8-1998

Search for sleptons in e+e- collisions at centre-of-mass energies up to 184 GeV ALEPH Collaboration

R. BARATE

Manoj THULASIDAS
Singapore Management University, manojt@smu.edu.sg

EUROPEAN LABORATORY FOR PARTICLE PHYSICS (CERN)

CERN-EP/98-077
20 May 1998

Search for sleptons in e^+e^- collisions at centre–of–mass energies up to 184 GeV

The ALEPH Collaboration

Abstract

The data collected by the ALEPH experiment at LEP at centre–of–mass energies around 183 GeV are analysed to search for sleptons, the partners of leptons in supersymmetric theories. The previously published search for acoplanar leptons and missing energy has been updated. New searches have been developed to cover a wider range of slepton signals. These include single electrons, acoplanar leptons accompanied by two photons plus missing energy as well as particles with lifetime. No evidence for the production of any such particles is found. Slepton mass limits are reported within gravity mediated and gauge mediated SUSY breaking scenarios.

(To be submitted to Physics Letters B)

The ALEPH Collaboration

R. Barate, D. Buskulic, D. Decamp, P. Ghez, C. Goy, S. Jezequel, J.-P. Lees, A. Lucotte, F. Martin, E. Merle, M.-N. Minard, J.-Y. Nief, B. Pietrzyk

Laboratoire de Physique des Particules (LAPP), IN^{2}P^3-CNRS, F-74019 Annecy-le-Vieux Cedex, France

R. Alemany, G. Boix, M.P. Casado, M. Chmeissani, J.M. Crespo, M. Delfino, E. Fernandez, M. Fernandez-Bosman, Ll. Garrido,[15] E. Graugès, A. Juste, M. Martinez, G. Merino, R. Miquel, Ll.M. Mir, P. Morawitz, I.C. Park, A. Pascual, I. Riu, F. Sanchez

Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), E-Spain[7]

A. Colaleo, D. Creanza, M. de Palma, G. Gelao, G. Iaselli, G. Maggi, M. Maggi, S. Nuzzo, A. Ranieri, G. Raso, F. Ruggieri, G. Selvaggi, L. Silvestris, P. Tempesta, A. Tricomi,[3] G. Zito

Dipartimento di Fisica, INFN Sezione di Bari, I-70126 Bari, Italy

X. Huang, J. Lin, Q. Ouyang, T. Wang, Y. Xie, R. Xu, S. Xue, J. Zhang, L. Zhang, W. Zhao

Institute of High-Energy Physics, Academia Sinica, Beijing, The People's Republic of China[8]

D. Abbaneo, U. Becker, P. Bright-Thomas, D. Casper, M. Cattaneo, V. Ciulli, G. Dissertori, H. Drevermann, R.W. Forty, M. Frank, F. Gianotti, R. Hagelberg, J.B. Hansen, J. Harvey, P. Janot, B. Jost, I. Lehraus, P. Maley, P. Mato, A. Minten, L. Moneta,[20] N. Qi, A. Pacheco, F. Ranjard, L. Rolandi, D. Rousseau, D. Schlatter, M. Schmitt,[1] O. Schneider, W. Tejessy, F. Teubert, I.R. Tomalin, M. Vreeswijk, H. Wachsmuth

European Laboratory for Particle Physics (CERN), CH-1211 Geneva 23, Switzerland

Z. Ajaltouni, F. Badaud G. Chazelle, O. Deschamps, A. Falvard, C. Ferdi, P. Gay, C. Guicheney, P. Henrard, J. Jousset, B. Michel, S. Monteil, J-C. Montret, D. Pallin, P. Perret, F. Podlyski, J. Proriol, P. Rosnet

Laboratoire de Physique Corpusculaire, Université Blaise Pascal, IN^{2}P^3-CNRS, Clermont-Ferrand, F-63177 Aubière, France

J.D. Hansen, J.R. Hansen, P.H. Hansen, B.S. Nilsson, B. Rensch, A. Wäänänen

Niels Bohr Institute, 2100 Copenhagen, DK-Denmark[9]

G. Daskalakis, A. Kyriakis, C. Markou, E. Simopoulou, A. Vayaki

Nuclear Research Center Demokritos (NRCD), GR-15310 Attiki, Greece

A. Blondel, J.-C. Brient, F. Machefert, A. Rougé, M. Rumpf, R. Tanaka, A. Valassi,[6] H. Videau

Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN^{2}P^3-CNRS, F-91128 Palaiseau Cedex, France

E. Focardi, G. Parrini, K. Zachariadou

Dipartimento di Fisica, Università di Firenze, INFN Sezione di Firenze, I-50125 Firenze, Italy

R. Cavanaugh, M. Corden, C. Georgiopoulos, T. Huehn, D.E. Jaffe

Supercomputer Computations Research Institute, Florida State University, Tallahassee, FL 32306-4052, USA [13,14]

A. Antonelli, G. Bencivenni, G. Bologna,[4] F. Bossi, P. Campana, G. Capon, F. Cerutti, V. Chiarella, G. Felici, P. Laurelli, G. Mannocchi,[5] F. Murtas, G.P. Murtas, L. Passalacqua, M. Pepe-Altarelli

Laboratori Nazionali dell'INFN (LNF-INFN), I-00044 Frascati, Italy

M. Chalmers, L. Curtis, A.W. Halley, J.G. Lynch, P. Negus, V. O'Shea, C. Raine, J.M. Scarr, K. Smith, P. Teixeira-Dias, A.S. Thompson, E. Thomson, J.J. Ward

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ,United Kingdom[10]

O. Buchmüller, S. Dhamotharan, C. Geweniger, G. Graefe, P. Hanke, G. Hansper, V. Hepp, E.E. Kluge, A. Putzer, J. Sommer, K. Tittel, S. Werner, M. Wunsch

Institut für Hochenergiephysik, Universität Heidelberg, D-69120 Heidelberg, Germany[16]

R. Beuselinck, D.M. Binnie, W. Cameron, P.J. Dornan,[12] M. Girone, S. Goodsir, E.B. Martin, N. Marinelli, A. Moutoussi, J. Nash, J.K. Sedgbeer, P. Spagnolo, M.D. Williams

Department of Physics, Imperial College, London SW7 2BZ, United Kingdom[10]

V.M. Ghete, P. Girtler, E. Kneringer, D. Kuhn, G. Rudolph

Institut für Experimentalphysik, Universität Innsbruck, A-6020 Innsbruck, Austria[18]

C.K. Bowdery, P.G. Buck, P. Colrain, G. Crawford, A.J. Finch, F. Foster, G. Hughes, R.W.L. Jones, A.N. Robertson, M.I. Williams

Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom[10]

I. Giehl, C. Hoffmann, K. Jakobs, K. Kleinknecht, M. Kröcker, H.-A. Nürnberger, G. Quast, B. Renk, E. Rohne, H.-G. Sander, P. van Gemmeren, C. Zeitnitz, T. Ziegler

Institut für Physik, Universität Mainz, D-55099 Mainz, Germany[16]

J.J. Aubert, C. Benchouk, A. Bonissent, G. Bujosa, J. Carr,[12] P. Coyle, A. Ealet, D. Fouchez, O. Leroy, F. Motsch, P. Payre, M. Talby, A. Sadouki, M. Thulasidas, A. Tilquin, K. Trabelsi

Centre de Physique des Particules, Faculté des Sciences de Luminy, IN^{2}P^3-CNRS, F-13288 Marseille, France

M. Aleppo, M. Antonelli, F. Ragusa

Dipartimento di Fisica, Università di Milano e INFN Sezione di Milano, I-20133 Milano, Italy.

R. Berlich, W. Blum, V. Büscher, H. Dietl, G. Ganis, H. Kroha, G. Lütjens, C. Mannert, W. Männer, H.-G. Moser, S. Schael, R. Settles, H. Seywerd, H. Stenzel, W. Wiedenmann, G. Wolf

Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, D-80805 München, Germany[16]

J. Boucrot, O. Callot, S. Chen, M. Davier, L. Duflot, J.-F. Grivaz, Ph. Heusse, A. Höcker, A. Jacholkowska, M. Kado, D.W. Kim,[2] F. Le Diberder, J. Lefrançois, L. Serin, E. Tournefier, J.-J. Veillet, I. Videau, D. Zerwas

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, IN^{2}P^3-CNRS, F-91898 Orsay Cedex, France

P. Azzurri, G. Bagliesi,[12] S. Bettarini, T. Boccali, C. Bozzi, G. Calderini, R. Dell'Orso, R. Fantechi, I. Ferrante, A. Giassi, A. Gregorio, F. Ligabue, A. Lusiani, P.S. Marrocchesi, A. Messineo, F. Palla, G. Rizzo, G. Sanguinetti, A. Sciabà, G. Sguazzoni, R. Tenchini, C. Vannini, A. Venturi, P.G. Verdini

Dipartimento di Fisica dell'Università, INFN Sezione di Pisa, e Scuola Normale Superiore, I-56010 Pisa, Italy

G.A. Blair, L.M. Bryant, J.T. Chambers, J. Coles, M.G. Green, T. Medcalf, P. Perrodo, J.A. Strong, J.H. von Wimmersperg-Toeller

Department of Physics, Royal Holloway & Bedford New College, University of London, Surrey TW20 OEX, United Kingdom[10]

D.R. Botterill, R.W. Clifft, T.R. Edgecock, S. Haywood, P.R. Norton, J.C. Thompson, A.E. Wright

Particle Physics Dept., Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 OQX, United Kingdom[10]

B. Bloch-Devaux, P. Colas, B. Fabbro, G. Faïf, E. Lançon,[12] M.-C. Lemaire, E. Locci, P. Perez, H. Przysiezniak, J. Rander, J.-F. Renardy, A. Rosowsky, A. Roussarie, A. Trabelsi, B. Vallage

CEA, DAPNIA/Service de Physique des Particules, CE-Saclay, F-91191 Gif-sur-Yvette Cedex, France[17]

S.N. Black, J.H. Dann, H.Y. Kim, N. Konstantinidis, A.M. Litke, M.A. McNeil, G. Taylor

Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA[19]

C.N. Booth, S. Cartwright, F. Combley, M.S. Kelly, M. Lehto, L.F. Thompson

Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom[10]

K. Affholderbach, A. Böhrer, S. Brandt, G. Cowan, J. Foss, C. Grupen, L. Smolik, F. Stephan

Fachbereich Physik, Universität Siegen, D-57068 Siegen, Germany[16]

G. Giannini, B. Gobbo, G. Musolino

Dipartimento di Fisica, Università di Trieste e INFN Sezione di Trieste, I-34127 Trieste, Italy

J. Putz, J. Rothberg, S. Wasserbaech, R.W. Williams

Experimental Elementary Particle Physics, University of Washington, WA 98195 Seattle, U.S.A.

