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Search for Excited Leptons in Z^0 Decay

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The ALEPH Collaboration

D. Decamp, B. Deschizeaux, J.-P. Lees, M.-N. Minard

Laboratoire de Physique des Particules (LAPP), IN^2P^3-CNRS, 74019 Annecy-le-Vieux Cedex, France

J.M. Crespo, M. Delfino, E. Fernandez[1], M. Martinez, R. Miquel, Ll.M. Mir, S. Orteu, A. Pacheco, J.A. Perlas, E. Tubau

Laboratorio de Fisica de Altas Energias, Universidad Autonoma de Barcelona, 08193 Bellaterra (Barcelona), Spain[9]

M.G. Catanesi, M. de Palma, A. Farilla, G. Iaselli, G. Maggi, S. Natali, S. Nuzzo, A. Ranieri, G. Raso, F. Romano, F. Ruggieri, G. Selvaggi, L. Silvestris, P. Tempesta, G. Zito

INFN Sezione di Bari e Dipartimento di Fisica dell' Università, 70126 Bari, Italy

H. Hu, D. Huang, J. Lin, T. Ruan, T. Wang, W. Wu, Y. Xie, D. Xu, R. Xu, J. Zhang, W. Zhao

Institute of High-Energy Physics, Academia Sinica, Beijing, The People's Republic of China[10]

H. Albrecht[2], W.B. Atwood[3], F. Bird, E. Blucher, T.H. Burnett[4], T. Charity, H. Drevermann, Ll. Garrido, C. Grab, R. Hagelberg, S. Haywood, B. Jost, M. Kasemann, G. Kellner, J. Knobloch, A. Lacourt, I. Lehraus, T. Lohse, D. Lüke[2], A. Marchioro, P. Mato, J. May, A. Minten, A. Miotto, P. Palazzi, M. Pepe-Altarelli, F. Ranjard, A. Roth, J. Rothberg[4], H. Rotscheidt, W. von Rüden, R. St.Denis, D. Schlatter, M. Takashima, M. Talby, H. Taureg, W. Tejessy, H. Wachsmuth, S. Wheeler, W. Wiedenmann, W. Witzeling, J. Wotschack

European Laboratory for Particle Physics (CERN), 1211 Geneva 23, Switzerland

Z. Ajaltouni, M. Bardadin-Otwinowska, A. Falvard, P. Gay, P. Henrard, J. Jousset, B. Michel, J-C. Montret, D. Pallin, P. Perret, J. Proriol, F. Prulhière

Laboratoire de Physique Corpusculaire, Université Blaise Pascal, IN^2P^3-CNRS, Clermont-Ferrand, 63177 Aubière, France

J.D. Hansen, J.R. Hansen, P.H. Hansen, R. Møllerud, G. Petersen

Niels Bohr Institute, 2100 Copenhagen, Danmark[11]

(Submitted to Physics Letters B)

E. Simopoulou, A. Vayaki

Nuclear Research Center Demokritos (NRCD), Athens, Greece

J. Badier, A. Blondel, G. Bonneaud, J. Bourotte, F. Braems, J.C. Brient, M.A. Ciocci, G. Fouque, R. Guirlet, A. Rougé, M. Rumpf, R. Tanaka, H. Videau, I. Videau[1]

Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN^{2}P^3-CNRS, 91128 Palaiseau Cedex, France

D.J. Candlin

Department of Physics, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom[12]

A. Conti, G. Parrini

Dipartimento di Fisica, Università di Firenze, INFN Sezione di Firenze, 50125 Firenze, Italy

M. Corden, C. Georgiopoulos, J.H. Goldman, M. Ikeda, J. Lannutti, D. Levinthal[17], M. Mermikides, L. Sawyer, G. Stimpfl

Supercomputer Computations Research Institute and Dept. of Physics, Florida State University, Tallahassee FL 32306, USA[14,15,16]

A. Antonelli, R. Baldini, G. Bencivenni, G. Bologna[5], F. Bossi, P. Campana, G. Capon, V. Chiarella, G. De Ninno, B. D'Ettorre-Piazzoli[6], G. Felici, P. Laurelli, G. Mannocchi[6], F. Murtas, G.P. Murtas, G. Nicoletti, P. Picchi[5], P. Zografou

Laboratori Nazionali dell'INFN (LNF-INFN), 00044 Frascati, Italy

B. Altoon, O. Boyle, A.W. Halley, I. ten Have, J.L. Hearns, I.S. Hughes, J.G. Lynch, W.T. Morton, C. Raine, J.M. Scarr, K. Smith[1], A.S. Thompson

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom[12]

B. Brandl, O. Braun, R. Geiges, C. Geweniger[1], P. Hanke, V. Hepp, E.E. Kluge, Y. Maumary, M. Panter, A. Putzer, B. Rensch, A. Stahl, K. Tittel, M. Wunsch

Institut für Hochenergiephysik, Universität Heidelberg, 6900 Heidelberg, Fed. Rep. of Germany[18]

A.T. Belk, R. Beuselinck, D.M. Binnie, W. Cameron[1], M. Cattaneo, P.J. Dornan, S. Dugeay, R.W. Forty, A.M. Greene, J.F. Hassard, S.J. Patton, J.K. Sedgbeer, G. Taylor, I.R. Tomalin, A.G. Wright

Department of Physics, Imperial College, London SW7 2BZ, United Kingdom[12]

P. Girtler, D. Kuhn, G. Rudolph

Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria[20]

