Search for Neutralinos in Z Decays

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ABSTRACT

A search for neutralinos produced in Z decays has been performed via the reactions $e^+e^- \rightarrow \chi\chi'$ and $e^+e^- \rightarrow \chi'\chi'$, where the next-to lightest neutralino, χ', decays into the lightest neutralino, χ, and either a photon or a fermion pair. This analysis is based on 1.8×10^6 hadronic Z decays collected with the L3 detector at LEP. Absence of any signal has been used to set upper limits of a few times 10^{-5} on the branching ratios $Z \rightarrow \chi\chi'$ and $Z \rightarrow \chi'\chi'$. In the framework of the Minimal Supersymmetric Standard Model, we exclude a lightest χ with m_χ less than 18 GeV, if either $\tan\beta > 2$ or the gluino mass $m_{\tilde{g}} > 100$ GeV.

1 Introduction

Supersymmetry (SUSY) [1], based on the assumption of symmetry between bosons and fermions, addresses a few problems of the Standard Model (SM) [2] and Grand Unified Theories (GUTs). It predicts the existence of a partner to every SM particle which differ in spin by half a unit. The partners of the γ, Z and the neutral higgs mix to form at least four mass eigenstates, the neutralinos [3] χ, χ', χ'' and χ''', in order of increasing mass. χ is supposed to be the lightest supersymmetric particle (LSP) and weakly interacting, therefore escapes any detection. The partners of the $W^\pm$ and $H^\pm$ mix to form two mass eigenstates, the charginos $\tilde{\chi}^\pm_{1,2}$. In the Minimal Supersymmetric Standard Model (MSSM) [3] the compositions and interactions of SUSY particles can be described by parameters M, μ and $\tan\beta$. The gaugino mass, M, is expected to be in the range $0 \leq M \leq 250$ GeV, the higgsino mass, μ, is bounded by $0 \leq |\mu| \leq 200$ GeV and the ratio of the vacuum expectation values of the two higgs doublets, $\tan\beta = v_2/v_1$, is constrained to $1 \leq \tan\beta \leq \frac{m_t}{m_b} \sim 50$, where v_2 gives mass to quarks of charge $\frac{2}{3}e$ and v_1 gives mass to charged leptons and quarks of charge $-\frac{1}{3}e$.

We present the event selection and results of our search for neutralinos, which are based on 1.8×10^6 hadronic Z decays collected in 1991 — 1993. These results are interpreted in the MSSM context as well as in a more general way.

2 The L3 Detector

The L3 detector [4] covers 99% of the 4π solid angle. It consists of a central tracking chamber (TEC), a forward–backward tracking chamber, a high resolution electromagnetic calorimeter (ECAL) composed of Bismuth Germanium Oxide (BGO) crystals, a ring of scintillation counters, a uranium brass hadron calorimeter with proportional wire chambers (HCAL), and a high-precision muon chamber spectrometer (MUCH). These detectors are located in a 12 m diameter magnet providing a uniform field of 0.5 T along the beam direction. Forward BGO arrays (LUMI) on each side of the detector measure the luminosity by detecting the energy deposit of small angle Bhabha events.

3 Event Selection

We searched for neutralinos produced in the reaction

$$e^+e^- \longrightarrow Z \longrightarrow \chi\chi' \text{ or } \chi'\chi'$$

with χ' decaying via

$$\chi' \longrightarrow \chi Z^* \longrightarrow \chi f\bar{f} \quad (f = q, \mu, e) \quad \text{or} \quad \chi' \longrightarrow \chi\gamma.$$

The signature is missing energy due to the undetected χ and one or two photons, two or four acollinear and acoplanar leptons, or one to four hadronic jets from the primary quarks. Due to the low visible energy and the small branching fraction, we did not investigate decays involving τ leptons.

