Analysis of Anomalous Interactions With Heavy Leptons at $ep$, $e^+e^-$ and $pp$ Colliders

A. T. Tasci* and A. T. Alan†

Abant Izzet Baysal University, Department of Physics, 14280 Bolu, Turkey

Abstract

We consider possible production of heavy leptons via anomalous interactions at future $ep$ colliders (THERA and LHeC), $e^+e^-$ colliders (ILC and CLIC) and $pp$ collider CERN LHC. The production, backgrounds and signatures of heavy leptons are analyzed. We obtain the upper mass limits of 800 GeV at LHeC, 450 GeV at ILC and 650 GeV at LHC for optimal choices of relevant parameters.

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*Electronic address: tasci.a@ibu.edu.tr
†Electronic address: alan.a@ibu.edu.tr
I. INTRODUCTION

Many models extending the standard theory of quarks and leptons predict the existence of new generations of fermions. New heavy leptons play an important role in the search for extensions of the Standard Model (SM) and any signal for the production of such fermions will play a milestone role in the discovery of new physics. Many analysis have been done for the production of these particles at future $e^−e^+$, at hadron and also at $ep$ colliders. The experimental upper bounds for the heavy lepton masses were found to be 44 GeV by OPAL, 46 GeV by ALEPH and 90 GeV by H1 Collaborations. Hence, these leptons could be detected at future high energy colliders as their masses could be as high as 1 TeV. In this work, we analyze possible production and decay processes of new heavy leptons via some anomalous interactions in ep, $e^−e^+$ and pp collisions at future ep colliders THERA and LHeC, at linear colliders ILC and CLIC, at the CERN Large Hadron Collider (LHC). The main parameters of these colliders are given in Table I.

In the SM, Flavor Changing Neutral Current (FCNC) processes receive contributions from only higher order corrections. Here we offer the following effective Lagrangian having magnetic moment type operators to describe the interactions of the heavy leptons by ordinary ones;

$$\mathcal{L}_{\text{eff}} = \frac{i\kappa_\gamma}{\Lambda} L \sigma_{\mu\nu} q^\nu A^\mu + \frac{g}{2 \cos \theta_W} L \left[ \gamma_\mu (c_v - c_a \gamma_5) + \frac{i \sigma_{\mu\nu} q^\nu}{\Lambda} \sigma_{\nu\lambda} \right] \gamma_\lambda Z^\mu + h.c.,$$

(1)

where $\kappa_\gamma$ and $\kappa_Z$ are the anomalous magnetic dipole moment factors, $c_v$ and $c_a$ are the corresponding anomalous non-diagonal Z couplings which are zero in the SM, $q$ 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, $A^\mu$ and $Z^\mu$ the fields of the photon and Z boson and $\Lambda$ is the new physics scale. In the numerical calculations we have taken $c_v$ and $c_a$ at the order of SM values.

Heavy leptons decay through the neutral current processes $L \to \gamma l$ and $L \to Z l$ via anomalous couplings in Eq. (1), where $l$ denotes one of the ordinary charged leptons ($e, \mu, \tau$). The branching ratios (BR) for these processes would be around 33% for each channel. Neglecting ordinary lepton masses the decay widths are obtained as,

$$\Gamma(L \to l\gamma) = \frac{\alpha \kappa_\gamma^2 m_L^3}{2\Lambda^2},$$

(2)
\[
\Gamma(L \to lZ) = \frac{\alpha^2 (m_L^2 - m_Z^2)^2}{16 \Lambda^2 m_L^2 M_Z^2 \sin^2 \theta_W \cos^2 \theta_W} \left[ \frac{\kappa^2 M_Z^4}{\hat{s} \hat{t}} + 2 M_Z^2 \left( \Lambda^2 (c_\alpha^2 + c_\alpha^2) + (\kappa^2 m_L^2 - 3 c_e \kappa Z \Lambda m_L) \right) + \Lambda^2 (c_\alpha^2 + c_\alpha^2) m_L^2 \right],
\]

where \(\alpha\) is the electromagnetic coupling constant, \(M_Z\) and \(m_L\) refer to masses of \(Z\) boson and decaying lepton, respectively.

