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Search for Neutralino Production in Z Decays

The ALEPH Collaboration*)

Abstract

Limits on Z decay branching ratios into neutralinos are reported. They were obtained from searches for monojets, acoplanar jets, acoplanar lepton pairs, single photons and acoplanar photon pairs as signatures for the reactions $e^+e^- \to \chi\chi'$ and $e^+e^- \to \chi'\chi'$, where χ is the lightest neutralino and χ' any heavier one. The data sample used for these searches corresponds to about 23000 events of Z decay into multihadrons, collected at LEP by the ALEPH detector for centre of mass energies at and near the Z peak. The results obtained are used to restrict the parameter space of the minimal supersymmetric standard model.

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1. Introduction.

In supersymmetric models,[1] the numbers of fermionic and bosonic degrees of freedom are equal within each supermultiplet. In particular, the massless spin 1 photon, with two helicity states, is associated with a spin 1/2 Majorana photino, also with two helicity states. The massive spin 1 Z boson, with three helicity states, is associated with two spin 1/2 Majorana zinos, for a total of 4 fermionic degrees of freedom, and with a spin 0 Higgs boson H which provides the missing bosonic degree of freedom.[2] Similarly, the W boson is associated with two spin 1/2 Dirac winos and with a charged Higgs boson. The occurrence of the latter implies that at least two doublets of Higgs fields are needed, and therefore in turn additional neutral Higgs bosons, h and A, together associated in a chiral supermultiplet with a spin 1/2 Majorana higgsino. The winos mix to form two mass eigenstates, known as "charginos." Similarly, the photino, the two zinos, and the higgsino mix to form four mass eigenstates, known as "neutralinos." The lighter of the charginos will be denoted $\chi^{\pm}$, the lightest of the neutralinos χ, and the heavier neutralinos collectively χ'. We will make the usual assumption that χ is the lightest supersymmetric particle, that it is stable (by R-parity conservation), and that it interacts only weakly with matter (because all scalar leptons and quarks are heavy).

The purpose of the present study is to extend the previous ALEPH analyses of the production of charginos and neutral Higgs bosons in Z decays[3,4,5] to a search for neutralino production. The relevant reactions are[6]

$$e^+e^- \to Z \to \chi\chi' \tag{1}$$
$$e^+e^- \to Z \to \chi'\chi'. \tag{2}$$

The data sample that we used corresponds to about 23000 Z multihadronic decays collected by ALEPH at LEP during a scan around the Z peak. In this sample, all major components of the detector were required to be simultaneously operational. A thorough description of ALEPH can be found in Ref. 8, and a brief account, together with a description of the relevant trigger conditions, in Ref. 4 for instance.

2. Neutralino search in the decay channel $\chi' \to \chi f\bar{f}$.

We will first assume that χ' decays proceed according to

$$\chi' \to \chi Z^* \to \chi f\bar{f}. \tag{3}$$

Since the χ's escape undetected, the signatures of processes (1) and (2) that we are led to search for are missing energy and acoplanar jets or monojets (depending on the masses of χ and χ'), or acoplanar lepton pairs.

Acoplanar jets were selected as in Ref. 5 where the reaction $e^+e^- \to H\nu\bar{\nu}$ was investigated for Higgs masses sufficient to lead to distinctly two-jet events. The selection criteria were:

- at least 6 good tracks [†] were required, with a total electric charge not exceeding 4 in absolute value, and forming two jets [‡],
- the sphericity axis determined from the charged tracks had to make an angle greater than 40° with respect to the beam axis,
- the magnitude of the vector sum of the track momenta transverse to the beam axis had to exceed 3 GeV/c,
- the total energy of the charged tracks had to be less than 35 GeV,
- the total energy in the electromagnetic calorimeter (ECAL) had to be less than 25 GeV, and the total energy in the luminosity calorimeter (LCAL) less than 3 GeV,
- the angle θ between any charged track and the vector sum of the track momenta had to be such that $\cos\theta > -0.75$.

No event satisfying these criteria was observed.