We assume that the masses of the lightest higgs, h^0 or A^0, and charginos, $\tilde{\chi}^\pm_1$, are sufficiently large [5] so that the decays $\chi' \rightarrow \chi h^0, \chi A^0$ and $\chi' \rightarrow \tilde{\chi}^\pm_1 f\bar{f}'$ are kinematically forbidden. However, the signature of such decays would be very similar to $\chi' \rightarrow \chi Z^* \rightarrow \chi q\bar{q}$ and could lead to even higher detection efficiencies. Because the SUSY partner of the electron, the selectron, is assumed to be heavier than 45 GeV [6], we neglect neutralino production via t-channel exchange, which is of the order of 10^{-3} relative to the s-channel contribution in the MSSM, if the neutralino is not a pure photino.

We used Monte Carlo event generators to estimate the background arising from all SM reactions. The main background sources for the fermionic neutralino decays are fermion pair production $e^+e^- \to q\bar{q}(\gamma)$ [7], $e^+e^- \to \tau^+\tau^-(\gamma)$ [8] and four-fermion processes $e^+e^- \to e^+e^- f\bar{f}$ [9]. The backgrounds for the radiative neutralino decays are $e^+e^- \to \nu\bar{\nu}\gamma$ [10] and $e^+e^- \to \gamma\gamma(\gamma)$ [11]. The detector response of the final state particles is simulated with the GEANT package [12]. The simulated events are reconstructed and analyzed in the same way as the real data.

Hadronic Final State

We select events with one or two jets in the final state, which may be interpreted as $Z \to \chi\chi' \to \chi\chi q\bar{q}$, $Z \to \chi'\chi' \to \chi q\bar{q}\chi\nu\bar{\nu}$, or $Z \to \chi'\chi' \to \chi q\bar{q}\chi q'\bar{q}'$ events. Calorimetric jets are reconstructed using the Durham clustering algorithm [13] with $y_{cut} = 0.04$ and are required to have at least one associated TEC track. Depending on the kinematics of the reaction, the two initial decay quarks may be reconstructed as one or two jets. We did not study the three and four-jet topology, because of the large background arising from SM $q\bar{q}(g)$ events. Also, their relative fraction compared to one and two-jet events was found to be small.
For hadronic one-jet events we require:

1. The jet to have at least 10 GeV transverse momentum in order to reject four-fermion background.
2. The event to contain at least 4 TEC tracks to remove single jets originating from one or three prong τ decays, where the other τ remains undetected.
3. There to be no TEC track in the r–ϕ plane in the hemisphere opposite to the jet direction, and the total calorimetric energy deposited in a cone of half opening angle of 30° around the missing energy direction to be less than 500 MeV. The contribution of most standard Z decays is therefore eliminated.

No events survive the one-jet selection which is consistent with a background expectation of less than 0.5 events.
For hadronic two-jet events we require:

1. The acoplanarity and acollinearity angle of the two jets to exceed 40° to remove most standard Z decays.
2. The total calorimetric energy deposited in a cone of half opening angle of 30° around the missing energy direction to be less than 500 MeV. There must be no TEC track within 30° of the missing energy direction in the r–ϕ plane. These requirements remove any remaining $q\bar{q}$ or $\tau^+\tau^-$ events.
3. We reduce the four-fermion background by requiring that the direction of the missing energy points more than 25° away from the beam axis, that each jet has at least 3 GeV transverse momentum and that no more than 10 GeV is deposited in the luminosity monitors.

Three events are left after applying the two-jet selection cuts which is consistent with an expected background from SM four-fermion processes of 0.9 ± 0.4 events.

Muon Final State

In order to select candidates of the type $Z \to \chi\chi' \to \chi\chi\mu^+\mu^-$, one of the two muons must be identified in the muon chambers and the other one either in the muon chambers or as an isolated TEC track. We reject cosmic rays as described in [14]. Further selection criteria are:

1. The acoplanarity between the two muons has to exceed 40°, and the TEC track multiplicity has to be at most 2 to suppress the four-fermion background.
2. The most energetic ECAL or LUMI cluster should not exceed 2 GeV in order to remove radiative dimuons and four-fermion events respectively. This requirement also ensures that a muon candidate which is only identified by a TEC track corresponds to a real muon.
3. If both muons have been identified in the MUCH, the most energetic one has to have momentum $p >$ 6 GeV. The missing transverse momentum of the event also has to exceed 6 GeV. In the case where one muon has been identified in the TEC, it should have a transverse momentum $p_T > 3$ GeV, while the other one (identified in the MUCH) should have $p > 10$ GeV. These cuts further reduce the four-fermion contribution.

