New Particle Searches

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1 Introduction

This review covers a few selected topics from the searches performed at the Tevatron, HERA, and LEP2. Details on the data samples analyzed at the time of the conference are given in Table 1.

collider	experiments	beams	$\sqrt{s}$	period	$\mathcal{L}$/expt (pb^{-1})
Tevatron	CDF/D0	$\mathbf{p\bar{p}}$	1.8 TeV	1987/1996	~ 110
HERA	H1/ZEUS	$\mathbf{e^+p}$	300 GeV	1994/1997	~ 40
		$\mathbf{e^-p}$	318 GeV	1998/1999	~ 15
LEP2	ALEPH/DELPHI	$\mathbf{e^+e^-}$	130 to 183 GeV	1995/1997	~ 90
	L3/OPAL	$\mathbf{e^+e^-}$	189 GeV	1998	~ 170
		$\mathbf{e^+e^-}$	192/196 GeV	1999	~ 105

Table 1: Data samples analyzed for the 1999 summer conferences by experiments at Tevatron, HERA, and LEP2. The last column gives the integrated luminosity per experiment for each of the data taking periods.

New particle searches are dominated by LEP, whose results come mostly from data up to 189 GeV except for some updates from 1999 data up to 196 GeV. Combined results from the four LEP experiments also exist on some subjects and are denoted ADLO.

After a brief outline of the searches on exotic particles, results on supersymmetric particles and Higgs bosons are detailed. All exclusion limits are at the 95% confidence level.

2 Exotic particles

Searches for exotic particles encompass a great variety of topics, such as technicolor particles [1], new Z' bosons [2, 3], four fermion contact interactions [4, 3], new, excited, or exotic fermions [5], and leptoquarks. Constraints are derived at the three colliders either from direct searches or from comparing precise measurements with Standard Model (SM) expectations.

As an illustration, the case of leptoquark (LQ) searches is detailed. The phenomenology of leptoquarks is described by three parameters: the LQ mass $\mathrm{M_{LQ}}$ and the LQ coupling λ_{lq} and the branching ratio β_l to a given SM lepton and quark. Results are interpreted either assuming leptoquarks to be coupled to a single SM generation, with fixed β_l (as in the BRW model [6]) or, in more generic models, assuming β_l variable and possible mixed couplings.

collider	LQ type	assumptions	limit (GeV/c^2)	couplings
Tevatron	1st gen. LQ	β_e=1	242	any λ_eq
Tevatron	2nd gen. LQ	β_μ=1	202	any $\lambda_{\mu\mathrm{q}}$
Tevatron	3rd gen. LQ	β_{ν_τ}=1	149	any $\lambda_{\nu_\tau\mathrm{q}}$
Tevatron	3rd gen. LQ	β_τ=1	99	any $\lambda_{\tau\mathrm{q}}$
HERA	1st gen. LQ	BRW model	265	$\lambda_\mathrm{eq}=0.3$
LEP2	1st or 2nd gen. $\mathrm{S}_{1,L}$	BRW model	370	$\lambda_\mathrm{lq}=0.3$

Table 2: Limits on leptoquarks from Tevatron, HERA and LEP2. Specific values have been assumed for the LQ branching ratios and/or couplings to SM particles. Precise measurement at LEP2 allow one to probe high masses in some specific cases only.

The current constraints in the first approach [7, 8] are summarized in Table 2. The interpretation in generic models has been pioneered by H1 [7]. As an example, Fig. 1 shows the regions excluded by H1 and DO in the plane $\mathrm{M_{LQ}}$ vs β_e for first generation leptoquarks. HERA sensitivity extends down to small β_e even for small couplings. For example, for $\beta_\mathrm{e} \sim 10\%$ and $\lambda_\mathrm{eq} \sim 0.05$, leptoquark masses up to 200 GeV/c^2 are excluded. The interesting case of mixed couplings has also been studied [7]. To cite one result, leptoquarks with couplings to both (e,q) and (τ,q) have been found to be excluded with a sensitivity similar to that quoted for pure first generation leptoquarks.

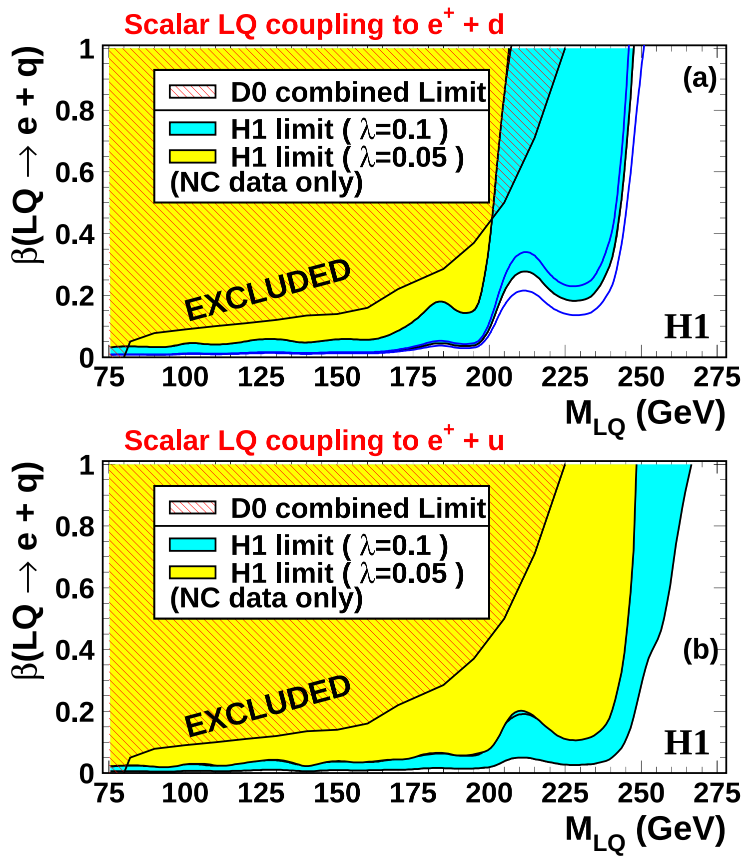


Figure 1: Constraints on first generation leptoquarks from H1 and DO. For $\lambda = 0.1$, the error bands illustrate the sensitivity to d and u quark densities.

3 Supersymmetric particles

All supersymmetric particle searches are conducted within the context of the Minimal Supersymmetric Standard Model (MSSM) with additional assumptions to decrease the number of free parameters. Depending on those assumptions, the phenomenology differs and so do the experimental signatures. At present, three theoretical frameworks are studied.

3.1 Constrained MSSM

The most common framework assumes R-parity conservation and soft supersymmetry breaking mediated by gravity. Soft breaking terms are thus unified at high energy (the so-called GUT scale) and the number of free parameters is reduced to five: the common sfermion[1] mass term at GUT scale m_0, the common gaugino mass term at GUT scale $m_{1/2}$, the common trilinear coupling at GUT scale A_0, the Higgs mixing parameter μ, and the ratio of the two Higgs doublet vacuum expectation values $\tan\beta$.

