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Search for scalar leptoquarks from Z^0 decays

DELPHI Collaboration

P. Abreu[a], W. Adam[b], F. Adami[c], T. Adye[d], T. Akesson[e], G.D. Alekseev[f], P. Allen[g],
S. Almehed[e], S.J. Alvsvaag[h], U. Amaldi[i], E. Anassontzis[j], P. Antilogus[k], W.-D. Apel[ℓ],
R.J. Apsimon[d], B. Åsman[m], P. Astier[n], J.-E. Augustin[o], A. Augustinus[p], P. Baillon[i],
P. Bambade[o], F. Barao[a], R. Barate[q], G. Barbiellini[r], D.Y. Bardin[f], A. Baroncelli[s],
O. Barring[e], W. Bartl[b], M.J. Bates[t], M. Battaglia[u], M. Baubillier[n], K.-H. Becks[v],
C.J. Beeston[t], M. Begalli[w], P. Beilliere[x], Yu. Belokopytov[y], P. Beltran[z], D. Benedic[aa],
J.M. Benlloch[g], M. Berggren[m], D. Bertrand[ab], F. Bianchi[ac], M.S. Bilenky[f], P. Billoir[n],
J. Bjarne[e], D. Bloch[aa], S. Blyth[t], V. Bocci[ad], P.N. Bogolubov[f], T. Bolognese[c], M. Bonapart[p],
M. Bonesini[u], W. Bonivento[u], P.S.L. Booth[ae], M. Boratav[n], P. Borgeaud[c], H. Borner[i],
C. Bosio[s], B. Bostjancic[i], O. Botner[af], B. Bouquet[o], M. Bozzo[w], S. Braibant[ab], P. Branchini[s],
K.D. Brand[ag], R.A. Brenner[ah], C. Bricman[ab], R.C.A. Brown[i], N. Brummer[p], J.-M. Brunet[x],
L. Bugge[ai], T. Buran[ai], H. Burmeister[i], J.A.M.A. Buytaert[i], M. Caccia[i], M. Calvi[u],
A.J. Camacho Rozas[aj], A. Campion[ae], T. Camporesi[i], V. Canale[ad], F. Cao[ab], F. Carena[i],
L. Carroll[ae], C. Caso[w], E. Castelli[r], M.V. Castillo Gimenez[g], A. Cattai[i], F.R. Cavallo[ak],
L. Cerrito[ad], A. Chan[aℓ], M. Chapkin[y], P. Charpentier[i], P. Checchia[ag], G.A. Chelkov[f],
L. Chevalier[c], P. Chliapnikov[y], V. Chorowicz[n], R. Cirio[ac], M.P. Clara[ac], P. Collins[t],
J.L. Contreras[am], R. Contri[w], G. Cosme[o], F. Couchot[o], H.B. Crawley[aℓ], D. Crennell[d],
G. Crosetti[w], M. Crozon[x], J. Cuevas Maestro[aj], S. Czellar[ah], S. Dagoret[o], E. Dahl-Jensen[an],
B. Dalmagne[o], M. Dam[h], G. Damgaard[an], G. Darbo[w], E. Daubie[ab], P.D. Dauncey[t],
M. Davenport[i], P. David[n], A. De Angelis[r], M. De Beer[c], H. De Boeck[ab], W. De Boer[ℓ],
C. De Clercq[ab], M.D.M. De Fez Laso[g], N. De Groot[p], C. De La Vaissiere[n], B. De Lotto[r],
A. De Min[u], C. Defoix[x], D. Delikaris[i], S. Delorme[i], P. Delpierre[x], N. Demaria[ac],
J. Derkaoui[ac,1], L. Di Ciaccio[ad], H. Dijkstra[i], F. Djama[aa], J. Dolbeau[x], M. Donszelmann[p],
K. Doroba[ao], M. Dracos[i], J. Drees[v], M. Dris[ap], Y. Dufour[x], W. Dulinski[aa], R. Dzhelyadin[y],
L.-O. Eek[af], P.A.-M. Eerola[i], T. Ekelof[af], G. Ekspong[m], A. Elliot Peisert[ag], J.-P. Engel[aa],
D. Fassouliotis[ap], M. Feindt[i], M. Fernandez Alonso[aj], A. Ferrer[g], T.A. Filippas[ap],
A. Firestone[aℓ], H. Foeth[i], E. Fokitis[ap], P. Folegati[r], F. Fontanelli[w], K.A.J. Forbes[ae],
H. Forsbach[v], B. Franek[d], P. Frenkiel[x], D.C. Fries[ℓ], A.G. Frodesen[h], R. Fruhwirth[b],
F. Fulda-Quenzer[o], K. Furnival[ae], H. Furstenau[ℓ], J. Fuster[i], G. Galeazzi[ag], D. Gamba[ac],
C. Garcia[g], J. Garcia[aj], C. Gaspar[i], U. Gasparini[ag], P. Gavillet[i], E.N. Gazis[ap], J.-P. Gerber[aa],
P. Giacomelli[i], K.-W. Glitza[v], R. Gokieli[i], V.M. Golovatyuk[f], J.J. Gomez Y Cadenas[i],
A. Goobar[m], G. Gopal[d], M. Gorski[ao], V. Gracco[w], A. Grant[i], F. Grard[ab], E. Graziani[s],
M.-H. Gros[o], G. Grosdidier[o], E. Gross[i], B. Grossetete[n], P. Grosse-Wiesmann[i], J. Guy[d],
F. Hahn[i], M. Hahn[ℓ], S. Haider[p], Z. Hajduk[p], A. Hakansson[c], A. Hallgren[af], K. Hamacher[v],
G. Hamel De Monchenault[c], F.J. Harris[t], B.W. Heck[i], T. Henkes[i], I. Herbst[v],
J.J. Hernandez[g], P. Herquet[ab], H. Herr[i], I. Hietanen[ah], C.O. Higgins[ae], E. Higon[g],
H.J. Hilke[i], S.D. Hodgson[t], T. Hofmokl[ao], R. Holmes[aℓ], S.-O. Holmgren[m], D. Holthuizen[p],
P.F. Honore[x], J.E. Hooper[an], M. Houlden[ae], J. Hrubec[b], P.O. Hulth[m], K. Hultqvist[m],
D. Husson[aa], P. Ioannou[j], D. Isenhower[i], P.-S. Iversen[h], J.N. Jackson[ae], P. Jalocha[aq],
G. Jarlskog[e], P. Jarry[c], B. Jean-Marie[o], E.K. Johansson[m], D. Johnson[ac], M. Jonker[i],

