CERN-TH-5596/89

Pursuing Supersymmetry in Z^0 Decays

John Ellis

CERN, Geneva, Switzerland

Giovanni Ridolfi

INFN, Sezione di Genova, Italy

and

Fabio Zwirner

CERN, Geneva, Switzerland

ABSTRACT

We use recent LEP and SLC data on Z^0 decays and $\bar{p}p$ collider limits on $W^\pm$, Z^0 and gluino production to constrain the parameters of the chargino-neutralino sector in the minimal supersymmetric extension of the Standard Model. We show that unsuccessful chargino searches, the $\bar{p}p$ collider ratio $R \equiv \sigma_{VV}^e / \sigma_Z^e$, and measurements of the total Z^0 width, peak hadronic cross section and invisible Z^0 width provide important constraints. The most stringent present bounds on invisible Z^0 decays assume the Standard Model for hadronic final states, and are therefore not directly applicable to supersymmetric models, which may have additional visible Z^0 decay modes. Possible signatures for supersymmetry in future Z^0 measurements include excesses in the total Z^0 width or in the invisible Z^0 width, but the most promising signal would be an observable cross-section for "zen" events, in which all the visible Z^0 decay products are in one hemisphere.

¹On leave from Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Italy.

The recent avalanche of initial data from LEP [1-8] has already added much to our knowledge of the Z^0 particle. The first $\sim 10^4$ decays observed at LEP have made possible unparalleled precision in measurements of the Z^0 mass, decay width, leptonic and hadronic branching ratios. So far all these measurements seem to be consistent with the Standard Model, and so provide some of the best available constraints on its parameters. For example, within the Standard Model the number of neutrino species has been determined [1-4,7-9] to be 3, although the possible existence of additional invisible Z^0 decays with a rate equivalent to a fraction of a neutrino species cannot be excluded. There are no reports of unexpected visible Z^0 decays, and lower limits have been published [5,6] on the masses of some species of charged supersymmetric particles.

Does this mean that the search for supersymmetry in Z^0 decays should be abandoned? Far from it! Although the negative results obtained so far constrain significantly the parameter space of supersymmetric models, they do leave open the possibility that signatures of supersymmetry could be observed with 10^4 Z^0 's, where $n = 5, 6, 7, 8, \dots$. In this paper, taking into account the existing data on the Z^0 and the $W^\pm$, and working in the minimal supersymmetric extension of the Standard Model¹, we explore the remaining possibilities for Z^0 decays into pairs of supersymmetric spin- $\frac{1}{2}$ fermions: the physical states considered in our analysis are then two charged and four neutral gaugino-Higgsino mixtures, usually called "charginos" and "neutralinos", respectively. Consistently with the existing constraints on charged sleptons [5,6] and with the model-independent upper bounds on $\Gamma_{\nu\nu}^{\text{vis}}[7,8]$, we assume that all supersymmetric spin-0 particles are too heavy to be pair-produced in Z^0 decays².

The constraints we impose include: (1) the published L3 and ALEPH lower limits [5,6] on the combined chargino-neutralino masses; (2) the $\bar{p}p$ collider limits [17,18] on $R \equiv \sigma_W/\sigma_Z$; (3) the LEP/SLC measurement of the total Z^0 width [1-4,9]; (4) the LEP/SLC constraints on the invisible Z^0 decay width [1-4,7-9]; (5) the coupled ALEPH [2] (OPAL [3]) constraint on the peak cross-section for (a selected class of) hadronic Z^0 decays and the total

¹For reviews and references see, for example, ref.[10].

²Previous work on $W^\pm$ and Z^0 decays into charginos and neutralinos can be found in refs.[11-15]. Some implications of the first LEP data for supersymmetric models have been recently studied in ref.[16].

