HIGGS AND BEYOND STANDARD MODEL SEARCHES AT LEP

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Extensive searches for Higgs bosons and other new phenomena predicted by extensions of the Standard Model have been performed at LEP. A summary is given reviewing the principal aspects and presenting a selection of results.

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1 Introduction

The LEP analyses devoted to searches benefitted from the impressive performance of the accelerator that, during a decade, provided $\mathrm{e^+e^-}$ collisions for an integrated luminosity of $900\,\mathrm{pb}^{-1}$ per experiment at centre-of-mass energies ranging from 88-95 GeV (LEP 1) and 130-209 GeV (LEP 2). Four detectors were operating: ALEPH, DELPHI, L3 and OPAL, all designed for precision physics at the Z peak and beyond, featuring large covering angle, good particle identification for leptons, photons and b quarks, and good jet and energy flow reconstruction. New phenomena could in fact be searched indirectly, via precision measurements, or directly, trying to identify unexpected $\mathrm{e^+e^-}$ events.

Precision measurements show that SM works very well and constraints can be derived to new contributions to the observables. As a general example, the agreement of the measured Z width with the SM prediction excludes new particles with a non negligible coupling to the Z if their masses are smaller than $\sim M_{\mathrm{Z}}/2$.

Direct searches rely on the highest centre-of-mass energy and the large integrated luminosity of the LEP 2 phase. The typical LEP-combined excluded cross section is of the order of $\sim 0.01-0.1\,\mathrm{pb}$ for pair-produced new particles up to masses around half the center-of-mass energy.

Three main streams can be recognized: searches for the Higgs bosons, searches for Supersymmetry (SUSY), and searches for a large variety of other non-SUSY extensions of the SM. The results, based on the full high-energy data sample, are presented in the form of 95% C.L. exclusion domains in the space of the relevant parameters, since no excess has been observed. When available, the LEP SUSY Working Groups combinations, based on the outcomes from all experiments (ADLO), are reported [1–3].

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2 Higgs bosons searches

In the Standard Model (SM), gauge bosons and fermions obtain their masses interacting with the vacuum Higgs fields. Associated with this description is the existence of massive scalar particles, the Higgs bosons, yet to be discovered.

The minimal SM requires one Higgs field doublet and predicts a single neutral Higgs boson, H. Indirect experimental bounds for the SM Higgs boson mass ($m_{\mathrm{H}} = 96^{+60}_{-38}\,\mathrm{GeV}/c^2$, $m_{\mathrm{H}} < 219\,\mathrm{GeV}/c^2$ at the 95% C.L.) are obtained from fits to precision measurements of electroweak observables [4]. The SM Higgs boson can be produced mainly via the Higgs–strahlung process $\mathrm{e^+e^-} \to \mathrm{ZH}$, up to Higgs boson masses below the "kinematic wall", approximately given by $\sqrt{s} + m_{\mathrm{Z}}$. The contribution from the WWH fusion channel, $\mathrm{e^+e^-} \to \mathrm{H}\nu_{\mathrm{e}}\overline{\nu}_{\mathrm{e}}$ and $\mathrm{e^+e^-} \to \mathrm{He^+e^-}$, normally negligible, plays also some role close to the kinematic limit. The main decay channels are $\mathrm{b\overline{b}}$ and $\tau^+\tau^-$ pairs, the latter marginally contributing ($\sim 8\%$).

Given the production mechanism and decays channels, four topologies, corresponding to different final states, have been searched for: the four-jet topology, $\mathrm{e^+e^-} \to (\mathrm{H} \to \mathrm{b\overline{b}})(\mathrm{Z} \to \mathrm{q\overline{q}})$, that occurs with a branching ratio of about 60%; the missing energy topology, $\mathrm{e^+e^-} \to (\mathrm{H} \to \mathrm{b\overline{b}})(\mathrm{Z} \to \nu\overline{\nu})$ that occurs with a branching ratio of about 17%; the leptonic topology, $\mathrm{e^+e^-} \to (\mathrm{H} \to \mathrm{b\overline{b}})(\mathrm{Z} \to \ell^+\ell^-)$ ($\ell = \mathrm{e}, \mu$) whose small branching ratio ($\sim 6\%$) is balanced by the intrinsic low background; the tau topology, $\mathrm{e^+e^-} \to (\mathrm{H} \to \tau^+\tau^-)(\mathrm{Z} \to \mathrm{q\overline{q}})$ or $\mathrm{e^+e^-} \to (\mathrm{H} \to \mathrm{b\overline{b}})(\mathrm{Z} \to \tau^+\tau^-)$, that occur with a branching ratio of about 10% in total. The Higgs boson is reconstructed by tagging the b jets from its decay whereas the remaining particle system is required to be kinematically compatible with a Z decay. All these criteria are often optimally exploited by using neural-network techniques.