L. Jonsson[e], P. Juillot[aa], G. Kalkanis[j], G. Kalmus[d], F. Kapusta[n], S. Katsanevas[j], E.C. Katsoufis[ap], R. Keranen[ah], J. Kesteman[ab], B.A. Khomenko[f], N.N. Khovanski[f], B. King[ae], N.J. Kjaer[i], H. Klein[i], W. Klempt[i], A. Klovning[h], P. Kluit[p], J.H. Koehne[ℓ], B. Koene[p], P. Kokkinias[z], M. Kopf[ℓ], M. Koratzinos[ac], K. Korcyl[aq], A.V. Korytov[f], V. Kostiukhin[y], C. Kourkoumelis[j], T. Kreuzberger[b], J. Krolikowski[ao], I. Kronkvist[e], J. Krstic[t], U. Kruener-Marquis[v], W. Krupinski[aq], W. Kucewicz[u], K. Kurvinen[ah], C. Lacasta[g], C. Lambropoulos[z], J.W. Lamsa[aℓ], L. Lanceri[r], V. Lapin[y], J.-P. Laugier[c], R. Lauhakangas[ah], G. Leder[b], F. Ledroit[q], R. Leitner[i], Y. Lemoigne[c], J. Lemonne[ab], G. Lenzen[v], V. Lepeltier[o], A. Letessier-Selvon[n], D. Liko[b], E. Lieb[v], E. Lillethun[h], J. Lindgren[ah], A. Lipniacka[ao], I. Lippi[ag], R. Llosa[am], B. Loerstad[e], M. Lokajicek[f], J.G. Loken[t], M.A. Lopez Aguera[aj], A. Lopez-Fernandez[o], M. Los[p], D. Loukas[z], A. Lounis[aa], J.J. Lozano[g], R. Lucock[d], P. Lutz[x], L. Lyons[t], G. Maehlum[i], J. Maillard[x], F. Mandl[b], J. Marco[aj], M. Margoni[ag], J.-C. Marin[i], A. Markou[z], S. Marti[g], L. Mathis[x], F. Matorras[aj], C. Matteuzzi[u], G. Matthiae[ad], M. Mazzucato[ag], M. Mc Cubbin[ae], R. Mc Kay[aℓ], R. Mc Nulty[ae], E. Menichetti[ac], G. Meola[w], C. Meroni[u], W.T. Meyer[aℓ], M. Michelotto[ag], W.A. Mitaroff[b], G.V. Mitselmakher[f], U. Mjoernmark[e], T. Moa[m], R. Moeller[an], K. Moenig[i], M.R. Monge[w], P. Morettini[w], H. Mueller[ℓ], W.J. Murray[d], G. Myatt[t], F. Naraghi[n], U. Nau-Korzen[v], F.L. Navarria[ak], P. Negri[u], B.S. Nielsen[an], B. Nijjhar[ae], V. Nikolaenko[y], V. Obraztsov[y], A.G. Olshevski[f], R. Orava[ah], A. Ostankov[y], A. Ouraou[c], R. Pain[n], H. Palka[p], T. Papadopoulou[ap], L. Pape[i], A. Passeri[s], M. Pegoraro[ag], V. Perevozchikov[y], M. Pernicka[b], A. Perrotta[ak], F. Pierre[c], M. Pimenta[a], O. Pingot[ab], M.E. Pol[i], G. Polok[aq], P. Poropat[r], P. Privitera[ℓ], A. Pullia[u], J. Pyyhtia[ah], D. Radojicic[t], S. Ragazzi[u], P.N. Ratoff[t], A.L. Read[ai], N.G. Redaelli[u], M. Regler[b], D. Reid[ae], P.B. Renton[t], L.K. Resvanis[j], F. Richard[o], M. Richardson[ae], J. Ridky[f], G. Rinaudo[ac], I. Roditi[i], A. Romero[ac], I. Roncagliolo[w], P. Ronchese[ag], C. Ronnqvist[ah], E.I. Rosenberg[aℓ], U. Rossi[ak], E. Rosso[i], P. Roudeau[o], T. Rovelli[ak], W. Ruckstuhl[p], V. Ruhlmann[c], A. Ruiz[aj], K. Rybicki[aq], H. Saarikko[ah], Y. Sacquin[c], G. Sajot[q], J. Salt[g], E. Sanchez[g], J. Sanchez[am], M. Sannino[w], M. Schaeffer[aa], S. Schael[ℓ], H. Schneider[ℓ], M.A.E. Schyns[i], F. Scuri[r], A.M. Segar[t], R. Sekulin[d], M. Sessa[r], G. Sette[w], R. Seufert[ℓ], R.C. Shellard[i], P. Siegrist[c], S. Simonetti[w], F. Simonetto[ag], A.N. Sissakian[f], T.B. Skaali[ai], G. Skjevling[ai], G. Smadja[c,k], G.R. Smith[d], N. Smirnov[y], R. Sosnowski[ao], T.S. Spassoff[q], E. Spiriti[s], S. Squarcia[w], H. Staeck[v], C. Stanescu[s], G. Stavropoulos[z], F. Stichelbaut[ab], A. Stocchi[o], J. Strauss[b], R. Strub[aa], M. Szczekowski[ao], M. Szeptycka[ao], P. Szymanski[ao], T. Tabarelli[u], S. Tavernier[ab], G. Theodosiou[z], A. Tilquin[ar], J. Timmermans[p], V.G. Timofeev[f], L.G. Tkatchev[f], T. Todorov[f], D.Z. Toet[p], A. Tomaradze[y], L. Tortora[s], M.T. Trainor[t], D. Treille[i], U. Trevisan[w], W. Trischuk[i], G. Tristram[x], C. Troncon[u], A. Tsirou[i], E.N. Tsyganov[f], M. Turala[aq], R. Turchetta[aa], M.-L. Turluer[c], T. Tuuva[ah], I.A. Tyapkin[f], M. Tyndel[d], S. Tzamarias[i], B. Ueberschaer[v], S. Ueberschaer[v], O. Ullaland[i], V.A. Uvarov[y], G. Valenti[ak], E. Vallazza[ac], J.A. Valls Ferrer[g], G.W. Van Apeldoorn[p], P. Van Dam[p], W.K. Van Doninck[ab], C. Vander Velde[ab], J. Varela[a], P. Vaz[i], G. Vegni[u], L. Ventura[ag], W. Venus[d], F. Verbeure[ab], L.S. Vertogradov[f], L. Vibert[n], D. Vilanova[c], N. Vishnevsky[y], E.V. Vlasov[y], S. Vlassopoulos[ap], A.S. Vodopyanov[f], M. Vollmer[v], S. Volponi[ak], G. Voulgaris[j], M. Voutilainen[ah], V. Vrba[s], H. Wahlen[v], C. Walck[m], F. Waldner[r], M. Wayne[aℓ], P. Weilhammer[i], J. Werner[v], A.M. Wetherell[i], J.H. Wickens[ab], J. Wikne[ai], G.R. Wilkinson[t], W.S.C. Williams[t], M. Winter[aa], D. Wormald[ai], G. Wormser[o], K. Woschnagg[af], N. Yamdagni[m], P. Yepes[i], A. Zaitsev[y], A. Zalewska[aq], P. Zalewski[ao], D. Zavrtanik[i], E. Zevgolatakos[z], G. Zhang[v], N.I. Zimin[f], M. Zito[c], R. Zitoun[n], R. Zukanovich Funchal[x], G. Zumerle[ag] and J. Zuniga[g]

