Search for leptoquarks in Z0 decays

Adeva, B.; Adriani, O.; Aguilar-Benitez, M.; Ahlen, S.P.; Akbari, H.; Alcaraz, J.; Aloisio, A.; Alverson, G.; Linde, F.L.

Published in:
Physics Letters B

DOI:
10.1016/0370-2693(91)91346-W

Search for leptoquarks in Z^0 decays

L3 Collaboration

B. Adeva [a], O. Adriani [b], M. Aguilar-Benitez [c], H. Akbari [d], J. Alcaraz [c], A. Aloisio [e], G. Alverson [f], M.G. Alviggi [e], Q. An [g], H. Anderhub [h], A.L. Anderson [i], V.P. Andreev [j], T. Angelov [i], L. Antonov [k], D. Antreasyan [ℓ], P. Arce [c], A. Arefiev [m], T. Azemoon [n], T. Aziz [o], P.V.K.S. Baba [g], P. Bagnaia [p], J.A. Bakken [q], L. Baksay [r], R.C. Ball [n], S. Banerjee [o], J. Bao [d], L. Barone [p], A. Bay [s], U. Becker [i], J. Behrens [h], S. Beingessner [t], Gy.L. Bencze [u,a], J. Berdugo [c], P. Berges [i], B. Bertucci [p], B.L. Betev [k], A. Biland [h], R. Bizzarri [p], J.J. Blaising [t], P. Blömeke [v], B. Blumenfeld [d], G.J. Bobbink [w], M. Bocciolini [b], R. Bock [v], A. Böhm [v,a], B. Borgia [p], D. Bourilkov [k], M. Bourquin [s], D. Boutigny [t], B. Bouwens [w], J.G. Branson [x], I.C. Brock [y], F. Bruyant [a], C. Buisson [z], A. Bujak [aa], J.D. Burger [i], J.P. Burq [z], J. Busenitz [r], X.D. Cai [g], M. Capell [ab], F. Carbonara [e], P. Cardenal [a], F. Carminati [b], A.M. Cartacci [b], M. Cerrada [c], F. Cesaroni [p], Y.H. Chang [i], U.K. Chaturvedi [g], M. Chemarin [z], A. Chen [ac], C. Chen [ad], G.M. Chen [ad], H.F. Chen [ae], H.S. Chen [ad], M. Chen [i], M.L. Chen [n], W.Y. Chen [g], G. Chiefari [e], C.Y. Chien [d], F. Chollet [t], C. Civinini [b], I. Clare [i], R. Clare [i], H.O. Cohn [af], G. Coignet [t], N. Colino [a], V. Commichau [v], G. Conforto [b], A. Contin [a], F. Crijns [w], X.Y. Cui [g], T.S. Dai [i], R. D'Alessandro [b], R. de Asmundis [e], A. Degré [a,t], K. Deiters [i], E. Dénes [u,a], P. Denes [q], F. DeNotaristefani [p], M. Dhina [h], D. DiBitonto [r], M. Diemoz [p], F. Diez-Hedo [a], H.R. Dimitrov [k], C. Dionisi [p], R. Divià [a], M.T. Dova [g], E. Drago [e], T. Driever [w], D. Duchesneau [s], P. Duinker [w], I. Duran [c], H. El Mamouni [z], A. Engler [y], F.J. Eppling [i], F.C. Erné [w], P. Extermann [s], R. Fabbretti [ag], G. Faber [h], M. Fabre [h], S. Falciano [p], Q. Fan [g], S.J. Fan [ah], O. Fackler [ab], J. Fay [z], J. Fehlmann [h], T. Ferguson [y], G. Fernandez [c], F. Ferroni [p,a], H. Fesefeldt [v], J. Field [s], F. Filthaut [w], G. Finocchiaro [p], P.H. Fisher [d], G. Forconi [s], T. Foreman [w], K. Freudenreich [h], W. Friebel [ai], M. Fukushima [i], M. Gailloud [aj], Yu. Galaktionov [m], E. Gallo [b], S.N. Ganguli [o], P. Garcia-Abia [c], S.S. Gau [ac], D. Gele [z], S. Gentile [p], M. Glaubman [f], S. Goldfarb [n], Z.F. Gong [ae], E. Gonzalez [c], A. Gordeev [m], P. Göttlicher [v], D. Goujon [s], G. Gratta [ak], C. Grinnell [i], M. Gruenewald [ak], M. Guanziroli [g], J.K. Guo [ah], A. Gurtu [o], H.R. Gustafson [n], L.J. Gutay [aa], H. Haan [v], A. Hasan [g], D. Hauschildt [w], C.F. He [ah], T. Hebbeker [v], M. Hebert [x], G. Herten [i], U. Herten [v], A. Hervé [a], K. Hilgers [v], H. Hofer [h], H. Hoorani [g], L.S. Hsu [ac], G. Hu [g], G.Q. Hu [ah], B. Ille [z], M.M. Ilyas [g], V. Innocente [e,a], E. Isiksal [h], H. Janssen [a], B.N. Jin [ad], L.W. Jones [n], A. Kasser [aj], R.A. Khan [g], Yu. Kamyshkov [m,af], Y. Karyotakis [t,a], M. Kaur [g], S. Khokhar [g], V. Khoze [j], M.N. Kienzle-Focacci [s], W. Kinnison [aℓ], D. Kirkby [ak], W. Kittel [w], A. Klimentov [m], A.C. König [w], O. Kornadt [v], V. Koutsenko [m,i], R.W. Kraemer [y], T. Kramer [i], V.R. Krastev [k], W. Krenz [v], J. Krizmanic [d], K.S. Kumar [am], V. Kumar [g], A. Kunin [m], V. Lalieu [s], G. Landi [b], K. Lanius [a], D. Lanske [v], S. Lanzano [e], P. Lebrun [z], P. Lecomte [h], P. Lecoq [a], P. Le Coultre [h], D. Lee [aℓ], I. Leedom [f], J.M. Le Goff [a], L. Leistam [a], R. Leiste [ai], M. Lenti [b], E. Leonardi [p], J. Lettry [h], P.M. Levchenko [j], X. Leytens [w], C. Li [ae,g], H.T. Li [ad], J.F. Li [g], L. Li [h], P.J. Li [ah], Q. Li [g], X.G. Li [ad], J.Y. Liao [ah], Z.Y. Lin [ae], F.L. Linde [y], B. Lindemann [v], D. Linnhofer [h], R. Liu [g], Y. Liu [g], W. Lohmann [ai], E. Longo [p], Y.S. Lu [ad], J.M. Lubbers [a], K. Lübelsmeyer [v], C. Luci [a], D. Luckey [ℓ,i], L. Ludovici [p], X. Lue [h], L. Luminari [p], W.G. Ma [ae], M. MacDermott [h], R. Magahiz [an], M. Maire [t], P.K. Malhotra [o], R. Malik [g], A. Malinin [m], C. Maña [c], D.N. Mao [n],

