NEW PARTICLE SEARCHES AT LEP2 AT $\sqrt{s} = 188.6$ GeV*

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Preliminary results are presented from searches for new particles in e^+e^- collisions at $\sqrt{s} = 188.6$ GeV. No evidence for new physics was found, but a significant range of parameters in various models was explored and excluded, in some cases with important theoretical implications.

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1. Introduction: LEP in 1998

The performance of the LEP accelerator in 1998 was extremely satisfactory. It delivered to each of the four experiments well above $2\,\mathrm{pb}^{-1}$ of integrated luminosity per day at peak performance and on average more than $1\,\mathrm{pb}^{-1}$ per day, which is by far better than the performances of previous years. Overall, the LEP experiments recorded $\sim 170\,\mathrm{pb}^{-1}$ of high energy data at $\sqrt{s} = 188.6$ GeV.

This article reports on the first results from searches for new particles in the above data samples, concentrating particularly in searches for Higgs bosons and Supersymmetric particles. The Higgs results are presented in the next Section, while Section 3 reviews the results from SUSY searches. A summary and conclusions follow in Section 4, along with the future prospects and the remaining potential for discovery of LEP.

It is important to note that the results reported here, are very preliminary as most of them were presented publicly by the LEP experiments only about a week after the end of data taking in November 1998. All limits presented are at 95% confidence level.

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2. Higgs searches

The search for the Standard Model Higgs boson is one of the most active and exciting fields at LEP2. The motivation for it is strong, since the potential for discovery is supported experimentally. The latest results from the fits of the precision electroweak measurements to the SM parameters, which involve logarithmically the Higgs mass, through radiative corrections, give [1]:

$$m_{\mathrm{H}} \leq 262\,\mathrm{GeV}/c^2 \quad (95\%\,\mathrm{C.L.})\,,$$

and a non-negligible likelihood that the Higgs mass has such a value that it can be discovered at LEP2.

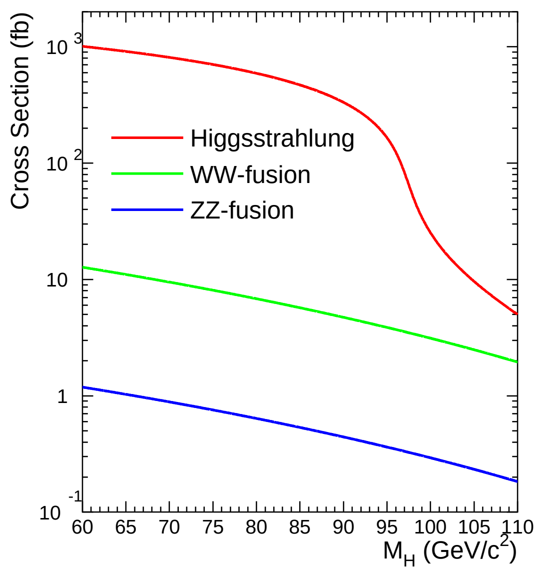

Fig. 1. The contributions to the production cross-section of the Standard Model Higgs boson at $\sqrt{s}$= 188.6 GeV.

The Standard Model Higgs boson production at LEP2 is dominated by the Higgs-strahlung process, $e^+e^- \rightarrow Z^* \rightarrow HZ$, with smaller contributions from the WW and ZZ fusion processes to the $\mathrm{H}\nu\bar{\nu}$ and He^+e^- final states. The cross-section as a function of the Higgs boson mass at $\sqrt{s}$= 188.6 GeV is shown in figure 1.

A significant difference compared to the Higgs searches in previous years, is that $\sqrt{s}$= 188.6 GeV is for the first time above the kinematic threshold for resonant Z boson pair production. This process has very similar characteristics to the signal production process (especially when the Higgs mass is close to m_Z, which is currently the region of interest), and therefore constitutes to a large degree a source of irreducible background.

