SEARCH FOR NEW PHENOMENA AT LEP

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Abstract

Recent searches for new particles and rare Z° decays performed at LEP are reviewed.

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Introduction

With the first few 10^4 events collected at LEP,[1] many searches have already been performed : pair-produced heavy fermions and scalar bosons, light Higgs boson from the Standard Model (SM) and its most popular supersymmetric extension (MSSM).

A large amount of territory has thus been already covered and one is left, after collecting 10^6 Z° events with the four LEP experiments, with the difficult task to explore the Higgs sector and other Z° decays with very low branching ratios, typically a few 10^{-5}. This experimental struggle already pushes the various detectors at the limit of their capabilities and takes advantage of specific properties : momentum resolution for muons, energy resolution for electrons and photons, identification properties for leptons, hadronic calorimetry and hermeticity for neutrinos.

The line shape measurements,[2] which have reached a high level of accuracy, provide an independent tool for searches. They allow, at the percent level, to exclude indirectly the presence of any new phenomena which might escape to searches carried on a specific final state. They uniquely allow, through the invisible width measurement, to explore the invisible channels predicted by supersymmetric models.

Rather than ordering the LEP searches through the numerous extensions of the SM, this paper will present a systematic exploration of LEP data based on specific channels. I will first describe the indirect method and give a set of limits on new particles obtained from the line shape measurements. In chapter 2, I will present searches based on channels either forbidden or strongly suppressed in the SM : pure photonic final states and flavour violating leptonic states. I will then present a systematic exploration of new phenomena based on leptonic final states (chapter 3). Hadronic final states with missing energy or the presence of isolated particles, leptons or photons, will serve to set limits primarily in the Higgs sector. At each stage of the discussion, I will indicate the implication of a given search on the theoretical models usually advocated : supersymmetry and compositeness. I will also recall briefly the concepts and define the variables used in these models.

Various subjects have been omitted due to a lack of time among which the test of QED using $\gamma\gamma$ final states and the search for leptoquarks, a domain actively explored at LEP and at hadronic colliders.

1. Z° widths measurements

The measured values of the total Z° width, Γ_Z, and of the invisible width, Γ_{inv}, can be used to derive upper limits on a partial width (visible or invisible) due to the Z° decaying into new final states implied by the SM or its extensions. Γ_Z comes from a straigthtforward adjustment of the line shape, while Γ_{inv} is usually deduced, through a fitting procedure, from the formula :

$$\Gamma_{inv} = \Gamma_\ell \left(\sqrt{\frac{12\pi R_Z}{M_Z^2 \sigma_0}} - R_Z - 3 \right) ,$$

where Γ_ℓ is the leptonic width, R_Z is the ratio of hadronic and leptonic widths, σ_0 is the hadronic cross section at the resonance. These quantities are unambiguously measured except for what concerns the definition of hadronic final states : exotic final states may or may not fulfill the multiplicity and energy selection criteria applied to define hadronic states. If they don't, the corresponding channel contributes to Γ_{inv}.

The method used to derive an upper limit on any new channel X is schematized in figure 1. One assumes a minimal value Γ^{th}_{Min} for the SM width. This value depends on the top mass, on α_s (if hadronic final states contribute to the width) and, to a lesser extent, on the Higgs mass. For a given measurement Γ_M, one may define an upper value Γ_{Max}, excluded at the 95 % C.L., which is given by :

$$\Gamma_{Max} = \Gamma_M + 1.65\ \sigma_\Gamma$$

where σ_Γ is the measurement error. The upper limit on the width is given by the difference $\Gamma_{Max} - \Gamma^{th}_{Min}$. This method, statistically sound, only works if

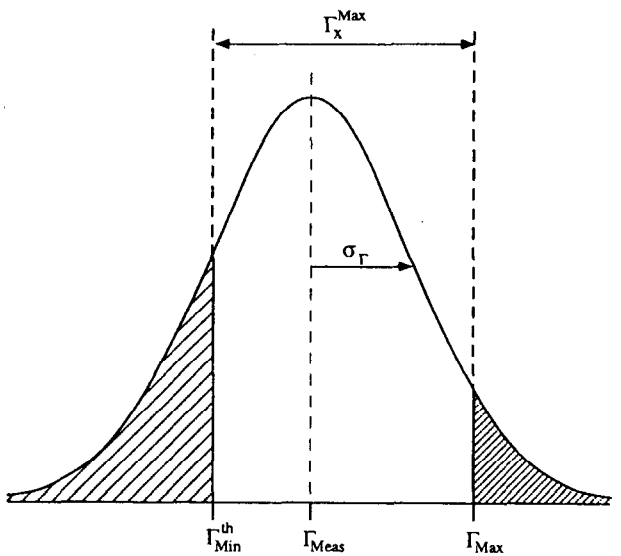


Fig. 1

Derivation of an upper limit from a measured width Γ_{Meas}. The left-handside shaded area is excluded from theory, the right-handside is excluded from the measurement itself (5 % of the area of the Gaussian). The 95 % C.L. upper limit on a extra contribution Γ_X is given by the distance between these two limits.

the errors are correctly estimated. In practice, this seems the case since one observes that the widths measured at LEP end up evenly distributed around the SM predictions.

With similar assumptions, the following limits are obtained:

$$\Gamma_{vis} < 28\text{MeV} \quad \text{and} \quad \Gamma_{inv} < 18\text{MeV} \quad \text{for DELPHI}^{[3]}$$

$$\Gamma_{vis} < 43\text{MeV} \quad \text{and} \quad \Gamma_{inv} < 20\text{MeV} \quad \text{for ALEPH}^{[4]} .$$

The discrepancy comes from the fact that DELPHI measures a smaller, although still compatible with the SM, total width.

Table I displays the limits obtained in[3] for various new channels.

Particle type	Lower bound (GeV)
top quark	43
b′ quark	45
$L^{\pm}$	33
L^0_{Dirac}	44
L^0_{Dirac}(from Γ_{inv})	45
$L^0_{Majorana}$	38
$L^0_{Majorana}$(from Γ_{inv})	40
u − type squark (L + R)	39
d − type squark (L + R)	40
squarks (L + R) (5flavours)	44
sleptons (L + R)	22
LSP sneutrino (from Γ_{inv})	36
chargino	44
$u*$	45
$d*$	45
$L^{\pm *}$	33
$\nu*$	45

Table I : 95 % C.L. mass limits from ref.[3]

Ref.[3] gives the set of formulae used in deriving these limits. One may remark that most mass limits fall close to the kinematical limit. This is not the case for the sequential charged lepton for which the direct search limit[5] reaches

44.3 GeV. For sleptons, as well, direct searches allow to reach the kinematical limit (see 3.1).

2. Forbidden Z° decays

In this category, I consider either strictly forbidden or highly suppressed decay modes.

2.1. Photonic final states

2.1.1. Single photon

Final states with one energetic photon seen in the detector can only occur through initial radiation in the $Z^\circ \to \nu\bar{\nu}$ channel (neutrino counting reaction), or through radiative low angle Bhabha scattering $e^+e^- \to e^+e^-\gamma$. The latter is easily eliminated by requiring a photon with a transverse momentum above 5 GeV/c, which, by momentum conservation, forces at least one of the final state e^+e^- into the detector. The absence of any background above 15 GeV (as shown in figure 2) provides strong limits on the following process :

$$Z^\circ \to \nu^*\nu \text{ followed by } \nu^* \to \nu\gamma,$$

a reaction predicted in the framework of composite models (see discussion in chapter 3.2). ALEPH gives[4] BR($Z \to \nu^*\nu$) $< 2.7\ 10^{-5}$ for m_{ν^*} up to 90 GeV. Note that light excited neutrinos are pair-produced and thus excluded from indirect measurements (see Table I).

2.1.2. Two photons

The Z°, a vector state, cannot decay into two photons without violating Bose-Einstein statistics[6] . The $\pi^\circ\gamma$ state, experimentally indistinguishable from the two photon state, is expected to couple to Z° with a branching ratio which can reach 10^{-3}[7] . From the analysis of the $\gamma\gamma$ line shape, which shows no resonant contribution, the four LEP experiments already give limits below this value (see Table II).

