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**Search for leptoquarks in e^+e^- collisions
at $\sqrt{s} = 189$ GeV**

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Abstract

A search has been made for single production of scalar and vector leptoquarks of the first generation using data taken at $\sqrt{s} = 189$ GeV with an integrated luminosity of 158 pb^{-1} using the DELPHI detector at LEP2. Limits at 95% C.L. on the leptoquark masses were set. A 95% C.L. upper limit is also given on the Yukawa coupling λ as a function of the leptoquark mass.

1 Introduction

Among possible new particles in physics beyond the Standard Model (SM) the leptoquarks are an interesting category of exotic colour triplets with Yukawa couplings λ to quark-lepton pairs. They are a generic prediction of Unified Theories [1], of models with quark-lepton substructure [2], of Technicolor schemes [3] and of Superstring Theories such as E_6 compactification [4].

There are 10 different types of leptoquarks (LQs) differing by their spin S (vector or scalar), fermion number F ($F = 3B + L$), isospin I and hypercharge Y . They have fractional electric charges $\pm 5/3$, $\pm 4/3$, $\pm 2/3$ and $\pm 1/3$ and decay into a charged or a neutral lepton and a quark according to the decay modes $LQ \rightarrow l^\pm q$ (charged decay mode) or $LQ \rightarrow \nu q$ (neutral decay mode).

At LEP1 all collaborations have searched for direct leptoquark pair production in Z^0 decays and have published mass limits which reach the LEP1 kinematical limit [5]. A search for singly produced leptoquarks at LEP1 by DELPHI gave mass limits up to $73 \text{ GeV}/c^2$ at 95% C.L. [6]. DELPHI results at LEP2 were published in [7].

Mass limits have been published at $242 \text{ GeV}/c^2$ ($340 \text{ GeV}/c^2$) for pair produced scalar (vector) leptoquarks of first generation, using Tevatron data [8]. The reported excess of high Q^2 events at HERA by the H1 and ZEUS collaborations [9] stimulated renewed research interest in leptoquarks. Recently leptoquark production has been excluded at HERA for $\lambda = \sqrt{4\pi a_{em}}$ for masses up to $280 \text{ GeV}/c^2$ ($F=0$) and up to $250 \text{ GeV}/c^2$ ($F=2$) for e^-p data [10].

The only leptoquarks that can be produced in $e\gamma$ scattering are first generation leptoquarks. In this paper we consider the single production of the first generation leptoquarks (scalar or vector) in e^+e^- collisions which utilises the quark content of a photon radiated off from one of the initial leptons (Weizsäcker-Williams approximation) [11]. The process we are considering is shown in Figure 1.

All Standard Model background processes were studied in parallel using various Monte Carlo Generators. Bhabha events were generated according to ref. [12]. $e e \rightarrow Z\gamma$, $e e \rightarrow W W$, $e e \rightarrow W e \nu$, $e e \rightarrow Z Z$ and $e e \rightarrow Z e e$ events were generated with PYTHIA [13]. Processes with four fermions in the final states were also simulated with the EXCALIBUR generator [14]. The two-photon physics events (including the VDM, QPM and QCD models) were generated according to the TWOGAM generator [15].

Two different procedures have been followed and corresponding data analyses have been used for the data set at $\sqrt{s} = 189 \text{ GeV}$, corresponding to an integrated luminosity of 158 pb^{-1} : A first analysis is using the ERATO-LQ [16] generator and the so-called Perturbative Approach (PA) method for the cross-section calculation. The ERATO-LQ generator takes into account the chirality of the LQ coupling.

A second analysis is using the PYTHIA [13] generator and the Doncheski [17] framework for the cross-section calculation based on the Resolved Photon Approximation (RPA). The LQ coupling used in this procedure is $k=1$.

Both simulated background and LQ signal events have been passed through the full DELPHI simulation and reconstruction programs [18]. A detailed description of the DELPHI detector and its performance, of the triggering conditions and of the readout chain can be found in reference [19].

2 Analysis A: ERATO-LQ Generator

ERATO-LQ can produce single scalar and vector leptoquarks of all charges at LEP2 energies. This generator uses a perturbative method using the mass of the light quark contained inside the photon and therefore gives full kinematical information of the final state.

By single leptoquark production in the ERATO-LQ generator we mean the following process:

$$e^+(p_1) + e^-(p_2) \rightarrow e^+(p'_1) + \bar{q}(p_3) + q(p_4) + e^-(p_5)$$

for which the main contribution comes from the phase space part where:

- the outgoing positron $e^+(p'_1)$ travels along the beam pipe and escapes the detection,
- the partonic system originating from one of the two quarks of the final state goes also along the beam pipe,
- and the finally remaining lepton-jet pair originates from the leptoquark.