No candidate events are observed after applying these cuts which is consistent with 0.5 background events.

Electron Final State

$Z \to \chi\chi' \to \chi\chi e^-e^+$ candidate events are selected by requiring at most three clusters in the ECAL. The two most energetic clusters are associated with a TEC track and must have more than 3 GeV and 2 GeV of energy. The energy of a possible third cluster has to be below 0.5 GeV. Furthermore:

1. The acoplanarity and acollinearity angle of the two most energetic clusters has to exceed 15° to reduce the four-fermion and Bhabha background.
2. The missing transverse momentum has to exceed 6 GeV and point more than 12° away from the beam axis and more than 5° away from the closest ECAL cluster to further reduce the $\tau^+\tau^-$ and four-fermion contamination.

3. The sum of the visible energy and missing momentum should not exceed the center-of-mass energy minus 5 GeV in order to suppress three-body final states with an undetected particle.

No events are left after applying these cuts consistent with 0.5 events expected from background.

Photon Final States

Photonic final states may result from the $\chi' \rightarrow \chi\gamma$ decay. They are selected by allowing up to three electromagnetic clusters in the ECAL and no other significant detector activity. The selection criteria are:

1. The most energetic cluster in the LUMI should not exceed 5 GeV, while the most energetic cluster in the HCAL has to be below 3 GeV. This reduces the background from radiative Bhabha scattering.
2. Radiative cosmic muon and four-fermion backgrounds are removed by requiring no tracks in the TEC or MUCH.
3. Single-photon events are selected starting 20° away from the beam line. The transverse momentum of the photon has to exceed 10 GeV to suppress events from radiative neutrino production $\nu\bar{\nu}(\gamma)$.
4. Events with two photons are selected allowing for a third cluster. To suppress the SM $\gamma\gamma(\gamma)$ final states, we require that the two most energetic photons have less than 40 GeV of energy each and an acoplanarity in excess of 3.5°. The missing transverse momentum has to be above 6 GeV.

No events survive the two-photon selection consistent with 0.7 ± 0.5 events expected from background. In the one-photon sample 13 events survive which is in good agreement with the SM expectation from $\nu\bar{\nu}\gamma$ and $\gamma\gamma(\gamma)$ events of 15.7 ± 1.5.

Results

No excess over the SM expectation has been observed. The efficiency to detect neutralinos is high in the case where the χ-χ' mass difference is greater than 10 GeV. It reaches 70% for the single-photon selection and up to 30% – 60% for signatures with hadronic jets, muons, electrons or two photons. The trigger efficiency for events passing all our cuts is more than 90% for most of the final state configurations.

In the absence of a neutralino signal, we set limits on the branching fractions BR($Z \rightarrow \chi\chi'$) and BR($Z \rightarrow \chi'\chi'$), which do not depend on the neutralino coupling constants. We subsequently interpret these results in the MSSM framework, excluding regions of the parameter space as well as establishing limits on the neutralino masses. BR($Z \rightarrow \chi\chi'$, $\chi'\chi'$) as a function of the neutralino masses, using the relative neutralino CP-sign that leads to the lowest detection efficiency. The branching ratios $\chi' \rightarrow \chi Z^* \rightarrow \chi(e^+e^-, \mu^+\mu^-, q\bar{q}, \nu\bar{\nu})$ are calculated according to the Z partial width of these channels, while the neutralino decay width to photons is assumed to be unknown. We then vary the relative photonic branching ratio between 0 and 1 and quote the highest, most conservative, limit obtained. The different channels are combined to calculate limits on the $Z \rightarrow \chi\chi'$ and $Z \rightarrow \chi'\chi'$ decay modes taking the different branching ratios, detection efficiencies, numbers of candidates and expected background events properly into account using Poisson statistics in the Bayesian approach. The 95% confidence level ($C.L.$) upper limits on BR($Z \rightarrow \chi\chi'$) and BR($Z \rightarrow \chi'\chi'$) are shown in Fig. 1 and 2 respectively.

