Parallel Session 30

Particle Search

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SEARCH FOR THE STANDARD HIGGS BOSON IN ALEPH

The ALEPH Collaboration

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ABSTRACT

This paper describes the search for the standard Higgs boson performed using the ALEPH detector at LEP. Using the data taken up to June 1990, we can exclude the standard Higgs mass range between 0 and 41.6 GeV at the 95 % confidence level.

The search for the standard Higgs boson at LEP is based on the decay of the Z^0, produced by the e^+e^- annihilation, into the Higgs boson and a virtual Z^0. All the couplings and decay modes are known, so the number of expected events in any given channel can be computed accurately, and compared to the data.

Using the data taken in the 1989 run, Aleph has already excluded [1,2] the mass range 32 MeV to 24 GeV at 95 % CL. The recent results presented at this conference allow to extend this domain down to and including 0 MeV, and up to 41.6 GeV, using the increased statistics accumulated in the first part of the 1990 run, together with some improved analysis methods.

VERY LIGHT HIGGS BOSON [3]

As a very light Higgs boson can only decay into photon or electron pair, his mean life is long enough such that it can frequently escape from the detector. Using the decay into a lepton pair of the virtual Z^0, the signature of such a very light Higgs boson is then an acoplanar lepton pair. The background is due to a radiative production of leptons (initial and final state radiation), where the photon is not detected. The requirements in the analysis are as follows:

1. Two charged particles with momentum greater that 30 GeV comming from the interaction point.
2. An acoplanarity angle between the two particles of more than 30 mrad.
3. The energy sum of isolated clusters in the electromagnetic calorimeter (ECAL) has to be less than 1 GeV, and the energy sum in the ECAL modules not hit by the particles has to be less than 1 GeV.
4. The energy sum of neutral clusters in the hadronic calorimeter in an area of ± 2 cm behind the ECAL cracks has to be less than 1 GeV.

Using the full 1989 statistics (corresponding to 22486 hadronic decay of Z^0), we see 3096 events after cut 1), 84 after cut 2), only 2 after cut 3), and zero event after cut 4. So we found no candidates for an escaping Higgs boson.

The detection efficiency depends on the lifetime, and then on the mass of the Higgs boson, and decrease from 41.5% at zero mass to 13.9% at 60 MeV. The expected number of events decreases from 9 to 3 in the same range. With zero observed events, we can then exclude the mass range 0 to 57 MeV at 95% CL, covering the window window which remained open after the previously published results.

HEAVY HIGGS BOSON

In this second new result [4], we are looking for heavy Higgs boson, which decays mostly into hadrons ($b\bar{b}$ 84%, $c\bar{c}$ 10%),and in $\tau^+\tau^-$ in about 6% of the cases. As the Z^* decays also mostly into hadrons, the most frequent topology is then a 4 jet event, difficult to exploit due to QCD background. We then concentrate on the channel $H^0 \rightarrow q\bar{q}$, $Z^* \rightarrow \nu\bar{\nu}$, which is characterized by an acolinear, acoplanar pair of jets, with missing energy and momentum. This analysis relies heavily on the energy reconstruction algorithm, which combines information from all the detectors to describe the energy

flow: Charged tracks as measured in the TPC, V^0 reconstructed and measured in the TPC, photons as neutral ECAL clusters with good longitudinal and transverse characteristics, and neutral hadrons as the part of the calorimetric energy which can not be explained by the charged tracks and the photons pointing to the cluster. With this algorithm, we obtain a 8 GeV resolution on the visible mass of a well contained hadronic Z^0 decay.

Control analysis

In order to check the reliability of this energy reconstruction for the Higgs boson search, we select radiative Z^0 decays : $Z^0 \rightarrow q\bar{q}\gamma$ where the photon has more than 30 GeV. We have 246 such events where the hadronic system satisfies the Higgs boson search criteria described later, in the whole statistics. We can measure the mass of the hadronic system by two methods, first using the energy reconstruction method (and omitting the high energy photon), or by computing the mass recoiling against the photon, which is well measured in the ECAL. Notice that with the 30 GeV cut, the hadronic system has a mass close to 50 GeV, the range of mass we want to explore for the Higgs boson. The difference of mass between the two methods is well reproduced (including the normalization) by the Monte-Carlo, is centered at zero and the resolution is around 6 GeV.

Event selection

In order to search for the $H^0 \rightarrow q\bar{q}, Z^* \rightarrow \nu\bar{\nu}$ channel, we use the full statistics collected up to June 1990, 101,200 hadronic decays of the Z^0. We require

- At least 5 tracks, with a sum of momenta greater than 8 GeV.

- Less than 3 GeV in a 12^0 cone around the beam line, where there are many cracks and then a poorer energy resolution. The loss due to accidentals (as measured with random triggers) is about 0.3%.

- The momentum parallel to the beam line has to be less than 30 GeV, to reject photon-photon events or hard initial state radiation.

- The transverse momentum has to be greater than 5 GeV to reject photon-photon and most $q\bar{q}$ events.

We then define "jets", by dividing the event in two hemispheres with respect to the Thrust axis, and calling "jet" each hemisphere. Events can then be monojets, or have two jets. In the latter case, we require one jet with at least 2 GeV and at more than 35^0 from the beam line, the acollinearity η such that $\cos \eta > -.95$, and the acoplanarity less than 175^0. With these cuts, there is no event with a visible mass less than 50 GeV. The overall search efficiency varies with the Higgs boson mass, but is over 75% in the mass range 25 to 42 GeV. This channel alone excludes the standard Higgs boson mass up to 39.8 GeV at 95% confidence level.

Other channels

We have also studied the channels $H^0 \rightarrow q\bar{q}$, $Z^0 \rightarrow l^+l^-$, an isolated lepton pair with an hadronic system. No events are found with a good pair (at least 10 and 5 GeV for the leptons, +− topology, mass of the pair greater than 5 GeV, both electrons or both muons) and a mass recoiling against the lepton pair less than 50 GeV. We have also studied the channels $H^0 \rightarrow \tau^+\tau^-$, $Z^0 \rightarrow \nu\bar{\nu}$ or l^+l^-, which are simple topologies, and no events are seen within very simple cuts.

CONCLUSION

Combining the various channels, and taking into account a systematic error of 3%, we conclude that the Higgs boson mass is excluded in the range between 0 and 41.6 GeV at 95% confidence level.

REFERENCES

1. D.Decamp et al,(ALEPH collaboration), *Phys. Let.* 236B (1990) 233.

2. D.Decamp et al,(ALEPH collaboration), *Phys. Let.* 241B (1990) 141.

3. D.Decamp et al,(ALEPH collaboration), *Phys. Let.* 245B (1990) 289.

4. D.Decamp et al,(ALEPH collaboration), *Phys. Let.* 246B (1990) 306

NEW PARTICLE SEARCHES IN ALEPH (part II)
by the ALEPH Collaboration

presented by

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ABSTRACT

This report is the second part of the ALEPH search report. It covers the search for super-symmetric particles (Higgs, charginos and neutralinos) within the framework of the Minimal Supersymmmetric Standard Model and the search for composit charged leptons and neutrinos. Lower limits of masses of such new particles are given. Most of them are very close to the LEP I kenematical limit.

This report follows a presentation on the search for the standard Higgs boson in ALEPH made at this conference [1]. It covers the search for super-symmetric particles (Higgs, charginos and neutralinos) within the framework of the Minimal Super-symmetric Standard Model and the search for composit charged leptons and neutrinos. Lack of space does not allow to give updates of the search for other supersymmetric particles and for new quarks and leptons. For the same reason the experimental selections are only briefly recalled because they are described in referenced previous publications.

SEARCH FOR SUPERSYMMETRIC HIGGS BOSONS

The Minimal Supersymmetric Standard Model (MSSM) is a model with two Higgs doublets coupled respectively to down and up-type quarks only. This very constrained model requires 5 physical Higgs states : 2 mixed scalar neutral h^o and A^o (mixing angle α), 1 pseudoscalar neutral A^o and 2 charged Higgs $H^{\pm}$. Masses and couplings depend only on two parameters M_h and $\beta = A \tan (v_2/v_1)$(where v_1 and v_2 are the vacuum expectation values of the 2 Higgs doublets). In particular according to the relation :

$$M_h \leq M_Z |\cos 2\beta| \qquad (1)$$

the h boson has to be lighter than the Z^o. The model relates the $Z \to hZ^*$ and $Z \to hA$ coupling constants :

$$g_{hZZ} = g \sin(\beta - \alpha), \qquad g_{ZhA} = g \cos (\beta - \alpha) \quad (2)$$

to the weak coupling constant g. When tgβ is very different from unity the $Z \to hA$ decay dominates. Otherwise it is the $Z \to hZ^*$ decay. The search for signatures of these two decays are complementary for exploring the tgβ, M_h plane of MSSM Higgs bosons.

The search for charged Higgs bosons described elsewhere [1] has not been updated for this report. We will restrict ourselves to the neutral Higgs search.

I - Search for $Z \to h^o Z^*$

The Z partial width expected for the mode $Z \to h^o Z^*$ in MSSM is, compared to its standard model value, reduced by a factor $\sin^2(\beta - \alpha)$ (eqn.2). For $M_h > 2M_\mu$, the search which rely on the observation of the Z^*, is identical to the standard model Higgs boson search. The Aleph limit, $M_H \geq 41.6$ GeV 95% C.L., reported at this conference [3], can be converted in the exclusion of a domain in the tgβ, M_h plane (curve A in figure 1). In this figure, the curve labelled T, limits the domain theoretically excluded by equation 1. From these two excluded domains, we get bounds on tgβ.

$$\text{tg}\,\beta > 1.60 \qquad \text{or} \qquad \text{tg}\,\beta < 0.63, \quad 95\% \text{ C.L.}$$
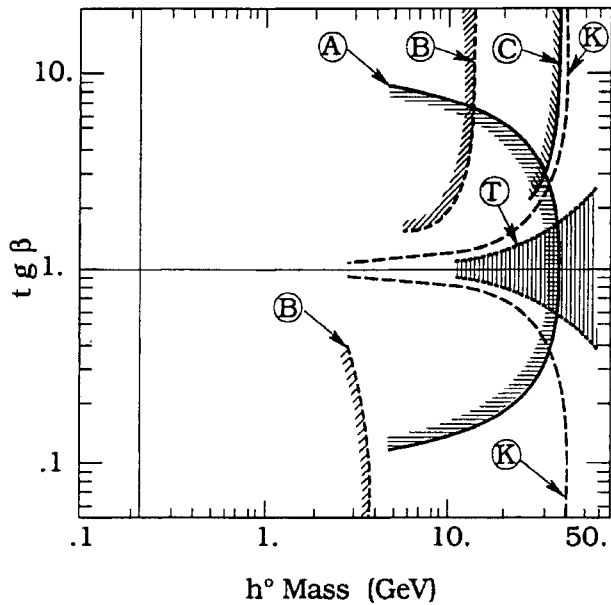
Fig.1 : Excluded domains in the $M_h, \text{tg}\,\beta$ plane for heavy Higgs. Altogether Aleph and theory exclude the hatched region (see text).

In the low M_h region ($M_h < 2\,M_\mu$) where the only decay modes are $h \to e^+e^-$ and $\gamma\gamma$, the h boson lifetime starts to exceed tens of picoseconds. The standard Higgs search described above is therefore limited to the exclusion of the domain inside curve 1 of figure 2.

Special additional searches, described in detail in [3] are therefore needed .

i) Very light Higgs are so stable that they escape detection. Only the Z^* decay is visible. Lepton pair decays associated to missing energy are searched for. No event are detected [2]. The domain inside curve 2 of fig.2 is 95% C.L. excluded.

ii) Intermediate mass light Higgs decays inside the Aleph tracking chamber system resulting in a detached vertex. Lepton pair decays of the h are looked for, whatever is the Z^* decay. No events are found excluding the domain inside curve 3 of fig. 2.

iii) In order to reach the high $\text{tg}\,\beta$ region, it is necessary to search for $Z \to hA$ decays. In the very light Higgs region under consideration, either the quasi-stable Higgs escapes detection or its decay products ($e^+e^-, \gamma\gamma$ pair) fail the $Z \to$ hadrons

selection. The Aleph measurement of the Z invisible width can be converted in the exclusion of the domain outside curve 4 of fig.2.

From these four negative searches displayed in figure 2, we can exclude (95% C.L.) any minimal supersymmetric light Higgs ($M_h < 2M_\mu$).
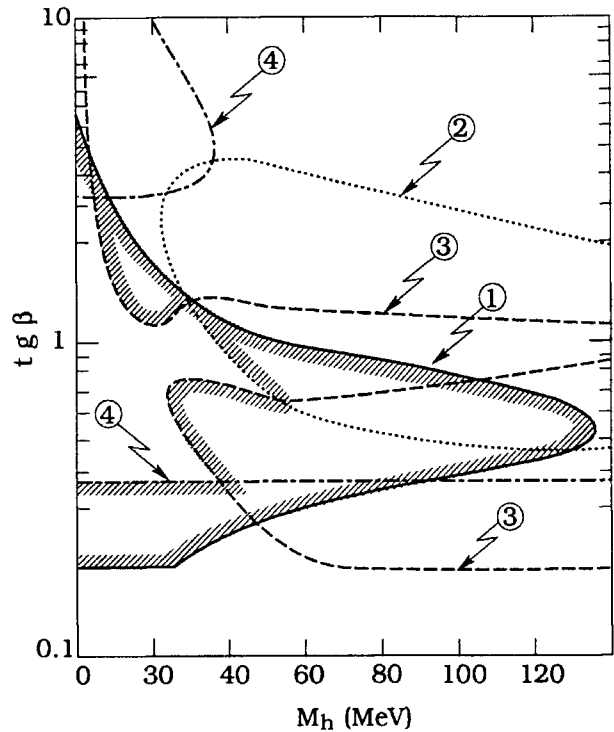
Fig.2 : Excluded domains in the $M_h, \text{tg}\,\beta$ plane for $M_h < 2M_\mu$ (see text) : the overall region is excluded.

II - Search for Z → h°A°

According to equation 2, the $Z \to hA$ decay width is, compared to the $Z \to$ leptons width, reduced by a factor $\cos^2(\beta - \alpha)$ which is sizable when $\text{tg}\,\beta$ differs appreciably from unity. h and A Higgs boson decay, depending on their mass, to the heaviest possible pair of identical flavours :

- g, μ, s, τ and b pairs for $\text{tg}\,\beta \gg 1$
- g and c pairs for $\text{tg}\,\beta \ll 1$.

Therefore different types of selection are needed to search for MSSM Higgs depending on their masses and $\text{tg}\,\beta$. They are precisely detailled in reference 4. We just recall the various search principles :

1) Low multiplicity states :

Each event is divided into two hemispheres with respect to the sphericity axis. The total charge of each hemisphere is required to be 0. The hemisphere charged track topology is selected to be 2 + 2 or 2 + 4. For 18600 hadronic Z decays we found [4] only 1 event. Hundred are expected from MSSM in the region B of the tgβ, M_h plane ploted in figure 1, which is 95% C.L. excluded.

2) $\tau\tau$ jet jet states :

Events with 2 "one track" jets of opposite charge (called "τ jets") and 2 additional jets are kept [4]. The energy of these 4 jets are rescaled to ensure energy-momentum conservation, allowing to look for the $Z \rightarrow hA$ signal in a "τ-τ" and "jet-jet" masses 2-dimentional histogram. For 101000 Z only one event ($M_h = 36$, $M_A = 51$) is found allowing to exclude the region C of figure 2 where $hA \rightarrow \tau\tau$ $b\bar{b}$ dominates.

3) 4 jets states :

This selection [4] which suffers a very high $Z \rightarrow q\bar{q}$ gg background appears to be not more efficient than the previous one. It results in the exclusion of region D of figure 2.

On figure 2, together with the various excluded domains (labelled A to C) curve K gives the LEP I kinematical limits $(M_h + M_A = M_Z)$. For tgβ > 1, which is theoretically favoured, almost all the kinematically allowed region (inside curve K) is excluded. For tgβ > 1, the same limits are displayed in figure 3 in the M_A, M_h plane. We can set the 95% C.L. bounds

$$M_h > 33.2 \text{ GeV} \quad \text{and} \quad M_A > 42.1 \text{ GeV}.$$

SEARCH FOR CHARGINOS AND NEUTRALINOS

In the Minimal Supersymmetric Standard Model (MSSM) the 6 superpartners of the gauge bosons and Higgs have to be looked for. They are :

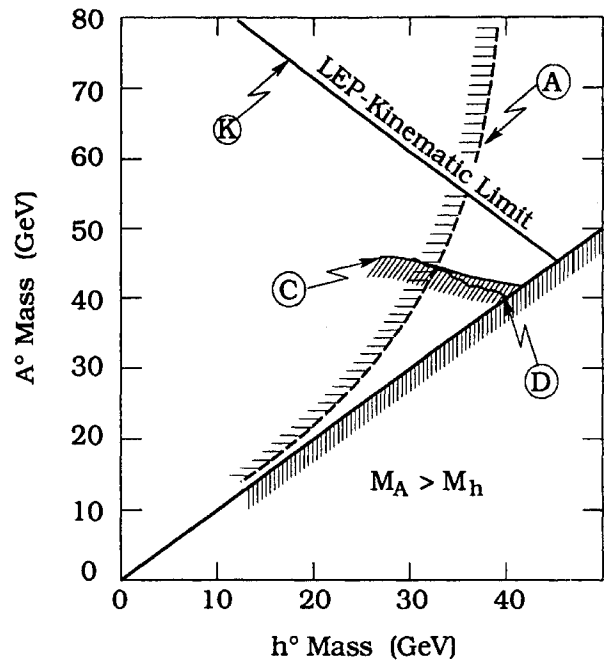* the $W^\pm$ and $H^\pm$ partners who mix to form 2 charginos: $\chi^\pm$ is the lightest.

Fig.3 : Excluded domains in the M_h, M_A plane for tgβ > 1 (see text).

* the Z^o and neutral Higgs partners who mix to form 4 neutralinos : χ is the lightest and χ' anyother one. The lightest of χ and $\chi^\pm$ has to be stable. Only two additional parameters M , and μ are needed to describe this sector.