[a] *LIP, Av. Elias Garcia 14 - 1e, P-1000 Lisbon Codex, Portugal*
[b] *Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften,*
Nikolsdorfergasse 18, A-1050 Vienna, Austria
[c] *DPhPE, CEN–Saclay, F-91191 Gif-Sur-Yvette Cedex, France*
[d] *Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK*
[e] *Department of Physics, University of Lund, Sölvegatan 14, S-223 63 Lund, Sweden*
[f] *Joint Institute for Nuclear Research, Dubna, Head Post Office, P.O. Box 79, SU-101 000 Moscow, USSR*
[g] *Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia–CSIC,*
and Departamento de Fisica Atomica Molecular y Nuclear,
Avda. Dr. Moliner 50, E-46100 Burjassot (Valencia), Spain
[h] *Department of Physics, University of Bergen, Allégaten 55, N-5007 Bergen, Norway*
[i] *CERN, CH-1211 Geneva 23, Switzerland*
[j] *Physics Laboratory, University of Athens, Solonos Street 104, GR-10680 Athens, Greece*
[k] *Université Claude Bernard de Lyon, 43 Boulevard du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France*
[ℓ] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Pf. 6980, W-7500 Karlsruhe 1, FRG*
[m] *Institute of Physics, University of Stockholm, Vanadisvägen 9, S-113 46 Stockholm, Sweden*
[n] *LPNHE, Universités Paris VI et VII, Tour 33 (RdC), 4 place Jussieu, F-75230 Paris Cedex 05, France*
[o] *Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Bâtiment 200, F-91405 Orsay, France*
[p] *NIKHEF-H, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands*
[q] *Institut des Sciences Nucléaires, Université de Grenoble 1, F-38026 Grenoble, France*
[r] *Dipartimento di Fisica, Università di Trieste and INFN, Via A. Valerio 2, I-34127 Trieste, Italy*
and Istituto di Fisica, Università di Udine, Via Larga 36, I-33100 Udine, Italy
[s] *Istituto Superiore di Sanità, Istituto Nazionale di Fisica Nucleare (INFN),*
Viale Regina Elena 299, I-00161 Rome, Italy
[t] *Nuclear Physics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[u] *Dipartimento di Fisica, Università di Milano and INFN, Via Celoria 16, I-20133 Milan, Italy*
[v] *Fachbereich Physik, University of Wuppertal, Pf. 100 127, W-5600 Wuppertal 1, FRG*
[w] *Dipartimento di Fisica, Università di Genova and INFN, Via Dodecaneso 33, I-16146 Genoa, Italy*
[x] *Laboratoire de Physique Corpusculaire, Collège de France, 11 place M. Berthelot, F-75231 Paris Cedex 5, France*
[y] *Institute for High Energy Physics, Serpukhov, P.O. Box 35, SU-142 284 Protvino (Moscow Region), USSR*
[z] *Institute of Nuclear Physics, N.R.C. Demokritos, P.O. Box 60628, GR-15310 Athens, Greece*
[aa] *Division des Hautes Energies, CRN–Groupe DELPHI and LEPSI, B.P. 20 CRO, F-67037 Strasbourg Cedex, France*
[ab] *Physics Department, Universitaire Instelling Antwerpen, Universiteitsplein 1, B-2610 Wilrijk, Belgium*
and IIHE, ULB–VUB, Pleinlaan 2, B-1050 Brussels, Belgium
and Service de Physique des Particules Elémentaires, Faculté des Sciences, Université de l'Etat Mons,
Av. Maistriau 19, B-7000 Mons, Belgium
[ac] *Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Via P. Giuria 1, I-10125 Turin, Italy*
[ad] *Dipartimento di Fisica, Università di Roma II and INFN, Tor Vergata, I-00173 Rome, Italy*
[ae] *Department of Physics, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, UK*
[af] *Department of Radiation Sciences, University of Uppsala, P.O. Box 535, S-751 21 Uppsala, Sweden*
[ag] *Dipartimento di Fisica, Università di Padova and INFN, Via Marzolo 8, I-35131 Padua, Italy*
[ah] *Department of High Energy Physics, University of Helsinki,*
Siltavuorenpenger 20 C, SF-00170 Helsinki 17, Finland
[ai] *Physics Department, University of Oslo, Blindern, N-1000 Oslo 3, Norway*
[aj] *Facultad de Ciencias, Universidad de Santander, av. de los Castros, E-39005 Santander, Spain*
[ak] *Dipartimento di Fisica, Università di Bologna and INFN, Via Irnerio 46, I-40126 Bologna, Italy*
[aℓ] *Ames Laboratory and Department of Physics, Iowa State University, Ames, IA 50011, USA*
[am] *Departamento de Fisica Atomica Molecular y Nuclear, Universidad Complutense,*
Avda. Complutense s/n, E-28040 Madrid, Spain
[an] *Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark*
[ao] *Institute for Nuclear Studies, and University of Warsaw, Ul. Hoża 69, PL-00681 Warsaw, Poland*
[ap] *Physics Department, National Technical University, Zografou Campus, GR-15773 Athens, Greece*
[aq] *High Energy Physics Laboratory, Institute of Nuclear Physics, Ul. Kawiory 26 a, PL-30055 Cracow 30, Poland*
[ar] *Faculté des Sciences de Luminy, Université d'Aix – Marseille II, Case 907 - 70,*
route Léon Lachamp, F-13288 Marseille Cedex 09, France