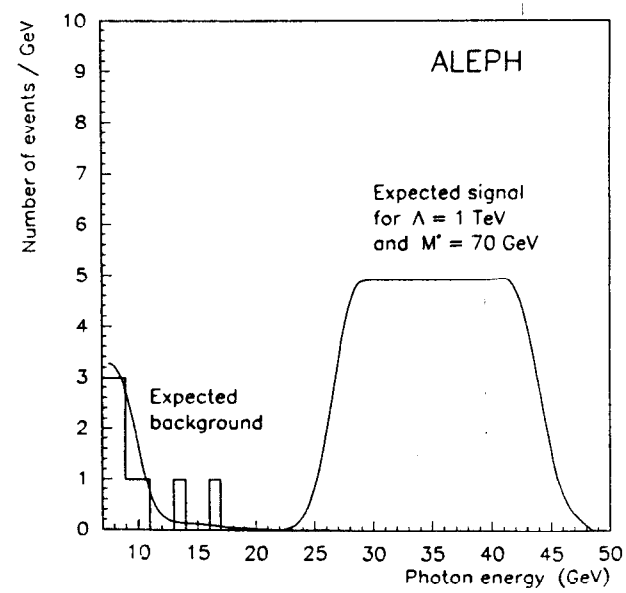


Fig. 2

Single photon energy spectrum measured in ref.[4] . The curve above 25 GeV shows the rate corresponding to a 70 GeV excited neutrino (3 flavours assumed) with a scale of compositeness of 1 TeV.

2.1.3. Three photons

The coupling to Z° is allowed at the loop level but with[8] BR($Z \to 3\gamma$) $\sim 10^{-9}$. If the Z° is composite, large BR are expected[8] :

$$BR \sim 2\ 10^{-4} < Q^6 >$$

where $< Q^6 >$ is the averaged sixth power of the charges of the constituents. The limits given in table II put significant restrictions on such theories.

	ALEPH	DELPHI	L_3	OPAL
$\pi^\circ\gamma$	9	15	24	14
3γ	2	14	5	3

Table II : 95 % C.L. limits on BR × 10^5

2.2. Lepton flavour violation (LFV)

The decay of a Z° into two different leptons is strictly forbidden in the SM. In various extensions of the SM, $Z^\circ \to \ell\ell'$ may occur with a BR at the level of 10^{-4}[9] . Stringent limits on LFV come from leptonic decays :

$$BR(\mu \to eee) < 1.10^{-12}$$

and

$$BR(\tau \to eee) < 1.310^{-5} \quad \text{From ARGUS latest}$$

$$BR(\tau \to \mu\mu\mu) < 1.310^{-5} \quad \text{updates.}^{[10]}$$

These limits can in principle be translated into limits on BR($Z \to \ell\ell'$) noting, however, that on-shell Z° decays may be sensitive to the so called "b couplings"[9] which are the tensor couplings and which are suppressed at low energy.

Experimentally the primary quality needed to separate, for instance $e\tau$ from $\tau\tau$, is energy resolution since the τ decay into $e\nu\nu$ has an end point which reaches the kinematical limit. Figure 3 shows the separation achieved by L_3 on this channel using the $\Delta E/E \sim 1\%$ resolution given by the BGO calorimeter. Table III summarizes the limits given by the four detectors together with the limits deduced from low energy measurements (ignoring the "b terms"). One remarks that LEP experiments with a small $\tau\tau$ sample have reached limits comparable to low energy data.

	$e\mu$	$e\tau$	$\mu\tau$
ALEPH[4]	2	12	10
DELPHI[15]	14	46	45
L_3[13]		3.9	5.6
OPAL[14]	4.6	7.2	35
$q^2 \sim 0$	$6\ 10^{-8}$	5.5	5.5

Table III : 95 % C.L. limits on BR × 10^5

3. Searches based on leptonic modes

In this chapter, I will describe various searches based on leptonic final states.

3.1. Two leptons with missing energy

Two acollinear leptons, with a reasonable amount of measured transverse momentum (to avoid the background from $\gamma\gamma \to \ell^+\ell^-$), and with large missing energy, would be a signal for a decay of a Z° into a pair of sleptons :

$$Z^\circ \to \tilde{\ell^+}\tilde{\ell^-} \quad \text{with} \quad \tilde{\ell^\pm} \to \ell^\pm\chi$$

where χ, the lightest SUSY particle (LSP), remains invisible.

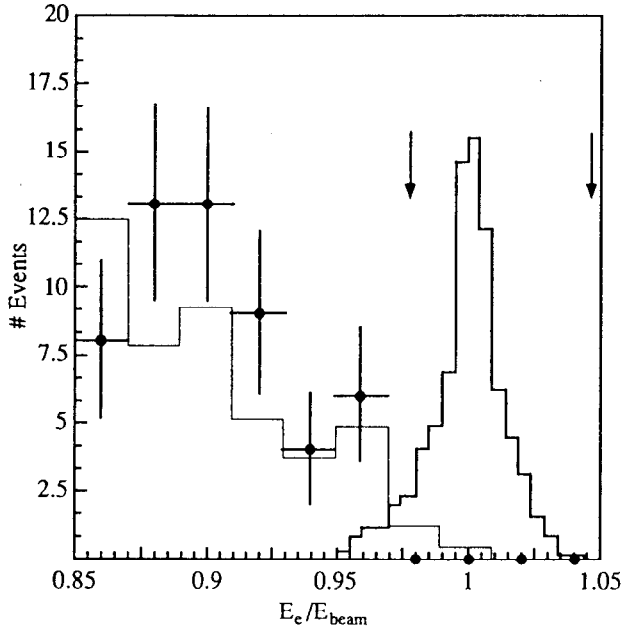


Fig. 3

Inclusive energy distribution (normalised to beam energy) of electrons associated to τ candidates measured in L3. The points with error bars are the measurements, the histogram below the points is the Monte-Carlo prediction, the histogram peaked at 1 is the shape expected for a τe signal. No candidate is left inside the cuts defined by the two arrows.

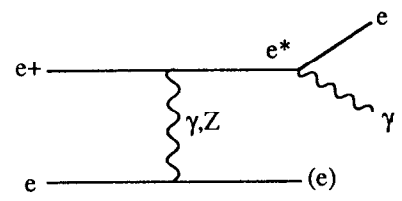
The various LEP experiments are able to exclude $\tilde{e}, \tilde{\mu}, \tilde{\tau}$ up to the kinematical limit except when $m\tilde{\ell} \sim m\tilde{\chi}$, in which case one remains with the limits given by the widths (Table 1).

3.2. Two leptons with an energetic γ

As shown in chapter 1, pair-produced excited leptons can already be excluded from the total width measurement. In composite models, one may also produce a single excited lepton in association with its standard partner. The gauge invariant effective coupling :

$$L_{eff} = \frac{e}{\Lambda}\ell^* \sigma^{\mu\nu}(c + d\gamma^5)\ell F_{\mu\nu}$$

depends on an arbitrary energy scale Λ and on two coefficients c and d. CP invariance constrains c and d to be real. In addition one often assumes c = ± d to avoid large contributions to g - 2. The relevant expressions are given in the Appendix. While $\tau*$ and $\mu*$ production proceeds primarily through the Z°, $e*$ may also be produced through the t-channel :



In this process, the spectator ($e^\pm$) travels along the beam direction and is not detected.

Experimentally one may search for an excess of events in the $\ell\ell\gamma$ topology or, better, search for a mass peak in the $\ell\gamma$ mass distribution. ALEPH[4] and DELPHI[11] have used this approach taking advantage of energy-momentum conservation to reach an excellent mass resolution :

$$\sigma_{e*} \sim \sigma_{\mu*} \sim 250 \text{ MeV in the s} - \text{channel}$$

$$\sigma_{e*} \sim 450 \text{ MeVin the t} - \text{channel}.$$

In practice, only measured angles are used, while the energies are computed through energy-momentum conservation. This method also allows to reconstruct $\tau\gamma$ masses with a resolution, $\sigma_{\tau*} = 2.5$ GeV, which reflects the uncertainty on the angle of the τ.

