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Search for supersymmetric particles with R-parity violation in Z decays

The ALEPH Collaboration*)

Abstract

Searches for supersymmetric particles produced in e^+e^- interactions at the Z peak have been performed under the assumptions that R-parity is not conserved, that the dominant R-parity violating coupling involves only leptonic fields, and that the lifetime of the lightest supersymmetric particle can be neglected. In a data sample collected by the ALEPH detector at LEP up to 1993, and corresponding to almost two million hadronic Z decays, no signal was observed. As a result, supersymmetric particle masses and couplings are at least as well constrained as under the usual assumption of R-parity conservation.

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1 Introduction

The vast majority of searches for supersymmetric particles has up to now been conducted under the assumption that R-parity [1] is a conserved multiplicative quantum number. Defined as

$$R = (-1)^{3B-L+2S},$$

with B and L the baryonic and leptonic quantum numbers, respectively, and S the spin, R-parity takes the value $+1$ for all the ordinary particles and -1 for their supersymmetric partners. Therefore, if R-parity is conserved, supersymmetric particles are produced in pairs, and they (cascade) decay to the lightest supersymmetric particle (LSP) which is stable. From cosmological arguments [2], this stable LSP is expected to be neutral and colourless, and because its interactions with ordinary matter involve the exchange of weak vector bosons or heavy supersymmetric particles, it behaves similarly to a neutrino. This is at the origin of the celebrated signature of supersymmetry: missing energy.

Requiring the theory to be supersymmetric, renormalizable, gauge invariant and minimal in terms of field content is however not sufficient to enforce R-parity conservation. The superpotential of the minimal supersymmetric extension of the Standard Model (MSSM) [3] contains the terms

$$hLH_1\overline{E},\ h'QH_1\overline{D},\ h''QH_2\overline{U},$$

where generation indices have been ignored for simplicity. Here L and Q are left-handed lepton and quark-doublet superfields; $\overline{E}$, $\overline{D}$, and $\overline{U}$ are right-handed singlet superfields for charged leptons, down and up-type quarks, respectively; and H_1 and H_2 are the two Higgs-doublet superfields necessary to give masses to down-type quarks and charged leptons, and to up-type quarks respectively. These terms are responsible for the Yukawa couplings of the Higgs fields to the ordinary fermions. They conserve lepton and baryon numbers, and thus R-parity. The most general superpotential, however, contains additional terms [4]:

$$\lambda LL\overline{E},\ \lambda' LQ\overline{D},\ \lambda''\overline{U}\overline{D}\overline{D}.$$

These terms[1] violate the lepton or baryon numbers and would lead, if simultaneously present, to proton decay at an unacceptable rate [5]. R-parity conservation was introduced to forbid all such terms, but this may be viewed as a somewhat *ad hoc* prescription. Whereas under R-parity all matter fields (L, $\overline{E}$, Q, $\overline{U}$, $\overline{D}$) change signs while the Higgs fields (H_1, H_2) remain invariant, one could equally well consider a baryonic parity, B-parity, under which the baryonic fields (Q, $\overline{U}$, $\overline{D}$) change signs while the Higgs and leptonic fields (L, $\overline{E}$, H_1, H_2) do not. This may seem unnatural in approaches inspired by grand unification considerations, in which quarks and leptons should be treated in a similar way, but in large classes of superstring inspired models the conservation of B-parity may even be favoured over that of R-parity [6].

[1]In principle, an LH_2 term could also be introduced. Such a term can however be rotated away by a redefinition of the H_1 and lepton fields.

B-parity conservation forbids the $\lambda''\overline{UDD}$ terms, which is sufficient to prevent fast proton decay, but still allows lepton number violation through the $\lambda LL\overline{E}$ and/or $\lambda' LQ\overline{D}$ terms. Restoring the generation indices and expanding the compact superfield notation to display the interactions among the ordinary and supersymmetric particles, the first lepton number violating term reads

$$\lambda_{ijk}[\tilde{\nu}^i\overline{\ell}^k_R\ell^j_L + \tilde{\ell}^j_L\overline{\ell}^k_R\nu^i_L + (\tilde{\ell}^k_R)^*(\overline{\nu}^i_L)^c\ell^j_L - (i \leftrightarrow j) + \text{h.c.}].$$

Thus, for the generation indices $ijk = 123$ for instance, decays such as $\tilde{\nu}_e \to \mu^+\tau^-$ or $\tilde{\mu}^- \to \tau^-\overline{\nu}_e$ are allowed. Similarly, the $\lambda' LQ\overline{D}$ term could induce decays such as $\tilde{\nu}_e \to \bar{\mathrm{s}}\mathrm{b}$. In view of the complexity resulting from the introduction of nine $\lambda_{ijk}L_iL_j\overline{E}_k$ terms, antisymmetric in the first two indices, and of twenty-seven $\lambda'_{ijk}L_iQ_j\overline{D}_k$ terms, most of the phenomenological analyses [7] incorporate the simplifying assumption that one of the R-parity violating couplings dominates over all the others, in a way similar to what happens with the top quark Yukawa coupling in the R-parity conserving sector of the theory.

These new couplings however will affect standard low energy processes because of additional interactions among ordinary particles mediated by supersymmetric particles. This has been investigated in Ref. [8], and the result is that some of these couplings are already rather constrained, for instance $\lambda_{123} < 0.04$ from charged current universality, while some others, such as λ'_{222} for instance, are essentially not. It would therefore not be justified either from a theoretical or from an experimental point of view to strictly assume R-parity conservation in the searches for supersymmetric particles.

The main consequence of R-parity non-conservation is that the LSP is no longer stable. As a particular example, if the λ_{123} coupling is dominant the lightest neutralino χ will decay to $\overline{\nu}_e\mu^+\tau^-$, or to $\overline{\nu}_\mu\mathrm{e}^+\tau^-$, or to $\nu_e\mu^-\tau^+$, or to $\nu_\mu\mathrm{e}^-\tau^+$, with an equal probability for all these modes up to phase space factors. These decays are mediated by scalar lepton or scalar neutrino exchange, as depicted in Fig. 1. The χ lifetime has been calculated in Ref. [9], and the resulting mean decay length is

$$0.3(p_\chi/m_\chi)(m_{\tilde{f}}/100\ \mathrm{GeV}/c^2)^4(1\ \mathrm{GeV}/c^2/m_\chi)^5(1/\lambda)^2\mathrm{cm},$$

where $m_{\tilde{f}}$ is the mass of the scalar particle exchanged in the χ decay and λ is the relevant R-parity violating coupling. For $m_\chi = 10\ \mathrm{GeV}/c^2$ and $p_\chi = 45\ \mathrm{GeV}/c$, the mean decay length is smaller than 1 cm as soon as λ exceeds 0.004 (if $m_{\tilde{f}} = 100\ \mathrm{GeV}/c^2$). Since on the one hand such an R-parity violating coupling value is allowed for most of the ijk combinations, and on the other hand such a short flight path leads to easily detectable decay products in a detector such as ALEPH at LEP, a search for supersymmetric particles produced in Z decays assuming that R-parity is not conserved is well motivated. This paper is devoted to such a search[2] in the case where the dominant R-parity violating coupling is of the $\lambda_{ijk}L_iL_j\overline{E}_k$ type.

