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Scalar leptoquark production at TESLA and CLIC based $e\gamma$ colliders

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Abstract. We study scalar leptoquark production at TESLA and CLIC based $e\gamma$ colliders. Both direct and resolved contributions to the cross section are examined. We find that the masses of scalar leptoquarks can be probed up to about 0.9 TeV at TESLA and 2.6 TeV at CLIC.

1 Introduction

In the standard model (SM) of electroweak (EW) and color (QCD) interactions, quarks and leptons appear as formally independent components. However, the observed symmetry between the lepton and quark sectors in the SM could be interpreted as a hint for common underlying structures. If quarks and leptons are made of constituents, then, at the scale of constituent binding energies, there should appear new interactions among leptons and quarks. Leptoquarks (LQs) are exotic particles carrying both lepton number (L) and baryon number (B), associated with a color (anti-) triplet, being scalar or vector particles which appear naturally in various unifying theories beyond the SM. The interactions of LQs with the known particles are usually described by an effective lagrangian that satisfies the requirement of baryon and lepton number conservation and respects the $SU(3)_C \times SU(2)_W \times U(1)_Y$ symmetry of the SM. There are nine scalar and nine vector leptoquark types according to the Buchmuller–Ruckl–Wyler (BRW) model [1]. The scalar leptoquarks (S, R) can be grouped into singlets, $(S_0, \widetilde{S}_0)$, doublets $(R_{1/2}, \widetilde{R}_{1/2})$ and the triplet (S_1).

The leptoquarks are constrained by different experiments. Direct limits on leptoquark states are obtained from their production cross sections at different colliders, while indirect limits are calculated from the bounds on the leptoquark induced four fermion interactions at low energy experiments. The mass limits for scalar leptoquarks from single and pair productions assuming electromagnetic coupling are $M_{\mathrm{LQ}} > 200\,\mathrm{GeV}$ [2] and $M_{\mathrm{LQ}} > 225\,\mathrm{GeV}$ [3], respectively. Other bounds on the ratio M_{LQ}/g can be obtained from low energy neutral current experiments (weak charge measurement for cesium atoms) [4].

The single production of scalar leptoquarks coupled to the eu and νd pair in $e\gamma$ collisions using only the resolved structure of the photon was suggested by [5]. The direct single production of scalar leptoquarks in $e\gamma$ collisions was analyzed in [6].

In order to make an analysis with the LQs we make the following assumptions: The leptoquarks couple to first generation leptons and quarks, and the couplings $g_{\mathrm{L,R}}$ within one generation of fermions satisfy flavor conservation. The product of the couplings g_{L} and g_{R} vanishes to respect the lepton universality. One of the scalar leptoquark types gives the dominant contribution compared with other leptoquark states, and we neglect the interference between different leptoquark states, i.e. there is no mixing among LQs. The different leptoquark states within isospin doublets and triplets are assumed to have the same mass. Under these assumptions, only the mass and the couplings to right-handed and/or left-handed leptons, denoted by g_{R} and g_{L}, remain as free parameters.

We study the potential of the TESLA and CLIC based $e\gamma$ colliders to search for scalar leptoquarks, taking into account both direct and resolved photon processes. We adopt the Buchmuller–Ruckl–Wyler model [1] which assumes lepton and baryon number conservation. In the model the interactions of scalar LQs, having fermion number $F = L + 3B$, with fermions can be described by the effective lagrangian with the dimensionless couplings and $\mathrm{SU}(3)_C\times \mathrm{SU}(2)_W\times \mathrm{U}(1)_Y$ invariance:

$$L_{\mathrm{eff}} = L_{F=0} + L_{|F|=2} + L_{\gamma,Z,g}, \tag{1}$$

$$L_{F=0} = g_{1/2\mathrm{L}}\overline{u}_{\mathrm{R}} l_{\mathrm{L}} R_{1/2} + g_{1/2\mathrm{R}}\overline{q}_{\mathrm{L}} \mathrm{i}\tau_2 e_{\mathrm{R}} R_{1/2} + \widetilde{g}_{1/2\mathrm{L}}\overline{d}_R l_{\mathrm{L}} \widetilde{R}_{1/2} + \mathrm{H.c.} \tag{2}$$

$$L_{|F|=2} = g_{0\mathrm{L}}\overline{q}^c_{\mathrm{L}} \mathrm{i}\tau_2 l_{\mathrm{L}} S_0 + g_{0\mathrm{R}}\overline{u}^c_{\mathrm{R}} e_{\mathrm{R}} S_0 + \widetilde{g}_{0\mathrm{R}}\overline{d}^c_{\mathrm{R}} e_{\mathrm{R}} \widetilde{S}_0 + g_{1L}\overline{q}^c_{\mathrm{L}} \mathrm{i}\tau_2 \overrightarrow{\tau} l_{\mathrm{L}} \cdot \overrightarrow{S}_1 + \mathrm{H.c.} \tag{3}$$

Here the indices of scalar leptoquarks S or R denote the weak isospin, and an additional subscript on the couplings indicates the coupled lepton chirality. A tilde sign is introduced to differentiate between leptoquarks with differ-

Table 1. Quantum numbers of scalar leptoquarks according to the BRW model. The numbers in parentheses in the last two columns denote the values for $g_{\mathrm{L}} = g_{\mathrm{R}}$

