SEARCH FOR SINGLE LEPTOQUARK PRODUCTION IN ELECTRON-PHOTON SCATTERING
AT $\sqrt{s} = 161$ AND 172 GEV

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A search for a first generation scalar leptoquark (LQ) has been performed using the data collected by the OPAL detector in 1996 at $e^+e^-$ centre-of-mass energies $\sqrt{s}$ of 161 and 172 GeV. It is assumed that a single leptoquark can be produced in the process $eq \rightarrow LQ$, where the initial state quark originates from a hadronic fluctuation of a quasi-real photon which has been radiated by one of the LEP beams. Lower limits at the 95% confidence level on the mass of a first generation scalar leptoquark of 131 GeV for $\beta = 0.5$ and $\beta = 1$, coupling values $\lambda$ larger than $\sqrt{\Delta \sigma_{\text{em}}}$ and leptoquark charges $-1/3$ or $-5/3$ are obtained.

1 Kinematics and Monte Carlo simulations

Leptoquarks are coloured spin 0 or spin 1 particles carrying both baryon and lepton quantum numbers. Recently it has been suggested to search for leptoquarks in electron-photon collisions at LEP\[\dagger\]. The photon, which has been radiated by one of the LEP beams, serves as a source of quarks through its fluctuations into hadronic states. The electron-quark interaction produces a leptoquark which is assumed to decay subsequently into an electron or a neutrino and a quark.\[\dagger\]

In electron-photon scattering first generation leptoquarks of charge $-1/3$, $-5/3$, $-2/3$ and $-4/3$ can be produced. The cross-section to produce charge $-2/3$ and $-4/3$ leptoquarks is suppressed, since there is less $d$ quark content in the photon than $u$ quark. The limits will therefore be given for leptoquark charges $-1/3$ or $-5/3$. The cross-sections in $e\gamma$ scattering for both charge states are identical, since it is equally probable to find a $u$ or a $\bar{u}$ quark in the photon. In principle this search is also sensitive to electron-charm states, since the probability for a photon to split into $c\bar{c}$ or $u\bar{u}$ is expected to be about equal for leptoquark masses $M \gg m_c$. Furthermore it has been assumed that either left or right handed couplings to quarks vanish. The cross-sections in $e\gamma$ scattering for both couplings are identical, whereas the branching ratio

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\[\dagger\] Charge conjugation is implied throughout this paper and positrons are referred to as electrons
The beta into eq final states is 1 for right handed couplings and 1/2 for left handed couplings.

The total cross-section for the production of scalar leptoquarks of mass $M$ is a convolution of the Weizsäcker-Williams effective photon distribution $f_{\gamma/e}(z)$, with $z$ being the momentum fraction carried by the photon, and the parton distribution functions $f_{q/\gamma}(x, \mu^2)$ of the photon, evaluated at the scale $\mu = M$:

$$\sigma(e^+e^- \rightarrow \text{LQ} + \text{X}) = \frac{\lambda^2 \pi}{2s} \int_{M^2/s}^1 \frac{dz}{z} f_{\gamma/e}(z, Q_{\text{max}}^2) f_{q/\gamma}(M^2/(zs), M^2).$$

The Monte Carlo simulation of this process is done with PYTHIA 5.722. In the simulation the maximum photon virtuality $Q^2_{\text{max}}$ used in the Equivalent Photon Approximation equals $s/4$, but the simulated photon is always real ($Q^2 = 0$). The GRV parametrisation of the parton distribution functions was used. In the kinematic region relevant for leptoquark production the variations of the cross-section due to the different parameterisations are small. Interference effects with deep-inelastic $e\gamma$ scattering are also neglected. The total cross-section in PYTHIA for $\sqrt{s} = 172$ is about 10-20% lower than the cross-sections given for $\sqrt{s} = 175$ in Ref. 1. Vector leptoquarks can currently not be simulated with PYTHIA. The limits are therefore given only for scalar leptoquarks. The standard PYTHIA Monte Carlo has been modified to include LQ $\rightarrow \nu_\ell d$ decays in addition to the standard LQ $\rightarrow e u$ decays.

2 Event Analysis

Jets were reconstructed using a cone jet finding algorithm with a cone size $R = 1$ and a cut on the minimum transverse jet energy $E_T$ of 15 GeV. Tracks and calorimeter clusters were used as input for the jet finding algorithm and for determining the missing transverse energy $E_T$ of the event. A matching algorithm between tracks and clusters is applied. The electron was identified using the standard OPAL neural net electron identification. All relevant Standard Model background processes were studied using Monte Carlo generators. The total data sample corresponds to an integrated luminosity of 20.5 pb$^{-1}$.

2.1 The electron plus hadronic jet channel

For this channel the identified electron with the largest momentum was assumed to be the electron from the leptoquark decay. The electron is usually reconstructed as a jet. Candidate events were selected based on the following cuts:
In order to reduce background from deep-inelastic $e\gamma$ and $e^+e^- \rightarrow \tau^+\tau^-$ events, exactly two jets must have been found in the event ($n_j = 2$).

