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# Searching For Leptoquarks at Gamma-p Colliders

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**Abstract**

A study for single and pair production of scalar and vector leptoquarks in the collision of high energy $\gamma$ and proton beams is presented. It is shown that future $\gamma p$ colliders may play a complementary role to investigate unknown leptoquark properties.

## 1. Introduction

### 1.1. Leptoquarks

There is no interaction vertex involving a lepton, a quark and a boson in the Standard Model. However, there are some theories having bosons which induce lepton-quark transitions, usually called leptoquarks. Examples for such theories are grand-unified models, the Pati-Salam SU(4) Model, technicolor models and composite models for quarks and leptons. Depending on the models, they occur with different spins, charges and couplings. So it is interesting to determine such properties of leptoquarks from experiments.

### 1.2. Lagrangian

The interactions of leptoquarks with known fermions and electroweak gauge bosons can be described by an effective lagrangian at low energies. It is reasonable to consider an effective lagrangian which is invariant with respect to $\mathrm{SU(3)_C \times SU(2)_W \times U(1)_Y}$ symmetry of the Standard Model. Our treatment is based on the following general effective Lagrangian [1, 2] for scalar leptoquarks

$$L_S = g_{1L}\overline{q^c_L}i\tau_2\ \ell_L S_1 + g_{1R}(\ \overline{u^c_R}e_R + \overline{d^c_R}\nu_R)S'_1 + \widetilde{g}_{1R}\overline{d^c_R}e_R\widetilde{S}_1$$

$$+\widetilde{g}'_{1R}\overline{u^c_R}\nu_R\widetilde{S}'_1 + g_{3L}\overline{q^c_L}i\tau_2\vec{\tau}\ell_L\vec{S}_3 \qquad (1)$$

$$+h_{2L}\overline{u}_R\ell_L R_2 + h_{2R}\overline{q}_L i\tau_2 e_R R'_2 + \widetilde{h}_{2L}\overline{d}_R\ell_L\widetilde{R}_2 + \widetilde{h}_{2R}\overline{q}_L i\tau_2\nu_R\widetilde{R}'_2$$

where $q_L$ and $\ell_L$ are the $SU(2)_W$ left handed quark and lepton doublets . Scalar leptoquarks $S_1, S_1'$, $\widetilde{S}_1$and $\widetilde{S}_1'$ are $SU(2)_W$ singlets, $R_2, R_2'$, $\widetilde{R}_2$ and $\widetilde{R}_2'$ are $SU(2)_W$ doublets, and $S_3$ is an $SU(2)_W$ triplet. $\psi^c = C\bar{\psi}^T$ is the charge conjugated fermion field. For vector leptoquarks

$$
\begin{aligned}
L_V = & (g_{2L}\bar{d}_R^c\gamma^\mu\ell_L + g_{2R}\bar{q}_L^c\gamma^\mu e_R)V_{2\mu} \\
& +\tilde{g}_{2L}\bar{u}_R^c\gamma^\mu\ell_L\tilde{V}_{2\mu} + g_{2R}'\bar{q}_L^c\gamma^\mu\nu_R V_{2\mu}' \\
& +(h_{1L}\bar{q}_L\gamma^\mu\ell_L + h_{1R}\bar{d}_R\gamma^\mu e_R + h_{1R}\bar{u}_R\gamma^\mu\nu_R)U_{1\mu} \\
& +\tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + \tilde{h}_{1R}'\bar{d}_R\gamma^\mu\nu_R\tilde{U}_{1\mu}' + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu\ell_L\vec{U}_{3\mu} + h.c.,
\end{aligned}
\tag{2}
$$

where vector leptoquarks $U_1$, $\tilde{U}_1$ and $\tilde{U}_1'$ are $SU(2)_W$ singlets, $V_2$, $V_2'$, $\tilde{V}_2$ are $SU(2)_W$ doublets and $U_3$ is an $SU(2)_W$ triplet. The subscripts L and R of the coupling constants refer to lepton chirality. The lagrangian (1) differs from the one of Ref.[1] with the terms having right handed neutrino. In our opinion, inclusion of these terms is quite reasonable because of lepton-quark symmetry. Each type of leptoquarks is color triplet. Some quantum numbers of scalar and vector leptoquarks appearing in the Lagrangians (1) and (2) are shown in Tables 1 and 2. The leptoquark types which couple to right handed neutrino are denoted in parentheses.

