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Physique subatomique/*Subatomic physics*

AVANCÉES EN PHYSIQUE DES PARTICULES :
LA CONTRIBUTION DU LEP

ADVANCES IN PARTICLE PHYSICS: THE LEP CONTRIBUTION

Looking for physics beyond the Standard Model

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Abstract Motivations for new physics beyond the Standard Model are presented. The most successful and best motivated option, supersymmetry, is described in some detail, and the associated searches performed at LEP are reviewed. These include searches for additional Higgs bosons and for supersymmetric partners of the standard particles. These searches constrain the mass of the lightest supersymmetric particle which could be responsible for the dark matter of the universe. ***To cite this article: P. Binétruy, J.-F. Grivaz, C. R. Physique 3 (2002) 1235–1243.***

Standard Model / Higgs boson / supersymmetry / new particles / dark matter

Au delà du Modèle Standard

Résumé Les motivations pour une physique au delà du modèle standard sont présentées. L'option supersymétrique, qui est la mieux motivée et rencontre un certain nombre de succès, est plus précisément considérée. Les recherches à LEP de bosons de Higgs supplémentaires et de partenaires supersymétriques des particules ordinaires sont exposées. Ces recherches contraignent la masse de la particule supersymétrique la plus légère, qui pourrait constituer la matière noire de l'univers. ***Pour citer cet article : P. Binétruy, J.-F. Grivaz, C. R. Physique 3 (2002) 1235–1243.***

Modèle Standard / bosons de Higgs / supersymétrie / nouvelles particules / matière noire

1. Unanswered questions

As shown elsewhere in this issue, the Standard Model has been tested at LEP to a degree of accuracy which could hardly be foreseen at the time this collider came into operation. The reason is that the Standard Model, although being a highly predictive theory, leaves, and often raises or reformulates, many unanswered questions.

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- The spontaneous breaking of the electroweak symmetry provides an origin to the masses of quarks and leptons through their couplings to the Higgs field, but it provides no clue to the diversity observed in the mass spectrum. Why is the electron more than five orders of magnitude lighter than the top quark?
- Why do quarks and leptons appear in three families which are exact replicas from the point of view of quantum numbers?
- Why is matter so much more abundant than antimatter in our universe, when particles and antiparticles are treated almost similarly in the Standard Model?
- Why are the symmetries of the Standard Model stable under quantum corrections? This absence of anomalous behaviour rests on a delicate cancellation between the quantum numbers of the observed particles, which remains unexplained at that level.
- How is gravity, which is described classically by general relativity, included into the quantum picture?

The solution to these problems involves new physics characterized by a scale which is often much larger than the Fermi scale typical of the Standard Model processes, i.e., $\sim$100 GeV. For example, the unification of all known interactions seems to occur at an energy scale M_U around 10^{16} GeV; this ‘grand unification’ may explain some relations between particle masses, as well as provide a rationale for the absence of quantum anomalies. The scale of quantum gravity is roughly of the same order: it is given by the Planck scale constructed out of Newton’s and Planck’s constants: $M_P \sim 10^{19}$ GeV. Such new physics involves new heavy particles whose indirect (virtual) effects on low energy physics should lead to departures from the Standard Model predictions. The non-observation of such effects at LEP puts very tight constraints on the type of new physics that can be expected. In particular the simplest versions of theories known under the generic name of technicolour, which attribute electroweak symmetry breaking to a condensate of fermions instead of a fundamental Higgs scalar field, have been ruled out.

