Searching for Single Production of Charged Heavy Leptons via Anomalous Interactions at Future Linear Colliders

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Abstract

We consider the possible discovery potential for single production of charged heavy leptons via anomalous interactions at future linear colliders ILC and CLIC. We calculate the production cross sections and decay widths of charged heavy leptons in the context of anomalous interactions at center of mass energies $\sqrt{s}=0.5$ TeV (ILC), $\sqrt{s}=1$ and 3 TeV (CLIC). The signal and corresponding backgrounds are studied in detail for the mass range 200-900 GeV.

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I. INTRODUCTION

At the present time, the experimental evidence for new physics beyond the Standard Model (SM) is insufficient. The observation of new heavy particles would change this situation completely, if they exist. Thus, any signal for the production of heavy leptons will play a milestone role in the discovery of new physics. We expect many exciting discoveries with start-up of the Large Hadron Collider (LHC), which will search for TeV scale energies and masses. Heavy lepton production at the LHC will be difficult to detect, due to large backgrounds and small production rate. A linear collider with clean experimental environment, can also provide complementary information for new physics with performing precision measurements that would complete the LHC results. Heavy leptons can be easily produced and detected at linear colliders up to the kinematic limits. Most popular proposed linear colliders with energies on the TeV scale and extremely high luminosity are International Linear Collider (ILC) [1] and Compact Linear Collider (CLIC) [2, 3].

In the SM, Flavor Changing Neutral Current (FCNC) processes receive very small contributions only from higher order corrections. Some models beyond the SM involves FCNC couplings which appears at tree-level. Although there are lots of studies on the new heavy leptons in the literature, namely, at future $e^-e^+$ [4, 5, 6, 7, 8, 9, 10, 11, 12], hadron [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24] and $ep$ colliders [25, 26, 27, 28, 29], further study via FCNC anomalous interactions is needed, since an anomalous coupling, which has the formalism in [30], that generalize the SM as effective operators of dimension greater than four, can have a considerable effect on heavy lepton production especially at future colliders with their high energies and luminosity. Any observation of these FCNC transitions would be the signal of new physics beyond the SM. Therefore, in the present work, we study possible production and decay processes of the new charged heavy leptons ($L$) via some anomalous interactions at linear colliders ILC ($\sqrt{s}=0.5$ TeV, $L^{int}=10^5$ pb$^{-1}$ per year) and CLIC ($\sqrt{s}=1$ and 3 TeV, $L^{int}=10^5$ pb$^{-1}$ per year).

The experimental upper bounds for the heavy lepton masses were found to be 44 GeV by OPAL [31], 46 GeV by ALEPH [32], 90 GeV by H1 [33] and 100 GeV by L3 [34] Collaborations. Considering these experimental upper bounds, we scan the mass range of heavy leptons between 200-900 GeV at the envisaged TeV energy linear colliders.
II. SINGLE PRODUCTION AND DECAYS OF $L$

The model independent effective Lagrangian having magnetic moment type operators that describes the anomalous interactions of $L$, by ordinary ones can be written from [35] with minor modifications as;

$$
\mathcal{L}_{\text{eff}} = \frac{ie\kappa_\gamma}{\Lambda}\sigma_{\mu\nu}q^\nu l A^\mu \\
+ \frac{ig}{2\cos\theta_W}\frac{\kappa_Z}{\Lambda}\sigma_{\mu\nu}q^\nu l Z^\mu \\
+ \frac{ig}{\sqrt{2}}\frac{\kappa_W}{\Lambda}\sigma_{\mu\nu}q^\nu P_L\nu W^\mu + \text{h.c.},
$$

(1)

where $\kappa_\gamma$, $\kappa_Z$ and $\kappa_W$ are the anomalous magnetic dipole moment factors, $l$ is the ordinary SM lepton ($e$, $\mu$ and $\tau$), $q$ is the momentum of the exchanged gauge boson, $\theta_W$ is the Weinberg angle, $e$ and $g$ denote the gauge couplings relative to $U(1)$ and $SU(2)$ symmetries respectively, $A^\mu$, $Z^\mu$ and $W^\mu$ are the vector fields of the photon, Z-boson and W-boson, respectively, $P_L$ is the left-handed projection operator and $\Lambda$ is the cutoff scale for new physics.

