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.
I. 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), color (anti)-triplet, 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 BRW model [1]. The scalar leptoquarks ($S, R$) can be grouped into singlets ($S_0, \tilde{S}_0$), doublets ($R_{1/2}, \tilde{R}_{1/2}$) and 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 $M_{LQ} > 200$ GeV [2] and $M_{LQ} > 225$ 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 $e\nu$ and $\nu d$ 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 $g_{L,R}$ within one generation of fermions satisfy flavour conservation. The product of 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 (BRW) 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 SU(3)$_C \times$ SU(2)$_W \times$ U(1)$_Y$ invariance:

\[
L_{\text{eff}} = L_{F=0} + L_{|F|=2} + L_{\gamma,Z,g}
\]

\[
L_{F=0} = g_{1/2} L R l R l_1/2 + g_{1/2} R L i \tau_2 e R R_{1/2} + \tilde{g}_{1/2} L l_1 R \tilde{R}_{1/2} + \text{H.c.}
\]

\[
L_{|F|=2} = g_0 L R i \tau_2 l R S_0 + g_0 R L e R S_0 + \tilde{g}_0 R R l R S_0 + g_{1} L l_1 R i \tau_2 l L \cdot \tilde{S}_1 + \text{H.c.}
\]

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 different hypercharge. 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. Charged conjugated quark field is defined as $q^C = Cq^T$ and $\overline{q}^C = q^TC$.

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

\[
L_{\gamma,Z,g} = \sum_{\Phi=S,R} (D_\mu \Phi)^\dagger (D^\mu \Phi) - M_\Phi^2 \Phi^\dagger \Phi
\]

where $\Phi$ is any type of scalar leptoquark, and $M_\Phi$ is the mass of the scalar leptoquark.

The covariant derivative is $D_\mu = \partial_\mu - ig e Q_SA_\mu - ig e Q_Z Z_\mu - ig s T^a C_\mu$, here $Q_S$ is the charge of scalar leptoquark and $g_e$ is the electromagnetic coupling constant. $Q_Z = (I_3 - Q_S \sin \theta_W)/\cos \theta_W \sin \theta_W$. In the above equation, $A_\mu, Z_\mu$ and $G_\mu$ denote the photon, $Z$-boson and gluon fields, respectively. $I_3$ is the third component of the weak isospin and $\theta_W$ 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 quantum numbers of scalar leptoquarks as given in Table II.

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 $e\gamma \rightarrow q\bar{q}e$ and $e\gamma \rightarrow q\bar{q}\nu$ are given in Table II.

II. SINGLE PRODUCTION OF SCALAR LEPTOQUARKS

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

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 $e\gamma \rightarrow Sq$ consists of $s, u$ and $t$ channels which correspond to
electron, quark and scalar LQ exchanges, respectively.

On the base of the effective lagrangian, the differential cross section for scalar LQ pro-
ductions through subprocess $e\gamma \rightarrow Sq$ is given by

$$
\frac{d\hat{\sigma}}{d\hat{t}} = \frac{N_c g^2 g_{\gamma}^2}{16\pi\hat{s}^2} (c_1^2 + c_2^2) \left[ -\frac{Q_e^2 \hat{s}}{\hat{s}} - \frac{Q_q^2 \hat{s} \hat{u}}{(\hat{u} - m_q^2)^2} + \frac{Q_s^2 \hat{t} (\hat{t} + M_{LQ}^2)}{(\hat{t} - M_{LQ}^2)^2} \right. \\
+ \left. \frac{2Q_e Q_q (\hat{s} + \hat{t}) (\hat{s} - M_{LQ}^2)}{\hat{s} (\hat{u} - m_q^2)} - \frac{Q_e Q_S (\hat{s} - 2M_{LQ}^2)}{\hat{s} (\hat{t} - M_{LQ}^2)} - \frac{Q_q Q_S \hat{t} (\hat{s} + \hat{t} + M_{LQ}^2)}{(\hat{u} - m_q^2) (\hat{t} - M_{LQ}^2)} \right] \tag{5}
$$

where we use the Lorentz invariant Mandelstam variables $\hat{s} = (k_1 + p_t)^2$, $\hat{u} = (p_2 - k_1)^2$
and $\hat{t} = (k_2 - k_1)^2$. $c_1$ and $c_2$ are the constants equal to 1/2 and $-(+)1/2$ corresponding to
left (right) couplings, respectively; $g$ is 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 scalar LQs with fermions as $g^2 = 4\pi\alpha\kappa$ with $\kappa = 1$ and color factor $N_c = 3$
. Since cross section varies with $\kappa$ we can simply rescale it for the various $\kappa$ values.