[2] R-parity violation is assumed here to play a negligible rôle in the production process; real or virtual resonant production of a scalar neutrino, $\mathrm{e}^+\mathrm{e}^- \to \tilde{\nu}$, is therefore not addressed. The non-zero vacuum expectation value developed by a scalar neutrino as a consequence of R-parity violation induces lepton-chargino and neutrino-neutralino mixing, which leads to decays such as $\mathrm{Z} \to \tau^+\chi^-$ or $\mathrm{Z} \to \nu\chi$; these processes are expected to occur at a very low rate [10] and are not considered here either.

It is assumed here that this coupling is strong enough for the LSP lifetime to be negligible in practice. In this respect, the relevant quantity is the impact parameter of the charged particle tracks coming from the decay of the LSP with respect to the interaction point. The analyses described in this paper rely on impact parameters smaller than 2 cm, which corresponds to flight paths shorter than a few centimeters, *i.e.* to R-parity violating coupling values larger than a few thousandths for m_χ=10 GeV/c^2. In the opposite extreme case where the R-parity violating coupling is so small that the LSP escapes the detector before decaying, the results of the searches already performed [11] under the assumption of R-parity conservation are recovered. To investigate intermediate coupling values, however, a further dedicated search for detached vertices should be performed.

Another assumption which is made here as in most phenomenological analyses is that the LSP is χ, the lightest neutralino. The cosmological arguments which impose that the LSP should be neutral and colourless do not hold however for an unstable LSP, and this last hypothesis is only supported by explicit model building.

The data sample analysed, corresponding to an integrated luminosity of 82 pb^{-1} and to 1.94 million hadronic Z decays, was collected by the ALEPH detector at LEP from 1989 to 1993, at energies at and close to the Z peak. A description of the ALEPH detector can be found in Ref. [12], and an account of its performance as well as a description of the standard analysis algorithms in Ref. [13]. The tracking system consists of a precision silicon vertex detector, of a cylindrical drift chamber and of a large time projection chamber (TPC), all immersed in a 1.5 T magnetic field provided by a superconducting solenoidal coil. Charged particle tracks are efficiently reconstructed down to 16° from the beam axis. Between the TPC and the coil, a highly granular electromagnetic calorimeter is used to identify electrons and photons and to measure their energy. Complemented by luminosity calorimeters, the coverage is hermetic down to 24 mrad from the beam axis. The iron return yoke is instrumented to provide a measurement of the hadronic energy and, together with external chambers, muon identification. All this information is combined in an energy flow algorithm which supplies the analysis programs with a list of "particles", categorized as charged particles, among which identified electrons and muons, photons and neutral hadrons.

To design the selection criteria and to evaluate their efficiencies, the Monte Carlo generators used in the former ALEPH searches for supersymmetric particles [11] have been supplemented with a program written specifically for this analysis in order to let the final state LSPs decay. Given the many possible channels and parameters, full simulations of the detector response were performed only for a restricted number of points, in particular close to the boundaries of the sensitivity domains, and a fast but nevertheless reasonably accurate simulation program was used to interpolate between those points. For all major standard processes ($e^+e^- \to f\bar{f}(\gamma)$, $\gamma\gamma \to f\bar{f}$ and $e^+e^- \to \ell^+\ell^- f\bar{f}(\gamma)$, where $f\bar{f}$ is any quark or lepton pair), large fully simulated Monte Carlo samples have been used, each corresponding to an integrated luminosity at least as large as that of the data.

2 Event selections

With the hypotheses mentioned in Section 1, the LSP is χ, the lightest neutralino, and it decays promptly into a neutrino and a lepton-antilepton pair, with the two leptons not necessarily of the same flavour. Among the various possibilities, two extreme cases can be distinguished:

- with a dominant λ_{122} coupling, the visible χ decay products form an eμ or $\mu\mu$ pair, and there is a moderate amount of neutrino-associated missing energy;
- with a dominant λ_{133} coupling on the other hand, the χ decay charged leptons form an eτ or $\tau\tau$ pair and, once the τs have decayed, the typical number of electrons and muons is only of order unity, but there is more neutrino-associated missing energy.

The selection criteria have been designed keeping in mind these two extreme possibilities. With one restriction discussed below at the end of Section 2.2, there are always two χs produced in an e^+e^- collision, either directly or after (cascade) decays of higher mass supersymmetric particles. The characteristic signals are therefore four leptons (electrons or muons) with some missing energy in the first of the extreme cases, or about two leptons and substantial missing energy in the other extreme case. In the following, the efficiencies quoted correspond to the case leading to the lowest values, namely to λ_{133} dominance. In the various figures, the signal distributions are also given in that same case.

To avoid repetitions, a few naming conventions are listed here. The term "track" stands for charged particle track. Only those tracks originating from within a cylinder of 2 cm radius and 20 cm length, coaxial with the beam axis and centered on the nominal interaction point, are considered in the analysis. The term "lepton" designates an electron or a muon, but not a tau. "Good leptons" exclude electrons which belong to track pairs consistent with originating from a photon conversion in the detector material. The energy carried by the good leptons is called "leptonic", and that carried by all the other particles "non-leptonic". Event "hemispheres" are defined by a plane perpendicular to the event thrust axis. "Event mass, energy, momentum" stand for mass, energy, momentum carried by all the reconstructed particles. "Hemisphere mass, energy, momentum" have similar definitions, using only the particles belonging to the relevant hemisphere. The "acollinearity" is the space angle between the hemisphere momenta, and the "acoplanarity" is the angle between the projections of these momenta onto a plane perpendicular to the beam axis.

2.1 Selections for χ pair searches

In contrast to what happens if R-parity is conserved, the pair production of LSPs leads to visible final states. It is therefore natural to begin with a search for $e^+e^- \to \chi\chi$.

In a preselection, exactly four tracks with zero total charge are required. None of these tracks should lie closer than 18° from the beam axis, and there should be no energy detected within 12° of that axis. The event mass should exceed 15 GeV/c^2. These criteria eliminate the bulk of $\gamma\gamma$ interactions.

