Mass Limits for Excited Electrons and Muons from Z^0 Decay

The L3 Collaboration

ABSTRACT

We searched for excited electrons and muons from Z^0 decay in the channels $ee \longrightarrow ee\gamma$, $ee \longrightarrow ee\gamma\gamma$, $ee \longrightarrow (e)e\gamma$, $ee \longrightarrow \mu\mu\gamma$, $ee \longrightarrow \mu\mu\gamma\gamma$, using the L3 detector at LEP. The lower mass limits for e^* is 45.0 GeV and for μ^* 45.3 GeV . The upper limits of ll^*Z^0 and $ll^*\gamma$ couplings at 95 % C.L. have been determined up to m_{l^*} close to the Z^0 mass.

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1. Introduction

The e^+e^- collider, LEP is ideal for the study of the production of new particles, since the initial state consists of pointlike particles and the production mechanism is purely electroweak.

The Standard Model[1] has been very successful in describing all data concerning electroweak interaction; however, it leaves many fundamental questions unexplained such as the lepton-quark spectrum, mass generation, the unnaturalness of the Higgs mechanism, and the large number of arbitrary parameters. A possible solution, which explains the family problem and makes the fermion masses and weak mixing angles calculable, would be to imagine that quarks, leptons and gauge bosons are all composites with an associated energy scale Λ[2]. One natural consequence of composite models is the existence of excited state, l^*, of known leptons l.

In this paper we describe our searches of excited electrons and muons produced in e^+e^- collisions at LEP at center of mass energies around the Z^0 mass. An excited lepton is assumed to have spin $\frac{1}{2}$ and to decay into an ordinary lepton and a photon with a 100 % branching ratio.

In e^+e^- colliders the excited leptons can be produced in pairs ($e^+e^- \rightarrow l^*l^*$) or produced singly ($e^+e^- \rightarrow ll^*$). While in the first case the l^* mass is obviously limited to the beam energy, in the second case it can reach mass regions close to the center of mass energy.

We have studied the processes $e^+e^- \rightarrow e^+e^- \gamma\gamma$, $e^+e^- \rightarrow e^+e^- \gamma$, $e^+e^- \rightarrow \mu^+\mu^- \gamma\gamma$ and $e^+e^- \rightarrow \mu^+\mu^- \gamma$. Since the excited electron production is completely dominated by very small angle scattering due to the t-channel photon exchange, we have also studied the process $e^+e^- \rightarrow (e^\pm)e^\mp\gamma$, in which one of the electrons escapes detection.

2. Coupling and Models

In this paper the Z^0 and γ are assumed to couple to spin $\frac{1}{2}$ excited lepton pairs in the same way as to ordinary lepton pairs. The lowest order pair-production cross section can be found in [3].

For the single production the effective lagrangian[4] is generally written as:

$$L_{eff} = \sum_{V=\gamma,Z} \frac{e}{\Lambda} \bar{\Psi}_F \sigma^{\mu\nu} (C_{Vl^*l} - D_{Vl^*l}\gamma_5) \Psi_f \partial_\mu V_\nu + h.c.$$

where Λ is the composite mass scale and C_V and D_V are the coupling constants. The precise g-2 measurements impose $\|C_V\| = \|D_V\|$. The coupling constants can be written as $C_\gamma = -\frac{1}{4}(f + f')$ and $C_{Z^0} = -\frac{1}{4}(f\, cot\theta_W - f'\, tan\theta_W)$ where f and f' are respectively the free parameters for SU(2) and U(1). Here we assume $f = f'$ so that $f/\Lambda (= \sqrt{2}\lambda/m_{l^*})$ is the only free parameter in the lagrangian. The differential and total cross section formulae can be found in [4,5]. Both for the single and pair production the reduction factor due to the effect of initial state radiation is taken into account in our calculations.

We use the Monte Carlo generator MMSTR[6] to simulate the single μ^* production. For pair production a Monte Carlo is made according to the differential cross section of [4].

For the single production of excited electrons in the channel $ee \longrightarrow ee\gamma$, we also use MMSTR by assuming that the mass effect is negligible, and that the t channel contribution for the large scattering angle (greater than 42^0 in our case) is small. The contribution from the t channel plus the interference is positive, so this procedure is safe for setting upper limits. We use the ESTAR[7] Monte Carlo to study the the e^* single production via the channel $ee \longrightarrow (e)e\gamma$ where one electron escapes down the beam pipe. For the e^* pair production we use the same procedure as in the muon case.

3. Data sample

The L3 detector and its performance in the detection of muons, electrons and photons is described in detail elsewhere [8]. It consists of a central tracking and vertex chamber (TEC), a BGO electromagnetic calorimeter, a hadron calorimeter made of uranium, brass and proportional wire chambers and a high precision muon chamber system. Luminosity is measured by detecting small angle Bhabha events in two forward BGO calorimeters. The BGO covers the polar angle from 42.3^0 to 137.7^0, the muon chamber from 36^0 to 144^0, and the hadron calorimeter from 5.5^0 to 174.5^0.