Monte Carlo (MC) signal samples were generated for leptoquark masses between 100 and 180 GeV/ c^2 at $\sqrt{s} = 189$ GeV both for scalar and vector leptoquarks.

The topology studied has a typical structure of an electron and a jet balancing each other's transverse momentum with some hadronic activity in the forward (backward) region. The initial electron which scatters off from the photon escapes the detection.

We studied the production of scalar leptoquarks $S_{1/2}$ with a charge $|Q_{LQ}| = 5/3$ and a fermion number $F = 0$, which couple to a lepton and anti-quark ($e_L \bar{u}$) with a coupling $C_{LQ} = \frac{\lambda^2}{4\pi a_{em}} = 1$ where λ is the Yukawa coupling and a_{em} is the electromagnetic one. The chirality of the LQ coupling has been taken into account according to experimental constraints by rare decays [20]. We also studied the production of vector leptoquarks, V_1 ($\bar{u}_R g^m e_L$) with the same charge and the same fermion number ($|Q_{LQ}| = 5/3$ and $F = 0$).

The same procedure had been followed for an analysis at a centre-of-mass energy of 183 GeV; the results are included in [21].

2.1 Preselection

Charged particles were considered in the analysis if they had a momentum greater than 100 MeV/ c and impact parameters below 4 cm in the transverse plane and below 10 cm in the beam direction. Clusters in the calorimeters were regarded as neutral particles if they were not associated to charged particles and if their energy exceeded 100 MeV.

Electron candidates had to have a momentum greater than 10 GeV/ c . They were identified as electrons if the total deposited energy in the electromagnetic calorimeter HPC was greater than 20 GeV, with no associated hits in the muon chambers and a ratio of the total deposited electromagnetic energy in HPC and FEMC calorimeters to the momentum (E/P) larger than 0.5 .

Charged particles were considered isolated if in a double cone, centered on the track with internal and external half angles of 5° and 20° , the total energy associated to charged and neutral particles was below 1 GeV and 2 GeV, respectively. Inside the inner cone no other charged track was allowed and the total energy associated to neutral particles had to be below 0.5 GeV.

All other charged and neutral particles (after the exclusion of the isolated charged lepton) were forced into one jet using the Durham [22] jet algorithm and requiring that the Durham resolution variable (y_{cut}) was smaller than 0.09.

The events which fulfill the above selection criteria (step 1) had the topology of one isolated electron and one jet. This step is common for the analyses of scalar and vector leptoquarks.

2.2 Selection criteria for scalar and vector leptoquarks

In step 2 events were selected according to the following requirements (values in parentheses apply to the vector LQ selection) :

- The event had to contain at least six charged particles,
- its visible energy had to be greater or equal $0.25\sqrt{s}$ and
- it shouldn't contain any isolated photon.
- The momentum of the electron had to be greater than 25 (30) GeV/ c .
- The momentum of the monojet had to be larger than 25 GeV/ c .
- The polar angles of the electron and of the monojet had to be between 30° and 150° .

Additional criteria (step 3) were applied in order to reduce the contamination mostly from WW and Zee events. These criteria were:

- The transverse momenta of the isolated electron and of the monojet had to be greater than 30 (25) GeV/ c .
- The angle between the electron and the monojet had to be greater than 125° (130°).
- The average opening angle of the monojet had to be lower than 54° (51°).
- The transverse missing momentum had to be lower than 50 GeV/ c .
- The ratio of electromagnetic charged energy of particles inside jet over the total energy of jet had to be lower than 35% (40%).
- If the invariant mass of the isolated electron and the missing momentum was between $78 \text{ GeV}/c^2 < M_{ev} < 82 \text{ GeV}/c^2$ the event was rejected, reducing background from WW production.

The number of events in data after each of the steps is shown in Table 1 together with the expectation for all the relevant Standard Model processes. Data and background simulation are in good agreement.

After all steps we expect a background of 3.26 ± 0.44 (2.9 ± 0.4) events for the scalar (vector) LQ selection from all Standard Model processes. Most of the remaining background comes from Zee processes which are an irreducible background. In data one event is observed in the scalar LQ selection and one event in the vector LQ selection. The signal efficiencies (ERATO-LQ) are given in Table 2.