For pairs of high mass χs, the topology consists of four tracks distributed in a roughly isotropic way, with a substantial amount of missing energy (Fig. 2a). The following criteria have been designed to select such events. To eliminate most of the $q\overline{q}$ and $\tau^+\tau^-$ background, the thrust is required to be smaller than 0.95 and the event acollinearity smaller than 165°. The remaining low multiplicity $q\overline{q}$ events are removed by the requirement that the neutral hadronic energy should not exceed 10 GeV. This is harmless for the signal since the only neutral hadronic energy could come from Cabibbo-suppressed τ decays in the form of K^0_L. The few $\tau^+\tau^-$ events which survive the thrust and acollinearity cuts, mostly because of an additional hard radiative photon, are removed by the requirement that all track triplets should have a mass in excess of 1.5 GeV/c^2. Four-fermion final states in which two energetic leptons are produced (the so-called $\ell\ell V$ topology [14]) are eliminated by the requirement that no charged particle should carry an energy in excess of 25 GeV. At this stage, the remaining background consists of $\tau^+\tau^- V$ events and of radiative τ pairs in which the photon has converted into an e^+e^- pair. Most of it is eliminated by the requirement that the smallest track-doublet mass (the V mass) should exceed 1.25 GeV/c^2. The effect of this last cut is demonstrated in Fig. 3. From the few events surviving in the Monte Carlo samples, it is inferred that about one background event is expected to be found in the data sample, while no events were actually selected. The search efficiency is 27% for a χ mass of 45 GeV/c^2.

For pairs of low mass χs, the topology consists of two back-to-back jets, each consisting of two tracks and with a substantial amount of missing energy (Fig. 2b). The following criteria have been designed to select such events, after the same preselection as above. In each hemisphere, the track multiplicity should be exactly two, and the charge should be zero. The angles with the beam axis of both hemisphere momenta should be larger than 45°. The hadronic neutral energy should not exceed 10 GeV. At least two leptons should be identified among the four charged particles. The $e^+e^-f\overline{f}$ and $\mu^+\mu^-f\overline{f}$ backgrounds are largely eliminated by the requirement that the total mass should be smaller than 80 GeV/c^2. Again, the remaining background is due to $\tau^+\tau^-f\overline{f}$ final states, and it is suppressed by the requirement that the angle formed by the two tracks opposite to the smallest mass track doublet should be smaller than 45°. Finally, the candidate events in which a track pair can be attributed to a photon conversion are eliminated. However, as this introduces an unacceptable inefficiency for very low mass χs, this cut is not applied if all four charged particles are identified as leptons. No events survived in any of the background Monte Carlo samples nor in the data. The search efficiency is 28% for a χ mass of 5 GeV/c^2. For intermediate masses, the efficiency achieved by combining the two selections is never smaller than 18%, a value obtained for $m_\chi = 10$ GeV/c^2.

2.2 Selections for scalar lepton pair searches

As discussed in Section 3, the search described above does not constrain the mass of the LSP if χ is essentially of the gaugino rather than higgsino type, in which case it is only weakly coupled to the Z. In such a situation,[3] the search must be directed toward more massive supersymmetric particles such as the scalar leptons.

For scalar neutrino pair production, followed by $\tilde{\nu} \to \nu\chi$, the topology is very similar to that resulting from χ pair production (Fig. 2a and b), with more missing energy due to the neutrinos coming directly from the $\tilde{\nu}$ decays. The same selection criteria can therefore be applied, with a typical efficiency of 20% for a $\tilde{\nu}$ mass of 45 GeV/c^2.

For charged scalar lepton pair production, followed by $\tilde{\ell} \to \ell\chi$, the extreme cases correspond to $\tilde{\ell} = \tilde{\mu}$ with λ_{122} dominance in the χ decay on the one hand, and to $\tilde{\ell} = \tilde{\tau}$ with λ_{133} dominance on the other.

In a preselection, exactly six tracks with zero total charge are required. None of these tracks should lie closer than 18° from the beam axis, and there should be no energy detected within 12° of that axis. The event mass should be larger than 15 GeV/c^2. The neutral hadronic energy should not exceed 10 GeV.

For pairs of high mass scalar leptons, the topology consists of six tracks not concentrated in two back-to-back jets, with some missing energy (Fig. 2c). However, compared with the preceding cases of χ or $\tilde{\nu}$ pairs, the amount of missing energy is reduced by the visible energy carried by the leptons coming directly from the scalar lepton decays. The following criteria have been designed to select such events. The thrust is required to be smaller than 0.95. No track triplet should have a mass smaller than 1.5 GeV/c^2. No charged particle energy should exceed 25 GeV. These cuts eliminate most of the $q\overline{q}$, $\tau^+\tau^-$, and four-fermion backgrounds. Finally, to remove the few remaining $q\overline{q}$ events, it is required that the event mass be smaller than 70 GeV/c^2 or that at least two good leptons be identified. The reason for this dual criterion is to maintain a good efficiency in both of the extreme cases defined above. With these criteria, the background expectation is a few tenths of an event, due to the $\tau^+\tau^- q\overline{q}$ final states, while the efficiency is typically 19% for a 45 GeV/c^2 mass scalar tau. No events were selected in the data.

Low mass scalar leptons have not been excluded by searches at lower energy machines in the case of R-parity violation. However, because of their large pair production cross-section at the Z peak, it is not necessary to design highly selective search criteria. The topology consists of two back-to-back jets, each consisting of three tracks with some missing energy (Fig. 2d). After the same preselection as above, it is required that each hemisphere contain exactly three tracks, with a total charge of ±1, and that at least two good leptons be identified. In contrast to most standard processes, the angular distribution for the production of scalar lepton pairs is proportional to $\sin^2\theta$, where θ is the polar angle with respect to the beam axis; a cut on the direction of the event thrust axis, $50° < \theta < 130°$, is therefore applied. For a scalar lepton mass of 10 GeV/c^2 and a χ mass of 5 GeV/c^2, the efficiency is 23%. A total of 39 events were selected in the

[3]The case of χ pair production by t-channel scalar electron exchange is discussed in Section 3.

data while about 27 are expected from the standard background processes, mostly $\tau^+\tau^-$ events with two misidentified leptons.