The only background processes related to the signal reaction \(ep \to LqX\) are \(q \to e\gamma q\) and \(q \to eZq\). In Table II we have presented the decay widths \(\Gamma(L \to \gamma e)\) and \(\Gamma(L \to Ze)\) for a wide range of \(m_L\). As seen from this table the branching ratio \(\text{BR}(L \to \gamma e)\) is extremely small compared with \(\text{BR}(L \to Ze)\), hence the background from \(\gamma e\) channel can be safely ignored.

### II. PRODUCTION OF HEAVY LEPTONS IN \(ep\) COLLISIONS

Using Eq. (1), the differential cross section for the subprocess \(eq \to Lq\), through the \(t\) channel mediated by \(\gamma\) and \(Z\) is obtained as:

\[
\frac{d\sigma(eq \to Lq)}{dt} = \frac{2 \kappa^2 \sigma^2 \pi \alpha^2}{\Lambda^2 \hat{s} \hat{t}} \left\{ \left( 2\hat{s} + \hat{t} \right) m_L^2 - 2\hat{s}(\hat{s} + \hat{t}) - m_L^4 \right\}
+ \frac{\pi \alpha^2}{8 \Lambda^2 \hat{s} \hat{t} \sin^4 \theta_W \cos^4 \theta_W \left[ (\hat{s} - m_Z^2)^2 + M_Z^2 \Gamma_Z^2 \right]} \left\{ 2 \kappa \Lambda \sigma^l (c_\alpha^2 + c_\alpha^2) (m_L^4 - \hat{s}) m_L \hat{t} + 4 \kappa \sigma^l \sigma^l (\Lambda \sigma^l - m_L \kappa Z) (m_L^4 - 2\hat{s} - \hat{t}) \right\}
+ \frac{\kappa \sigma^l \sigma^l (\hat{s} - m_Z^2)}{2 \Lambda^2 \hat{s} \hat{t} \sin^2 \theta_W \cos^2 \theta_W \left[ (\hat{s} - m_Z^2)^2 + M_Z^2 \Gamma_Z^2 \right]} \left\{ \kappa \sigma^l \sigma^l \left( m_L^4 - (2\hat{s} + \hat{t}) m_L^2 + 2\hat{s}(\hat{s} + \hat{t}) \right) + \Lambda m_L \left( c_\alpha^2 c_\alpha^2 (m_L^2 - 2\hat{s} - \hat{t}) + c_\alpha^2 c_\alpha^2 (\hat{s} - m_L^2) \right) \right\},
\]

where \(c_q\) is quark charge in units of \(e\), \(\Gamma_Z\) is the decay width of mediator \(Z\). The total production cross section is obtained by the integration of differential cross section over the parton distributions in the proton as:

\[
\sigma(ep \to LqX) = \int_{x_{\text{min}}}^{1} dx f_q(x, Q^2) \int_{t_{\text{min}}}^{t_{\text{max}}} \frac{d\sigma}{dt} dt,
\]

where \(x_{\text{min}} = m_L^2/s\), \(t_{\text{min}} = -s - m_L^2\) and \(t_{\text{max}} = 0\). For the parton distribution functions \(f_q(x, Q^2)\) we have used the CTEQ5 parametrization [21] providing the dependence
on momentum transfer which have been taken as $Q = m_L$ and for illustration, values of $\kappa_\gamma = \kappa_Z = 0.02$ have been taken for anomalous magnetic moment couplings.

We give the production cross sections for the signal as functions of the heavy lepton masses, $m_L$, in Fig. 1 for $\sqrt{s}=1$ and 1.4 TeV. We applied an optimal cut of $|M_{Ze} - m_L| < 50$ GeV for the considered heavy lepton mass range, in order to contain all signal events that are smeared by the experimental resolution. Fig. 2 shows the $p_T$ distributions of the final state particles for the relevant background process $e q \rightarrow e Z q$ in $e p$ collisions. These $p_T$ distributions have peaks around 50 GeV and suppressed at higher values. Fig. 3 shows the invariant mass distributions of $Ze$ system, after a cut of $p_T^{e,j} > 50$ GeV.