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We have searched for pair produced scalar leptoquarks each decaying to a quark and a charged lepton in a sample of 116 000 hadronic Z^0 events produced at LEP. No candidate was detected and cross section and branching ratio limits are set for the above process at 95% CL. Mass limits are found to be about 42 GeV$/c^2$ depending only slightly on the models used and a coupling times branching ratio exclusion line is drawn for a scalar leptoquark with a free coupling. We have also probed the mass region above 45 GeV$/c^2$ for a singly produced scalar leptoquark and set limits on the cross section and the coupling $\lambda^2/4\pi$ up to 60 GeV.

1. Introduction

Scalar coloured leptoquarks appear naturally as a common feature of various theories extending the standard model. Besides being present in the strong coupling version of the standard model, they also emerge in grand unifying models, in composite models, in technicolor or horizontal symmetry schemes and more recently, in E_6 superstring inspired models [1,2].

Since the leptoquark couples to a quark and a lepton, leptoquark pair production at Z^0 could provide a characteristic signal with an unlike-sign lepton pair which is accompanied by distant jet activity from the hadronization of the two quarks and could involve no missing energy.

As a guide in this search, E_6 compactification [2] results are used to consider mass degenerate scalar elementary leptoquarks D_0 D_0^c in the first two families. Each one is assumed to be a weak-isospin singlet, color triplet, of charge $-\frac{1}{3}$ and $+\frac{1}{3}$ respectively, with a branching ratio $\frac{2}{3}$ to the up quark and the charged lepton of its family. The other decay mode would be to the down quark and neutrino of the family with branching ratio $\frac{1}{3}$. D_0, D_0^c and $D_{1/2}$ constitute the new supersymmetric multiplet predicted by E_6. D_0 and D_0^c are the two supersymmetric partners of the corresponding fermion field $D_{1/2}$ in the same way as the left- and right-handed selectrons correspond to the electron field.