Monojets were selected in a fashion very similar to the one used in Ref. 10 where light Higgs bosons were searched for in the $e^+e^- \to H\nu\bar{\nu}$ reaction. The selection criteria were:

- at least two oppositely charged good tracks were required, with a total electric charge not exceeding 4 in absolute value,
- the sphericity axis determined from the charged tracks had to make an angle greater than 40° with respect to the beam axis,
- the magnitude of the vector sum of the track momenta transverse to the beam axis had to exceed 2.5 GeV/c,
- the angle θ between any charged track and the vector sum of the track momenta had to be such that $\cos\theta > -0.1$,
- the event was divided into two jets, the angle between which had to have a cosine in excess of -0.1,
- in no ECAL module in the hemisphere opposite to the vector sum of the charged track momenta was the energy to exceed 2 GeV,
- no neutral cluster of energy in the hadronic calorimeter (HCAL), in that same hemisphere, was to exceed 1 GeV,
- the total energy in LCAL had to be less than 5 GeV.

One event survived these cuts, compatible with the expectation from $e^+e^- \to \tau^+\tau^-$, with close to all of the energy of one of the τ's given to its neutrino daughter(s).

[†] A good track has at least 4 reconstructed space points in the TPC, a distance of closest approach to the interaction point of less than 4 cm in the plane perpendicular to the beam axis, and of less than 7 cm parallel to the beam axis.

[‡] The LUCLUS algorithm[9] was used, with d_{join}=2.5 GeV.

Acoplanar lepton pairs were selected in the following way, with no particle identification so as to keep some efficiency for acoplanar τ pairs:

- exactly two oppositely charged good tracks were required, with momenta above 2 GeV/c and more than 25.8° away from the beam axis,
- the two track acollinearity angle had to have a cosine larger than -0.95,
- the two track acoplanarity angle had to be less than 170°,
- the magnitude of the vector sum of the track momenta transverse to the beam axis had to exceed 2.5 GeV/c,
- no neutral electromagnetic cluster in ECAL was to be found with an energy above 1 GeV unless its angle with any of the charged tracks had a cosine above 0.95, or its invariant mass with any of the charged tracks was less than the τ mass,
- no neutral cluster of energy in HCAL was to be found with an energy in excess of 1 GeV,
- the total energy in LCAL had to be less than 5 GeV.

No event survived these selection criteria.

In order to interpret those results in terms of limits on neutralino production in Z decays, we wrote Monte-Carlo generators for processes (1), (2) and (3). We explicitly checked that the production and decay processes could be factorized without any visible inaccuracy introduced by this approximation.[11] On the other hand, the kinematics of the production and decays not only depend on the χ and χ' masses, but also on η, their relative CP, a feature that we have taken into account. We fully simulated these processes† for a number of χ and χ' mass values sufficient to model the efficiencies of the whole procedure as smooth functions of M_χ and $M_{\chi'}$, for both values of η. From those, we could infer contours in the $(M_\chi, M_{\chi'})$ plane, corresponding to 95% C.L. upper limits on the values of the branching ratios $BR(Z \to \chi\chi')$ and $BR(Z \to \chi'\chi')$. These are shown in Fig. 1 for the less favourable case $\eta = +1$. In most of the domain kinematically accessible, branching ratios at the level of a few 10^{-4} are excluded.

Up to now, we have made the assumption that the only χ' decay channel leading to $\chi f \bar{f}$ is (3). But diagrams involving scalar leptons or quarks may also contribute to this final state. Normally, the effect of these is simply to enhance the leptonic final states, as scalar leptons are expected to be lighter than scalar quarks. This is harmless for the present analysis except if the scalar neutrino $\tilde{\nu}$ is light enough for the invisible decay mode $\chi' \to \nu\tilde{\nu}$ (with $\tilde{\nu} \to \nu\chi$) to become dominant. However, from the ALEPH measurement of the Z invisible width,[13] one can infer that the mass of three degenerate species of scalar neutrinos has to exceed 37 GeV, and the masses of charged scalar leptons and of scalar quarks have already been severely restricted.[3,14,15] In any case, the contours in Fig. 1 can conservatively be interpreted as 95% C.L. upper limits on the products of branching ratios $BR(Z \to \chi\chi') \times BR(\chi' \to \chi Z^*)$ and $BR(Z \to \chi'\chi') \times BR(\chi' \to \chi Z^*)^2$, provided interference effects can be neglected.

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† The hadronization of the $q\bar{q}$ systems was done using the parton shower program JETSET 6.3.[12]

3. Search in the decay channel $\chi' \rightarrow \chi\gamma$. Comments on other decay modes.

It has been pointed out that the decay mode

$$\chi' \rightarrow \chi\gamma \qquad (4)$$

can become sustantial.[7,16] This is why we have also performed a search for single high energy photons as a signature of reaction (1) and for acoplanar photon pairs as a signature of reaction (2).