At the masses of interest, the dominant decays of the Higgs boson are to b quarks ($\mathcal{BR}(H \to b\bar{b}) \sim 83\%$, for m_H=95 GeV/c^2), followed by the ones to $\tau^+\tau^-$ ($\mathcal{BR}(H \to \tau^+\tau^-) \sim 8\%$, for m_H=95 GeV/c^2). These decay modes, together with the Z decays to quarks, neutrinos and leptons, produce four distinct event topologies which are used in the searches and constitute about 90% of all HZ final states:

- $H \to b\bar{b}$ and $Z \to q\bar{q}$ ($\mathcal{BR} \sim 58\%$). The characteristics are four distinct quark jets, two of them identified as b quark jets, and the other two giving an invariant mass consistent with m_Z. These provide the handles for suppressing the background; among them the identification of b quark jets plays the most important role. More than half of the remaining background comes from ZZ, with the rest shared between the WW and $q\bar{q}$ (with gluon radiation) processes. Typical efficiencies are around 40%.

- $H \to b\bar{b}$ and $Z \to \nu\bar{\nu}$ ($\mathcal{BR} \sim 17\%$). Two acoplanar b quark jets and missing mass consistent with m_Z. Here too, the identification of b quark jets is important for the background rejection. The background is again dominated by ZZ, with the remaining contributions from WW, $We\nu$, and $q\bar{q}$ (with two initial state radiation photons escaping detection). Typical efficiencies are about 35%.

- $H \to b\bar{b}$ (or $\tau^+\tau^-$) and $Z \to e^+e^-$ or $\mu^+\mu^-$ ($\mathcal{BR} \sim 6\%$). A pair of two leptons with invariant mass close to m_Z is the characteristic signature of this final state. Despite its small branching ratio, this channel is very important, as it has high efficiency ($\sim 70\%$) and very good resolution for the Higgs boson mass (taken as the recoil mass to the lepton pair). Almost 90% of the background is ZZ and the rest mostly Ze^+e^-.

- $H \to \tau^+\tau^-$ and $Z \to q\bar{q}$ ($\mathcal{BR} \sim 5\%$) or $H \to b\bar{b}$ and $Z \to \tau^+\tau^-$ ($\mathcal{BR} \sim 3\%$). Final states with taus are characterized by two, thin, low multiplicity jets from tau decays. The identification of such jets is essential in order to reduce the background. b quark jet identification is also useful for the case $H \to b\bar{b}$. The background is mainly ZZ and WW and typical efficiencies are below 30%.

Overall, more than a third of the produced signal events would be observed. For m_H=95 GeV/c^2, this corresponds to more than ten events per experiment with the integrated luminosity collected at $\sqrt{s}$= 188.6 GeV. The observations from the four experiments are consistent with the expectations from Standard Model background processes. Figure 2 shows the distribution of the reconstructed higgs mass for the data and the simulated background

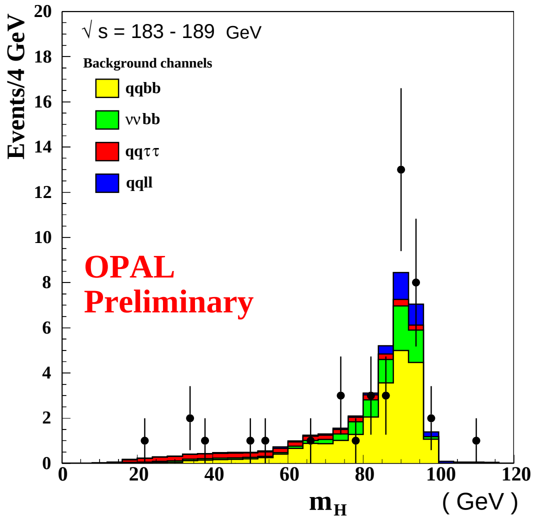

Fig. 2. Distribution of the reconstructed Higgs mass in the data (dots with error bars) and the simulation of background Standard Model processes (cumulative shaded histograms) from the OPAL experiment.