2. Beyond the Standard Model: Supersymmetry

Direct searches for physics beyond the Standard Model (SM) have been performed at LEP along many more or less motivated directions [1]. Among those can be quoted: sequential heavy leptons or quarks belonging to a fourth replica of the known three families; excited states of the standard quarks and leptons, which could appear in models where observed particles are composite; right handed neutrinos, although at a scale much lower than unified theories would suggest; or charged Higgs particles from two-Higgs-doublet models. As mentioned above, precision studies have also been an important tool to set constraints on extensions of the standard model. These studies are covered in other contributions to this volume, for instance the search for anomalous three-gauge-boson couplings (contribution by Buchmüller et al. [2]). Here, the attention will be focused on the currently most successful and best motivated extension of the standard model, namely supersymmetry (SUSY) [3,4]. In particular, the three gauge couplings measured at LEP with high precision unify near M_U with much better accuracy within a supersymmetric framework.

Supersymmetry is a rather unique spacetime symmetry which relates bosons (integer spin) with fermions (half integer spin). In SUSY theories, the quantum corrections to any low energy process are kept under control, which is essential for any beyond-the-SM theory because of the absence of observed deviations with respect to the SM predictions. In the Higgs sector, the presence of any superheavy field would tend to destabilize the Fermi scale. It has been seen that such superheavy particles occur in most theories beyond the SM, but supersymmetry allows this so-called ‘hierarchy’ problem to be alleviated through a delicate cancellation between bosonic and fermionic quantum fluctuations.

To each degree of freedom of the standard model, supersymmetry associates a partner differing by half a unit of spin, but with otherwise the same quantum numbers. There are two scalar electrons, or selectrons. They are denoted $\tilde{\mathrm{e}}_\mathrm{R}$ and $\tilde{\mathrm{e}}_\mathrm{L}$ according to the electron chirality state with which they are associated. Similarly, there are smuons, staus, and sneutrinos, and also squarks among which two stops. The gauge bosons have spin one-half supersymmetric partners too, generically called gauginos: gluinos $\tilde{\mathrm{g}}$ are associated to the gluons, a photino $\tilde{\gamma}$ to the photon, etc.... Two doublets of Higgs fields, at least, are required in any supersymmetric model, out of which remain, after electroweak symmetry breaking, three neutral Higgs bosons (two CP-even, h and H, and one CP-odd, A), and a pair of charged Higgs bosons $H^{\pm}$. These Higgs bosons too have SUSY partners, called higgsinos. The charged gauginos and higgsinos mix to form charginos $\chi^{\pm}$, and the neutral and colourless gauginos and higgsinos mix to form neutralinos, denoted $\chi, \chi', \chi'', \ldots$ in increasing mass order.

If SUSY were an exact symmetry, the SM particles and their supersymmetric counterparts would have the same masses, in clear contradiction with observation. Supersymmetry is therefore broken, hopefully spontaneously, i.e., with SUSY present at the level of the Hamiltonian if not realized in the particle spectrum. The scale of supersymmetry breaking should be kept low enough if SUSY is to provide the required solution to the hierarchy problem. This is naturally obtained with SUSY partner masses up to a $\mathrm{TeV}\cdot c^{-2}$ or so. In addition to the immediate interest of the discovery of physics beyond the Standard Model, the study of supersymmetric particles would open a precious window on the physics of SUSY breaking, presumably at a scale not too distant from the unification M_U or Planck M_P mass.

3. SUSY Higgs boson searches

While the masses of supersymmetric particles, although low compared to the GUT scale, may still be too high for the current accelerators, a generic prediction of supersymmetric models falls rather naturally in the LEP energy range, namely that of a low mass neutral Higgs boson h. This is even more so in the Minimal Supersymmetric extension of the Standard Model (MSSM), where this mass is predicted to be lower than about 130 $\mathrm{GeV}\cdot c^{-2}$. Furthermore, this neutral Higgs boson behaves similarly to the SM Higgs boson in a large fraction of the MSSM parameter space. The searches described in the contribution (by Janot and Kado [5]) devoted to the SM Higgs boson therefore apply in this framework, and their negative outcome provides by itself tight constraints on supersymmetric models.

