SEARCHES FOR NEW PARTICLES WITH THE OPAL DETECTOR AT LEP

KEITH RILES
University of California, Riverside
Riverside, CA 92521

for the OPAL Collaboration

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

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

where $P_\perp^i$ is the momentum component of particle i perpindicular 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

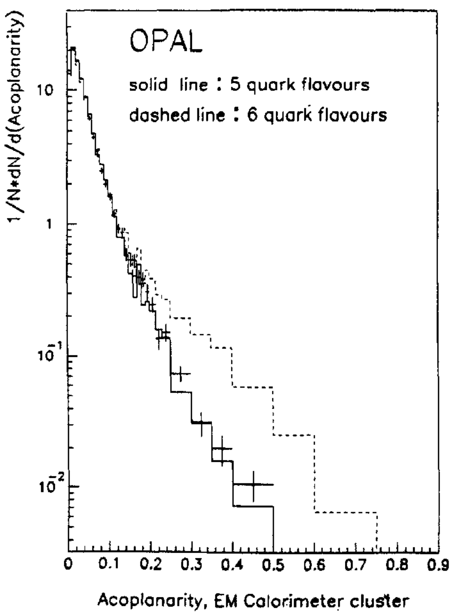

Figure 1. Distribution in acoplanarity of hadronic events for the data (points), for the five-quark expectation (solid) and for a top mass of 35 GeV.

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:

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

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.

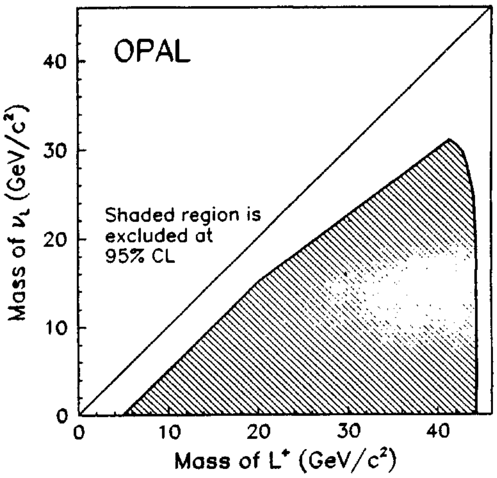

Figure 2. The shaded region indicates charged and neutral lepton masses excluded at 95% under the assumption that the neutral lepton is stable.

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 $\Gamma(Z^0 \to \nu\bar{L}^0 \text{or} \bar{\nu}L^0)/\Gamma(Z^0 \to q\bar{q})$, 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.

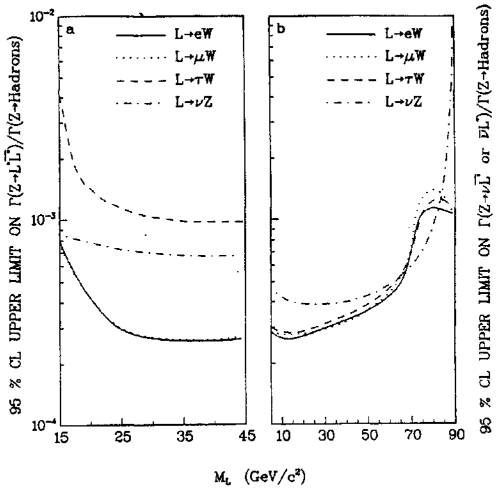

Figure 3. Upper limits (95% CL) on the fractional widths $\Gamma(Z^0 \to L^0\bar{L}^0)/\Gamma(Z^0 \to q\bar{q})$ and $\Gamma(Z^0 \to \nu\bar{L}^0 \text{or} \bar{\nu}L^0)/\Gamma(Z^0 \to q\bar{q})$ *vs* neutral lepton mass for various decay channels of the heavy lepton. In each charged-current decay, the 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 $\ell^* \to \ell\gamma$, both in pair production $e^+e^- \to \ell^*\ell^* \to \ell\ell\gamma\gamma$ and in single production $e^+e^- \to \ell\ell^* \to \ell\ell\gamma$. 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

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

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.

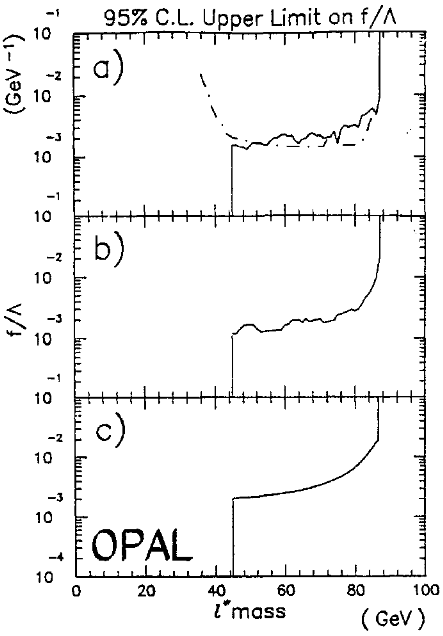

Figure 4. Upper limits on the coupling f/Λ *vs* the mass of the excited leptons: a) e^*, b) μ^*, and c) τ^*. The dash-dotted limit in a) is derived from $(e^{\pm})e^{\mp}\gamma$ events.