The phenomenology at low energy is derived using renormalization group equations. The lightest supersymmetric particle (LSP) is in most cases the lightest neutralino, $\tilde{\chi}_1^0$. Due to R-parity conservation, sparticles are produced in pairs and decay to their SM partner and a sparticle. At the end of the decay chain, the LSP appears and, because it is stable, gives rise to missing energy. Results on all types of sparticles have been reported at the conference.

Sfermions

Charged sleptons and light squarks are searched for at LEP through the decays summarized in Table 3, which are the dominant decays if the sparticle considered is the next lightest one after the LSP. The experimental sensitivity depends on both the sfermion mass and the mass difference ΔM between the sfermion and the LSP. For the LEP experiments at 189 GeV [9], the experimental sensitivity starts from ΔM above a few GeV/c^2 and covers sfermion masses up to 70 to 90 GeV/c^2, depending on the sfermion, as can be seen in Table 3. Similar sensitivities are reached by the individual LEP experiments at 196 GeV [10]. All LEP results are derived for minimal production cross-sections and hence have a general validity.

Light squarks are also searched for at the Tevatron [11]. The experimental sensitivity is complementary to that of LEP, because it covers higher squark masses and starts at higher ΔM, as illustrated in Table 3. Searches for heavy squarks and gluinos belong exclusively to the Tevatron [12]. The final states result from $\tilde{q}$ and $\tilde{g}$ cascade decays to the LSP and quarks, gluons, and W or Z bosons. The present experimental reach is about 250 GeV/c^2, but it must be noted that most results are derived for specific values of some mSUGRA parameters ($A_0 = 0$, $\mu < 0$, and $\tan\beta = 2$), which restricts their range of validity.

Charginos and neutralinos

Due to its excellent coverage of the various signatures of supersymmetry, LEP provides limits on the masses of the lightest chargino and neutralino which are practically absolute in the constrained MSSM framework.

[1] Tevatron experiments use a somewhat different and more constrained scheme, called minimal supergravity (mSUGRA), which defines m_0 as a common scalar mass term at the GUT scale and assumes in addition radiative EW symmetry breaking, so that μ is fixed up to a sign.

experiment	sfermion	decay	obs. limit (GeV/c^2)	exp. limit (GeV/c^2)	ΔM (GeV/c^2)
ADLO 189 GeV	$\tilde{\mathrm{e}}_\mathrm{R}$	$\mathrm{e}\ \tilde{\chi}_1^0$	89	90	> 15
	$\tilde{\mu}_\mathrm{R}$	$\mu\ \tilde{\chi}_1^0$	84	83	> 15
	$\tilde{\tau}_\mathrm{R}$	$\tau\ \tilde{\chi}_1^0$	71	77	> 15
ADLO 189 GeV	$\tilde{\mathrm{t}}_1$	$\mathrm{c}\ \tilde{\chi}_1^0$	87	84	> 10
	$\tilde{\mathrm{t}}_1$	$\mathrm{b\ l}\ \tilde{\nu}$	90	87	> 10
	$\tilde{\mathrm{b}}_1$	$\mathrm{b}\ \tilde{\chi}_1^0$	80	68	> 10
CDF run I	$\tilde{\mathrm{t}}_1$	$\mathrm{c}\ \tilde{\chi}_1^0$	89	-	> 40
	$\tilde{\mathrm{b}}_1$	$\mathrm{b}\ \tilde{\chi}_1^0$	105	-	> 40

Table 3: Lower limits on sfermion masses. Combined LEP results up to 189 GeV are given as well as CDF results from run I. The LEP expected limits are computed from simulation only, assuming no signal. The last column gives the range of validity of the limits expressed as a minimal difference between the masses of the sfermion and the LSP ($\tilde{\chi}_1^0$ or $\tilde{\nu}$).

Direct searches for the lightest chargino $\tilde{\chi}_1^\pm$ provide limits on $m_{\tilde{\chi}_1^\pm}$ close to the kinematical limit in most of the parameter space [10]. As $\tilde{\chi}_1^0$ cannot be detected, direct neutralino searches rely on the production of heavier neutralinos (*e.g.* $\tilde{\chi}_1^0\,\tilde{\chi}_2^0$ or $\tilde{\chi}_2^0\,\tilde{\chi}_2^0$) and thus bring little constraint on $m_{\tilde{\chi}_1^0}$ except when $\tan\beta$ is close to 1. But, combining the results from $\tilde{\chi}_i^0$ and $\tilde{\chi}_1^\pm$ searches provides a limit on $m_{\tilde{\chi}_1^0}$ valid for large m_0 for any values of the other parameters [10].

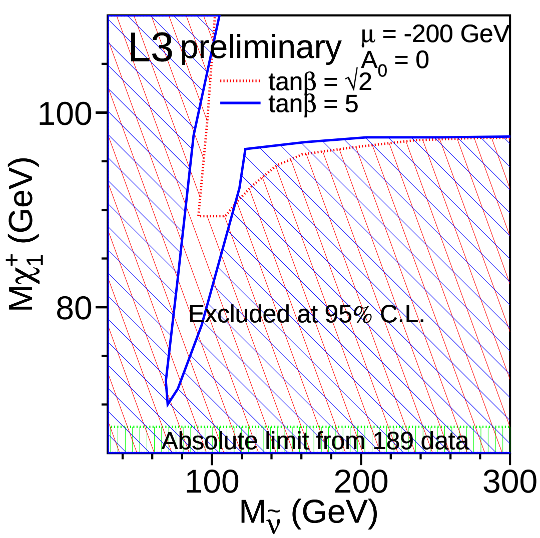
For low values of m_0 (which imply light $\tilde{\nu}$), the $\tilde{\chi}_1^\pm$ production cross-section drops due to the negative interference between the s-channel production process and the t-channel $\tilde{\nu}$ exchange diagram. The $\tilde{\chi}_1^\pm$ decay into $\mathrm{l}\ \tilde{\nu}$ becomes dominant and escapes detection when $\tilde{\chi}_1^\pm$ and $\tilde{\nu}$ become degenerate. Under the same conditions, the $\tilde{\chi}_i^0$ production increases (because of a positive interference term), but the $\tilde{\chi}_i^0$ decay into $\nu\ \tilde{\nu}$ opens, leading to invisible final states. However, low values of m_0 also mean light sleptons, which are thus within experimental reach. Combining $\tilde{\chi}_i^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\mathrm{l}}$ searches, limits on $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$ valid for A_0=0, and for all values of the other parameters can be derived [13, 14], as illustrated in Table 4 and Fig. 2. Preliminary studies varying A_0 (that is allowing for $\tilde{\tau}$ mixing) show that the limit on $m_{\tilde{\chi}_1^\pm}$ may be affected, but not that on $\tilde{\chi}_1^0$ [14].