TABLE I

Expected and observed 95% C.L. mass limits for the Standard Model Higgs boson, from the four LEP experiments. The ALEPH result is given with ZZ background subtraction only (unlike the others, which are derived applying full background subtraction); preliminary studies have shown that the sensitivity is above 95 GeV/c^2, when full background subtraction is performed.

	m_H limit (GeV/c^2)	
	Expected	Observed
ALEPH	93.4	90.4
DELPHI	94.8	95.2
L3	94.9	95.5
OPAL	95.2	94.0

processes from OPAL. The observed and expected mass limits are listed in Table I.

Several possibilities for Higgs production open up in extensions of the Standard Model. In the most popular of those, the MSSM, there exist five Higgs bosons, three neutral and two charged. From the neutral Higgs bosons, the ones with most relevant masses for the searches at LEP2 are the lightest

CP-even boson h and the CP-odd boson A. These can be produced at LEP in two ways: *(i)* the Higgs-strahlung process, $e^+e^- \to Z^* \to hZ$, as in the Standard Model; *(ii)* the associated production $e^+e^- \to Z^* \to hA$; this is complementary to the former one, in the sense that its cross-section is proportional to $\cos^2(\beta-\alpha)$, while the corresponding cross-section for $e^+e^- \to hZ$ is proportional to $\sin^2(\beta-\alpha)$ (with $\tan\beta$ the ratio of vacuum expectation values of the two Higgs fields and α the mixing angle in the CP-even sector). The event selections for the Standard Model Higgs boson mentioned above,

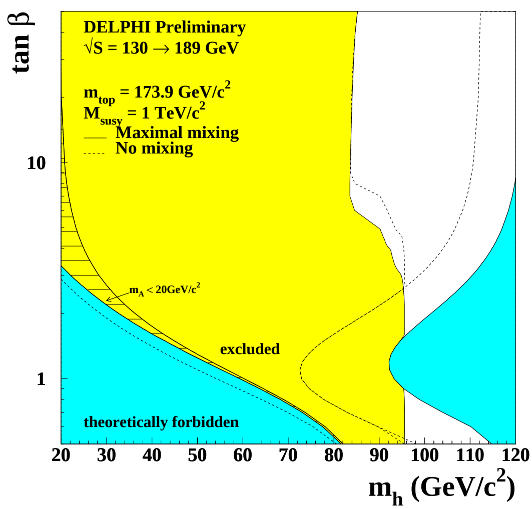

Fig. 3. The excluded region in the MSSM plane $[m_h, \tan\beta]$ from DELPHI (light shaded). The dark shaded regions are theoretically excluded, based on the calculations from [3].

are used also here for the Higgs-strahlung process, reinterpreted using the appropriate cross-section and branching ratios. The associated production gives rise to two final states, $b\bar{b}b\bar{b}$, when both h and A decay to b quarks and $b\bar{b}\tau^+\tau^-$, when one of them decays to a τ lepton pair. Special analyses are employed to select these final states, relying more heavily on the identification of b quark jets. The preliminary results at $\sqrt{s}$= 188.6 GeV are given in Table II. The excluded region in the MSSM plane $[m_h, \tan\beta]$ from DELPHI is shown in figure 3. Although it is implied by this plot that a region at low $\tan\beta$ is completely excluded, this is not strictly true due to experimental uncertainties (for example, in the top quark mass) and new theoretical calculations [2], which push the theoretically excluded region to higher values of m_h.

Charged Higgs bosons are expected in all two-Higgs doublet models. At LEP, they would be produced in pairs, $e^+e^- \to H^+H^-$, and decay to $c\bar{s}$

TABLE II

Expected and observed 95% C.L. lower limits on m_h in the MSSM. The ALEPH result is extracted with ZZ background subtraction only; about $2\,\mathrm{GeV}/c^2$ are expected to be gained in sensitivity with full background subtraction.

	m_h limit (GeV/c^2)		Comments
	Expected	Observed	
ALEPH	79.8	82.2	$\tan\beta = 10$
DELPHI	80.5	83.5	$\tan\beta > 0.5$
OPAL	—	76.0	$\tan\beta > 1.0$

or $\tau\nu$, with the branching fractions depending on the model parameters. Three topologies arise from the above decays: four jets ($c\bar{s}s\bar{c}$), two jets and a τ ($c\bar{s}\tau^+\nu$) and two τ leptons ($\tau^+\nu\tau^-\bar{\nu}$). The principal, partly irreducible background is WW, which gives similar final states. Searches are performed in all three topologies and limits are set as a function of $\mathcal{BR}(\tau\nu)$. Figure 4 shows the exclusion plot from L3. Charged Higgs bosons with masses below $72\,\mathrm{GeV}/c^2$ are excluded, independent of $\mathcal{BR}(\tau\nu)$.