C.K. Bowdery[1], T.J. Brodbeck, A.J. Finch, F. Foster, G. Hughes, N.R. Keemer, M. Nuttall, B.S. Rowlingson, T. Sloan, S.W. Snow

Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom[12]

T. Barczewski, L.A.T. Bauerdick, K. Kleinknecht[1], B. Renk, S. Roehn, H.-G. Sander, M. Schmelling, F. Steeg

Institut für Physik, Universität Mainz, 6500 Mainz, Fed. Rep. of Germany [18]

J-P. Albanese, J-J. Aubert, C. Benchouk, A. Bonissent, D. Courvoisier, F. Etienne, E. Matsinos, S. Papalexiou, P. Payre, B. Pietrzyk[1], Z. Qian

Centre de Physique des Particules, Faculté des Sciences de Luminy, IN^{2}P^3-CNRS, 13288 Marseille, France

W. Blum, P. Cattaneo, G. Cowan, B. Dehning, H. Dietl, M. Fernandez-Bosman, D. Hauff, A. Jahn, E. Lange, G. Lütjens, G. Lutz, W. Männer, H-G. Moser, Y. Pan, R. Richter, A.S. Schwarz, R. Settles, U. Stiegler, U. Stierlin, J. Thomas, G. Waltermann

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, 8000 München, Fed. Rep. of Germany[18]

V. Bertin, G. de Bouard, J. Boucrot, O. Callot, X. Chen, A. Cordier, M. Davier, G. Ganis, J.-F. Grivaz, Ph. Heusse, P. Janot, V. Journé, D.W. Kim, J. Lefrançois, A.-M. Lutz, J.-J. Veillet, F. Zomer

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, IN^{2}P^3-CNRS, 91405 Orsay Cedex, France

S.R. Amendolia, G. Bagliesi, G. Batignani, L. Bosisio, U. Bottigli, C. Bradaschia, I. Ferrante, F. Fidecaro, L. Foà[1], E. Focardi, F. Forti, A. Giassi, M.A. Giorgi, F. Ligabue, A. Lusiani, E.B. Mannelli, P.S. Marrocchesi, A. Messineo, F. Palla, G. Sanguinetti, S. Scapellato, J. Steinberger, R. Tenchini, G. Tonelli, G. Triggiani

Dipartimento di Fisica dell'Università, INFN Sezione di Pisa, e Scuola Normale Superiore,56010 Pisa, Italy

J.M. Carter, M.G. Green, P.V. March, T. Medcalf, M.R. Saich, J.A. Strong[1], R.M. Thomas, T. Wildish

Department of Physics, Royal Holloway & Bedford New College, University of London, Surrey TW20 OEX, United Kingdom[12]

D.R. Botterill, R.W. Clifft, T.R. Edgecock, M. Edwards, S.M. Fisher, J. Harvey, T.J. Jones, P.R. Norton, D.P. Salmon, J.C. Thompson

Particle Physics Dept., Rutherford Appleton Laboratory, Chilton, Didcot, OXON OX11 OQX, United Kingdom[12]

E. Aubourg, B. Bloch-Devaux, P. Colas, C. Klopfenstein, E. Lançon, E. Locci, S. Loucatos, L. Mirabito, E. Monnier, P. Perez, F. Perrier, J. Rander, J.-F. Renardy, A. Roussarie, J.-P. Schuller

Département de Physique des Particules Élémentaires, CEN-Saclay, 91191 Gif-sur-Yvette Cedex, France[19]

J.G. Ashman, C.N. Booth, F. Combley, M. Dinsdale, J. Martin, D. Parker, L.F. Thompson

Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom[12]

S. Brandt, H. Burkhardt, C. Grupen, H. Meinhard, E. Neugebauer, U. Schäfer, H. Seywerd

Fachbereich Physik, Universität Siegen, 5900 Siegen, Fed. Rep. of Germany[18]

B. Gobbo, F. Liello, E. Milotti, F. Ragusa[7], L. Rolandi[1]

Dipartimento di Fisica, Università di Trieste e INFN Sezione di Trieste, 34127 Trieste, Italy

L. Bellantoni, J.F. Boudreau, D. Cinabro, J.S. Conway, D.F. Cowen, Z. Feng, J.L. Harton, J. Hilgart, R.C. Jared[8], R.P. Johnson, B.W. LeClaire, Y.B. Pan, T. Parker, J.R. Pater, Y. Saadi, V. Sharma, J.A. Wear, F.V. Weber, Sau Lan Wu, S.T. Xue, G. Zobernig

Department of Physics, University of Wisconsin, Madison, WI 53706, USA [13]

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[1] Now at CERN.

[2] Permanent address: DESY, Hamburg, Fed. Rep. of Germany.

[3] On leave of absence from SLAC, Stanford, CA 94309, USA.

[4] On leave of absence from University of Washington, Seattle, WA 98195, USA.

[5] Also Istituto di Fisica Generale, Università di Torino, Torino, Italy.

[6] Also Istituto di Cosmo-Geofisica del C.N.R., Torino, Italy.

[7] Now at INFN Milano.

[8] Permanent address: LBL, Berkeley, CA 94720, USA.

[9] Supported by CAICYT, Spain.

[10] Supported by the National Science Foundation of China.

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Abstract

We have looked for evidence of excited lepton production in Z^0 decay observed in the ALEPH detector at LEP. We find no $\ell\ell\gamma\gamma$ events and set new limits at 95% C.L. on ℓ^* masses at 44.6, 44.6 and 41.2 GeV/c^2 for e^*, μ^* and τ^* respectively. Observed events in the $\ell\ell\gamma$ channels are consistent with radiative effects and we set limits for the first time on the $\ell^*\ell Z$ coupling for ℓ^* masses in the range up to 86 GeV/c^2.