Examples of mass spectra are given in figure 4. No narrow structure is observed which can be translated into a limit on Λ^{-1} (or $\lambda/m*$ as defined in the appendix) below 1 TeV^{-1} for masses below 80 GeV.

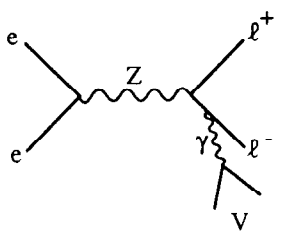
	ALEPH updated	DELPHI updated	L_3	OPAL
$\mu*, e*$	0.85	0.9	2	2.1
$e*_{tchan.}$	0.5	0.8	0.4	1.4
$\tau*$	0.7	1.2	3.0	1.4
$\nu*$	0.4		1.3	

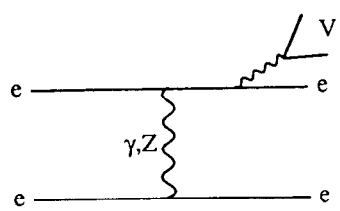
Table IV : 95 % C.L. limits on $\lambda/m*$ in TeV^{-1} for $45 < m_{\ell*} < 80$ GeV

Table IV summarizes the results of the four LEP experiments. Excited leptons and neutrinos which can be pair-poduced, as has been said, are already excluded by the width method. Direct searches have also been performed and very few candidates showing two acollinear charged leptons with two energetic and isolated photons are selected. Surprisingly, L_3 has already observed[12] one e^+e^- event with three energetic photons (respectively 18.2, 19.8 and 28.1 GeV). Since no accurate calculations are presently available, it is not possible to give a probability for such an event.

3.3. Two leptons and a virtual photon

The main processes involved are :





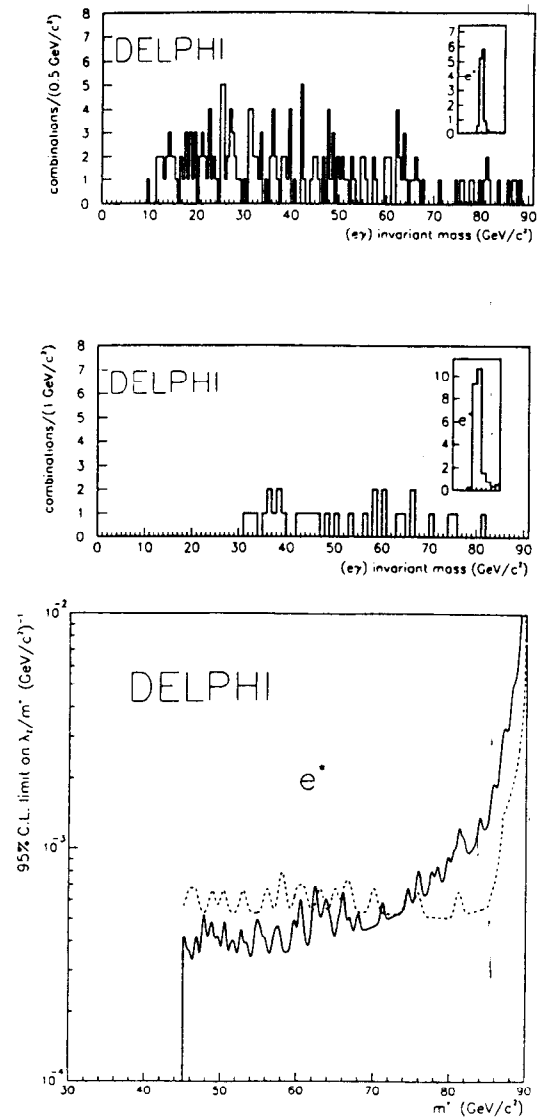
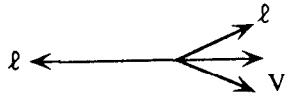


Fig. 4

Search for excited electrons in ref.[11] . The top histograms show the γe mass spectrum obtained with, respectively, two and one electron (or positron) detected. The windows give the mass spectrum shape expected for an 80 GeV excited electron. The curves give, in GeV^{-1}, the 95 % C.L. limit on λ/m_* defined in the Appendix : the dotted curve corresponds to the t-channel limit, the full curve to the s-channel.

where V is a low mass pair of leptons ($e^+e^-, \mu^+\mu^-$) or, through VDM, a light vector meson, mainly a ρ decaying into $\pi^+\pi^-$. As for a real photon, the V is preferentially emitted at small angle with respect to the leptons and appears with the following topology :



ALEPH[16] has published an analysis of this channel based on the 200k Z°'s recorded in 1989/90. Four and six charged tracks events were selected. After various selections against $\tau^+\tau^-$ events, $\ell\ell\gamma$ events with a converted photon and hadronic events, 35 candidates are left as shown in table below.

	$ee V$	$\mu\mu V$	$\tau\tau V$
seen	10	10	15
predicted	7.2	6.6	3.2

Table V: results of ALEPH 89-90

Clearly one observes a significant excess in the $\tau\tau V$ channel with respect to the prediction. Even if the absolute normalisation of the Monte Carlo is left free and assuming an uncertainty of 20 % in the relative normalisation of the $\tau\tau V$ channel, ALEPH concludes that the probability to observe such a fluctuation in any of the three channels is below 1 %.

At the Geneva Conference, three new results were reported. DELPHI,[17] using a sample which corresponds to 200k Z°'s and selecting 4 charged tracks, observes a fair agreement with predictions in the three channels (Table VI). OPAL[18] using a sample of 140k Z°'s and allowing for 6 charged tracks, observes no excess in $\tau\tau V$. Finally, with a new sample of 100k Z°'s, ALEPH[19] finds only one $\tau\tau V$ candidate. Adding up these three new sets of data, one observes no excess in the $\tau\tau V$ channel and a fair agreement with the prediction from Monte Carlo for the three channels.

	$ee V$	$\mu\mu V$	$\tau\tau V$
OPAL	10 (8.5)	8 (5.1)	5 (4.9)
DELPHI	7 (5.6)	5 (5.4)	4 (3.3)
ALEPH91	2 (4.1)	4 (3.7)	1 (1.8)
SUM	19 (18.2)	17 (14.2)	10 (10)

Table VI : ( ) → M.C. prediction

At this point, one should mention that the Monte Carlo used by the LEP collaborations only computes leptonic decays of V's, while, for V→ $\pi^+\pi^-$, the result is estimated from V→ $\mu^+\mu^-$ using the measured $e^+e^- \to \pi^+\pi^-/e^+e^- \to \mu^+\mu^-$ ratio.

The excess observed by ALEPH could be due to contaminations from $Z^\circ \to q\bar{q}$ or $Z^\circ \to \tau^+\tau^-$. The hadronic background should appear mostly in the 6-prong topology whereas, as pointed out by ALEPH, all 6-prong events have at least two leptons. The $\tau^+\tau^-$ events, with $\tau \to 3\pi$, are removed by demanding $m_{3pr} > 1.7$ GeV. This value is not conservative, however one observes that only two candidates have $1.7 < m_{3pr} < 2.5$ GeV which indicates a low dependence on this cut.

One may thus conclude that the effect observed by ALEPH seems to be a statistical fluctuation and that, based on a larger sample which includes new

data from ALEPH, there is a good agreement between data and M.C. in the $\ell\ell V$ channel.

4. Search for anomalies in hadronic channels

This chapter mainly deals with Higgs boson search. First, I will discuss the most recent results on the SM neutral Higgs boson. Then I will present the searches performed assuming the two Higgs doublet model in the most general case and in the framework of supersymmetry (MSSM)[20] . Loop corrections will be discussed.

Neutralino searches, a topic also related to MSSM, will be briefly reviewed and some conclusions drawn on the lower limit of the lightest SUSY particle (LSP).

Finally, through the analysis of hadronic channels with one isolated photon, limits will be given on composite scalars and excited quarks.

