

Composite vector leptoquarks in e^+e^- , γe , and $\gamma\gamma$ colliders

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We study the signals for composite vector leptoquarks in e^+e^- colliders (CERN e^+e^- collider, LEP II, Next Linear Collider, and CERN Linear Collider) through their effects on the production of jet pairs, as well as their single and pair productions. We also analyze their production in γe and $\gamma\gamma$ collisions.

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I. INTRODUCTION

The standard electroweak theory provides a very satisfactory description of most elementary particle phenomena up to the presently available energies. However, there are experimental facts, such as the proliferation of the fermion generations and their complex pattern of masses and mixing angles, that are not predicted by the standard model. A rather natural explanation for the existence of the fermion generations is that the known particles (leptons, quarks, and vector bosons) are composite. In general, composite models exhibit a very rich spectrum which includes many new states such as excitations of the known particles and bound states which cannot be viewed as excitations of the familiar particles, since they possess rather unusual quantum numbers. Among these are leptoquarks, which are particles carrying simultaneously leptonic and baryonic number. Leptoquarks are naturally present in a variety of theories beyond the standard model such as some technicolor models [1], grand unified theories [2], E_6 superstring-inspired models [3], and composite models [4].

In the present work we study the production of vector leptoquarks in e^+e^- , $e\gamma$, and $\gamma\gamma$ collisions. We shall consider two sources of photons: they can be produced either by bremsstrahlung or by backscattering laser light of the incident positron (electron) beam [5]. Here an intense hard-photon beam is generated by backward Compton scattering of soft photons from a laser of a few eV energy. We shall not consider beamstrahlung photons since its spectrum depends strongly on the machine design.

For definiteness we shall consider the vector leptoquarks predicted by the Abbott-Farhi model [4]. The La-

grangian of this model has the same form as the standard model one. However, the parameters determining the potential for the scalar field and the strength of the $SU(2)_L$ gauge interaction are such that no spontaneous symmetry breaking occurs and the $SU(2)_L$ gauge interaction is confining. The model is essentially the confining version of the standard model and is also called the strongly coupled standard model (SCSM). The spectrum of physical particles in the SCSM consists of $SU(2)_L$ gauge singlets, including fundamental particles which are neutral with respect to the $SU(2)_L$ force, such as the right-handed fermions and the $U(1)$ gauge boson. For instance, the physical left-handed fermions are bound states of a preonic scalar and a preonic dynamical left-handed fermion, while the vector bosons are P -wave bound states of the scalar preons. Provided some dynamical assumptions on the model hold true, it has been shown [6] that the predictions of the SCSM model are consistent with the present experimental data.

We denote the preonic left-handed fermionic doublet by ψ_L^a , with the flavor index a running from 1 to 12 for three families. ψ_L^a belongs to a $\mathbf{2}$ representation of the $SU(2)_L$ and to the $(0, \frac{1}{2})$ representation of the Lorentz group. The vector leptoquarks in the SCSM model are bound states of the form $\psi_L^{a\dagger}\psi_L^b$, where ψ_L^a carries baryon number while ψ_L^b carries lepton number. We define V_μ^{ab} as the interpolating field for the vector leptoquarks, which is an $SU(2)_L$ singlet, belongs to the $(\frac{1}{2}, \frac{1}{2})$ representation of the Lorentz group and is a triplet under $SU(3)_{\text{color}}$. From its preonic content it follows that these particles have an electric charge $-\frac{2}{3}$.

The SCSM model cannot be analyzed perturbatively since it is strongly interacting at the energy scale of interest. Instead, we describe the interaction between leptoquarks and physical left-handed fermions by an effective Lagrangian [7]. We assume that

$$\mathcal{L}_{\text{int}} = -F \frac{e}{2\sqrt{2}\sin\theta_W} \left(V_\mu^{ab\dagger} \bar{L}^a \gamma^\mu L^b + \text{H.c.} \right) \quad (1)$$

describes the low-energy interactions of V_μ^{ab} , where L^a

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are physical left-handed doublets under the global $SU(2)$ symmetry of the model [6], and θ_W is the weak mixing angle. The parameter F is a measure of the strength of this interaction compared to the $Wq\bar{q}'$ vertex. Notice that the vector leptoquarks couple to both upper (or lower) components of the lepton and quark doublets. It is important to realize that the above \mathcal{L}_{int} conserves charge, color, and baryonic and leptonic numbers.