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

$$\sigma_D = \int_{y_{\text{min}}}^{0.83} dy \ f_\gamma(y) \ \hat{\sigma}(y \cdot s)$$  \hspace{1cm} (6)$$

where \( y_{\text{min}} = M_{LQ}^2/s \), and \( f_\gamma \) is the energy spectrum of the Compton backscattered photons from electrons,

$$f_\gamma(y) = \frac{1}{D(\varsigma)} \left[ 1 - y + \frac{1}{(1 - y)^2} - \frac{4y}{\varsigma(1 - y)} + \frac{4y^2}{\varsigma^2(1 - y)^2} \right]$$  \hspace{1cm} (7)$$

where

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

with \( \varsigma = 4E_e\omega_0/m_e^2 \), and \( y = E_\gamma/E_e \) is the ratio of backscattered photon energy to the initial electron energy. The energy \( E_\gamma \) of converted photons is restricted by the condition \( y_{\text{max}} = 0.83 \). The value \( y_{\text{max}} = \varsigma/(\varsigma + 1) = 0.83 \) corresponds to \( \varsigma = 4.8 \). Energy spectrum of 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 total cross section comes from the quark exchange diagram in Figs. 1b and 2b. For this reason, the total cross sections for production of scalar leptoquarks \( R_{1/2}(-5/3) \), \( S_0(-1/3) \) and \( S_1(-1/3) \) practically coincide. This is also true for \( R_{1/2}(-2/3) \), \( \tilde{R}_{1/2}(-2/3) \), \( \tilde{S}_0(-4/3) \) and \( S_1(-4/3) \) type scalar leptoquark production.

The scalar leptoquarks can also be produced in \( e\gamma \) collisions by the resolved photon processes, Fig. 3. 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 \( R \))

$$e + q_\gamma \rightarrow S \rightarrow e + q$$  \hspace{1cm} (9)$$

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

$$\hat{\sigma}(\hat{s}) = \frac{\pi^2 \kappa \alpha}{2M_{LQ}} \delta(M_{LQ} - \sqrt{\hat{s}})$$  \hspace{1cm} (10)$$
For CLIC and TESLA based $e\gamma$ colliders, the total cross section for resolved photon contribution is obtained by convoluting with the backscattered laser photon distribution and photon structure function. The photon structure function consists of perturbative pointlike parts and hadronlike parts $f_{q/\gamma} = f_{q/\gamma}^{PL} + f_{q/\gamma}^{HL}$ [3]. The pointlike part can be calculated in the leading logarithmic approximation and is given by

$$f_{q/\gamma}^{PL}(y) = \frac{3\alpha Q^2}{2\pi} \left[ y^2 + (1 - y)^2 \right] \log \frac{Q^2}{\Lambda^2}$$  \hspace{1cm} (11)$$

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

$$\sigma_R = \frac{\pi^2 \alpha K}{s} \int_{x_{\text{min}}}^{0.83} \frac{dx}{x} f_{\gamma/e}(x) \left[ f_{q/\gamma}(z, Q^2) - f_{q/\gamma}^{PL}(z, Q^2) \right]$$  \hspace{1cm} (12)$$

where $z = M_{LQ}^2 / x s$, $x_{\text{min}} = M_{LQ}^2 / s$, and $Q^2 = M_{LQ}^2$. Since the contribution from the pointlike 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. Here, $f_{q/\gamma}$ is a $Q^2$-dependent parton distribution function [8] within the backscattered photon.

Both 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

$$\sigma = \sigma_D + \sigma_R$$  \hspace{1cm} (13)$$

here $\sigma_D$ and $\sigma_R$ denotes the direct and resolved contribution to the total cross sections. The total cross sections including both direct and resolved contributions are plotted in Figs. [3][4] for TESLA and CLIC based $e\gamma$ colliders. In Tables [11] and [14] direct and resolved contribution to the scalar leptoquark production are shown for TESLA and CLIC based $e\gamma$ colliders, respectively. From the figures [3][4] the contribution from resolved process is dominant for small leptoquark masses. The distribution function of partons within the photon has the order $O(\alpha/\alpha_s)$ where $\alpha$ is due to the photon splitting into $q\bar{q}$ and $\alpha_s^{-1}$ due to the QCD evolution. Therefore, the contribution from resolved photon is $O(\alpha^2/\alpha_s)$ where the hard subprocess in the resolved photon case has $O(\alpha)$. The direct contribution has $O(\alpha^2)$. 

