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PARTICLE SEARCHES AT LEP^{a)}

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Abstract

The present status of particle searches at LEP is reviewed.

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1. INTRODUCTION

The present Standard Model of electroweak and strong interactions describes well all available experimental data [1]. A few items predicted by the Standard Model (SM) are still missing and are being searched for: the top quark and the Higgs boson; the tau neutrino has not yet been observed directly, but it should have been produced, and limits on its mass come from τ decays. There are many reasons to consider the SM as incomplete or as a kind of low-energy model: it shows a mass hierarchy problem and at very high energies, at the Planck scale, it does not contain gravity [2]. It is thus plausible to search for new physics and new particles beyond the SM.

This review deals with the searches for new particles at the LEP e^+e^- collider, running around the Z^0 peak, by the four experiments ALEPH, DELPHI, L3 and OPAL [3]. Positron-electron collisions have an advantage over higher-energy hadron-hadron collisions because the situation is cleaner and because the cross-sections for the production of new particles are generally calculable. Therefore the limits established may often be considered to be final if the upper limits are below the evaluated cross-sections. The analyses at the Z^0 resonance present the further attractive feature of larger cross-sections. Early searches, performed with the data of the 1989 and 1990 running periods, were essentially complete as far as searches of pair-produced particles with well-defined couplings and with masses up to $m_{Z^0}/2$ are concerned. The searches for other particles, like the Higgs bosons, require much higher integrated luminosities. The higher-energy phase of LEP (LEP 200) will allow all searches to be extended to higher masses.

It has to be remembered that the four LEP detectors are refined 4π general-purpose detectors, which include precision microvertex detectors, tracking chambers in strong magnetic fields, electromagnetic and hadron calorimeters, muon detectors, and forward detectors for luminosity measurements. In summary, these detectors provide large acceptance, hermeticity, particle identification and redundancy of information.

Most of the particle searches performed at LEP are based on the direct observation or reconstruction of the particle searched for; for instance in the case of a neutral particle which decays into two charged leptons, the effective invariant mass of the two leptons is measured.

In other cases the method is more indirect; for instance in the case of heavy quarks, they lead to more "spherical" multihadron events, and one may analyse event-shape variables, see Section 2.1.

Several indirect limits on new particle production may be obtained from the measurements of the Z^0 line shape [1]. For instance, these measurements prove that there are only three light neutrino species (and three fermion families). It is nevertheless worthwhile to make direct searches for particles of a fourth family (which could be weakly coupled to the Z^0). From the Z^0 line shape and radiative corrections (to which the undiscovered top quark gives sizeable contributions) it is possible to estimate the mass of the top quark, around 145 ± 25 GeV [1] (the latest update gives 160^{+16+18}_{-18-19} GeV). One may use the value $m_t \sim 137$ GeV ($\sim 1/\alpha$) for mnemonic reasons.

In the framework of the SM, with the additional input of the masses of the top quark and of the Higgs boson, one may calculate the expected values for the total width and for the invisible width of the Z^0 . The comparison of the measured values with the expected values allows one to look for an excess over the predicted value. An excess for the total width would be indicative of the Z^0 decaying into new particles regardless of decay mode. An excess for the invisible width would be indicative of the Z^0 decaying into

channels that fail the hadronic and leptonic event-selection criteria. At present, from the combined results of the four experiments, the limits are $\Gamma_x < 25$ MeV, $\Gamma_x^{\text{inv}} < 17$ MeV at the 95% confidence level (CL), for the total width and the invisible width, respectively.

In the years 1989 to 1991 more than 500 000 Z^0 's were recorded by each LEP experiment at the Z^0 peak and at nearby energies; with the 1992 running period, the number increased to about 1.2 million per experiment for a total number of about 5 million Z^0 's, see Table 1 (in 1992 there was no energy scan and all events were recorded at the Z^0 peak). Thus the searches for rare Z^0 decays have been capable of yielding percentage limits at the level of 10^{-5} per experiment. Combining all data, one should soon be able to reach the 10^{-6} level.

Table 1: Number of multihadron and charged-lepton events observed at LEP by the four experiments (in thousands) [1]. Not all the available events have been used in the searches published until April 1993.

	Multihadrons ($q\bar{q}$)	$\ell^+\ell^-$
ALEPH	1140 k	138 k
DELPHI	1047 k	101 k
L3	1103 k	102 k
OPAL	1168 k	148 k
Total	4460 k	490 k

It has to be mentioned that some early searches were performed with low statistics at the Z^0 peak at the SLAC linear collider (SLC) [4] and that other searches are being performed with higher statistics. Many particle searches have been performed at lower energies, at the PEP, PETRA and TRISTAN e^+e^- colliders, and at higher energies at the CERN and FERMILAB $p\bar{p}$ colliders.

In this paper we shall first briefly recall the LEP searches for the missing items of the Standard Model, with the exception of the Higgs boson. In the third Section we shall discuss the searches for supersymmetric particles, while the fourth Section deals with Higgs boson searches, from the Standard Model Higgs to supersymmetric Higgses and to doubly charged Higgs particles. Searches for compositeness are considered in Section 5, while leptoquark searches are taken up in Section 6 and other searches in Section 7. In Section 8 the perspectives offered by LEP 200 for the Standard Model Higgs boson will be discussed; the conclusions are in Section 9. For each search the discussion is in general rather schematic, with few exceptions (for unstable photinos, the SM Higgs particle, doubly charged Higgses, and leptoquark bosons). Mass limits will generally be quoted at the 95% CL, unless otherwise stated.

A few caveats are in order. There may be some approximations and some of the limits may not be exact or not up to date (they are frequently updated). We apologize for these and for eventual omissions. We hope that the readers will inform us.

2. SEARCHES FOR MISSING ITEMS OF THE STANDARD MODEL

The missing items of the minimal Standard Model are the top quark t , and the neutral Higgs boson H_{SM}^0 ; there is also a need to detect the tau neutrino ν_τ . As already stated, the SM does not predict the number of fermion families. The Z^0 line shape measurements limit the number to three neutrino families. Table 2 recalls the fundamental fermions and bosons of the Standard Model.

Table 2: Fundamental fermions and bosons of the Standard Model.

Fermions			Bosons	
u	c	t	γ	H_{SM}^0
d	s	b	$W^\pm, Z^0$	
ν_e	ν_μ	ν_τ	8g	
e^-	μ^-	τ^-		

Lepton universality predicts that the coupling of the charged and neutral currents to the three known leptonic doublets are equal. This is well verified for the neutral current at LEP [1].

It may also be worth recalling that the symmetry structure of the SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$.

The measurements of the Z^0 line shape yield a very precise value of the mass of the Z^0 : $m_{Z^0} = (91187 \pm 7) \text{ MeV}$ [1]. The same measurements yield precise values of the total and invisible widths of the Z^0 . The measured values, together with the predictions of the Standard Model for a specific assumption of m_t and $m_{H_{\text{SM}}^0}$, are given in Table 3. From the comparison of the measured and predicted values, one may obtain the excess widths (and branching ratios) over those predicted by the SM. These may be used to place upper limits on new phenomena and new physics beyond the Standard Model. As already stated, any excess in the total width would indicate Z^0 decays into new channels; any excess in the invisible width would indicate Z^0 decays into non-hadronic and non-charged leptonic channels.

Table 3: Measured and predicted values of the total width and of the invisible width of the Z^0 [1]. Also given are the approximate 95% CL upper limits for the widths. (Data presented at the 1992 Dallas Conference; the March 1993 update yields $\Gamma_Z = 2488 \pm 7 \text{ MeV}$ and $N_\nu = 2.99 \pm 0.03$.)

	Measured (MeV)	Standard Model (MeV)	Width limits (MeV)
Γ_Z	2493 ± 7	2489	< 25
Γ_Z^{inv}	504.6 ± 5.8	500	< 17

Later in this section we shall briefly recall some of the searches for the missing items of the Standard Model, in particular for the top quark and for possible members of a fourth family of quarks and leptons. Some searches for neutral leptons beyond the SM are also discussed. The Higgs boson searches will be discussed in Section 4.

2.1 Top and b' quarks

Measurements of the Z^0 line shape have proven that the number of fermion families is only three. The third family includes the t-quark as the weak isodoublet partner of the b-quark. Whilst the t-quark has not yet been found, its existence is supported by the calculation of radiative corrections, the measurement of $\Gamma(Z^0 \rightarrow b\bar{b})$ and the measured forward-backward charge asymmetry of the b-quark in e^+e^- annihilation experiments, and by the absence of flavour-changing neutral-current decays. As stated in the introduction, the mass estimate of the top quark from the Z^0 line shape and radiative corrections is $145 \pm 25 \text{ GeV}$ (more recently: $160_{-18}^{+16+18} \text{ GeV}$) [1]. In an eventual fourth family the b' or 'down-quark' member of that family could be lighter than the t-quark.

The LEP experiments made direct searches for the t and b' quarks using the relatively few multihadronic events at the Z^0 resonance of the first running periods [5]. The following decays of t and b' were considered:

$$\begin{array}{lll}
 \text{- charged current} & t \rightarrow bW^* & b' \rightarrow cW^* \\
 \text{- flavour-changing neutral currents} & & b' \rightarrow b\gamma, b' \rightarrow bg \\
 \text{- charged Higgs} & t \rightarrow bH^+ & b' \rightarrow cH^-
 \end{array} \quad (1)$$

A quark q or a gluon g each lead to one jet of hadrons, while W^* , $H^\pm$ lead to hadrons or leptons ($W^* \rightarrow \ell\nu_\ell, qq'$; for $H^\pm$ see Section 4.2.2).

The final-state multihadron events produced by slowly moving heavy quarks are rather 'spherical'; this is not the case for the known light quarks. Thus, shape variables such as acoplanarity, thrust, sphericity, and others are sensitive to the presence of new heavy quarks. Figure 1 shows the acoplanarity and thrust distributions for a sample of multihadron events from OPAL: it is seen that they agree well with the predictions of the JETSET 7.2 [6] Monte Carlo simulation with five quark flavours. The same figure shows the predictions of the same Monte Carlo with six flavours, the sixth quark being either t or b' : both would give measurable contributions for acoplanarity values larger than 0.2 and for thrust values smaller than 0.8. From graphs of this type, updated, we can exclude the production of t and b' , placing the lower limits at $m_t, m_{b'} > 45.5 \text{ GeV} \simeq m_{Z/2}$. This search is a typical example of how we rely on one or more Monte Carlo simulations to establish limits.

Figure 1: Acoplanarity and thrust distributions measured by the OPAL electromagnetic calorimeter [5]. The dashed and dotted histograms represent the expectations including a sixth quark, either t or b' , with a mass of 35 GeV.

In the final multihadron event from heavy quarks there should be copious production of isolated hadrons with high momentum. These also have been searched for, and the yield was compared with the predictions of the JETSET Monte Carlo with five and with six quark flavours. Also in these analyses there is no indication of b' or t [5].

2.2 New charged heavy leptons

These searches concern a sequential, fourth-generation-type, charged heavy lepton-antilepton pair, L^+L^- , produced in e^+e^- collisions at the Z^0 resonance [5, 7]

$$e^+e^- \rightarrow Z^0 \rightarrow L^+L^- \quad (2)$$

The heavy lepton L^- then decays (the values in parentheses are relative abundances)

$$\begin{aligned} L^- & \rightarrow \nu_L e^- \bar{\nu}_e \quad (1/9) \\ & \rightarrow \nu_L \mu^- \bar{\nu}_\mu \quad (1/9) \\ & \rightarrow \nu_L \tau^- \bar{\nu}_\tau \quad (1/9) \\ & \rightarrow \nu_L \bar{u}d \quad (1/3) \\ & \rightarrow \nu_L \bar{c}s \quad (1/3) \end{aligned} \quad \left. \vphantom{\begin{aligned} L^- & \rightarrow \nu_L e^- \bar{\nu}_e \quad (1/9) \\ & \rightarrow \nu_L \mu^- \bar{\nu}_\mu \quad (1/9) \\ & \rightarrow \nu_L \tau^- \bar{\nu}_\tau \quad (1/9) \end{aligned}} \right\} (1/3) \quad (3)$$

and similarly for L^+ . The number of unseen neutrinos is four in 1/9 of the cases, three in 4/9 of the cases, and two in 4/9 of the cases. Forty-five per cent of L^+L^- pairs are expected to decay into a system containing at least one isolated energetic electron or muon. The Z^0 is assumed to couple to L^+L^- in the same way as it couples to lighter charged leptons.

On the basis of what has been said above, two different types of searches for $L^\pm$ were carried out using two independent signatures:

- i) multihadron events with missing energy and missing momentum transverse to the beam direction;
- ii) multihadron events with an isolated high-momentum electron or muon.

The first search is sensitive to semileptonic and leptonic decays of a heavy lepton; the second is sensitive only to events with at least one leptonic decay.

At the 95% CL, the results exclude a charged heavy lepton of mass less than ~ 45 GeV, the precise value depending on the mass of the neutrino partner. Figure 2a presents the limits on $m_{L^\pm}$ for the case of a massive and stable neutrino.

2.3 New neutral leptons

A fourth family of quarks and leptons could exist; in this context one should have a fourth-generation neutrino, which could be heavy and which could be produced in $e^+e^- \rightarrow Z^0 \rightarrow L^0\bar{L}^0$ with the same cross-section as for light neutrinos, apart from phase-space factors. The heavy neutrino may or may not mix with the ν_e, ν_μ, ν_τ states. In the first case the weak eigenstates would be mixtures of the mass eigenstates, $\nu_L = \sum_{j=1}^4 U_{Lj} \nu_j'$. The heavy neutrino could decay via a charged-current process, $L^0 \rightarrow eW^*, \rightarrow \mu W^*, \rightarrow \tau W^*$, in which case it may be searched for via an isolated charged lepton of the first three families (e, μ, τ), or via a neutral-current process $L^0 \rightarrow \nu Z^*$, in which case it may be searched via missing energy and momentum.

The LEP experiments made general searches for neutral heavy leptons in Z^0 decays, and for also those which are predicted by extensions of the Standard Model. We shall

briefly discuss here these searches, even if the particles searched for are not strictly part of the Standard Model.

Figure 2: a) The 95% CL limits on m_{L^+} and m_{ν_L} if ν_L is massive and stable (OPAL) [7]. The limits of the excluded region are based on the combination of the missing p_T and isolated lepton searches. b) The 95% CL upper limits on the coupling constant $|U_\ell|^2$ as a function of the mass of the isosinglet neutral heavy lepton N_ℓ (L3) [7]. The solid line is the limit for N_e , the dashed line for N_μ and the dotted line for N_τ .

Isosinglet Neutral Heavy Leptons (INHLs) are predicted in extended electroweak models and in some Grand Unified Theories of the fundamental interactions. The INHL (N_ℓ) could be produced in association with its isodoublet neutrino partner, $e^+e^- \rightarrow Z^0 \rightarrow N_\ell + \bar{\nu}_\ell$. The decays of the N_ℓ may proceed via neutral-current interactions ($N_\ell \rightarrow Z^*\nu$, $Z^* \rightarrow e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\bar{\nu}$, $q\bar{q}$) or via charged-current interactions ($N_\ell \rightarrow W^*\ell$, $W^* \rightarrow e\nu$, $\mu\nu$, $\tau\nu$, qq'). The OPAL searches for neutral heavy leptons used two signatures:

- i) events with large missing energy and transverse momentum imbalance;
- ii) events with an isolated lepton (e or μ) and a second isolated track.

