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# New Particle Searches at LEP

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# New particle searches at LEP

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Considerable effort has been expended by the LEP collaborations since the start of data taking on the search for new particles and phenomena.

Two early results provided evidence that only three families of quarks and leptons exist in nature: the width of the Z established to high precision the existence of only three neutrinos and a direct search for particles belonging to a fourth family proved negative.

The search for the mass mechanism of the Standard Model has taken up much effort. Different models predict the existence of one or more Higgs bosons, of supersymmetric particles or of effects arising from compositeness; so far no evidence has been found for any such particles.

The paper describes the principles, techniques and results of these searches by the four LEP collaborations. Improvements to some of the published limits, obtained by combining the separate results of the collaborations, are presented.

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## 1. Introduction

LEP has greatly improved out knowledge of Standard Model parameters as is clear from other papers in these proceedings. However, there are still two major gaps in our understanding: we do not known why there are just three families of quarks and leptons and we have no unique explanation for the origin of symmetry breaking in the electroweak interaction.

Early work quickly established that there are just three light neutrinos species and the search for the top quark and for members of a hypothetical fourth family ruled out these particles up to a mass of $\frac{1}{2}M_Z$, the kinematic limit imposed by the energy at which LEP has run.

The search for other new particles from three very specific models has also been made: the Higgs mechanism which leads to the existence of one or more additional bosons; supersymmetry in which the known fermions have new bosonic partners and the bosons have fermionic partners and which also requires five Higgs bosons; compositeness, in which it is postulated that some or all of the fermions and bosons are made up of smaller particles (preons) thus predicting the existence of excited states.

More than 50% of the published papers from the LEP collaborations have concerned these searches. The results presented here are in general from the total data taken during the 1989–90 LEP runs, typically about 8 $\text{pb}^{-1}$ per experiment. All limits are at the 95% confidence level (c.l.) unless otherwise stated.

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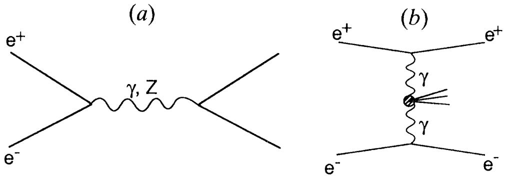

Figure 1. (*a*) Pair production through *s*-channel γ and Z exchange; (*b*) the two-photon process.

## 2. Principles of the search techniques

The most convincing way of demonstrating the existence of a new particle at LEP would be to find events which cannot be explained by the particles already known. However, some final states cannot be directly observed, for example the production of fourth generation neutrinos, or would be very difficult to observe because they produce similar event configurations to normal Z decays. Then a less sensitive, indirect argument based on measurements of the width of the Z has to be used.

### (*a*) *Indirect searches – limits from width measurements*

The cross section for the production of spin-$\frac{1}{2}$ fermion pairs through *s*-channel γ and Z exchange (figure 1*a*) is given in lowest order by

$$\sigma_{\frac{1}{2}}(\beta) = \frac{4\pi\alpha^2}{3s} N_\mathrm{C}^\mathrm{f}\beta\left\{\tfrac{1}{2}Q_\mathrm{f}^2(3-\beta^2) - 2Q_\mathrm{f}\, v_\mathrm{e}\, v_\mathrm{f}\frac{s(s-M_\mathrm{Z}^2)}{(s-M_\mathrm{Z}^2)^2+M_\mathrm{Z}^2\Gamma^2}\tfrac{1}{2}(3-\beta^2)\right.$$

$$\left. + (v_\mathrm{e}^2+a_\mathrm{e}^2)\frac{s^2}{(s-M_\mathrm{Z}^2)^2+M_\mathrm{Z}^2\Gamma^2}(\tfrac{1}{2}v_\mathrm{f}^2(3-\beta^2)+a_\mathrm{f}^2\beta^2)\right\}, \qquad (1)$$

where

$\beta_\mathrm{f} = \surd(1-M_\mathrm{f}^2/s)$ (velocity of fermion),
$N_\mathrm{C}^\mathrm{f}$ = colour factor (= 1 for leptons and 3 for quarks),
$v_\mathrm{f} = (I_3^\mathrm{f} - 2Q_\mathrm{f}\sin^2\theta_\mathrm{W})/2\sin\theta_\mathrm{W}\cos\theta_\mathrm{W}$,
$a_\mathrm{f} = I_3^\mathrm{f}/2\sin\theta_\mathrm{W}\cos\theta_\mathrm{W}$.

Then each available fermion decay channel contributes to the Z width the amount

$$\Gamma_\mathrm{f} = \frac{N_\mathrm{f}^\mathrm{C}\, G_\mathrm{F} M_\mathrm{Z}^3}{24\ 2^{\frac{1}{2}}\pi}[\tfrac{1}{2}(3-\beta_\mathrm{f}^2)\, v_\mathrm{f}^2 + \beta_\mathrm{f}^2\, a_\mathrm{f}^2]. \qquad (2)$$

The dependence of $\Gamma_\mathrm{f}$ on $M_\mathrm{f}$ is shown in figure 2 for different species of fermion.

Limits on $M_\mathrm{f}$ can be set by determining upper limits on the difference between the measured Z widths and the Standard Model values. The mean value of the invisible width for the four experiments, $\Gamma_\mathrm{inv}$, determined from fits to the hadronic and leptonic cross sections, is 492 ± 9 MeV. The Standard Model value has uncertainties due to unknown top and Higgs masses and its minimum value is 497 MeV. Thus the 95% c.l. limit on $\Gamma_\mathrm{inv}$ is 11 MeV and the mass limit on a Dirac neutrino is 44.5 GeV/$c^2$. If we assume that the lepton channels have no non-standard contributions the limit on the excess of $\Gamma_\mathrm{tot}$ can be determined by comparing the measured value of $\Gamma_\mathrm{tot}/\Gamma_\mathrm{l}$ (29.80 ± 0.19) with the standard model value of 29.84 ± 0.15 giving $\Gamma_\mathrm{tot} < 38$ MeV. Corresponding mass limits for up and down type quarks are 41.5 and 44.5 MeV/$c^2$ respectively.