0370-2693/91/$ 03.50 © 1991 – Elsevier Science Publishers B.V. (North-Holland)

Y.F. Mao [ad], M. Maolinbay [h], P. Marchesini [h], A. Marchionni [b], B. Martin [a], J.P. Martin [z], L. Martinez-Laso [a], F. Marzano [p], G.G.G. Massaro [w], T. Matsuda [i], K. Mazumdar [o], P. McBride [am], T. McMahon [aa], D. McNally [h], Th. Meinholz [v], M. Merk [w], L. Merola [e], M. Meschini [b], W.J. Metzger [w], Y. Mi [g], G.B. Mills [aℓ], Y. Mir [g], G. Mirabelli [p], J. Mnich [v], M. Möller [v], B. Monteleoni [b], G. Morand [s], R. Morand [t], S. Morganti [p], N.E. Moulai [g], R. Mount [ak], S. Müller [v], E. Nagy [u], M. Napolitano [e], H. Newman [ak], C. Neyer [h], M.A. Niaz [g], L. Niessen [v], H. Nowak [ai], D. Pandoulas [v], F. Plasil [af], G. Passaleva [b], G. Paternoster [e], S. Patricelli [e], Y.J. Pei [v], D. Perret-Gallix [t], J. Perrier [s], A. Pevsner [d], M. Pieri [b], P.A. Piroué [q], V. Plyaskin [m], M. Pohl [h], V. Pojidaev [m], N. Produit [s], J.M. Qian [n], K.N. Qureshi [g], R. Raghavan [o], G. Rahal-Callot [h], P. Razis [r], K. Read [af], D. Ren [h], Z. Ren [g], S. Reucroft [f], A. Ricker [v], S. Riemann [ai], O. Rind [n], C. Rippich [y], H.A. Rizvi [g], B.P. Roe [n], M. Röhner [v], S. Röhner [v], U. Roeser [h], L. Romero [c], J. Rose [v], S. Rosier-Lees [t], R. Rosmalen [w], Ph. Rosselet [aj], A. Rubbia [i], J.A. Rubio [a,c], M. Rubio [a], W. Ruckstuhl [s], H. Rykaczewski [h], M. Sachwitz [ai,a], J. Salicio [a,c], J.M. Salicio [c], G. Sanders [aℓ], M.S. Sarakinos [i], G. Sartorelli [ℓ,g], G. Sauvage [t], A. Savin [m], V. Schegelsky [j], K. Schmiemann [v], D. Schmitz [v], P. Schmitz [v], M. Schneegans [t], H. Schopper [ao], D.J. Schotanus [w], S. Shotkin [i], H.J. Schreiber [ai], R. Schulte [v], S. Schulte [v], K. Schultze [v], J. Schütte [am], J. Schwenke [v], G. Schwering [v], C. Sciacca [e], I. Scott [am], R. Sehgal [g], P.G. Seiler [ag], J.C. Sens [w], I. Sheer [x], D.Z. Shen [ah], V. Shevchenko [m], S. Shevchenko [m], X.R. Shi [y], K. Shmakov [m], V. Shoutko [m], E. Shumilov [m], N. Smirnov [j], E. Soderstrom [q], A. Sopczak [x], C. Spartiotis [d], T. Spickermann [v], B. Spiess [h], P. Spillantini [b], R. Starosta [v], M. Steuer [ℓ,i], D.P. Stickland [q], F. Sticozzi [i], W. Stoeffl [ab], H. Stone [s], K. Strauch [am], B.C. Stringfellow [aa], K. Sudhakar [o,v], G. Sultanov [g], R.L. Sumner [q], L.Z. Sun [ae,g], H. Suter [h], R.B. Sutton [y], J.D. Swain [g], A.A. Syed [g], X.W. Tang [ad], E. Tarkovsky [m], L. Taylor [f], C. Timmermans [w], Samuel C.C. Ting [i], S.M. Ting [i], Y.P. Tong [ac], F. Tonisch [ai], M. Tonutti [v], S.C. Tonwar [o], J. Tóth [u,a], G. Trowitzsch [ai], C. Tully [ak], K.L. Tung [ad], J. Ulbricht [h], L. Urbán [u], U. Uwer [v], E. Valente [p], R.T. Van de Walle [w], I. Vetlitsky [m], G. Viertel [h], P. Vikas [g], U. Vikas [g], M. Vivargent [t,i], H. Vogel [y], H. Vogt [ai], G. Von Dardel [a], I. Vorobiev [m], A.A. Vorobyov [j], An.A. Vorobyov [j], L. Vuilleumier [aj], M. Wadhwa [g], W. Wallraff [v], C.R. Wang [ae], G.H. Wang [y], J.H. Wang [ad], Q.F. Wang [am], X.L. Wang [ae], Y.F. Wang [b], Z. Wang [g], Z.M. Wang [g,ae], A. Weber [v], J. Weber [h], R. Weill [aj], T.J. Wenaus [ab], J. Wenninger [s], M. White [i], C. Willmott [c], F. Wittgenstein [a], D. Wright [q], R.J. Wu [ad], S.L. Wu [g], S.X. Wu [g], Y.G. Wu [ad], B. Wysłouch [i], Y.Y. Xie [ah], Y.D. Xu [ad], Z.Z. Xu [ae], Z.L. Xue [ah], D.S. Yan [ah], X.J. Yan [i], B.Z. Yang [ae], C.G. Yang [ad], G. Yang [g], K.S. Yang [ad], Q.Y. Yang [ad], Z.Q. Yang [ah], C.H. Ye [g], J.B. Ye [h,ae], Q. Ye [g], S.C. Yeh [ac], Z.W. Yin [ah], J.M. You [g], M. Yzerman [w], C. Zaccardelli [ak], L. Zehnder [h], P. Zemp [h], M. Zeng [g], Y. Zeng [v], D.H. Zhang [w], Z.P. Zhang [ae,g], J.F. Zhou [v], R.Y. Zhu [ak], H.L. Zhuang [ad] and A. Zichichi [a,g]

[a] *European Laboratory for Particle Physics, CERN, CH- 1211 Geneva 23, Switzerland*
[b] *INFN – Sezione di Firenze and University of Firenze, I-50125 Florence, Italy*
[c] *Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, CIEMAT, E-28040 Madrid, Spain*
[d] *Johns Hopkins University, Baltimore, MD 21218, USA*
[e] *INFN – Sezione di Napoli and University of Naples, I-80125 Naples, Italy*
[f] *Northeastern University, Boston, MA 02115, USA*
[g] *World Laboratory, FBLJA Project, CH-1211 Geneva, Switzerland*
[h] *Eidgenössische Technische Hochschule, ETH Zürich, CH-8093 Zurich, Switzerland*
[i] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[j] *Leningrad Nuclear Physics Institute, SU-188 350 Gatchina, USSR*
[k] *Central Laboratory of Automation and Instrumentation, CLANP, Sofia, Bulgaria*
[ℓ] *INFN – Sezione di Bologna, I-40126 Bologna, Italy*
[m] *Institute of Theoretical and Experimental Physics, ITEP, SU-117 259 Moscow, USSR*
[n] *University of Michigan, Ann Arbor, MI 48109, USA*

