EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PPE/96–60

6 May 1996

Study of radiative leptonic events with hard photons and search for excited charged leptons at $\sqrt{s} = 130 - 136$ GeV

DELPHI Collaboration

Abstract

During the last 1995 data acquisition period at LEP, the DELPHI experiment collected an integrated luminosity of 5.9 pb^{-1} at centre-of-mass energies of 130 GeV and 136 GeV. Radiative leptonic events (e, μ, τ) with high energy photons were studied and compared to Standard Model predictions. The data were used to search for charged excited leptons decaying through an electromagnetic transition. No significant signal was found. From the search for pair produced excited leptons, the limits $m_{e^*} > 62.5$ GeV/c^2, $m_{\mu^*} > 62.6$ GeV/c^2 and $m_{\tau^*} > 62.2$ GeV/c^2 at 95% confidence level were established. For single excited lepton production, upper limits on the ratio λ/m_{ℓ^*} of the coupling of the excited charged lepton to its mass were derived.

(To be submitted to Phys. Lett. B)

P.Abreu[21], W.Adam[50], T.Adye[37], E.Agasi[31], I.Ajinenko[42], R.Aleksan[39], G.D.Alekseev[16], R.Alemany[49], P.P.Allport[22], S.Almehed[24], U.Amaldi[9], S.Amato[47], A.Andreazza[28], M.L.Andrieux[14], P.Antilogus[9], W-D.Apel[17], Y.Arnoud[39], B.Åsman[44], J-E.Augustin[25], A.Augustinus[9], P.Baillon[9], P.Bambade[19], F.Barao[21], R.Barate[14], M.Barbi[47], G.Barbiellini[46], D.Y.Bardin[16], A.Baroncelli[40], O.Barring[24], J.A.Barrio[26], W.Bartl[50], M.J.Bates[37], M.Battaglia[15], M.Baubillier[23], J.Baudot[39], K-H.Becks[52], M.Begalli[6], P.Beilliere[8], Yu.Belokopytov[9,53], A.C.Benvenuti[5], M.Berggren[47], D.Bertini[25], D.Bertrand[2], F.Bianchi[45], M.Bigi[45], M.S.Bilenky[16], P.Billoir[23], D.Bloch[10], M.Blume[52], T.Bolognese[39], M.Bonesini[28], W.Bonivento[28], P.S.L.Booth[22], C.Bosio[40], O.Botner[48], E.Boudinov[31], B.Bouquet[19], C.Bourdarios[9], T.J.V.Bowcock[22], M.Bozzo[13], P.Branchini[40], K.D.Brand[36], T.Brenke[52], R.A.Brenner[15], C.Bricman[2], R.C.A.Brown[9], P.Bruckman[18], J-M.Brunet[8], L.Bugge[33], T.Buran[33], T.Burgsmueller[52], P.Buschmann[52], A.Buys[9], S.Cabrera[49], M.Caccia[28], M.Calvi[28], A.J.Camacho Rozas[41], T.Camporesi[9], V.Canale[38], M.Canepa[13], K.Cankocak[44], F.Cao[2], F.Carena[9], L.Carroll[22], C.Caso[13], M.V.Castillo Gimenez[49], A.Cattai[9], F.R.Cavallo[5], V.Chabaud[9], Ph.Charpentier[9], L.Chaussard[25], J.Chauveau[23], P.Checchia[36], G.A.Chelkov[16], M.Chen[2], R.Chierici[45], P.Chliapnikov[42], P.Chochula[7], V.Chorowicz[9], V.Cindro[43], P.Collins[9], J.L.Contreras[19], R.Contri[13], E.Cortina[49], G.Cosme[19], F.Cossutti[46], H.B.Crawley[1], D.Crennell[37], G.Crosetti[13], J.Cuevas Maestro[34], S.Czellar[15], E.Dahl-Jensen[29], J.Dahm[52], B.Dalmagne[19], M.Dam[29], G.Damgaard[29], P.D.Dauncey[37], M.Davenport[9], W.Da Silva[23], C.Defoix[8], A.Deghorain[2], G.Della Ricca[46], P.Delpierre[27], N.Demaria[35], A.De Angelis[9], W.De Boer[17], S.De Brabandere[2], C.De Clercq[2], C.De La Vaissiere[23], B.De Lotto[46], A.De Min[36], L.De Paula[47], C.De Saint-Jean[39], H.Dijkstra[9], L.Di Ciaccio[38], F.Djama[10], J.Dolbeau[8], M.Donszelmann[9], K.Doroba[51], M.Dracos[10], J.Drees[52], K.-A.Drees[52], M.Dris[32], J-D.Durand[25], D.Edsall[1], R.Ehret[17], G.Eigen[4], T.Ekelof[48], G.Ekspong[44], M.Elsing[52], J-P.Engel[10], B.Erzen[43], M.Espirito Santo[21], E.Falk[24], D.Fassouliotis[32], M.Feindt[9], A.Fenyuk[42], A.Ferrer[49], S.Fichet[23], T.A.Filippas[32], A.Firestone[1], P.-A.Fischer[10], H.Foeth[9], E.Fokitis[32], F.Fontanelli[13], F.Formenti[9], B.Franek[37], P.Frenkiel[8], D.C.Fries[17], A.G.Frodesen[4], R.Fruhwirth[50], F.Fulda-Quenzer[19], J.Fuster[49], A.Galloni[22], D.Gamba[45], M.Gandelman[6], C.Garcia[49], J.Garcia[41], C.Gaspar[9], U.Gasparini[36], Ph.Gavillet[9], E.N.Gazis[32], D.Gele[10], J-P.Gerber[10], M.Gibbs[22], R.Gokieli[51], B.Golob[43], G.Gopal[37], L.Gorn[1], M.Gorski[51], Yu.Gouz[45,53], V.Gracco[13], E.Graziani[40], G.Grosdidier[19], K.Grzelak[51], S.Gumenyuk[28,53], P.Gunnarsson[44], M.Gunther[48], J.Guy[37], F.Hahn[9], S.Hahn[52], Z.Hajduk[18], A.Hallgren[48], K.Hamacher[52], W.Hao[31], F.J.Harris[35], V.Hedberg[24], R.Henriques[21], J.J.Hernandez[49], P.Herquet[2], H.Herr[9], T.L.Hessing[35], E.Higon[49], H.J.Hilke[9], T.S.Hill[1], S-O.Holmgren[44], P.J.Holt[35], D.Holthuizen[31], S.Hoorelbeke[2], M.Houlden[22], J.Hrubec[50], K.Huet[2], K.Hultqvist[44], J.N.Jackson[22], R.Jacobsson[44], P.Jalocha[18], R.Janik[7], Ch.Jarlskog[24], G.Jarlskog[24], P.Jarry[39], B.Jean-Marie[19], E.K.Johansson[44], L.Jonsson[24], P.Jonsson[24], C.Joram[9], P.Juillot[10], M.Kaiser[17], F.Kapusta[23], K.Karafasoulis[11], M.Karlsson[44], E.Karvelas[11], S.Katsanevas[3], E.C.Katsoufis[32], R.Keranen[4], Yu.Khokhlov[42], B.A.Khomenko[16], N.N.Khovanski[16], B.King[22], N.J.Kjaer[29], H.Klein[9], A.Klovning[4], P.Kluit[31], B.Koene[31], P.Kokkinias[11], M.Koratzinos[9], K.Korcyl[18], V.Kostioukhine[42], C.Kourkoumelis[3], O.Kouznetsov[13,16], P.