At the Z^0 peak, the pair production cross section [3] is almost independent of the unknown Yukawa coupling λ of the leptoquark to the lepton and the quark, depending mostly on the $Z^0 D_0 \bar{D}_0$ gauge coupling c, i.e.

$$\frac{d\sigma}{d\cos\theta}=3\pi\frac{\alpha^2}{4s}\beta^3\sin^2\theta\frac{s^2}{(s-M^2)^2+M^2\Gamma^2}\times c^2(v^2+a^2)\,.$$

Here θ is the production angle of the D_0 with respect to the e^- beam, $\beta=\sqrt{1-4m^2/s}$ is the center-of-mass velocity of the leptoquark,

$$v=\frac{1}{\sin\theta_w\cos\theta_w}\left(\tfrac{1}{4}-\sin^2\theta_w\right)\,,$$

$$a=\frac{1}{4}\frac{1}{\sin\theta_w\cos\theta_w}$$

are the standard model electron couplings and

$$c=\frac{1}{\sin\theta_w\cos\theta_w}\left(I_3^w-Q\sin^2\theta_w\right)$$

is fixed by gauge symmetry for the leptoquark of charge Q and weak isospin I_3^w. The above expressions are valid for the leptoquarks of most other models. Phenomenologically, the leptoquark coupling $g^2=c^2$ to the neutral current and the branching ratio into quarks and charged leptons could be considered as free parameters.

In the following, besides searching for pairs of scalar leptoquarks, one also looked for the process

$$\begin{array}{lll} e^+e^-\to \underset{\to \ell^- q}{D_0}\,\ell^+\bar{q} & \text{or } \underset{\to \ell^+ \bar{q}}{\bar{D}_0}\,\ell^- q, & (+D_0\leftrightarrow D_0^c)\,, \end{array}$$

where only one of the leptoquarks D_0, $\bar{D}_0$, (D_0^c, $\bar{D}_0^c$), is produced on-shell and thus probe [4] part of the mass region $\frac{1}{2}m_{Z^0}<m_D<m_{Z^0}$. The cross section for this process depends on the $D_0\ell q$ Yukawa coupling λ and is proportional to $\alpha_\lambda=\lambda^2/4\pi$, assumed equal to α (fine structure constant) [3,4].

The width of the scalar leptoquark is of the order $\alpha_\lambda m$ which corresponds to a life-time of $\sim 10^{-23}$ s for a mass of 40 GeV$/c^2$.

Various experimental constraints have been im-

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[1] Permanent address: Département de Physique, Faculté des Sciences d'Oujda, Oujda, Morocco.

posed on scalar composite leptoquarks with $Q=\frac{2}{3}$. The JADE Collaboration [5] has excluded masses in the range 5–20.8 GeV/c^2 for a leptoquark decaying into second family fermions. The UA1 Collaboration [6] has also placed a limit of $m>33$ GeV/c^2 for second family composite leptoquarks with $Q=\frac{2}{3}$ and $\mathrm{BR}(\mu+\mathrm{quark})\geqslant 0.1$. KEK experiments from the AMY and VENUS Collaborations [7] searching for similar $Q=\frac{2}{3}$ composite leptoquarks and considering only the γ propagator, imply a limit $m>21$ GeV/c^2 for $Q=-\frac{1}{3}$ and $\mathrm{BR}=\frac{2}{3}$ in the second family at KEK energies.

2. The detector

The DELPHI detector is described in detail elsewhere [8]; here we just give a brief summary of the tracking detectors and calorimeters used in this analysis. Charged particle tracks are measured in the 1.2 T magnetic field with three cylindrical detectors: the Inner Detector (ID) covering polar angles between 29° and 151°, the Time Projection Chamber (TPC) covering angles between 21° and 159° and the Outer Detector (OD) covering angles between 42° and 138°.

The calorimeters are the High Density Projection Chamber (HPC), which measures the electromagnetic energy with high granularity covering angles between 40° and 140°, the Electromagnetic Calorimeter in the endcaps (EMF), consisting of 2×4500 lead glass blocks and covering angles between 10° and 35.5° and between 144.5° and 170°, and the Hadron Calorimeter (HCAL), measuring the hadronic energy and covering all angles between 10° and 170°.

3. Data sample

The exotic events were sought in a hadronic sample that initially was selected from the 1990 data so that

(i) the number of charged particle tracks was at least five, and

(ii) all the particles, charged and neutral, had to form at least two clusters as defined by the LUND cluster algorithm LUCLUS [9] used with default parameters ($d_{\mathrm{join}}=2.5$ GeV). This condition is very efficient in eliminating beam–gas events.

Charged particles were considered if they had momentum exceeding 100 MeV/c and if their extrapolated distance to the vertex in the transverse plane and along the beam axis was less than 10 cm each.

To estimate the number of produced Z^0 hadronic events to which the above selected sample corresponds, the preceding cuts as well as a $|\cos\theta_{\mathrm{thrust}}|<0.8$ cut were applied to the 1990 data sample taken on and around the Z^0 mass peak. This left a sample of 88 195 hadronic decays of Z^0. In a simulated sample of 40K hadronic reconstructed events the above thrust cut led to a 22.9% loss. This taken together with a 1.54% loss due to (i) + (ii) and with a hadronic trigger efficiency of 99.5%, led to a total number of $116\,175\pm 445$ Z^0 hadronic events produced.

4. Search for leptoquark pairs

The topology that was looked for was that of two jets and two isolated particles. Such events were sought within four jets reconstructed from charged and neutral particles using the LUCLUS algorithm with default parameters. The event charged particle multiplicity was required to be at least six and the charged multiplicity of each jet at least one. In addition:

(i) Two of the reconstructed jets should be single charged particles of opposite sign. These two particles were then considered as isolated if they satisfied (iii), as well.