In this section, it has been assumed up to now that scalar leptons decay via a gauge coupling to their ordinary partner and to the lightest neutralino. It could be however that the R-parity violating coupling, λ_{ijk}, is large enough for new decay modes to become dominant, such as $\tilde{\ell}_i \to \bar{\nu}_j \ell_k$ or $\tilde{\nu}_i \to \bar{\ell}_j \ell_k$. In the case of $\tilde{\ell}_i$ pair production, the signature is then identical to that expected from $\tilde{\ell}_k$ pair production if R-parity is conserved, with the final state neutrinos playing the rôle of massless LSPs. This topology (an acoplanar lepton pair) has already been considered in the standard searches for supersymmetric particles [11], resulting in the exclusion of any charged scalar lepton up to 45 GeV/c^2. A scalar neutrino with mass below 30 GeV/c^2 would contribute sufficiently to the Z width to be excluded by a comparison of the precision measurement thereof [15] with its standard model expectation. For larger scalar neutrino masses, the topology is similar to that from a standard four-lepton final state, except that all lepton pair angles tend to be large. The search for pairs of high mass χs described in Section 2.1 can be applied with the two following modifications: *i)* the acollinearity cut is removed in order to be sensitive to final states with no missing energy; *ii)* and instead, the angle between the two tracks opposite to the V is required to be smaller than 120°. The background level expected is similar, about one event, and no events were selected in the data. The selection efficiency is 20% for a $\tilde{\nu}$ mass of 45 GeV/c^2.

2.3 Selections for scalar quark pair searches

In the searches for scalar quarks, pair produced and decaying into an ordinary quark and an LSP ($\tilde{\mathrm{q}} \to \mathrm{q}\chi$), the selections are applied only to those events containing at least five tracks, such that the total energy carried by charged particles is larger than 8 GeV, and with less than 3 GeV detected within 12° of the beam axis.

When both the scalar quark and the χ masses are large, the characteristic topology is that of four isolated tracks with some missing energy, from the two χ decays, in an hadronic environment due to the quarks produced in the scalar quark decays(Fig. 2e). The following criteria were designed to select such events out of the large background from hadronic systems produced in Z decays or in $\gamma\gamma$ interactions. The event acollinearity should be smaller than 165°, and the acoplanarity smaller than 175°. The angle of the thrust axis with the beam should exceed 25°, and the component of the total momentum along the beam axis should be smaller than 25 GeV/c. The total visible mass should be in the 25—65 GeV/c^2 range. There should be at least two good leptons identified, and the total leptonic energy should exceed 4 GeV. In addition, the non-leptonic energy should be smaller than 35 GeV, or at least four good leptons should be identified. Here too, such a dual criterion allows a simultaneous treatment of the various cases of λ_{ijk} dominance. In order to extract the isolated leptons or τs originating from the χ decays, jets are reconstructed using the JADE algorithm [16] with a y_{cut} value of 6 10^{-4}. Two "τ-jets" are required, where a τ-jet contains only one charged particle and has a mass smaller than 1.8 GeV/c^2. These τ-jets should be isolated by more than 30° with respect to all other jets. The effect of this last cut is shown in Fig. 4. No events remain in any of the background Monte Carlo samples, and no events were selected in the data. The search efficiency is 35% for a scalar quark mass of 45 GeV/c^2 and a χ mass of 40 GeV/c^2.

For high mass scalar quarks, this selection becomes less efficient as the χ mass decreases. This is because the two tracks from the same χ decay become less isolated from each other (Fig. 2f). The following set of criteria was designed to cope with this topology. The angle of the thrust axis with the beam should again exceed 25°. The total visible mass should lie in the 25—80 GeV/c^2 range. The component of the total momentum transverse to the beam axis should be larger than 8 GeV/c. At least two good leptons should be identified, and the non-leptonic energy should be smaller than 60 GeV. The JADE algorithm is again used, but now with a y_{cut} value of 6 10^{-3} in order to separate four jets: two "χ-jets" and two "quark-jets". Only four-jet events in which all jet energies are smaller than 30 GeV are retained, and the quark-jets are chosen as the two largest charged particle multiplicity jets. One of the χ-jets should have a charged particle multiplicity of at most two, and the other of at most four; both should contain at least one charged particle; at least one of the χ-jets should contain a good lepton. All the jet-jet angles should be in the range 25°—110°. In the signal, it is expected that the two quark-jets should have similar energies, and so should also the two χ-jets, except for some degradation due to the χ-decay neutrinos. Therefore, the difference between the quark-jet energies is required to be smaller than 7 GeV, and the difference between the χ-jet energies smaller than 14 GeV. The effect of these last cuts is shown in Fig. 5. All events in the background Monte Carlo samples are eliminated, and no candidate was found in the data. The search efficiency is about 10% for a scalar quark mass of 45 GeV/c^2 and a χ mass of 3 GeV/c^2.

Again, low mass scalar quarks have not been excluded by searches at lower energy machines in the case of R-parity violation. They are expected to show up as two back-to-back hadronic jets, containing leptons and with some missing energy (Fig. 2g). The angle of the thrust axis with the beam is required to exceed 50° to take advantage of the $\sin^2\theta$ angular distribution of the signal. The event visible mass should be smaller than 80 GeV/c^2, and both hemisphere energies should be smaller than 40 GeV. Three good leptons at least should be identified, with at least one in each hemisphere. The total leptonic energy should exceed 10 GeV, and the non-leptonic energy should be smaller than 40 GeV. Finally, the total energy should be smaller than 60 GeV, or at least four good leptons should be identified. Again, a dual criterion allows a simultaneous treatment of the various cases of λ_{ijk} dominance. About 200 background events are expected to be found in the data sample, while 240 events were actually selected. For a scalar quark mass of 8 GeV/c^2 and a χ mass of 4 GeV/c^2 the search efficiency is 11%.

3 Results

Although each set of selection criteria was designed in view of a specific channel and for some specific supersymmetric particle mass range(s), most of these searches have a non-negligible efficiency for other channels and/or other mass ranges. For instance, pair produced χs lead to multiplicities larger than four for final states involving τs decaying into three charged particles. Such topologies are not addressed by the dedicated selections described in Section 2.1, but the searches for scalar quarks reported in Section 2.3 are indeed sensitive to them. For a χ mass of 45 GeV/c^2 and in the case of λ_{133} dominance, 10% are added this way to the initial 27% selection efficiency. In a similar fashion, the searches for pairs of high mass scalar quarks described in Section 2.3 rely on the identification of isolated low multiplicity and low mass jets. An alternative and in some instances more efficient approach consists in characterizing such events by the missing energy carried away by the final state neutrinos. Such an approach has been used in the search for acoplanar jets reported in Ref. [17], designed to be sensitive to the production of a Higgs boson in the reaction $e^+e^- \to HZ^*$, with $H \to$ hadrons and $Z^* \to \nu\bar{\nu}$. With the selection criteria used in that search, the efficiency for 45 GeV/c^2 scalar quarks, with $m_\chi = 40$ GeV/c^2 and for λ_{133} dominance, increases from 35% to 50%.