By using the likelihood ratio method, a LEP-wide test-statistic $Q(\mathrm{data}|m_{\mathrm{H}})$ is built from the outcomes of these searches by all experiments [1]. For any given m_{H}, it allows the compatibility of the selected events with the signal-plus-background ("s+b") hypothesis or with the background-only ("b") hypothesis to be evaluated. $Q(\mathrm{data}|m_{\mathrm{H}})$ is compared with the expected pdf's of $Q(\mathrm{s+b}, m_{\mathrm{H}})$ and $Q(\mathrm{b}, m_{\mathrm{H}})$ (both computed by using MC simulations) and two probabilities $\mathrm{C}L_{\mathrm{s+b}}$ and $1 - \mathrm{C}L_{\mathrm{b}}$, known as *confidence levels*, are derived. They represent the probabilities that the outcome of a new experiment is more "s+b"-like or "b"-like, respectively, than the outcome represented by the set of selected events.

The LEP combined test-statistic Q as a function of the hypothetical m_{H} is shown in Fig. 1(a), in the more convenient and normally used form of $-2\ln Q$ that can be simply written as a sum of observed event weights. The negative broad minimum crossing the "s+b" expected curve at $m_{\mathrm{H}} \sim 115\,\mathrm{GeV}/c^2$ favours the signal hypothesis for an Higgs boson mass around that value. The significance is limited to 2.3σ overall, but, as the expected curves indicate, it is compatible with the sensitivity achievable for that mass range. The "b" confidence level, visible in Fig. 1(b), is 8%, with a corresponding "s+b" confidence level of 37%. This excess concentrates into the ALEPH data set at the level of 2.8σ and it is mainly due to four-jet candidates with clean b tags and kinematic properties [5]. It is not confirmed neither excluded from the other experiments but has been demonstrated to be robust and stable [6]. However, since no unambiguous signal has been observed, a lower limit on the SM Higgs boson mass of $114.4\,\mathrm{GeV}/c^2$ has been set, slightly below the expected value ($115.3\,\mathrm{GeV}/c^2$).

Except simplicity there is no a priori reason justifying the presence of only one Higgs doublet in the SM. The two-Higgs-doublet models (2HDM) represent the simplest extensions of the SM

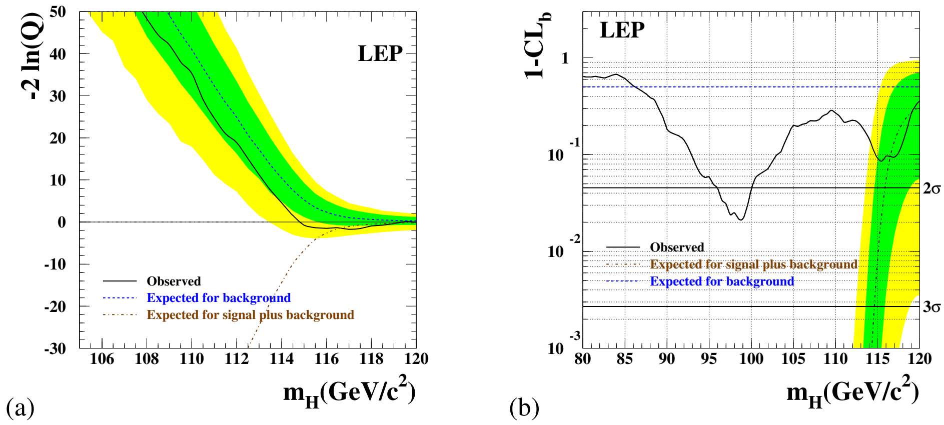

Fig. 1. (a) The test-statistic as a function of m_{H}. The dashed line represents the expectation in the "b" only hypothesis with the 1σ and 2σ probability bands; the solid line is the observed results, whereas the dotted line is the median result expected in presence of a $m_{\mathrm{H}} = 115\,\mathrm{GeV}/c^2$ signal. (b) $1 - \mathrm{CL}_{\mathrm{b}}$ as a function of m_{H}; the line at 0.5 is median result in the absence of a signal, the solid curve is observed result and the dashed curve is median result expected for a signal.

Higgs sector. LEP searches have also addressed their phenomenology [1].

In the context of a general 2HDM, the Higgs sector comprises five physical Higgs bosons: two neutral CP-even scalars, h^0 and H^0 (with $m_{\mathrm{h}^0} < m_{\mathrm{H}^0}$), one CP-odd scalar, A^0, and two charged scalars, $\mathrm{H}^{\pm}$. Their masses are free parameters and the choice of the couplings between the Higgs bosons and the fermions determines the type of the 2HDM model: in the Type-I models the quarks and leptons only couple to the second Higgs doublet; in the Type-II models the first Higgs doublet couples only to down-type fermions and the second Higgs doublet couples only to up-type fermions.