-H.Kramer[52], M.Krammer[50], C.Kreuter[17], I.Kronkvist[24], Z.Krumstein[16], W.Krupinski[18], P.Kubinec[7], W.Kucewicz[18], K.Kurvinen[15], C.Lacasta[49], I.Laktineh[25], S.Lamblot[23], J.W.Lamsa[1], L.Lanceri[46], D.W.Lane[1], P.Langefeld[52], V.Lapin[42], I.Last[22], J-P.Laugier[39], R.Lauhakangas[15], F.Ledroit[14], V.Lefebure[2], C.K.Legan[1], R.Leitner[30], Y.Lemoigne[39], J.Lemonne[2], G.Lenzen[52], V.Lepeltier[19], T.Lesiak[18], J.Libby[35], D.Liko[50], R.Lindner[52], A.Lipniacka[36], I.Lippi[36], B.Loerstad[24], J.G.Loken[35], J.M.Lopez[41], D.Loukas[11], P.Lutz[39], L.Lyons[35], J.MacNaughton[50], G.Maehlum[17], A.Maio[21], V.Malychev[16], F.Mandl[50], J.Marco[41], R.Marco[41], B.Marechal[47], M.Margoni[36], J-C.Marin[9], C.Mariotti[40], A.Markou[11], T.Maron[52], C.Martinez-Rivero[41], F.Martinez-Vidal[49], S.Marti i Garcia[49], F.Matorras[41], C.Matteuzzi[9], G.Matthiae[38], M.Mazzucato[36], M.Mc Cubbin[9], R.Mc Kay[1], R.Mc Nulty[22], J.Medbo[48], M.Merk[31], C.Meroni[28], S.Meyer[17], W.T.Meyer[1], A.Miagkov[42], M.Michelotto[36], E.Migliore[45], L.Mirabito[25], W.A.Mitaroff[50], U.Mjoernmark[24], T.Moa[44], R.Moeller[29], K.Moenig[9], M.R.Monge[13], P.Morettini[13], H.Mueller[17], L.M.Mundim[6], W.J.Murray[37], B.Muryn[18], G.Myatt[35], F.Naraghi[14], F.L.Navarria[5], S.Navas[49], K.Nawrocki[51], P.Negri[28], S.Nemecek[12], W.Neumann[52], N.Neumeister[50], R.Nicolaidou[3], B.S.Nielsen[29], M.Nieuwenhuizen[31], V.Nikolaenko[10], P.Niss[44], A.Nomerotski[36], A.Normand[35], M.Novak[12], W.Oberschulte-Beckmann[17], V.Obraztsov[42], A.G.Olshevski[16], A.Onofre[21], R.Orava[15], K.Osterberg[15], A.Ouraou[39], P.Paganini[19], M.Paganoni[9], P.Pages[10], H.Palka[18], Th.D.Papadopoulou[32], K.Papageorgiou[11], L.Pape[9], C.Parkes[35], F.Parodi[13], A.Passeri[40], M.Pegoraro[36], L.Peralta[21], H.Pernegger[50], M.Pernicka[50], A.Perrotta[5], C.Petridou[46], A.Petrolini[13], M.Petrovyck[28,53], H.T.Phillips[37], G.Piana[13], F.Pierre[39], M.Pimenta[21], M.Pindo[28], S.Plaszczynski[19], O.Podobrin[17], M.E.Pol[6], G.Polok[18], P.Poropat[46], V.Pozdniakov[16], M.Prest[46], P.Privitera[38], N.Pukhaeva[16], A.Pullia[28], D.Radojicic[35], S.Ragazzi[28], H.Rahmani[32], J.Rames[12], P.N.Ratoff[20], A.L.Read[33], M.Reale[52], P.Rebecchi[19], N.G.Redaelli[28], M.Regler[50], D.Reid[9], P.B.Renton[35], L.K.Resvanis[3], F.Richard[19], J.Richardson[22], J.Ridky[12], G.Rinaudo[45], I.Ripp[39], A.Romero[45], I.Roncagliolo[13], P.Ronchese[36], L.Roos[14], E.I.Rosenberg[1], E.Rosso[9], P.Roudeau[19], T.Rovelli[5], W.Ruckstuhl[31], V.Ruhlmann-Kleider[39], A.Ruiz[41], K.Rybicki[18], H.Saarikko[15], Y.Sacquin[39], A.Sadovsky[16], O.Sahr[14], G.Sajot[14], J.Salt[49], J.Sanchez[26], M.Sannino[13], M.Schimmelpfennig[17], H.Schneider[17], U.Schwickerath[17], M.A.E.Schyns[52], G.Sciolla[45], F.Scuri[46], P.Seager[20], Y.Sedykh[16], A.M.Segar[35], A.Seitz[17], R.Sekulin[37], L.Serbelloni[38], R.C.Shellard[6], I.Siccama[31], P.Siegrist[39], S.Simonetti[39], F.Simonetto[36], A.N.Sisakian[16], B.Sitar[7], T.B.Skaali[33], G.Smadja[25], N.Smirnov[42], O.Smirnova[24], G.R.Smith[37], A.Sokolov[42], R.Sosnowski[51], D.Souza-Santos[6], E.Spiriti[40], P.Sponholz[52], S.Squarcia[13], C.Stanescu[40], S.Stapnes[33], I.Stavitski[36], K.Stevenson[35], F.Stichelbaut[9], A.Stocchi[19], J.Strauss[50], R.Strub[10], B.Stugu[4], M.Szczekowski[51], M.Szeptycka[51], T.Tabarelli[28], J.P.Tavernet[23], O.Tchikilev[42], J.Thomas[35], A.Tilquin[27], J.Timmermans[31], L.G.Tkatchev[16], T.Todorov[10], S.Todorova[10], D.Z.Toet[31], A.Tomaradze[2], B.Tome[21], A.Tonazzo[28], L.Tortora[40], G.Transtromer[24], D.Treille[9], W.Trischuk[9], G.Tristram[8], A.Trombini[19], C.Troncon[28], A.Tsirou[9], M-L.Turluer[39], I.A.Tyapkin[16], M.Tyndel[37], S.Tzamarias[22], B.Ueberschaer[52], O.Ullaland[9], V.Uvarov[42], G.Valenti[5], E.Vallazza[9], C.Vander Velde[2], G.W.Van Apeldoorn[31], P.Van Dam[31], W.K.Van Doninck[2], J.Van Eldik[31], N.Vassilopoulos[35], G.Vegni[28], L.Ventura[36], W.Venus[37], F.Verbeure[2], M.Verlato[36], L.S.Vertogradov[16], D.Vilanova[39], P.Vincent[25], L.Vitale[46], E.Vlasov[42], A.S.Vodopyanov[16], V.Vrba[12], H.Wahlen[52], C.Walck[44], M.Weierstall[52], P.Weilhammer[9], C.Weiser[17], A.M.Wetherell[9], D.Wicke[52], J.H.Wickens[2], M.Wielers[17], G.R.Wilkinson[35], W.S.C.Williams[35], M.Winter[10], M.Witek[18], K.Woschnagg[48], K.Yip[35], O.Yushchenko[42], F.Zach[25], A.Zaitsev[42], A.Zalewska[9], P.Zalewski[51], D.Zavrtanik[43], E.Zevgolatakos[11], N.I.Zimin[16], M.Zito[39], D.Zontar[43], G.C.Zucchelli[44], G.Zumerle[36]

