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# HEAVY LEPTON PRODUCTION AT LINAC⊗LHC

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We investigate the production, signatures and backgrounds of new heavy leptons via string inspired $E_6$ model at the proposed Linac⊗LHC. Assuming maximal mixing, the production rate is found to be 2000 events per year for masses up to 3 TeV.

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## 1. Introduction

Although the Standard Model (SM) is very successful in explaining the physics of many phenomena under a few hundred GeV, it is not a complete description of the physics at higher energies. The most fundamental problems with SM are the mass hierarchy and the number of fermion generations. There are many models extending the SM to overcome these problems. Almost all of these new models include new fermions in addition to the ordinary ones. We investigate the possibility of the single production of new heavy leptons suggested by string inspired $E_6$ model in *ep* collisions. There are many analysis of the heavy lepton production at future linear colliders [1–3], at hadron colliders [4–6] and also at *ep* collider HERA [7]. For the searches of new physics beyond the SM, the linac-ring type *ep* colliders have as much potential as lepton colliders [8].

## 2. Production of heavy leptons

The model that we use in the single production of a new heavy lepton is the string inspired $E_6$ model [9,10]. We, therefore, assume the new heavy lepton interactions in the following flavor changing neutral current (FCNC) Lagrangian:

$$\mathcal{L}_{\rm nc} = g_z \sin\theta_{\rm mix}\psi_L\gamma^\mu(1+\gamma_5)\psi_e Z^\mu + \text{h.c.}$$

and similar terms for the other leptonic families. Here $\theta_{\rm mix}$ are the mixing angles between right handed components of the ordinary and new heavy charged leptons. Throughout this paper we will suppose an upper limit $\sin\theta_{\rm mix} < 0.1$ coming from the high precision measurements of the $Z$ properties at LEP/SLC [11]. We use the parameter $b_{lLZ}$ for $\sin\theta_{\rm mix}$ to denote the mixing in the vertex $l-L-Z$ explicitly. In $E_6$, the parton level process $eq \to Lq$, responsible for the heavy lepton production in $ep$ collision occurs via FCNC $Z$ exchange in the $t$-channel.

The differential cross section for the subprocess $eq \to Lq$ in the framework of $E_6$ model is given by

$$\begin{aligned}\frac{d\hat{\sigma}}{d\hat{t}} \;=\; & \frac{\pi\,\alpha^2\, b_{lLZ}^2}{\sin^4\theta_{\rm W}\cos^4\theta_{\rm W}\hat{s}^2\left[\left(\hat{t}-M_Z^2\right)^2+M_Z^2\Gamma_Z^2\right]} \\ & \times\left[(a_q+v_q)^2\hat{t}^2+(a_q+v_q)^2\left(2\hat{s}-m_L^2\right)\hat{t}+2\hat{s}\left(a_q^2+v_q^2\right)\left(\hat{s}-m_L^2\right)\right],\end{aligned}$$

where $\theta_{\rm W}$ is the weak angle, $\alpha$ is the fine structure constant, $\hat{s}$ and $\hat{t}$ are the Mandelstam variables and $\hat{s}=xs$ is the square of the center of mass energy for the subprocess while $x$ is the momentum fraction of the parton inside the proton. The total cross section can be obtained by folding the subprocess cross section $\hat{\sigma}$ over the parton distribution functions as

$$\sigma(ep\to LqX) = \int_{x_{\rm min}}^{1} dx f_q(x,Q^2)\int_{t_{\rm min}}^{t_{\rm max}}\frac{d\hat{\sigma}}{d\hat{t}}\,d\hat{t}\,,$$

where $x_{\rm min}=m_L^2/s$, $\hat{t}_{\rm min}=-(\hat{s}-m_L^2)$ and $\hat{t}_{\rm max}=0$. These relations are obtained for the massless lepton and quark case. We give the production cross sections for the signal as function of the heavy lepton mass, $m_L$, in Fig. 1 for different values of $b_{lLZ}$. In Fig. 2, we display the invariant mass distribution of the background process $ep\to qZeX$ as function of invariant mass of $Ze$ system at future lepton–hadron collider Linac⊗LHC with the main parameters $\sqrt{s}=5.3$ TeV and $\mathcal{L}=10^{33}$ cm$^{-2}$s$^{-1}$ [12]. We have used the COMPHEP package [13] to calculate the cross sections, decay widths