[o] Tata Institute of Fundamental Research, Bombay 400 005, India
[p] INFN - Sezione di Roma and University of Rome "La Sapienza", I-00185 Rome, Italy
[q] Princeton University, Princeton, NJ 08544, USA
[r] University of Alabama, Tuscaloosa, AL 35486, USA
[s] University of Geneva, CH-1211 Geneva 4, Switzerland
[t] Laboratoire de Physique des Particules, LAPP, F-74519 Annecy-le-Vieux, France
[u] Central Research Institute for Physics of the Hungarian Academy of Sciences, H-1525 Budapest 114, Hungary
[v] I. Physikalisches Institut, RWTH, W-5100 Aachen, FRG [1]
and III. Physikalisches Institut, RWTH, W-5100 Aachen, FRG [1]
[w] National Institute for High Energy Physics, NIKHEF, NL-1009 DB Amsterdam, The Netherlands
and NIKHEF-H and University of Nijmegen, NL-6525 ED Nijmegen, The Netherlands
[x] University of California, San Diego, CA 92182, USA
[y] Carnegie Mellon University, Pittsburgh, PA 15213, USA
[z] Institut de Physique Nucléaire de Lyon, IN2P3-CNRS/Université Claude Bernard, F-69622 Villeurbanne Cedex, France
[aa] Purdue University, West Lafayette, IN 47907, USA
[ab] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[ac] High Energy Physics Group, Taiwan, ROC
[ad] Institute of High Energy Physics, IHEP, Beijing, China
[ae] University of Science and Technology of China, Hefei, Anhui 230 029, China
[af] Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA
[ag] Paul Scherrer Institut (PSI), Würenlingen, Switzerland
[ah] Shanghai Institute of Ceramics, SIC, Shanghai, China
[ai] High Energy Physics Institute, O-1615 Zeuthen-Berlin, FRG [1]
[aj] University of Lausanne, CH-1015 Lausanne, Switzerland
[ak] California Institute of Technology, Pasadena, CA 91125, USA
[al] Los Alamos National Laboratory, Los Alamos, NM 87544, USA
[am] Harvard University, Cambridge, MA 02139, USA
[an] Union College, Schenectady, NY 12308, USA
[ao] University of Hamburg, W-2000 Hamburg, FRG

Received 5 March 1991

We have searched for direct leptoquark production in Z^0 decays from a scan of the Z^0 resonance, in the energy range $88.2 \leqslant \sqrt{s} \leqslant 94.2$ GeV, using 5.2 pb^{-1} of data. We exclude the existence of scalar leptoquarks with masses less than 41 to 44 GeV, depending on the charge assignments, at the 95% confidence level.

1. Introduction

Leptoquarks are proposed in theories beyond the standard model, such as GUTs, composite models, technicolor and superstring models [1]. Leptoquarks are color triplets under $SU(3)_c$ which couple to quark–lepton pairs. In some models their mass can be substantially smaller than the grand unification mass [2]. The electrical charge, the spin, and the weak isospin of the leptoquarks are model dependent, which makes the production cross section dependent on specific assumptions.

In the present search, we estimate the expected rate of scalar leptoquarks produced in e^+e^- collisions near the Z^0 resonance according to the pair production formula given in refs. [3,4]

$$\frac{d\sigma}{d\cos\theta} = \frac{3\pi\alpha^2}{8s}\beta^3(1-\cos^2\theta)\sum_{j=L,R}|C_j|^2 ,$$

where $\beta=\sqrt{1-(4M_D^2/s)}$ is the velocity of the leptoquark, M_D is the mass of the leptoquark generically called D in this paper, s is the square of the center of mass energy, and C_j contains the propagators and the known couplings for a given leptoquark charge Q_D. At $\sqrt{s}=M_Z$, the Born cross section reduces to $\sigma\approx 0.14\beta^3$ nb for a leptoquark with $Q_D=-\frac{1}{3}$. We neglect the γ, and possible $Z^{0\prime}$ contributions for E(6) type leptoquarks in the s-channel, since these are rel-

[1] Supported by the German Bundesministerium für Forschung und Technologie.

atively small in the region of the Z^0 resonance. More elaborate calculations, including a t-channel Yukawa type interaction in addition to the s-channel gauge boson exchanges, are given in refs. [3,4]. We also ignore the small t-channel contribution in the calculation of the cross section.

In this analysis we assume three types of leptoquarks, one for each generation, with an electric charge of $Q_D = -\frac{1}{3}$ or $\frac{2}{3}$ [5,6]. They decay into a quark and a lepton belonging to the particular family type. We report on a search for events containing two jets and two isolated leptons. The best leptoquark mass limit which has been published to date is given by the AMY collaboration: $M_D > 22.6$ GeV at the 95% confidence level [7].