I - Search for charginos $(M_{\chi^\pm} > M_\chi)$

Charginos are pair produced in the reaction $e^+e^- \rightarrow Z \rightarrow \chi^+\chi^-$. We search for their semileptonic decay into the lightest stable neutralino : $\chi^\pm \rightarrow \ell^\pm\chi\nu$ (branching fraction $\sim$ 10%). The selection requires the observation of an acoplanar lepton pair associated with missing energy [5]. For 72000 hadronic Z decays this set a 95% lower limit on $M_{\chi^\pm}$ which ranges from 45.0 to 46.9 GeV (for M_χ < 20 GeV) depending upon the chargino mix-

II - Search for neutralinos

Neutralinos are pair produced through the decays $Z \rightarrow \chi\chi'$ and $\chi'\chi'$. If χ is the lightest superpartner it is stable, while two χ' decay possibilities are considered as described in ref.6 :

• $\chi' \rightarrow \chi f \bar{f}$: the selection looks for a lepton or jet acoplanar pair with missing energy or, in order to cover the case where χ and χ' are both lights, it searchs for monojet events.

• $\chi' \rightarrow \chi\gamma$: the selection requires one or two acoplanar γ. The lower branching ratio expected for this mode is compensated by the advantage of a much cleaner selection.

No events are selected for 101000 hadronic Z decays.

Additional constraints [6] on the neutralino masses can be pull out from the Z line shape measurements. Decays like $Z \rightarrow \chi\chi$ should contribute to the invisible width while $Z \rightarrow \chi\chi', \chi'\chi', \chi^+\chi^-$ may be visible, depending on the masses but independently of the $\chi, \chi', \chi^{\pm}$ decay mode. In particular we can also exclude cases where $\chi^{\pm}$ is the lightest superpartner.

The direct search and the line shape constraints set a 95% C.L. limit in the MSSM parameter plane M, μ given in reference 7. Unfortunatly we have no space to reproduce it in this written report. The result is given in the "naturality" domain ($|M|$ and $|\mu| < 2\ M_Z$) where theory expect these parameters to lie. The part of this domain kinematically accessible to LEP I $\left(M_\chi + M'_\chi \leq M_Z\right)$ is completly excluded for $\mathrm{tg}\,\beta \geq 2$.There is only room for a future improvement at LEP I, in the region $1.6 \leq \mathrm{tg}\,\beta \leq 2$. The excluded domain corresponds to the 95% C.L. limit $M_\chi > 30$ GeV.

SEARCH FOR COMPOSITNESS

Composite leptons ℓ^* have been looked for in Aleph, through their decay into a lepton-photon pair. Pair and single productions are studied. The search has been made for excited charged leptons and excited neutrinos.

Pair production : $Z \rightarrow \ell^*\ell^*$

* Excited charged leptons : the selection requires to detect an acoplanar lepton pair with two energetic γ emitted away from both leptons [7]. No candidate

is found. The standard model coupling is taken for the $Z^o \rightarrow \ell^*\ell^*$ coupling and the excited lepton is assumed to decay only into $\ell^*\gamma$. One can exclude (95% C.L.) excited electrons, muons and taus respectively below 45.6, 45.6 and 45.4 GeV.

* Excited neutrinos : events in which we observe only two acoplanar γ with missing energy are kept [8]. No candidate is found. The mass limit we can derive depends on f :

$$f = \frac{g\ (Z \rightarrow \nu^*\nu)}{g\ (Z \rightarrow \nu\nu)} \times BR\left(\nu^* \rightarrow \nu\gamma\right).$$

Depending on the excited neutrino type (Dirac, Majorana) and on the structure of the composite object, f is a priori unknown ($f \leq 1$). The expected rate depends also on the number of such neutrinos, light enough to be produced. Excited neutrinos with masses below 40 GeV are excluded (95% C.L.) if f exceeds 4.7% for 1 neutrino and 2.7% for 3 mass-degenerated neutrinos.

Another limit on excited neutrinos can be derived from their contribution to the Z total width measured from the Z line shape. Such a limit is independent on the neutrino decay mode. 95% C.L. lower limit on the excited neutrino mass are derived. For one such neutrino (resp. 3 mass-degenerated neutrinos) the limit is 35.7 GeV (resp. 44.3) for a Dirac type and 26.9 GeV (resp. 37.7) for a Majorana type.

Single production of charged leptons :
$Z \rightarrow \ell\ell^*$

The selection requires to detect an acoplanar lepton pair with one energetic photon emitted away from both leptons [7]. Events of that kind are found which originate from the radiative production $e^+e^- \rightarrow \ell^+\ell^-\gamma$. For any mass of each $\ell\gamma$ pair, the level of observed events is compared to the sum background + expected number of excited leptons.

The branching ratio $BR\left(Z \rightarrow \ell\ell^*\right)$ depend on the ratio of the magnetic coupling constant λ (introduced through a phenomenological lagrangian) to the lepton mass $m_\ell *$. For values of $\lambda/m_{\ell*}$ ex-

ceeding 2 10^{-3} one can exclude (95% C.L.) excited electrons, muons and taus respectively below 84, 84 and 78 GeV.

Search for excited electrons can also be performed by looking to their production through the quasi-real compton scattering ; $\gamma e \to e^* \to \gamma e$ where the incident γ is a hard initial-state bremsstrahlung photon. $e\gamma$ events satisfying the kinematic of this process are selected. As before, for values of $\lambda/m_e{}^*$ exceeding 2 10^{-3}, one can exclude (90% C.L.) excited electron below 90 GeV.

CONCLUSION

From a sample of 100 000 hadronic Z decays, Aleph has made negative searches for the following particles.

In the framework of the Minimal Supersymmetric Standard Model we have derived the limit :

$$\text{tg}\,\beta > 1.60 \quad \text{or} \quad \text{tg}\,\beta < 0.63$$

For $\text{tg}\,\beta > 1$ we set limits on the neutral Higgs masses :

$$M_h > 33.2 \text{ GeV} \quad \text{and} \quad M_A > 42.1 \text{ GeV}$$

Most of the kinematically accessible domain of LEP I is excluded with respect to the production of charginos ($M_{\chi^\pm} > 45$ GeV), neutralinos ($M_\chi > 30$ GeV) and composit charged leptons and neutrinos.

References

1. Search for the standard Higgs boson in Aleph, O. Callot this conference report.

2. A search for pair-produced charged Higgs bosons in Z° decays, Phys. Lett. B241 (1990) 623.

3. Search for very light boson in Z decays, Phys. Lett. B245 (1990) 289.

4. Search for neutral Higgs bosons from supersymmetry in Z decays, Phys. Lett. B237 (1990) 291.

5. Search for supersymmetric particles using acoplanar charged-particle pairs from Z° decays, Phys. Lett. B236 (1990) 86.

6. Search for neutralino production in Z decays, Phys. Lett. B244 (1990) 541.

7. Search for excited leptons in Z° decay, Phys. Lett. B326 (1990) 501.

8. Search for excited neutrinos in Z° decay, CERN-EP preprint 90-107, submitted to Phys. Lett. B.

Search for Higgs Bosons
using the OPAL detector at LEP

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Abstract

Using data from e^+e^- collisions at LEP, recorded by the OPAL detector, a search has been made for evidence of Higgs bosons produced by the reactions $e^+e^- \rightarrow (e^+e^-, \mu^+\mu^-, \nu\bar{\nu}, \text{ or } \tau^+\tau^-) + H^0, H^0 \rightarrow (q\bar{q} \text{ or } \tau^+\tau^-)$. No candidates were observed in a sample of approximately 8 pb^{-1} of data taken at centre of mass energies between 88.2 and 95.0 GeV. The existence of a Standard Model Higgs boson with mass in the range $3 < m_H < 44$ GeV/c^2 is excluded at the 95% confidence level. The same search limits the allowed mass ranges for Higgs bosons predicted by the Minimal Supersymmeteric Model.

1 Introduction

The Standard Model of electroweak interactions[1] requires the existence of one or more scalar particles,the Higgs bosons[2], which have not yet been observed. The minimal Standard Model(MSM) predicts a single Higgs of unspecified mass m_H with well-defined couplings to point-like bosons and fermions, which could be produced in e^+e^- collisions in association with a virtual Z^{0*}. The searches presented here exploit the distinctive signatures which result when the Higgs decays into $b\bar{b}, c\bar{c}$ or $\tau^+\tau^-$, while the Z^{0*} decays to $\nu\bar{\nu}, e^+e^-$ or $\mu^+\mu^-$. Masses in the range $0.0 < m_H < 0.2$ GeV/c^2 and $3.0 < m_H < 25.3$ GeV/c^2 have already been excluded by this experiment in earlier publications[3,4], and to date this and other experiments have excluded the range $0.0 < m_H < 41.6$ GeV/c^2 at the 95% confidence level.[3,4,5,6,7,8,9]. Models with 2 Higgs doublets[10] predict more Higgs bosons,including a charged Higgs pair on which this experiment has set mass limits[4]. In the specific case of the minimal Supersymmetric model, only a light scalar h^0 and possibly a CP-odd scalar A^0 would be accessible at LEP 1. Limits on their production have been set by this collaboration in a previous publication[11], and are here extended by applying the MSM search procedure to the channel $e^+e^- \rightarrow Z^0 \rightarrow h^0 Z^{0*}$.

This analysis used data accumulated by the OPAL detector during the 1989 and 1990 scan of the Z^0 resonance. The sample corresponds to an integrated luminosity of 8.0pb^{-1}, or about 170,000 reconstructed multihadron events.[1]

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[1]5.2pb^{-1} had been analysed before presentation in Singapore

2 The OPAL detector

OPAL[12] is a versatile apparatus for LEP physics combining good hermeticity and total energy resolution with good lepton identification. It is centred around a system of cylindrical tracking chambers,situated inside a solenoidal coil which provides a magnetic field of 0.435 Tesla. This central detector is surrounded by a time-of-flight counter array and a lead-glass electromagnetic calorimeter with a presampler. Beyond these is an iron magnetic flux return yoke, instrumented to act as a hadron calorimeter , and covered by four layers of muon tracking chambers. The endcap system incorporates a low angle forward detector, which measures luminosity with a systematic error of better than 2.2%[13] using small angle Bhabha scattering. The overall coordinate system is defined with z along the positron beam direction, θ and ϕ being the polar and azimuthal angles.

3 Event Selection and Simulation

Several basic properties were required of each event to ensure that it was well measured, had a high final state multiplicity , and did not originate from a beam-gas or beam-wall interaction. At least five tracks, one with a transverse momentum $p_T > 100$ MeV/c, were required to originate from the interaction region and to be well-measured by the central tracking chambers. These good tracks had to form more than 20% of the total number.

At least five electromagnetic energy clusters were also required; furthermore not more than 2 GeV of energy deposit was permitted in the forward detectors. Higgs boson production and decay was simulated[4] using the Berends and Kleiss Monte Carlo[14], incorporating the improved Born approximation[15] and the top quark triangle graph at the $Z^0 Z^{0*} H^0$ vertex[16] (leading to a negligible dependence on the top quark mass).The decay branching ratios included QCD corrections[17]. The multihadronic background was simulated using the JETSET7.2 Monte Carlo[18]. Signal and background events were further processed by a program simulating the response of the OPAL detector.

4 Missing Energy Search

In events of the type $e^+ e^- \rightarrow Z^{0*} H^0$, $Z^{0*} \rightarrow \nu\bar{\nu}$, $H^0 \rightarrow q\bar{q}$, the invisible final state neutrino energy provides an obvious detection signature. To ensure that events were sufficiently well contained for the missing energy to be adequately measured, and to remove tau pair events, less than 35% of the electromagnetic energy was permitted to be within cones of $|cos\theta| > 0.90$, and the event thrust was required to be less than 0.95. The total 4-momentum of each event was calculated from the measured tracks, and from energy clusters in the electromagnetic and hadron calorimeters,correcting for double counting of charged tracks. This yields a missing momentum vector p_{miss}, which was required to satisfy $|cos\theta_{pmiss}| < 0.90$.

The mass distribution of the remaining events, normalised to the centre-of-mass energy, showed that most were due to multihadronic decays of the Z^0. Apart from some two-photon contribution at low mass, this mass distribution was well reproduced by the multihadron Monte-Carlo simulation. In order to suppress the multihadron background and exploit the acollinear topology of the $\nu\bar{\nu}H^0$ final state, events were divided into two hemispheres and the 4-momentum of each half summed as previously described. For all events with energy > 3 GeV in each hemisphere, the momentum vectors of the two hemispheres were required to be acollinear ($> 26°$) and acoplanar ($> 16°$). This effectively removed most two-jet events. Two-photon events were eliminated by requiring that the total transverse momentum with respect to the beam axis exceeded 6 GeV/c. Next the missing energy signature was emphasised by requiring that the summed track momenta and cluster energies

within $30°$ of the missing momentum vector be less than 2 GeV. This eliminated mis-matched multijets and heavy flavour decays. No events remained with a normalised mass below 0.62, which is already incompatible with $m_H \leq 50$ GeV/c^2. However to retain sensitivity to higher masses, no mass cut was applied. The remaining high mass events (mostly asymmetric three- and four- jet types) also had high masses in at least one hemisphere, in contrast with the low mass heavy quark jets expected from Higgs boson decay. They were all removed by requiring either that the average mass of the two hemispheres was less than 12.5 GeV/c^2 (consistent with b-quark jets), or that the lower of the two hemisphere energies be less than 3 GeV (consistent with a monojet). The overall efficiency of this selection for detecting a simulated Higgs boson of mass 40 GeV/c^2 in the missing energy channel was 59%.

5 Search for Isolated Lepton Pairs

After the same general selection cuts, a search was made for events of the type $Z^0 \rightarrow (e^+ e^-$ or $\mu^+ \mu^-) + H^0$. Pairs of well-measured, oppositely charge lepton candidates were selected, with opening angle $> 30°$ and with each track having a momentum > 5 GeV/c. The lepton selection criteria demanded that the candidate track had appropriate associated energy or hit patterns in the electromagnetic and hadron calorimeters. In addition, the summed electromagnetic energy of an $e^+ e^-$ pair or the summed scalar momentum of a $\mu^+ \mu^-$ pair was required to exceed 25 GeV/c.

Events were accepted if the two leptons were both isolated, with less than 5 GeV each of corrected electromagnetic, charged or hadronic calorimeter energy within $30°$ around each track. To allow for asymmetric Z^{0*} decays, events were also accepted if the same condition was satisfied for cones of half-angle $45°$ and $15°$, providing the lepton in the $45°$ cone had an energy exceeding 20 GeV, and that there was less than 1 Gev of unassociated energy accompanying the lepton in the $15°$ cone.

This selection eliminated all events, but extensive background studies suggested requiring less than 1 GeV/c^2 of charged momentum within $15°$ of each lepton, to make future analysis more robust. The overall efficiency of the complete selection for detecting a 40 GeV/c^2 Higgs boson in the isolated lepton pair channel is 53%.

6 Search for $Z^0 \rightarrow \tau^+\tau^-$ jet jet

To obtain a clear signature for this channel, high sphericity ($S > 0.1$) events with more than seven charged tracks were required to contain two isolated oppositely charged tracks from the single prong decays of the $\tau^+\tau^-$. Multi-jet events were rejected by requiring each isolated track to have momentum greater than 3 GeV/c, to be more than $30°$ from any other track and to have no more than 0.5 GeV of electromagnetic energy within a $15°$ to $30°$ annular region surrounding it. The $30°$ isolation cones were required to be fully contained within the fiducial region, which implies track polar angles restricted to the range $45° < \theta < 135°$. 186 events remained, for each of which the mass of the pair was less than 7.5 GeV/c^2. Requiring a minimum pair mass of 10.0 GeV/c^2 gave an overall efficiency for this selction of 5% for $H^0 \rightarrow \tau^+\tau^-$ and 8% for $Z^{0*} \rightarrow \tau^+\tau^-$, assuming a Higgs boson mass of 40 GeV/c^2.

7 Systematic Uncertainties and Mass Limits

The errors due to luminosity measurement (2.2%) and Higgs boson cross-section (2%) were common to all the analyses.

For the missing energy channel, the charged multiplicity cut introduced a sytematic error of 1.6%, due to B decay modelling uncertainties. A 2% uncertainty was attributed to fragmentation dependence based on studying the acceptance change as fragmentation and QCD parameters were varied. Imperfect simulation of the calorimeter response introduced a further 3% systematic error.

For the di-lepton search, the sytematic errors came from uncertainties in the simulation of final state radiation (1%) and of the detector response to isolated leptons (4%).

Both the above searches therefore had a combined systematic error of 5%. For the $Z^0 \rightarrow \tau^+\tau^-$ jet jet channel, which made a relatively small contribution to the final mass limit, a 10% systematic uncertainty was estimated[4]. The expected numbers of observed events, reduced by their respective systematic errors, are shown in Fig 1, as a function of Higgs boson mass, for each channel separately and for the combination of all channels.
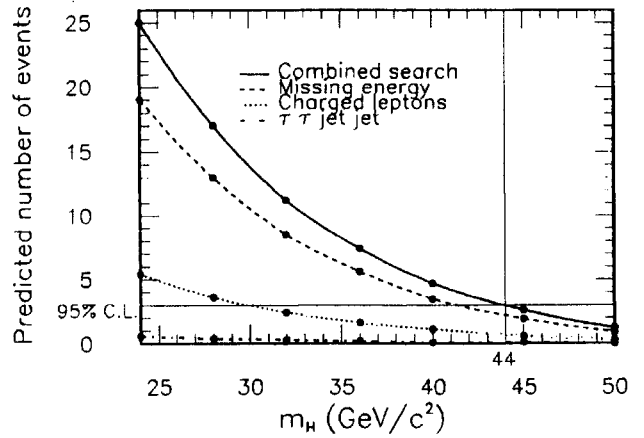

Figure 1: Expected Number of Events as a Function of the Higgs Boson Mass

A minimal standard model Higgs boson is excluded for $m_H < 44$ GeV/c^2 at the 95% confidence level.