Therefore, for all the channels analysed, the search efficiencies have been evaluated using the combination of all the selections described in Section 2 and of the search for acoplanar jets described in Ref. [17], excluding however the two searches for pairs of low mass scalar leptons and of low mass scalar quarks which are too heavily contaminated by background. The number of background events expected in this "combined selection" is $1.4^{+1.1}_{-0.7}$, while no events were found in the data. These search efficiencies have been folded with the supersymmetric particle production cross-sections at the Z resonance, which can be found in Refs. [18] or [19] for instance, to derive the following results. Conservatively, all results are given for the case of λ_{133} dominance which leads to the lowest efficiencies.

The Z decay width into scalar neutrinos is $0.5\Gamma_{\nu\bar{\nu}}\beta^3$ for a single flavour. Here and in the following, the Z partial width for one neutrino flavour is denoted $\Gamma_{\nu\bar{\nu}}$, and β designates the centre-of-mass velocity of one of the pair produced supersymmetric particles. Such scalar neutrinos are excluded up to 46.0 GeV/c^2. (This value is larger than $m_Z/2$ because of the data taken above the peak during the scan of the Z resonance.) The Z decay width into scalar leptons is $0.11\Gamma_{\nu\bar{\nu}}\beta^3$ for scalar partners of right handed ordinary leptons, with $\sin^2\theta_W = 0.232$. For the same mass, the width into scalar partners of left handed leptons is even larger. Scalar leptons of all flavours are excluded from about 12 GeV/c^2 up to 45.6 GeV/c^2. Lower masses are excluded by the specific search for pairs of low mass scalar leptons reported in Section 2.2, even without background subtraction. In contrast to what happens in the case of R-parity conservation, there is no unexcluded region for small mass differences between the scalar lepton and the LSP. This is because the latter decays into visible products.

It has been assumed above that the scalar lepton mass eigenstates are identical to the weak eigenstates. This is justified since all lepton masses are small compared to the supersymmetry breaking masses responsible for the mass difference between ordinary and scalar leptons. The same assumption can be made in practice for scalar quarks, except possibly for the scalar partners of the top quark. The Z decay width into scalar quarks is $0.035\Gamma_{\nu\bar{\nu}}\beta^3$ for scalar partners of right handed down-type quarks. The widths into scalar partners of left handed down-type quarks or into scalar partners of up-type quarks are all larger. Scalar quarks of all types, except possibly for scalar top quarks as discussed hereafter, are excluded from 12 GeV/c^2 up to 45.3 GeV/c^2. Lower masses are excluded by the specific search for pairs of low mass scalar quarks reported in Section 2.3, even without background subtraction. As for scalar leptons, there is no unexcluded region for small mass differences between the scalar quark and the LSP. In the scalar top quark sector, strong mixing may occur among the weak eigenstates, as indicated above, because of the large value of the top quark mass, and the coupling to the Z of the lower mass eigenstate might even vanish [20]. Scalar top production then proceeds only via s-channel photon exchange, with a much lower cross-section. Even then, scalar top quarks are excluded at the 95% confidence level from 11 to 41 GeV/c^2. It should be noted however that all these limits on scalar quarks apply only if the gluino is sufficiently heavy to forbid the $\tilde{q} \to q\tilde{g}$ decay, an assumption which cannot be substantiated by the negative results of gluino searches at hadron colliders [21] since those were performed assuming R-parity conservation.

The Z coupling to charginos is very large, leading to a Z partial decay width ranging, for very light charginos, from ~ 0.5 to $4.5\Gamma_{\nu\bar{\nu}}$, depending on the chargino field content. This is reduced by a phase space factor which is much more favourable than for scalar leptons or quarks. As a result, the precision measurement of the Z width [15] provides a sufficient constraint, when compared to its standard model expectation, to exclude charginos up to $m_Z/2$, with no need for any dedicated search. In this respect, whether R-parity is conserved or not is irrelevant.

The supersymmetric partners of the neutral gauge and Higgs bosons mix to form mass eigenstates called neutralinos. Their couplings to the Z are strongly model dependent, and even parameter dependent within a given model such as the MSSM. Therefore, an unambiguous χ mass lower limit cannot be deduced from a negative search for χ pair production, but rather an upper limit on the $Z\chi\chi$ squared coupling $|C_{\chi\chi}|^2$ as a function of the χ mass, normalized in such a way that the $Z \to \chi\chi$ partial width reads $|C_{\chi\chi}|^2\Gamma_{\nu\bar{\nu}}\beta^3$. The result is presented in Fig. 6. It can be seen that, for masses up to 40 GeV/c^2, the squared coupling is smaller than a few 10^{-4}. In the MSSM, this means that the LSP, if light, is essentially gaugino-like since the neutralinos couple to the Z through their higgsino components [19]. Such light gauginos could still be produced in e^+e^- collisions via t-channel scalar electron exchange. This has already been investigated by the OPAL Collaboration at LEP [22] in the case of pure photinos, assuming a specific R-parity violating coupling of the λ_{123} type. The exclusion domain in the ($m_{\tilde{\gamma}}$,$m_{\tilde{e}}$) plane presented in Fig. 4 of Ref. [22] is extended by the searches described here toward larger scalar electron masses (from 140 to 220 GeV/c^2 for $m_{\tilde{\gamma}} = 15$ GeV/c^2) and toward smaller photino masses (from 5 to 2 GeV/c^2 for $m_{\tilde{e}} < 220$ GeV/c^2).

Dedicated searches for the other neutralinos, either in pair production, $Z \to \chi'\chi'$, or in associate production, $Z \to \chi\chi'$, have not been attempted. However, the combined search used in this section can be applied with substantial efficiency to these reactions. For instance, the overall efficiency is 45% for $m_{\chi'} = 50$ GeV/c^2 and $m_\chi = 30$ GeV/c^2 if χ' decays to χZ^*, with $Z^* \to f\bar{f}$, and it is 31% for the same masses if χ' decays to $\chi\gamma$. Conservatively, the lower efficiency is chosen for every mass combination. The results need three parameters to be interpreted: two masses, m_χ and $m_{\chi'}$, and the $Z\chi'\chi'$ or $Z\chi\chi'$ squared couplings.[4] It is commonly preferred to translate these results into the parameter

[4]The relative CP of χ and χ' has a small influence on the selection efficiencies; this has been taken into account.

space of the MSSM [19], namely in terms of $m_{\tilde{\gamma}}$, the gaugino mass term combination associated with the photino field, μ, the Higgs mixing supersymmetric mass term, and v_2/v_1, the ratio of the vacuum expectation values of the two Higgs doublets. This has been done in Ref. [11] in the case of R-parity conservation, incorporating also the results deduced from the Z width measurement (which are essentially equivalent to an upper limit of $m_Z/2$ on the chargino mass). The results obtained with R-parity violation are shown in Fig. 7 for two values of v_2/v_1. Comparing with Fig. 7.4 of Ref. [11], it can be seen that the excluded domains are substantially larger, essentially because of the increased sensitivity to the $\chi\chi$ final state which can be addressed only through the invisible width measurement if R-parity is conserved. For low values of v_2/v_1, a vanishing $m_{\tilde{\gamma}}$ value is not excluded. While, if R-parity is conserved, limits from searches for gluinos at hadron colliders [21] can be used to exclude such a configuration, assuming gaugino mass unification, this is no longer true if R-parity is not conserved since there exists no relevant gluino mass limit in that case.

4 Conclusions

Previously to those presented here, results on searches for supersymmetric particles with R-parity violation had been reported by the OPAL Collaboration at LEP [22] and by the H1 Collaboration at HERA [23]. The OPAL analysis is restricted to a search for pure photinos, assuming a specific R-parity violating coupling of the λ_{123} type. The excluded domain in the ($m_{\tilde{\gamma}}$,$m_{\tilde{e}}$) plane presented in Ref. [22] is substantially extended by the searches reported here. The H1 analysis concentrates on a search for resonant scalar quark production in electron-quark collisions. No direct comparison can be made with the results presented here since it is a coupling of the λ' rather than λ type which is involved in that reaction.

In the searches reported here, it has been assumed that the dominant R-parity violating coupling involves only leptonic fields, that the LSP is the lightest neutralino and that its lifetime can be neglected. Under these assumptions, scalar leptons, scalar neutrinos, scalar quarks and charginos are all excluded up to the kinematic limit of $m_Z/2$ (except perhaps for a scalar top not coupled to the Z for which the excluded range is 11 to 41 GeV/c^2). In the neutralino sector, the constraints obtained are more severe than in the case of R-parity conservation, due to the increased sensitivity to Z decays into χ pairs. This analysis represents the first comprehensive search for supersymmetric particles performed under the assumption that R-parity is not conserved.

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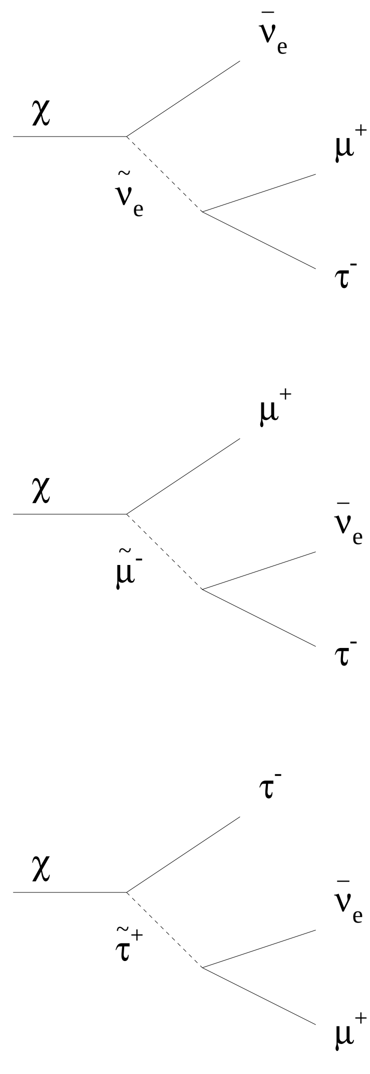

Figure 1: Diagrams responsible for the $\chi \to \overline{\nu}_e \mu^+ \tau^-$ decay.

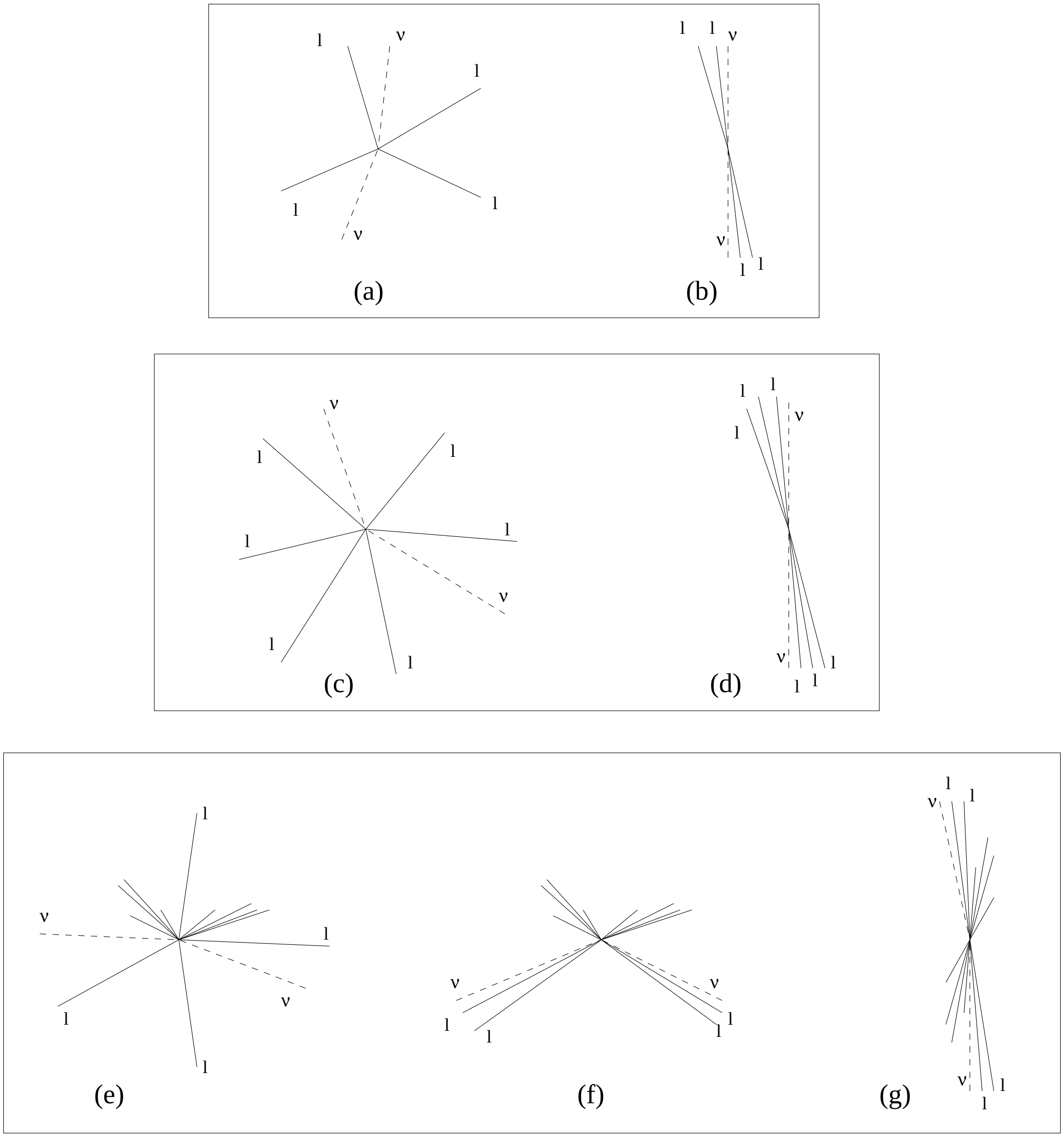

Figure 2: Topologies addressed by the various selections: heavy χ pair (a); light χ pair (b); heavy $\tilde{\ell}$ pair (c); light $\tilde{\ell}$ pair (d); heavy $\tilde{q}$ pair with heavy χ (e); heavy $\tilde{q}$ pair with light χ (f); light $\tilde{q}$ pair (g).

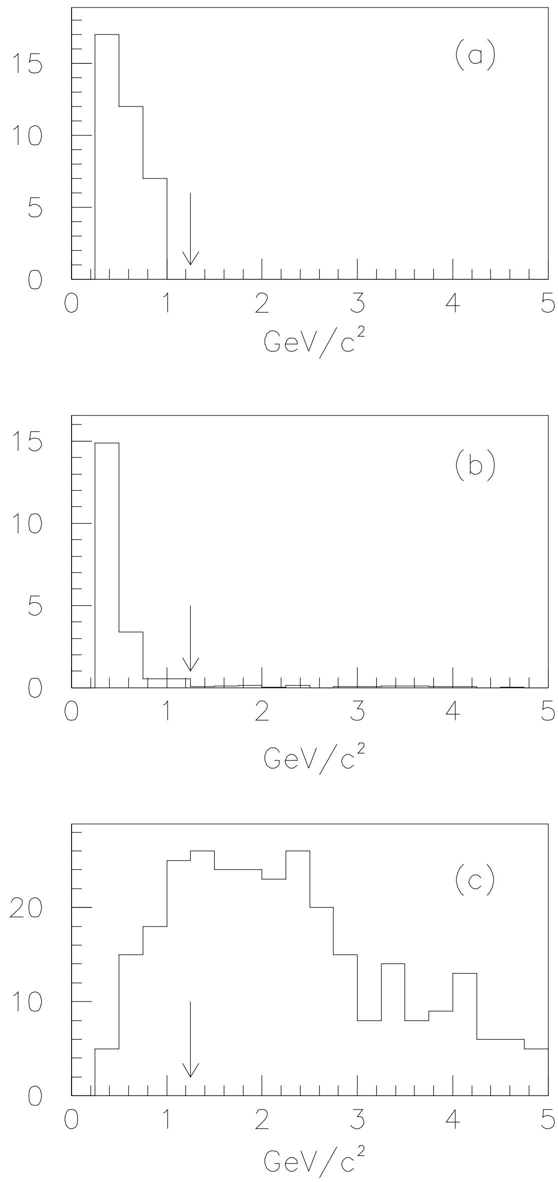

Figure 3: Minimum track-doublet mass (V mass) for the data (a), the normalized background (b) and the signal (c), after all other cuts. For the signal, $m_\chi = 45$ GeV/c^2. The cut location is indicated by an arrow.

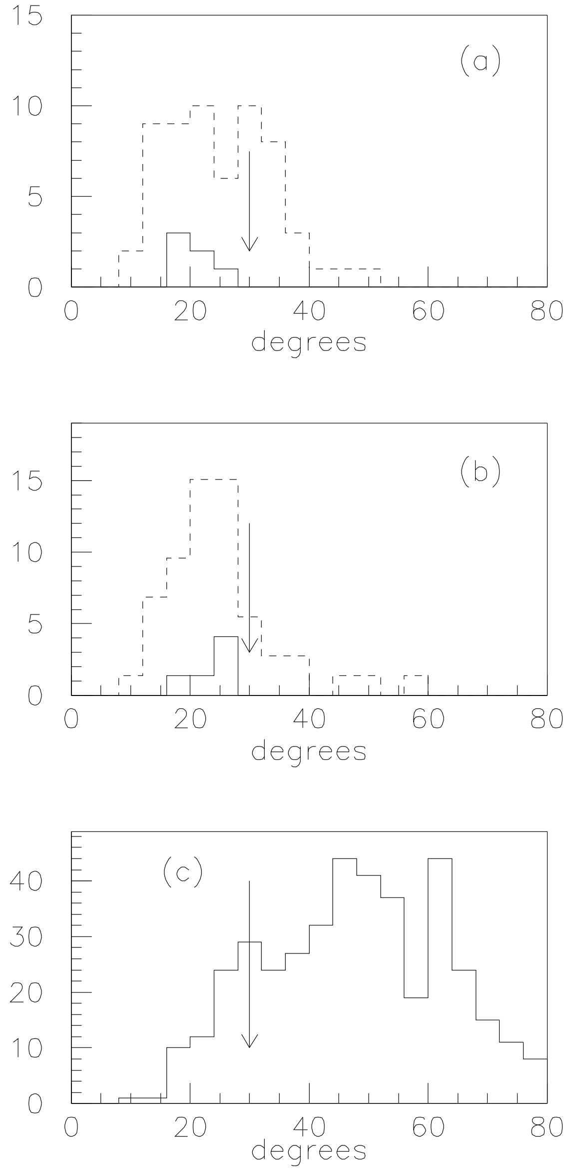

Figure 4: Minimum τ-jet isolation angle for the data (a), the normalized background (b) and the signal (c). The full histograms are drawn after all other cuts and, for the data and the background, the dashed ones without the cut at 65 GeV/c^2 on the total visible mass. For the signal, $m_{\tilde{q}} = 45$ GeV/c^2 and $m_\chi = 40$ GeV/c^2. The cut location is indicated by an arrow.