Z^0 width; (6) the UA2 [19] and CDF [20] lower limits on the gluino mass $m_{\tilde{g}}$. We then present predictions consistent with the constraints, for the following observable signatures of supersymmetric particles: (A) $\Gamma(Z^0 \rightarrow \text{all})$, (B) $\Gamma(Z^0 \rightarrow \text{invisible neutrals})$, and (C) $\Gamma(Z^0 \rightarrow \text{"zen" events})$ ³. We find possible signatures of supersymmetry in all these measurements, for ranges of the model parameters that are not yet excluded. In particular, we show that searches for "zen" events have the largest discovery potential at LEP I.

We now review the structure of the chargino-neutralino sector. The two chargino mass eigenstates, $\tilde{\chi}^\pm$ and $\tilde{\chi}'^\pm$ in order of increasing mass, are superpositions of winos $\tilde{W}^\pm$ and Higgsinos $\tilde{H}_{2,1}^\pm$, and the mixing is described by the 2×2 mass matrix

$$\begin{pmatrix} M_2 & \sqrt{2}m_W \sin \beta \\ \sqrt{2}m_W \cos \beta & \mu \end{pmatrix}. \quad (1)$$

In eq.(1), M_2 is the SU(2) gaugino mass, μ is a Higgs mixing term, and $\tan \beta \equiv v_2/v_1$; $v_{1,2}$ are the vacuum expectation values of the $Y = \mp \frac{1}{2}$ Higgses $H_{1,2}^0$, and it is not restrictive to assume $v_{1,2} \geq 0$. The same parameters M_2 , μ and $\tan \beta$ characterize the 4×4 neutralino mass matrix, which in the $(\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0)$ basis reads

$$\begin{pmatrix} M_1 & 0 & -m_Z \cos \beta \sin \theta_W & m_Z \sin \beta \sin \theta_W \\ 0 & M_2 & m_Z \cos \beta \cos \theta_W & -m_Z \sin \beta \cos \theta_W \\ -m_Z \cos \beta \sin \theta_W & m_Z \cos \beta \cos \theta_W & 0 & -\mu \\ m_Z \sin \beta \sin \theta_W & -m_Z \sin \beta \cos \theta_W & -\mu & 0 \end{pmatrix}. \quad (2)$$

Under the usual grand-unification assumption, the gaugino masses obey

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3, \quad (3)$$

where the α_i ($i=1,2,3$) are the $SU(3) \times SU(2) \times U(1)$ gauge couplings. We expect from naturalness arguments [21] that $0 \leq M_2 \leq 200$ GeV and $0 \leq |\mu| \leq 250$ GeV, and we will restrict our considerations to that region of parameter space⁴; in any case, the extension of our analysis to different

³"Zen" events are defined [12] to be those in which the Z^0 decays into two neutral particles, one of which is invisible and the other decays visibly. In most such events, all the visible Z^0 decay products are contained in one hemisphere.

⁴Assuming CP is conserved in the chargino-neutralino sector, it is always possible to choose the $M_i > 0$, whilst μ may be either positive or negative.

regions is straightforward. In the limit of very small $M_2(|\mu|)$, the lightest neutralino is a photino (Higgsino), but in general these states mix to give four Majorana mass eigenstates: we denote them by $\tilde{\chi}_{1,2,3,4}$, in order of increasing mass. In most of our parameter space, $\tilde{\chi}_1 \equiv \tilde{\chi}$ is also the lightest supersymmetric particle, called the LSP. Finally, in dynamical models of radiative $SU(2) \times U(1)$ breaking, $1 \leq \tan \beta < 10$, and we will take as representative values $\tan \beta = 1, 2, 4$.

We now discuss in more detail the six constraints mentioned above.

