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THE SEARCH FOR NEW PHYSICS AT LEP*

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1. Introduction

Since beginning operation in 1989, the LEP accelerator has provided a wealth of physics through copious production of Z bosons at c.m. energies near 91 GeV. Much effort has gone into precise measurements of electroweak parameters and into the study of heavy quark properties, especially b quark decays [1].

In parallel with these measurements and tests of conventional theory, LEP physicists have also searched for evidence of new phenomena in the form of new particles and unexpected Z decays. There have been searches for particles produced singly or in pairs, including a host of postulated supersymmetric partners of conventional partices and including of course the Higgs boson(s), as predicted in the Standard Model and its many considered extensions. Searches have also been carried out for rare or strictly forbidden Z decays. A handful of unusual events have been found, which are marginally consistent with rare Standard Model backgrounds. These events more than likely provide object lessons in the hazards of low statistics, but, if we are lucky, they may point the way to an interesting future. That future will include operation at higher energies, above the threshold for W^+W^- production, where one can search for more massive particles and begin seriously to constrain supersymmetric theories.

This article is organized as follows. Section 2 briefly summarizes the status of searches for new pair-produced particles, for which cross sections are typically well defined. Consequently, unambiguous mass limits can usually be determined, limits bounded roughly by the beam energy. Section 3 discusses searches for new particles produced together with a light, conventional partner, where cross sections depend on unknown mixing parameters, but where the mass reach of searches can extend well beyond the beam energy. Section 4 describes in more detail searches for supersymmetric particles, especially gauginos. Section 5 considers the continuing search for the Higgs boson(s), as expected in both the Standard Model and many extensions, in particular, minimal supersymmetry. Section 6 describes searches for exotic (a.k.a. miscellaneous) new phenomena, including monopoles, free quarks, rare Z decays, CP violation, and contact interactions. Section 7 discusses two unexpected apparent anomalies that each excited attention for a while, but which now appear to have arisen from statistical fluctuations. Section 8 concludes with a brief consideration of the outlook for the future at LEP 200.

This article emphasizes *direct* searches for new phenomena. One can also obtain useful limits on new processes through indirect means. For example, for

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particles that are difficult to detect, such as new stable neutrinos, or which lead to final states nearly indistinguishable from conventional Z decays, limits on deviations of the measured partial and total decay widths of the Z from expectation constrain the allowed production of new particles. Most notably, limits on the so-called invisible width of the Z, presumed to arise only from decays to the three known neutrino families, preclude not only a fourth generation of light neutrinos, but other potential contributions, such as from sneutrinos.

Other indirect limits come from comparison of the Z line shape and the fermion-antifermion asymmetries measured in Z decays with expectation from the Standard Model. These comparisons allow limits to be placed, for example, on the top quark mass (and in principle on the Higgs mass). Limits can also be placed on couplings and masses of a higher mass Z′ and on theories of Technicolor. Such indirect constraints are considered in detail by Langacker [2].

For lack of space, the four major LEP experiments will not be described in detail here. All are reasonably hermetic 4π general-purpose, cylindricially symmetric detectors. Each detects charged particles with inner tracking devices surrounding the beam pipe and immersed in a solenoidal magnetic field. An electromagnetic calorimeter envelops the tracking detectors and is in turn surrounded by a hadronic calorimeter. Beyond the hadronic calorimeter are detectors for escaping muons. Much more detail may be found in [3, 4, 5, 6]. As of the end of 1992, each of the four detectors had collected more than 10^6 hadronic and leptonic Z decays, from an integrated luminosity of about 40 pb^{-1} at c.m. energies near the Z resonance.

2. Pair Production

The Z boson has the virtue of coupling to nearly every known elementary particle, and in most plausible extensions of the standard model, the Z also couples to predicted new particles, often with a well defined strength. In particular, the expected rate of pair production of a new particle via Z decay is typically well known given a hypothetical mass. Moreover, that rate is typically large for masses not too close to the beam energy, where limited phase space suppresses production. The result is that for many pair production searches, one can place limits on the mass that approach or exceed the mean beam energy. Table 1 presents lower limits (95% C.L.) on mass of a variety of new particles expected in modest extensions of the Standard Model. These are new heavy quarks and charged or neutral leptons. Limits on the top quark mass are given only for completeness; searches at the Tevatron provide much better sensitivity. Table 2 shows 95% CL lower limits on masses of excited fermions. Table 3 shows similar limits for supersymmetric particles (discussed further in section 4). Table 4 gives limits on charged Higgs masses (discussed further in section 5) and on masses of leptoquarks of various charge/generation assignments.

3. Singlet Production with Conventional Partner

The mass limits based on direct searches for pair-produced particles are limited to values near the beam energy. It is possible to extend the mass reach,

Table 1: Lower limits (95% CL) on mass (GeV) for various conventional particles that would be pair produced in Z decays. The limits shown in this and the following tables are from *direct* searches only. In some cases, slightly more stringent lower limits may be derived indirectly from comparison of the Z total and partial widths with expectation within the Standard Model.

Particle	ALEPH [7]	DELPHI [8, 9]	L3 [10]	OPAL [11, 12, 13, 14]
t	45.8	44.0	—	44.5
b'	46.0	44.5	—	45.2
$L^{\pm}$ (stable)	—	—	44.6	42.8
$L^{\pm}$ (unstable)	—	—	44.3	44.3
L^0 (Dirac)	42.7	—	46.4	45.7
L^0 (Majorana)	—	38.2	45.1	—

Table 2: Lower limits (95% CL) on mass (GeV) for various excited fermions that would be pair produced in Z decays.

Particle	ALEPH [15]	DELPHI [16]	L3 [17, 18, 19]	OPAL [20]
e^*	46.1	45.6	45.6	44.9
μ^*	46.1	45.6	45.6	44.9
τ^*	46.0	45.3	45.6	44.9
ν^*	47	—	—	—
q^*	45	—	45	—

Table 3: Lower limits (95% CL) on mass (GeV) for various supersymmetric particles that would be pair produced in Z decays.

Particle	ALEPH [15]	DELPHI [21, 22, 23, 24, 25]	L3 [26, 17]	OPAL [27]
$\chi_1^{\pm}$	45.2	45	44†	45
$\tilde{e}$	45	44	46	43.4
$\tilde{\mu}$	45	44	46	43.0
$\tilde{\tau}$	45	44	46	43.0
$\tilde{\ell}$(stable)	—	40	—	—
$\tilde{d}$	—	42	—	—
$\tilde{u}$	—	43	—	—
$\tilde{t}$	—	37	—	—

† Assumes $\chi_1^{\pm} \equiv W^{\pm}$.