The h^0 and A^0 bosons are expected to be predominantly produced via the Higgs-strahlung, $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{Zh}^0$ and ZH^0, and the associated production, $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{h}^0\mathrm{A}^0$ and $\mathrm{H}^0\mathrm{A}^0$. The decay properties of the Higgs bosons, while quantitatively different depending on models and their parameters, maintain a certain similarity with the SM case: $\mathrm{b\bar{b}}$ and $\tau^+\tau^-$ are the relevant decays channels but only if the cascade decays (i.e. $\mathrm{h}^0 \rightarrow \mathrm{A}^0\mathrm{A}^0$) are not kinematically allowed and dominant. These similarities very often allow the SM Higgs boson searches to be used for 2HDM Higgs bosons. Nevertheless special situations may occur for which specific analyses need to be developed: searches for $\mathrm{h}^0\mathrm{Z}$ and $\mathrm{h}^0\mathrm{A}^0$ independently on the flavour of the decay channel [1], and searches for $\mathrm{h}^0\mathrm{Z}$ independently on the decay channel [7] are just two examples.

The most important implementation of a 2HDM model, Type II, is the Minimal Supersymmetric Model or MSSM (see Sec. 3). Due to its importance, the MSSM is used to challenge the LEP capability to detect 2HDM Higgs bosons by interpreting the search results within special MSSM benchmark scenarios. The "m_{h^0}-max" scenario, designed to maximise the theoretical m_{h^0} upper bound, provides a wider parameter space and therefore more conservative exclusion

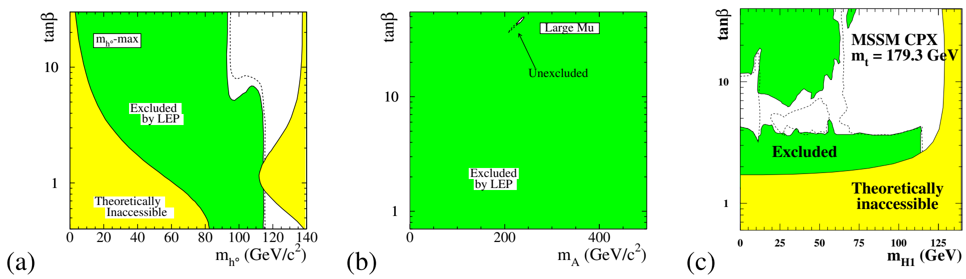

Fig. 2. The MSSM exclusions for various benchmarks: (a) the m_{h^0}-max scenario in the $(m_{h^0}, \tan\beta)$ projection, with $m_t = 179.3\,\mathrm{GeV}/c^2$.; (b) the large-$\mu$ scenario in the $(m_{A^0}, \tan\beta)$ projection; (c) the CP-violating CPX scenario, for $m_t = 179.3\,\mathrm{GeV}/c^2$, in the $(m_{H_1}, \tan\beta)$ projection. The dashed lines indicate the boundaries of the expected exclusions.

limits, as shown in Fig. 2(a). In the "large-μ" scenario the lightest Higgs boson is everywhere kinematically accessible but its detection is expected to be difficult since the $b\bar{b}$ decay mode, on which most of the searches rely, is strongly suppressed; nevertheless, thanks to the flavour independent searches, this scenario is almost entirely excluded, as visible in Fig. 2(b).

All these scenarios are CP-conserving (CPC). In general, however, the neutral Higgs bosons h^0, A^0 and H^0 can mix into three states H_1, H_2, H_3 with not defined CP quantum numbers giving rise to CP-violating models (CPV) that are also studied. Their phenomenology remain similar either for production ($e^+e^- \rightarrow H_iZ$, $e^+e^- \rightarrow H_iH_j$, $i, j = 1, 2, 3$, $i \neq j$) and decay ($b\bar{b}$, $\tau^+\tau^-$ and cascades $H_j \rightarrow H_iH_i$, $j > i$). A benchmark model, know as "CPX", has been chosen to maximise the phenomenological differences with respect to the CP-conserving scenarios. A CPX exclusion example is shown in Fig. 2(c).

General models can also yield to other interesting Higgs boson signals that not necessarily are contemplated into the considered MSSM scenarios: few examples are given here [1]. The "invisible" Higgs boson decays into an undetectable final state, as a neutralino pair. The selections designed to address its strahlung production rely on the visible recoil system from the Z decay and allow mass limits of the order of $\gtrsim 110\,\mathrm{GeV}/c^2$ to be set, assuming a SM like production cross section. Within the MSSM, charged Higgs bosons $H^\pm$ are normally heavier than other Higgs bosons; nevertheless specific selections exist by which mass limits of the order of $\sim 77 - 78\,\mathrm{GeV}/c^2$ are set for all possible decay channels. A Higgs boson that does not couple to fermions, known as "fermiophobic", is possible in 2HDM models of Type I. Specific analyses for such Higgs boson, consisting of a search for strahlung production and decay into photons, allow mass limits around $110\,\mathrm{GeV}/c^2$ to be set for a decay branching ratio into photons exceeding $\sim 10\%$.