In the MSSM, there are exactly two Higgs doublets, and the Higgs sector is fully specified by two parameters, once the spectrum of supersymmetric particles is fixed. The usual practice at LEP is to display the results using m_{h} and $\tan\beta$ as independent parameters, where $\tan\beta$ is the ratio of the two Higgs doublet vacuum expectation values. Other choices, such as m_{h} and m_{A} are occasionnally made. As input to calculations, m_{A} and $\tan\beta$ are particularly convenient. When m_{A} is sufficiently large, the lighter CP-even Higgs boson h behaves in a SM-like fashion; this configuration is known as the decoupling limit. A light SM-like Higgs boson also arises when $\tan\beta \sim 1$, even for small or moderate values of m_{A}. In the other cases, the h couplings are modified with respect to their SM values, which leads to a reduction of the cross section of the Higgsstrahlung process $e^+e^- \to hZ$ discussed in the context of the SM Higgs boson searches.

The resulting loss of sensitivity is however compensated, if the A boson is light enough, by a simultaneous increase of the cross section of the associated production process $e^+e^- \to hA$. Moreover, in the cases where associated production is relevant, it turns out that the masses of the h and A bosons of the MSSM are similar. The resulting final states, consisting of four b jets in ~80% of the cases, can be addressed with methods similar to those developed for the SM Higgs boson, with the replacement of the Z-mass constraint used in the searches for the Higgsstrahlung process by an equal mass constraint for the h and A decay systems.

No excesses of events with respect to the expectations from the standard model backgrounds were observed by the LEP experiments in their searches for associated hA production. These results, together with those on hZ production by Higgsstrahlung, lead to the exclusion domain in the $(m_{\mathrm{h}}, \tan\beta)$ plane of the MSSM shown in Fig. 1. In this figure, a standard set of parameters, corresponding to a scenario dubbed 'maximal mixing', specifies the model. The values of these parameters essentially determine the size of the domain theoretically accessible, but have little impact on the shape of the experimentally excluded region. For low values of $\tan\beta$, the Higgsstrahlung process is the most constraining; values of m_{h} lower than 114 $\mathrm{GeV}\cdot c^{-2}$ are excluded, as in the case of the Standard Model. For large values of $\tan\beta$, the constraints

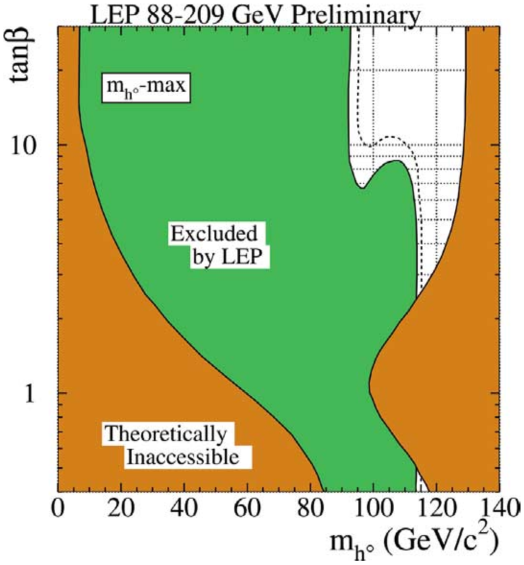

Figure 1. Domain excluded in the $(m_{\mathrm{h}}, \tan\beta)$ plane, obtained by a combination of the four LEP experiments [6] in the 'maximal mixing' scenario. The region coloured in brown is not theoretically accessible. The region coloured in green is excluded by the searches for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{hZ}$ (mostly at low $\tan\beta$) and for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{hA}$ (mostly at high $\tan\beta$).

are provided by the associated production process instead, and values of m_{h} and m_{A} lower than 91 GeV$\cdot c^{-2}$ are excluded.