- (1) The L3 collaboration published [5] the 95% c.l. lower limit $m_{\tilde{\chi}^\pm} > 41$ GeV, assuming that $\tilde{\chi}^\pm \equiv \tilde{W}^\pm$ and $\tilde{\chi}^\pm \rightarrow e^\pm \nu \tilde{\chi}$, with $m_{\tilde{\chi}} \leq 20$ GeV. Since the cross-section for $e^+e^- \rightarrow \tilde{\chi}^+ \tilde{\chi}^-$ rises very rapidly above threshold, we believe that this constraint is only marginally weakened when extended to all possible $\tilde{\chi}^\pm$ compositions. A similar limit has been subsequently published by the ALEPH Collaboration [6], but considering different chargino compositions and in the form of 95% c.l. contours in the $(m_{\tilde{\chi}^\pm}, m_{\tilde{\chi}})$ -plane². Both L3 and ALEPH have assumed in their analyses a branching ratio of 11% for the decay $\tilde{\chi}^\pm \rightarrow e^\pm \nu \tilde{\chi}$: if all the sleptons are indeed heavy, as we have assumed, this assumption is a very good approximation. Comparable limits on charginos have also been published by the UA2 Collaboration [22], but they assume that $\tilde{\chi}^\pm \equiv \tilde{W}^\pm$ and $m_{\tilde{\nu}} < m_{\tilde{\chi}^\pm}$, a possibility we discard.
- (2) The UA1 [23], UA2 [17] and CDF [18] Collaborations have published measurements of

$$R \equiv \frac{\sigma_W^e}{\sigma_Z^e} \equiv \frac{\sigma(\bar{p}p \rightarrow W + X)B(W \rightarrow e\nu)}{\sigma(\bar{p}p \rightarrow Z + X)B(Z \rightarrow e e)}, \quad (4)$$

which are consistent with the Standard Model. We interpret these data as constraining Γ_Z/Γ_W , where $\Gamma_Z = \Gamma_Z^{SM} + \Delta\Gamma_Z$, $\Gamma_W = \Gamma_W^{SM} + \Delta\Gamma_W$. $\Gamma_Z^{SM} \sim 2.5$ GeV, $\Gamma_W^{SM} \sim 2.1$ GeV are the Standard Model predictions, and $\Delta\Gamma_{Z,W}$ the contributions from decays into pairs of supersymmetric spin- $\frac{1}{2}$

²One would also expect that the L3 bound could be expressed in such a form, but this has not yet been published.

particles. In particular, the decay width for $W^\pm \rightarrow \tilde{\chi}^\pm \tilde{\chi}$ is given by

$$\Gamma(W^\pm \rightarrow \tilde{\chi}^\pm \tilde{\chi}) = \frac{g^2}{16\pi m_W} \sqrt{\left[1 - \frac{(m_{\tilde{\chi}^\pm} + m_{\tilde{\chi}})^2}{m_W^2}\right] \left[1 - \frac{(m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}})^2}{m_W^2}\right]} \left\{ m_W^2 - m_{\tilde{\chi}^\pm}^2 - m_{\tilde{\chi}}^2 + \left[m_W^2 - \frac{(m_{\tilde{\chi}^\pm}^2 - m_{\tilde{\chi}}^2)^2}{m_W^2} \right] \frac{O_1^2 + O_2^2}{3} - 4O_L O_R m_{\tilde{\chi}^\pm} m_{\tilde{\chi}} \right\}, \quad (5)$$

where we use the notation of ref.[13], but we generalize their formula to the case of non-negligible neutralino masses. Combining the latest UA2 and CDF measurements of R gives

$$\frac{R}{R^{SM}} \equiv \frac{\Gamma_Z}{\Gamma_W} \frac{\Gamma_W^{SM}}{\Gamma_Z^{SM}} = 0.958 \pm 0.068, \quad (6)$$

from which we extract the 95% c.l. constraint: $0.825 < (R/R^{SM}) < 1.091$. (3) We have averaged the measurements of the total Z^0 width by the four LEP experiments [1-4] and by Mark II [9] at the SLC, to give

$$\Gamma_Z = 2.545 \pm 0.048. \quad (7)$$

This is to be compared with the range

$$\Gamma_Z^{SM} = 2.487 \pm 0.023 \quad (8)$$

expected [24] in the Standard Model for $m_{Z^0} = 91.17$ GeV and different values of m_t and m_H . Comparing eq.(7) with eq.(8), we infer that any increment $\Delta\Gamma_Z$ in the total Z^0 width due to non-standard decay channels must obey

$$\Delta\Gamma_Z < 0.175 \text{ GeV}, \quad (9)$$

where, in order to be conservative, we have combined the 95% c.l. upper limit from eq.(7) with the minimum value of Γ_Z^{SM} allowed by eq.(8). We use this directly as an upper bound on Z^0 decays into pairs of spin- $\frac{1}{2}$ supersymmetric fermions, adding together all kinematically accessible combinations.

