

SEARCH FOR SUPERSYMMETRY, EXTRA DIMENSIONS AND EXOTIC PHENOMENA AT LEP

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Abstract

The latest results on searches for supersymmetry, extra dimensions and exotic phenomena from the LEP collaborations are presented. No significant signal-like excess is observed in the data. The results are interpreted in various models and robust constraints are placed.

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1 Introduction

The Standard Model (SM) accurately describes the observed phenomena but leaves several fundamental questions unanswered. Many extensions of the SM have been developed to solve these puzzles. The LEP collider with its multi-purpose detectors ALEPH, DELPHI, L3 and OPAL provided an excellent environment to explore possibilities beyond the SM both through direct searches for new processes and through precise measurements of electroweak (EW) parameters. Since 1996 when the centre-of-mass energy first reached the WW production threshold, 700 pb^{-1} of data per experiment were collected at $\sqrt{s} = 161 - 210 \text{ GeV}$, of which 130 pb^{-1} were recorded at $\sqrt{s} > 206 \text{ GeV}$.

In the following the latest LEP results are summarised on the various flavours of supersymmetric models, theories with extra dimensions and a few selected topics from the rich field of exotic phenomena. For each model the phenomenological framework, the search strategy and the achieved results (constraints at the 95% confidence level) are briefly discussed.

In most cases the experiments provide limits on the production cross-section of the studied processes with minimal model assumptions, which are then interpreted within the framework of a given model to derive constraints on the model parameters, particle masses. Where available, the combined results of the four LEP experiments, labelled by ADLO, are presented.

2 Supersymmetry

Supersymmetry (SUSY) is a particularly promising extension of the SM being theoretically well-motivated and also very successful from the phenomenological point of view.

For each SM particle chirality state SUSY predicts a superpartner differing in spin by half a unit. If SUSY were an exact symmetry the particles and their superpartners would be degenerate in mass, thus SUSY must be broken. Traditionally two theoretical scenarios are examined¹: gravity-mediated and gauge-mediated SUSY breaking. Both mechanisms assume that SUSY is broken in a *hidden* sector and SUSY breaking is transmitted from there to the *visible* sector where the SM and SUSY particles (sparticles) live. In models with gravity mediated SUSY breaking (supergravity) the visible and hidden sectors are coupled via gravitational interaction, while in models with gauge mediated SUSY breaking (GMSB) the hidden

¹Recently a third scenario, anomaly-mediation, also gains popularity.

sector couples to a *messenger* sector which in turn couples to the visible sector via gauge interactions.

SUSY fields can mix, thus the interaction eigenstates can differ from the mass eigenstates. The mixing of left- and right-handed scalar fermions (L-, R-fermions, \tilde{f}_L, \tilde{f}_R) is proportional to the corresponding fermion mass and is negligible for the first two generations. The fermionic partners of the weakly interacting gauge and Higgs² bosons form six mass eigenstates: the charged higgsino and wino states give two charginos ($\tilde{\chi}_i^\pm$), and the neutral bino, wino and higgsino states give four neutralinos ($\tilde{\chi}_j^0$), where the indices i, j are ordered by increasing mass. The fermionic partners of the strongly interacting gluons called gluinos (\tilde{g}) do not mix with other states.

2.1 Supergravity

In the most general case, MSSM has more than a hundred parameters in addition to the SM ones. They include the couplings in the superpotential and the masses and couplings in the soft SUSY breaking terms.

In a constrained framework of MSSM (CMSSM), also called minimal supergravity, the soft SUSY breaking parameters take a simple form at the Planck scale: the scalar squared masses and the scalar couplings are flavour diagonal and universal. Taking also the more general prediction of the unification of gaugino masses, the number of parameters in the soft SUSY breaking term can be reduced to four: the common scalar mass (m_0), scalar trilinear coupling (A_0), gaugino mass ($m_{1/2}$) and the bilinear coupling of Higgs fields (B_0). B_0 can be exchanged to the ratio of the vacuum expectation values (v.e.v.'s) of the Higgs fields ($\tan\beta$) and $m_{1/2}$ to the SU(2) gaugino mass parameter at the EW scale (M_2).³ The mass parameters should not exceed $\mathcal{O}(\text{TeV})$ so that SUSY remains a solution to the naturalness problem.

In addition to the coupling μ of the Higgs fields, the superpotential can also contain R -parity violating couplings $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ and μ'_i , where i, j, k are generation indices. R -parity is a multiplicative quantum number which takes the value of +1 for SM particles and -1 for their superpartners. If R -parity is conserved the constrained model can be described by only five extra parameters.

²The Higgs sector of the SM needs to be expanded to accommodate SUSY; in the Minimal Supersymmetric extension of the SM (MSSM) two complex scalar Higgs doublets are required leading to five Higgs bosons (h, H, A, H[±]).

³The assumption of gaugino mass unification at the GUT scale leads to $M_1 = 5/3 \tan^2\theta_W M_2$ for the U(1) gaugino mass parameter.