It is also natural to assume that vector leptoquarks V_μ^{ab} interact with the photon and the physical Z . In this work we assume that the couplings of vector leptoquarks to Z 's and γ 's are similar to the W boson ones to these particles. Therefore, we postulate the Feynman rules (see Fig. 1)

$$\Gamma_{\alpha\beta\rho}^{\gamma V^- V^+} = ieQ_V \{g_{\alpha\beta}(p_1 - p_2)_\rho + g_{\beta\rho}(p_2 - p_3)_\alpha + g_{\rho\alpha}(p_3 - p_1)_\beta\}, \quad (2)$$

$$\Gamma_{\alpha\beta\rho\sigma}^{\gamma\gamma V^+ V^-} = -ie^2 Q_V^2 \{2g_{\alpha\beta}g_{\rho\sigma} - g_{\alpha\sigma}g_{\beta\rho} - g_{\alpha\rho}g_{\beta\sigma}\}, \quad (3)$$

$$\Gamma_{\alpha\beta\rho}^{ZV^- V^+} = -iF_Z^2 e \cot\theta_W \times \{g_{\alpha\beta}(p_1 - p_2)_\rho + g_{\beta\rho}(p_2 - p_3)_\alpha + g_{\rho\alpha}(p_3 - p_1)_\beta\}, \quad (4)$$

where $Q_V (= -\frac{2}{3})$ is the electric charge of the vector leptoquark and F_Z is a free parameter. The couplings in Eqs. (2) and (3) were obtained via minimal substitution and assuming that V_μ^{ab} has an anomalous magnetic moment $\kappa = 1$.

The absence of experimental evidence for compositeness constrains the low-energy phenomenology of the SCSM. These constraints can, in principle, place bounds on the vector leptoquark mass (M_V) and coupling constants (F and F_Z). In fact, the analyses of the contribution of vector leptoquarks to the four-fermion Fermi interaction at low energies lead to the constraint [7]

$$M_V > 197 F \text{ (GeV)}. \quad (5)$$

In practice, contributions from other states soften this bound [8], so that M_V and F are in reality free param-

eters. However, an educated guess for the coupling F can be made as follows. In the SCSM model the Z and the W are bound states of two preonic scalars; therefore, it is natural to assume that the coupling of vector leptoquarks to physical left-handed fields is of the same order of the coupling of these fermions to W 's and Z 's, i.e., F is of order 1. Analogously, we expect that $F_Z \simeq F \simeq 1$.

We can constrain the couplings F and F_Z imposing that unitarity is respected at the tree level [9]. For instance, the process $e^+e^- \rightarrow V^+V^-$ violates unitarity at high energies for arbitrary values of the couplings. However, if we choose $F = F_Z = \sqrt{|Q_V|} = \sqrt{\frac{2}{3}}$, unitarity at tree level is restored.

The main decay mode of vector leptoquarks is into a pair lq or $\nu q'$, therefore, its signal is a lepton plus a jet, or a jet plus missing energy. Using the couplings given above we obtain that the width of a vector leptoquark is given by

$$\Gamma_V = \frac{\alpha F^2}{4 \sin^2 \theta_W} M_V, \quad (6)$$

where we neglected all the fermion masses and summed over the possible decay channels.

The outline of this paper is the following. The analysis of the indirect signals for leptoquarks is contained in Sec. II: One way to look for vector leptoquarks in e^+e^- colliders is through their effects on the production of jet pair ($e^+e^- \rightarrow q\bar{q}$), since they can be exchanged in the t channel. Another way to search for these particles is to study the forward-backward asymmetry in the production of $b\bar{b}$ pairs. In Sec. III, we study the single production of vector leptoquarks through $e\gamma \rightarrow V^{eq}$, where the photons come either from bremsstrahlung or from laser backscattering. In Sec. III we also discuss the signal and its potential backgrounds. Pairs of vector leptoquarks can also be produced provided that there is enough available energy. Section IV exhibits the study of the production of vector-leptoquark pairs in e^+e^- and $\gamma\gamma$ colliders. We summarize our results in Sec. V. The Appendix presents the relevant expressions for the photon distribution functions used throughout this paper.

II. INDIRECT EVIDENCE FOR VECTOR LEPTOQUARKS

We can look for signals of leptoquarks even when the available center-of-mass energy is not enough to produce these particles on shell. This can be done through the study of their effects as an intermediate state of reactions like $e^+e^- \rightarrow$ dijets and $e^+e^- \rightarrow b\bar{b}$.

A. Total cross section $e^+e^- \rightarrow q\bar{q}$

The existence of vector leptoquarks can be investigated through the analysis of the reaction $e^+e^- \rightarrow q\bar{q}$, where they lead to a new t -channel contribution, in addition to the usual exchange of γ and Z in the s channel. Using the vertices derived from the interaction Lagrangian (1), the cross section for this process is given by

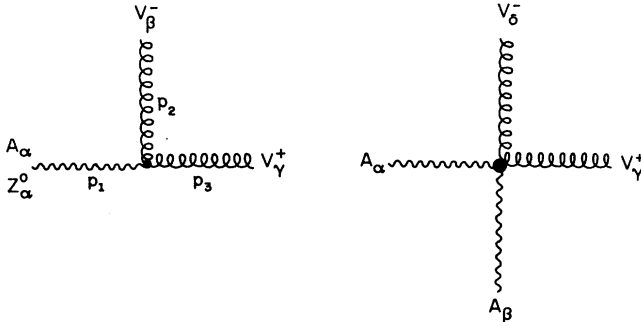


FIG. 1. Feynman rules for the vertices $\gamma V^+ V^-$, $\gamma\gamma V^+ V^-$, and $Z_0 V^+ V^-$.