In Tables III and IV we present the production and total background cross sections depending on the heavy lepton masses for suitable ranges at THERA and LHeC. The number of signal events per year can easily be estimated from the integrated luminosities of the colliders. The branching ratios BR$_1$ and BR$_2$ refer to BR($L \rightarrow Ze$) and BR($Z \rightarrow e^+ e^-, \mu^+ \mu^-$), respectively. As shown in Table IV production of heavy leptons provides a clean signature with small backgrounds. According to Poisson statistics, the statistical significance (SS) of the signal for the discovery at 95% confidence level obeys the relation,

$$\frac{S}{\sqrt{S + B}} \geq 3,$$

where $S$ and $B$ are the numbers of signal and background events, respectively. LHeC, with an integrated luminosity of $10^4$ pb$^{-1}$ yields 12 events per year for 800 GeV leptons, hence a good place to search for heavy leptons. On the other hand THERA seems capable for only about five 100 GeV leptons with SS$\simeq 2$ which is not sufficient for observation.

**III. SINGLE AND PAIR PRODUCTION OF HEAVY LEPTONS IN $e^+e^-$ COLLISIONS**

**A. Single Production**

The single production of heavy leptons $L$, in $e^-e^+$ collisions occur through the $s$ and $t$ channels via the process $e^-e^+ \rightarrow L^-e^+$ represented by four Feynman diagrams, two for $Z$ mediation plus two for photon mediation. The corresponding total cross section is obtained
as follows;

\[
\frac{d\sigma}{dt} = \frac{\pi \alpha^2}{8\Lambda^2 s^2 \sin^4 \theta_W \cos^4 \theta_W ((s - M_Z^2) + M_Z^2 \Gamma_Z^2) ((t - M_Z^2) + M_Z^2 \Gamma_Z^2)} \\
\times \left\{ 2\Lambda \kappa Z c_v \epsilon \gamma t(s - t) m_L \left[ c_a^2 (7(s + t) - 6m_L^2) + c_v^2 (s + t - 2m_L^2) \right] \right. \\
\left. - \kappa Z^2 (c_a^2 + c_v^2) \times [((s + t) m_L^4 - 2(s^2 + t^2) m_L^2 + 2(s^3 + t^3)] + \Lambda^2 [(c_a^4 + c_v^4) (2(s^4 - t^2 s^2 + t^4) \\
- (s + t)(2s^2 - 3st + 2t^2) m_L^2) - 2c_a^2 c_v^2 ((s - 2t)(2s - t)(s + t)m_L^2 \\
- 2(s^4 - 3t^2 s^2 + t^4))] + M_Z^2 [2\kappa Z (c_a^2 + c_v^2) (2m_L^4 - 2(s + t)m_L^2 + (s + t)^2) st \\
+ 2\kappa Z c_v \Lambda (s - t) m_L \left[ c_a^2 (3s^2 + 3t^2 + 8st - 3(s + t)m_L^2) + c_v^2 (s^2 + t^2 - (s + t)m_L^2) \right] \\
- 2\Lambda^2 (c_a - c_v)^2 (c_a + c_v)^2 (s^3 + t^3 - (s^2 + t^2) m_L^2) - (M_Z^2 + \Gamma_Z^2) \\
\times [\kappa Z^2 (c_a^2 + c_v^2) (s + t)(m_L^4 - (s + t)m_L^2 + 2st) + \Lambda^2 (c_a - c_v)^2 (c_a + c_v)^2 \\
\times ((s + t)m_L^2 - s^2 - t^2)] \right\} - \frac{2\pi \alpha^2 \kappa \gamma Z_m}{\Lambda^2 s^4 t} \left\{ (s + t)m_L^4 - 2(s^2 + t^2) m_L^2 + 2(s^3 + t^3) \right\} \\
+ \frac{\pi \alpha^2 \kappa \gamma Z}{\Lambda^2 s^2 \sin^2 \theta_W \cos^2 \theta_W ((s - M_Z^2) + M_Z^2 \Gamma_Z^2)} \left\{ \kappa Z c_v m_L^4 - 2\Lambda (c_a^2 + c_v^2) m_L^3 \\
- 2\kappa Z c_v m_L^2 s + \Lambda (c_a^2 (3s + 2t) + c_v^2 (s + 2t)) m_L + \kappa Z m_L (2s - t)(s + t) \right\} \\
+ \frac{\pi \alpha^2 \kappa \gamma Z}{\Lambda^2 s^2 \sin^2 \theta_W \cos^2 \theta_W ((s - M_Z^2) + M_Z^2 \Gamma_Z^2)} \left\{ \kappa Z c_v (m_L^4 - 2m_L^2 - (s - 2t)(s + t)) \\
+ \Lambda ((c_a^2 + c_v^2)(2m_L^2 - 2s - t) - 2c_a^2 t) m_L \right\}. \tag{7}
\]