1 Introduction

The start of operation of the LEP collider provides the opportunity to search for new phenomena in Z^0 decay. Searches for new particles can be extended up to $M_Z/2$ for pair production and up to M_Z for single production. In this paper we present a search for compositeness in the leptonic sector by looking for single and pair production of e^*, μ^* and τ^* in Z^0 decay, assuming that these states couple to the Z^0.

Compositeness [1] has been introduced as a possible solution to Standard Model problems such as the lepton-quark spectrum, the mass generation, the unnaturalness of the Higgs mechanism and the large number of arbitrary parameters. Guided by the known layers in the structure of matter, one might reasonably expect that some simple underlying substructure could explain the lepton and quark family pattern, as well as the mass spectrum of both fermions and bosons [2].

One possible effect of compositeness is the existence of excited states, ℓ^*, of known leptons, ℓ (in this study $\ell = e$, μ or τ). If these states carry electroweak charges similar to the ordinary leptons, they will be readily produced at LEP as $\ell^*\ell^*$ pairs if their mass is less than $M_Z/2$. We assume, as is usual, that the branching ratio for ℓ^* decay to $\ell\gamma$ is close to 100% and we search for pair production in the $\ell\ell\gamma\gamma$ final state. Depending on the mass, m^*, of the ℓ^* and on the strength of the $\ell^*\ell Z$ coupling, any such new object could also be singly produced in an $\ell^*\ell$ state if m^* is less than M_Z and hence observed in the $\ell\ell\gamma$ final state.

Simplest models [3] of compositeness suppose that excited leptons form spin 1/2 doublets and that electroweak couplings to γ, W and Z bosons exist within this excited doublet as well as from the excited doublet to the standard one. These models greatly reduce the number of independent parameters; all the coupling constants are expressed in terms of θ_W, the weak mixing angle, and two additional parameters. As a consequence, in such models the coupling $\ell^*\ell\gamma$ is in general different from the coupling $\ell^*\ell Z$. In this study we are searching for ℓ^* production in Z^0 decays. We therefore differentiate between λ^Z/m^*, the $\ell^*\ell Z$ coupling studied here, and λ^γ/m^* the corresponding $\ell^*\ell\gamma$ coupling already constrained by previous experiments.

Production of heavy excited objects being characterized by energetic photons, we have made a search for one or two gamma rays with energy above 5 GeV accompanying e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states. We find no two-gamma events and the one-gamma events observed are consistent with radiative effects in standard di-lepton production.

2 The ALEPH detector

The data presented here were collected with the ALEPH detector running at LEP from 20 September to 6 November 1989 and correspond to an integrated luminosity of 0.38 pb^{-1} at centre of mass energies between 90.0 and 92.5 GeV.

A detailed description of the ALEPH detector is in preparation [4]. Two detector elements are crucial to the present measurements:

- An inner tracking drift chamber, ITC, and a time projection chamber, TPC, situated in the 1.5 T magnetic field of a superconducting solenoid provide a charged particle momentum resolution $\Delta p/p^2$ of typically 0.0015 $(\mathrm{GeV/c})^{-1}$.
- An electromagnetic calorimeter, ECAL, also located inside the solenoid, measures the energy of electrons and detects and measures the energy of the photons. This calorimeter covers the polar angle range from 11° to 169°. The cathode readout is divided into 73,728 projective towers, each of about $1^\circ \times 1^\circ$ solid angle. The signals from each tower are read out from three stacks of 4, 9 and 9 radiation lengths in depth. This geometry gives useful information on the longitudinal and transverse development of electromagnetic showers and, in particular, provides a powerful identification and measurement of isolated photons. The energy resolution of ECAL is $18\%/\sqrt{E}$ $(\mathrm{GeV}^{-1/2})$ and the angular resolution is $3.5/\sqrt{E}$ (mr× $\mathrm{GeV}^{-1/2}$).

A hadron calorimeter, HCAL, consisting of 23 layers of streamer tubes interspersed in the iron return yoke of the magnet and covering the polar angle from 6° to 174°, was an essential trigger element for the di-lepton channels. ALEPH has several independent triggers. An energy trigger required a total deposition of energy greater than 6.5 GeV in the ECAL central section, or greater than 3.8 GeV in either ECAL endcap or greater than 1.6 GeV in each in coincidence. Charged track triggers required signals in at least 5 of the 8 ITC wire layers, in coincidence in azimuthal segment either with an HCAL signal from 4 double planes (corresponding to a penetration of at least 40 cm of iron), or with an energy deposition of more than 1.3 GeV in ECAL. In all our channels each particle can independently trigger the event. A single electron or photon above 6.5 GeV has a trigger efficiency of 94% and muons above 2.5 GeV (which completely penetrate the iron) have an efficiency of 90%. As a consequence, for both $\ell\ell\gamma$ and $\ell\ell\gamma\gamma$ events within our acceptance, the overall trigger inefficiency is less than 1%.

3 Event Selection

The data were processed through the standard ALEPH data acquisition and reconstruction programs. A first selection was made of events with two and only two reconstructed charged tracks. The tracks were required to have at least four coordinates measured by the TPC, a momentum greater than 5 GeV/c, to originate from a 1 cm radius and 10 cm long cylinder around the nominal beam position and to have a polar angle, θ, such that $|\cos\theta| < 0.95$. An ECAL or an HCAL signal was also required to be associated to each track. These cuts result in a sample of 1577 events (an event from the final $\mu\mu\gamma$ sample is shown in figure 1).