2.3 Results of analysis A

In this analysis first generation singly produced scalar and vector leptoquarks were searched for in the decay channel $LQ \rightarrow e^\pm q$. In the search for scalar leptoquarks one event was found in data at $\sqrt{s}=189$ GeV and the expected MC background rate was 3.26 ± 0.44 . A limit was obtained for the mass of scalar leptoquarks with charge $\pm 5/3$ at

	Leptoquark	
	<i>scalar</i> <i>Data(SM)</i>	<i>vector</i> <i>Data(SM)</i>
Step 1	311 (323.22±69.30)	311 (323.22±69.30)
Step 2	9 (12.43 ± 0.89)	9 (12.43±0.89)
Step 3	1 (3.26±0.44)	1 (2.9±0.4)

Table 1: Number of events after each step, normalised to the data luminosity at 189 GeV, in the search for scalar and vector leptoquarks. The quoted errors are statistical.

M_{LQ} (GeV/ c^2)	100	120	140	160	180
$\epsilon\%$ - scalar	1.9 ± 0.4	18.5 ± 1.4	31.5 ± 2.0	36.6 ± 2.2	24.6 ± 1.7
$\epsilon\%$ - vector	1.6 ± 0.4	20.0 ± 1.5	29.6 ± 1.9	32.9 ± 2.1	26.4 ± 1.8

Table 2: Efficiencies, in percent, for detecting scalar and vector leptoquarks.

95% C.L., $M_{LQ} \geq 171$ GeV/ c^2 , for a branching ratio to charged leptons (β) of 1 and for a coupling $\lambda = \sqrt{4\pi a_{em}}$.

For vector leptoquarks one event was found in the data at $\sqrt{s}=189$ GeV and the expected MC background rate was 2.9 ± 0.4 . A limit was obtained for the mass of vector leptoquark with charge $\pm 5/3$ at 95% C.L., $M_{LQ} \geq 181$ GeV/ c^2 , for $\beta = 1$ and for a coupling $\lambda = \sqrt{4\pi a_{em}}$.

These limits, together with those for additional leptoquark states, are summarised in Tables 3 to 5. In Figure 2 the observed limits are shown in comparison with the expected number of signal events as a function of the leptoquark mass. The limits on the couplings for several scalar and vector leptoquark states are shown, within this framework, in Figure 3.

$Q_{LQ} = \pm 5/3, \pm 1/3, \lambda = \sqrt{4\pi a_{em}}, \beta = 1$	M_{LQ} (GeV/ c^2)
SCALAR	171
VECTOR	181

Table 3: Limits on scalar and vector leptoquarks with charge $Q_{LQ} = \pm 5/3, \pm 1/3$ at $\sqrt{s}=189$ GeV using the ERATO-LQ MC Event generator.

$Q_{LQ}=\pm 4/3, \pm 2/3, \lambda = \sqrt{4\pi a_{em}}, \beta=1$	$M_{LQ} \text{ (GeV}/c^2)$
SCALAR	153
VECTOR	164

Table 4: Limits on scalar and vector leptoquarks with charge $Q_{LQ}=\pm 4/3, \pm 2/3$ at $\sqrt{s}=189$ GeV using the ERATO-LQ MC Event generator.

$\lambda = \sqrt{4\pi a_{em}}, \beta=0.5$	$M_{LQ} \text{ (GeV}/c^2)$
SCALAR $Q_{LQ}=\pm 5/3, \pm 1/3$	144
VECTOR $Q_{LQ}=\pm 4/3, \pm 2/3$	125

Table 5: Limits on scalar and vector leptoquarks with $\beta=0.5$ at $\sqrt{s}=189$ GeV using the ERATO-LQ MC Event generator.

3 Analysis B: PYTHIA Generator

In this analysis the leptoquark signals (both for scalar and vector) were generated for different mass values using the PYTHIA generator [13]. The leptoquark production cross section was taken from ref. [23]. The generated LQ signal events have been passed through the full DELPHI simulation and reconstruction programs [18].

Charged decays of singly produced high mass leptoquarks are characterised by a high transverse momentum jet recoiling against a lepton. In the neutral decay mode only the jet is detected. The initial electron which scatters off the quasi real photon is assumed to escape detection. The event topologies searched for are characterised by an energetic monojet. In the leptoquark charged decay mode a well isolated charged lepton should also be present in the events.

In this analysis the minimum required charged multiplicity was six and all particles (excluding the isolated charged lepton, if present) were forced into one jet using the Durham jet algorithm [22]. Charged tracks were considered to be isolated energetic leptons if they originated at the interaction point and if in a double cone, centred on each track with internal and external half-angles of 5° and 25° , the charged energy and the neutral energy were less than 1 GeV and 2 GeV respectively. Inside the inner cone no other charged track was allowed. A detailed description of the hadronic selection criteria can be found in reference [24]. Leptons were identified as electrons if there were no associated hits in the muon chambers, if the electromagnetic energy to the momentum ratio (E/P) was larger than 0.2 and if the lepton electromagnetic energy normalised to its total energy was larger than 0.9.