Leptoquark	F	I_3	Q_{em}	Decay	Coupling	BR($S \to lq$)	BR($S \to \nu q$)
S_0	2	0	$-1/3$	$e_{\mathrm{L}}u_{\mathrm{L}}$	$g_{0\mathrm{L}}$	$\frac{g_{0\mathrm{L}}^2+g_{0\mathrm{R}}^2}{2g_{0\mathrm{L}}^2+g_{0\mathrm{R}}^2}\left(\frac{2}{3}\right)$	$\frac{g_{0\mathrm{L}}^2}{2g_{0\mathrm{L}}^2+g_{0\mathrm{R}}^2}\left(\frac{1}{3}\right)$
				$e_{\mathrm{R}}u_{\mathrm{R}}$	$g_{0\mathrm{R}}$		
				νd_{L}	$-g_{0\mathrm{L}}$		
$\widetilde{S}_0$	2	0	$-4/3$	$e_{\mathrm{R}}d_{\mathrm{R}}$	$\widetilde{g}_{0\mathrm{R}}$	1	0
S_1	0	1	$2/3$	νu_{L}	$\sqrt{2}g_{1\mathrm{L}}$	0	1
		0	$-1/3$	$\nu d_{\mathrm{L}}, e_{\mathrm{L}}u_{\mathrm{L}}$	$-g_{1\mathrm{L}}$	1/2	1/2
		-1	$-4/3$	$e_{\mathrm{L}}d_{\mathrm{L}}$	$-\sqrt{2}g_{1\mathrm{L}}$	1	0
$R_{1/2}$	0	1/2	$-2/3$	$\nu\overline{u}_{\mathrm{R}}$	$g_{1/2\mathrm{L}}$	$\frac{g_{1/2\mathrm{R}}^2}{g_{1/2\mathrm{R}}^2+g_{1/2\mathrm{L}}^2}\left(\frac{1}{2}\right)$	$\frac{g_{1/2\mathrm{L}}^2}{g_{1/2\mathrm{R}}^2+g_{1/2\mathrm{L}}^2}\left(\frac{1}{2}\right)$
		1/2	$-2/3$	$e_{\mathrm{R}}\overline{d}_{\mathrm{L}}$	$-g_{1/2\mathrm{R}}$		
		$-1/2$	$-5/3$	$e_{\mathrm{L}}\overline{u}_{\mathrm{R}}$	$g_{1/2\mathrm{L}}$	1	0
		$-1/2$	$-5/3$	$e_{\mathrm{R}}\overline{u}_{\mathrm{L}}$	$g_{1/2\mathrm{R}}$		
$\widetilde{R}_{1/2}$	0	1/2	1/3	$\nu\overline{d}_{\mathrm{R}}$	$\widetilde{g}_{1/2\mathrm{L}}$	0	1
		$-1/2$	$-2/3$	$e_{\mathrm{L}}\overline{d}_{\mathrm{R}}$	$\widetilde{g}_{1/2\mathrm{L}}$	1	0

ent hypercharges. The l_{L} and q_{L} are the left-handed lepton and quark doublets while e_{R} and q_{R} are the right-handed charged lepton and quark singlets, respectively. The charged conjugated quark field is defined by $q^C = C\overline{q}^{\mathrm{T}}$ and $\overline{q}^C = q^{\mathrm{T}}C$.

The gauge interaction of scalar leptoquarks with the EW and QCD gauge bosons can be described by

$$L_{\gamma,Z,g} = \sum_{\Phi=S,R} \left(D_\mu\Phi\right)^\dagger \left(D^\mu\Phi\right) - M_\Phi^2\Phi^\dagger\Phi, \tag{4}$$

where Φ is any type of scalar leptoquark, and M_Φ is the mass of the scalar leptoquark. The covariant derivative is $D_\mu = \partial_\mu - \mathrm{i}g_eQ_SA_\mu - \mathrm{i}g_eQ_ZZ_\mu - \mathrm{i}g_{\mathrm{s}}T^aG_\mu^a$; here Q_{S} is the charge of the scalar leptoquark and g_e is the electromagnetic coupling constant. $Q_Z = (I_3 - Q_{\mathrm{S}}\sin\theta_{\mathrm{W}})/\cos\theta_{\mathrm{W}} \times \sin\theta_{\mathrm{W}}$. In the above equation, A_μ, Z_μ and G_μ denote the photon, Z-boson and gluon fields, respectively. I_3 is the third component of the weak isospin and θ_{W} is the Weinberg angle. T^a are the Gell-Mann matrices and g_{s} is the strong coupling constant. From the effective interaction lagrangian (1) one can deduce the quantum numbers of the scalar leptoquarks as given in Table 1.

In this work, a search for singly produced scalar leptoquarks is presented at electron–photon colliders. The decay of a heavy LQ into a quark and a charged lepton leads to final states characterized by an isolated energetic charged lepton and a hadronic jet, while for decays into a quark and a neutrino, the final state would have large missing energy and a jet. Therefore, under our assumptions on the couplings, the topologies resulting from the processes $e\gamma \to q\overline{q}'e$ and $e\gamma \to q\overline{q}'\nu$ are given in Table 2.

2 Single production of scalar leptoquarks

Scalar leptoquarks can be produced singly in $e\gamma$ collisions via the process $e\gamma \to Sq$ where S is any type of scalar leptoquark (S or R). At $e\gamma$ colliders, with a photon beam produced by Compton backscattering, the maximum $e\gamma$ center of mass energy is about 91% of the available energy. The projects of TESLA [7] and CLIC [8] colliders will be working at $\sqrt{s_{e^+e^-}} = 1\,\mathrm{TeV}$ and $\sqrt{s_{e^+e^-}} = 3\,\mathrm{TeV}$, respectively. A high energy photon beam can be obtained from the linacs with energies $\simeq 415\,\mathrm{GeV}$ and $\simeq 1245\,\mathrm{GeV}$ for TESLA and CLIC, respectively.

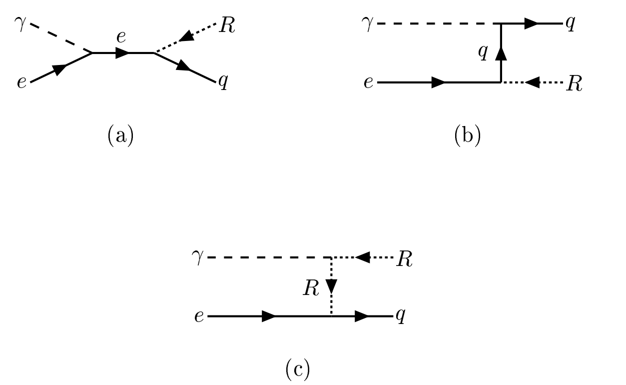


Fig. 1a–c. Feynman diagrams for $|F| = 0$ scalar leptoquarks in $e\gamma$ collisions

The relevant diagrams for single direct production of scalar leptoquarks with fermion number $F = 0$ (R type) and $|F| = 2$ (S type) are shown in Figs. 1 and 2. The Feynman amplitude for the subprocess $e\gamma \longrightarrow Sq$ consists of s, u and t channels which correspond to electron, quark and scalar LQ exchanges, respectively.