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On the other hand, direct contribution is effective for large masses up to the kinematical limit.

### III. SIGNALS AND BACKGROUNDS

When 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 $2j + \not{p}_T$ (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

$$\Gamma = \frac{g^2 M_{LQ}}{16\pi}$$

(14)

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

All scalar leptoquark types and signals at the $e\gamma$ collisions are given in Table II. The numbers in paranthesis 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 $e\gamma \to W^- \nu$ consists of $t$ and $s$ channels which correspond to $W^-$ and electron exchanges, respectively. The differential cross section for this process is given by

$$\frac{d\hat{\sigma}}{dt} = \frac{-g_W^2 g_e^2}{32\pi s^3 (tm_W - m_W^3)^2} \left[ \hat{s}\hat{t}(s^2 + \hat{s}\hat{t} + 2\hat{t}^2) - (3\hat{s}^3 + 2\hat{s}^2\hat{t} + 5\hat{s}\hat{t}^2 + \hat{t}^3)m_W^2 \right. $$

$$+ (\hat{s}^2 + 5\hat{t}^2)m_W^4 + (\hat{s} - 5\hat{t})m_W^6 + m_W^8 \right]$$

(15)

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

\[
\frac{d\hat{\sigma}}{dt} = \frac{(c_V^2 + c_A^2) g_L^2 g_Z^2}{64\pi \hat{s} \hat{t} \hat{s}^2 g_L^2 g_Z^2} \left[ 2(\hat{s} + \hat{t})(2\hat{s}^2 + 2\hat{s}\hat{t} + \hat{t}^2 m_Z^2) - 2(\hat{s} + \hat{t})^2 m_Z^4 + 2(3\hat{s} + \hat{t}) m_Z^6 - 2 m_Z^8 \right]
\]

(16)

here \(\hat{s} = (p_e + p_\gamma)^2\), \(\hat{t} = (p_\gamma - p_Z)^2\); \(c_V = -1/2 + 2\sin^2\theta_W\) and \(c_A = -1/2\).

For the background processes \(e\gamma \rightarrow W\nu\) and \(e\gamma \rightarrow Ze\) 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.

IV. RESULTS AND DISCUSSIONS

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 takes place 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 III and IV. The resolved contribution is effective relatively at 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 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 direct contribution. The coupling for lepton-quark-leptoquark vertex can be parametrized as \(g_{LQ}^2 = 4\pi\alpha\kappa\) where \(\kappa\) is a parameter. For smaller values of this parameter the cross section decreases with \(\kappa\).

From the Table V, we find accessible upper mass limits of scalar leptoquarks for TESLA based \(e\gamma\) collider with the center of mass energy \(\sqrt{s_{e\gamma}}\) \(\approx 911\) GeV and luminosity \(L = 10^9\) pb\(^{-1}\). The scalar leptoquarks of types \(S_0, S_1^0\) and \(R_{1/2}^{-1/2}\) can be produced up to mass \(M_{LQ} \approx 900\) GeV, and \(R_{1/2}^{1/2}, S_0, S_1^{-1}, R_{1/2}^{-1/2}\) up to \(M_{LQ} \approx 850\) GeV in the 2\(j\) + \(e\) channel. However, the leptoquarks of type \(S_0, S_1^1\) can be produced up to \(M_{LQ} \approx 850\) GeV and \(R_{1/2}^{1/2}\) up to \(M_{LQ} \approx 650\) GeV in the 2\(j\) + \(p_T\) channel. For the CLIC based \(e\gamma\) collider with \(\sqrt{s_{e\gamma}} \approx 2733\)
GeV and luminosity $L = 10^5 \text{ pb}^{-1}$, the scalar leptoquarks of type $S_0, S_1^0, R_{1/2}^{-1/2}$ could be produced up to mass $M_{LQ} \approx 2600$ GeV and $\tilde{R}_{1/2}^{-1/2}, \tilde{S}_0, S_1^{-1}$ up to mass $M_{LQ} \approx 2500$ GeV and $R_{1/2}^{1/2}$ up to $M_{LQ} \approx 2100$ GeV in $2j + e$ channel, and scalar leptoquarks of type $R_{1/2}^{1/2}$ up to 700 GeV, $S_0$ up to 900 GeV and $S_1^0$ up to 1300 GeV in the $2j + p_T$ channel. The statistical significance for these channels are given in Table VI.