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{em}^2}{4s} \left\{ Q^2(1 + \cos^2 \theta) + \frac{1}{16 \sin^4 \theta_W \cos^4 \theta_W} \frac{s^2}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \right. \\ \times [(C_V^e)^2 + (C_A^e)^2](C_V^q)^2 + (C_A^q)^2(1 + \cos^2 \theta) + 8C_V^e C_A^e C_V^q C_A^q \cos \theta] \\ - \frac{Q}{2 \sin^2 \theta_W \cos^2 \theta_W} \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} [C_V^e C_V^q(1 + \cos^2 \theta) + 2C_A^e C_A^q \cos \theta] \\ + \frac{F^2}{\sin^2 \theta_W} \frac{(1 + \cos \theta)^2}{\cos \theta - \eta} \left[\frac{F^2}{4 \sin^2 \theta_W} \frac{1}{\cos \theta - \eta} + \frac{Q}{2} \right. \\ \left. \left. - \frac{1}{8 \sin^2 \theta_W \cos^2 \theta_W} (C_V^q + C_A^q)(C_V^e + C_A^e) \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \right] \right\}, \quad (7)$$

where M_Z is the mass of the Z boson, θ_W is the weak mixing angle, and $\eta = 1 + 2M_V^2/s$. According to our conventions the charge of a quark is Qe ($e > 0$), $C_V = I_z - 2Q \sin^2 \theta_W$, and $C_A = I_z$.

The exchange of a vector particle in the t channel modifies the high-energy behavior of this process: within the scope of the standard model this cross section decreases as the center-of-mass energy increases, however, the new contribution alters this behavior, yielding a constant cross section at high energies which is given by

$$\sigma_{\text{limit}}(e^+e^- \rightarrow q\bar{q}) \simeq \frac{\pi}{4} \frac{\alpha^2 F^4}{\sin^4 \theta_W} \frac{1}{M_V^2}. \quad (8)$$

This is a dramatic signal because there will be many more dijets than expected in the scope of the standard model at high energies. In Fig. 2, we exhibit the cross section $\sigma(e^+e^- \rightarrow q\bar{q})$ as a function of center-of-mass energy for different values of the vector leptoquark mass and for $F = \sqrt{2/3}$. This figure was obtained imposing the cut $|\cos \theta| < 0.9$, and assuming the existence of three vector leptoquarks (V^{ed} , V^{es} , V^{eb}), which have the same mass and values for the coupling constants. Notice that after the Z peak the results, which include the leptoquark,

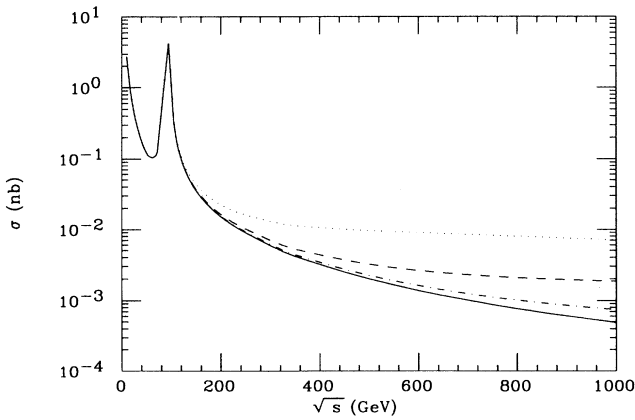


FIG. 2. Total cross section for the production of two jets as a function of the collider center-of-mass energy. The solid line stands for the standard model result, while the dotted, dashed, and dot-dashed lines include the contribution of a vector leptoquark of mass 300, 700, and 1500 GeV, respectively.

depart significantly from the standard model prediction.

In order to estimate the capabilities of the different colliders [CERN e^+e^- collider (LEP II), Next Linear Collider (NLC), CERN Linear Collider (CLIC)] to search for leptoquarks, we evaluate the largest mass of a vector leptoquark, keeping F fixed, for which the cross section for dijet production differs by 10% from the standard model result. In our estimates we were conservative assuming that only one vector leptoquark contributes to this reaction. We have defined

$$\Delta \equiv \frac{\sigma - \sigma_{WS}}{\sigma_{WS}}, \quad (9)$$

where σ is the total cross section including the leptoquark contribution and σ_{WS} is the standard model result. Figure 3 displays F as a function of M_V , which satisfies the constraint $\Delta(F, M_V) = 10\%$, for several collider center-of-mass energies. From this figure, we can learn that an e^+e^- collider with center-of-mass energy of 200 (1000) GeV will be able to unravel the existence of vector leptoquarks of masses up to 400 (2000) GeV, assuming $F = \sqrt{2/3}$.