Several combinations of production and decay modes of neutral heavy leptons have been studied. These combinations and the corresponding search methods are the following:

$$\begin{array}{ll}
 - e^+e^- \rightarrow L^0\bar{L}^0 & \\
 \quad - \bar{L}^0 \text{ and } L^0 \rightarrow eW^* & \text{isolated track search} \\
 \quad - \bar{L}^0 \text{ and } L^0 \rightarrow \mu W^* & \text{" " " } \\
 \quad - \bar{L}^0 \text{ and } L^0 \rightarrow \tau W^* & \text{" " " } \\
 \quad - \bar{L}^0 \text{ and } L^0 \rightarrow \nu Z^* & \text{missing energy and missing } p_T \\
 \\
 \left. \begin{array}{l}
 - e^+e^- \rightarrow \nu\bar{L}^0 \\
 - e^+e^- \rightarrow \bar{\nu}L^0
 \end{array} \right\} & \text{missing energy and missing } p_T \text{ for all four } L^0 \text{ decay modes indicated above.}
 \end{array}$$

It is assumed that L^0 and $\bar{L}^0$ would decay into the light lepton for which mixing would predominate. The channel $L^0 \rightarrow \nu Z^*$ is included for completeness since it is allowed in some models.

The OPAL searches exclude a Standard Model fourth-generation neutral lepton up to a mass $m_{Z^0}/2$ if L^0 mixes with e, μ or τ (because of energy scans above the Z^0 peak, even a slightly larger mass is excluded in the first two cases) [7]. These limits are valid if the mixing parameters $|U_{iL}|^2$ are larger than 10^{-7} for $m_L = 20$ GeV, 10^{-9} for $m_L = 45$ GeV.

For the INHL, the L3 collaboration established a limit of the order of 3×10^{-5} on the branching ratio $\text{BR}(Z^0 \rightarrow N_\ell \bar{\nu}_\ell)$ for N_ℓ masses up to m_Z , see Fig. 2b [3].

2.4 Standard Model neutral Higgs boson

The Higgs boson is an essential particle of the Standard Model of electroweak interactions. A minimum of one neutral physical boson (H_{SM}^0) must be left after spontaneous symmetry breaking in order to provide masses for the $W^\pm$ and Z^0 bosons while keeping the theory renormalizable. The subject will be discussed in detail in Section 4.1.

In conclusion, the early LEP searches established the number of fermion families to be three, and placed lower limits on the top-quark mass and on the H_{SM}^0 mass.

3. SEARCHES FOR SUSY PARTICLES

3.1 Generalities

Supersymmetry (SUSY) links the known particles with (super) partners (with identical couplings) whose spin differs by half a unit, see Table 4. Besides the interest in the symmetry itself, other basic justifications for SUSY are the better ultraviolet behaviour, in particular the stability of the hierarchy ($m_w \ll m_{\text{Planck}}$), the possibility of allowing coupling constants' unification in a GUT scheme and the connection with gravitation through "supergravity".

Table 4: Fundamental particles and their supersymmetric partners (denoted with a $\tilde{}$). R is a new multiplicative quantum number which equals +1 for the known bosons and fermions, -1 for their SUSY partners. The neutral mass eigenstates Higgs bosons are h^0 , H^0 , A^0 (in SUSY models there are at least two complex doublets Higgs fields, H_1 and H_2 ; of the eight degrees of freedom, three are taken by the $W^\pm$ and the Z^0 , three give rise to the h^0 , H^0 and A^0 and the remaining two give rise to the $H^\pm$); the $\tilde{\gamma}$, $\tilde{Z}^0$, $\tilde{H}_1^0$, $\tilde{H}_2^0$ mix to form four neutralinos and the $\tilde{W}^\pm$, $\tilde{H}^\pm$ mix to form charginos (see Section 4.2 for the Higgs boson sector). The quarks and squarks exist in three colour states, the gluons and gluinos in eight colour states.

Particles, $R = +1$			Sparticles, $R = -1$			
Particle	Spin	Charge	Sparticle	Spin	S-name	Mass eigenstates
e	1/2	-1	$\tilde{e}_L, \tilde{e}_R$	0	selectron	
μ	1/2	-1	$\tilde{\mu}_L, \tilde{\mu}_R$	0	smu	
τ	1/2	-1	$\tilde{\tau}_L, \tilde{\tau}_R$	0	stau	
$\nu = \nu_e, \nu_\mu, \nu_\tau$	1/2	0	$\tilde{\nu}$	0	sneutrino	
$q = u, d, s, c, b, t$	1/2	2/3, -1/3	$\tilde{q}_L, \tilde{q}_R$	0	squark	
g	1	0	$\tilde{g}$	1/2	gluino	
γ	1	0	$\tilde{\gamma}$	1/2	photino	neutralinos ($\tilde{\chi}^0 - \tilde{\chi}^{0'''}$)
Z^0	1	0	$\tilde{Z}$	1/2	zino	
$H_1^0, H_2^0 (h^0, H^0, A^0)$	0	0	$\tilde{H}_1^0, \tilde{H}_2^0$	1/2	neutral Higgsinos	
$H^\pm$	0	± 1	$\tilde{H}^\pm$	1/2	charged Higgsino	
$W^\pm$	1	± 1	$\tilde{W}^\pm$	1/2	wino	charginos ($\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$)
G	2	0	$\tilde{G}$	3/2	gravitino	

	Spin		
	0	1/2	1
	$\tilde{\ell}$	ℓ	
Particles and Sparticles	$\tilde{q}$	q	
	H_1^0, H_2^0	$\tilde{\chi}^0 - \tilde{\chi}^{0'''}$	γ, Z^0
	$H^\pm$	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$W^\pm$

The SUSY partners of the spin 1/2 fermions have spin 0; their names are obtained by adding the prefix 's' to the fermion names. The super partners of the gauge bosons have spin 1/2 (with the exception of the graviton); their names are obtained by adding the postfix 'ino' to the names of the normal gauge particles.

Things are in reality complicated, as partially indicated in Table 4. The neutral weak eigenstate sparticles $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}_1^0$, and $\tilde{H}_2^0$ mix giving rise to a complex of four Majorana-type mass eigenstates, called neutralinos, $\tilde{\chi}^0, \tilde{\chi}^{0'}, \tilde{\chi}^{0''}, \tilde{\chi}^{0'''}$. Similarly, charged weak eigenstate sparticles $\tilde{H}^\pm, \tilde{W}^\pm$ mix giving rise to two mass eigenstates, called charginos, $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$. Moreover, left-handed and right-handed fermions (which are a sort of different particle in the SM) give rise to different superpartners which may have different masses; we shall neglect this possibility.

It seems impossible to relate the known fundamental bosons and fermions. Therefore the supersymmetric particles must all be new particles. The new sparticles are expected to be much heavier than the known particles; on the other hand, if supersymmetry

is to solve the hierarchy problem, supersymmetric particles cannot be much heavier than ~ 1 TeV.

A new quantum number, R , must be conserved: R may be defined as a multiplicative quantum number, R parity, which is $+1$ for ordinary particles and -1 for their SUSY partners. It is $R = (-1)^{2S+3(B-L)}$. Conservation of R implies that SUSY particles must be produced in pairs, that the lightest SUSY particle (LSP) is absolutely stable, and that the other SUSY particles decay into the LSP. The LSP could be the $\tilde{\gamma}$, or more generally, a neutralino, $\tilde{\chi}^0$, or $\tilde{\nu}$, or $\tilde{G}$. The LSP would be an obvious candidate for astrophysical Dark Matter.

In general SUSY models there are many free parameters. A more restrictive scheme is the minimal supersymmetric extension of the Standard Model (MSSM), where all relevant physical quantities may be expressed in terms of five parameters (plus the top mass), which may be chosen to be:

- the mass of the neutral CP-odd Higgs boson, m_{A^0} ;
- the universal scalar mass term, m_0 ;
- the universal gaugino mass term, $m_{1/2}$;
- the superpotential Higgs mass, μ ;
- the ratio of the vacuum expectation values of the two Higgs doublets, $\tan \beta = v_2/v_1$, with $1 \lesssim \tan \beta \leq m_t/m_b$.

(Other, non-independent, parameters are the masses M_1 , M_2 and M_3 , the SU(3), SU(2) and U(1) gaugino masses.)

The neutralino, chargino, squark and slepton sectors depend only on three of the above five parameters; the Higgs sector depends on two, while the gluino sector depends on only one. The MSSM parametrization is the most economical and theoretically the most motivated.

In the following Sections we discuss several SUSY searches; SUSY-related Higgs bosons are considered in Section 4. Supersymmetry has been the subject of a recent workshop at CERN [8]; the implications for Grand Unified Theories have been discussed in a number of papers [9].

3.2 Scalar charged leptons

For each charged lepton ℓ there should be two charged scalar (spin-0) supersymmetric partners, which correspond to the two chiral (helicity) states, $\tilde{\ell}_L$ and $\tilde{\ell}_R$. Together they form a chiral supermultiplet. The mass eigenstates are almost identical to the interaction eigenstates (with the exception of many supergravity models) and no distinction will be made in the following.

Figure 3 shows Feynman diagrams for the production and decay of sleptons (scalar leptons). The channels under study are

$$e^+e^- \rightarrow Z^0 \rightarrow \tilde{\ell}\tilde{\ell}, \quad \tilde{\ell} \rightarrow \ell\tilde{\chi}^0, \quad \ell = e, \mu, \tau. \quad (4)$$

The lightest neutralino $\tilde{\chi}^0$ leaves the apparatus unseen. Thus in the final state we have two leptons with missing energy and momentum.

Figure 3: a) Feynman diagram for the production of a pair of SUSY sleptons decaying into $\tilde{\chi}^0 \ell$ (ℓ is e, μ, τ ; the neutralinos $\tilde{\chi}^0$ are not observed).

b) For selectron production there is also the diagram with the t-channel exchange of a neutralino.

The LEP experiments have searched for acoplanar lepton pairs (see Fig. 4) [10]. This class of events includes the above-mentioned SUSY particles, but is more general. No events with pairs of acoplanar electromagnetic clusters, muons, or taus, were observed at the level of 4×10^{-4} . The production cross-sections of SUSY particles were computed in the Born approximation, also taking into account initial-state bremsstrahlung. Assuming $m_{\tilde{l}_L} \simeq m_{\tilde{l}_R} \simeq m_{\tilde{l}}$, the cross-section for production of smuon pairs is $\beta^3/4$ times the cross-section for muon-pair production; $\beta^2 = 1 - 4m_{\tilde{l}}^2/m_Z^2$. The cross-section for selectron pairs is somewhat larger because of the extra possibility of t-channel photino (neutralino) exchange, Fig. 3b. The cross-section for staus is similar to that for smuons.

The cross-section for the production of charged slepton pairs of mass $m_{\tilde{l}}$ is

$$\sigma_{\tilde{l}^+ \tilde{l}^-} \simeq \frac{1}{8} \beta^3 \sigma_{\nu \bar{\nu}}, \quad (5)$$

where $\sigma_{\nu \bar{\nu}}$ is the neutrino-pair cross-section at the Z^0 mass. The LEP data exclude the production of sleptons up to the kinematical limit of 45.5 GeV, see Fig. 5 (the limit could be slightly higher because of data collected at energies slightly above the Z^0 pole).

As already stated, in the MSSM the slepton and squark sectors depend on three parameters, which are usually chosen to be m_0 , $m_{1/2}$ and $\tan \beta$.

Figure 4: Production of an acoplanar lepton-antilepton pair. The acoplanarity angle θ is the angle between the projections of ℓ^- and ℓ^+ momenta in the plane perpendicular to the e^+e^- beams.

Figure 5: Excluded regions in the $m_{\tilde{\chi}^0}$ versus $m_{\tilde{\ell}_R}$ planes for $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$ (ALEPH). The diagonal lines indicate the limit $m_{\tilde{\ell}} = m_{\tilde{\chi}^0} + m_{\tilde{\ell}}$. The region to the left of each vertical dashed line is excluded by the invisible-width measurement of the ALEPH Collaboration.

From the measurements of the Z^0 invisible width, one can infer a lower mass limit for scalar charged leptons and for scalar neutrinos, since the corresponding final-state topologies are not present in the hadronic and standard leptonic selections. The present indirect limit is (at the 95% CL): $m_{\tilde{\ell}} > 30.6$ GeV (if $m_{\tilde{\ell}_R} \simeq m_{\tilde{\ell}_L}$) and $m_{\tilde{\ell}} > 16$ GeV (if $m_{\tilde{\ell}_R} < m_{\tilde{\ell}_L}$).

3.3 Sneutrinos

The sneutrinos are the super partners of the neutrinos. Sneutrinos may be pair-produced as in the charged slepton case: $e^+e^- \rightarrow Z^0 \rightarrow \tilde{\nu}\tilde{\nu}$. If the sneutrino is the LSP, both $\tilde{\nu}$'s leave the apparatus unseen. If the neutralino is the LSP, then we will have the decay $\tilde{\nu} \rightarrow \nu\tilde{\chi}^0$, which is also not observable. Possible observable decays would be $\tilde{\nu} \rightarrow \nu\tilde{\chi}^{0'}$ or $\tilde{\nu} \rightarrow \ell^\mp\tilde{\chi}^\pm$, which have not been searched for at LEP; they would be observed in the searches for neutralinos and for charginos.

The “invisible” channels may be searched for in the same way as for the neutrino counting reaction, i.e. by searching for photons radiated by the initial state. At present the statistics are not adequate for a meaningful search in this channel.

Indirect limits have been obtained from the limits on the total and the invisible widths, see Fig. 6. The width limit $\Gamma_Z^{\text{inv}} < 17$ MeV implies $m_{\tilde{\nu}} > 37$ GeV for a single sneutrino. If the three sneutrinos are mass degenerate, then the limit becomes $m_{\tilde{\nu}_{\text{deg}}} > 41.7$ GeV. These LEP limits are the only existing ones for sneutrinos. They rule out the sneutrinos as Dark Matter candidates.

3.4 Charginos

The winos $\tilde{W}^\pm$ are the super partners of the $W^\pm$ bosons. The charged Higgsinos $\tilde{H}^\pm$ are the super partners of charged Higgs bosons, which are present in two-doublet models. Charginos $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$ are the mass eigenstates corresponding to the linear combinations of charged Higgsinos $\tilde{H}^\pm$ and winos $\tilde{W}^\pm$.

Charginos have been searched for via the following pair production and decays

$$e^+e^- \rightarrow Z^0 \rightarrow \tilde{\chi}^+\tilde{\chi}^-, \quad \tilde{\chi}^\pm \rightarrow W^\pm\tilde{\chi}^0 \rightarrow q\bar{q}\tilde{\chi}^0, \rightarrow \ell\nu\tilde{\chi}^0 \quad (6)$$

The corresponding Feynman diagrams are similar to those of slepton-pair production, Fig. 3. The searched-for topology is similar to that of charged sleptons, that is acoplanar lepton pairs. The limit is at $m_{Z^0}/2$.

In the MSSM the chargino sector depends on three parameters, which are usually chosen to be $m_{1/2}$, μ and $\tan\beta$.

The charginos should have been abundantly produced at the Z^0 peak, in particular if they were almost pure winos (that is the supersymmetric partners of the $W^\pm$). Interesting limits can thus be obtained (see Fig. 6): from the total width of the Z^0 , $m_{\tilde{\chi}^\pm} > m_{Z^0}/2$ for pure winos, $m_{\tilde{\chi}^\pm} > 44.9$ GeV for pure Higgsinos; from the invisible width $m_{\tilde{\chi}^\pm} > 45.3$ GeV for $m_{\tilde{\chi}^\pm} \simeq m_{\tilde{\chi}^0}$. We shall globally quote the limit $m_{\tilde{\chi}^\pm} > m_{Z^0}/2$.