To search for photons, an analysis of both longitudinal and transverse characteristics of neutral clusters in the electromagnetic calorimeter was made. The efficiency of the method was found to be 94% for photon energies greater than 15 GeV, decreasing to 80% at 5 GeV. Then, to be considered as photon candidates, the isolated electromagnetic clusters had to fulfil the following criteria

- $|\cos\theta_\gamma| < 0.95$,
- $E_\gamma > 5$ GeV,
- the angle between the photon and the closest track had to be larger than 30°.

Comparisons between data and electroweak expectations are shown in figure 2 for the photon sample accompanying the e^+e^- and $\mu^+\mu^-$ final states.

To allow for a direct comparison of the observed events with the expected Standard Model background coming from the radiative processes $e^+e^- \to e^+e^- + n\gamma's$, $e^+e^- \to \mu^+\mu^- + n\gamma's$ and $e^+e^- \to \tau^+\tau^- + n\gamma's$, the analysis of each ℓ^* channel took place in two steps. First, for each final state of interest, a set of cuts was defined to select the Standard Model process (the cuts are very similar to those previously used for the determination of the leptonic branching ratios [5] of the Z^0). Second, by removing some cuts, the selection was enlarged to enable the search for the hypothetical production of the corresponding excited lepton. At each step, careful comparison was made with generated events (Standard Model as well as excited lepton production) which were passed through the detector simulation, reconstruction algorithms and selection programs.

3.1 The processes $e^+e^- \to e^+e^-\gamma$ and $e^+e^- \to e^+e^-\gamma\gamma$

Events were retained as Bhabha candidates if

1. the sum of the two charged track momenta exceeded 40% of $\sqrt{s}$,
2. the acollinearity angle between the two charged tracks was less than 20 degrees,
3. each track had an ECAL associated cluster recognized as an electromagnetic shower by its longitudinal and transverse characteristics.

The resulting sample contained 632 events. No final state with two photons was observed; for 6 events a hard photon satisfying the photon criteria accompanied the two charged tracks. Normalized to the number of observed Bhabha candidates, the Monte Carlo simulation using the BABAMC program [6] predicted 6.3±1.1 events with a hard photon passing the same cuts.

To search for an e^*, cuts 1 and 2 were removed from the selection allowing acollinear events as well as low momentum final state tracks to be detected. Cut 3, the only remaining cut, selected the most general two electron final states. The corresponding data sample contained 660 events. Again, no final state with two photons was observed, but there were 10 events with a hard photon accompanying the two electrons, within the photon acceptance. Various distributions from measured and Standard Model simulated events were compared and found to be in excellent agreement as shown in figure 3(a) for the angular distribution. Normalized to the number of observed events, the Monte Carlo program for the Bhabha reaction predicted 8.5±1.2 events with a hard photon within the same cuts. The $e\gamma$ invariant mass distribution is shown in figure 4 together with the standard electroweak expectation.

3.2 The processes $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma\gamma$

Events were retained as standard μ-pair candidates if

1. the sum of the two charged track momenta exceeded 50% of $\sqrt{s}$,
2. the acollinearity angle between the two charged tracks was less than 15 degrees,
3. each track had an ECAL associated cluster with the following conditions: one cluster was required to be compatible within 3σ with a minimum ionizing particle energy deposition, the other cluster being required to have an energy deposition less than 4 GeV to allow for soft radiative muon events.

The resulting sample contained 385 events. No final state with two photons was observed, but 2 events had a hard photon satisfying the photon criteria. This sample was compared to a simulated one using KORALZ Monte Carlo [7] generated events. Both samples were found to be in very good agreement. The generated sample, normalized to the number of observed $\mu\mu$ pairs, predicted 2.2±0.3 events with a hard photon in similar cuts.

Again, to allow for acollinear as well as for low momentum final state muons to be detected, cuts 1 and 2 were removed. The final sample, with cut 3 only, contained 418 events. No two photon event was found, but 8 events had a hard photon within the photon acceptance. Various measured distributions were found in very good agreement with the generated ones using the Standard Model μ-pair simulation. The angular distribution is shown in figure 3(b). Normalized to the number of observed events, this simulation predicted 6.4±0.6 events containing a hard photon within the same criteria. Figure 4 represents the $\mu\gamma$ invariant mass distribution together with the standard electroweak expectation.

3.3 The processes $e^+e^- \to \tau^+\tau^-\gamma$ and $e^+e^- \to \tau^+\tau^-\gamma\gamma$

The search for τ^* events was limited to the detection of hard photons accompanying final states where the τ's decay giving a 1-1 topology. The efficiency of our preselection on such topology was measured directly on the observed τ sample used to determine the leptonic branching ratios [5] of the Z^0 and found to be 38% of the total number of τ events, i.e. about 52% of the expected 1-1 topology; most losses are due to the 5 GeV/c momentum cut.

To separate the standard τ-pair reaction from the preselected sample, the following cuts were applied

1. at least one track had a transverse momentum greater than 2.5 GeV/c,
2. at least one track had a momentum less than 30 GeV/c,
3. the acollinearity angle between the two charged tracks was less than 26 degrees,
4. each track had an associated ECAL cluster with an energy deposition less than 30 GeV.

The resulting sample contained 164 events. No final state with two photons was observed, but 1 event was found with a hard photon satisfying the photon criteria. The observed sample agreed well with that generated by the KORALZ Monte Carlo. This generated sample, normalized to the number of observed τ pairs, predicted 1.5±0.3 events with a hard photon in similar conditions.