To compare the linear colliders, we display the total cross sections as functions of the heavy lepton masses in Fig. 4 by assuming \( \Lambda = m_L \) and taking the anomalous coupling parameters as \( \kappa_\gamma = \kappa_Z = 0.02 \). Here, we applied the same cut, \( |M_{Ze} - m_L| < 50 \text{ GeV} \), as in \( \text{e}^- \text{e}^+ \) collisions.

Fig. 4 shows the \( p_T \) distributions of the final state particles at three different linear colliders. The character of this distribution is similar to that of \( \text{e}^- \text{e}^+ \) collisions. In Fig. 5 we give the invariant mass distributions \( M_{Ze} \), with cut \( p_T^{e_1 e_2} > 50 \text{ GeV} \).

In Tables VI, VII and VIII, we presented the signal and total background cross sections for the single production of heavy lepton depending on its mass \( m_L \), for 0.5, 1 and 3 TeV energy \( e^-e^+ \) colliders, respectively. As seen from these tables, the SS values are high enough for observability limit, for mass values up to the center of mass energies of the colliders.

In the single production case we expect 777 events per year for 450 GeV leptons, 903 events for 900 GeV leptons and 810 events for 2750 GeV leptons at 0.5, 1 and 3 TeV, respectively.
B. Pair Production

Pair production of heavy leptons via anomalous couplings occur through the $t$-channel flavor changing neutral current process $e^-e^+ \rightarrow L^-L^+$. The differential cross section has the form:

\[
\frac{d\sigma_{\text{tot}}}{dt} = \frac{\pi \alpha^2 \kappa^2}{\Lambda^2 s^2 t^2} \left\{ 2m_L^8 - 4tm_L^6 + t(4s + 3t)m_L^4 - 2t^2(4s + t)m_L^2 + t^2(2s + t)^2 \right\}
\]

\[
+ \frac{\pi \alpha^2}{16M_Z^4 \Lambda^4 s^2 \sin^4 \theta_W \cos^2 \theta_W [(t - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]}
\]

\[
\times \left\{ \Lambda^4 (c_a^2 + c_v^2)m_L^4 [(m_L^2 - t)^2 + 4M_Z^2 s] - 2\Lambda^2 M_Z^2 \kappa^2 m_L^2 t[m_L^2 + t(t + 2s - 2m_L^2)] + M_Z^2 \Lambda^4 [(c_a^4 + c_v^4)(m_L^4 - 2t^2 + 2s - 2tm_L^2)]
\]

\[
+ 2c_a^2 c_v^2 (3m_L^4 - 2t^2 + 2sm_L^2 + 2s^2 + 3t^2 + 6st)
\]

\[
- 2\kappa^2 \Lambda^2 [4(c_a^4 + c_v^4)(m_L^4 + st + t^2) + (c_a^2 + 2c_v^2)(m_L^6 - 2t^2m_L^4 + t^2m_L^2 + 10c_a^4 mt_L^2 + \kappa_Z^2 [2m_L^6 - 4t^2m_L^4 + tm_L^4(4s + 3t)] - 2t^2(4s + t)m_L^2 + t^2(2s + t)^2) \}
\]

\[
\frac{\pi \alpha^2 \kappa^2 (t - M_Z^2)}{2M_Z^2 \Lambda^4 s^2 t \sin^2 \theta_W \cos^2 \theta_W [(t - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]}
\]

\[
\times \left\{ \kappa_Z^2 M_Z^2 [2m_L^6 - 4t^2m_L^4 + t(4s + 3t)m_L^2 - 2t^2(4s + t)m_L^2 + t^2(2s + t)^2] - 2\Lambda^2 M_Z^2 m_L^2 [(c_a^2 + c_v^2)(m_L^4 + t^2 - 2tm_L^2)]
\]

\[
+ st(2c_a^2 - c_v^2) - c_v^2 \Lambda^2 tm_L^2 [m_L^4 - 2tm_L^2 + (2s + t)t] \}
\]  

(8)

The total cross sections as functions of heavy lepton masses $m_L$ are displayed in Fig. 7 for three options.

