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Search for Leptoquarks and FCNC in e^+e^- annihilations at $\sqrt{s} = 183$ GeV

DELPHI Collaboration

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Abstract

A search for events with one jet and at most one isolated lepton used data taken at LEP-2 by the DELPHI detector. These data were accumulated at a center-of-mass energy of 183 GeV and correspond to an integrated luminosity of 47.7 pb^{-1}. Production of single scalar and vector leptoquarks was searched for. Limits at 95% confidence level were derived on the masses (ranging from 134 GeV/c^2 to 171 GeV/c^2 for electromagnetic type couplings) and couplings of the leptoquark states. A search for top-charm flavour changing neutral currents ($e^+e^- \to \bar{t}c$ or charge conjugate) used the semileptonic decay channel. A limit on the flavour changing cross-section via neutral currents was set at 0.55pb (95% confidence level).

1. Introduction

In e^+e^- colliders such as LEP searches for new physics can be made with high sensitivity in places where the expected Standard Model (SM) contributions are small. Events where all or most particles are grouped in one direction in space, in a mono-jet type topology, with one isolated lepton (charged or neutral), are a good example of such processes. SM extensions related to leptoquark models or single top production via Flavour Changing Neutral Currents can have such a signature. In this paper we report on a topological search for events in these two channels.

Leptoquarks are coloured spin 0 or spin 1 particles with both baryon and lepton quantum numbers. These particles are predicted by a variety of extensions of the SM, including Grand Unified Theories [1], Technicolor [2] and composite models [3]. They have electric charges of $\pm 5/3$, $\pm 4/3$, $\pm 2/3$ and $\pm 1/3$, and decay into a charged or neutral lepton and a quark, $L_q \to l^{\pm} q$ or $L_q \to \nu q$. Two hypotheses are considered in this paper, one where only the charged decay mode is possible (charged branching ratio $B = 1.0$), and one, for leptoquark charges below 4/3, where both charged and neutral decay modes are equally probable. If the leptoquark does not couple to the charged decay mode ($B = 0$) then these leptoquarks can not be produced singly in e^+e^- collisions. Leptoquarks may be produced singly or in pairs at e^+e^- colliders. For single production, leptoquark mass limits can be set up to almost the kinematical limit. For this reason only single leptoquark production is considered in this analysis. The largest contribution to the production cross-section at LEP is predicted to come from processes involving hadrons coming from resolved photons [4], radiated from the incoming beams, which are treated using the Weizacker-Williams approximation. The corresponding Feynman diagram is shown in Fig. 1 a. Decays of singly produced high mass leptoquarks to a charged lepton are characterised by a high transverse momentum jet recoiling against a lepton. In the decay to a neutrino only the jet is detected. The initial electron which scatters off the quasi real photon is assumed to escape detection down the beam pipe. Below the TeV mass range and for couplings of the order of the electromagnetic coupling, the leptoquarks should not couple to diquarks in order to prevent proton decay. They should also couple chirally to either left or right handed quarks but not to both, and mainly diagonally. This implies that they should couple to a single leptonic generation and to a single quark generation and hence this measurement searches only for decays to e and ν.

The properties of leptoquarks are indirectly constrained by experiments at lower energy [5], by precision measurements of the Z width [6], and by direct searches at higher energies [7–10]. The mass of scalar leptoquarks decaying to electron plus jet was constrained to be above 225 GeV/c^2 using Tevatron data [7]. Limits on leptoquark masses and couplings were set at HERA using the e^-p data [8], giving $M_{Lq} > 216$–275 GeV/c^2. An excess of events was found in the e^+p data. The H1 collaboration measured a jet-lepton invariant mass of these events ranging from 187.5 GeV/c^2 up to 212.5 GeV/c^2. Rare processes, which are forbidden in the SM, also

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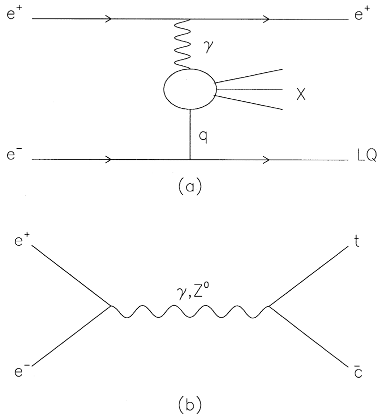

Fig. 1. (a) The resolved photon contribution for single leptoquark production and (b) single top production via FCNC in e^+e^- collisions.

provide strong bounds on the λ/m_{Lq} ratio [11], where λ is the leptoquark-fermion Yukawa type coupling and m_{Lq} is the leptoquark mass.