**Table 1.** Properties of scalar leptoquarks described by the Lagrangian (1).

| Leptoquark | Charge | Chirality | $SU(2)_W$ |
|---|---|---|---|
| $S_1(S_1')$ | -1/3 | LH(RH) | 1 |
| $\widetilde{S}_1(\widetilde{S}_1')$ | -4/3 | RH(RH) | 1 |
| $\vec{S}_3$ | -4/3, -1/3, 2/3 | LH | 3 |
| $R_2(R_2')$ | 2/3, 5/3 | LH(RH) | 2 |
| $\widetilde{R}_2(\widetilde{R}_2')$ | 2/3, -1/3 | LH(RH) | 2 |

**Table 2.** Properties of vector leptoquarks described by the Lagrangian

| Leptoquark | Charge | Chirality | $SU(2)_W$ |
|---|---|---|---|
| $U_1$ | 2/3 | LH,RH | 1 |
| $\widetilde{U}_1$ | 5/3 | RH | 1 |
| $\vec{U}_3$ | -1/3, 2/3, 5/3 | LH | 3 |
| $V_2$ | -4/3, -1/3 | LH,RH | 2 |
| $\widetilde{V}_2$ | -1/3, 2/3 | LH | 2 |
| $(\widetilde{U}_1')$ | -1/3 | RH | 1 |
| $(V_2')$ | -1/3, 2/3 | RH | 2 |

The best places to discover leptoquarks are

- $pp(p\bar{p})$ machines for high $\sqrt{s}$ and high luminosity
- $ep$ machines for s-channel eq-type resonance.

We consider $\gamma p$ colliders as complementary machines to

- reveal leptoquark properties such as couplings, spin, charge, mass
- be better than corresponding $ep$ colliders for $\mu q$ and $\tau q$ type leptoquarks
- study anomalous coupling of vector leptoquarks at photon vertex.

**Table 3.** Calculated upper mass values for single and pair vector leptoquark production at LHC when the search limit is 100 events/year.

| pp | LHC($10^5 pb^{-1}$,14 TeV) |
|---|---|
| $M_{LQ}$ (single vector LQ production) | 2700-3500 GeV |
| $M_{LQ}$ (pair vector LQ production) | 1700 GeV |

**Table 4.** s-channel eq-type resonance production for scalar leptoquarks when leptoquark-fermion coupling constant is about $\alpha_{em}$

| ep | HERA | LHC/LEPI | LHC/LEPII |
|---|---|---|---|
| $M_{LQ}$ (scalar) | 270 GeV | 1100 GeV | 1300 GeV |

## 2. Leptoquark Production at $\gamma p$ Colliders

### 2.1. Pair Production of Scalar Leptoquarks

The scalar leptoquark pair is produced through the subprocess $\gamma g \to S^+S^-$ where $S$ denotes scalar leptoquark. The unknown parameters are the mass and electromagnetic charge of a leptoquark in this process which is the simplest case to investigate these parameters. Upper values which can be reached for scalar leptoquark masses for proposed colliders[3, 4] are given in Table 5[5]

**Table 5.** Parameters of gamma-proton colliders and upper mass limits for scalar leptoquark if the search limit is 100 events/year. Numbers in parentheses stand for electromagnetic charges of leptoquarks.

| Colliders | $\sqrt{s_{\gamma p}}^{max}$ | $\mathcal{L}_{\gamma p}(10^{30} cm^{-2} s^{-1})$ | $M_S$(5/3) | $M_S$(-1/3) |
|---|---|---|---|---|
| HERA+LC | 1.16 TeV | 25 | 0.27 TeV | 0.12 TeV |
| LHC+e-Linac | 2.77 TeV | 500 | 0.75 TeV | 0.45 TeV |
| LHC+TESLA | 5.06 TeV | 500 | 1.15 TeV | 0.62 TeV |

### 2.2. Pair Production of Vector Leptoquarks

In order to understand the gauge structure of vector leptoquarks in a model independent way the proposed high energy $\gamma p$ colliders are complementary tools. The following effective Lagrangian is responsible for the interactions of vector leptoquarks with photons and gluons:

$$L_V = -\frac{1}{2}G^{\dagger}_{\mu\nu}G^{\mu\nu} + M_V^2 V_\mu^\dagger V^\mu - ie\kappa_\gamma V_\mu^\dagger F_1^{\mu\nu} V_\nu - ig_s\kappa_g V_\mu^\dagger F_2^{\mu\nu} V_\nu$$

Here $\kappa_\gamma$ and $\kappa_g$ are anomalous couplings of vector leptoquarks to photons and gluons. $F_1$ , $F_2$ and $G$ are field strength tensors of photon, gluon and leptoquark fields. It is clear that the production of vector leptoquark pair via $\gamma g \to V^+V^-$ is one of the simple cases to investigate anomalous couplings. Taking 100 events per year as search limit we give the upper observable mass limits of the vector leptoquarks $V$ for $\kappa_\gamma = \kappa_g$ in Table 6 [6].