B. Forward-backward asymmetry for $b\bar{b}$ pairs

Another indirect way to look for the vector leptoquark V^{eb} is studying the forward-backward asymmetry in the

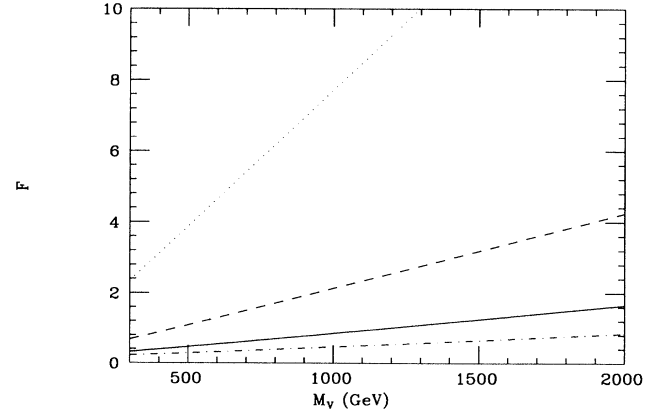


FIG. 3. F as a function of M_V for several \sqrt{s} : the dotted, dashed, solid, and dot-dashed lines stand for $\sqrt{s} = 100, 200, 500, \text{ and } 1000$ GeV, respectively.

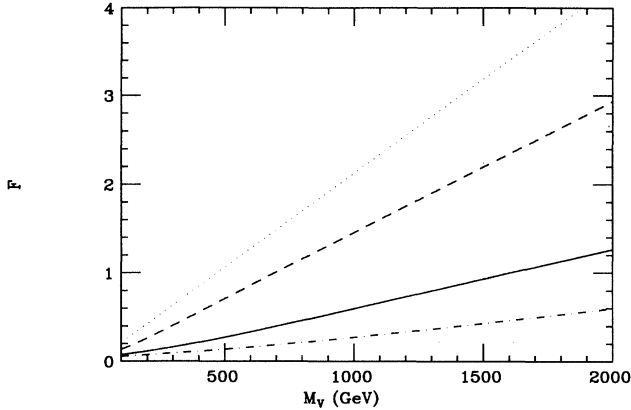


FIG. 4. Allowed values of the coupling F and M_V from the experimental results from LEP for $b\bar{b}$ production (dotted line). The dashed, solid, and dot-dashed lines are the region for which the forward-backward asymmetry is 5%, for center-of-mass energies of 200, 500, and 1000 GeV, respectively.

production of $b\bar{b}$ pairs. Recently at LEP this asymmetry has been measured [10] and it is in agreement with the standard model prediction. Imposing that the contribution of this vector leptoquark to this reaction is at most of the size of the experimental error (5%), we can exclude a region of the plane $M_V \times F$, as is shown by the dotted line in Fig. 4. Assuming $F = \sqrt{\frac{2}{3}}$, the data constrain the mass of the eb leptoquark to be bigger than $\simeq 370$ GeV.

From Fig. 4, we can also foresee the potential of the future e^+e^- machines for discovering the leptoquark V^{eb} : The dashed, solid, and dot-dashed lines indicate the region for which the forward-backward asymmetry is 5%, for center-of-mass energies of 200, 500, and 1000 GeV, respectively. For $F = \sqrt{\frac{2}{3}}$, LEP II (NLC, CLIC) should be able to look for V^{eb} with mass up to 600 (1300, 2300) GeV.

III. SINGLE PRODUCTION OF VECTOR LEPTOQUARKS

We can produce a single vector leptoquark V^{eq} ($q = d, s, b$) through the process $\gamma e^- \rightarrow V^{eq}q$. This process can take place in e^+e^- colliders, with the γ being produced by bremsstrahlung, or in γe machines, with the γ originating from laser backscattering. The elementary cross section for this reaction is

$$\frac{d\hat{\sigma}}{d\hat{t}} = -N_c \frac{\pi}{36} \frac{F^2 \alpha^2}{\sin^2 \theta_W} \frac{[\hat{s} + 3(\hat{t} - M_q^2)]^2}{M_V^2 (\hat{s} + \hat{t} - M_q^2)^2 (\hat{t} - M_q^2)^2 \hat{s}^3} \times \left\{ (\hat{t} - M_q^2) [M_q^2 (\hat{s} + \hat{t})^2 + 2\hat{s}^2 M_V^2 + 4M_V^6 + M_q^6] - 4\hat{t} M_V^4 (\hat{s} + \hat{t}) + 2\hat{t} M_V^2 M_q^2 (\hat{s} - 2\hat{t} + M_V^2 + M_q^2) + 2\hat{s} M_q^6 + 2M_q^4 M_V^4 + 2\hat{t}^3 M_V^2 \right\}, \quad (10)$$

where $N_c = 3$ is the numbers of colors, \hat{s} is the center of

mass energy squared of the subprocess, $\hat{t} = M_V^2 - \frac{\hat{s}}{2}(1 - \beta \cos \theta^*)$, with β being the V^{eq} velocity in the subprocess c.m. and θ^* its angle with respect to the incident electron in this frame. In order to obtain the cross section for this reaction we must fold the above expression with the γ distribution function $[f_{\gamma/e}(x)]$ (see Appendix)

$$\sigma = \int_{x_{\min}}^1 dx f_{\gamma/e}(x) \hat{\sigma}(xs), \quad (11)$$

where $x_{\min} = (M_q + M_V)^2/s$. Figure 5 exhibits the behavior of σ as a function of M_V . As expected, the process initiated by laser backscattering possesses a cross section that is one order of magnitude larger than the processes initiated by bremsstrahlung photons, with the same M_V and s .