In the SM, Flavour Changing Neutral Currents (FCNC) are absent at tree level. Neutral currents such as $e^+e^- \to t\bar{c}(t\bar{u})$ can be present at the one loop level, but the rates are severely supressed [12].

Flavour changing vertices are present in many extensions of the SM like supersymmetry [13], multi-Higgs doublet models [14] and anomalous t-quark production [15], which could enhance the production of top quarks. For instance, in the SM the $t \to cZ$ branching ratio is around 10^{-13} while in the context of a two Higgs doublet model without natural flavour conservation the rates can be higher by more than six orders of magnitude [14], depending on the chosen parameters. At tree level, single top production is possible via FCNC anomalous couplings ($e^+e^- \to t\bar{c}$) [15]. The corresponding Feynman diagram is shown in Fig. 1 (b). The $t \to cZ$ and $t \to c\gamma$ vertices are described by two anomalous coupling constants k_Z and k_γ respectively. Present constraints from LEP–2 data were set [15] at ($m_t = 175\,\mathrm{GeV}/c^2$):

$$k_\gamma^2 < 0.176 , \quad k_Z^2 < 0.533$$

In single top production at LEP, the $t\bar{c}(t\bar{u})$, pair should be produced almost at rest as the top mass is close to the centre-of-mass energy. The top quark decays subsequently to a b quark and a W. Only leptonic decays of the W are searched for in this letter. It is an almost background free signature characterised by one energetic mono-jet and one isolated charged lepton.

2. The DELPHI detector and data samples

A detailed description of the DELPHI detector, its performance, the triggering conditions and the read-out chain can be found in Ref. [16]. This analysis relies on the charged particle detection provided by the tracking system and energy reconstruction provided by the electromagnetic and hadronic calorimeters.

The main tracking detector of DELPHI is the Time Projection Chamber, which covers the angular range $20° < \theta < 160°$, where θ is the polar angle defined with respect to the beam direction. Other detectors contributing to the track reconstruction are the Vertex Detector (VD), the Inner and Outer Detectors and the Forward Chambers. The VD consists of three cylindrical layers of silicon strip detectors, each layer covering the full azimuthal angle.

Electromagnetic shower reconstruction is performed in DELPHI using the barrel and the forward electromagnetic calorimeters, including the STIC (Small angle TIle Calorimeter), the DELPHI luminosity monitor.

The energy resolutions of the barrel and forward electromagnetic calorimeters are parameterized respectively as $\sigma(E)/E = 0.043 \oplus 0.32/\sqrt{E}$ and $\sigma(E)/E = 0.03 \oplus 0.12/\sqrt{E} \oplus 0.11/E$, where E is expressed in GeV and the symbol '$\oplus$' implies addition in quadrature.

The hadron calorimeter covers both the barrel and forward regions. It has an energy resolution of $\sigma(E)/E = 0.21 \oplus 1.12/\sqrt{E}$ in the barrel.

The effects of experimental resolution, both on the signals and on backgrounds, were studied by generating Monte Carlo events for the possible signals and for the SM processes, and passing them through the full DELPHI simulation and reconstruction chain.

The leptoquark signal was generated for different mass values using the PYTHIA generator [17]. The leptoquark production cross-section was taken from [18].

The $t\bar{c}(\bar{u})$ signal was implemented in the PYTHIA generator [17] by producing a top and c (u) quark pair and allowing the top quark to decay into a b quark and a W boson. A singlet colour string was formed between the b and c(u) quarks.