Signal and total background cross sections depending again on the heavy lepton masses, are presented in Tables VIII and IX at 0.5, 1 and 3 TeV, respectively.

We applied an initial cut on the electron and jet transverse momentum $p_T^{e,j} > 50$ GeV for the background analysis. Fig. 8 show the $p_T$ distributions of the final state particles at the colliders. The distribution of invariant mass $M_{Ze}$ is presented in Fig. 9 at $\sqrt{s} = 0.5, 1$ and 3 TeV.

From Table X it is seen that the number of signal events could be as high as $8 \times 10^4$ for 1250 GeV leptons at $\sqrt{s} = 3$ TeV.
IV. PRODUCTION OF HEAVY LEPTONS AT THE CERN LHC

In $pp$ collisions heavy lepton production occurs via parton level subprocess $q\bar{q} \to Ll$, which are $\gamma$ and $Z$ exchanged $s$ channel FCNC reactions.

The form of the differential cross section is as follows;

$$
\frac{d\sigma(q\bar{q} \to Ll)}{dt} = \frac{2e^2_c\kappa\gamma^2\pi\alpha^2}{\Lambda^2\hat{s}^3} \left\{ (\hat{s} + 2\hat{t})m_L^2 - m_L^4 - 2\hat{t}(\hat{s} + \hat{t}) \right\}
$$

$$
+ \frac{\pi\alpha^2}{8\Lambda^2\hat{s}^2 \sin^4 \theta_W \cos^4 \theta_W [ (\hat{s} - M_Z^2)^2 + M_Z^2 \Gamma_Z^2 ]} \times \left\{ \kappa_Z^2(c_a^q + c_b^q)\hat{s}((\hat{s} + 2\hat{t})m_L^2 - 2\hat{t}(\hat{s} + \hat{t}) - m_L^4) + 2\kappa_Z\Lambda\hat{s}m_L(c_v(c_a^q + c_b^q)(\hat{s} - m_L^2) - 2c_ac_v^q(c_v^q(m_L^2 - \hat{s} - 2\hat{t}))) + \Lambda^2[(c_a^2 + c_b^2)(c_a^q + c_b^q)(\hat{s}^2 + 2\hat{t}^2 + 2\hat{s}\hat{t} - (\hat{s} + 2\hat{t})m_L^2) + 4c_a c_v^q c_b^q \hat{s}(\hat{s} + 2\hat{t} - m_L^2)] \right\}
$$

$$
+ \frac{e^2_c\pi\alpha^2\kappa\gamma M_Z \Gamma_Z}{\Lambda^2\hat{s}^2 \sin^2 \theta_W \cos^2 \theta_W [ (\hat{s} - M_Z^2)^2 + M_Z^2 \Gamma_Z^2 ]} \times \left\{ \kappa_Z^2 c_v^q (m_L^4 - (\hat{s} + 2\hat{t})m_L^2 + 2\hat{t}(\hat{s} + \hat{t})) + \Lambda m_L(c_a c_v^q (m_L^2 - \hat{s} - 2\hat{t}) + c_a c_v^q (m_L^2 - \hat{s})) \right\}
$$

The total production cross section is obtained by the integration over the parton distributions as;

$$
\sigma(q\bar{q} \to Ll) = \int_{m_L^2/s}^1 d\tau \int_{\tau}^1 dx \left[ f_{q/p}(x, Q^2) f_q(x/\tau, Q^2) + f_q(x/\tau, Q^2) f_q(x, Q^2) \right] \sigma(\hat{s})
$$

where $\hat{s} = \tau s$. As in the $ep$ collisions, here we use the CTEQ5 parametrization with $Q = m_L$ and we take $\kappa_\gamma = \kappa_Z = 0.02$ and $\Lambda = m_L$.