Such events trigger the detector by an energy deposit in the electromagnetic calorimeter in excess of 6.6 GeV in the barrel part or of 3.5 GeV in one of the endcaps. Events with reconstructed charged tracks were rejected.

Candidate events for reaction (1) were further selected by requiring:

- a neutral shower with an energy above 7 GeV and more than 42° away from the beam axis,
- and no other shower with an energy above 200 MeV (400 MeV) in any barrel (endcap) module of ECAL, or above 5 GeV in LCAL,

and candidate events for reaction (2) by requiring:

- two neutral showers with energies above 7 GeV and more than 18.2° away from the beam axis,
- the acoplanarity angle of the two showers to be less than 179.5°,
- the sum of the energies of the two showers to be less than 70 GeV,
- and the direction of the missing momentum to be in the angular acceptance of ECAL and LCAL, that is more than 50 mrad away from the beam axis.

To eliminate the background from cosmic rays, it was required that:

- the energy deposit(s) be in time with the beam crossing within 280 ns,
- the longitudinal and transverse shower profiles be consistent with those of an electromagnetic shower,
- the line(s) of flight, as determined from those profiles, miss the interaction point by less than 60 cm in the direction parallel to the beam axis.

No event survived these cuts, which leads to 95% C.L. upper limits on the products of branching ratios $BR(Z \rightarrow \chi\chi') \times BR(\chi' \rightarrow \chi\gamma)$ and $BR(Z \rightarrow \chi'\chi') \times BR(\chi' \rightarrow \chi\gamma)^2$ shown as contours in Fig. 2. Exclusion levels of a few 10^{-4} are achieved. The fine granularity of the ALEPH electromagnetic calorimeter was instrumental in this analysis.

If kinematically accessible, the decays $\chi' \rightarrow \chi h$ or χA would be dominant. However, on the one hand the masses of h and A have already been severely restricted by ALEPH,[4,5] and on the other hand we have verified that the efficiencies of our searches for monojets and acoplanar jets are sufficient for the limits in Fig. 1 to be unaltered if $\chi' \rightarrow \chi Z^*$ is replaced by $\chi' \rightarrow \chi h$ or χA. They would actually become even more restrictive in such a case.

Finally, if kinematically allowed, the decay channel $\chi' \to \chi^{\pm} W^* \to \chi^{\pm} f \bar{f}'$ followed by $\chi^{\pm} \to \chi f \bar{f}'$ should also be taken into account. However, this is normally disfavoured with respect to (3) as we know that the $\chi^{\pm}$ mass cannot be smaller than about half M_Z.[3,14]

4. Interpretation in the minimal supersymmetric standard model.

In the minimal supersymmetric extension of the standard model (MSSM),[17] the Lagrangian at the scale of grand unification is globally supersymmetric, except for a set of "soft breaking" terms. Among these, M_1, M_2 and M_3 are direct gaugino mass terms associated with the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ gauge groups respectively. These mass terms are commonly assumed to be equal at unification scale. However, they get renormalized differently, with in particular $M_1 = (5/3) M_2 \tan^2 \theta_{\mathrm{W}}$. Here, we will use the combination

$$M = M_1 \cos^2 \theta_{\mathrm{W}} + M_2 \sin^2 \theta_{\mathrm{W}},$$

which is associated with the photino field (for $\sin^2 \theta_W = 0.23$, $M = 0.61 M_2$). Another important parameter not present in the minimal standard model is μ, the supersymmetric mass term which mixes the two Higgs superfields. Finally, the ratio v_2/v_1 of the vacuum expectation values of the two Higgs doublets completes the specification of the parameters relevant for the present study.

Within the MSSM, for any triplet of values for M, μ and v_2/v_1, one can compute all chargino and neutralino masses, with their relative CP's for the latter, and all their couplings to the Z.[18] Therefore, the above results can be used to exclude domains in the space of these three parameters. Examples of such exclusion contours in the (M, μ) plane are shown in Fig. 3, for $v_2/v_1 = 2$ and 4. Here, we have assumed that scalar exchanges and charginos can be ignored in χ' decays. The gap in the excluded domain around $M = -\mu$ corresponds to a decoupling of the Z from all accessible $\chi\chi'$ and $\chi'\chi'$ final states.