- (4) The four LEP experiments [1-4] and Mark II [9] at the SLC have measured the Z^0 decay width into invisible neutral particles, assuming that the Standard Model describes correctly all decays into hadronic final states.

We average their data to obtain for the number N_ν of equivalent neutrino species within the Standard Model

$$N_\nu = 3.02 \pm 0.16, \quad (10)$$

which gives $N_\nu < 3.33$ at 95 % c.l.. According to our assumptions, sneutrinos are too heavy to contribute to invisible Z^0 decays. Nevertheless, the interpretation of this bound is not immediate in a supersymmetric model, since there may well be additional visible Z^0 decays involving hadronic final states. Quite generally, it is not correct to apply the N_ν constraint of eq.(10) naively in models with other visible Z^0 decay modes. We interpret eq.(10) as implying that

$$\frac{\Delta\Gamma_{Z^0}^{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} < 0.33 \quad (95\% \text{ c.l.}) \quad \text{if} \quad \Delta\Gamma_{Z^0}^{\text{vis}} < 23 \text{ MeV}. \quad (11)$$

Because of this constraint on $\Delta\Gamma_{Z^0}^{\text{vis}}$, eq.(11) cannot be used [25] to rule out dark matter candidates unless the standard model is assumed to describe all visible Z^0 decays. $Z^0 \rightarrow \tilde{\chi}\tilde{\chi}$ decays might contribute [11,13,14,26] to $\Gamma_{Z^0}^{\text{vis}}$ by an amount $0 \leq (\Delta\Gamma_{Z^0}^{\text{vis}}/\Gamma_{\nu\bar{\nu}}) \leq 1$. However, in the minimal supersymmetric extension of the Standard Model, the bound of eq.(11) is almost empty because of the restriction on $\Delta\Gamma_{Z^0}^{\text{vis}}$, which receives contributions from $Z^0 \rightarrow \tilde{\chi}^+\tilde{\chi}^-$ and $Z^0 \rightarrow \tilde{\chi}_i\tilde{\chi}_j$ ($1 \neq i \leq j$). Fortunately, the ALEPH [7] and OPAL [8] collaborations have also presented bounds on $\Gamma_{Z^0}^{\text{inv}}$ that do not rely on assumptions on the hadronic Z^0 decay width, and can be directly applied to supersymmetric models. We combine them to give the bound

$$\frac{\Delta\Gamma_{Z^0}^{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} < 0.36 \quad (95\% \text{ c.l.}). \quad (12)$$

(5) The ALEPH collaboration has published [2] an approximately elliptical allowed region in the (σ_0, Γ_Z) plane where σ_0 is the visible hadronic peak cross-section:

$$\sigma_{had}^0 = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}, \quad (13)$$

and Γ_Z is the total Z^0 decay width. We take as a constraint the 90 % c.l. region in the (σ_0, Γ_Z) plane. The OPAL collaboration has published [3] an

analogous allowed region in the $(\hat{\sigma}_0, \Gamma_Z)$ plane, where $\hat{\sigma}_0$ is the peak cross-section for hadrons subject to some non-trivial cuts on total energy and momentum balance. In the absence of a detailed Monte Carlo calculation, it seems reasonable to regard these cuts as removing “zen” events due to $Z^0 \rightarrow \tilde{\chi}\tilde{\chi}'$ (where $\tilde{\chi}'$ is any of the three heavy neutralinos $\tilde{\chi}_{2,3,4}$), but retaining Z^0 decays into pairs of unstable charginos or neutralinos ($Z^0 \rightarrow \tilde{\chi}^+\tilde{\chi}^-, \tilde{\chi}\tilde{\chi}'$):

$$\hat{\sigma}_{had}^0 \simeq \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}[\Gamma_{had} - \Gamma_{zen}]}{\Gamma_Z^2}. \quad (14)$$

We have checked that the OPAL constraint is entirely contained within the ALEPH one, mainly because of the larger Z^0 sample analysed in the second of ref.[2].

