Exotic Searches at LEP

Philip Seager.
DAPNIA/SPP, CEA Saclay,
91191 Gif sur Yvette CEDEX, France.

The search for exotic processes at LEP is presented. The Standard Model Higgs has as yet not been observed. This provides freedom to search for processes beyond the Standard Model and even beyond the minimal version of the supersymmetric extension to the Standard Model. This paper outlines the searches for charged Higgs bosons, fermiophobic Higgs bosons, invisibly decaying Higgs bosons, technicolour, leptoquarks, unstable heavy leptons and excited leptons. The results presented are those from the LEP collaborations using data taken up to a centre-of-mass energy of $\sqrt{s} = 202$ GeV.

1 Introduction

The Standard Model (SM) is a spontaneously broken SU(2) $\otimes$ U(1) gauge theory with a single doublet of complex scalar fields which is used to give mass to the gauge bosons the W and the Z. The choice of a single doublet is one of simplicity. The SM is the lowest order theory of this type which can give particles their masses. The fact that the Higgs boson has not yet been discovered, the limits presented in this conference [1] are now up to 107.7 GeV/c^2, means that one is free to extend the SM or even to propose alternatives to the SM. This is the subject of this paper.

The results presented correspond to data taken by the four LEP experiments ALEPH, L3, OPAL and DELPHI in 1999. This data set corresponds to an integrated luminosity of $\sim$ 900pb^{-1} taken at four centre-of-mass energies 192, 196, 200 and 202 GeV.

2 The search for charged Higgs bosons

One can extend the Higgs sector of the SM to a two-Higgs-doublet model (2HDM). With this choice there are now two doublets of complex scalar fields to give mass to the gauge bosons the W and the Z. Counting up the number of degrees of freedom, one is left with 5 Higgs bosons, 3 of which of neutral and 2 charged [2]. It is these charged Higgs bosons which constitute the subject of the search at LEP. The Minimal Supersymmetric Standard Model (MSSM) is also a 2HDM. Constraints within the MSSM require that the charged Higgs bosons be at least more massive than the W boson mass $m_{\rm W}$ according to the relation $m^2_{\rm H^\pm} = m^2_{\rm W} + m^2_{\rm A}$ where A corresponds to one of the light neutral Higgs bosons. This relation is only weakly altered by the effects of radiative corrections. The sensitivity to the charged Higgs boson search at LEP is restricted to masses below $m_{\rm W}$ and therefore discovery of the charged Higgs boson at LEP would rule out the MSSM as a viable theory.

The search is performed assuming that the charged Higgs boson decays with negligible lifetime and that the width of the decay is completely saturated by the decays $\rm H \rightarrow \tau\nu_\tau$ and $\rm H \rightarrow c\bar{s}$ with all other decay channels assumed to be negligible. As a consequence, $\rm e^+e^- \rightarrow H^+H^-$ pair production leads to three dominant final states ($\rm c\bar{s}\bar{s}\bar{c}$, $\rm c\bar{s}\tau^-\bar{\nu}_\tau/\bar{c}s\tau^+\nu_\tau$ and $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$) for which separate searches are performed. The dominant background to the search is from $\rm e^+e^- \rightarrow W^+W^-$ final states.

The four experiments at LEP have each updated their searches for charged Higgs bosons using the data taken in 1999. The ALEPH collaboration has renewed the analyses in each of the search channels [3]. Linear discriminants are used in the $\rm c\bar{s}s\bar{c}$ and $\rm c\bar{s}\tau^-\bar{\nu}_\tau/\bar{c}s\tau^+\nu_\tau$ channels and in particular the use of the different states of the polarisation of the τ lepton from charged Higgs bosons and W bosons is exploited in the $\rm c\bar{s}\tau^-\bar{\nu}_\tau/\bar{c}s\tau^+\nu_\tau$ channel. The L3 collaboration have updated their $\rm c\bar{s}s\bar{c}$ analysis using a neural net to improve the sensitivity in this channel whilst the remaining two channels are searched for using the same analyses that were used with previous data [4]. The OPAL collaboration have completely unchanged analyses and simply updated their limits with the new data [5]. The DELPHI collaboration have improved the $\rm c\bar{s}\tau^-\bar{\nu}_\tau/\bar{c}s\tau^+\nu_\tau$ and $\rm c\bar{s}s\bar{c}$ analyses. Together with this they use an algorithm to identify charm quarks within jets for the $\rm c\bar{s}\tau^-\bar{\nu}_\tau/\bar{c}s\tau^+\nu_\tau$ and $\rm c\bar{s}s\bar{c}$ analyses and the τ polarisation information in each of the $\rm c\bar{s}\tau^-\bar{\nu}_\tau/\bar{c}s\tau^+\nu_\tau$ and $\tau^+\nu_\tau\tau^-\bar{\nu}_\tau$ channels. These variables are then used with the reconstructed mass as discriminating variables in the estimator to increase the sensitivity of the analysis. The results of the searches for each experiment are listed in table 1.