**Table 6.** Upper limits for vector leptoquark masses for anomalous couplings $\kappa = 0$ and $\kappa = 1$ in the case of pair production at proposed gamma-proton colliders with $Q_V = 5/3$.

| Colliders | $M_V(\kappa = 0)$ | $M_V(\kappa = 1)$ |
|---|---|---|
| HERA+LC | 0.36 TeV | 0.41 TeV |
| LHC+e-Linac | 0.92 TeV | 1.02 TeV |
| LHC+TESLA | 1.54 TeV | 1.74 TeV |

### 2.3. Single Production of Leptoquarks

It is known that $(eu)$ and $(ed)$ type leptoquarks can be produced singly at the $ep$ collider HERA via an electron-quark fusion process. In hadron colliders single leptoquarks of $(eq)$, $(\mu q)$ and $(\tau q)$ type are produced in association with leptons through quark-gluon collisions. In addition, single leptoquarks of any type can also be produced in $\gamma p$ colliders by exploiting photon-quark collisions such as $\gamma q \to \ell V$ $(\ell S)$. It is here that we expect to study unknown couplings of leptoquarks to fermions . We use the conventional parametrization $g_i^2 = 4\pi\alpha_{em}k_i$ to scale coupling contants to electromagnetic coupling, where $g_{2L}$,..$h_{3L}$ are replaced by $g_i$. Using the parameters of proposed $\gamma p$ colliders upper mass limits of vector leptoquarks are shown in Table 7 [7]for the coupling parameter $k_i = 1$, $\kappa_\gamma = 0$ and 100 events per year for leptoquark searches.

**Table 7.** Upper observable mass limits for vector leptoquarks with $k_i = 1$ and $Q_V = 5/3$.

| Colliders | $M_V(eq)$ | $M_V(\mu q)$ | $M_V(\tau q)$ |
|---|---|---|---|
| HERA+LC | 0.66 TeV | 0.60 TeV | 0.55 TeV |
| LHC+e-Linac | 1.80 TeV | 1.70 TeV | 1.60 TeV |
| LHC+TESLA | 2.90 TeV | 2.70 TeV | 2.55 TeV |

### 2.4. Signals and SM Backgrounds

| Signals (Pair LQ Production) | SM Backgrounds |
|---|---|
| 2j+$\ell\overline{\ell}$ | No |
| 2j+$\ell + P_T^{miss}$ | No |
| 2j+$P_T^{miss}$ | No |

The signal for pair production of leptoquarks shows a pair of sharp peaks with the same invariant mass $M_{j\ell}$. Moreover, the jets in leptoquark decay will be widely separated. The pair production of leptoquarks is , in principle, free of SM background.

| Signals (Single LQ Production) | SM Backgrounds |
|---|---|
| j+2$\ell$ | $\gamma q \to Zq$ |
| j+$\ell + P_T^{miss}$ | $\gamma q \to Wq$ |
| j+$P_T^{miss}$ | $\gamma q \to Zq$ |

In single production of leptoquarks, in order to eliminate SM background effects we impose the requirement that the leptoquark signal should have a sharp invariant mass peak in $M_{j\ell}$ at $M_{LQ}$ which is absent in the SM processes. Furthermore, W and Z signals include mass peaks in $M_{\ell\nu}$ and $M_{\ell\ell}$ at $M_W$ and $M_Z$ which are not present in leptoquark production. When compared with hadron colliders, $\gamma p$ machines may have a clearer background for the leptoquark production.

## 3. Conclusion

If leptoquark type events are discovered it will be important to determine quantum numbers, gauge couplings and underlying physics of these events. Therefore a more comprehensive study, such as detailed background calculations (MC reconstruction) under experimental conditions are needed to make a reliable decision about the possible advantages of $\gamma p$ colliders.

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