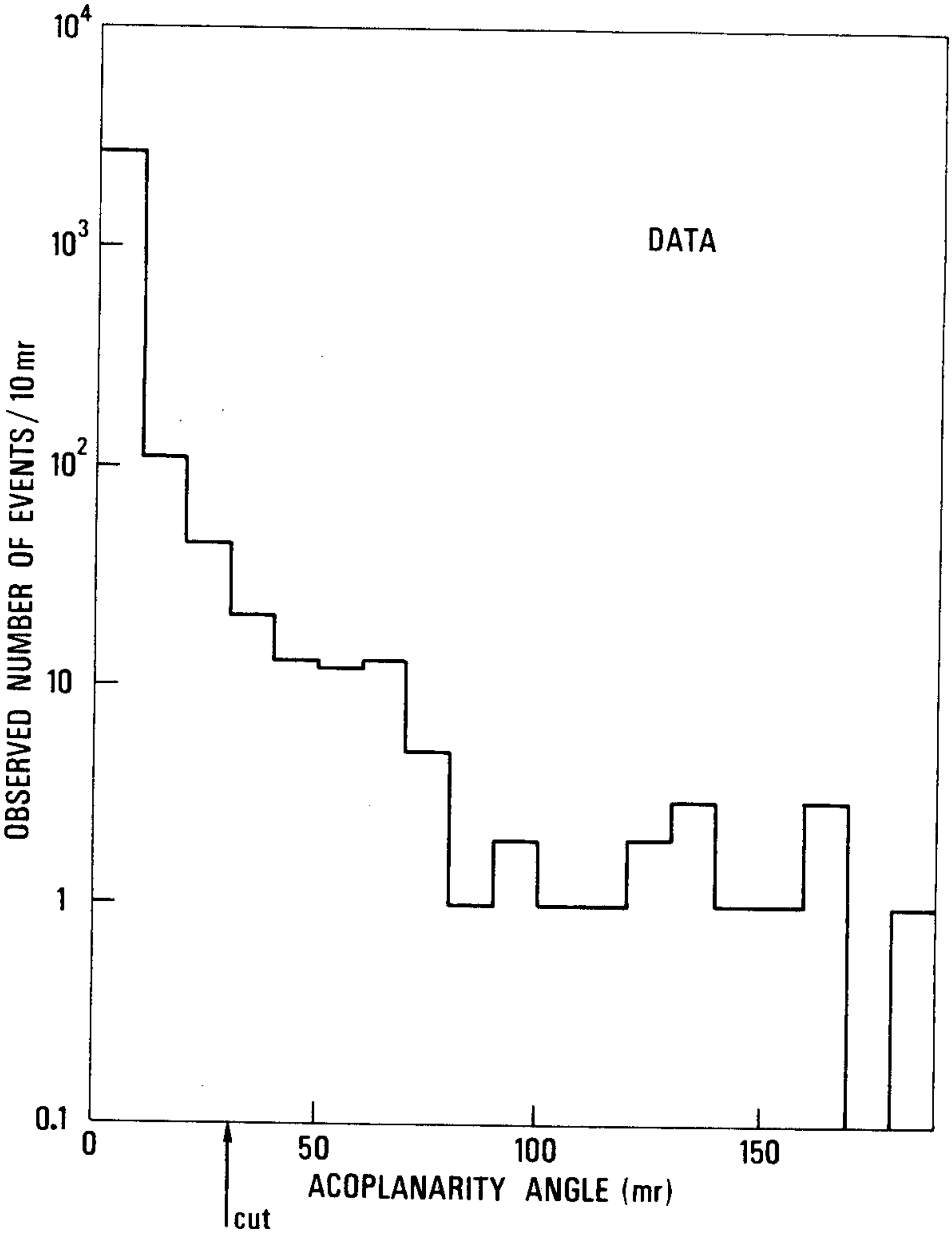

10^4
10^3
10^2
10
1
0.1
EXPECTED NUMBER OF EVENTS/10 mr
MONTE CARLO
ℓ+ℓ−(γ)
ℓ+ℓ− H0
τ+τ−
0
50
100
150
ACOPLANARITY ANGLE (mr)
cut