3 SUSY searches

Theories with Supersymmetry (SUSY) are the most promising extensions of the Standard Model (SM). The simplest version is the Minimal Supersymmetric Model (MSSM), which contains the

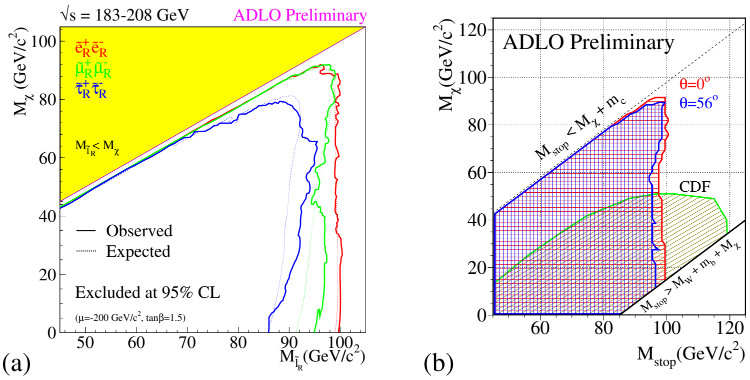

Fig. 3. LEP SUSY Working Group results for sfermions: (a) slepton mass exclusion plot; (b) stop mass exclusion plot in case of $\tilde{\mathrm{t}} \to \mathrm{c}\chi$ decay for minimal ($\theta_{\tilde{\mathrm{t}}} = 56°$) and maximal production cross section ($\theta_{\tilde{\mathrm{t}}} = 0°$).

minimal number of additional particles. The scalar fermions or *sfermions*, $\tilde{\mathrm{f}}_{\mathrm{L}}$ and $\tilde{\mathrm{f}}_{\mathrm{R}}$, are the partners of the left- and right-handed SM fermions and mix to form the mass eigenstates. The mixing angle $\theta_{\tilde{\mathrm{f}}}$ is so defined that $\tilde{\mathrm{f}} = \tilde{\mathrm{f}}_{\mathrm{L}} \cos\theta_{\tilde{\mathrm{f}}} + \tilde{\mathrm{f}}_{\mathrm{R}} \sin\theta_{\tilde{\mathrm{f}}}$ is the lightest sfermion. In general mixing is relevant for the third family, while $\tilde{\mathrm{f}} \equiv \tilde{\mathrm{f}}_{\mathrm{R}}$ otherwise. The SM gauge boson as well as MSSM Higgs bosons states have fermionic super-partners, *gauginos* and *higgsinos*. The neutral higgsinos and gauginos mix into four mass eigenstates, the *neutralinos* χ, χ_2, χ_3, χ_4 ($M_{\chi_4} > M_{\chi_3} > M_{\chi_2} > M_{\chi}$). The charged gauginos and higgsinos mix into two mass eigenstates, the *charginos* $\chi^{\pm}$ and $\chi_2^{\pm}$ ($M_{\chi_2^{\pm}} > M_{\chi^{\pm}}$).

The lepton and baryon number conservation is normally embedded into SUSY models through the "R-parity" conservation. The LSP (Lightest Supersymmetric Particle) is stable and must be also neutral and weakly interacting to fit the cosmological observations. Within the standard MSSM the LSP is the lightest neutralino χ or, less likely, the sneutrino, $\tilde{\nu}$. At LEP the sparticles are pair produced and the decay brings to final states containing at least one LSP.

Except few pathological cases, sparticle pair production leads to the typical acoplanar particles topology due to missing energy ($\not{E}$) and momentum ($\not{P}$) from escaping LSP's. The energy of the visible system is related to the mass difference between the sparticle $\widetilde{\mathrm{P}}$ and the LSP ($\Delta M = M_{\widetilde{\mathrm{P}}} - M_{\mathrm{LSP}}$). The acoplanar topologies studied cover each type of visible final state (leptons, hadronic jets, γ's).

The analyses for slepton signals ($\mathrm{e}^+\mathrm{e}^- \to \tilde{\ell}^+\tilde{\ell}^-$, $\tilde{\ell} \to \ell\chi$) search for acoplanar leptons by using the powerful lepton and tau identification of LEP detectors, and the LEP combined cross section upper limits range from 10 to 60 fb. The resulting mass lower limits are $100\,\mathrm{GeV}/c^2$, $94\,\mathrm{GeV}/c^2$ and $86\,\mathrm{GeV}/c^2$ for $\tilde{\mathrm{e}}_{\mathrm{R}}$, $\tilde{\mu}_{\mathrm{R}}$ and $\tilde{\tau}_{\mathrm{R}}$ respectively, valid for $\Delta M > 10\,\mathrm{GeV}/c^2$, as shown in Fig. 3(a) [2].