On the basis of the effective lagrangian, the differential cross section for scalar LQ productions through the subprocess $e\gamma \longrightarrow Sq$ is given by

$$\frac{\mathrm{d}\widehat{\sigma}}{\mathrm{d}\widehat{t}} = \frac{N_cg^2g_e^2}{16\pi\widehat{s}^2}(c_1^2 + c_2^2)\left[-\frac{Q_e^2\widehat{u}}{\widehat{s}} - \frac{Q_q^2\widehat{s}\widehat{u}}{\left(\widehat{u} - m_q^2\right)^2}\right. \tag{5}$$

Table 2. Scalar leptoquark final states; the numbers in parentheses denote the electric charge of the scalar leptoquarks

Initial				Signal	Initial				Signal
$\gamma e_{\mathrm{L}}^{-}$	$\rightarrow$	$u_{\mathrm{L}} S_0(-1/3)$	$\nearrow$ $\searrow$	$2j + e^-$ $2j + \not{p}_{\mathrm{T}}$	$\gamma e_{\mathrm{R}}^{-}$	$\rightarrow$	$u_{\mathrm{R}} S_0(-1/3)$	$\rightarrow$	$2j + e^-$
$\gamma e_{\mathrm{L}}^{-}$	$\rightarrow$	$u_{\mathrm{L}} S_1(-1/3)$	$\nearrow$ $\searrow$	$2j + e^-$ $2j + \not{p}_{\mathrm{T}}$	$\gamma e_{\mathrm{R}}^{-}$	$\rightarrow$	$d_{\mathrm{R}} \widetilde{S}_0(-4/3)$	$\rightarrow$	$2j + e^-$
$\gamma e_{\mathrm{L}}^{-}$	$\rightarrow$	$d_{\mathrm{L}} S_1(-4/3)$	$\rightarrow$	$2j + e^-$	$\gamma e_{\mathrm{R}}^{-}$	$\rightarrow$	$\overline{d}_{\mathrm{L}} R_{1/2}(-2/3)$	$\rightarrow$	$2j + e^-$
$\gamma e_{\mathrm{L}}^{-}$	$\rightarrow$	$\overline{u}_{\mathrm{R}} R_{1/2}(-5/3)$	$\rightarrow$	$2j + e^-$	$\gamma e_{\mathrm{R}}^{-}$	$\rightarrow$	$\overline{u}_{\mathrm{L}} R_{1/2}(-5/3)$	$\rightarrow$	$2j + e^-$
$\gamma e_{\mathrm{L}}^{-}$	$\rightarrow$	$\overline{d}_{\mathrm{R}} \widetilde{R}_{1/2}(-2/3)$	$\rightarrow$	$2j + e^-$					

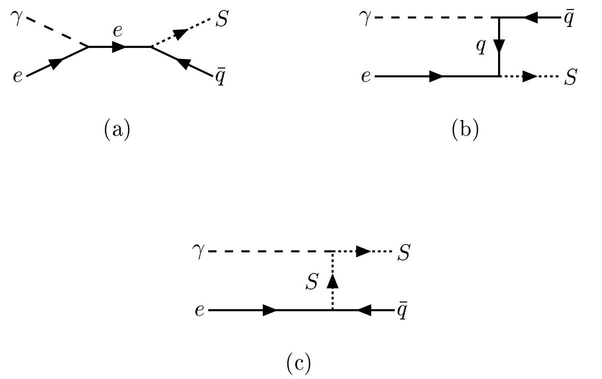


Fig. 2a–c. Feynman diagrams for $|F| = 2$ scalar leptoquarks in $e\gamma$ collisions

$$+\frac{Q_S^2 \widehat{t}\left(\widehat{t}+M_{\mathrm{LQ}}^2\right)}{\left(\widehat{t}-M_{\mathrm{LQ}}^2\right)^2}+\frac{2Q_eQ_q\left(\widehat{s}+\widehat{t}\right)\left(\widehat{s}-M_{\mathrm{LQ}}^2\right)}{\widehat{s}\left(\widehat{u}-m_q^2\right)}$$
$$-\frac{Q_eQ_S\widehat{t}\left(\widehat{s}-2M_{\mathrm{LQ}}^2\right)}{\widehat{s}\left(\widehat{t}-M_{\mathrm{LQ}}^2\right)}-\left.\frac{Q_qQ_S\widehat{t}(\widehat{s}+\widehat{t}+M_{\mathrm{LQ}}^2)}{\left(\widehat{u}-m_q^2\right)\left(\widehat{t}-M_{\mathrm{LQ}}^2\right)}\right],$$

where we use the Lorentz invariant Mandelstam variables $\widehat{s}=(k_1+p_1)^2$, $\widehat{u}=(p_2-k_1)^2$ and $\widehat{t}=(k_2-k_1)^2$. c_1 and c_2 are the constants equal to 1/2 and $-(+)1/2$ corresponding to left (right) couplings, respectively; g is the LQ–lepton-quark coupling constant; Q_e, Q_q and Q_S denote electron, quark and LQ charges, respectively. We denote the interaction coupling constants of the scalar LQs with fermions as $g^2 = 4\pi\alpha\kappa$ with $\kappa = 1$ and the color factor $N_c = 3$. Since the cross section varies with κ we can simply rescale it for the various κ values.