3.2 R-parity breaking ($\not{R}_p$)

In the second theoretical framework, soft supersymmetry breaking is still mediated by gravity but R-parity ($\mathrm{R_p}$) is assumed to be broken via an extra term in the

experiment	$\sqrt{s}$ (GeV)	searches combined	limit (GeV/c^2)	validity
OPAL	196	$\tilde{\chi}_1^\pm$	$m_{\tilde{\chi}_1^\pm} > 97.6$	large m_0, $\Delta M > 10$ GeV/c^2
ALEPH	196	$\tilde{\chi}_1^\pm$, $\tilde{\chi}_i^0$	$m_{\tilde{\chi}_1^0} > 34.0$	large m_0
L3	189	$\tilde{\chi}_1^\pm$, $\tilde{\chi}_i^0$, $\tilde{l}$	$m_{\tilde{\chi}_1^\pm} > 67.7$	A_0=0
L3	189	$\tilde{\chi}_1^\pm$, $\tilde{\chi}_i^0$, $\tilde{l}$	$m_{\tilde{\chi}_1^0} > 32.5$	absolute

Table 4: Lower limits on $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$, from LEP. As more results are used, the range of validity of the limits extends.



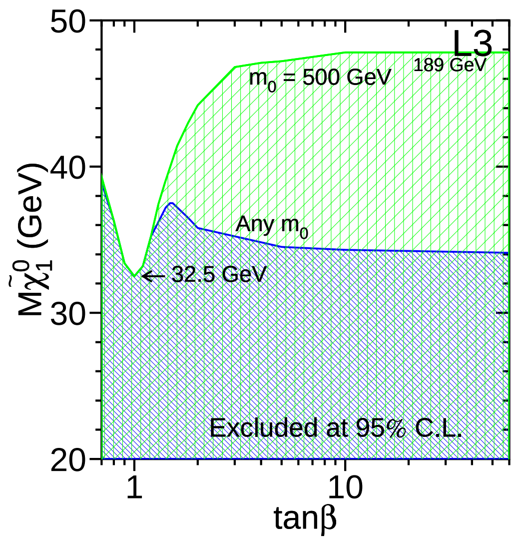


Figure 2: Left: L3 Limit on $m_{\tilde{\chi}_1^\pm}$ as a function of $m_{\tilde{\nu}}$. The absolute limit from data up to 189 GeV is compared with the 1999 limits obtained for two sets of the MSSM parameters. For a heavy $\tilde{\nu}$ the kinematical limit is almost reached while for a $\tilde{\nu}$ around 70 GeV/c^2, the limits drop. Right: L3 limit on $m_{\tilde{\chi}_1^0}$ as a function of $\tan\beta$ from data up to 189 GeV. The limit obtained at large m_0, varying the other parameters, is compared with the limit obtained when m_0 is also allowed to vary. The absolute limit corresponds to $\tan\beta$=1.

superpotential of the form:

$$\mathcal{W} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \quad (1)$$

where ijk denote generation indices and the capital letters refer to superfields associated to left-handed doublets of leptons (L) and quarks (Q), and right-handed singlets of charged leptons (E), down-type quarks (D), and up-type quarks (U). $\mathcal{W}$ implies violation of the leptonic and baryonic numbers. In addition to the five parameters related to supersymmetry breaking (m_0, $m_{1/2}$, A_0, μ, and $\tan\beta$), R_p breaking introduces 45 couplings (9 λ_{ijk}, 27 λ'_{ijk}, and 9 λ''_{ijk}). For sake of simplicity, searches are conducted assuming that only one coupling dominates at a time and all sparticles decay close to the interaction vertex. This latter hypothesis corresponds to assuming the $\not{R}_p$ couplings to be greater than values which are at least two orders of magnitude below the current experimental limits on most couplings.

Compared to R_p conservation, $\not{R}_p$ modifies the phenomenology at low energy. Single sparticle production is possible, the LSP (which is still $\tilde{\chi}^0_1$ in most cases) is no longer stable and the sparticle decay patterns change a lot. A sparticle can decay into SM particles through one $\not{R}_p$ vertex (as shown for the $\tilde{\nu}$ case in Fig. 3a) or via an R_p conserving vertex leading to an off-shell sparticle that decays through an $\not{R}_p$ vertex (as shown for the $\tilde{\chi}^0_1$ and $\tilde{\chi}^{\pm}_1$ in Fig. 3a). These decays are referred to as direct decays. A second type of decays, called indirect decays, involves cascade decays to SM particles through several R_p conserving and $\not{R}_p$ vertices with some sparticles on-shell, as shown in Fig. 3b.

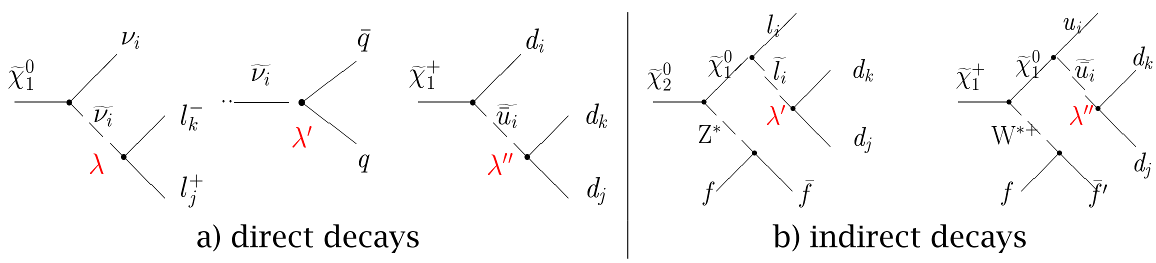


Figure 3: Examples of decays allowed by R_p violation.

Thus, there are many final states to consider, with multileptons and/or multijets and possibly missing energy from neutrinos. As in the constrained MSSM case, all types of sparticles have been searched for.

Charginos and neutralinos

As in the R_p conserving scheme, LEP sets constraints on charginos and neutralinos which are valid over wide ranges of the underlying parameters (except A_0 which is set to 0). The $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_i$ production modes are as in the R_p conserving case, while their decay pattern is completely modified. The most notable change concerns the LSP whose production leads to observable final states whatever the dominant $\not{R}_p$ coupling. All experimental signatures expected from the production and decays of $\tilde{\chi}^+_1\,\tilde{\chi}^-_1$, $\tilde{\chi}^0_1\,\tilde{\chi}^0_1$, and $\tilde{\chi}^0_2\,\tilde{\chi}^0_1$ have been investigated at LEP2. Because $\tilde{\chi}^0_1$ is detectable, combining $\tilde{\chi}^0_i$ and $\tilde{\chi}^{\pm}_1$ searches alone suffices to derive constraints [15] on the sparticle masses valid for $A_0 = 0$ and all values of the other parameters, as illustrated in Table 5.