As to conclude, the scalar leptoquarks can be produced with a 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 the latter contribution is important and can not be ignored especially for small leptoquark masses. Looking at the final state particles and their signature in detectors scalar leptoquarks of some types can be identified.

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TABLE I: Quantum numbers of scalar leptoquarks according to BRW model. The numbers in the parenthesis in the last two columns denote the values for $g_L = g_R$.

| Leptoquark F | $I_3$ | $Q_{em}$ | Decay | Coupling | $\text{BR}(S \rightarrow lq)$ | $\text{BR}(S \rightarrow \nu lq)$ |
|--------------|-------|----------|--------|----------|----------------------------|-------------------------------|
| $S_0$        | 2     | 0        | $e_L u_L$ $\nu d_L$ | $g_0 L$ | $g_{0R}$ | $\frac{g_{0L}^2 + g_{0R}^2}{2g_{0L}^2 + g_{0R}^2} \left( \frac{2}{3} \right)$ | $\frac{g_{0L}^2}{2g_{0L}^2 + g_{0R}^2} \left( \frac{1}{3} \right)$ |
| $\tilde{S}_0$| 2     | 0        | $e_R d_R$ | $\bar{g}_{0R}$ | 1 | 0 |
| $S_1$        | 0     | 0        | $\nu d_L, e_L u_L$ | $-g_{1L}$ | $1/2$ | $1/2$ |
| $R_{1/2}$    | $1/2$| $-2/3$  | $\nu u_R$ | $g_{1/2 L}$ | 0 | 1 |
| $R_{1/2}$    | $1/2$| $-2/3$  | $e_R d_L$ | $-\sqrt{2} g_{1L}$ | 1 | 0 |
| $\tilde{R}_{1/2}$ | $1/2$| $1/3$  | $\nu d_R$ | $\bar{g}_{1/2 L}$ | 0 | 1 |
| $\tilde{R}_{1/2}$ | $-1/2$| $-2/3$ | $e_R d_R$ | $\bar{g}_{1/2 L}$ | 1 | 0 |

TABLE II: Scalar leptoquark final states, the numbers in the parenthesis denote the electric charge of scalar leptoquarks.

| Initial | Signal | | Initial | Signal |
|---------|--------| |---------|--------|
| $\gamma e^-_L \rightarrow u_L S_0(-1/3)$ | $\uparrow 2j + e^-$ | | $\gamma e^-_R \rightarrow u_R S_0(-1/3)$ | $2j + e^-$ |
| $\gamma e^-_L \rightarrow u_L S_1(-1/3)$ | $\uparrow 2j + e^-$ | | $\gamma e^-_R \rightarrow d_R \bar{S}_0(-4/3)$ | $2j + e^-$ |
| $\gamma e^-_L \rightarrow d_L S_1(-4/3)$ | $\rightarrow 2j + e^-$ | | $\gamma e^-_R \rightarrow \bar{d}_L R_{1/2}(-2/3)$ | $2j + e^-$ |
| $\gamma e^-_L \rightarrow \bar{u}_R R_{1/2}(-5/3)$ | $\rightarrow 2j + e^-$ | | $\gamma e^-_R \rightarrow \bar{u}_L R_{1/2}(-5/3)$ | $2j + e^-$ |
| $\gamma e^-_L \rightarrow \bar{d}_R \tilde{R}_{1/2}(-2/3)$ | $\rightarrow 2j + e^-$ |
TABLE III: 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 $\sqrt{s_{e^+e^-}} = 1$ TeV.

| $\sqrt{s_{e^+e^-}}$ (GeV) | $|Q| = 5/3$ | $|Q| = 4/3$ | $|Q| = 5/3$ | $|Q| = 4/3$ |
|---------------------------|------------|------------|------------|------------|
| $M_{LQ}$ (GeV) | $\sigma_D$ (pb) | $\sigma_R$ (pb) | $\sigma_D$ (pb) | $\sigma_R$ (pb) |
| 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 x 10^{-2} |
| 600 | 0.69 | 0.19 | 6.39 x 10^{-2} | 2.46 x 10^{-2} |
| 700 | 0.53 | 0.14 | 1.35 x 10^{-2} | 3.05 x 10^{-3} |
| 800 | 0.38 | 9.78 x 10^{-2} | 0.0 | 0.0 |
| 900 | 6.63 x 10^{-2} | 1.66 x 10^{-2} | 0.0 | 0.0 |

TABLE IV: The same as Table III, but for $\sqrt{s_{e^+e^-}} = 3$ TeV.