The data used in these searches were taken with the L3 detector at LEP during an energy scan of the Z^0 resonance at center of mass energies between 88.3 and 94.3 GeV . The integrated luminosity used in this analysis was about 1.0 pb^{-1} for e^* search from the 1990 data and 1.5 pb^{-1} for μ^* search from the 1989 and 1990 data.

4. Search for Excited Electrons

We first look for excited electrons in the processes $ee \longrightarrow ee\gamma$,$ee\gamma\gamma$, by selecting large angle e^+e^- events via the following criteria:

i) There are two and only two electrons with energies between 3 GeV and 55 GeV. The electrons are identified by an electromagnetic cluster matched with a track in the TEC.

ii) There are only 2 tracks in the TEC.

iii) There are less than 12 electromagnetic clusters with energy greater than 50 MeV.

iv) Total energy in the electromagnetic calorimeter is greater than $0.7\sqrt{s}$.

The cut (i) removes cosmic events; the cut (ii) removes $\gamma\gamma$ events. It also discards $ee\gamma$ events with photon conversion. The photon conversion probability is 1.5% in our case. The cuts (iii) and (iv) remove hadronic and $\tau\tau$ events. The remaining background is less than 0.3%. The trigger efficiency is greater than 99.5%. We obtain a total of 705 e^+e^- events which are used for normalization. The total efficiency of our selection determined using BABAMC[9] within the angular region of the BGO is $64.2 \pm 4.0\%$.

We then search for excited electrons in both pair and single production.

(1) The pair production $e^+e^- \longrightarrow e^*\bar{e}^* \longrightarrow e^+e^-\gamma\gamma$

For this channel events are selected by applying two further cuts :

v) The acollinearity angle between the two electrons is greater than 5^0.

vi) There are two photons with energies greater than 1 GeV. They are isolated from the electrons by at least 5°.

Three events pass all cuts. From visual scanning they are all confirmed to be $ee\gamma\gamma$ events. The different combinations of the invariant mass of these events do not show any structure except for one event which gives twice 18.6 GeV invariant mass for one combination. With such a e^* mass we expect more than 300 e^*e^* events. We conservatively assume that the background from Bhabha scattering is zero.

Using Monte Carlo simulation we determine a total efficiency for the pair production of 30% . After normalizing to the number of Bhabha events and correcting for the efficiency, we determine the lower mass limit for excited electrons at 95% C.L. to be 45.0 GeV.

(2) The single production $e^+e^- \longrightarrow ee^* \longrightarrow e^+e^-\gamma$

For this channel events are selected using the cuts described for pair production with cut (vi) replaced by:

vi) There is only one photon with energy greater than 1 GeV. It is isolated from the electrons by at least 5^0.

A total of 15 events pass all of these cuts. BABAMC predicts 15.3 ± 3.2 events for the corresponding luminosity and efficiency. Fig. 1a shows both $e\gamma$ invariant mass combinations for each of these 15 events compared with the prediction of BABAMC. To reconstruct the $e\gamma$ invariant mass we impose momentum conservation: $m_{e\gamma} = \sqrt{(E_\gamma + E_{e_{2(1)}})^2 - P^2_{e_{1(2)}}}$ in order to improve the mass resolution, which is typically 0.7 GeV. From the plot we conclude that all of these events are consistent with being background from Bhabha scattering.

The efficiency of the above selection for e^*, determined using MMSTR, is $48.7 \pm 2.7\%$. The efficiency is almost independent of the e^* mass. By comparing bin-by-bin(5 GeV /bin) the data with the background, the upper limits at 95% C.L. of the cross section and the coupling constant λ^V/m_{e^*} as a function of m_{e^*} are obtained using Poisson statistics[10]. For the cross section we use the analytic expression which also includes initial state radiative corrections. For the mass range above the limit of 45.0 GeV extracted from the pair production we show the results in Fig.2 together with those from other experiments at LEP[11]. The beam energy and the energy cut for electrons limits our investigation to an m_{e^*} mass below 88.3 GeV.

We also search for excited electrons through t-channel photon exchange by studying the following reaction:

(3) The single production $e^+e^- \longrightarrow ee^* \longrightarrow (e)e\gamma$

For this channel one electron escapes down the beam pipe and the excited electron decays into an electron and a photon which are both detected by the BGO calorimeter.

The events are selected by the following criteria :

i) There are only one electron and only one photon each of which has energy between 3 and 55 GeV. To be sure that these two clusters are electromagnetic, we require that the ratio of the energy sum of 9 BGO crystals surrounding the most energetic crystal to that of 25 BGO crystals is greater than 0.95.

ii) There are less than 12 electromagnetic clusters with energy greater than 50 MeV.

iii) There is only one track in the TEC.

iv) The energy deposited in the hadron calorimeter is less than 5 GeV. This cut ensures that there is no missing energy in the endcap region ($> 5.5^0$)

v) The energy deposited in the BGO is greater than 0.4 $\sqrt{s}$ GeV.

vi) The sum of energy in the BGO plus the missing energy is greater than $0.7\sqrt{s}$. Here the missing energy is calculated using 3-body kinematics assuming one escapes down in the beam pipe, and the other two are the electron and the photon.

vii) The acollinearity angle between the electron and the photon is greater than 10°.