S.R. Armstrong, A.P. Betteridge, E. Charles, P. Elmer, D.P.S. Ferguson, Y. Gao, S. González, T.C. Greening, O.J. Hayes, H. Hu, S. Jin, P.A. McNamara III, J.M. Nachtman,[21] J. Nielsen, W. Orejudos, Y.B. Pan, Y. Saadi, I.J. Scott, J. Walsh, Sau Lan Wu, X. Wu, G. Zobernig

Department of Physics, University of Wisconsin, Madison, WI 53706, USA[11]

---

[1]Now at Harvard University, Cambridge, MA 02138, U.S.A.
[2]Permanent address: Kangnung National University, Kangnung, Korea.
[3]Also at Dipartimento di Fisica, INFN Sezione di Catania, Catania, Italy.
[4]Also Istituto di Fisica Generale, Università di Torino, Torino, Italy.
[5]Also Istituto di Cosmo-Geofisica del C.N.R., Torino, Italy.
[6]Supported by the Commission of the European Communities, contract ERBCHBICT941234.
[7]Supported by CICYT, Spain.
[8]Supported by the National Science Foundation of China.
[9]Supported by the Danish Natural Science Research Council.
[10]Supported by the UK Particle Physics and Astronomy Research Council.
[11]Supported by the US Department of Energy, grant DE-FG0295-ER40896.
[12]Also at CERN, 1211 Geneva 23,Switzerland.
[13]Supported by the US Department of Energy, contract DE-FG05-92ER40742.
[14]Supported by the US Department of Energy, contract DE-FC05-85ER250000.
[15]Permanent address: Universitat de Barcelona, 08208 Barcelona, Spain.
[16]Supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Germany.
[17]Supported by the Direction des Sciences de la Matière, C.E.A.
[18]Supported by Fonds zur Förderung der wissenschaftlichen Forschung, Austria.
[19]Supported by the US Department of Energy, grant DE-FG03-92ER40689.
[20]Now at University of Geneva, 1211 Geneva 4, Switzerland.
[21]Now at University of California at Los Angeles (UCLA), Los Angeles, CA 90024, U.S.A.

1 Introduction

In 1997 centre–of–mass energies up to 184 GeV were achieved at LEP. Data corresponding to an integrated luminosity of 0.2, 3.9, 51.0, 1.9 pb^{-1} were collected with the ALEPH detector at energies of 181, 182, 183, 184 GeV respectively. With these data the searches for sleptons published in [1] and for long–lived, heavy, charged particles published in [2] are updated. These analyses have been extended to cover a wider range of possible slepton signals.

Low–energy supersymmetric extensions of the Standard Model with the conservation of R–parity [3], a multiplicative quantum number distinguishing between ordinary particles and their supersymmetric partners, are taken as reference models. R–parity conservation implies that supersymmetric particles have to be produced in pairs and that the lightest supersymmetric particle (LSP) is stable; following cosmological arguments [4], the LSP is also assumed to be neutral and weakly interacting. The nature of the LSP depends on the supersymmetry breaking mechanism. Possible candidates are the lightest neutralino, the lightest sneutrino and the gravitino ($\widetilde{\mathrm{G}}$). In most of the searches for supersymmetry performed at LEP, and also in [1], the gravitino has been assumed heavy enough for its interactions in the LEP environment to be safely neglected. This corresponds to the case where the supersymmetry breaking is propagated to the matter sector by gravity. Throughout this letter this scenario is referred to as MSSM. There is, however, renewed interest in a class of models, the so–called Gauge Mediated Supersymmetry Breaking models [5], where the supersymmetry breaking is mediated by gauge interactions; in this case the gravitino is expected to be very light and to have a phenomenological impact on the searches for supersymmetry at LEP. Hereafter these scenarios are referred to as GMSB.

Sleptons are the supersymmetric partners of charged leptons. One complex scalar field is associated with each chirality component of the Dirac fermionic field: the resulting scalar particles are called "right-handed" ($\widetilde{\ell}_R$) and "left-handed" ($\widetilde{\ell}_L$) sleptons.

Assuming common scalar and gaugino masses (m_0 and $m_{1/2}$) at the GUT scale, there is a relation among the masses of the scalar particles at the electroweak scale [6], and among M_1 and M_2, the soft supersymmetry breaking parameter associated with the $U(1)$ and the $SU(2)_L$ groups ($M_2 = 3/5 \cot^2\theta_W M_1 \simeq 0.81 m_{1/2}$). For charged sleptons one obtains:

$$
\begin{aligned}
M^2_{\widetilde{\ell}_R} &= m_0^2 + 0.22 M_2^2 - \sin^2\vartheta_W M_Z^2 \cos 2\beta, \\
M^2_{\widetilde{\ell}_L} &= m_0^2 + 0.75 M_2^2 - 0.5(1 - 2\sin^2\vartheta_W) M_Z^2 \cos 2\beta,
\end{aligned}
$$

where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. From these relations and assuming $\tan\beta$ larger than 1, the left–handed slepton is expected to be heavier than the right–handed one. For selectrons and smuons the interaction eigenstates are expected to be a good approximation of the mass eigenstates. In the case of staus, a larger mixing between the two interaction eigenstates is expected.

The production of smuons ($\widetilde{\mu}$) and staus ($\widetilde{\tau}$) proceeds via γ or Z exchange in the s channel only, whereas selectrons ($\widetilde{\mathrm{e}}$) can also be produced by exchanging neutralinos in the t channel. The dependence of the cross section for smuon and stau production on supersymmetric parameters is only through the masses and the mixing angle in the case of staus. The selectron cross section [7] depends on the selectron mass and, via the t channel, on $\tan\beta$, M_2 and μ, the Higgs mixing parameter.

In the MSSM, sleptons dominantly decay into their partner lepton and the lightest neutralino if the slepton is the Next to Lightest Supersymmetric Particle (NLSP). If the slepton is not the NLSP cascade decays may be possible. The branching ratio of these decays depends on the supersymmetric parameters.

Table 1: Final state topologies studied in the different scenarios.

	NLSP	Production	Decay mode	Topology	Comment
MSSM	$\tilde{\ell}$	$\tilde{\ell}\tilde{\ell}$	$\tilde{\ell} \to l\chi$	Acoplanar leptons	
		$\tilde{e}_R\tilde{e}_L$	$\tilde{e} \to e\chi$	Single electron	Small $m_{\tilde{e}_R} - m_\chi$
GMSB	$\tilde{\ell}$	$\tilde{\ell}\tilde{\ell}$	$\tilde{\ell} \to l\tilde{G}$	Acoplanar leptons Impact parameter Kinks Stable sleptons	According to lifetime
	χ	$\tilde{\ell}\tilde{\ell}$	$\tilde{\ell} \to l\chi$ $\to l\tilde{G}\gamma$	Acoplanar leptons plus photons	
				Acoplanar photons	Small $m_{\tilde{\ell}} - m_\chi$

In GMSB models if the slepton is the NLSP (preferentially the stau if its mixing is not negligible) it decays into a lepton of the same family plus a gravitino. Otherwise the NLSP is the lightest neutralino (although a small region of the parameter space where it is the sneutrino exists) and then the slepton decays into a lepton and a photon plus gravitino produced by the neutralino.

The topologies arising from slepton production depend on these decay patterns and the possible lifetime of these particles. The topologies studied are summarised in Table 1.

The usual topology in the MSSM is acoplanar leptons plus missing energy. If the mass difference between right–handed selectron and the lightest neutralino is very small the search for $\tilde{\ell}_R\tilde{\ell}_R$ has no sensitivity. In this case $\tilde{e}_R\tilde{e}_L$ production leading to final states with a single visible electron may be the only possibility to detect sleptons if the left–handed slepton is too heavy to be produced in pairs.

In GMSB models the NLSP slepton lifetime depends on the gravitino mass $m_{\tilde{G}}$. Its decay length, given by [5]

$$L \simeq (100\ \mu\text{m}) \left(\frac{100\ \text{GeV}/c^2}{m_{\tilde{\ell}}}\right)^5 \left(\frac{m_{\tilde{G}}}{2.4\ \text{eV}}\right)^2 \sqrt{\frac{E_{\tilde{\ell}}^2}{m_{\tilde{\ell}}^2} - 1}$$

can be non-negligible compared to the dimensions of the ALEPH detector, since the gravitino mass could be as large as a few keV. The full range of possible lifetimes is covered by searches for acoplanar leptons plus missing energy, tracks with large impact parameters, kinks in the detector volume, and heavy stable charged particles.