$R\!\!\!/_p$ coupling type	limits (GeV/c^2) $M_{\tilde\chi_1^0}$	$M_{\tilde\chi_2^0}$	$M_{\tilde\chi_1^\pm}$
λ, λ' couplings:	30	50	94
λ'' couplings:	32	67	94

Table 5: L3 limits on $\tilde\chi_1^0$, $\tilde\chi_2^0$, and $\tilde\chi_1^\pm$ masses in the $R\!\!\!/_p$ scheme, from data up to 189 GeV.

Sneutrinos

Another appreciable change due to $R\!\!\!/_p$ is the allowed decay of sneutrinos which makes them directly observable. Sneutrinos can appear at LEP through both double and single production.

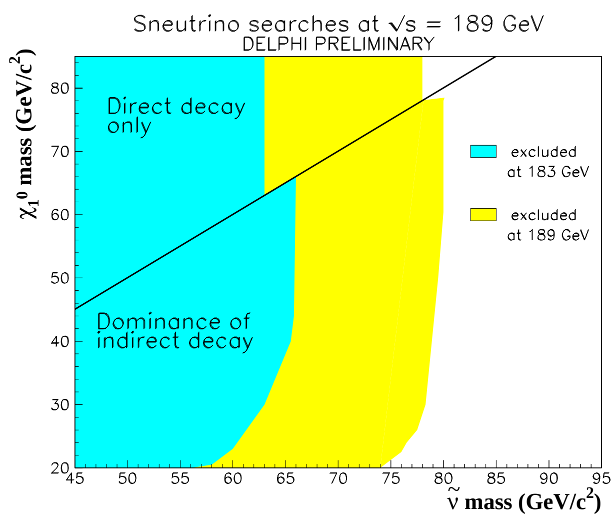


Figure 4: DELPHI limit on sneutrino pair production as allowed by $R\!\!\!/_p$ with a dominant λ_{133} coupling.

All final states expected from pair production have been searched for. As an example, a result for a dominant λ_{133} coupling is given in Fig. 4. Using also the limit on $m_{\tilde\chi_1^0}$, exclusion limits can be derived for each of the three $R\!\!\!/_p$ coupling classes. The current limits [15] are presented in Table 6. They are valid for all values of the underlying parameters, except A_0 which is set to 0.

$\not R_p$ coupling type	experiment	limit on $m_{\tilde{\nu}}$ (GeV/c^2)	$\tilde{\nu}$ flavor
λ couplings:	DELPHI	78	any $\tilde{\nu}$ flavor
λ' couplings:	ALEPH	56	any $\tilde{\nu}$ flavor
λ'' couplings:	ALEPH	77	$\tilde{\nu}_e$ only

Table 6: LEP limits on $\tilde{\nu}$ masses in the $\not R_p$ scheme, from data up to 189 GeV.

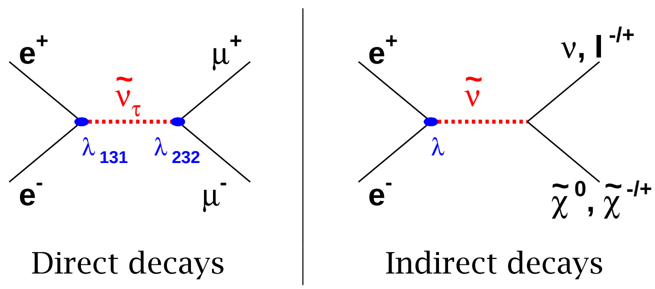


Figure 5: Single production of sneutrinos at LEP as allowed by $\not R_p$.

Single production of $\tilde{\nu}_\mu$ or $\tilde{\nu}_\tau$ sneutrinos is also possible at LEP, as illustrated in Fig. 5. Sneutrino direct decays would lead to effects observable as deviations from SM expectations, while indirect decays would manifest themselves as specific final states that require dedicated searches. In both cases, constraints on sneutrino masses have been derived as a function of the $\not R_p$ couplings. Currently, masses up to 100 to 200 GeV/c^2 are probed, and limits on couplings are of the order of a few 10^{-2} [16].

Charged sleptons and squarks

Charged sleptons and light squarks are searched for at LEP. The coverage of the final states expected in case of $\not R_p$ (from direct and indirect decays and for any type of couplings) is not yet as complete as for the other sparticles. The results achieved so far [15] are summarized in Table 7. As for other LEP results, they hold for $A_0 = 0$, irrespective of the values of the other underlying parameters.

Finally, there are also constraints on heavy squarks and gluinos if R_p is violated. The LEP experiments can reinterpret their results for leptoquark searches [17], while dedicated searches are performed at HERA and Tevatron for particular $\not R_p$ couplings. The HERA experiments have access mostly to λ'_{1j1} couplings and derive constraints on heavy squark masses as a function of λ'_{1j1}, varying the underlying parameters of the MSSM. Currently, masses up to 240 GeV/$c^2$are excluded

$\not R_p$ coupling type	experiment	sparticle	mass limit (GeV/c^2)
λ couplings:	ALEPH	$\tilde{e}_R$	84
λ couplings:	ALEPH	$\tilde{\mu}_R$, $\tilde{\tau}_R$	60
λ' couplings:	OPAL	$\tilde{t}_1$	84
λ'' couplings:	OPAL	$\tilde{t}_1$	79

Table 7: LEP limits on charged slepton and light squark masses in the $\not R_p$ scheme, from data up to 189 GeV. The $\tilde{t}_1$ limits are valid for any value of the stop mixing angle.

for $\lambda'_{1j1} \sim 0.3$ [18]. Using multilepton events in run I data, Tevatron experiments have probed both the λ'_{1jk} and λ_{121} couplings, and constrained gluino and heavy squark masses. The limits achieved are around 250 (respectively, 350) GeV/c^2 for the λ'_{1jk} (respectively, λ_{121}) coupling analysis [19]. These limits are valid for $A_0 = 0$, $\mu < 0$, and $\tan\beta = 2$. Most of the other choices (in particular, higher values of $\tan\beta$ or $\mu > 0$) would lead to lower limits, due to a loss in sensitivity resulting from reduced branching fractions into leptons, softer leptons, and other factors [19].

3.3 Gauge mediated supersymmetry breaking (GMSB)

The third theoretical framework assumes R_p conservation and soft supersymmetry breaking mediated by gauge interactions. Such models [20] usually need six basic parameters: the supersymmetry breaking scale $\sqrt{F}$, the universal mass scale of supersymmetric particles Λ, the messenger mass scale M_s, the number of messenger generations n_s, the Higgs mixing parameter μ, and the ratio of the two Higgs doublet vacuum expectation values $\tan\beta$. The breaking scale is expected to be much lower than in gravity-mediated models, down to about 10^4 GeV.