Applying the null result to the search for the light supersymmetric Higgs scalar h^0 yields an excluded region in the plane defined by the mass of the h^0 and the ratio $\tan\beta$ of the vacuum expectation values of the two Higgs doublets. This is shown in Fig. 2, which incorporates results from our previous publications[3,4].
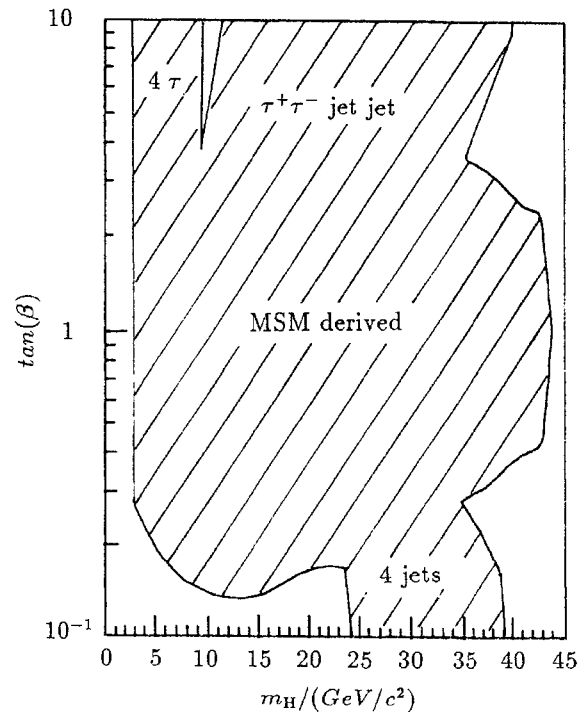

Figure 2: Excluded Region in the $m_H - \tan\beta$ plane for MSSM Higgs Boson

8 Conclusion

The existence of a minimal Standard Model Higgs boson has been excluded at the 95% confidence level in the mass range $3 < m_H < 44\ GeV/c^2$. Limits on the existence of minimal supersymmetric Higgs bosons have been extended. The searches were limited by available statistics and should remain sensitive for higher Higgs masses as the OPAL experiment collects more data.

9 Acknowledgements

10 References

[1] S.L.Glashow,J.Iliopoulos and L.Maiani, *Phys.rev.* **D2** (1970)1285; S.Weinberg, *Phys.Rev. Lett* **19** (1967) 1264; A. Salam, *Elementary Particle Theory*, ed. N. Svartholm (Almquist and Wiksells,Stockholm,1969),p.367.

[2] P.W. Higgs, *Phys. Lett.* **12** (1964) 132; F.Englert and R. Brout, *Phys.Rev.Lett.* **13** (1964) 321; G.S.Guralnik,C.R.Hagen and T.W.Kibble, *Phys.Rev.Lett* **13** (1964) 585.

[3]OPAL Collaboration, M.Z. Akrawy et al., CERN-PPE/90-116 (1990) (*submitted to Phys.Lett B*)

[4]OPAL Collaboration, M.Z. Akrawy et al., CERN-EP/90-100 (1990) (*submitted to Zeit. Phys. C*)

[5]OPAL Collaboration, M.Z. Akrawy et al., *Phys. Lett.* **B236** (1990) 224.

[6]ALEPH Collaboration, D.Decamp et al., *Phys. Lett.* **B236** (1990) 233; *Phys. Lett.* **B241** (1990) 141; *Phys. Lett.* **B246** (1990) 306.

[7]DELPHI Collaboration, P.Abreu et al., CERN-EP/90-44 (1990).

[8]ALEPH Collaboration, D.Decamp et al., *Phys. Lett.* **245** (1990) 289.

[9]L3 collaboration, B. Adeva et al., L3 preprint 10 (1990); L3 preprint 19 (1990)

[10]S.Dawson,J.F.Gunion,H.E.Haber and G.L.Kane, *The Higgs Hunter's Guide* ,BNL-**41644** , (1989), *submitted to Phys. Rep.*

[11]OPAL Collaboration, M.Z. Akrawy et al., CERN-EP/90-38 (1990).

[12]OPAL Collaboration, K.Ahmet et al., CERN-PPE/90-114 (1990) , *submitted to Nucl.Instr.and Meth.*

[13]OPAL Collaboration, M.Z. Akrawy et al., *Phys. Lett.* **B240** (1990) 497.

[14]F.A. Berends and R. Kleiss, *Nucl. Phys* **B260** (1985) 32.

[15]M.Consoli and W.Hollik, CERN 89-8,**V.1**,p.39.

[16]Z.Hioki, *Phys. Lett.* **B224** (1989) 417.

[17]F.Braaten and J.P.Leveille, *Phys.Rev* **D22** (1980) 715; N.Sakai, *Phys. Rev.* **D22** (1980) 2220; T.Inami and T.Kubota, *Nucl.Phys.* **B179** (1981) 171; M.Drees and K.Hikasa, *Phys.Lett.* **B240** (1990) 455.

[18]T.Sjostrand, *Comp.Phys.Comm.* **39** (1986) 347; *Comp.Phys.Comm.* **43** (1987) 367; M.Bengtsson and T.Sjostrand, *Nucl.Phys.* **B289** (1987) 810.

SEARCHES FOR NEW PARTICLES WITH THE OPAL DETECTOR AT LEP

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ABSTRACT

Results of searches for new particles with the OPAL detector at LEP are presented. We have looked for new heavy quarks and leptons, excited leptons, and supersymmetric partners of leptons and gauge bosons. No evidence for new particle production is observed, allowing limits to be placed on Z^0 branching ratios and on new particle masses. Limits are also placed on Z^0 decays that produce one or more highly energetic photons.

INTRODUCTION

The large numbers of Z^0 decays observed in the first year of data taking at the LEP e^+e^- collider allow sensitive searches for new physical phenomenon to be carried out. Reported here are direct searches for new particles, for rare or forbidden decays of the Z^0, and for compositeness of the Z^0. Searches for Higgs bosons, expected both in the Standard Model and in its minimal supersymmetric extension, have also been performed and are described elsewhere in these proceedings [1].

OPAL is a general-purpose 4π detector [2] with charged particle tracking provided by three central drift chamber systems within a solenoidal magnetic field of 0.435 T and electromagnetic calorimetry provided by lead-glass blocks. The instrumented magnet return yoke provides hadron calorimetry and muon detection, with 4 layers of additional muon tracking beyond the calorimetry.

NEW HEAVY QUARKS

The Standard Model predicts the existence of a top quark, the isodoublet partner of the bottom quark. It also accommodates a fourth-generation quark b' that is lighter than the top quark. We have searched [3] for the decays $t \to bW$, $t \to bH$, $b' \to cW$, $b' \to bg$, $b' \to b\gamma$, and $b' \to cH$, where the charged Higg particle H is assumed to have a mass greater than 23 GeV and to decay predominantly into $c\bar{s}$ final states.

Production of a heavy t or b' quark in Z^0 decays at LEP would give rise to an excess of multihadronic events with large sphericalness, which we quantify by the variable

$$A = 4\,\mathrm{Min}\left[\sum_i |P^i_\perp| / \sum_i |P^i|\right]^2$$

where $P^i_\perp$ is the momentum component of particle i perpendicular to the direction yielding the minimum of A. Figure 1 shows the observed acoplanarity distribution for multihadronic events, along with the expectation from 5 quarks and from a top quark with a mass of 35 GeV.

Requiring $A > 0.25$ leaves 107 events in the data compared with 92 expected from five quarks. For comparison, a t quark with a 35 GeV mass decaying to the b would produce
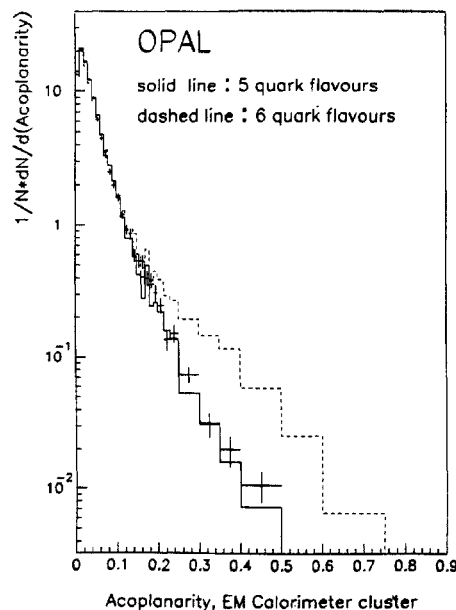

Figure 1. Distribution in acoplanarity of hadronic events for the data (points), for the five-quark expectation (solid) and for a top mass of 35 GeV.

230 events with $A > 0.25$. From these results, one obtains the 95% confidence level (CL) preliminary mass limits shown in table 1.

Table 1. Lower limits (95% CL) on the mass (GeV) of a sixth quark derived from an acoplanarity analysis.

| $t \to bW$	$b' \to cW$	$b' \to bg$	$b' \to b\gamma$	$t \to bH$	$b' \to cH$
45.1	45.1	45.4	41.1	45.3	45.5

For the production of b' followed by the decay $b' \to b\gamma$, one can look directly for the associated photon, which will in general be highly energetic and isolated. We have searched [4] for isolated photons with a momentum transverse to the event thrust axis greater than 10 GeV in a sample of 77000 multihadronic events. 44 events are observed with 38.8 events expected from final state quark radiation and from neutral hadron backgrounds. The good agreement leads to the following preliminary limit on b' production and decay:

$$\frac{\Gamma(Z^0 \to b' + \bar{b}')}{\Gamma(Z^0 \to hadrons)} \cdot BR(b' \to \gamma + X) \le 8.7 \times 10^{-4}$$

NEW HEAVY LEPTONS

A straightforward extension of the Standard Model allows for a fourth generation lepton doublet consisting of a heavy, unstable charged lepton and a neutrino partner which may be massive. In both hadronic and leptonic decays of the heavy lepton, one expects missing energy and momentum because of undetected neutrinos in the final state. Two searches [5] have been performed. The first selects events with total missing momentum transverse to the beam direction greater than 12 GeV and with visible energy less than 55 GeV, where the thrust must be less than 0.95 and there must be less than 2 GeV of energy within a 60° cone centered about the direction of the missing momentum. Two candidates are seen, consistent with expected multihadronic backgrounds.

The second search is for events with an isolated electron or muon, missing transverse momentum greater than 6 GeV, and an acoplanarity between the isolated lepton and the remainder of the event greater than 200 mrad. Here and in what follows, the acoplanarity of two directions is defined to be the acolinearity of their respective components transverse to the beam direction. (This is *not* the acoplanarity defined above for the heavy quark search.) No events satisfy all requirements imposed. Combining the two searches, we obtain the 95% CL limits on allowed unstable charged and stable neutral lepton masses shown in fig. 2.
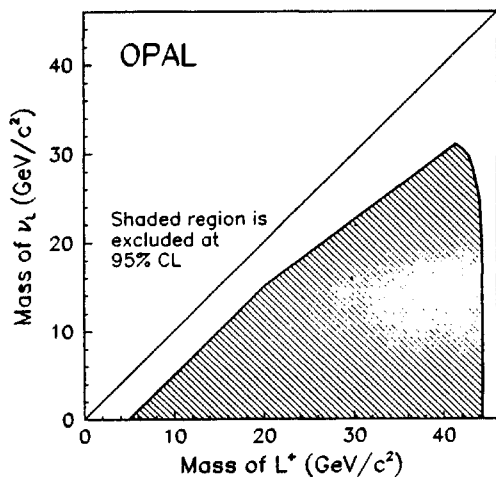
Figure 2. The shaded region indicates charged and neutral lepton masses excluded at 95% under the assumption that the neutral lepton is stable.

A less straightforward extension of the Standard Model allows for heavy unstable neutral leptons that mix with conventional light leptons. In the simplest model, the mixing occurs only in the charged-current decay, with neutral-current decay forbidden by the GIM mechanism. In other models neutral-current mixing is permitted, giving rise in addition to single production in association with light neutrinos. We have searched [6] for pair and single production, allowing for neutral current decay in both cases. Again, two searches are used, one based on missing energy and transverse momentum, the other based on the presence of an isolated lepton and another isolated particle, with requirements similar to those used in the heavy charged lepton search. Limits are placed on the fractional decay widths $\Gamma(Z^0 \to L^0\bar{L}^0)/\Gamma(Z^0 \to q\bar{q})$ and $\Gamma(Z^0 \to \nu\bar{L}^0 or \bar{\nu}L^0)/\Gamma(Z^0 \to q\bar{q})$, as shown in fig. 3. Because

of finite-lifetime effects, the limits shown for pair production assume a mixing parameter squared greater than 5×10^{-7} at $M_L = 20$ GeV, dropping to 10^{-9} at $M_L = 45$ GeV. Limits are shown for the charged- and neutral-current decays separately, assuming in each case that the decay proceeds strictly in that channel.
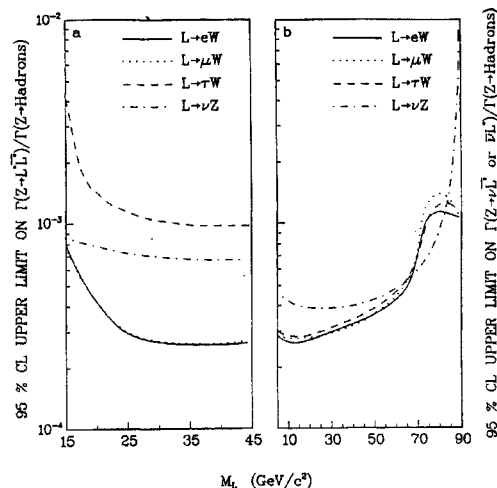
Figure 3. Upper limits (95% CL) on the fractional widths $\Gamma(Z^0 \to L^0\bar{L}^0)/\Gamma(Z^0 \to q\bar{q})$ and $\Gamma(Z^0 \to \nu\bar{L}^0 or \bar{\nu}L^0)/\Gamma(Z^0 \to q\bar{q})$ *vs* neutral lepton mass for various decay channels of the heavy lepton. In each charged-current decay, the coupling to the respective conventional lepton flavor is assumed to be 100%.

EXCITED QUARKS AND LEPTONS

We have searched [7] for production of excited leptons l^*, decaying via $l^* \to l\gamma$, both in pair production $e^+e^- \to l^*l^* \to ll\gamma\gamma$ and in single production $e^+e^- \to ll^* \to ll\gamma$. In addition, we have looked for evidence of e^* production in the process $e^+e^- \to (e^\pm)e^\mp\gamma$, where one electron scatters at small angles and escapes detection.

The effective Lagrangian for the magnetic transition of spin $\frac{1}{2}$ excited leptons to ordinary leptons is most simply expressed as

$$L_{eff} = \sum_{V=\gamma,Z^0} \frac{e}{\Lambda}\frac{f}{4}\bar{l}^*\sigma^{\mu\nu}c_V(1-\gamma^5)l F^V_{\mu\nu} + H.C.$$

where $C_\gamma = 2$, $C_{Z^0} = \cot\theta_W - \tan\theta_W$, and f/Λ describes the strength of the coupling. Radiative dilepton events are chosen where the photon candidate(s) must have at least 10% of the beam energy and be isolated from tracks and other electromagnetic showers by at least 10° (15°) for e,μ (τ).

We see no $e^+e^-\gamma\gamma$ events, one $\mu^+\mu^-\gamma\gamma$ and no $\tau^+\tau^-\gamma\gamma$ events, yielding lower limits on m_{e^*}, m_{μ^*}, m_{τ^*} of 44.9 GeV at 95% CL. For single l^* production, we observe 29 $e^+e^-\gamma$, 19 $\mu^+\mu^-\gamma$, and 27 $\tau^+\tau^-\gamma$ events, where we expect 31.3 ± 0.6, 21.8 ± 1.6, and 25.9 ± 3.0 events, respectively, from conventional backgrounds. Two $e^\pm\gamma$ events are seen, consistent with the 2.6 ± 0.2 events expected from radiative Bhabha scattering. The good agreement between expectation and observation permits placing the 95% CL limits on m_{l^*} and f/Λ shown in fig. 4.
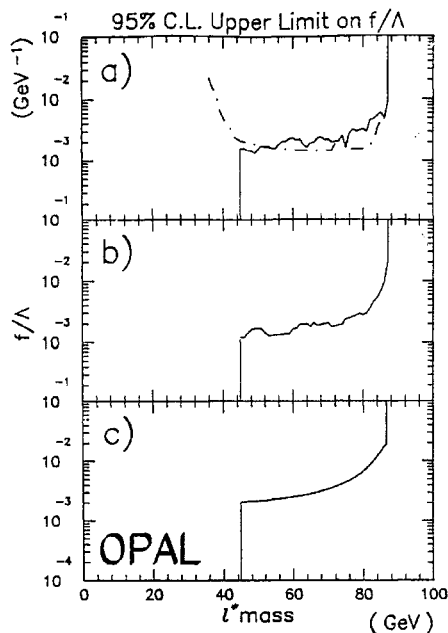
Figure 4. Upper limits on the coupling f/Λ vs the mass of the excited leptons: a) e^*, b) μ^*, and c) τ^*. The dash-dotted limit in a) is derived from $(e^\pm)e^\mp\gamma$ events.

Figure 5. a-c) Mass limit (95% CL) contours for right-handed sleptons and photinos. d) exclusion contours for chargino mass and chargino hadronic branching ratio. Curves labelled a and c assume zero photino mass; curves b and d assume a photino mass of 20 GeV.

SUPERSYMMETRIC PARTICLES

Supersymmetry (SUSY) predicts a large number of new particles, many of which could, in principle, be produced at LEP energies. We have searched [8] for pair production of scalar leptons (partners of charged leptons) $\tilde{l}$ ($=\tilde{e},\tilde{\mu},\tilde{\tau}$) and of charginos $\chi^\pm$ (partners of charged W and Higgs bosons). Each type of particle is expected to decay into final states containing conventional particles and the photino $\tilde{\gamma}$, which is assumed to escape detection. One thus expects events with large missing energy and momentum, as for heavy charged lepton production. We search for four topologies: acoplanar electron pairs, muon pairs, low-multiplicity pairs of jets, and pairs of high-multiplicity jets. The first three are sensitive to slepton production and to purely leptonic decays of the chargino, the last to hadronic decays of the chargino. Acoplanarity requirements are 10° for the electrons, 20° for the muons and low-multiplicity jets, and 50° for the high-multiplicity jets. No events are observed for the first three searches, while 11 are seen for the fourth, consistent with the 12±4 events expected from hadronic Z^0 decays. Figure 5a-c shows the resulting limits on right-handed $m_{\tilde{l}}$ and $m_{\tilde{\gamma}}$ (mass limits on left-handed and degenerate-mass sleptons are slightly higher). Since the hadronic and leptonic branching ratios of the chargino are not uniquely defined, we show in fig. 5d resulting limits on $m_{\chi^\pm}$ for arbitrary hadronic branching ratios and for two values of the photino mass (0 and 20 GeV). The three leptonic decay widths are assumed to be equal.