The LEP Higgs Working Group has combined the results from the four experiments to set limits on the mass of the charged Higgs bosons. Details of the combination can be found described elsewhere [7]. The result of the combined limit as a function of the branching ratio $\rm B(H^+ \rightarrow \tau^+\nu_\tau)$ is shown in figure 1.

Table 1: Expected and oberserved limits at 95% CL for charged Higgs bosons from each LEP experiment.

	ALEPH	L3	OPAL	DELPHI
Sensitivity (GeV/c^2)	76.4	73.2	73.9	72.5
Limit (GeV/c^2)	77.7	65.0	75.4	70.7

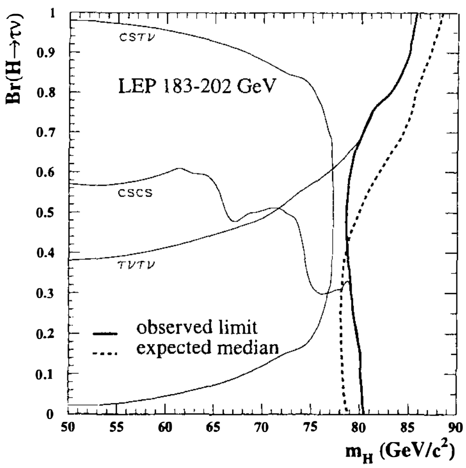

Figure 1: The 95% CL bounds on the mass of the charged Higgs boson as a function of the branching ratio $B(H^+ \to \tau^+\nu_\tau)$, combining the data collected by the four LEP experiments at energies from 183 to 202 GeV/c^2. The expected exclusion limits are indicated by the dashed line and the observed limits by the full line.

The LEP combined limit is 78.6 GeV/c^2 for an expected limit of 78.0 GeV/c^2.

3 The search for fermiophobic Higgs bosons

The photon being a massless particle is not expected to couple directly to the SM Higgs boson. Any coupling is therefore necessarily through loops of charged particles, *i.e.*, W's, quarks or leptons and the branching ratio is expected to be small ($\sim 10^{-3}$ for Higgs masses [8] of $\sim$ 90 GeV/c^2).

The branching fraction $h \to \gamma\gamma$ can however be enhanced in several scenarios.

- The direct couplings of the Higgs boson to fermions are suppressed. This can occur in 2HDM's [9] in which only the first doublet couples to fermions and the second doublet couples to bosons.
- The direct couplings to gauge bosons are enhanced by anomolous couplings [10]. These couplings are described in the most general formulation with four effective six-dimensional operators of strength f_i/Λ^2, where Λ is the scale of the new interaction.
- The couplings of the Higgs boson to fermions and bosons is modified, as in the case of the MSSM [11].
- Additional charged particles enter the loops which couple the Higgs boson to photons, as is again the case in the MSSM.

With some particular choices of parameters, the branching ratio $h \to \gamma\gamma$ can be enhanced by a factor of three in the MSSM and can be close to 100% in other fermiophobic models. It follows therefore that the Higgs boson could escape the SM Higgs search for the Higgs-strahlung process $e^+e^- \to hZ \to hf\bar{f}$ with the Higgs decaying to $b\bar{b}$. The complementary search $e^+e^- \to hZ \to \gamma\gamma f\bar{f}$ is therefore performed.