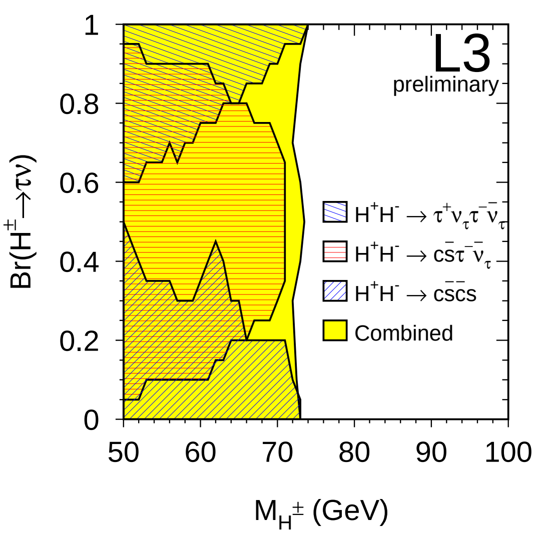

Fig. 4. Excluded charged Higgs masses as a function of $\mathcal{BR}(\tau\nu)$ from the L3 experiment.

Finally, searches have also been performed for Higgs bosons produced by the Higgs-strahlung process and decaying either invisibly (for example to two neutralinos in extensions of the MSSM) or to two photons in fermiophobic Higgs scenaria. In the former case, the topologies comprise a pair of acoplanar jets or leptons from the Z decay, while in the latter case, two energetic photons are also present. No evidence for such decays was found. For a cross-section equal to the one for the Standard Model Higgs-strahlung, the searches for invisible Higgs decays exclude Higgs masses below $87.5\,\mathrm{GeV}/c^2$ (ALEPH), while the h$\to \gamma\gamma$ search from OPAL excludes masses below $98.5\,\mathrm{GeV}/c^2$ and below $96\,\mathrm{GeV}/c^2$ in the model of Ref. [4].

3. Searches for SUSY particles

Supersymmetry is theoretically one of the most appealing extensions of the Standard Model. Its phenomenology contains a rich spectrum of new particles which makes the experimental searches exciting. Most of the results presented here refer to the MSSM with $\mathcal{R}$-parity conservation; some results from searches for signatures from $\mathcal{R}$-parity violating and gauge mediated SUSY breaking (GMSB) models are also shown.

At LEP, in the MSSM scenario with $\mathcal{R}$-parity conservation, the SUSY particles are pair-produced via s or t channel diagrams and decay to Standard Model particles and the Lightest Supersymmetric Particle (LSP) which is neutral and stable (usually the lightest neutralino) and therefore escapes detection. The energy carried away by the two LSP's in a signal event, which translates to missing energy in the event, is the characteristic signature of $\mathcal{R}$-parity conserving SUSY.

Although there is a wide range of particles to be searched for, the signals arrange themselves into just four distinct topologies:

- four jets + missing energy (charginos)
- two jets + lepton + missing energy (charginos)
- two acoplanar leptons + missing energy (charginos, neutralinos, sleptons)
- two acoplanar jets + missing energy (neutralinos, squarks)

In all cases, the signal event properties and the background composition depend critically on the mass difference, ΔM, between the produced SUSY particles and the LSP. When ΔM is small, there is little energy left to the visible system and the two photon process is the dominant background. When ΔM is large, the missing energy is small in signal events and it is, therefore, not so powerful in rejecting the background, which is dominated by the four-fermion processes and particularly WW. At these extreme regions of ΔM, the searches are rather inefficient.