[1] Ames Laboratory and Department of Physics, Iowa State University, Ames IA 50011, USA
[2] Physics Department, Univ. Instelling Antwerpen, Universiteitsplein 1, B-2610 Wilrijk, Belgium
and IIHE, ULB-VUB, Pleinlaan 2, B-1050 Brussels, Belgium
and Faculté des Sciences, Univ. de l'Etat Mons, Av. Maistriau 19, B-7000 Mons, Belgium
[3] Physics Laboratory, University of Athens, Solonos Str. 104, GR-10680 Athens, Greece
[4] Department of Physics, University of Bergen, Allégaten 55, N-5007 Bergen, Norway
[5] Dipartimento di Fisica, Università di Bologna and INFN, Via Irnerio 46, I-40126 Bologna, Italy
[6] Centro Brasileiro de Pesquisas Físicas, rua Xavier Sigaud 150, RJ-22290 Rio de Janeiro, Brazil
and Depto. de Física, Pont. Univ. Católica, C.P. 38071 RJ-22453 Rio de Janeiro, Brazil
and Inst. de Física, Univ. Estadual do Rio de Janeiro, rua São Francisco Xavier 524, Rio de Janeiro, Brazil
[7] Comenius University, Faculty of Mathematics and Physics, Mlynska Dolina, SK-84215 Bratislava, Slovakia
[8] Collège de France, Lab. de Physique Corpusculaire, IN2P3-CNRS, F-75231 Paris Cedex 05, France
[9] CERN, CH-1211 Geneva 23, Switzerland
[10] Centre de Recherche Nucléaire, IN2P3 - CNRS/ULP - BP20, F-67037 Strasbourg Cedex, France
[11] Institute of Nuclear Physics, N.C.S.R. Demokritos, P.O. Box 60228, GR-15310 Athens, Greece
[12] FZU, Inst. of Physics of the C.A.S. High Energy Physics Division, Na Slovance 2, 180 40, Praha 8, Czech Republic
[13] Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genova, Italy
[14] Institut des Sciences Nucléaires, IN2P3-CNRS, Université de Grenoble 1, F-38026 Grenoble Cedex, France
[15] Research Institute for High Energy Physics, SEFT, P.O. Box 9, FIN-00014 Helsinki, Finland
[16] Joint Institute for Nuclear Research, Dubna, Head Post Office, P.O. Box 79, 101 000 Moscow, Russian Federation
[17] Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 6980, D-76128 Karlsruhe, Germany
[18] Institute of Nuclear Physics and University of Mining and Metalurgy, Ul. Kawiory 26a, PL-30055 Krakow, Poland
[19] Université de Paris-Sud, Lab. de l'Accélérateur Linéaire, IN2P3-CNRS, Bât. 200, F-91405 Orsay Cedex, France
[20] School of Physics and Chemistry, University of Lancaster, Lancaster LA1 4YB, UK
[21] LIP, IST, FCUL - Av. Elias Garcia, 14-1°, P-1000 Lisboa Codex, Portugal
[22] Department of Physics, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, UK
[23] LPNHE, IN2P3-CNRS, Universités Paris VI et VII, Tour 33 (RdC), 4 place Jussieu, F-75252 Paris Cedex 05, France
[24] Department of Physics, University of Lund, Sölvegatan 14, S-22363 Lund, Sweden
[25] Université Claude Bernard de Lyon, IPNL, IN2P3-CNRS, F-69622 Villeurbanne Cedex, France
[26] Universidad Complutense, Avda. Complutense s/n, E-28040 Madrid, Spain
[27] Univ. d'Aix - Marseille II - CPP, IN2P3-CNRS, F-13288 Marseille Cedex 09, France
[28] Dipartimento di Fisica, Università di Milano and INFN, Via Celoria 16, I-20133 Milan, Italy
[29] Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen 0, Denmark
[30] NC, Nuclear Centre of MFF, Charles University, Areal MFF, V Holesovickach 2, 180 00, Praha 8, Czech Republic
[31] NIKHEF-H, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands
[32] National Technical University, Physics Department, Zografou Campus, GR-15773 Athens, Greece
[33] Physics Department, University of Oslo, Blindern, N-1000 Oslo 3, Norway
[34] Dpto. Fisica, Univ. Oviedo, C/P. Pérez Casas, S/N-33006 Oviedo, Spain
[35] Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
[36] Dipartimento di Fisica, Università di Padova and INFN, Via Marzolo 8, I-35131 Padua, Italy
[37] Rutherford Appleton Laboratory, Chilton, Didcot OX11 OQX, UK
[38] Dipartimento di Fisica, Università di Roma II and INFN, Tor Vergata, I-00173 Rome, Italy
[39] Centre d'Etudes de Saclay, DSM/DAPNIA, F-91191 Gif-sur-Yvette Cedex, France
[40] Istituto Superiore di Sanità, Ist. Naz. di Fisica Nucl. (INFN), Viale Regina Elena 299, I-00161 Rome, Italy
[41] Instituto de Fisica de Cantabria (CSIC-UC), Avda. los Castros, S/N-39006 Santander, Spain, (CICYT-AEN93-0832)
[42] Inst. for High Energy Physics, Serpukov P.O. Box 35, Protvino, (Moscow Region), Russian Federation
[43] J. Stefan Institute and Department of Physics, University of Ljubljana, Jamova 39, SI-61000 Ljubljana, Slovenia
[44] Fysikum, Stockholm University, Box 6730, S-113 85 Stockholm, Sweden
[45] Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Via P. Giuria 1, I-10125 Turin, Italy
[46] Dipartimento di Fisica, Università di Trieste and INFN, Via A. Valerio 2, I-34127 Trieste, Italy
and Istituto di Fisica, Università di Udine, I-33100 Udine, Italy
[47] Univ. Federal do Rio de Janeiro, C.P. 68528 Cidade Univ., Ilha do Fundão BR-21945-970 Rio de Janeiro, Brazil
[48] Department of Radiation Sciences, University of Uppsala, P.O. Box 535, S-751 21 Uppsala, Sweden
[49] IFIC, Valencia-CSIC, and D.F.A.M.N., U. de Valencia, Avda. Dr. Moliner 50, E-46100 Burjassot (Valencia), Spain
[50] Institut für Hochenergiephysik, Österr. Akad. d. Wissensch., Nikolsdorfergasse 18, A-1050 Vienna, Austria
[51] Inst. Nuclear Studies and University of Warsaw, Ul. Hoza 69, PL-00681 Warsaw, Poland
[52] Fachbereich Physik, University of Wuppertal, Postfach 100 127, D-42097 Wuppertal 1, Germany
[53] On leave of absence from IHEP Serpukhov

1 Introduction

Despite the success of the Standard Model (SM) in describing current data, there are still several open questions, such as the large number of parameters, the number of generations, the particle masses and the hierarchy problem. Compositeness would cure some of these problems [1], and could give rise to detectable excited states of charged leptons. Excited leptons would be produced at LEP in pairs or singly and decay promptly to their ground state, mainly by photon emission. The study of leptonic events with isolated high energy photons thus constitutes an appropriate probe in the search for new physics.

This paper presents a search for events with charged leptons and isolated hard photons in data recently taken by the DELPHI experiment at LEP. The statistics correspond to an integrated luminosity of 5.9 pb^{-1} at centre-of-mass energies of 130 and 136 GeV. Limits on the production of excited charged leptons are obtained.