| $\sqrt{s_{e^+e^-}}$ (GeV) | $|Q| = 5/3$ | $|Q| = 4/3$ | $|Q| = 5/3$ | $|Q| = 4/3$ |
|---------------------------|------------|------------|------------|------------|
| $M_{LQ}$ (GeV) | $\sigma_D$ (pb) | $\sigma_R$ (pb) | $\sigma_D$ (pb) | $\sigma_R$ (pb) |
| 300 | 0.53 | 0.16 | 1.27 | 1.09 |
| 500 | 0.39 | 0.11 | 0.34 | 0.25 |
| 700 | 0.29 | 8.31 x 10^{-2} | 0.14 | 9.86 x 10^{-2} |
| 900 | 0.23 | 6.37 x 10^{-2} | 7.43 x 10^{-2} | 4.76 x 10^{-2} |
| 1100 | 0.18 | 4.97 x 10^{-2} | 4.32 x 10^{-2} | 2.54 x 10^{-2} |
| 1300 | 0.14 | 3.92 x 10^{-2} | 2.75 x 10^{-2} | 1.41 x 10^{-2} |
| 1500 | 0.11 | 3.12 x 10^{-2} | 1.82 x 10^{-2} | 7.78 x 10^{-3} |
| 1700 | 9.34 x 10^{-2} | 2.52 x 10^{-2} | 1.18 x 10^{-2} | 3.94 x 10^{-3} |
| 1900 | 7.75 x 10^{-2} | 2.06 x 10^{-2} | 6.50 x 10^{-3} | 1.56 x 10^{-3} |
| 2100 | 6.49 x 10^{-2} | 1.71 x 10^{-2} | 2.06 x 10^{-4} | 2.18 x 10^{-4} |
| 2300 | 5.34 x 10^{-2} | 1.38 x 10^{-2} | 0.0 | 0.0 |
| 2500 | 3.84 x 10^{-2} | 9.75 x 10^{-3} | 0.0 | 0.0 |
| 2700 | 8.24 x 10^{-3} | 2.06 x 10^{-3} | 0.0 | 0.0 |
TABLE V: The number of events and signal significance for $2j + e$ and $2j + \not{p_T}$ channels of scalar leptoquark decays. The lower and upper indices on scalar leptoquarks $S$ or $R$ denote weak isospin $I$ and $I_3$, respectively.

| $\sqrt{s_{ee}} = 1$ TeV | Number of Events | $\frac{s}{\sqrt{B}}(e\gamma \rightarrow q\bar{q}e)$ | $\frac{s}{\sqrt{B}}(e\gamma \rightarrow q\bar{q}\nu)$ |
|--------------------------|-----------------|-----------------|-----------------|
| $L_{int} = 10^5$ pb$^{-1}$ | $(\sigma_D + \sigma_R) \times L_{int}$ | $S_0$ $S_0^0$ $R_{1/2}^{-1/2}$ $R_{1/2}^{1/2}$ | $S_0$ $S_1^0$ $R_{1/2}^{1/2}$ |
| 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 | - |

FIG. 1: Feynman diagrams for $|F| = 0$ scalar leptoquarks in $e\gamma$ collision.
TABLE VI: The same as Table V, but for CLIC based $e\gamma$ collider.

| $\sqrt{s_{ee}}$ = 3 TeV | Number of Events $(\sigma_D + \sigma_R) \times L_{int}$ | $\frac{S}{\sqrt{B}}(e\gamma \rightarrow q\bar{q}e)$ | $\frac{S}{\sqrt{B}}(e\gamma \rightarrow q\bar{q}\nu)$ |
|--------------------------|-------------------------------------------------|---------------------------------|---------------------------------|
| $L_{int} = 10^5$ pb$^{-1}$ | $|Q| = 5/3$ | $|Q| = 4/3$ | $S_0$ | $S_1^0$ | $R_{1/2}^{-1}$ | $R_{1/2}^{1}$ | $\bar{R}_{1/2}^{-1}$ | $\bar{S}_0, S_1^{-1}$ | $S_0$ | $S_1^0$ | $R_{1/2}^{1}$ |
| 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 | - | - | - |

FIG. 2: Feynman diagrams for $|F| = 2$ scalar leptoquarks in $e\gamma$ collision.
FIG. 3: Energy spectrum of backscattered photons.

FIG. 4: Resolved process for single production of scalar leptoquarks. a) correspond to $F = 0$, and b) for $|F| = 2$ type.
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 $\sqrt{s_{e^+e^-}} = 1$ 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 $\sqrt{s_{e^+e^-}} = 3$ TeV.

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