As far as phenomenology at low energy is concerned, R_p conservation implies as usual sparticle pair production and a stable LSP. As a consequence of gauge-mediated breaking, the LSP is the gravitino, $\tilde{G}$, whose mass depends on $\sqrt{F}$ and thus is expected to be very small, in the range 10^{-6} eV to 1 keV. The next lightest sparticle (NSLP) is either $\tilde{\chi}^0_1$ or a charged slepton ($\tilde{\tau}_1$ or three degenerate $\tilde{l}$). The NSLP lifetime is governed by the $\tilde{G}$ mass and hence can be non-negligible, giving rise to specific topologies, some of which are experimental challenges.

$\tilde{\chi}_1^0$ NLSP

The main decay of a $\tilde{\chi}_1^0$ NLSP would be to $\gamma\tilde{G}$. Thus, $\tilde{\chi}_1^0$ searches rely on final states with photons, either single-photon or diphoton events. Such final states provide clean experimental signatures and have been used for a long time to chase new physics, whatever the underlying theoretical framework. Results are usually expressed as model-independent upper limits on the cross-section times branching fraction, as a function of the mass of the unknown particle that decays to a photon plus missing energy. These cross-section limits are then compared with predictions from various models [21, 22], such as the GMSB scenario invoked to explain an ee$\gamma\gamma$ event reported by CDF some years ago. To quote one result (even if it is not strictly a GSMB model), cross-section limits have been converted into a lower limit on the mass of a superlight $\tilde{G}$, assuming all other sparticles to be above threshold. The current limit from single-photon events at LEP2 [21] is 10^{-5} eV/c^2, similar to the result reached by CDF using monojet events [23].

Topologies more specific to GMSB models have also been searched for. The first example is given by $\tilde{\chi}_1^0$ searches in case of long neutralino lifetimes. The decay photons would not be produced at the interaction point but,instead, would have large impact parameters. Searches for non-pointing single-photon events [21] cover that case. Searches for sparticles heavier than $\tilde{\chi}_1^0$ have also been performed. So far, these have considered charginos and sleptons [24] only. Compared with the topologies expected in the gravity-mediated scheme, the final states are identical except for additional photons that can be detected if the NLSP lifetime is not too long. Because photons help to better discriminate against background, the exclusion limits for negligible or moderate NSLP lifetimes are usually tighter than those in the gravity-mediated framework.

$\tilde{\tau}_1$ NLSP

The main decay of a $\tilde{\tau}_1$ NLSP would be in $\tau\,\tilde{G}$, thus giving the same experimental signature as in the gravity-mediated case only if the $\tilde{\tau}_1$ lifetime is negligible. In the opposite case, $\tilde{\tau}_1$ decays would lead to kinks, large impact parameters, or decay vertices. Eventually, a $\tilde{\tau}_1$ decaying outside the detector would appear as a stable charged particle. All these experimental signatures have been used in $\tilde{\tau}_1$ searches [24]. An example of a result is given in Fig. 6, which illustrates the interplay of the different signatures. The limits are plotted as a function of the $\tilde{G}$ mass, which determines the $\tilde{\tau}_1$ mean decay length. Irrespective of the $\tilde{G}$ mass, these results exclude a $\tilde{\tau}_1$ NLSP up to 73 GeV/c^2. The limit is 6 GeV/c^2 higher if the results are reinterpreted in a scenario with three degenerate co-NLSP charged sleptons.

Searches for sparticles heavier than $\tilde{\tau}_1$, including charginos, neutralinos, and

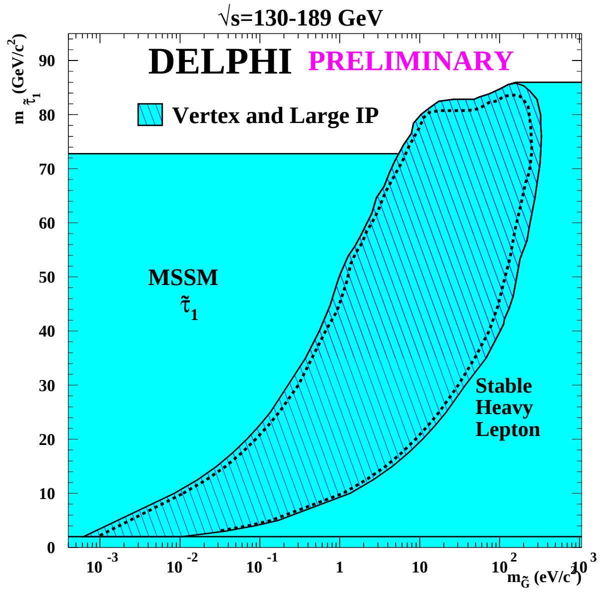


Figure 6: DELPHI lower limit on the $\tilde{\tau}_1$ mass as a function of the $\tilde{G}$ mass in GMSB models, from data up to 189 GeV.

sleptons [24], have also been performed, but only for negligible NLSP lifetimes.

Constraining underlying parameters

Even if not complete, the coverage of the final states expected from GMSB models is at present sufficient to exclude large fractions of the parameter space in order to set constraints on the key parameters of the model, such as the NLSP mass and Λ. A first attempt has been reported in [25] for a minimal GMSB model.

3.4 Other searches, recent developments

To conclude with supersymmetry, it is worth mentioning a few complementary results from LEP, either recent ones or results outside the main stream of searches described in the previous sections.

There is an ongoing effort to combine the four experiment results (on $\tilde{\chi}_1^{\pm}$, $\tilde{e}_R$, $\tilde{\tau}_1$ searches, using also Higgs searches and the Γ_Z constraint) to derive an absolute limit on the $\tilde{\chi}_1^0$ mass in the mSUGRA framework. Preliminary results [26] from data up to 189 GeV give a limit of 44 GeV/c^2 if the difference between the $\tilde{\tau}_1$ and $\tilde{\chi}_1^0$ masses is above 5 GeV/c^2, irrespective of the values of the underlying parameters (except A_0, which is set to 0). Recently, dedicated searches have been performed to cover mass differences below 5 GeV/c^2, and the first results confirmed the validity of the above limit also in that case [27]. The next step should be to check the impact of A_0, which is expected to be large.

For $\not{R}_p$, the superpotential quoted in equation (1) is not the most complete R_p violating potential. Extra bilinear terms of the form $\varepsilon_i L_i H_2$, where H_2 is the Higgs superfield with positive hypercharge, are also possible candidates to generate $\not{R}_p$. First results have been reported recently on a search for stops decaying through a bilinear term into a bτ pair [28].

Finally, if R_p is conserved, the stability of the LSP restricts the experimental sensitivity to other sparticles to mass differences between the sparticle and the LSP in excess of a few GeV/c^2. Searches have been conducted to explore nearly mass-degenerate cases for the lightest chargino [29] and more recently for the lightest selectron [30]. Note that sparticles degenerate with the LSP can exist in restricted regions of the parameter space of the constrained MSSM as defined in Section 3.1, but they may occur more easily in other supersymmetric scenarios, such as a constrained MSSM without gaugino mass unification at the GUT scale or the recent anomaly mediated SUSY breaking models [20].