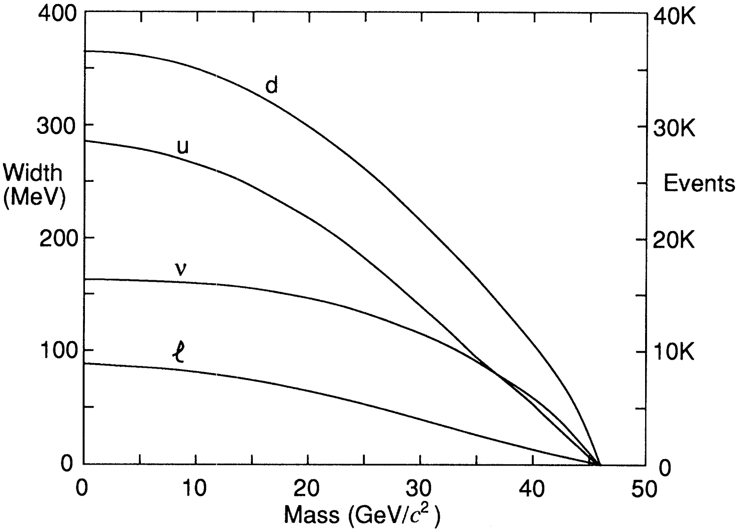

Figure 2. Contribution to the Z width from pair production of massive fermions; the right-hand scale shows the approximate number of events produced per experiment.

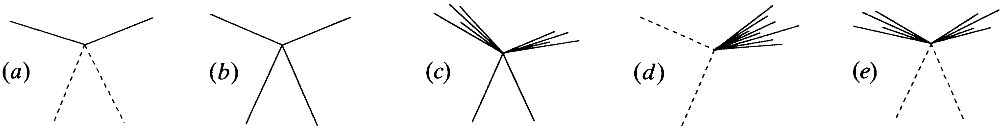

Figure 3. Typical event topologies expected for new particle production: (*a*) two acoplanar leptons; (*b*) four isolated leptons; (*c*) two jets plus two isolated leptons; (*d*) a monojet, (*e*) two acoplanar jets.

These limits are valid only if no mechanism exists which reduces the Z width. Hence wherever possible direct searches for new particles must also be made.

### (*b*) *Direct searches*

Decays of the Z are dominated by the production of $l\bar{l}$ and $q\bar{q}$, already discussed extensively elsewhere in these proceedings. The former gives rise to back-to-back lepton pairs occasionally accompanied by a radiated photon while the latter produces a pair of back-to-back jets accompanied rather more frequently by a third or even a fourth jet from radiated gluons.

Production of new particles results in quite different topologies including events containing a pair of particles which are acoplanar with the beam as a result of missing (unobserved) particles, acoplanar jets of particles, acoplanar jets with one or more isolated leptons and events with isolated high energy photons (figure 3).

These topologies are schematically distinct from the dominant channels. However, three problems arise in the search for potential signal events so that a small number of events can simulate the production of new particles: there are fluctuations in the dominant channels including missing energy from neutrinos; the detectors have finite resolution and small areas with lower efficiency; there is one particular background which must be carefully treated – the so-called two-photon process (figure 1*b*) in which the $e^+$ and $e^-$ remain undetected in the beam pipe while the two virtual photons interact to produce a small number of final state particles and a large missing energy.

Table 1. *Mass limits in* GeV/$c^2$ *for new quarks and leptons*

| | t | b′ | $L^{\pm}$ | $L^0$ |
|---|---|---|---|---|
| ALEPH | 45.8 | 46.0 | 45.6 | 42.7 |
| DELPHI | 44.0 | 44.5 | | |
| L3 | 46.0 | 46.0 | 43.9 | 46.5 |
| OPAL | 44.5 | 45.5 | 42.8 | 46.5 |

A typical analysis procedure is to find event parameters which discriminate between signal and background and put cuts on these parameters so as to reject as many background events as possible (ideally at a level better than 1 in $10^5$) while maintaining a high efficiency for the topology sought.

To achieve this it is essential to have a large sample of Monte Carlo standard Z events on which cuts can be developed and a sample of Monte Carlo events of the process sought so that the efficiency of the analysis can be determined.

Details of the cuts applied in the different searches are not described in this paper. They frequently differ between the collaborations since a healthy spirit of competition exists to devise the optimal cuts for the highest sensitivity.

## 3. New quarks and leptons

Within the first few days of running in 1989 LEP had the major achievement of establishing that there are just three light neutrino species. Although this result is evidence for the existence of just three families of quarks and leptons, efforts to search for the b′ quark and heavy charged ($L^{\pm}$) and neutral ($L^0$) members of a fourth lepton family have continued. In addition the t quark from the third family is as yet undiscovered.

Prior to LEP model independent mass limits for these particles had been set by experiments at TRISTAN and were typically 30 GeV/$c^2$. The CDF experiment at Fermilab has set limits of 89 GeV/$c^2$ for the t quark mass (Sliwa 1990) and 72 GeV/$c^2$ for the b′ mass (Abe *et al.* 1990*a*) for decays via charge currents but these limits are invalidated if neutral current processes exist (e.g. $b' \rightarrow b\gamma$ or $b' \rightarrow bg$) or if there is a charged Higgs with a mass such that $M_t > M_H + M_b$.

The LEP collaborations have therefore looked for direct evidence for the production of these particles. ALEPH (1990*a*) has searched for b′ and t quarks and the $L^0$ through the isolated charged particle that would arise from the leptonic or semi-leptonic decays of these particles. Both DELPHI (1990*a*) and OPAL (1990*a*) have looked for spherical multijet events which would arise from hadronic decays of the b′ and t. ALEPH and OPAL have also looked for flavour changing neutral current decays of the b′ through a search for a high energy isolated photon or for four-jet events. L3 (1990*a*), OPAL (1990*b*) and ALEPH (1990*a*) have set mass limits on stable and unstable heavy leptons, principally by searching for isolated muons.