In this letter, section 2 summarizes how the compositeness model is used and the excited lepton production and decay mechanisms. In section 3 a short description of the relevant detectors of DELPHI used in the present analysis is given. Section 4 presents an inclusive analysis of radiative leptonic events with hard photons. Finally, in section 5, an optimized analysis for excited charged leptons is presented and limits on the excited electron, muon and tau masses are extracted for single and double production.

2 Production of excited leptons

A clear sign of compositeness would be the existence of excited leptons decaying into their ground state, with the emission of a real photon. Excited charged leptons (e^*, μ^* and τ^*) can be produced at LEP according to the following processes:

- single production, $e^+e^- \to \ell\ell^* \to \ell\ell\gamma$;
- double production, $e^+e^- \to \ell^*\ell^* \to \ell\ell\gamma\gamma$.

Single excited muons and taus are produced through γ and Z exchange in the *s-channel*. On the contrary, single production of e^* is dominated by *t-channel* exchanges [2] and therefore the spectator electron is often emitted at low polar angles and for this reason can be undetected.

The single production Lagrangian [2] associated to magnetic transitions from excited spin 1/2 charged fermions f^* to their normal ground state charged fermions f has the form

$$L_{eff} = \sum_{V=\gamma,Z} \frac{e}{\Lambda} \bar{f}^* \sigma^{\mu\nu} (c_{Vf^*f} - d_{Vf^*f}\gamma_5) f \partial_\mu V_\nu + h.c.$$

where Λ corresponds to the compositeness mass scale and c_{Vf^*f} and d_{Vf^*f} are model dependent parameters. Usually $|c_{Vf^*f}| = |d_{Vf^*f}|$ is assumed [2]. Specific models [3] assumed that excited leptons form a weak doublet which couples to the left-handed lepton doublets, and these parameters can then be related to two other parameters, f and f' [2], which describe the change from the Standard Model coupling constants g and g'. With the assumption $f = f'$ the cross section depends simply on the parameter f/Λ which is related to the excited lepton mass according to $f/\Lambda = \sqrt{2}\lambda/m_{\ell^*}$, where λ is the coupling of the excited charged lepton.

The double production of excited fermions is described by a Lagrangian of the type

$$L_{eff} = \sum_{V=\gamma,Z} e\bar{f}^* (A_{Vf^*}\gamma^\mu V_\mu + \frac{k_{Vf^*}}{2m_{f^*}} \sigma^{\mu\nu} \partial_\mu V_\nu) f^* + h.c.$$

where the k_{Vf^*} parameters are related to the anomalous magnetic moments of the excited leptons, which are assumed to be zero in this analysis and A_{Vf^*} are form factors defined according to reference [2]. Single and double excited charged lepton events were generated according to their cross sections defined in [2] involving γ and Z exchange. The particle decays were simulated by JETSET 7.4 [4]. The initial state radiation effect was included at the level of the generator for the single production, while for the double production it is taken into account in the total cross section. For excited lepton masses above the W and Z mass, the decays $\ell^* \to \ell$W and $\ell^* \to \ell$Z are also possible [5]. In this analysis, only the relevant electromagnetic decay of the excited lepton $\ell^* \to \ell\gamma$ was searched for, assuming a $(1 + \cos\theta)$ decay angular dependence [2], where θ is the angle of the final lepton with respect to the electron beam in the ℓ^* rest frame. The dependence of the branching ratio on the excited lepton mass was also taken into account [5].

3 The DELPHI detector and the standard processes simulation

A detailed description of the DELPHI apparatus can be found in reference [6]. This analysis relies on the charged particle and photon detection performed by the tracking system and by the electromagnetic calorimeters.

The main tracking detector is the Time Projection Chamber which covers the angular range $20° < \theta < 160°$, where θ is the polar angle defined with respect to the beam direction. Other detectors contributing to the track reconstruction are the MicroVertex Detector, the Inner and Outer Detectors, the Forward Chambers and the Muon Chambers. The best momentum resolution obtained for muons is $\sigma(1/p) = 0.57 \times 10^{-3}(\mathrm{GeV}/c)^{-1}$.

The Barrel and Forward electromagnetic calorimeters HPC and FEMC, and the STIC are used for electromagnetic energy reconstruction. The STIC (Small angle TIle Calorimeter), the DELPHI luminosity monitor, was used for electromagnetic shower detection at very low polar angle and has a resolution of 2.7% for 45 GeV electrons. The resolution of the HPC (High density Projection Chamber) and FEMC (Forward Electromagnetic Calorimeter) calorimeters is parameterized as $\sigma(E)/E = 0.043 \oplus 0.32/\sqrt{E}$ and $\sigma(E)/E = 0.03 \oplus 0.12/\sqrt{E} \oplus 0.11/E$ respectively, where E is expressed in GeV, and the symbol $\oplus$ indicates the addition in quadrature.

The influence of the detector on the analysis was studied by generating events for the Standard Physics processes and passing them through the full DELPHI simulation and reconstruction chain. Bhabha events and $e^+e^- \to \mathrm{Z}\gamma$ events with Z$\to f\bar{f}$, were generated with PYTHIA [4]. The "$\gamma\gamma$" physics events were generated according to the TWOGAM [7] generator for the muon, tau and quark channels and the Berends, Daverveldt and Kleiss generator [8] for the electron channel.

A simplified simulation model, using a parameterization of the detector response, was used to obtain the efficiency for excited charged lepton detection as a function of mass, after imposing the cuts. A comparison with full simulation results was made and reasonable agreement was found.

4 Radiative leptonic events with hard photons

The inclusive search for radiative leptonic events with high energy photons was based on the selection of low multiplicity events with at least one isolated and energetic photon. The specific selection criteria were the following:

- a total number of charged particles between 2 and 6;
- at least one charged particle with momentum p larger than 3 GeV/c and polar angle θ greater than 20°;
- all charged particles with $p > 1$ GeV/c and $\theta > 20°$ had to be grouped in two isolated cones of 5°, the axis of each cone being the direction of the most energetic particle within the cone: the angle between the axes of the cones had to be greater than 15°;
- at least one isolated electromagnetic cluster with an energy greater than 2 GeV and with $\theta > 10°$. The isolation angle † was set to 15°.

The events selected with the above cuts include electron, muon and tau pairs accompanied by any number n of hard photons ($n = 1, 2, 3...$). For the $e^+e^- \to \ell\ell\gamma$ topology, 60 coplanar events (sum of angles between particles greater than 355°) were found, while for the $e^+e^- \to \ell\ell\gamma\gamma$ topology 3 events were observed. No event was found with more than two hard isolated photons. The number of events expected from Standard Physics processes with one photon and with two photons were 74.8±3.7 and 3.5±0.7, respectively.

For the three and four body topologies, the energy measurement can be significantly improved by using the polar and azimuthal angles, which are well measured in the detector, and imposing energy and momentum conservation. The method can be applied to tau events since the charged decay products essentially follow the direction of the primary tau. The mass resolution of the lepton-photon pair, after applying the kinematic constraints, is about 1 GeV/c^2 for electrons and muons and about 2 GeV/c^2 for taus.

A comparison between the measured and calculated momenta and energies was made for the charged particles and photons on a χ^2 basis. The χ^2 parameter was defined as follows for the charged particles:

$$\chi^2_{charged} = \frac{1}{2} \sum_{i=1,2} \left(\frac{p_i^{calc} - p_i^{meas}}{\sigma_i} \right)^2$$

where p_i^{meas} is the measured momentum, p_i^{calc} is the calculated momentum obtained by application kinematic constraints, and σ_i is the quadratic sum of the errors on p_i^{calc} and p_i^{meas}. The p_i^{meas} error contribution depends on the polar angle and was taken from reference [6] while the p_i^{calc} contribution was parameterized as $\sigma_p = 0.25/\tan(\alpha_i/2)$ GeV/c, where α_i is the angle between the direction of particle i and that of the nearest object (cluster or charged cone axis). For the electron candidates, the measurement error was scaled by a factor 1.2 in order to account for Bremsstrahlung losses.