The data used in this analysis were collected during the 1990 LEP running period. A total integrated luminosity of 5.2 pb^{-1} corresponding to approximately 110000 hadronic and 9500 leptonic Z^0 decays has been recorded.

2. The L3 detector

The L3 detector covers 99% of 4π [8]. It consists of a central tracking chamber, a high resolution electromagnetic calorimeter composed of bismuth germanium oxide (BGO) crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and an accurate muon chamber system. These detectors are located in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. Forward BGO arrays, on either side of the detector, measure the luminosity by detecting small-angle Bhabha events.

For the present analysis, we retain data collected in the following ranges of polar angles where the trigger efficiency is close to 100%:
- Central tracking chamber: $40° \leqslant \theta \leqslant 140°$.
- Electromagnetic calorimeter: $42° \leqslant \theta \leqslant 138°$.
- Hadron calorimeter: $5° \leqslant \theta \leqslant 175°$.
- Muon chambers: $36° \leqslant \theta \leqslant 144°$.

The response of the L3 detector has been modeled with the GEANT3 [9] detector simulation program which includes the effects of energy loss, multiple scattering and showering in the detector materials and the beam pipe. Hadronic showers in the calorimeters are simulated with the GHEISHA [10] program.

3. Direct search for leptoquarks

We search for leptoquarks in the following event samples:

$$e^+e^- \to e^+e^-X\,,\ \mu^+\mu^-X\,,\ \tau^+\tau^-X\,,\ \nu\bar{\nu}X\,.$$

The signature of a leptoquark event is two leptons and two jets. In order to determine the acceptance for leptoquark events, we have written a Monte Carlo generator program and generated events in the mass range 20–45 GeV. The generator assumes a $\sin^2\theta$ angular dependence [3] and accounts for initial-state radiation. The fragmentation is done according to the JETSET 7.2 [11] prescription, where the b-quark fragmentation function is adjusted to match our measured inclusive muon data [12]. Generated events are passed through the detector simulation program and are reconstructed in the same way as the data.

The most important contribution to the background is due to hadronic events; it is computed with the JETSET 7.2 Monte Carlo program. For the estimate of the background from the reactions $e^+e^- \to \mu^+\mu^-(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$, we use the KORALZ Monte Carlo program [13], while the $e^+e^- \to e^+e^-(\gamma)$ background is determined with the BABAMC Monte Carlo program [14].

All Monte Carlo background events are input to the detector simulation program and reconstructed by the same program that is used to reconstruct the data.

3.1. e^+e^-X data sample

The following criteria are used to select the leptoquark candidate events in the electron sample:
- Two electron candidates each with a minimum energy of 2 GeV must be observed in the BGO calorimeter. The sum of their energies must be greater than 20 GeV. At least one of them is required to have an associated track in the central tracking chamber.
- The electrons must satisfy the following isolation requirement:

$$E^{(1)}_{\rm cone}/E^{(1)}_{\rm e} + E^{(2)}_{\rm cone}/E^{(2)}_{\rm e} < 0.2\,,$$

where $E^{(i)}_{\rm e}$ is the energy of electron i, and $E^{(i)}_{\rm cone}$ is the

energy contained in a cone of 30° around the electron (excluding $E_e^{(i)}$).
- The number of clusters (constructed by grouping together neighbouring calorimeter hits which are likely to be produced by the same particle) in the calorimeters must be greater than 9, and the visible energy must satisfy $0.5 < E_{vis}/\sqrt{s} < 1.5$.

The cluster requirement is used to remove Bhabha events from the data sample. Hadronic background is removed with the isolation cut.

The above selection criteria yield an acceptance of $(36 \pm 2)\%$ for leptoquark events near the kinematic limit, where the acceptance directly influences the mass limit. We observe no events in the data or in the background Monte Carlo sample after applying these cuts.

3.2. $\mu^+\mu^-X$ data sample

We use the following requirements to select leptoquark candidate events in the muon sample:
- The event is required to have two tracks in the muon chambers inside the fiducial volume $|\cos\theta| < 0.8$, which satisfy the following requirements:

(i) At least one track must be associated with a scintillator that has fired within 3 ns of the bunch crossing, after a correction for the time of flight has been applied.

(ii) Both muons must have a momentum greater than 4 GeV and at least one must have a momentum of less than 40 GeV. In addition, the sum of the two momenta must be greater than 15 GeV.

(iii) The distance of closest approach to the interaction point in the transverse and longitudinal planes must be less than 100 mm for both muons.
- Each of the muons is required to be isolated; a muon is considered to be isolated if less than 7 GeV has been deposited in the calorimeter in a cone of 15° around the muon track.
- The number of clusters in the calorimeters must be greater than 15, and the visible energy must satisfy: $0.5 < E_{vis}/\sqrt{s} < 1.5$.