When the neutralino is the NLSP, topologies either with two leptons and two photons or two photons only (when the mass difference between the slepton and the lightest neutralino is very small) have to be searched for.

This letter is organised as follows. In Section 2 the ALEPH detector is described. Details about the event selections are given in Section 3. Possible sources of systematic uncertainties and their evaluation are described in Section 4. Finally, the results are presented and discussed in Section 5.

2 The ALEPH Detector

The ALEPH detector and its performance are described in detail in Ref. [8, 9]. A description of the components relevant for the presented analyses is given here.

Charged particle tracks are measured by a silicon vertex detector (VDET), a multiwire drift chamber (ITC) and a time projection chamber (TPC). The VDET has a length of approximately 40 cm with two concentric layers of silicon wafers at average radii of 6.3 and 11 cm. The ITC consists of eight drift chamber layers of 2 m length between an inner radius of 16 cm and an outer radius of 26 cm. The TPC measures up to 21 space points in the radial range from 40 cm to 171 cm and an overall length of 4.4 m. These chambers are immersed in an axial magnetic field of 1.5 T and together achieve a transverse momentum resolution $\sigma(p_T)/p_T = 0.0006 p_T \oplus 0.005$ (p_T in GeV/c). The TPC also provides up to 338 measurements of the ionisation energy loss. It is surrounded by the electromagnetic calorimeter (ECAL) which covers the angular range $|\cos\theta| < 0.98$. The ECAL is finely segmented in projective towers of approximately 0.9° by 0.9° which are read out in three segments of depth. The energy resolution is $\delta E/E = 0.18/\sqrt{E} + 0.009$ (E in GeV). The iron return yoke is instrumented with streamer tubes as a hadron calorimeter (HCAL) and covers polar angles down to 110 mrad. Surrounding the HCAL are two additional layers of streamer tubes called muon chambers. The luminosity monitors (LCAL and SICAL) extend the calorimetric coverage down to polar angles of 34 mrad.

Using the energy flow algorithm described in Ref. [9], the measurement of the tracking detectors and the calorimeters are combined into "objects" classified as charged particles, photons, and neutral hadrons. A *good track* is defined as a charged particle track originating from the interaction region (with transverse impact parameter $|d_0| < 1$ cm and longitudinal impact parameter $|z_0| <$ 5 cm), having at least four TPC hits, a transverse momentum greater than 200 MeV and a minimum polar angle of 18.2°. In order to get the correct charged multiplicity, for all analyses photon conversions into e^+e^- are reconstructed with a standard pair finding algorithm [9]. Electrons are identified using the shower profile in the electromagnetic calorimeter and the measurement of the specific ionisation energy loss. The tagging of muons makes use of the hit patterns in HCAL and the muon chambers.

3 Selection criteria

Several selection algorithms have been developed to address the different final states described above. Searches for acoplanar lepton pairs (Section 3.1) and single electrons (Section 3.2) cover the main signatures in the MSSM scenario. Searches for an acoplanar lepton pair and two photons (Section 3.3) and long or medium lived particles (Section 3.4) address the final states expected in GMSB scenarios.

All selections are developed using Monte Carlo techniques. Monte Carlo samples corresponding to at least 10 times the collected luminosity of all major background processes have been generated using the same programs as in Ref. [1]. The position of the most important cuts are determined using the $\bar{N}_{95}$ prescription [10]. The expected background from WW production is subtracted in the search for acoplanar leptons according to the prescription described in [11]. For all analyses not published in Ref. [1] or [2] data collected at centre–of–mass energies of 161, 170 and 172 GeV, which corresponds to integrated luminosities of 11.1, 1.1, 9.5 pb^{-1} respectively, are used in addition to the data taken at $181 - 184$ GeV.

Typical efficiencies and the expected background for the various analyses are listed in Table 2.

3.1 Events with acoplanar leptons

For final states with acoplanar leptons, the selections developed for energies between 161 GeV and 172 GeV [1] are reoptimised to account for the increase in energy and luminosity as well as the changes in the composition of the background. The search for acoplanar taus is extended to smaller

Table 2: Signal cross section for selectrons $\sigma_{\tilde{e}}$ ($\tan\beta = 2$, $\mu = -200$ GeV/c^2), smuons and staus $\sigma_{\tilde{\mu},\tilde{\tau}}$, efficiency ϵ and background cross section σ_B for the search of acoplanar leptons, events with single electrons and acoplanar leptons plus photons ($\sqrt{s} = 183$ GeV).

$e^+e^- \to \tilde{\ell}\,\tilde{\ell} \to \ell^+\chi\ell^-\chi$				selectrons		smuons		staus	
$m_{\tilde{\ell}}$ [GeV/c^2]	M_χ [GeV/c^2]	$\sigma_{\tilde{e}}$ [fb]	$\sigma_{\tilde{\mu},\tilde{\tau}}$ [fb]	ϵ [%]	σ_B [fb]	ϵ [%]	σ_B [fb]	ϵ [%]	σ_B [fb]
	0	1026		62	149	66	136	43	117
	30	686		64	121	64	100	45	117
75	60	274	134	57	9	62	3	38	64
	70	190		36	23	44	31	7	35
	72	176		11	14	13	18	0.5	30

$e^+e^- \to \tilde{e}_R\tilde{e}_L \to e^+\chi e^-\chi$				selectrons	
$m_{\tilde{e}_L}$ [GeV/c^2]	$m_{\tilde{e}_R}$ [GeV/c^2]	M_χ [GeV/c^2]	$\sigma_{\tilde{e}}$ [fb]	ϵ [%]	σ_B [fb]
102	60		868	68	77
102	60.5		845	50	77
102	61	60	822	45	1
103	62		775	49	2
105	65		626	58	2

$e^+e^- \to \tilde{\ell}\,\tilde{\ell} \to \ell^+\tilde{G}\gamma\ell^-\tilde{G}\gamma$				selectrons		smuons		staus	
$m_{\tilde{\ell}}$ [GeV/c^2]	M_χ [GeV/c^2]	$\sigma_{\tilde{e}}$ [fb]	$\sigma_{\tilde{\mu},\tilde{\tau}}$ [fb]	ϵ [%]	σ_B [fb]	ϵ [%]	σ_B [fb]	ϵ [%]	σ_B [fb]
	0	1026		27		44		18	
	30	686		41		61		27	
75	60	274	134	47	9	66	11	34	16
	70	190		44		63		24	
	72	176		37		54		19	
	$75 - m_\ell$	153		49	15	49	15	15	

mass differences (ΔM) between the stau and the neutralino by means of a new dedicated selection. The complete list of cuts is summarised in Table 3.

3.1.1 Updated acoplanar leptons analyses

In the following an outline of the general concept of the selections for selectrons and smuons as well as staus at high ΔM is given, with a detailed description for new or modified cuts only.

The reconstruction of hadronic tau decays is modified with respect to [1]. To select a pure sample of taus, events are clustered into two jets. The sum of all energy flow objects within a cone with half–angle of 15° around the jet axis is considered as a tau if the following set of quality cuts is fulfilled: its invariant mass is less than 2 GeV/c^2; it contains either one or three charged particle tracks; the sum of the momenta along the jet axis is greater than 98% of the sum of the total momenta of all energy flow objects in the cone.

After selecting events containing two leptons (e, μ or τ) of the same flavour with no other charged particle tracks, kinematic cuts are applied. Background from two–photon processes is reduced with cuts on the energy E_{12} measured in a 12° cone around the beam axis, the visible mass M_{vis}, the lepton transverse momenta $p_{\text{T}1}, p_{\text{T}2}$, the missing transverse momentum p_{T} and the scalar sum ρ of transverse momenta with respect to the two–dimensional thrust axis [1]. Events from lepton pair production are rejected with restrictions on the acoplanarity Φ_{aco} and the momenta p_1 and p_2 of identified electrons and muons. Events with a single photon converting into e^+e^- before reaching the tracking chambers are rejected by a cut on the acollinearity α. Fermion pair production with a radiated photon in the detector is removed by a neutral veto. This neutral veto rejects events containing a neutral energy flow object of more than 5 GeV with an angle to each of the two lepton directions greater than 10° and an invariant mass with each of the two leptons greater than 2 GeV/c^2.

To reduce background from W pair production, where both W's decay into leptons, cuts on the momenta of identified electrons or muons are applied. For selectrons and smuons, it is required that the lepton momenta fall in the range kinematically allowed for a signal with the considered values of slepton and neutralino masses ("sliding cut" in Table 3). To save efficiency for slepton masses similar to the W–mass, further cuts against W pair production are omitted in the search for selectrons and smuons with large ΔM. For staus at high ΔM, events with more than one identified electron or muon are rejected if the momentum of the leading lepton is greater than 24 GeV/c or the momentum of the second lepton is greater than 18 GeV/c. If only one electron or muon is found, its momentum is required to be less than 25 GeV/c.

For the search of selectrons and smuons with small ΔM the same analysis as in [1] is applied. Background from fermion pair production and four–fermion events is effectively suppressed by tight cuts on the leading lepton momentum and the visible momentum p_{vis}. As the slepton signal for small ΔM is similar to the two–photon process, cuts on the missing transverse momentum and the variable ρ are less stringent than for large ΔM. The two–photon background is further reduced by a cut on the polar angle of the missing momentum and a Fisher discriminant analysis, as described in [1].