In the MSSM at tree level, it is predicted that $m_{\mathrm{h}} < M_{\mathrm{Z}}$. The above result would therefore be sufficient to rule out this model. Radiative corrections essentially due to the large top quark mass however modify this prediction. For a top quark mass of 174 GeV$\cdot c^{-2}$ as measured at the Tevatron, the theoretical upper limit on m_{h} becomes ~115 GeV$\cdot c^{-2}$, assuming a common mass of 1 TeV$\cdot c^{-2}$ for the stops. This upper limit is further increased to ~130 GeV$\cdot c^{-2}$ if the mass splitting between the two stops is large; this corresponds to the 'maximal mixing' configuration of Fig. 1. It can be seen that values of $\tan\beta$ lower than 2.4 are excluded even for this conservative choice of parameters. This result rules out an elegant scenario, known as the 'low-$\tan\beta$ infrared quasi-fixed point'.

The searches for Higgs bosons of the MSSM performed at LEP have allowed a territory to be explored which was, as for the Standard Model Higgs boson, essentially virgin previously. These searches have considerably restricted the allowed parameter configurations within the MSSM. Some room is nevertheless left at moderate to large values of $\tan\beta$, even for a SM-like Higgs boson heavier than 114 GeV$\cdot c^{-2}$. It should also be kept in mind that models slightly less minimal than the MSSM, e.g., with an additional singlet of Higgs fields, are less constrained by the current results, even if they also predict a light neutral Higgs boson.

4. SUSY models: supergravity and *R*-parity

Had a light Higgs boson been discovered, this would however not have been sufficient to prove supersymmetry. A definitive proof can only come from the observation of supersymmetric particles, but the masses of those particles are much less constrained theoretically than m_{h}. As already mentioned, rather compelling naturalness arguments nevertheless suggest that the stop masses should not be much larger than a TeV$\cdot c^{-2}$. Additional guidelines are provided in models where one specifies the physics at a large scale, such as the grand unification M_U or Planck M_P scale. Physics at this scale is (maybe wrongly) assumed to be simpler. At such a scale, gravitational corrections are supposed to play a role and gravity should be incorporated. Supersymmetry becomes a local symmetry known as supergravity (SUGRA). This is why some of the corresponding models are often referred to as SUGRA models.

If one wants to treat gravity in a fully quantum fashion, one must invoke the only known quantum theories of gravity, i.e., superstring theories for which supersymmetry represents a basic ingredient. A key property of superstring models is that they involve a larger number of spatial dimensions (nine instead of three). The energy scale associated with these extra dimensions could be as low as the TeV. An exploratory search of the effects of such extra dimensions has been performed at LEP, but only future colliders such as the LHC will really be able to probe the relevant energy range.

Most of the phenomenological work performed at LEP has disregarded the full intricacies of superstring theories and has made simplifying assumptions. Supersymmetry breaking is effectively parametrized by a number of unknown mass terms. These ‘soft SUSY-breaking’ mass terms come in quite limited number in models commonly designated as SUGRA-inspired (although supergravity by itself does not constrain the SUSY-breaking parameters). Gaugino masses are controlled by two parameters, $m_{1/2}$ and μ; the slepton and squark masses depend on m_0 in addition. The m_0 and $m_{1/2}$ parameters actually represent common masses for all sfermions and for all gauginos, respectively, at a scale close to M_P. When renormalized down to the Fermi scale, the masses of the weakly interacting gauginos end up substantially smaller than the mass of the gluino, and the masses of the sleptons also tend to be much smaller than those of the squarks. Since Higgs bosons are scalar particles just as squarks and sleptons, their masses are also derived from m_0 in the model known as minimal supergravity (mSUGRA). The large top quark mass allows one of the Higgs mass terms to be driven negative at the Fermi scale by renormalization effects, thus inducing a spontaneous breakdown of the electroweak symmetry. The μ parameter can then be calculated (up to a sign) from the known Z boson mass.