These limits summarized in table 1, have reached $\frac{1}{2}M_Z$ and cannot be significantly improved by adding more data. Some of the heavy lepton limits depend mildly on assumptions about mixing or stability; the importance of these assumptions can be reduced by the addition of more data.

More recently, measurements of the width of the $W^{\pm}$ boson at $\bar{p}p$ colliders (Abe *et al.* 1990*b*; Alitti *et al.* 1990; Aljabar *et al.* 1990*a*), lead to a model independent limit of 51 GeV/$c^2$ for the top mass. The UA1 collaboration (Aljabar *et al.* 1990*b*) has also looked for $t \rightarrow H^+$ decays and has set a limit $M_t > 61$ GeV/$c^2$ provided the charged Higgs mass is above about 45 GeV/$c^2$, a value now almost reached by LEP (§4*b*).

Finally a rather imprecise determination of $M_t$ can be made from its virtual effects on the Z and W bosons; in particular $M_Z$, $\Gamma_{ll}$ and $M_W$ depend upon $M_t$. The first two quantities have been determined precisely at LEP and the ratio $M_W/M_Z$ has been measured at $\bar{p}p$ colliders. When these measurements are combined a value of $M_t$ of $118 \pm 30$ GeV/$c^2$ is obtained assuming a neutral Higgs mass of 200 GeV/$c^2$ with an additional uncertainty of about ±20 GeV/$c^2$ when $M_H$ is allowed to vary between 50 GeV/$c^2$ and 1 TeV/$c^2$.

## 4. The Higgs boson

$SU(2) \times U(1)$ gauge invariance of the Standard Model would require the gauge bosons to have zero mass. The Higgs mechanism breaks this symmetry and in its minimal form introduces a complex doublet of Higgs fields. Three of these degrees of freedom are absorbed in the masses of the $W^\pm$ and Z bosons while one physical particle, the Higgs boson appears. Although its mass, $M_H$, is not predicted, it must be less than about 1 TeV/$c^2$ otherwise the perturbative approach within the mechanism breaks down.

### (*a*) *The minimal Standard Model Higgs*

As we shall see, the LEP experiments have now excluded the minimal Standard Model (MSM) Higgs boson from zero mass to close to 50 GeV/$c^2$. Before LEP many experiments had looked for this particle through a variety of techniques (Gunion *et al.* (1990) give a thorough review of these searches). Although the validity of most of these early searches is qualified by theoretical uncertainties, taken together they rule out the Higgs below 3.5 GeV/$c^2$

If the Higgs boson exists with a mass below $M_Z$ then it will be produced at LEP via the Bjorken process (figure 4). The branching ratio of the Z for this process depends on $M_H$ as shown in figure 5; it drops rapidly with mass reaching a level of about $10^{-5}$ at $M_H = 60$ GeV/$c^2$.

The decay branching ratios of the Z* to different $f\bar{f}$ final states are well known but since the Higgs couples to fermions via its mass its decay is dominated by the heaviest $f\bar{f}$ pair kinematically allowed; hence the final state produced varies considerably with $M_H$ (figure 6) and different regions of $M_H$ must be considered separately.

$0 \leqslant M_H \leqslant 2M_\mu$

In this region the Higgs decays to an $e^+e^-$ pair (or $\gamma\gamma$ for $M_H \leqslant 2M_e$) but with a lifetime proportional to $1/M_H^2$. Thus, for example, the mean decay path for $M_H =$ 50 MeV/$c^2$ is around 400 cm and the best search channel for a very light Higgs is an acoplanar lepton pair and nothing else (figure 3*a*).

In the high mass end of this region the Higgs will decay inside the detector leading to a visible $e^+e^-$ pair. The $\nu\bar{\nu}$ decay of the Z* results in a particular conspicuous topology of two very acoplanar tracks.

After detection efficiencies have been taken into account all four experiments would have seen tens of events if the Higgs had existed in this mass region. No such signal has been seen (ALEPH 1990*b*; DELPHI 1990*b*; L3 1990*b*; OPAL 1990*d*).

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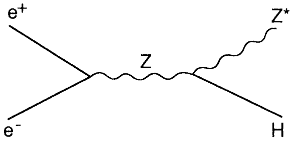

Figure 4. Standard Higgs production through the process $Z \rightarrow H^0 + Z^*$.

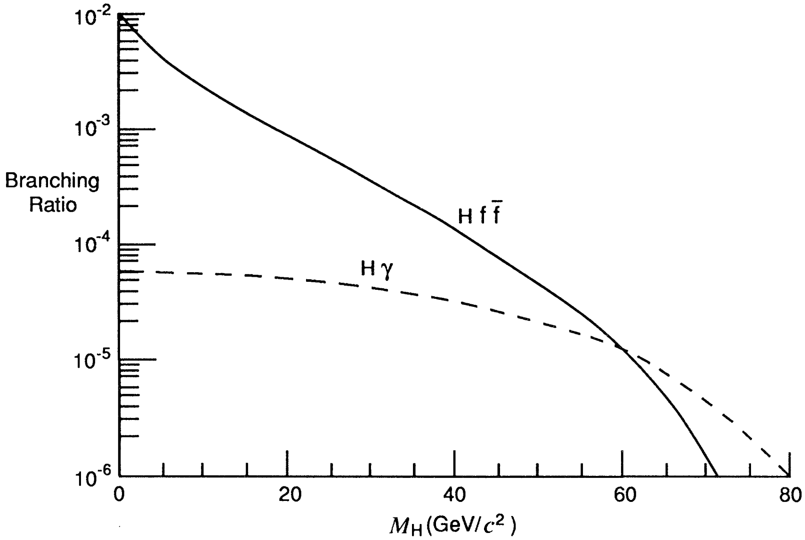

Figure 5. Branching ratio $Z \rightarrow H^0$ as a function of Higgs mass.

