EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PPE/93–161

5 August 1993

Limits on the production of scalar leptoquarks from Z^0 decays at LEP

DELPHI Collaboration

Abstract

A search has been made for pairs and for single production of scalar leptoquarks of the first and second generations using a data sample of 392000 Z^o decays from the DELPHI detector at LEP 1. No signal was found and limits on the leptoquark mass, production cross section and branching ratio were set. A mass limit at 95 % confidence level of 45.5 GeV/c^2 was obtained for leptoquark pair production. The search for the production of a single leptoquark probed the mass region above this limit and its results exclude first and second generation leptoquarks D_o with masses below 65 GeV/c^2 and 73 GeV/c^2 respectively, at 95% confidence level, assuming that the $D_o lq$ Yukawa coupling α_λ is equal to the electromagnetic one. An upper limit is also given on the coupling α_λ as a function of the leptoquark mass m_{D_o}.

(To be submitted to Physics Letters B)

P.Abreu[20], W.Adam[7], T.Adye[37], E.Agasi[30], R.Aleksan[39], G.D.Alekseev[14], A.Algeri[13], P.Allen[49], S.Almehed[23], S.J.Alvsvaag[4], U.Amaldi[7], A.Andreazza[27], P.Antilogus[24], W-D.Apel[15], R.J.Apsimon[37], Y.Arnoud[39], B.Åsman[45], J-E.Augustin[18], A.Augustinus[30], P.Baillon[7], P.Bambade[18], F.Barao[20], R.Barate[12], G.Barbiellini[47], D.Y.Bardin[14], G.J.Barker[34], A.Baroncelli[41], O.Barring[7], J.A.Barrio[25], W.Bartl[50], M.J.Bates[37], M.Battaglia[13], M.Baubillier[22], K-H.Becks[52], M.Begalli[36], P.Beilliere[6], Yu.Belokopytov[43], P.Beltran[9], D.Benedic[8], A.C.Benvenuti[5], M.Berggren[18], D.Bertrand[2], F.Bianchi[46], M.S.Bilenky[14], P.Billoir[22], J.Bjarne[23], D.Bloch[8], J.Blocki[51], S.Blyth[34], V.Bocci[38], P.N.Bogolubov[14], T.Bolognese[39], M.Bonesini[27], W.Bonivento[27], P.S.L.Booth[21], G.Borisov[43], H.Borner[7], C.Bosio[41], B.Bostjancic[44], S.Bosworth[34], O.Botner[48], B.Bouquet[18], C.Bourdarios[18], T.J.V.Bowcock[21], M.Bozzo[11], S.Braibant[2], P.Branchini[41], K.D.Brand[35], R.A.Brenner[7], H.Briand[22], C.Bricman[2], L.Brillault[22], R.C.A.Brown[7], P.Bruckman[16], J-M.Brunet[6], A.Budziak[16], L.Bugge[32], T.Buran[32], H.Burmeister[7], J.A.M.A.Buytaert[7], M.Caccia[7], M.Calvi[27], A.J.Camacho Rozas[42], R.Campion[21], T.Camporesi[7], V.Canale[38], F.Cao[2], F.Carena[7], L.Carroll[21], M.V.Castillo Gimenez[49], A.Cattai[7], F.R.Cavallo[5], L.Cerrito[38], V.Chabaud[7], A.Chan[1], M.Chapkin[43], Ph.Charpentier[7], L.Chaussard[18], J.Chauveau[22], P.Checchia[35], G.A.Chelkov[14], L.Chevalier[39], P.Chliapnikov[43], V.Chorowicz[22], J.T.M.Chrin[49], V.Cindro[44], P.Collins[34], J.L.Contreras[25], R.Contri[11], E.Cortina[49], G.Cosme[18], F.Couchot[18], H.B.Crawley[1], D.Crennell[37], G.Crosetti[11], M.Crozon[6], J.Cuevas Maestro[33], S.Czellar[13], E.Dahl-Jensen[28], B.Dalmagne[18], M.Dam[32], G.Damgaard[28], G.Darbo[11], E.Daubie[2], A.Daum[15], P.D.Dauncey[34], M.Davenport[7], J.Davies[21], W.Da Silva[22], C.Defoix[6], P.Delpierre[26], N.Demaria[46], A.De Angelis[47], H.De Boeck[2], W.De Boer[15], S.De Brabandere[2], C.De Clercq[2], M.D.M.De Fez Laso[49], C.De La Vaissiere[22], B.De Lotto[47], A.De Min[27], H.Dijkstra[7], L.Di Ciaccio[38], J.Dolbeau[6], M.Donszelmann[7], K.Doroba[51], M.Dracos[7], J.Drees[52], M.Dris[31], Y.Dufour[7], F.Dupont[12], D.Edsall[1], L-O.Eek[48], P.A.-M.Eerola[7], R.Ehret[15], T.Ekelof[48], G.Ekspong[45], A.Elliot Peisert[35], M.Elsing[52], J-P.Engel[8], N.Ershaidat[22], D.Fassouliotis[31], M.Feindt[7], A.Ferrer[49], T.A.Filippas[31], A.Firestone[1], H.Foeth[7], E.Fokitis[31], F.Fontanelli[11], K.A.J.Forbes[21], J-L.Fousset[26], S.Francon[24], B.Franek[37], P.Frenkiel[6], D.C.Fries[15], A.G.Frodesen[4], R.Fruhwirth[50], F.Fulda-Quenzer[18], H.Furstenau[15], J.Fuster[7], D.Gamba[46], C.Garcia[49], J.Garcia[42], C.Gaspar[7], U.Gasparini[35], Ph.Gavillet[7], E.N.Gazis[31], J-P.Gerber[8], P.Giacomelli[7], D.Gillespie[7], R.Gokieli[51], B.Golob[44], V.M.Golovatyuk[14], J.J.Gomez Y Cadenas[7], G.Gopal[37], L.Gorn[1], M.Gorski[51], V.Gracco[11], A.Grant[7], F.Grard[2], E.Graziani[41], G.Grosdidier[18], E.Gross[7], B.Grossetete[22], J.Guy[37], U.Haedinger[15], F.Hahn[52], M.Hahn[15], S.Haider[30], A.Hakansson[23], A.Hallgren[48], K.Hamacher[52], G.Hamel De