A large number of $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow e^+e^-$ events are rejected by requiring a minimum number of 5 reconstructed tracks ($n_{ch} \geq 5$). In addition, the ratio $E_{\text{ECAL}}/\sqrt{s}$ has to be less than 0.9, where $E_{\text{ECAL}}$ is the energy in the electromagnetic calorimeter.

The missing transverse energy $E_T^m$ must be less than 15 GeV in order to reduce background from $\tau^+\tau^-$ and $W^+W^-$ pair production.

An isolation cut is applied on the identified electron. The jet with the smallest angular distance to the electron is chosen to be the electron jet. The difference between the energy $E_j$ of this jet and the energy $E_e$ of the electron must be less than 4 GeV. Most multihadronic $e^+e^- \rightarrow q\bar{q}$ events are removed by this cut.

Events where an electron was scattered at a small angle are rejected by requiring for the angle of the electron $|\cos \theta_e| < 5\%$.

The total multiplicity $n_q$ of the quark jet must be $n_q \geq 7$, where $n_q$ is the total number of tracks and calorimeter clusters associated to this jet. The cuts on the transverse momenta of the jets and on the angle $|\cos \theta_e|$ of the electron reduce significantly the sensitivity to find a leptoquark which is lighter than approximately $M_Z/2$, the region excluded by the LEPI searches. These cuts are necessary to reduce the background from deep-inelastic $e\gamma$ events which becomes increasingly important at small masses.

After all cuts we expect a background of $5.2 \pm 0.4$ events from all Standard Model processes. In the data four events are observed with jet-jet invariant masses $M_{jj}$ of 36, 37, 62 and 98 GeV. In Fig. 4 the $M_{jj}$ distribution of the four candidate events is shown together with the sum of all Monte Carlo background distributions. Also shown is a possible leptoquark signal for $\lambda = \sqrt{\frac{4\pi a_{em}}{\alpha}}$ and different LQ masses. The mass distribution of the candidate events is consistent with the expectation from the background Monte Carlo simulation.

2.2 The neutrino plus hadronic jet channel

This search has to be optimized for a single hadronic jet in the detector. Its transverse energy $E_T^\nu$ must be balanced by the neutrino. The cuts are therefore:

- In order to reject events with large missing transverse energy due to badly measured tracks, the ratio of the energy $E_{\text{ECAL}}$ to the total visible energy $E_{\text{vis}}$ has to be larger than 20 %.
• Exactly one jet has to be found \((n_j = 1)\) with \(E_T^j > 15\) GeV. The jet direction in the laboratory frame is required to lie within a pseudorapidity range \(|\eta| < 2\) to reject events where a single jet, usually due to an electron, was found in the forward detectors.

• \(n_{ch} \geq 5\) and \(n_q \geq 7\).

• The missing transverse energy \(\not{E}_T\) must be greater than 15 GeV and it should be mainly due to the jet. Therefore we require \(|E_T^j - \not{E}_T| < 3\) GeV and \(E^j/E_{vis} > 0.5\).

Since no additional cuts on electron variables are necessary, the efficiency to detect a leptoquark is higher in the \(\nu_e q'\) channel than in the \(eq\) channel. For \(M = 100\) GeV the efficiency is about 61 % in the \(\nu_e q'\) and 55 % in the \(eq\) channel.

![Figure 1: Number of (a) LQ → eq and (b) LQ → \(\nu_e q'\) events expected with \(\lambda = \sqrt{4\pi \alpha_{em}}\) in 20.5 pb\(^{-1}\) of data after all cuts for \(M = 45, 80, 120\) and 140 GeV (histograms) and the candidate events (data points). The sum of all background contributions expected from the simulation of the Standard Model processes is also shown normalized to the data luminosity.](image)

The leptoquark mass was reconstructed by calculating the transverse mass \(M_T = 2\not{E}_T\). The transverse mass \(M_T\) of the two candidate events at 38 and 46 GeV is shown in Fig. 1b together with the background distribution from the simulation. The expected background rate is \(1.81 \pm 0.05\) events. The transverse mass distribution for a leptoquark production cross-section using \(\lambda = \sqrt{4\pi \alpha_{em}}\) is also indicated.
3 Mass limit for a scalar leptoquark

The systematic error includes (a) the luminosity measurement with 1 %, (b) the model dependence of the leptoquark fragmentation with 4 %, (c) the electron identification efficiency with 2 % and (d) the Monte Carlo statistics with 1 %. The model dependence of the leptoquark fragmentation was estimated by varying the cut on the average charged multiplicity by one unit in the Monte Carlo while keeping it fixed in the data.

The limit was obtained separately for $\beta = 1$ and for $\beta = 0.5$. The 95 % confidence level (CL) upper limit was calculated taking into account the candidates, the background, the experimental resolution and the systematic errors. The cross-section was determined using PYTHIA. The upper limit at 95 % CL of the coupling $\lambda$ as a function of the leptoquark mass $M$ is given in Fig. 2. The mass limits are $M > 131 \text{ GeV}$ for both $\beta = 0.5$ and $\beta = 1$ and for $\lambda = \sqrt{\frac{4\pi}{\alpha_{\text{em}}}}$.

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