(ii) In the samples of Monte Carlo simulated $D_0\bar{D}_0$ pairs it was found that one (case iia) or both leptons (case iib) from the $D_0\bar{D}_0$ decays were often interpreted as one or two jets, respectively. The clustering algorithm assigned to them several very low energy fragments produced at wide angles from the fragmentation of the quarks. Therefore if condition (i) was not satisfied, the jets were further examined: if a jet had at most total multiplicity 3 and the charged leader in the jet carried at least 90% of the jet energy and satisfied the kinematic conditions of (iii), then this "jet" was considered as an isolated particle (case iia). If two such isolated particles could be recovered, the event would be classified in case iib. Fig. 1 shows the

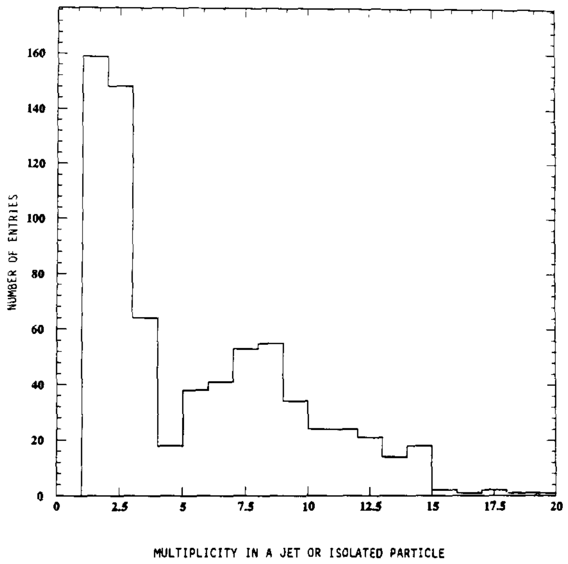

Fig. 1. Multiplicity distribution for each of the four jets in the selected MC events at the leptoquark mass $m=42$ GeV/c^2 (four entries per event).

distribution for the total multiplicity for the hadronic jets or isolated particles defined as above in the 180 selected MC events out of a sample of 428 for $m=42$ GeV/c^2. The two peaks seen are due to the two isolated particles and the two jets.

(iii) Both isolated particles from case (i) or (ii) were required to satisfy the angular condition with respect to the beams $|\cos\theta_i|<0.85$ and have momentum larger than 3 GeV/c. The hadronic jets were also required to have energy larger than 3 GeV.

The efficiencies with these selection criteria were studied using samples of events at various masses m generated with a Monte Carlo program using a $D_0\bar{D}_0\to c\mu^-\bar{c}\mu^+$ generator which was based on LUND program [9] Jetset 6.3 for hadronization. Subsequently, the detailed detector simulation was used and the events were processed through the same processing chain as the real data. It was found that the events with two isolated particles of class i satisfying the above selection criteria, also had both particles satisfying the condition $\rho>1.8$ GeV$^{1/2}$ on the isolation parameter

$$\rho=\sqrt{2E_{\mathrm{iso}\,\ell}(1-\cos\theta_{\mathrm{iso}\,\ell,\mathrm{jet}})}\ ,$$

where $\theta_{\mathrm{iso}\,\ell,\mathrm{jet}}$ is the minimum angle between an isolated particle and the hadronic jets and $E_{\mathrm{iso}\,\ell}$ is the energy of the isolated particle in GeV. This condition $\rho>1.8$ GeV$^{1/2}$ was then applied on the events in the Monte Carlo samples (iia) and (iib).

The same selection procedure was applied on the hadronic data sample and on a Monte Carlo sample of 97 000 hadronic Z^0 events. Compatible numbers of candidates were obtained from the two samples, when the selection conditions were relaxed from the ones mentioned above. For example, when the leader in the candidate for isolated particle had energy greater than 50% of the jet energy and this jet had multiplicity up to five, then the number obtained from the two samples were 185±14 and 165±13 (normalized), respectively.

The main background for this signal comes from the semileptonic decays of the $b\bar{b}$ and $c\bar{c}$ events giving topologies of two jets+two charged leptons. Using a sample of a mixture of 2000 such Monte Carlo events where both heavy quarks decay semileptonically, a simulation program allowed to estimate that, in this hadronic sample, approximately two heavy flavour events having two jets and two isolated leptons with isolation parameter $\rho>1.8$ GeV$^{1/2}$ were expected. Concerning the four-fermion background, $e^+e^-\to q\bar{q}\ell^+\ell^-$, it is expected [10] to contribute at most 0.3 events, for $\ell=\mu$ or e and under similar cuts.

With the conditions (i)–(iii) and $\rho>1.8$ GeV$^{1/2}$ applied, no candidate remained from the data sample, whereas one event in class (iia) survived from the Monte Carlo hadronic Z^0 sample. This Monte Carlo event was found to be of the type $Z^0\to b\bar{b}$.

The detection efficiencies found for second family leptoquarks with masses up to 42 GeV/c^2, using conditions (i)–(iii), $\rho>1.8$ GeV$^{1/2}$ and without asking for lepton identification are given in table 1. The error quoted is statistical only. Fig. 2 gives the distribution of the ρ values of the isolated particles of the finally selected $D_0\bar{D}_0$ events in the Monte Carlo sample with leptoquark mass $m=42$ GeV/c^2.