In fact, a substantial fraction of the parameter space could already be excluded prior to this analysis by the ALEPH measurement of the Z line shape.[13] The peak hadronic cross section σ_0, in particular, is sensitive to any contribution $\Delta\Gamma$ to the Z width Γ arising from "new physics." It is reduced by a relative amount $\Delta\sigma_0/\sigma_0 \simeq -2\Delta\Gamma/\Gamma$ with respect to the standard model value if all of the new physics contribution is invisible, and by $\Delta\sigma_0/\sigma_0 \simeq -\Delta\Gamma/\Gamma$ at least if some of it contributes to hadronic final states (this method is explained in greater details in Ref. 19). The most conservative result is obtained assuming that $Z \to \chi^+\chi^-$ and all $Z \to \chi\chi'$ or $\chi'\chi'$ contribute to the hadronic width, while only $Z \to \chi\chi$ contributes to the invisible width. The result†, which is independent of any assumption on the chargino and neutralino decay modes, is shown in Fig. 4. A small additional domain, obtained using Fig. 4 of Ref. 3, is excluded by our direct chargino search. It corresponds to the case where $\chi^{\pm}$ is mostly higgsino-like, and therefore contributes less to the Z width than when it is mostly gaugino-like.

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† A similar analysis has been performed in Ref. 20.

It can be seen in Fig. 4 that the direct search for neutralinos reported here enlarges quite substantially the region excluded. In particular, most of the domain potentially accessible in Z decays is excluded for $v_2/v_1 >\sim 4$, provided M and μ take values within some "naturalness bounds"[21] (typically, M and $\mu <\sim 200$ GeV). In these same conditions, it is found that the χ mass cannot be less than ~ 30 GeV.

5. Conclusion.

We have searched for signals of neutralino production in Z decays. No evidence was found, and 95% C.L. upper limits at the level of a few 10^{-4} have been set on the corresponding branching ratios. These results, together with others previously obtained by ALEPH, have been used to restrict the parameter space of the minimal supersymmetric standard model.

The results on neutralino searches reported here considerably improve on the previous ones on this topic which had been obtained either at lower energies and under restrictive assumptions on the field contents of χ and χ',[22] or from a substantially smaller Z sample.[23]

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Figure Captions.

1. Equal value contours, labelled by capital letters, for the 95% C.L. upper limits on $10^4 \times BR(Z \rightarrow \chi\chi')$ (a) and $10^4 \times BR(Z \rightarrow \chi'\chi')$ (b) in the $(M_\chi, M_{\chi'})$ plane. Here χ' is assumed to decay 100% to χZ^*. The hatched region is inaccessible to the searches reported here.

2. Equal value contours, labelled by capital letters, for the 95% C.L. upper limits on $10^4 \times BR(Z \rightarrow \chi\chi')$ (a) and $10^4 \times BR(Z \rightarrow \chi'\chi')$ (b) in the $(M_\chi, M_{\chi'})$ plane. Here χ' is assumed to decay 100% to $\chi\gamma$. The hatched region is inaccessible to the searches reported here.

3. Domains in the (M, μ) plane of the MSSM, for $v_2/v_1 = 2$ and 4, excluded at 95% C.L. by our searches for $Z \rightarrow \chi\chi'$ (A) and for $Z \rightarrow \chi'\chi'$ (B). Also indicated, the region (C) where $\chi^\pm$ is lighter than χ, a theoretically disfavoured case for which this search does not apply. Dotted contour: limit of the domain kinematically accessible in Z decays into neutralinos. Dashed contour: the same, excluding the invisible mode $Z \rightarrow \chi\chi$.

4. For various values of v_2/v_1, 95% C.L. excluded domains in the (M, μ) plane of the MSSM: from our Z line shape measurement[13] (A); and from our direct search for charginos[3] (B); and from our direct search for $Z \rightarrow \chi\chi'$(C); and from our direct search for $Z \rightarrow \chi'\chi'$(D). Dotted contour: limit of the domain kinematically accessible in Z decays into charginos and neutralinos. Dashed contour: the same, excluding the invisible mode $Z \rightarrow \chi\chi$.