(6) The UA2 [19] (CDF [20]) Collaboration has published a lower limit on the gluino mass

$$m_{\tilde{g}} > 79 \text{ GeV}, \quad (m_{\tilde{g}} > 73 \text{ GeV}), \quad (15)$$

assuming that $\tilde{g} \rightarrow \tilde{q}\tilde{q}$ where $\tilde{\chi}$ is invisible and $m_{\tilde{\chi}} \ll (\leq) \frac{1}{2}m_{\tilde{g}}$. These limits may well be improved soon by a factor ~ 2 , given the larger statistics now available to CDF. It is well known that in many models other gluino decay modes (such as $\tilde{g} \rightarrow \tilde{q}\tilde{q}^*$ or $\tilde{\chi}^0$ or $\tilde{\chi}^\pm$ or $\tilde{\chi}^0 \rightarrow \tilde{\chi} + \text{visible particles}$) can become important. As a result, the limit in eq.(15) and its prospective improvement may be weakened, as analyzed in detail in ref.[27]. However, the decay channel $\tilde{g} \rightarrow \tilde{q}\tilde{q}$ is suppressed if $\tilde{\chi}$ is predominantly a Higgsino rather than a gaugino, and this happens for small values of $|\mu|$. As shown below, this region is ruled out by other experimental constraints. For large values of $|\mu|$, the CDF/UA2 limits on the gluino mass are only slightly affected by the exact computation of $B(\tilde{g} \rightarrow \tilde{q}\tilde{q})$. As a conservative bound, we will assume in the following $m_{\tilde{g}} \geq 70 \text{ GeV}$, which is translated by eq.(3) into $M_2 \geq 20 \text{ GeV}$.

In Fig. 1 we show the effects of the constraints (1) to (6) above on the (μ, M_2) plane for three choices of $\tan\beta$. We discuss the impact of each of the constraints in turn, starting with the case $\tan\beta = 2$ in Fig. 1b, and then commenting on the principal differences for $\tan\beta = 1, 4$. The chargino constraint (1) excludes a large region of the $\mu > 0$ area in Fig. 1b, and a smaller region with $\mu < 0$. The “window” when $\mu > 0$ corresponds to cases where $m_{\tilde{\chi}}$ is close to $m_{\tilde{\chi}^\pm}$. In much of this “window”, the $\tilde{\chi}^\pm$ is

actually the LSP, which is disallowed by cosmology [28]. In any case, the “window” is contained within the large $\mu > 0$ region excluded by the total width constraint (3). Constraint (2) on Γ_W/Γ_Z has a very similar effect to (1), due to the large $\Gamma(Z^0 \rightarrow \tilde{\chi}^+ \tilde{\chi}^-)$ whenever this channel is kinematically open. Constraint (1) is shown in its model-independent form, which is the more restrictive in our model. Constraint (5) is the most restrictive of all, essentially by virtue of the correlation between Γ_Z and Γ_Z^{inv} it takes into account, and of the statistical impact of the most recent ALEPH data. Finally, we have constraint (6) which excludes a strip of low values of M_2 independent of the values of μ and $\tan\beta$.

Figure 1a for $\tan\beta = 1$ exhibits similar features, except that in this case the “window” in constraint (1) at $\mu > 0$ is significantly enlarged towards higher M_2 values. Constraint (2) is again very similar in effect to (1), apart from the fact that the window opens up to connect with the large allowed region with $\mu \leq 0$. As before, most of this “window” is excluded by cosmology, and all of it is excluded by the constraints (3) and (5). In this case, constraint (1) provides no extra information, since $\Gamma(Z^0 \rightarrow \tilde{\chi} \tilde{\chi}) = 0$, whilst constraint (6) on $m_{\tilde{g}}$ acts as before to exclude small M_2 .