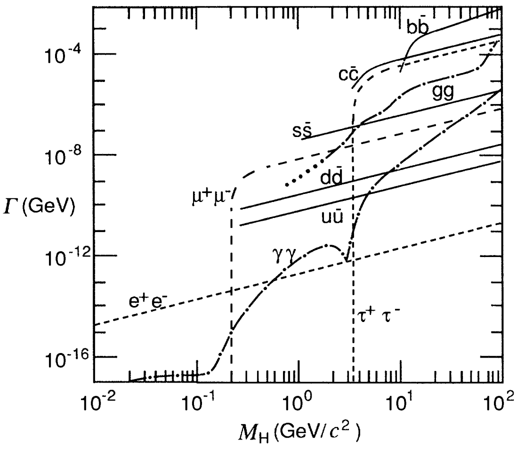

Figure 6. Contributions to the Higgs decay width.

### $2M_\mu \leqslant M_H \leqslant 15$ GeV/$c^2$

Figure 6 shows that the decay modes of the Higgs change considerably through this mass region. At the lower end first $\mu^+\mu^-$ then simple hadronic states are produced while at the upper end it is $\tau^+\tau^-$ and $q\bar{q}$ that dominate. Thus the negative search for acoplanar pairs described in the last section excludes the $\mu^+\mu^-$ decay of the Higgs from threshold to about 10 GeV/$c^2$.

Table 2. *High mass Higgs final state topologies*

| $H^0$ decay | $Z^*$ decay | event fraction | topology |
|---|---|---|---|
| $\tau^+\tau^-$ | $\nu\bar{\nu}$ | 0.012 | acoplanar leptons |
| | $l\bar{l}$ | 0.006 | four leptons |
| | $q\bar{q}$ | 0.042 | two jets plus two leptons |
| $q\bar{q}$ | $\nu\bar{\nu}$ | 0.188 | two acoplanar jets |
| | $l\bar{l}$ | 0.092 | two jets plus two leptons |
| | $q\bar{q}$ | 0.660 | four jets |

For a Higgs mass less than about 15 GeV/$c^2$ the ratio of its mass to momentum is less than unity and the final state hadrons tend to emerge from the interaction region together in a 'monojet' (figure 3*d*). Thus searches in this region concentrate on the channel $H^0 \rightarrow$ hadrons, $Z^* \rightarrow \nu\bar{\nu}$, background coming from the two-photon process and from $e^+e^- \rightarrow \tau^+\tau^-$ when almost all of the momentum of one of the τs is carried away by neutrinos. This background is principally removed by a cut against low total transverse momentum. The monojet search excludes the Higgs from 2 to 15 GeV/$c^2$.

### $M_H \geqslant 15$ GeV/$c^2$

In this mass region the decay of the Higgs is dominated by $q\bar{q}$ (94%) and $\tau^+\tau^-$ (6%) leading to two separated 'jets' (which may each be just one or three particles for the $\tau^+\tau^-$ channel). The object now is to extend the search to as high a mass as possible. The different decay channels and resulting topologies are summarized in table 2.

Apart from the four-jet topology which is particulary difficult because of the large background from QCD events, all other channels have been used to push the search to as high a mass as possible. The principal problem is to find cuts to apply to the data which maximize the efficiency for the Higgs channels while reducing the number of events from the QCD background to a minimum.

The search for acoplanar leptons and for four-lepton events is straightforward and in the channels with two jets and two leptons the requirement of at least one isolated high-energy lepton is particularly powerful. The final state with two acoplanar jets is the most difficult and, although the analyses by the four experiments will not be described here, it is interesting to note that this channel shows the greatest difference in approach of all the searches (ALEPH 1991*a*; DELPHI 1990*c*; L3 1991*a*; OPAL 1990*e*).

Figure 7 shows the predicted number of events for each experiment as a function of mass. The 95% c.l. Higgs mass limit is at three events and can be determined for each experiment from this graph. A significant improvement is obtained by combining the four experiments to give a limit of 50 GeV/$c^2$.

### (*b*) *Extended Higgs models*

There is no fundamental reason for there to be just one Higgs doublet and models with more have been considered in detail. The addition of a second doublet introduces four more Higgs bosons giving five in total, being two charged particles, $H^+$ and $H^-$, and three neutral particles, $h^0$ and $H^0$ with CP even, and $A^0$ with CP odd. The model has six free parameters: the masses of four Higgs bosons, the ratio of the

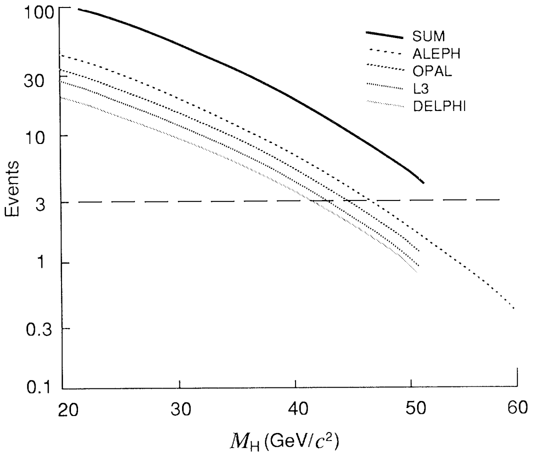

Figure 7. Predicted number of events in the high mass Higgs region for each of the LEP collaborations and their sum.

vacuum expectation values $v_2/v_1$ ($\tan\beta$) and the $h^0$–$H^0$ mixing angle $\alpha$. To reduce the number of parameters a more specific model, such as supersymmetry (§ 5), is frequently chosen.

The Z width for the pair production of spin-0 $H^{\pm}$ is different from equation (2) being given by:

$$\Gamma(Z\rightarrow H^+H^-) = (G_F M_Z^3/12\,2^{\frac{1}{2}}\pi)\,\beta_{\pm}^3(1-2\sin^2\theta_W)^2 = \tfrac{1}{3}\Gamma_{\mu\mu}\beta_{\pm}^3, \tag{3}$$

where $\beta_{\pm}$ is the velocity of the $H^{\pm}$ in units of $c$. As an example, for $M_{\pm} = 35\ \mathrm{GeV}/c^2$ the Z branching ratio to $H^{\pm}$ is 0.26%.