Monchenault[39], W.Hao[30], F.J.Harris[34], V.Hedberg[23], T.Henkes[7], J.J.Hernandez[49], P.Herquet[2], H.Herr[7], T.L.Hessing[21], I.Hietanen[13], C.O.Higgins[21], E.Higon[49], H.J.Hilke[7], S.D.Hodgson[34], T.Hofmokl[51], S-O.Holmgren[45], P.J.Holt[34], D.Holthuizen[30], P.F.Honore[6], M.Houlden[21], J.Hrubec[50], K.Huet[2], P.O.Hulth[45], K.Hultqvist[45], P.Ioannou[3], P-S.Iversen[4], J.N.Jackson[21], P.Jalocha[16], G.Jarlskog[23], P.Jarry[39], B.Jean-Marie[18], E.K.Johansson[45], M.Jonker[7], L.Jonsson[23], P.Juillot[8], G.Kalkanis[3], G.Kalmus[37], F.Kapusta[22], M.Karlsson[7], E.Karvelas[9], S.Katsanevas[3], E.C.Katsoufis[31], R.Keranen[7], B.A.Khomenko[14], N.N.Khovanski[14], B.King[21], N.J.Kjaer[7], H.Klein[7], A.Klovning[4], P.Kluit[30], A.Koch-Mehrin[52], J.H.Koehne[15], B.Koene[30], P.Kokkinias[9], M.Koratzinos[32], A.V.Korytov[14], V.Kostioukhine[43], C.Kourkoumelis[3], O.Kouznetsov[14], P.H.Kramer[52], M.Krammer[50], C.Kreuter[15], J.Krolikowski[51], I.Kronkvist[23], U.Kruener-Marquis[52], W.Krupinski[16], K.Kulka[48], K.Kurvinen[13], C.Lacasta[49], C.Lambropoulos[9], J.W.Lamsa[1], L.Lanceri[47], V.Lapin[43], I.Last[21], J-P.Laugier[39], R.Lauhakangas[13], G.Leder[50], F.Ledroit[12], R.Leitner[29], Y.Lemoigne[39], J.Lemonne[2], G.Lenzen[52], V.Lepeltier[18], T.Lesiak[16], J.M.Levy[8], E.Lieb[52], D.Liko[50], J.Lindgren[13], R.Lindner[52], I.Lippi[35], B.Loerstad[23], M.Lokajicek[10], J.G.Loken[34], A.Lopez-Fernandez[7], M.A.Lopez Aguera[42], M.Los[30], D.Loukas[9], J.J.Lozano[49], P.Lutz[6], L.Lyons[34], G.Maehlum[32], J.Maillard[6], A.Maio[20], A.Maltezos[9], F.Mandl[50], J.Marco[42], M.Margoni[35], J-C.Marin[7], A.Markou[9], T.Maron[52], S.Marti[49], C.Martinez-Rivero[42], F.Matorras[42], C.Matteuzzi[27], G.Matthiae[38], M.Mazzucato[35], M.Mc Cubbin[21], R.Mc Kay[1], R.Mc Nulty[21], J.Medbo[48], G.Meola[11], C.Meroni[27], W.T.Meyer[1], M.Michelotto[35], I.Mikulec[50], L.Mirabito[24], W.A.Mitaroff[50], G.V.Mitselmakher[14], U.Mjoernmark[23], T.Moa[45], R.Moeller[28], K.Moenig[7], M.R.Monge[11], P.Morettini[11], H.Mueller[15], W.J.Murray[37], B.Muryn[16], G.Myatt[34], F.L.Navarria[5], P.Negri[27], S.Nemecek[10], R.Nicolaidou[3], B.S.Nielsen[28], B.Nijjhar[21], V.Nikolaenko[43], P.E.S.Nilsen[4], P.Niss[45], A.Nomerotski[35], V.Obraztsov[43], A.G.Olshevski[14], R.Orava[13], A.Ostankov[43], K.Osterberg[13], A.Ouraou[39], M.Paganoni[27], R.Pain[22], H.Palka[16], Th.D.Papadopoulou[31], L.Pape[7], F.Parodi[11], A.Passeri[41], M.Pegoraro[35], J.Pennanen[13], L.Peralta[20], H.Pernegger[50], M.Pernicka[50], A.Perrotta[5], C.Petridou[47], A.Petrolini[11], L.Petrovykh[43], G.Piana[11], F.Pierre[39], M.Pimenta[20], S.Plaszczynski[18], O.Podobrin[15], M.E.Pol[17], G.Polok[16], P.Poropat[47], V.Pozdniakov[14], P.Privitera[38], A.Pullia[27], D.Radojicic[34], S.Ragazzi[27], H.Rahmani[31], J.Rames[10], P.N.Ratoff[19], A.L.Read[32], P.Rebecchi[7], N.G.Redaelli[27], M.Regler[50], D.Reid[7], P.B.Renton[34], L.K.Resvanis[3], F.Richard[18], J.Richardson[21], J.Ridky[10], G.Rinaudo[46], I.Roditi[17], A.Romero[46], I.Roncagliolo[11], P.Ronchese[35], C.Ronnqvist[13], E.I.Rosenberg[1], E.Rosso[7], P.Roudeau[18], T.Rovelli[5], W.Ruckstuhl[30], V.Ruhlmann-Kleider[39], A.Ruiz[42], K.Rybicki[16], H.Saarikko[13], Y.Sacquin[39], G.Sajot[12], J.Salt[49], J.Sanchez[25], M.Sannino[11,40], S.Schael[7], H.Schneider[15], M.A.E.Schyns[52], G.Sciolla[46], F.Scuri[47], A.M.Segar[34], A.Seitz[15], R.Sekulin[37], M.Sessa[47], R.Seufert[15], R.C.Shellard[36], I.Siccama[30], P.Siegrist[39], S.Simonetti[11], F.Simonetto[35], A.N.Sisakian[14], G.Skjevling[32], G.Smadja[39,24], N.Smirnov[43], O.Smirnova[14], G.R.Smith[37], R.Sosnowski[51], D.Souza-Santos[36], T.S.Spassoff[12], E.Spiriti[41], S.Squarcia[11], H.Staeck[52], C.Stanescu[41], S.Stapnes[32], G.Stavropoulos[9], F.Stichelbaut[2], A.Stocchi[18], J.Strauss[50], J.Straver[7], R.Strub[8], B.Stugu[4], M.Szczekowski[7], M.Szeptycka[51], P.Szymanski[51], T.Tabarelli[27], O.Tchikilev[43], G.E.Theodosiou[9], A.Tilquin[26], J.Timmermans[30], V.G.Timofeev[14], L.G.Tkatchev[14], T.Todorov[8], D.Z.Toet[30], O.Toker[13], A.Tomaradze[2], B.Tome[20], E.Torassa[46], L.Tortora[41], D.Treille[7], W.Trischuk[7], G.Tristram[6], C.Troncon[27], A.Tsirou[7], E.N.Tsyganov[14], M.Turala[16], M-L.Turluer[39], T.Tuuva[13], I.A.Tyapkin[22], M.Tyndel[37], S.Tzamarias[21], S.Ueberschaer[52], O.Ullaland[7], V.Uvarov[43], G.Valenti[5], E.Vallazza[46], J.A.Valls Ferrer[49], C.Vander Velde[2], G.W.Van Apeldoorn[30], P.Van Dam[30], M.Van Der Heijden[30], W.K.Van Doninck[2], J.Van Eldik[30], P.Vaz[7], G.Vegni[27], L.Ventura[35], W.Venus[37], F.Verbeure[2], M.Verlato[35], L.S.Vertogradov[14], D.Vilanova[39], P.Vincent[24], L.Vitale[13], E.Vlasov[43], A.S.Vodopyanov[14], M.Vollmer[52], M.Voutilainen[13], V.Vrba[41], H.Wahlen[52], C.Walck[45], F.Waldner[47], A.Wehr[52], M.Weierstall[52], P.Weilhammer[7], A.M.Wetherell[7], J.H.Wickens[2], G.R.Wilkinson[34], W.S.C.Williams[34], M.Winter[8], M.Witek[16], G.Wormser[18], K.Woschnagg[48], N.Yamdagni[45], P.Yepes[7], A.Zaitsev[43], A.Zalewska[16], P.Zalewski[18], D.Zavrtanik[44], E.Zevgolatakos[9], N.I.Zimin[14], M.Zito[39], D.Zontar[44], R.Zuberi[34], R.Zukanovich Funchal[6], G.Zumerle[35], J.Zuniga[49]