4 Search for extra dimensions

It was pointed out recently [31, 20] that extra spatial dimensions, which are present in any superstring theory, can also solve the hierarchy problem, independently of the underlying theoretical framework. Indeed, if n extra compact spatial dimensions of radius R exist, the quantum gravity scale in n+4 dimensions, M_D, is related to the Planck scale, M_{Pl}, by $M_{Pl}^2 \sim R^n M_D^{2+n}$. If R and n are such that M_D is of the order of the electroweak (EW) scale, the hierarchy vanishes. The case n=1 is ruled out because it would imply quantum gravity effects observable over solar system distances.

At low energy, extra spatial dimensions are expected to manifest themselves through the production of gravitons, G, observable in both direct searches and precise measurements. Searching for the associated production of a pair (γ, G) in single photon final states at LEP2 leads to constraints on M_D depending on n. As an example, M_D has been found to be greater than 1.1 TeV, 0.7 TeV, and 0.53 TeV for 2, 4, or 6 extra dimensions, respectively [32]. Gravitons would also be responsible for deviations from the SM in precise measurements. Combining observables in several final states at LEP, the ultra-violet cut-off of the underlying quantum gravity theory has been constrained to be larger than 0.8 TeV (respectively, 1.1 TeV) if the interference between the SM and G exchange amplitudes is negative (respectively, positive) [32].

5 Higgs bosons

The phenomenology of Higgs bosons is not very model-dependent, and this allows one to cover several theoretical frameworks with a limited number of searches. The results to be discussed encompass neutral Higgs bosons as expected in the SM, MSSM and beyond, as well as charged Higgs bosons in two Higgs doublet models.

5.1 The Standard Model Higgs boson

In the mass range currently under study, around 100 GeV/c^2, only LEP would be sensitive to the SM Higgs boson. The main production process leads to pairs of Higgs and Z bosons, with the Z boson on-shell. Due to the clean experimental environment, all Z final states are exploited. In addition, the Higgs boson is expected to decay mainly into a $b\bar{b}$ pair (the branching fraction is $\sim$ 82% for a 100 GeV/c^2 Higgs boson) so that the excellent b-tagging capabilities of the LEP detectors help a lot in these searches.

	bkg	data	exp. limit (GeV/c^2)	obs. limit (GeV/c^2)	1-CL$_b$ at obs. lim.
ALEPH	44.4	53	95.9	92.9	4%
DELPHI	172.7	187	94.6	94.1	20%
L3	91.1	94	94.8	95.3	64%
OPAL	35.4	41	94.9	91.0	4%

Table 8: Rates and exclusion limits obtained at LEP in the SM Higgs boson searches in 189 GeV data. Results observed in data are compared with expectations from background simulation. The last column gives the probability of having a less background-like result than that observed.

The results obtained at 189 GeV by the four LEP experiments [33] are detailed in Table 8, which gives the numbers of selected events that are compared with simulation to test the background and signal+background hypotheses and derive exclusion limits or discovery significances. To achieve the highest sensitivity to the signal, these derivations rely on a test-statistic which, in addition to the overall rates, take into account the properties of the selected events (the reconstructed Higgs boson mass, m_H, or m_H and another discriminant variable like the event b-quark content) [34]. The more information in the comparison, the earlier the event selection procedure is stopped. This is illustrated in Table 8 by the different selection levels in the four experiments. There is an excess number of events in the data in three experiments, and these are partly signal-like in two

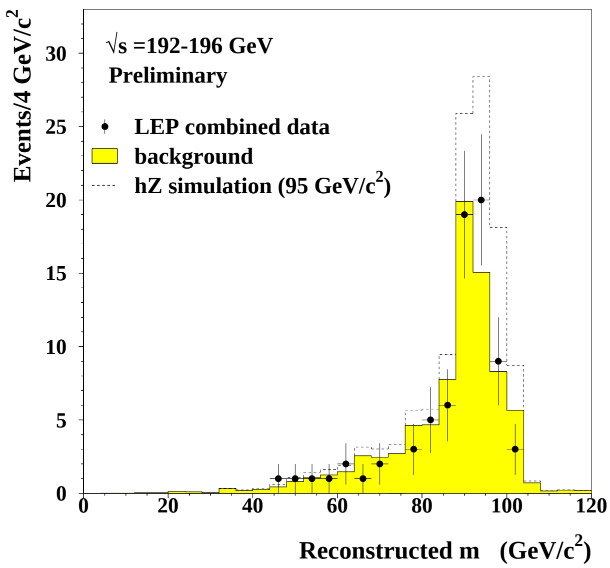


Figure 7: Reconstructed Higgs boson mass spectrum in LEP data at 192 and 196 GeV. Data (dots) are compared with background simulation (full histogram) and with signal simulation in the hypothesis of a SM Higgs boson of 95 GeV/c^2(dashed histogram). 74 events are selected in data while 81.1 are expected from background.

	$\mathcal{L}$ (pb^{-1})	bkg	data	exp. limit (GeV/c^2)	obs. limit (GeV/c^2)
ALEPH	98	32.3	27	99.9	98.8
DELPHI	84	15.4	15	97.0	97.3
L3	109	42.2	38	97.3	98.7
OPAL	85	21.0	23	97.3	95.4

Table 9: Rates and exclusion limits obtained at LEP in the SM Higgs boson searches in data at 192 and 196 GeV. Results observed in data are compared with expectations from background simulation.

cases, as revealed by the difference of a few GeV/c^2 between the observed and expected exclusion limits. After investigation, part of the excess was attributed to a systematic bias. When combining the four LEP experiments, the exclusion limit is 95.2 GeV/c^2, compared with an expectation of 97.2 GeV/c^2 [35].

A preliminary update at 196 GeV was reported at the conference [36], as shown in Table 9. The reconstructed Higgs boson mass distribution after tighter selections is given in Fig. 7. The excess seen at 189 GeV has not been confirmed at higher energies, and the data agree with expectations. After the conference, these results were combined, giving an exclusion limit of 102.6 GeV/c^2, for an expected limit of 102.3 GeV/c^2 [37]. At the end of the 1999 run, which reached $\sqrt{s}$=202 GeV, experiments reported preliminary limits up to 106 GeV/c^2, in good agreement with the expected ones [38]. Prospects for the last run of LEP at $\sqrt{s}$ up to 206 GeV are 114 GeV/c^2 for the 95% exclusion or 3σ discovery potentials and 111 GeV/c^2 for the 5σ discovery sensitivity, when the four experiments are combined [39]. Higher masses up to 180 GeV/c^2 should be accessible in the future high luminosity run at the Tevatron [40].