The four experiments at LEP have each updated their searches for fermiophobic Higgs bosons using the data taken in 1999. The resulting exclusion limits are 101, 98.8 and 97.8 GeV/c^2 for the ALEPH [12], L3 [13] and OPAL [5] collaborations, respectively in the context of a fermiophobic model. The DELPHI

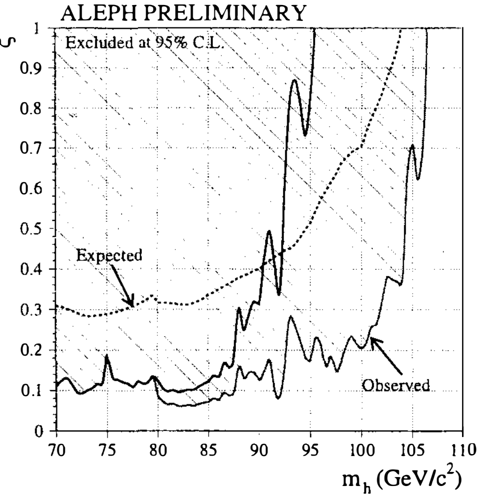

Figure 2: The region excluded at the 95% CL in the (m_h, ξ^2) plane. The full curve inside the exclusion domain is the limit obtained using 1998 data.

collaboration has searched for the decay $h \to \gamma\gamma$ in the context of models with anomolous couplings and have also set limits in a general 2HDM scenario [14]. They set a limit for $B(h \to \gamma\gamma) = 100\%$ at 98 GeV/c^2.

4 The search for invisibly decaying Higgs bosons

Higgs boson decays to invisible final states are predicted by various SM extensions. In particular within the MSSM the lighter CP-even Higgs boson h can decay into a pair of lightest neutralinos $h \to \chi\chi$ when the neutralino is light enough. If the gaugino masses are unified at the GUT scale the absence of a signal in the direct neutralino searches essentially excludes the possibility of observing this channel at LEP. If one however relaxes the assumption, new regions of parameter space become available [15].

This leads to final states of acoplanar lepton or quark-jet pairs, with the principle background arising from radiative Z return two-fermion processes. In general, the production cross section of this reaction can be expressed as $\xi^2\sigma_{SM}(e^+e^- \to hZ)$, where ξ^2 represents a model-dependent constant which reduces the cross section with respect to that of the production of the SM Higgs boson. All LEP experiments have renewed their searches for invisibly decaying Higgs bosons for the acoplanar jet pair analyses using the data taken in 1999. The ALEPH collaboration uses several neural nets trained at several input Higgs masses in order to increase the search sensitivity [16]. The L3 [17], OPAL [5] and DELPHI [18] collaborations have unchanged analyses with respect to previous data. The results of the four experiments are listed in table 2. The exclusion in the plane of $\xi^2\sigma_{SM}(e^+e^- \to hZ)$ against the mass of the Higgs boson is shown in figure 2 for the ALEPH collaboration.

Table 2: Expected and oberserved limits at 95% CL for invisible Higgs bosons from each LEP experiment.

	ALEPH	L3	OPAL	DELPHI
Limit (GeV/c^2)	106.4	100.5	94.4	92.1

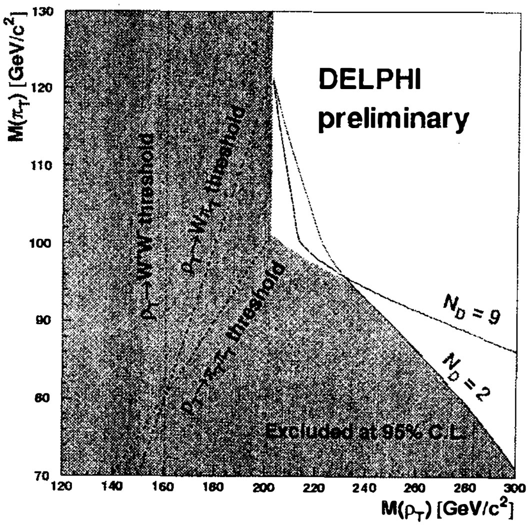

Figure 3: The region in the (M_{ρ_T}, M_{π_T}) plane (filled area) excluded at 95% CL for all values of $W_L - \pi_T$ mixing.