For this channel the trigger efficiency is found to be better than 99.5%. Four events pass these cuts. The background from Bhabha scattering for the corresponding luminosity and efficiency is estimated to be 3.3 ± 0.6 events from EEG[7] . Fig. 1b shows the $e\gamma$ invariant mass for each of the 4 events compared with the background predicted by EEG. From the plot we conclude that all events are compatible with the expectation from Bhabha scattering.

We generated Monte Carlo events using the ESTAR generator. The efficiency of the above selection for events generated with a maximum angle for the undetected electron of 7^0 and a minimum acceptable photon angle of 42^0 is $92.0 \pm 3.0\%$. The efficiency is almost independent of the e^* mass. The typical mass resolution of our detector for this channel is about 0.5 GeV.

Using the ESTAR Monte Carlo and following the same procedure as for $ee\gamma$, we determine an upper limit at 95% C.L. for the coupling constant λ^V/m_{e^*} as a function of m_{e^*} as shown in Fig.2. Note that this channel gives a much lower limit for the coupling constant because the t channel of γ exchange is dominant. The beam energy and the energy cut for electrons limited our investigation to an m_{e^*} mass below 86.8 GeV.

5. Search for Excited Muons

To study the processes $ee \longrightarrow \mu\mu\gamma, \mu\mu\gamma\gamma$, we first select 2μ events by using the following cuts:

i) There are two and only two muons which have their momentum and angle measured in the muon chamber. The energy cut for muons is:

$$0.04 < \frac{E_\mu}{\sqrt{s}} < 1.0 \ .$$

ii) The event is required to survive the following scintillator and vertex cuts:

a) At least one of the muons is required to be associated with a scintillator that is in time with the bunch crossing($<$ 3 ns). The scintillator time difference is required to be inconsistent with a cosmic ray ($<$ 4ns or $>$ 20ns).

b) Both muons are required to satisify the following vertex cut:

$$r < 100 \ mm \text{ or } |z| < 200 \ mm;$$

where r is the transverse and z the longitudinal distance of closest approach to the vertex.

c) In addition, one of the two cuts listed below must be satisfied:

c1) Both muons should satisfy the following vertex cut:

$$r < 25 \ mm \text{ or } |z| < 50 \ mm;$$

c2) Both muons should be associated with scintillator hits which are in time ($<$ 3ns). The time difference should be consistant with two particles coming from the interaction point ($<$ 4ns).

iii) The energy deposited in the hadron calorimeter is less than 20 GeV.

iv) The sum of the two muon energies is greater than $0.5\sqrt{s}$.

The cut (ii) removes cosmic events; the cuts (iii) and (iv) remove $\tau\tau$ and hadronic events. The remaining background, mainly from τ decays, is less than 1%. The trigger efficiency is greater than 99.5%. We obtain a total of 770 dimuon events which are used for normalization. The total efficiency calculated from KORALZ[12] is $56.4 \pm 1.2\%$.

We search for excited muons produced via two processes denoted (1) and (2) which are discussed below.

(1) The pair production $e^+e^- \longrightarrow \mu^*\bar{\mu}^* \longrightarrow \mu^+\mu^-\gamma\gamma$

We applied the cuts (i) through (iii) listed above and two additional cuts:

iv) The acollinearity angle between the two muons is greater than 5°.

v) There are two photons with energies greater than 1 GeV. The angle between the photon and the closest muon must be larger than 5°.

Two events pass all cuts. Both of them were visually scanned. One is a genuine $\mu\mu\gamma\gamma$ event but the other one is an $ee\mu\mu$ event. All possible invariant mass combinations of this event do not show any structure (7, 15, 30, 52 GeV). The background of $\mu\mu\gamma\gamma$ predicted by the KORALZ is less than 3 at 95% C.L.

The total efficiency for pair produced μ^* is found to be 33% from Monte Carlo. After normalizing to the number of dimuon events and correcting for the efficiency, we determine the lower mass limit for excited muons at 95% C.L. to be 45.3 GeV.

(2)The single production $e^+e^- \longrightarrow \mu\mu^* \longrightarrow \mu^+\mu^-\gamma$

For this channel events are selected with the same cuts as for pair production with cut (v) replaced by:

v) There is one photon with energy greater than 1 GeV. The angle between the photon and the closest muon must be greater than 5^0.

A total of 21 events pass all of these cuts. KORALZ predicts 21.8 ± 3.9 events for the corresponding luminosity and efficiency. Fig. 3 shows both $\mu\gamma$ invariant mass combinations for each of these 21 events compared with the prediction of KORALZ . To reconstruct the invariant mass of $\mu\gamma$ pairs we again impose momentum conservation: $m_{\mu\gamma} = \sqrt{(E_\gamma + E_{\mu_{2(1)}})^2 - P^2_{\mu_{1(2)}}}$ in order to improve the mass resolution, which is typically 1.3 GeV. From Fig.3 we conclude that all events are compatible with expected dimuon events.

We generate Monte Carlo events for $m_{\mu^*} = 80$ GeV using MMSTR. We determine a total efficiency of $35.7 \pm 1.9\%$, which is almost independent of the μ^* mass.