Figure 6: In the m_{LSP} versus $m_{\tilde{\chi}^\pm}$ plane, excluded domains from the Z^0 width measurements (A), and from the direct searches (B) in the pure Higgsino (light lines) and pure wino (heavy lines) cases, assuming: a) $\text{LSP} = \tilde{\chi}^0$ and W -exchange dominance in $\tilde{\chi}^\pm$ decays; b) $\text{LSP} = \tilde{\nu}$. Notice that $m_{\tilde{\nu}} > 41$ GeV from the Z^0 invisible-width measurement, assuming three mass-degenerate scalar neutrinos (C) (ALEPH) [3].

3.5 Scalar quarks

Scalar quarks, the superpartners of quarks, may be produced in pairs according to the following scheme

$$e^+e^- \rightarrow Z^0 \rightarrow \tilde{q}\tilde{q} \rightarrow \tilde{\chi}^0 q \tilde{\chi}^0 \bar{q} \quad (7)$$

where the $\tilde{\chi}^0$ is the LSP. This reaction leads to the production of two jets of hadrons which are acollinear and acoplanar because of the large missing energy and momentum (carried

away by the undetected $\tilde{\chi}^0$'s). The limits reported in [11], and in updates, essentially reach the kinematic limit, $m_{\tilde{q}} > m_{Z^0}/2$. These limits do not compete with those obtained at $p\bar{p}$ colliders; for instance the CDF limit at Fermilab is $m_{\tilde{q}} > 126$ GeV [8, 12].

The stop has to be treated separately. There have been speculations about the possibility $m_{\tilde{t}} < m_t$, because the large top mass may allow large $\tilde{t}_R - \tilde{t}_L$ mixing. One could have the decay $\tilde{t} \rightarrow c\tilde{\chi}^0$, which would yield topologies similar to those of light squark decays. DELPHI has discussed this case in detail [11].

The indirect limit from the total Z^0 width yields $m_{\tilde{q}} > 44.5$ GeV if the five-quark masses are degenerate and if $m_{\tilde{q}_R} \simeq m_{\tilde{q}_L}$. Otherwise the limits are slightly smaller, at about 40 GeV, regardless of decay modes.

3.6 Neutralinos

The photino $\tilde{\gamma}$, the zino $\tilde{Z}^0$ and the Higgsinos are the weak eigenstate super partners of the photon, Z^0 and neutral Higgs bosons, respectively. The superpartners of the Z^0 , of the two neutral Higgs bosons (see Section 4.2) and of the photon will in general mix, giving rise to four fermion mass eigenstates called neutralinos and denoted $\tilde{\chi}^0$, $\tilde{\chi}^{0'}$, $\tilde{\chi}^{0''}$, $\tilde{\chi}^{0'''}$ in order of increasing mass:

$$\tilde{\chi}^{0i} = c_1^i \tilde{\gamma} + c_2^i \tilde{Z}^0 + c_3^i \tilde{H}_1^0 + c_4^i \tilde{H}_2^0 \quad (8)$$

For certain parameter combinations the neutralinos may coincide with the photino or the lower-mass Higgsino.

In e^+e^- interactions at the Z^0 mass, the Z^0 can decay into any combination of two neutralinos, with a branching ratio that depends on their content of weak eigenstate fields. The $Z^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$ is invisible and can only be investigated through the analysis of the invisible width of the Z^0 . The main channels to be directly searched for are $Z^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^{0'}$, $Z^0 \rightarrow \tilde{\chi}^{0'} \tilde{\chi}^{0'}$. The $\tilde{\chi}^{0'}$ can decay into a $\tilde{\chi}^0$ plus a pair of fermions (quarks or leptons), $\tilde{\chi}^{0'} \rightarrow \tilde{\chi}^0 f\bar{f}$, via a virtual Z^0 . Alternatively the $\tilde{\chi}^{0'}$ can decay into a $\tilde{\chi}^0$ plus a photon, $\tilde{\chi}^{0'} \rightarrow \tilde{\chi}^0 \gamma$. Thus the channels to be looked for are the following:

$$e^+e^- \rightarrow Z^0 \rightarrow \tilde{\chi}^{0'} \tilde{\chi}^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 f\bar{f} \quad (9a)$$

$$\rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \gamma \quad (9b)$$

(we shall not discuss the channel $e^+e^- \rightarrow \tilde{\chi}^{0'} \tilde{\chi}^{0'}$).

The signature for the process (9a) ($\tilde{\chi}^0 \tilde{\chi}^0 f\bar{f}$) is an event topology of large missing momentum and large acoplanarity, due to the two undetected neutralinos. In the case of $f\bar{f} = q\bar{q}$ one looks for acoplanar two-jet events with small visible energy; in some cases the two jets may merge forming a monojet ("Zen" events). If $f\bar{f} = \ell\bar{\ell}$ one looks for two acoplanar tracks.

The process (9b) ($e^+e^- \rightarrow \tilde{\chi}^0 \tilde{\chi}^0 \gamma$) may be observed as 'single-photon' events. There may be a background from $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, which may be calculated. Another source of background might be $e^+e^- \rightarrow e^+e^-\gamma$ when the final e^+ , e^- are emitted at small angles and are not detected.

Both types of searches have been performed with negative results [13]. One way of presenting the limits is in terms of a bidimensional graph of $m_{\tilde{\chi}'}$ versus $m_{\tilde{\chi}}$ with contours indicating the branching ratio $\text{BR}(Z^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^{0'})$ at 95% CL, see Fig. 7. The excluded regions correspond to $\text{BR} \sim 10^{-4}$.

Figure 7: Upper limit on the branching ratio $BR(Z^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^0)$ at 95% CL (OPAL). Curves A, B, C, and D indicate the contours of $1.5, 2.0, 3.0,$ and 5.0×10^{-4} . This limit is valid for all branching ratios $BR(\tilde{\chi}^{0'} \rightarrow \tilde{\chi}^0 \gamma)$ and $\eta\eta' = \pm 1$ (η and η' are the signs in the Majorana condition of χ and χ'). The cross-hatched area is not considered or not accessible to the analysis reported here.

In general SUSY models, the masses and mixing angles of the neutralinos are free parameters. In the framework of the MSSM, in the neutralino and chargino sectors, all relevant physical quantities can be expressed in terms of only three parameters, which are usually chosen to be two masses ($\mu, m_{1/2}$) and the ratio between the vacuum expectation values of the two Higgs doublets ($\tan \beta = v_2/v_1$). The limits can be expressed as exclusion contours in the space of these parameters.

Figure 8 shows the excluded regions (limits at 95% CL) in the plane ($\mu, m_{1/2}$). The shaded regions are excluded by the analysis of the total and invisible widths of the Z^0 (the reaction $e^+e^- \rightarrow Z^0 \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$ would be unobserved, but it would give a contribution to Γ_{inv}); the hatched regions are excluded by the neutralinos decaying into hadronic modes. The situation is valid for $\tan \beta = 4$; similar plots have been made for $\tan \beta = 1, 2$. The excluded region covers most of the kinematically allowed region.

Indirect limits from the Z^0 total and invisible widths are model-dependent. For the MSSM one obtains the substantial limits shown in Fig. 8.

It is not easy to derive precise limits for the lightest neutralino mass. In the context of the MSSM the lightest neutralino mass should be larger than about 20 GeV, for $\tan \beta = v_2/v_1 > 3$.

Figure 8: Excluded regions for neutralino production in the plane of the two parameters of the MSSM, μ and m (DELPHI) [13]. The shaded regions are excluded by the analysis of the total and invisible widths of the Z^0 ; the hatched regions are excluded by the direct search for neutralinos decaying into hadronic modes. Also shown are the limits of the regions in which the decays of the Z^0 to neutralinos are kinematically allowed; the dotted line is for the $\tilde{\chi}^0 \tilde{\chi}^0$ channel and the dashed line for $\tilde{\chi}^0 \tilde{\chi}^{0'}$ ($\tan \beta = 4$).

3.7 Gluinos

Experiments at the CERN Sp $\bar{p}$ S and at the Fermilab Tevatron Colliders exclude the existence of a gluino with $few \text{ GeV} < m_{\tilde{g}} < m_{Z^0}$ [8, 12].

As far as we know, no dedicated search for gluinos has been performed at LEP. Gluino production may be computed via the Feynman diagrams of Fig. 9.

The gluino could decay into a neutralino and a quark-antiquark pair, $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow q\bar{q}\chi^0 \rightarrow 2 \text{ jets} + \chi^0$. But the high-mass region allowed by $p\bar{p}$ collider results, $m_{\tilde{g}} > m_{Z^0}$, is not accessible at LEP. One remains with the light gluino possibility, $m_{\tilde{g}} < few \text{ GeV}$. In this case the gluino cannot decay into a neutralino, since LEP results have placed a lower bound on the neutralino mass of at least a few GeV (for reasonable values of $\tan \beta$). This statement is not valid in a class of SUSY-breaking models for which $m_{1/2} = 0$ and the partners of the massless gauge bosons (gluino and photino) are orders of magnitude lighter than squarks and sleptons. In this case there would be little mixing of photino with zino and Higgsinos. The gluinos could be pair produced in $e^+e^- \rightarrow \dots + g \rightarrow \dots + \tilde{g} + \tilde{g}$ (vertex $g\tilde{g}\tilde{g}$) and would decay as $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$. There may be three windows open for different gluino mass intervals [14]:

- i) $m_{\tilde{g}} < 0.7 \text{ GeV}$. The gluino would have a lifetime $\tau_{\tilde{g}} \sim 10^{-9} \text{ s}$ (dependent on $m_{\tilde{q}}$) and could thus be searched for in the context of studies of K^0 , Λ^0 production. The photino mass could be very small (hundreds of MeV) and there could exist rather

stable bound states ($g\tilde{g}$) of 1–2 GeV mass (glueballinos) [14].

- ii) $2.6 < m_{\tilde{g}} < 4$ GeV, for example with $m_{\tilde{q}} \sim 500$ GeV, $m_{\tilde{\gamma}} \sim 600$ MeV, $\tau_{\tilde{g}} \sim 10^{-12}$ s. There could also exist ($g\tilde{g}$) states of 3–6 GeV mass and lifetimes 10^{-12} s. At LEP, the final states would be $q\bar{q}\tilde{\gamma} + q\bar{q}\tilde{\gamma}$ and would thus lead to four jets of hadrons plus missing energy plus two secondary vertices, like for B-events, but without charged leptons.
- iii) $m_{\tilde{g}} > 3$ GeV; for example $m_{\tilde{g}} \simeq 4$ GeV, $m_{\tilde{\gamma}} \sim 700$ MeV, $m_{\tilde{q}} \sim 5$ TeV, $\tau_{\tilde{g}} \sim 10^{-9}$ s. The methods for a search in this mass range could be a combination of those of the previous two cases.

Another possibility is if the gluino were the LSP, in which case it would leave any LEP apparatus unseen. This is highly unlikely since it seems that Dark Matter is colourless. In any case, the reaction which could be investigated at LEP is the one illustrated by the Feynman diagram of Fig. 9a: $e^+e^- \rightarrow q\bar{q}\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g} + 2$ jets. This corresponds to the topology of two acollinear hadron jets plus missing energy and momentum. It may be worthwhile to investigate in more detail this topology, even if it is a difficult one.

Figure 9: Feynman diagrams for gluino production at LEP 100. The rate for process a) is expected to be much larger than that of processes b) [15].

3.8 Discussion

The experimental limits quoted in this Section, plus other limits from $p\bar{p}$ colliders and limits on non-minimal Higgses, see Section 4.2, have been used to place constraints on some parameters of the MSSM. In particular Ellis et al. [3] placed limits in the $M_2 - \mu$ plane. They suggest that further limits may be placed from a search for “Zen events”. These are defined as events in which the Z^0 decays into two neutral particles, one of which decays visibly and the other is not observed. In most such events the Z^0 decay products are contained in one hemisphere. The authors stress that a dedicated search at the level of 10^{-5} should be possible and would explore a wider region in the $M_2 - \mu$ parameter space.

3.9 Unstable photinos that violate R parity

As an example of a non-conventional theory we consider the model of Babu and Mohapatra [16]. They have shown that the apparent anticorrelation of the solar-neutrino signal with the 11-year sunspot cycle [17] could be explained within the framework of an unusual supersymmetric extension of the Standard Model with R -parity-violating interactions. In this model the neutrinos have a large transition magnetic moment such that a ν_e can transform into a ‘sterile’ ν_μ in the sun’s magnetic field. A discrete symmetry between e and μ lepton families is introduced. Individual lepton number conservation does not hold, but the combination $(L_e - L_\mu)$ remains a good quantum number. The presence of $(L_e - L_\mu)$ symmetry forbids rare processes such as $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ as well as neutrinoless double-beta decay. In this model the mass of the selectron, $\tilde{e}$, is restricted to lie in the mass range below ≈ 100 GeV, if a sufficiently large neutrino magnetic moment ($\approx 10^{-10}\mu_B$, where μ_B is the proton Bohr magneton) is to be achieved.

OPAL [18] has searched for the reaction

$$e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma} \quad (10)$$

where $\tilde{\gamma}$ is the lightest supersymmetric particle assumed here to be a pure photino. This reaction proceeds by the exchange of a selectron (see Fig. 10), and has a cross-section which depends on $m_{\tilde{e}}$, the selectron mass. Following Ref. [18] we assume that the photino decays into the following modes which violate R parity and L_τ but not $(L_e - L_\mu)$:

$$\tilde{\gamma} \rightarrow \tau^+e^-\nu_\mu, \quad \rightarrow \tau^-e^+\bar{\nu}_\mu, \quad \rightarrow \tau^+\mu^-\nu_e, \quad \rightarrow \tau^-\mu^+\bar{\nu}_e \quad (11)$$

Events from reaction (10) followed by the decays (11) would have two leptons in each hemisphere. In the discussion that follows, it is assumed that the photino is in a pure quantum state and its mixing with Higgsinos and zinos is negligible. The photinos rapidly decay (with a lifetime of $\leq 10^{-12}$ seconds) into three fermions via intermediate massive scalar particles $\tilde{e}$, $\tilde{\mu}$ or $\tilde{\tau}$ as shown in Fig. 10b. The final-state system has angular and energy distributions different from those of the leptonic decay particles from a τ , since in the latter case the intermediate state is a vector boson $W^\pm$. The primary leptons tend to be more energetic than those from $\tau^\pm$ decays.

Figure 10: (a) Feynman diagram for photino production in e^+e^- annihilations by the Babu-Mohapatra mechanism. (b) Feynman diagram for the decay of the photino via an intermediate massive scalar particle.

A typical $\tilde{\gamma}\tilde{\gamma}$ event would contain two or four charged tracks in each hemisphere. After imposing this condition in one hemisphere only, no event remains. In the framework of the model, in Fig. 11, the 95% CL exclusion is displayed as a function of $m_{\tilde{\gamma}}$ and $m_{\tilde{e}}$ for the region $m_{\tilde{\gamma}} \geq 5$ GeV. Mass limits from previous direct searches for $\tilde{e}$ are also shown.

If $\tilde{\chi}^0$ is not a pure photino but has an important zino or Higgsino component, the conclusion can be weakened, unless the dominant $\tilde{\chi}^0$ decays remain those listed in Ref. [18].

This search could be taken as an example; there are other models which for instance predict $\tilde{\gamma} \rightarrow \gamma + X$, where X could be a neutrino, a gravitino, etc.