3.1.2 Staus with small mass difference

For staus with small ΔM the WW background can be reduced more effectively and cuts against $\gamma\gamma$ events can be relaxed to gain efficiency. To reduce the WW background, new tight cuts on the jet energies E_1, E_2 and the leading lepton momentum p_1 are introduced. The distribution of the energy from the leading jet is shown in Fig. 1a. With respect to the high ΔM analysis the τ tagging is looser, by also allowing two charged tracks in a τ jet. The number of identified electrons (muons) N_{e} (N_μ) should not be greater than one. The variable ρ should be larger than 1 GeV/c and larger than 3 GeV/c if $M_{\text{vis}} > 20$ GeV/c^2. Events from $\gamma\gamma$ background tend to be coplanar, have a small visible mass and transverse energy E_{T}. The cuts on these quantities are listed in Table 3 (anti–$\gamma\gamma$ cuts). Compared to the high ΔM selection the cuts on M_{vis} and p_{T} can be relaxed. The cuts on E_1, E_2 and p_1 are optimised as a function of ΔM.

For a given stau and neutralino mass the $\bar{N}_{95}$ prescription is employed to decide whether to use the high or low ΔM analysis.

3.2 Events with single electrons

For the signature of single electrons, one or two charged tracks are required in the event. Events from two–photon background are rejected by demanding one identified electron with a transverse momentum of at least $6\%\sqrt{s}$. If there is a second charged track with a transverse momentum greater than $0.5\%\sqrt{s}$ or an acoplanarity with respect to the electron greater than 150° the event is rejected to reduce background from fermion pair production and four–fermion processes. For this requirement tracks with less than four points in the TPC are also considered if they are measured

Table 3: Selection criteria for the searches of acoplanar leptons. The sliding cut is explained in the text.

	selectron $\tilde{\mathrm{e}}$, **smuon** $\tilde{\mu}$		**stau** $\tilde{\tau}$	
	$\Delta M \geq 6$ GeV/c^2	$\Delta M < 6$ GeV/c^2	large ΔM	small ΔM
charged tracks	two identified leptons (e, μ, τ)			
neutral veto	yes			
energy in 12°	$E_{12} = 0$			
acollinearity	$\alpha > 2°$			
acoplanarity	$\Phi_{\text{aco}} < 170°$			
visible mass	$M_{\text{vis}} > 4$ GeV/c^2		$M_{\text{vis}} > 6$ GeV/c^2	$M_{\text{vis}} > 4$ GeV/c^2
visible momentum		$p_{\text{vis}} < 10\%\sqrt{s}$		
missing momentum	$p_{\text{T}} > 3\%\sqrt{s}$	$p_{\text{T}} > 1\%\sqrt{s}$ $\lvert\cos\theta\rvert < 0.9$	if $M_{\text{vis}} < 30$ GeV/c^2: $p_{\text{T}} > 6\%\sqrt{s}$ $\lvert\cos\theta\rvert < 0.866$	if $M_{\text{vis}} < 30$ GeV/c^2: $p_{\text{T}} > 2.3\%\sqrt{s}$
ρ	$\rho > 2$ GeV/c	$\rho > 1$ GeV/c	$\Phi_{\text{aco}} < 15.6\rho + 130$	$\rho > 1$ GeV/c if $M_{\text{vis}} > 20$ GeV/c^2: $\rho > 3$ GeV/c
momenta of identified e and μ	$p_{\text{T1}}, p_{\text{T2}} > 0.5\%\sqrt{s}$ $p_1, p_2 < 46.5\%\sqrt{s}$ sliding cut	$p_1, p_2 < 10\%\sqrt{s}$	$p_1, p_2 < 24$ GeV/c $\min(p_1, p_2) < 18$ GeV/c if $N_{\text{e}} + N_\mu = 1$: $p_1 < 25$ GeV/c	$p_1, p_2 < 8.5 + 0.66\Delta M$ $p_1, p_2 < 25$ GeV/c
Fisher variable		$y > -15$		
no. of leptons				$N_{\text{e}}, N_\mu \leq 1$
anti–$\gamma\gamma$				if $M_{\text{vis}} < 10$ GeV/c^2: $E_{\text{T}} > 4$ GeV $\Phi_{\text{aco}} < 7.5E_{\text{T}} + 70$ if $M_{\text{vis}} < 20$ GeV/c^2 and $E_{\text{T}} < 20$ GeV: $\Phi_{\text{aco}} < 160°$
Jet energies				$E_1 < 4.4 + 1.5\Delta M$ $E_2 < 6 + 0.9\Delta M$

with at least four ITC hits. The neutral veto (defined as above, but using only the track with higher momentum) is applied to reduce radiative bhabha events. In addition there should be no neutral particle with an acoplanarity to the electron greater than 150°. After these cuts are applied the only significant background is coming from Weν and Zee events.

The momentum of the detected charged particles must be compatible with the kinematics for a signal with the considered values of slepton and neutralino masses. The distribution of the leading particle momentum is shown for data, background Monte Carlo and signal ($m_{\tilde{\mathrm{e}}_R} = 60$ GeV/c^2, $m_{\tilde{\mathrm{e}}_L} = 101.8$ GeV/c^2 and $M_\chi = 60$ GeV/c^2) in Fig. 1b.

The efficiency for $\tilde{\mathrm{e}}_R\tilde{\mathrm{e}}_L$ production mainly depends on the mass difference between the right–handed selectron to the neutralino as shown in Fig. 2a. In order to achieve sensitivity for all mass differences the single electron and acoplanar electron searches are combined; the resulting efficiency, with a smoother dependence on ΔM, is also shown in Fig. 2a. In the complete data sample a background of 6.6 events is expected.

3.3 Events with acoplanar leptons plus photons

The signature of sleptons decaying into leptons and neutralinos which then decay into gravitinos and photons is similar to that of the acoplanar leptons except for the presence of isolated photons. Because of the neutral veto, the acoplanar lepton analyses are not sensitive to these topologies. Therefore a dedicated search has been developed.

3.3.1 Events with acoplanar electrons or muons plus photons

As in the acoplanar lepton pair analysis two identified leptons must be found, each with transverse momentum greater than $0.5\%\sqrt{s}$ and acollinearity α greater than $2°$. The value of E_{12} must be equal to zero and M_{vis} must be greater than 4 GeV/c^2. In addition there must be at least two photons with energies greater than 3 GeV in the event with the requirement that the energy of the most energetic photon be greater than 5 GeV. The cut on missing transverse momentum is tightened so that p_{T} must be greater than $6\%\sqrt{s}$. After applying these cuts, the expected background in the smuon channel is 0.8 events. However to suppress radiative Bhabha events which amount to approximately 70 events at this stage, additional requirements must be made for the selectron channel; the angle between the two photons and each track must be greater than $23°$ and after dividing the event into two hemispheres the angle between the vector sum of the momenta in these hemispheres should be less than $172°$. The minimum polar angle of the tracks has to be $26°$. The thrust should be less than 0.92 and the missing energy of the event must be greater than $10\%\sqrt{s}$. The background in the selectron channel is then expected to be 0.6 events.

3.3.2 Events with acoplanar taus plus photons

When searching for acoplanar taus with photons the two most isolated photons in the event are identified as the two photons with energy greater than 1 GeV and the largest angle from each of the two most back–to–back tracks. These are excluded while the remaining charged and neutral objects in the event are clustered into jets and tau tagging is applied in the same way as for the large ΔM acoplanar tau analysis. Two identified taus must be found with acollinearity greater than $2°$ and a minimum polar angle of $18.2°$. The event is required to have at least two photons with an angle to the taus of at least $20°$.

The energy in a $12°$ cone around the beam pipe must be equal to zero and missing transverse momentum of the event must be greater than $6\%\sqrt{s}$. To reject bhabha events, cuts on the lepton momenta are applied in the same way as for the acoplanar tau analysis at large ΔM. The polar angle of the total momentum of the taus has to be at least $18.2°$ and Φ_{aco} has to be lower than $165°$. The polar angle of the most isolated photon must be more than $32°$. An additional cut on the ratio of the energy of the most isolated photon (E_{phot1}) and the second isolated photon (E_{phot2}) is required to further reduce the dilepton background: $E_{\mathrm{phot1}}/E_{\mathrm{phot2}} < 2.7$. The energy distribution for the most isolated photon is shown in Fig. 1c. After all cuts are applied a total background of 1.0 event is expected.

3.3.3 Events with acoplanar photons

The efficiency of the selections described in Sec. 3.3.1 drops rapidly as the mass difference between the slepton and the neutralino decreases below 1 GeV/c^2. The selection based on the acoplanar photon analysis described in Ref. [12] has been modified, as follows, to cover this scenario. The requirement that there be no additional charged tracks in the event is removed. However, to reduce the background from tau decays, any tracks present must have an invariant mass above 1.5 GeV/c^2 when paired with either of the two most energetic photons. The cut on additional energy in the event is relaxed from 1 GeV to 8 GeV. The value of E_{12} must be equal to zero. Both photons are required to have an energy of at least 3 GeV. The cosmic veto based on a penetrating HCAL pattern is not applied if the event contains an identified muon originating from the interaction region. The background to this selection is estimated to be 2.7 events, coming mostly from the $\nu\bar{\nu}\gamma(\gamma)$ final state.

3.4 Sleptons with lifetime

To search for sleptons with a significant lifetime different selections have been developed. In Section 3.4.1 searches are described for long–lived particles which decay outside the ALEPH tracking volume (Radius $R > 1.8$ m). Section 3.4.2 describes searches for particles which decay within the detector volume ($O(1\text{ cm}) < R < 1.5$ m). For shorter lifetimes the searches for acoplanar leptons described in Section 3.1 are used. Fig. 2b gives an example of the efficiencies for staus obtained in the various analyses.