4.1. Standard Higgs searches

The dominant production mechanism leads to a Higgs boson accompanied by a virtual Z^*. For a heavy Higgs, the searches require a pair of leptons or a large missing energy signaling the decay of the Z^* into neutrinos. The $Z^\circ \to H\gamma$ mode, which has no direct coupling, gives a smaller contribution (figure 5) in the whole mass domain accessible at LEP.

The Higgs decay modes are well known except in the resonance region which extends between the muon threshold and the mass region where the partonic description applies ($\sim$ 2 GeV for light quarks). This region has already been excluded by ALEPH, DELPHI and L3 with conservative hypotheses on the Higgs decay modes. A new analysis from OPAL[21] covers all possibilities. For purely neutral Higgs decays, OPAL uses the $\nu\bar{\nu}H$ final state which, as shown in 2.1.1., is background free. For charged modes, they use e^+e^- or $\mu^+\mu^-H$ final states, which, as shown in 3.3, receives a very small background from $\ell\ell$V. This search covers, as shown in figure 6, the mass domain up to 10 GeV and thus eliminates

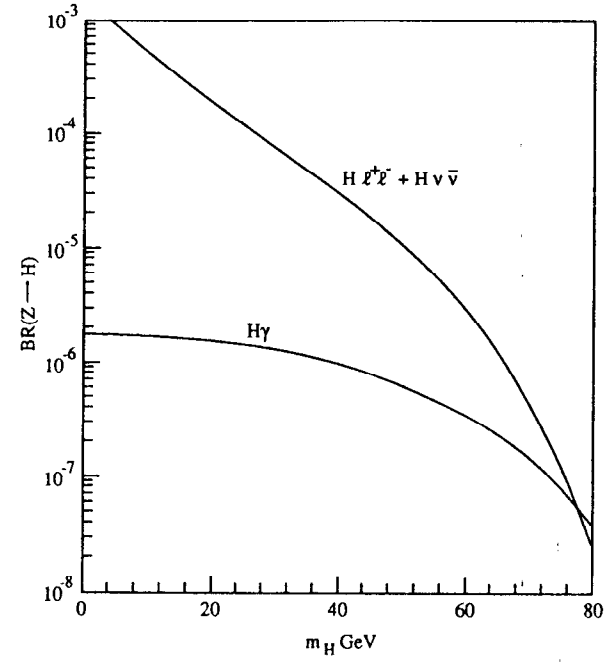


Fig. 5

Branching ratio of the Z° into Higgs and a virtual Z° decaying into neutrinos or charged leptons (upper curve) and Z° into Higgs and a photon (lower curve).

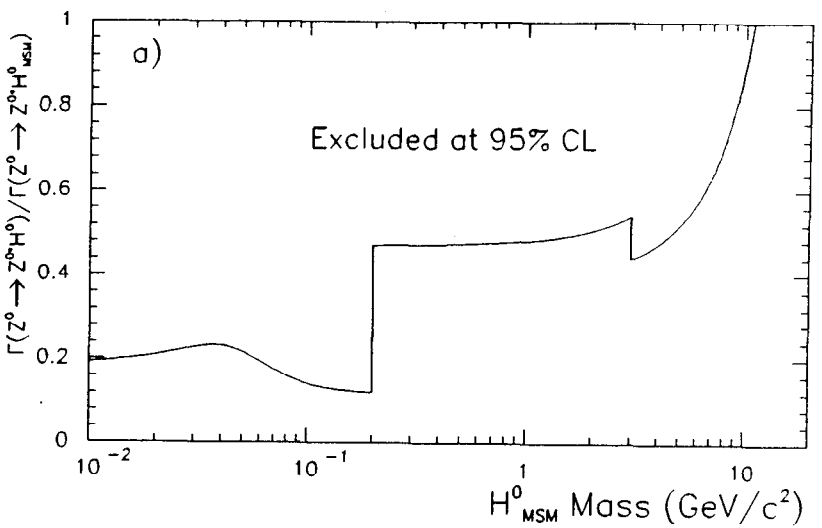


Fig. 6

Results of a decay mode independent search[21] for a light Higgs boson in the low mass range.

any possibility of a light Higgs escaping previous searches.

The heavy Higgs search is most efficiently performed with the $H\nu\bar{\nu}$ channel (19 % BR). For a hadronic decay of H, one is left with jets with large missing energy and momentum. The properties of the detector relevant to this analysis are calorimetry (only way to reconstruct the Higgs mass) and hermeticity, i.e., the absence of dead regions. At the expense of a certain loss of efficiency, one can avoid dead regions by vetoing events with the missing momentum pointing in the neighbourhood of such regions. The four experiments were able to achieve an analysis which leads to zero candidate with an efficiency ranging from 50 up to 70 %.

For the leptonic modes, the leptons may come from Z^* decays into the 3 types of leptons ($3 \times 3.$ 2 % BR) or from the decay of the Higgs itself into $\tau^+\tau^-$ ($\sim$ 6 % BR). One He^+e^- candidate from DELPHI passes the selections with $m_H = 35 \pm 5$ GeV. Table VII summarizes the results presented at the Geneva conference by the four experiments .

	Z Sample ($\rightarrow q\bar{q}$)	ϵ % $m_H = 50$ GeV	$m_H >$ GeV (95 % $C.L.$)
$ALEPH$[22]	290k	68	51
$DELPHI$[23]	210k	53	42
$L3$[24]	220k	61	47.5
$OPAL$[25]	270k	$\sim$ 48	47.3

Table VII : H^0_{SM} mass limits

Since the DELPHI candidate only affects masses below 45 GeV, one may combine the four LEP experiments[26] and reach the zero background limit (see figure 7) :

$$m_H > 57 \text{ GeV at } 95 \text{ \% } C.L.$$

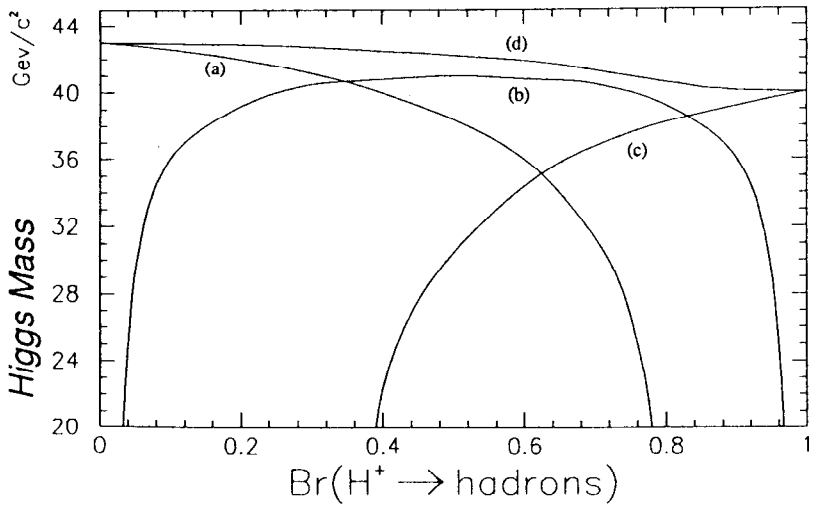


Fig. 7

Combined limits on SM Higgs searches from the four LEP experiments. The number of expected events from each experiment are added giving the upper curve which crosses the 95 % C.L. limit at 57 GeV.

4.2. Two Higgs doublet model

Two Higgs doublets are requested in supersymmetric theories which, up to now, provide the only satisfactory theoretical framework if the Higgs boson is an elementary object[20] . In such a model there are six degrees of freedom :

- Two CP even bosons h and H formed by mixing (α) the two doublet eigenstates;
- One CP odd boson A;
- A pair of charged Higgs $H^{\pm}$;
- Two vacuum expectations v_1 and v_2 with $tan\beta = v_2/v_1$.

The standard production cross section[20] for $Z^{\circ} \rightarrow Z^{*}h$ is simply multiplied by $sin^2(\alpha - \beta)$. $Z^{\circ} \rightarrow hA$ is also allowed with a cross section proportional to $cos^2(\alpha - \beta)$. The two processes are clearly complementary provided hA remains kinematically accessible (i.e., A not too heavy) and therefore one may derive limits independent of α and β. Charged Higgs bosons are pair–produced with a cross section[20] which does not depend on mixing angles and therefore LEP can give a model independent result on this channel.