To allow for a more general search of τ^* events, cuts 1 and 3 were removed from the selection producing a final sample of 181 events. No two photon final state was found but 4 events had a hard photon passing the criteria. The KORALZ prediction for the enlarged selection is 1.9±0.4 events.

4 Search for excited leptons

Assuming that excited leptons are spin 1/2 members of weak isospin doublets, then any such particle with a mass less than $M_Z/2$ can be pair produced via the normal electroweak gauge couplings. The differential cross-section for pair production via the s-channel in the Born approximation is:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16s}\beta \Big\{ & \left[|G_{LL}|^2 + |G_{RR}|^2\right](1+\beta\cos\theta)^2 \\ & + \left[|G_{LR}|^2 + |G_{RL}|^2\right](1-\beta\cos\theta)^2 \\ & + 2\left(1-\beta^2\right)\mathrm{Re}\left[G_{LL}G^*_{LR} + G_{RR}G^*_{RL}\right]\Big\} \end{aligned} \qquad (1)$$

where

$$\begin{aligned} G_{AB} &= 1 + \frac{g_A g_B}{\sin^2\theta_W\cos^2\theta_W} \quad \frac{s}{s - M_Z^2 + iM_Z\Gamma_Z} \\ g_L &= \sin^2\theta_W - \tfrac{1}{2} \\ g_R &= \sin^2\theta_W \\ \beta &= v/c \qquad \text{for the } \ell^*. \end{aligned}$$

At the Z^0 peak the single production of an excited lepton essentially depends on the $\ell^*\ell Z$ coupling, λ^Z/m^*, and has been discussed in detail by several authors [8,9,10]. The general form of the effective Lagrangian for $\ell^*\ell\gamma$ and $\ell^*\ell Z$ transitions is

$$\mathcal{L}_{eff} = \sum_{V=\gamma,Z} \frac{\lambda^V e}{2m^*}\bar{\ell}\sigma^{\mu\nu}\left(c - d\gamma^5\right)\ell F^V_{\mu\nu} + h.c. \qquad (2)$$

CP invariance and $g-2$ impose $|c| = |d| = 1$; the strengths of the $\ell^*\ell$V couplings, λ^V/m^*, must be determined experimentally.

At LEP energies radiative corrections are large, being dominated by QED initial state radiation. They have been carefully calculated [11] and used to extract the hadronic cross section on the Z^0 peak [12]. The same corrections have been applied to both the $\ell^*\ell^*$ and $\ell^*\ell$ channels.

4.1 The process $e^+e^- \to \ell^*\ell^*$

We have determined the number of events we expect to observe in each channel as follows.

Events were generated at a series of ℓ^* masses according to the distribution of equation (1) for $\sqrt{s} = 91.4$ GeV, $M_Z = 91.2$ GeV/c^2 and $\Gamma_Z = 2.68$ GeV [12]. Both ℓ^*'s were allowed to decay to $\ell\gamma$ with a uniform distribution in their centre of mass systems. For the $\tau^*\tau^*$ channel we further allowed the τ's to decay using routines from the ALEPH modified Lund Monte Carlo library. The preselection cuts (two tracks only, each with $p > 5$ GeV/c and $|\cos\theta| > 0.95$) were applied to the generated events. For the e^* and μ^* channels the energy cut has no effect for an ℓ^* mass greater than 28 GeV/c^2 and the angle cut removes typically 18% of the events, varying only very slowly with mass. Losses in the τ^* channel are much larger since the τ branching ratio to one charged track is 85.7% and the energy distribution of the final state charged particles is much softer.

Corrections were applied for radiative effects (0.75 ± 0.04), photon conversions (0.94 ± 0.02 per photon), the photon finding efficiency (0.93 ± 0.02 per photon) and the event selection efficiency (0.85 ± 0.02 for e^*e^*, 0.89 ± 0.02 for $\mu^*\mu^*$ and 0.87 ± 0.02 for $\tau^*\tau^*$). The predicted number of events for each lepton corresponding to our luminosity is shown in figure 5. Since we have seen no $\ell^*\ell^*$ candidate in any of the three channels we determine the 95% confidence limits for excited lepton masses as 44.6 GeV/c^2, 44.6 GeV/c^2 and 41.2 GeV/c^2 for e^*, μ^* and τ^* respectively. These limits are shown in figure 6 as vertical lines.

4.2 The process $e^+e^- \to \ell^*\ell$

The clear agreement, as shown in figures 2 and 3, between observed distributions for Monte Carlo and data, in both shape and normalization, suggests that the observed $\ell\ell\gamma$ events arise from standard di-lepton production with a radiated photon. The effective mass plots of figure 4 also show excellent agreement.

The 95% confidence limits on λ^Z/m^* for single e^* and μ^* production have been extracted [13] from figure 4 as a function of effective mass using the expression of Hagiwara *et al.* [10] for the cross-section for excited lepton production. Since for τ^* decays we cannot obtain the $\tau\gamma$ effective mass plot due to the unobserved neutrinos, the 95% confidence limit of 7.4 signal events for 4 observed on a predicted background of 1.9 is used at all masses.

The resulting limits for the three channels are shown in figure 6 together with previous best limits set for λ^γ/m^* at TRISTAN [14] and by the CELLO group at PETRA [15].

5 Summary

The absence of any signal for l^*l^* production in the initial data taken with ALEPH at LEP raises the mass limit for excited leptons to close to $M_Z/2$.