5 The search for technicolour

Technicolour provides an elegant scheme to generate the masses of the W and Z bosons. While the minimal model seems to be disfavoured by the precise electroweak measurements performed at LEP and at the SLC, more elaborate models such as "walking technicolour" [19] can not be excluded. The conclusion of such models is that perturbative calculations can not be made to give reliable results and the theory is therefore no longer excluded. These extensions call for a large number of technidoublets N_D and therefore additional scalar (π_T, π'_T) and vector (ρ_T, ω_T) mesons.

The DELPHI collaboration has performed a search for technicolour using the data taken in 1999[20]. The search is performed using the invariant mass spectrum of the $e^+e^- \to \mu^+\mu^-(+n\gamma)$ events and the search for the final states of $e^+e^- \to \rho_T \to \pi_T\pi_T$, $\pi_T W$ and W^+W^-. No significant excess is observed and limits are set on technicolour production. The 95% CL excluded region in the (M_{ρ_T}, M_{π_T}) plane is shown in figure 3. It is valid for all values of N_D.

6 The search for leptoquarks

Leptoquarks are coloured spin 0 and spin 1 particles which carry both baryon and lepton quantum numbers. These particles are predicted in a variety of SM extensions from Grand Unified Theories [21] to Technicolour [22] and composite models [23]. Leptoquarks have electric charges $\pm 5/3$, $\pm 4/3$, $\pm 2/3$ and $\pm 1/3$ and decay into a lepton and quark pair through the charged decay mode $L_q \to \ell^\pm q$ and/or the neutral decay mode $L_q \to \nu q$. Leptoquarks can be pair or singly produced at e^+e^- colliders.

Experimentally the existence of leptoquarks has been constrained by direct searches at HERA where limits on the mass of scalar leptoquarks were set at $M_{LQ} > 216 - 275$ GeV/c^2 and at the TEVATRON where the mass of scalar leptoquarks was constrained to be greater than 225 GeV/c^2.

The DELPHI collaboration has performed a search for leptoquarks using the data taken in 1999[24]. Only single leptoquark production is considered in the analysis and two hypotheses are considered, firstly where the charged decay mode is possible (charged branching ratio $\beta = 1$) and secondly where the charged and neutral decay modes are equally probable (charged branching ratio $\beta = 0.5$). The results of each case, too numerous to be collated here can be found in their paper.

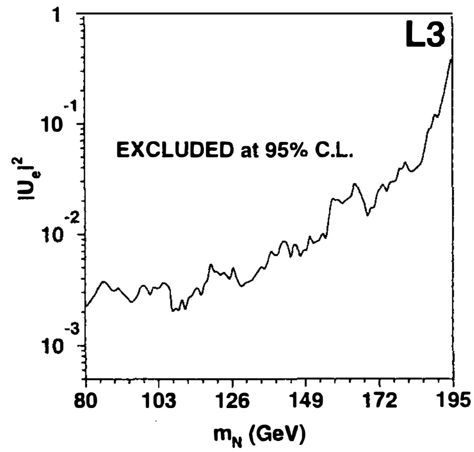

Figure 4: Upper limits at 95% CL on the mixing amplitude as a function of the isosinglet heavy neutrino mass.

7 The search for unstable heavy leptons

Exotic leptons can be classified as three types [25].

- Sequential leptons : these exist in the simplest extension to the SM where one simply adds to the known fermionic spectrum a fourth family with the same quantum numbers.
- Vector leptons : these leptons have both left and right-handed components in weak isodoublets. For example they are predicted in a gauge theory with E_6 symmetry [26].
- Mirror leptons [27] : these particles have chiral properties which are opposite to those of ordinary leptons, *i.e.*, right-handed components are in weak isodoublets and left-handed components are in weak isosinglets. Mirror fermions provide a way to restore left-right symmetry at the scale of electroweak symmetry breaking
- Isosinglet neutrinos : these particles are the most discussed in the literature. They arise in models such as Grand Unified Theories, Superstring models, left-right symmetric models and see-saw models [28]

Sequential, vector and mirror heavy leptons would be produced through the s-channel γ and Z exchange for charged leptons (L^+, L^-) whilst for heavy neutrinos ($L^0, \bar{L}^0$) only Z exchange is present. The neutral heavy leptons can be either Dirac or Majorana types, the difference being the dependence of the cross section on the velocity. The searches are generally performed assuming that heavy leptons couple to electron, muon or tau families and the possibility of mixing between light leptons is neglected.