2.1.1 *R-parity conserving MSSM*

The assumption of *R*-parity conservation has a crucial impact on supersymmetric phenomenology. It implies that sparticles are always produced in pairs and decay through cascade processes to SM particles and to the lightest supersymmetric particle (LSP), which is stable. If the LSP is neutral and weakly interacting, as favoured by cosmological considerations, it escapes detection, resulting in sizable missing energy.

All sparticles are expected to be pair-produced at LEP via *s*-channel γ or *Z* exchange. For third generation sfermions the production cross-section depends on the mixing between the left- and right-handed fields. $\tilde{e}, \tilde{\nu}_e, \tilde{\chi}_1^\pm$ and $\tilde{\chi}_i^0$ pair-production has *t*-channel contribution, as well, and their cross-section strongly depends on the model parameters.

SUSY phenomenology is largely determined by the nature of the LSP and the next-to-LSP (NLSP). The LSP is usually considered to be the lightest neutralino (or the sneutrino). Accordingly, the following processes are searched for:

- **Chargino:** $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (\tilde{\chi}_1^0 \tilde{f}\tilde{f}') (\tilde{\chi}_1^0 \tilde{f}\tilde{f}')$ with $\tilde{\chi}_1^\pm$ decaying via $\tilde{\chi}_1^0 W^\pm$ or $\tilde{f}\tilde{f}'$;
 $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\nu} \ell^+ \tilde{\nu} \ell^-$;
- **Neutralino:** $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 (\tilde{\chi}_1^0 \tilde{f}\tilde{f})$ and $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow (\tilde{\chi}_1^0 \tilde{f}\tilde{f}) (\tilde{\chi}_1^0 \tilde{f}\tilde{f})$ with $\tilde{\chi}_2^0$ decaying via $\tilde{\chi}_1^0 Z, \tilde{\chi}_1^0 h/A$ or $\tilde{f}\tilde{f}$;
- **Sleptons:** $\tilde{\ell}^+ \tilde{\ell}^- \rightarrow (\tilde{\chi}_1^0 \ell^+) (\tilde{\chi}_1^0 \ell^-)$;
- **Light squarks and sbottom:** $\tilde{q}\tilde{q} \rightarrow (\tilde{\chi}_1^0 q) (\tilde{\chi}_1^0 \bar{q})$;
- **Stop:** $\tilde{t}_1 \tilde{t}_1 \rightarrow (\tilde{\chi}_1^0 q) (\tilde{\chi}_1^0 \bar{q})$ via loop diagram with $q=c,u$;
 $\tilde{t}_1 \tilde{t}_1 \rightarrow (\tilde{\chi}_1^+ b) (\tilde{\chi}_1^- \bar{b}) \rightarrow (\tilde{\nu} \ell^+ b) (\tilde{\nu} \ell^- \bar{b})$.

The chargino production cross-section is large except if $\tilde{\nu}_e$ is light and the destructive interference between *s*- and *t*-channel processes becomes important. In this case the search for neutralino production improves our sensitivity for SUSY. If sfermions are heavy ($m_0 > 500$ GeV), $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay dominantly via a *W* and a *Z* boson, respectively.

The event properties depend significantly on the mass difference (ΔM) between the pair-produced sparticle and the LSP. In the chargino search, for example, the case of $200 \text{ MeV} < \Delta M < 3 \text{ GeV}$ is treated separately using a dedicated analysis of events with initial state radiation, and for $\Delta M < 200 \text{ MeV}$ events with tracks displaying kinks or impact parameter offsets and events with heavy stable charged particles are studied. In CMSSM low ΔM is expected in the Higgsino

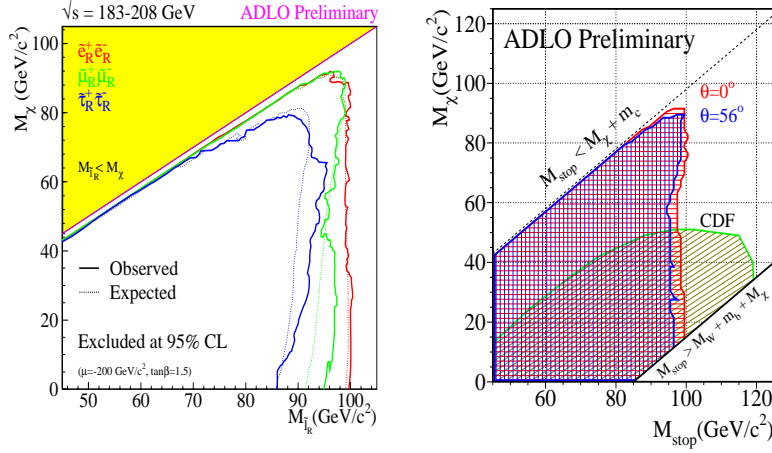


Figure 1: (left) Expected and observed exclusion domains in the $\tilde{\ell}_R - \tilde{\chi}_1^0$ mass plane taking into account the $\tilde{\ell}_R \rightarrow \tilde{\ell} \tilde{\chi}_1^0$ branching ratio. (middle) Excluded domains in the $\tilde{t}_1 - \tilde{\chi}_1^0$ mass plane for no mixing and for the mixing angle giving the smallest cross-section. (right) Excluded domains in the $\tilde{q} - \tilde{g}$ mass plane assuming five degenerate \tilde{q} flavours.

region ($|\mu| \ll M_2$); a lower limit on the chargino mass of 92.4 GeV is obtained independent of ΔM by the ADLO combination ^{1, 2}).