Figure 11: Exclusion contour at 95% CL in the $(m_{\tilde{\gamma}}, m_{\tilde{e}})$ plane deduced from the OPAL search for $\tilde{\gamma}$'s that violate R parity. The region allowed by the Babu-Mohapatra model is indicated with dashed lines. Also indicated are the regions excluded by previous direct searches for $\tilde{e}$ at LEP.

4. HIGGS SEARCHES

The discovery of the Higgs particle(s) could lead to an understanding of particle masses and could give information on the mechanism of symmetry breaking.

In the minimal Standard Model the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ electroweak symmetry necessitates the introduction of a complex doublet of scalar Higgs fields [19]. As the fields acquire a vacuum expectation value, three of the four degrees of freedom are taken by the Z^0 and $W^\pm$ bosons which thus acquire mass; the last degree of freedom gives rise to the physical neutral Higgs boson, H_{SM}^0 . The same mechanism gives mass to fermions.

However, there is no reason why the Higgs sector could not be more complicated. In fact many models beyond the Standard Model have been proposed. In the following we shall discuss experimental searches for a limited sample of possibilities.

The coupling of the Higgs particle(s) to fermions is proportional to their mass. Therefore the Higgs particle(s) preferentially decays into the heaviest fermion pair kinematically accessible. The Higgs particle mass is not predicted by the theory and therefore experimentally one has to search over a large mass range.

4.1 The Standard Model neutral Higgs boson

Prior to LEP, there existed a few experimental limits [20], which excluded a Higgs boson with a mass lighter than a few GeV. These limits are subject to some theoretical uncertainties. LEP represents, so far, the best accelerator for searches for the Standard Model Higgs boson. The main production reaction at LEP is given by the so-called Bjorken mechanism (bremsstrahlung process) [21]:

$$e^+e^- \rightarrow Z^0 \rightarrow Z^{0*} H_{\text{SM}}^0 \rightarrow f\bar{f} H_{\text{SM}}^0 \quad (12)$$

with the subsequent decay of the H_{SM}^0 into an $f'\bar{f}'$ fermion pair. The Feynman diagram of this process is shown in Fig. 12.

Figure 12: Feynman diagram of the Bjorken mechanism for H_{SM}^0 production.

The cross-section of this process is steeply falling with increasing Higgs boson mass, as shown in Fig. 13. Even for very low Higgs boson masses, this cross-section never exceeds 1% of the Z^0 total cross-section.

Another production reaction is:

$$e^+e^- \rightarrow H_{\text{SM}}^0 \gamma$$

which proceeds via a loop involving the W boson and charged fermions, including the top quark. However the cross-section of this process is smaller than that of the Bjorken mechanism, up to $m_{H_{\text{SM}}^0} \sim 70$ GeV. Moreover, the high background from $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}\gamma$ decays, makes this channel very difficult to explore at LEP 100. Thus the Bjorken process is the only one which was used to search for the H_{SM}^0 at LEP 100.

Figure 13: Total cross-section for $e^+e^- \rightarrow H_{\text{SM}}^0 f\bar{f}$ as a function of m_{H^0} at the Z^0 peak. The dashed curve includes radiative corrections.

The topology of the $H_{\text{SM}}^0 f\bar{f}$ events varies significantly with the mass of the Higgs boson; several analyses have been performed to cover different mass intervals and different decay channels. We shall divide the analyses in three mass intervals [22]: the very low-mass ($0 \leq m_{H_{\text{SM}}^0} < 2 m_\mu$), the intermediate-mass ($2 m_\mu \leq m_{H_{\text{SM}}^0} \leq 2m_b$) and the high-mass ($m_{H_{\text{SM}}^0} \geq 2m_b$) regions.

The number of predicted Higgs boson events, for a given Higgs boson mass, and for a given decay channel, is given by

$$N_{\text{exp}}(m_{H^0}) = \sigma_{\text{Bjorken}}(m_{H^0}) \times BR \times \varepsilon \times L, \quad (13)$$

where σ_{Bjorken} is the cross-section of the Bjorken process, BR is the branching ratio of the studied channel, ε is the selection efficiency and L is the integrated luminosity. By repeating this calculation for various Higgs masses, one obtains a curve representing the number of expected events as a function of the Higgs boson mass. From the comparison of the observed and predicted number of events and using the Poisson statistics, one can then compute the lower limit for the Higgs boson mass at a given confidence level, using the method discussed by the Particle Data Group [23].

In the Standard Model, the Higgs cannot couple to photons at the tree level; however the $H_{\text{SM}}^0 \rightarrow \gamma\gamma$ decay may proceed via one-loop diagrams involving charged fermions and W bosons. The L3 Collaboration presented a limit of $\sigma(e^+e^- \rightarrow H^0 + \text{hadrons}) \cdot BR(H^0 \rightarrow \gamma\gamma) \sim 1 \text{ pb}$ for $10 < m_{H_{\text{SM}}^0} < 70 \text{ GeV}$ [3].

4.1.1 The very low-mass region ($0 < m_{H_{\text{SM}}^0} < 2m_\mu$)

A Higgs boson with a mass smaller than $2m_\mu$ could only decay into an e^+e^- or $\gamma\gamma$ pair. The branching ratio of the latter channel is expected to be of the order of 10^{-3} compared to the first one. The mass region covered by the searches for a very low-mass

Higgs boson produced at LEP can be effectively subdivided into two further mass regions. If the Higgs boson were lighter than approximately 50 MeV, then it would have a relatively long lifetime and would decay outside the detector. Events where the virtual Z^{0*} decays into an e^+e^- or $\mu^+\mu^-$ pair would have a signature characterized by an acollinear lepton pair, see Fig. 14. The main background to this process comes from radiative di-lepton events, where the photon escapes detection.

If the Higgs boson mass is slightly higher, then it would decay inside the detector at a detectable distance from the primary vertex. This would lead to a pair of tracks coming from the same decay point (V^0) and recoiling against an accompanying lepton pair from the primary vertex. The V^0 would be most often isolated, therefore giving a clear experimental signature, as indicated in Fig. 15 for the charged leptons. Possible background to these events would come from radiative di-lepton pairs, where the photon converts in the material of the detector, or from hadronic Z^0 decays containing a long-lived neutral hadron.

The results of the analyses performed at LEP exclude, at the 99% CL, the existence of a Higgs boson in this mass interval [24], as shown in Fig. 16.

Figure 14: Sketch of a very low-mass Higgs event, where the Higgs boson decays outside the detector.

Figure 15: Sketch of a Higgs V^0 event ($H_{SM}^0 e^+ e^-$, $H_{SM}^0 \mu^+ \mu^-$ final states), where the H_{SM}^0 decays inside a tracking detector.

Figure 16: Number of expected very low-mass Standard Model Higgs boson events from the analyses performed by (a) the OPAL and (b) the L3 Collaborations.

4.1.2 The low-mass region ($2m_\mu < m_{H_{SM}^0} < 2m_b$)

This mass interval can also be split in two regions. In the range $2m_\mu < m_{H^0} < 2m_\tau$ the theoretical predictions are not unambiguous and rely on the extrapolation of some low-energy QCD theorems [25]. In this region the Higgs boson would decay mostly into two charged particles (two pions, two kaons, two muons). It has been searched for by looking at events containing two fermions (originating from the Z^{0*}) plus two charged prongs. The topology is shown in Fig. 17 for the case in which the two fermions are quarks and thus give rise to two jets of hadrons.

Figure 17: Sketch of an event with two charged prongs and two jets, for an H_{SM}^0 mass in the range $2m_\mu < m_{H^0} < 2m_\tau$ (the solid lines indicate charged particles, the dashed lines indicate neutral particles).

The ALEPH Collaboration studied all possible decays of the Z^{0*} , while the DELPHI Collaboration concentrated on the channel $Z^{0*} \rightarrow q\bar{q}$, see Fig. 18. The results of these studies [26] exclude, at 95% CL, the existence of a Higgs boson with $2m_\mu < m_{H^0} < 1.5$ GeV, see Fig. 18.

The L3 Collaboration studied the reaction $Z^0 \rightarrow \ell^+ \ell^- H_{SM}^0$, where the H_{SM}^0 can decay into anything. They confirm the limit just mentioned.

The OPAL Collaboration used the decays $Z^{0*} \rightarrow e^+ e^-$, $\mu^+ \mu^-$ with the H_{SM}^0 decaying into a non-electromagnetic final state (that is into anything, except photons and/or $e^+ e^-$ pair final states), and $Z^{0*} \rightarrow \nu \bar{\nu}$ with the H_{SM}^0 decaying into an electromagnetic final state. They exclude a Higgs boson with a mass below 11 GeV.

Figure 18: Number of expected events by the DELPHI experiment, for a light Standard Model Higgs boson for the two jets plus two charged prongs channel.

If the H_{SM}^0 is heavier than $2m_\tau$, then it would most often decay into a quark pair or a τ pair. The channels in which these decays are accompanied by an electron, muon or neutrino pair originating from the decay of the Z^{0*} have been searched for. Owing to the dynamics of the reaction, these events have a simple experimental signature: two isolated, high-momentum, oppositely charged leptons recoiling against the H_{SM}^0 decay products. The two leptons have an opening angle which depends on the Higgs boson mass. In the case of a very low mass H_{SM}^0 the two leptons are emitted almost back-to-back, while the opening angle decreases as the Higgs mass increases. The opposite is true for the H_{SM}^0 decay products.

In this mass range the H_{SM}^0 decay products (mostly two quarks) would tend to merge in a monojet-like topology. Therefore the events would contain two leptons and a monojet of hadrons, as sketched in Fig. 19.

Chronologically this was the first mass range investigated by all LEP collaborations [26], since the cross-section for a Higgs boson of this mass is still relatively high, allowing a search for it, even with the limited statistics (luminosity) available in the first year of data-taking. The results obtained by all four LEP collaborations exclude the existence of a Higgs boson in this mass range.

Figure 19: Sketch of an event with a monojet from the decay of a Standard Model Higgs boson plus two charged leptons.

4.1.3 The high-mass region ($m_{H_{SM}^0} > 2m_b$)

If the Higgs mass is heavier than ~ 15 GeV, the Higgs boson would decay in 94% of the cases into a $q\bar{q}$ (mostly $b\bar{b}$) pair. In Table 5 are presented the products of the relative branching ratios ($H_{SM}^0 \rightarrow$) ($Z^{0*} \rightarrow$) for a Higgs boson in this mass range.

Table 5: Products of the relative decay branching ratios ($H_{SM}^0 \rightarrow$) ($Z^{0*} \rightarrow$) for a Standard Model Higgs boson heavier than 15 GeV.

$H_{SM}^0 \rightarrow$	$Z^{0*} \rightarrow$	BR (%)
$q\bar{q}$	$\nu\bar{\nu}$	18.9
$q\bar{q}$	e^+e^-	3.2
$q\bar{q}$	$\mu^+\mu^-$	3.2
$q\bar{q}$	$\tau^+\tau^-$	3.2
$q\bar{q}$	$q\bar{q}$	65.5
$\tau^+\tau^-$	$\nu\bar{\nu}$	1.2
$\tau^+\tau^-$	e^+e^-	0.2
$\tau^+\tau^-$	$\mu^+\mu^-$	0.2
$\tau^+\tau^-$	$\tau^+\tau^-$	0.2
$\tau^+\tau^-$	$q\bar{q}$	4.2

In the channel where the H_{SM}^0 decays into $q\bar{q}$ and the Z^{0*} yields a muon or an electron pair, the signature would be two energetic and acollinear charged leptons plus two acollinear jets, as shown in Fig. 20. The background due to the semileptonic decays of heavy quarks can be effectively reduced by requiring the charged lepton pair to be isolated in the event. An irreducible background is instead represented by the rare four-fermion decays of the Z^0 boson. The channel where the H_{SM}^0 is produced in association with a τ pair has a more complicated topology, due to the decay of the two leptons, resulting in a lower efficiency of the analysis. This channel is therefore slowly being abandoned and will not be used when computing the LEP combined limit.

Figure 20: Topology of a high-mass Higgs boson event
 $(Z^{0*} \rightarrow e^+e^-, \mu^+\mu^-; H_{\text{SM}}^0 \rightarrow q\bar{q} \rightarrow 2 \text{ jets})$.

In the case where the $Z^{0*} \rightarrow \nu\bar{\nu}$, the events would have two jets and a large amount of missing energy and momentum. The background is represented by beam-gas and beam-wall interactions: both these processes can produce events with large missing momentum along the beam pipe. Other sources of background are photon-photon processes or semileptonic decays of heavy quarks with neutrino production. For the search in this channel it is essential that the detector be as hermetic as possible over the whole solid angle.

The channel in which both the H_{SM}^0 and the Z^{0*} decay into a $q\bar{q}$ pair has the largest branching ratio but also has the largest background, given by QCD processes with a $q\bar{q}$ pair and one or more gluons. Therefore this channel has not yet been searched for by any of the LEP experiments.

The results on the Higgs boson mass limits obtained by the four LEP experiments [27], for the 1992 summer conferences are: ALEPH 56.8 GeV, DELPHI 50 GeV, L3 53.4 GeV and OPAL 54.2 GeV. These limits are now being updated, using also the 1992 data. New (preliminary) limits are: ALEPH 58.2 GeV, DELPHI 54.7 GeV, L3 57.7 GeV and OPAL 57.9 GeV.

The four limits may be combined to form a global LEP lower limit on the Higgs boson mass. In order to do this, one has to take into account the efficiencies, at various values of the Higgs mass, of each analysis of the four experiments, using the relative statistical and systematic errors. For the 1992 summer conferences the total number of hadronic events was more than two million and the combined limit was $m_{H_{\text{SM}}^0} > 60$ GeV [3, 27, 28], at 95% CL. With the 1992 data the limit is larger than 63 GeV. The combined limit is shown in Figs. 21 and 22 together with the individual limits obtained by the four LEP collaborations. In Fig. 22 we show all the results presented by the LEP experiments as a function of the collected luminosity. Also shown in Fig. 22 are the theoretical curves corresponding to 50% and 100% analysis efficiencies [28], respectively. These curves have been obtained using the $H_{\text{SM}}^0 \nu\bar{\nu}$, $H_{\text{SM}}^0 e^+e^-$ and $H_{\text{SM}}^0 \mu^+\mu^-$ channels. There are few candidate Higgs events with masses not close to 63 GeV. Therefore their presence does not modify the combined limit.

LEP 100 will not allow the investigation of Higgs boson masses much larger than about 70 GeV; some improvement might be possible if the channel $e^+e^- \rightarrow H_{\text{SM}}^0 Z^{0*} \rightarrow 4 \text{ jets}$ could be used. The possibilities opened up by LEP 200 will be discussed in Section 8.

Figure 21: Lower limits on the Higgs boson mass from each LEP experiment and combined.

Figure 22: Higgs boson mass lower limits obtained by the four LEP experiments as a function of the integrated luminosity. Also shown is the combined LEP limit.

4.2 Non-minimal Higgs bosons

In models with more than one Higgs doublet the production rates and decay properties depend on the Higgs boson masses and also on additional parameters. In supersymmetric models a minimum of two Higgs doublets are needed such that one doublet gives masses to the up-type quarks and leptons and the other doublet to the down-type fermions.

The Higgs boson sector with two complex Higgs doublets contains five physical Higgs particles

$$H^+, H^-, H^0, h^0, A^0, \quad (14)$$

where the A^0 is a CP-odd state, while the h^0 and H^0 are CP-even. These five states plus the three degrees of freedom carried by the massive $W^\pm$ and Z^0 result from the eight degrees of freedom of the two complex doublets H_1 and H_2 fields, which in the spontaneous symmetry breaking acquire vacuum expectation values v_1 and v_2 . The sparticle Higgs sector manifests into neutralinos and charginos, see Table 3. Note that the decays $Z^0 \rightarrow h^0 h^0$ and $Z^0 \rightarrow A^0 A^0$ are forbidden by Bose symmetry.