We give the production cross sections for the signal as functions of the heavy lepton masses, $m_L$, in Fig. 10 for the center of mass energy of $\sqrt{s} = 14$ TeV. We applied an optimal cut of $|M_{Ze} - m_L| < 50$ GeV for the considered heavy lepton mass range. Fig. 11 shows the $p_T$ distribution of the final state particles for the relevant background process $q\bar{q} \to eZl$ in $pp$ collisions. This $p_T$ distribution has a peak around 50 GeV and suppressed at higher values. Fig. 12 shows the invariant mass distributions of $Ze$ system, after a cut of $p_T^e,j > 50$ GeV.
In Table XI we present the production cross sections and the number of signal events depending on the heavy lepton masses for a suitable range. The branching ratios BR$_1$ and BR$_2$ refer to BR$(L \to Ze)$ and BR$(Z \to e^+e^-, \mu^+\mu^-)$, respectively. Production of heavy leptons provides a clean signature, as shown in this table. Taking into account the SS, LHC can observe heavy leptons with masses up to about 650 GeV. For 650 GeV leptons we expect 11 events per year at the LHC.

We have used the high energy package CompHEP for calculations of background cross sections reported in this study [22].

V. CONCLUSION

In conclusion, the present work gives an analysis of possible production of heavy leptons via anomalous interactions in $ep$, $e^+e^-$ and $pp$ collisions. It is shown that, after kinematical cuts a statistical significance of SS $\geq 3$ can be achieved and for anomalous magnetic moment factors of $\kappa_\gamma = \kappa_Z = 0.02$, heavy leptons with masses about 800 GeV at LHeC, 450 GeV at ILC and 650 GeV at the LHC can be observed. Among the others ILC seems the most convenient place to search for heavy leptons as providing a high event number of $8 \times 10^4$. LHeC and LHC are also good places for searching heavy leptons besides the other major high energy experiments. Hence, these collider options seem to be capable of probing new physics in the case of anomalous interactions are valid as being an underlying theory.

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TABLE I: Main parameters of $ep$ and $e^+e^-$ and $pp$ colliders, $L^{int}$ denotes the integrated luminosity for one year.

| $ep$ Colliders | $E_e$ (TeV) | $E_p$ (TeV) | $\sqrt{s_{ep}}$ (TeV) | $L^{int}_{ep}$ (pb$^{-1}$) |
|----------------|-------------|-------------|------------------------|----------------------------|
| THERA          | 0.25        | 1           | 1                      | 40                         |
| LHeC           | 0.07        | 7           | 1.4                    | $10^4$                     |

| $e^+e^-$ Colliders | $E_{e^+}$ (TeV) | $E_{e^-}$ (TeV) | $\sqrt{s_{e^+e^-}}$ (TeV) | $L^{int}_{e^+e^-}$ (pb$^{-1}$) |
|-------------------|-----------------|-----------------|---------------------------|--------------------------------|
| ILC               | 0.25            | 0.25            | 0.5                       | $10^5$                         |
| CLIC              | 0.5             | 0.5             | 1.0                       | $10^5$                         |
| CLIC              | 1.5             | 1.5             | 3.0                       | $10^5$                         |

| $pp$ Collider | $E_p$ (TeV) | $E_p$ (TeV) | $\sqrt{s_{pp}}$ (TeV) | $L^{int}_{pp}$ (pb$^{-1}$) |
|---------------|-------------|-------------|------------------------|----------------------------|
| LHC           | 7           | 7           | 14                     | $10^4$                     |

TABLE II: Decay widths of heavy leptons.

| $m_L$ (GeV) | $\Gamma(L \to \gamma e)$ (GeV) | $\Gamma(L \to Ze)$ (GeV) | $\Gamma_{Total}$ (GeV) |
|-------------|---------------------------------|--------------------------|------------------------|
| 250         | $7.30 \times 10^{-4}$           | 3                        | 3                      |
| 500         | $1.46 \times 10^{-3}$           | 21                       | 21                     |
| 750         | $2.19 \times 10^{-3}$           | 72                       | 72                     |
| 1000        | $2.92 \times 10^{-3}$           | 171                      | 171                    |
| 1250        | $3.65 \times 10^{-3}$           | 333                      | 333                    |
| 1500        | $4.38 \times 10^{-3}$           | 576                      | 576                    |
| 1750        | $5.11 \times 10^{-3}$           | 914                      | 914                    |
| 2000        | $5.84 \times 10^{-3}$           | 1365                     | 1365                   |
| 2250        | $6.57 \times 10^{-3}$           | 1943                     | 1943                   |
| 2500        | $7.30 \times 10^{-3}$           | 2666                     | 2666                   |
TABLE III: The signal and background cross sections and SS depending on the heavy lepton masses for THERA with $\sqrt{s} = 1$ TeV.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|-------------|---------------|----------------|----------------------------------|----------------|----------------|
| 100         | 12.26         | 4.05           | 0.13                             | $4.53 \times 10^{-5}$ | 2              |
| 150         | 8.21          | 2.71           | 0.09                             | $2.54 \times 10^{-4}$ | 2              |
| 200         | 5.50          | 1.82           | 0.06                             | $2.39 \times 10^{-4}$ | 2              |