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

- the total visible energy was required to be larger than $0.2\sqrt{s}$;
- no isolated photons were allowed in the event;
- the momentum of the monojet was required to be larger than 30 GeV/c;
- in channels with one isolated charged lepton its momentum had to be greater than 10 GeV/c.

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

- Events should have a clear monojet topology. This cut was implemented requiring the Durham resolution variable in the transition from two to one jet, y_{cut} , to have a $-\log_{10}(y_{cut})$ higher than 1.1.
- The monojet polar angle had to be between 30° and 150° .
- The ratio between the monojet electromagnetic energy and its total energy had to be smaller than 0.95. This cut reduces the contamination from Bhabha events.

In order to further reduce background contamination, mostly coming from $q\bar{q}$ and WW events, additional criteria were applied depending on the final channel (level 3).

For the leptoquark charged decay mode it was required that

- the lepton was identified as an electron and its polar angle was between 30° and 150° ;
- that the angle between the electron and the monojet was larger than 100° .

For the leptoquark neutral decay mode, where the contamination of $q\bar{q}$ is higher, all particles were also forced into two jets, and the following additional criteria were applied:

- The momentum of the second jet had to be smaller than 10 GeV/ c , whenever the angle between the two jets was larger than 45° .
- The invariant mass of the two jets had to be smaller than 40 GeV/ c^2 .

In Table 6 the number of events which passed the different levels of selection are shown, together with the expected SM background. Figure 4 shows, at level 2, the lepton and jet momenta and the angle between the lepton and the jet, together with the SM expectation. A good agreement is observed.

	Leptoquark	
	<i>ChargedDecay</i> <i>Data(SM)</i>	<i>NeutralDecay</i> <i>Data(SM)</i>
Level 1	337 (319.3±9.5)	6326 (5837.0±42.6)
Level 2	45 (43.8 ± 3.7)	13 (9.0±1.5)
Level 3	2 (3.2±0.7)	2 (3.7±0.9)

Table 6: Number of data events and expected SM contributions for the charged and neutral decay modes at different levels of selection criteria.

3.1 Results for analysis B

Only first generation leptoquarks were searched for in this analysis. As discussed previously, the contribution to the total production cross section relevant for this search comes from the resolved photon contribution. The total production cross section is taken from reference [17], which uses the resolved photon distribution approach where a Weizsäcker-Williams photon is assumed to radiate off from one of the initial electrons.

The Glück-Reya-Vogt parameterisation (GRV) [25] 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 $q = -1/3(-2/3)$ and $q = -5/3(-4/3)$ have similar production cross sections [23].

The approach used in [23] is independent of the leptoquark chirality and is almost insensitive to whether the leptoquark is scalar or vector.

3.2 Charged Decay Mode

In this channel two events were found in the data at $\sqrt{s} = 189$ GeV and the expected SM background was 3.2 ± 0.7 .

The jet-lepton invariant masses, calculated using the lepton energy, are 104 GeV/ c^2 and 79 GeV/ c^2 . The mass resolution at 160 GeV/ c^2 is around 16 GeV/ c^2 . Within the low statistics there is good agreement between data and SM predictions.

The efficiency was found to be between 25% and 41% for leptoquark masses in the range from 120 GeV/ c^2 up to the kinematic limit.

3.3 Neutral Decay Mode

In this channel two events were found and the expected SM background was 3.7 ± 0.9 .

The invariant masses, calculated using the monojet transverse momentum, are 39 GeV/ c^2 and 45 GeV/ c^2 . The mass resolution at 160 GeV/ c^2 is around 26 GeV/ c^2 . Within the low statistics there is good agreement between data and SM predictions.

The efficiency was found to be between 24% and 40% for leptoquark masses in the range from 120 GeV/ c^2 up to the kinematic limit.

3.4 Leptoquark Mass and Coupling Limits

Using the obtained invariant mass distributions it is possible to set limits on the leptoquark coupling parameter λ . For $\beta = 1$ the invariant mass distribution for the charged decay mode was used to set the limits. For $\beta = 0.5$ the invariant mass distributions of the charged and the neutral decay modes were combined to set the limits.

3.5 Doncheski framework

Within this framework the coupling definitions used are the ones of [17] ($\lambda = \sqrt{4\pi k \alpha_{em}}$) taking $k=1.0$. These limits, as a function of the leptoquark mass, are shown in Figure 5 for both scalar and vector leptoquarks of different types and for the different charged decay branching ratios ($\beta = 1$ or $\beta = 0.5$). The lower limits at 95% confidence level on the mass of a first generation leptoquark for the above coupling parameter definition are given in Table 7, where different leptoquark types and branching ratios are considered [26]. This corresponds to the assumptions made in [7].