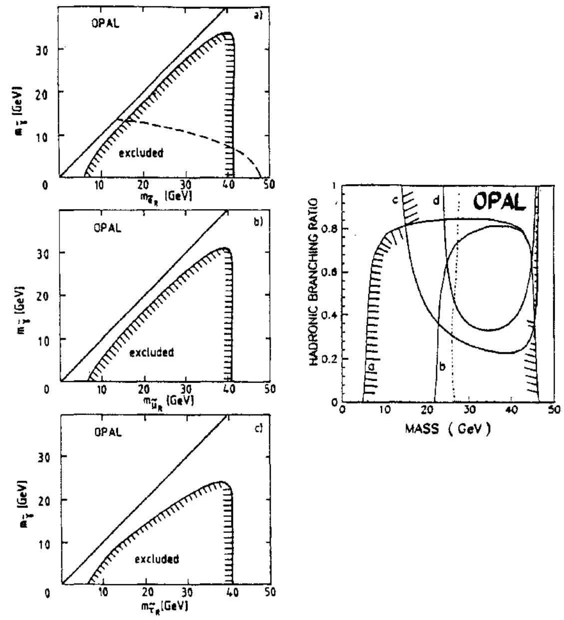

Figure 5. a-c) Mass limit (95% CL) contours for right-handed sleptons and photinos. d) exclusion contours for chargino mass and chargino hadronic branching ratio. Curves labelled a and c assume zero photino mass; curves b and d assume a photino mass of 20 GeV.

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) $\tilde{\ell}$ $(=\tilde{e},\tilde{\mu},\tilde{\tau})$ 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 $m_{\tilde{\ell}}$ 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 $e^+e^- \to \chi\chi'$ where χ and χ' are the lightest and next-to-lightest neutralinos, respectively, and where $\chi' \to \chi f\bar{f}$ and $\chi' \to \chi\gamma$ 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 $\chi' \to \chi\gamma$ 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_γ = 11 GeV), consistent with the 0.6 events expected from the background $e^+e^- \to \nu\bar{\nu}\gamma$. To obtain limits on $B(Z^0 \to \chi\chi')$ independent of the relative branching ratios of $\chi' \to \chi f\bar{f}$ and $\chi' \to \chi\gamma$, we combine the two analyses. For each point in the $(m_\chi, m_{\chi'})$ plane, the value of $B(\chi' \to \chi\gamma)$ that gives the *worse* limit on $B(Z^0 \to \chi\chi')$ is taken. The resulting conservative limits on $B(Z^0 \to \chi\chi')$ 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 $Z^0 \to \gamma\gamma$, for the rare decays $Z^0 \to \gamma\pi^0$, $Z^0 \to \gamma\eta$, and more generally, for the decay $Z^0 \to \gamma X$, where X is a multihadronic final state.

The cleanest signature for $Z^0 \to \gamma\gamma$, $Z^0 \to \gamma\pi^0(\pi^0 \to \gamma\gamma)$, and $Z^0 \to \gamma\eta(\eta \to \gamma\gamma)$ is quite dramatic. One expects two back-to-back electromagnetic showers, each containing the full beam energy, with no charged tracks present.

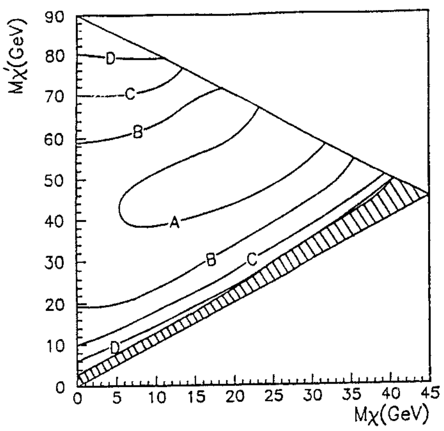

Figure 6. Upper limit (95% CL) on $B(Z^0 \to \chi'\chi)$ for $m_{\chi'}$ *vs* m_χ: contours A) 1.5×10^{-4}, B) 2.0×10^{-4}, C) 3.0×10^{-4}, and D) 5.0×10^{-4}.

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 $\sigma_{e^+e^-\to\gamma\gamma}(|\cos\theta_\gamma| < 0.90) = 30.7\pm4.1$ 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:

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

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

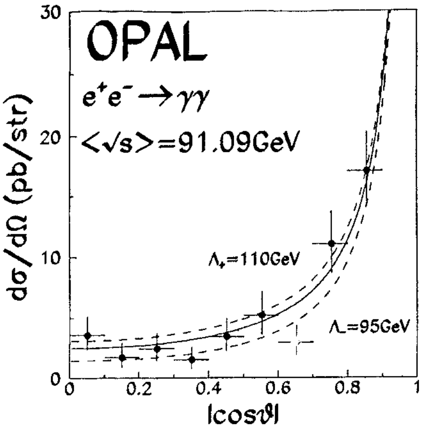

Figure 7. The measured differential cross section $d\sigma/d\Omega$ for $e^+e^- \to \gamma\gamma$ (points) and the QED expectation (solid). The dashed curves show the expectations for $\Lambda_+ = 110$ GeV and $\Lambda_- = 95$ GeV.

ACKNOWLEDGEMENTS

It is a pleasure to thank the SL Division for the efficient operation of the machine, the precise information on the absolute energy, and their continuing close cooporation with our experimental group. In addition to the support staff at our institutions we are pleased to acknowledge the following: The Bundesministerium fur Forschung und Technologie, FRG; The Department of Energy, USA; The Institute de Recherche Fondamentale du Commissariat a l'Energie Atomique; The Israeli Ministry of Science; The Minerva Gesellschaft; The National Science Foundation, USA; The Natural Sciences and Engineering Research Council, Canada; The Japanase Ministry of Education, Science and Culture (the Monbusho) and a grant under Monbusho International Science Research Program; The American Israeli Bi-national Science Foundation; The Science and Engineering Research Council, UK and The A. P. Sloan Foundation.

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).