In the MSSM the five Higgs boson masses depend on two parameters, which may be chosen to be m_{A^0} and $\tan \beta = v_2/v_1$. Experimentalists prefer to replace the two theoretically preferred parameters $m_{A^0}, \tan \beta$ with m_{h^0}, m_{A^0} .

At the tree level the following relations are expected to hold:

$$\begin{aligned} m_{h^0} &\leq m_{Z^0} \quad \text{and} \quad m_{H^\pm} \geq m_{W^\pm} \\ m_{A^0} &> m_{h^0} \quad \text{and} \quad m_{H^0} > m_{Z^0} \\ m_{h^0} &\simeq m_{A^0} \quad \text{if} \quad \tan \beta \text{ is large.} \end{aligned}$$

The introduction of loop corrections removed some of these constraints. In particular m_{h^0} is now required to be lighter than 110 GeV if $m_t \sim 140$ GeV, and m_{A^0} may be smaller than m_{h^0} [29].

4.2.1 Neutral Higgs bosons

At the Z^0 mass the reactions leading to h^0 (and A^0) production are the following:

$$e^+e^- \rightarrow Z^0 \rightarrow Z^{0*}h^0 \rightarrow f\bar{f}h^0 \quad (15a)$$

$$e^+e^- \rightarrow Z^0 \rightarrow A^0h^0 \quad (15b)$$

The first is the well-known Bjorken mechanism; the second is a neutral pair production process.

Since the h^0 and A^0 decay into the heaviest particles kinematically allowed, many types of searches have to be performed to exclude each possible mass range [30]. The Higgs decay patterns may be the following.

Mass range (GeV)	h^0	A^0
0-0.21	$\gamma\gamma, e^+e^-, A^0A^0$	$\gamma\gamma, e^+e^-$ (long lifetime)
0.21-3	2-4 prongs, A^0A^0	2-4 prongs
3-10	$\tau^+\tau^-, c\bar{c}, A^0A^0$	$\tau^+\tau^-, c\bar{c}$
>10	$b\bar{b}, (c\bar{c}), \tau^+\tau^-, A^0A^0$	$b\bar{b}, (c\bar{c}), \tau^+\tau^-$

Let us consider a few examples.

- Search for SUSY Higgs particles through the $\tau^+\tau^-$, $q\bar{q}$ final states. The search for the CP-even neutral Higgs h^0 and the CP-odd A^0 was performed studying the $\tau^+\tau^-$, $b\bar{b}$ final state at the Z^0 mass [30]. The process is the following:

$$e^+e^- \rightarrow Z^0 \rightarrow h^0 + A^0 \quad (16)$$

$\begin{array}{l} \searrow \rightarrow b\bar{b} \\ \downarrow \rightarrow \tau^+\tau^- \end{array}$

The $h^0 \rightarrow \tau^+\tau^-$ has a branching ratio of about 6%. Since one limits the analysis to single-track decays of the τ 's, the process leads to a final state with two isolated charged tracks with a large opening angle accompanied by two jets of hadrons.

- Search for heavy h^0 via the channel $e^+e^- \rightarrow Z^0 \rightarrow h^0 Z^{0*}$, $h^0 \rightarrow b\bar{b}(c\bar{c})$, $Z^{0*} \rightarrow \nu\bar{\nu}$. The topology of these events is the same as that of H_{SM}^0 : $e^+e^- \rightarrow Z^0 \rightarrow H^0 Z^{0*}$, $H^0 \rightarrow q\bar{q}$, $Z^{0*} \rightarrow \nu\bar{\nu}$. It is therefore already covered in H_{SM}^0 searches.
- Search for a SUSY Higgs particle in the six- τ -lepton channel. OPAL searched for the h^0 and A^0 resulting in a six- τ -lepton final state when the mass of the h^0 is larger than twice that of the A^0 and if the mass of the A^0 is between the $\tau^+\tau^-$ threshold and the $b\bar{b}$ threshold:

$$\begin{aligned} e^+e^- \rightarrow Z^0 \rightarrow h^0 A^0 \rightarrow A^0 A^0 A^0 \rightarrow 6\tau & \quad \text{a)} \\ m_{h^0} > 2m_{A^0} & \quad \text{b)} \\ 2m_\tau < m_{A^0} < 2m_b & \quad \text{c)} \end{aligned} \quad (17)$$

The last condition ensures, for models with $\tan \beta > 1$, a large branching ratio for $A^0 \rightarrow \tau^+\tau^-$.

For the general two-doublet case, Fig. 23a shows the 95% CL contour limits obtained from searches for $h^0 A^0$ and $h^0 Z^{0*}$ by the DELPHI Collaboration.

In the framework of the MSSM the excluded regions are larger. The OPAL search excludes the existence of any m_{h^0} , m_{A^0} mass combination in the mass regions relevant to this channel. When combined with previously published results the analysis excludes a MSSM A^0 boson in the range $2m_\tau < m_{A^0} < 2m_b$, independent of the h^0 mass. Figure 23b shows the DELPHI limit; the comparison with Fig. 23a shows clearly the improvement in the excluded regions when going from a general two-doublet model to the MSSM.

It is difficult to state precise lower limits for the h^0 and A^0 bosons. In the framework of the MSSM and including the recently calculated radiative corrections, the DELPHI Collaboration placed the following limits: $m_{h^0} \geq 42$ GeV, $m_{A^0} \geq 36$ GeV [30].

Figure 23: Contour limits, at 95% CL, obtained from searches for $h^0 A^0$ and $h^0 Z^{0*}$ channels (a) in the general two-doublet case (curve A is valid for any value of $\tan \beta$, curve B is obtained with $\tan \beta \geq 1$) and (b) in the MSSM (with $\tan \beta \geq 1$, $m_t = 135$ GeV and $m_{\tilde{g}} = 1$ TeV) (DELPHI, ref. [30]). Note in (a) the limit obtained by the precise measurement of Γ_Z .

4.2.2 Singly charged Higgs bosons

Searches were made for the following channels [31]:

$$\begin{aligned}
 e^+e^- \rightarrow Z^0 \rightarrow H^+H^- \rightarrow (cs)(\tau\nu) & \quad \text{a)} \\
 & \rightarrow (\tau\nu)(\tau\nu) \quad \text{b)} \\
 & \rightarrow (cs)(cs) \quad \text{c)}
 \end{aligned} \tag{18}$$

The multihadron sample is used for the three searches.

- The $(cs)(\tau\nu)$ mode leads to an event topology with two hadron jets from c, s, and one isolated charged track plus missing energy and momentum on the lepton side.
- The $(\tau\nu)(\tau\nu)$ mode leads to an event topology of an acoplanar τ pair with large missing momentum carried by the undetected neutrinos.
- The $(cs)(cs)$ mode leads to a four-jet structure which has different characteristics for a low-mass $H^\pm$ (say for less than 30 GeV) than for a large-mass $H^\pm (> 30$ GeV).

It might be possible to extend the search above $m_{Z^0}/2$ via the process $Z^0 \rightarrow H^+(H^-)^* \rightarrow H^+\tau^-\bar{\nu}_\tau$ with a subsequent leptonic decay $H^+ \rightarrow \tau^+\nu_\tau$; $(H^-)^*$ is a virtual particle, effectively light. In this case the τ^+ and τ^- are not back to back. If $\tan \beta$ is sufficiently large this search could be used to reach $H^\pm$ masses up to 75–80 GeV [31].

At present, the absence of a signal allows a limit to be placed at essentially $m_{Z^0}/2$, see Fig. 24 [32].

Figure 24: The excluded regions of the charged Higgs mass as a function of $\text{Br}(H^\pm \rightarrow \text{hadrons})$ by analysing $H^+H^- \rightarrow c\bar{s}cs$ (contour A) and $H^+H^- \rightarrow \tau^+\nu\tau^-\bar{\nu}$ (contour B). The contour C shows a combined limit of the two decay channels (DELPHI).

It has to be noted that in the MSSM the masses of the charged Higgses are predicted to be larger than the $W^\pm$ masses, $m_{H^\pm} > m_{W^\pm}$. Thus at LEP 100 they are not accessible experimentally.

The search for $H^\pm$ is also useful for placing limits on charged technipions, predicted by the technicolour model [32]. Although technipions should be composite particles, their sizes are expected to be of the order of $1/\Lambda$ where Λ is the typical energy scale of the technicolour model ($\Lambda \sim 1$ TeV). Therefore they should behave as point-like particles at Z^0 energies. At PETRA energies the limit on the technipion mass was 19 GeV, at LEP 100 the limit has been extended to 45.5 GeV.

4.2.3 Doubly charged Higgs particles

The possible existence of doubly charged Higgs particles H^{++} and H^{--} is a feature of some models that extend the Standard Model to allow small neutrino masses or that explore different possibilities for the Higgs sector [33]. For pair-produced $H^{++}H^{--}$ at the Z^0 energy the only appreciable decay channel would be into a lepton pair, $H^{++} \rightarrow \ell^+\ell^+$.

The Z^0 partial width for decay into $H^{++}H^{--}$ pairs is, neglecting radiative corrections [34],

$$\Gamma(Z^0 \rightarrow H^{++}H^{--}) = \frac{G_F m_Z^3}{6\pi\sqrt{2}} (I_3^L - Q \sin^2\theta_W)^2 \left(1 - \frac{4m_H^2}{m_Z^2}\right)^{\frac{3}{2}}, \quad (19)$$

where m_Z is the mass of the Z^0 boson, $\sin^2\theta_W$ is the electroweak mixing parameter, G_F is the Fermi coupling constant and m_H , Q , I_3^L are the mass, charge, and third component

of weak isospin, respectively, of the $H^{\pm\pm}$; the value of I_3^L is model-dependent, and can take any of the three possible values 1, 0 or -1 . The width would correspond to a sizeable fraction of the total Z^0 width, comparable to $\Gamma(Z^0 \rightarrow \mu^+\mu^-)$ for low-mass $H^{\pm\pm}$. Equation (19) with $I_3^L = 1/2$ and $Q = 1$ is also valid for singly charged Higgses, $H^\pm$.

The partial width for $H^{\pm\pm}$ to decay to leptons of the same family is given by

$$\Gamma(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = \sum_{\ell=e,\mu,\tau} \frac{g_{\ell\ell}^2 m_H}{8\pi} \left[1 - \frac{2m_\ell^2}{m_H^2} \right] \left[1 - \frac{4m_\ell^2}{m_H^2} \right]^{\frac{1}{2}}, \quad (20)$$

where $g_{\ell\ell}$ are the unknown Yukawa coupling constants, and m_ℓ is the mass of the leptons.

The $H^{\pm\pm}$ decay width into two charged leptons depends on the coupling constant $g_{\ell\ell}$. For very small $g_{\ell\ell}$, the $H^{\pm\pm}$ traverse the LEP detectors and decay outside. For relatively large $g_{\ell\ell}$ the $H^{\pm\pm}$ decay inside the beam pipe and one should observe four leptons in the tracking chambers of the LEP detectors. (Lepton universality, that is $g_{ee} = g_{\mu\mu} = g_{\tau\tau}$ and $g_{\ell\ell'} = 0$ for $\ell \neq \ell'$ was assumed.) Two types of searches were performed by OPAL using the 1990 data, corresponding to an integrated luminosity of 6.8 pb^{-1} [34].

Search for four-lepton final states. The selection required four-track final states with total charge track momentum $\sum |\vec{p}| > 20 \text{ GeV}/c$.

Search for long-lived H^{++} and H^{--} . For a small coupling ($g_{\ell\ell} \lesssim 10^{-7}$), a substantial fraction of $H^{\pm\pm}$ would traverse the tracking chamber without decaying. A distinct signature of a long-lived $H^{\pm\pm}$ is a track with a large ionization loss.

The searches yielded two events, consistent with the expected background of 3.1. Limits have been placed in the $m_H - g_{\ell\ell}$ plane.

The exclusion region for the process $Z^0 \rightarrow H^{++}H^{--} \rightarrow \ell_1^+ \ell_2^+ \ell_3^- \ell_4^-$ ($\ell = e, \mu, \tau$) for short-lived $H^{\pm\pm}$ is labelled 'A' in Fig. 25. It extends from the $H^{\pm\pm} \rightarrow \ell_1^\pm \ell_2^\pm$ threshold to an upper limit of 45.6 GeV.

The search for long-lived $H^{\pm\pm}$ includes the final states where one, or both, of the $H^{\pm\pm}$ escape the central chamber without decaying. The mass range extends from twice the electron mass to 45.6 GeV. The upper $g_{\ell\ell}$ boundary of the excluded region is determined by the $H^{\pm\pm}$ lifetime: as $g_{\ell\ell}$ increases, the $H^{\pm\pm}$ lifetime decreases, and with it the likelihood that one of the $H^{\pm\pm}$ traverses the tracking chamber without decaying. The excluded region in the $(m_H, g_{\ell\ell})$ plane for this channel is labelled 'B' in Fig. 25.

The existence of the decay mode $Z^0 \rightarrow H^{++}H^{--}$ would increase the total width of the Z^0 relative to the Standard Model prediction. Therefore, the value of $\Gamma_{Z^0}^{\text{Meas}} - \Gamma_{Z^0}^{\text{SM}}$, where $\Gamma_{Z^0}^{\text{Meas}}$ is the measured width of the Z^0 [1], and $\Gamma_{Z^0}^{\text{SM}}$ is the Standard Model prediction of the Z^0 width [35], gives a lower bound on the $H^{\pm\pm}$ mass. The prediction is a function of the parameters α_s , m_t and m_{H^0} (the strong coupling constant, the top mass and the mass of the Standard Model Higgs boson) which were varied in the ranges $0.11 \leq \alpha_s \leq 0.13$, $89 \leq m_t \leq 200 \text{ GeV}$ and $50 \leq m_{H^0} \leq 1000 \text{ GeV}$. The lower bound on the $H^{\pm\pm}$ width was 25 GeV for $I_3^L = 0$, and 30 GeV for $I_3^L = \pm 1$; it is now around $m_Z/2$.

The two approaches, together with the measured width of the Z^0 , were used to exclude the existence of the $H^{\pm\pm}$ with mass less than 45.6 GeV, and for values of $g_{\ell\ell}$ that extend down to zero.

Figure 25: The $H^{\pm\pm}$ exclusion regions in the $m_H - g_{\mu\mu}$ plane (OPAL). The unhashed zones show the regions excluded at the 95% CL. The regions labelled 'A' are excluded by the search for the short-lived $H^{\pm\pm}$. Those labelled 'B' (which extend down to $g_{\mu\mu} = 0$) are excluded by the search for the long-lived $H^{\pm\pm}$. $H^{\pm\pm}$ with mass less than 25.5 GeV ($I_3^L = 0$) or 30.4 GeV ($I_3^L = \pm 1$) are excluded by measurements of Γ_{Z^0} , as indicated by the dotted lines.

5. COMPOSITENESS

The existence of three families is a strong motivation for substructures of quarks and leptons. The situation would be similar to the one encountered in the previous steps in the structure of matter. Other motivations for substructures (compositeness) are the large number of parameters of the Standard Model, the similarities in flavour and chiral properties of quarks and leptons, the mass generation problem. In composite models, quarks, leptons and gauge bosons are composite with an associated energy scale Λ . The eventual discovery of excited states of leptons and quarks would be an unambiguous and characteristic signal for substructures. If the known quarks and leptons are composite, they may be regarded as the ground states of a spectrum of excited states.