The cross section for the direct production of scalar leptoquarks via the subprocess $e\gamma \to Sq$ is given by

$$\sigma_{\mathrm{D}} = \int_{y_{\min}}^{0.83} \mathrm{d}y\; f_\gamma(y)\;\widehat{\sigma}(y\cdot s), \qquad (6)$$

where $y_{\min} = M_{\mathrm{LQ}}^2/s$, and f_γ is the energy spectrum of the Compton backscattered photons from electrons,

$$f_\gamma(y) = \frac{1}{D(\varsigma)}\left[1-y+\frac{1}{(1-y)}\right.$$

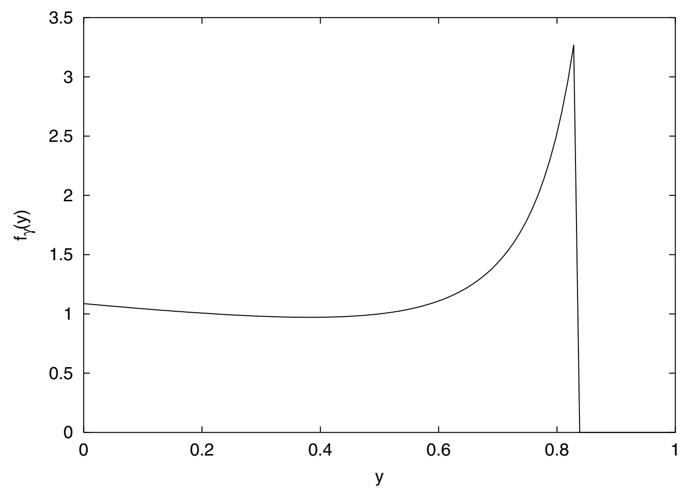


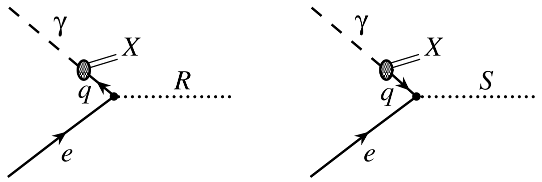
Fig. 3. Energy spectrum of backscattered photons

$$\left.-\frac{4y}{\varsigma(1-y)}+\frac{4y^2}{\varsigma^2(1-y)^2}\right], \qquad (7)$$

where

$$D(\varsigma) = \left(\frac{1}{2}+\frac{8}{\varsigma}-\frac{1}{2(1+\varsigma)^2}\right) + \left(1-\frac{4}{\varsigma}-\frac{8}{\varsigma^2}\right)\ln(1+\varsigma), \qquad (8)$$

with $\varsigma = 4E_e\omega_0/m_e^2$, and $y = E_\gamma/E_e$ is the ratio of the backscattered photon energy to the initial electron energy. The energy E_γ of converted photons is restricted by the condition $y_{\max} = 0.83$. The value $y_{\max} = \varsigma/(\varsigma+1) = 0.83$ corresponds to $\varsigma = 4.8$ [9]. The energy spectrum of the backscattered photon is given in Fig. 3. When calculating the production cross sections for scalar leptoquarks, the divergencies due to the u-channel exchange diagram in Figs. 1b and 2b are regulated by taking into account the corresponding quark mass m_q. The main contribution to the total cross section comes from the quark exchange diagram in Figs. 1b and 2b. For this reason, the total cross sections for the production of the scalar leptoquarks $R_{1/2}(-5/3)$, $S_0(-1/3)$ and $S_1(-1/3)$ practically coincide. This is also true for $R_{1/2}(-2/3)$, $\widetilde{R}_{1/2}(-2/3)$, $\widetilde{S}_0(-4/3)$ and $S_1(-4/3)$ type scalar leptoquark production.



(a) (b)

Fig. 4a,b. Resolved process for single production of scalar leptoquarks. **a** corresponds to $F = 0$, and **b** is for $|F| = 2$ type

The scalar leptoquarks can also be produced in $e\gamma$ collisions by the resolved photon processes, Fig. 4. In order to produce leptoquarks in the resonant channel through the quark component of the photon, we study the following signal for the scalar leptoquark S (or R):

$$e + q_\gamma \to S \to e + q \tag{9}$$

Using the effective lagrangian, the parton level cross section for scalar leptoquark resonant production can be found to be

$$\widehat{\sigma}(\widehat{s}) = \frac{\pi^2 \kappa \alpha}{2M_{\mathrm{LQ}}} \delta(M_{\mathrm{LQ}} - \sqrt{\widehat{s}}). \tag{10}$$

For CLIC and TESLA based $e\gamma$ colliders, the total cross section for the resolved photon contribution is obtained by convoluting with the backscattered laser photon distribution and photon structure function. The photon structure function consists of perturbative point-like parts and hadron-like parts, $f_{q/\gamma} = f^{\mathrm{PL}}_{q/\gamma} + f^{\mathrm{HL}}_{q/\gamma}$ [10]. The point-like part can be calculated in the leading logaritmic approximation and is given by

$$f^{\mathrm{PL}}_{q/\gamma}(z, Q^2) = \frac{3\alpha Q_q^2}{2\pi} \left[z^2 + (1-z)^2\right] \log \frac{Q^2}{\Lambda^2}, \tag{11}$$

where Q_q is the charge of quark content of the photon. The cross section for the hadronic contribution from the resolved photon process can be obtained as follows:

$$\sigma_{\mathrm{R}} = \frac{\pi^2 \alpha \kappa}{s} \int_{x_{\min}}^{0.83} \frac{\mathrm{d}x}{x} f_{\gamma/e}(x) \times \left[f_{q/\gamma}(z, Q^2) - f^{\mathrm{PL}}_{q/\gamma}(z, Q^2)\right], \tag{12}$$

where $z = M^2_{\mathrm{LQ}}/xs$, $x_{\min} = M^2_{\mathrm{LQ}}/s$, and $Q^2 = M^2_{\mathrm{LQ}}$. Here, $f_{q/\gamma}$ is a Q^2-dependent parton distribution function [10] within the backscattered photon. Since the contribution from the point-like part of the photon structure function was already taken into account in the calculation of the direct part it was subtracted from $f_{q/\gamma}(z, Q^2)$ in the above formula to avoid double counting on the leading logarithmic level. This procedure was illustrated explicitly for the simpler example of the subprocess $\gamma q_i \to V q_j$ $(V = Z, W)$ in [11].