[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] Collège de France, Lab. de Physique Corpusculaire, IN2P3-CNRS, F-75231 Paris Cedex 05, France
[7] CERN, CH-1211 Geneva 23, Switzerland
[8] Centre de Recherche Nucléaire, IN2P3 - CNRS/ULP - BP20, F-67037 Strasbourg Cedex, France
[9] Institute of Nuclear Physics, N.C.S.R. Demokritos, P.O. Box 60228, GR-15310 Athens, Greece
[10] FZU, Inst. of Physics of the C.A.S. High Energy Physics Division, Na Slovance 2, CS-180 40, Praha 8, Czechoslovakia
[11] Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genova, Italy
[12] Institut des Sciences Nucléaires, IN2P3-CNRS, Université de Grenoble 1, F-38026 Grenoble, France
[13] Research Institute for High Energy Physics, SEFT, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland
[14] Joint Institute for Nuclear Research, Dubna, Head Post Office, P.O. Box 79, 101 000 Moscow, Russian Federation
[15] Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 6980, D-7500 Karlsruhe 1, Germany
[16] High Energy Physics Laboratory, Institute of Nuclear Physics, Ul. Kawiory 26a, PL-30055 Krakow 30, Poland
[17] Centro Brasileiro de Pesquisas Físicas, rua Xavier Sigaud 150, RJ-22290 Rio de Janeiro, Brazil
[18] Université de Paris-Sud, Lab. de l'Accélérateur Linéaire, IN2P3-CNRS, Bat 200, F-91405 Orsay, France
[19] School of Physics and Materials, University of Lancaster, GB-Lancaster LA1 4YB, UK
[20] LIP, IST, FCUL - Av. Elias Garcia, 14-1^o, P-1000 Lisboa Codex, Portugal
[21] Department of Physics, University of Liverpool, P.O. Box 147, GB-Liverpool L69 3BX, UK
[22] LPNHE, IN2P3-CNRS, Universités Paris VI et VII, Tour 33 (RdC), 4 place Jussieu, F-75252 Paris Cedex 05, France
[23] Department of Physics, University of Lund, Sölvegatan 14, S-22363 Lund, Sweden
[24] Université Claude Bernard de Lyon, IPNL, IN2P3-CNRS, F-69622 Villeurbanne Cedex, France
[25] Universidad Complutense, Avda. Complutense s/n, E-28040 Madrid, Spain
[26] Univ. d'Aix - Marseille II - CPP, IN2P3-CNRS, F-13288 Marseille Cedex 09, France
[27] Dipartimento di Fisica, Università di Milano and INFN, Via Celoria 16, I-20133 Milan, Italy
[28] Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen 0, Denmark
[29] NC, Nuclear Centre of MFF, Charles University, Areal MFF, V Holesovickach 2, CS-180 00, Praha 8, Czechoslovakia
[30] NIKHEF-H, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands
[31] National Technical University, Physics Department, Zografou Campus, GR-15773 Athens, Greece
[32] Physics Department, University of Oslo, Blindern, N-1000 Oslo 3, Norway
[33] Dpto. Fisica, Univ. Oviedo, C/P.Jimenez Casas, S/N-33006 Oviedo, Spain
[34] Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
[35] Dipartimento di Fisica, Università di Padova and INFN, Via Marzolo 8, I-35131 Padua, Italy
[36] Depto. de Fisica, Pontificia Univ. Católica, C.P. 38071 RJ-22453 Rio de Janeiro, Brazil
[37] Rutherford Appleton Laboratory, Chilton, GB - Didcot OX11 OQX, UK
[38] Dipartimento di Fisica, Università di Roma II and INFN, Tor Vergata, I-00173 Rome, Italy
[39] Centre d'Etude de Saclay, DSM/DAPNIA, F-91191 Gif-sur-Yvette Cedex, France
[40] Dipartimento di Fisica-Università di Salerno, I-84100 Salerno, Italy
[41] Istituto Superiore di Sanità, Ist. Naz. di Fisica Nucl. (INFN), Viale Regina Elena 299, I-00161 Rome, Italy
[42] C.E.A.F.M., C.S.I.C. - Univ. Cantabria, Avda. los Castros, S/N-39006 Santander, Spain
[43] Inst. for High Energy Physics, Serpukov P.O. Box 35, Protvino, (Moscow Region), Russian Federation
[44] J. Stefan Institute and Department of Physics, University of Ljubljana, Jamova 39, SI-61000 Ljubljana, Slovenia
[45] Fysikum, Stockholm University, Box 6730, S-113 85 Stockholm, Sweden
[46] Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Via P. Giuria 1, I-10125 Turin, Italy
[47] 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
[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-5600 Wuppertal 1, Germany

1. Introduction

Among possible new particles in physics beyond the Standard Model, the leptoquarks are an interesting category of exotic colour triplets with couplings to quark-lepton pairs. They are a generic prediction of unified theories [1], of models with quark-lepton substructure [2] and of technicolor schemes [3]. Specific calculations of their production cross-sections are model dependent [4].

Some theoretical frameworks, in particular low energy predictions of superstring theories such as E_6 [5] and composite models [2], allow leptoquarks to be naturally light with masses compatible with constraints from low energy processes. These predictions have inspired a series of searches at present colliders.

Constraints on leptoquark pair production have been obtained, prior to LEP, by JADE [6] at the PETRA e^+e^- collider, AMY [7] at the TRISTAN e^+e^- collider and UA1 [8] at the CERN $\bar{p}p$ collider.

At LEP 1, all collaborations have searched for direct leptoquark pair production in Z^o decays and have published mass limits which reach the LEP 1 allowed kinematical limit [9,10].