3.4.1 Long–lived sleptons

A search for pair–produced heavy stable charged particles has already been performed by ALEPH analysing the data collected at centre–of–mass energies up to 172 GeV [2]. Two analyses were developed in order to cover a wide mass interval of the heavy particles. The low–mass analysis was based on kinematic cuts while the intermediate–mass one was based on specific ionisation loss measurements. These analyses are applied to the data collected at $181-184$ GeV. All the cuts and the efficiency parametrisation are expressed as a function of the γ of the heavy particle. Typical efficiencies range between $40-70\%$ for values of $1/\gamma = m/E_{\text{beam}}$ in the range $0.52-0.98$. With the luminosity collected at 183 GeV approximately 0.3 background events are expected, the dominant source being double–radiative dimuon events. The high–mass analysis described in [2], which looks for tracks that saturate the TPC electronics, has not been applied here since it covers a mass range (88–91 GeV/c^2) where the slepton cross section is expected to be too small to be observable with the collected luminosity.

3.4.2 Medium–lived sleptons

If a slepton decays before leaving the tracking devices but with significant lifetime, two different scenarios have to be considered. If the particle decays after having produced a reconstructable track (i.e. $R > 40$ cm) the typical signature to search for is a kink. If it decays before, only the decay products are observable. For a large enough decay radius ($R > O(1\text{ cm})$) these tracks in general have large distances to the beam axis (impact parameters). Therefore two different selections have been developed to search for kinks and tracks with large impact parameter.

For both selections photon conversions are identified and removed using the procedure mentioned in Section 3.1.1. A common preselection is applied. In order to suppress 2–photon events, at least one track with six hits in the TPC and with a transverse momentum greater than $3\%\sqrt{s}$ is required. The total measured energy is required to be in excess of $3\%\sqrt{s}$; in determining this quantity for the kink search, the track possibly assigned to the decaying slepton is removed from the energy flow objects list. Dilepton events are suppressed by an upper cut on the total measured energy: $90\%\sqrt{s}$ and $65\%\sqrt{s}$, respectively for the kink and impact parameters searches. The cut is tighter in the latter case because there both sleptons can be expected to decay within the detector and therefore at least two neutral particles escaping the detector are produced. No electron identification is used in these analyses. In the search for smuons background events without muons are suppressed by requiring loose muon identification based on the muon trigger [8].

A major source for charged tracks not originating from the primary vertex are cosmic muons crossing the detector volume. Most of these events are rejected using the ECAL timing information [13]. In addition events are removed if there is a track present with at least eight TPC hits and a momentum of more than 1.5 times the beam energy or if two tracks are found with an acollinearity larger than 178° each with either muon identification or hits close to the edge of the tracking volume.

Search for kinks: In the search for kinks the number of tracks with hits in the TPC is limited to six. Kinks are reconstructed by searching for tracks of the same charge crossing in the plane transverse to the beam axis ($r\phi$–plane) or approaching each other in this projection closer than 5 cm. Their separation in the z direction at this point should be less than 20 cm and the kink vertex is required to lie within the tracking detectors. To be sensitive to the case where the slepton is a stau, no restriction on the total number of tracks originating from a kink (outer tracks) is applied. Several requirements are made to ensure that the used tracks are well measured in the detector and that together they are compatible with the hypothesis of a real kink. The track assigned to the slepton (inner track) must have a closest distance to the beam axis of less than 0.5 cm while for the outer track this has to be more than 1 cm. The outer track is also required to have at least four hits in the TPC, a momentum of more than $1\%\sqrt{s}$ and its angle to the beam axis must be larger than 18.2°. The presence of hits assigned to the inner (outer) track after (before) the reconstructed decay vertex is used to remove fake kinks. To reject kinks produced by bremsstrahlung, the angle between the inner and the outer track must be larger than 5° at the kink vertex. If the inner track has no TPC coordinates assigned, this cut is tightened to 10°. The distribution of this angle is shown in Fig. 1d.

At this point an important residual background comes from ditau events with hadronic interactions in the detector material. Since in these events the hadron that interacts hadronically is often accompanied by other collinear particles, they are suppressed by requiring that the energy, deposited in the calorimeters within 5° around the extrapolation of a straight line from the primary vertex to the kink, is less than 5 GeV if the kink is found in the material region (radius between 26 and 34 cm).

Search for large impact parameters: In the search for tracks with large impact parameters only tracks are considered with at least 4 hits in the TPC and a minimum momentum of $0.5\%\sqrt{s}$. Tau identification is attempted on 3 prong jets: sets of exactly three tracks, where for each possible pair the angle at the point of closest approach in the $r\phi$–plane is less than 11.5°, are called taus. In the following a tau will be treated as one track taking the mean value of the three impact parameters as the tau impact parameter and the summed momenta as its direction. Events are rejected if they do not consist of exactly two tracks, of which at most one should be associated to a 3 prong tau.

To reject background from dilepton, bhabha and $\gamma\gamma$ events the two tracks must have an acoplanarity below 175° and an acollinearity greater than 11.5°. At least one (non-tau) track must have an impact parameter of more than 1 cm. A minimum of one hit in ITC or VDET and an angle to the beam axis larger than 18.2° are required. The impact parameter of the other track should be larger than 0.025 cm.

Combination: The efficiency of the two selections separately and of the combination are shown in Fig. 2b for stau decays. For selectrons and smuons the efficiency is higher, mainly due to the absence of 3 prong decays and higher momenta of the decay products. The trigger efficiency in the smuon search has been studied using a simulation and was found to be above 80%, found in the most pessimistic configuration of masses and lifetimes.

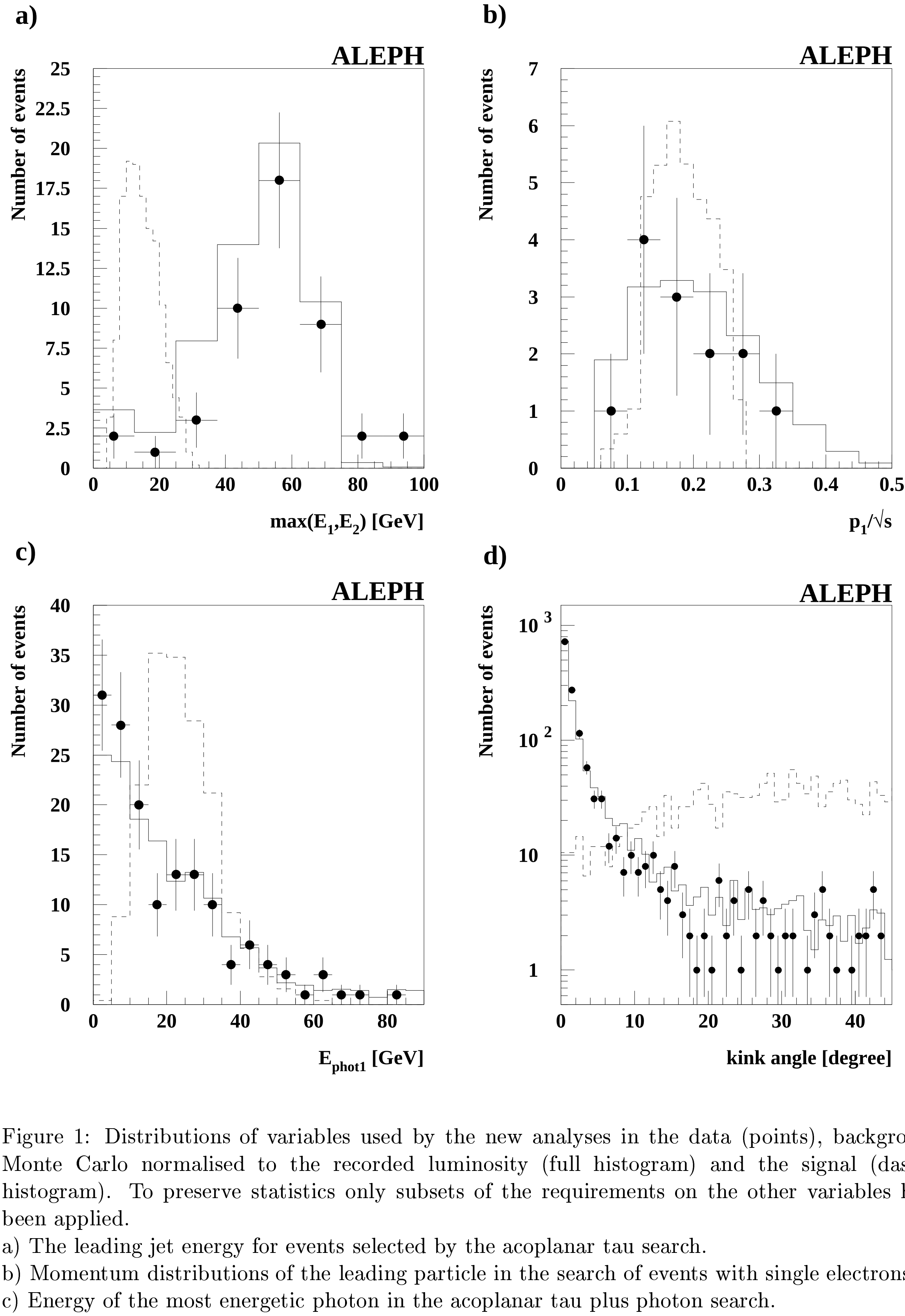

Figure 1: Distributions of variables used by the new analyses in the data (points), background Monte Carlo normalised to the recorded luminosity (full histogram) and the signal (dashed histogram). To preserve statistics only subsets of the requirements on the other variables have been applied.
a) The leading jet energy for events selected by the acoplanar tau search.
b) Momentum distributions of the leading particle in the search of events with single electrons.
c) Energy of the most energetic photon in the acoplanar tau plus photon search.
d) Angle between inner and outer track for kinks.