The cross-section for $\tilde{\ell}_R$ is smaller than for $\tilde{\ell}_L$, therefore $\tilde{\ell}_L$ is usually assumed to be out of the reach for the experiments and results for $\tilde{\ell}_R$ are given. For staus mixing may be sizable: the mass limits ³) shown on fig.1 worsen by a few GeV when the Z boson is decoupled ($\theta_{\tilde{\tau}} = 52^\circ$).

Using the standard searches for chargino and slepton production, and developing dedicated analyses for $\tilde{e}_L^+ \tilde{e}_R^-$ to cover the small ΔM region and for $\tilde{\chi}_1^0 \tilde{\chi}_3^0$ in the so-called *corridor* where the chargino and the sneutrino are degenerate in mass, the ALEPH collaboration set absolute lower limits on the \tilde{e}_R, \tilde{e}_L and $\tilde{\nu}_e$ masses ⁴) of 73, 107 and 84 GeV, respectively, assuming sfermion and gaugino mass unification and no sfermion mixing. Including the constraints from neutral Higgs boson searches, the results on the selectron masses can be improved to 77 and 115 GeV for a top mass of 175 GeV. Within CMSSM for $A_0 = 0$ the obtained bounds are 95, 152 and 130 GeV, respectively.

If kinematically allowed, the $\tilde{t}_1 \rightarrow \tilde{\nu} \ell^+ b$ decay mode is dominant over $\tilde{\chi}_1^0 c$. The combined LEP results ⁵) exclude stop and sbottom masses up to 94–100 GeV for $\Delta M > 10$ GeV depending on the search channel and the mixing angle. If charginos and sleptons are light, four-body stop decays $\tilde{t}_1 \tilde{t}_1 \rightarrow (\tilde{\chi}_1^+ b) (\tilde{\chi}_1^- \bar{b}) \rightarrow (\tilde{\chi}_1^0 f \bar{f} b) (\tilde{\chi}_1^0 \bar{f} f \bar{b})$ can be enhanced, leading to less stringent limits on the stop mass ⁶) than those on fig.1.

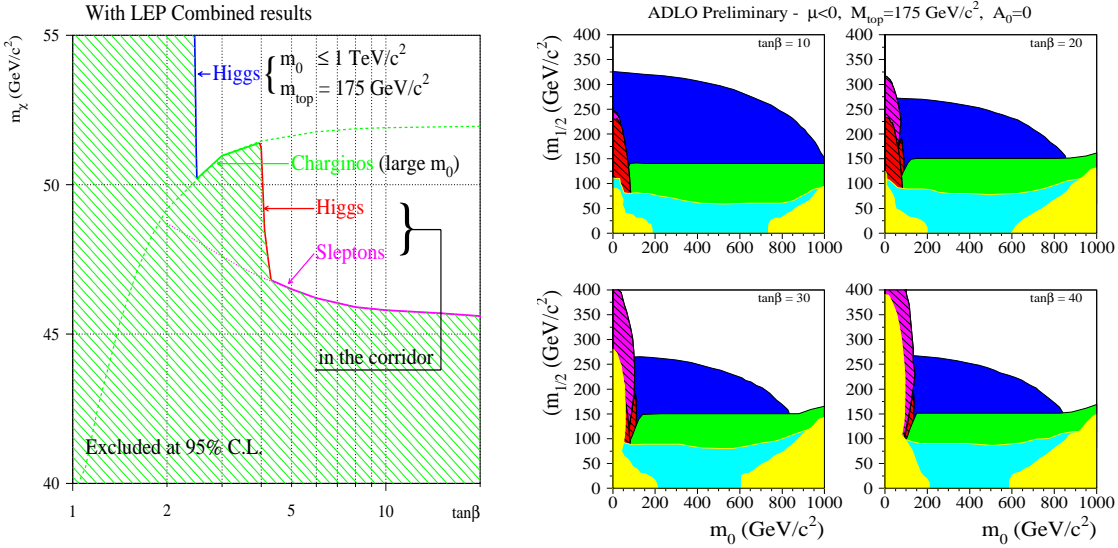


Figure 2: (left) Lower limit on the $\tilde{\chi}_1^0$ LSP mass. The results at low $\tan\beta$ depend strongly on the top mass via the Higgs constraint. The theoretical uncertainty is $\mathcal{O}(1 \text{ GeV})$ due to the use of tree level gaugino masses and lowest order relations for gaugino unification. (right) Excluded regions in CMSSM in the $m_0 - m_{1/2}$ plane by no CMSSM solution (yellow), constraints from LEP1 (light blue), chargino (green), standard slepton (red), standard hZ (dark blue), neutralino stau cascade (brown), heavy stable stau (magenta) searches.