For photons the χ^2 definition involving the measured and calculated energies was as follows:

$$\chi^2_{photons} = \frac{1}{n} \sum_{i=1,n} \left(\frac{E_i^{calc} - E_i^{meas}}{\sigma_i} \right)^2$$

where E_i^{calc} and E_i^{meas} are the calculated and measured electromagnetic energies, respectively, and n is the number of photons. The error σ_i was taken as just the E_i^{meas} contribution [6], since the E_i^{calc} contribution was estimated to be negligible.

† The isolation angle of an electromagnetic cluster or photon is defined as its minimum angle with respect to the axes of the charged particle cones.

The $\ell\ell\gamma$ sample was further purified by requiring a good agreement ($\chi^2 < 5$) between the measured and the calculated values, either for the photons or for the charged leptons. This cut eliminated 8 events in the data. The fact that the condition $\chi^2 < 5$ is not applied simultaneously to both photons and charged leptons allows $ee\gamma$ and $\mu\mu\gamma$ events with photons near borders of the calorimeter modules, where the electromagnetic energy can be badly reconstructed, to be kept. In $\tau\tau\gamma$ events, the $\chi^2_{charged}$ is expected to be large because of the missing momenta associated with the neutrinos, and one therefore relies only on the measurement of the photon energy. The number of events expected after all cuts is 69.4 ± 3.4.

Figure 1a) shows the invariant mass for the lepton-lepton pairs using the calculated momenta obtained from the kinematic constraint applied to the $\ell\ell\gamma$ sample. The two possible $\ell\gamma$ invariant mass combinations are plotted in figure 1b). The radiative return to the Z is seen in the lepton pair mass spectrum. The overall agreement between data and simulation is reasonable.

Figure 2 presents the energy and the isolation angle of the radiated photon. There is satisfactory agreement between data and simulation. In the tail of events with very isolated photons, five events were observed with isolation angle above 120°, while 1.8 ± 0.6 were expected from SM processes. Higher statistics foreseen at LEP2 will allow more detailed studies of this interesting region.

5 Searches for excited charged leptons

The search for the production of excited charged leptons followed the criteria used in the selection of leptonic events with hard photons, as explained in section 4. However, the cuts were adjusted in order to optimize the selection efficiency and to minimize the standard physics backgrounds. In the topologies selected, the trigger efficiency is close to 1 for all channels.

5.1 Pair production of excited charged leptons

Three $\ell\ell\gamma\gamma$ events were observed in the inclusive analysis of section 4. Table 1 presents the characteristics of these events. Two of them have an electromagnetic energy associated to both charged leptons of magnitude greater than 0.2 p and were classified as $ee\gamma\gamma$. The remaining event has hits in the muon chambers associated to both charged tracks and was classified as $\mu\mu\gamma\gamma$.

The $\mu\mu\gamma\gamma$ event has a missing energy of about 30 GeV and a missing momentum of the same order pointing in a direction near the beam pipe. For the $ee\gamma\gamma$ events there is good agreement between the measured momentum values and those obtained with the kinematic constraint assuming only four particles in the event. For these two events, the energies, momenta and invariant masses quoted in table 1 are the calculated ones.

The hypothesis of double excited lepton production implies the existence in the same event of two $\ell\gamma$ combinations with compatible invariant mass values (the resolution on the mass difference is around 3 GeV/c^2). Only one event satisfies such a condition but the mass value is about 17 GeV/c^2, which is excluded at much more than 95% confidence level by searches at LEP1, which set mass limits of order $m_Z/2$ [9].

The detection efficiency for the double production was found to be independent of the mass of the excited lepton and around 45%, 49% and 34% for excited electrons, muons and taus, respectively. In the available kinematic region ($M_{\ell^*} < \sqrt{s}/2$), the decay branching ratio $\ell^* \to \ell\gamma$ is assumed to be 100%.

run	event	leptons		photons		invariant mass						flavour
		p_1	p_2	E_1	E_2	$\ell\ell$	$\gamma\gamma$	$\ell_1\gamma_1$	$\ell_2\gamma_1$	$\ell_1\gamma_2$	$\ell_2\gamma_2$	tagging
63905	6267	44.8	26.4	39.0	20.1	68.2	55.5	82.3	17.5	15.9	43.8	$ee\gamma\gamma$
64561	34951	44.1	47.7	29.2	15.3	84.0	24.9	65.1	55.7	26.8	53.3	$ee\gamma\gamma$
64179	888	27.4	24.4	39.9	9.1	49.7	33.7	34.1	59.6	18.6	18.5	$\mu\mu\gamma\gamma$

Table 1: Characteristics of the $\ell\ell\gamma\gamma$ events. Momenta are expressed in GeV/c and masses in GeV/c^2.

The lower limits at 95% confidence level on the excited lepton masses are 62.5 GeV/c^2 for electrons, 62.6 GeV/c^2 for muons and 62.2 GeV/c^2 for taus. These values take into account a mass resolution of 2 GeV/c^2, and the luminosities, production cross sections and efficiencies at the different centre-of-mass energies. No background was subtracted.

5.2 Single production of excited charged leptons

The production of excited leptons proceeds through *s-channel* exchange for muons and taus and through s and *t-channels* for electrons. For the *t-channel* exchange the single production cross section increases very rapidly with decreasing polar angle, and can be two orders of magnitude higher than the *s-channel* contribution [2]. For this reason the spectator electron recoiling against the excited electron would usually be produced at very low polar angles, and in most cases it would escape detection by remaining inside the beam pipe.

Electron channel
The selection cuts used in section 4 were modified in order to identify the electrons and extended to increase the acceptance and to include events with one electron in the beam pipe. The cuts were also optimized in order to reduce drastically the radiative Bhabha and Compton backgrounds [10] by requiring the presence of a hard photon in the Barrel region.

When the two charged leptons were detected in the tracking system, the following additional cuts were applied to the sample selected as described in section 4:

- at least one charged particle with $p > 10$ GeV/c and with associated electromagnetic energy of magnitude greater than 0.2 p;
- one isolated electromagnetic cluster with energy greater than 10 GeV and $\theta > 40°$.

When only one of the charged leptons was detected in the tracking system, the following cuts were applied:

- a total number of charged particles between 1 and 6;
- at least one charged particle with $p > 10$ GeV/c and with associated electromagnetic energy of magnitude greater than 0.2 p;
- all charged particles with $p > 1$ GeV/c and $\theta > 20°$ grouped in one cone of 5°;
- one isolated electromagnetic cluster with energy greater than 10 GeV and $\theta > 40°$, the angle between the cluster and the most energetic charged particle being between 15° and 179°.

Events with an additional cluster having $\theta < 20°$ and energy greater than 2 GeV were also accepted. In these events the second electron was not properly reconstructed as a charged track, being detected by its electromagnetic signature. When there was no additional cluster, it was assumed that the spectator electron is along the beam direction.

The events that survived these cuts were then checked for their coplanarity and for compatibility between the measured and the calculated momenta (the $\chi^2_{charged}$ was required to be below 5). A total of 25 events passed all the selection criteria while 20.7 ± 1.8 were expected from the simulation of the SM processes. Among these selected events, 12 had only one electron and one photon detected.