The production of a squark pair results into an acoplanar jet topology. These hadronic events can be selected by using event variables and requiring $\not{E}$ and $\not{P}$. In case of $\mathrm{e}^+\mathrm{e}^- \to \tilde{\mathrm{t}}\bar{\tilde{\mathrm{t}}}$, $\tilde{\mathrm{t}} \to \mathrm{c}\chi$, the mass lower limit is $94\,\mathrm{GeV}/c^2$ for $\Delta M > 10\,\mathrm{GeV}/c^2$ and any mixing, as visible in Fig. 3(b) [2].

Further specialized selections are used for other squark processes: b-tagging is effective for $\mathrm{e^+e^-} \to \tilde{\mathrm{b}}\bar{\tilde{\mathrm{b}}}$, $\tilde{\mathrm{b}} \to \mathrm{b}\chi$, allowing a limit of $92\,\mathrm{GeV}/c^2$ to be set ($\Delta M > 10\,\mathrm{GeV}/c^2$, any $\theta_{\tilde{\mathrm{b}}}$); leptons are required in case of $\mathrm{e^+e^-} \to \tilde{\mathrm{t}}\bar{\tilde{\mathrm{t}}}$, $\tilde{\mathrm{t}} \to \mathrm{b}\ell\tilde{\nu}$, leading to a mass lower limit of $95\,\mathrm{GeV}/c^2$ ($\Delta M > 10\,\mathrm{GeV}/c^2$, any $\theta_{\tilde{\mathrm{t}}}$). The stop decay $\tilde{\mathrm{t}} \to \mathrm{b}\chi\mathrm{f_u}\bar{\mathrm{f}}_\mathrm{d}$ leads to a multi-body final state topology addressed by a dedicated ALEPH selection [8]. As an example, assuming the decay $\tilde{\mathrm{t}} \to \mathrm{b}\chi\mathrm{W}^*$, the result is $M_{\tilde{\mathrm{t}}} > 77\,\mathrm{GeV}/c^2$ ($\Delta M > 10\,\mathrm{GeV}/c^2$, any $\theta_{\tilde{\mathrm{t}}}$). ALEPH analyses also consider the case in which a stop quasi-degenerate with the LSP acquires a sizeable lifetime and hadronizes [9]. This scenario has been excluded searching for long-lived heavy hadrons and an absolute stop mass lower limit of $63\,\mathrm{GeV}/c^2$ has been set for any $\theta_{\tilde{\mathrm{t}}}$, any branching ratio and any ΔM [8].

Topologies with two or more visible fermions in the final state plus $\not{E}$ and $\not{P}$ are expected in case of charginos and neutralinos production [10]. The processes are of the type $\mathrm{e^+e^-} \to \chi_{i>1}\chi$ and $\mathrm{e^+e^-} \to \chi_{i>1}\chi_{j>1}$ with $\chi_{i>1} \to \chi\mathrm{f}\bar{\mathrm{f}}$, and $\mathrm{e^+e^-} \to \chi^+\chi^-$ with $\chi^\pm \to \chi\mathrm{f_u}\mathrm{f}'_\mathrm{d}$. Cross section upper limits of ~ 0.1–$0.3\,\mathrm{pb}$ are obtained by the LEP-wide outcome of dedicated selections [2].

Topologies with photon(s) can be very powerful in detecting new phenomena [2], in general being sensitive to pair produced sparticles radiatively decaying into the LSP. Within the MSSM this case applies to neutralino production processes like $\mathrm{e^+e^-} \to \chi_2\chi_2$ and $\mathrm{e^+e^-} \to \chi_2\chi$ with $\chi_2 \to \chi\gamma$. In this hypotheses the cross section upper limits range between $10\,\mathrm{fb}$ and $0.1\,\mathrm{pb}$ depending on the process [2].

The negative results of the search for sparticle production can be translated into constraints on the parameter space in the context of specific SUSY models. This method allows the exclusions to be extended to sparticles otherwise not accessible, either because invisible, as the LSP, either because too heavy to be produced [10].

A widely accepted framework is the constrained MSSM (CMSSM). The unification of masses and couplings at the GUT scale allow the EW scale phenomenology to be set by few parameters: $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets; μ, the Higgs sector mass parameter; M_2, the EW scale common gaugino mass; m_0, the GUT scale common scalar mass; the trilinear couplings A_f, that enter in the prediction of the sfermion mixing and are generally set to fit the no-mixing hypothesis.