The vertex and minimum momentum requirements are used to reject calorimeter punch-through. The number of clusters and maximum momentum cuts remove $e^+e^- \to \mu^+\mu^-(\gamma)$ events from the data sample. Hadronic background events are removed with the isolation cut.

Near the kinematic limit, these selection criteria give an acceptance of $(47 \pm 2)\%$ for leptoquark events. No events are observed in the data or in the Monte Carlo background sample after applying the above requirements.

3.3. $\tau^+\tau^-X$ data sample

The following criteria are used to select leptoquark candidates in the tau sample:
- The event is required to have exactly four jets, each with energy greater than 7 GeV, where an isolated muon or electron is considered to be a single jet.
- The event is required to contain at least one isolated electron or muon with an energy greater than 10 GeV. The lepton is considered to be isolated if less than an additional 2% of the lepton's energy is observed in a cone of 30° around it.
- The number of clusters is required to be greater than 9 and less than 50, and the total visible energy of the event has to be greater than 40 and less than 75 GeV.

Background from $e^+e^-(\gamma)$ and $\mu^+\mu^-(\gamma)$ events is removed with the requirement on the minimum number of clusters. The four-jet requirement removes the $\tau^+\tau^-$ background. All cuts are required to remove hadronic background from the sample.

We obtain an acceptance of $(3.0 \pm 0.5)\%$ for leptoquark events. This low value is due to the stringent requirement of an isolated lepton. No events survive the above requirements in the data or in the background Monte Carlo samples.

3.4. $\nu\bar{\nu}X$ data sample

We use the following requirements to select leptoquark candidate events in the neutrino sample:
- The event must contain exactly two jets, one of which must have an energy greater than 7 GeV. The angle between the most energetic jet and the beam axis must be greater than 20°, and the angle between the two jets must be less than 140°.
- At least four charged tracks, with a transverse momentum greater than 50 MeV, must be observed in the central tracking chamber.
- We find the minimum opening angle cone which contains all of the calorimetric energy, allowing at most 1 GeV outside of it. The projection of all the

calorimetric clusters onto the axis of the cone is then required to be greater than $0.4E_{\rm vis}$.
- The total energy of the event must be less than 75 GeV, the longitudinal energy imbalance less than $0.8E_{\rm vis}$, and the perpendicular energy imbalance must be greater than 15 GeV.

The first two cuts remove cosmic ray and beam-gas events from the data sample. Residual background from hadronic and $\tau^+\tau^-(\gamma)$ events is removed with the last two cuts.

Near the kinematic limit, these selection criteria give an acceptance of $(56\pm2)\%$ for leptoquark events. No events are observed in the data sample, and only one $e^+e^-\to\tau^+\tau^-(\gamma)$ Monte Carlo background event survives the above requirements.

4. Results

Applying the selection criteria described in the last section to the data samples, we find that no events survive. Only one background Monte Carlo event survives in the neutrino selection. We calculate the expected number of $D\bar{D}$ pairs produced as a function of the leptoquark mass taking into account our acceptances, which have been conservatively reduced by one standard deviation. Fig. 1 shows the expected number of events for different channels, assuming the branching fractions shown in table 1. Because of the high mass of the top quark, decays of leptoquarks associated with the third family have only one allowed decay mode for the mass region under study.

In the determination of the rate of $e^+de^-\bar{d}$, $\mu^+s\mu^-\bar{s}$ and $\tau^+b\tau^-\bar{b}$ events, we have assumed the same isospin ($I_3=0$) for the $Q_D=\frac{2}{3}$ as for the $Q_D=-\frac{1}{3}$ leptoquarks, hence, the production cross section of the $Q_D=\frac{2}{3}$ leptoquarks is a factor of 4 larger. We can directly determine a lower mass limit for pair-produced third-family leptoquarks with $Q_D=\frac{2}{3}$ from fig. 1; we obtain a limit of 41.6 GeV at the 95% confidence level.