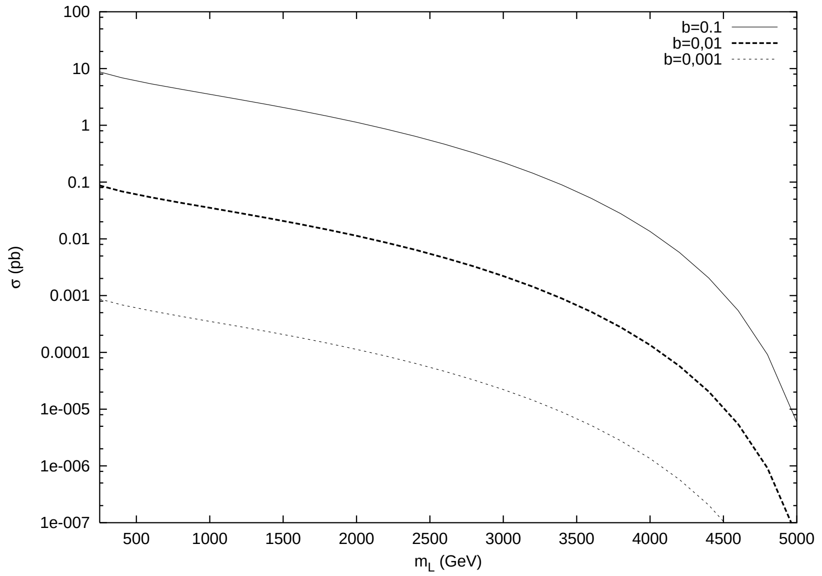


Fig. 1. Total production cross sections as functions of the heavy lepton masses ($m_L$) at $\sqrt{s} = 5.3\,\mathrm{TeV}$ for different $l - L - Z$ couplings $b$.

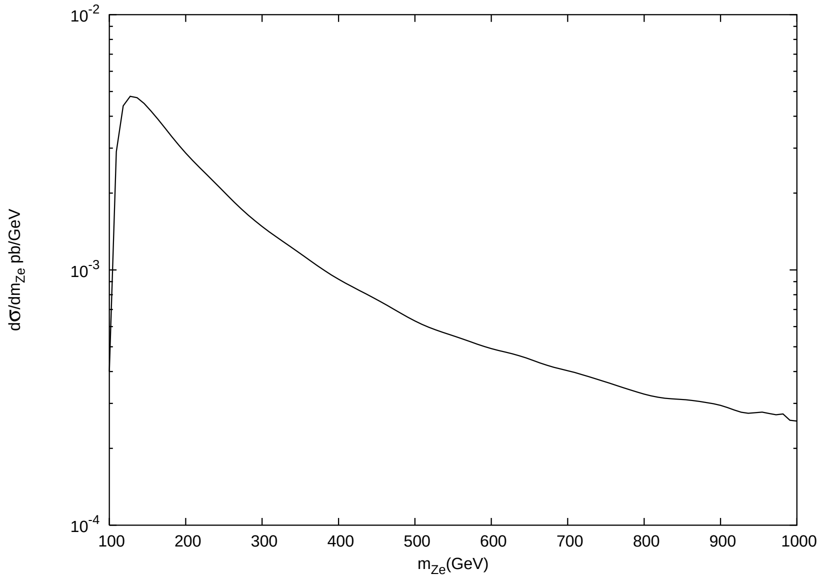


Fig. 2. The invariant mass distribution of the $Ze$ system for the background process $ep \to qZeX$.

and branching ratios. For the parton distribution functions $f_q(x, Q^2)$ we have used MRS [14] with the factorization scale $Q^2 = m_L^2$.

The heavy lepton production cross sections ($\sigma\times$BR) and the number of signal events depending on the mass $m_L$ are shown in Table I. For decreasing values of the $l - L - Z$ couplings, $b$, the production cross section and, therefore, the number of events decreases.

TABLE I

Cross sections depending on the heavy lepton mass $m_L$ for $b = 0.1$. The branching ratios $\mathrm{BR}_1$ and $\mathrm{BR}_2$ denote $\mathrm{BR}(L \to Ze)$ and $\mathrm{BR}(Z \to e^+e^-, \mu^+\mu^-)$, respectively. The total decay width of the heavy lepton is given in the last column.