The negative outcome of charginos and neutralinos searches can be used to exclude regions in the (μ, M_2) plane, as shown, as an example, in Fig. 4(a) in which the sleptons are assumed to decouple (i.e. large m_0). Figure 4(b) shows how neutralino searches allow chargino exclusions to be improved for small $\tan\beta$ and $\mu < 0$. If the sleptons are lighter (small m_0 values), the chargino and neutralino cross sections decrease for the enhancement of negative-interfering slepton-exchange diagrams. The consequent loss of sensitivity is recovered by slepton searches in such a way that lower mass limits on gauginos and other sparticles as $\tilde{\mathrm{e}}_\mathrm{R}$ or $\tilde{\nu}$ could be set. Among these, the most important is the LSP limit, i.e. the mass lower limit on χ. The LSP mass lower limits from LEP experiments fall around $36 - 39\,\mathrm{GeV}/c^2$ and are set for $\tan\beta \sim 1$ [10].

The LEP mass lower limits on the Higgs boson mass m_{h^0} can be also used to further exclude small $\tan\beta$ ranges. Roughly, this just derives from the MSSM tree-level relation $m_{\mathrm{h}^0} < m_\mathrm{Z}|\cos\beta|$. However, the details of the exclusion depend on M_2, m_0 and the stop mass because of the large radiative corrections to m_{h^0}. Adding the Higgs constraints the LSP mass lower limit substantially improves (up to $\sim 47\,\mathrm{GeV}/c^2$) and moves towards high $\tan\beta$, as shown in Fig. 4(c) [2].

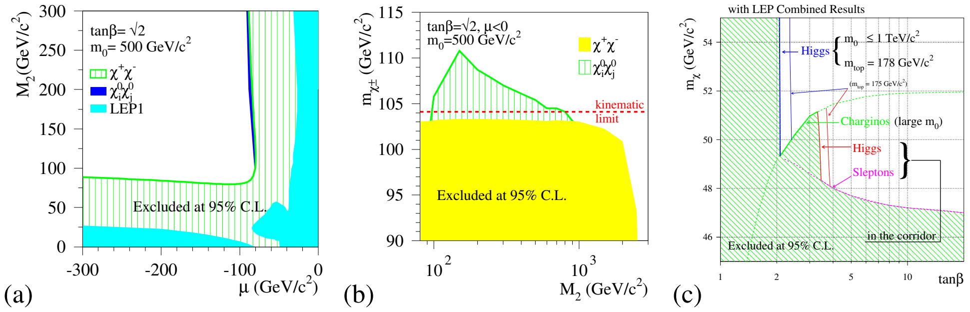

Fig. 4. (a) ALEPH exclusion in the M_2 versus negative μ plane for $\tan\beta=\sqrt{2}$ and $m_0=500\,\mathrm{GeV}/c^2$; (b) ALEPH chargino mass lower limits for $\mu<0$; (c) Absolute lower limit on the LSP mass in the CMSSM as a function of $\tan\beta$.

The robustness of the LSP limit has been checked with respect to the mixing effects in the third family, neglected in the above discussion. A stau getting light for mixing may be mass degenerate with the LSP, making the chargino decays into staus difficult to detect. Dedicated selections for $\chi^{\pm}\to\tilde{\tau}\nu_\tau\to\tau\chi\nu_\tau$ with soft taus, $\mathrm{e^+e^-}\to\chi_2\chi$ and $\mathrm{e^+e^-}\to\chi_2\chi_2$ with $\chi_2\to\tau\tau\chi$, and for chargino production in association with an ISR photon ($\mathrm{e^+e^-}\to\chi^+\chi^-\gamma$) allow to solve this problem. The LSP limits reported above have been demonstrated to hold by using this studies, extended also considering the mixing configurations for $\tilde{\tau}$, $\tilde{\mathrm{t}}$ and $\tilde{\mathrm{b}}$ that can be explored by setting A_τ, A_t and A_b to zero.

