Search for charginos and neutralinos at LEP

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A summary of the search for charginos and neutralinos at LEP is given, with the latest results from the $\sqrt{s} = 189$ GeV run. The emphasis will be on models that provide a stable Lightest Supersymmetric Particle, which could turn out to constitute an important part of the dark matter.

1. Introduction

The interest in supersymmetry as an extension of the Standard Model was boosted in 1990, when it was shown that the unification of the gauge coupling constants at a higher energy scale, M_{GUT}, was achieved in a supersymmetric theory, while this was not the case in the Standard Model. A further benefit of this model is the reduction of radiative corrections to the mass of scalar particles, such as the Higgs particle, thus keeping it at the electroweak scale without having to resort to unphysical *fine tuning*.

Spin	0	$\frac{1}{2}$		1
	$\tilde{\ell}^{\pm}_{L,R} \rightarrow \tilde{\ell}^{\pm}_{1,2}$	$\ell^{\pm}_{L,R}$		
	$\tilde{\nu}_L$	ν_L		
	$\tilde{q}_{L,R} \rightarrow \tilde{q}_{1,2}$	$q_{L,R}$		
		$\tilde{g}$		g
	h^0,H^0,A^0	$\tilde{\gamma}$ $\tilde{h}^0$,$\tilde{H}^0$ $\tilde{Z}^0$	$\tilde{\chi}^0_i$	γ Z^0
	$H^{\pm}$	$\tilde{H}^{\pm}$ $\widetilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_j$	$W^{\pm}$

Table 1
Particle contents of the minimal supersymmetric model (MSSM)

2. The Minimal Supersymmetric Model

The so-called Minimal Supersymmetric Model (MSSM) [1] is minimal in the sense of the number of additional particles that have to be added to the Standard Model. For fermions, each helicity state has a scalar superpartner, and it is also required to add a second Higgs doublet, resulting in a Higgs sector containing five Higgs bosons, where two of them carry electric charge. The superpartners of the gauge bosons and the Higgs particles are called gauginos. There are two mass eigenstates formed by a mixing of the superpartners of the charged gauge bosons and charged Higgs bosons called *charginos*, $\tilde{\chi}^{\pm}{}_{1,2}$, and four mass eigenstates associated with the neutral gauge bosons and neutral Higgs bosons called *neutralinos* $\tilde{\chi}^0_{1,2,3,4}$, where the indices are ordered with increasing mass.

An important concept of supersymmetry is *R-parity* , a multiplicative quantum number introduced to ensure lepton and baryon number conservation. This means that in processes which conserve R-parity, SUSY particles are produced in pairs, and their decay must contain at least another SUSY particle hence it also implies the stability of the Lightest Supersymmetric Particle (LSP). This has the important consequence of providing a possible candidate for non-baryonic dark matter. This article will only treat the case where R-parity is conserved.

The general formulation of MSSM contains

124 free parameters, including all sfermion masses, the Higgs mass and mixing matrices and M_1,M_2,M_3, the U(1), SU(2) and SU(3) gaugino masses. With so many free parameters it is not a very predictive theory, there are however ways of reducing this number considerably. From the non-observation of supersymmetric particles, it can be inferred that the symmetry has to be broken at lower energies. By constructing models how of this breaking takes place, relations between different parameters can be obtained. The breaking of supersymmetry could occur through gravitational interactions at the energy scale $M_{SUSY} \simeq 10^{11}$ GeV or via ordinary gauge interactions at $M_{SUSY} \simeq 10^5$ GeV. The first option is commonly referred to as the *supergravity* (SUGRA) scenario and the latter as *gauge mediated supersymmetry breaking* (GMSB).

2.1. The SUGRA scenario

In the SUGRA scenario a Constrained MSSM (CMSSM) is used to guide the analysis. By assuming that all sfermions have a common mass, m_0, and that the gauginos have a common mass, $m_{1/2}$, at some ultra high energy scale $M_X \simeq M_{GUT}$, reduces the number of parameters drastically. A further assumption is a common trilinear coupling parameter A_0. These parameters, in addition to μ and $\tan\beta$, give a model that completely describes its low energy behaviour with five parameters: $\{\ m_{1/2}, m_0, A_0, \tan\beta, \mu\ \}$
All masses, cross-sections and branching ratios at the electroweak scale can be obtained by evolving the GUT scale parameters using renormalization group equations. For instance, the condition of a common gaugino mass at M_X leads to the important relation between M_1 and M_2 at the electroweak scale:

$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \ \sim 0.5 M_2 \qquad (1)$$

In the presented analyses this relation is assumed, and also that the $\tilde{\chi}^0_1$ is the LSP.