Certain kinematic regions of the direct processes contribute to the evolution of $f_{q/\gamma}(z, Q^2)$ which is already included in the lowest order process. Both double counting and the mass singularities are removed when we subtract the contribution of point-like part in which the u-channel exchanged quark is on-shell and collinear with the parent photon. In general, the values of Q^2 and Λ are arbitrary and the final result for the sum of resolved and direct contributions (13) should not depend essentially on the choice of these two scales.

Direct and resolved schemes give comparable results for the single production cross section. Therefore, we add their contribution to form the signal. In this case, the total cross section for the single production of scalar LQs is

$$\sigma = \sigma_{\mathrm{D}} + \sigma_{\mathrm{R}}. \tag{13}$$

Here σ_{D} and σ_{R} denote the direct and resolved contribution to the total cross sections. The total cross sections including both direct and resolved contributions are plotted in Figs. 5–8 for TESLA and CLIC based $e\gamma$ colliders. In Tables 3 and 4, the direct and resolved contributions to the scalar leptoquark production are shown for TESLA and CLIC based $e\gamma$ colliders, respectively. From Figs. 5–8 the contribution from the resolved process is dominant for small leptoquark masses.

In our calculations we use the scale parameter $\Lambda = 0.3\,\mathrm{GeV}$ for regularizing the u-pole of the collinear singularity which determines the cut-off scale of the photon structure functions. The resolved contributions for different types of scalar leptoquarks at different values of Λ are shown in Figs. 9 and 10 for TESLA based $e\gamma$ collider with $\sqrt{s_{e^+e^-}} = 1\,\mathrm{TeV}$. As can be seen from these figures, when the parameter Λ increases the resolved contribution also increases at large leptoquark mass region. For the small leptoquark mass region the resolved contribution are not sensitive to the value of cut-off scale Λ. Here, we may compare our results with that of the [5]; the difference is due to the double counting problem. The authors of [5] do not subtract the perturbative point-like part from the photon structure function. This term cannot be neglected for large Q^2.

The distribution function of partons within the photon is of the order $O(\alpha/\alpha_{\mathrm{s}})$, where α is due to the photon splitting into $q\bar{q}$ and α_{s}^{-1} due to the QCD evolution. Therefore, the contribution from resolved photon is $O(\alpha^2/\alpha_{\mathrm{s}})$ where the hard subprocess in the resolved photon case is $O(\alpha)$. The direct contribution is $O(\alpha^2)$. On the other hand, the direct contribution is effective for large masses up to the kinematical limit.

3 Signals and backgrounds

For the scalar leptoquarks singly produced at $e\gamma$ colliders the signal will be double jets and a charged lepton $2j+l$ (S and R leptoquarks), or double jets plus a neutrino $2j + \not{p}_{\mathrm{T}}$ (S leptoquarks). Since leptoquarks generate a peak in the invariant (lj) mass distribution, singly produced leptoquarks are easy to detect up to the mass values close to the kinematical limit. A scalar leptoquark decays into a lepton and a quark. The partial decay width for every decay channel is given by the formula

Table 3. The direct and resolved contribution to the cross section for the scalar leptoquark charges $|Q| = 5/3$ and $|Q| = 4/3$ at the center of mass energy $\sqrt{s_{e^+e^-}} = 1\,\text{TeV}$

$\sqrt{s_{e^+e^-}} = 1\,\text{TeV}$	σ_D (pb)		σ_R (pb)	
M_LQ (GeV)	$\lvert Q\rvert = 5/3$	$\lvert Q\rvert = 4/3$	$\lvert Q\rvert = 5/3$	$\lvert Q\rvert = 4/3$
200	2.75	0.79	1.77	1.30
300	1.86	0.53	0.61	0.42
400	1.31	0.37	0.23	0.17
500	0.94	0.26	0.14	7.01×10^{-2}
600	0.69	0.19	6.39×10^{-2}	2.46×10^{-2}
700	0.53	0.14	1.35×10^{-2}	3.05×10^{-3}
800	0.38	9.78×10^{-2}	0.0	0.0
900	6.63×10^{-2}	1.66×10^{-2}	0.0	0.0

Table 4. The same as Table 3, but for $\sqrt{s_{e^+e^-}} = 3\,\text{TeV}$

$\sqrt{s_{e^+e^-}} = 3\,\text{TeV}$	σ_D (pb)		σ_R (pb)	
M_LQ (GeV)	$\lvert Q\rvert = 5/3$	$\lvert Q\rvert = 4/3$	$\lvert Q\rvert = 5/3$	$\lvert Q\rvert = 4/3$
300	0.53	0.16	1.27	1.09
500	0.39	0.11	0.34	0.25
700	0.29	8.31×10^{-2}	0.14	9.86×10^{-2}
900	0.23	6.37×10^{-2}	7.43×10^{-2}	4.76×10^{-2}
1100	0.18	4.97×10^{-2}	4.32×10^{-2}	2.54×10^{-2}
1300	0.14	3.92×10^{-2}	2.75×10^{-2}	1.41×10^{-2}
1500	0.11	3.12×10^{-2}	1.82×10^{-2}	7.78×10^{-3}
1700	9.34×10^{-2}	2.52×10^{-2}	1.18×10^{-2}	3.94×10^{-3}
1900	7.75×10^{-2}	2.06×10^{-2}	6.50×10^{-3}	1.56×10^{-3}
2100	6.49×10^{-2}	1.71×10^{-2}	2.06×10^{-4}	2.18×10^{-4}
2300	5.34×10^{-2}	1.38×10^{-2}	0.0	0.0
2500	3.84×10^{-2}	9.75×10^{-3}	0.0	0.0
2700	8.24×10^{-3}	2.06×10^{-3}	0.0	0.0