Table 4: Lower limits (95% CL) on mass (GeV) for various singly and doubly charged Higgs bosons and for leptoquarks D_i of different electric charge where i refers to the fermion generation to which the leptoquark couples.

Particle	ALEPH [15]	DELPHI [28, 29]	L3 [30, 31]	OPAL [32, 33, 34]
$H^{\pm}$	41.7	37	36.5	35
$H^{\pm\pm}$	—	—	—	45.6
$D_1\,(Q=-\frac{1}{3})$	44	42	43.2	44.2
$D_2\,(Q=-\frac{1}{3})$	44	42	43.4	44.2
$D_3\,(Q=-\frac{1}{3})$	45	42	—	41.4
$D_1\,(Q=+\frac{2}{3})$	—	42	44.6	—
$D_2\,(Q=+\frac{2}{3})$	—	42	44.7	—
$D_3\,(Q=+\frac{2}{3})$	—	42	41.6	—
$D_1\,(Q=-\frac{4}{3})$	—	—	—	45.5
$D_2\,(Q=-\frac{4}{3})$	—	—	—	45.5
$D_3\,(Q=-\frac{4}{3})$	—	—	—	43.3

however, by looking for a new particle that can be produced together with a lighter conventional partner. An excited charged lepton, for example, may well be produced together with its ground-state partner with a coupling strength parametrized at the $\ell^{\pm *}$–$\ell^{\pm}$–(Z,γ) vertex by g/Λ, where Λ characterizes the scale of compositeness. One event signature is pair production of charged leptons accompanied by an energetic isolated photon emitted in the excited lepton decay $\ell^{\pm *} \to \ell^{\pm}\gamma$. For e^* there is also t-channel production of $(e)e\gamma$ where one electron is lost along the beam direction. Distortions in the angular distribution of $\gamma\gamma$ final states can also indicate t-channel exchange of e^*. Using all of these signatures, the ALEPH[15] experiment finds limits $[O(10^{-4})\ \mathrm{GeV}^{-1}]$ on g/Λ for m_{ℓ^*} well above the beam energy. The other three LEP experiments have found similar results [16, 35, 20]. One can also search for single excited neutrino production, where the nominal signature is a single energetic photon in the detector from $\nu^* \to \nu\gamma$ decay. ALEPH[36] and L3[18] have searched without success for such events and consequently place limits on the coupling strength for ν^*–ν–Z comparable to those for $\ell^{\pm *}$–$\ell^{\pm}$–Z. These limits assume $\mathrm{B}(\nu^* \to \nu\gamma) \approx 100\%$. The L3 experiment has relaxed this requirement and also searched for $\nu^* \to \ell^{\pm}W^{\mp}$ decay. The energetic single photon signature has also been used to search for neutralinos (ALEPH[15], OPAL[37]), a composite Z(L3[38]), and a superlight gravitino (L3[38]).

The OPAL[14] and L3[39] experiments have searched for single production of an unstable isosinglet neutral heavy lepton (INHL) accompanied by a conventional light neutrino. These searches are complicated by the many possible charged- and neutral-current decay modes one must consider for the INHL and by the strong dependence of the difference signatures on the assumed INHL mass. The recent L3 results, based on data taken through the end of 1992 imply upper limits smaller

Table 5: Expected fermions and bosons expected in minimal supersymmetric theories.

Conventional Particles	Supersymmetric Partners	
$\ell_L^\pm, \ell_R^\pm$	$\tilde{\ell}_L^\pm, \tilde{\ell}_R^\pm$	Charged Sleptons
ν_L	$\tilde{\nu}_L$	Sneutrinos
q_L, q_R	$\tilde{q}_L, \tilde{q}_R$	Squarks
g	$\tilde{g}$	Gluino
γ, Z, h^0, A^0	$\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$	Neutralinos (mixed states)
$W^\pm, H^\pm$	$\chi_1^\pm, \chi_2^\pm$	Charginos (mixed states)

than $O(10^{-4})$ on $|U_\ell|^2$ for $\approx$3 GeV $< M_L <$ $\approx$50 GeV, where U_ℓ is the effective mixing parameter between L and ν_ℓ for $\ell = e, \mu, \tau$. Upper limits on $U_\ell|^2$ smaller than $O(10^{-3})$ persist for M_L as high as $\approx$70 GeV.

4. Supersymmetric Particle Searches (non-Higgs)

According to supersymmetry theory (see, *e.g.*, [40]), every known elementary particle has a supersymmetric partner with identical quantum numbers except for intrinsic spin, which differs by half of a unit. Masses differ too, of course, the difference depending on the energy scale at which supersymmetry is broken. Unfortunately, the predicted masses of supersymmetry particles (sparticles) depend on unknown parameters, such as μ, which characterizes the Higgs mass scale, $\tan\beta$ which gives the ratio of vacuum expectation values of the Higgs doublet, and M_i ($i = 1, 2, 3$), the unbroken gaugino masses. Depending upon the author, additional constraints, such as equality of the M_i at the grand unification scale, may be applied to yield "Minimal SUSY." One fairly strong theoretical prejudice is the expectation that $\tan\beta > 1$, given the apparently large ratio of top quark to bottom quark masses. At least at tree-level, there are also strong constraints on allowed Higgs masses, as described in section 5.

Table 5 lists conventional particles and their partners. Some of these, such as sleptons and charginos would be pair produced copiously in Z decay if light enough, giving distinct event signatures. Thus they have been excluded for masses below $\approx M_Z/2$, as shown in table 3. If light enough, sneutrinos would also be pair produced but if the sneutrino were the lightest supersymmetric particle (LSP) and R-parity were conserved, the final state would be invisible. One could look for the final state of a single photon, as has been done for neutrino counting, but a more powerful limit can be derived from combined fits to line shape parameters that constrain the "invisible" Z decay width. The most recent measurements of electroweak parameters[1] yield $m_{\tilde{\nu}} > 43$ GeV.