Bhabha events were simulated with the Berends, Hollik and Kleiss generator [19]. PYTHIA was used to simulate $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to Z\gamma$, $e^+e^- \to W^+W^-$, $e^+e^- \to W^{\pm}e^{\mp}\nu$, $e^+e^- \to ZZ$, and $e^+e^- \to Ze^+e^-$ events. In all four fermion channels, studies with the EXCALIBUR generator [20] were also performed. The two-photon (''$\gamma\gamma$'') physics events were simulated using the TWOGAM [21] generator for quark channels and the Berends, Daverveldt and Kleiss generator [22] for the electron, muon and tau channels.

Data corresponding to an integrated luminosity of 47.7 pb^{-1} were collected at a centre-of-mass energy $\sqrt{s}$ of 183 GeV.

3. Event selection

This analysis looks for events with one energetic mono-jet. Leptoquark decays to a charged lepton and $t\bar{c}$ decays also require an isolated charged lepton. The recoil electron in Fig. 1 (a) is expected to pass undetected down the beam pipe while the products of the recoil (X) in Fig. 1 (a) and the c-quark in Fig. 1 (b) are of low energy and are absorbed into the mono-jet or lepton.

Charged particles were considered only if they had momentum greater than 0.1 GeV/c and impact parameters in the transverse plane and in the beam direction below 4 cm and 10 cm respectively. Neutral clusters were defined as energy depositions in the calorimeters unassociated with charged particle tracks. All electromagnetic (hadronic) neutrals of energy above 100 MeV (1 GeV) were selected. In the present analysis the minimum required charged multiplicity was six.

Charged particles were considered isolated if, in a double cone centred on their track with internal and external half angles of 5° and 25°, the total energy associated to charged and neutral particles was below 1 GeV and 2 GeV respectively. The energy of the particle was redefined as the sum of the energies of all the charged and neutral particles inside the inner cone. This energy was required to be greater than 4 GeV. No other charged particle was allowed inside the inner cone.

Energy clusters in the electromagnetic calorimeters were considered to be from photons if there were no tracks pointing to the cluster, there were no hits inside a 2° cone in more than one layer of the Vertex Detector and if at least 90% of any hadronic energy was deposited in the first layer of the hadron calorimeter. Photons were considered to be isolated if, in a double cone centred on the cluster and having internal and external half angles of 5° and 15°, the total energy deposited was less than 1 GeV. The energy of the photon was redefined as the sum of the energies of all the particles inside the inner cone and no charged particles above 250 MeV/c were allowed inside this cone.

All charged and neutral particles (excluding any isolated charged lepton, if present) were forced into one jet using the Durham jet algorithm [23]. The jet was classified as charged if it contained at least one charged particle.

A detailed description of the basic selection criteria can be found in Ref. [24]. Isolated charged particles were identified as electrons if there were no associated hits in the muon chambers, if the ratio of the energy measured in the electromagnetic calorimeters, E, to the momentum measured in the tracking chambers, p, was larger than 0.2 and if the energy deposited in the electromagnetic calorimeters by the lepton candidate was at least 90% of the total energy deposited in both electromagnetic and hadronic calorimeters.

The following criteria were applied to the events (level 1):

- the total visible energy was required to be larger than $0.2\sqrt{s}$;
- events with isolated photons were rejected;
- the momentum of the monojet was required to be larger than 10 GeV/c;
- in channels with one isolated charged particle its momentum had to be greater than 10 GeV/c; for the leptoquark search exactly one isolated charged particle was required in the event; for the FCNC search at least one charged isolated particle was required.