Using the same method as above, an upper limit of the coupling constant λ^V/m_{μ^*} at 95% C.L. as a function of m_{μ^*} is obtained. Our result is shown in Fig.4 for the mass range above the limit of 45.3 GeV extracted from the pair production search, together with those from other experiments[11] at LEP. The beam energy and the momentum cut for muons limits our range for m_{μ^*} searches to 87.6 GeV.

6. Summary

We have searched for excited electrons and muons through the reactions $ee \longrightarrow ee\gamma$, $ee \longrightarrow ee\gamma\gamma$, $ee \longrightarrow (e)e\gamma$, $ee \longrightarrow \mu\mu\gamma$, $ee \longrightarrow \mu\mu\gamma\gamma$, using the L3 detector at LEP. The observed events are consistent with the standard model expectations and we have no evidence for excited electrons and muons. From the pair production search the lower mass limits for e^* and μ^* are found to be greater than 45.0 and 45.3 GeV respectively. From the single production search we set upper limits on the ll^*Z^0 and $ll^*\gamma$ couplings up to l^* masses close to the Z^0 mass.

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FIGURE CAPTIONS

Fig.1. The $e\gamma$ invariant mass compared with background predicted from Monte Carlo. a) Events come from the channel $ee \longrightarrow ee\gamma$ b) Events come from the channel $ee \longrightarrow (e)e\gamma$.

Fig.2. The upper limit of the coupling constant λ^V/m_{e^*} at 95 % C.L. as a function of m_{e^*}. The excluded region is above and left of the curves.

Fig.3. The $\mu\gamma$ invariant mass from channel $ee \longrightarrow \mu\mu\gamma$ compared with KORALZ as the background.

Fig.4. The upper limit of the coupling constant λ^V/m_{μ^*} at 95 % C.L. as a function of m_{μ^*}. The excluded region is above and left of the curves.

The L3 Collaboration:

B.Adeva,[15] O.Adriani,[13] M.Aguilar-Benitez,[21] H.Akbari,[5] J.Alcaraz,[21] A.Aloisio,[23] G.Alverson,[9] M.G.Alviggi,[23] Q.An,[16] H.Anderhub,[34] A.L.Anderson,[12] V.P.Andreev,[14] T.Angelov,[12] L.Antonov,[31] D.Antreasyan,[7] A.Arefiev,[22] T.Azemoon,[3] T.Aziz,[8] P.V.K.S.Baba,[16] P.Bagnaia,[27] J.A.Bakken,[26] L.Baksay,[29] R.C.Ball,[3] S.Banerjee,[8,16] J.Bao,[5] L.Barone,[27] A.Bay,[17] U.Becker,[12,15] J.Behrens,[34] S.Beingessner,[4] Gy.L.Bencze,[10,29] J.Berdugo,[21] P.Berges,[12] B.Bertucci,[27] B.L.Betev,[31] A.Biland,[34] R.Bizzarri,[27] J.J.Blaising,[4] P.Blömeke,[1] B.Blumenfeld,[5] G.J.Bobbink,[2] M.Bocciolini,[13] W.Böhlen,[32] A.Böhm,[1] T.Böhringer,[19] B.Borgia,[27] D.Bourilkov,[31] M.Bourquin,[17] D.Boutigny,[4] J.G.Branson,[28] I.C.Brock,[25] F.Bruyant,[15] C.Buisson,[20] J.D.Burger,[12] J.P.Burq,[20] X.D.Cai,[34] D.Campana,[23] C.Camps,[1] M.Capell,[3] F.Carbonara,[23] F.Carminati,[13] A.M.Cartacci,[13] M.Cerrada,[21] F.Cesaroni,[27] Y.H.Chang,[12] 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B.Monteleoni,[13] G.Morand,[17] R.Morand,[4] S.Morganti,[27] V.Morgunov,[22] R.Mount,[24] E.Nagy,[10,15] M.Napolitano,[23] H.Newman,[24] L.Niessen,[1] W.D.Nowak,[33] D.Pandoulas,[1] G.Paternoster,[23] S.Patricelli,[23] Y.J.Pei,[1] D.Perret-Gallix,[4] J.Perrier,[17] E.Perrin,[17] A.Pevsner,[5] M.Pieri,[13] P.A.Piroué,[26] V.Plyaskin,[22] M.Pohl,[34] V.Pojidaev,[22] N.Produit,[17] J.M.Qian,[12,16] K.N.Qureshi,[16] R.Raghavan,[8] G.Rahal-Callot,[34] P.Razis,[34] K.Read,[26] D.Ren,[34] Z.Ren,[16] S.Reucroft,[9] T.Riemann,[33] C.Rippich,[25] S.Rodriguez,[21] B.P.Roe,[3] M.Röhner,[1] S.Röhner,[1] Th.Rombach,[1] L.Romero,[21] J.Rose,[1] S.Rosier-Lees,[4] R.Rosmalen,[2] Ph.Rosselet,[19] J.A.Rubio,[15,21] W.Ruckstuhl,[17] H.Rykaczewski,[34] M.Sachwitz,[33] J.Salicio,[21] G.Sauvage,[4] A.Savin,[22] V.Schegelsky,[14] D.Schmitz,[1] P.Schmitz,[1] M.Schneegans,[4] M.Schöntag,[1] H.Schopper,[35] D.J.Schotanus,[2] H.J.Schreiber,[33] R.Schulte,[1] S.Schulte,[1] K.Schultze,[1] J.Schütte,[11] J.Schwenke,[1] G.Schwering,[1] C.Sciacca,[23] P.G.Seiler,[34] J.C.Sens,[2] I.Sheer,[28] V.Shevchenko,[22] S.Shevchenko,[22] X.R.Shi,[25] K.Shmakov,[22] V.Shoutko,[22] E.Shumilov,[22] N.Smirnov,[14] A.Sopczak,[24,28] C.Souyri,[4] C.Spartiotis,[5] T.Spickermann,[1] B.Spiess,[32] P.Spillantini,[13] R.Starosta,[1] M.Steuer,[7,12] D.P.Stickland,[26] B.Stöhr,[34] H.Stone,[17] K.Strauch,[11] K.Sudhakar,[8,1] G.Sultanov,[15] R.L.Sumner,[26] H.Suter,[34] R.B.Sutton,[25] A.A.Syed,[16] X.W.Tang,[6] E.Tarkovsky,[22] J.M.Thenard,[4] E.Thomas,[16] C.Timmermans,[2] Samuel C.C.Ting,[12] S.M.Ting,[12] Y.P.Tong,[36] M.Tonutti,[1] S.C.Tonwar,[8] J.Tòth,[10] K.L.Tung,[6] J.Ulbricht,[32] L.Urbàn,[10] U.Uwer,[1] E.Valente,[27] R.T.Van de Walle,[2] H.van der Graaf,[2] I.Vetlitsky,[22] G.Viertel,[34] P.Vikas,[16] M.Vivargent,[4,12] H.Vogel,[25] H.Vogt,[33] M.Vollmar,[1] G.Von Dardel,[15] I.Vorobiev,[22] A.A.Vorobyov,[14] An.A.Vorobyov,[14] L.Vuilleumier,[19] W.Walk,[15] W.Wallraff,[1] C.R.Wang,[18] 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1 I. Physikalisches Institut, RWTH, Aachen, Federal Republic of Germany§