In general, neutralinos are far more difficult to exclude than charginos, not only because the final state may well be invisible, but also because the couplings to the Z are not known, as the expected four neutralino eigenstates ($\chi_i^0, i = 1, 2, 3, 4$) are unknown mixtures of $\tilde{\gamma}, \tilde{Z}, \tilde{H}_1, \tilde{H}_2$. In particular the Z–$\tilde{\gamma}$–γ coupling vanishes,

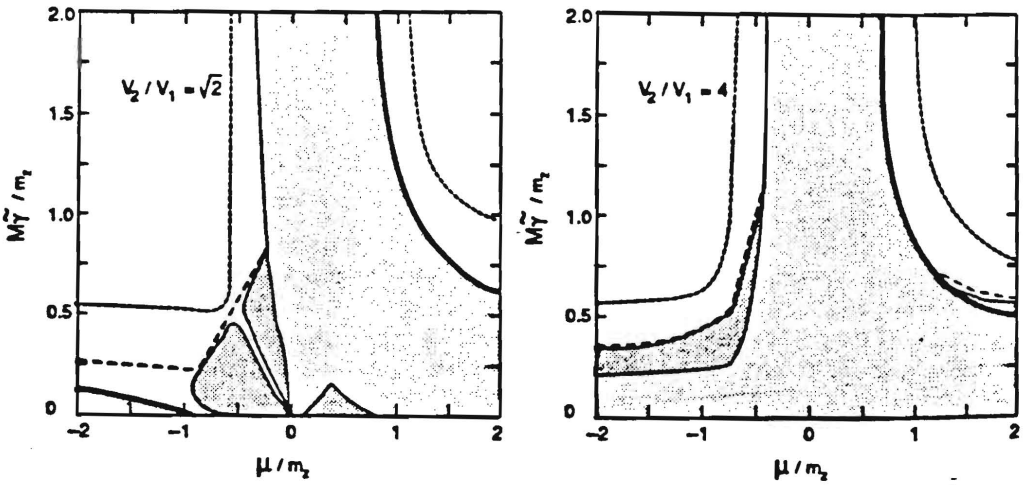

Figure 1: Regions excluded by ALEPH in the plane of photino mass (defined as appropriate mixture of χ_i^0 mass eigenstates) *vs.* Higgs scale parameter μ (both $M_{\tilde{\gamma}}$ and μ are divided by the Z mass M_Z). Excluded regions are shown for $\tan\beta = \sqrt{2}$ and $\tan\beta = 4$. The lightly shaded regions are excluded by indirect constraints from Z width measurements. The darkly shaded regions are excluded from direct searches for neutralinos. The dotted contour indicates the limit of the kinematic domain accessible to Z decays into neutralinos and charginos. The dashed contour is the same, excluding the invisible mode $Z \to \chi_1^0\chi_1^0$.

thwarting attempts to set indirect limits on χ_1^0 production from the invisible Z width, as was done for $\tilde{\nu}$ production. There is still hope, however, of detecting neutralino production via the processes $e^+e^- \to \chi_1^0\chi_2^0$ ($m_{\chi_1^0} + m_{\chi_2^0} \leq M_Z$) and $e^+e^- \to \chi_2^0\chi_2^0$ ($m_{\chi_2^0} \leq M_Z/2$) where χ_2^0 decays into the invisible χ_1^0 with emission of a fermion-antifermion pair, a higgs particle, or possibly a photon. All of these processes lead to distinctive final states. Unsuccessful searches by three LEP experiments (ALEPH[15],DELPHI[41]OPAL[37]) have led to limits on the coupling parameters $g_{\chi_1^0\chi_2^0 Z}$ and $g_{\chi_2^0\chi_2^0 Z}$. Together with limits on the Z invisible width, these allow exclusions in the plane of "photino mass" (defined as the appropriate mixture of χ_i mass states) *vs.* the parameter μ. Such contours are shown in fig. 1 from the ALEPH experiment for two choices of $\tan\beta(\equiv v_1/v_2)$. For higher values of $\tan\beta$, one can derive absolute lower limits on the photino mass of about 20 GeV.

The above limits assume that the LSP is indeed stable, that is, R-parity is conserved. The OPAL experiment [42] has also looked for pair production of an unstable photino (through t-channel selectron exchange) where each photino decays (violating lepton flavor conservation) to two conventional charged leptons and a neutrino, as in the model of [43]. No candidates were found, permitting exclusion of selectron masses up to 130 GeV and unstable photino masses between about 5 and 42 GeV.

5. Higgs Searches

5.1. Standard Model Higgs

No particle search at LEP has created as much interest as that for the elu-

sive Higgs boson(s). In the Standard Model, the production rate of a single Higgs in Z decays is predicted absolutely, given the Higgs mass. Moreover, except for some difficult mass regions where non-perturbative QCD effects are somewhat uncertain, the Higgs decay channels are known, and their rates can be calculated with confidence [44, 45].

Although the channel $e^+e^- \to H^0\gamma$ (via loop diagrams containing fermions and charged bosons) potentially provides a distinctive signature of a hard, monoenergetic photon, the production rate is quite small. For Higgs masses below about 80 GeV, the Bjorken [46] bremsstrahlung process $e^+e^- \to Z \to H^0(Z^* \to f\bar{f})$ dominates.

Because its coupling to fermions is proportional to their masses, the Higgs tends to decay predominantly into the heaviest fermion-antifermion pair that is kinematically accessible. As a result, the branching ratios into various channels vary dramatically as the hypothetical mass rises from zero through the various lepton and quark thresholds. Relative stability sets in for $m_H^0 > 15$ GeV, where $b\bar{b}$ ($\approx$87%), $c\bar{c}$ ($\approx$7%), and $\tau^+\tau^-$ ($\approx$6%) make up the bulk of the decays. This persists for Higgs masses accessible at LEP.

For very light Higgs masses ($0 < M_{H^0} < 2M_\mu$), the allowed decay modes are $H^0 \to \gamma\gamma, e^+e^-$. As the Higgs mass is allowed to decrease, the lifetime steadily increases until a large fraction of decays occur beyond the outside of the detector, making the Higgs effectively invisible. On the other hand, the virtual Z decays into hadronic final states about 70% of the time, into each charged lepton channel about 3% of the time, and about 20% into a $\nu\bar{\nu}$ final state. Distinctive signatures therefore are acoplanar lepton pairs from $[H^0 \to invisible, Z \to \ell^+\ell^-]$ and isolated showers in the electromagnetic calorimetry from $(H^0 \to [\gamma\gamma, e^+e^-), Z \to \nu\bar{\nu}]$. All experiments have searched in vain for such decays and exclude the region $M_{H^0} < 2M_\mu$ [47, 48, 17, 49].

The so-called intermediate region (for LEP) of Higgs masses ($2M_\mu < M_{H^0} <$ 15 GeV) is messy, particularly below 3 GeV, where hadronization effects in the hadronic Higgs decays are important. All four experiments have looked without success in this region under varying assumptions about hadronic branching ratios [47, 50, 17, 51]. Perhaps the most conservative analysis comes from OPAL, which has set a model-independent lower limit on M_{H^0} by searching for two complementary cases: 1) $H^0 \to$"Ecal" with $Z \to \nu\bar{\nu}$ and 2) $H^0 \to$"Not-Ecal" with Z$\to e^+e^-, \mu^+\mu^-$, where "Ecal" indicates the presence of showering in the electromagnetic calorimeter from Higgs decay products. The limits on $\Gamma(Z \to Z^*H)/\Gamma(Z \to Z^*H_{SM})$ found by OPAL are shown in fig. 2.