We have also searched [9] for neutralinos, the SUSY partners of neutral gauge vector and Higgs bosons, where the lightest of the neutralinos is believed to be stable and undetectable. We therefore look for $e^+e^- \rightarrow \chi\chi'$ where χ and χ' are the lightest and next-to-lightest neutralinos, respectively, and where $\chi' \rightarrow \chi f\bar{f}$ and $\chi' \rightarrow \chi\gamma$ are the assumed dominant decay modes ($f\bar{f}$ are fermion-antifermion pairs). Again, the undetected χ particles lead to events with large missing energy and momentum.

A jet-finding algorithm is applied to each event and the resulting number of jets required to be two, where both jets
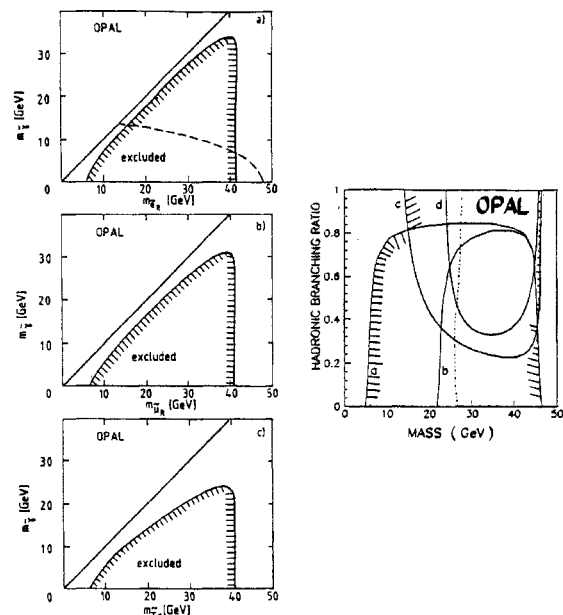
must have at least 1 energetic charged particle and a direction not too near the beam direction($|cos\theta| < 0.8|$), and where the acoplanarity between the two jets must be greater than 25°. In addition, the total visible energy must be less than half the c.m. energy, and the missing transverse momentum must be greater than 5 GeV. No candidates satisfy these requirements.

The decay $\chi' \rightarrow \chi\gamma$ leads to the dramatic signature of a single energetic photon. We demand exactly one electromagnetic shower with energy greater than 10 GeV, no other shower with energy greater than 2 GeV, and no accepted tracks in the central drift chamber. To remove cosmic-ray backgrounds, it is required that there be no signals in the muon chambers or hadron calorimeter indicating the passage of a muon. In addition, the shape of the electromagnetic shower must be consistent with that of a photon originating from the beam collision point. With these requirements, one candidate event is observed ($E_\gamma = 11$ GeV), consistent with the 0.6 events expected from the background $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. To obtain limits on $B(Z^0 \rightarrow \chi\chi')$ independent of the relative branching ratios of $\chi' \rightarrow \chi f\bar{f}$ and $\chi' \rightarrow \chi\gamma$, we combine the two analyses. For each point in the $(m_\chi, m_{\chi'})$ plane, the value of $B(\chi' \rightarrow \chi\gamma)$ that gives the worse limit on $B(Z^0 \rightarrow \chi\chi')$ is taken. The resulting conservative limits on $B(Z^0 \rightarrow \chi\chi')$ are shown in fig. 6.

RARE OR FORBIDDEN Z^0 DECAYS

Z^0 decays that produce highly energetic photons could indicate new physical phenomena. We have searched [10] for the forbidden decay $Z^0 \rightarrow \gamma\gamma$, for the rare decays $Z^0 \rightarrow \gamma\pi^0$, $Z^0 \rightarrow \gamma\eta$, and more generally, for the decay $Z^0 \rightarrow \gamma X$, where X is a multihadronic final state.

The cleanest signature for $Z^0 \rightarrow \gamma\gamma$, $Z^0 \rightarrow \gamma\pi^0(\pi^0 \rightarrow \gamma\gamma)$, and $Z^0 \rightarrow \gamma\eta(\eta \rightarrow \gamma\gamma)$ is quite dramatic. One expects two back-to-back electromagnetic showers, each containing the full beam energy, with no charged tracks present.
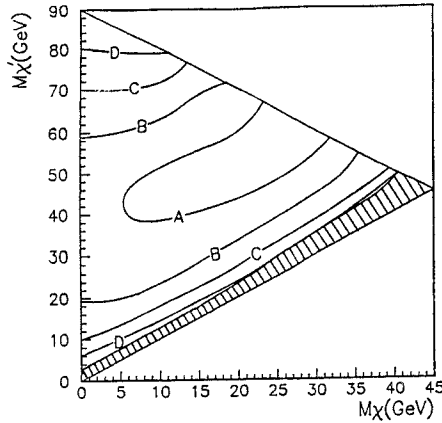
Figure 6. Upper limit (95% CL) on $B(Z^0 \to \chi'\chi)$ for $m_{\chi'}$ vs m_χ: contours A) 1.5×10^{-4}, B) 2.0×10^{-4}, C) 3.0×10^{-4}, and D) 5.0×10^{-4}.

Because of the appreciable probability of photon conversion, however, the signature $e^+e^- \to \gamma(e^+e^-)$ is also considered in this analysis, where the electron pair is highly collimated. It is required there be at least two electromagnetic showers, each with $|\cos\theta| < 0.90$ and having more than 20% of the beam energy, at least one of which must be isolated by more than 45° from any charged tracks. In addition, the acolinearity angle between the two showers must be less than 5°. The QED process $e^+e^- \to \gamma\gamma$ is expected to yield 102 events satisfying all selection cuts, while 97 are observed in the data. Assuming the signal events are all from the QED process, then one obtains the cross section $\sigma_{e^+e^- \to \gamma\gamma}(|\cos\theta_\gamma| < 0.90)$ = 30.7±4.1 pb, where the QED expectation is 32.1 pb. By fitting the cross section's dependence on $\sqrt{s}$, one obtains the following 95% CL limits on the contribution from Z^0 decays: $B(Z^0 \to \gamma\gamma) < 1.3 \times 10^{-4}$, $B(Z^0 \to \gamma\pi^0) < 1.3 \times 10^{-4}$, and $B(Z^0 \to \gamma\eta) < 1.9 \times 10^{-4}$.

One may also examine the differential cross section to search for a deviation from QED expectation parametrized according to the following:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\frac{1 + \cos^2\theta}{1 - \cos^2\theta}\left(1 \pm \frac{s^2}{2\Lambda_\pm^4}(1 - \cos^2\theta)\right)$$

where $\Lambda_\pm$ are cutoff parameters of the electron propagator. Fitting the differential distribution shown in fig. 7, we obtain the lower limits $\Lambda_+ > 110$ GeV and $\Lambda_- > 95$ GeV at 95% CL.

Finally, from the search [4] for multihadronic events with isolated, energetic photons used to exclude $b' \to b\gamma$ decays, one may also place limits on the general process $Z^0 \to \gamma X$ where X is a multijet hadronic system that is assumed to decay according to phase space. We find $\Gamma(Z^0 \to \gamma X) < 3.2$ MeV at 95% CL.

CONCLUSION

No evidence is seen for the production of new particles, for any violation of QED expectation on the Z^0 resonance, or for the compositeness of the Z^0. Lower limits are placed on masses of various new particles that can be pair-produced in Z^0 decays, and simultaneous limits on masses and couplings are derived for particles that can be singly produced in Z^0 decays. Our results are in agreement with those from other searches for new phenomena in Z^0 decays carried out at LEP
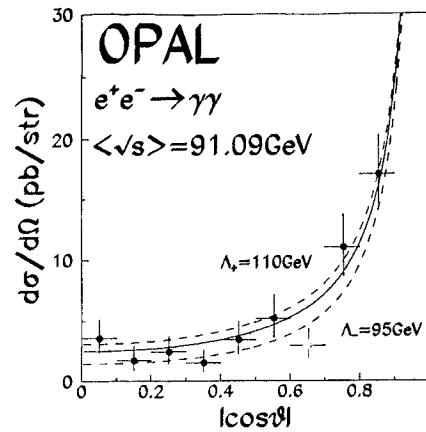
Figure 7. The measured differential cross section $d\sigma/d\Omega$ for $e^+e^- \to \gamma\gamma$ (points) and the QED expectation (solid). The dashed curves show the expectations for $\Lambda_+ = 110$ GeV and $\Lambda_- = 95$ GeV.

and SLC [11-14]. The Standard Model remains in exasperatingly good shape.

ACKNOWLEDGEMENTS

REFERENCES

1. A. Ball, these proceedings.
2. M.Z. Akrawy et al., submitted to Nucl. Instr. Meth., CERN-PPE/90-114 (August 1990).
3. M.Z. Akrawy et al., Phys. Lett. B236 (1989) 364.
4. M.Z. Akrawy et al., Phys. Lett. B246 (1990) 285.
5. M.Z. Akrawy et al., Phys. Lett. B240 (1990) 250.
6. M.Z. Akrawy et al., Phys. Lett. B247 (1990) 448.
7. M.Z. Akrawy et al., Phys. Lett. B242 (1990) 135.
8. M.Z. Akrawy et al., Phys. Lett. B240 (1990) 261.
9. M.Z. Akrawy et al., Phys. Lett. B248 (1990) 211.
10. M.Z. Akrawy et al., Phys. Lett. B241 (1990) 133.
11. A. Roussarie, (ALEPH) these proceeding.
12. B. Koene, (DELPHI) these proceedings.
13. H. Newman, (L3) these proceedings.
14. For a review of recent LEP and SLC searches, see M. Oreglia, to appear in Proceedings of the Neutrino 90 Conference, (June, 1990).

THE SEARCH FOR HIGGS

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ABSTRACT

We searched for the production of the Standard Model Higgs H° and the Minimum Super-symmetric Standard Model Higgs h° and A° in ~65,000 Z° decays observed by the L3 detector at LEP. No signature was found. We obtained the mass limit of $M_{H^\circ} > 36.2$ GeV and $M_{h^\circ}, M_{A^\circ} > 41.5$ GeV at the 95% confidence level.

Introduction

The Higgs particle, associated with the electroweak symmetry breaking mechanism of the Standard Model (SM), has been elusive. Theoretically, only the upper limit placed at ~1 TeV seems robust. The previous experimental limits for the low mass Higgs obtained by K^+ and Υ decays have been plagued by the theoretical ambiguities [1,2]. It is important to search for the Higgs particle in an experimentally clean and theoretically unambiguous process and extend its search to as high a mass as possible.

At the e^+e^- collider LEP, the Higgs H° can be searched at the Z° peak in the process

$$e^+e^- \rightarrow Z^\circ \rightarrow H^\circ + f^+f^-$$

where f^+f^- is a fermion pair originating from the decay of off-shell Z°. For f^+f^- being $\nu\bar{\nu}, e^+e^-$ and $\mu^+\mu^-$, the event has a clean signature and can be detected unambiguously. In the framework of the Standard Model, the rate can be calculated precisely [2].

In the Minimal Supersymmetric extention of the Standard Model (MSSM), the symmetry beaking is achieved by two Higgs doublets, each doublet being coupled exclusively to up-type or down-type quarks (leptons). The model has 5 physical Higgs particles, of which h° (CP-even) and A° (CP-odd) may be observed at LEP in the following processes;

$$e^+e^- \rightarrow Z^\circ \rightarrow h^\circ + A^\circ$$
$$e^+e^- \rightarrow Z^\circ \rightarrow h^\circ + f^+f^-$$

In this paper, we report a search of H° and h°/A° by using the L3 detector [3].

The L3 Detector

The L3 detector consists of a time expansion chamber (TEC) for the charged particle detection, a high resolution electromagnetic calorimeter composed of BGO crystals, an array of plastic scintillation counters, a uranium hadron calorimeter with proportional chamber readout and a high precision muon chamber system. The calorimeters cover 99% of 4π. The BGO and the muon chamber covers approximately $| \cos(\theta) |< 0.7$.

These detectors are installed in a 12 m diameter solenoidal magnet of 0.5 tesla. The beam pipe is made of two layers of beryllium, each 1.4 mm thick, constituting less than 0.01 radiation lengths of materials in front of the TEC. The detector and its performance are reported in detail in [4].

Event Selection for H°

$e^+e^- \rightarrow H^\circ + \nu\bar{\nu}, \quad M_{H^\circ} > 2$ GeV

For M_{H° above 2 GeV, H° predominantly decays into a pair of heavy quarks or τ's. The final state $H^\circ + \nu\bar{\nu}$ will be detected as a 1 or 2 jet event with large missing energy and energy imbalance due to the undetected $\nu\bar{\nu}$. The separation of H° from the main background, $Z^\circ \rightarrow$ hadrons, is shown in Fig.1.

To achieve an optimum separation of H°, we define a variable P_H from the following observables X_i.

X_1=Total Energy
X_2=Transverse Energy Imbalance
X_3=Acollinearity Angle of 2 Most Energetic Jets
X_4=Acoplanarity Angle of 2 Eenergetic Jets
X_5=Recoil Energy of 2 Most Energetic Jets
X_6=Number of Calorimetric Clusters

X_7=Number of Charged Tracks
X_8=Polar Angle of Thrust Axis

After applying loose preselection criteria, we calculate the variable $P_H = N^{sel}/N^{tot}$ for each preseleted event by using H° Monte Carlo events, where N^{tot} is the total number of generated events and N^{sel} is the number of selected H° Monte Carlo events satisfying the conditions

$$X_i^{ev} - 2\sigma_{X_i} < X_i < X_i^{ev} + 2\sigma_{X_i}$$

for i=1,8.

The value X_i^{ev} is calculated for each candidate and σ_{X_i} is pre-calculated as the r.m.s. width of the variable X_i in the H° Monte Carlo.
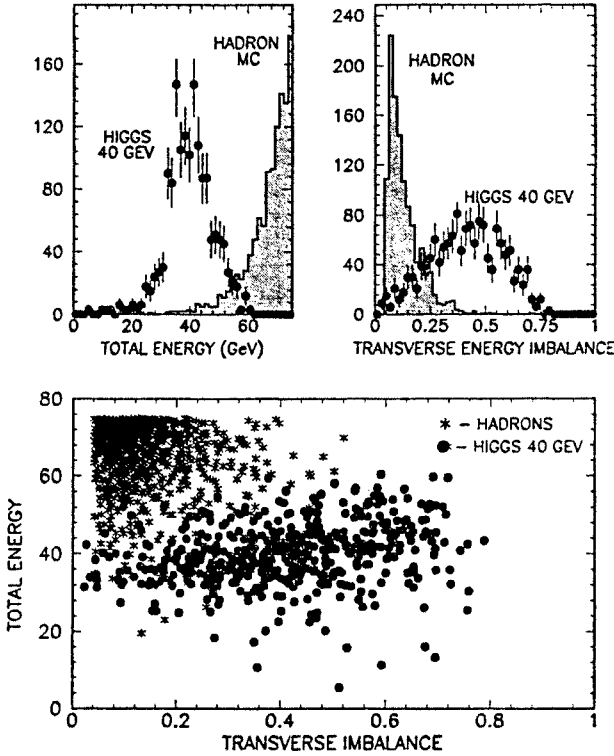

Figure.1   Separation of H° Event

The variable P_H serves for an effective single variable for the separation of H°. By construction, P_H has a large value for H° and is concentrated near 0 for the background events. After applying the cut $P_H > 0.07$, we are left with no H° candidate out of 65,000 Z° hadronic decays. The detection efficiency of this method has been calculated by the Monte Carlo and is shown in Fig.2.

$$e^+e^- \to H^\circ + (e^+e^-, \mu^+\mu^-), \quad M_{H^\circ} < 2 \text{ GeV}$$

Below the mass of 2 GeV, we expect H° to decay predominantly into a pair of hadrons or muons. The decay mechanism is dominated by the non

perturbative effects and theoretical estimates of the branching ratios are highly model dependent [2]. As the signature of leptons is very clean, we only require very loose constraints on Higgs decay products; one charged track in TEC associated with the energy deposit in BGO.

We select events with high energy and non-collinear lepton pairs. We first require two leptons with E_1 and E_2 greater than 30 GeV for e^+e^- and $P_1 + P_2$ greater than 30 GeV for $\mu^+\mu^-$, where E_1 and E_2 are the electron energies measured in BGO and P_1 and P_2 are the muon momenta measured in the muon chamber. The acollinearity angle ξ of the two leptons must be $\xi > 4^\circ$. Moreover, we require that there should be no additional energy deposit in the calorimeter besides the one by the muon itself in a 30° cone around the muon. This is to remove the background $Z^\circ \to \mu^+\mu^- +$ hadrons originating from the semileptonic decays of heavy quarks.

The detection efficiency for each decay channel, $H^\circ \to \mu^+\mu^-, KK$ and $\pi\pi$ can be reliably calculated by the Monte Carlo since our requirement on the Higgs decay products is simple. It ranges between $\sim$28% for the most efficient channel of $H^\circ \to \mu^+\mu^-$ and $\sim$15% for $H^\circ \to \pi\pi$ where the decay into $\pi^\circ\pi^\circ$ is not detected.

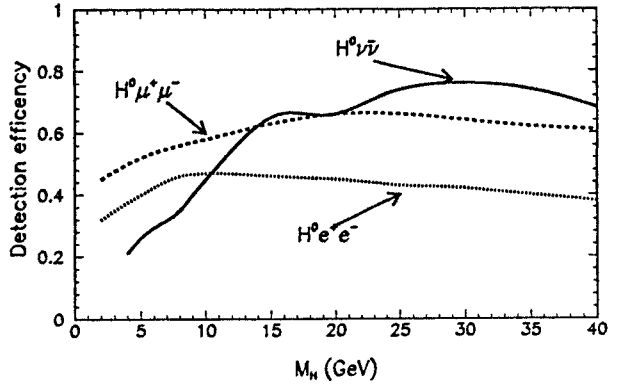We observed 4 candidates satisfying the above criteria from the data sample corresponding to 70,000 hadronic decays of Z°.

Figure.2   Detection Efficiency of $H^\circ + f^+f^-$

$$e^+e^- \to H^\circ + (\mu^+\mu^-, e^+e^-), \quad M_{H^\circ} < 2M_\mu$$

When the Higgs mass is below $2M_\mu$, the fermion decay channel is limited to $H^\circ \to e^+e^-$. Due to the quadratic mass dependence of the decay width, H° becomes long-lived and a significant fraction of the produced H°'s decays only outside of the BGO

calorimeter. As the interaction of H° with ordinary matter particles is very weak, this leads to an event with energetic and non-collinear leptons where the corresponding missing energy is not detected in the BGO. The search of H° in this mass region, therefore, must be done for l^+l^- + "nothing" in addition to the l^+l^- + "one charged track".