ALEPH performed a search for stop production with small ΔM looking for charged particle tracks with significant lifetime. The obtained absolute mass limit is 63 GeV independent of the values of $\Delta M, \mu$ and $\tan\beta$ explored in the scan ⁶).

The searches for acoplanar jets can be translated into constraints shown in fig.1 on mass degenerate squarks (left- and right-handed $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}$) within the MSSM with lowest order GUT relations between the soft SUSY-breaking gaugino mass terms ⁵).

When combining the negative results of chargino, neutralino, slepton and Higgs boson searches, limits on the $\tilde{\chi}_1^0$ LSP mass can be obtained as shown in fig.2 assuming gaugino and sfermion mass unification at the GUT scale and negligible mixing in the stau sector ⁷). Stau mixing may lead to scenarios with mass degenerate stau and LSP and weaken the derived $\tilde{\chi}$ limits at large $\tan\beta$. Dedicated searches for $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu$ and $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau$ cover this region.

Within CMSSM, using also the constraints from the measurement of the Z width and the searches for heavy stable stau production, the obtained bounds on the parameters, see fig.2, can be translated into 52.0–59.0 GeV lower limits on the LSP mass ⁸) depending on sign μ and the top mass for $A_0 = 0$ and $m_0 < 1 \text{ TeV}$.

2.1.2 R -parity violating MSSM

There are no theoretical or experimental arguments excluding R -parity violation (RPV), moreover, the branching ratios of R -parity violating decay modes of sparticles can be comparable or even larger than the R -parity conserving ones. If R -parity is violated, sparticles can be singly produced and can decay directly to SM particles. Therefore, the predicted signatures differ from the characteristic missing energy signature of R -parity conserving processes.

With the MSSM particle content, R -parity violating interactions are described with a gauge-invariant superpotential that includes the following Yukawa terms⁴:

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k,$$

where L and Q are lepton and quark left-handed doublet superfields, \bar{E} , \bar{D} and \bar{U} are right-handed singlet charge-conjugate superfields for the charged leptons, down- and up-type quarks, respectively, and i, j, k are the generation indices of the superfields. λ_{ijk} is non-vanishing only if $i < j$, and λ''_{ijk} is non-vanishing only for $j < k$, therefore there are a total of 45 R -parity violating Yukawa couplings.

It is usually assumed that the sparticles are pair-produced via R -parity conserving processes described in sec.2.1.1. Two different scenarios are then probed. In the first scenario, called indirect decays, the decays of sfermions via the lightest neutralino, $\tilde{\chi}_1^0$, are considered, where $\tilde{\chi}_1^0$ is treated as the LSP and assumed to decay via an R -parity violating Yukawa coupling. In the second scenario, direct decays of sparticles to SM particles are investigated. In this case, the sparticle is assumed to be the LSP, such that R -parity conserving decay modes do not contribute. In both scenarios, it is assumed that only one of the 45 Yukawa couplings is non-zero at a time, motivated by constraints from low energy experiments. It is also assumed that the LSP decays promptly, implying a very short lifetime, and therefore a mass larger than 10 GeV for the lightest neutralino.

The topologies resulting from RPV decays of pair-produced sparticles are numerous and extremely varied: direct decays of sfermions lead to 4-fermion, direct decays of charginos and neutralinos to 6-fermion, indirect decays of sfermions to 8-fermion and finally indirect decays of charginos to 10-fermion final states with almost any combination of species and flavours of final state particles.

The first LEP combined results⁹⁾ are shown in fig.3 for indirect decays of sleptons via λ couplings. In general the limits for λ' and λ'' couplings¹⁰⁾ are less

⁴ R -parity could be spontaneously broken through a $\tilde{\nu}$ acquiring a non-zero v.e.v. This can be described by a bilinear term $\mu'_i L_i H_2$.

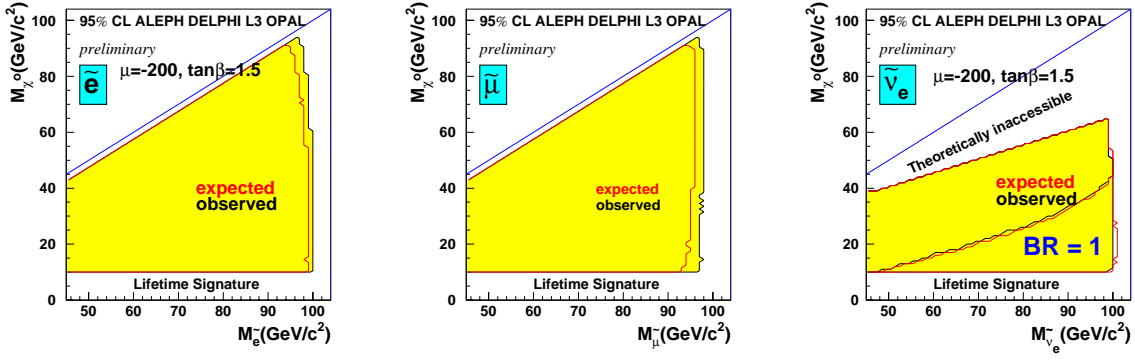


Figure 3: Excluded regions in the $\tilde{\ell}(\tilde{\nu}) - \tilde{\chi}_1^0$ mass plane from searches for indirect slepton decays via a λ coupling in RPV CMSSM.