Supersymmetric particles differ from their SM partners by half a unit of spin, but share the same baryon and lepton numbers. A new multiplicative quantum number, R-parity, allows standard and SUSY particles to be distinguished. It is defined as $R = (-1)^{2S+L+3B}$, where S is the spin, and B and L are the baryon and lepton numbers. For the ordinary SM particles $R = 1$, while $R = -1$ for their supersymmetric partners. The virtual exchange of SUSY particles would induce an unacceptably fast proton decay if R-parity were violated in an arbitrary fashion. The simplest way out is to impose R-parity conservation, in which case SUSY particles can be produced only in pairs, and their decay cascades end up with the lightest supersymmetric particle (LSP) which is stable. The absence of heavy isotopes constrains the LSP to be neutral and colourless. The most natural candidate fulfilling these conditions is the lightest neutralino χ. Such an LSP is weakly interacting, and constitutes an ideal candidate for the dark matter component of the universe.

5. SUSY particle searches

Under the hypothesis of R-parity conservation, the production of SUSY particles leads to the characteristic signature of missing mass and missing energy carried away by the decay LSP’s. A few examples particularly relevant at LEP are listed below.

- Scalar muon pair production, $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$. Followed by the decays $\tilde{\mu}^\pm \to \mu^\pm\chi$, this leads to an observable final state consisting of a pair of muons rendered acoplanar with the beam by the transverse momentum carried away by the two invisible χ’s. For light LSPs, this final state is almost indistinguishable from muon pairs arising from W pair production, $e^+e^- \to W^+W^- \to \mu\nu\mu\nu$, but its contribution would lead to an abnormally large measured $W \to \mu\nu$ branching ratio. For massive χ’s, the kinematics of the muon pairs are notably different; in particular, the energy of the muons is smaller in the case of a smuon signal than for W pairs.
- Chargino pair production, $e^+e^- \to \chi^+\chi^-$. Charginos typically decay via a virtual W, $\chi^\pm \to W^*\chi$, and therefore ultimately into $\ell\nu\chi$ or $q\bar{q}'\chi$. The topologies arising from chargino pair decays are thus (i) an acoplanar pair of leptons, not necessarily of the same flavour, (ii) a multi-jet system, or (iii) a mixed final state containing a lepton and a hadronic system. All these final states exhibit missing mass and missing energy, in a way which allows them to be disentangled from the almost identical

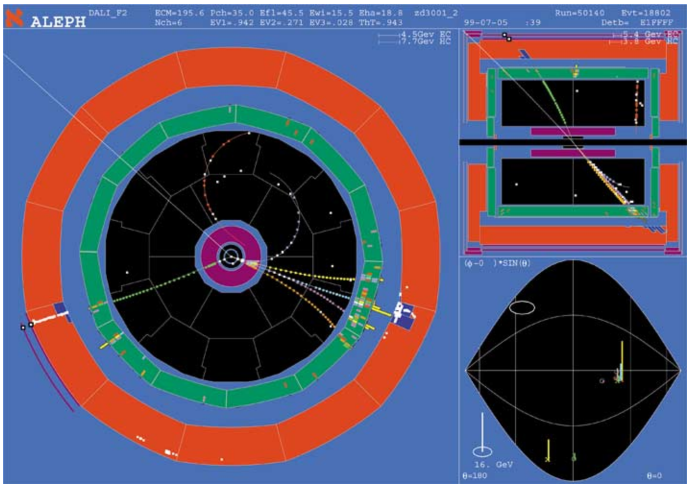

Figure 2. Chargino candidate selected in the mixed topology at a centre-of-mass energy of 195.6 GeV. The isolated penetrating track is a muon. The other tracks and calorimeter energy deposits result from a collimated hadron jet. The straight solid line visualizes the direction of the missing momentum. The likely SM interpretation of this event is that it arises from W pair production. One of the Ws decays into $\tau\nu$, with $\tau \to \mu\nu\nu$, which accounts for the low momentum of the muon (9 GeV$\cdot c^{-1}$). The other W decays into hadrons; with a visible mass of 16 GeV$\cdot c^{-2}$, it is widely off mass shell. There is no sign of detector activity in the direction of the missing momentum.

final states arising from W pair production. For instance, in the mixed topology, the neutrino from $\mathrm{W^+W^-} \to \mathrm{q\bar{q}}'\ell\nu$ produces missing energy, but no missing mass, in contrast to the $\nu\chi\chi$ system from $\chi^+\chi^- \to \mathrm{q\bar{q}}'\chi\ell\nu\chi$. An example of candidate event for chargino pair production in this topology is displayed in Fig. 2.