We require two energetic leptons with E_1 and E_2 greater than 30 GeV for e^+e^- and $P_1 > 10$ GeV and $P_2 > 30$ GeV for $\mu^+\mu^-$. The acoplanarity angle Δ_ϕ must be greater than 2.9°. There should be no energy detected besides the one associated with leptons in the first 22 radiation lengths of the calorimeters. To remove the contamination of $l^+l^-(\gamma)$ events, we also require the missing momentum vector reconstructed from l^+l^- to be more than 8° away from any two leptons and greater than 35° from the beam line.

With the above cuts, we saw no events for the data sample corresponding to 70,000 hadronic Z° decays. The detection efficiency calculated by the Monte Carlo is 13-18% depending on $M_{H°}$.

Limits on H° Mass

$\underline{M_{H°} \text{ above } 2 \text{ GeV}}$;   The number of expected H° events satisfying above selection criteria is shown in Fig.3 for $Z° \rightarrow H° + \nu\bar\nu$ and $Z° \rightarrow H° + l^+l^-$ [5]. We have reduced the expected number by 9% to take into account the systematic error mainly due to the uncertainty in estimating the detection efficiency. We found no candidate in this mass region and exclude 2.0 GeV $< M_{H°} < 36.2$ GeV at 95% c.l..
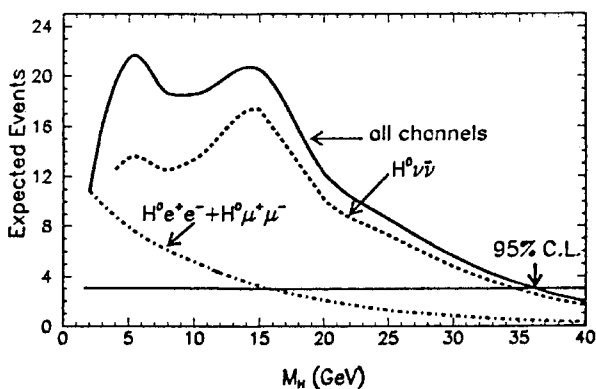

Figure.3   Number of Expected Events

$2M_\mu < M_{H°} < 2$ GeV;   We found 2 candidates; one $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ event with an invariant mass of ~0.6 GeV and another event of $e^+e^- \rightarrow$

e^+e^- + two charged hadrons forming an invariant mass of ~1.0 GeV. The probability to observe these two events from the expected number of H° events shown in Fig.4 is less than 1% for any combination of the branching ratios into $\mu^+\mu^-$, $\pi\pi$ and KK. We exclude the region $2M_\mu < M_{H°} < 2$ GeV at 99% c.l.. Both candidate events are consistent with the 4 fermion decay of Z°.

$M_{H°}$ below $2M_\mu$;   We found two $e^+e^- \rightarrow e^+e^-e^+e^-$ events with invariant mass of ~80 MeV. From the expected number of H° events shown in Fig.5, we exclude the region of $0 < M_{H°} < 2M_\mu$ at the 99% c.l.. The observed two candidates are consistent with $e^+e^- \rightarrow e^+e^-\gamma$ events with the photon conversion in the beam pipe.
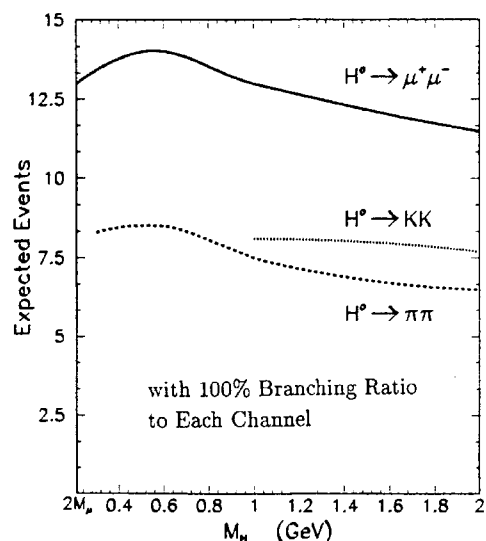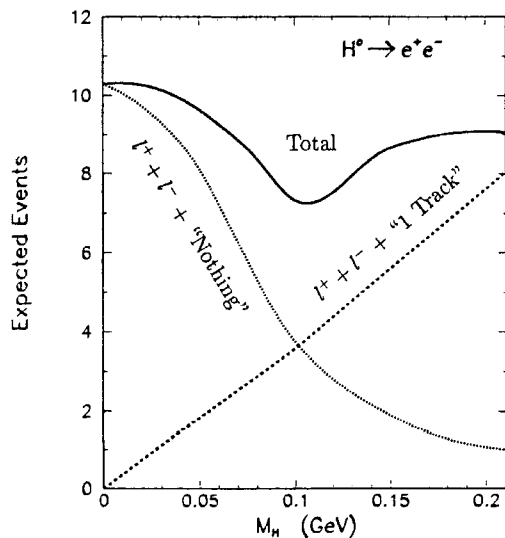

Figure.4   Number of Expected Events

Figure.5   Number of Expected Events

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Search for h° and A°

The decay branching ratio of $Z^\circ \to h^\circ + A^\circ$ is determined by the parameter $\tan\beta = v2/v1$, where v1 and v2 are the vacuum expectation values of the two Higgs doublets. For a large value of the top quark mass, $\tan\beta \gg 1$ is theoretically favoured. The h° and A° decay predominantly into $b\bar{b}$ or $\tau^+\tau^-$ in this case.

We search for the $h^\circ + A^\circ$ events in the following 4 categories;

A. The hadronic 4-jet events where the invariant masses of 2 jets fall in the search region of M_{h° and M_{A°. $(b\bar{b}b\bar{b})$

B. The low thrust hadronic events associated with 2 muons from the semileptonic decay of the b quarks. $(b\bar{b}b\bar{b})$

C. The events with two narrow jets in one hemisphere recoiling against low thrust hadronic jets. $(b\bar{b}\tau^+\tau^-)$

D. The low energy hadronic events composed of 4 narrow jets. $(\tau^+\tau^-\tau^+\tau^-)$

In the data sample corresponding to 71,000 hadronic decays of Z°, we have observed no signatures of the h° and A° production. The excluded mass regions of M_{h° and M_{A° are shown as contours A-D in Fig.6.
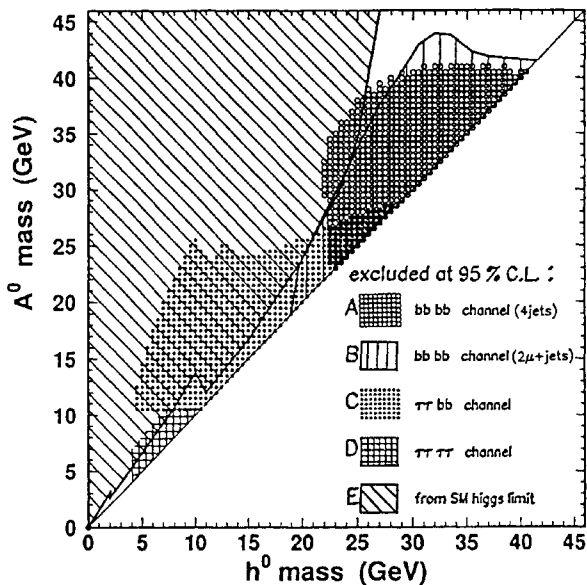

Figure.6   Excluded Region of M_{h° and M_{A°

The event signature of h° (MSSM) production in $Z^\circ \to h^\circ + f^+f^-$ is almost identical to the corresponding process of H° (SM) production. The limit obtained from $Z^\circ \to H^\circ + l^+l^-$ and $Z^\circ \to H^\circ + \nu\bar{\nu}$ can be translated into the limit of M_{h° by correcting for the difference in branching ratios [2,3]. The detection efficiencies of the h° and H° are almost identical except for the $h^\circ + \nu\bar{\nu}$ for $M_{h^\circ} < 11$ GeV, where the event is identified by detecting the Higgs decays into $\tau^+\tau^-$ and hadrons. The different admixture of $\tau^+\tau^-$ and hadron decays of h° compared to H° requires a correction in the detection efficiency.

The excluded region from this analysis is shown as contour E in Fig.6.

Conclusions

We have searched for the production of H° (SM) and h°/A° (MSSM) Higgs particles from the Z° decay. No signature was found. We have obtained the mass limit of $M_{H^\circ} > 36.2$ GeV and $M_{h^\circ}, M_{A^\circ} > 41.5$ GeV at the 95% confidence level. The results of M_{H° is free from the theoretical ambiguity of the Higgs decay branching ratios in the low mass region.

References

1. S. Dawson et al., "The Higgs Hunter's Guide", 1990, Addison-Weslay, Massachusetts

2. M. Drees et al., "Z Physics at LEP 1", CERN report CERN-89-08, eds. G.Altarelli et al., Vol.2 p.59.

3. Some of the results are finalized after the conference and submitted for publication.
   B. Adeva et al., "Search for the Neutral Higgs Bosons of the Minimal Supersymmetric Standard Model from Z° Decays", to be published in Phys. Lett. B,
   B. Adeva et al., "Search for a Low Mass Neutral Higgs Boson in Z° Decay", to be published in Phys. Lett. B.

4. B. Adeva et al., Nucl. Instr. and Meth. A289 (1990) 35.

5. B. Adeva et al., Phys. Lett. B248 (1990) 203.

SEARCH FOR NEW PARTICLES
IN L3 AT LEP:
BEYOND THE STANDARD MODEL

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Abstract

L3 has performed searches for new heavy sequential leptons, stable leptons, excited leptons, fourth-family neutrinos, supersymmetric particles $(\tilde{\mu}, \tilde{e}, \tilde{W}, \tilde{q})$, charged and neutral Higgs, and new families of quarks decaying via flavor changing neutral currents. While no new particles have been found, the searches have reemphasized the physics discovery potential of a detector with precision measurements of photons and leptons, combined with good resolution and granularity for hadron jets. This is illustrated by a search for new heavy resonances which decay into multiphotonic final states.

INTRODUCTION: BEYOND THE STANDARD MODEL

The opening of the era of LEP experiments, as presented at this conference [1,2,3], has re-emphasized the striking success of the Standard Model in describing the data on electroweak interactions. Because of the many fundamental questions which are left unexplained by the Standard Model – such as the lepton-quark spectrum, mass generation, the Higgs mechanism, and the large number of arbitrary parameters – the possibility of the existence of many new fundamental particles remains wide open [4,5][†].

THE L3 DETECTOR at LEP

L3 is a 4π detector which is optimized for the precision measurement of electrons, photons and muons, combined with good resolution and granularity for the measurement of hadron jets [6]. The L3 BGO crystal calorimeter measures electrons and photons with an energy resolution of $\sigma_E/E = 1.3\%/\sqrt{E} + 0.5\%$, and a position resolution of ~ 1 mm. The L3

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*Presented on behalf of the L3 Collaboration.

[†] My report focuses on L3 searches for new particles outside the Standard Model. A complementary report on L3 searches for the Standard or Supersymmetric Higgs is being presented by F. Fukushima at this session.

muon chamber system measures a 100 GeV particle decaying into a pair of muons with a mass resolution of 1.7%. A hadron calorimeter composed of uranium and brass plates interleaved with wire chambers measures hadron energy with an energy resolution of $55\%/\sqrt{E} + 5\%$, and an angular resolution for jets of $\Delta\Theta = 3.0°, \Delta\Phi = 2.5°$. Excellent electron/pion separation has been achieved by the L3 detector through:

- Precision measurement of the transverse shower shape, using the energy sharing among neighboring crystals;

- Matching the momentum measured in the inner time expansion chamber (TEC), with the energy deposited in the BGO electromagnetic calorimeter; and

- Measurement of the energy deposited in the hadron calorimeter, behind an energy cluster in the electromagnetic calorimeter.

DIRECT PARTICLE SEARCHES WITH L3

L3 has used its particular ability to measure electrons, muons and photons precisely to search for a host of new particles. The data used for the searches corresponded to an integrated luminosity of 2.2 pb^{-1}, or approximately 70,000 events taken in the region

of the Z^0. The results of many of the direct particle searches, and the corresponding 95% C.L. lower level mass limits on the existence of new charged leptons, fourth-family heavy neutrinos (Dirac or Majorana), squarks, sleptons, Winos, charged and neutral Higgs, and new heavy quarks decaying via FCNC are summarized in Table 1 [7,8,9,10,11]. As shown in the table, the limits approach the LEP beam energy for most of the particles which are pair-produced; and they approach the LEP center of mass energy for singly-produced excited leptons (with the relative coupling $\lambda = 1$) [‡]. The relationship between

Table 1: L3 Direct New Particle Searches: 95% C. L. Lower Limits (GeV)

NEW CHARGED	LEPTONS
M_{e^*} (Excited e)	45.0; 88 ($\lambda = 1$)
M_{μ^*} (Excited μ)	45.3; 85 ($\lambda = 1$)
M_{τ^*} (Excited τ)	45.5; 89 ($\lambda = 1$)
$M_{L\pm}$ (Sequential)	43.9
$M_{L\pm}$ (Stable)	38
FOURTH FAMILY	L^0 (DIRAC)
$M_{L^0}(L^0 \rightarrow \mu W^*)$	46.5
$M_{L^0}(L^0 \rightarrow e W^*)$	46.5
$M_{L^0}(L^0 \rightarrow \tau W^*)$	46.4
FOURTH FAMILY	L^0 (MAJORANA)
$M_{L^0}(L^0 \rightarrow \mu W^*)$	45.5
$M_{L^0}(L^0 \rightarrow e W^*)$	45.5
$M_{L^0}(L^0 \rightarrow \tau W^*)$	45.1
SUPERSYMMETRY	
$M_{\tilde{\mu}}$ (Smuon)	44
$M_{\tilde{W}}$ (Wino)	44
$M_{\tilde{e}}$ (Selectron)	41
$M_{\tilde{q}}$ (Squark)	45.4
HIGGS	
M_{H^0} (MSM Higgs)	36.2
M_{h^0} (MSSM Higgs)	41
M_{A^0} (MSSM Higgs)	26 (tan $\beta \approx 1$)
M_{A^0} (MSSM Higgs)	40 (tan $\beta \gg 1$)
$M_{H\pm}$ ($\rightarrow \tau$'s)	42.5
$M_{H\pm}$ ($\rightarrow$ jets)	37.5
NEW FAMILY:	FCNC
$M_{b'}(b' \rightarrow b + gluon)$	45.5
$M_{b'}(b' \rightarrow b + \gamma)$	45.5

the physics signatures, and particular detector features, is summarized in Table 2. The table illus-

[‡] In the table, the Minimal Standard Model is denoted by MSM, and the Minimal Supersymmetric Model is labeled MSSM

trates the variety of particles which may be searched for through relatively few experimental techniques, singly and in combination. Some of the most powerful techniques are (1) the identification and precise measurement of isolated leptons and photons, (2) missing energy measured in granular calorimeters with good resolution, (3) non-collinear event topologies (4) mass reconstruction of lepton-photon and multiphoton combinations in the BGO calorimeter, with high resolution and $e-\gamma-\tau$ separation provided by the inner track detector, and (5) mass reconstruction of jet-pairs and multijets in the calorimeters. A

Table 2: L3 at LEP: SIGNATURES for NEW PHYSICS

(1) Isolated e, μ, γ:
Lepton and Photon Identification;
Precise Energy Measurement

- $e^*, \mu^*, \tau^*, L^0, \tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{q},$
$L^\pm$(Stable), $L \pm$(Sequential), $H^0, H^\pm, Y^0, b'$

(2) Missing Energy:
Electromagnetic and Hadron Calorimetry

- $e^*, \mu^*, \tau^*, \tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{q}, L \pm$(Sequential), $H^0, H^\pm$

(3) Acollinearity, Acoplanarity

- $e^*, \mu^*, \tau^*, \tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{q}, L \pm$(Sequential), H^0

(4) e, γ, τ, Jet Separation:
Granular Calorimeters and Charged Tracks

- $\tau^*, H^0, H^\pm, h^0 A^0, \gamma\gamma\gamma, Y^0, b'$

(5) Mass Reconstruction in BGO:
$M(\ell\gamma), M(\gamma\gamma), ..., M(n\gamma)$

- e^*, μ^*, Y^0

(6) Mass Reconstruction in Calorimeters:
$M(Jet_1 \; Jet_2)$

- $h^0 A^0, H^\pm, b'$

(7) Event Shapes Measured in Calorimeters

- $h^0 A^0, H^\pm, b'$

few examples which exploit the particular abilities of the L3 detector are summarized in the following sections.

DIRECT SEARCH for UNSTABLE FOURTH FAMILY NEUTRINOS

A distinctive signature for an unstable heavy fourth family neutrino[11] (neutral lepton) is hadronic events with isolated electrons or muons. After selecting hadronic Z^0 decays [12], we rejected the background from heavy quark and tau decays by requiring:

- Calorimetric energy > 30 GeV.

- Electron or muon momentum p_ℓ > 8 GeV.

- An isolated lepton, defined as less than 6.5 GeV of additional energy in a cone of 60° around the lepton direction.

- Only one charged track with momentum $\geq$ 0.25 GeV within 15° of the lepton.

- Thrust T < 0.90.

This results in a typical efficiency of 45-50% for the heavy neutrino $L^0 \rightarrow eW^*$ or μW^*, or 15-20% for $L^0 \rightarrow \tau W^*$.

Figure 1 shows the number of events expected as a function of the heavy neutrino mass, for fourth-family Dirac neutrinos (threshold factor $\propto 1/4\,\beta(3+\beta^2)$) decaying into inclusive e, μ and τ final states, and for fourth-family Majorana neutrinos ($\propto \beta^3$). The corresponding 95% C.L. lower mass limits are $M_{L^0} > 46.5$ GeV (Dirac), and $M_{L^0} > 45.5$ GeV (Majorana).

SEARCH for CHARGED HIGGS
$$e^+e^- \rightarrow H^+H^-$$

We searched for charged Higgs, through the process $e^+e^- \rightarrow H^+H^-$, where each of the Higgs can decay into $\tau\bar{\nu}$ or $c\bar{s}$. The distinctive signature used by L3 for final states with one $H \rightarrow \tau\bar{\nu}$ and one $H \rightarrow c\bar{s}$ is a well-isolated high energy electron or muon, accompanied by hadron jets which are not collinear with the lepton. Events where both Higgs decay via $H \rightarrow \tau\bar{\nu}$ can also lead to acollinear μe final states.