In order to check the consistency with analysis A the coupling has been changed to $k=0.5$. Under this assumption the lower limits at 95% confidence level on the mass of a first generation leptoquark for $\beta = 1$ and for electromagnetic type couplings are given in Table 8, where different leptoquark types are considered [26].

	$ Q =1/3,5/3$		$ Q =2/3,4/3$	
	$\beta = 0.5$	$\beta = 1.0$	$\beta = 0.5$	$\beta = 1.0$
scalar	181	181	-	166
vector	-	185	176	176

Table 7: Lower limits (in GeV/c^2) at 95% confidence level on the the mass of a first generation leptoquark for a coupling parameter of $\lambda=\sqrt{4\pi k\alpha_{em}}$, defined according to reference [17] and taking $k=1$.

	$ Q =1/3,5/3$	$ Q =2/3,4/3$
	$\beta = 1.0$	$\beta = 1.0$
scalar	175	150
vector	182	166

Table 8: Lower limits (in GeV/c^2) at 95% confidence level on the the mass of a first generation leptoquark for electromagnetic type couplings $\lambda=\sqrt{4\pi k\alpha_{em}}$, defined according to reference [17] and taking $k=0.5$ for compatibility with ERATO.

4 Conclusions

A search for first generation single scalar and vector leptoquarks was performed based on data collected in 1998 by the DELPHI experiment at a e^+e^- centre-of-mass energy of 189 GeV. The data correspond to an integrated luminosity of 158 pb^{-1} . Two different procedures have been used for the data analysis based on two different generators and two different theoretical methods for the cross-section calculation were used, the so called Perturbative Approach (PA) method followed by the ERATO-LQ generator and the Resolved Photon Approximation (RPA) method used in the Doncheski framework.

Under the same conventions and taking into account the chirality of the LQ coupling the two different analyses are consistent. Therefore, conservatively we quote mass limits for LQ charge states $|Q| = 5/3$ or $1/3$ and for $\beta = 1$ (Table 9).

$Q_{LQ}=\pm 5/3, \pm 1/3, \lambda = \sqrt{4\pi a_{em}}, \beta=1$	$M_{LQ} (\text{GeV}/c^2)$
SCALAR	171
VECTOR	181

Table 9: Limits on scalar and vector leptoquarks with charge $Q_{LQ}=\pm 5/3, \pm 1/3$ at $\sqrt{s}=189 \text{ GeV}$ using ERATO-LQ MC Event generator.

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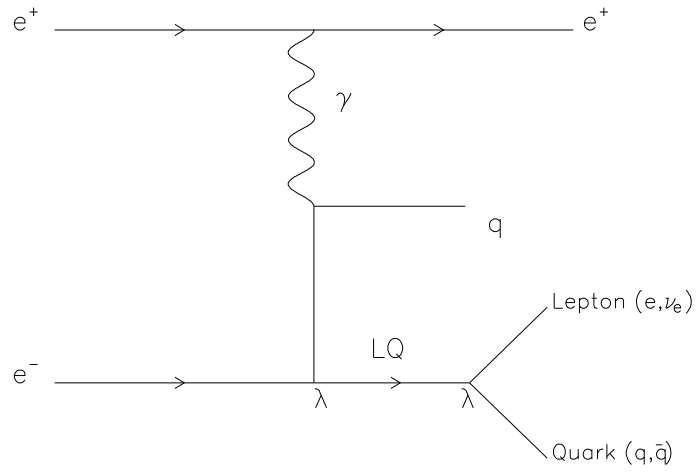


Figure 1: Diagram of the production of a leptoquark (LQ) in electron-photon scattering. The photon is radiated off one of the LEP beams (Weizsäcker-Williams approximation).