Once the leptoquark couples to eq and $\nu q'$ with the same strength, the signal for its single production is either $(e)jj\bar{p}_T$ or $(e)jje$, where the spectator e is usually lost in the beam pipe in the case of e^+e^- colliders. The main background for the signal $(e)jj\bar{p}_T$ [$(e)jje$] comes from the process $\gamma e \rightarrow W\nu$ ($e\gamma \rightarrow Ze$) with the W (Z) decaying into two jets [11]. However, this background can be easily eliminated by requiring that the invariant mass of the jet pair is not close to M_W (M_Z).

At first sight, another potential background is the Bethe-Heitler production of hadrons ($\gamma e \rightarrow q\bar{q}$), which exhibits a large cross section. However, the main contribution to the cross section in this case is due to the region of small transverse momenta of the produced particles. This allows us to reject with a high efficiency this class of events by demanding that the observed particles and jets have a sufficiently high p_T .

In order to access the capability of the future colliders to establish the existence of leptoquarks through the reaction $e\gamma \rightarrow V^{eq}q$, we require the occurrence of 5000 events per year with the final state jje^- . Once the couplings $V^{eq}eq$ and $V^{eq}\nu q'$ are expected to be ap-

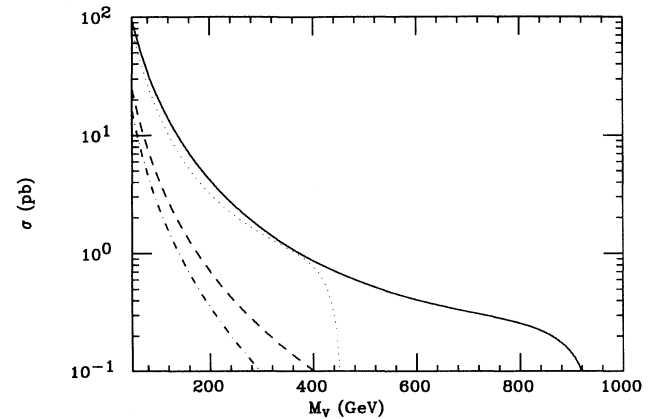


FIG. 5. Total cross section for the process $e^- \gamma \rightarrow V^- q$ as a function of M_V : (a) laser backscattering at $\sqrt{s} = 500$ GeV (dotted line); (b) laser backscattering at $\sqrt{s} = 1000$ GeV (solid line); (c) bremsstrahlung at $\sqrt{s} = 500$ GeV (dot-dashed line); (d) bremsstrahlung at $\sqrt{s} = 1000$ GeV (dashed line).

proximately equal, we take that $\sigma(jje^-) = \sigma(V^{eq})/2$. Assuming an integrated luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for the future machines, the maximum observable mass for an e^+e^- collider is $M_V = 300$ (400) GeV for $\sqrt{s} = 500$ (1000) GeV, while a collider γe using laser backscattering can unravel the existence of leptoquarks of mass up to $M_V = 450$ (900) GeV for a center-of-mass energy of 500 (1000) GeV.

IV. PAIR PRODUCTION OF VECTOR LEPTOQUARKS

A. $e^+e^- \rightarrow V^+V^-$

Pairs of vector leptoquarks can be produced in e^+e^- collisions provided that there is enough available energy ($\sqrt{s} \geq 2M_V$). This process takes place through the exchange of a quark in the t channel and through a Z and γ in the s channel. Using the interaction Lagrangians of Sec. I, it is easy to evaluate the cross section for this reaction, resulting that