In addition to these signatures, L3 used its granular calorimeters to select four jet events which could result from $H^+H^- \rightarrow c\bar{s}\bar{c}s$. Cuts on the jet energy, event thrust, and most importantly on the jet-pair invariant masses and opening angles (summarized below), are used to suppress the four-jet QCD backgrounds from $q\bar{q}gg, q\bar{q}q\bar{q}$, etc.:
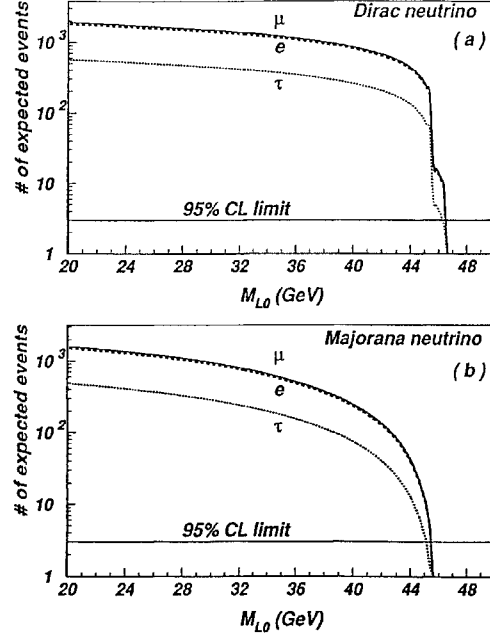
Figure 1: L3 limits on the masses of fourth-family heavy neutrinos, from a direct search for events with isolated leptons.

Cuts to Select Four Jet Events from Charged Higgs, and Reject QCD Backgrounds.

- Select hadron events [12], with four jets: $y_{CUT} = 0.02$.

- Lowest jet energy > 12 GeV.

- $63° < \theta_{\text{Thrust}} < 126°$.

- $(E_1 + E_2 - E_{\text{beam}})^2 + (E_3 + E_4 - E_{\text{beam}})^2 < 16$ GeV^2

- $\| \cos(\theta_{12}) - \cos(\theta_{34}) \| < 0.3$.

- Thrust cut (Higgs mass dependent).

- Cut on reconstructed Higgs mass.

The acceptance after these cuts is typically 4%.

The power of these cuts is illustrated in Figure 2, for the example of a 25 GeV charged Higgs. The top two graphs in the figure show L3's ability to pick out cleanly the charged Higgs, and to measure its mass with a resolution of $\approx$ 4%, while the bottom two graphs show that the QCD background is suppressed down to the level $\approx 10^{-4}$.

The mass limits after cuts, for all H^+H^- decay channels as a function of the branching ratio for $H \rightarrow \tau\bar{\nu}$, are shown in Figure 3. The region to the

Invariant mass reconstruction
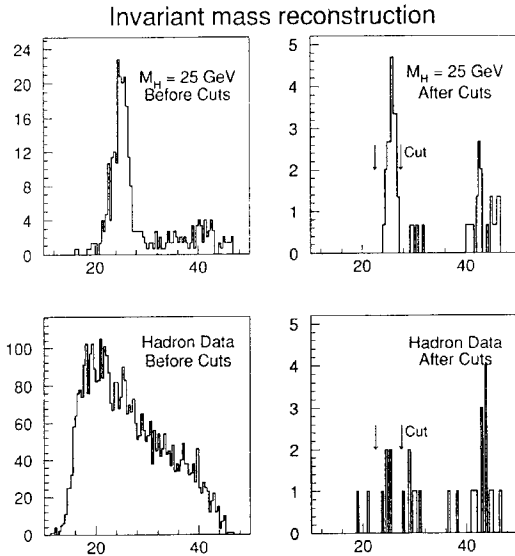
Figure 2: Invariant mass reconstruction of jet pairs in L3, before and after cuts, for simulated $e^+e^- \to H^+H^-$ events (top graphs), and for real four-jet hadron events in L3 (bottom graphs).

left of the solid line in the figure is excluded.

## SEARCH for MULTIPHOTON PRODUCTION in $Z^0 \to$ HADRONS

We have used the the high energy resolution of the L3 BGO calorimeter, together with the granular hadron calorimeter and the Time Expansion Chamber inner track detector, to search for new heavy resonances decaying into multiphotonic final states.

We prepared for this analysis, and verified the detector performance, by extracting clean signals for $e^+e^- \to \pi^0, \eta^0,$ and ω^0, where $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $\omega \to \pi^0\gamma$. After selecting hadron events, we extracted events containing isolated electromagnetic clusters by requiring:

- One cluster, well within the BGO barrel region ($|\cos\theta| < 0.74$), with at least 90% of its energy localized in 3×3 BGO crystals.

- No matching cluster in the hadron calorimeter.

- Isolation: no other cluster in $\Delta\Theta < 6°$. The maximum energy of the $\gamma\gamma$ system was thus limited to:
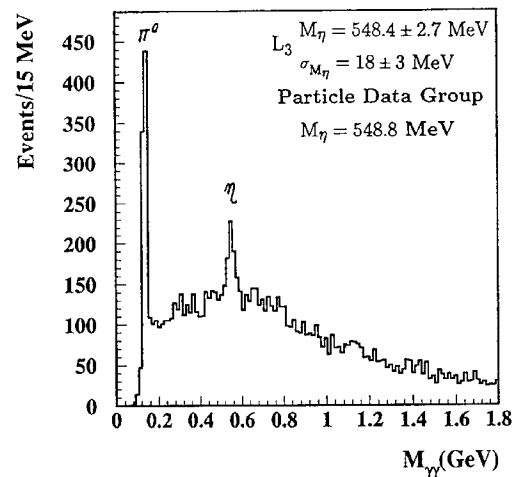
$$E_{Max} = M_{\gamma\gamma}/(\tan(6°/2)) \approx 19M_{\gamma\gamma}.$$
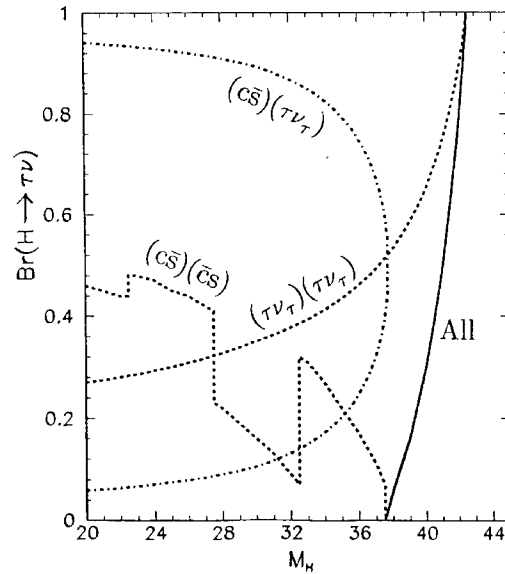
Figure 3: L3's mass limits on the existence of charged Higgs $H^{\pm}$.

- Identification as a photon in the TEC: no track within $|\Delta\phi| = 25$ mrad.

The results of these analyses are shown in Figure 4 ($E_\gamma > 0.7$ GeV) and Figure 5 ($E_\gamma > 1.3$ GeV), which illustrate the resolution and accuracy in the masses, Figures 6 and 7 illustrate the sensitivity to a new

Figure 4: The inclusive $\gamma\gamma$ spectrum measured with the L3 BGO calorimeter, showing clear π^0 and η signals.

heavy resonance decaying into multiphotons:

$$e^+e^- \to Z^0 + Y^0; \quad Y^0 \to n\gamma,$$

corresponding to $M_Y^0 = 30$ GeV ($\to 3\gamma$), and $M_Y^0 = 40$ GeV ($\to 4\gamma$) respectively. A cut on each
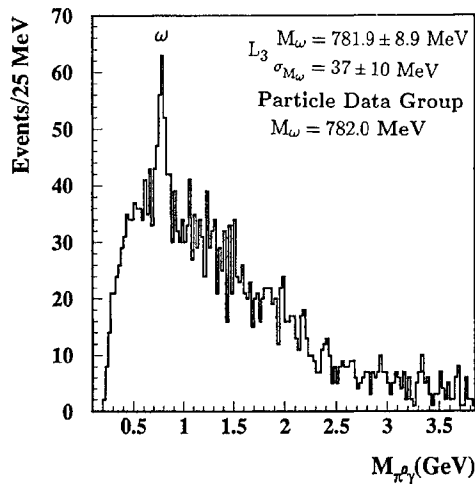
Figure 5: The inclusive $\pi^0\gamma$ spectrum measured with the L3 BGO calorimeter, showing a clear ω signal.

$E_\gamma > 3$ GeV completely eliminates any background; the events outside the narrow peaks result from combinations of photons from the new resonance with other relatively high energy photons resulting from fluctuations in jet fragmentation. The correspond-
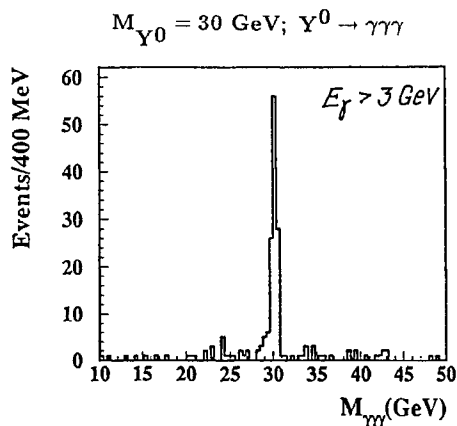

Figure 6: The inclusive mass spectrum expected for a new 30 GeV resonance $Y^0 \to \gamma\gamma$.

ing 95% C.L. upper limits on the relative branching ratios $BR_{n\gamma}$, where $BR_{n\gamma}$ is defined as:

$$BR_{n\gamma} \equiv \frac{\Gamma(Z^0 \to Y^0 + X)}{\Gamma_{Z^0}} * BR(Y^0 \to n\gamma)$$

are summarized in Table 3. With a larger data sample at LEP, L3 expects to reach the 10^{-5} level of sensitivity in 1991.

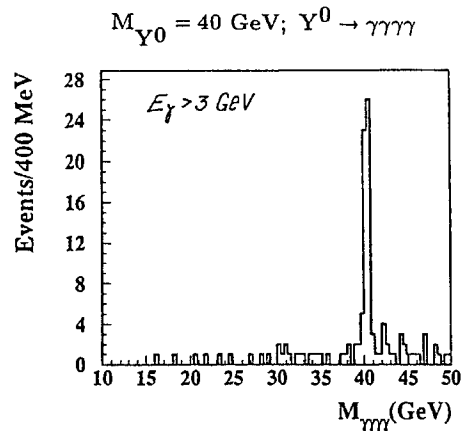**Figure 7:** The inclusive mass spectrum expected for a new 40 GeV resonance $Y^0 \to \gamma\gamma\gamma\gamma$.

INDIRECT PARTICLE SEARCHES WITH L3

Mass limits on the existence of many new particles also have been obtained through L3's precise measurements of the Z^0, by considering the 95% C.L. upper limits on the Z^0's hadronic decay width $\Gamma_{had} = 1.748 \pm 0.035$ GeV, its invisible width $\Gamma_{invisible} = 0.502 \pm 0.018$ GeV, and its partial width into muon pairs $\Gamma_{invisible} = 0.(• 33 \pm 0.015$ GeV. The results of these "indirect searches" are summarized in Table 4. L3 also has obtained indirect limits on

Table 4: Indirect L3 Mass Limits (95% C.L.) from Measurements of the Partial Widths of the Z^0

PARTICLE	LOWER LIMIT (GeV)	From
4th Family Quark	46.0	Γ_{had}
4th Dirac ν	44.2	Γ_{inv}
Majorana ν	37.6	Γ_{inv}
Sneutrino $\tilde\nu$	31.9	Γ_{inv}
Up-Squark $\tilde u$	39.4	Γ_{inv}
Down-Squark $\tilde d$	33.2	Γ_{inv}
Stable Lepton	27	$\Gamma_{\mu\mu}$

the mass of the top quark, in the context of the Standard Model, by combining its measurements of M_Z and Γ_Z with data from νN and $p\bar p$ experiments, with the result:

$$M_{TOP} = 134^{+36}_{-41} \text{ GeV}$$

Table 3: BR Upper Limits (95% C.L.) for Multi-γ Resonance Production

M(GeV)	$Y^0 \to 2\gamma$	$Y^0 \to 3\gamma$	$Y^0 \to 4\gamma$
20	1.2×10^{-4}	1.6×10^{-4}	2.1×10^{-4}
30	1.0×10^{-4}	1.4×10^{-4}	1.9×10^{-4}
40	1.0×10^{-4}	1.5×10^{-4}	1.7×10^{-4}

CONCLUSIONS

L3's search for new particles at LEP may be summarized as follows:

- Based on a relatively small data sample, no new particles have been found.

- The search for many types of new particles has re-emphasized the sensisitivity for new physics – within the confines of the Standard Model or beyond it – of a detector with:

  o Precision measurements of photons and leptons, and

  o Good resolution and granularity for hadron jets.

- We look forward to the continuation of the search, with much more data and higher energies at LEP, next year and in the years to come.

ACKNOWLEDGEMENTS

References

[1] S. C. C. Ting, Talk presented at this conference.

[2] L3 Collaboration, *A Determination of Electroweak Parameters from Z^0 Decay Into Charged Leptons*, L3 Preprint No. 17, August, 1990.

[3] F. Dydak, Talk presented at this conference.

[4] C. Jarlskog, Talk presented at this conference.

[5] L. Okun, Talk presented at this conference.

[6] L3 Collaboration, B. Adeva *et al.*, NIM **A289** (1990) 35.

[7] L3 Collaboration, Phys. Lett. **B247** (1990) 177.

[8] L3 Collaboration, Phys. Lett. **B248** (1990) 203.

[9] L3 Collaboration, *Search for Excited Taus from Z^0 Decay*, L3 Preprint No. 14, August, 1990.

[10] L3 Collaboration, *A Search for the Neutral Higgs Boson of the Minimal Supersymmetric Standard Model*, L3 Preprint No. 15, August, 1990.

[11] L3 Collaboration, *A Search for Heavy Charged and Neutral Leptons from Z^0 Decays*, L3 Preprint No. 16, August, 1990.

[12] L3 Collaboration, *A Precision Measurement of the Number of Neutrino Species*, L3 Preprint No. 9, July, 1990.

SEARCH FOR NEUTRAL HIGGS BOSONS USING THE DELPHI DETECTOR

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ABSTRACT

The results of a search for neutral Higgs bosons using the DELPHI detector are reported. In the minimal standard model (MSM) the possibility of a very light Higgs, with mass below the muon-pair threshold, is now excluded by the DELPHI results at the 95% confidence level. The high mass limit has also been considerably improved and it is found that $m_{H^\circ} > 34$ GeV at the 95% c.l.. In the minimal supersymmetric extension to the standard model (MSSM) the high mass limit of the lightest Higgs h° has also been considerably improved and is $m_h > 42$ GeV for the case $m_h \simeq m_A$, where A° is the CP-odd pseudo-scalar boson.

DATA SAMPLE

The number of hadronic Z° decays recorded by the DELPHI detector is about 13,000 in 1989 and about 83,000 in 1990, upto mid July. In the searches described below samples of upto 70,000 events are used. A description of the detector and data reduction procedure can be found in [1]. The basic method for a particular search is to find a set of cuts (based on, eg, charged multiplicity, isolated leptons, jet properties, acollinearity, p_T, energy in the small angle tagger (SAT) etc.) which retains a large fraction of the potential signal but beats down the background from conventional physics by a factor of about 10^4 or better.

MINIMAL STANDARD MODEL NEUTRAL HIGGS

In the MSM there is one Higgs doublet which, after spontaneous symmetry breaking, leads to one physical neutral Higgs boson H°. The H° mass m_H is unspecified. The decay modes depend on the mass and, for the mass range studied here, the decay is primarily to the heaviest kinematically allowed fermion-antifermion pair, $H^\circ \rightarrow f\bar{f}$. The production is by the Bjorken process $e^+e^- \rightarrow H^\circ Z^*$, with the off-mass shell Z° decaying in the usual way.

Details of the search using the 1989 data can be found in [2]. The mass range 210 MeV $\leq m_H \leq$ 14 GeV was excluded (95% c.l.). A light Higgs, below the $\mu\mu$ threshold, would have a long lifetime and a long mean decay length (typically 500 cm for $m_H = 50$ MeV). The search for a light Higgs was conducted in two parts:

a) $0 \leq m_H \lesssim 60$ MeV. In this range there is a large probability that the $H^\circ \rightarrow ee(\gamma\gamma)$ decay is outside the detector. The topology searched for was an acoplanar ($> 5°$) lepton-pair ($\ell = e$ or μ) and nothing else (ie, electromagnetic energy < 2 GeV and no hadron calorimeter activity). The selection efficiency, estimated by a full detector Monte Carlo simulation, was $\epsilon \sim 30\%$ (for $m_H = 0$ MeV). The cuts are designed to render negligible the potential background of radiative lepton pairs.

b) $60 \lesssim m_H \leq 210$ MeV. In this range the $H^\circ \rightarrow ee$ decay would frequently be inside the fiducial region of the tracking chambers. A search was made for an isolated V° (either alone for the $e^+e^- \rightarrow H^\circ Z^* \rightarrow H^\circ \nu\bar{\nu}$ channel or with a lepton pair for the $H^\circ \ell^+\ell^-$ ($\ell = e$, μ or τ) channels). The V° search algorithm was successfully tested by finding K° and Λ° decays in normal hadronic events. The main potential background is from $\gamma\gamma$ events.

There were no candidates remaining after cuts in either a) or b), and combining these two searches excludes a light Higgs in the range zero to 210 MeV at the 95% confidence level.