For $M_{H^0} > 15$ GeV, there are two main channels that prove useful: 1) $H^0 \to q\bar{q}, Z \to \nu\bar{\nu}$ ($\approx$19% of Higgs events produced) and 2) $H^0 \to q\bar{q}, Z \to \ell^+\ell^-$ with $\ell = e, \mu$ ($\approx$6%). The remaining Higgs events are either completely hadronic and thus hard to distinguish from QCD multi-jet backgrounds or contain τ decays whose associated decay neutrinos make clean identification difficult. The first signal is characterized by acoplanar jets (or monojets for low M_{H^0}) with missing energy and transverse momentum from the neutrinos. The main potential backgrounds to this signature comes from extreme tails of Standard Model $Z \to q\bar{q}$ with missing momentum due to semi-leptonic heavy quark decay, from cracks in detector acceptance that lead to

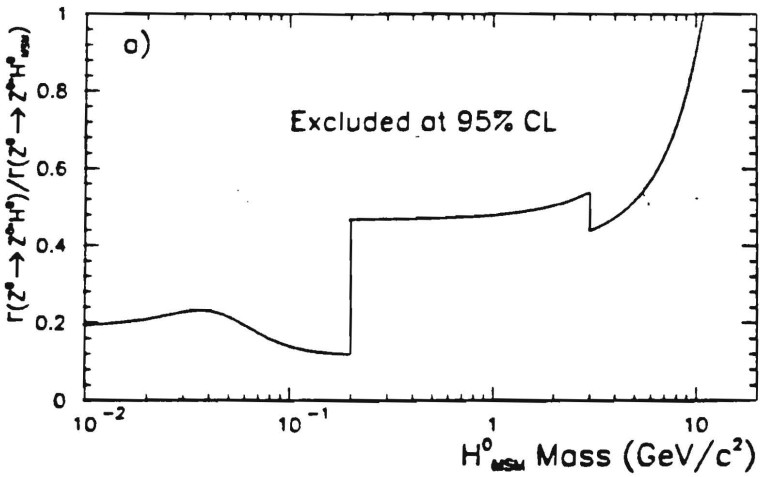

Figure 2: Upper limits (95% CL) from the OPAL experiment on the production rate of a minimal Standard Model Higgs boson given as fraction of the expected decay width $\Gamma(Z \rightarrow H_{SM} Z^*)$.

Table 6: Lower limits (95% CL) on mass (GeV) for a neutral higgs boson in the Standard Model.

ALEPH[53]	DELPHI[54]	L3[55]	OPAL[56]	Combined
58.4	50	57.7	57.5	62.5

false missing momentum, and from gross mismeasurement of hadronic jet energies in $Z \rightarrow q\bar{q}$. None of the four experiments has yet reported a surviving Higgs candidate in channel 1). Several candidates have been reported for channel 2), however, candidates which appear consistent with expected Standard Model backgrounds from four-fermion production. L3 has two such high-mass Higgs candidates, at 68 and 70 GeV, a mass region where Standard Model backgrounds are expected to dominate. The effect of these candidates can be seen in fig. 3 from L3, where the limit on Higgs production rate is plotted *vs.* Higgs mass, along with the number of events expected after correction for efficency loss in the detector. From these curves, which show rates expected for both channels 1) and 2) above, L3 derives a lower limit on the Standard Model Higgs mass of 57.7 GeV. Table 6 shows the best lower limits to date from the four experiments on this quantity. Combining the curves corresponding to those in fig. 3 for all four experiments gives an approximate LEP lower limit of 62.5 GeV. It has been pointed out [52] that sensitivity at LEP 100 ($E_{CM} \approx M_Z$) to the Higgs mass is approaching saturation, *i.e.*, ever greater integrated luminosities are required to increment the lower limit on M_{H^0} by a given amount. Given the steady tightening of event selection requirements with time in order to exclude encroaching backgrounds in both channels 1) and 2), [52] concludes that LEP 100 limits are unlikely much to exceed by much the value 65 GeV.

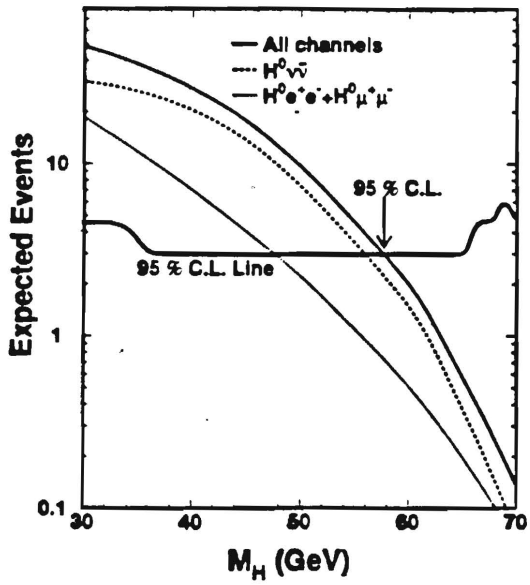

Figure 3: Number of Standard Model Higgs events expected by the L3 experiment in various production channels *vs.* the Higgs mass. The 95% CL line is also shown; the structure in that line below 36 GeV and above 66 GeV arise from candidate events. The arrow indicates the resulting 95% CL lower limit on the Higgs mass of 57.7 GeV.

5.2. Beyond Standard Model Higgs

The simplest extension of the Higgs sector in the Standard Model is to a complex doublet with eight degrees of freedom. Three of these degrees are "used up" in imparting masses to the weak vector bosons, leaving five real physical Higgs states: two CP-even particles h^0 and H^0 ($h^0 < H^0$), one CP-odd particle A^0, and a charged pair $H^\pm$. In general, six free parameters are needed to define the Higgs sector, one set being the four physical masses, $\tan\beta$ (defined above in context of supersymmetry), and α, the mixing angle between h^0 and H^0.

In searching for the the lighter neutral scalar h^0, two complementary approaches are normally used. One can search for the reaction analogous to that described above for the Standard Model Higgs ($Z \to h^0 Z^*$), and in fact the Standard Model limits can be applied immediately to limits on h^0 using the relation $\Gamma(Z \to h^0 Z^*) = \Gamma(Z \to Z^* H_{SM}) \sin^2(\beta - \alpha)$. The other approach is to search for $Z \to h^0 A^0$ (assuming $M_{h^0} + M_{A^0} \leq M_Z$) for which the following relation holds: $\Gamma(Z \to h^0 A^0) = [\bar{\beta}(M_{h^0}, M_{A^0}, M_Z)^3/2]\,\Gamma(Z \to \nu\bar{\nu}) \cos^2(\beta - \alpha)$, where $\bar{\beta} \leq 1$. Thus despite the arbitrariness of the parameters β, α in the general case, one can obtain unambiguous limits in the M_{h^0}, M_{A^0} plane by simultaneously constraining the values of $\cos^2(\beta - \alpha)$ and $\sin^2(\beta - \alpha)$.