Recently more stringent mass limits have been published for pair production of a first generation scalar leptoquark decaying into a quark and an electron, by the UA2 collaboration [11], 67 GeV/c^2, and by the CDF collaboration [12], 82 GeV/c^2 at 95% confidence level for a branching ratio into an electron and a jet of 50%. For single leptoquark production of the first generation the ZEUS collaboration [13] at HERA has published mass limits of 168 GeV/c^2 and 176 GeV/c^2 depending on the chirality of the leptoquark couplings to the quark-electron pair and the H1 collaboration has given limits [14] ranging from 145 to 192 GeV/c^2 for e^-q and from 98 to 121 GeV/c^2 for $e^-\bar{q}$ states.

The present study extends the search for first and second generation leptoquarks in e^+e^- collisions, to include single leptoquark production which gives the opportunity to explore a mass region up to about 80 GeV/c^2 at LEP 1. Although the accessible mass range is smaller than at HERA, the present DELPHI search is also sensitive to leptoquarks of the second generation.

2. Leptoquark signals

Although the scalar leptoquarks predicted by various models have different quantum numbers, they have a common feature: they decay to a lepton-quark pair, which gives the distinctive event topologies.

The aim of the present work is to search for leptoquarks using a model-independent selection and analysis of event topologies. Model predictions provide hypothetical leptoquark cross-sections and decay configurations to be compared with the data. The E_6 compactification in superstring-inspired models [5], is used to evaluate the experimental limits, since it gives the lowest number of expected events.

This analysis considers the decays to quarks and charged leptons of the first two generations of the isosinglet, charge $Q = \pm\frac{1}{3}$, colour triplet, mass degenerate scalar leptoquarks D_o, D_o^c, with a branching ratio $\frac{2}{3}$ to the up quark and charged lepton of each generation, as predicted to emerge by E_6 compactification [15,16]. D_o, D_o^c and $D_{\frac{1}{2}}$ constitute the new supersymmetric multiplet predicted by E_6. D_o and D_o^c are the two supersymmetric partners of the corresponding fermion field $D_{\frac{1}{2}}$ in the same way as the left and right-handed squarks correspond to the fermion quark field. Although $D_o(Q=-\frac{1}{3})$ and $D_o^c(Q=+\frac{1}{3})$ are different particles each one with its own antiparticle $\bar{D}_o(Q=+\frac{1}{3})$ and $\bar{D}_o^c(Q=-\frac{1}{3})$ respectively, they are assumed to be mass degenerate in order to simplify the cross-section calculations. Generation mixing decays are not considered to avoid an increase of parameters.

In the framework of composite models, the same production cross-sections can be obtained by considering a scalar leptoquark with $Q = -\frac{1}{3}$ and a $Z^o D_o \bar{D}_o$ coupling fixed by gauge symmetry. The branching ratios to the various decay modes are free parameters in composite models.

The scalar leptoquark decay modes to quarks and charged leptons ($e^+e^- \rightarrow ql^- \ \bar{q}l^+$) provide a characteristic signature of an opposite-sign dilepton pair isolated from hadronic jets, with no missing energy. The signal from this topology is conveniently separable from the Standard Model background in e^+e^- collisions. The main background, coming from $Z^o \rightarrow b\bar{b}$ with both b's decaying semileptonically, gives an event shape with the two jet-lepton pairs widely separated from each other.

Another possible background may come from the four-fermion final state $e^+e^- \rightarrow q\bar{q}l^+l^-$, which is expected [17] to contribute less than 1.1 events, for $l = e$ or μ after cuts similar to the ones used in this search, and for the integrated luminosity of 16.3 pb^{-1}.

A similar signal, with 2 jets and a l^-l^+ pair, could come from Standard Model Higgs-boson production [18]. The branching fraction for $Z^o \rightarrow Z^{o*}H^o \rightarrow H^o l^+l^-$ is $\simeq 2\times 10^{-6}(4.5\times 10^{-7})$ for a Higgs-boson mass $m_{H^o} = 50$ GeV/c^2 (60 GeV/c^2) and is comparable to any leptoquark signal rate [19]. These events, should they occur, can be easily separated from the leptoquark signal by imposing kinematical constraints.

Thus, the signals for single and pair leptoquark production in e^+e^- scattering are clearly distinguishable from Standard Model background sources.

3. Data Sample

This analysis is based on the 1990 and 1991 data samples collected by the DELPHI detector. They comprise 392000 recorded Z^o decays, from an integrated luminosity of 16.3 pb^{-1}.

A detailed description of the DELPHI detector, of the triggering conditions and of the event processing chain can be found in Ref. [20]. Here, only the specific properties relevant to the following analysis are summarized.

The charged particle tracks were measured in the 1.2 T magnetic field by a set of three cylindrical tracking detectors: the Inner Detector (ID) covering polar angles between 29^o and 151^o, the Time Projection Chamber (TPC) covering angles between 21^o and 159^o and the Outer Detector (OD) covering polar angles between 42^o and 138^o.

The electromagnetic energy was measured by the High Density Projection Chamber (HPC) in the barrel region, and by the Forward Electromagnetic Calorimeter (FEMC) in the end caps. The HPC is a high granularity gas sampling calorimeter covering polar angles 40^o to 140^o. The FEMC consists of 2×4500 lead glass blocks covering polar angles from 10^o to 36^o on each side. Hadron shower energies were measured by combining measurements from the Hadron Calorimeter (the instrumented iron return yoke of the magnet) and the electromagnetic calorimeters.

The data analysis relies on the identification of electrons and muons. The muon identification was mainly based on the muon chambers and is described in detail in Ref.[21]. Muon chamber hits were combined with the tracking information and a candidate was retained if matching hits were found in at least 2 layers.

The electron identification [22] was performed using the energy and longitudinal shape of the shower measured in the HPC and the ionization loss measured in the TPC. The identification criteria required charged particles with momentum larger than 3 GeV/c and an associated shower in the HPC with at least 1 GeV of energy.

The average identification efficiency has been measured to be 70 % for muons and about 55 % for electrons from $b\bar{b}$ events in the barrel region of the detector. In the present analysis, the average muon identification efficiency is $(78 \pm 3)\%$, determined from Monte Carlo simulated events with leptoquark signal.

4. Event analysis

Charged particles were considered in the analysis if they had a momentum greater than 100 MeV/c, a measured track length above 30 cm and were emitted at more than 25^o with respect to the beam axis, where tracks are well reconstructed by the TPC. They were also selected to originate at the interaction point within 10 cm in the longitudinal coordinate and 4 cm in the radial direction.

The events were selected according to the following requirements for the Z^o hadronic decays :

- At least seven charged particles; this cut eliminates the $\tau^+\tau^-$ contamination.
- Total energy of charged particles larger than 14% of the nominal center of mass energy.
- Event thrust axis satisfying the condition: $|cos\theta_{thr}| \leq 0.85$.