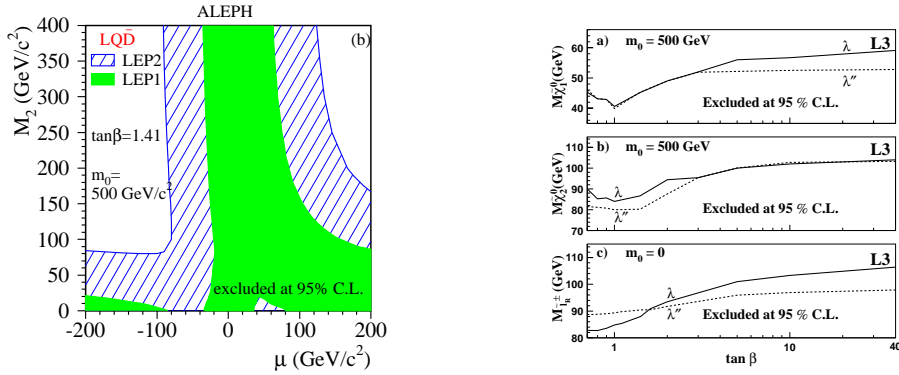


Figure 4: (left) Excluded regions in the $\mu - M_2$ plane from searches for gaugino decays via λ' coupling in RPV CMSSM. (right) Absolute lower limits on the sparticle masses for $0 \leq M_2 \leq 1$ TeV and -0.5 TeV $\leq \mu \leq 0.5$ TeV. The indicated values of m_0 correspond to the global minima on the mass limit.

stringent due to the presence of more final state quark jets.

The results of the chargino and neutralino searches are used to constrain the $\mu - M_2$ plane for a given m_0 and $\tan \beta$ as shown in fig.4. When combining all RPV searches absolute lower limits are also derived on the sparticle masses from a scan of the CMSSM parameter space.

By studying single $\tilde{\nu}$ production in the $e\gamma \rightarrow \tilde{\nu}\ell$ process the ALEPH collaboration set upper limits on λ_{1jk} couplings assuming that the sneutrinos are degenerate in mass. These results improve existing limits from charged current universality for masses $M_{\tilde{\nu}} < 190$ GeV ¹¹⁾. From the search for resonant $\tilde{\nu}$ production ¹²⁾ the DELPHI collaboration derived limits on λ_{1j1} couplings most stringent (few times 10^{-3}) for $\tilde{\nu}$ masses close to the LEP centre-of-mass energies.

2.2 GMSB

In the minimal version of GMSB, six new parameters are introduced in addition to the SM parameters: the SUSY breaking scale (\sqrt{F}), the messenger scale (M), the messenger index giving the number of messenger particle sets (N), the mass scale which determines the SUSY particle masses at the messenger scale (Λ), the ratio of the v.e.v.'s of the two Higgs doublets ($\tan\beta$) and the sign of the Higgs sector mixing parameter ($\text{sign}\mu$).

In GMSB, the SUSY partner of the graviton, the gravitino (\tilde{G}), is expected to be the LSP with a mass, typically less than 1 GeV, determined by \sqrt{F} . The NLSP is either the lightest neutralino or a slepton. In the latter case two possibilities are considered: a stau NLSP or slepton co-NLSPs when all sleptons are light and degenerate in mass. The experimental signatures crucially depend on the NLSP decay length which can take basically any value.

In the neutralino NLSP scenario neutralinos are either produced in pairs directly or indirectly via slepton ($\tilde{\ell}^+\tilde{\ell}^- \rightarrow \tilde{\chi}_1^0\ell^+ \tilde{\chi}_1^0\ell^-$) and chargino ($\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0W^{+*} \tilde{\chi}_1^0W^{-*}$) pair-production or neutralino cascade decay ($\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0Z^*$), if the corresponding sparticles are light. The lightest neutralino will decay into a gravitino and a photon, giving topologies with photon pairs and missing energy. Depending on its lifetime the photons are either originating from the interaction point or have a large impact parameter. Indirect production of neutralinos plays an important role if the neutralino lifetime is long, and therefore the direct pair-production is invisible. In fig.5 the upper limit on the cross-section of neutralino production is shown for prompt decays, together with the excluded regions on the $\tilde{\chi}_1^0 - \tilde{e}$ mass plane ^{13, 14}). Combining searches for all lifetimes the ALEPH collaboration reports ¹⁵) a neutralino LSP mass limit of 54 GeV.