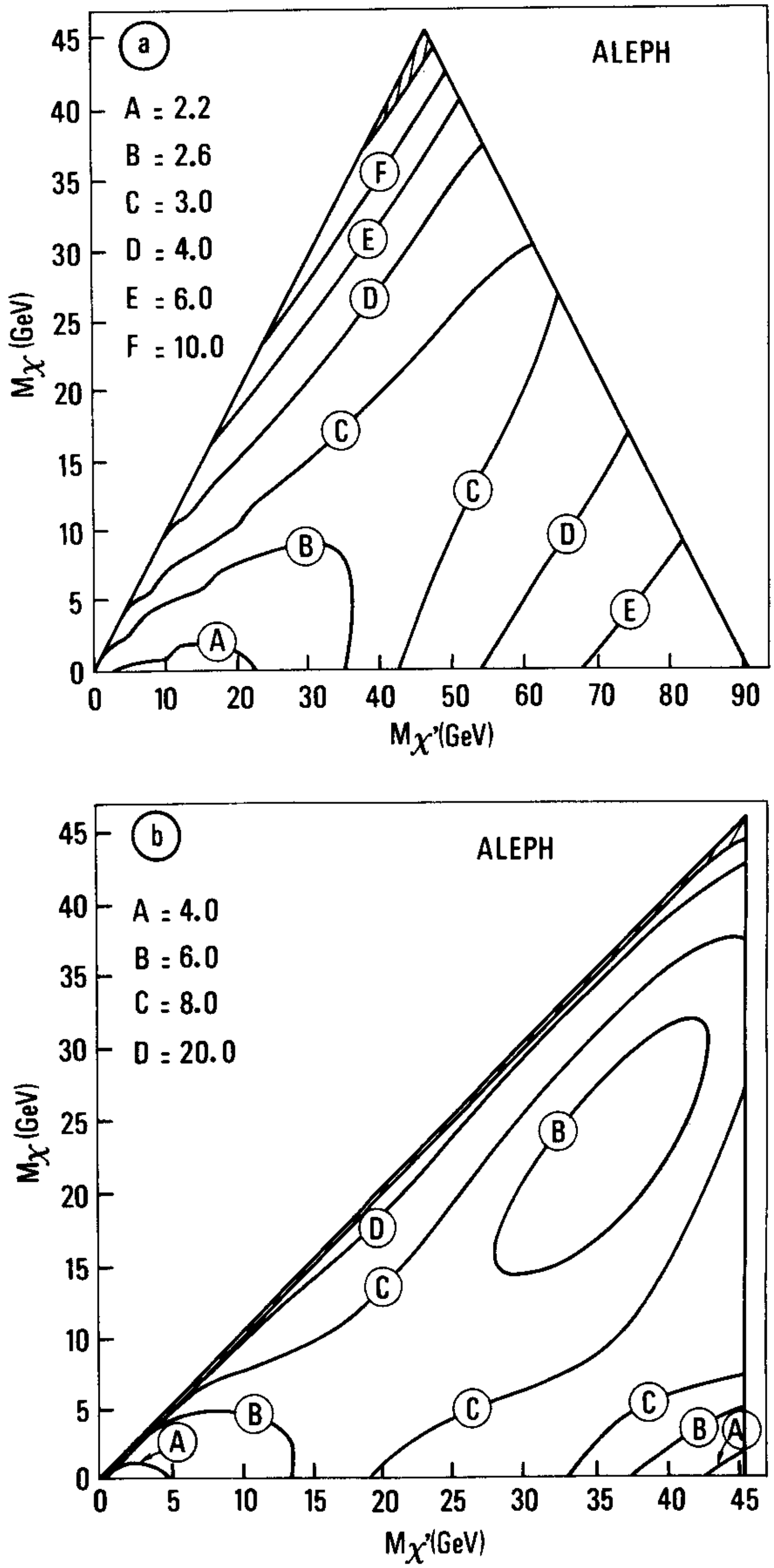
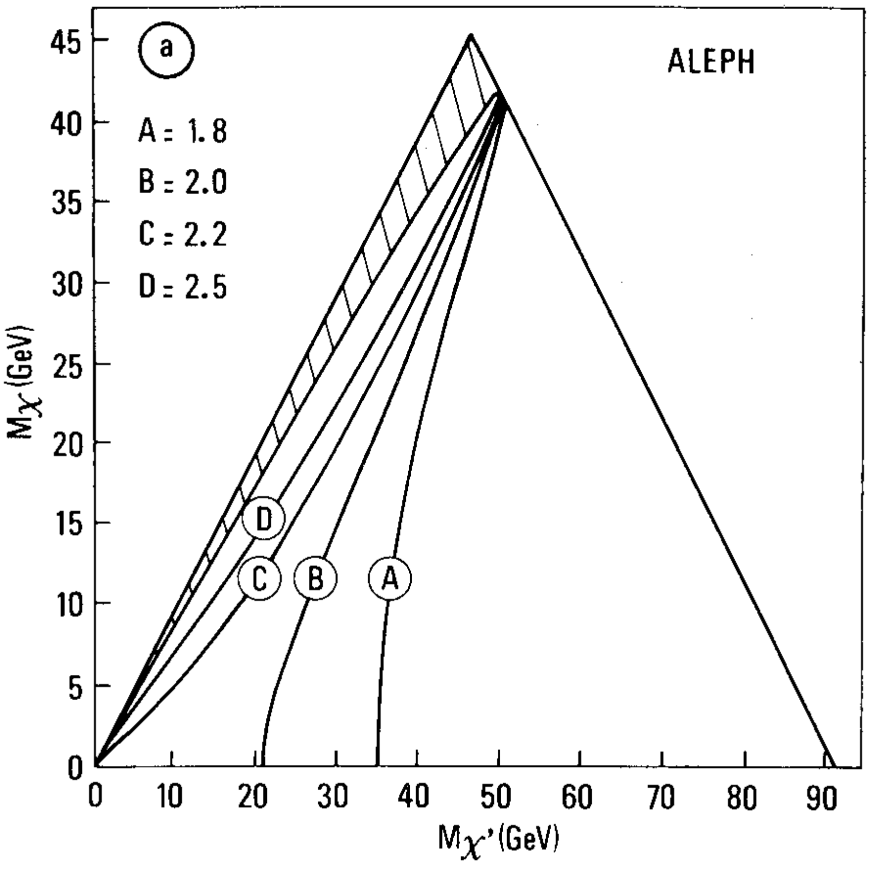