Muon channel

The selection cuts used in section 4 were modified in order to identify the muons. The additional criteria used for single excited muons were the following:

- two charged particles with associated electromagnetic energy less than 20% of the measured momentum, and at least one with an associated hit in the muon chambers;
- the momentum of the most energetic charged particle larger than 10 GeV/c;
- one isolated electromagnetic cluster with energy greater than 10 GeV.

The events that survived the cuts were then checked for their coplanarity and for compatibility between the measured and the calculated momenta (the $\chi^2_{charged}$ should be less than 5). A total of 7 events passed all the cuts while 8.0 ± 0.9 events were expected from the Standard Physics.

Tau channel

An additional cut was applied to the sample selected as described in section 4 in order to optimize the search for excited taus:

- one isolated electromagnetic cluster with energy greater than 10 GeV.

The events that survived these cuts were then checked for their coplanarity. The measured and the calculated momenta for the $\tau\tau\gamma$ candidates were required to disagree for the charged particles and be compatible for the photon. The χ^2 variable defined in section 4 was required to be greater than 5 for the charged particles and smaller than 5 for the photon.

A total of 2 events passed all the selection criteria while 5.9 ± 1.0 events were expected from the simulation of the Standard Physics processes.

Figure 3 shows the invariant mass distribution for all possible lepton-photon combinations in electron, muon and tau events, as well as the simulation predictions for Bhabha and Zγ events. Two entries per event are shown except when the electron remains in the beam pipe where just one entry was considered.

The efficiency for detecting excited electrons was found to be roughly constant (around 43%) for masses between 90 and 130 GeV/c^2. The efficiency for detecting excited muons was found to be around 56% for masses between 90 and 130 GeV/c^2. The efficiency for detecting excited taus was found to be around 43% for masses between 90 and 110 GeV/c^2 and to decrease to 30% for masses of 130 GeV/c^2.

The evolution of the branching ratio for $\ell^* \to \ell\gamma$ as a function of the ℓ^* mass was taken into account according to reference [5]. Figure 4 shows the upper limit at 95% confidence level for the ratio λ/M_{ℓ^*}, as a function of the ℓ^* mass. The limits were calculated using a Poisson distribution with background and assuming a mass resolution of 2 GeV/c^2. These new limits extend the mass region up to 136 GeV/c^2 but in the kinematic region accessible to LEP phase 1 (masses below 90 GeV/c^2) are not competitive with the published limits [9] due to the low statistics.

6 Conclusions

An analysis of the DELPHI data corresponding to a total luminosity of 5.9 pb^{-1} at centre-of-mass energies of 130 and 136 GeV has been performed.

Events with charged leptons and very energetic and isolated photons were searched for and compared with the SM predictions. Reasonable agreement between data and simulation was found in all spectra.

These data were used to search for production of excited charged leptons decaying into their mass ground state (the ordinary lepton) by the emission of a photon. No significant signal was observed. The search for double production of excited charged leptons gave the following 95% confidence level limits on the masses of the composite states: $m_{e^*} > 62.5$ GeV/c^2, $m_{\mu^*} > 62.6$ GeV/c^2 and $m_{\tau^*} > 62.2$ GeV/c^2. Limits on the ratio of the coupling constant to the mass were extracted from the search in the single production channels and considerably extended the limits set at LEP1 and HERA [9]. Similar limits on excited leptons in this energy range have recently been reported by the L3 collaboration [11].

Acknowledgements

We would like to thank Torbjorn Sjöstrand for the very useful discussions and for an improved version of PYTHIA. We are greatly indebted to our technical collaborators and to the funding agencies for their support in building and operating the DELPHI detector, and to the members of the CERN-SL Division for the excellent performance of the LEP collider.

References

[1] M.E. Peskin, Proceedings of the 1981 Int. Symp. on Lepton and Photon Interactions at High Energies, p. 80, eds. W. Pfeil et al. (Bonn, 1981);
R. Barbieri, L. Maiani, R. Petronzio, Phys. Lett. **B96** (1980) 63;
L. Lyons, Progress in Particle and Nuclear Physics **10** (1983) 227.

[2] K. Hagiwara, S. Komamiya, D. Zeppenfeld, Z. Phys. **C29** (1985) 115.

[3] F.M. Renard, Phys. Lett. **B116** (1982) 264;
F. del Aguila, A. Méndez, R. Pascual, Phys. Lett. **B140** (1984) 431;
M. Suzuki, Phys. Lett. **B143** (1984) 237.

[4] T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74;
T. Sjöstrand, Pythia 5.7 and Jetset 7.4, CERN-TH/7112-93.

[5] F. Boudjema, A. Djouadi and J.L. Kneur, Z. Phys. **C57** (1993) 425.

[6] DELPHI Collaboration, P. Aarnio et al., Nucl. Instr. Methods **A303** (1991) 233;
DELPHI Collaboration, P. Abreu et al., "Performance of the DELPHI Detector", CERN-PPE/95-194, to be published in Nucl. Instr. Methods A.

[7] S. Nova, A. Olchevski and T. Todorov, "TWOGAM, a Monte Carlo event generator for two photon physics", DELPHI note DELPHI 90-35 PROG 152.

[8] F.A. Berends, P.H. Daverveldt, R. Kleiss, Comp. Phys. Comm. **40** (1986) 271.

[9] ALEPH Collaboration, D. Decamp et al., Phys. Lett. **B250** (1990) 172.
DELPHI Collaboration, P. Abreu et al., Z. Phys. **C53** (1992) 41.
H1 Collaboration, I. Abt et al., Nucl. Phys. **B396** (1993) 3.
L3 Collaboration, M. Acciarri et al., Phys. Lett. **B353** (1995) 136.
OPAL Collaboration, M.Z. Akrawy et al., Phys. Lett. **B257** (1991) 531.
ZEUS Collaboration, M. Derrick et al., Z. Phys. **C65** (1994) 627.

[10] Min-Shih Chen, P. Zerwas, Phys. Rev. **D12** (1975) 187.

[11] L3 Collaboration, M. Acciarri et al., Phys. Lett. **B370** (1996) 211.