In the case of slepton NLSP, which is expected to decay into a lepton and a gravitino, the events are characterised by leptons and missing energy. In the slepton co-NLSP case the sleptons are either pair-produced directly, or through chargino ($\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\ell}^+\nu_\ell \tilde{\ell}^-\bar{\nu}_\ell$) and neutralino production ($\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\ell}^\pm\ell^\mp \tilde{\ell}^\pm\ell^\mp$). The picture is slightly different in the stau-NLSP scenario, where stau production can also happen through \tilde{e} or $\tilde{\mu}$ pair-production ($\tilde{\ell}^+\tilde{\ell}^- \rightarrow \tilde{\chi}_1^0\ell^+ \tilde{\chi}_1^0\ell^- \rightarrow \tilde{\tau}^\pm\ell^\mp\ell^+ \tilde{\tau}^\pm\ell^\mp\ell^-$). On fig.5 the excluded regions are shown in the $\tilde{\tau}$ mass - lifetime plane from the searches for slepton pair-production with different lifetimes ¹⁶).

By scanning the GMSB parameter space constraints on the parameters and absolute limits on the sparticle masses can be derived. The excluded regions on the $\Lambda - \tan\beta$ plane ¹⁵) are shown in fig.6 together with the obtained mass limits ¹⁷).

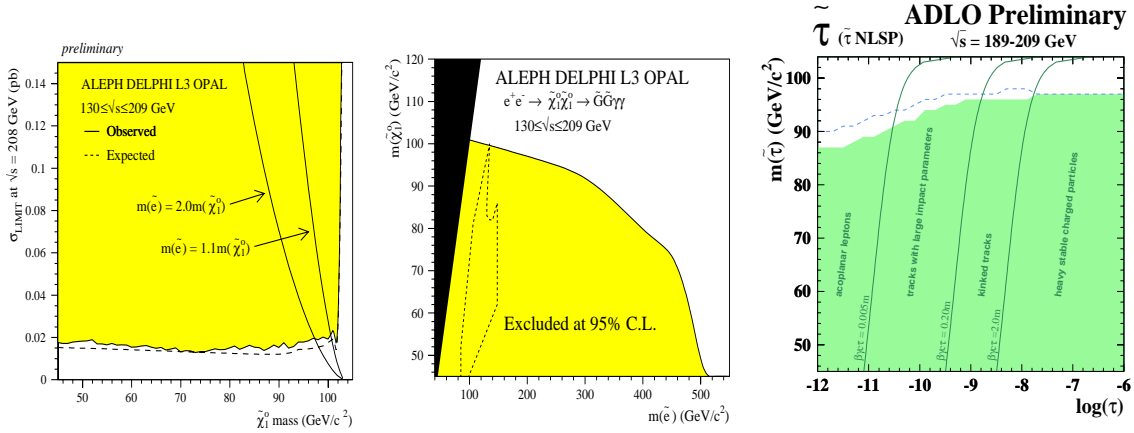


Figure 5: (left) Observed and expected cross-section limits for $\tilde{\chi}^0$ pair-production with theoretical cross-section curves for different \tilde{e} masses in GMSB. (middle) Excluded region overlaid on the area consistent with the CDF $ee\gamma\gamma + \text{missing } E_T$ event. \tilde{e}_L and \tilde{e}_R are assumed to be degenerate in mass and the $\tilde{\chi}_1^0$ is assumed to be pure bino. (right) Observed and expected exclusion regions on the $\tilde{\tau}$ mass - lifetime plane, indicating the corresponding search topologies.

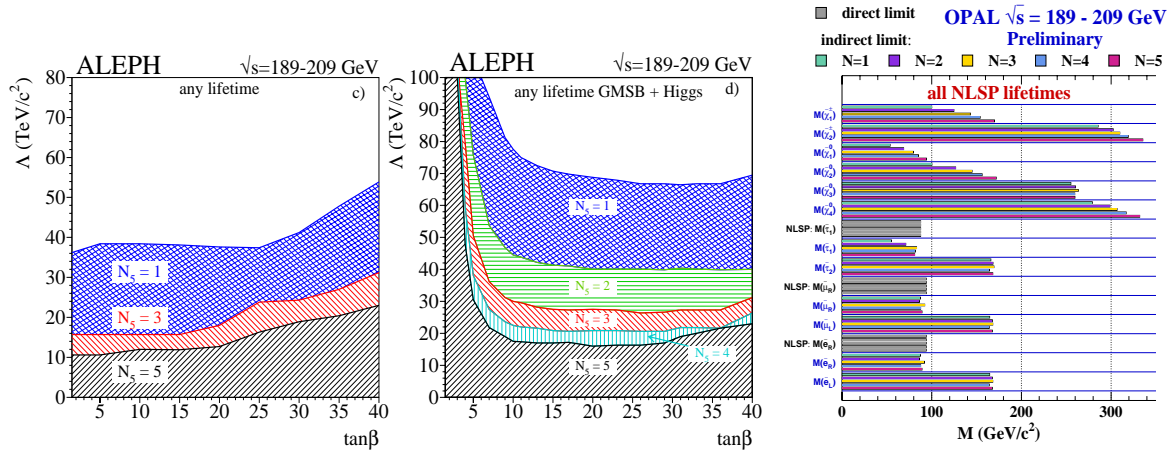


Figure 6: Excluded regions on the $\Lambda - \tan\beta$ plane (left) from GMSB searches and (middle) in combination with Higgs searches. (right) Limits on sparticle masses from GMSB parameter scan.

