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O.Çakır and S.Atağ

May 1994

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O. Çakır and S. Atağ

*Ankara University, Faculty of Sciences, Department of Physics
Tandoğan, Ankara, Turkey*

We study the prospect for the detection of vector leptoquarks in the collision of high energy γ and proton beams. It is shown that proposed γp colliders make the single and pair production of vector leptoquarks quite feasible.

PACS number(s) : 14.80. -j, 12.60. -i

Typeset Using *REVTEX*

I. INTRODUCTION

The physics of elementary particles has been shaped by the identification of quarks and leptons as fundamental constituents of matter and by the gauge theory unification of the fundamental interactions. The "Standard Model" of QCD plus the $SU(2)_W \times U(1)_Y$ electroweak theory has turned out to be the basic theory of the elementary particle phenomenology, consistent with the data at presently available energies (100 GeV). It is of great importance to continue to test the standard model at higher energies. However, it is widely believed that a new phenomena must occur at the TeV energy scale.

We consider preonic models as the prominent candidates for the physics beyond the standard model. In any of preonic models, there are excitations of the known particles (leptons, quarks and vector bosons) and the particles carrying unusual quantum numbers. Leptoquarks are the particles which carry both lepton and baryon numbers.

For a more complete understanding of new physics, multi-TeV high luminosity colliders must be needed. The plans are being developed for construction of future high energy colliders like the familiar pp , e^+e^- and standard type ep machines. The most proper way of achieving the TeV scale at a constituent level is colliding of protons from a large hadron machine with electrons from a linac.

Along side the known machines above, the possibility of γ -proton colliders [1-3] has been discussed to explore the realm of the TeV scale at a subprocess level. The construction of γp colliders will be possible on the basis of Linac-Ring type ep machines [1, 4, 5]. The high energy real photon beam can be realized by means of Compton backscattering of laser photons off a beam of linac electrons. This was originally proposed for the construction of γe and $\gamma\gamma$ colliders on the basis of e^+e^- linacs [6-9]. The physics at γe and $\gamma\gamma$ colliders has been extensively discussed [10-14] in recent years. In the search for new physics beyond the standard model, there is much

to be learned from γp colliders. Earlier studies have described some of the physics capabilities of the future γp colliders, including the single and pair productions of scalar leptoquarks [15–18].

In this work, we proceed to study the development of physics program of γp colliders by investigating the signature for the production of vector leptoquarks.

For vector leptoquark interactions with fermions we write the following most general lagrangian [19] which is invariant under $SU(3)_C \times SU(2)_W \times U(1)_Y$:

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

where q_L and ℓ_L are the $SU(2)_W$ left handed quark and lepton doublets, and $\psi^c = C\bar{\psi}^T$ is the charge conjugated fermion field. 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.[19] 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. There are constraints imposed on leptoquark masses and coupling constants from low energy experiments [20, 21]. From here on the conventional parametrization $g_i^2 = 4\pi\alpha_{em}k_i$ will be used to scale coupling constants to electromagnetic coupling, where $g_{2L}, \dots, h_{3L}$ are replaced by g_i .

II. SINGLE PRODUCTION OF VECTOR LEPTOQUARKS

Single vector leptoquarks can be produced through the subprocess $\gamma q \rightarrow V\ell$ where q refers to u and d quarks, and V to any type of vector leptoquarks. The

Feynman amplitude consists of t, u and s channels which correspond to lepton, leptoquark and quark exchanges, respectively. Using the interaction lagrangian (1) it is straightforward to obtain the differential cross section