![Feynman diagrams relevant for single production of $L$ in $e^-e^+$ collisions.](image)

The single production of $L$ occur via the $t$-channel $\gamma$ and $Z$-boson exchange $e^-e^+ \rightarrow Le^+$ process in $e^-e^+$ collision. Corresponding Feynman diagrams and their subsequent decays are shown in Fig. 1. The differential cross section of this process is given by,
\[
\frac{d\sigma}{dt} = \left( \frac{1}{128\pi s^2} \right) \left\{ \frac{16e^4}{s t} \left( \frac{\kappa_\gamma}{\Lambda} \right)^2 (2(s^2 + t^2)m_L^2 - (s + t)m_L^4 - 2(s^3 + t^3)) 
+ \frac{e^4(a_l^2 + v_l^2)}{\sin^4\theta_W \cos^4\theta_W} \left( \frac{\kappa_Z}{\Lambda} \right)^2 \left[ \frac{((s + 2t)m_L^2 - m_L^4 - 2t(s + t))s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \right] 
\right. 
+ \frac{((2s + t)m_L^2 - m_L^4 - 2s(s + t))t}{(t - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} 
+ \frac{2st(s + t - m_L^2)(s + t - M_Z^2)(M_Z^2 - (s + t - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)}{(t - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)} 
+ \frac{8e^4v_lM_Z\Gamma_Z}{\sin^2\theta_W \cos^2\theta_W((s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)((t - M_Z^2)^2 + M_Z^2 \Gamma_Z^2)} \left( \frac{\kappa_Z}{\Lambda} \right) \left( \frac{\kappa_L}{\Lambda} \right) 
\times \left[ (s^2 + t^2)m_L^4 - 2(s^3 + t^2)m_L^2 + (2m_L^4 - 2(s + t)m_L^2 + (s + t)^2)(M_Z^2 - \Gamma_Z^2) - 2((s + t)m_L^4 - 2(s^2 + t^2)m_L^2 + 2(s^3 + t^3))M_Z^2 + (s + t)^2(2s^2 - 3st + 2t^2) \right] \right\} \quad (2)
\]

where \(v_l\) and \(a_l\) refer to vector and axial vector couplings, \(m_L\) is the mass of \(L\), \(\Gamma_Z\) and \(M_Z\) are decay width and mass of the \(Z\)-boson, respectively.

Heavy leptons decay via charged and neutral currents through the mixing with an ordinary lepton through the processes \(L \to \gamma l, L \to Zl\) and \(L \to W\nu_l\) via anomalous couplings defined in Eq. (1). Neglecting ordinary lepton masses the decay widths are obtained as,

\[
\Gamma(L \to \gamma l) = \frac{e^2}{8\pi} \left( \frac{\kappa_\gamma}{\Lambda} \right)^2 m_L^3, \quad (3)
\]

\[
\Gamma(L \to Zl) = \frac{e^2}{64\pi \sin^2\theta_W \cos^2\theta_W} \left( \frac{\kappa_Z}{\Lambda} \right)^2 \left( 2m_L^3 - 3M_Z^2 m_L + \frac{M_W^6}{m_L^3} \right), \quad (4)
\]

\[
\Gamma(L \to W\nu_l) = \frac{e^2}{16\pi \sin^2\theta_W} \left( \frac{\kappa_W}{\Lambda} \right)^2 \left( 2m_L^3 - 3M_W^2 m_L + \frac{M_W^6}{m_L^3} \right). \quad (5)
\]

### III. NUMERICAL ANALYSIS

In order to search for potential discovery of \(L\) at ILC and CLIC, the anomalous vertices given in Eq. (1) are implemented into the tree-level event generator CompHEP \[36\]. In Table \[II\] we present the branching ratios (BR) and decay widths of \(L\) for the given decay channels for the mass range 200-900 GeV. We assume \((\kappa/\Lambda)=1\) TeV\(^{-1}\) in all our numerical calculations by taking anomalous magnetic moment couplings as \(\kappa_\gamma = \kappa_Z = \kappa_W = \kappa\).

In Fig. \[2\] we plot the production cross sections for as function of \(m_L\) for three center of mass energies 0.5 TeV (dotted-line), 1 TeV (dashed-line) and 3 TeV (solid-line) by using the calculated differential cross section given in Eq. (2). Furthermore, the simultaneous dependence of cross section to \((\kappa/\Lambda)\) and \(m_L\) are shown in Figs. \[3\] and \[4\].
TABLE I: Branching ratios (%) and total decay widths of heavy leptons depending on its mass values.

| \( m_L \) (GeV) | \( BR(L \rightarrow \gamma l) \) | \( BR(L \rightarrow Zl) \) | \( BR(L \rightarrow W\bar{\nu}_l) \) | \( \Gamma_{\text{tot}} \) (GeV) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 200             | 6.3             | 6.2             | 20.8            | 0.49            |
| 300             | 5.5             | 6.6             | 21.2            | 1.93            |
| 400             | 5.2             | 6.8             | 21.3            | 4.79            |
| 500             | 5.1             | 6.9             | 21.3            | 9.52            |
| 600             | 5.1             | 6.9             | 21.4            | 16.66           |
| 700             | 5.0             | 6.9             | 21.4            | 26.61           |
| 800             | 5.0             | 6.9             | 21.4            | 39.87           |
| 900             | 5.0             | 6.9             | 21.4            | 56.94           |

FIG. 2: The total cross sections for the process \( e^- e^+ \rightarrow L^- e^+ \), as function of \( m_L \) for \( \sqrt{s} = 0.5 \) TeV (dotted-line), 1 TeV (dashed-line) and 3 TeV (solid-line) with \( L^{\text{int}} = 10^5 \text{pb}^{-1} \).