The detection efficiencies of table 1 include a reduction by 10% to conservatively account for systematic uncertainties in the Monte Carlo hadronization [11] [#1], coming from string fragmentation or independent fragmentation. For the first family, $D_0\bar{D}_0\to$

For footnote see next page.

Table 1
Detection efficiency (%) for second family leptoquarks of various masses (in GeV/c^2).

Case	m					
	20	25	35	42	50	60
(i)	6.5	5.5	10.2	7.5	11.1	5.9
(iia)	16.4	15.0	19.3	18.9	17.7	12.2
(iib)	14.5	12.5	10.2	11.9	8.3	8.3
total	37.4±3.3	33.0±3.2	39.7±2.0	38.3±2.2	37.1±2.9	26.4±2.5

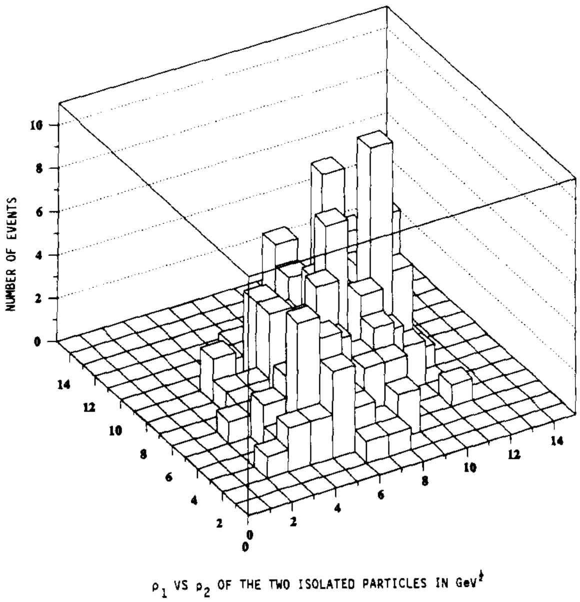

Fig. 2. Distribution of the isolation parameter ρ_1 versus ρ_2 of the two isolated particles for the selected MC events at $m=42$ GeV/c^2.

$ue^-\bar{u}e^+$, a conservative estimate was made for the detection efficiencies by reducing further those of the second family by 15%, to account for the lower reconstruction efficiencies for two electrons relatively to two muons, as measured in $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ decays, respectively.

The number of $D_0\bar{D}_0$ events expected to be seen from the second family alone [12], as well as from the second and first combined (neglecting the mixing between mass-degenerate first and second family D's) are plotted in fig. 3 for the E_6 inspired model of elementary leptoquarks [3]. The same number of events would generally be expected for any leptoquark with charge $Q=-\frac{1}{3}$ and coupling c fixed by gauge symmetry (section 1). In the same plot are given the expectations for a composite leptoquark with $Q=\frac{2}{3}$ (just a factor of 4 larger). In finding the expected numbers

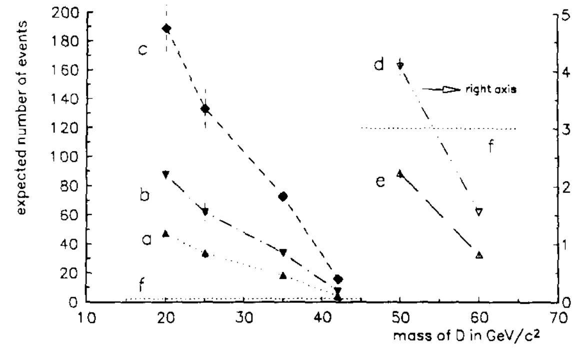

Fig. 3. Expected number of events from the hadronic sample of 116 000 produced Z^0 with two jets+two charged isolated particles, BR$=\frac{2}{3}$. (a) $D_0\bar{D}_0 \to$ two jets+two charged isolated particles within the second family for the E_6 inspired model [3], $Q=-\frac{1}{3}$, BR$=\frac{2}{3}$, or, for a composite leptoquark with $Q=-\frac{1}{3}$, BR$=\frac{2}{3}$ and coupling c fixed by gauge symmetry (left scale). (b) As in (a) but combining the two family when the first and second family D's are mass degenerate (left scale). (c) As in (a) but for a composite leptoquark with $Q=\frac{2}{3}$ (left scale). (d) Expected events with two jets and two charged isolated particles, when only one D_0 is produced on shell for the E_6 inspired model [4], $Q=-\frac{1}{3}$, BR$=\frac{2}{3}$ (first and second family D's are mass degenerate), $\alpha_\lambda=\alpha$ (right scale). (e) Same as (d) but for the second family only (i.e. no mass degeneracy of the D's) (right scale). (f) Line of 95% confidence level.

[#1] The number of events for the first family are obtained from those of the second by multiplying with 0.85. The first family cross section limits are obtained from those of the second by dividing by 0.85 and the BR limits by dividing those of the second family by 0.92.

of events and all the limits mentioned in the paper, we have scaled the expected leptoquark cross sections by a factor 0.74 to account for initial state radiation effects [12]. From these plots one finds the mass limits 42.1, 43.0, 43.4 GeV/c^2 for the three cases, respectively, at 95% confidence level.