A considerable improvement in the high mass limit has been made from a study of the channels $e^+e^- \rightarrow H^\circ Z^*$ with $Z^* \rightarrow e^+e^-$, $\mu^+\mu^-$ and $\nu\bar{\nu}$. For the charged leptonic channels a search was made for 2 high energy leptons (at least one > 10 GeV), well isolated from the decay products of the Higgs (isolation angle $\alpha > 25°$ for $n_{ch} > 8$ and $\alpha > 15°$ for $6 \leq n_{ch} \leq 8$). One $e^+e^-H^\circ$ and no $\mu^+\mu^-H^\circ$ candidates remain after the cuts. The e^+e^- candidate has a recoil mass of about 55 GeV, and is outside the current range of sensitivity. For the channel $\nu\bar{\nu}H^\circ$ the topology searched for was that of two acoplanar and acollinear jets (with a cut on $\cos\xi$ of 0.8 in both of these variables). To reject possible background from $\gamma\gamma$ events, the energy in the SAT was

required to be < 8 GeV. After these, plus some additional cuts, ten candidates remained. Careful examination of these events showed that they were all compatible with the final state $q\bar{q}\gamma$ (ie radiation of a hard photon(s) in $e^+e^- \to q\bar{q}$, where the photon was not fully reconstructed). Thus no candidates remain in any of these channels. The efficiency of the cuts applied in retaining the H° signal was estimated by Monte Carlo to be in the range 40–60%, depending on m_H. Fig.1 shows the expected number of events in the different channels as a function of m_H. Taking into account the exclusion of a low mass Higgs, the limit from the DELPHI experiment is

$$\boxed{m_H > 34 \text{ GeV}} \quad 95\% \text{ c.l.}$$

SEARCH FOR HIGGS IN MSSM

In the minimal supersymmetric extension to the standard model (MSSM) there are two Higgs doublets which give rise to 5 physical Higgs bosons (H^+, H^-, h°, H°, A°). There are two CP-even scalars h° and H° which mix with some angle α and one CP-odd pseudoscalar A°. The model has two parameters, which can be chosen to be m_h (the mass of the lightest scalar) and $\tan\beta = v_2/v_1$, where v_2 and v_1 are the vacuum expectation values of the Higgs fields which couple only to down-type quarks and leptons and to up-type quarks and leptons respectively. The masses are constrained such that $m_{H^\pm} > m_{W^\pm}$ and the lightest neutral satisfies $m_h < m_z|\cos 2\beta|$. The mixing angle $\alpha \approx -\beta$ in the kinematic range considered here.

Neutral Higgs production is through the two processes
i) $e^+e^- \to Z^\circ \to h^\circ A^\circ \quad \sigma \sim 0.5\cos^2(\beta - \alpha)\sigma_{\nu\bar{\nu}}$
ii) $e^+e^- \to h^\circ Z^* \quad \sigma \sim \sin^2(\beta - \alpha)\sigma_{SM}$
These two reactions are thus complementary in the search. Note that $\cos^2(\beta - \alpha) \approx m_h^2/m_A^2$ and also that, in the limit $\tan\beta = 1$, the model is equivalent to the MSM. The decay modes of interest are to those $f\bar{f}$ pairs which are kinematically allowed. Because of the Higgs couplings, the branching fractions depend strongly on β (and α) such that

$$BR(h \to \tau\bar{\tau} : c\bar{c} : b\bar{b}) = 1 : 2.1(\cot\alpha.\cot\beta)^2 : 19\beta_b^3,$$
$$BR(A \to \tau\bar{\tau} : c\bar{c} : b\bar{b}) = 1 : 2.1(\cot\beta)^4 : 19\beta_b^3,$$

where β_b is the b-quark velocity in the Higgs rest frame. Since $\alpha \simeq -\beta$, the decay fractions for h° and A° are roughly similar. Thus for $\tan\beta > 1$ (which is theoretically favoured) $\tau^+\tau^-$ and $b\bar{b}$ dominate. The $\tau^+\tau^-$ mode is still sizeable ($\gtrsim 6\%$) even above the $b\bar{b}$ threshold. For $\tan\beta < 1$, the $c\bar{c}$ mode dominates.

The results of the search methods used to analyse the 1989 data can be found in [3]. The current

limits for m_h, as a function of $\tan\beta$, are shown in Fig.2. Different methods, corresponding to different decay modes and different topologies, are used in the various domains of the plot. Contour b) corresponds to the channel $e^+e^- \to h^\circ Z^*$, whereas the others are for $e^+e^- \to h^\circ A^\circ$. Briefly, the methods for the different domains are as follows:

a) $\tau^+\tau^-$+hadrons (mainly $\tau^+\tau^- b\bar{b}$). The method is to search for two isolated tracks (from τ decays) accompanied by one or two jets. The signal efficiency is $\simeq 15\%$ for $m_h \simeq m_A \simeq 40$ GeV. The 95% confidence level contour, taking into account the one candidate which survives the cuts, is shown as region a). For $m_h \approx m_A$ this gives $m_h > 42$ GeV.

b) This contour is obtained directly from the standard model search described above and corresponds to $m_h > 34$ GeV (95% cl) for $\tan\beta = 1$.

c) This corresponds to the low mass domain where the decays are preferentially to pairs of μ, π or K. This is described in detail in [3].

d) In this intermediate mass region the final state is mainly two hadronic jets. In terms of string fragmentation in hA events (unlike normal $q\bar{q}$ events) there is no coloured string connecting the two jets, and hence less particles are expected at wide angles from the jet axis. As described in [3], the method consists in plotting $\cos\theta_{th}$, where θ_{th} is the polar angle of the thrust axis, in events with no tracks outside a 40 cone around this axis. The method has been improved (no longer requiring a comparison with Monte Carlo as in [3]) by performing a fit to $1 + \epsilon\cos^2\theta_{th}$, from which an upper limit of 15% (95% cl) on a $\sin^2\theta_{th}$ component (that expected from hA) is found.

e) and f) correspond to searches in the 4-jet final state, the first one being based on inclusive charm tagging through $D^{*\pm}$ production, the second on a global shape analysis. These curves have not been updated from [3].

g) corresponds to a 4-jet analysis in which a fit, using energy and momentum constraints (an improved version of that described in [3]), is used to improve the mass resolution. After the fit the 4-jets are combined to 6 dijets with masses M_{ij} and opening angles θ_{ij}. Two sets of cuts are applied depending on the value of m_h

For $m_h < 25$ GeV,

$\quad M_{ij} > 9\text{GeV} \ \& \ \theta_{ij} > 0.5$ rad. for all i,j.

For $m_h > 25$ GeV,

$\quad M_{ij} > 15$ GeV$\& \ \theta_{ij} > 1.0$ rad. for all i,j.

Each of the three pairs of dijet masses is entered on a Dalitz plot of smallest versus largest

dijet masses. Monte Carlo studies show that a signal would result in a spike with a width of about 1.5 GeV. A search is made in 'windows' of (m_h, m_A), with the background (from QCD) computed by extrapolating the observed distribution averaged over a wider window about the point of interest. The efficiency of the method is $\gtrsim 27\%$ and, as can be seen from Fig.2, considerably improves the high mass limit for $\tan\beta < 1$.

SUMMARY AND CONCLUSIONS

From the DELPHI experiment the neutral Higgs in the Minimal Standard Model is now **excluded** for the range

$$0 \leq m_H \leq 34 \text{ GeV} \qquad 95\% \text{ c.l.}$$

For the Minimal Supersymmetric extension to the Standard Model the upper mass limits have been considerably increased and are now

$$
\begin{aligned}
m_h &> 42 \text{ GeV} && \text{for } m_h \simeq m_A, \\
&> 32 \text{ GeV} && \text{for } \tan\beta > 1, \\
&> 28 \text{ GeV} && \text{for all } \tan\beta,
\end{aligned}
$$

all at the 95% c.l.

REFERENCES

1. Delphi Collaboration, P. Aarnio *et al.*, CERN-PPE/90-122 (1990) and P. Abreu *et al.*, *Phys. Lett.* **B241** (1990) 435.
2. Delphi Collaboration, P. Abreu *et al.*, *Nucl. Phys.* **B342** (1990) 1.
3. Delphi Collaboration, P. Abreu *et al.*, *Phys. Lett.* **B245** (1990) 276.

FIGURE CAPTIONS

Fig.1. Expected number of events for a SM Higgs as a function of $m(H^\circ)$ for the channels $e^+e^- \rightarrow H^\circ Z^*$ with $Z^* \rightarrow \nu\bar\nu$, e^+e^- and $\mu^+\mu^-$. The sum of these channels is also shown and the dashed line is the 95% c.l.

Fig.2. Regions in the $\tan\beta$ v m_h plane excluded in the MSSM Higgs search. The methods used in the domains a to g are described in the text. The kinematic limit accessible at LEP1 is shown by the dashed line.
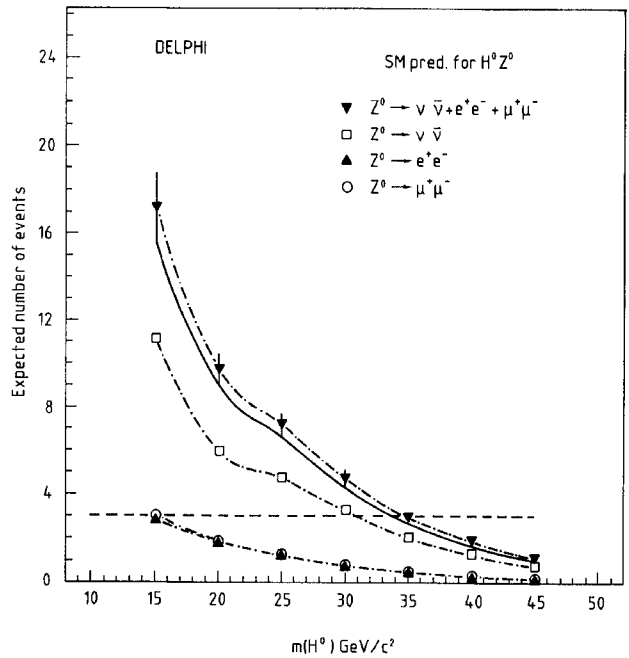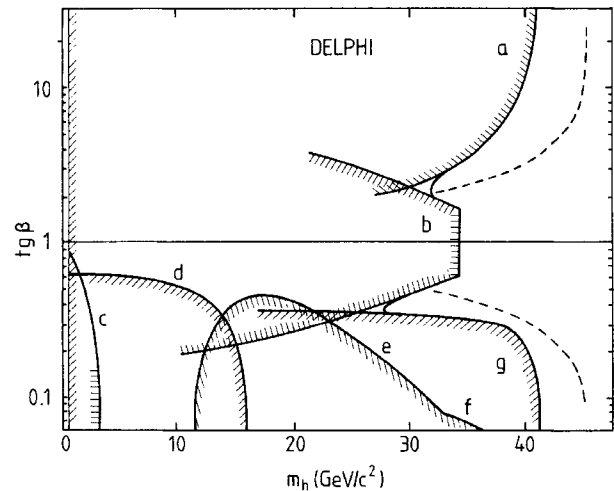

Fig.1

Fig.2

DISCUSSION

Q. **M. Drees** *(CERN)*: How many of the c-quarks in $Z \to hA \to c\bar{c}c\bar{c}$ events do you require to fragment into D^* mesons?

A. **P. Renton**: Only one, since the efficiency of this method is only $\sim 20\%$. Even so, there is *no* significant D^* signal in the 4-jet sample.

Q. **A. Roussarie** *(CEN-Saclay)*: When you say that you have no-signal in the D^* tagging looking for $hA \to c\bar{c}$ candidates what does that mean? You should at least see the D^* contained in hadronic events.

A. **P. Renton**: In fact if the SM higgs would be there you would see much more D^* at low P_T^2 making them visible.

PARTICLE SEARCHES WITH THE DELPHI DETECTOR: CHARGED HIGGS BOSONS AND SUPERSYMMETRIC PARTICLES

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Abstract

Search limits from the DELPHI experiment at LEP are reported on the basis of data analyzed upto July 1990. The search for pair production of charged Higgs bosons has resulted in a mass limit that varies from 43 GeV/c² to 37 GeV/c² as a function of the branching fraction into hadrons. Scalar quarks with masses below 42 GeV/c² (up-type) or 43 GeV/c² (down-type) have been excluded. The excluded mass regions for sleptons and charginos almost reach the kinematical limit.This includes the case were these particles would be long-lived instead of decaying into a light photino.

1. SEARCH FOR CHARGED HIGGS BOSONS

In the minimal supersymmetric extension of the Standard Model (MSSM), the charged Higgs boson $H^\pm$ is heavier than the W boson. However, inclusion of an extra Higgs singlet in the MSSM Higgs sector can lead to a light charged Higgs, allowing pair production at the Z peak. The $Z - H^\pm$ coupling is model independent and equals one third of the $Z - \mu$ coupling times a phase space factor β^3. The $H^\pm$ boson decays either into a quark pair, mostly $c\bar{s}$, or leptonically into $\tau\nu_\tau$. Considering one-prong τ decays only, three classes of final states are thus to be considered: (a) acoplanar two-prong events ($\tau\nu+\tau\nu$) with photon veto against the background of radiative lepton pair production; (b) an isolated track recoiling against a pair of jets ($\tau\nu+c\bar{s}$); (c) 4-jet final states ($c\bar{s}+\bar{c}s$).

A description of the three different analyses can be found in the previously published result [1] based on the 1989 data. In the 4-jet analysis, the first step towards reduction of the large QCD background consists of the reconstruction of di-jet invariant masses and requiring the two di-jet masses to be equal within the experimental resolution. Here, the analysis has been improved by taking full advantage of the energy and momentum conservation constraints, leading to di-jet mass resolutions of 2 GeV/c². Further, a

discriminant variable built from event shape variables (sphericity and third Fox-Wolfram moment) and jet energies has been introduced. Choosing a cut on this variable where the QCD 4-jet background is reduced by a factor of 60, the signal of a $H^\pm$ pair would pass with 20 % efficiency at m($H^\pm$) = 40 GeV/c².

The analyzed data sample corresponds to 60,000 hadronic Z decays. The absence of a signal results in the 95% C.L. limits plotted in fig. 1.
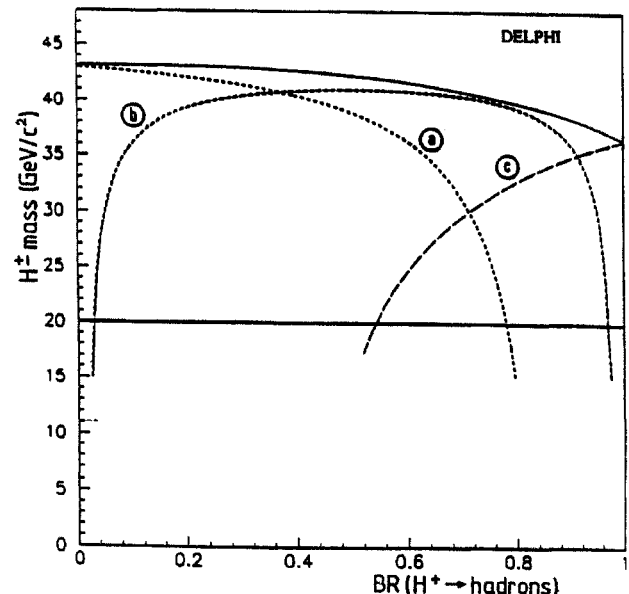

Figure 1. $H^\pm$ exclusion regions from the searches (a), (b) and (c) described in the text. The solid curve corresponds to the combined limit.

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The solid curve represents the combined mass limit from the three event classes (a), (b) and (c). It decreases smoothly from 43 GeV/c^2 for purely leptonic $H^\pm$ decay to 37 GeV/c^2 for purely hadronic decay.

squark are 43 and 42 GeV/c^2 if m(LSP) < 20 GeV/c^2; for a heavier LSP (up to 2 GeV/c^2 below the squark mass) the limits extend to 38 and 36 GeV/c^2, respectively. Degeneracy between left and right handed fields is assumed in all cases.

2. SQUARK SEARCH

Squarks, the scalar superpartners of quarks, couple to the Z analogously to the corresponding fermionic quark fields. The decay $Z \to \tilde{q}\tilde{q}$ has been searched for under the assumption that each squark decays immediately (i.e. before fragmentation) into a quark and the undetected lightest supersymmetric particle (LSP). Previous searches for such processes were based on the signature of momentum imbalance (acollinear jets; large missing transverse momentum), which assumes that the LSP mass is much smaller than the squark mass. The DELPHI data have in addition been subjected to a new analysis method, that applies to heavy invisible objects, i.e. to the signature of low visible energy. The machine background and the contribution from $\gamma\gamma$ events can be reliably subtracted by virtue of their nearly flat dependence on the beam energy. After correction for standard Z decays that pass the selection criteria, the remaining non-standard low-visible-energy signal was -0.09 ± 0.14 nb on the Z peak. This work has been published [2]. Fig.2 shows the 95 % C.L. exclusion contour in the m($\tilde{q}$) vs. m(LSP) plane for the case of 6 flavours degenerate in mass. Limits for a single down or single up

3. SEARCH FOR SLEPTONS AND CHARGINOS

In the supersymmetric scheme, one expects two pairs of charginos (superpartners of charged gauge bosons) and four neutralinos. The lightest chargino pair is denoted as $\chi^\pm$, the lightest neutralino (often called photino) as χ. Sleptons, $\tilde{l}_R^\pm$ and $\tilde{l}_L^\pm$, are the scalar superpartners of the standard chiral leptonic states. We present an update on slepton and chargino searches, based on an event sample that corresponds to about 40,000 hadronic Z decays. If the photino is the lightest supersymmetric particle, the decays $\tilde{l}^\pm \to \chi l^\pm$, and $\chi^\pm \to \chi W^*$ with $W^* \to l^\pm \nu$, lead to the signature of acollinear two-prongs for Z decay into a pair of sleptons or charginos. The analysis procedure has been described in the DELPHI publication [3] based on the 1989 data. For the 1990 analysis, cuts for background rejection from the $\gamma\gamma$ process and from $\tau^+\tau^-$ production have been refined. The photon veto against acoplanar events produced by final-state radiation was restricted to isolated photons ($> 15°$ from each track); photons close to the charged tracks were not vetoed, in order to accept π^0's from τ decays in SUSY events. No supersymmetric candidates were observed. The derived slepton mass limits are shown in fig.3, both with and without the assumption of left-right mass degeneracy. Charginos are excluded up to the kinematical limit.