Fig. 1(a)



10⁴
10³
10²
10
1
0.1
OBSERVED NUMBER OF EVENTS / 10 mr
DATA
0
50
100
150
ACOPLANARITY ANGLE (mr)
cut

Fig. 1(b)

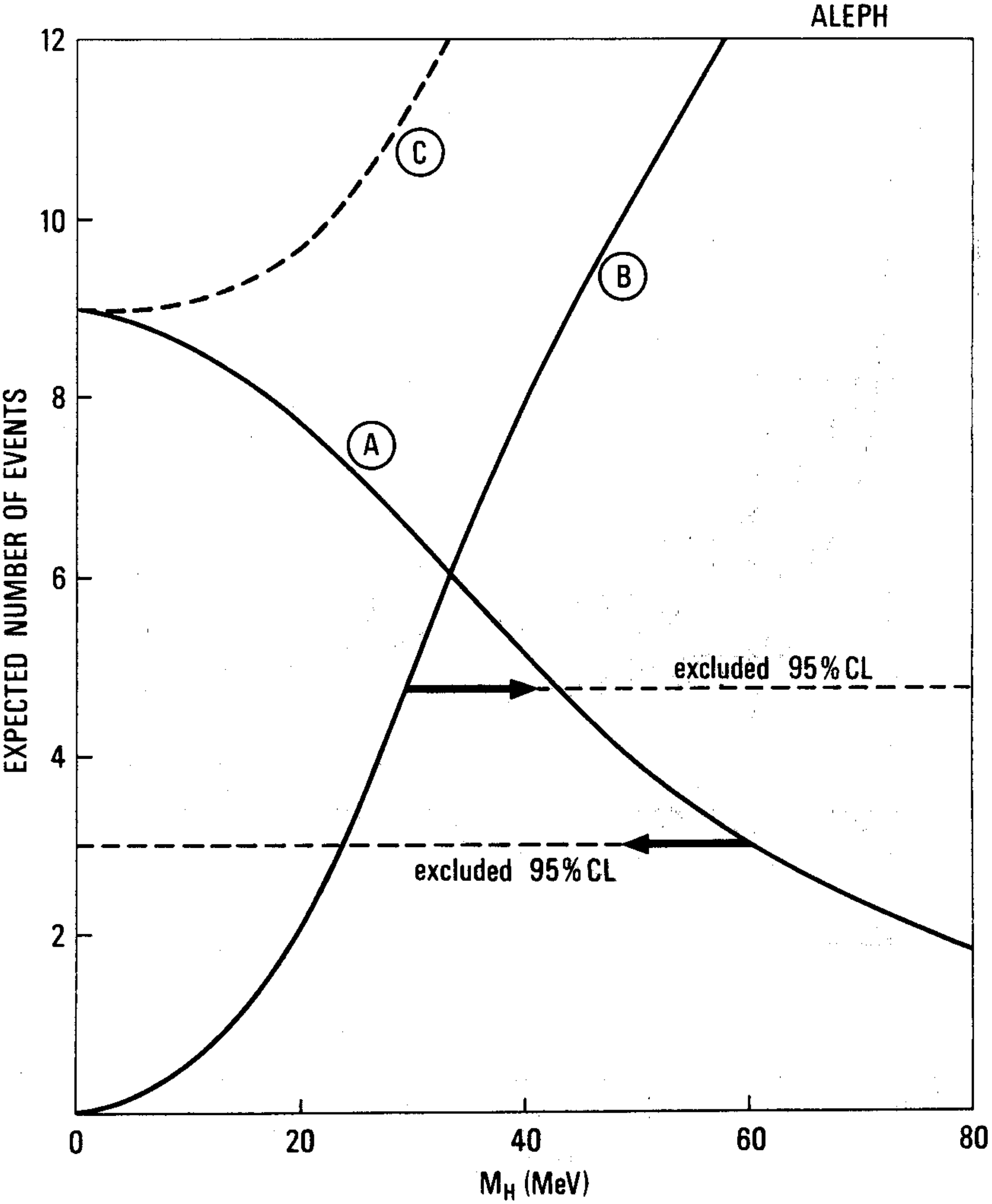

ALEPH
EXPECTED NUMBER OF EVENTS
M_H (MeV)
0
20
40
60
80
2
4
6
8
10
12
Ⓐ
Ⓑ
Ⓒ
excluded 95% CL
excluded 95% CL