Limits within the MSSM

In addition to the limits on BR($Z \rightarrow \chi\chi'$) and BR($Z \rightarrow \chi'\chi'$), we use the constraints coming from the precise LEP Z lineshape measurements*

$$\begin{aligned} \Delta\Gamma_Z &< 23.1 \text{ MeV } (95\%\ C.L.) \\ \Delta\Gamma_{inv} &< 8.4 \text{ MeV } (95\%\ C.L.) \end{aligned}$$

to restrict the MSSM parameter space using

$$\begin{aligned} \Delta\Gamma_Z &= \Gamma(Z \rightarrow \chi\chi) + \Gamma(Z \rightarrow \chi\chi') + \Gamma(Z \rightarrow \chi\chi'') + \\ &\quad \Gamma(Z \rightarrow \chi\chi''') + \Gamma(Z \rightarrow \chi'\chi') + \Gamma(Z \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-) \\ \Delta\Gamma_{inv} &= \Gamma(Z \rightarrow \chi\chi). \end{aligned}$$

Changing the limits on $\Delta\Gamma_Z$ and $\Delta\Gamma_{inv}$ by a factor of two does not change the excluded MSSM parameter space significantly. The excluded regions for different values of $\tan\beta$ are shown in Fig. 3. For moderate or high values of $\tan\beta$, a significant part of the accessible parameter space is excluded.

All neutralino masses are functions of the parameters M, μ and $\tan\beta$. Therefore, constraints on the MSSM parameter space translate into limits on these masses, summarized in Table 1.

Particle	$\tan\beta > 1$	$\tan\beta > 2$	$\tan\beta > 3$	$m_{\tilde{g}} > 100$ GeV all $\tan\beta$
χ	0 GeV	20 GeV	23 GeV	18 GeV
χ'	0 GeV	46 GeV	52 GeV	20 GeV
χ''	60 GeV	78 GeV	84 GeV	60 GeV
χ'''	90 GeV	115 GeV	127 GeV	98 GeV

Table 1: Lower neutralino mass limits (95% $C.L.$)

*The limits on $\Delta\Gamma_Z$ and $\Delta\Gamma_{inv}$ are obtained with the method described in [4] using the results given by [15]. We have used $m_{H^0} = 1000$ GeV, $m_t = 131$ GeV, $\alpha_s = 0.117$, $m_Z = 91.180$ GeV, $\Gamma_Z = 2490 \pm 7$ MeV and $\Gamma_{inv} = 498.2 \pm 4.2$ MeV, which are the values that give the most conservative constraints.

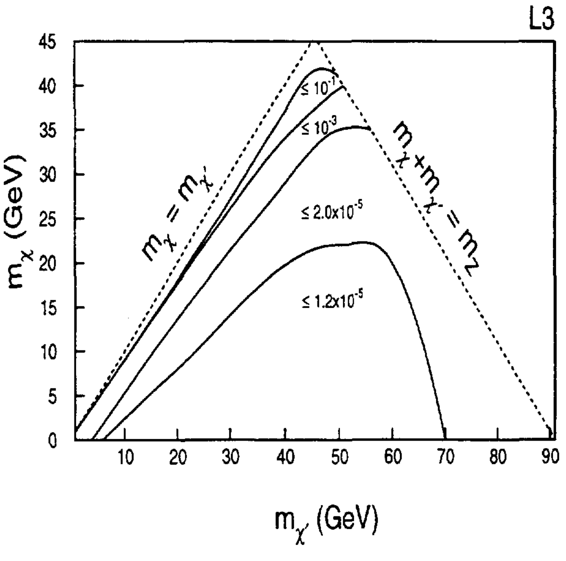

Figure 1: Contour plot of the 95% $C.L.$ upper limits on $Br(Z \to \chi\chi')$ versus the χ and χ' masses. The solid lines separate the regions, where the limit on the branching ratio is smaller than the value shown, while the dashed lines show the kinematical limits of the channel.