| $m_L$(GeV) | $\sigma$(pb) | $\sigma \times \mathrm{BR}_1$(pb) | $\sigma \times \mathrm{BR}_1 \times \mathrm{BR}_2$(pb) | $\Gamma$(GeV) |
|---|---|---|---|---|
| 200 | 9.423 | 3.109 | 0.105 | 0.59 |
| 400 | 6.873 | 2.267 | 0.076 | 5.18 |
| 600 | 5.384 | 1.776 | 0.059 | 17.53 |
| 800 | 4.333 | 1.429 | 0.048 | 41.53 |
| 1000 | 3.519 | 1.161 | 0.039 | 81.05 |
| 2000 | 1.129 | 0.373 | 0.012 | 647.16 |
| 3000 | 0.221 | 0.073 | 0.002 | 2142.88 |

After their production, heavy leptons will decay via the neutral current process $L \to lZ$, where $l$ is a light lepton (e, $\mu$, $\tau$). The branching ratio for these processes would be around 33% for each channel.

The backgrounds for the signal process $ep \to LqX$ with the subsequent decays $L \to Z\mu$ or $L \to Z\tau$ and $Z \to e^+e^-$ are expected to be at very low rate. By applying appropriate cuts to the final state particles this type of backgrounds can be kept at very low levels. Still we may need at least 10 signal events in the final state after all cuts. Therefore, the $ep$ collider Linac$\otimes$LHC can probe heavy lepton masses up to about 3 TeV as can be deduced from Table I. For a heavy lepton with a mass of 200 GeV we expect $10^3$ signal events for the coupling value of $b = 0.1$.

We applied an initial cut on the electron and jet transverse momentum $p_{\mathrm{T}}^{e,q} > 10$ GeV for the signal and background analysis. These cuts reduce the background by about 20%. The total background cross section is ($\sigma\times$BR)=0.055 pb after the cuts. This improves the statistical significance $S/\sqrt{B}$, where $S$ and $B$ denote the total signal and background events, respectively. The calculated $3\sigma$ and $5\sigma$ discovery contours for heavy lepton masses and couplings, are displayed in Fig. 3.

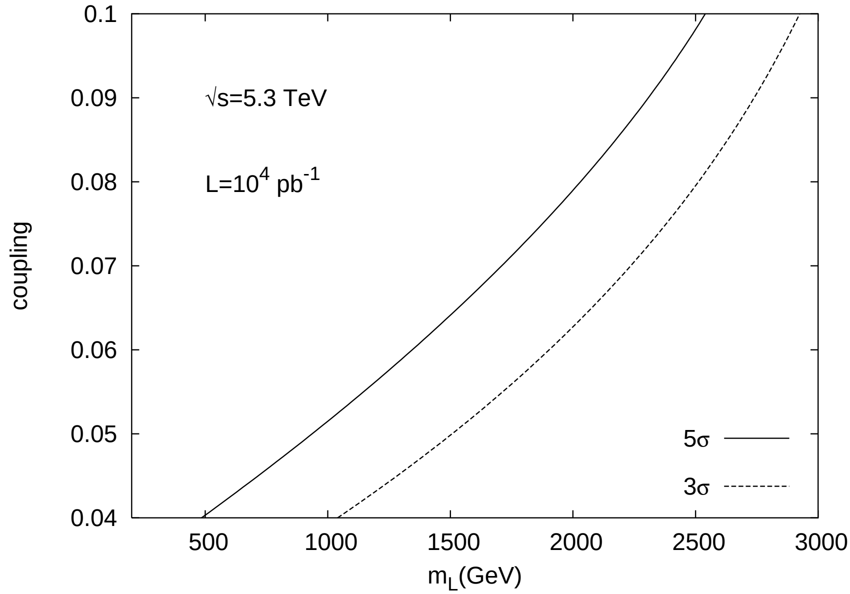


Fig. 3. Attainable mass limits depending on the coupling $b$ for heavy leptons at Linac⊗LHC.

We also have performed the same calculations for the THERA ($\sqrt{s} = 1\,\mathrm{TeV}$, $\mathcal{L} = 40\ \mathrm{pb}^{-1}$) collider [15]. Unfortunately, we have seen that at this collider it is not possible to observe a heavy lepton with mass greater than 200 GeV. Taking the $l - L - Z$ coupling value of 0.1 for a heavy lepton with a mass of 200 GeV, the production rate is 100 events per year.

## 3. Conclusions

This work shows that some of future high energy lepton–hadron colliders can test the existence of heavy leptons. Linac⊗LHC has very promising discovery potential for heavy leptons with masses up to 3 TeV at $3\sigma$ significance, that is, it offers the opportunity of the manifestations of new physics beyond the SM, while at THERA it does not seem to be likely to achieve masses greater than 200 GeV.

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