Fig. 2

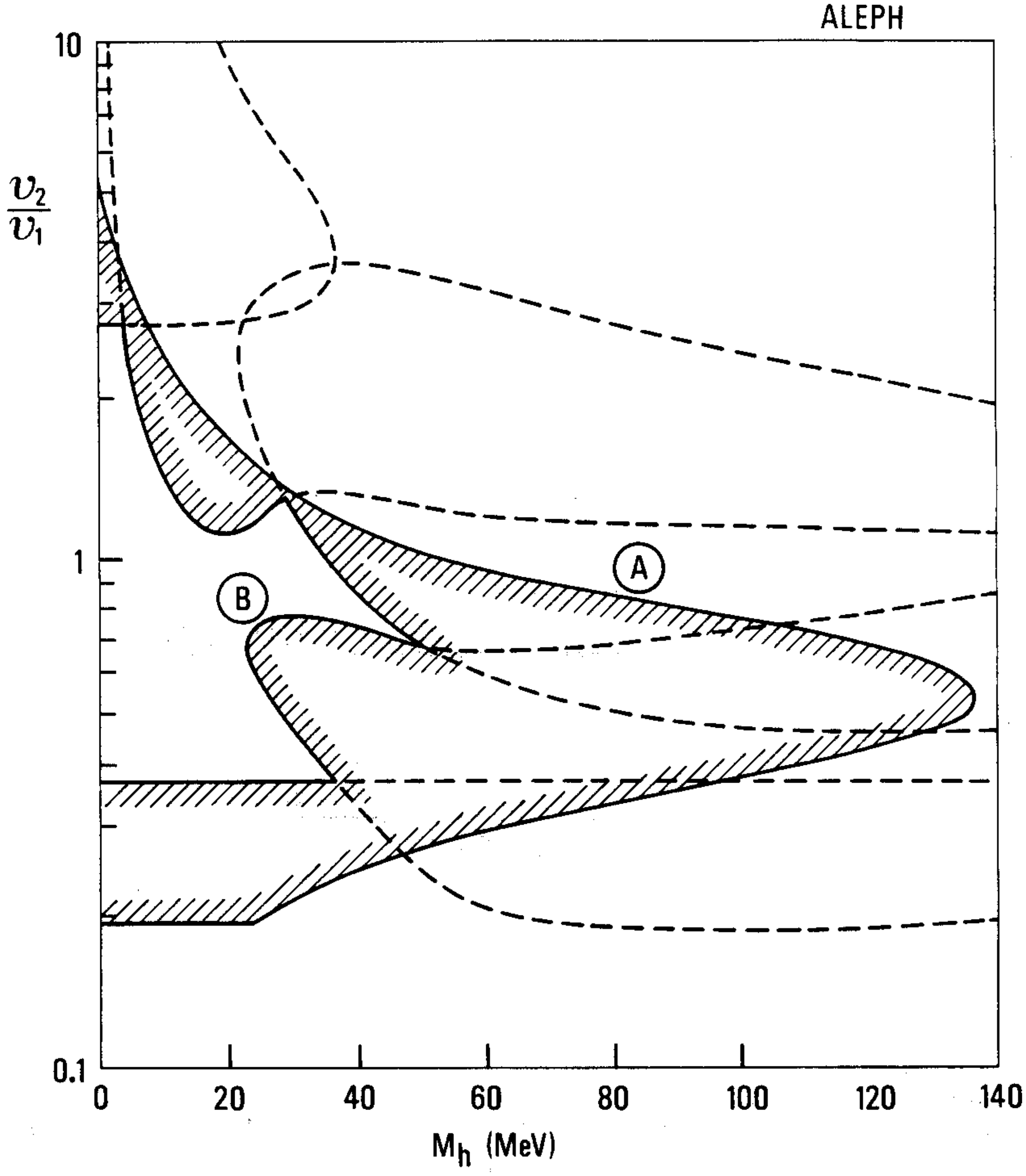


Fig. 3