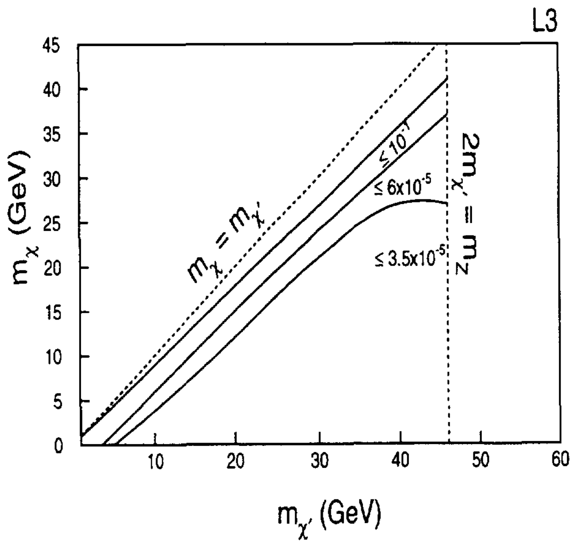

Figure 2: Contour plot of the 95% $C.L.$ upper limits on $Br(Z \to \chi'\chi')$ versus the χ and χ' masses. The solid lines separate the regions, where the limit on the branching ration is smaller than the value shown, while the dashed lines show the kinematical limits of the channel.

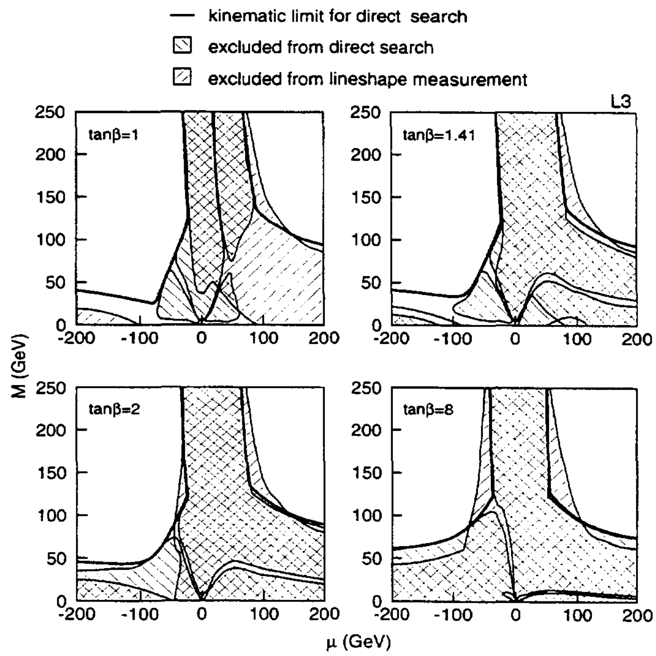

Figure 3: The excluded regions of the MSSM parameter space at the 95% $C.L.$ as a function of the parameters M and μ. The kinematical limit corresponds to the the sum of the lightest and next to lightest neutralino masses being equal to the center-of-mass energy. The exclusion coming from the lineshape measurement goes beyond the kinematic limit of the direct search.

These neutralino mass limits can be further improved by using a limit on the gluino mass $m_{\tilde g} > 100$ GeV [16], as suggested by Hidaka [17], which limits the parameter M via

$$m_{\tilde g} = \frac{\alpha_s}{\alpha}\sin^2\theta_W \mathrm{M} \qquad \text{thus} \qquad \mathrm{M} \approx 0.3 m_{\tilde g} > 30 \text{ GeV}.$$

This further restriction leads to mass limits for all $\tan\beta$ values, which are also shown in Table 1.

Conclusion

Using the 1991–1993 data of the L3 experiment, we have searched for neutralinos with a large variety of event signatures. No evidence for neutralinos was found and upper limits of a few times 10^{-5} have been set on the branching ratio for Z decaying to $\chi\chi'$ or $\chi'\chi'$. A significant part of the MSSM parameter space accessible at LEP has been excluded. In this paper the branching ratio limits are significantly improved compared to earlier results [18] and the dependence on assumptions on the neutralino decay modes has been minimized. In the MSSM the lightest neutralino is found to be heavier than 18 GeV, if either $\tan\beta > 2$ or $m_{\tilde g} > 100$ GeV.

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