5.1 Excited charged leptons

Two types of direct searches for excited charged leptons have been performed, corresponding to single and pair production [36]:

$$e^+e^- \rightarrow Z^0 \rightarrow \ell^{*\pm}\ell^\mp \rightarrow \ell^+\ell^-\gamma \quad (21)$$

$$e^+e^- \rightarrow Z^0 \rightarrow \ell^{*\pm}\ell^{\mp*} \rightarrow \ell^+\ell^-\gamma\gamma \quad (22)$$

These searches assume that the excited leptons $\ell^* = e^*, \mu^*, \tau^*$ are spin-1/2 particles, that the Z^0 couples to the $\ell^{*+}\ell^{*-}$ pair in the same way as to ordinary lepton pairs, and

that the excited leptons decay exclusively as $\ell^* \rightarrow \ell\gamma$. In composite models the effective Lagrangian which describes this decay is a function of the parameter f/Λ , where Λ is the compositeness mass scale and f is the coupling constant. If the mass of an excited lepton is lighter than half the centre-of-mass energy ($\sqrt{s}/2 \sim m_{Z^0}/2$) it can be pair-produced, reaction (22). The single production of ℓ^* is possible via $\gamma\ell^*\ell$ and $Z^0\ell^*\ell$ couplings up to a mass m_{Z^0} and the signature is $\ell^+\ell^-\gamma$ (reaction 21). In typical searches the procedures described below were followed:

- The search for $e^+e^-\gamma(\gamma)$ events required at least 3 (4) electromagnetic clusters and two tracks in the tracking chambers.
- The search for $\mu^+\mu^-\gamma(\gamma)$ events required two charged tracks of $p_t > 4$ GeV/c, consistent with being muons and 1 (2) electromagnetic cluster(s).
- The search for $\tau^+\tau^-\gamma(\gamma)$ events required isolation of two low-multiplicity jets compatible with τ candidates and 1 (2) electromagnetic cluster(s).

Since no event was found, the $\ell^+\ell^-\gamma\gamma$ searches exclude the production of pair-produced ℓ^* up to a mass $m_{Z^0}/2$; the $\ell^+\ell^-\gamma$ sets upper limits on the coupling f/Λ in the mass region $m_{Z^0}/2 - m_{Z^0}$ at the level of less than 10^{-3} [36].

5.2 Excited neutrinos

The excited neutrinos are the weak isospin $-1/2$ partners of the excited charged leptons; if they are assumed to be of the Dirac type they should have the same couplings with the vector bosons as normal Dirac neutrinos. As for the charged excited leptons, they could be produced in pairs, $e^+e^- \rightarrow \nu^*\bar{\nu}^* \rightarrow \nu\bar{\nu}\gamma\gamma$, or singly, $e^+e^- \rightarrow \nu\bar{\nu}^* \rightarrow \nu\bar{\nu}\gamma$ [37].

The single production events appear like the events for the neutrino counting reaction, $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, where the γ comes as initial-state radiation. In this case the photon has a typical bremsstrahlung spectrum, while in the excited lepton case the photon is harder. The searched topologies are events with a single or two photons. None was found compatible with the excited neutrino hypothesis [37]; this is so also for the channel $\nu^* \rightarrow eW$ (which would be important if the $\gamma\nu\nu^*$ coupling does not exist). The limit, assuming Standard Model couplings, is up to the kinematical limit, $m_{Z^0}/2$ for pair production, m_{Z^0} for single production. Alternatively, the excluded branching ratios are up to $\sim 6 \times 10^{-5}$ for pair and single production.

The DELPHI Collaboration searched for excited neutrinos produced in association with multihadronic events (in the framework of a light Higgs search). The excited neutrino would be produced in the primary interaction and would decay after 0.5–2 m in the central tracking chambers giving an even number of tracks. Such a possibility was suggested by a neutrino experiment at Fermilab (CCFR experiment), where the possible excited neutrino could have a mass around 0.5–2 GeV and would have an average decay length of 1 m [38]. Out of 350 000 multihadronic events no candidate was found in the DELPHI search. This leads to an upper limit branching fraction around 10^{-4} .

5.3 Excited quarks

An excited quark should decay into a quark and a photon, $q^* \rightarrow q\gamma$, or into a quark and a gluon, $q^* \rightarrow qg$. Assuming that the coupling λ/m_{q^*} is the same for the vertices $qq^*\gamma$ and qq^*g , the branching ratios should be proportional to $\alpha_{e.m.}$ and α_s , yielding an 8% branching ratio for $q^* \rightarrow q\gamma$ and 92% for $q^* \rightarrow qg$.

Isolated energetic photons (with $E_\gamma > 10$ GeV) in multihadronic final states may arise from (a) bremsstrahlung from the initial e^+ or e^- , (b) bremsstrahlung from a final quark or from (c) an excited quark, $q^* \rightarrow q\gamma$ (see Fig. 26). The experimental data are consistent with the first two sources and exclude the third source [39]. The fact that one does not find any photon above the number predicted by standard photon sources may be used to place a lower limit on excited quark masses: $m_{q^*} > m_{Z^0}$.

The L3 Collaboration has searched for the pair production of excited quarks, which then decay into $q\bar{q}$: $e^+e^- \rightarrow q^*q^* \rightarrow q\bar{q}q\bar{q} \rightarrow 4$ jets of hadrons [3]. The four jets are combined into two pairs of jets by taking the combination which gives the smallest difference between two invariant masses, in order to satisfy the hypothesis of the production and decay of two identical states. From this search, they exclude the presence of any excited quark up to a mass of $m_{Z^0}/2$, independently of the coupling constant λ and for a branching ratio $\text{BR}(q^* \rightarrow q\bar{q})$ larger than 17% for a down-type quark and larger than 25% for an up-type quark.

Figure 26: Feynman diagrams for the production of one hard photon in multihadronic events by a) the initial e^+ or e^- , b) the final q or $\bar{q}$, and c) from an excited q^* .

5.4 The reaction $e^+e^- \rightarrow \gamma\gamma$

The reaction $e^+e^- \rightarrow \gamma\gamma$ is a pure electromagnetic process, which at first order proceeds via the t-channel exchange of a virtual electron. It may thus be used to provide a clean test of QED. Measurements of the angular distribution and of the total cross-section were performed by the four collaborations [3, 40] using different data samples. The electromagnetic calorimeters of the four LEP detectors, together with the absence of tracks in central detectors, clearly play a dominant role in the selection of the events. The agreement between data and QED predictions is very good. A deviation from the QED behaviour would be attributed to the contact term diagram illustrated in Fig. 27a. The cross-section for the reaction $e^+e^- \rightarrow \gamma\gamma$ is then given by the square of an electromagnetic amplitude (EM), the square of a contact amplitude (C^2) and by an interference term. One may neglect the term C^2 . Depending on the chirality of the electron currents and on the (real) contact amplitude, one may have different models, each with two different Λ -scales. We shall only recall the simplest “cut-off” model. The cross-section is given by

$$\frac{d\sigma}{d\Omega} = |\text{EM} + C|^2 \simeq |\text{EM}|^2 + 2\text{Re EM } C \Rightarrow \frac{\alpha^2}{s} \frac{1 + \cos^2 \theta}{1 - \cos^2 \theta} \left[1 \pm \frac{s^2}{2\Lambda_{\pm}^4} (1 - \cos^2 \theta) \right] \quad (23)$$

Maximum-likelihood fits to the angular distributions yield cutoff parameters Λ_+ and Λ_- between 100 and 140 GeV, which are considerably larger than those determined at lower e^+e^- energies.

The $e^+e^- \rightarrow \gamma\gamma$ reaction may also proceed via the exchange of a virtual excited electron e^* of mass m_{e^*} . Assuming that the $\gamma e^* e$ coupling is equal to the γee coupling, ALEPH obtained a lower limit for the e^* mass at the level $m_{e^*} > 99$ GeV.

The analysis of the $e^+e^- \rightarrow \gamma\gamma$ channel may be used to produce byproducts on the branching ratios of rare Z^0 decays, like $Z^0 \rightarrow \gamma\gamma$, $Z^0 \rightarrow \pi^0\gamma$, $Z^0 \rightarrow \eta\gamma$ and $Z^0 \rightarrow \gamma\gamma\gamma$. The limits, all at the level of few 10^{-5} , will be discussed in Section 7.

5.5 Four-lepton contact terms

In this Section we shall briefly discuss the contribution of possible contact terms, of the form indicated in Fig. 27b, to the reactions $e^+e^- \rightarrow \ell_i^+\ell_i^-$, where $\ell_i = e, \mu, \tau$, ℓ (ℓ is the average behaviour of e, μ, τ). The basic idea is that the Standard Model is a part of a more general theory characterized by an energy scale Λ . At energies below Λ the observable effects reduce to an effective point interaction, called the contact term. More generally, the formalism of contact terms is a useful parametrization of possible deviations from the Standard Model, deviations which could have different dynamical origins such as excited fermion exchanges, a composite nature of the Z^0 , new bosons, etc.

Figure 27: Diagrams for contact terms in the reactions (a) $e^+e^- \rightarrow \gamma\gamma$ and (b) $e^+e^- \rightarrow \ell^+\ell^-$, where $\ell = e, \mu, \tau$.

ALEPH has studied in detail the four lepton contact terms [40]. Figure 28 shows the differential cross-sections for the reaction $e^+e^- \rightarrow \ell^+\ell^-$ at different LEP energies. The differential cross-sections for all leptons combined are taken as the sums of those for individual lepton flavours, assuming a universal energy scale Λ . The Standard Model predictions, represented by the solid lines, agree quite well with the measured data.

The presence of a contact term would modify the cross-section in a way very similar to Eq. (23).

$$\frac{d\sigma}{d\Omega} \simeq |\text{SM} + C|^2 \quad (24)$$

The SM contribution at lowest order is given by γ and Z^0 exchanges in the s-channel; for the reaction $e^+e^- \rightarrow e^+e^-$ one has to add γ exchange in the t-channel. The interference term in (24) has a form similar to that of (23). But now the SM contribution at the Z^0 resonance is mainly imaginary; thus there may be more sensitivity outside the Z^0 resonance.

The 95% CL limits on Λ obtained by the ALEPH Collaboration, for the contact terms $eeee$, $ee\mu\mu$, $ee\tau\tau$, $eell$, range from 0.9 to 4.7 TeV for the different models considered.

$e^+e^- \rightarrow \ell^+\ell^-$ ALEPH

Figure 28: Differential cross-sections for the reaction $e^+e^- \rightarrow \ell^+\ell^-$ at various LEP energies. The curves are the Standard Model predictions. The t-channel contribution is subtracted both from the data and from the Standard Model prediction [ALEPH].

6. LEPTOQUARK BOSONS

The Standard Model does not contain any motivation for the symmetry between quarks and leptons. In order to explain such properties, several models have been proposed. Some of these models, as for instance several technicolour and composite models, predict the existence of leptoquark bosons D , which are colour triplets and have electric charges $1/3$, $2/3$ and which carry lepton number as well as baryon number [41]. They thus decay into a quark and a lepton. The quantum numbers and couplings of the leptoquarks are specific to each theory and therefore their production and decay depend on the particular assumptions. In this review we shall restrict ourselves to the possibility that a leptoquark decays only to quarks and leptons of the same family. This implies the existence of a family structure also for leptoquarks.

We shall first discuss pair-produced leptoquarks at the Z^0 energy

$$e^+e^- \rightarrow Z^0 \rightarrow D + \bar{D} \quad (25)$$

Each leptoquark then decays into a lepton and a quark

$$D \rightarrow \ell q, \quad \bar{D} \rightarrow \bar{\ell} \bar{q} \quad (26)$$

The decay of a heavy leptoquark into a quark and a charged lepton gives rise to the distinctive signature of an isolated charged lepton with an energy of about half the beam energy. The decay into a quark and a neutrino leads to a jet and a missing energy of about half the beam energy. In both cases the leptons are isolated from the rest of the event.

Figure 29 shows sketches of the event topologies expected for decays into leptons and quarks of the second family, which involves leptons $= \mu, \nu_\mu$ and quarks $= s, c$.

Figure 29: Examples of event topologies for leptoquark events.

a) $D\bar{D} \rightarrow q\bar{q}\nu_\mu\bar{\nu}_\mu$, b) $D\bar{D} \rightarrow q\bar{q}\nu_\mu\mu^+$, c) $D\bar{D} \rightarrow q\bar{q}\mu^-\mu^+$.

The differential cross-section for the production of a leptoquark pair is given by

$$\frac{d\sigma}{d\cos\theta} = \frac{3}{4}\beta^3\sin^2\theta \left(\frac{\pi\alpha^2}{s}e_D^2 - \frac{\alpha G_\mu}{\sqrt{2}}e_D c_D v_e \frac{m_Z^2(s - m_Z^2)}{F(s)} + \frac{G_\mu^2}{8\pi}c_D^2(v_e^2 + a_e^2) \frac{s m_Z^2}{F(s)} \right) \quad (27)$$

where $\beta = p/E$ is the velocity of the leptoquark, s the square of the centre-of-mass energy, $F(s) = (s - m_Z^2)^2 + (\Gamma_Z m_Z)^2$, $v_e = -1 + 4 \sin^2 \theta_W$ and $a_e = -1$ are the vector and axial couplings of the electron, e_D and c_D are the charge and the coupling of the leptoquark to the Z^0 , and α and G_μ are the electromagnetic and Fermi couplings. In the OPAL simulation, the differential cross-section was folded with the effect of initial-state radiation, which reduces the cross-section by about 30%. The leptoquarks were then made to decay isotropically into leptons and quarks; the quarks were hadronized and the response of the detector was simulated. The following searches were performed by the OPAL Collaboration[42]:

Search for $D\bar{D} \rightarrow q\bar{q}e^+e^-$, $q\bar{q}\mu^+\mu^-$. These events would yield two isolated charged tracks of opposite sign and two jets of hadrons. Figure 30 shows the inclusive distribution of the isolation density for the tracks satisfying quality cuts for the data and for Monte Carlo leptoquarks.

Search for $D\bar{D} \rightarrow q\bar{q}\nu\bar{\nu}$, $q\bar{q}\mu\nu$. These events would contain an isolated charged lepton and a substantial amount of missing energy.

Search for $D\bar{D} \rightarrow q\bar{q}\tau^+\tau^-$, $q\bar{q}\tau\nu$. The predominant decay modes of the tau into one charged particle and neutrals lead to a less energetic charged track than seen in the electron and muon decay modes of the leptoquark.

Search for $D\bar{D} \rightarrow q\bar{q}\nu\bar{\nu}$. This leads to two jets of hadrons. This topology is similar to that of the search for the Standard Model Higgs boson in the process $Z^0 \rightarrow H_{SM}^0 Z^{0*}$, $H_{SM}^0 \rightarrow q\bar{q} \rightarrow 2 \text{ jets}$, $Z^{0*} \rightarrow \nu\bar{\nu}$.

From the absence of a signal for leptoquarks, limits can be set on their production cross-section, interpreted in terms of the leptoquark mass, their coupling c_D to the Z^0 and of their decay branching fractions. Figure 31 shows the expected number of leptoquark pairs from studies made by the L3 Collaboration.

In conclusion no evidence has been found for pair-produced leptoquarks in searches which involve decays into any of the three generations of fermions. At 95% CL the mass limit may be placed at 45 GeV [42]. The best present limits are from CDF at the Tevatron $p\bar{p}$ collider (113 GeV) and from the H1 (145–192 GeV) and ZEUS (168–176 GeV) experiments at HERA [43].