If one now considers a special case, that of minimal supersymmetry, then further constraints are imposed on the Higgs sector. The six free parameters above are reduced to two. The pair usually preferred by experimentalists are (M_{h^0}, M_{A^0}), while theorists generally prefer $(M_{A^0}, \tan\beta)$ or $(M_{H^\pm}, \tan\beta)$. These additional relations

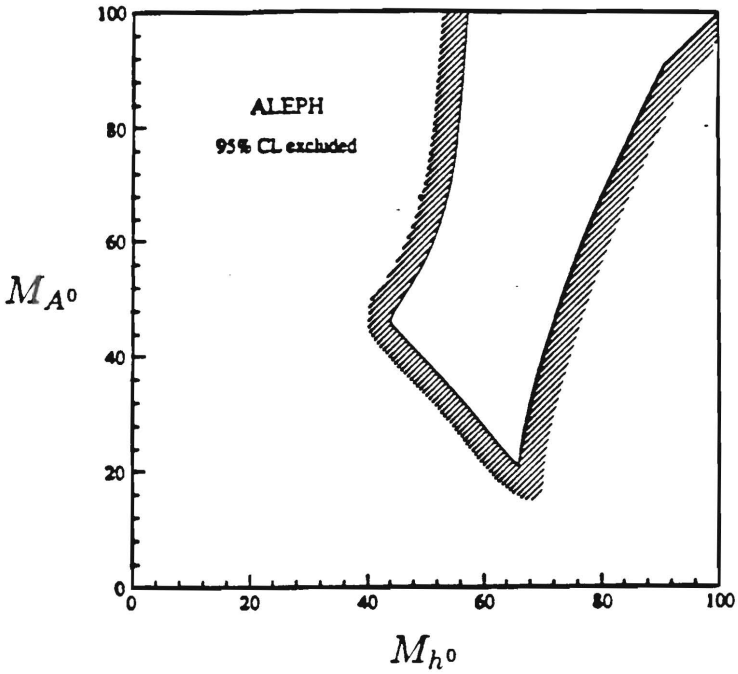

Figure 4: Regions in the M_{A^0}-M_{h^0} plane excluded (95% CL) by the ALEPH experiment within the minimal supersymmetric model. The region toward the right is excluded by theory for $M_t < 180$ GeV and $M_{\tilde{t}} > M_t$. The region toward the upper left is excluded by theory and by searches for $Z \to h^0 Z^*$. The region toward the lower left is excluded by searches for $Z \to h^0 A^0$.

yield direct constraints on the Higgs mass spectrum. At tree-level, one expects $M_{h^0} \leq M_Z \leq M_{H^0}$; $M_{h^0} \leq M_{A^0}$; and $M_W \leq M_{H^\pm}$. Thus one expects *at least one* Higgs boson with mass smaller than M_Z. Unfortunately, as realized in 1991, there are important radiative corrections [57] that can distort these relations considerably, corrections that depend on the top quark and stop squark masses; relaxing GUTS constraints introduces further uncertainties. As a result, it is no longer necessarily true that $M_{h^0} \leq M_Z$ or even that $M_{h^0} \leq M_{A^0}$. In fact, one can have $M_{A^0} \leq 2M_{h^0}$ so that $h^0 \to A^0 A^0$ is allowed. These new uncertainties complicate both the search strategy one must use and the interpretation given to the negative result of a search. For example, a point in the M_{h^0}-M_{A^0} plane may be excluded for one value of $\tan\beta$, but not for another, where both satisfy the theoretical expectation $\tan\beta > 1$.

All four LEP experiments have carried out new susy Higgs searches [58, 59, 60, 61] with these uncertainties in mind and have reevaluated previous limits. Figure 4 from ALEPH is representative of the constraints obtained on M_{h^0} and M_{A^0} when the $\tan\beta$ ambiguity and the present uncertainty on the top quark mass are taken into account. Taking the worst cases, ALEPH finds absolute lower limits of 44 GeV and 21 GeV on M_{h^0} and M_{A^0}, respectively. As in the Standard Model Higgs search, mass constraints are near saturation. Increasing integrated luminosity tenfold at present c.m. energies while observing no new candidates would increase the excluded region in fig. 4 only slightly.

The above searches have assumed decay of h^0 into visible particles. For low values of $\tan\beta$ (disfavored theoretically), one has the possibility of $h^0 \to \chi_1^0\chi_1^0$. If χ_1^0 is indeed the LSP and R-parity is conserved, the h^0 decay products would be invisible. ALEPH has searched for this process via $Z \to (h^0 \to \chi_1^0\chi_1^0), (Z^* \to q\bar{q}, \ell^+\ell^-)$, which leads to a signature of a pair of acoplanar leptons or hadronic jets. One interesting candidate is found in the leptonic channel where an electron pair of mass 3.3 GeV and transverse momentum 20.3 GeV recoils against undetected particles of total mass 61 GeV. About one such event is expected in their data from Standard Model processes giving $e^+e^- \to \ell^+\ell^-\nu\bar{\nu}$, but both the candidate's relatively large mass and its large transverse momentum make it quite unusual. Further events with this signature are eagerly awaited. From this search, ALEPH sets limits on the ratio $\Gamma(Z \to h^0 Z^*)/\Gamma(Z \to H_{SM} Z^*)$ *vs.* M_{h^0}, under the assumption of invisible decay modes. The upper limit on this ratio is found to vary from $\approx 3 \times 10^{-3}$ at zero mass to unity at ≈ 65 GeV.

Searches have also been carried out for single and doubly charged Higgs particles. The singly charged Higgs is expected to be amply pair-produced in Z decay and for heavy Higgs mass, to decay predominantly into $\tau\nu$ and $c\bar{s}$. Even allowing for uncertainties in the relative leptonic and hadronic branching ratios, mass lower limits near $M_Z/2$ were set by all four LEP experiments relatively early on [62, 28, 30, 32]. Results are shown in table 4. In certain models one expects doubly charged Higgs particles that decay into two like-sign charged leptons. At LEP, one would expect an abundance of four-lepton events. OPAL[33] has searched without success for such events and places lower limits on the doubly charged Higgs mass of $M_Z/2$ except for a narrow range of $g_{H\ell\ell}$ coupling where finite lifetime effects degrade detection efficiency.