The mixing between the isosinglet neutrinos and the associated isodoublet neutrino allows single production to occur via the process $e^+e^- \to N_\ell \nu_\ell$. The mixing amplitude U_ℓ associates each generation of neutrino with the corresponding isosinglet neutrino N_ℓ. The dominant single production process proceeds through s-channel Z exchange for all generations. For the first generation N_ℓ there is an additional contribution from t-channel W exchange which enhances the production cross section. It is for this reason that the search is performed only for the first generation isosinglet neutrino N_e.

The heavy leptons are assumed to decay via the charged or neutral current processes. The decays $L^0 \to \ell^\pm W^\mp$ and $L^\pm \to \nu_\ell W^\pm$ are however the dominant modes and in general are the only ones considered.

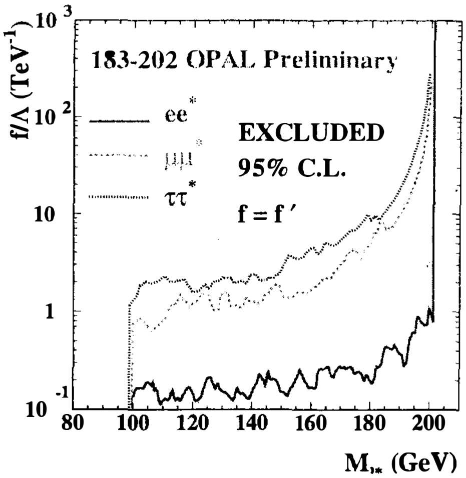

Figure 5: 95% CL upper limits on the ratio of the coupling to the compositeness scale, f/Λ, as a function of the excited lepton mass showing the limits on e^*, μ^* and τ^* with $f = f'$. The regions above and to the left of the curves are excluded by the single and pair production searches, respectively.

The OPAL[29] and L3[30] collaborations have both updated their searches for unstable heavy leptons using the data taken in 1999. The results for Sequential, Vector and Mirror leptons too numerous to be collated here are listed in the references provided. Limits are placed almost at threshold in each case. The L3 collaboration has performed a search for an isosinglet neutrino. The exclusion in the plane of the mixing amplitude squared $|U_e|^2$ against the mass of the isosinglet electron neutrino m_{N_e} is shown in figure 4.

8 The search for excited leptons

If the hierarchy of masses of the SM fermions is due to underlying substructure or compositeness, it is natural to expect excited states of the known fermions which would undergo decays via a photon into a ground state, or if sufficiently heavy, also decay via the W or Z bosons. These theories are generally parameterised by the compositeness scale Λ, and the relative weights associated with the SU(2) and U(1) gauge couplings, f and f' respectively.

At LEP excited leptons would be produced singly or in pairs, leading to the final states of $e^+e^- \to \ell^*\ell, \nu^*\nu$ and $e^+e^- \to \ell^*\ell^*, \nu^*\nu^*$ respectively.

The OPAL[29] collaboration has searched for these final states in all decay channels. In the search for pair produced excited leptons the cross section is independent of the couplings and limits are set for charged and neutral excited leptons. The results of the search using the data taken in 1999 are listed in the reference provided. Limits are placed close to the threshold of production in each case. The single production cross section depends on f and f' and limits are set in the plane of f/Λ and the mass of the excited leptons. The result of such limits are shown in figure 5 from the OPAL collaboration.

9 Conclusions

Exotic searches have been performed at LEP using data collected in 1999. No significant excess above that expected from SM processes has been observed and limits have been set on the production cross sections for the processes considered. The scheduled restart up of the LEP accelerator with higher energies is eagerly awaited.

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