The decay widths of $H^{\pm}$ into fermions are:

$$\Gamma(H^{\pm}\rightarrow l\nu_l) \propto M_l^2\tan^2\beta,$$
$$\Gamma(H^{\pm}\rightarrow u_i\,d_j) \propto 3|V_{ij}|^2(M_i^2\cot^2\beta+M_j^2\tan^2\beta),$$

where $i$ and $j$ label the up and down type quarks and $V_{ij}$ are the elements of the Cabibbo–Kobayashi–Maskawa matrix.

For values of $M_{\pm} \geqslant 20\ \mathrm{GeV}/c^2$ the decay is dominated by $\tau\nu_\tau$ if $\tan^2\beta \gg 1$ and by $c\bar{s}$ if $\tan^2\beta \ll 1$. Hence the topologies of interest in the $H^{\pm}$ search are:

| | |
|---|---|
| $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ | acoplanar pair; |
| $\tau^+\nu_\tau\bar{c}s$ | two acoplanar jets plus isolated track; |
| $c\bar{s}\bar{c}s$ | four jets. |

The absence of signal in acoplanar pair searches has already been described (§4*a*). The principal features of the second topology are an isolated track (no other track in a cone of typically 25° around the track), a large missing energy and two jets with total energy *ca.* $\frac{1}{2}M_Z$. The searches have found no signal in this topology. The third topology is the most difficult; its analysis involves use of standard jet algorithms such as LUCLUS (Sjöstrand & Bengtsson 1987) to select four-jet events followed by cuts on jet–jet angles to reduce gluon bremsstrahlung leaving typically a few hundred events. Limits are then determined by looking for a peak in one- or two-dimensional plots of dijet effective mass for these remaining events.

Figure 8

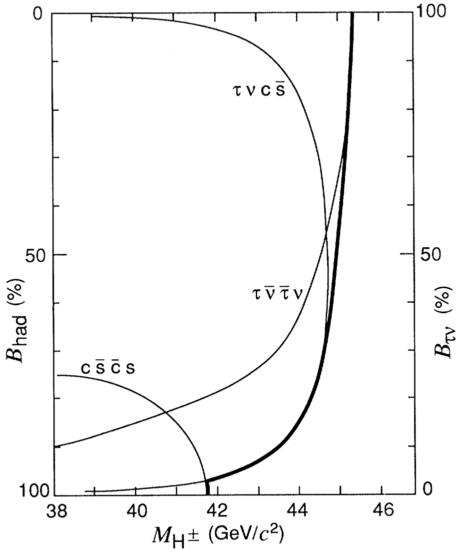

Figure 9

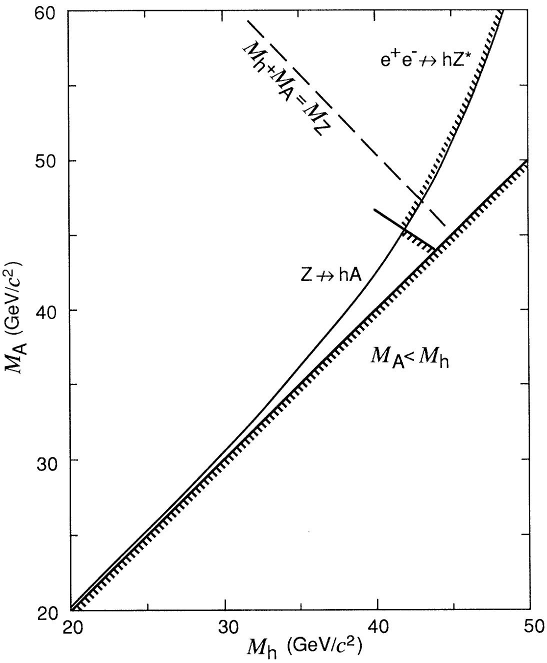

Figure 8. Charged Higgs mass limit as a function of the decay branching ratio.

Figure 9. SUSY Higgs mass limit in the plane $M_A$ against $M_h$.

Since the branching ratio of $H^\pm$ to hadrons is unknown the mass limit is presented as a function of this ratio. ALEPH (1991*b*) has the best limit at present (figure 8) although the other collaborations have also published results (DELPHI 1990*c*; L3 1990*c*; OPAL 1990*f*).

The additional constraints imposed by supersymmetry on masses and couplings in the two Higgs doublet model (ignoring radiative corrections) are (i) the charged Higgs mass is larger than $M_W$; (ii) the $h^0$ is lighter and the $H^0$ is heavier than the Z; (iii) the $A^0$ has mass greater than $M_h$; (iv) only two parameters are needed in the model, normally chosen as $M_h$ and tan $\beta$, or $M_h$ and $M_A$.

Thus in this model only the search for $h^0$ and $A^0$ is possible on the Z peak. The former is produced either through the Bjorken process $Z \rightarrow hZ^*$ (figure 4) or in association with $A^0$ in $Z \rightarrow h^0A^0$. Limits on the first can immediately be inferred from the search for $Z \rightarrow H^0Z^*$ already described in §4*a*. The final states in $Z \rightarrow h^0A^0$ are:

| | | |
|---|---|---|
| $h^0 \rightarrow q\bar{q}$ | $A^0 \rightarrow q\bar{q}$ | 4 jets; |
| $h^0 \rightarrow \tau^+\tau^-$ | $A^0 \rightarrow q\bar{q}$ | 2 jets plus 2 leptons; |
| $h^0 \rightarrow \tau^+\tau^-$ | $A^0 \rightarrow \tau^+\tau^-$ | 4 leptons. |

The searches for these final states have already been discussed. After the signal efficiency has been determined for each channel by Monte Carlo calculation regions on the plot of $M_A$ against $M_h$ are excluded. Figure 9 has been obtained by combining the results from the four collaborations (ALEPH 1991*b*; DELPHI 1990*c*; L3 1990*d*; OPAL 1991*a*); the lower limits on $M_h$ and $M_A$ separately are 41 and 46 GeV/$c^2$ respectively.