6. Exotica

In this section, we consider miscellaneous searches for new phenomena that do not fall naturally into the categories considered above. These include searches for contact interactions, lepton flavor violation, new stable particles, CP violation, and rare Z decays.

All four LEP experiments [15, 63, 64, 65] have searched for evidence of a contact interaction in the QED process $e^+e^- \to \gamma\gamma$, parametrizing the angular distribution according to

$$\frac{d\sigma}{d\Omega_\gamma} = \frac{\alpha^2}{s}\frac{1+\cos^2\theta_\gamma}{1-\cos^2\theta\gamma} \pm \frac{\alpha^2 s}{2\Lambda_\pm^4}(1+\cos^2\theta\gamma)$$

Since generally good agreement is seen between the data and QED expectation, each experiment has set limits on Λ_+ and Λ_-, as shown in table 7. In addition, the ALEPH experiment has looked for evidence of distortion of the angular distribution in $e^+e^- \to \ell^+\ell^-$ events as an indication of a four-lepton contact interaction [66]. No distortion is observed, and lower limits in the range 0.9 to 4.7 TeV are placed on the scale Λ_{ij} characterizing such a contact interaction among the charged leptons.

Each LEP experiment has also looked for lepton flavor violation [67, 68, 69,

Table 7: Lower limits (95% CL) on $\Lambda^{\pm}$ which parametrizes deviations in the angular distribution of $e^+e^- \to \gamma\gamma$ from QED expectation.

	ALEPH[15]	DELPHI[63]	L3[64]	OPAL[65]
Λ^+	120	113	139	117
Λ^-	129	95	108	110

Table 8: Upper limits (95% CL) on $B(Z \to \ell_i^+ \ell_j^-) \times 10^5$ where $i, j = e, \mu, \tau$ with $i \neq j$.

Channel	ALEPH[67]	DELPHI[68]	L3[69, 70]	OPAL[71]
$Z \to e\mu$	1.0	3.2	1.5	4.6
$Z \to e\tau$	8.0	11	1.4	7.2
$Z \to \mu\tau$	5.5	14	2.2	35

70, 71] via $Z \to \ell_i^+ \ell_j^-$ where $i, j = e, \mu, \tau$) with $i \neq j$. The signature for $e\mu$ production is extremely clean, with back-to-back beam-energy electrons and muons. This channel is not competitive, however, with limits derived from low-energy searches for $\mu \to eee$ [72]. The $e\tau$ and $\mu\tau$ channels are more interesting, but backgrounds do exist from radiative electron and muon pair production and (more importantly) from the end-point spectra of $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\bar{\nu}\nu$ decays. These backgrounds place a premium on precise energy resolution for electrons and muons. Table 8 shows the limits on B($Z \to \ell_i^+ \ell_j^-$) obtained by the four experiments.

Although one expects in QCD that neither quarks nor gluons can be observed in a free energy state, it doesn't hurt to look just to make sure. ALEPH has searched for free quarks [73] with charges $|Q| = \frac{1}{3}, \frac{2}{3}, \frac{4}{3}$ via unusual ionization in their time projection chamber. No evidence of fractionally charged particles was found, allowing the limit $\sigma(e^+e^- \to Q\bar{Q} + hadron))/\sigma(e^+e^- \to \mu^+\mu^-) \leq 3 \times 10^{-3}$ to be placed for 5 GeV $< m_Q <$ 43 GeV. The OPAL experiment has looked for free gluons [74], expected to leave isolated and neutral hadronic showers in the calorimetry. No excess of such showers over expected backgrounds was observed, placing a limit on the gluon confining potential [75] of $V_M > 47$ GeV.

Aside from the four major LEP experiments considered so far, there is also a small experiment called MODAL, located in one of LEP's small, alternate interaction region and dedicated to searching for production of magnetic monopoles via their expected high ionization in layers of CR-9 plastic. No evidence of such ionization has been observed, allowing MODAL [76] to place a lower limit on the magnetic monopole mass of 44.9 GeV.

A nonzero weak dipole moment for the τ lepton could lead to manifest CP violation in $Z \to \tau^+\tau^-$ decays. One useful signature [77] is a nonzero expectation value for the manifestly CP-odd tensor elements defined by

$$T_{ij} \quad \equiv \quad (\vec{q}^- - \vec{q}^+)_i (\vec{q}^- \times \vec{q}^+)_j \quad + \quad [i \leftrightarrow j]$$

where $\vec{q}^{\pm}$ are the 3-momenta of the charged decays products of the $\tau^{\pm}$. In an effective

Table 9: Upper limits (95% CL) on branching ratios $B \times 10^5$ for various Z decays expected to be very rare or forbidden.

Decay	ALEPH[80]	DELPHI[63, 81]	L3[64]	OPAL[65]
$Z \to \gamma\gamma$	—	—	12	14
$Z \to \pi^0\gamma$	16	15	12	14
$Z \to \eta\gamma$	2.9	28	18	20
$Z \to \eta'\gamma$	2.5	—	—	—
$Z \to \gamma\gamma\gamma$	0.9	2.3	3.3	6.6
$Z \to gg\gamma$	9.2	—	—	—

Table 10: Upper limits (95% CL) on branching ratios $B \times 10^5$ from the ALEPH experiment [80]for additional Z decays expected to be rare.

Z Decay Channel	$X^{\mp}W^{\pm}$	$\pi^{\mp}W^{\pm}$	$K^{\mp}W^{\pm}$	$\rho^{\mp}W^{\pm}$	$D^{\mp}W^{\pm}$
ALEPH Limit	3.7	2.2	2.2	2.6	4.4

theory of CP violation, the expectation value of the elements of this tensor can be expressed:

$$< T_{ij} > \quad = \quad d_\tau(M_Z)\frac{M_Z}{e}c_{ab}\begin{pmatrix} -\frac{1}{6} & 0 & 0 \\ 0 & -\frac{1}{6} & 0 \\ 0 & 0 & +\frac{1}{3} \end{pmatrix}$$

where $i = 3$ indicates the beam direction, d_τ is the weak dipole moment of the τ, and c_{ab} are decay-mode-dependent coefficents. Using the most sensitive tensor element, T_{33}, OPAL searched in 1991 [78] for lepton-lepton, lepton-hadron, and hadron-hadron decay mode combinations, and found no significant deviation from zero for T_{33}, allowing the limit $|d_\tau| < 7.0 \times 10^{-17}$ e-cm to be placed. Using a large number of exclusive decay channels (to reduce degradation from averaging over different c_{ab}), ALEPH also searched without success [79] for non-vanishing T_{33}. This resulted in a limit $d_\tau < 3.7 \times 10^{-17}$ e-cm.