3 Extra dimensions

Models with extra dimensions have been introduced to solve the hierarchy problem of the SM through geometrical considerations. The original model of Arkani-Hamed–Dimopoulos–Dvali (ADD) of large extra dimensions appeared in 1998 and triggered the development of a vast number of new models.

Most LEP results are derived in the ADD framework, which assumes n compact extra dimensions of size R , with the Planck scale, M_D , in $D = 4 + n$ dimensions set close to the EW scale. SM particles propagate in the usual four, while gravity in D dimensions. The 4-dimensional Planck scale, M_{Planck} , satisfies $M_{\text{Planck}}^2 \sim R^n M_D^{n+2}$.

The Klauza-Klein (KK) excitations of the graviton (G_{KK}) couple to the momentum tensor and contribute to most SM processes. The fermion- and boson-pair cross-sections are modified

$$\sigma = \sigma_{\text{SM}} + \alpha_G \sigma_{\text{int}} + \alpha_G^2 \sigma_{\text{grav}}$$

with $\alpha_G = \frac{2\lambda}{\pi} M_S^{-4}$. λ depends on the details of the model and it is usually set either to $+1$ or -1 to allow for both positive and negative interference. M_S is the ultraviolet cut-off scale close to M_D . The most stringent constraint, $M_S > 1.18/1.17$ TeV for $\lambda = +1/-1$, comes from Bhabha scattering ¹⁸⁾. The combination of the results of the LEP experiments is expected to only slightly improve the limits. The combined result from photon pair-production ¹⁹⁾ gives $M_S > 0.93/1.01$ TeV for $\lambda = +1/-1$, whereas the individual experiments placed lower bounds between 0.80 and 0.96 TeV.

The search for direct graviton production in the process $e^+e^- \rightarrow \gamma G_{\text{KK}}$ or ZG_{KK} is sensitive to the D -dimensional Planck scale itself ¹⁴⁾. The results for different numbers of extra dimensions are shown in fig.7.

4 Exotic phenomena

4.1 Single top production

At LEP single top production can be searched for in several theoretical frameworks, such as flavour changing neutral currents (FCNC), 4-fermion contact interactions or R-parity violating SUSY ²⁰⁾.

In the SM FCNC is forbidden at tree level in good agreement with the observed low rates of such processes, thus all extensions of the SM must face the

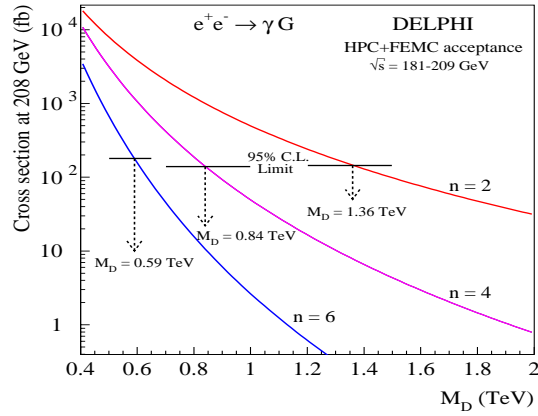


Figure 7: Search for direct graviton production in ADD. Limits on M_D can be turned into constraints on the size of the extra dimensions giving $R < 0.25$ mm, 13 pm, 54 fm for $n=2,4,6$, respectively.

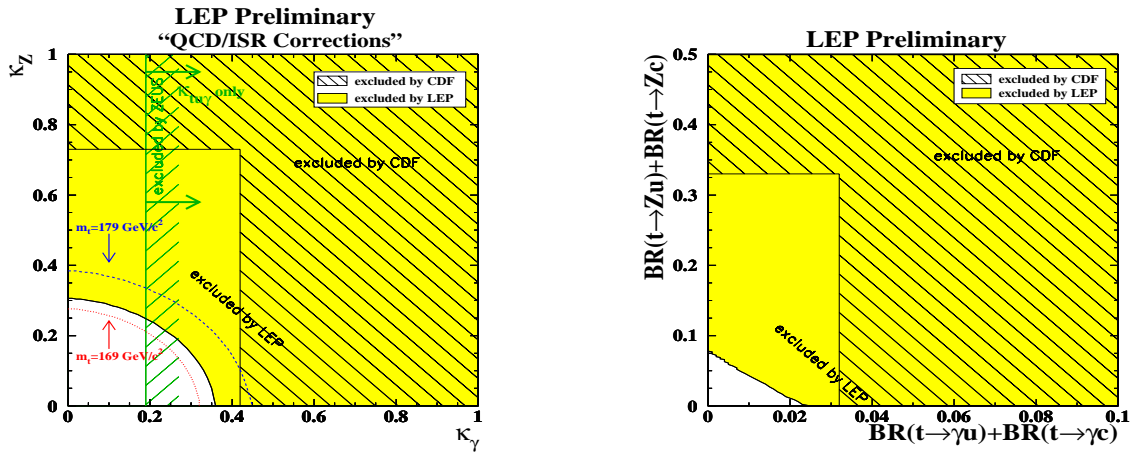


Figure 8: Single top production via FCNC. Excluded regions in the (left) $\kappa_\gamma - \kappa_Z$ and (right) $Br(t \rightarrow \gamma q) - Br(t \rightarrow Z q)$ planes

challenge to sufficiently suppress FCNC. On the other hand FCNC processes are ideal to look for new physics due to the small SM background.