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{|M_{if}|^2}{16\pi(\hat{s} - M_q^2)^2}, \quad (2)$$

$$|M_{if}|^2 = (4\pi\alpha_{em})^2 k \left\{ \frac{Q_\ell^2}{(\hat{t} - M_\ell^2)^2} A_1 + \frac{Q_V^2}{(\hat{u} - M_V^2)^2} A_2 + \frac{Q_q^2}{(\hat{s} - M_q^2)^2} A_3 \right. \\ \left. + \frac{Q_\ell Q_V}{(\hat{t} - M_\ell^2)(\hat{u} - M_V^2)} A_4 + \frac{Q_\ell Q_q}{(\hat{t} - M_\ell^2)(\hat{s} - M_q^2)} A_5 \right. \\ \left. + \frac{Q_V Q_q}{(\hat{u} - M_V^2)(\hat{s} - M_q^2)} A_6 \right\}, \quad (3)$$

where the expressions A_i are given in the Appendix and $\hat{s} = (p_\gamma + p_q)^2$, $\hat{t} = (p_\ell - p_\gamma)^2$, $\hat{u} = (p_\ell - p_q)^2$ are Lorentz invariant Mandelstam variables, and p_γ , p_q , p_ℓ and M_V denote photon, quark, lepton momenta and vector leptoquark masses, respectively. Q_ℓ , Q_q and Q_V are lepton, quark and vector leptoquark charges. The cross sections are equal for both left handed and right handed leptoquarks (polarized beam calculations will help to study chirality of the couplings).

By changing $q \leftrightarrow e^-$ in Eq. (3) it easy to extract the differential cross section for the vector leptoquark production through the subprocess $\gamma e^- \rightarrow V q$ [13].

The integration over $\hat{t}$ can be carried out analytically. Further integrations over the photon spectrum and quark distribution in the proton should be performed to get the cross section for the reaction $\gamma p \rightarrow V \ell X$:

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^1 \frac{dx}{x} f_\gamma\left(\frac{\tau}{x}\right) f_q(x) \hat{\sigma}(\tau s), \quad (4)$$

where

$$\tau_{min} = \frac{(M_\ell + M_V)^2}{s}, \quad \hat{s} = \tau s,$$

and f_γ is the energy spectrum of the backscattered photons from electrons [7]

$$f_\gamma(y) = \frac{1}{D} \left[1 - y + \frac{1}{(1-y)} - \frac{4y}{\xi(1-y)} + \frac{4y^2}{\xi^2(1-y)^2} \right], \quad (5)$$

with $D \simeq 1.84$ for $\xi \simeq 4.8$. $f_q(x)$ is the sum of valence and sea quark distribution functions with momentum fraction x inside the proton, taken from Eichten *et al.*, set 1 in Ref. [22].

The possible types of vector leptoquarks which can be produced in γp collision are shown in Table I. In numerical calculations we consider the subprocess $\gamma u \rightarrow V e^-$ as an illustration. The total cross sections against leptoquark masses are plotted in Fig. 1 (a)-(d) for various proposed γp machines whose parameters are given in Table II. Recent parameters of proposed e^+e^- colliders in Ref.[23] have been considered in the calculation of luminosities in Table II.

Since the leptoquark couples to $q\ell$ and $q\nu$, one anticipates the following signals for single leptoquark production: (a) $j + 2\ell$, (b) $j + \ell + p_T^{miss}$ or (c) $j + p_T^{miss}$. The background comes from the standard model processes: $\gamma q \rightarrow Zq$ for the case (a) and (c), and $\gamma q \rightarrow Wq$ for the case (b). In order to eliminate these effects we make the requirement that the leptoquark signal has a sharp invariant mass peak in $M_{j\ell}$ at M_V which is absent in the standard model processes. Furthermore, W and Z signals include mass peaks in $M_{\ell p_T^{miss}}$ and $M_{\ell^+\ell^-}$ at M_W and M_Z which are not present in the leptoquark production. The signal (a) is the most striking one for the existence of leptoquarks. Thus, when compared with hadron colliders γp machines have a clear background for the leptoquark production. This allows us to demand 100 or less events per year for the discovery limit for the leptoquark searches. Using the γp luminosities from Table II and cross sections from Fig. 1 (a)-(d) we find the upper mass limits for the vector leptoquarks. We consider two cases of scaling parameter $k = 1$ and $k = 0.1$ for the coupling constants and the resultant upper mass limits

are given in Table II. Furthermore, we give observable mass limits even at smaller couplings for some colliders in Table III. It is seen that for the coupling parameters as small as $k \simeq 10^{-2} - 10^{-3}$ single vector leptoquarks can be observed with masses at 200-300 GeV.