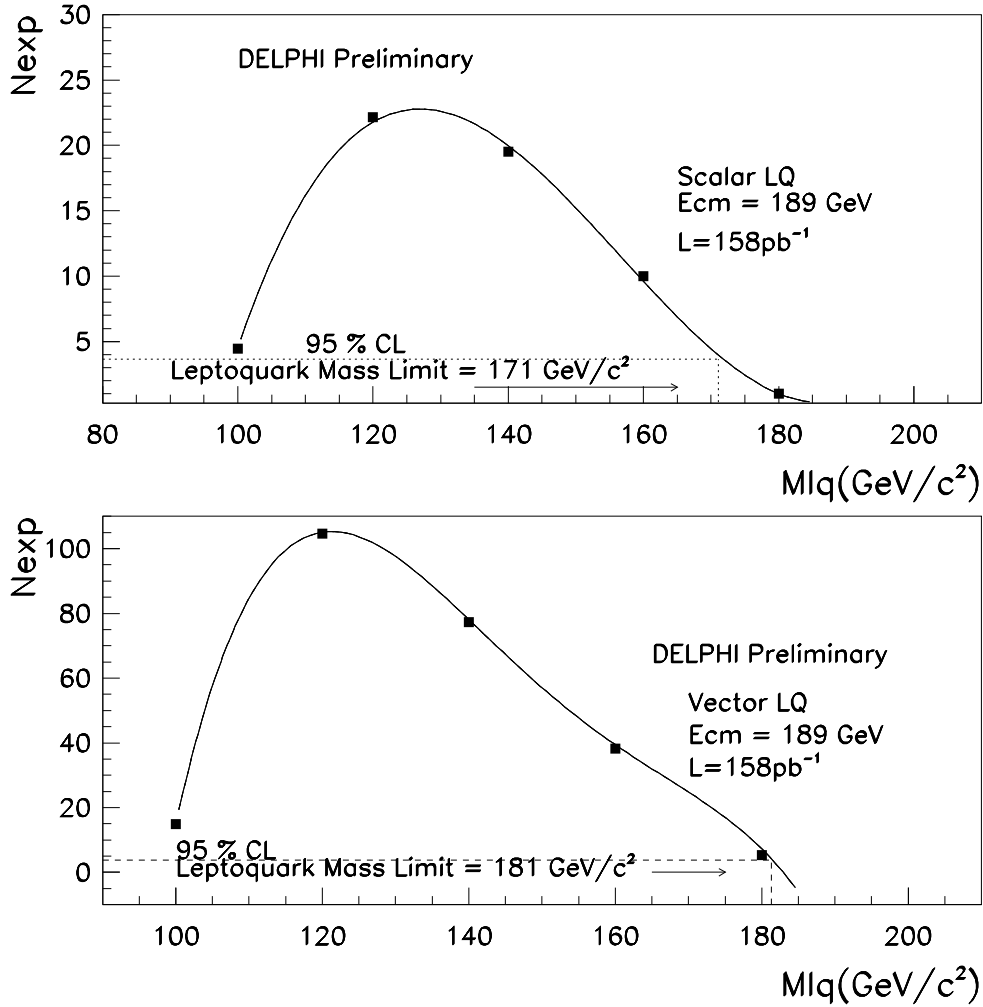
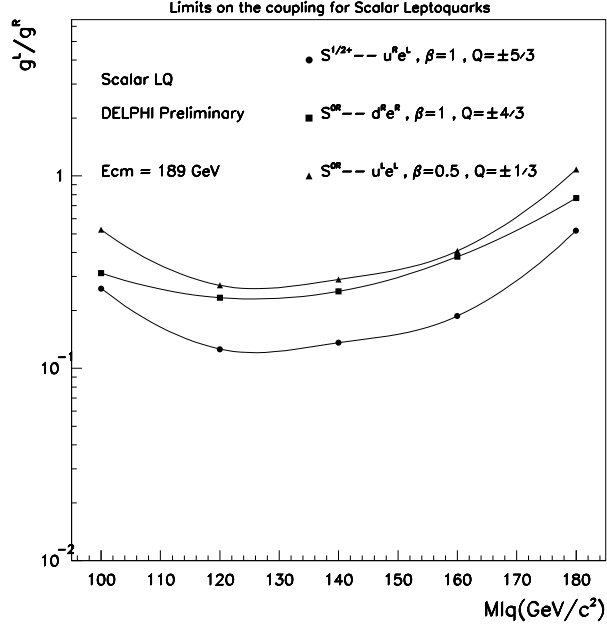
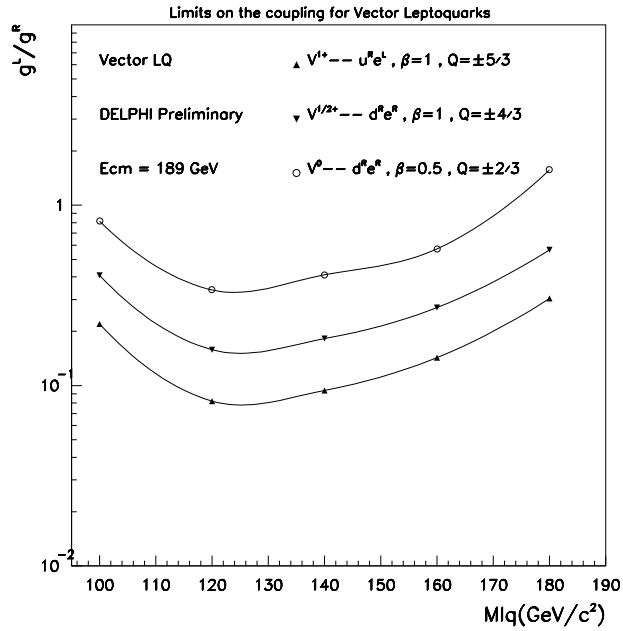


Figure 2: Analysis A: the expected number of events as a function of the leptoquark mass M_{LQ} for the state $S_{1/2}$ (in case of scalar leptoquarks) and for the state V_1 (in case of vector leptoquarks). The horizontal line is the 95% C.L. limit.