TABLE IV: The signal and background cross sections and SS depending on the heavy lepton masses for LHeC with $\sqrt{s} = 1.4$ TeV.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|-------------|---------------|----------------|----------------------------------|----------------|----------------|
| 200         | 9.43          | 3.11           | 0.194                            | $4.75 \times 10^{-4}$ | 32             |
| 400         | 2.80          | 0.93           | 0.031                            | $2.28 \times 10^{-4}$ | 17             |
| 600         | 0.68          | 0.22           | 0.007                            | $8.69 \times 10^{-5}$ | 9              |
| 800         | 0.11          | 0.04           | 0.001                            | $2.19 \times 10^{-5}$ | 3              |

TABLE V: The signal and background cross sections and SS depending on the heavy lepton masses at $\sqrt{s} = 0.5$ TeV for single production.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|-------------|---------------|----------------|----------------------------------|----------------|----------------|
| 100         | 4.63          | 1.53           | 0.0504                            | $1.28 \times 10^{-2}$ | 63             |
| 200         | 3.90          | 1.29           | 0.0424                            | $5.10 \times 10^{-3}$ | 62             |
| 300         | 2.88          | 0.95           | 0.0314                            | $2.05 \times 10^{-3}$ | 54             |
| 400         | 1.51          | 0.50           | 0.0165                            | $4.83 \times 10^{-4}$ | 40             |
### TABLE VI: The signal and background cross sections and SS depending on the heavy lepton masses at $\sqrt{s} = 1$ TeV for single production.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|------------|----------------|-----------------------------|--------------------------------------|----------------|----------------|
| 100        | 4.89           | 1.61                        | 0.053                                | $1.43 \times 10^{-2}$ | 65             |
| 300        | 4.30           | 1.42                        | 0.047                                | $4.60 \times 10^{-3}$ | 65             |
| 500        | 3.51           | 1.16                        | 0.038                                | $2.36 \times 10^{-3}$ | 60             |
| 700        | 2.35           | 0.78                        | 0.026                                | $1.04 \times 10^{-3}$ | 50             |
| 900        | 0.83           | 0.27                        | 0.009                                | $1.81 \times 10^{-4}$ | 30             |

### TABLE VII: The signal and background cross sections and SS depending on the heavy lepton masses at $\sqrt{s} = 3$ TeV for single production.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|------------|----------------|-----------------------------|--------------------------------------|----------------|----------------|
| 250        | 4.74           | 1.56                        | 0.052                                | $6.37 \times 10^{-3}$ | 68             |
| 750        | 4.44           | 1.46                        | 0.048                                | $3.55 \times 10^{-3}$ | 67             |
| 1250       | 3.91           | 1.29                        | 0.043                                | $3.04 \times 10^{-3}$ | 63             |
| 1750       | 3.12           | 1.03                        | 0.034                                | $2.44 \times 10^{-3}$ | 56             |
| 2250       | 2.06           | 0.68                        | 0.022                                | $1.43 \times 10^{-3}$ | 46             |
| 2750       | 0.74           | 0.25                        | 0.008                                | $3.06 \times 10^{-4}$ | 28             |

### TABLE VIII: The signal and background cross sections and SS depending on the heavy lepton masses at $\sqrt{s} = 0.5$ TeV for pair production.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|------------|----------------|-----------------------------|--------------------------------------|----------------|----------------|
| 100        | 3.95           | 1.30                        | 0.0430                                | $3.22 \times 10^{-2}$ | 50             |
| 150        | 3.76           | 1.24                        | 0.0409                                | $9.20 \times 10^{-3}$ | 58             |
| 200        | 3.83           | 1.26                        | 0.0417                                | $1.78 \times 10^{-3}$ | 63             |
| 240        | 2.79           | 0.92                        | 0.0304                                | $1.98 \times 10^{-2}$ | 43             |
TABLE IX: The signal and background cross sections and SS depending on the heavy lepton masses at $\sqrt{s} = 1$ TeV for pair production.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|-------------|---------------|-----------------|-------------------------------|----------------|----------------|
| 100         | 4.51          | 1.49            | 0.0491                        | $9.92 \times 10^{-3}$ | 64             |
| 200         | 4.48          | 1.48            | 0.0488                        | $4.91 \times 10^{-3}$ | 67             |
| 300         | 5.72          | 1.89            | 0.0623                        | $7.31 \times 10^{-3}$ | 75             |
| 400         | 9.44          | 3.12            | 0.1028                        | $4.24 \times 10^{-3}$ | 99             |