After this selection, more specific criteria were applied (level 2):

- Events were required to have only one jet with the Durham resolution variable (y_{cut}) [23] in the transition from one to two jets smaller than 0.09.
- The monojet polar angle had to be between 30° (20°) and 150° (160°) for the leptoquark search (for the FCNC search).
- The ratio between the monojet electromagnetic energy and its total energy had to be smaller than 0.9. This removes most Bhabha events.
- The sum of the transverse momentum of the charged particles in the jet (relative to the event thrust axis) normalized to the total visible mo-

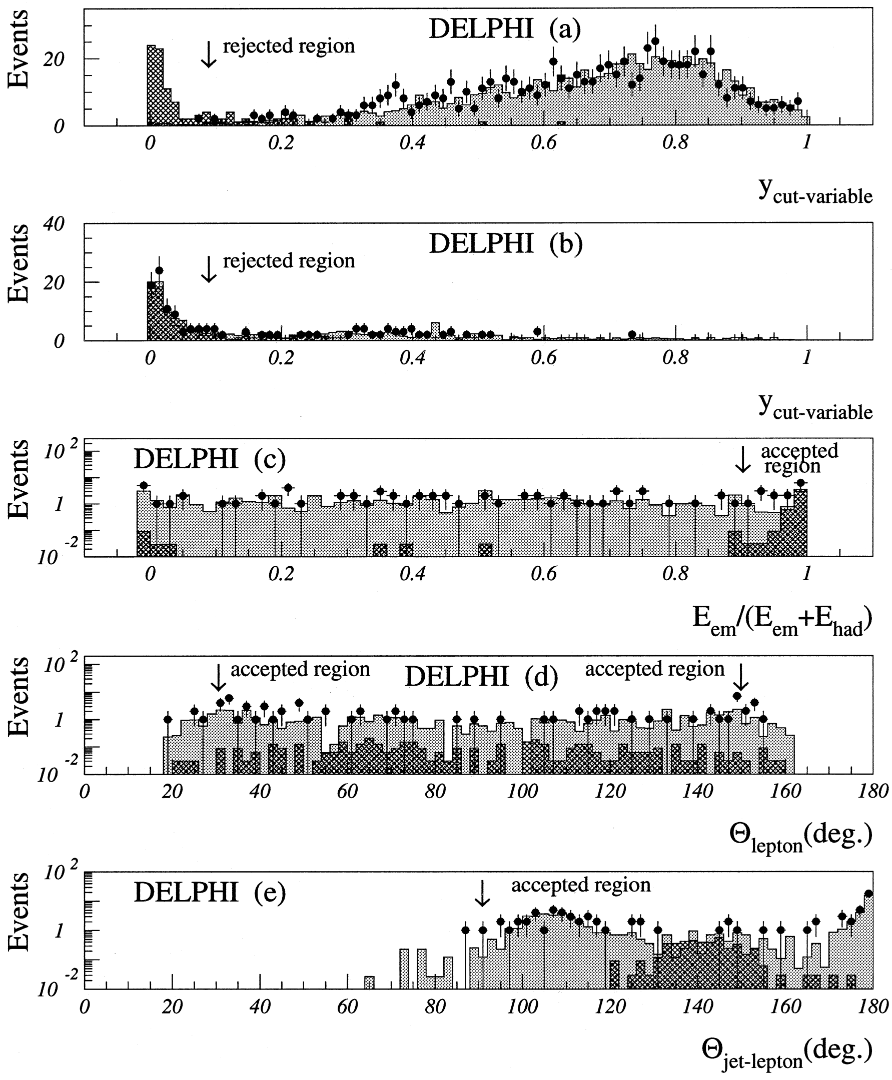

Fig. 2. Leptoquark search: (a) the y_{cut} variable distribution for neutral decays (level 1), (b) the y_{cut} variable distribution for charged decays (level 1), (c) the ratio between the energy deposited in the electromagnetic calorimeters by the lepton candidate and the total energy deposited in both electromagnetic and hadronic calorimeters (level 2), (d) the lepton polar angle (level 2) and (e) the angle between the jet and the lepton (level 2). The dots show the data and the shaded region shows the SM simulation. The dark region is the expected signal behaviour for a leptoquark mass of 120 GeV/c^2. The vertical arrows show the cut used to select events. The accepted or rejected region is also shown.