In fig. 4, the model independent cross section limits are given for any pair-produced spin-0 object of mass m decaying to a quark and a charged lepton in the mass interval 20–43 GeV/c^2, assuming the branching ratio to be BR = 1 (second family [#2]). In the same figure, we also give the limit for the branching ratio into a quark and a charged lepton, at 95% confidence level (second family [#2]), assuming the cross section and standard gauge coupling given in section 1. Using these values, limits can be placed on the coupling times branching ratio $|g|\cdot \mathrm{BR}(\mathrm{D_0}\to \mathrm{q}\ell)$ for a leptoquark, where g and BR are treated as free parameters (second family [#2]). These are plotted in the same figure using the scale on the right side.

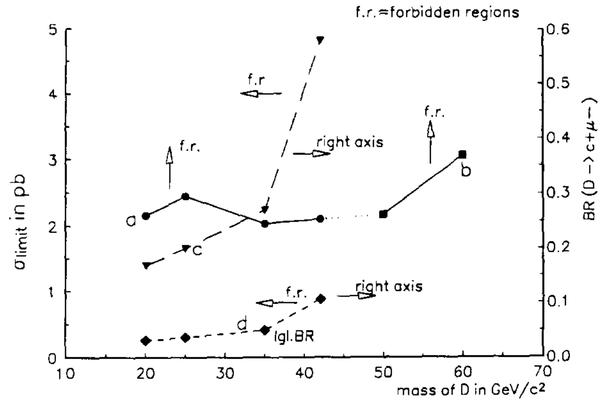

Fig. 4. Limits at 95% CL: (a) Model independent cross section limits for a pair produced scalar object decaying to a quark and a charged isolated particle (second family [12]). Arrows show excluded area in 20–45 GeV/c^2 (left scale). (b) Cross section limits in the 45–60 GeV/c^2 interval for a singly produced scalar leptoquark decaying to a quark and a charged isolated particle (second family (see also footnote 2)) using efficiencies based on the kinematics of E_6 inspired class of models [4] (left scale). (c) Model independent branching ratio limit for a scalar leptoquark to decay to a quark and a charged isolated particle (second family, right scale) (see also footnote 2). (d) $|g|\cdot$BR limit for a scalar leptoquark with free coupling g decaying to a quark and a charged isolated particle (second family, right scale) (see also footnote 2).

5. Search for a singly produced leptoquark

This search has been extended to leptoquark masses higher than $\frac{1}{2}m_{\mathrm{Z^0}}$, by applying the same selection procedure as for $\mathrm{D_0}\,\bar{\mathrm{D}}_0$ above, to Monte Carlo samples of events with one real leptoquark with $m=50$ and 60 GeV/c^2. These were generated according to the matrix element of ref. [4] inspired by E_6 superstrings and then processed as the real data, after a detailed simulation of the detector. The detection efficiencies, reduced by 10% to account for systematic uncertainties as for the pair production case, are given in table 1.

In fig. 3, the expected number of events is given (see also footnote 2), neglecting the mixing between leptoquarks of the first and second family, assuming that they are mass degenerate and taking a Yukawa coupling λ of the leptoquark to the lepton and the quark such that $\alpha_\lambda=\lambda^2/4\pi=\alpha$.

In fig. 4, the cross section limits for the second family have been included (see also footnote 2) which are found for the single $\mathrm{D_0}$ process based on the detection efficiencies of table 1. The expected total cross section values [4] at 50 and 60 GeV/c^2 for each family (including $\mathrm{D_0}$, $\bar{\mathrm{D}}_0$, $\mathrm{D_0^c}$ and $\bar{\mathrm{D}}_0^{\mathrm{c}}$), corrected by Monte Carlo for the cuts applied in ref. [4] and for initial state radiation effects are 1.6 and 0.8 pb, respectively, for $\alpha_\lambda=\alpha$. The upper limits found on the Yukawa coupling λ of the leptoquark to the lepton and the quark, are $\alpha_\lambda<0.8\alpha$ for $m=50$ GeV/c^2 and $\alpha_\lambda<2.2\alpha$ for $m=60$ GeV/c^2 at 95% confidence level, if the leptoquarks of the first and second family have the same mass and we neglect mixing.

6. Conclusions

We have searched for pair produced scalar leptoquarks in event topologies with two jets and two isolated charged particles. No candidate was found for the first or second family. Model independent cross section limits at 95% confidence level are given (fig.

[#2] The leptoquark events were generated with independent fragmentation. We have used string fragmentation in comparable samples of events with $m=25$, 35 and 42 GeV/c^2 and a fast detector simulation, and observed a relative decrease in the detection efficiency of at most 10%.

4) of the order of 2 pb in the leptoquark mass interval 20–45 GeV/c^2. Also, branching ratio limits, as well as $|g|\cdot$BR have been deduced, when the coupling $|g|$ and BR are free parameters in the latter case.

Mass limits have been set at about 42–43 GeV/c^2 for E_6 superstring inspired or composite models (fig. 3) for a branching ratio of $\frac{2}{3}$ for decay into a quark and a charged lepton. Due to the steep fall-off of the cross section near $\frac{1}{2}m_{Z^0}$ because of the β^3 factor, our bound depends only slightly on the particular model considered. Similar results have been obtained by other LEP experiments [13].

We have also searched for one on-mass-shell E_6-superstring inspired leptoquark, in a mass region above $\frac{1}{2}m_{Z^0}$ where cross section limits are found and upper limits are set on the coupling $\lambda^2/4\pi$ at 50 and 60 GeV/c^2 of 0.8α and 2.2α, respectively, at 95% confidence level, if mass degeneracy is assumed for the leptoquarks of the first and second family.

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