(a)



(b)

Figure 3: Analysis A: (a) 95% confidence level limits on the Yukawa coupling λ as a function of the scalar leptoquark mass M_{LQ} for charge states $Q = \pm 5/3 (\pm 1/3)$ and $Q = \pm 4/3 (\pm 2/3)$ and for $\beta = 1$. and $\beta = 0.5$. (b) 95% confidence level limits on the Yukawa coupling λ as a function of the vector leptoquark mass M_{LQ} for charge states $Q = \pm 5/3 (\pm 1/3)$ and $Q = \pm 4/3 (\pm 2/3)$ and for $\beta = 1$. and $\beta = 0.5$.

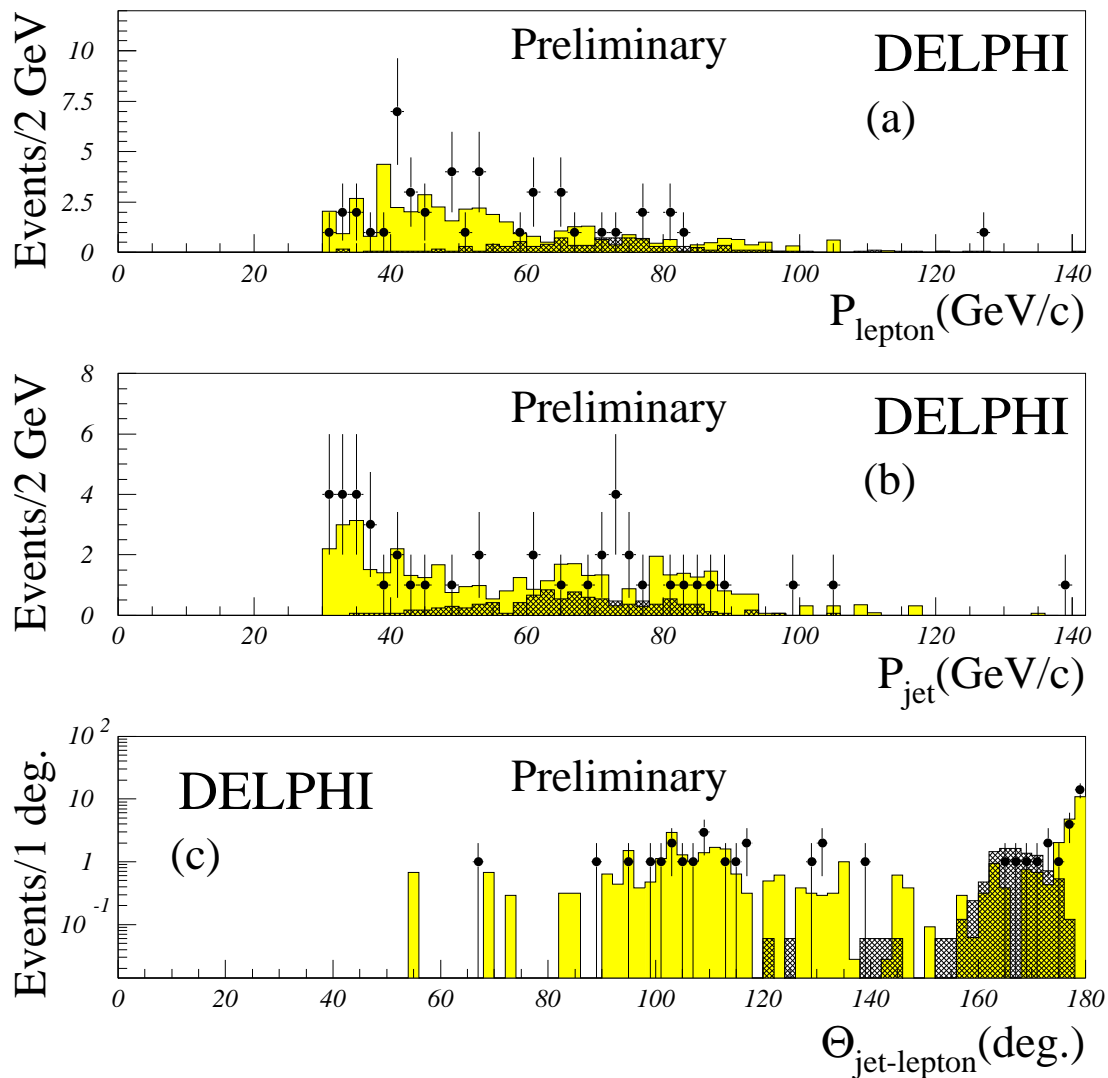


Figure 4: Analysis B: the electron momenta (a), the charged jet momentum (b) and the angle between the jet and electron momenta (c). The dots show the data and the shaded region shows the SM simulation. The shadowed region is the signal simulation for a LQ with a mass of $160 \text{ GeV}/c^2$.