The possibility that the photino would be heavier than sleptons or charginos, which would thus not decay inside the detector, has also been explored. The two tracks are then well aligned, but their momenta are lower than the beam momentum. The DELPHI momentum measurement error, $dp/p^2 = 2 \times 10^{-3}(GeV/c)^{-1}$, allows the identification of particles heavier than 25 GeV/c^2 (lower masses have already been excluded at TRISTAN and PETRA.) For masses close to the kinematical limit, the particles become non-relativistic, and will produce anomalously high dE/dx signals in the TPC. An event sample corresponding to 60,000 hadronic Z's was submitted to a search for back-to-back highly ionizing tracks. The dE/dx measurement uses the truncated mean of the 192 ionization samples collected on the TPC wires. The resolution measured on dimuon events is 6.5 %. The two search methods (low momen –
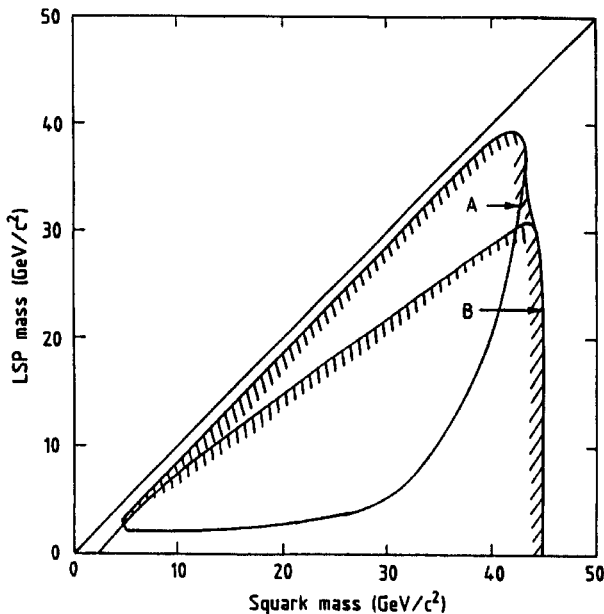

Figure 2. Scalar quark exclusion contours from low-visible-energy (A) and acollinear-jet (B) analyses in the case of 6 degenerate flavours.

tum or high specific ionization) together cover the
mass domain $25 - 45$ GeV/c^2, with comfortable
overlap. The absence of a signal excludes stable
sleptons with masses between 25 and 44.8 GeV/
c^2 in the case of left-right mass degeneracy, and
upto 44.5 Gev/c^2 in the non-degenerate case. The
upper exclusion limit for stable charginos is 45
GeV/c^2 .

DELPHI results on neutralino searches and on
MSSM parameter constraints derived from the
gaugino search limits can be found in [3].

References

1. DELPHI Collaboration,
   P.Abreu *et al.Phys.Lett.* **B241** (1990)449.

2. DELPHI Collaboration,
   P.Abreu *et al.Phys.Lett.* **B247** (1990)148.

3. DELPHI Collaboration,
   P.Abreu *et al.Phys.Lett.* **B247** (1990)157.

DISCUSSION

Q. **M. Drees** *(CERN)*: Did your bounds on the mass
of a single squark flavor assume degenerate left- and
right-handed squarks?

A. **B. Koene**: Yes.
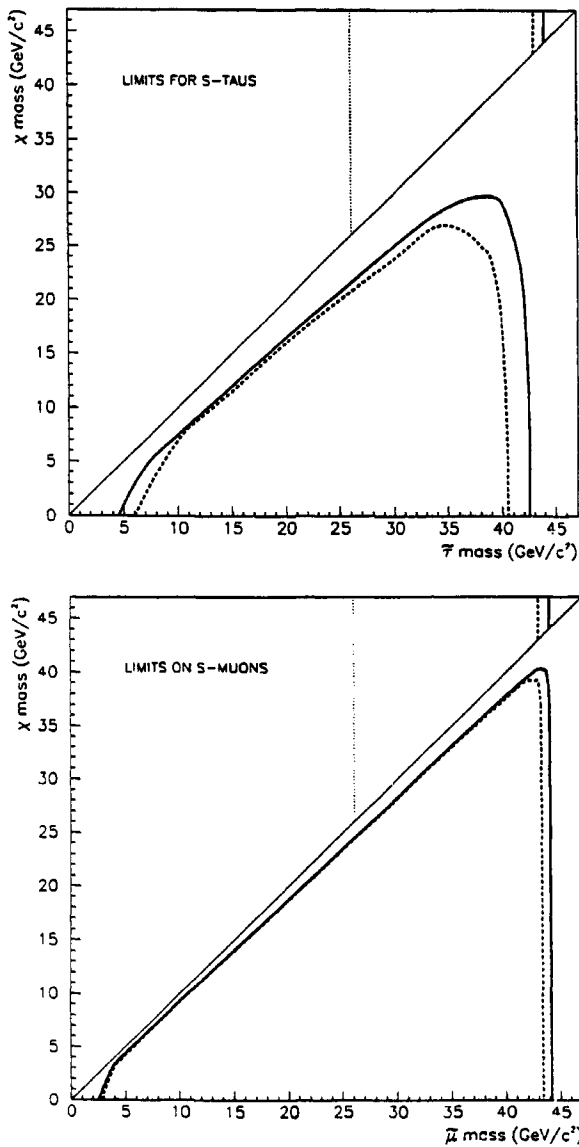
Figure 3. Excluded mass regions at 95% C.L. for s-muons
and s-taus. The s-electron result is almost
identical to the s-muon plot. The solid curves
apply if left- and right-handed sleptons are
mass-degenerate, the dashed curves corre-
spond to the non-degenerate case. The lines
above the diagonal represent limits on stable
sleptons.

Exotic Particle Searches at CDF

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Abstract

An analysis of $p\bar{p}$ collision events at $\sqrt{s} = 1.8$ TeV sets limits on the existence of several types of exotic particles. Supersymmetric squarks and gluinos are excluded up to masses of approximately 150 GeV at the 90%CL. New intermediate vector bosons are also searched for. We exclude the existence of new W' bosons to the mass 478 GeV, and new Z' bosons to the mass of 380 GeV at the 95% CL.

Introduction

. Extensions to the Standard Model are expected to appear as higher and higher energies are explored. During the 1987-1988 Tevatron Collider run, the CDF experiment collected 4.1 pb^{-1} of $p\bar{p}$ data at 1.8 TeV center-of-mass energy. This paper describes searches of this data for supersymmetry, W' bosons, and Z' bosons.

Supersymmetry

Supersymmetry (SUSY) is a symmetry that links fermions and bosons. In this theory the fundamental fermions have supersymmetric partners. In particular the quark, gluon and photon have supersymmetric partners the squark ($\tilde{q}$), gluino ($\tilde{g}$) and photino ($\tilde{\gamma}$). We assume a rigorous conservation of R-parity, which implies that supersymmetric particles are pair-produced. We further assume that the photino is the lightest SUSY particle. The photino is also stable and does not deposit energy in the detector. The presence of photinos thus causes events with large missing transverse energy, $\not{E}_T$. The dominant particle production and decay modes depend on the relative masses of the quark and the gluino. The case $m_{\tilde{q}} < m_{\tilde{g}}$ yields two jets, and the case $m_{\tilde{g}} < m_{\tilde{q}}$ yields four jets. We note that the final states are always composed of normal quarks and gluons and photinos.

Data were filtered by the following requirements:

(1) The missing E_T, ($\not{E}_T$), was required to be greater than 40 GeV.

(2) The highest E_T calorimeter cluster was required to be central ($| \eta | < 1.0$), and to have $E_T \geq 15$ GeV, charged fraction > 0.2, and $0.1 <$ electromagnetic fraction (EMF) < 0.9. The second jet was required to have $E_T \geq 15$ GeV, $| \eta | < 3.5$ and $0.1 < EMF < 0.9$.

(3) The significance of the E_T of an event, $\not{E}_T/\sqrt{E'_T}$, was required to be > 2.4.

(4) An important source of background events with large $\not{E}_T$ was two-jet events where the energy of one of the jets was mismeasured. Any event with a cluster of $E_T \geq 5$ GeV within $\pm$ 30 ° in ϕ from the back-to-back direction of the highest E_T cluster was removed.

(5) Mismeasured multijet events were rejected by requiring that the $\not{E}_T$ direction was not parallel to any jet direction. Thus all events with $| \phi_{jet} - \phi_{\not{E}_T} | < 30°$ were removed.

(6) All events with electron candidates with $E_T > 15$ GeV were removed.

(7) All events with muon candidates with $P_T > 15$ GeV/c were removed.

The final sample consisted of 98 events, 3 of which had $\not{E}_T > 100$ GeV.

To understand if the set of 98 events is consistent with Standard Model background, we studied several sources. Important SM sources of $\not{E}_T$ events are: $W \rightarrow e \, \nu$ jets; $W \rightarrow \mu \, \nu$ jets; $W \rightarrow \tau \, \nu$ jets; and $Z \rightarrow \nu \, \bar{\nu}$ jets. Bosons produced at high P_T have recoil jets that can satisfy the selection cuts.

To estimate the rates for these processes, we took the observed CDF data set of $W \rightarrow e\nu$, and replaced the electron information with simulated data for τ's or muons. To simulate ν's, the electron data was deleted. We note that the P_T distribution for W's and Z's are very similar, so the process $Z \rightarrow \nu \, \bar{\nu}$ can be studied using W's.

Another source of $\not{E}_T$ events was QCD events where a jet was mismeasured or had a heavy quark

(c,b) decay. This rate was estimated to be 4 ± 4 events.

In summary we estimate from our own data that there are 92.4 ± 18.2 events from intermediate Boson decays and QCD. The uncertainty is combined statistical plus systematic.

We have estimated the expected number of SUSY events for different combinations of $(m_{\tilde{q}}, m_{\tilde{g}})$ in the mass range 140- 500 GeV using ISAJET.[2] The systematic uncertainty in our expected SUSY events comes from the following factors: (1) The uncertainty in our integrated luminosity (6.7%); (2) The uncertainty in the choice of Q^2 scale in ISAJET(15%); (3) The uncertainty in the overall calorimetry energy scale(1%); (4) The uncertainty in the $\not{E}_T$ trigger efficiency(4%); (5) We use EHLQ1 structure functions[3], which have the lowest predicted cross sections. No systematic uncertainty is included for structure function uncertainty.

The total systematic uncertainty is 17%, adding the various contributions in quadrature.

We have seen that the number of observed events (98) is consistent with that expected from the standard model plus QCD (92.4 ± 18.2). To actually set the limits we consider 2 cases:

(1) $m_{\tilde{q}} < m_{\tilde{g}}$

We have 3 events with $\not{E}_T > 100$ GeV and 2 or more jets. We estimate the background is 1.3 events with a systematic uncertainty of 8% and a statistical uncertainty of 100%for a 90% C.L. limit of 6.0 predicted events.

(2) $m_{\tilde{q}} > m_{\tilde{g}}$

We have 2 events with $\not{E}_T > 40$ GeV and 4 or more jets. We estimate the background is 1.3 events with a systematic uncertainty of 8% and a statistical uncertainty of 100% for a 90% C.L. limit of 4.8 predicted events. The preliminary results are shown in Fig. 1.

W' Search

We searched for the presence of heavy W' bosons in our data set. These particles by hypothesis decay to electron + ν similar to standard W bosons. These new particles would manifest themselves by the presence of events with very high P_T electrons and with large $\not{E}_T$. For this analysis, we selected events by the following principal cuts:

(1) Fiducial cuts were made to the electron candidates to avoid cracks and other areas where detector measurement errors could occur.

(2) Electron quality cuts were imposed:

The ratio of hadronic to electromagnetic calorimeter energy was required to be less than 10%
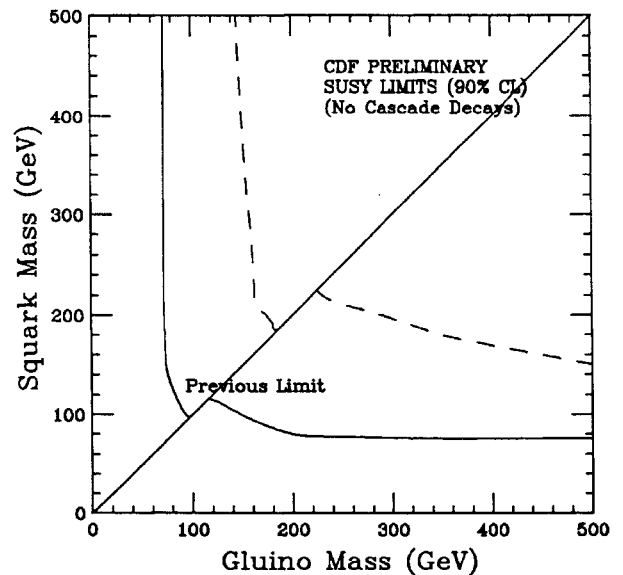

Figure 1. The 90 C.L. excluded region in the () plane.

for successful electron candidates.

A high P_T track observed by the central tracking chamber was required to point to a strip chamber cluster in the electromagnetic calorimeter.

The strip chamber cluster profile was required to be consistent with that of an electron.

The electron cluster was required to be isolated, less than 5 GeV of energy in the calorimeter border towers to the cluster.

(3) The $\not{E}_T$ of the event was required to be $> 30 GeV$

(4) Z's were removed by requiring only one high P_T electron.

The transverse mass

$$M_T = \sqrt{(2 E_T \not{E}_T (1 - cos(\Delta\phi^{e-\nu})))}$$

was studied. 4 events had $M_T > 120$ GeV, and none were above 140 GeV.

A Monte Carlo was used to study the efficiency of the cuts for various masses of the W'. W''s with masses between 90 and 50 0 GeV were simulated, the selection cuts were applied, and the M_T distribution was calculated. We then fit the observed CDF transverse mass distribution to a linear combination of a simulated W M_T distribution and various W' M_T distributions:

$$dN/dM_{T,obs} = \alpha * W\prime(M_T) + \beta * W(M_T) \ .$$

We then calculated α and β for each choice of M_T.

For masses of$M_{W\prime}$ below about 90 GeV, the expected M_T distribution was very similar to that of the W. This analysis was not sensitive to such light W' 's.

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Systematic uncertainties include W' P_T distribution, electron acceptance, and uncertainty in the CDF luminosity. The predicted W' cross section is a function of choice of structure functions. We chose EHLQ set 1, which has the lowest predicted cross section. The uncertainty in electron acceptance was estimated to be less than 4%. Uncertainty in the W' P_T distribution is important for light W''s, since the predicted M_T distribution is very similar to that of the W. For these low masses of W', the systematic uncertainty due to P_T is large, 54% for $M_{W'} = 90$ GeV, falling rapidly to less than 1% above 200 GeV. Uncertainty in detector response for the events contributes a 10% uncertainty at low $M_{W'}$, falling to 1 % at 250 GeV. The uncertainty in luminosity for this analysis was 15%.

For each mass of W', a maximum likelyhood fit to the M_T distribution was made, and 95%CL upper limits on α were determined, incorporating the listed systematic uncertainty. Figure 2 shows the 95% CL limit to $\lambda^2 B$ normalized to the Standard Model. λ^2 is coupling strength, = 1 for a "standard coupling" W', and B is the ratio of branching fractions to electrons for the W' and W, = 1 for a "standard" W'. The limit with "standard couplings" is 478 GeV.
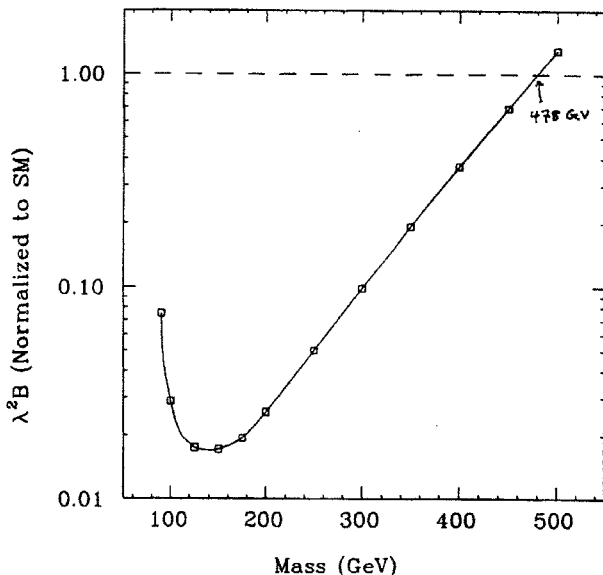

Figure 2. The 95 %C.L. limit on coupling strength of W''s.

Z' Search

Certain extensions[4] of the standard model predict the existence of new neutral heavy bosons, Z' 's. If the Z' decays in a manner similar to standard Z's, it would produce events with a pair of energetic electrons. The invariant mass of the electron

pair would be that of the Z'. The search consisted of selecting events with two high E_T electrons and checking if the invariant mass distribution is consistent with Standard Model expectations. To increase event acceptance, only one good quality electron was required. The second electron was permitted to satisfy less stringent criteria.

Event Selection: (1) The 1st electron was required to have $E_T > 15$ GeV, and to be central, | η | < 1.0 . (2) The ratio of hadronic/electromagnetic cluster energy was required to be less than an energy-dependent value, 10% at 100 GeV. (3) A high P_T charged track was required to be associated with the electron calorimeter cluster, and match the location of the strip chamber cluster. (4) The ratio of the electron calorimeter cluster to the track momentum, E/P, was required to be less than 2. (5) The strip chamber profile, and the calorimeter cluster lateral profile were required to be consistent with that of an electron. (6) Isolation cuts were imposed to remove background. (7) Looser cuts were imposed on the second electron to increase angular coverage.

The probability for a heavy Z' event to pass our cuts depended on the mass of the Z'. At $M_{Z'} = 100$ GeV, the efficiency was approximately 40%, and increased with mass. For high invariant mass dielectron pairs, we relaxed the selection cuts to increase acceptance. For invariant mass pairs > 200 GeV, the estimated acceptance was 57%. No event was seen with invariant mass > 200 GeV in a data set of 4.1 pb^{-1} . Our estimated total systematic uncertainty in the ratio of number of Z' events expected divided by number of Z events observed is 17.8%. Incorporating statistical and systematic errors, we used the non-observation of any electron pair with mass > 200 GeV to set limits on the production of new Z''s. At the 95% CL, $\sigma_{Z'} B(Z' \to ee) < 1.36$ pb for heavy Z''s. For standard coupling, Z''s are excluded to masses of 380 GeV.

References

1. F. Abe et al. Phys. Rev. Lett. **62**, 1825 (1990).

2. F. Paige and S. Protopopesceau, BNL report No. BNL 38034, 1986 (unpublished). We use ISAJET version 6.25 .

3. E. Eichten, I. Hinchcliffe, K. Lane, and C. Quigg, Rev. Mod. Phy. **56**, 579 (1984).

4. for example, P. Langacker, R. Robinett, J. Rosner, Phys. Rev. D., **30**, 1470 (1984).