III. PAIR PRODUCTION OF VECTOR LEPTOQUARKS

The vector leptoquark pair can be produced via the subprocess $\gamma g \rightarrow V^+ V^-$ in γp collision. The Feynman diagrams contributing to this process include t and u channels which correspond to the V exchange, and the quartic vertex $\gamma g V^+ V^-$. With usual steps, the total cross section for the subprocess is found to be

$$\hat{\sigma} = \frac{N_c \pi \alpha_{em} \alpha_s Q_V^2}{(1 - \beta^2) \hat{s}} \left[2\beta(22 - 9\beta^2 + 3\beta^4) + 3(1 - \beta^2 - \beta^4 + \beta^6) \ln \left(\frac{1 - \beta}{1 + \beta} \right) \right], \quad (6)$$

with

$$\beta = \sqrt{1 - \frac{4M_V^2}{\hat{s}}},$$

where $\hat{s}$, α_s and $N_c = 1/2$ are the Mandelstam variable, strong coupling constant and color factor from the average over all incoherent sum, respectively. Following the similar steps of the previous section we integrate Eq. (6) over gluon and photon distributions in order to obtain the total cross section for the process $\gamma p \rightarrow V^+ V^- X$:

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^1 \frac{dx}{x} f_\gamma \left(\frac{\tau}{x} \right) G(x, Q^2) \hat{\sigma}(\tau s), \quad (7)$$

with

$$\tau_{min} = \frac{4M_V^2}{s},$$

where $G(x, Q^2)$ is the gluon distribution function in the proton [22] which is given by

$$G(x, Q^2) = \frac{1}{x} (2.62 + 9.17x) (1 - x)^{5.90}. \quad (8)$$

The strong coupling constant α_s has been evaluated at $Q^2 = \hat{s}/2$ with the parametrization of Eichten *et al.*, in Ref. [22]. Figs. 2 (a)-(b) show the behaviour of the cross sections as a function of vector leptoquark masses for several γp colliders. One should note that the coupling constant is model independent in the case of pair production.

The pair production of leptoquarks gives the signals (a) $2j + \ell\bar{\ell}$ (b) $2j + \ell\nu$ (c) $2j + \nu\bar{\nu}$. The recognition of (a) is the easiest one since the signal for pair production of leptoquark shows a pair of sharp peaks with same invariant mass $M_{j\ell}$. Moreover, the jets in leptoquark decay will be widely separated. Thus, the pair production of leptoquarks is, in principle, free of background coming from the standard model processes. Taking 100 events per year as discovery limit we give the upper observable mass limits of the vector leptoquarks in Table IV.

IV. CONCLUSION

In this paper we have investigated the manifestation of preonic models through the production of vector leptoquarks at proposed γp colliders. It turns out that high energy γp colliders are sensitive to leptoquark masses up to a few TeV and have clear standard model background in most cases. Additional studies will be interesting to examine the polarization effects on the leptoquark couplings to fermions by means of the polarized photons and possibly protons. In searching for the vector leptoquarks, among the familiar colliders, γp machines will play their own roles in the future.

ACKNOWLEDGMENTS

We are grateful to S. Sultansoy for suggesting the problem and valuable discussions. We would also like to thank Harun Artuner for his kind help with e-mail facility. This research was supported in part by TUBITAK under TBAG/ÇG-1.