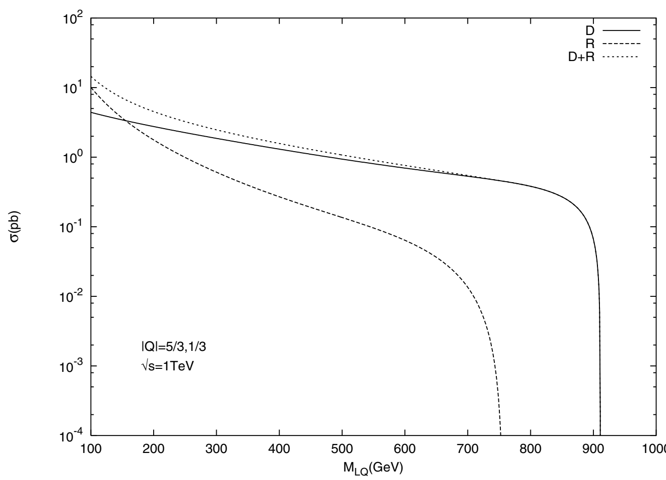


Fig. 5. The direct (D) and resolved (R) contributions to the cross section depending on scalar leptoquark mass M_LQ with charge $|Q| = 5/3$ (1/3) and $\sqrt{s_{e^+e^-}} = 1\,\text{TeV}$

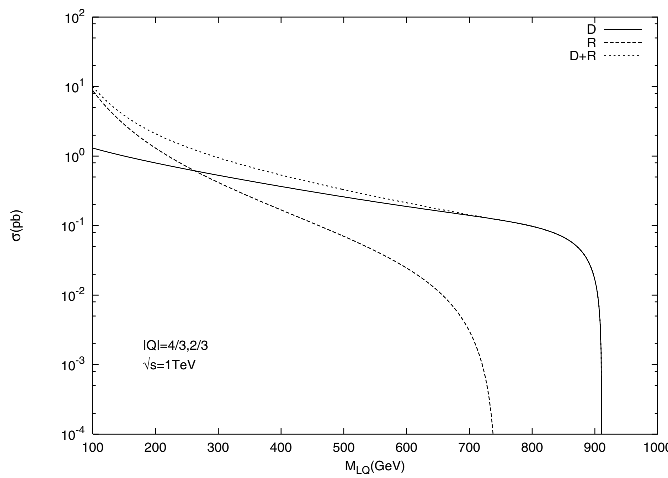


Fig. 6. The same as Fig. 5, but for the charge $|Q| = 4/3$ (2/3)

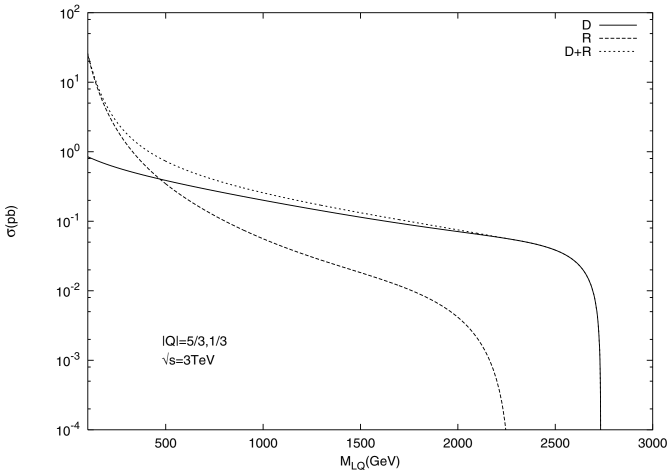


Fig. 7. The same as Fig. 5, but for the center of mass energy $\sqrt{s_{e^+e^-}} = 3\,\text{TeV}$

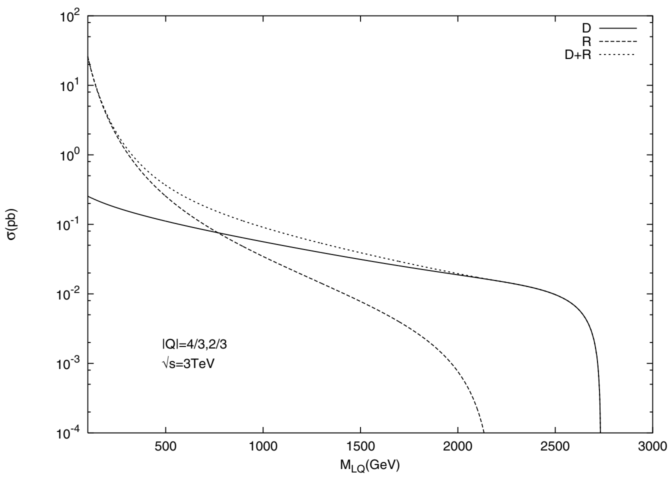


Fig. 8. The same as Fig. 6, but for the center of mass energy $\sqrt{s_{e^+e^-}} = 3\,\text{TeV}$

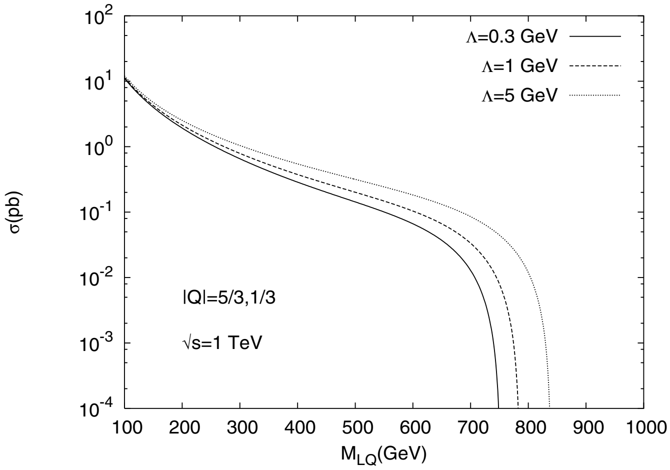


Fig. 9. The cross sections for scalar leptoquark production due to resolved photon contributions at different cut-off scales Λ in the $e\gamma$ collider with $\sqrt{s_{e^+e^-}} = 1\,\text{TeV}$