A number of rare or forbidden Z decays to conventional particles offer the prospect of detecting the indirect effects of new physics at energies higher than presently accessible. Potentially interesting rare decays include $Z \to \pi^0\gamma$, $Z \to \gamma\gamma\gamma$, and $Z \to gg\gamma$. Limits on the forbidden decay $Z \to \gamma\gamma$ are obtained by searching for resonant behavior with respect to $\sqrt{s}$ among the $e^+e^- \to \gamma\gamma$ events expected from QED. Each LEP experiment has searched without success for some or all of these decays, with resulting limits shown in table 9. In addition, the ALEPH experiment has searched [80] for $Z \to h^{\pm}W^{\mp}$ [$h \equiv$ hadron(s)] and obtained limits shown in table 10.

7. The Unexpected – Hints or Herrings?

The searches described up to this point were designed from the beginning to look for a given phenomenon, but failed to find evidence of it. Invariably, though, when casting the net for unusual events, one finds something unexpected. We now

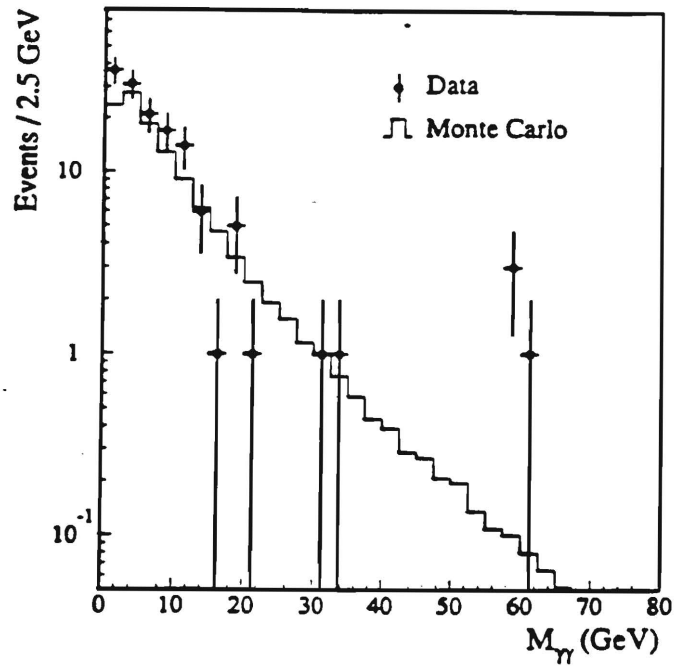

Figure 5: Original distribution in $M_{\gamma\gamma}$ observed by the L3 experiment for $e^+e^- \to \ell^+\ell^-\gamma\gamma$ events with $\ell = e, \mu, \tau$ using the 1990, 1991, and partial 1992 data. Data are indicated by points and Monte Carlo expectation by the histogram.

consider two such surprises: 1) an apparent excess of $e^+e^- \to \tau^+\tau^-$ "V" events reported in 1991 by ALEPH in 1991, and 2) an apparent excess of $e^+e^- \to \ell^+\ell^-\gamma\gamma$ events with $m_{\gamma\gamma} \approx 60$ GeV reported by L3 in 1992. The $\tau^+\tau^-$ "V" excess will be discussed only briefly below, while the more recent $\ell^+\ell^-\gamma\gamma$ excess will be discussed at greater length.

ALEPH [82] found in its 1990 data 15 events of the type $e^+e^- \to \tau^+\tau^-$ "V" where V indicates a charged particle and its antiparticle (hadron or lepton). Only 3.2 such events were expected from Standard Model four-fermion production. No excess was observed in the $e^+e^- \to e^+e^-$ "V" or $e^+e^- \to \mu^+\mu^-$ "V" channels; the mass spectra of the V pairs showed no obvious evidence of new-particle production. This excess did not reoccur in ALEPH's 1991 data [83], and no corroboration came from the other LEP experiments[83, 84]. The original excess of $\tau^+\tau^-$ "V" events in ALEPH data now appears to have been merely a statistical fluctuation of Standard Model backgrounds.

More recently, L3 [85] observed four $e^+e^- \to \ell^+\ell^-\gamma\gamma$ events with $m_{\gamma\gamma} \approx 60$ GeV in the 1990, 1991 and partial 1992 data samples, three in the $\mu^+\mu^-\gamma\gamma$ and one in the $e^+e^-\gamma\gamma$ channels. Figure 5 shows the invariant mass spectrum for $e^+e^-\gamma\gamma$, $\mu^+\mu^-\gamma\gamma$, and $\gamma\gamma$ events for the original L3 data sample. The probability estimated for a QED fluctuation giving four events with $m_{\gamma\gamma}$ within 5 GeV of one another and all greater than 50 GeV was estimated by L3 to be $O(10^{-3})$.

A natural mechanism for producing an excess of such events would be Bjorken bremsstrahlung of a new particle X from the Z, where $X \to \gamma\gamma$ and $Z \to \ell^+\ell^-$. This

explanation runs into serious difficulties, however, as 1) no excess of $X \to \gamma\gamma, Z^* \to q\bar{q}$ events is seen at $m_{\gamma\gamma} \approx 60$ GeV, despite an expected production rate ≈ 7 times that for $X \to \gamma\gamma, Z \to \ell^+\ell^-$; and 2) no excess of $X \to \gamma\gamma, Z \to \nu\bar{\nu}$ events is seen, despite a nearly complete absence of background, high efficiency, and a nominal production rate twice that for $\ell^+\ell^-\gamma\gamma$. In addition, the four L3 events are *not* consistent with a single m_X value. Explaining the excess as X production then requires reducing the number of signal events by at least one or postulating a large decay width $\Gamma_X > 1$ GeV. Such a large width would be unexpected for a particle whose only apparent decay mode is $\gamma\gamma$ (for comparison, $\alpha^2 \times 60$ GeV $\approx$ 3 MeV). The kinematics of the events also suggest caution, as three of the four events contain an opening angle between a photon and final-state lepton smaller than 20 degrees, or $\cos\theta_{\ell\gamma} > 0.94$, a characteristic one expects from QED background.