APPENDIX

The expressions A_i appearing in Eq. (3) for the single production of vector leptoquarks through the subprocess $\gamma q \rightarrow V\ell$ are given by

$$A_1 = -\frac{1}{2M_V^2} \left\{ M_\ell^4(M_q^2 + M_V^2 - \hat{t}) + M_\ell^2 M_q^2(3M_q^2 + 4M_V^2 - \hat{s} - 7\hat{t}) \right. \\ \left. - 2M_\ell^2 M_V^2(2M_V^2 + \hat{s}) + M_\ell^2 \hat{t}(\hat{s} + 4\hat{t}) - M_q^4 \hat{t} \right. \\ \left. + M_q^2 \hat{t}(-2M_V^2 + \hat{s} + 2\hat{t}) + M_V^2 \hat{t}(2\hat{s} + \hat{t}) - \hat{t}^2(\hat{s} + \hat{t}) \right\}, \quad (A1)$$

$$A_2 = \frac{1}{4M_V^4} \left\{ M_\ell^2 \left[2M_q^2[2(\hat{s} + \hat{t})^2 + 7M_V^2(\hat{s} + \hat{t})] - M_q^4(6\hat{s} + 5\hat{t} + 7M_V^2) \right. \right. \\ \left. - M_V^2(5\hat{s}^2 + 8\hat{s}\hat{t} + 5\hat{t}^2) - \hat{t}(\hat{s} + \hat{t})^2 + 2M_V^4(3\hat{s} - \hat{t}) + 2M_q^6 + 8M_V^6 \right] \\ \left. - M_\ell^4[M_q^2(5\hat{s} + 6\hat{t} + 7M_V^2) - 2(\hat{s} + \hat{t})(M_V^2 + \hat{t}) - 4M_q^4 + 4M_V^4] \right. \\ \left. + 2M_q^4[(M_V^2 + \hat{s})(\hat{s} + \hat{t}) - 2M_V^4] \right. \\ \left. - M_q^2[M_V^2(5\hat{s}^2 + 8\hat{s}\hat{t} + 5\hat{t}^2) + \hat{s}(\hat{s} + \hat{t})^2 + 2M_V^4(\hat{s} - 3\hat{t}) - 8M_V^6] \right. \\ \left. + M_\ell^6(2M_q^2 + M_V^2 - \hat{t}) + M_q^6(M_V^2 - \hat{s}) + 2M_V^2[\hat{s}^2(\hat{s} + 2\hat{t}) + \hat{t}^2(\hat{t} + 2\hat{s})] \right. \\ \left. + 2M_V^4(\hat{s} - \hat{t})^2 - 12M_V^6(\hat{s} + \hat{t}) + 8M_V^8 \right\}, \quad (A2)$$

$$A_3 = -\frac{1}{2M_V^2} \left\{ M_\ell^4(3M_q^2 - \hat{s}) + M_\ell^2 M_q^2(M_q^2 + 4M_V^2 - 7\hat{s} - \hat{t}) \right. \\ \left. + M_\ell^2 \hat{s}(-2M_V^2 + 2\hat{s} + \hat{t}) + M_q^4(M_V^2 - \hat{s}) - 2M_q^2 M_V^2(2M_V^2 + \hat{t}) \right. \\ \left. + M_q^2 \hat{s}(4\hat{s} + \hat{t}) + M_V^2 \hat{s}(\hat{s} + 2\hat{t}) - \hat{s}^2(\hat{s} + \hat{t}) \right\}, \quad (A3)$$