Table 3. *The particles and their supersymmetric partners*

| particle | | spin | SUSY particle | | spin |
|---|---|---|---|---|---|
| slepton | l | $\frac{1}{2}$ | slepton | $\tilde{\mathrm{l}}$ | 0 |
| quark | q | $\frac{1}{2}$ | squark | $\tilde{\mathrm{q}}$ | 0 |
| photon | $\gamma$ | 1 | photino | $\tilde{\gamma}$ | $\frac{1}{2}$ |
| gluon | g | 1 | gluino | $\tilde{\mathrm{g}}$ | $\frac{1}{2}$ |
| | $\mathrm{W}^{\pm}$ | 1 | wino | $\tilde{\mathrm{W}}^{\pm}$ | $\frac{1}{2}$ |
| | Z | 1 | zino | $\tilde{\mathrm{Z}}$ | $\frac{1}{2}$ |
| Higgs | H | 0 | higgsino | $\tilde{\mathrm{H}}$ | $\frac{1}{2}$ |

It has been recently realized (Ellis 1991) that radiative corrections in the supersymmetric Higgs sector are likely to be large because of the large top quark mass, invalidating several of the assumptions on which the above searches have been based. New analyses which include radiative corrections are in progress.

## 5. Supersymmetry

The introduction of one or more Higgs bosons with mass less than about 1 TeV/$c^2$ provides a mass mechanism for the gauge bosons. However, this model has several problems, one of which, the so-called naturalness problem, is that one loop corrections to $M_{\mathrm{H}}$ are much larger than the bare mass term and a mechanism is required for their removal.

Supersymmetry (SUSY) achieves this by introducing new particles with spin values differing from those of the known particles by half a unit (table 3). In the limit of exact supersymmetry the supersymmetric particles would have the same masses as their normal partners and would exactly cancel the higher-order terms in the Higgs mass. If such particles existed they would already have been seen at lower-energy machines so we know that the symmetry is not exact. Nevertheless if supersymmetry is the solution to the naturalness problem, then its mass scale is less than 1 TeV/$c^2$ to keep the Higgs mass in the same range.

Most SUSY models have a multiplicatively conserved quantum number, $R$, which has a value $+1$ for normal particles and $-1$ for SUSY particles. This has important consequences for SUSY particles: they are always produced in pairs, e.g. $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-$; each decays into another SUSY particle, e.g. $\tilde{\mu} \rightarrow \mu\tilde{\gamma}$; the lightest is absolutely stable.

Mixing of certain SUSY particles can occur giving mass eigenstates that are mixtures of $\tilde{\mathrm{W}}^{\pm}$ and $\tilde{\mathrm{H}}^{\pm}$ called charginos ($\chi^{\pm}$) or mixtures of $\tilde{\gamma}$, $\tilde{\mathrm{Z}}$ and $\tilde{\mathrm{H}}$ called neutralinos ($\chi$). The lightest neutralino is stable and escapes detection since it has only weak interactions.

Sleptons and charginos will be pair produced through $s$-channel Z exchange (figure 1$a$) with a width given by

$$\Gamma(\mathrm{Z} \rightarrow \tilde{\mathrm{l}}\tilde{\mathrm{l}}) = \tfrac{1}{4}\Gamma_{\mu\mu}\beta_{\tilde{\mathrm{l}}}^{3}.$$

They decay via $\tilde{\mathrm{l}} \rightarrow \mathrm{l}\chi$ or $\chi^{\pm} \rightarrow \mathrm{l}\nu\chi$. Thus the signal for these particles is an acoplanar lepton pair and large missing energy. Non-observation of such events, already discussed, allows mass limits to be set close to $\frac{1}{2}M_{\mathrm{Z}}$ apart from a small region with $M_{\chi^{\pm}}$ close to $M_{\tilde{\mathrm{l}}}$ where the very low momentum final state leptons have low detection efficiency. DELPHI has also excluded the existence of a stable $\tilde{\mathrm{l}}$ for a mass up to about 40 GeV/$c^2$.

Table 4. *Mass limits on supersymmetric particles; those for* $\tilde{q}$ *and* $\tilde{g}$ *are from* $\bar{p}p$ *experiments*

| SUSY particle | $\tilde{e}$ | $\tilde{\mu}$ | $\tilde{\tau}$ | $\tilde{\nu}$ | $\tilde{q}$ | $\tilde{g}$ | $\chi^{\pm}$ | $\chi$ | $\chi'$ |
|---|---|---|---|---|---|---|---|---|---|
| mass limit | 44 | 44 | 43 | 32 | 74 | 79 | 45 | 10 | 45 |

The dominant decay mode of neutralinos is expected to be $\chi' \rightarrow \chi Z^* \rightarrow \chi f\bar{f}$. Possible neutralino production and decay channels are therefore:

$$\chi\chi' \rightarrow q\bar{q}\chi\chi \qquad \text{2 acoplanar jets;}$$

$$\chi'\chi' \rightarrow q\bar{q}\nu\bar{\nu}\chi\chi \qquad \text{2 acoplanar jets;}$$

$$\rightarrow q\bar{q}l\bar{l}\chi\chi \qquad \text{2 jets and 2 leptons.}$$

Again no signal is seen and limits can be set on the branching ratios for $Z \rightarrow \chi\chi'$ and $\chi'\chi'$ of about $10^{-4}$ over most of the $(M_{\chi}, M_{\chi'})$ plane accessible at $\sqrt{s} = M_Z$. This limit is strong enough to exclude the mass region $M_{\chi'} < 45\ \mathrm{GeV}/c^2$ for all reasonable values of parameters of SUSY models. All collaborations have published limits on supersymmetric particles (ALEPH 1990*c*, *d*; DELPHI 1990*d*; L3 1989*a*; OPAL 1990*g*, *h*).

The UA2 experiment at the CERN $\bar{p}p$ collider (Alitti *et al.* 1990*b*) has set 90% c.l. limits for squarks ($74\ \mathrm{GeV}/c^2$) and gluinos ($79\ \mathrm{GeV}/c^2$) under the assumption that $\tilde{q} \rightarrow q\tilde{g}$ or $q\chi$ and $\tilde{g} \rightarrow q\bar{q}\chi$ which are valid if $M_{\chi} < 20\ \mathrm{GeV}/c^2$. DELPHI (1990*e*) has excluded the $\tilde{q}$ up to $45\ \mathrm{GeV}/c^2$ for $\tilde{q}$-$\chi$ mass difference greater than $2\ \mathrm{GeV}/c^2$. Roszkowski (1990) has recently shown that combining the LEP neutralino data and the UA2 gluino limit leads to a limit on $M_{\chi}$ of about $10\ \mathrm{GeV}/c^2$.