- Associated production of neutralinos, $\mathrm{e^+e^-} \to \chi\chi'$. The heavier neutralino χ' typically decays via a virtual Z, $\chi' \to \mathrm{Z}^*\chi$, thus into $\mathrm{q\bar{q}}\chi$, $\ell\ell\chi$ or $\nu\nu\chi$. The final state topologies are therefore an acoplanar pair of jets, an acoplanar pair of leptons, or even invisible in the case of $\chi' \to \nu\nu\chi$. Except of course for the last one, these final states can be addressed with techniques similar to those described above.

In these examples, the background from W pair production has been emphasized. Indeed, it is usually the most relevant one when the mass difference between the decaying SUSY particle and the LSP is substantial. But if this mass difference becomes small, there is little phase space available for the visible decay products, and the main backgrounds are of a different nature, arising mostly from '$\gamma\gamma$ interactions' ($\mathrm{e^+e^-} \to \mathrm{e^+e^-f\bar{f}}$, where the outgoing electrons escape undetected along the beam axis). This is the reason why, for a given production process and a given decay chain, different event selections had to be designed in order to cope with the diverse configurations arising from various mass difference ranges. In the end, no significant excesses of events with respect to the SM background processes were observed, and the various topological selections were combined to provide limits on masses or couplings of supersymmetric particles.

6. SUSY particle mass limits

Mass limits can be obtained in a straightforward way in some cases. For instance, $\tilde{\mu}_\mathrm{R}$ pair production proceeds only via s-channel photon and Z exchange; the cross section at a given centre of mass energy is thus fully determined once a single parameter, namely the smuon mass, is fixed. A production cross section upper limit deduced from the search for acoplanar muons therefore directly translates into a smuon mass lower limit, as shown in Fig. 3. (The production cross section is larger for $\tilde{\mu}_\mathrm{L}$, hence these $\tilde{\mu}_\mathrm{R}$ mass limits can be regarded as conservative smuon mass limits.) It can be seen that the $\tilde{\mu}_\mathrm{R}$ mass limit becomes weaker, and even vanishes, as the $\tilde{\mu}_\mathrm{R} - \chi$ mass difference becomes smaller; this is due to the reduced detection

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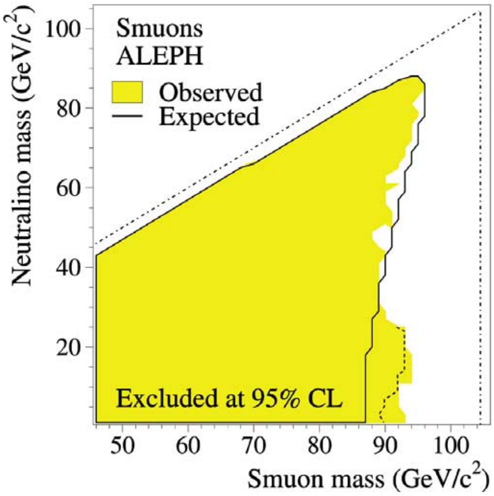

Figure 3. Domain excluded in the $(m_{\tilde{\mu}_{\mathrm{R}}}, m_\chi)$ plane [7]. The region excluded experimentally by the search for acoplanar muons is displayed in yellow, with the corresponding expected limit indicated by the solid line. The dashed line indicates how the excluded domain is reduced when cascade decays are taken into account, for $\tan\beta = 2$ and $\mu = -200$ GeV$\cdot c^{-2}$.

efficiency when the final state visible energy becomes too small. For very large mass differences, i.e., for small m_χ, the expected limit also degrades somewhat, because the acoplanar muon final state originating from the signal is more difficult to distinguish from the one arising from W pair production. The *expected limit*, a concept used at LEP to rate the a priori sensitivity of an analysis, is the limit which would be obtained, on average, from the analysis considered if no signal were present in the data. In Fig. 3, it turns out that the actual limit does not degrade for small m_χ because of a 'favourable' statistical fluctuation. Such things happen...