In the case of $\tan\beta = 4$ in Fig. 1c, the chargino constraint (1) and the $\sigma_W/\sigma_Z^{\text{inv}}$ constraint (2) now exclude a larger region with $\mu > 0$, and also a substantial region with $\mu < 0$. The “window” has now disappeared. Almost equivalent domains of $\mu > 0$ and $\mu < 0$ are excluded by the constraints (3) and (5). As in the case of $\tan\beta = 2$, constraint (4) is contained within (3) and (5), whereas constraint (6) acts as before. We have checked that for $\tan\beta > 4$ one obtains qualitatively the same results as in Fig. 1c, with only minor deformations of the contours.

We turn finally to the possible signatures of supersymmetry that remain after all these constraints are applied, and discuss how they might be revealed among the next $10^6 Z^0$'s. In Fig. 2 we discuss the three possible signatures mentioned in the introduction, namely: (A) the total Z^0 decay width, (B) $Z^0 \rightarrow$ invisible neutrals, and (C) the Z^0 branching ratio for “zen” events. The solid lines delimit the region which is not yet excluded but in which Z^0 decays into pairs of spin- $\frac{1}{2}$ supersymmetric particles are still kinematically allowed: one can see that a large part of the parameter space is still waiting to be explored at LEP I.

Looking first at the case $\tan\beta = 2$ in Fig. 2b, we see that (A) estab-

lishing an upper bound of 50 MeV on non-standard contributions to the total Z^0 decay width⁶ would not significantly improve the existing limits. Looking (B) for invisible Z^0 decays at a level $\Delta N_\nu \geq 0.05$, which appears feasible for the four LEP experiments combined, in the neutrino-counting experiment above the Z^0 peak, could exclude instead a non-negligible range of negative μ . A much larger region of $\mu < 0$ can be explored by (C) searching for “zen” events with a branching ratio down to 10^{-4} . We note that whenever there is an observable $\Delta\Gamma_Z^{\text{inv}}$, there is also an observable rate for “zen” events. This means that any interpretation of a possible $\Delta N_\nu \neq 0$ in terms of decays into supersymmetric fermion pairs could be confirmed by a search for “zen” events.

In the case $\tan\beta = 1$ (Fig. 2a), we see that again (A) putting a 50 MeV upper bound on $\Delta\Gamma_Z$ would not be sensitive to new regions of the (μ, M_2) -plane. In this case, there is no $Z^0 \rightarrow \tilde{\chi} \tilde{\chi}$ decay, and so (B) measuring $\Delta\Gamma_Z^{\text{inv}}$ does not apply any additional constraints. A large region of small $|\mu|$ could be explored by looking (C) for “zen” events with a branching ratio down to 10^{-4} .

Turning lastly to the case $\tan\beta = 4$ in Fig. 2c, we see that (A) establishing the bound $\Delta\Gamma_Z < 50$ MeV would exclude a small extra region of parameter space for small $|\mu|$. There are also (B) regions of $\mu > 0$ and $\mu < 0$ which would give an observable $\Delta\Gamma_Z^{\text{inv}}$. On the other hand, the search (C) for “zen” events with a branching ratio down to 10^{-4} would exclude large regions of $\mu > 0$ and $\mu < 0$. As in the case of $\tan\beta = 2$, whenever $\Delta\Gamma_Z^{\text{inv}}$ is observable there should also be an observable rate for “zen” events. We stress again that values of $\tan\beta$ larger than 4 would give rise to a situation very close to the one represented in Fig. 2c.

We believe that the search for “zen” events to the level of 10^{-4} or 10^{-5} should not present insurmountable experimental problems. Already the ALEPH Collaboration [29] has published a search for $Z^0 \rightarrow H^0 + \bar{\nu}\nu$ at the level of a few times 10^{-4} for $m_{H^0} \leq 15$ GeV. We hesitate to interpret this directly as an upper bound on “zen” events, since the experimental acceptance for hadronic systems accompanied by missing energy appears to decrease for larger hadronic jet-pair masses. However, we do think that

⁶Even if Γ_Z could be measured with a precision of 20-30 MeV, one cannot forget about the theoretical uncertainty in eq.(8).

a dedicated search for “zen” events could reach a sensitivity of 10^{-4} or 10^{-5} , which would explore a wide domain of the supersymmetric parameter space, as shown in fig.2.