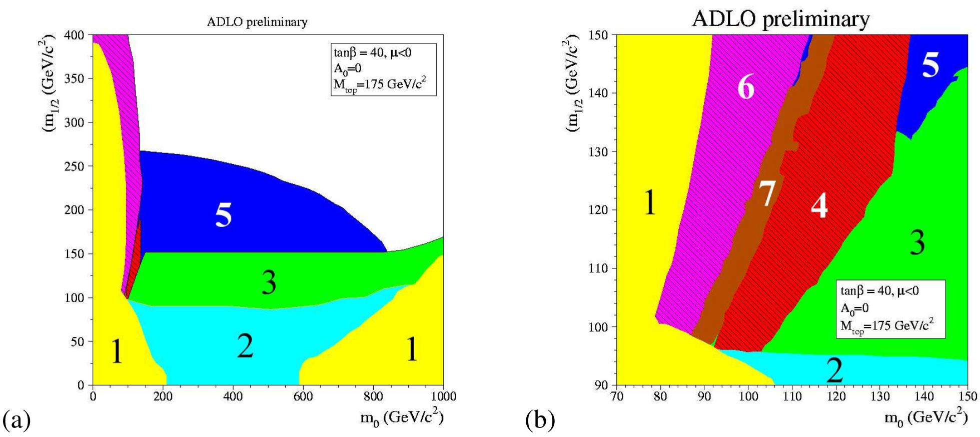

Fig. 5. (a) LEP combined exclusion domains in the mSUGRA $m_{1/2}$ versus m_0 plane for $\tan\beta=40$, $A_0=0$ and $\mu<0$; a peculiar area is zoomed in (b) to show the interplay between selections. Numbers indicate the search excluding the corresponding area: (1) theoretically not allowed, (2) LEP1, (3) chargino, (4) stau and selectron, (5) Higgs, (6) $\chi\to\tilde{\tau}$ cascade and (7) heavy stable charged particles.

The results have been also interpreted within an even more constrained version of the CMSSM, usually referred to as Minimal Supergravity (mSUGRA). The relevant parameters are: $\tan\beta$, the sign of μ and m_0; $m_{1/2}$, the GUT scale common gaugino mass, that replaces M_2; A_0, the GUT scale common trilinear coupling.

On top of LEP1 exclusions and theory-forbidden regions, small m_0 and $m_{1/2}$ areas are constrained from sleptons and gaugino searches, respectively. Higgs boson searches are also effective, even in the large $\tan\beta$ range. As an example, Fig. 5(a) illustrates $m_{1/2}$ versus m_0 excluded domains for $\tan\beta = 40$, $\mu < 0$ and $A_0 = 0$. The zoomed area of Fig. 5(b) focuses on the pathological region in which, for the mixing, $\tilde{\tau}$ and χ are almost degenerate and the selections for stau-cascades and stable staus have to be used. The resulting mSUGRA LSP mass lower limits lie between 52 and $59\,\mathrm{GeV}/c^2$, depending on the top mass, and turn out to be $\sim$ 8–9 GeV/c^2 lower if A_0 is allowed to assume values other than zero [2].

Gauge-mediated SUSY breaking (GMSB) models are characterized by the following distinctive features: the LSP is always the gravitino $\tilde{\mathrm{G}}$, and the next-to-LSP (NLSP) is, in general, either the lightest χ or a slepton; the NLSP decay length could be even comparable or larger than the detector dimension depending on parameters. Within GMSB, double- or single-photon final state may occur in case of neutralino pair production and radiative decay into gravitinos ($\mathrm{e}^+\mathrm{e}^- \to \chi\chi \to \tilde{\mathrm{G}}\tilde{\mathrm{G}}\gamma\gamma$). A complete addressing of GMSB topologies requires, in general, the use of searches for acoplanar particles as well as searches for kinks and/or impact parameter for the intermediate lifetime range, and for heavy stable charged particles for the long lifetime range [2].

Supersymmetry does not necessarily require R-parity conservation (RPC) and R-parity violation (RPV) can be introduced still complying with low energy limits on barion and lepton number conservation. Two of the main characteristics of SUSY processes at LEP are heavily affected: sparticles can also be singly produced and mainly, since LSP is no more stable, the decay final state is build up of standard model particles with many leptons and/or quarks, and the missing mass signature is generally lost. The huge amount of possible and complex final states foreseen in this scenario are addressed by many LEP analyses with results comparable to the RPC case. The study of these decays allowed to test very peculiar topologies, otherwise unsearched for.

4 Search for extra-dimensions: an example of "exotic" searches

The searches of beyond SM phenomena that do not fit within supersymmetric models are generally said as "exotic". The huge amount of work done by LEP collaboration on this topic can not be covered here [3]. As a representative example the search for extra dimension is briefly reviewed.

In order to address the hierarchy problem, a new class of theories assume the Standard Model to be confined into a four-dimensional hypersurface (brane), whereas the gravitational fields are also allowed to propagate in extra dimensions inside the full space-time (bulk). Two different extra dimensions scenarios have been studied at LEP: the ADD and the Randall-Sundrum scenarios.