5.2 MSSM neutral Higgs bosons

Most results about neutral Higgs bosons in the MSSM come also from LEP, which is sensitive to the two lightest bosons, h and A. There are two production processes, $e^+e^- \to hZ$, as in the SM case, and $e^+e^- \to hA$. The two processes are complementary in the parameter space. In the mass range between 80 and 110 GeV/c^2, the main decay mode of both bosons is again $b\bar{b}$ in most of the parameter space, with branching fractions greater than in the SM ($\sim$ 91%). The dominant hZ final states are the same as in the SM case, while hA is expected to give mostly $b\bar{b}b\bar{b}$ and $\tau^+\tau^-b\bar{b}$ final states. Here again, b-tagging plays a crucial role.

The theoretical framework of these searches is the MSSM with R_p conservation and soft breaking terms unified at the EW scale. In the MSSM the Higgs boson masses are connected to each other, so that at tree level, there are only two free parameters: $\tan\beta$ and one Higgs boson mass, or, alternatively, two Higgs boson masses, *e.g.*, m_A and m_h. The properties of the MSSM Higgs bosons, and in particular the mass relationships, are modified by radiative corrections. These introduce five additional parameters: the mass of the top quark, the Higgs mixing parameter μ, the common sfermion mass term at the EW scale M_S, the common SU(2) gaugino mass term[2] at the EW scale M_2, and the common squark tri-linear coupling at the EW scale A. The interpretation of the experimental results depend on the values assumed for these parameters.

Benchmark hypotheses

Using leading order two-loop calculations of the radiative corrections [41], benchmark values have been defined for the parameters beyond tree-level [42]: 175 GeV/c^2

[2]The U(1) gaugino mass term at the EW scale M_1, is related to M_2 through the GUT relation $M_1 = (5/3)\tan^2\theta_W M_2$, while the SU(3) gaugino mass term, M_3, is set via the gluino mass, which is taken equal to M_S.

for the top mass, 1 TeV/c^2 for M_S, and 1.6 TeV/c^2 for M_2. Two benchmark scenarios [42] have been defined for the parameters A and μ, which determine the mixing in the stop sector: no mixing (A= 0, $\mu = -100$ GeV) and maximal mixing (A= $\sqrt{6}M_S$, $\mu = -100$ GeV). The no mixing hypothesis leads to minimal radiative corrections to m_h while the maximal mixing induces the largest corrections. This defines the usual framework for the interpretation of the MSSM neutral Higgs boson searches.

Results obtained at LEP at 189 GeV in the hA channel are summarized in Table 10. These results, together with the hZ results reinterpreted in the MSSM framework, allow one to set constraints on m_h, m_A, and $\tan\beta$. As an example, Fig. 8 represents the region of the ($\tan\beta$, m_h) plane excluded by the combination of the LEP results up to 189 GeV in the less favorable case of the maximal mixing [35]. Whatever the mixing hypothesis, these combined results exclude Higgs bosons up to 80.7 GeV/c^2 for m_h and 80.9 GeV/c^2 for m_A, for $\tan\beta$ greater than 0.4. At $\tan\beta \sim 1$, the experimental lower limit on m_h is above the theoretical upper bound on m_h so that $\tan\beta$ is excluded between 0.9 and 1.6 (0.6 and 2.6) in the maximal mixing (no mixing) hypothesis. The expected limits on both masses are 5 GeV/c^2 higher while the expected excluded ranges in $\tan\beta$ agree with the observed ones.

	bkg	data	m_h limits (GeV/c^2)		m_A limits (GeV/c^2)	
			observed	expected	observed	expected
ALEPH	7.5	10	82.5	83.1	83.1	83.6
DELPHI	22.6	24	82.1	81.1	83.1	82.2
L3	140.6	153	76.0	78.0	76.0	79.0
OPAL	12.9	15	74.8	76.4	76.5	78.2

Table 10: Rates and exclusion limits obtained at LEP in the MSSM hA Higgs boson searches in 189 GeV data. Results observed in data are compared with expectations from background simulation.

It must be noted that, contrary to the limits on masses, the limit on $\tan\beta$ is very sensitive to the values of the underlying parameters which have a large impact on the theoretical upper bound on m_h. As an example, this upper bound increases with increasing top quark masses and no limit on $\tan\beta$ is obtained if the top mass is moved by two standard deviations. The pure MSSM parameters or the order of the radiative correction calculations have also a non negligible effect. So, the excluded ranges in $\tan\beta$ cannot be taken as an absolute result, even if the maximal mixing hypothesis is a pessimistic scenario.

Also displayed in Fig. 8 is the recent CDF result [43] at large $\tan\beta$. In this region, the production cross-section is large enough to make Tevatron sensitive

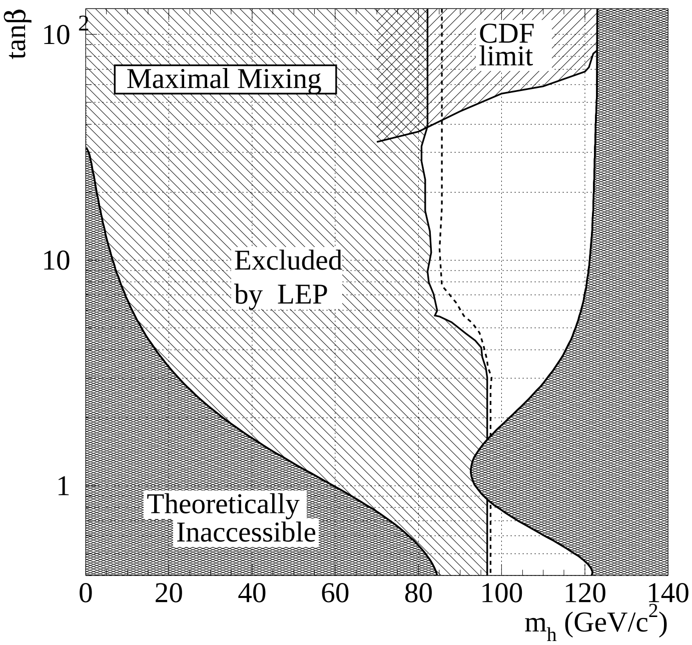


Figure 8: Regions in the (m_h, $\tan\beta$) plane excluded by the MSSM Higgs boson searches at LEP in data up to 189 GeV, and at CDF in run I data. The regions not allowed by the MSSM for a top mass of 175 GeV/c^2 a SUSY scale of 1 TeV/c^2 and maximal mixing in the stop sector are also indicated. The dotted curve is the LEP expected limit.

to the production process $p\bar{p} \rightarrow b\bar{b}$ h, H, A in which one Higgs boson is emitted off a bottom quark, leading to four b-tagged jets in the final state.