Table 1
Number of selected data events and expected SM contributions for the charged and neutral decay modes at different levels of selection criteria

	Leptoquark		FCNC
	charged decay data (SM)	neutral decay data (SM)	charged decay data (SM)
level 1	537 (501 ± 12)	3159 (2917 ± 28)	572 (542 ± 12)
level 2	76 (64 ± 4)	4 (2.6 ± .7)	101 (96 ± 5)
level 3	1 (1.1 ± .5)	1 (1.0 ± .4)	0 (1.1 ± .4)

mentum had to be lower then 0.17. This cut reduces the contamination from semileptonic decays of *WW* pairs.

In the case of the leptoquark neutral decays the y_{cut} criterion is the most effective for distinguishing signal from background. This is illustrated in Fig. 2 (a) where the dots show the data, the shaded region the SM simulation and the dark region the expected signal behaviour. The same distributions are shown in Fig. 2 (b) for the leptoquark charged decays.

Additional criteria (level 3) were applied in order to reduce the contamination from background events, mostly $q\bar{q}$ and *WW*. These criteria were different for the different channels:

- For the leptoquark charged decay mode it was required that:
  (i) the lepton was identified as an electron and its polar angle had to be between 30° and 150°;
  (ii) the angle between the electron and the mono-jet had to be larger than 90°.
- For the leptoquark neutral decay mode, where the contamination of $q\bar{q}$ is higher, all particles were

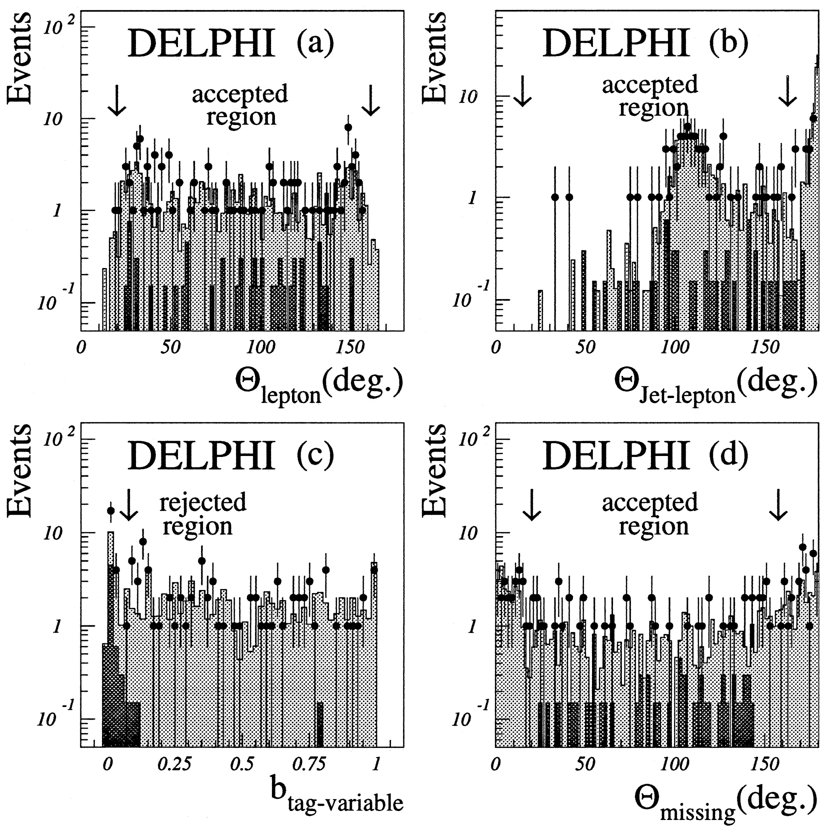

Fig. 3. FCNC search: (a) the lepton polar angle, (b) the jet-lepton angle, (c) the b-tag variable (see text) and (d) the missing momentum polar angle. The dots show the data and the shaded region shows the SM simulation. The dark region is the expected signal behaviour. The vertical arrows show the cut used to select events. The accepted or rejected region is also shown.

also forced into two jets, and the following additional criteria were applied:
(i) the angle between the two jets had to be smaller than 155°;
(ii) the momentum of the second jet had to be smaller than 10 GeV/c, whenever the angle between the two jets was larger than 60°.
- For the single top production:
(i) the polar angle of the most energetic lepton had to be between 20° and 160°, and the angle between the lepton and the monojet had to be between 15° and 165°;
(ii) events with a B hadron decay were selected by requiring the b-tag variable [25] to be below 0.06;
(iii) the polar angle of the missing momentum had to be between 20° and 160°.