a
ALEPH
A = 2.2
B = 2.6
C = 3.0
D = 4.0
E = 6.0
F = 10.0
A
B
C
C
D
D
E
E
F
M_{χ} (GeV)
$M_{\chi'}$(GeV)
0
5
10
15
20
25
30
35
40
45
0
10
20
30
40
50
60
70
80
90
b
ALEPH
A = 4.0
B = 6.0
C = 8.0
D = 20.0
A
A
B
B
B
C
C
C
D
M_{χ} (GeV)
$M_{\chi'}$(GeV)
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
25
30
35
40
45

Figure 1


a
ALEPH
A = 1.8
B = 2.0
C = 2.2
D = 2.5
D
C
B
A
M_χ (GeV)
$M_{\chi'}$ (GeV)
0
5
10
15
20
25
30
35
40
45
0
10
20
30
40
50
60
70
80
90

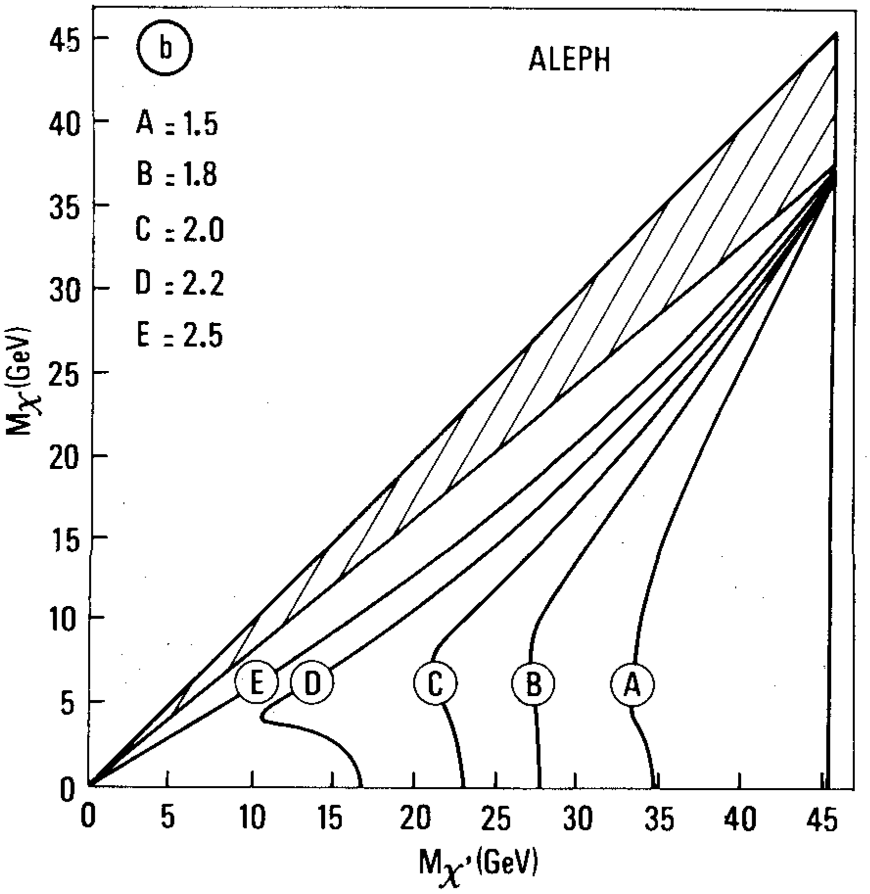

b
ALEPH
A = 1.5
B = 1.8
C = 2.0
D = 2.2
E = 2.5
E
D
C
B
A
M_χ (GeV)
$M_{\chi'}$ (GeV)
0
5
10
15
20
25
30
35
40
45
0
5
10
15
20
25
30
35
40
45