$$\begin{aligned}
A_4 = \frac{1}{8M_V^4} \Big\{ & M_\ell^2 \left[M_q^2 [\hat{s}^2 + 4\hat{s}\hat{t} + 3\hat{t}^2 + M_V^2(\hat{s} + 29\hat{t}) - 2M_q^4] \right. \\
& - [M_V^2 \hat{t}(11\hat{s} + 13\hat{t}) - 2M_V^4(4\hat{s} - \hat{t}) + \hat{t}^2(\hat{s} + \hat{t}) - 16M_V^6] \\
& \left. - M_q^4(\hat{s} + 2\hat{t} + 11M_V^2) \right] - M_\ell^4 \left[M_q^2(3\hat{s} + 5\hat{t} + 4M_V^2) \right. \\
& \left. - [M_V^2(\hat{s} + 4\hat{t}) + \hat{t}(\hat{s} + 2\hat{t}) - 6M_V^4] - 2M_q^4 \right] \\
& - M_q^2[\hat{t}(9M_V^2 + \hat{s})(\hat{s} + \hat{t}) - 2M_V^4(2\hat{s} + 5\hat{t}) + 4M_V^6] \\
& + M_\ell^6(M_V^2 - \hat{t} + 2M_q^2) \\
& + 2M_V^2[\hat{t}(2\hat{s}^2 + 3\hat{s}\hat{t} + 2\hat{t}^2) - 2M_V^4(2\hat{s} + 3\hat{t}) + 4M_V^6 - 4M_V^2\hat{s}\hat{t}] \\
& \left. + M_q^4[M_V^2(4\hat{s} + 3\hat{t}) - 4M_V^4 + \hat{s}\hat{t}] \right\}, \tag{A4}
\end{aligned}$$

$$\begin{aligned}
A_5 = \frac{1}{2M_V^2} \Big\{ & M_\ell^4(M_V^2 - \hat{t}) + M_\ell^2 M_V^2(-3M_q^2 + M_V^2 - \hat{s} - \hat{t}) \\
& + 2M_\ell^2 \hat{s}\hat{t} + M_q^4(M_V^2 - \hat{s}) + M_q^2 M_V^2(M_V^2 - \hat{s} - \hat{t}) \\
& \left. + 2M_q^2 \hat{s}\hat{t} - 2M_V^6 + 2M_V^4(\hat{s} + \hat{t}) + \hat{s}\hat{t}(M_V^2 - \hat{s} - \hat{t}) \right\}, \tag{A5}
\end{aligned}$$

$$\begin{aligned}
A_6 = \frac{1}{8M_V^4} \Big\{ & M_\ell^2 \left[M_q^2[3\hat{s}^2 + 4\hat{s}\hat{t} + \hat{t}^2 + M_V^2(29\hat{s} + \hat{t}) - 2M_q^4] \right. \\
& - M_q^4(5\hat{s} + 3\hat{t} + 4M_V^2) \\
& \left. - \hat{s}(9M_V^2 + \hat{t})(\hat{s} + \hat{t}) + 2M_V^4(5\hat{s} + 2\hat{t}) + 2M_q^6 - 4M_V^6 \right] \\
& - M_\ell^4[M_q^2(2\hat{s} + \hat{t} + 11M_V^2) - M_V^2(3\hat{s} + 4\hat{t}) - 2M_q^4 + 4M_V^4 - \hat{s}\hat{t}] \\
& - M_q^2[M_V^2\hat{s}(13\hat{s} + 11\hat{t}) + \hat{s}^2(\hat{s} + \hat{t}) + 2M_V^4(\hat{s} - 4\hat{t}) - 16M_V^6] \\
& + M_q^4[M_V^2(4\hat{s} + \hat{t}) + \hat{s}(2\hat{s} + \hat{t}) - 6M_V^4] + M_q^6(M_V^2 - \hat{s}) \\
& \left. + 2M_V^2\hat{s}(2\hat{s}^2 + 3\hat{s}\hat{t} + 2\hat{t}^2) - 4M_V^6(3\hat{s} + 2\hat{t}) + 8M_V^8 - 8M_V^4\hat{s}\hat{t} \right\}. \tag{A6}
\end{aligned}$$

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FIGURES

FIG. 1. (a)-(d) Total cross sections for single production of vector leptoquarks as a function of their masses for proposed colliders.

FIG. 2. (a)-(b) Total cross sections for pair production of vector leptoquarks as a function of their masses for proposed colliders.