4.2.1. Charged Higgs

The signature of final states only depends on the leptonic branching ratio $BR(H \rightarrow \ell\nu)$. For a heavy charged Higgs, $\ell = \tau$ should dominate but this is an unnecessary restriction since the limits given below can only improve if $\ell = e, \mu$.

If the leptonic branching ratio goes to zero, one can still reach a good sensitivity by searching for a mass accumulation in the jet–jet combinations. This standard technique, which uses energy conservation to rescale jet energies, leads to mass resolutions on $m_{H^{\pm}}$ of the order a few GeV. Searching for the various possible combinations – two leptons, one lepton plus jets, purely hadronic states – the four LEP experiments are able to give a limit independent of the leptonic branching ratio (figure 8). The most recent updates are given below (95 % C.L.

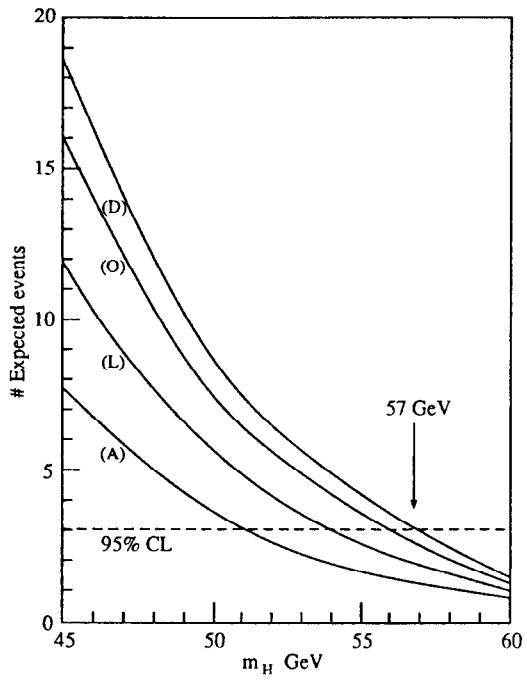


Fig. 8

Charged Higgs limits[27] for the three possible channels : purely leptonic (a), one lepton plus jets (b) and four jets (c). The resulting curve (d) is above 40 GeV for any value of the hadronic branching ratio.

limits) :

$$m_{H^\pm} > 41.7 \text{ GeV for ALEPH}^{[4]}$$

$$m_{H^\pm} > 40 \text{ GeV for DELPHI}^{[27]}.$$

4.2.2. Neutral Higgs

4.2.2.1. General case

As already pointed out, it is in principle possible to derive a model independent limit on mh combining Z^*h and hA searches. ALEPH[29] has performed this analysis assuming that $mh = mA$. The results are summarized as contours in the mh, $sin^2(\alpha - \beta)$ plane which allows to clearly visualize the complementarity of the two analyses (figure 9). Note also that the limit derived on hA using the widths is sufficiently good to complement hZ^* up to $mh = 25$ GeV so that the direct hA reach is only relevant for heavy h where the search proceeds as for H^+H^-. Assuming $mh = mA$, ALEPH excludes the mass domain $2m_\mu < mh < 43.4$ GeV at 95 % $C.L.$

If $mh \neq mA$, extended searches are needed, in particular including the possibility that $h \to 2A$. One should also not forget that the model independent approach completely fails if mA is too heavy to allow $Z^\circ \to hA$.

4.2.2.2. Supersymmetric Higgs

In a supersymmetric scenario[20] one may restrict considerably the range of possibilities on the six parameters and thus derive definite limits. At the tree level, one is left with two independent parameters, e.g., mh and $tan\beta$ or mh and mA. In addition one has :

$$mh < M_Z|cos2\beta|$$

$$mh < mA$$

which imply that the h should be lighter than the Z° and that $h \to 2A$ is a closed channel. The most natural possibility[20] is $tan\beta > 1$, which implies that h and A decay primarily into $\tau\tau$ and $b\bar{b}$. This clear scenario, considered in the previous

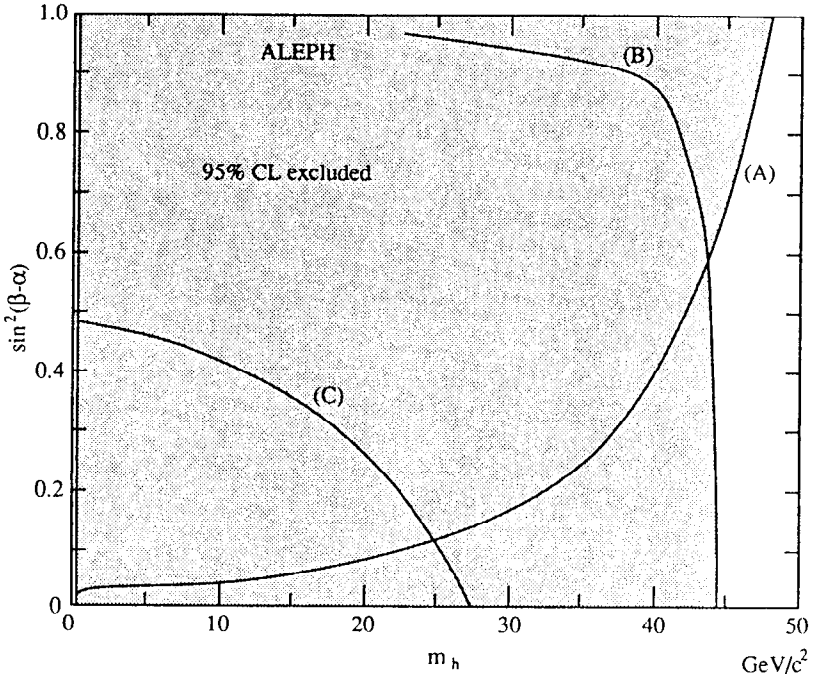


Fig. 9

Neutral Higgs limits[29] in a two doublet model in terms of $sin^2(\alpha-\beta)$ and mh assuming that $mA = mh$. Curve (A) is the 95 % C.L. contour limit given by the hZ^* search, curve (B) is given the hA search for heavy Higgs bosons and (C) is obtained from the total width limit.

previous analyses of LEP data, is considerably modified when one takes into account loop corrections[28] . Due to the heavy top, the CP even mass term receives a very large correction which can, approximately, be written as :

$$\delta m^2 h \sim m^2 t \left(\frac{m_t}{630 \text{ GeV}}\right)^2 \ell n \left(\frac{m\tilde{t}^2}{mt^2}\right)$$

where mt and $m\tilde{t}$ are, respectively, the top and the squark mass. With mt = 135 GeV and $m\tilde{t}$ = 1 TeV, one gets : δmh^2 = (58 GeV)^2. This effect implies that the h can be heavier than the Z° such that $Z^* \rightarrow hZ$ becomes inacessible even at LEP200. It also implies that h can be heavier than A, and thus $h \rightarrow 2A$, a decay mode not considered so far , becomes possible.

To illustrate, schematically, the change occurring through this loop effect, one can draw, in the mh, mA plane, the allowed regions for both situations (figure 10). Figure 10b can be intuitively understood by saying that the $mA = 0$ axis is unaffected by loop corrections while the $mh = 0$ axis (which also corresponds to $tan\beta = 1$) is moved by δmh^2 (a more accurate approximation is $\delta mh^2(1 - \delta mh^2/M_Z^2)$). The maximal value for mh^2, M_Z^2 at the tree level approximation, similarly moves by δmh^2. For a light h, below a mass of about 50 GeV, the allowed domain corresponds to $mh > mA$ (up to now only the opposite has been assumed !) with the possibility that $h \rightarrow 2A$. For a heavier h, one recovers the standard situation $mh < mA$ and there is an upper bound on mh which moves to 110 GeV for mt = 140 GeV.