$$\begin{aligned} \frac{d\sigma}{dt} = & \frac{F^4 \pi \alpha^2}{16s^2 t^2 M_V^4 \sin^4 \theta_W} [3st^2 M_V^2 - 4sM_V^6 + (t^2 + 4M_V^4)(t - M_V^2)(u - M_V^2)] \\ & + \frac{\pi \alpha^2 Q_V^2}{2s^4 M_V^4} [t(s^2 + tM_V^2)(u - M_V^2) + s^2 M_V^2 (s - u - 10M_V^2) + 2st^2 M_V^2 + stuM_V^2 \\ & - 4sM_V^4 (t - u) + 2su^2 M_V^2 + tu^2 M_V^2 + 8tuM_V^4 - u^2 M_V^4 - 8M_V^8] \\ & + \frac{F^2 \pi \alpha^2 Q_V}{4s^3 t M_V^4 \sin^2 \theta_W} [s^2 t M_V^2 + 4s^2 M_V^4 + st^2 (u - 3M_V^2) - 3st M_V^2 (u - M_V^2) + 4sM_V^4 (u + M_V^2) \\ & - 2t^2 M_V^2 (u - M_V^2) - 2tM_V^4 (u - M_V^2) + 4M_V^6 (u - M_V^2)] \\ & + \frac{F_Z^4 \pi \alpha^2}{8s^2 M_V^4 \sin^4 \theta_W} (C_V^2 + C_A^2) \frac{1}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} [s^2 M_V^2 (s - t - u - 10M_V^2) + s^2 tu + 8tuM_V^4 \\ & + stM_V^2 (2t + u - 4M_V^2) + 2suM_V^2 (u - 2M_V^2) + t^2 M_V^2 (u - M_V^2) \\ & + u^2 M_V^2 (t - M_V^2) - 8M_V^8] \\ & + \frac{F_Z^2 \pi \alpha^2 C_V Q_V}{2s^3 M_V^4 \sin^2 \theta_W} \frac{s - M_Z^2}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} [s^2 M_V^2 (s - u - 10M_V^2) + s^2 t (u - M_V^2) + t^2 M_V^2 (u - M_V^2) \\ & + stM_V^2 (2t + u - 4M_V^2) + 2suM_V^2 (u - 2M_V^2) \\ & + u^2 M_V^2 (t - M_V^2) + 8tuM_V^4 - 8M_V^8] \\ & + \frac{F_Z^2 F^2 \alpha^2}{8s^2 t M_V^4 \sin^4 \theta_W} (C_V + C_A) \frac{s - M_Z^2}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} [s^2 t M_V^2 + 4s^2 M_V^4 + st^2 u \\ & - 3st M_V^2 (t + u - M_V^2) + 4sM_V^4 (u + M_V^2) \\ & - 2tM_V^2 (u - M_V^2) (t + M_V^2) + 4M_V^6 (u - M_V^2)] \end{aligned}$$

where $t = M_V^2 - \frac{s}{2}(1 - \beta \cos \theta)$, with θ being the scattering angle between the e^- and the negatively charged leptoquark in the laboratory frame, and $\beta = \sqrt{1 - 4M_V^2/s}$. This cross section exhibits a bad high-energy behavior ($\sigma \propto s$), and violates unitarity in this limit for an arbitrary choice of the couplings F and F_Z . However, this violation of unitarity can be avoided by a careful choice of the couplings: for $F = F_Z = \sqrt{\frac{2}{3}}$ this cross section

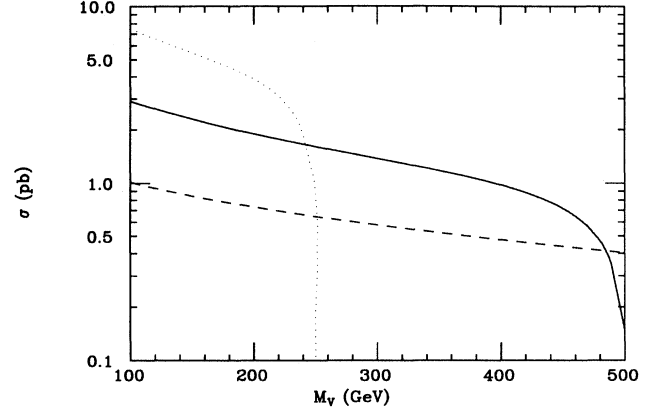


FIG. 6. Cross section of the process $e^+e^- \rightarrow V^+V^-$ as a function of M_V for several collider energies: $\sqrt{s} = 500$ (dotted line); 1000 (solid line); 2000 (dashed line) GeV. It was assumed that $F = F_Z = \sqrt{\frac{2}{3}}$.

has a good high-energy behavior. Moreover, for these values of the couplings, the cross section for this process is $4/9\sigma(e^+e^- \rightarrow W^+W^-)$. Therefore, we must make this choice if we want to preserve unitarity at tree level.

Figure 6 exhibits the total cross section for the process $e^+e^- \rightarrow V^+V^-$ as a function of M_V for $F = F_Z = \sqrt{\frac{2}{3}}$. The signal for such a process is either $jje e$, $jje p_T$, or $j j p_T$. Certainly the identification of the leptoquark is

very easy in the mode $j\bar{j}e\bar{e}$ since the backgrounds, such as $e^+e^- \rightarrow ZZ$, can be efficiently eliminated by looking at the invariant mass of the pairs ee and/or $j\bar{j}$. Moreover, the signal is very striking since it consists of two pairs $e\bar{j}$ with (approximately) the same invariant mass. Assuming an integrated luminosity of 10^5 pb^{-1} per year, there will be more than 10^5 events per year, which is more than enough to establish the existence of the leptoquarks.