Results from LEP experiments with data up to 196 GeV were also reported at the conference [36], as shown in Table 11. These results were combined later on, giving exclusion limits of 84.3 GeV/c^2 on m_h and 84.5 GeV/c^2 on m_A, independent of the mixing hypothesis, and excluded ranges in $\tan\beta$ between 0.8 and 1.9 (0.5 and 3.2) in the maximal mixing (no mixing) hypothesis [37]. At the end of the 1999 data taking, LEP experiments reported mass limits up to 90 GeV/c^2 and excluded ranges in $\tan\beta$ somewhat larger than the combined result at 196 GeV [38]. The excess in data observed by OPAL in the hA channel at 196 GeV was not confirmed at higher energies nor by the other experiments.

	$\mathcal{L}$ (pb^{-1})	bkg	data	m_h limits (GeV/c^2) observed	expected
ALEPH	98	4.8	1	85.2	86.1
OPAL	85	6.8	14	74.3	79.1

Table 11: Rates and exclusion limits obtained at LEP in the MSSM hA Higgs boson searches in 192 and 196 GeV data. Results observed in data are compared with expectations from background simulation.

General scans

More general interpretations of the LEP Higgs boson searches have been performed, scanning over the MSSM underlying parameters. The parameter space is, however, usually restricted by imposing additional constraints, *e.g.*, the experimental results on supersymmetric particles or the Γ_Z constraint. It was shown that the benchmark limits hold in more than 99.99% of the parameter sets [44] and that the mass limits from general scans are only a few GeV/c^2 weaker than the benchmark ones [45]. As general scans usually also vary the top mass quark within two standard deviations, the limit on $\tan\beta$ vanishes.

Recent developments

Recent theoretical work led to two-loop calculations of the radiative corrections at the next-to-leading order and to a redefinition of the benchmark values for the underlying parameters [46]. In particular, the theoretical upper bound on m_h was found to be underestimated by $\sim$7 GeV/c^2 in the maximal mixing scenario previously used. The new scenario now proposed (called $m_h{}^{max}$ scenario) should lead to more realistic bounds on $\tan\beta$. Another new scenario (called the large μ scenario), in which the h boson is within the kinematical reach at LEP but with vanishing branching fraction into $b\bar{b}$, was proposed to check the sensitivity of LEP to Higgs bosons with non-dominant b decays. Future LEP results will be derived in these new benchmark schemes.

5.3 Neutral Higgs bosons beyond MSSM

Searches for neutral Higgs bosons as expected beyond the MSSM have also been performed, mostly at LEP. Three lines of searches have been followed. First, the existing LEP analyses on MSSM h and A bosons have been used, either as such or with some modifications (*e.g.*, relaxing the *b*-tagging requirements) to cover the final states expected in more general models. Thus, a first study showed that LEP is sensitive to neutral Higgs bosons of two Higgs doublet models (2HDM), even in a scenario with dominant decays into $c\bar{c}$ or in a model with CP violation [47]. Recently, the 2HDM parameter space (with CP conservation) has been explored in a detailed scan [48]. Finally, for the first time, a non minimal supersymmetric model containing one gauge-singlet Higgs field in addition to the MSSM has also been investigated [49].

As a second research line, the case of a Higgs boson h decaying invisibly has been studied. Dedicated searches in the hZ channel translate into upper limits on the production cross-section times branching ratio, which are compared with expectations from specific models [50]. As an example, assuming a SM production rate and a 100% branching ratio into invisible products, a lower limit on m_h at 95.4 GeV/c^2 is obtained.

The third topic deals with a Higgs boson h with anomalous couplings to photons. From dedicated searches in the hZ, hγ, and hA channels, general constraints are set on the production cross-section times branching ratio or directly on the anomalous couplings. They are again compared with expectations from specific models [51, 36]. As an example, assuming a SM production rate and a fermiophobic Higgs boson, a lower limit on m_h at 97.5 GeV/c^2 is achieved.

5.4 Charged Higgs bosons

Recent results on charged Higgs bosons, $H^\pm$, have been reported by the LEP experiments. The framework of these searches is the general 2HDM scheme with as sole free parameters the $H^\pm$ mass and its leptonic decay branching fraction, assuming that the hadronic decays (into $c\bar{s}$) and leptonic decays (into $\tau\nu_\nu$) saturate the width of the particle. This is the case in the mass range below m_W that is presently tested.

	bkg	data	expected limit (GeV/c^2)	observed limit (GeV/c^2)
ALEPH	333.5	302	69.5	65.5
DELPHI	213.0	215	66.5	66.9
L3	523.5	499	71.2	67.5
OPAL	241.1	252	68.5	68.7

Table 12: Rates and exclusion limits obtained at LEP in the charged Higgs boson searches in 189 GeV data. Results observed in data are compared with expectations from background simulation.

The results obtained by the LEP experiments at 189 GeV [52] are shown in Table 12. Once combined, these results exclude an $H^\pm$ boson up to 77.3 GeV/c^2

whatever its leptonic decay branching ratio, while the expected limit is 74.9 GeV/c^2 [35]. Results from data up to 196 GeV were combined after the conference. This gave no improvement in the mass limit independent of the branching ratio due to the large background from WW pairs which is penalizing for the analyses in the hadronic mode. On the other hand, $H^{\pm}$ bosons with pure (50%) leptonic decays have been excluded up to 84.9 (78.4) GeV/c^2 by the same results [37]. Individual limits reported at the end of the 1999 data taking were below the combined results at 196 GeV [38].

Higher masses were excluded at the Tevatron run I in the search for $H^{\pm}$ in decays of pair-produced top quarks. The mass limits are $\tan\beta$ dependent and restricted to those values of $\tan\beta$ for which the top quark branching fraction into H^{+}b is large enough. In the most favorable case ($\tan\beta$=150), masses up to 153 GeV/c^2 have been excluded [53].

6 Conclusions

New particle searches cover an impressive variety of topics and topologies. The way results are interpreted has undergone substantial changes during the past few years. To get higher sensitivity to the researched signals, different channels and/or experiments are combined and more information is put in the statistical analysis of the results, as in the Higgs boson searches. There is also an effort to go to more model-independent results by relaxing theoretical assumptions, scanning parameter values, or testing more general models. Supersymmetric particle searches are examples of this trend.

To give but a few results, in gravity-mediated SUSY breaking models, the lightest neutralino has been excluded up to 32 GeV/c^2 whether R_p is conserved or not, while the lightest chargino has been excluded up to 68 (94) GeV/c^2 if R_p is conserved (broken). A SM Higgs boson has been excluded up to 106 GeV/c^2, MSSM neutral Higgs bosons up to 90 GeV/c^2, and 2HDM charged Higgs bosons up to 77 GeV/c^2.

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Discussion

Lee Roberts (Boston University): Can you comment again on the limits on tanβ from the Higgs searches?

Ruhlmann-Kleider: The limits on tanβ have been derived with two-loop leading order calculations of the radiative corrections and for specific values of the underlying parameters so they cannot be regarded as absolute, even if the maximal mixing scenario represents a difficult case. Going to next-to-leading order two-loop calculations, varying the underlying parameters or increasing the top quark mass will make the excluded range in tanβ decrease if not vanish.