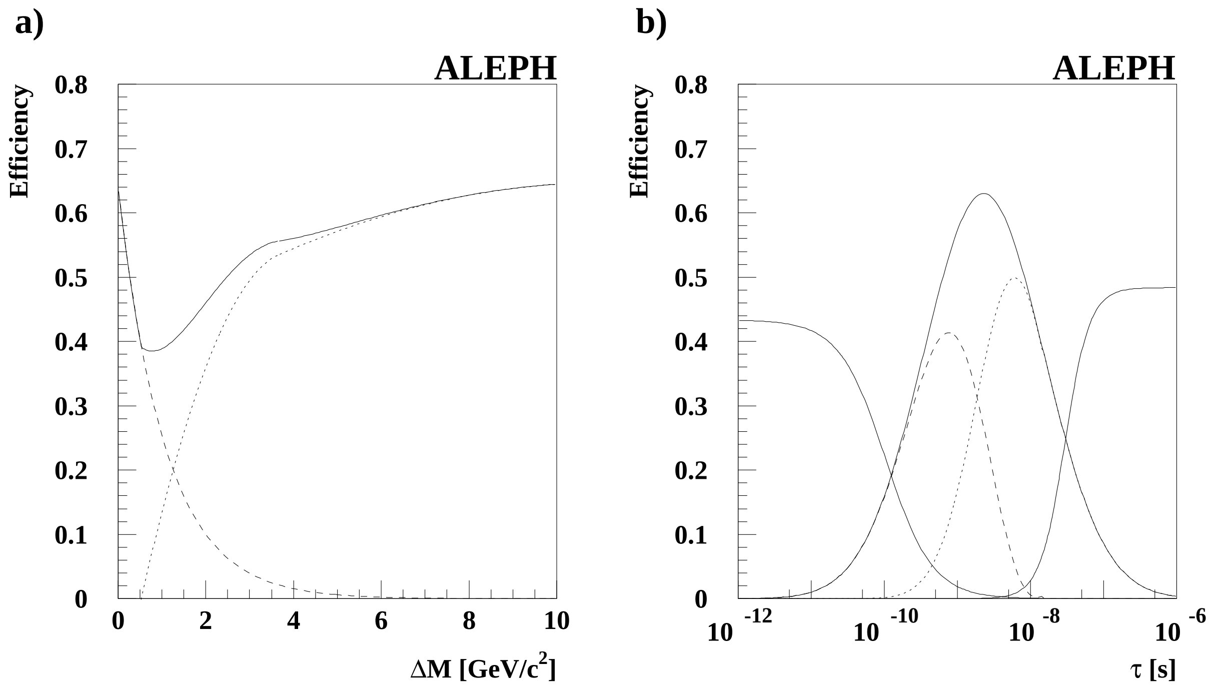

Figure 2: a) The efficiency for $\tilde{e}_R\tilde{e}_L$ production of the search for events with single electron (dashed line) and acoplanar electrons (dotted line) is given as function of the mass difference (for $m_{\tilde{e}_L} - M_\chi = 40$ GeV/c^2). The total efficiency is indicated by the full line.
b) The efficiency for $\tilde{\tau}_R\tilde{\tau}_R$ production of the dedicated selections as function of the $\tilde{\tau}_R$ lifetime. The insensitive region between the search for acoplanar taus ($\tau \lesssim 10^{-10}$ s) and the search for stable particles ($\tau \gtrsim 10^{-7}$ s) is closed by the search for short–lived (dashed line) and medium-lived (dotted line) sleptons. The efficiency for the combination of these two analyses is given by the full line (10^{-10} s $\lesssim \tau \lesssim 10^{-7}$ s).

The background remaining in the kink search comes from ditau events and for data taken at $181-184$ GeV centre–of–mass energy 0.1 events are expected. In the large impact parameter search for selectrons and staus 0.22 events are expected from $\gamma\gamma \to e^+e^-$ and ditau events. Due to the additional trigger requirement 0.02 events are expected for smuons. The remaining background from cosmic muons is estimated to be less than 0.5 events for the combination of both the kink and large impact parameter selections.

To derive results for different slepton masses and lifetimes, the appropriate combination of the various selections is chosen by the $\bar{N}_{95}$ prescription.

4 Systematic uncertainties

The systematic effects of lepton identification are investigated by using events from two–photon processes and lepton pair production. The probability of identifying leptons is in good agreement between data and Monte Carlo. The detector response to acoplanar leptons are checked with events which are kinematically similar to the signal. These are two–photon events with a scattered electron in the luminosity calorimeters and dilepton events with an isolated photon in the detector. This scattered electron or isolated photon is removed from the analysis. The relevant quantities are well reproduced by the Monte Carlo simulation. These effects ($< 2\%$) and the Monte Carlo statistics (2%) are estimated as a total systematic error of 3% and the efficiency is reduced by one standard deviation.

The stable sleptons analysis relies mainly on track reconstruction and energy loss measurements. All the variables used in the analysis are checked using $\mu^-\mu^+$ samples selected with criteria independent from the ones used in the analysis. A good agreement between data and Monte Carlo simulation is found for all the variables except for the momentum difference between the two reconstructed tracks normalised to the momentum reconstruction error. For this variable the efficiency in the data is lower than in the Monte Carlo due to the underestimate of the momentum reconstruction error; this discrepancy has been taken into account by reducing the selection efficiency used to derive the limits.

5 Results

Six, seven and six candidates are observed in the search for acoplanar electrons, muons and taus, where 10.2, 9.2 and 9.5 are expected from standard model processes, respectively. There is no overlap in observed candidates, where the expected overlap is 0.3 events. The probability for a deviation as large as this or larger is 9%, thus the observed numbers are consistent with a statistical fluctuation. Using the acoplanar electron selection and requiring both one identified electron and one muon 19 events are selected with an expectation of 18.2, supporting the above statement. Five candidates are selected in the search for single electrons, compatible with the background of 6.6 events expected mainly from four–fermion processes.

For the acoplanar slepton search with photons, no candidates are found in the data for the selectron and smuon channels. The number of events expected from dilepton processes is 0.6 and 0.8 events respectively. One candidate event containing two energetic photons (45, 28 GeV) and consistent with ditau background is selected by the search in the stau channel where 1.1 events are expected. Three candidates are selected in the selection for the acoplanar slepton search with photons at very small mass difference, in agreement with the 2.7 events expected. These events were also selected in the acoplanar two photon analysis [12], and are compatible with the $\nu\bar{\nu}\gamma(\gamma)$ background.

For the long lifetime analysis no candidates are found in the data while the search for medium–lived sleptons selects one event. In this event two charged particle tracks are measured in the TPC, one with a closest distance to the beam axis of more than 2.5 cm. Both particles are identified as electrons and therefore the event is not taken into account in the search for $\widetilde{\mu}$ production. In addition a photon is detected in the ECAL. Therefore, the most probable standard model explanation for this event is a $\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-$ event with one of the electrons loosing energy by a hard bremsstrahlung in the material between ITC and TPC. Due to this sudden change in momentum the track does not point back to the primary vertex.

For a given supersymmetric model the non–observation of any excess of candidates can be interpreted as lower mass limits for selectrons, smuons and staus. Such limits are presented in the context of gravity mediated and gauge mediated SUSY breaking models.

5.1 Limits in the MSSM

The limits are derived by combining the results presented here with the ALEPH results obtained at $\sqrt{s} = 161 - 172$ GeV. Unless otherwise stated, limits are set taking into account $\widetilde{\ell}_R\widetilde{\ell}_R$ production only. The expected background from WW production is subtracted in the search for acoplanar leptons.

The mass limit for right–handed selectrons depends on the supersymmetric parameters. In Fig. 3a the actual and expected limits and the effect of cascade decays, such as $\widetilde{\mathrm{e}}_R \to \mathrm{e}\chi'$ are shown for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2. For smuons and staus the cross section is independent of $\tan\beta$ and μ. The actual and expected limits for smuons are shown in Fig. 3b assuming $\mathrm{BR}(\widetilde{\mu}_R \to \mu\chi) = 100\%$. The effect of cascade decays is shown for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2. Mixing may be non–negligible for staus, as the tau is much heavier than the electron and the muon. In the case where $\widetilde{\tau}_R$ and $\widetilde{\tau}_L$ mix, limits are set on the mass of the lightest stau ($\widetilde{\tau}_1$), choosing the mixing angle such that $\widetilde{\tau}_1$ decouples from the Z. Limits for staus are calculated in mixed and unmixed scenarios and shown in Fig. 3c.

Assuming a common scalar mass at the GUT scale, the relation between the masses of right– and left–handed sleptons can be used to combine results of the search for acoplanar leptons and the search for events with single electrons. The result for $\tan\beta = 2$ and $\mu = -100$ GeV/c^2 is shown in Fig. 3d. This value of μ minimises the product of cross section and branching fraction for the process $e^+e^- \to \widetilde{e}_R\widetilde{e}_L$, $\widetilde{e}_L \to e\chi$ for vanishing ΔM. Staus are not used because the highest sensitivity is reached combining only the searches for right– and left–handed selectrons and smuons. For ΔM below 3 GeV/c^2 the search of $\widetilde{\ell}_R\widetilde{\ell}_R$ loses sensitivity very rapidly. As the left–handed sleptons are too heavy to be produced in pairs, only the search for $\widetilde{e}_R\widetilde{e}_L$ is used here.