A summary of limits on supersymmetric particles is given in table 4.

## 6. Compositeness

A radically different approach to the mass problem is that of compositeness. Guided by the known layers of substructure of matter it is but a small step to suggest that the quarks, leptons and possibly even the gauge bosons have subcomponents. The major problem with such models is reconciling the GeV mass scale of the quarks with the compositeness scale (TeV or greater) as deduced from non-observation of effects at lower-energy accelerators. A recent review of this topic is given by Boudjema & Renard (1989).

The most dramatic prediction of such a model is the existence of excited states of quarks and leptons. Such excited fermions can be produced either in pairs or singly; in the former case the cross section will be as given in equation (1) while for single production there is an unknown $Zf^*f$ coupling which can suppress the production rate.

The dominant decay of excited charged leptons is expected to be $l^* \rightarrow l\gamma$ resulting in a final state lepton pair accompanied by one or two photons, the background being lepton pair events with one or two radiated photons. However, while this background consists predominantly of low-energy photons at small angles to the leptons, signal events will contain high-energy photons which in general are at much wider angles. Any such acollinear leptons accompanied by high-energy isolated photons are readily observed with a high efficiency; thus since the background rate for two radiated photons is low and the predicted pair production signal is high the mass limit for excited leptons has been pushed to $\frac{1}{2}M_Z$ at LEP (ALEPH 1990*e*; L3 1990*e*, *f*; OPAL

Table 5. *Mass limits on excited fermions in* GeV/$c^2$

(Column (*a*) pair production; column (*b*) single production assuming Zl*l coupling equal to Zll.)

| excited state | (*a*) | (*b*) |
|---|---|---|
| e* | 45.6 | 89 |
| μ* | 45.6 | 89 |
| τ* | 45.5 | 89 |
| ν* | 43.2 | 91 |
| q* (up type) | 41.5 | 86 |
| q* (down type) | 44.5 | 86 |

1990*i*). Above this mass it is only possible to place a limit on the coupling as a function of mass or to give a mass limit assuming for example that the Zf*f coupling is equal to the Zff coupling.

Excited neutrinos with a mass below about 45 GeV/$c^2$ are excluded by the limit on the Z invisible width (§2*a*). Above 45 GeV/$c^2$ only single production is allowed. ALEPH (1990*f*) and L3 (1990*g*) have looked for the νγ decay of the ν* and L3 has looked for the eW decay also. The former produces a single-photon final state with background from $\nu\bar{\nu}$ production accompanied by initial state radiation. L3's eW search was for an isolated electron together with an additional acoplanar lepton or two acoplanar jets. Assuming that the Zν*ν coupling is the same as Zνν leads to a ν* mass limit of 91 GeV/$c^2$.

Excited quarks would decay by either gluon or photon emission, a naive model giving the relative rates in the ratio 94:6 (Boudjema & Renard 1989). The final states from excited quark pair production are therefore four jets, three jets plus a photon, or two jets and two photons. Single production will give rise to three jets or two jets and a photon. OPAL (1990*j*) has analysed hadronic events with isolated photons and given improved limits on q* production. However, this result depends on assumptions on the $q^* \rightarrow q\gamma$ branching ratio and a combined analysis of the gluon and photon channels is still awaited. Thus at present the best q* mass limits come from the Z width and are 41.5 and 44.5 GeV/$c^2$ for a single u or d type excited quark respectively. These limits improve, if, as expected, the five known quarks have approximately degenerate excited states.

A summary of excited fermion limits is given in table 5.

If the Z itself is composite then decay modes not expected in the Standard Model may be observed. At present no such anomalous decays have been observed by any experiment in spite of several careful searches.

## 7. Summary and future prospects

One of the great achievements of LEP to date has been to establish that there are three light neutrinos in nature and consequently probably three generations of quarks and leptons. Model-independent lower limits have been set for the t quark and for fourth generation quarks and leptons at about 46 GeV/$c^2$. No evidence has been found for any Higgs boson and the MSM Higgs boson mass limit is now 50 GeV/$c^2$. No new particles predicted by supersymmetry have been observed and a large part of the accessible parameter space has been excluded. No evidence has been found for compositeness and model independent mass limits for excited states are around 45 GeV/$c^2$.

During the next two years further data will be taken at the Z peak giving sensitivity to the MSM Higgs mass up to about 65 GeV/$c^2$. No significant improvement will be made on mass limits from pair production processes since these have already reached the kinematic limit. However, the increase in statistics will improve branching ratio and coupling limits for some channels. The search for unexpected decay modes of the Z will become important during this phase.

Increasing the energy of LEP increases the sensitivity to higher masses for pair produced particles and any running above the Z peak will be welcomed by those involved in searches.

## References

Abe, F., *et al.* 1990*a* Search for new heavy quarks in electron–muon events at the Fermilab Tevatron Collider. *Phys. Rev. Lett.* **64**, 147–151.

Abe, F., *et al.* 1990*b* Measurement of the ratio $\sigma(\mathrm{W}\rightarrow \mathrm{e}\nu)/\sigma(\mathrm{Z}\rightarrow \mathrm{ee})$ in $\bar{\mathrm{p}}\mathrm{p}$ collisions at $\sqrt{s} =$ 1.8 TeV. *Phys. Rev. Lett.* **64**, 152–156.

Albajar, C., *et al.* 1990*a* Measurement of the ratio $R \equiv \sigma_{\mathrm{W}} Br\,(\mathrm{W}\rightarrow \mu\nu)/\sigma_{\mathrm{W}} Br\,(\mathrm{Z}\rightarrow \mu\mu)$ and $\Gamma_{\mathrm{W}}^{\mathrm{tot}}$ at the CERN proton–antiproton collider. *Phys. Lett.* B **253**, 503–510.