In Table 1 the number of events which survived the different levels of selection is shown, together with the expected SM background. The WW and $q\bar{q}$ events are the main source of background. At level 3 the expected background contribution from WW and $q\bar{q}$ events is: for the leptoquark neutral decay mode, 0.12 ± 0.12 and 0.46 ± 0.33 respectively; for the leptoquark charged decay mode 0.12 ± 0.12 and 0.69 ± 0.4 respectively; for the FCNC 0.49 ± 0.25 and 0.23 ± 0.23 respectively. Fig. 2 (c) shows (at level 2), for the leptoquark search, the ratio between the energy deposited in the electromagnetic calorimeters by the lepton candidate and the total energy deposited in both electromagnetic and hadronic calorimeters, (d) the lepton polar angle and (e) the angle between the jet and the lepton. The dots show the data and the shaded region shows the SM simulation. The dark region is the expected signal behaviour for a 120GeV/c^2 leptoquark mass. No upper bound was imposed in the jet lepton angle to allow good signal efficiency up to threshold (where the jet and the lepton are essentially back to back). However the selection on Fig. 2 (c) removes almost all the SM background on Fig. 2 (e).

Fig. 3 shows (at level 2), for the FCNC search, (a) the lepton polar angle, (b) the jet-lepton angle, (c) the b-tag variable [25] and (d) the missing momentum polar angle. The dots show the data and the shaded region shows the SM simulation. The dark region is the expected signal behaviour. A good agreement is observed.

4. Results for leptoquarks

Only first-generation leptoquarks were searched for in this analysis ($L_q \to e^{\pm} q$, $L_q \to \nu_e q$). As discussed previously, the highest contribution to the production cross-section relevant for this search comes from the resolved photon contribution. The Glück-Reya-Vogt parameterization [26] of the parton distribution was used. Since the photon has different u-quark and d-quark contents and the production cross-section is proportional to $(1+q)^2$ (where q is the leptoquark charge), leptoquarks of charge $q = -1/3$ and $q = -5/3$ (as well as leptoquarks of charge $q = -2/3$ and $q = -4/3$) have similar production cross-sections [18]. The cross-sections used here were calculated within the assumption above.

4.1. Charged decay mode

In this channel one event was found in the data at $\sqrt{s} = 183$ GeV and the expected SM background was 1.1 ± 0.5.

The leptoquark invariant mass estimated from the energies and directions of the jet and lepton is 89.9 GeV/c^2. The mass resolution ranges from 15 GeV/c^2 to 25 GeV/c^2 for leptoquark masses from 100 GeV/c^2 up to the kinematical limit.

Within the low statistics there is good agreement between data and SM predictions.

The efficiency was found to be between 22% and 30% for leptoquark masses in the range from 100 GeV/c^2 up to the kinematic limit.

4.2. Neutral decay mode

In this channel one event was found and the expected SM background was 1.0 ± 0.4.

The leptoquark invariant mass estimated from the monojet transverse momentum is 72.1 GeV/c^2. The mass resolution ranges from 20 GeV/c^2 to 34 GeV/c^2 for leptoquark masses from 100 GeV/c^2 up to the kinematical limit. Within the low statistics there is good agreement between data and SM predictions.

The efficiency was found to be between 20% and 41% for leptoquark masses in the range from 100 GeV/c^2 up to the kinematic limit.

4.3. Leptoquark mass and coupling limits

Limits were set on the leptoquark coupling parameter λ [4]. These limits, which depend on the leptoquark mass, are shown in Fig. 4 for both scalar and vector leptoquarks of different types and for charged decay branching ratios $B=1$ and $B=0.5$. For $B=1$ the invariant mass plot for the charged decay mode was used to set the limits. For $B=0.5$ the invariant mass plots of the charged and the neutral decay modes were combined to set the limits. Different values of the charged decay branching ratio B, although theoretically not motivated, would imply similar limits.