It must be noted however that these smuon mass limits were derived under the implicit assumption that the $\tilde{\mu}_{\mathrm{R}} \to \mu\chi$ decay mode has a 100% branching ratio, which is certainly the case if the $\tilde{\mu}_{\mathrm{R}}$ is the next to lightest SUSY particle (NLSP). This assumption is in general justified because if, for instance, charginos were lighter than smuons, it is likely that they would have been already discovered in dedicated searches, being produced with a larger cross section. This argument does not hold, however, for neutralinos, which cannot be produced by photon exchange and whose coupling to the Z may be reduced, depending on their field content. Decay chains such as $\tilde{\mu}_{\mathrm{R}} \to \mu\chi'$ followed by $\chi' \to \chi\gamma$ would lead to final states not selected by the acoplanar muon search, which would reduce the smuon mass limit accordingly.

This problem, and similar ones, can be handled only within more specific models, such as those inspired from supergravity. For instance, the masses and couplings of all neutralinos are fixed, once the parameters $\tan\beta$, μ and $m_{1/2}$ (or m_χ) are given. The reduction of the $\tilde{\mu}_{\mathrm{R}} \to \mu\chi$ branching ratio due to cascade decays can then be calculated, and the resulting impact on the smuon mass limit can be seen in Fig. 3, for a typical choice of $\tan\beta$ and μ values.

The case of smuon production is particularly simple, and was therefore discussed in some detail. In contrast, selectron, chargino or neutralino productions involve the t-channel exchange of neutralinos, sneutrinos or selectrons, respectively. To overcome these complications, models inspired by supergravity are commonly used to calculate the masses and couplings of all SUSY particles, and therefore all production cross sections and all decay branching ratios, in terms of a limited number of parameters. The chosen parameters are generally $m_{1/2}$, m_0, μ and $\tan\beta$. A set of these parameters is declared excluded if it is expected to lead to excesses with respect to the SM expectation in some of the topological searches, while none was observed. A scan of the parameter space is performed, and the ensemble of excluded sets may be such that some *absolute* SUSY particle mass limits can be inferred. For instance, an absolute selectron mass limit of 73 GeV$\cdot c^{-2}$ is obtained in this way [8], where the search for $\tilde{\mathrm{e}}_{\mathrm{R}}$ pair production in the acoplanar electron pair topology plays the major role; but a number of others channels (e.g., $\mathrm{e}^+\mathrm{e}^- \to \tilde{\mathrm{e}}_{\mathrm{L}}\tilde{\mathrm{e}}_{\mathrm{R}}$, $\chi^+\chi^-$, $\chi\chi''$, ...) are needed to cover various loopholes.

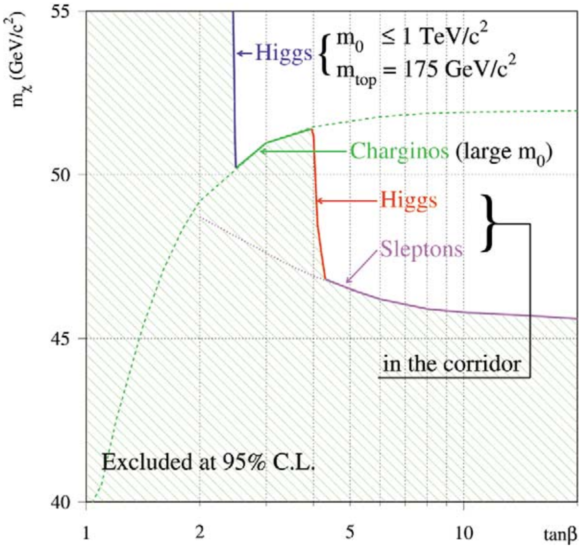

Figure 4. LSP mass limit as a function of $\tan\beta$, obtained by a combination of the four LEP experiments [9]. The contributions from Higgs boson, chargino and slepton searches are indicated. The 'corridor' designates the configuration in which the chargino and sneutrino are almost mass degenerate.