Figure 2

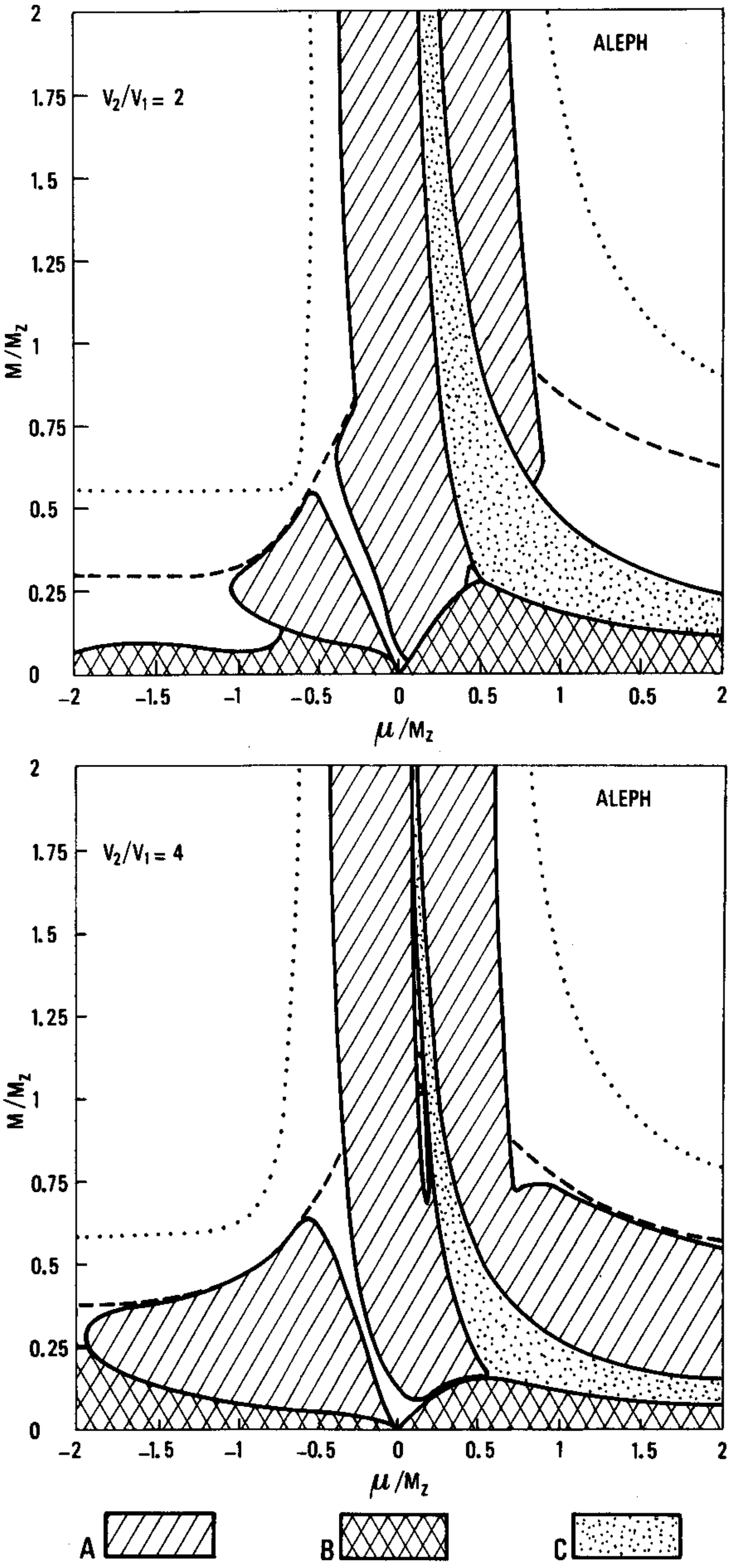

ALEPH
V₂/V₁ = 2
M/M_Z
μ/M_Z
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
−2
−1.5
−1
−0.5
0
0.5
1
0.5
2
ALEPH
V₂/V₁ = 4
M/M_Z
μ/M_Z
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
A
B
C