TABLES

TABLE I. Types and charges (Q_V) of vector leptoquarks (V) which can be produced in γp collision. LH and RH denote left handed and right handed.

Process	Q_V	Type and Chirality
$\gamma u \rightarrow Ve^-$	5/3	$\tilde{U}_1(RH), U_3(LH)$
$\gamma u \rightarrow Ve^+$	-1/3	$V_2(RH), \tilde{V}_2(LH)$
$\gamma d \rightarrow Ve^-$	2/3	$U_1(LH), U_1(RH), U_3(LH)$
$\gamma d \rightarrow Ve^+$	-4/3	$V_2(LH), V_2(RH)$
$\gamma u \rightarrow V\nu$	2/3	$U_1(LH), U_3(LH), U_1(RH)$
$\gamma u \rightarrow V\bar{\nu}$	2/3	$\tilde{V}_2(LH), V'_2(RH)$
$\gamma d \rightarrow V\nu$	-1/3	$U_3(LH), \tilde{U}'_1(RH)$
$\gamma d \rightarrow V\bar{\nu}$	-1/3	$V_2(LH), V'_2(RH)$

TABLE II. Parameters of γp colliders and discovery limits for vector leptoquark masses M_V with the charge $Q_V = 5/3$ for the single production. The results are presented for the two values of the coupling parameter $k = 1$ and $k = 0.1$ (The numbers in parantheses). $s_{\gamma p}^{max} = 0.83s_{ep}$.

Machines	$\sqrt{s_{ep}}$ (TeV)	$\mathcal{L}_{\gamma p}$ ($10^{30}cm^{-2}s^{-1}$)	M_V (TeV)
HERA+DLC	1.28	25	0.66(0.43)
UNK+VLEPP	3.46	30	1.33(0.66)
LHC+CLIC	7.85	50	2.30(1.00)
LHC+TESLA	5.50	500	2.90(1.90)
LHC+Linac1	3.04	500	1.80(1.35)
SSC+NLC	8.94	350	3.88(2.17)
SSC+LSC	28.3	200	5.75(2.20)
SSC+Linac2	8	800	4.10(2.65)
Fermilab+NLC	2	20	0.86(0.49)
Fermilab+Linac1	1.1	60	0.65(0.47)

TABLE III. Observable upper masses of vector leptoquarks at various γp machines for different coupling parameter k in the case of single production.

k	$M_V(\text{TeV})$				
	HERA+DLC	LHC+Linac1	LHC+TESLA	SSC+NLC	SSC+LSC
0.50	0.59	1.70	2.62	3.37	4.30
0.05	0.35	1.17	1.60	1.70	1.55
0.01	0.20	0.77	0.92	0.87	0.75
0.005	—	0.60	0.68	0.62	0.55
0.001	—	0.32	0.33	0.30	0.27

TABLE IV. Parameters of γp colliders and discovery limits for vector leptoquark masses M_V with the charge $Q_V = 5/3$ for the pair production. $s_{\gamma p}^{max} = 0.83s_{ep}$.

Machines	$\sqrt{s_{ep}}$	$\mathcal{L}_{\gamma p}$	M_V
	(TeV)	($10^{30}cm^{-2}s^{-1}$)	(TeV)
HERA+DLC	1.28	25	0.37
UNK+VLEPP	3.46	30	0.86
LHC+CLIC	7.85	50	1.70
LHC+TESLA	5.50	500	1.56
LHC+Linac1	3.04	500	0.93
SSC+NLC	8.94	350	2.28
SSC+LSC	28.3	200	5.10
SSC+Linac2	8	800	2.22
Fermilab+NLC	2	20	0.52
Fermilab+Linac1	1.1	60	0.34

FIG. 1(a).

FIG. 1(b).

FIG. 1(c).

FIG. 1(d).

FIG. 2(a).

FIG. 2(b).