A comparison of the observed events in $\ell\ell\gamma$ final states shows that these are compatible with radiative di-lepton events. Consequently we set limits for the first time on the $\ell^*\ell Z$ coupling for e^* and μ^* masses up to to 86 GeV/c^2 and for the τ^* mass range up to 72 GeV/c^2. Over most of the mass regions these are lower than the $\ell^*\ell\gamma$ coupling limits obtained by previous experiments.

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Figure Captions

Figure 1. x-y view of a $\mu\mu\gamma$ event in the ALEPH detector.

Figure 2. Distribution of the angle between the photon and the closest track for the photon sample accompanying the e^+e^- and $\mu^+\mu^-$ final states; also shown is the energy distribution of those photons which are above the angular cut. The dashed lines are the electroweak expectations.

Figure 3. Angular distributions for the final e^- (a) and μ^+ (b) from the samples obtained through the enlarged e and μ selections. The solid points represent the data and the dashed lines represent the simulation normalized to the data.

Figure 4. The invariant mass distribution for lepton-photon pairs for $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ (two entries per event). The dashed lines represent the electroweak expectations.

Figure 5. Predicted number of events for e^*, μ^* and τ^* as a function of mass; the endpoint regions are shown expanded in the insets. The shaded areas indicate the $\pm 1\sigma$ errors on the predictions arising from uncertainties in the corrections; the 95% C.L. limits are at 3 events.

Figure 6. The 95% C.L. upper limits for λ^V/m^* ($V = Z$ for ALEPH, $V = \gamma$ for previous studies) as a function of f^* mass for e^*, μ^* and τ^*. These limits are derived from the reactions (a) $ee \to \ell\ell\gamma\gamma$, (b) $ee \to \ell\ell\gamma$ (also included $ee \to e\gamma(e)$) and (c) $ee \to \gamma\gamma$. Also shown is the 95% C.L. limit for the coupling $We^*\nu$ obtained by the UA2 collaboration [16] from the search of the decay sequence $W \to e^*\nu \to e\gamma\nu$. Excluded regions for excited leptons are above and left of the curves.

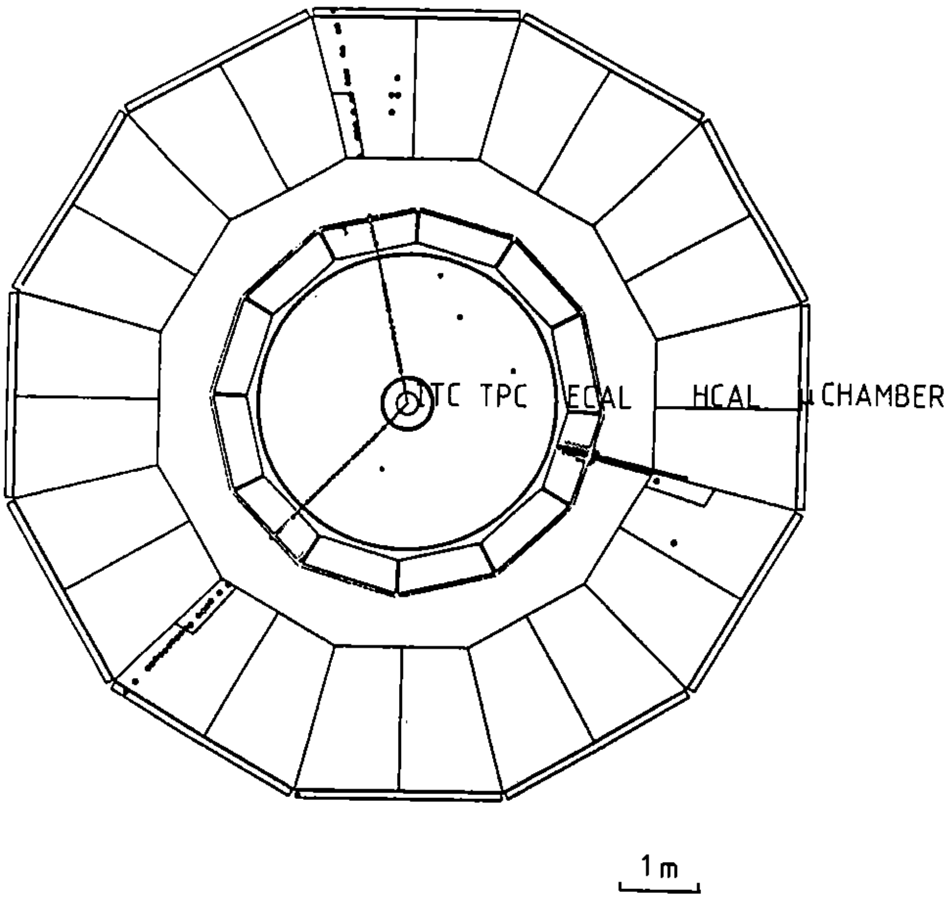
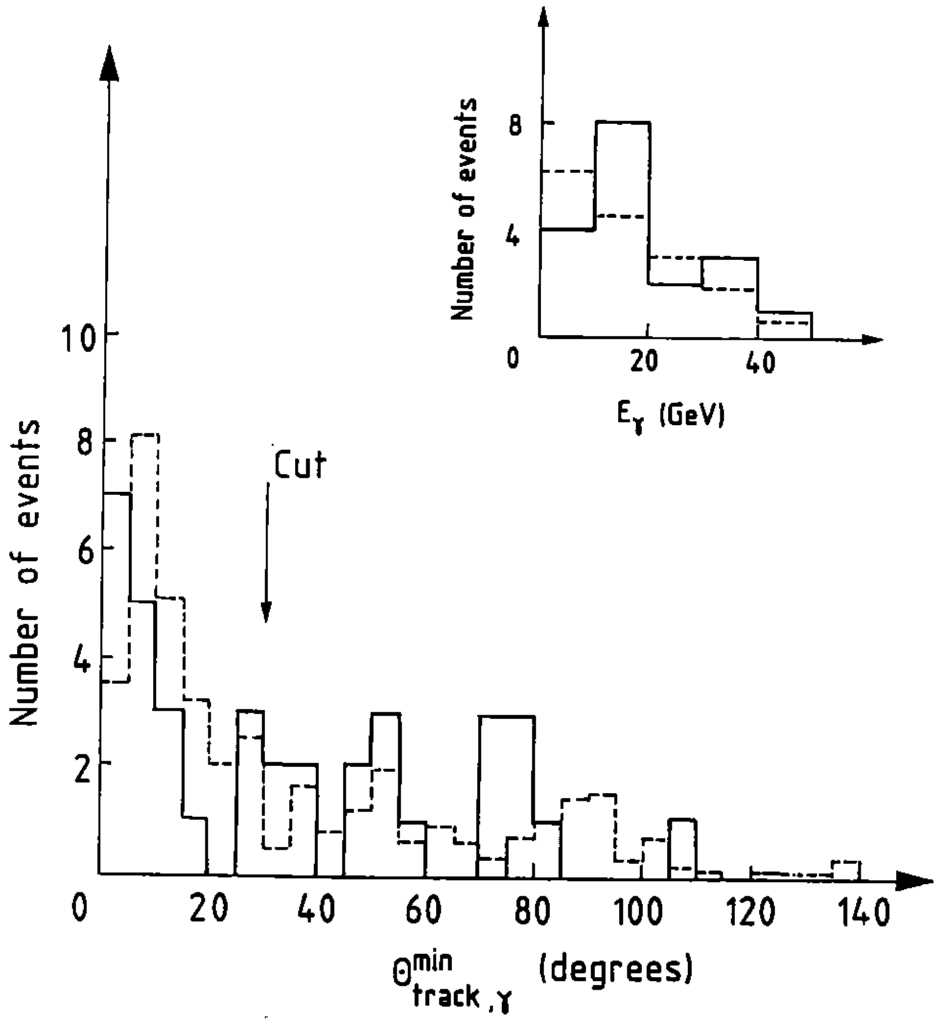