The amplitude of $e^+e^- \rightarrow \bar{t}c(u)$ via FCNC is parametrised in terms of anomalous vertices with strength κ_Z and κ_γ . The top quark decay $\bar{t} \rightarrow \bar{b}W^-$ would then lead to 4-fermion final states of $\bar{b}\ell^-\bar{\nu}_\ell c(u)$ and $\bar{b}q\bar{q}'c(u)$. The combined LEP results²¹⁾ set a strong bound on κ_Z and κ_γ which can also be expressed as branching ratio limits as shown in fig.8.

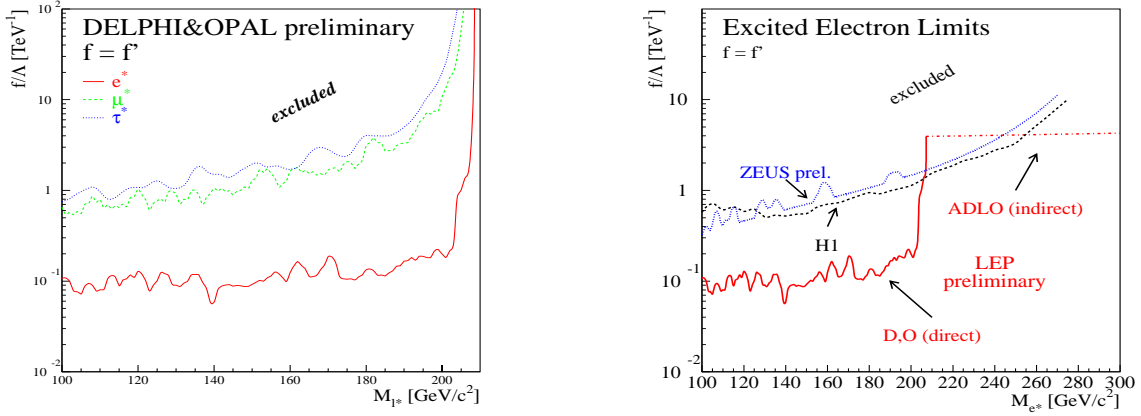


Figure 9: *Exited lepton production. lower bounds on the parameter f/Λ (left) for the three exited lepton flavours from direct and (right) for excited electrons from direct and indirect searches.*

4.2 Exited leptons

Models in which fermions have substructure at a scale Λ attempt to explain the pattern of fermion generations. The existence of excited states of the SM fermions would be natural in such models.

Exited leptons can be produced in pairs or in association with a SM lepton, both proceeding through s -channel γ or Z exchange. There is also a t -channel contribution for the first generation. Exited leptons are expected to decay via the emission of an EW gauge boson (γ , Z or W).

Searches for the pair-production process yield mass limits very close to the kinematic limit. Single production provides a tool to extend the mass reach. The search channels include

- $\nu^*\nu \rightarrow \gamma\nu\nu, W\nu\nu, Z\nu\nu$
- $l^*l \rightarrow \gamma ll, W\nu l, Zll$

leading to widely different event topologies.

In the phenomenological models used at LEP the couplings $Vl^*\ell$ associated to the two gauge groups $SU(2) \times U(1)$ are proportional to the factors f/Λ and f'/Λ , respectively. It is usual to set $|f| = |f'|$ when deriving limits.

For excited electrons, if $f \neq -f'$, the experimental reach can be further increased by measuring the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ which can have a contribution from t -channel e^* production. The latest results of the LEP collaborations ²²⁾ are shown in fig.9.

4.3 Technicolor

Technicolor (TC) solves the naturalness and hierarchy problems of the SM by predicting new strong interactions which break dynamically the EW symmetry without the presence of an elementary Higgs scalar. Simple versions of TC disagree with the observations, thus more and more refined proposals were born. The LEP searches are guided by the Walking Extended TC (Straw Man Model). It predicts TC scalar and vector mesons, π_T and ρ_T , which can be light enough to be observed at LEP.

OPAL looked for the process $\rho_T^0 \rightarrow \pi_T^+ \pi_T^-, \pi_T^0 \gamma$, while DELPHI also considered $\rho_T^0 \rightarrow \pi_T^+ W_L^-, W_L^+ W_L^-$ and $\rho_T^0 \rightarrow q\bar{q}$. Lower limits on the techni-rho mass above 200 GeV have been set ²³⁾.

5 Conclusion

The LEP experiments explored all main areas and many corners for new physics during the last years, but no significant deviation from the SM has been found. In particular, the LEP constraints on SUSY are rather robust for variations of the model. We should therefore continue to look for the signs of a more fundamental theory at the TeV scales beyond LEP reach at the next generation of colliders.

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