The production of a leptoquark pair, or of a single leptoquark, is clearly identified by the presence of two opposite sign isolated leptons accompanied by hadronic jets. In the case of decays without generation mixing, as considered in this analysis, the two leptons are of the same generation.

Based on a study of simulated events with pair and single leptoquark production, a method, independent of jet algorithms, was developed for event selection.

According to this study, an event must contain two opposite sign muons or electrons. In case of more lepton candidates, the two opposite sign leptons of the same generation with the highest momentum were chosen to search for isolated leptons.

As a measure of isolation the following quantity was used:

$$\rho_i = min\{2E_iE_j(1 - cos\theta_{ij})\}^{\frac{1}{2}}$$

where i = 1,2 are the two most energetic leptons of the same generation, j scans all particles with $(i \neq j)$, θ_{ij} is the angle between lepton i and a charged or neutral particle j with momentum greater than 500 MeV/c and E_i (E_j) are the corresponding energies of the two particles.

The isolated leptons had to fulfill the following requirements:

- Their momentum had to be greater than 5 GeV/c.

- The most isolated lepton had to have $\rho_1 > 2.0$ GeV.
- The next isolated lepton had to have $\rho_2 > 1.5$ GeV.
- The opening angle between the two leptons had to be larger than 30^o in order to suppress the contribution from sequential leptonic decays of b quarks.

Samples of Z^o decays to the leptoquark topologies studied in this paper were generated using a detailed simulation of the DELPHI detector [23]. The same program was also used to produce much larger event samples for background studies.

The distributions of ρ_1 and ρ_2 for data and Monte Carlo simulations of leptoquark production, and of the background, are shown in figure 1.

4.1 Pair Production

At the Z^o peak, the cross-section for pair production of scalar leptoquarks is almost independent of the unknown Yukawa coupling of the leptoquark to the lepton and the quark [16] . It depends mostly on the $Z^o D_o \bar{D}_o$ coupling which is fixed by gauge symmetry.

The efficiency of the selection criteria was studied using samples of events at various leptoquark masses generated with a Monte Carlo program using a $D_o \bar{D}_o \to c\mu^- \bar{c}\mu^+$ generator with parton shower model fragmentation based on the LUND program JETSET 7.3 [24] and a detailed simulation of the DELPHI detector.

To estimate the Standard Model background a sample of 250000 $Z^o \to q\bar{q}$ simulated decays and a sample of 120000 $Z^o \to b\bar{b}$ and $Z^o \to c\bar{c}$ events with semileptonic decays giving a muon or an electron, were processed using the same analysis as for the data.

No events were observed in the data or in the simulated background samples after applying the cuts.

The detection efficiencies found for second generation pair produced leptoquarks of mass up to 44 GeV/c^2 are given in the first row of Table 1.

The detection efficiency for the first generation leptoquark, $D_o \bar{D}_o \to ue^- \bar{u}e^+$ was calculated from the simulated decays for the second generation leptoquarks by rescaling the muon detection efficiency. In this procedure the overall electron detection efficiency was taken to be 60 % that of the muons, a conservative estimate to account for the lower reconstruction efficiencies of the two electrons relatively to the two muons and the systematic errors due to the electron identification. Figure 2 shows the expected number of events with $D_o \bar{D}_o$ pair production as a function of the leptoquark mass for a scalar leptoquark of the first and second generation with $Q = -\frac{1}{3}$ and branching ratio to a quark and a charged lepton equal to $\frac{2}{3}$ as expected from E_6 compactification. The expected number of events for scalar, mass degenerate, leptoquark production of the first two generations is also shown.

In calculating all the limits and the expected number of events, the leptoquark cross-section was reduced by a factor 0.74 to take into account initial state radiation and electroweak effects [9,10].

A mass limit of $m_{D_o} > 45.5$ GeV/c^2 at 95% confidence level is obtained for pair produced scalar leptoquarks from the combined results for the first two generations. The limit is only slightly less for leptoquarks of each generation separately. These results reach the kinematical limit allowed by LEP 1 and, due to the characteristic β^3

threshold factor for scalar pair production in e^+e^- annihilation, this bound depends only slightly on the specific model considered.

4.2 Single Production

Single leptoquark production in e^+e^- collisions can proceed through:

$$e^+e^- \to Z^o \to D_o \quad l^+\bar{q}, \quad e^+e^- \to Z^o \to \bar{D}_o \quad l^-q \quad (+D_o \leftrightarrow D_o^c)$$

where only one of the leptoquarks is produced on-shell. This process probes part of the mass region $\frac{1}{2}m_{Z^o} < m_{D_o} < m_{Z^o}$.

The cross-section for single leptoquark production is proportional to the model dependent qlD_o Yukawa type coupling which can be parametrized as:

$$\alpha_\lambda = \frac{g_D^2}{4\pi} = k\alpha_{em}$$

assuming that the leptoquarks D_o and D_o^c are mass degenerate and have equal couplings. The production cross-sections were calculated according to the matrix elements of Ref [15] inspired by E_6 superstring models, assuming a qlD_o coupling with $k = 1$. In this case the strength of the coupling is equal to that of the electromagnetic one, α_{em}.

The event topology for single leptoquark production is similar to that for pair production, but as the leptoquark becomes heavier, the distribution of quarks and leptons becomes more isotropic.

Events were generated by a Monte Carlo program with single leptoquark production of various masses and with parton shower model fragmentation. These events were subjected to the same selection criteria as the data.

m_{D_0} (GeV/c^2)	25.	30.	35.	40.	44.	55.	65.	75.	80.
ϵ(%)-pair	60 ± 3	62 $\pm$ 3	60 ± 3	57 ± 3	51 ± 3				
ϵ(%)-single						49 ± 4	45 ± 4	41 ± 4	30 ± 3

Table 1: Detection efficiency (%) for scalar leptoquarks of the second generation ($D_0 \to \mu^- c$) for various masses (GeV/c^2)

The detection efficiencies found for single leptoquarks of the second generation produced with masses from 55 GeV/c^2 to 80 GeV/c^2 are given in the second row of Table 1. Figure 2 shows the number of expected events as a function of the leptoquark mass for a scalar leptoquark ($Q = -\frac{1}{3}$) of the first and second generation with a Yukawa coupling equal to α_{em} and a branching ratio equal to $\frac{2}{3}$. The slopes of our curves differ from the corresponding ones of Ref [15] due to the different cuts used.

The analysis can be extended to exclude production of single leptoquarks with masses below 55 GeV/c^2. Assuming the efficiency for their detection is at least (49 $\pm$ 4) %, the extrapolation of the single leptoquark limits are also shown in figure 2 down to the kinematical mass limit for pair leptoquark production allowed at LEP 1.