2.2. The GMSB scenario

In contrast to the gravity mediated SUSY breaking scenario, the gravitino, $\tilde{\mathrm{G}}$, is very likely to be the LSP in the GMSB model. This is due to the fact that particles acquire their masses from ordinary gauge interactions and that the SUSY breaking scale, $\sqrt{F}$, is much lower. The gravitino mass can be expressed as:

$$m_{\tilde{\mathrm{G}}} = \frac{F}{\sqrt{3}M_{Pl}} = 2.37\times10^{-2}\left(\frac{\sqrt{F}}{10\ \mathrm{TeV}}\right)^2\ \mathrm{eV} \qquad (2)$$

A characteristic feature of a given model is then the nature of the next-to-lightest supersymmetric particle (NLSP). There are a numerous options at hand, but only the case with a neutralino NLSP will be considered here.

3. MSSM phenomenology

In SUSY models with R-parity conservation, each SUSY process has at least two LSPs in the final state. Thus the canonical signature for SUSY is missing transverse energy, $\not{E}_T$, [2]. The production of charginos (neutralinos) can proceed either with an exchange of a Z/γ (Z) in the s-channel or a $\tilde{\nu}$ (ẽ) in the t-channel. In the region where the gaugino is mostly higgsino-like, usually called the *higgsino region*, $M_2 \gg |\mu|$, only the s-channel contribution is important, while both s- and t-channel are important in the *gaugino region* , $|\mu| \gg M_2$, provided that the mass of the slepton involved is not too large, *i.e.* for low enough m_0. It is noteworthy that the s- and t-channel interference is destructive for charginos while the opposite is true for neutralinos. In most cases however, the production cross-section is considerably larger for charginos than for neutralinos.

In SUGRA models were the lightest neutralino $\tilde{\chi}^0_1$ is the LSP, the most important chargino and neutralino production processes are $\tilde{\chi}^+_1\tilde{\chi}^-_1$ and $\tilde{\chi}^0_1\tilde{\chi}^0_2$ or $\tilde{\chi}^0_1\tilde{\chi}^0_3$, since the $\tilde{\chi}^0_1\tilde{\chi}^0_1$ production is invisible. For most of the parameter space the charginos decay through a W*, leading to hadronic, semi-leptonic or leptonic final states, in addition to the escaping LSPs, and neutralinos decay through a Z* giving either hadronic or leptonic final states. For the case of small m_0 however, the leptonic decay channels are enhanced.

The detection efficiency depends largely on the mass difference $\Delta M = m_{\tilde{\chi}} - m_{LSP}$, where $\tilde{\chi}$ is the heavier SUSY particle produced. The analysis is optimized to reach the best signal to background ratio for the different topologies and also for different ΔM. For $\Delta M < 10$ GeV the background comes mainly from $\gamma\gamma$ processes, while for large ΔM four fermion processes constitute the most difficult background.

In the GMSB scenario, the situation for charginos are similar to the one described above. There is however an important difference. Since the LSP in this model is the $\tilde{\mathrm{G}}$ the decay $\tilde{\chi}_1^0 \to \tilde{\mathrm{G}}\gamma$ reduces the missing energy signature, but gives instead an energetic photon. In this model the production of charginos would give similar signatures as above with the addition of a pair of energetic photons. For neutralino searches the most important production processes becomes $\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0\tilde{\mathrm{G}}$ with the subsequent decay $\tilde{\chi}_1^0 \to \tilde{\mathrm{G}}\gamma$, leading to final states consisting of a pair of acoplanar photons or a single photon. The Standard Model background for such signatures is very small and comes mainly from $\mathrm{e^+e^-} \to \nu\nu\gamma(\gamma)$ and $\mathrm{e^+e^-} \to \nu\nu\gamma\gamma(\gamma)$, with a cross-section of the order of a few pb. Depending on $m_{\tilde{\mathrm{G}}}$, the life-time of the $\tilde{\chi}_1^0$ could be considerable. In that case the direction of the photon would not point towards the primary interaction point. A more detailed description of GMSB phenomenology can be found in [3].

4. Experimental results

The results presented here was primarily obtained with the data collected by the four LEP experiments at the 189 GeV run in 1998, and should all be considered preliminary. Since no signal was found the results are presented as 95% C.L. on production cross-sections and masses.

4.1. Results in SUGRA

All four LEP experiments have been searching for the production of $\tilde{\chi}_2^0\tilde{\chi}_1^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ [4]. The searches all rely on the signatures expected from an R-parity conserving model with a $\tilde{\chi}_1^0$ LSP. The cross-section limits have been calculated assuming that the relative weight of the different decay modes is the same as in the decay of a Z or $\mathrm{W}^\pm$ boson respectively. The L3 cross-section limit on $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and OPAL limit on $\tilde{\chi}_2^0\tilde{\chi}_1^0$ production is shown in Fig.1.

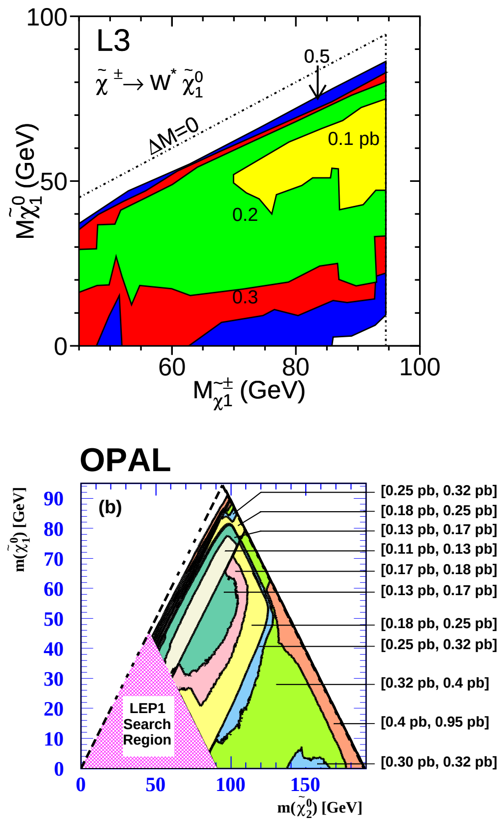

Figure 1. Top: The cross-section limits for $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production obtained by L3, as a function of $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$, assuming $\mathrm{W}^\pm$ branching ratios. Bottom: Cross-section limits for $\tilde{\chi}_2^0\tilde{\chi}_1^0$ production, as a function of $(m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0})$ obtained by OPAL, assuming Z branching ratios

In the context of CMSSM these model-independent cross-section limits can be translated into mass limits. In order to do that the parameter space where scanned, for each point the expected number of events is calculated and by taking into the account the expected background and the number of observed events the point can either be excluded with a 95 % C.L or not. All LEP experiments usually present the excluded region in the CMSSM space as a projection onto the the (M_2,μ) plane. In Fig. 2 the region excluded by DELPHI is shown for $\tan\beta = 1.5$ and $m_0 = 1000\text{GeV}/c^2$.

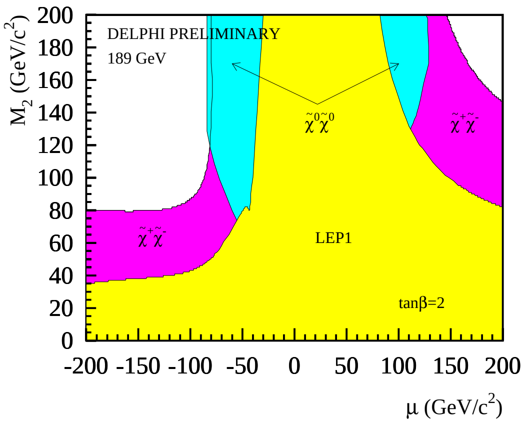

Figure 2. Excluded region of the MSSM parameter space in the (M_2, μ) plane for $M_2 = 1000$ GeV$/c^2$ and $\tan\beta$=1.5

In Fig. 3, the points excluded by OPAL is shown in the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$ plane, which can be interpreted as a limit on the chargino mass. For $m_0 > 500$ GeV$/c^2$ and $\Delta M > 5$ GeV$/c^2$ a chargino mass lower than 93.6 GeV$/c^2$ is excluded for $\tan\beta = 1.5$, while allowing for any value of m_0 reduces the limit to 78.0 GeV$/c^2$. It should be noted that in order to put limits in the low m_0 region, the chargino and neutralino searches have to be supplemented by the results obtained in slepton searches and also searches for the $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$ decay. This is also the case for the lower limit on the LSP mass. In Fig. 4 the DELPHI LSP mass limit is shown as a function of $\tan\beta$. The LSP

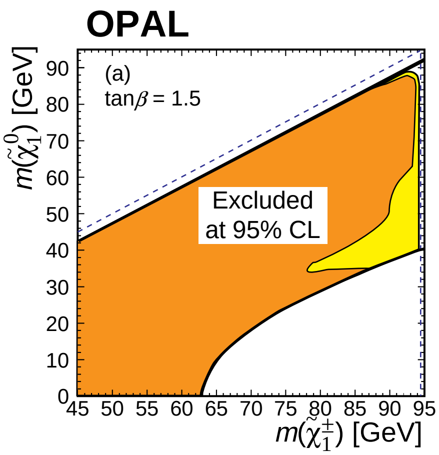

Figure 3. Exclusion regions in the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$ plane obtained by OPAL, for $\tan\beta = 1.5$. The darker shaded region is excluded for any value of m_0, while the lighter shaded region is only excluded for $m_0 > 500$ GeV$/c^2$.

mass is constrained to be above 31.2 GeV$/c^2$ for any m_0.

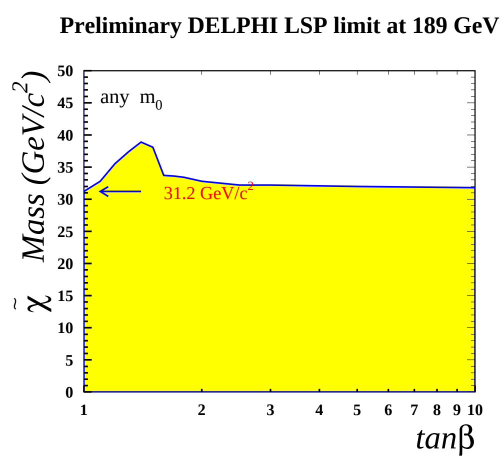

Figure 4. The DELPHI mass limit on the LSP for any value of m_0

4.2. Results in GMSB

All LEP experiments have also searched for anomalous photon production. In the data collected in 1998 no signal was found [5]. The search for $\gamma + \not{E}_T$ or $\gamma\gamma + \not{E}_T$ topologies can then be used to set limits on supersymmetric models where such a signature is expected. This is the case in models with a gravitino LSP and a neutralino NLSP where the decay $\tilde{\chi}^0_1 \rightarrow \tilde{\mathrm{G}}\gamma$ give rise to such signatures following either $\tilde{\mathrm{G}}\tilde{\chi}^0_1$ or $\tilde{\chi}^0_1\tilde{\chi}^0_1$ production. In Fig. 5 the distribution of all events containing a single or two acoplanar photons, selected by the L3 experiment, is shown. This agrees well with Standard Model expectations. In the search for $\gamma + \not{E}_T$ events DELPHI finds 145 events within there barrel region, where 157.7 was expected. This can be translated into a limit on the production cross-section of $\tilde{\mathrm{G}}\tilde{\chi}^0_1$, shown in Fig. 6.

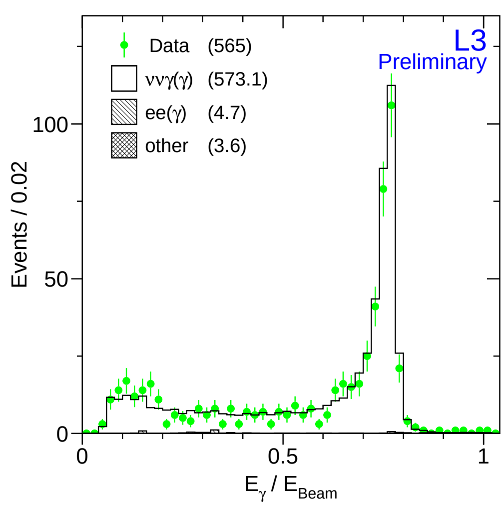

Figure 5. Distribution of the photon energy for single photon or acoplanar photon pair events, from the L3 data collected at $\sqrt{s} = 188.7$ GeV.

In Fig. 7 the cross-section limit is given for a process that gives a signature equal to what would be expected from a $\tilde{\chi}^0_1\tilde{\chi}^0_1$ production, with a gravitino LSP and where the $\tilde{\chi}^0_1$ decays promptly.

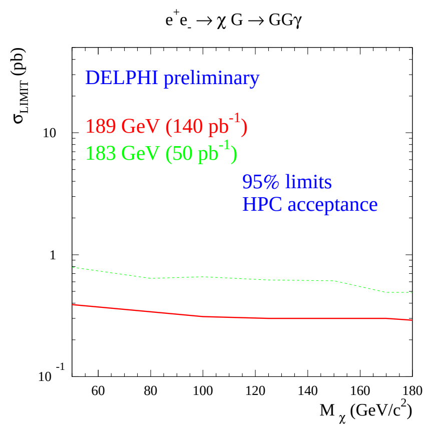

Figure 6. DELPHI cross-section limit on $\tilde{\mathrm{G}}\tilde{\chi}^0_1$ production from the single photon signature expected from the $\tilde{\chi}^0_1 \rightarrow \tilde{\mathrm{G}}\gamma$ decay. In this case only photons detected in the barrel region are used.

Limits have also been put on specific models. The MGM model described in [7], is a model with a neutralino NLSP, where the signature is two acoplanar photons and missing energy. In this particular selection the energy of the least energetic photon was required to exceed 36 GeV. The excluded NLSP mass as a function of its lifetime is shown in Fig. 8. The mass limit obtained within this model is $m_{\tilde{\chi}^0_1} > 91 \mathrm{GeV}/c^2$, for a neutralino with lifetime < 3 ns. For larger lifetimes the exclusion is obtained by using the non-pointing photon search.

5. Conclusions

The work of many people in the LEP experiments has been dedicated to find any evidence for the existence of supersymmetric particles. However so far without any sign of that yet. The

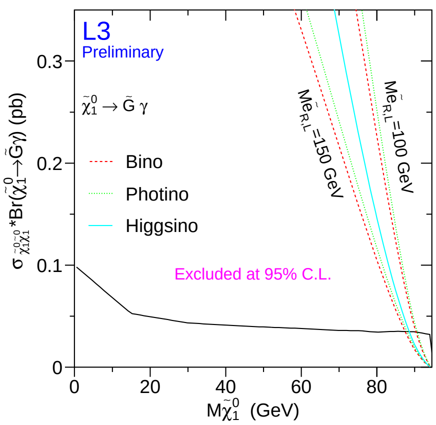

Figure 7. L3 cross-section limits on processes that could be interpreted as $\tilde{\chi}^0_1\tilde{\chi}^0_1$ production, which would produce a acoplanar photon pair signature. The figure also shows the predicted cross-section for three extreme cases of the $\tilde{\chi}^0_1$ composition and for two different $\tilde{e}$ masses as a function of the $\tilde{\chi}^0_1$ mass in the model of [6]

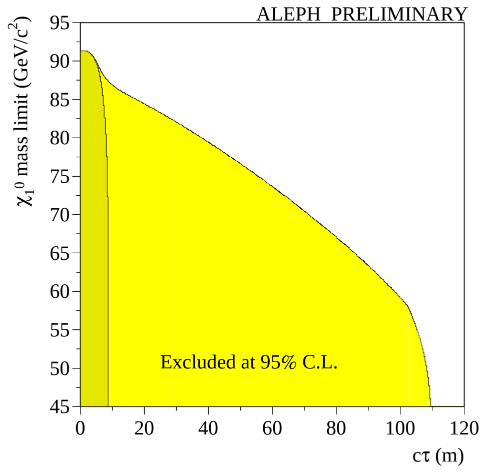

Figure 8. Mass limits of a neutralino NLSP in the MGM model [7], obtained by ALEPH.

results have nevertheless already put some stringent bounds for different models. In the SUGRA inspired CMSSM model, charginos are found to be heavier than $\sim$ 94.3GeV/c^2 for the case of heavy sfermions and with $\Delta M > 5$ GeV/c^2, and $\sim$ 78.0 GeV/c^2 for any m_0. In the same scenario the mass of the lightest neutralino is found to be $>$ 32.3 GeV/c^2. In the GMSB scenario, cross-section limits for processes resulting in single photon or acoplanar photon pairs + $\not\!\!E_T$ are found to be below 0.1 and 0.4 pb respectively. In the MGM model, the mass of the lightest neutralino is found to be $>$ 91 GeV/c^2 for a neutralino NLSP with life-time $<$ 3ns.

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