Figure 1



Number of events
10
8
6
4
2
0
20
40
60
80
100
120
140
Cut
$\Theta^{min}_{track,\gamma}$ (degrees)
Number of events
8
4
0
20
40
E_γ (GeV)

Figure 2

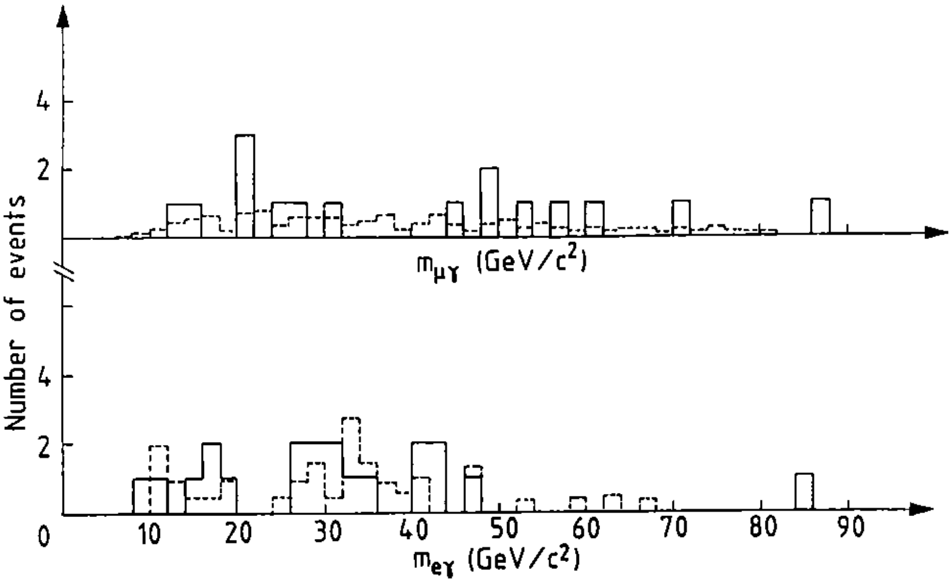

Number of events
4
2
$m_{\mu\gamma}$ (GeV/c^2)
4
2
0
10
20
30
40
50
60
70
80
90
$m_{e\gamma}$ (GeV/c^2)