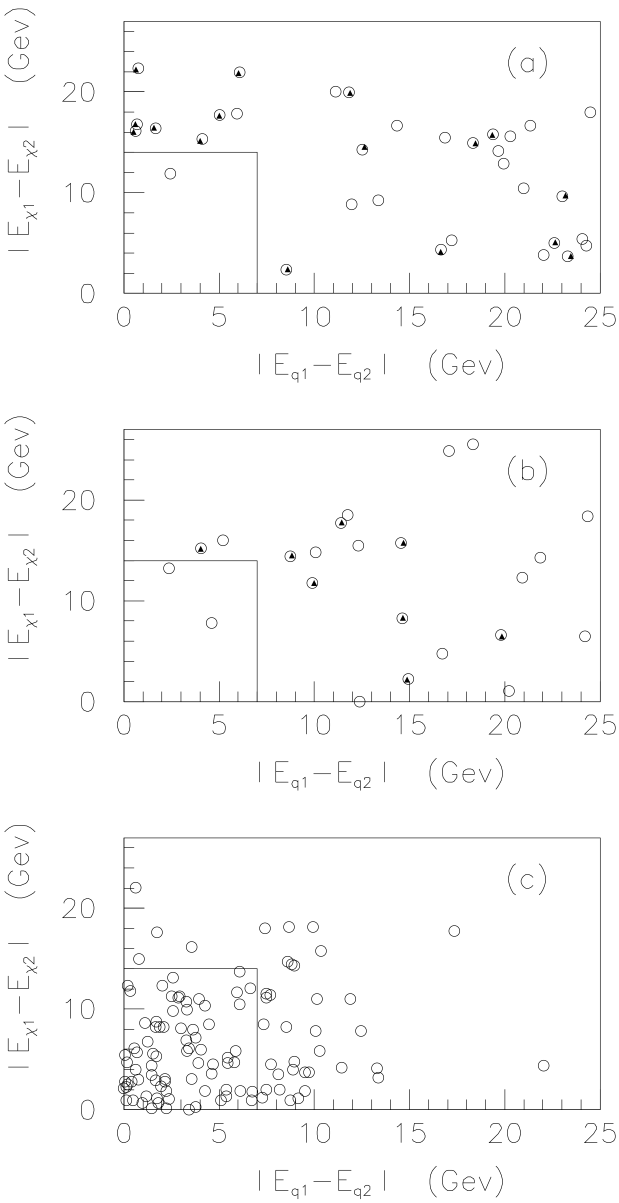

Figure 5: χ-jet energy difference *vs.* quark-jet energy difference for the data (a), the $q\overline{q}$ background (b) and the signal (c). For the data and the background, the black triangles are drawn after all other cuts, and the open circles without the cut at 30 GeV on the jet energies. For the signal, $m_{\tilde{q}} = 45$ GeV/c^2 and $m_\chi = 7$ GeV/c^2. The cuts are indicated by full lines.

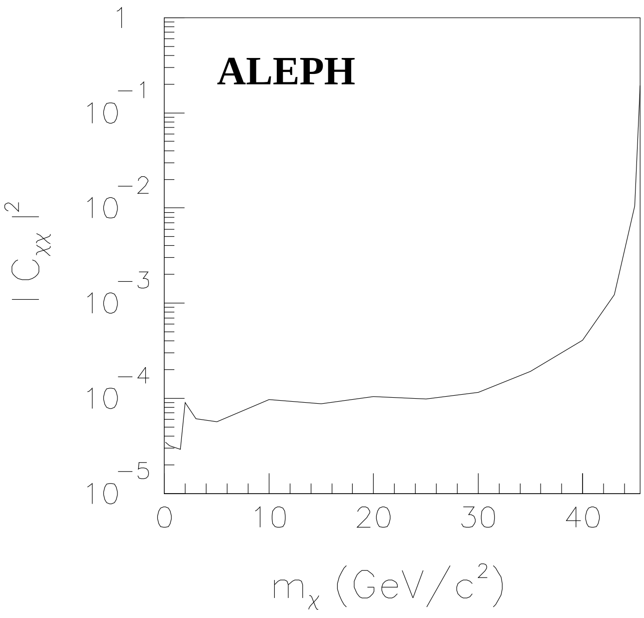

Figure 6: 95% C.L. upper limit on the squared $Z\chi\chi$ coupling, $|C_{\chi\chi}|^2$, as a function of the χ mass.

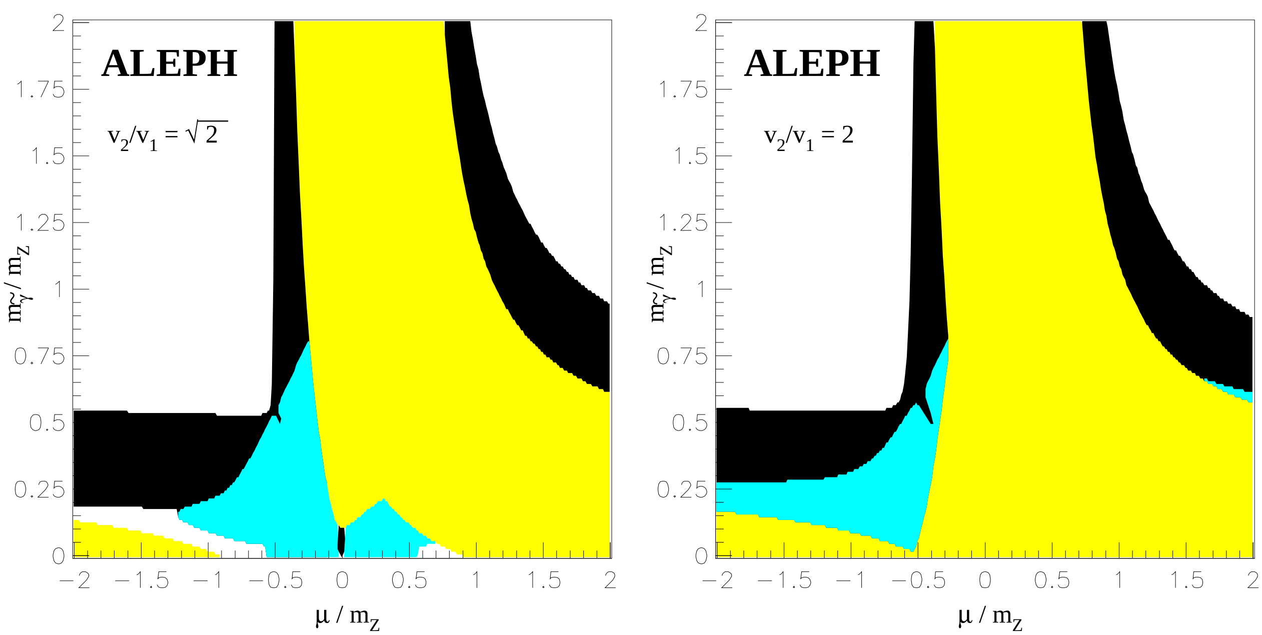

Figure 7: For two values of v_2/v_1, 95% C.L. excluded domains in the $(m_{\tilde{\gamma}}, \mu)$ plane of the MSSM: from the Z width measurement (light grey), from the search for neutralinos in the $Z \to \chi\chi'$ and $Z \to \chi'\chi'$ modes (heavy grey), and from the search in the $Z \to \chi\chi$ mode (black).