In fig. 2 we show the excluded leptoquark region as a function of the mass and of the $D\to\ell q$ and $D\to\nu_\ell q$ branching ratios for $Q_D=-\frac{1}{3}$. By combining results from the complementary decay modes, within the same generation, we obtain the combined leptoquark mass limits at the 95% confidence level, also shown in fig. 2. The branching-ratio independent mass limit is then given by the minimum of the combined limit and is presented in table 2. We obtain a conservative lower mass limit of 43 GeV for the first and second generation leptoquarks. Expected production rates for $Q_D=\frac{2}{3}$ leptoquarks are higher than for $Q_D=-\frac{1}{3}$ lep-

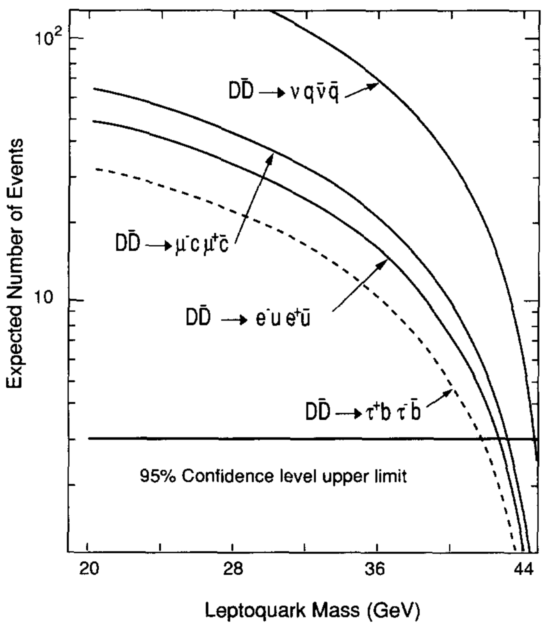

Fig. 1. Expected number of leptoquark pair events as a function of the leptoquark mass taking into account the branching ratios given in table 1 and our acceptances in table 2. The solid lines correspond to a leptoquark charge of $-\frac{1}{3}$ and the dashed line to a leptoquark charge of $\frac{2}{3}$. Our 95% confidence level upper limit on the number of events is also shown.

Table 1
Branching fractions for various leptoquark decay modes used to calculate the expected event rates in fig. 1, allowing leptoquarks to decay into right-handed and left-handed leptons and quarks (e.g. for the first generation: $D\to e_R u_R$, $e_L u_L$, $\nu_L d_L$) at equal rate; only one decay mode is allowed for the third family in the present mass range.

Decay channel	Q_D	Branching ratio
$D\to\nu_e d$	$-\frac{1}{3}$	$\frac{1}{3}$
$D\to e^-u$	$-\frac{1}{3}$	$\frac{2}{3}$
$D\to\nu_\mu s$	$-\frac{1}{3}$	$\frac{1}{3}$
$D\to\mu^-c$	$-\frac{1}{3}$	$\frac{2}{3}$
$D\to\nu_\tau b$	$-\frac{1}{3}$	1
$D\to\tau^+b$	$+\frac{2}{3}$	1

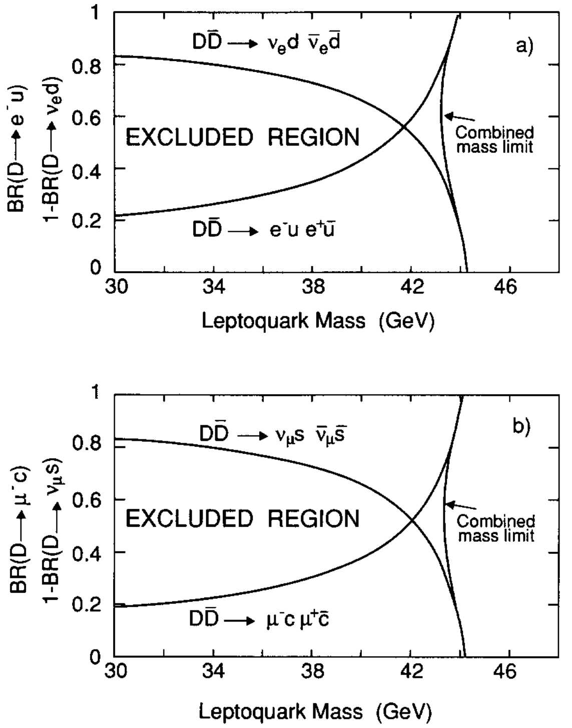

Fig. 2. The excluded region at the 95% confidence level in terms of the mass and branching ratios, BR, for the decay modes of the leptoquarks belonging to the (a) electron and (b) muon family ($Q_D = -\frac{1}{3}$). The mass limit found by combining the two decay modes is also shown.

Table 2
Experimental acceptances near the kinematic limit of 45 GeV and the 95% confidence level lower mass limits for pair-produced leptoquarks. The mass limits are branching ratio independent.