B. $\gamma\gamma \rightarrow V^+V^-$

We can also produce pairs V^+V^- in $\gamma\gamma$ collisions, where the photons are generated either by bremsstrahlung or by laser backscattering. There are three Feynman diagrams that contribute to this process: there is the exchange of a V in the t and u channels and the quartic vertex $\gamma\gamma VV$. The cross section for this reaction is equal to the one for $\gamma\gamma \rightarrow W^+W^-$ scaled by a factor Q_V^4 , since the couplings $V\gamma$ and $W\gamma$ are assumed to be proportional. It is straightforward to obtain that the subprocess cross section is

$$\frac{d\hat{\sigma}}{d\hat{t}} = Q_V^4 \frac{8\pi\alpha^2}{M_V^2} \left[\frac{(16x^2 + 3)M_V^6}{2(\hat{t} - M_V^2)^2(\hat{u} - M_V^2)^2} - \frac{(8x + 3)M_V^2}{8x(\hat{t} - M_V^2)(\hat{u} - M_V^2)} + \frac{3}{64x^2 M_V^2} \right], \quad (12)$$

where we defined $x = \hat{s}/4M_V^2$. One characteristic of this process is that the cross section is peaked at the forward region at high energies. Furthermore, due to exchange of a spin-1 particle in the t and u channels, the cross section goes to a constant at high energies

$$\hat{\sigma}_{\text{limit}} \simeq \frac{128 \pi \alpha^2}{81 M_V^2}. \quad (13)$$

We can obtain the total cross section for this process folding $\hat{\sigma}$ with the photon distribution functions:

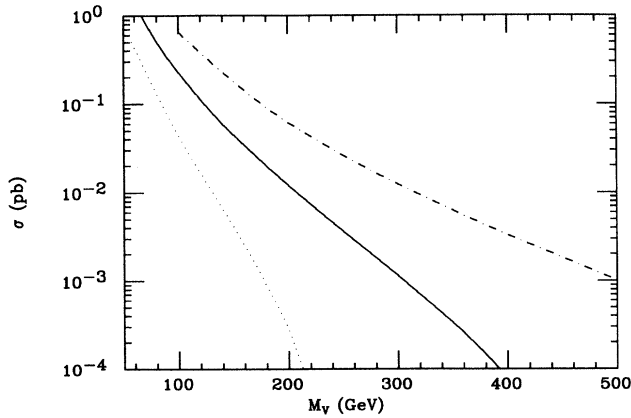


FIG. 7. Cross section for the process $\gamma\gamma \rightarrow V^+V^-$, with the γ originating from bremsstrahlung, for several energies: (a) $\sqrt{s} = 500$ (dotted line); (b) 1000 (solid line); (c) 2000 GeV (dot-dashed line).

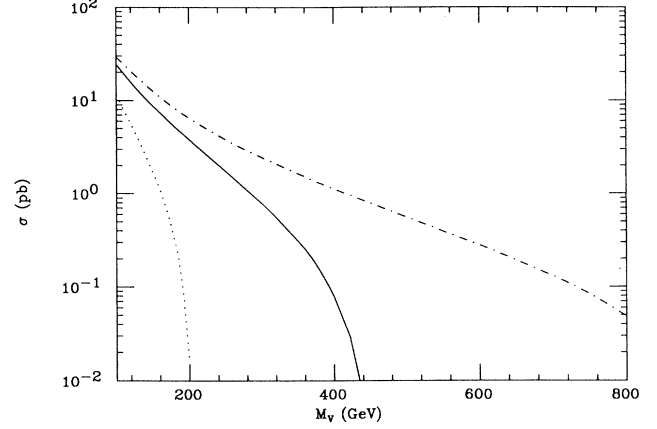


FIG. 8. Same as in Fig. 7, but with the γ 's produced by laser backscattering.

$$\sigma = \int dx_1 \int dx_2 f_{\gamma/e}(x_1) f_{\gamma/e}(x_2) \hat{\sigma}(\hat{s} = x_1 x_2 s). \quad (14)$$

Figures 7 and 8 show the behavior of the cross section of the process $\gamma\gamma \rightarrow V^+V^-$ as a function of M_V for bremsstrahlung and laser backscattering photons, respectively. In this case also, the cross section for the process initiated by backscattered photons is one to two orders of magnitude larger than the one for bremsstrahlung photons due to the distribution of backscattered photons being harder than the one for bremsstrahlung. From Fig. 7 we can infer that this reaction is observable for leptoquark masses up to $\simeq 100$ (200) GeV in an e^+e^- machine with $\sqrt{s} = 500$ (1000) GeV. Analogously, we can see from Fig. 8, that this process is observable for masses up to $\simeq 200$ (400) GeV in a $\gamma\gamma$ collider with $\sqrt{s} = 500$ (1000) GeV.