Recently the DELPHI Collaboration studied single leptoquark production [42] in the reactions:

$$e^+e^- \rightarrow Z^0 \rightarrow D\ell^+\bar{q}, \quad e^+e^- \rightarrow Z^0 \rightarrow \bar{D}\ell^-q \quad (28)$$

The D leptoquark decays into a quark and a lepton. Single leptoquark production is proportional to the model-dependent $q\ell D$ Yukawa type coupling, which can be parametrized as:

$$\alpha_\lambda = \frac{g^2 \times D}{4\pi} = k\alpha_{e.m.} \quad (29)$$

The event topology for single leptoquark production is similar to that for pair production, but, due to the higher leptoquark mass explored, the distribution of leptons and hadrons from jets would be more isotropic.

The DELPHI limit for the mass of singly produced leptoquarks is $m_D \geq 77$ GeV at the 95% confidence level, see Fig. 32.

Figure 30: The inclusive distribution for the isolation parameter ρ for all tracks satisfying the quality requirements for the decay $D\bar{D} \rightarrow q\bar{q}e^+e^-$ [42] (OPAL). The points are the data, the solid line the prediction of the JETSET Monte Carlo simulation for standard events, and the dashed line the prediction of the leptoquark Monte Carlo simulation.

Figure 31: The expected number of leptoquark pairs as a function of leptoquark mass taking into account branching ratios and acceptances. Solid lines correspond to leptoquarks with $q = -1/3$, dashed lines to $q = 2/3$ [42] (L3).

Figure 32: The expected number of events of pair-produced leptoquark and of singly produced leptoquarks in the DELPHI experiment [42].

7. OTHER SEARCHES

Several searches for rare Z^0 decays have been performed by the four LEP experiments using the more than two million Z^0 's available from the 1989–1991 running periods; as already stated, including the 1992 data the number of events is about five million. No new particle or anomalously high branching ratios for rare Z^0 decays have been reported. The branching ratios' upper limits at 95% CL from the 1989–1991 data are of the order of 10^{-5} per experiment. It is expected that the limits using the 1992 data and combining all results from the four experiments may soon reach the 10^{-6} level. We shall briefly summarize some of the searches, recalling that many rare decays of the Z^0 are sensitive to physics beyond the Standard Model. Detailed reports on rare Z^0 decays were presented at several meetings [44]. It may be worth recalling that some decays are expected to have branching ratios of $\sim 10^{-10}$ or less (Z^0 decays into a pseudoscalar and a vector particle) or to be absolutely forbidden (lepton-flavour violation decays).

In this Section we shall also include a number of other miscellaneous searches, like the searches for free gluons, free quarks and free magnetic monopoles.

7.1 Search for lepton-flavour violation

The conservation of lepton flavour is an important feature of the Standard Model. Lepton-flavour violation is expected in a number of models which include physics beyond the Standard Model. For instance lepton-flavour violation in Z^0 decays could arise through mixing with new particles or from one-loop contributions from new particles, such as a heavy neutral lepton, SUSY particles and leptoquarks. Lepton-flavour-changing branching ratios as high as 10^{-4} have been predicted [44].

Stringent limits on lepton-flavour violation at low q^2 are based on the non-observation of the neutrinoless decays $\mu \rightarrow eee$, $\tau \rightarrow eee$, $\tau \rightarrow \mu\mu\mu$. These yield indirect upper limits on $Z^0 \rightarrow e\mu$, $Z^0 \rightarrow e\tau$, $Z^0 \rightarrow \mu\tau$ branching ratios.

Searches have been performed at LEP on the simplest lepton-flavour-changing decays

$$Z^0 \rightarrow e\mu, \quad Z^0 \rightarrow e\tau, \quad Z^0 \rightarrow \mu\tau \quad (30)$$

(see the Feynman diagrams of Fig. 33). The good electron and muon energy resolution of the LEP detectors is essential in reducing the background. No indication of lepton-flavour violation is detected. The best present upper limits from a single LEP experiment are at the following levels [45]:

$$\begin{aligned} \text{BR}(Z^0 \rightarrow e\mu) &< 2 \times 10^{-5} \\ \text{BR}(Z^0 \rightarrow e\tau) &< 3 \times 10^{-5} \\ \text{BR}(Z^0 \rightarrow \mu\tau) &< 5 \times 10^{-5} \end{aligned}$$

Figure 33: Feynman diagrams for simple lepton-flavour violation processes in Z^0 decays.

7.2 Rare decays of the Z^0

The Standard Model predictions for rare Z^0 decays, like $Z^0 \rightarrow \text{pseudoscalar} + \text{vector particles}$, range from 10^{-11} to 10^{-7} and are thus considerably below the LEP sensitivity. For instance the following predictions exist: $\text{BR}(Z^0 \rightarrow \pi^\pm W^\mp) \simeq 3 \times 10^{-10}$ and $\text{BR}(Z^0 \rightarrow \pi^0 \gamma) \simeq 3 \times 10^{-11}$; however other authors pointed out the possibility of much larger branching ratios, even at the level of 10^{-4} .

Table 6 gives a compilation of the 95% CL upper limits in units of 10^{-5} available at the time of the 1992 Dallas Conference [40, 46].

Table 6

Decay	Experiment Data			
	ALEPH 89-91	DELPHI 90-91	L3 90-91	OPAL 89-90
$Z^0 \rightarrow \gamma\gamma$	–	–	12	14
$Z^0 \rightarrow \pi^0\gamma$	16	15	12	14
$Z^0 \rightarrow \eta\gamma$	2.9	28	4.7	20
$Z^0 \rightarrow \eta'\gamma$	2.5	–	2.5	–
$Z^0 \rightarrow J\gamma$	–	–	2.9	–
$Z^0 \rightarrow \gamma\gamma\gamma$	1.9 [†]	2.3	3.3	6.6
$Z^0 \rightarrow \pi W$	2.2	–	2.5*	–
$Z^0 \rightarrow KW$	2.2	–	2.6*	–
$Z^0 \rightarrow \rho W$	2.6	–	3.9*	–
$Z^0 \rightarrow DW$	4.4	–	–	–
$Z^0 \rightarrow XW$	3.7	–	–	–

[†] 89/90 data

* data up to July 1992

7.3 Search for narrow resonances

Searches have been performed for narrow resonances in the following Z^0 decays [47]:

$$\begin{aligned}
 Z^0 &\rightarrow \gamma + Y && \text{a)} \\
 &\quad \hookrightarrow \ell^+\ell^-, q\bar{q} \\
 Z^0 &\rightarrow \text{hadrons} + S && \text{b)} \\
 &\quad \hookrightarrow \gamma\gamma
 \end{aligned} \tag{31}$$

The upper limit (95% CL) on the branching ratios in units of 10^{-5} are reported in the Table 7 [44, 47]:

Table 7

	$Y \rightarrow e^+e^-$	$Y \rightarrow \mu^+\mu^-$	$Y \rightarrow \tau^+\tau^-$	$Y \rightarrow q\bar{q}$	$H^0 \rightarrow \gamma\gamma$	Mass range (GeV)
DELPHI	–	–	–	37	–	10–80
L3	6.6	6.9	5.9	32	3.6	30–86
OPAL	11	9	11	–	–	60–80

Recently, the L3 Collaboration analysed the hadronic lineshape of the Z^0 to search for narrow vector resonances with masses within the Z^0 -mass range. Their results exclude, at the 95% confidence level, the existence of a narrow vector resonance (a quarkonium state) in the mass range from 87.7 to 94.7 GeV [47]

7.4 Search for $Z^0 \rightarrow \ell^+\ell^-V$

The ALEPH Collaboration analysed in detail events of the type $\ell^+\ell^-V$, where the V indicates two charged tracks of opposite sign coming directly from the primary vertex [48]. They found an excess of such events in the $\tau^+\tau^-V$ channel, compared to a normal rate for the e^+e^-V and $\mu^+\mu^-V$ channels. Soon after the other three Collaborations, analysed their data for this effect. The results were negative and new ALEPH data did not confirm the excess either. Table 8 summarizes the observed and expected number of events by the four collaborations using data up to 1991 [44, 48]. The DELPHI and OPAL Collaborations

have also estimated that the background to the $\tau^+\tau^-V$ events, originating from normal $\tau^+\tau^-$ and multihadronic events, is important (3.2 background events for DELPHI) [48].

Table 8

Experiment	e^+e^-V		$\mu^+\mu^-V$		$\tau^+\tau^-V$	
	Data	MC	Data	MC	Data	MC
ALEPH (1989–1991)	18	18.2	18	15.1	18	7.4
DELPHI (1990–1991)	11	9.5	9	9.3	7	3.9
L3 (1991)	8	6.3	5	4.0	4	4.0
OPAL (1990–1991)	21	27.7	18	15.3	11	9.5

7.5 High-mass $\gamma\gamma$ pairs

The L3 Collaboration reported four events of the type $e^+e^-\gamma\gamma$, $\mu^+\mu^-\gamma\gamma$ with a $\gamma\gamma$ invariant mass in the range 58–62 GeV [49]. These four events have to be compared with the expectation of one event from ordinary QED doubly radiative events. At a recent CERN seminar the other three Collaborations have reported two more events [49]. Thus, combining the data “by eye” there seems to be consistency with ordinary QED events. Moreover, if the $\ell^+\ell^-\gamma\gamma$ events were due to a scalar particle such as a Higgs, one should have found a larger signal in $\nu\bar{\nu}\gamma\gamma$ and $q\bar{q}\gamma\gamma$ final states. These channels are more difficult to analyse; nevertheless no signal has been found.

The KEK experiments performed a scan between 54 and 64 GeV c.m. energies, analysing the $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \gamma\gamma$ reactions; they found no indication for a heavy neutral spinless particle [50]

7.6 Additional heavy gauge bosons

Many unifying theories predict additional gauge bosons, Z' . Direct searches for Z' production have been performed at $p\bar{p}$ colliders. At LEP, limits may be obtained via the analysis of virtual effects of a Z' on the Z^0 resonance. The Z' modifies the couplings of the Z^0 to fermions and thus influences the Z^0 line shape, if there is mixing between Z' and Z^0 . The L3 Collaboration obtained $m_{Z'} > 100$ GeV for a class of models. The mixing angle θ_M between the Z^0 and the Z' , is constrained to be, in different models, in the interval $-0.029 < \theta_M < 0.020$ [3].

7.7 Search for new weakly interacting particles

The ALEPH Collaboration presented limits on the production of an X^0 particle which would couple to the Z^0 like the H_{SM}^0 , but with unknown production and decay strengths [51]. The reaction considered is similar to the Bjorken process for H_{SM}^0 production: $e^+e^- \rightarrow Z^0 \rightarrow Z^{0*}X^0$. Two cases were considered:

$Z^{0*} \rightarrow \ell^+\ell^-$, X^0 escapes the detector and is thus not detected. This event topology, an acollinear pair of charged leptons, has already been considered in the context of other searches (see scalar charged leptons) with no events surviving the cuts. Thus a quasi stable X^0 is excluded up to a mass of 8 GeV with $R = BR(Z^0 \rightarrow X^0\ell^+\ell^-)/BR(Z^0 \rightarrow \ell^+\ell^-) > 7.2 \times 10^{-4}$; note that the ratio R is related to the production coupling $Z^0Z^{0*}X^0$.

$Z^{0*} \rightarrow \nu\bar{\nu}$, $X^0 \rightarrow q\bar{q} \rightarrow 2$ jets. Also this type of events, with two acoplanar jets of hadrons, has already been considered in the context of other searches (see the non-minimal Higgs searches, $Z^{0*} \rightarrow \nu\bar{\nu}$, $h^0 \rightarrow q\bar{q}$). This search excludes an X^0 with $8 < m_{X^0} < 60$ GeV and $R > 7.2 \times 10^{-4}$.

In conclusion there is no indication of a new neutral weakly interacting particle with a mass smaller than 60 GeV and $R > 7.2 \times 10^{-4}$. The limit applies specifically to a scalar X^0 , but is also valid for a non-scalar X^0 .

7.8 Search for free gluons

The existence of free gluons was suggested in a phenomenological model [52] as a possible explanation for the observation of cosmic ray muons from the direction of Cygnus-X3 ('cynnets'). In this model $SU(3)_C$ colour symmetry would be broken so as to produce free gluons and not free quarks. The free gluon would have a mass smaller than 100 MeV and its production would be regulated by a potential well of the type

$$V(r) = 3\sigma r e^{-\mu r} \quad (32)$$

with $V_m = 3\sigma/\mu e$ at a typical confining radius $r_m = 1/\mu$. The string tension σ is about 1 GeV/fm. The free gluon would be stable if colour symmetry is violated locally.

OPAL has searched for free gluons in multihadronic events [53]. The free gluon would in general be isolated from the produced quark-antiquark pair which fragments in two jets of hadrons. Assuming that a free gluon has an interaction rate typical of hadrons, say 25 mb, they would cross the central detector and interact in the electromagnetic and hadron calorimeters. In this hypothesis a free gluon would simulate a neutral hadron isolated from the charged hadrons. Two candidate events were selected by these selection criteria. A Monte Carlo analysis shows that this number of events is expected from ordinary hadrons. A simulation of free-gluon production allows one to estimate the barrier height at $V_m \geq 47$ GeV, see Fig. 34.

Figure 34: The number of expected free-gluons as a function of the barrier height V_m [53].

7.9 Search for particles with fractional charge

One of the open experimental questions is if free quarks can be produced. Quark confinement, though widely accepted, is not really necessary in the Standard Model. At

the Z^0 pole, quarks are produced with high momenta mainly via the weak interaction; they could become free without contradicting any known experimental limit.

The ALEPH Collaboration made a search for fractional and integer charged particles based on the dE/dx measurements in the central tracking detector, the Time Projection Chamber TPC [54]. They used the data taken in 1989 and 1990 corresponding to more than two million tracks. Only cuts based on the quality of the data have been used. Excluding a band around the background expected from track overlap reduces the number of candidates to zero for masses above 5 GeV. A compilation of the upper limits obtained is presented in Fig. 35 for particles with $q = 1/3, 2/3, 4/3$ and 1. The limits for fractional charges extend to 43 GeV; in addition the limits for heavy long-lived particles of charge $q = 1$ extend to 70 GeV. The production of such stable new charged particles is ruled out at the level of 10^{-3} of the dimuon production cross-section.

Figure 35: The 90% CL limits for the ratio $R_x = \sigma(e^+e^- \rightarrow x\bar{x} + \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$ for the inclusive production of charged particles with unexpected mass and charge, assuming particles distributed in momentum according to Model II of Ref. [54]. The areas above the curves are excluded (ALEPH).

7.10 Search for Dirac magnetic monopoles

Magnetic monopoles were hypothesized by P.A.M. Dirac in 1931 to explain the quantization of the electric charge. Since then, many experimental searches for these “classical” monopoles have been performed at nearly every new high-energy accelerator, employing a variety of direct and indirect methods. The searches are based on the hypothesis that the poles should have a large magnetic charge, $g = n g_{\text{Dirac}} = n\hbar c/2e$, with $n = 1, 2, \dots$. In the c.g.s. symmetric system of units $g_D = 68.5 e$. Fast poles should ionize heavily and their detection would therefore be easy. In particular in plastic nuclear track detectors, such as CR39, a monopole would leave a “latent” track in the form of ruptured polymeric bonds along the path of the pole. This track would be easily detected after appropriate chemical etching and scanning, even in the presence of a large background. The MODAL experiment at LEP surrounded the I5 intersection region with stacks of CR39 sheets and after a relatively long exposure, the sheets were etched and scanned [55].