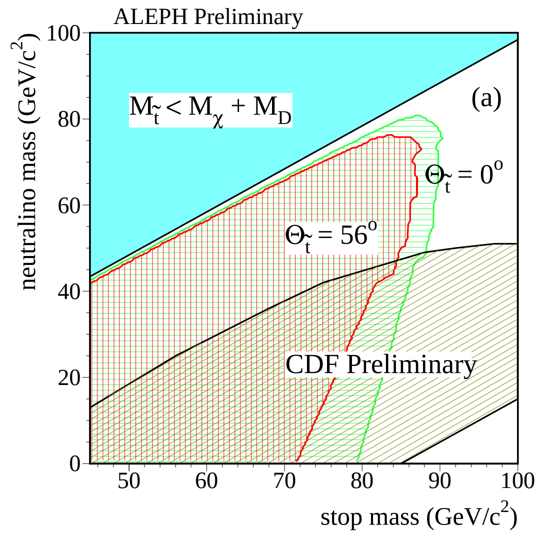

Fig. 5. The excluded $\tilde{t}_1$ masses as a function of the neutralino mass in the $\tilde{t} \to c\chi$ decay from ALEPH.

Squarks are generally expected to be heavy. It is possible, however, that, due to the large top quark mass, the mixing in the stop sector leads one of the stop mass eigenstates to be light. This is also the case for $\tilde{b}$ in a different region of the MSSM parameter space. Searches for $\tilde{t} \to c\chi$, $\tilde{t} \to b\ell\tilde{\nu}$ and $\tilde{b} \to b\chi$ showed no evidence for such signals. The derived limits depend additionally on the mixing angle in the mass matrix, since this affects the squark coupling to the Z and therefore the squark production cross section. The excluded region from the ALEPH $\tilde{t} \to c\chi$ search is shown in figure 5; this, in fact, is a good demonstration of the complementarity of the squark searches at LEP and at the Tevatron.

Limits from slepton searches are derived for $e^+e^- \to \tilde{\ell}^+_R\tilde{\ell}^-_R$ production, since the $\tilde{\ell}_R$ is expected to be lighter than the $\tilde{\ell}_L$. Single experiment limits go up to $\sim 80\,\mathrm{GeV}/c^2$ for smuons, $\sim 90\,\mathrm{GeV}/c^2$ for selectrons (thanks to the enhancement of their production cross section from the neutralino t channel exchange) and to about $72\,\mathrm{GeV}/c^2$ for staus (due to the poorer detection efficiency). These limits are valid when ΔM is more than a few GeV/c^2. The exclusions cannot easily reach the kinematic limit due to the β^3 suppression of their cross section near threshold. Therefore, here too, the combination of the results of the four experiments will be beneficial.

Charginos are excluded up to the kinematic limit ($m_{\chi^+} > 94\,\mathrm{GeV}/c^2$), except in special circumstances. This result, together with the negative direct neutralino searches, can be used to derive exclusion domains in the

MSSM plane $[M_2, \mu]$, assuming gaugino mass unification at the GUT scale. The regions excluded by ALEPH for fixed $\tan\beta$ and m_0 are shown in figure 6. By including also the slepton searches, an absolute lower limit on the mass of the lightest neutralino can be derived; the preliminary value from L3 is $28.2\,\mathrm{GeV}/c^2$.

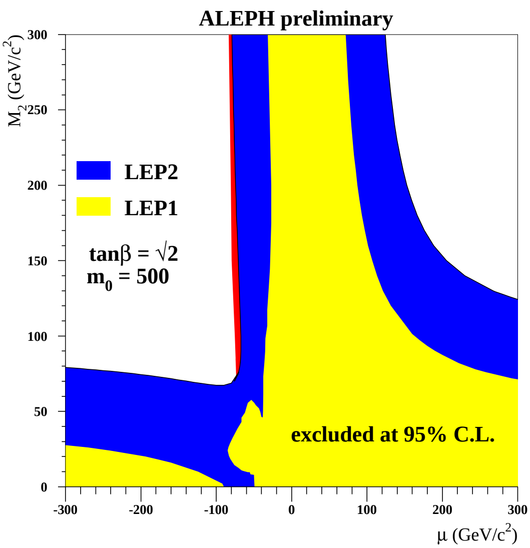

Fig. 6. The regions excluded by ALEPH in the $[M_2, \mu]$ plane.