We wish our experimental colleagues good luck!

One of us (G.R.) would like to thank the Theory Group of the Lawrence Berkeley Laboratory for the kind hospitality while part of this work was done.

References

1. B. Adeva et al. (L3 Collaboration), Phys. Lett. B231 (1989) 509.
2. D. Decamp et al. (ALEPH Collaboration), Phys. Lett. B231 (1989) 519 and preprint CERN-EP/89-169.
3. M.Z. Akrawy et al. (OPAL Collaboration), Phys. Lett. B231 (1989) 530.
4. P. Aarnio et al. (DELPHI Collaboration), Phys. Lett. B231 (1989) 539.
5. B. Adeva et al. (L3 Collaboration), preprint L3#002 (1989).
6. D. Decamp et al. (ALEPH Collaboration), preprint CERN-EP/89-158.
7. D. Decamp et al. (ALEPH Collaboration), preprint CERN-EP/89-141 and preprint CERN-EP/89-169.
8. M.Z. Akrawy et al. (OPAL Collaboration), preprint CERN-EP/89-147.
9. G.S. Abrams et al. (MARK II Collaboration), Phys. Rev. Lett. 63 (1989) 721; Phys. Rev. Lett. 63 (1989) 2173.
10. H.-P. Nilles, Phys. Rep. 110 (1984) 1;
H.E. Haber and G.L. Kane, Phys. Rep. 117 (1985) 75.
11. J.A. Grifols, X.Mor-Mur and J.Solá, Phys. Lett. B114 (1982) 35;
J. Ellis and G.G. Ross, Phys. Lett. B117 (1982) 397;
J.A. Grifols, Phys. Lett. B120 (1982) 217;
S. Weinberg, Phys. Rev. Lett. 50 (1983) 387;
R. Arnowitt, A.H. Chamseddine and P. Nath, Phys. Rev. Lett. 50 (1983) 232;
P. Fayet, Phys. Lett. B125 (1983) 178;
D.A. Dicus, S. Nandi and X. Tata, Phys. Lett. B129 (1983) 451;
V. Barger, R.W. Robinett, W.Y. Keung and R.J.N. Phillips, Phys. Lett. B132 (1983) 436 and Phys. Rev. D28 (1983) 2912.