Figure 36 shows a compilation of present upper limits obtained from experiments at high-energy accelerators up to a mass of 0.9 TeV.

Figure 36: Compilation of upper limits for Dirac magnetic monopole production in pN , $p\bar{p}$ and e^+e^- high-energy collisions [55]. Solid and dashed lines refer to direct and indirect experiments.

The significance of the limits depends on the physical process by which the monopoles are presumed to be produced. For Dirac monopoles in e^+e^- collisions the most obvious mechanism is monopole pair production via the electromagnetic interaction. For a single-photon process the lowest-order cross-section σ_D for a pointlike monopole of mass m scales with the cross-section for unlike-sign dimuons ($e^+e^- \rightarrow \mu^+\mu^-$) times a phase space factor:

$$\sigma_D(m; s) = \left(\frac{g_D}{e}\right)^2 \sigma_{\mu\mu}(> 2m; s) \sqrt{1 - \frac{4m^2}{s}}. \quad (33)$$

The limits may thus be expressed as limits on the quantity $R_D = \sigma(m)/\sigma_D(m)$, which would be expected to be of order unity for pointlike Dirac monopoles with magnetic charge g_D at energies above threshold. If the naive lowest-order limit is valid, one may conclude that pointlike Dirac monopoles with mass below 44.9 GeV are ruled out. However, it has been speculated that monopoles may have non-pointlike structure, resulting in a reduction of the cross-section by orders of magnitude.

It should be recalled that the main present emphasis of monopole searches concerns very massive monopoles, such as those predicted by Grand Unified Theories of the electroweak and strong interactions. Such supermassive monopoles ($m \sim 10^{16}$ GeV) cannot be produced by any present and future man-made accelerator.

7.11 Test of CP invariance

Several tests of conservation laws may be performed using the high-statistics LEP data. We shall mention only one example, a test of CP invariance.

The violation of CP invariance has only been observed in $\Delta S = 2$ transitions between the K^0 and the $\bar{K}^0$ (and maybe in some $\Delta S = 1$ transitions). It is important to investigate other channels, hoping to obtain informations on the origin of CP violation. In the Standard Model of electroweak interactions with three-fermion families, CP violation is described by a phase in the quark mixing matrix, which enters in the weak charged-current couplings among quarks. The same model does not predict observable CP violation effects for neutral-current interactions. These may exist in models beyond the Standard Model.

The ALEPH and OPAL Collaborations analysed the reaction $e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$, where each τ decays into one charged prong plus neutrals [56]. Using the three-momenta $\vec{q}_-$ and $\vec{q}_+$ of the final-state charged particles the following type of observable may be constructed

$$T_{ij} = (\vec{q}_- - \vec{q}_+)_i (\vec{q}_- \times \vec{q}_+)_j + (i \leftrightarrow j) \quad (34)$$

This quantity is odd under the CP operation. Based on 5558 $Z^0 \rightarrow \tau^+\tau^-$ events OPAL found no evidence for a CP-violating contribution to the reaction $e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$. From this null result they placed a limit on the weak dipole moment of the τ -lepton at $|d_\tau| \leq 7 \times 10^{-17} e \cdot \text{cm}$ at 95% CL. Note that in some models the magnitude of the lepton dipole moment depends on m_τ^2 ; note also that there is no a priori connection between the magnitudes of the weak and electric dipole moments.

8. PERSPECTIVES: SEARCH FOR THE STANDARD MODEL HIGGS BOSON AT LEP 200

In this Section we shall briefly discuss, as an example, the possibilities for a search for the Standard Model Higgs Boson at LEP 200. It is not yet clear what will be the highest centre-of-mass energy of LEP 200. At the moment the approved project has $\sqrt{s}_{\text{max}} \sim 176$ GeV.

At LEP 200 the main reaction which might produce a Higgs boson is still the Bjorken mechanism Eq. (12), $e^+e^- \rightarrow Z^{0*} \rightarrow Z^0 H_{\text{SM}}^0$, but where the Z^0 exchanged is now virtual, while the final Z^0 is real. One may observe from Figs. 37 and 38 [3, 28], that at LEP 200 energies the cross-section for producing an H_{SM}^0 heavier than 60 GeV is much larger than at LEP 100. The sensitivity is dependent on the maximum $\sqrt{s}$ attainable. A simple golden rule is that, with 500 pb⁻¹ of integrated luminosity, the sensitivity of LEP 200 goes up to $m_{H_{\text{SM}}^0} = \sqrt{s} - 100$ GeV. Notice that the cross-section has a sharp

threshold and reaches its maximum for $\sqrt{s} \simeq m_{H_{SM}^0} + 100$ GeV; the value of the maximum decreases slowly with increasing $m_{H_{SM}^0}$.

Figure 37: $\sigma(e^+e^- \rightarrow H_{SM}^0 f\bar{f})$ as a function of centre-of-mass energy for different Higgs boson masses.

Up to $m_{H_{SM}^0} = 80$ GeV the search for the Standard Model Higgs boson can be considered a relatively easy task at LEP 200. The analyses for the $e^+e^- \rightarrow H_{SM}^0 Z^0 \rightarrow q\bar{q}\ell^+\ell^-$ channel can take advantage of the real Z^0 produced in the reaction. At energies near or greater than $2m_{Z^0}$, the background comes mainly from $Z^0 Z^0$ events, whose cross-section is roughly a factor of two higher than that for producing an 80-GeV H_{SM}^0 . The efficiencies for the various searches should be higher than at LEP 100. The $q\bar{q}\nu\bar{\nu}$ channel suffers from the background originating from $W^+W^- \rightarrow \tau\nu + \text{hadrons}$ and $W^+W^- \rightarrow q\bar{q}\gamma\gamma$. The channel $H_{SM}^0 Z^0 \rightarrow q\bar{q}q'\bar{q}'$ has the highest branching ratio, but suffers from the large background from WW , $Z^0 Z^0$ and $q\bar{q}gg$ events.

If the Higgs boson is heavier than 80 GeV, it becomes necessary to find a way to disentangle it from a Z^0 . The most efficient way is to perform a b-tagging of the decay products of the H_{SM}^0 . Indeed the Higgs boson decays in 90% of the cases into a $b\bar{b}$ pair, while a Z^0 produces a $b\bar{b}$ pair only 15% of the time. Moreover a W boson cannot decay directly into a $b\bar{b}$ pair. Therefore the b-tagging becomes essential for all analyses searching for an H_{SM}^0 which is almost degenerate in mass with the Z^0 .

Algorithms for b-tagging can use some jet topological features (thrust, oblateness, etc.), or some jet particle-composition characteristics, like the average number of leptons or the average number of kaons in a jet. Another way of performing b-tagging is through the search for secondary vertices. In fact the b quarks at these energies have flight paths which can be resolved by the very refined microvertex detectors of the LEP experiments. Some preliminary studies show that a b-quark purity of 85% with an efficiency of 50% is attainable using the microvertex detector information. This translates into a rejection factor of the order of 10 for $Z^0 Z^0$ pairs and of roughly a factor of 100 for W^+W^- pairs.

In Figs. 39 and 40 are shown the results expected for a Higgs boson with a mass of 90 GeV by the DELPHI Collaboration [57] using the $q\bar{q}q'\bar{q}'$ channel, and by the ALEPH collaboration [58] using the $q\bar{q}\nu\bar{\nu}'$ channel. Both these studies assumed $\sqrt{s} = 190$ GeV; DELPHI used 500 pb^{-1} of integrated luminosity while ALEPH used 1000 pb^{-1} . Figure 41 shows the integrated luminosities needed to have $(\text{signal}/\sqrt{\text{background}})$ values equal to 3 and 5 as a function of Higgs mass at different centre-of-mass energies [59].

The LEP 200 perspectives have also been discussed in workshops and in the LEPC Committee [59].

Figure 38: $\sigma(e^+e^- \rightarrow H_{\text{SM}}^0 f\bar{f})$ as a function of the H_{SM}^0 mass at LEP 100 and LEP 200.

Figure 39: The histograms with solid lines are the number of expected events for an H_{SM}^0 with a mass of 90 GeV studying the $q\bar{q}q'\bar{q}'$ channel with the DELPHI detector, with and without b-tagging. The dashed points are without a Higgs boson.

Figure 40: Number of expected events for an H_{SM}^0 with a mass of 90 GeV studying the $q\bar{q}\nu\bar{\nu}$ channel with the ALEPH detector, with and without b-tagging. The dot-filled histograms are the expected background events without a Higgs boson.

Figure 41: The integrated luminosities needed to have $S/\sqrt{B} = 3$ and $S/\sqrt{B} = 5$ as a function of the Higgs mass for centre-of-mass energies of 210 GeV, 190 GeV and 175 GeV (L3).

9. CONCLUSIONS

A very large number of particle searches, albeit all negative, have been performed in the first years of operation of LEP 100. Table 9 gives a summary of the searches and of the limits obtained. Notice that most searches for pair-produced particles reach the kinematic limit of $m_{Z^0}/2$; some of the searches for singly produced particles reach the limit of m_{Z^0} . In almost all cases the limits have improved considerably from those existing in the pre-LEP time.

Table 9: Summary of present mass limits for particle searches at LEP 100 (95% CL).

Particle	Symbol	Mass limit (GeV)	Comments
Top quark	t	$m_{Z^0}/2$	From Z^0 line shape: $m_t \sim 160$ GeV
Tau neutrino	ν_τ	—	No limits from LEP
4th generation charged leptons	$L^\pm$	$m_{Z^0}/2$	Only 3 families from Z^0 width
4th generation neutral lepton	L^0	$m_{Z^0}/2$	" "
4th generation down-type quark	b'	$m_{Z^0}/2$	" "
Isosinglet neutral heavy lepton	N_ℓ	m_{Z^0}	See Section 2.3
Charged sleptons	$\tilde{\ell}^\pm$	$m_{Z^0}/2$	Pair production
Sneutrinos	$\tilde{\nu}$	37	41.7 GeV if 3 mass degeneracy
Charginos	$\tilde{\chi}^\pm$	$m_{Z^0}/2$	Pair production
Scalar quarks	$\tilde{q}$	$m_{Z^0}/2$	Theory + MSSM + GUT+...
Neutralinos	$\tilde{\chi}^0/\tilde{\chi}^{0'}$	18.4/45	See Fig. 8
Gluinos	$\tilde{g}$	—	See Section 3.7
Photinos	$\tilde{\gamma}$		R parity violation; see Fig. 11
Standard Model Higgs	H_{SM}^0	63	See Figs. 21 and 22
Non minimal Higgs	h^0	42	MSSM – DELPHI limit
" "	A^0	36	" " "
" "	$H^\pm$	$m_{Z^0}/2$	Pair production; see Fig. 24
Doubly charged Higgs	$H^{\pm\pm}$	$m_{Z^0}/2$	Pair production; see Fig. 25
Excited Charged leptons (e^*, μ^*, τ^*)	ℓ^*	$m_{Z^0}/2$	Pair production
" " " "		$f/\lambda < 10^{-3}$	For $m_{Z^0}/2 < m_{\ell^*} < m_{Z^0}$
Excited neutrinos	ν^*	$m_{Z^0}/2$	Pair production
" "		m_{Z^0}	Single production
Excited quarks	q^*	m_{Z^0}	" "
Leptoquarks	D	$m_{Z^0}/2$ (77)	Pair (single) production, Fig. 32
New heavy gauge bosons	Z'	100	From Z^0 line shape and models
Free quarks	q	43	From dE/dx in TPC of ALEPH
Magnetic monopoles	MM	$m_{Z^0}/2$	Nuclear track detectors

The following comments can be made on the particle searches at LEP.

Early LEP searches excluded a low-mass top quark and a fourth family of leptons and quarks. Also the analysis of the Z^0 line shape excluded a fourth family of leptons and quarks with masses smaller than $m_{Z^0}/2$. No mass limit from LEP is available on tau neutrinos, though they should be present in many τ decays. From radiative corrections one predicts a top mass around 140–160 GeV. A brief discussion on neutral heavy leptons beyond the Standard Model was made in Section 2.3.

The searches for supersymmetric particles exclude the production of pair-produced particles up to the kinematic limit of $m_{Z^0}/2$, with the exception of neutralinos, for which the limit is lower, see Section 3.6. A similar statement may be made on unstable photinos that violate R -parity, see Fig. 11. At LEP there are no good limits on gluinos; it could be interesting to search for gluinos of low mass, see Section 3.7. It may be also interesting to search for Zen events, see Section 3.8.

Each LEP experiment has ruled out, at 95% CL, the existence of a Standard Model Higgs boson lighter than 53–58 GeV. By combining the results of the four collaborations, one can exclude a Higgs boson lighter than 63 GeV. LEP 100 should allow the investigation of the existence of an H_{SM}^0 with a mass up to about 70 GeV. Above this mass region an increase in the energy of the accelerator becomes necessary. LEP 200 should allow the search for the Standard Model Higgs boson up to a mass of 90 GeV, provided that the centre-of-mass energy of LEP reaches 190 GeV. If LEP 200 could reach the maximum centre-of-mass energy allowed by the magnets, 240 GeV [60], the discovery limit would be raised, with an integrated luminosity of 300 pb^{-1} , to $m_{H_{SM}^0} \sim 130 \text{ GeV}$. This would allow the coverage of a mass region which is difficult to cover with future high-energy hadron colliders.

Also the searches for non-minimal Higgses (h^0 , H^0 , A^0 , $H^\pm$, $H^\mp$) yield mass upper limits below the kinematical limit, mainly because the production cross-sections decrease quickly with increasing Higgs mass. The limits on the h^0 and A^0 are stringent in the $m_{h^0} - m_{A^0}$ plane in the framework of the MSSM. If LEP 200 could reach an energy of 210 GeV one would essentially cover all the allowed parameter space and confirm or disprove the Higgs sector of the MSSM. For pair-produced charged Higgses the kinematical limit, $m_{Z^0}/2$, is reached.

The limit on pair-produced doubly charged Higgs particles is at the kinematic limit, $m_{Z^0}/2$.

The present mass limits for pair-produced and for singly produced excited charged leptons, excited neutral leptons and excited quarks are at the kinematic limits, $m_{Z^0}/2$ and m_{Z^0} , respectively; but considerations of branching fractions have to be made. The analyses of the $e^+e^- \rightarrow \gamma\gamma$ reaction lead to QED cut-off parameters $\Lambda_\pm$ between 100 and 140 GeV. The 95% CL limits for the $eeee$, $ee\mu\mu$, $ee\tau\tau$, $eell$ contact terms range from 0.9 to 4.7 TeV.

Pair-produced leptoquark bosons have been considered in the framework of a leptoquark decay into a quark and a lepton of the same family. The present mass limit is at $m_{Z^0}/2$. Also single leptoquark production has been investigated, leading to a lower mass limit of 77 GeV.

More exotic searches include the search for a free gluon, which gave a limit for the height of the potential barrier, a search for free quarks, using the dE/dx in the ALEPH central detector, which yielded $m_q > 43 \text{ GeV}$, and a search for the Dirac monopole (by the MODAL Collaboration with nuclear track detectors) which yielded the kinematic limit,

$$m_{MM} > m_{Z^0}/2.$$

The searches for rare Z^0 decays are limited mainly by the available statistics to branching ratios of few 10^{-5} per experiment. These searches will certainly benefit from future increases in statistics.

Several other searches and tests of conservation laws have been performed, see Section 7 and Ref. [3].

In perspective: most particle searches will benefit greatly from higher luminosities and then from the planned energy increase of LEP, as exemplified by the H_{SM}^0 search discussed in Section 8.

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