V. CONCLUSIONS

We studied the signals of vector leptoquarks in e^+e^- , $e\gamma$, and $\gamma\gamma$ machines. In order to do so, we postulated the interaction Lagrangian of the vector leptoquarks with the quarks and leptons. Demanding that unitarity is satisfied at tree level, in the different process analyzed [9], we discovered that the couplings F and F_Z are constrained to the value $\sqrt{\frac{2}{3}}$. In this case, our effective theory for the Abbott-Farhi model becomes a spontaneously broken gauge theory (for details see Ref. [9]), in which the W^\pm , Z_0 , and vector leptoquarks are some of its gauge bosons. This suggests that this effective theory would be a part of a grand unified theory (GUT) with a gauge group such as SU(5) or SO(10) or even larger, depending on the flavors of quarks and leptons that the vector leptoquarks couple to.

In e^+e^- machines, we can look for these particles through their effect in $e^+e^- \rightarrow q\bar{q}$, and the existence of leptoquark can be established provided their masses are smaller than $O(2\sqrt{s})$. In these machines, vector leptoquarks can also be single produced through the reaction $e\gamma \rightarrow V^{eq}q$, where the γ originates from bremsstrahlung.

This process is observable for leptoquark masses up to 300 (400) GeV, in a collider with $\sqrt{s} = 500$ (1000) GeV. We have also studied the production of leptoquark pairs, either through $e^+e^- \rightarrow V^+V^-$ or $\gamma\gamma \rightarrow V^+V^-$, with the two photons coming from bremsstrahlung.

In a $e\gamma$ collider, leptoquarks can be produced in association with jets through $e\gamma \rightarrow V^{eq}q$. For hard photons produced by laser backscattering, we can detect this process provided that the leptoquark mass is smaller than 450 (900) GeV, for a collider with $\sqrt{s} = 500$ (1000) GeV. We also investigated the production of V^+V^- pairs in $\gamma\gamma$ collisions, and we found that this process can be observed for leptoquarks with masses up to 200 (400) GeV, if $\sqrt{s} = 500$ (1000) GeV.

Finally, we should remark that the above results rely on the fact that $F \sim 1$. In the Abbott-Farhi model this is a natural assumption since the W^\pm and vector leptoquarks are composite objects and consequently their interactions with fermion should have approximately the same strength. However, it is known that in strongly interacting theories, such as QCD, we have $F \simeq 1/16\pi^2$. If the couplings of the Abbott-Farhi model turn out to be of this order, the capability of the next generation of accelerators to unravel the existence of vector leptoquarks will be drastically reduced.

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APPENDIX

The contribution arising from the conventional bremsstrahlung photons were computed using the well-known Weiszäcker-Williams distribution [12]

$$f_{\gamma/e}^{\text{WW}}(x) = \frac{\alpha}{2\pi} \frac{1 + (1-x)^2}{x} \ln\left(\frac{s}{4m_e^2}\right), \quad (\text{A1})$$

where m_e is the electron mass, and s is the center-of-mass energy of the e^+e^- pair. This spectrum is peaked at small x , i.e., most of its photons are soft.

Hard photons can be obtained by laser backscattering, which converts an e beam into a γ one. Here the intense photon beam is generated by backward Compton scattering of soft photons from a laser of a few eV energy. The energy spectrum of the backscattered laser photons is [5]

$$f_{\gamma/e}^L(x, \xi) \equiv \frac{1}{\sigma_c} \frac{d\sigma_c}{dx} = \frac{1}{D(\xi)} \left[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right], \quad (\text{A2})$$

where σ_c is the total Compton cross section. For the photons going in the direction of the initial electron, the fraction x represents the ratio between the scattered photon and the initial electron energy ($x = \omega/E$). In writing Eq. (A2), we defined

$$D(\xi) = \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2}, \quad (\text{A3})$$

with

$$\xi \equiv \frac{4E\omega_0}{m^2} \cos^2 \frac{\alpha_0}{2} \simeq \frac{2\sqrt{s}\omega_0}{m^2}, \quad (\text{A4})$$

where ω_0 is the laser photon energy and ($\alpha_0 \sim 0$) is the electron-laser collision angle. It is easy to verify that the maximum value of x possible in this process is

$$x_m = \frac{\omega_m}{E} = \frac{\xi}{1 + \xi}. \quad (\text{A5})$$

From Eq. (A2) we can see that the fraction of photons with energy close to the maximum value grows with E and ω_0 . Usually, the choice of ω_0 is such that it is not possible for the backscattered photon to interact with the laser and create e^+e^- pairs; otherwise, the conversion of electrons to photons would be dramatically reduced. In our numerical calculations, we assumed $\omega_0 \simeq 1.26$ eV, which is below the threshold of e^+e^- pair creation ($\omega_m\omega_0 < m^2$). Thus for the NLC beams ($\sqrt{s} = 500$ GeV), we have $\xi \simeq 4.8$, $D(\xi) \simeq 1.9$, and $x_m \simeq 0.83$.

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