III. Physikalisches Institut, RWTH, Aachen, Federal Republic of Germany§
2 National Institute for High Energy Physics, NIKHEF, Amsterdam; NIKHEF-H and University of Nijmegen, Nijmegen, The Netherlands
3 University of Michigan, Ann Arbor, United States of America
4 Laboratoire de Physique des Particules, LAPP, Annecy, France
5 Johns Hopkins University, Baltimore, United States of America
6 Institute of High Energy Physics, IHEP, Beijing, China
7 INFN-Sezione di Bologna, Italy
8 Tata Institute of Fundamental Research, Bombay, India
9 Northeastern University, Boston, United States of America
10 Central Research Institute for Physics of the Hungarian Academy of Sciences, Budapest, Hungary
11 Harvard University, Cambridge, United States of America
12 Massachusetts Institute of Technology, Cambridge, United States of America
13 INFN Sezione di Firenze and University of Firenze, Italy
14 Leningrad Nuclear Physics Institute, Gatchina, Soviet Union
15 European Laboratory for Particle Physics, CERN, Geneva, Switzerland
16 World Laboratory, FBLJA Project, Geneva, Switzerland
17 University of Geneva, Geneva, Switzerland
18 Chinese University of Science and Technology, USTC, Hefei, China
19 University of Lausanne, Lausanne, Switzerland
20 Institut de Physique Nucléaire de Lyon, IN2P3-CNRS/Université Claude Bernard, Villeurbanne, France
21 Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, CIEMAT, Madrid, Spain
22 Institute of Theoretical and Experimental Physics, ITEP, Moscow, Soviet Union
23 INFN-Sezione di Napoli and University of Naples, Italy
24 California Institute of Technology, Pasadena, United States of America
25 Carnegie Mellon University, Pittsburgh, United States of America
26 Princeton University, Princeton, United States of America
27 INFN-Sezione di Roma and University of Roma, "La Sapienza", Italy
28 University of California, San Diego, United States of America
29 Union College, Schenectady, United States of America
30 Shanghai Institute of Ceramics, SIC, Shanghai, China
31 Central Laboratory of Automation and Instrumentation, CLANP, Sofia, Bulgaria
32 Paul Scherrer Institut, PSI, Würenlingen, Switzerland
33 High Energy Physics Institute, Zeuthen-Berlin, German Democratic Republic
34 Eidgenössische Technische Hochschule, ETH Zürich Switzerland
35 University of Hamburg, Federal Republic of Germany
36 High Energy Physics Group, Taiwan, China
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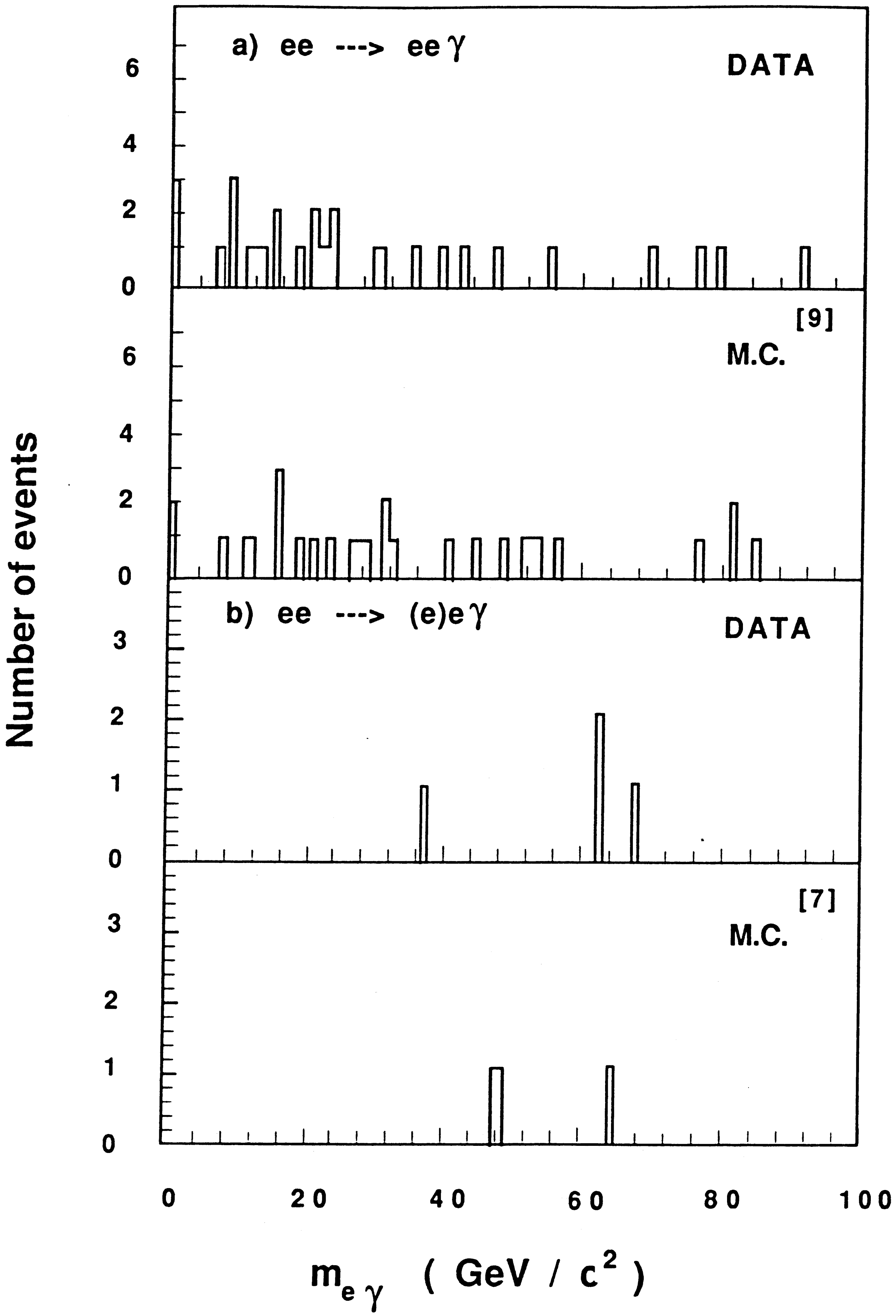
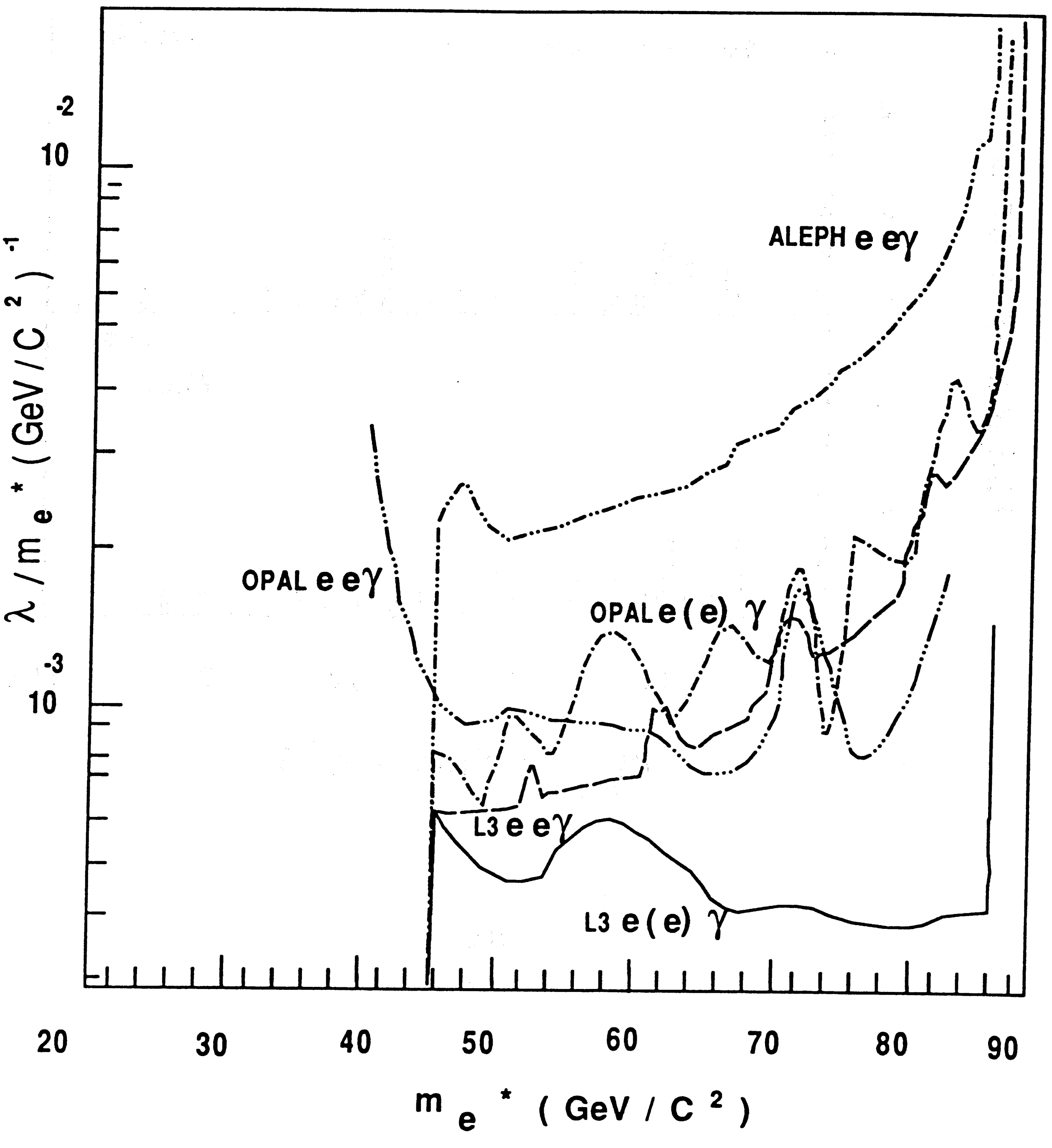