The four LEP experiments have analyzed these data taking into account the loop correction. ALEPH[29] has given results both in terms of mh, mA and $tan\beta$, mA. Only the $tan\beta > 1$ case is considered and the decay $h \rightarrow 2A$ is taken into account both for hZ^* and hA final states. The results are shown in figure 11 where the forbidden zone is shown for a given value of the top mass (mt = 140 GeV and $m\tilde{t}$ = 1 TeV). The (A) and (B) exclusion contours are model independent (cf 4.2.2.1.) and simply obtained by combining Z^*h and hA processes. The hatched contours, which give the highest exclusion limit on mh and mA, are model dependent in the sense that they use the MSSM formulae

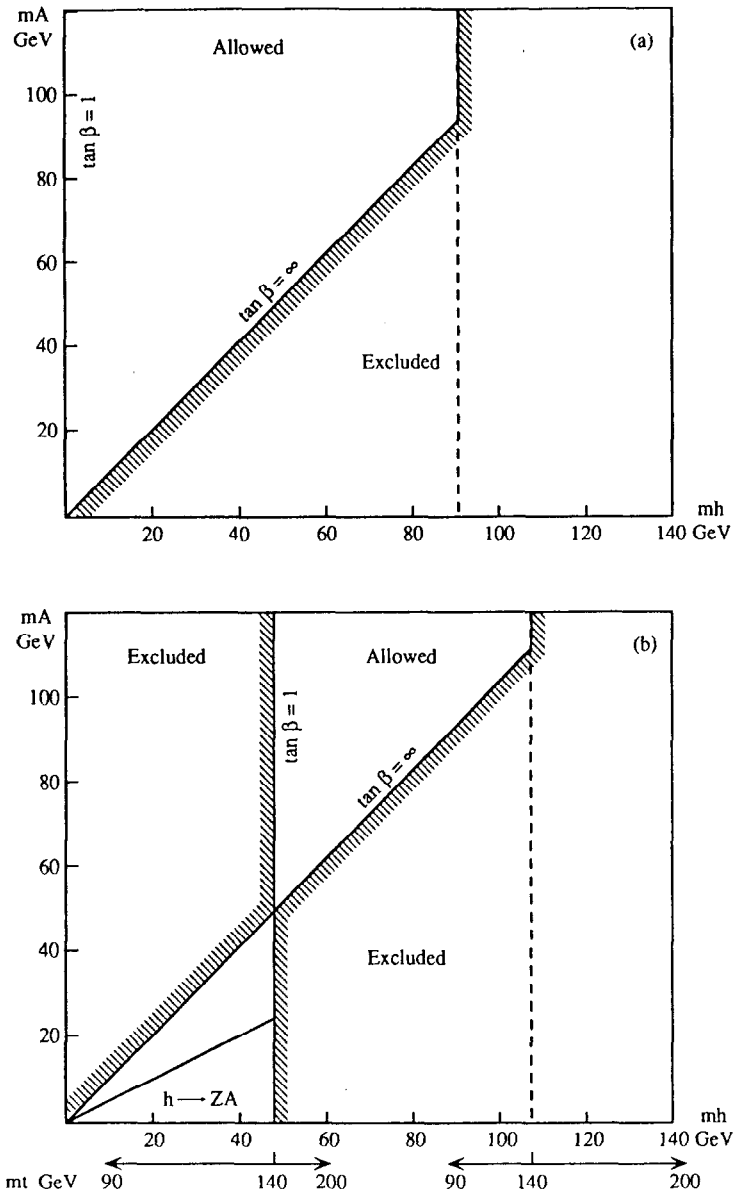


Fig. 10

Schematic description in the mA, mh plane of the theoretically allowed areas in the MSSM model. Figure 10a is valid at the tree level, while figure 10b takes into account the loop corrections. The dependence on the top mass of the $tan\beta = 1$ axis and of the upper limit on mh are indicated. The squark mass is fixed at 1 TeV.

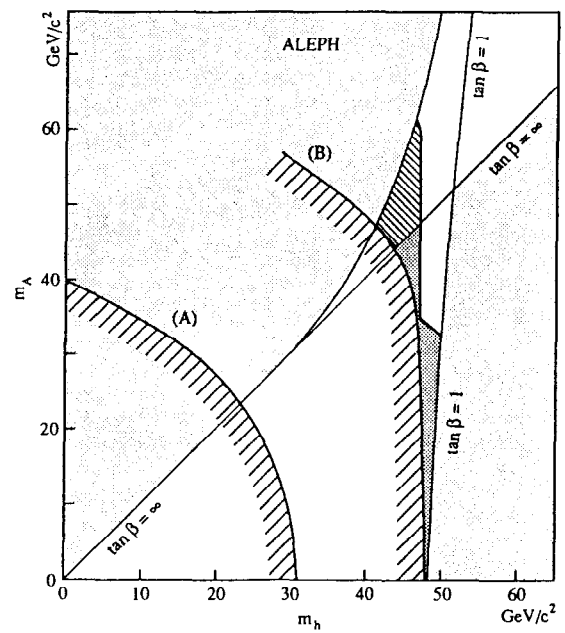


Fig. 11

Results from ref.[29] on neutral Higgs bosons in terms of mh and mA, for $tan\beta > 1$. Curve (A) defines an exclusion contour derived using the hZ^* channel searches and the width limit, curve (B) combines the hZ^* and hA searches. The theoretically forbidden zones, in light gray, are obtained with a top mass of 140 GeV and a squark mass of 1 TeV. Assuming MSSM, the dark region is also excluded while the hatched area is only excluded if the lower solution is taken for $tan\beta$.

to compute the cross-sections. For the given choice of mt and $m\tilde{t}$:

$$mh > 46 \text{ GeV}$$

$$mA > 44 \text{ GeV}.$$

The limit on mh is quite insensitive to the choice of mt and $m\tilde{t}$. For the worse case one gets :

$$mh > 41 \text{ GeV}.$$

The limit on mA is very sensitive to mt :

$$mA > 44 \text{ GeV} \qquad mt = 140 \text{ GeV}$$

$$mA > 20 \text{ GeV} \qquad mt = 200 \text{ GeV}.$$

DELPHI[30] has given results in terms of $tan\beta$ and mA. The decay $h \rightarrow 2A$ is taken into account for the hA channel only. The weak dependence on mt and $m\tilde{t}$ of the limit on mh is well illustrated in figure 12.

OPAL[31] and L3[24] have not yet included the decay $h \rightarrow 2A$ in their searches. In figure 13 , OPAL results are given in the mh, mA plane both for $tan\beta > 1$ and $tan\beta < 1$. The forbidden regions are obtained by varying mt and $m\tilde{t}$ in a domain consistent with present experimental limits and theoretical prejudices.

SUMMARY

- There is no model independent limit in the two doublet model. One can only say that assuming $mh = mA$, then $mh < 43$ GeV is excluded (but there could still be a very light Higgs with a mass below the muon threshold).
- In the framework of minimal SUSY and taking into account loop corrections $mh > 41$ GeV. The bound on mA varies from 44 GeV at $mt = 140$ GeV to 20 GeV at $mt = 200$ GeV.
- There is no limit on $tan\beta$, that is $tan\beta = 1$ is allowed (see figure 11). At the tree level the inequality $|cos2\beta| > \frac{mh}{m_Z}$ gave a bound on $tan\beta$ (e.g., 40 GeV $\rightarrow tan\beta > 1.6$). With the available data, one can no more set a limit on $tan\beta$ when the loop corrections are included.