The same procedure has been applied with great care to determine a mass lower limit for the lightest supersymmetric particle, a case in which no explicit direct search is available because the reaction $e^+e^- \to \chi\chi$ leads to an invisible final state. The result is displayed in Fig. 4 as a function of $\tan\beta$. The main channel which contributes to the χ mass limit is chargino pair production, $e^+e^- \to \chi^+\chi^-$. Chargino searches loose their sensitivity, however, when the chargino and sneutrino are almost mass degenerate, because the final state arising from the $\chi^\pm \to \ell\tilde{\nu}$ decay is then essentially invisible. But since slepton and sneutrino masses are correlated, slepton searches provide the needed alternative constraints in that situation. In addition, it has been seen above that the negative Higgs boson searches tightly constrain the low $\tan\beta$ regime. All these contributions are visible in Fig. 4. In the end, an absolute LSP mass limit in excess of 45 GeV$\cdot c^{-2}$ is obtained. In the more constrained mSUGRA model, pathological mass configurations are more unfrequent, which results in an increased LSP mass limit of 60 GeV$\cdot c^{-2}$ (for a top quark mass of 175 GeV$\cdot c^{-2}$).

7. Awaiting higher energies

Because the LSP of the SUGRA-inspired models with R-parity conservation fulfils all the required conditions to be the main component of the dark matter of the universe for a broad range of parameters, this model has received the most acute attention at LEP. Other approaches to supersymmetry breaking have nevertheless been studied.

- In gauge mediated SUSY breaking (GMSB) models, the LSP is a light gravitino, $\widetilde{G}$, the SUSY partner of the graviton. If the lightest neutralino χ is the NLSP, it decays according to $\chi \to \widetilde{G}\gamma$; final states containing photons accompanied by missing energy have beeen searched for to cope with this configuration.
- In anomaly mediated SUSY breaking (AMSB) models, the LSP is a neutralino, but which now tends to be very close in mass to the chargino. A number of dedicated searches were designed to study these models, including for instance searches for long-lived charged particles which are needed if the $\chi^\pm - \chi$ mass difference is so small that the chargino becomes almost stable.

All varieties of models in which R-parity is not conserved have also been considered. In such models, the LSP decays to SM particles with violation of the lepton number (e.g., $\chi \to \mu^+\tau^-\nu$) or of the baryon number (e.g., $\chi \to$ udd). The characteristic signature of SUSY particle production is no longer missing energy, and final states consisting of many leptons and/or jets had to be searched for instead.

Altogether, it is hard to imagine that supersymmetry could have escaped detection if within the energy reach of LEP. Charged supersymmetric particles such as selectrons or charginos are excluded up to masses of $\sim$100 GeV$\cdot c^{-2}$, except for some fine tuned parameter configurations. In the most popular SUGRA-inspired models, also neutralino masses and couplings are tightly constrained, a total novelty with respect to the pre-LEP era. In particular, LSP mass lower limits in the range of 45 to 60 GeV$\cdot c^{-2}$ have been obtained, depending on specific model choices.

Nevertheless, if there is some truth in the widely shared belief that low energy supersymmetry underlies the standard model, it is quite likely that SUSY manifestations should be 'just around the corner'. It could even be that the hint of neutral Higgs boson with a mass of 115 GeV$\cdot c^{-2}$ is indeed the first evidence for SUSY… It will now take a few years for the Tevatron, perhaps even the LHC, to substantiate or to contradict this indication.

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