Since no leptoquark candidates were found, a lower mass limit of 65 GeV/c^2 and 73 GeV/c^2, at 95 % confidence level, for first and second generation scalar leptoquarks respectively, is obtained assuming that the Yukawa coupling is equal to α_{em}. Under the additional assumption of mass degeneracy for the first and second generation scalar leptoquarks, the lower mass limit is found to be 77 GeV/c^2.

5. Limits on Leptoquark production

The model-independent cross-section upper limit, σ_{lim}, is given in figure 3a as a function of D_o mass for pair and singly produced scalar leptoquarks of the second generation ($D_o \rightarrow \mu^- c$), assuming the branching ratio to be 100%. Extrapolation of the single leptoquark limits into the (45 - 55) GeV/c^2 leptoquark mass interval under the same assumptions described previously for figure 2 is also shown in figure 3a.

The branching ratio limit, at 95% confidence level, for pair produced leptoquarks is displayed as a contour plot in figure 3b for the same generation.

Single production of leptoquarks is given in terms of the unknown $D_o lq$ Yukawa coupling, α_λ. The contour given in figure 3c shows the upper limit (at 95% confidence level) on α_λ as a function of m_{Do}, for the second generation leptoquark and a branching ratio BR $=\frac{2}{3}$.

6. Conclusions

A data sample of 392000 Z^o decays corresponding to an integrated luminosity of 16.3 pb^{-1} from the DELPHI detector at LEP 1 has been used to search for scalar leptoquarks both in pair and single production.

No evidence was found for leptoquark production from the analysis of events with two isolated opposite-sign leptons of the same generation, accompanied by hadrons.

A limit was obtained for the mass of pair produced leptoquarks which reaches the kinematical limit of LEP 1, $m_{D_o} \geq 45.5$ GeV/c^2 at 95% confidence level. Model-independent cross-section limits as a function of the leptoquark mass m_{D_o}, at 95% confidence level, are also given (figure 3a).

The results of the search for single leptoquark production exclude first and second generation leptoquarks with masses below 65 and 73 GeV/c^2 respectively, assuming that the $D_o lq$ Yukawa coupling α_λ is equal to the electromagnetic one. An upper limit is also given on the coupling α_λ as a function of the mass m_{D_o} at 95% confidence level.

Acknowledgements

We are greatly indebted to our technical staff and collaborators and 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.

We are grateful to T.Sjöstrand and especially to N.D. Tracas and S.D.P. Vlassopoulos for illuminating discussions.

References

[1] J.C. Pati and A. Salam, Phys. Rev. **D10** (1974) 275; H. Georgi and S.L. Glashow, Phys. Rev. Lett. **32** (1974) 438.

[2] B. Schrempp and F. Schrempp, Phys.Lett. **B 153** (1985) 101; W. Buchmüller, Acta Phys. Aust.Suppl. XXVII (1985) 517; W. Buchmüller and D. Wyler, Phys. Lett. **B177** (1986) 377.

[3] S. Dimopoulos and L. Susskind, Nucl. Phys. **B155** (1979) 237; S. Dimopoulos, Nucl. Phys. **B168** (1980) 69; E. Eichten and K. Lane, Phys. Lett. **B90** (1984) 125.

[4] W. Buchmüller, R. Ruckl and D. Wyler, Phys. Lett. **B191** (1987) 442.

[5] V. Angelopoulos et al., Nucl. Phys. **B 292** (1987) 59.

[6] JADE Collab., W. Bartel et al., Zeit. Phys. **C36** (1987) 15.

[7] AMY Collab., G.N. Kim et al., Phys. Lett. **B240** (1990) 243.

[8] S. Geer (UA1 Collab) talk at Intern. Europhysics Conf. on High Energy Physics (Uppsala, Sweden, 1987).

[9] L3 Collab., B. Adeva et al., Phys. Lett. **B261** (1991) 169; OPAL Collab., M. Akrawy et al., Phys. Lett. **B263** (1991) 123; ALEPH Collab., D. Decamp et al., Phys. Rep. **216** (1992) 25.

[10] DELPHI Collab., P. Abreu et al., Phys. Lett. **275** (1992) 222.

[11] UA2 Collab., J. Alitti et al., Phys. Lett. **B274** (1992) 507.

[12] S. Moulding et al., presented at the Seventh Meeting of the American Physical Society (DPF) Fermilab (November 1992), FERMILAB-Conf-92/341-E.

[13] ZEUS Collab., M. Derrick et al., Phys. Lett. **B306** (1993) 173;

[14] H1 Collab., I. Abt et al., Nucl. Phys. **B396** (1993) 3.

[15] N.D. Tracas and S.D.P. Vlassopoulos, Phys. Lett. **B220** (1989) 285.

[16] D. Schaile and P. Zerwas, in: Proc. Workshop on Physics on future accelerators (La Thuile and Geneva), CERN report CERN 87-07, Vol.II (1987), p. 251; J.L. Hewett and T.G. Rizzo, Phys. Rev. **D36** (1987) 3367.

[17] E.N. Argyres et al., Nucl. Phys. **B354** (1991) 1.

[18] T.G. Rizzo, Phys. Rev. **D44** (1991) 186.

[19] J.F. Gunion et al., The Higgs Hunter's Guide (Addison-Wesley, Redwood City, CA, 1990).

[20] DELPHI Collab., P. Aarnio et al., Nucl. Instr. Methods **A303** (1991) 233.

[21] DELPHI Collab., P. Abreu et al., Phys. Lett. **B275** (1992) 231.

[22] P. Bambade and P. Zalewski, DELPHI Note 92-32 PROG183 (1992), unpublished.

[23] DELPHI Collab., DELPHI Event Generation and Detector Simulation-User's Guide, DELPHI Note 89-67 (1989), unpublished.

[24] T. Sjöstrand, Comput. Phys. Com, **27** (1982) 243; **28** (1983) 229; T. Sjöstrand and M. Bengtsson, Comput. Phys. Com. **43** (1987) 367.

Figure Captions

Figure 1: Distributions of the isolation parameters ρ_1 and ρ_2:

(a) and (b) Distribution of ρ_1 and ρ_2 for the data (black dots) and simulated background (line) normalized to the data sample for both the electron and muon channel.

(c) and (d) Distribution of ρ_1 and ρ_2 for a simulated leptoquark signal from pair ($m_{D_o} =$ 40 GeV/c^2) and single ($m_{D_o} = 75$ GeV/c^2, hatched) production.

Figure 2: Expected number of events for pair and single leptoquark production as a function of the mass m_{D_o} for a scalar leptoquark of the first and second generation with $Q = -\frac{1}{3}$ and $BR = \frac{2}{3}$. For the single leptoquark production, the unknown Yukawa coupling α_λ, was set equal to the electromagnetic one α_{em}. The expected number of events for mass degenerate leptoquarks, combining the two generations, is also shown, as well as the 95% confidence level line .