Figure 3

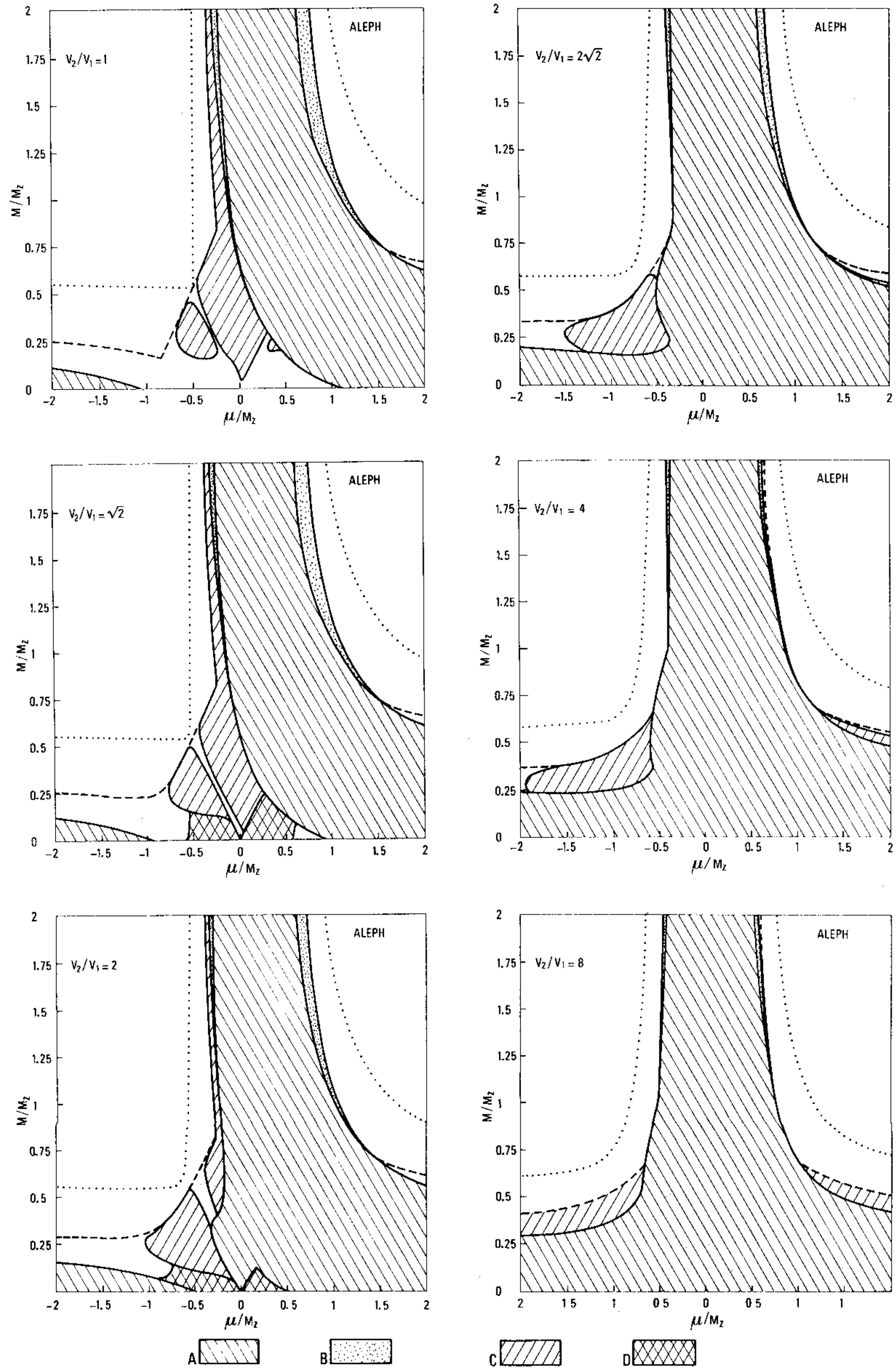

ALEPH
V2/V1 = 1
V2/V1 = 2√2
V2/V1 = √2
V2/V1 = 4
V2/V1 = 2
V2/V1 = 8
M/Mz
μ/Mz
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
A
B
C
D

Figure 4