In $\mathcal{R}$-parity violating models, the LSP is no longer stable. Hence, the signature of missing energy gives its place to more leptons and/or quark jets, depending on which $\mathcal{R}$-parity violating term in the SUSY Lagrangian is non-vanishing. Therefore, the signal topologies are numerous. No evidence for signal has been observed and the limits derived cover similar parameter regions as in the $\mathcal{R}$-parity conserving case. An interesting possibility is the s channel sneutrino exchange, which would affect the lepton cross-sections and asymmetries. This allows to probe sneutrino masses up to $\sqrt{s}$ and even beyond. Limits on the relevant $\mathcal{R}$-parity violating couplings as a function of the sneutrino mass are shown in figure 7.

In GMSB models, the gravitino ($\tilde{G}$) is the LSP. The phenomenology depends on the next-to-lightest SUSY particle (NLSP). If the NLSP is the neutralino, it would decay to $\tilde{G}$ and a photon. The signal topology in that case would be two acoplanar photons. As the $e^+e^- \to \chi\chi$ is produced via a t channel exchange of a selectron, the cross-section depends on the selectron mass and thus limits are derived as a function of it, as shown in figure 8. Alternatively, a slepton (usually assumed to be the $\tilde{\tau}_R$) can be the NLSP, in which case there are acoplanar leptons in the final state. A complication,

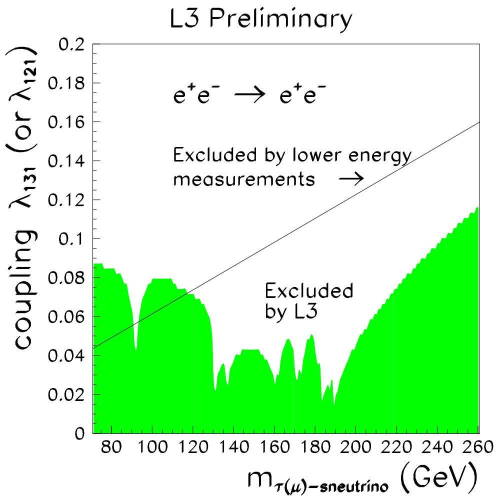

Fig. 7. Excluded values of the λ_{121} $\mathcal{R}$-parity violating coupling as a function of the sneutrino mass from L3.

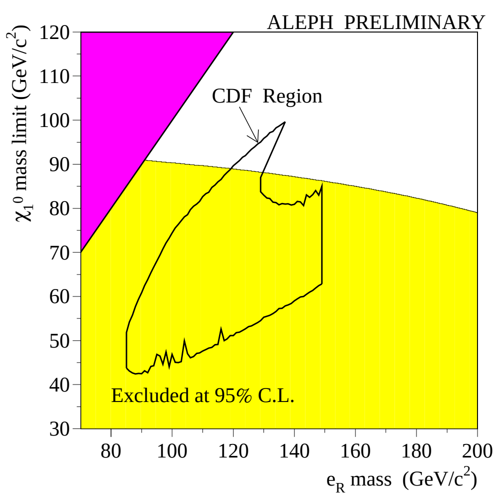

Fig. 8. The excluded region in the neutralino, selectron mass plane from ALEPH. Overlayed is the region determined from the properties of the CDF event assuming the reaction $q\bar{q}\rightarrow \tilde{e}_R\tilde{e}_R \rightarrow ee\chi\chi \rightarrow ee\gamma\gamma\tilde{G}\tilde{G}$ (taken from Ref. [5]). The dark shaded region corresponds to a topology not covered by the particular analysis.

which has to be taken into account in designing these searches, arises from the fact that the coupling of the NLSP to the gravitino may be weak leading to significant lifetime for the NLSP. A lower limit of 65 GeV/c^2 is set by ALEPH on the mass of the $\tilde{\tau}_R$ independent of it lifetime.