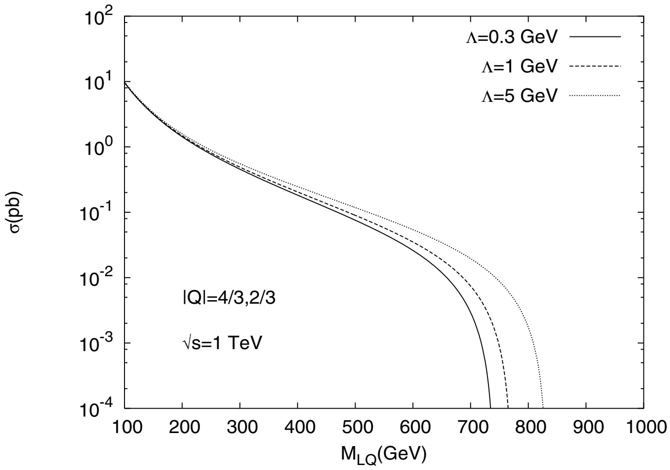


Fig. 10. The same as Fig. 9, but for the leptoquark charge $|Q| = 4/3, 2/3$

$$\Gamma = \frac{g^2 M_{\text{LQ}}}{16\pi}. \tag{14}$$

The leptoquark branchings predicted by the BRW model [1] are given in Table 1. In the case of $g_{\text{L}} = g_{\text{R}}$ the branchings for S_0 can be obtained as 2/3 for the $LQ \to lq$ and 1/3 for the $LQ \to \nu q$ channels. For a given electron-quark, the branching ratio is defined as $\text{BR}(LQ \to lq)$ and the branching ratio to the neutrino-quark is $\text{BR}(LQ \to \nu q) = 1 - \text{BR}(LQ \to lq)$ by definition.

All scalar leptoquark types and signals at the $e\gamma$ collisions are given in Table 2. The numbers in parentheses denote the leptoquark charge. In order to calculate the statistical significance $S/\sqrt{B}$ at each mass value of a scalar leptoquark for each decay channel we need also to calculate the relevant background cross sections. The Feynman amplitude for the background subprocess $e\gamma \longrightarrow W^-\nu$ consists of t and s channels which correspond to W^- and electron exchanges, respectively. The differential cross section for this process is given by

$$\begin{aligned}\frac{\mathrm{d}\widehat{\sigma}}{\mathrm{d}\widehat{t}} &= \frac{-g_W^2 g_e^2}{32\pi\widehat{s}^3(\widehat{t}m_W - m_W^3)^2} \\ &\quad \times \left[\widehat{s}\widehat{t}(\widehat{s}^2 + \widehat{s}\widehat{t} + 2\widehat{t}^2) - (3\widehat{s}^3 + 2\widehat{s}^2\widehat{t} + 5\widehat{s}\widehat{t}^2 + \widehat{t}^3)m_W^2 \right. \\ &\quad \left. + (\widehat{s}^2 + 5\widehat{t}^2)m_W^4 + (\widehat{s} - 5\widehat{t})m_W^6 + m_W^8\right]; \end{aligned} \tag{15}$$

here $\widehat{s} = (p_e + p_\gamma)^2$ and $\widehat{t} = (p_\gamma - p_W)^2$ are the Lorentz invariant Mandelstam variables. The Feynman amplitude for the background subprocess $e\gamma \longrightarrow Ze$ consists of s and u channels which both correspond to electron exchanges. The differential cross section for this subprocess can be written as follows:

$$\begin{aligned}\frac{\mathrm{d}\widehat{\sigma}}{\mathrm{d}\widehat{t}} &= \frac{(c_V^2 + c_A^2)g_e^2 g_z^2}{64\pi\widehat{s}^3 m_Z^2(\widehat{s} + \widehat{t} + m_e^2 - m_Z^2)^2} \\ &\quad \times \left[2(\widehat{s} + \widehat{t})(2\widehat{s}^2 + 2\widehat{s}\widehat{t} + \widehat{t}^2 m_Z^2 \right. \\ &\quad \left. - 2(2\widehat{s} + \widehat{t})^2 m_Z^4 + 2(3\widehat{s} + \widehat{t})m_Z^6 - 2m_Z^8)\right], \end{aligned} \tag{16}$$

where $\widehat{s} = (p_e + p_\gamma)^2$, $\widehat{t} = (p_\gamma - p_Z)^2$; $c_V = -1/2 + 2\sin^2\theta_{\text{W}}$ and $c_A = -1/2$.

Table 5. The number of events and signal significances for the $2j+e$ and $2j+\not{p}_T$ channels of scalar leptoquark decays. The lower and upper indices on the scalar leptoquarks S or R denote weak isospin I and I_3, respectively

$\sqrt{s_{e^+e^-}}=1$ TeV, $L_{\text{int}}=10^5$ pb^{-1}	Number of events $(\sigma_{\text{D}}+\sigma_{\text{R}})\times L_{\text{int}}$		$\frac{S}{\sqrt{B}}(e\gamma\to q\bar{q}e)$					$\frac{S}{\sqrt{B}}(e\gamma\to q\bar{q}'\nu)$		
M_{LQ} (GeV)	$\|Q\|=5/3$	$\|Q\|=4/3$	S_0	S_1^0	$R_{1/2}^{-1/2}$	$R_{1/2}^{1/2}$	$\widetilde{R}_{1/2}^{-1/2},\widetilde{S}_0,S_1^{-1}$	S_0	S_1^0	$R_{1/2}^{1/2}$
200	452407	210085	704	556	1113	258	517	89	135	63
300	247050	94763	401	304	608	117	233	49	74	28
400	157382	53386	255	194	387	66	131	31	47	16
500	107389	32904	174	132	264	40	81	21	32	10
600	76050	21310	123	94	187	26	52	15	23	6
700	54541	14335	88	67	134	18	35	11	16	4
800	38152	9782	62	47	94	12	24	7	11	–
900	6629	1660	11	8	16	2	4	1	2	–