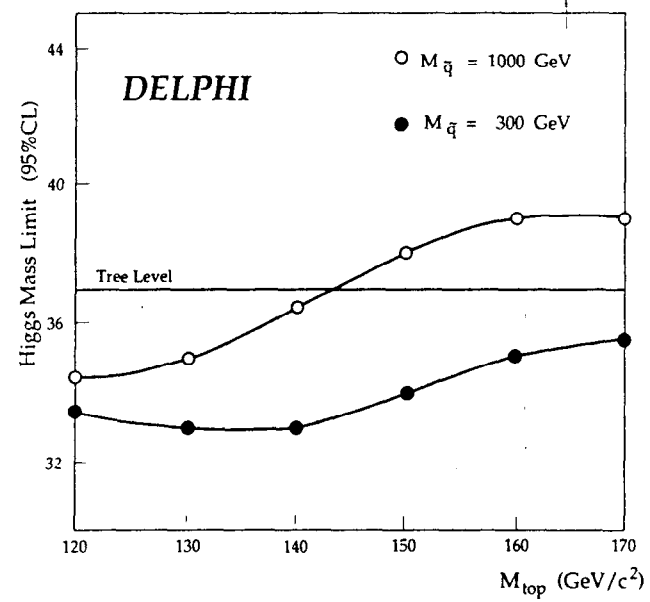


Fig. 12

Higgs boson h mass limits[30] versus the top mass in the MSSM model with loops. The two curves are given for squark masses of 1000 GeV and 300 GeV.

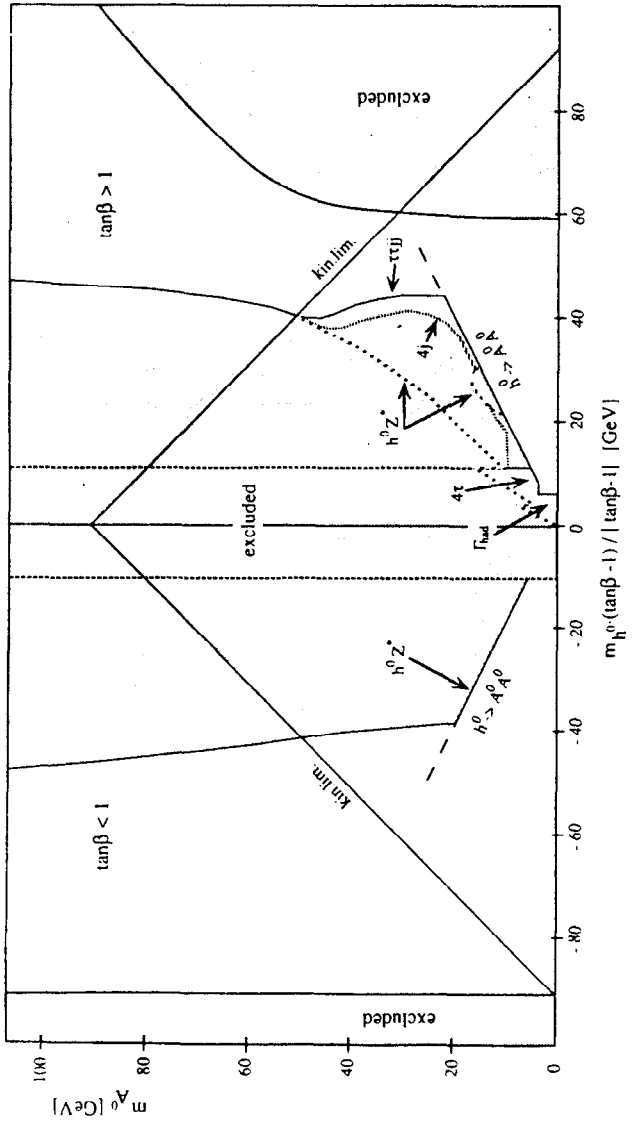


Fig. 13

Results from ref.[31] on neutral Higgs bosons in terms of mh and mA, for $tan\beta > 1$ (right-handside plot) and for $tan\beta < 1$ (left-handside plot). Theoretically excluded zones are given using expected ranges for the top and squark masses. Exclusion contours coming from hZ^*, hA and the hadronic width limit are indicated.

– For the preferred mt value, $\sim$ 135 GeV, the upper bound on mh only moves by 20 % with the loop corrections, which means that LEP200 may be able to reach this value and disprove (or...) the MSSM model.

4.3. Search for neutralinos

In supersymmetry γ, Z°, h and H have four fermionic partners which give rise, through mixing, to the four physical states χ, χ'... called neutralinos. χ, the lightest neutralino, is presumably the lightest SUSY particle (LSP) and should be stable (R parity conservation). The coupling of the Z° to neutralinos depends on mixing angles which, in SUSY, are related to two mass parameters M and μ and to $tan\beta$[32] .

Through direct searches, which exclude $Z^\circ \to \chi\chi'$ at the level of a few 10^{-5}, and through the widths limits, it is possible to exclude a wide set of parameters for μ and M. ALEPH[4] and DELPHI[30] have recently published some updates on these searches. A very light LSP, a possible dark matter candidate, cannot be excluded in the absence of any bound on $tan\beta$ (figure 14). One can thus conclude that the two searches are tightly connected and that only a better bound of mh will allow us to draw a clear conclusion on m_{LSP}.

4.4. Hadronic states with isolated photons

In close analogy with the leptonic states described in 3.2., one may search for $q\bar{q}\gamma$ states with the restriction that the γ be well isolated from the hadronic jets. Such selections keep about one $^\circ/_{\circ\circ}$ of the hadronic events thus allowing a good sensitivity to new phenomena.

4.4.1. Search for a new scalar

If the Z° is composite, there may be a lighter scalar particle Y with the radiative transition $Z^\circ \to Y\gamma$. The rate will however depend on an unknown coupling.[8] DELPHI[33] and L3[13] have searched for narrow peaks in the photon energy distribution and reached limits of $\sim$ 3 10^{-4} on $BR(Z \to Y\gamma)$. These

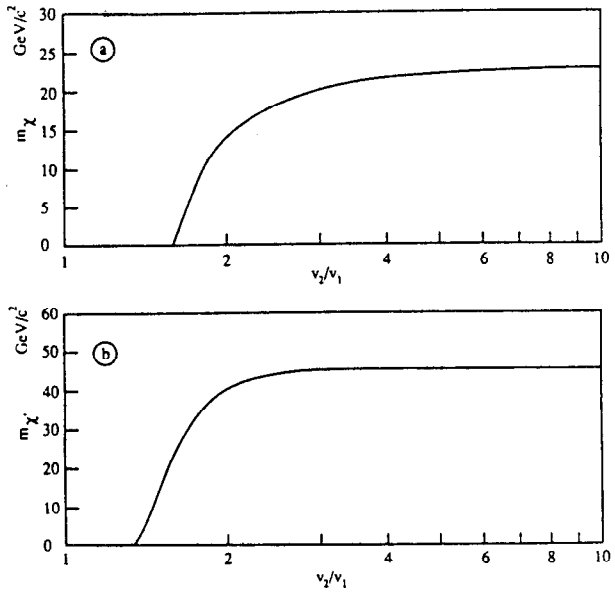


Fig. 14

Neutralino mass limits[4] derived in terms of $tan\beta$. Figure (a) is for the lightest neutralino χ, figure (b) is for the next to lightest neutralino χ'.

results are shown in figure 15. The predicted rate for $Z^\circ \rightarrow H\gamma$ is two orders of magnitude below the present limit for $m_H \sim 40$ GeV. Increase in statistics will not allow to improve very efficiently this result since, as shown in figure 16, the background is already non negligible. Note however that the mass window taken by L3, which reflects the energy resolution of the photon, corresponds to $\pm\ 3\sigma$ ($\sigma \sim 0.8$ GeV at 40 GeV). This conservative choice was intended to allow for a Y with a finite mass width but is not necessary for the $H\gamma$ channel.

4.4.2. Search for excited quarks

In complete analogy with excited leptons, one may search for excited quarks (see Appendix). Pair-produced excited quarks are already excluded up to the kinematical limit (see table I). Single production of excited quarks can be searched for by using the technique described in 3.2 . Forcing the jet algorithm to reconstruct two jets, one can estimate the direction of the two quarks. The energies are obtained by imposing momentum energy conservation. This technique was used by DELPHI[34] and L3[13] . In the case of an up quark (which, according to the Appendix, corresponds to the smallest rate) one obtains the following limits (assuming $45 < m_{q^*} < 80$ GeV).