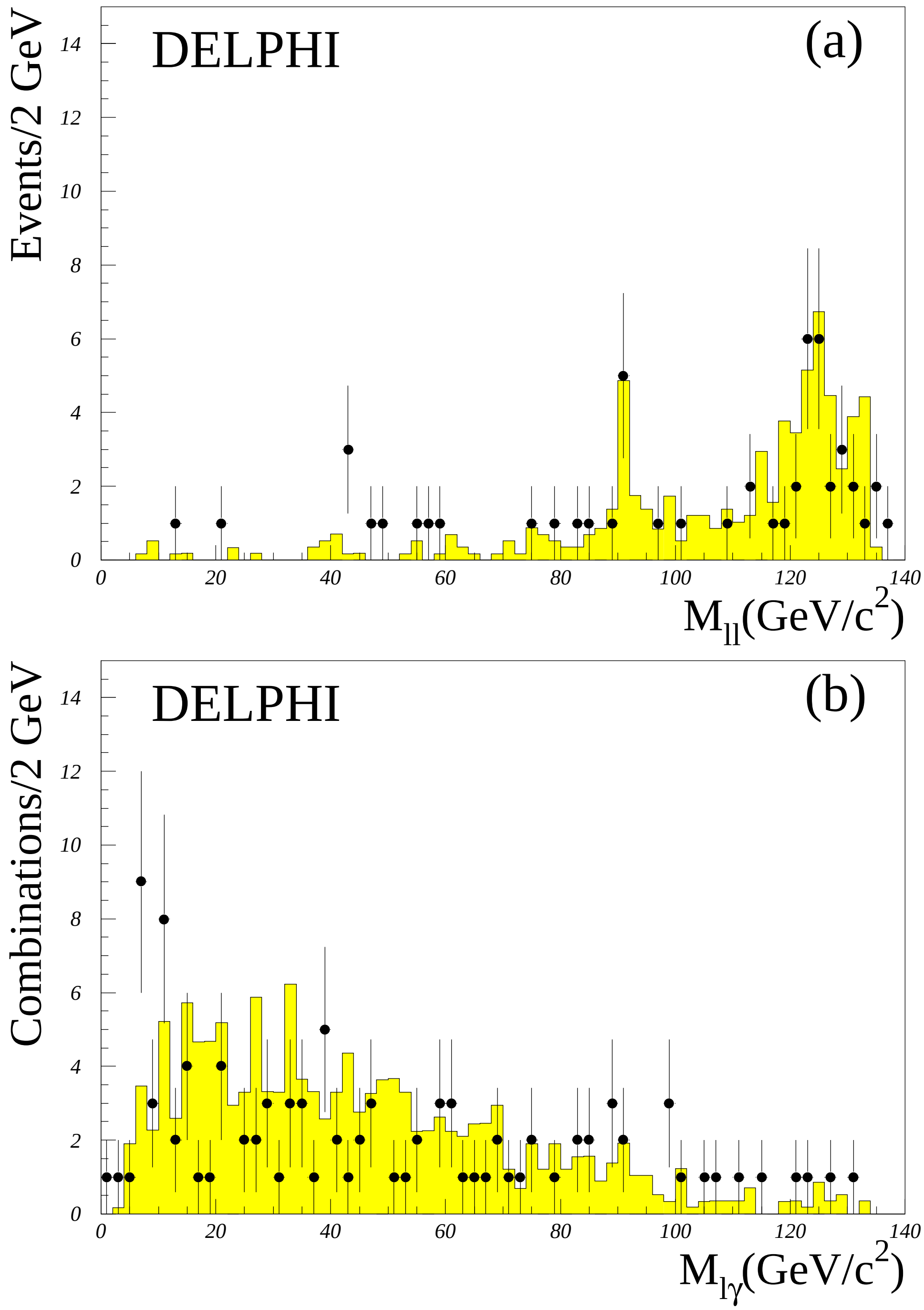

Figure 1: Invariant mass of lepton pairs (a) and lepton-photon pairs (b) for the $\ell\ell\gamma$ sample. The dots are the data and the shaded area is the simulation.

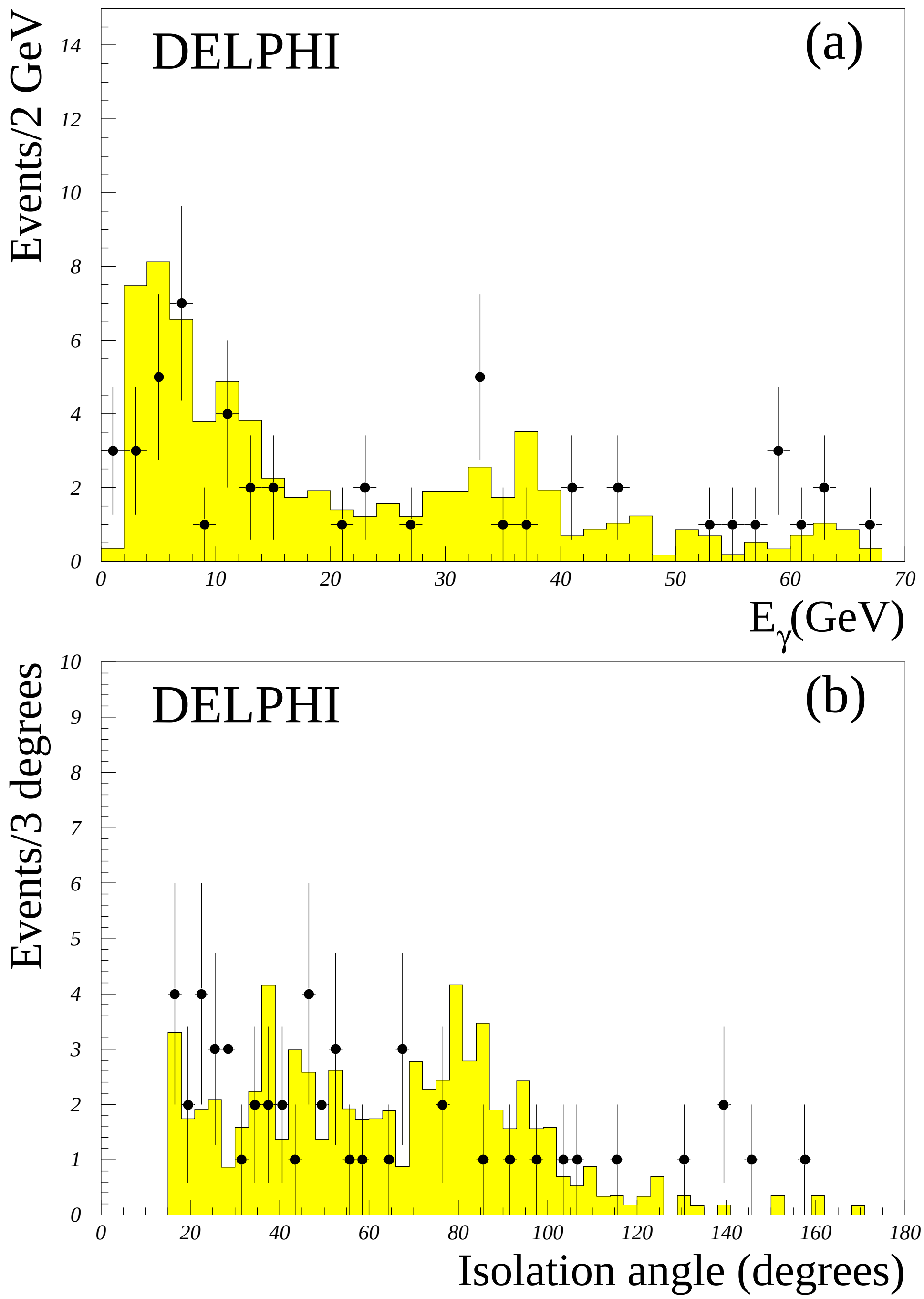

Figure 2: $\ell\ell\gamma$ sample: (a) the photon energy and (b) the photon isolation angle. The dots are the data and the shaded area is the simulation.