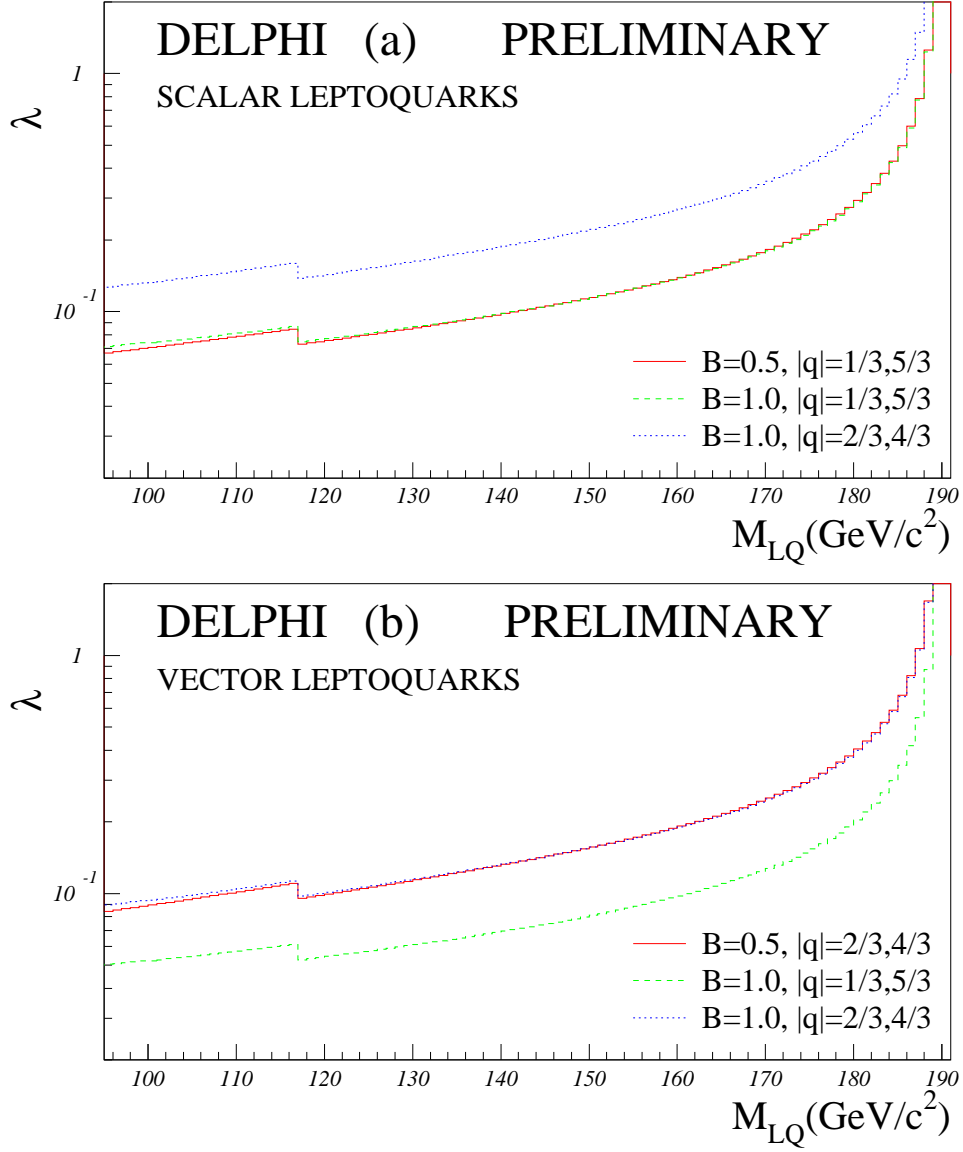


Figure 5: Analysis B: 95% confidence level limits on the coupling λ as a function of the leptoquark mass for scalar (a) and vector (b) $\lambda = \sqrt{4\pi k \alpha_{em}}$, defined according to reference [17] and taking $k=1$ (Doncheski framework).