5.2 Limits in GMSB models

Mass limits are derived from the results of the acoplanar lepton with photons searches under the assumption that only $\widetilde{\ell}_R\widetilde{\ell}_R$ production contributes. When cascade decays are taken into account, conservatively assuming no efficiency, these limits are reduced. The limits obtained for right–handed selectrons are shown in Fig. 4a. These are dependent on the supersymmetric parameters and are shown for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2. The mass limits for right–handed smuons and staus do not have this dependence; they are shown in Fig. 4b and Fig. 4c respectively. The effect of cascade decays for selectrons and smuons for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2 is given by the short dashed lines.

A limit on $M_{\widetilde{\ell}}$ is derived assuming mass degeneracy of the three slepton flavours. The highest sensitivity is reached when only selectrons and smuons are combined, because staus are selected with similar background but lower efficiency. The result obtained for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2 is shown in Fig. 4d.

The search for heavy stable particles translates into a 95% confidence level upper limit on the production cross section of the order of 0.07 pb for masses in the range $45 - 87$ GeV/c^2. This cross section upper limit implies a lower mass limit of 81 GeV/c^2 for stable right–handed staus (or right–handed smuons) and of 82 GeV/c^2 for stable left–handed staus (or left–handed smuons).

A combination of the different searches for sleptons yields lifetime dependent lower limits on the slepton masses. The results obtained at 95% confidence level for selectrons, smuons and staus are shown in Fig. 5. For the selectrons the production cross section was calculated neglecting contributions from t channel processes. Assuming that the three sleptons have the same mass a lower limit on this mass is derived by combining the selections for selectrons and smuons (Fig. 5d).

6 Conclusions

In the data sample of 57 pb^{-1} recorded in 1997 by the ALEPH detector at LEP at centre–of–mass energies around 183 GeV, searches for signals of scalar lepton production have been performed. The number of candidate events observed is consistent with the background expected from standard model processes.

In the MSSM the following lower mass limits for right–handed are set at 95% confidence level if ΔM is greater than 15 GeV/c^2 ($\mu = -200$ GeV/c^2 and $\tan\beta = 2$, where relevant):

- 81 GeV/c^2 for selectrons

- 71 GeV/c^2 for smuons
- 65 GeV/c^2 for staus.

Assuming a common scalar mass at the GUT scale, $\tan\beta = 2$ and $\mu = -100$ GeV/c^2 a slepton mass limit of 65 GeV/c^2 is set independently of ΔM.

In GMSB models the search for acoplanar lepton pairs plus photons leads to the following limits (CL=95%), for any ΔM:

- 77 GeV/c^2 for selectrons ($\mu = -200$ GeV/c^2 and $\tan\beta = 2$),
- 77 GeV/c^2 for smuons,
- 52 GeV/c^2 for staus,
- 82 GeV/c^2 for mass degenerate sleptons.

If the slepton is the NLSP the following limits are derived independent of the slepton lifetime:

- 71 GeV/c^2 for selectrons (using only s channel contribution),
- 75 GeV/c^2 for smuons,
- 57 GeV/c^2 for staus,
- 80 GeV/c^2 for mass degenerate sleptons.

Acknowledgements

It is a pleasure to congratulate our colleagues from the accelerator divisions for the successful operation of LEP at high energy. We would like to express our gratitude to the engineers and support people at our home institutes without whose dedicated help this work would not have been possible. Those of us from non–member states thank CERN for its hospitality.

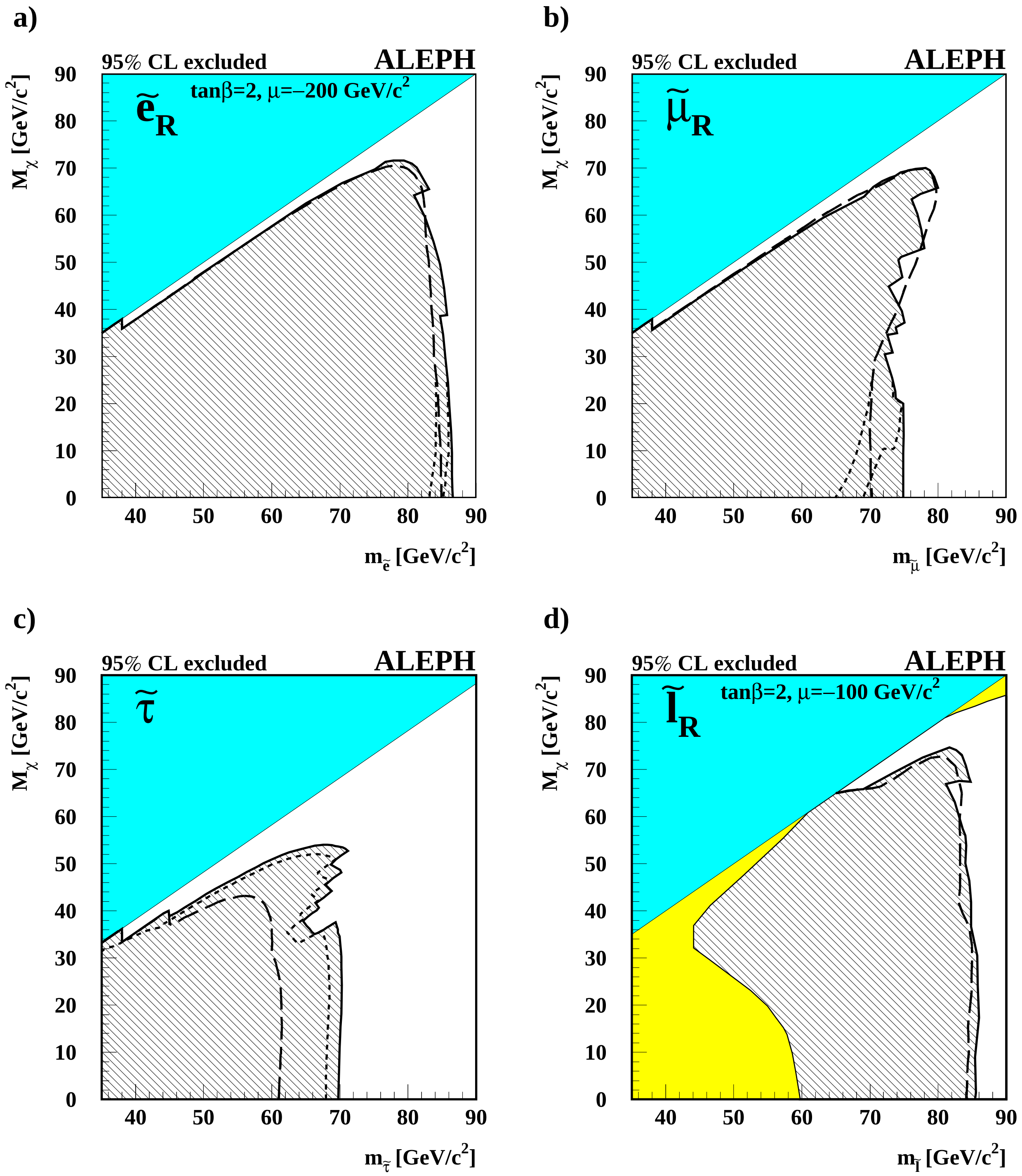

Figure 3: The actual (full line) and expected (long dashed line) mass limit for sleptons in the MSSM assuming BR($\tilde{\ell} \to \ell\chi$) = 100% are given by the full lines. The short dashed curves in plots a) and b) show the effect of cascade decays for $\tan\beta = 2$ and $\mu = -200$ GeV$/c^2$ assuming no efficiency for these decays.
a) $\tilde{e}_R$ mass limit for $\tan\beta = 2$ and $\mu = -200$ GeV$/c^2$.
b) The mass limit for $\tilde{\mu}_R$.
c) The $\tilde{\tau}_R$ mass limit and the limit for a mixed state $\tilde{\tau}_1$ decoupling from the Z (short dashed line).
d) The mass limits for sleptons assuming a common scalar mass at the GUT scale and $\tan\beta = 2$ and $\mu = -100$ GeV$/c^2$. The light shaded region is theoretically inaccessible.