The single production of \( L \) is assumed to be produced via signal processes \( e^- e^+ \rightarrow L^- e^+ \) with \( L \rightarrow lZ(\gamma) \) and \( L \rightarrow W\bar{\nu}_l \). The final states, \( e^- Ze^+ \) and \( e^-\gamma e^+ \), which occurs from these signal processes can be compared with the ones having the same final state SM background processes. In this study, we consider the process \( e^- e^+ \rightarrow e^- Ze^+ \) for the signal and corresponding background analysis.

Photon radiation from incoming electrons and positrons is called as the initial state
FIG. 3: The total cross sections for the process $e^-e^+ \rightarrow L^-e^+$, as functions of $\kappa/\Lambda$ and $m_L$ for $\sqrt{s} = 0.5$ TeV.

radiation (ISR). The spectrum of ISR scale inherent to the process under consideration. We take into account this spectrum in our calculations by using the CompHEP program with beamstrahlung spectra. Beamstrahlung is process of energy loss by the incoming electron (positron) in the field of the positron (electron) bunch moving in the opposite direction. The
FIG. 5: The total cross sections for the process $e^-e^+ \rightarrow L^-e^+$, as functions of $\kappa/\Lambda$ and $m_L$ for $\sqrt{s} = 3$ TeV.

TABLE II: Collider parameters relevant for the calculation of beamstrahlung.

| Collider | ILC | CLIC |
|----------|-----|------|
| parameter | 500 GeV | 1 TeV | 3 TeV |
| $N(10^{10})$ | 2 | 0.4 | 0.4 |
| $\sigma_x$(nm) | 655 | 115 | 43 |
| $\sigma_y$(nm) | 5.7 | 1.75 | 1 |
| $\sigma_z$(µm) | 300 | 30 | 30 |
| $\Upsilon$ | 0.045 | 1.014 | 8.068 |
| $N_\gamma$ | 1.22 | 1.04 | 1.74 |

beamstrahlung parameter ($\Upsilon$), average number of photons per electron ($N_\gamma$) and collider parameters relevant for the calculation of beamstrahlung are given in Table II [38].

The essential experimental method searching for new particles is, selecting the distributions of kinematical observables that can separate the signal from the SM backgrounds. One of them is the final state invariant mass distribution. We display the differential invariant mass distributions of final state $Ze^-$ system in Figs. 6, 7 and 8 for $\sqrt{s}=0.5$, 1 and 3 TeV, respectively. From these figures, it is obviously seen that, the peaks shows the signal with
various $m_L$ values for each center of mass energies.

FIG. 6: The invariant mass distribution of $Ze^-$ for the process $e^-e^+ \rightarrow e^-Ze^+$ at $\sqrt{s} = 0.5$ TeV.

FIG. 7: The invariant mass distribution of $Ze^-$ for the process $e^-e^+ \rightarrow e^-Ze^+$ at $\sqrt{s} = 1$ TeV.

The transverse momentum distributions of the final state electron for the signal and SM background processes are given in Figs. 9, 10 and 11 for $\sqrt{s}=0.5, 1$ and 3 TeV, respectively. For a single $L$ production with a mass of $m_L$, the $p_T$ distributions in these figures shows a peak around half of $m_L$ values. In order to obtain the signal over the background, we apply the cuts $p_T^{e^\pm} > 20$ GeV, $|\eta^{e^\pm}| < 2.5$ and for $Ze^-$ system, invariant mass interval of
FIG. 8: The invariant mass distribution of $Ze^-$ for the process $e^-e^+ \rightarrow e^-Ze^+$ at $\sqrt{s} = 3$ TeV.

$m_L - \Gamma_L < m_{Ze^-} < m_L + \Gamma_L$. Here, $\eta$ denotes the rapidity and $\Gamma_L$ is the decay rate of $L$.

In Tables III and IV we generate the cross sections of signal ($\sigma_S$) and background ($\sigma_B$)

FIG. 9: Transverse momentum distribution of the final state electron for the subprocess $e^-e^+ \rightarrow e^-Ze^+$ at $\sqrt{s} = 0.5$ TeV.

processes after the cuts, and corresponding statistical significance (SS) for $\sqrt{s}=1$ and 3 TeV,
FIG. 10: Transverse momentum distribution of the final state electron for the subprocess $e^- e^+ \rightarrow e^- Ze^+$ at $\sqrt{s} = 1$ TeV.