The lower limits at 95% confidence level on the mass of a first generation leptoquark for a coupling parameter $\lambda=\sqrt{4\pi\alpha_{em}}$ are given in Table 2, where different leptoquark types and branching ratios are considered [27]. These limits are expected to change at the level of some percent depending on the different theoretical predictions for the total production cross section [28].

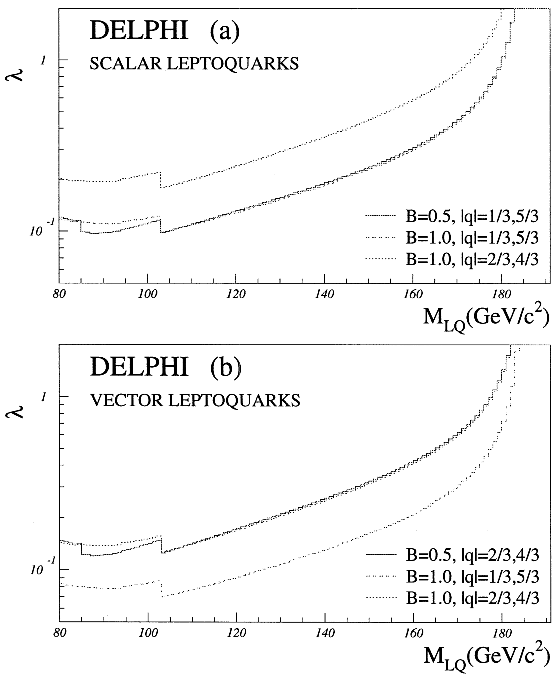

Fig. 4. 95% confidence level upper limits on the coupling λ as a function of the leptoquark mass for (a) scalar and (b) vector leptoquarks (B is the branching ratio of the leptoquark to charged leptons and q is the leptoquark charge).

Table 2
Lower limits (in GeV/c^2) at 95% confidence level on the the mass of a first generation leptoquark for a coupling parameter of $\lambda=\sqrt{4\pi\alpha_{em}}$

	$B=0.5$		$B=1.0$	
	$q=1/3$	$q=2/3$	$q=1/3,5/3$	$q=2/3,4/3$
scalar	161	–	161	134
vector	–	149	171	150

5. Results for top-charm FCNC

In the present analysis no events were found while the expected SM background is 1.1 ± 0.4. The detection efficiency, including the W leptonic branching ratio, is $(11.5 \pm 2.0)\%$.

With the present luminosity of 47.7 pb^{-1}, an upper limit on the $e^+e^- \to t\bar{c}$ Flavour Changing Neutral Current total cross-section can be set at 0.55 pb (95% confidence level).

This value can be translated into a limit on the anomalous coupling constants k_γ and k_Z, according to the parametrization described in Ref. [15]. It was assumed that both channels $e^+e^- \to t\bar{c}$ and $e^+e^- \to t\bar{u}$ contributed to the total cross-section. With a luminosity of 47.7 pb^{-1} the 95% confidence level upper limit on k_γ is 2, for a k_Z value of zero, and the corresponding upper limit on k_Z is 1.5, for a k_γ value of zero. The results are not yet competitive with other experimental results [29].

6. Conclusions

A search for first generation leptoquarks was performed using the data collected by the DELPHI detector at $\sqrt{s}=183$ GeV. Both neutral and charged decay modes of scalar and vector leptoquarks were searched for. No evidence for a signal was found in the data. Limits on leptoquark masses were set ranging from 134 GeV/c^2 to 171 GeV/c^2 at 95% confidence level, assuming electromagnetic type couplings.

A search for $t\bar{c}$ flavour changing neutral currents was also performed. No signal was found in the data. A limit on the FCNC cross-section was set at 0.55 pb (95% confidence level).

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