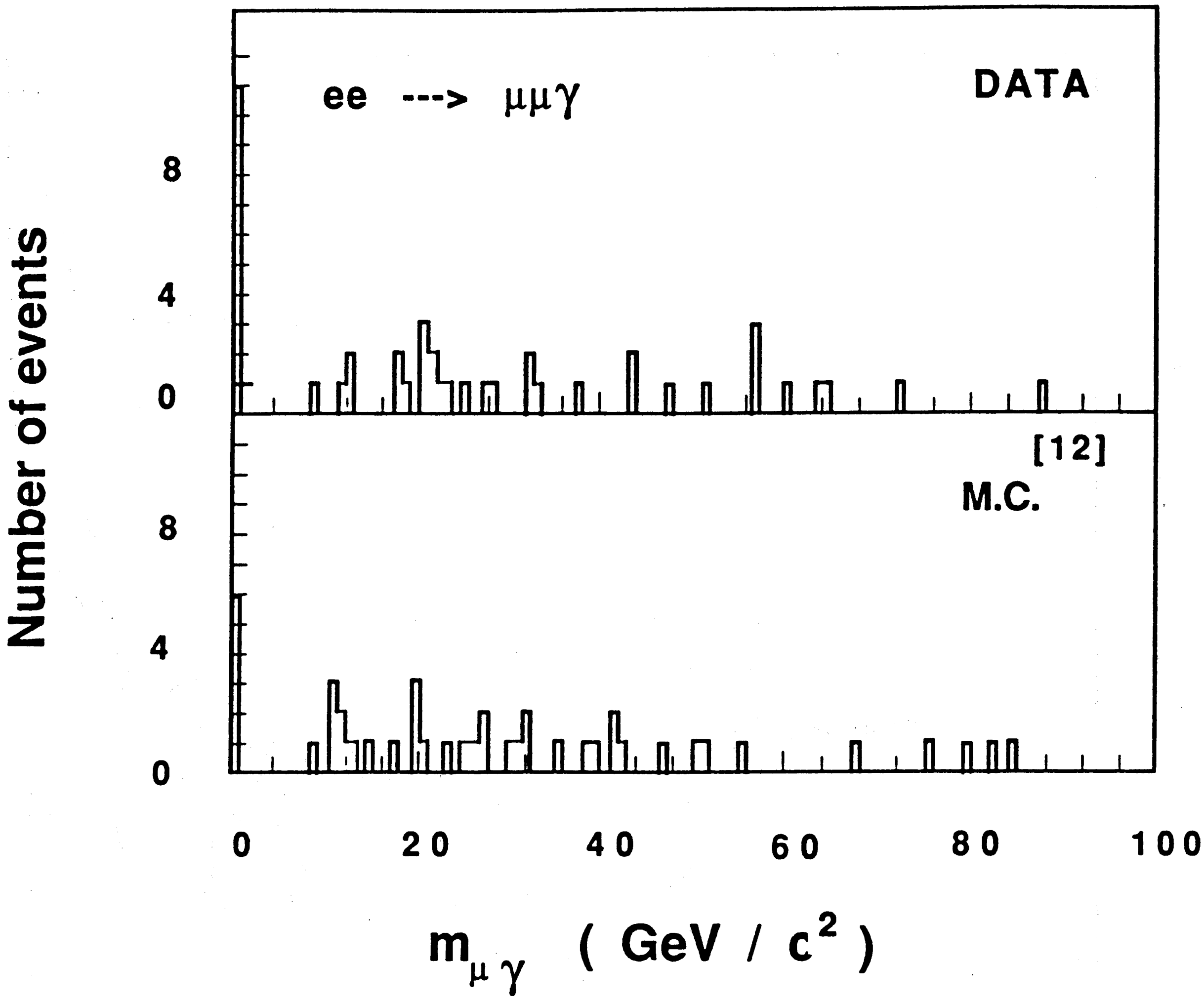
a) ee ---> ee γ
DATA
M.C.
[9]
b) ee ---> (e)e γ
DATA
M.C.
[7]
Number of events
0
2
4
6
0
1
2
3
0
20
40
60
80
100
$m_{e\gamma}$ (GeV / c^2)