TABLE X: The signal and background cross sections and SS depending on the heavy lepton masses at $\sqrt{s} = 3$ TeV for pair production.

| $m_L$ (GeV) | $\sigma$ (pb) | $\sigma \times BR_1$ (pb) | $\sigma \times BR_1 \times BR_2$ (pb) | $\sigma_B$ (pb) | $S/\sqrt{S+B}$ |
|-------------|---------------|-----------------|-------------------------------|----------------|----------------|
| 250         | 4.72          | 1.56            | 0.0514                        | $2.11 \times 10^{-3}$ | 70             |
| 500         | 6.12          | 2.02            | 0.0666                        | $3.32 \times 10^{-4}$ | 81             |
| 750         | 15.03         | 4.96            | 0.1637                        | $4.11 \times 10^{-4}$ | 128            |
| 1000        | 39.49         | 13.03           | 0.4300                        | $1.93 \times 10^{-4}$ | 207            |
| 1250        | 77.64         | 25.62           | 0.8455                        | $1.32 \times 10^{-5}$ | 291            |
TABLE XI: The signal and background cross sections and SS depending on the heavy lepton masses for the LHC ($\sqrt{s} = 14$ TeV).

| $m_L$ (GeV) | $\sigma \times 10^{-2}$ (pb) | $\sigma \times 10^{-2} \times \text{BR}_1$ (pb) | $\sigma \times 10^{-2} \times \text{BR}_2 \times 10^{-4}$ (pb) | $\sigma_B \times 10^{-4}$ (pb) | $S/\sqrt{S+B}$ |
|-------------|-------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------|-----------------|
| 150         | 9.22                          | 3.04                                          | 10.0                                            | 4.96                          | 8               |
| 250         | 6.80                          | 2.24                                          | 7.4                                             | 4.05                          | 7               |
| 350         | 4.58                          | 1.51                                          | 5.0                                             | 2.80                          | 6               |
| 450         | 2.86                          | 0.95                                          | 3.1                                             | 1.84                          | 4               |
| 550         | 1.70                          | 0.56                                          | 1.9                                             | 1.14                          | 3               |
| 650         | 0.98                          | 0.32                                          | 1.1                                             | 0.65                          | 3               |

FIG. 1: The total cross sections as function of the heavy lepton masses for lepton-hadron colliders THERA ($\sqrt{s} = 1$ TeV) and LHeC ($\sqrt{s} = 1.4$ TeV).
FIG. 2: $p_T$ distributions of the background for lepton-hadron colliders THERA and LHeC.

FIG. 3: The invariant mass distributions of the $Z\phi$ system for the background for lepton-hadron colliders THERA and LHeC.

FIG. 4: The total cross sections as function of the heavy lepton masses for linear colliders ILC ($\sqrt{s} = 0.5$ TeV) and CLIC ($\sqrt{s} = 1$ and 3 TeV) for single production.
FIG. 5: $p_T$ distribution of the background for linear colliders ILC and CLIC for single production.

FIG. 6: The invariant mass distribution of the $Ze$ system for the background for linear colliders ILC and CLIC for single production.

FIG. 7: The total cross sections as function of the heavy lepton masses for linear colliders ILC and CLIC for pair production.
FIG. 8: $p_T$ distribution of the background for linear colliders ILC and CLIC for pair production.

FIG. 9: The invariant mass distribution of the $Ze$ system for the background for linear colliders ILC and CLIC for pair production.

FIG. 10: The total cross sections as function of the heavy lepton masses for LHC ($\sqrt{s} = 14$ TeV).
FIG. 11: $p_T$ distribution of the background for LHC.

FIG. 12: The invariant mass distribution of the $Ze$ system for the background for LHC.