Albajar, C., *et al.* 1990*b* Limits on t-quark decay into charged Higgs from a direct search at the CERN $\bar{\mathrm{p}}\mathrm{p}$ collider. *Phys. Lett.* B **257**, 459–468.

ALEPH 1990*a* A search for new quarks and leptons from $\mathrm{Z}^0$ decay. *Phys. Lett.* B **236**, 511–522.

ALEPH 1990*b* Search for a very light Higgs boson in Z decays. *Phys. Lett* B **245**, 289–297.

ALEPH 1990*c* Search for supersymmetric particles using acoplanar charged particle pairs from $\mathrm{Z}^0$ decays. *Phys. Lett.* B **236**, 86–94.

ALEPH 1990*d* Search for neutralino production in Z decays. *Phys. Lett.* B **244**, 541–550.

ALEPH 1990*e* Search for excited leptons in $\mathrm{Z}^0$ decay. *Phys. Lett.* B **236**, 501–510.

ALEPH 1990*f* Search for excited neutrinos in Z decay. *Phys. Lett.* B **250**, 172–182.

ALEPH 1991*a* Searches for the standard Higgs boson produced in the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{H}^0\mathrm{Z}^*$. CERN preprint *CERN-PPE/91–19*.

ALEPH 1991*b* Searches for non-minimal Higgs bosons. CERN preprint *CERN-PPE/91–19*.

Alitti, J., *et al.* 1990 Measurement of W and Z production cross sections at the CERN $\bar{\mathrm{p}}\mathrm{p}$ collider. *Z. Phys.* C **47**, 11–22.

Boudjema, F. & Renard, F. M. 1989 Z. physics at LEP 1, *CERN 89–08*, vol. 3, pp. 182–211.

DELPHI 1990*a* Search for the t and b′ quarks in hadronic decays of the $\mathrm{Z}^0$ boson. *Phys. Lett.* B **242**, 536–546.

DELPHI 1990*b* Search for light neutral Higgs particles produced in $\mathrm{Z}^0$ decays. *Nucl. Phys* B **342**, 1–14.

DELPHI 1990*c* Search for Higgs bosons using the DELPHI detector. CERN preprint *CERN-PPE/90–163*.

DELPHI 1990*d* A search for sleptons and gauginos in $\mathrm{Z}^0$ decays. *Phys. Lett.* B **247**, 157–166.

DELPHI 1990*e* Search for scalar quarks in $\mathrm{Z}^0$ decays. *Phys. Lett.* B **247**, 148–156.

Ellis, J. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 247. (This volume.)

Gunion, J. F., Haber, H. H., Kane, G. & Dawson, S. 1990 *The Higgs hunter's guide*, ch. 3. Addison-Wesley.

L3 1989 Mass limits for scalar muons, scalar electrons, and winos from $\mathrm{e}^+\mathrm{e}^-$ collisions near $\sqrt{s} =$ 91 GeV. *Phys. Lett.* B **233**, 530–537.

L3 1990*a* A search for heavy charged and neutral leptons from $\mathrm{Z}^0$ decays. *Phys. Lett.* B **251**, 321–330.

L3 1990*b* Search for a low mass neutral Higgs boson in $\mathrm{Z}^0$ decay. *Phys. Lett.* B **252**, 518–524.

L3 1990*c* Search for the charged Higgs boson in $\mathrm{Z}^0$ decays. *Phys. Lett.* B **252**, 511–517.

L3 1990*d* Search for neutral Higgs bosons of the minimal supersymmetric Standard Model. *Phys. Lett.* B **251**, 311–320.

L3 1990*e* Mass limits for excited leptons and muons from $\mathrm{Z}^0$ decay. *Phys. Lett.* B **247**, 177–184.

L3 1990*f* Excited taus from $Z^0$ decays. *Phys. Lett.* B**250**, 205–211.

L3 1990*g* Excited neutrinos from $Z^0$ decays. *Phys. Lett.* B**252**, 525–532.

L3 1991 Search for the neutral Higgs boson. *Phys Lett.* B**257**, 450–458.

OPAL 1990*a* A search for the top and b′ quarks in hadronic $Z^0$ decays. *Phys. Lett.* B**236**, 364–374.

OPAL 1990*b* A direct search for new charged heavy leptons at LEP. *Phys. Lett.* B**240**, 250–260.

OPAL 1990*c* Limits on neutral heavy lepton production from $Z^0$ decay. *Phys. Lett.* B**247**, 448–457.

OPAL 1990*d* Limits on a light Higgs boson in $e^+e^-$ collisions at LEP. *Phys. Lett.* B**251**, 211–222.

OPAL 1990*e* Search for the minimal Standard Model Higgs boson. *Phys. Lett.* B**253**, 511–523.

OPAL 1990*f* A search for technipions and charged Higgs bosons at LEP. *Phys. Lett.* B**242**, 299–308.

OPAL 1990*g* A search for acoplanar pairs of leptons or jets in $Z^0$ decays: mass limits on supersymmetric particles. *Phys. Lett.* B**240**, 250–260.

OPAL 1990*h* A direct search for neutralino production at LEP. *Phys. Lett.* B**248**, 211–219.

OPAL 1990*i* Search for excited leptons at LEP. *Phys. Lett.* B**244**, 135–142.

OPAL 1990*j* Evidence for final state photons in multihadronic decays of the $Z^0$. *Phys. Lett.* B**246**, 285–296.

OPAL 1991 A search for minimal supersymmetric Higgs bosons. CERN preprint *CERN-PPE/91–19.*

Roszkowski, L. 1990 Lower bound on the neutralino mass. *Phys. Lett.* B**252**, 471–475.

Sliwa, K. 1990 A new limit on the mass of the top quark. *Proc. XXVth Rencontres de Moriond*, pp. 459–464, Editions Frontières.

Sjöstrand, T. & Bengtsson, M. 1987 The Lund Monte Carlo for jet fragmentation and $e^+e^-$ physics. *Comput. Phys. Commun.* **43**, 367–379.