Figure 1



10^-2
10^-3
λ / m_e* (GeV / C²)^-1
ALEPH e eγ
OPAL e eγ
OPAL e (e) γ
L3 e eγ
L3 e (e) γ
20
30
40
50
60
70
80
90
m_e* (GeV / C²)

Figure 2



ee ---> μμγ
DATA
[12]
M.C.
Number of events
8
4
0
8
4
0
0
20
40
60
80
100
m μγ (GeV / c²)

Figure 3

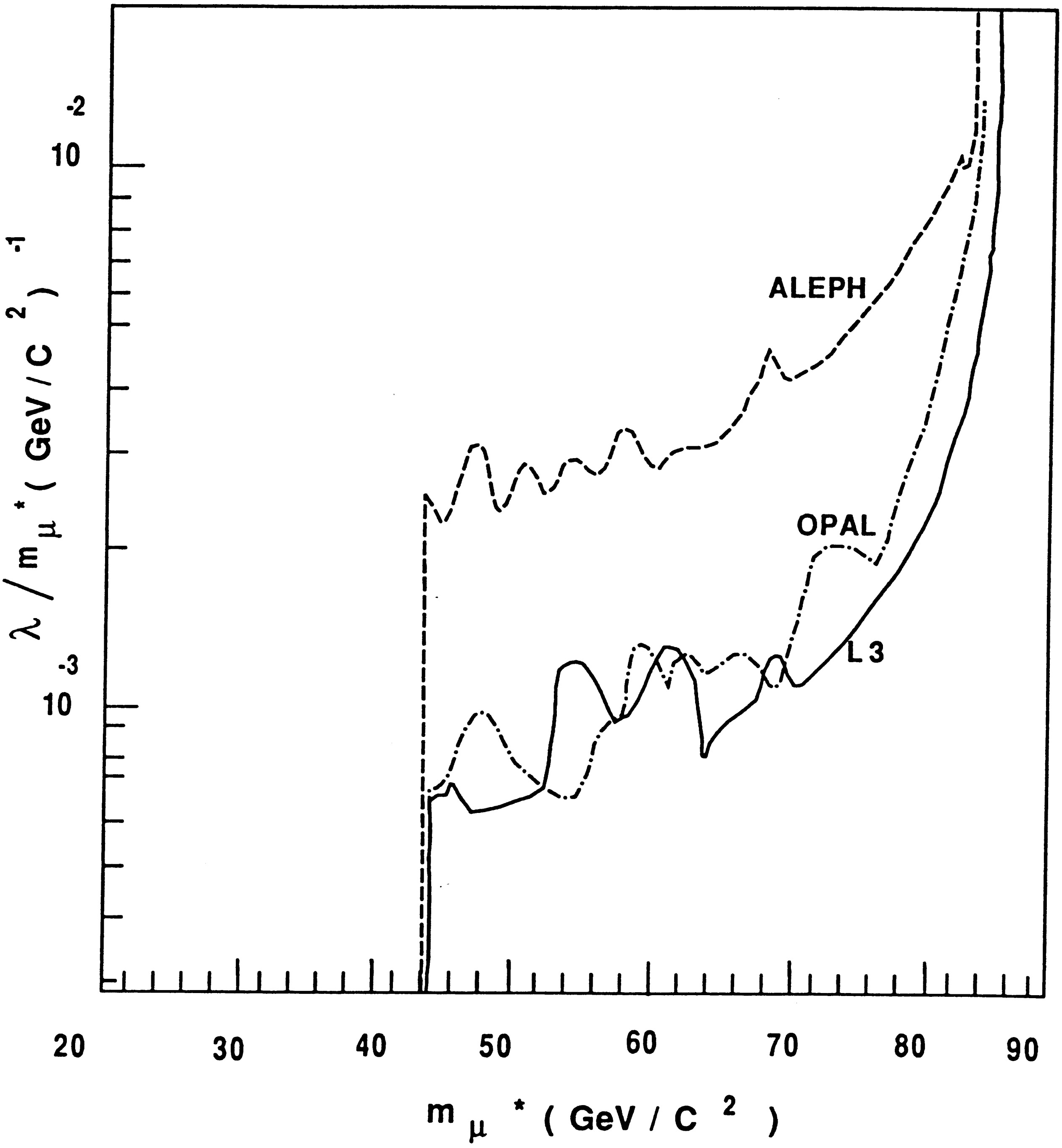


Figure 4

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