The reported excess prompted the other experiments to reexamine their data (OPAL had already reported in 1991 [86] on $e^+e^- \to \ell^+\ell^-\gamma$ production without observing unusual behavior among the $\ell^+\ell^-\gamma\gamma$ events), and further data arrived in 1992 before the end of the run, increasing total event samples by $\approx$70%. In the new data L3 found no new candidates at $m_{\gamma\gamma} \approx 60$ GeV, causing the calculated probability of QED fluctuation to rise from $O(10^{-3})$ to $O(10^{-2})$. More important, the other three experiments [87, 88, 89] failed to corroborate a significant excess at 60 GeV. The combined $m_{\gamma\gamma}$ distribution reported by the other three collaborations for $m_{\gamma\gamma} > 20$ GeV is shown in fig. 6 (caution: the four experiments used various selection cuts and have differing acceptances, making the combined $m_{\gamma\gamma}$ distribution useful for *qualitative* comparisons only). Although there are three events from the other experiments just below 60 GeV, the rest of the combined $m_{\gamma\gamma}$ distribution suggests these are consistent with QED background. The other experiments also fail to see an excess of $q\bar{q}\gamma\gamma$ or $\nu\bar{\nu}\gamma\gamma$ events, with the possible exception of ALEPH, which sees one interesting event with two photons of $m_{\gamma\gamma} = 58.5$ GeV and no charged particles. The presence of a third, low-energy neutral electromagnetic shower and the relatively small missing transverse momentum of the event make this event questionable, however, as signature for new physics. .

Other cross checks come from looking for $e^+e^- \to (e^+e^-)X$, where the final state electrons escape along the beam direction. Given the apparently large decay width of X implied by the four L3 events, one might expect a relatively large cross section for this two-photon production of X. ALEPH, DELPHI, and OPAL have searched for this process, characterized by a coplanar but acolinear pair of photons in the detector with $m_{\gamma\gamma} = 60$ GeV. Candidates are found that are consistent with expected background from doubly radiative Bhabha scattering. The absence of excess allows the following limits to be placed on the product $\Gamma_X \cdot B(X \to \gamma\gamma)^2$: ALEPH(2.9 MeV), DELPHI(5 MeV), and OPAL(2.6 MeV). These are inconsistent with $\Gamma_X > 1$ GeV, given the apparent predominance of the $X \to \gamma\gamma$ channel. Finally, searches have been conducted without success by the TRISTAN experiments for an enhancement in the cross section for $e^+e^- \to \gamma\gamma$ in the vicinity of $\sqrt{s} = 60$ GeV [90].

Although one cannot rule out the possibility of a true excess of $\ell^+\ell^-\gamma\gamma$ events at $m_{\gamma\gamma} = 60$ GeV, the evidence in favor of such an excess is not compelling. As

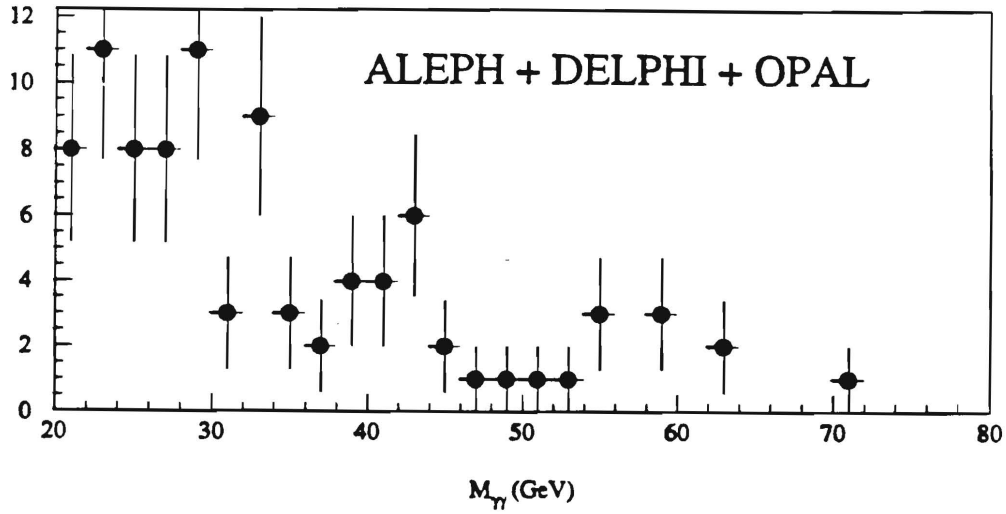

Figure 6: Distribution in $M_{\gamma\gamma}$ observed by the *other three* LEP experiments for $e^+e^- \to \ell^+\ell^-\gamma\gamma$ events. The apparent large excess at $M_{\gamma\gamma} \approx 60$ GeV in fig. 5is not confirmed. **Note:** the four experiments used various selection cuts and have differing acceptances, making this combined distribution useful for only *qualitative* comparisons.

one would expect, the original L3 publication prompted the rapid appearance of theoretical publications attempting to explain the apparent excess. It should be noted, however, that the model of Kang and White [91] which predicts massive η_6 particles with $\gamma\gamma$ decay modes predated the L3 publication.

8. Summary and Outlook for the Future

So far the results of searches for new phenomena at LEP have been disappointing. The searches have not been fruitless, since much that had been thought possible before LEP began taking data has been excluded. For example, limits on the Standard Model Higgs mass, which had been controversial and weak four years ago are now unambiguous, ruling out a mass below 62.5 GeV. In addition, we now know with overwhelming certainty that nature contains only three fermion generations with light, conventional neutrinos. Nevertheless, discovering a new particle would have livened up the field of high energy physics considerably. With most plausibly motivated particle searches at LEP 100 approaching saturation, one has little hope of such a discovery appearing in the remaining data at $\sqrt{s} \approx M_Z$.

Fortunately, there is relief in sight, namely the anticipated start of LEP 200 running in early 1995, with an initial c.m. energy of 176 GeV, well above threshold for W^+W^- production. The c.m. energy is expected to be raised still higher in later years, the ultimate limit of ≈240 GeV coming from the dipole magnets, with perhaps a more immediate limit coming from financial constraints. At these higher energies, one should relatively quickly explore the mass range for pair-produced particles up to $\sqrt{s}/2$. Searches for Standard Model Higgs will also benefit dramatically from the increase in energy. Instead of searching for $Z \to HZ^*$, one will look for $Z^* \to HZ$, giving a mass reach for 500 pb^{-1} of $M_{H^0} \approx \sqrt{s} - 100$ GeV [92]. For $M_{H^0} \approx M_Z$, there is a potentially serious background from $e^+e^- \to ZZ$, but the silicon vertex detectors

now installed in every detector should provide powerful b-jet tagging to enhance the relative fraction of Higgs events.

Similarly, searches for supersymmetric Higgs particles will benefit directly from the increase in energy, with a mass reach for h^0 close to that for H_{SM}. Direct sensitivity to M_{A^0} via h^0A^0 production is expected to saturate at ≈90-100 GeV [92]. For $e^+e^- \to h^0A^0$ searches, a potential background is $e^+e^- \to W^+W^-$, which as above, can be greatly suppressed with b-tagging requirements. Raising LEP 200 energy to the highest possible value holds out the promise of finally confirming or excluding minimal supersymmetry via the Higgs sector.

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