12. J.-M. Frère and G.L. Kane, Nucl. Phys. B223 (1983) 331;
J.Ellis, J.S. Hagelin, D.V. Nanopoulos and M., Srednicki, Phys. Lett. B127 (1983) 233;
13. J. Ellis, J.-M. Frère, J.S. Hagelin, G.L. Kane and S.T. Petcov, Phys. Lett. B132 (1983) 436.
14. B. Grinstein, J. Polchinski and M. Wise, Phys. Lett. B130 (1983) 285.
15. A.H. Chamseddine, P. Nath and R. Arnowitt, Phys. Lett. B129 (1983) 445, (E) B132 (1983) 467;
P. Fayet, Phys. Lett. B133 (1983) 363;
D.A. Dicus, S. Nandi, W.W. Repko and X. Tata, Phys. Rev. Lett. 51 (1983) 1030, Phys. Rev. D29 (1984) 67 and Phys. Rev. D29 (1984) 1317;
16. H. Komatsu, Phys. Lett. B177 (1986) 201;
A. Bartl, H. Fraas and W. Majerotto, Z. Phys. C30 (1986) 441;
H. Baer, K. Hagiwara and X. Tata, Phys. Rev. D35 (1987) 1598 and Phys. Rev. D38 (1988) 1485;
R. Barbieri, G. Gamberini, G.F. Giudice and G. Ridolfi, Phys. Lett. B195 (1987) 500 and Nucl. Phys. B296 (1988) 75;
A. Bartl, W. Majerotto and N. Oshimo, Phys. Lett. B216 (1989) 233;
A. Bartl, S. Stüppel, W. Majerotto and N. Oshimo, preprint HEPHY-PUB 522/89.
17. R. Barbieri, I. Ferrante, F. Fidecaro, M. Frigeni and J.-F. Grivaz, in "Z. Physics at LEP I", CERN Yellow Report 89-08 (G. Altarelli, R. Kleiss and C. Verzegnassi eds.), Vol.2, p.119.
18. H. Baer, M. Drees and X. Tata, preprint CERN-TH.5582/89.
19. K. Einsweiler (UA2 Collaboration), seminar given at CERN, December 12, 1989 and T. Åkesson et al. (UA2 Collaboration), preprint CERN-EP, to appear.
20. L. Nodulman (CDF Collaboration), talk given at the EPS-HEP Conference, Madrid, September 1989, to appear in the Proceedings.
19. J. Alitti et al. (UA2 Collaboration), preprint CERN-EP/89-151.
20. F. Abe et al (CDF Collaboration), Phys. Rev. Lett. 62 (1989) 1825.
21. J. Ellis, K. Enqvist, D.V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. A1 (1986) 57;
R. Barbieri and G.F. Giudice, Nucl. Phys. B306 (1988) 63.
22. T. Åkesson et al. (UA2 Collaboration), preprint CERN-EP/89-172.
23. C. Albajar et al. (UA1 Collaboration), preprint CERN-EP-88/168.
24. F.A. Herends et al., in "Z. Physics at LEP I", CERN Yellow Report 89-08 (G. Altarelli, R. Kleiss and C. Verzegnassi eds.), Vol.1, p.89.
25. K. Griest and J. Silk, preprint CERN-TH-89-014;
L.M. Krauss, preprint YCTP-P14-89;
J. Lopez and D.V. Nanopoulos, preprint CTF-TAMU-62/89.
26. J. Ellis and F. Zwirner, preprint CERN-TH.5460/89, to appear in Nuclear Physics B.
27. H. Baer, J. Ellis, G.B. Gelmini, D.V. Nanopoulos and X. Tata, Phys. Lett. B161 (1985) 175;
G. Gamberini, Z. Phys. C30 (1986) 605;
R.M. Barnett, H.E. Haber and G.L. Kane, Nucl. Phys. B267 (1986) 625;
H. Baer, D. Karatas and X. Tata, Phys. Lett. B183 (1987) 220;
R. Barbieri, G. Gamberini, G.F. Giudice and G. Ridolfi, Nucl. Phys. B301 (1988) 15;
G. Gamberini, G.F. Giudice, B. Mele and G. Ridolfi, Phys. Lett. B203 (1988) 453;
H. Baer, X. Tata and J. Woodside, Phys. Rev. Lett. 63 (1989) 352.
28. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, Nucl. Phys. B238 (1984) 453.
29. D. Decamp et al. (ALEPH Collaboration), preprint CERN-EP/89-157.

Figure Captions

Figure 1

Regions of the (μ, M_2) -plane excluded by the constraints (t)-(f) discussed in the text, for the typical values (a) $\tan\beta = 1$, (b) $\tan\beta = 2$ and (c) $\tan\beta = 4$. For graphical clarity, when two or more lines would be almost superimposed, only the one corresponding to the most stringent constraint has been drawn.

Figure 2

Regions of the (μ, M_2) -plane accessible to further supersymmetry searches at LEP 1, for the same values of $\tan\beta$ as in Fig. 1. Solid lines delimit the presently allowed region which is kinematically accessible in some supersymmetric Z^0 decays. Dotted and dashed-dotted lines correspond to $\Delta\Gamma_Z = 50$ MeV and $\Delta\Gamma_Z^{nu}/\Gamma_{ee} = 0.05$, respectively. In the case of “zen” events, branching ratios of 10^{-4} and 10^{-5} are shown by dashed lines.

Fig. I

Fig. I (continued)

Fig. 2

Fig. 1 (continued)

Fig. 2 (continued)

Fig. 2 (continued)