Table 6. The same as Table 5, but for a CLIC based $e\gamma$ collider

$\sqrt{s_{e^+e^-}}=3$ TeV, $L_{\text{int}}=10^5$ pb^{-1}	Number of events $(\sigma_{\text{D}}+\sigma_{\text{R}})\times L_{\text{int}}$		$\frac{S}{\sqrt{B}}(e\gamma\to q\bar{q}e)$					$\frac{S}{\sqrt{B}}(e\gamma\to q\bar{q}'\nu)$		
M_{LQ} (GeV)	$\|Q\|=5/3$	$\|Q\|=4/3$	S_0	S_1^0	$R_{1/2}^{-1/2}$	$R_{1/2}^{1/2}$	$\widetilde{R}_{1/2}^{-1/2},\widetilde{S}_0,S_1^{-1}$	S_0	S_1^0	$R_{1/2}^{1/2}$
300	181523	124657	648	491	981	337	674	33	49	34
500	73182	35515	261	198	396	99	197	13	20	10
700	43722	18168	156	118	236	49	98	8	12	5
900	30084	11135	107	81	163	30	60	5	8	3
1100	22141	7513	79	60	120	20	41	4	6	–
1300	16929	5335	60	46	92	14	29	–	5	–
1500	13251	3906	47	36	72	11	21	–	4	–
1700	10520	2922	38	28	57	8	16	–	–	–
1900	8406	2225	30	23	45	6	12	–	–	–
2100	6705	1728	24	18	36	5	9	–	–	–
2300	5340	1377	19	14	29	4	7	–	–	–
2500	3842	975	14	10	21	–	5	–	–	–
2700	824	206	3	2	4	–	1	–	–	–

For the background processes $e\gamma\to W\nu$ and $e\gamma\to Ze$ we find the total cross sections 41.20 (49.48) pb and 2.36 (0.49) pb at $\sqrt{s_{e^+e^-}}=1$ (3) TeV, respectively. We multiply these cross sections with the branching ratios for corresponding channels. We take the branching ratios 68.5% and 69.89% for the W boson and Z boson decaying into hadrons, respectively.

4 Results and discussion

The scalar leptoquarks of any type can be produced with a large cross section due to direct and resolved processes at $e\gamma$ colliders. The production cross sections for scalar leptoquarks with the charges $|Q|=5/3$ and $1/3$ are practically the same; the same situation occurs for the scalar leptoquarks with the charges $|Q|=4/3$ and $2/3$. The contribution to the cross sections from direct and resolved processes can be compared in Tables 3 and 4. The resolved contribution is effective at a relatively low mass range. Depending on the center of mass energy this contribution decreases sharply beyond the leptoquark mass value of about 70% of the collider energies. The direct contribution for the scalar leptoquark with $|Q|=5/3$ is larger than the scalar leptoquark with $|Q|=4/3$. This can be explained due to the quark charge dependence of the cross sections for the direct contribution. The coupling for the lepton-quark–leptoquark vertex can be parametrized as $g_{\text{LQ}}^2=4\pi\alpha\kappa$ where κ is a parameter. For smaller values of this parameter the cross section decreases with κ.

From Table 5, we find acccessible upper mass limits of scalar leptoquarks for a TESLA based $e\gamma$ collider with the center of mass energy $\sqrt{s_{e\gamma}^{\max}}\simeq 911$ GeV and luminosity $L=10^5$ pb^{-1}. The scalar leptoquarks of types S_0, S_1^0 and $R_{1/2}^{-1/2}$ can be produced up to mass $M_{\text{LQ}}\approx 900$ GeV, and $R^{1/2}_{1/2}, \widetilde{S}_0, S^{-1}_1, \widetilde{R}^{-1/2}_{1/2}$ up to $M_{\rm LQ} \approx 850\,{\rm GeV}$ in the $2j + e$ channel. However, the leptoquarks of type S_0, S^0_1 can be produced up to $M_{\rm LQ} \approx 850\,{\rm GeV}$ and $R^{1/2}_{1/2}$ up to $M_{\rm LQ} \approx 650\,{\rm GeV}$ in the $2j+ \not{p}_{\rm T}$ channel. For the CLIC based $e\gamma$ collider with $\sqrt{s^{\rm max}_{e\gamma}} \simeq 2733\,{\rm GeV}$ and luminosity $L = 10^5\,{\rm pb}^{-1}$, the scalar leptoquarks of type $S_0, S^0_1, R^{-1/2}_{1/2}$ could be produced up to mass $M_{\rm LQ} \approx 2600\,{\rm GeV}$ and $\widetilde{R}^{-1/2}_{1/2}, \widetilde{S}_0, S^{-1}_1$ up to mass $M_{\rm LQ} \approx 2500\,{\rm GeV}$ and $R^{1/2}_{1/2}$ up to $M_{\rm LQ} \approx 2100\,{\rm GeV}$ in the $2j + e$ channel, and scalar leptoquarks of type $R^{1/2}_{1/2}$ up to 700 GeV, S_0 up to 900 GeV and S^0_1 up to 1300 GeV in the $2j+ \not{p}_{\rm T}$ channel. The statistical significances for these channels are given in Table 6.

To conclude, the scalar leptoquarks can be produced in large numbers at both TESLA and CLIC based $e\gamma$ colliders. We have analyzed the contributions from direct and resolved photon processes to the total cross section. We find that the latter contribution is important and cannot be ignored especially for small leptoquark masses. Looking at the final state particles and their signature in the detectors, scalar leptoquarks of some types can be identified.

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