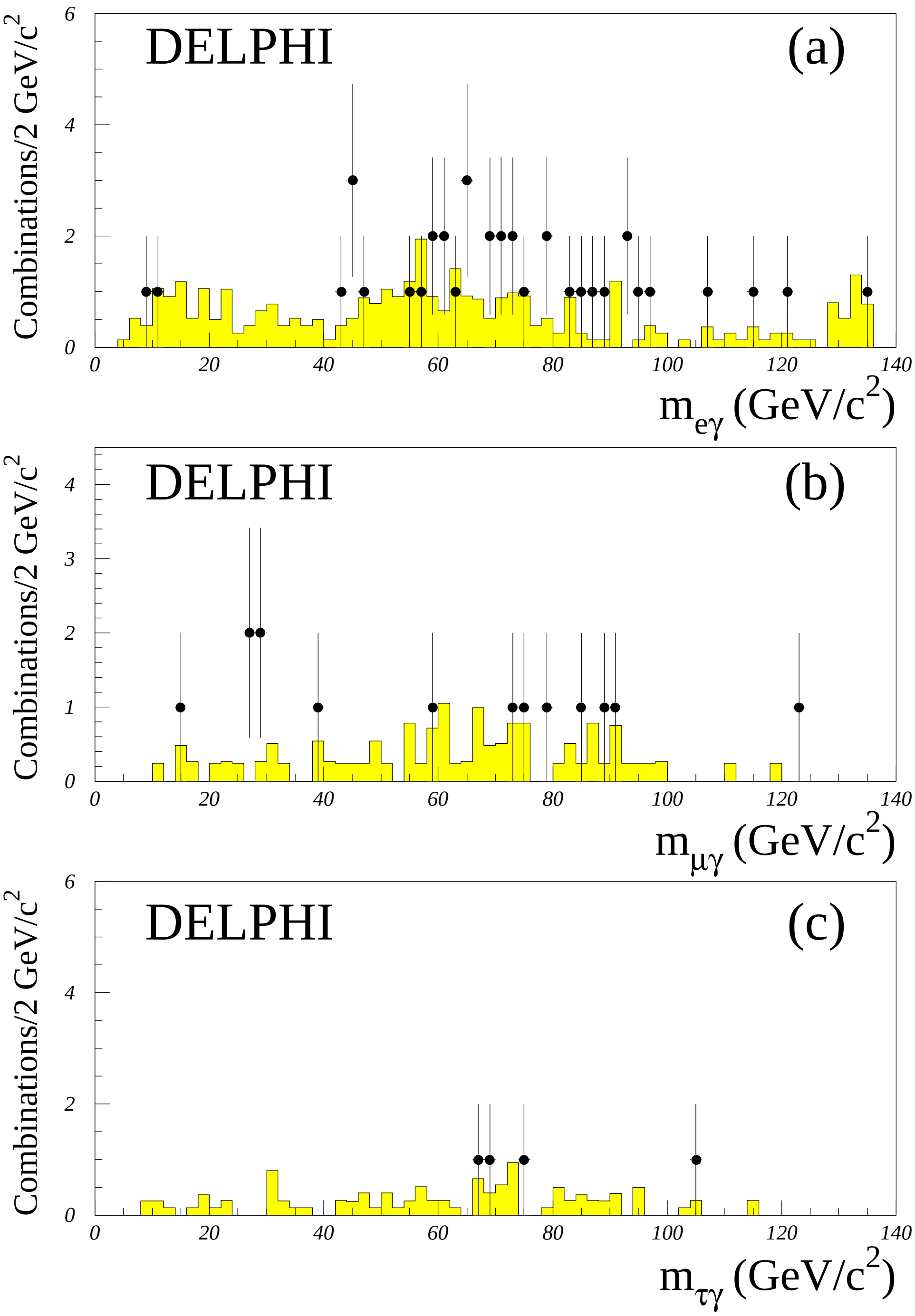

Figure 3: Invariant masses for all possible lepton-photon combinations in single production searches: electron (a), muon (b) and tau (c) channels. The dots are the data and the shaded area is the simulation.

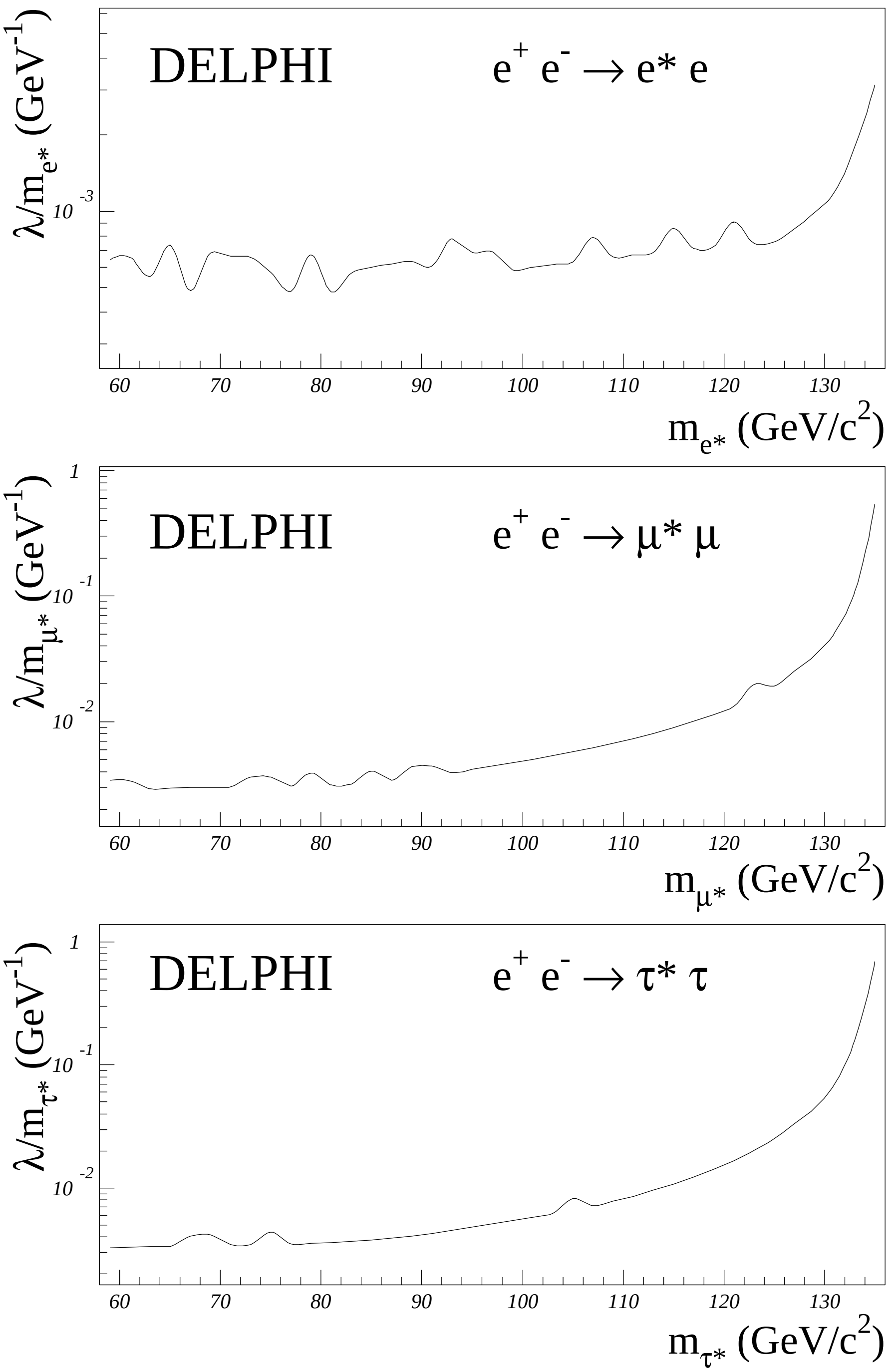

Figure 4: Single production of excited charged leptons: the line shows the compositeness limits at 95% confidence level of the ratio of the coupling of the excited charged lepton to the mass ($\lambda/m_{\ell*}$) as a function of the mass for the electron, muon and tau channels.