4. Summary and outlook

The four LEP experiments have looked for evidence of new physics in a wide variety of final states, including typical signatures such as photons, leptons, quark jets, and missing energy. The searches use standard signals (Higgs, SUSY) as guidelines, but attempt to be as model independent as possible.

Despite the wide range of searches, no deviations from the Standard Model expectations were observed in almost 700 pb^{-1} of e^+e^- data at $\sqrt{s}$=188.6 GeV.

In the Higgs sector, the sensitivity to the Standard Model Higgs boson has increased substantially and will reach the kinematic threshold ($m_H \sim$ 97 GeV/c^2) when the results of all four experiments are combined. At present, the highest single experiment mass limit is $m_h > 95.5$ GeV/c^2. In the MSSM, the lightest CP-even neutral Higgs boson h should have a mass above 83.5 GeV/c^2 for all values of $\tan\beta > 0.6$. A significant increase in sensitivity (of the order of 5 GeV/c^2) is expected for the combined LEP result. Of particular interest is the exclusion in the low $\tan\beta$ region, which is theoretically appealing in the context of the Infrared Fixed Point scenario of the MSSM. Although, with the experimental uncertainties (such as in the mass of the top quark) and recent theoretical calculations [2] taken into account, no values of $\tan\beta$ can be excluded completely, the latest negative results raise questions within the theory community about the naturalness of the remaining points [6].

No evidence for charged Higgs production was found and the exclusion has been extended up to 72 GeV/c^2, independent of the $\mathcal{BR}(H^\pm \to \tau^\pm \nu)$. Here also, the results would benefit from the combination of all LEP data. Finally, the searches for invisible Higgs decays or photonic decays of a fermiophobic Higgs boson were also negative, resulting to lower mass limits of 87.5 GeV/c^2 and 98.5 GeV/c^2 respectively for unit branching ratio and production cross-section equal to the one of the Standard Model Higgs Boson.

In the SUSY sector, the mass limits on the charginos in the MSSM have been extended to the new kinematic threshold. No sleptons or squarks were observed and lower mass limits were set between 75 and 95 GeV/c^2; here again the combination of all LEP data will be beneficial. The combination of the above negative results allows to set an absolute lower limit on the mass of the LSP close to 30 GeV/c^2. Finally, no signatures of $\mathcal{R}$-parity violating or GMSB models were detected.

The successful operation of LEP in 1998 lends great confidence and optimism for its performance in 1999 and 2000, the last two years of data taking. It is expected that already in 1999 the centre-of-mass energy will reach 200 GeV and, by the end of 2000, around 200 pb^{-1} will have been collected by each experiment at the highest centre-of-mass energy. This data will offer to the LEP experiments sensitivity to very interesting parameter regions. In the SUSY particle spectrum, another $6\,\mathrm{GeV}/c^2$ over the existing limits will become accessible. In the Higgs sector, the conclusions are similar for the pair production of Higgs bosons, while for a Higgs boson produced via the Higgs-strahlung process $e^+e^- \to hZ$, the explorable mass range will increase by almost $12\,\mathrm{GeV}/c^2$. This is a particularly interesting mass range, both in view of the results from the electroweak precision measurements, but also in the MSSM framework at low $\tan\beta$. In this way, it will be possible to exclude the existence of a Standard Model Higgs boson with mass up to $110\,\mathrm{GeV}/c^2$, or discover it if it has a mass up to $107\,\mathrm{GeV}/c^2$ or so. For example, in the scenario $\sqrt{s}$=200 GeV, $\mathcal{L} = 200\,\mathrm{pb}^{-1}$/experiment, a Higgs boson with m_h= $105\,\mathrm{GeV}/c^2$ would give rise to the production of about 120 signal events and about 40 of them would be selected, making a statistically compelling discovery.

I would like to thank warmly the organizers for their hospitality and the excellent organisation of the conference. I also wish to congratulate my colleagues from the accelerator division of CERN for the very successful operation of LEP in 1998, and finally thank my colleagues from the four LEP collaborations for offering swiftly material for this review.

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