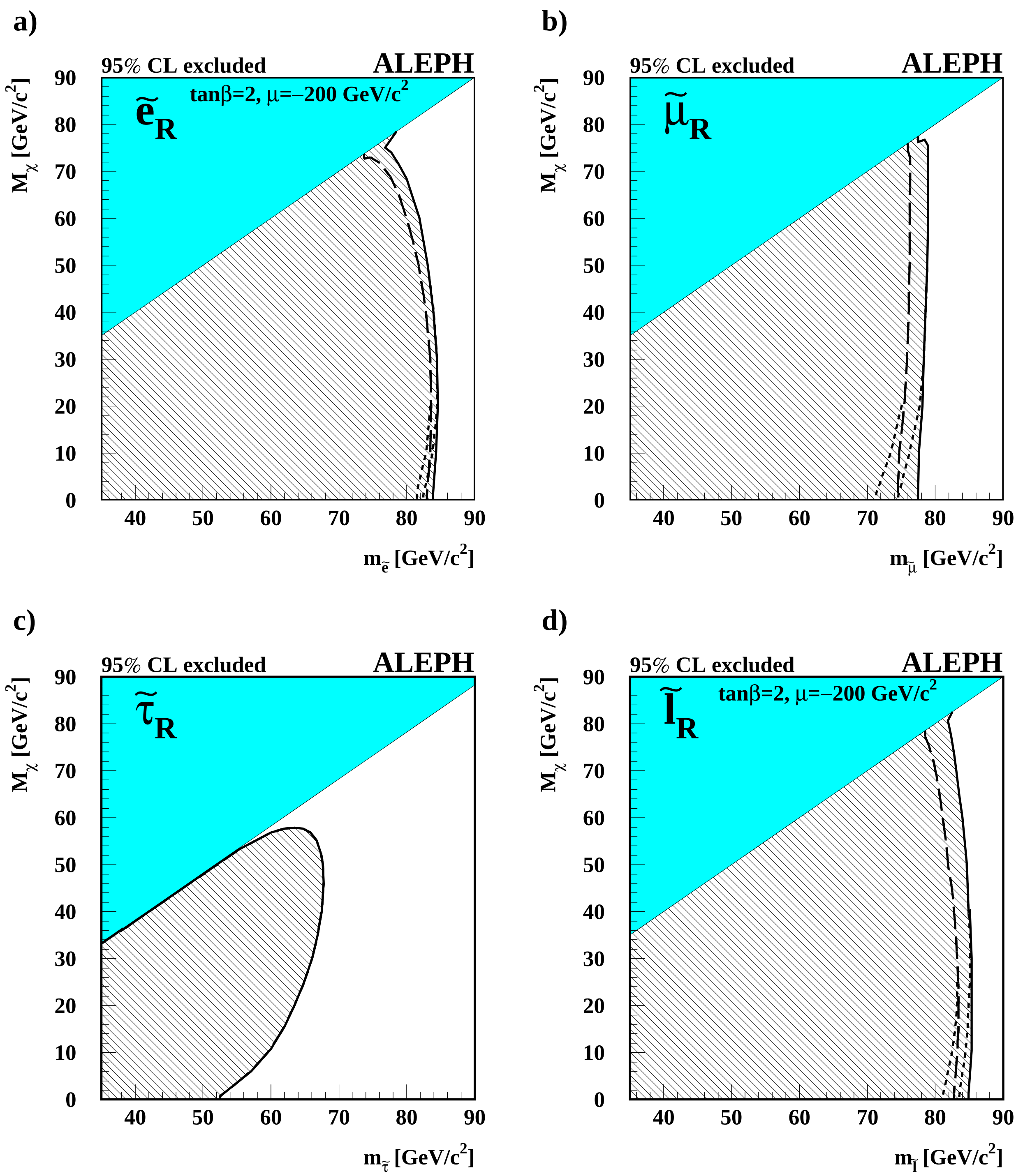

Figure 4: The actual (full line) and expected (long dashed line) mass limits for right–handed sleptons in GMSB models with neutralino NLSP assuming BR($\tilde{\ell} \to \ell\chi$) = 100% are given by the full lines. The short dashed curves show the effect of cascade decays for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2 assuming no efficiency for these decays.
a) The $\tilde{e}_R$ mass limit for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2.
b) The mass limit for $\tilde{\mu}_R$.
c) The curve gives the $\tilde{\tau}_R$ mass limit.
d) The limit for degenerate sleptons.

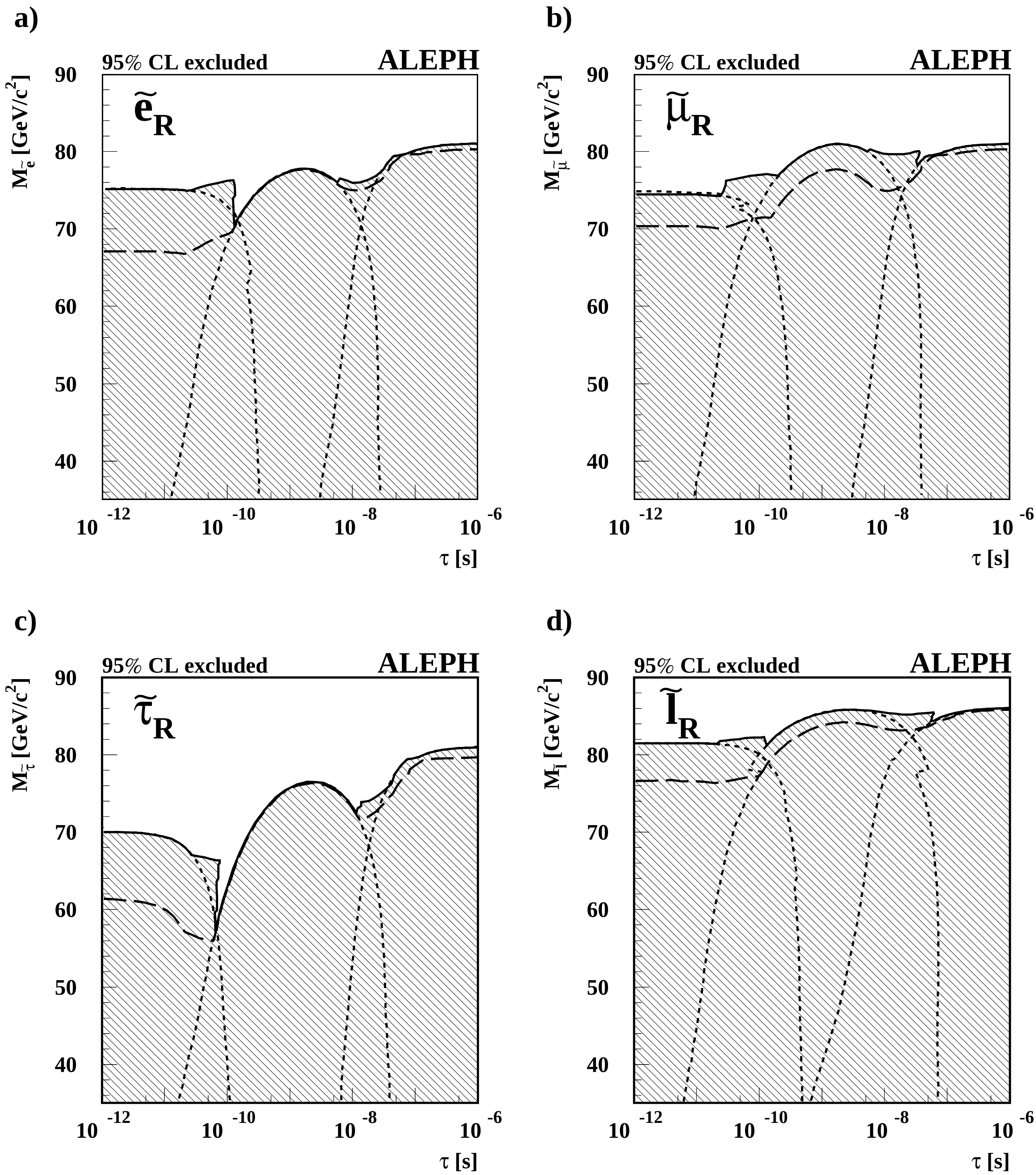

Figure 5: The actual (full line) and expected (long dashed line) mass limits for right–handed sleptons in GMSB models with slepton NLSP as a function of their lifetime. The short dashed lines indicate the excluded region by the acoplanar lepton search, the search for tracks with large impact parameter and kinks and by the search for stable sleptons.
a) The $\tilde{e}_R$ mass limit, assuming only the s channel contribution.
b) The mass limit for $\tilde{\mu}_R$.
c) The $\tilde{\tau}_R$ mass limit.
d) The limit for degenerate sleptons.

References

[1] ALEPH Collaboration, *Search for sleptons in* e^+e^- *collisions at centre–of–mass energies of 161 GeV and 172 GeV.* Phys. Lett. **B 407** (1997) 377.

[2] ALEPH Collaboration, *Search for pair–production of long–lived heavy charged particles in* e^+e^- *annihilation.* Phys. Lett. **B 405** (1997) 379.

[3] For a compilation of review articles, see: Ed. M. Jacob, *Supersymmetry and Supergravity.* North-Holland and World Scientific, 1986.

[4] J. Ellis *et al.*, *Supersymmetric relics from the big bang.* Nucl. Phys. **B 238** (1984) 453.

[5] For a review see: G.F. Giudice and R. Rattazzi, *Theories with Gauge–Mediated Supersymmetry Breaking.* CERN TH/97–380 (hep–ph/9801271), to appear in *Physics Reports.*

[6] K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, *Aspects of grand unified models with softly broken supersymmetry.* Prog. Theor. Phys. **68** (1982) 927;
K. Inoue, A. Kakuto, H. Komatsu and S. Takeshita, *Renormalization of supersymmetry breaking parameters revisited.* Prog. Theor. Phys. **71** (1984) 413.

[7] A. Bartl, H. Fraas and W. Majerotto, *Gaugino–Higgsino mixing in selectron and sneutrino pair production.* Z. Phys. **C 34** (1987) 411.

[8] ALEPH Collaboration, *ALEPH: A detector for electron–positron annihilations at LEP.* Nucl. Inst. Meth. **A 294** (1990) 121.

[9] ALEPH Collaboration, *Performance of the ALEPH detector at LEP.* Nucl. Inst. Meth. **A 360** (1995) 481.

[10] J.-F. Grivaz and F. Le Diberder, *Complementary analyses and acceptance optimization in new particles searches.* LAL preprint # 92–37 (1992);
ALEPH Collaboration, *Search for the standard model Higgs boson.* Phys. Lett. **B 313** (1993) 299.

[11] The Particle Data Group, *Review of Particle Physics.* Phys. Rev. **D 54** (1996).

[12] ALEPH Collaboration, *Searches for supersymmetry in the photon(s) plus missing energy channels at* $\sqrt{s}$ *= 161 GeV and 172 GeV.* CERN PPE/97–122;
ALEPH Collaboration, *A study of single– and multi–photon production in* e^+e^- *collisions at a centre–of–mass energy of 183 GeV.* CERN EP/98–053.

[13] ALEPH Collaboration, *Search for excited neutrinos in Z decay.* Phys. Lett. **B 250** (1990) 172.