	ALEPH[4]	DELPHI[34]	L3[13]
λ/m_{u*} TeV^{-1}	2.7	1.4	1.5

Table VIII : 95 % C.L. on λ/m_{u*} in TeV^{-1} for $45 < m_{q^*} < 80$ GeV

These results are obtained assuming[8] that $q* \rightarrow q\gamma$ in 8 % of the cases (the rest being $q* \rightarrow qg$).

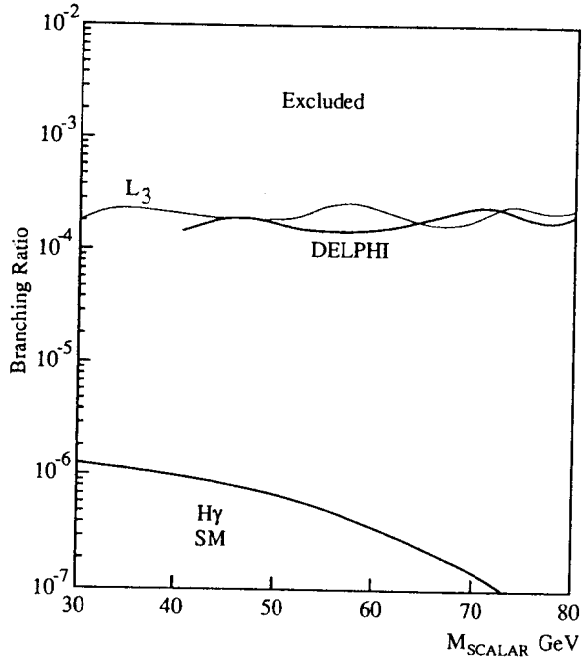


Fig. 15

Upper limits[33,13] on BR($Z^\circ \to Y\gamma$), where Y is a narrow scalar resonance decaying into quark pairs. The lowest curve indicates the expectation for a SM Higgs boson.

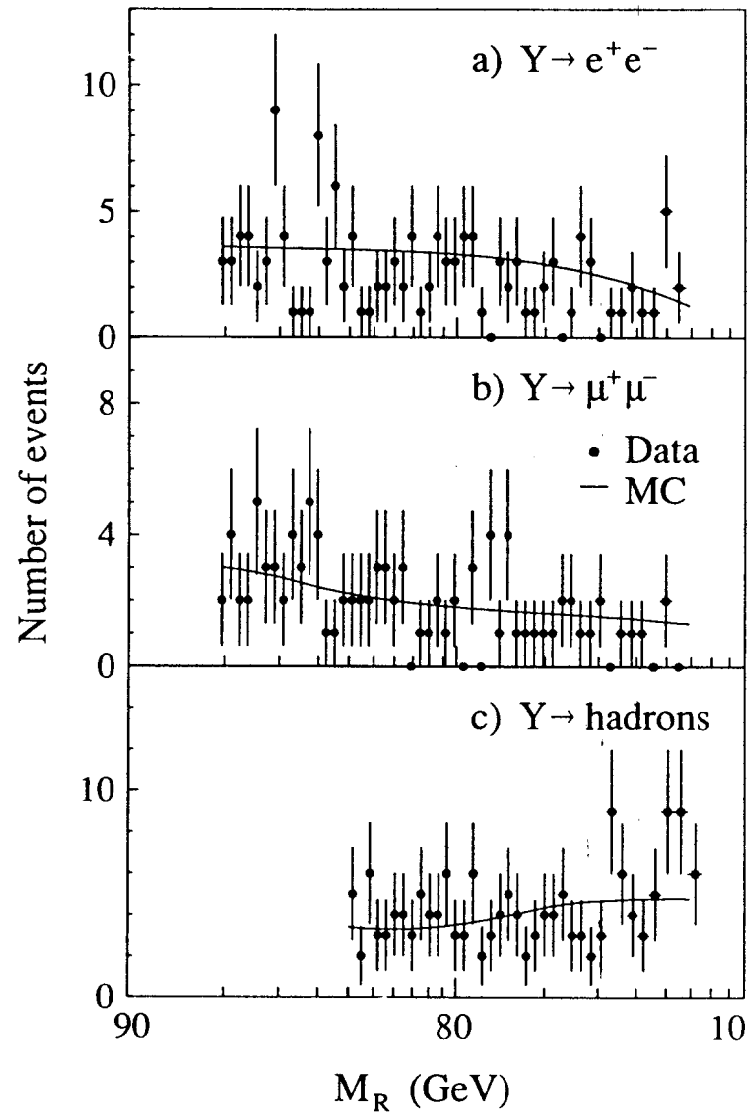


Fig. 16

Measured mass spectra[13] for $Z^\circ \to Y\gamma$, where Y is a narrow scalar resonance decaying into e^+e^- (a), $\mu^+\mu^-$ (b), or quark pairs (c).

SUMMARY AND CONCLUSIONS

1. Higgs and SUSY

The SM Higgs is excluded, at 95 % C.L., up to 57 GeV by combining the 4 LEP experiments (up to 51 GeV if one takes the best result).

In the Minimal Supersymmetric extension of the SM, which corresponds to the two Higgs doublet scenario, one can exclude the lightest CP even Higgs up to 41 GeV, taking into account loop corrections. The CP odd Higgs A is most likely ($mt < 200$ GeV) heavier than 20 GeV. $tan\beta$=1 cannot be excluded. All SUSY particles are excluded up to the kinematical limit ($\sim$ 45 GeV) except neutralinos. If $tan\beta \sim 1$, there is no lower limit on the mass of the lightest neutralino (LSP).

2. Compositeness

Excited fermions are excluded up to 45 GeV from the total width limit. Single production of excited fermions is excluded up to 80 GeV if the composite energy scale is below 1 TeV.

A composite Z° into 3γ is excluded, at 95 % C.L., down to a BR of 2 10^{-5}; if it decays radiatively into a scalar Y, the limit becomes 3 10^{-4}.

3. Rare decays

$Z^\circ \rightarrow \pi^\circ\gamma$ is not found which sets an upper limit on the BR at 10^{-4}.

Flavour changing neutral currents have an upper limit on BR of 5 10^{-5} in the $\ell\tau$ mode.

Many searches are now energy limited and can only significantly progress with the advent of LEP200. In the meanwhile, more work can be done on rare Z° decays where LEP provides an exceptionally clean environment (e.g., lepton flavour violation, 3 γ modes). For Higgs searches, new theoretical results have created a certain turmoil not yet settled at the experimental level. More work is needed to reach a less model dependent result (e.g. $h \rightarrow 2A$ or $tan\beta < 1$). This example demonstrates the need for very open-minded searches making full use of the high potential of LEP detectors.

Acknowledgements

I wish to thank the four LEP collaborations for kindly providing their latest results with very helpful explanations.

APPENDIX

In the effective coupling of Z° to $\ell^*\ell$ introduced in 3.2. :

$$L_{eff} = \frac{e}{\Lambda}\ell^*\sigma^{\mu\nu}(c_Z + d_Z\gamma^5)\ell F_{\mu\nu} .$$

c_Z and d_Z can be decomposed into the SU(2) (f) and U(1) (f') contributions :

$$c_Z = -\frac{1}{4}(f cot\theta_W - Y f' tg\theta_W)$$

and one usually takes $f = f'$. Y is the hypercharge of the excited fermion :

$$Y = \pm 1 \text{ for } \ell^* \text{ and } \nu^*,\ Y = \pm\frac{1}{3} \text{ for } u^* \text{ and } d^* .$$

At the Z° pole, the partial width for $Z^\circ \to f^*\bar{f}$ is :

$$\Gamma_{f^*f} = \alpha\frac{f^2}{\Lambda^2}\, m_Z{}^3\, \frac{N_C}{3}\, (c_Z^2 + d_Z^2)(1-x)^2(1+2x)$$

where $x = \frac{m_{f^*}{}^2}{m_Z{}^2}$ and N_C is the color factor for excited quarks. Limits on the f^*f process are usually translated into a limit on f/Λ (remember one assumes $f = f'$). At PEP/PETRA the limits on compositeness are usually given in terms of a coupling term λ_γ/m^*. Both definitions are consistent provided one takes :

$$\lambda/m^* = f/\sqrt{2}\,\Lambda .$$

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