Channel	Q_D	Acceptance near the kinematic limit [%]	Leptoquark mass limit [GeV]
$D\bar{D} \to e^- u e^+ \bar{u}$	$-\frac{1}{3}$	36 ± 2	
$D\bar{D} \to \nu_e d \bar{\nu}_e \bar{d}$	$-\frac{1}{3}$	56 ± 2	43.2
$D\bar{D} \to \mu^- c \mu^+ \bar{c}$	$-\frac{1}{3}$	47 ± 2	
$D\bar{D} \to \nu_\mu s \bar{\nu}_\mu \bar{s}$	$-\frac{1}{3}$	56 ± 2	43.4
$D\bar{D} \to e^+ d e^- \bar{d}$	$+\frac{2}{3}$	36 ± 2	
$D\bar{D} \to \bar{\nu}_e u \nu_e \bar{u}$	$+\frac{2}{3}$	56 ± 2	44.6
$D\bar{D} \to \mu^+ s \mu^- \bar{s}$	$+\frac{2}{3}$	47 ± 2	
$D\bar{D} \to \bar{\nu}_\mu c \nu_\mu \bar{c}$	$+\frac{2}{3}$	56 ± 2	47.7
$D\bar{D} \to \tau^+ b \tau^- \bar{b}$	$+\frac{2}{3}$	3.0 ± 0.5	41.6

toquarks, and therefore the mass limits are also slightly higher.

In e^+e^- collisions it is possible to produce single leptoquarks either in Z^0 decays [5] or via the reaction $e\gamma \to D\bar{u}$ [2]. If the coupling is assumed to be the same as the electroweak coupling, the production cross sections are low and the number of expected events is marginal in the accessible mass region given our integrated luminosity. We determine our acceptance for such events by applying the same cuts as for the pair-produced leptoquarks to Monte Carlo samples of isotropically produced leptoquarks with masses of 50 to 70 GeV. We obtain acceptances for the e^+e^-X, $\mu^+\mu^-X$ and $\nu\bar{\nu}X$ channels between 33% and 50%, depending on the specific decay mode. No leptoquark candidates are found in this search. This yields upper limits on the products of the branching ratio times the cross section of 2.7, 2.5 and 1.6 pb for the three channels respectively at the 95% confidence level.

5. Conclusions

We have searched for direct leptoquark production in Z^0 decays from a scan of the Z^0 resonance in the energy range $88.2 \leqslant \sqrt{s} \leqslant 94.2$ GeV with 5.2 pb^{-1} of data. We exclude the existence of pair-produced scalar leptoquarks with masses less than 41–44 GeV, depending on the charge assignments, at the 95% confidence level.

Acknowledgement

We wish to express our gratitude to the CERN accelerator divisions for the excellent performance of the LEP machine. We acknowledge the effort of all engineers and technicians who have participated in the construction and maintenance of this experiment. We are grateful to P. Zerwas for useful discussions.

References

[1] J. Pati and A. Salam, Phys. Rev. D 10 (1974) 275;
S. Dimopoulos, Nucl. Phys. B 168 (1980) 69;
C.H. Albright, Phys. Rev. D 29 (1984) 2595;
B. Schrempp and F. Schrempp, Nucl. Phys. B 242 (1984) 203;
V.D. Angelopoulos et al., Nucl. Phys. B 292 (1987) 59.

[2] J.L. Hewett and S. Pakvasa, Phys. Lett. B 227 (1989) 178.

[3] D. Schaile and P.M. Zerwas, CERN report CERN 87-07, Vol. II (CERN, Geneva, 1987) p. 251.

[4] F.M. Renard, Basics of electron positron collisions (Editions Frontières, Dreux, 1981) p. 64;
J.L. Hewett and T.G. Rizzo, Phys. Rev. D 36 (1987) 3367, and references therein.

[5] N.D. Tracas and S.D.P. Vlassopoulos, Phys. Lett. B 220 (1989) 285.

[6] B. Schrempp and F. Schrempp, Phys. Lett. B 153 (1985) 101.

[7] AMY Collab., G.N. Kim et al., Phys. Lett. B 240 (1990) 243.

[8] L3 Collab., B. Adeva et al., Nucl. Instrum. Methods A 289 (1990) 35.

[9] R. Brun et al., GEANT3 User's Guide, CERN report CERN/DD/EE/1987.

[10] H. Fesefeldt, RWTH Aachen, report PITHA 85/02.

[11] T. Sjöstrand and M. Bengtsson, The Lund Monte Carlo programs JETSET 7.2, CERN report CERN/DD 1 (November 1989).

[12] L3 Collab., B. Adeva et al., Phys. Lett. B 241 (1990) 416.

[13] S. Jadach et al., KORALZ, Proc. Workshop on Z physics at LEP, eds. G. Altarelli, R. Kleiss and C. Verzegnassi, CERN report 89-08, Vol. III (CERN, Geneva, 1989) p. 69.

[14] R. Kleiss, F.A. Berends and W. Hollik, BABAMC, Proc. Workshop on Z physics at LEP, eds. G. Altarelli, R. Kleiss and C. Verzegnassi, CERN report 89-08, Vol. III (CERN, Geneva, 1989) p. 1.