In the ADD scenario, the $n > 1$ extra dimensions are assumed to be compactified, normally on a torus with radius R. The fundamental gravitational scale M_D is related to the Planck scale $M_{\mathrm{Pl}} \sim 10^{19}$ GeV through R ($M_{\mathrm{Pl}}^2 \sim M_D^{2+n} R^n$), and can be lowered to the TeV range with the

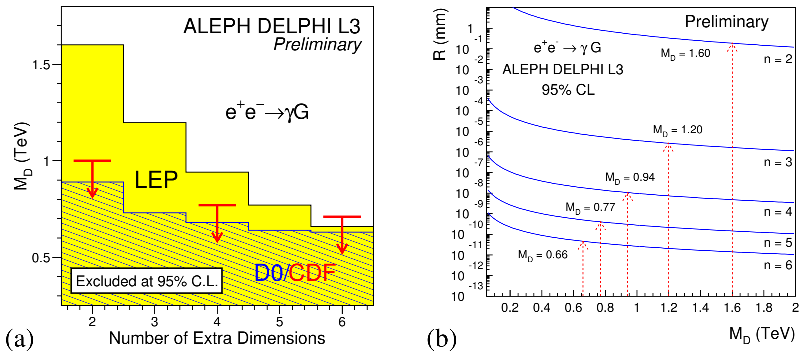

Fig. 6. (a) The exclusion contours in the M_D vs n plane for the graviton-photon emission at LEP (ADL combined). Current limits from D0 and CDF are also shown. (b) The radii of the extra dimensions, R, as functions of the gravity scale M_D, for $n = 2 - 6$. Arrows indicate the upper limits on R.

extra dimension size being as large as a millimeter. Gravitational fields propagating in the bulk can be expressed as a series of states known as a Kaluza-Klein towers. An observer trapped on the brane sees the graviton modes propagating in extra dimensions as massive spin-2 neutral particles which can couple to the SM fields on the brane. In the presence of large extra dimensions, events with a single photon and missing energy could be enhanced by $\mathrm{e^+e^-} \to \mathrm{G}\gamma$ processes where the graviton G escapes detection. Since no indication of a signal has been observed [3], limits on the scale of gravity M_D, shown in Fig. 6(a), are derived. These can be converted into upper limits on R, as shown in Fig. 6(b).

In addition to gravitons, the effective ADD four-dimensional theory of gravity predicts also the existence of *branons* $\tilde{\pi}$, massive scalars related to the deformations of the brane within the bulk that could be pair produced ($\mathrm{e^+e^-} \to \tilde{\pi}\tilde{\pi} + \gamma/\mathrm{Z}$), with cross section depending on the number of branons n_b, their mass and the brane tension f. A specific L3 search [11] for such processes allows branon mass limits to be set as a function of f, as shown in Fig. 7(a).

In the Randall-Sundrum scenario two branes are assumed to exist: one where SM is confined, one, the Planck brane, where the gravity is confined. There is only one extra dimension and the gravity is "weak" because of its exponential suppression with the distance between the SM and Planck branes. Fluctuations of this distance give rise to a massive scalar, the *radion*, that can mix with the SM Higgs bosons, having the same quantum numbers. The resulting Higgs-like and a radion-like eigenstates can be produced at LEP through the strahlung process and thus searched for by using the Higgs boson selections. A result of these searches from OPAL [12] is shown in Fig. 7(b), where the limits on the radion-like state mass m_r are given as a function of the mixing parameter ξ and the mass scale on the SM brane Λ_W.

5 Conclusion

LEP has extensively searched for Higgs bosons of minimal and non-minimal models, for sparticles within the most promising supersymmetric scenarios and for many other possible new

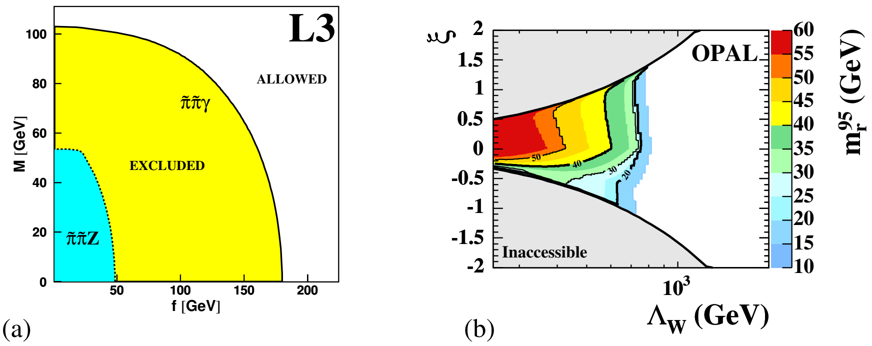

Fig. 7. (a) Regions in the plane $(f, m_{\tilde{\pi}})$, excluded by the searches for $e^+e^- \to \tilde{\pi}\tilde{\pi} + \gamma/Z$; (b) radion-like state mass limits as a function of ξ and Λ_W.

phenomena beyond the Standard Model. More than the negative outcome, the wide and detailed lessons learned in this challenge are the important part of the LEP legacy that will result crucial for future experiments.

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