FIG. 11: Transverse momentum distribution of the final state electron for the subprocess $e^- e^+ \rightarrow e^- Ze^+$ at $\sqrt{s} = 3$ TeV.

respectively. We obtain the estimations of SS of signal by assuming,

$$SS = \frac{\sigma_S}{\sqrt{\sigma_S + \sigma_B}} \sqrt{L^{\text{int}}}. \quad (6)$$

While calculating the SS values, we consider the leptonic decay of Z boson with the branching via $Z \rightarrow l^- l^+$. From Tables [III] and [IV] we can see that $L$ can be observed at CLIC with
TABLE III: The signal and SM background cross sections for the process $e^-e^+ \rightarrow e^-Ze^+$ and SS depending on the heavy lepton masses with $\sqrt{s} = 1$ TeV, $L^{int} = 10^5 \text{pb}^{-1}$. While calculating the SS values we assume the $Z$ boson decays leptonically.

| $m_L$ (GeV) | $\sigma_S$ (pb) | $\sigma_B$ (pb) | SS   |
|------------|----------------|----------------|------|
| 200        | $7.31 \times 10^{-2}$ | $1.97 \times 10^{-4}$ | 11.07 |
| 300        | $7.29 \times 10^{-2}$ | $5.34 \times 10^{-4}$ | 11.03 |
| 400        | $6.64 \times 10^{-2}$ | $1.12 \times 10^{-3}$ | 10.47 |
| 500        | $5.83 \times 10^{-2}$ | $1.99 \times 10^{-3}$ | 9.73  |
| 600        | $4.94 \times 10^{-2}$ | $2.91 \times 10^{-3}$ | 8.85  |
| 700        | $3.87 \times 10^{-2}$ | $4.08 \times 10^{-3}$ | 7.67  |
| 800        | $2.71 \times 10^{-2}$ | $5.23 \times 10^{-3}$ | 6.18  |
| 900        | $1.62 \times 10^{-2}$ | $5.35 \times 10^{-3}$ | 4.52  |

TABLE IV: The signal and SM background cross sections for the process $e^-e^+ \rightarrow e^-Ze^+$ and SS depending on the heavy lepton masses with $\sqrt{s} = 3$ TeV, $L^{int} = 10^5 \text{pb}^{-1}$. While calculating the SS values we assume the $Z$ boson decays leptonically.

| $m_L$ (GeV) | $\sigma_S$ (pb) | $\sigma_B$ (pb) | SS   |
|------------|----------------|----------------|------|
| 200        | $5.43 \times 10^{-2}$ | $1.82 \times 10^{-4}$ | 9.53  |
| 300        | $5.36 \times 10^{-2}$ | $3.98 \times 10^{-4}$ | 9.45  |
| 400        | $4.99 \times 10^{-2}$ | $6.19 \times 10^{-4}$ | 9.09  |
| 500        | $4.57 \times 10^{-2}$ | $9.09 \times 10^{-4}$ | 8.68  |
| 600        | $4.14 \times 10^{-2}$ | $1.17 \times 10^{-3}$ | 8.22  |
| 700        | $3.77 \times 10^{-2}$ | $1.48 \times 10^{-3}$ | 7.81  |
| 800        | $3.46 \times 10^{-2}$ | $1.69 \times 10^{-3}$ | 7.44  |
| 900        | $3.17 \times 10^{-2}$ | $1.85 \times 10^{-3}$ | 7.09  |

a mass in the range of 200-900 GeV. The SS value for the heavy lepton with a mass of 200 GeV is 10.18 while $\sigma_S=6.20 \times 10^{-2}$ pb and $\sigma_B=3.16 \times 10^{-4}$ pb with the energy of ILC.
IV. CONCLUSION

In this study, we have investigated the effects of anomalous magnetic moment type interactions on single production and decays of charged heavy leptons at future linear colliders. We present the total cross section and experimental kinematic distributions of $e^-e^+ \rightarrow e^-Ze^+$ process for $\sqrt{s} = 0.5$ TeV option for ILC and $\sqrt{s} = 1$ and 3 TeV options for CLIC. The results obtained show that, 200 GeV leptons at ILC and 200-900 GeV leptons at CLIC can be seen, in the case of $(\kappa/\Lambda) = 1$ TeV$^{-1}$. Hence, CLIC would outperform the earlier colliders in finding the signals of charged heavy leptons. If a heavy lepton signal between the mass range of 200-900 GeV found at future linear colliders, slightly lower limits can be obtained for $(\kappa/\Lambda)$.

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