Figure 4

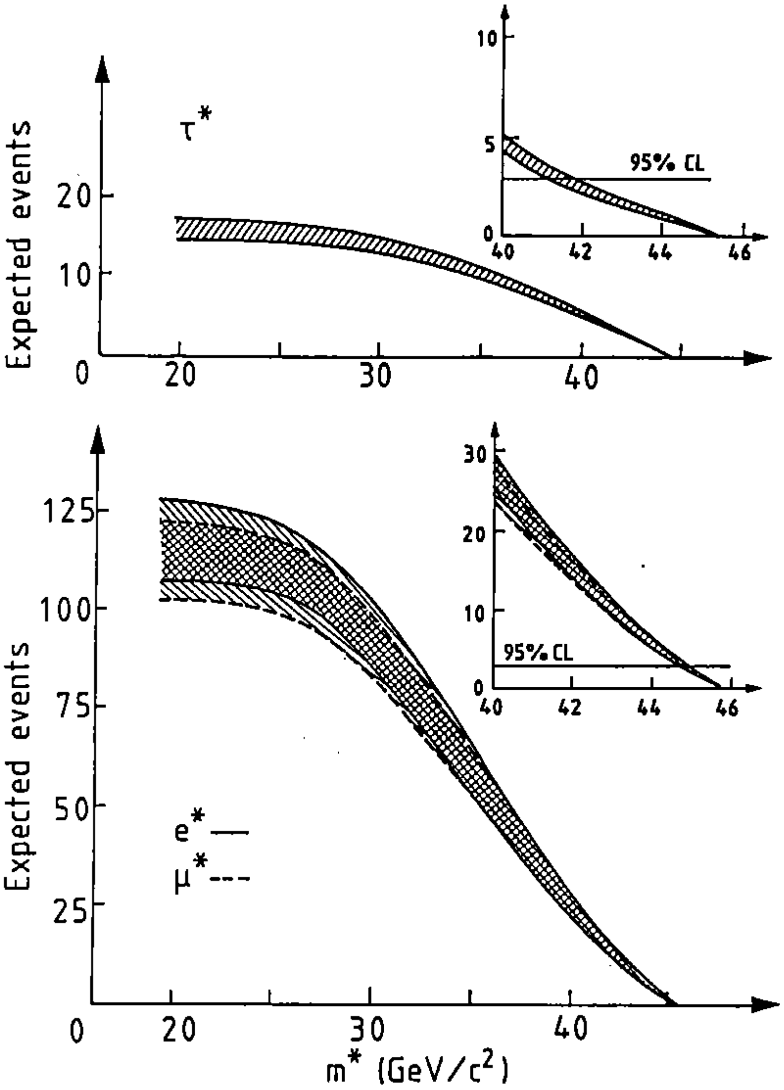

τ*
Expected events
20
10
0
20
30
40
10
5
0
95% CL
40
42
44
46
125
100
75
50
25
Expected events
0
20
30
40
m* (GeV/c²)
e* —
μ* ---
30
20
10
0
95% CL
40
42
44
46

Figure 5

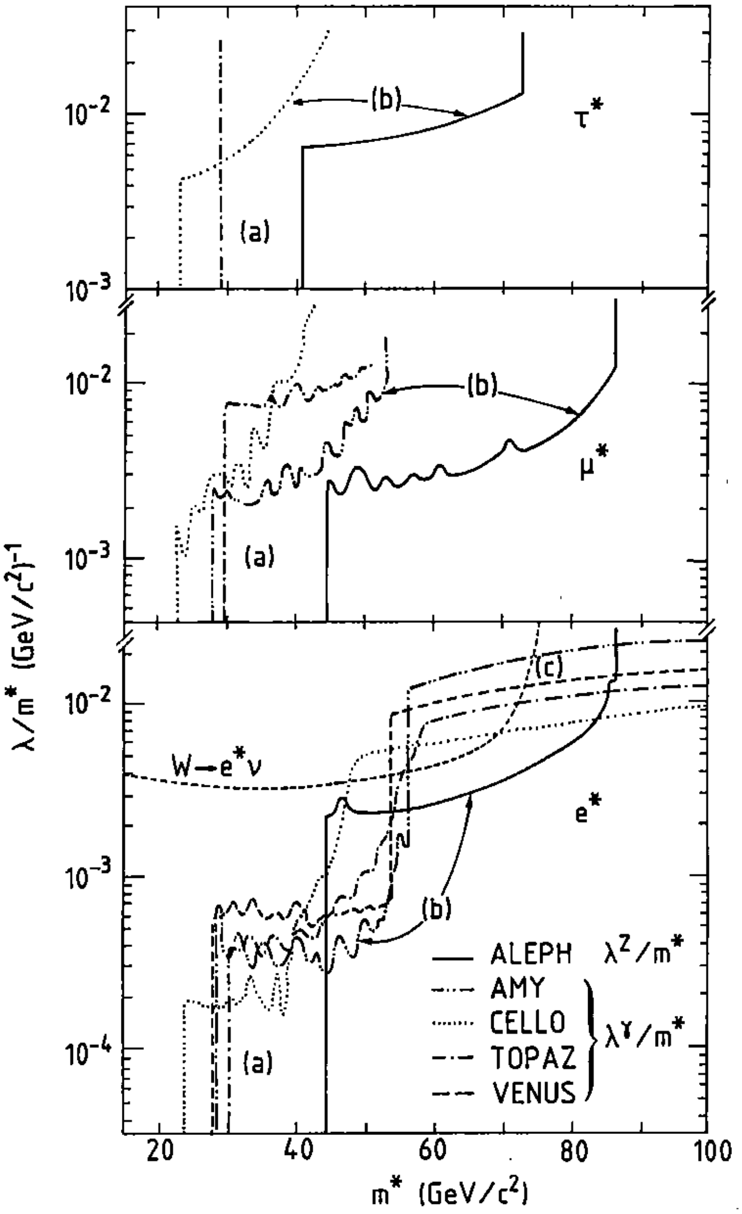

λ/m* (GeV/c²)⁻¹
10⁻²
10⁻³
(a)
(b)
τ*
10⁻²
10⁻³
(a)
(b)
μ*
10⁻²
10⁻³
10⁻⁴
W→e*ν
(c)
e*
(b)
(a)
ALEPH λ^Z/m*
AMY
CELLO
TOPAZ
VENUS
λ^γ/m*
20
40
60
80
100
m* (GeV/c²)

Figure 6