Figure 3: Limits at 95% CL for a scalar leptoquark with charge $Q = -\frac{1}{3}$:

(a) Model-independent cross-section limits as a function of the mass for a leptoquark of the second generation $D_o \to \mu^- c$) with BR = 100% for (I) pair and (II) single production.

(b) The contour in the plane of mass and branching ratio for the second generation ($D_o \to \mu^- c$) pair produced leptoquarks.

(c) Limits on the $D_o lq$ Yukawa coupling as a function of the mass for the second generation single leptoquark production of the E_6 inspired model with $Q = -\frac{1}{3}$ and $BR = \frac{2}{3}$.

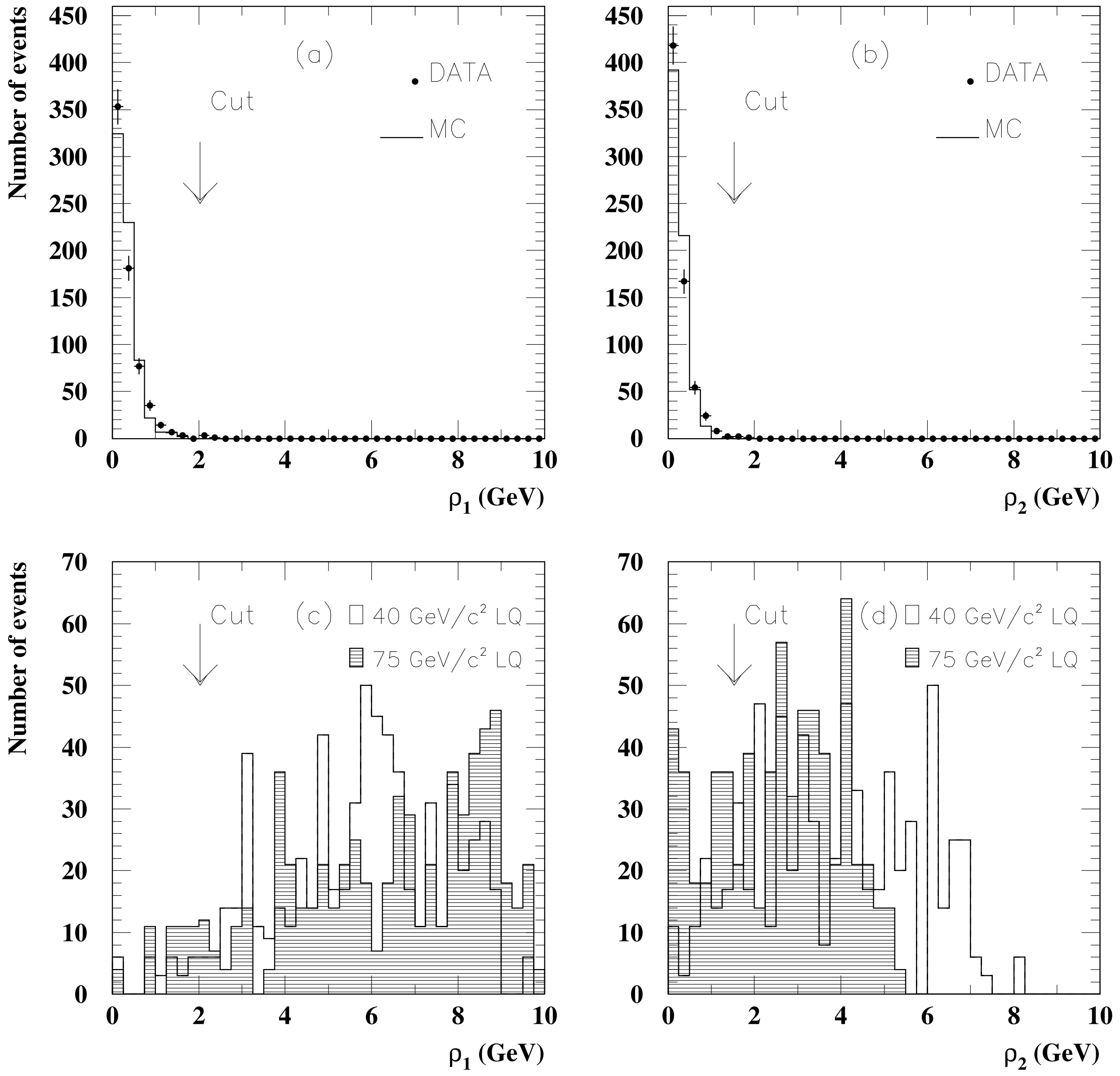

Number of events
450
400
350
300
250
200
150
100
50
0
(a)
DATA
Cut
MC
0
2
4
6
8
10
ρ_1 (GeV)
(b)
DATA
Cut
MC
ρ_2 (GeV)
70
60
50
40
30
20
10
Cut
(c)
40 GeV/c² LQ
75 GeV/c² LQ
ρ_1 (GeV)
(d)
40 GeV/c² LQ
75 GeV/c² LQ
ρ_2 (GeV)

Figure 1:

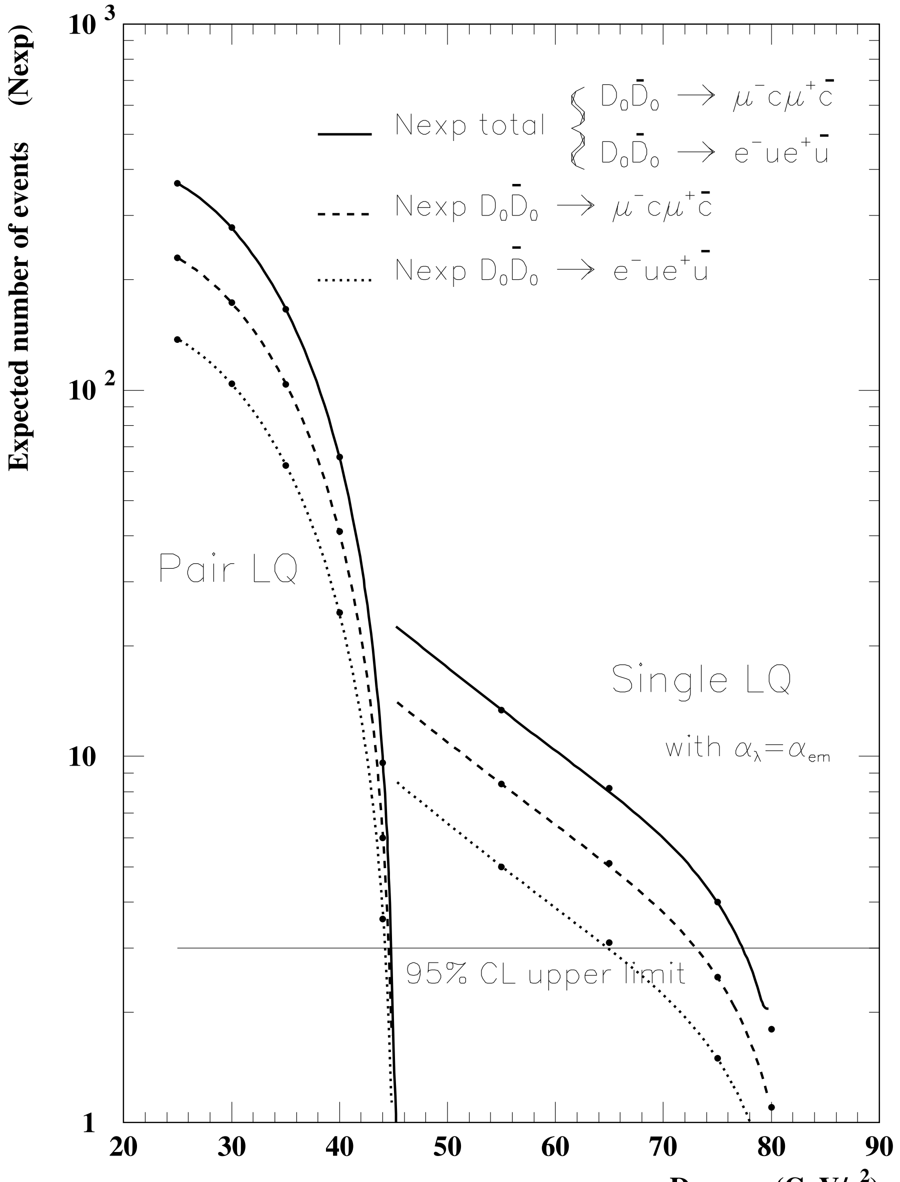
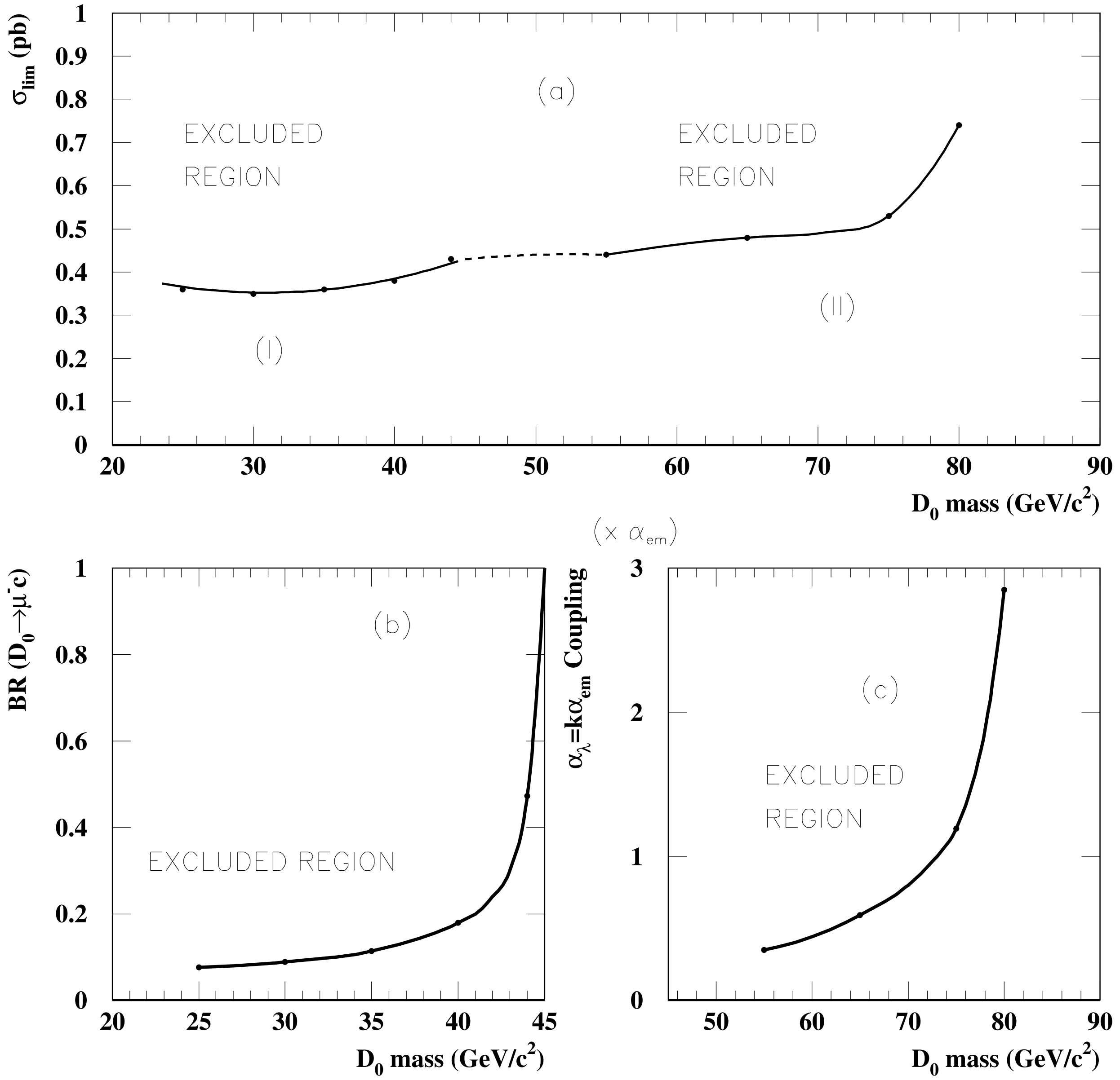

Expected number of events (Nexp)
10^3
10^2
10
1
20
30
40
50
60
70
80
90
D_0 mass (GeV/c^2)
Nexp total $\left\{ \begin{array}{l} D_0\bar{D}_0 \rightarrow \mu^- c \mu^+ \bar{c} \\ D_0\bar{D}_0 \rightarrow e^- u e^+ \bar{u} \end{array} \right.$
Nexp $D_0\bar{D}_0 \rightarrow \mu^- c \mu^+ \bar{c}$
Nexp $D_0\bar{D}_0 \rightarrow e^- u e^+ \bar{u}$
Pair LQ
Single LQ
with $\alpha_\lambda = \alpha_{em}$
95% CL upper limit

Figure 2:



σlim (pb)
(a)
EXCLUDED
REGION
EXCLUDED
REGION
(I)
(II)
D0 mass (GeV/c2)
(x αem)
BR (D0→μ-c)
(b)
EXCLUDED REGION
D0 mass (GeV/c2)
αλ=kαem Coupling
(c)
EXCLUDED
REGION
D0 mass (GeV/c2)

Figure 3: