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Pair Production of New Heavy Leptons with $U(1)'$ Charge at Linear Colliders

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Abstract

We study the pair production of new heavy leptons within a new $U(1)'$ symmetry extension of the Standard Model. Because of the new symmetry, the production and decay modes of the new heavy leptons would be different from those of three families of the standard model. The pair production cross sections depending on the mixing parameter and the mass of heavy leptons have been calculated for the center of mass energies of 0.5 TeV, 1 TeV and 3 TeV. The accessible ranges of the parameters have been obtained for different luminosity projections at linear colliders. We find the sensitivity to the range of mixing parameter $-1 < x < 1$ for the mass range $M_{l'} < 800$ GeV at $\sqrt{s} = 3$ TeV and $L_{int} = 100$ fb^{-1}

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I. INTRODUCTION

The standard model (SM) of particle physics has been shown to successfully describe fundamental particle interactions. However, some of the problems (such as symmetry breaking, dark matter, flavor and CP violation) do not find adequate answers within the standard model of three fermion families, and there are considerable interest in new heavy fermions to be searched at high energy colliders. On the quark sector, the direct searches performed by the ATLAS collaboration excludes the heavy quark masses $m_{b'} \lesssim 670$ GeV and $m_{t'} \lesssim 656$ GeV [1], and CMS collaborations have ruled out new heavy down-type and up-type quarks with masses $m_{b'} \lesssim 611$ GeV and $m_{t'} \lesssim 570$ GeV [2]. In these experimental bounds, the branching of decay $b' \to tW$ or $t' \to bW$ is assumed to be unity; relaxing them leads to slightly weaker bounds as discussed in [3]. On the lepton sector, the LEP measurement of the Z boson width strongly supports the fact there are only three light active neutrinos [4]. This measurement leads to a mass constraint for a new heavy stable neutrino of mass $m_{\nu'} > 45$ GeV. In addition, direct production searches at LEPII establish a lower limit of the order of 100 GeV for a new charged lepton (l') and unstable neutrino. It is also straightforward to check that the recent discovery of Higgs boson with mass of 125 GeV tune the new neutrino mass $m_{\nu'} > m_H/2$. Furthermore, the off-diagonal lepton mixings are required to be smaller than 0.115 consistent with the recent global fits [5].

One of the simplest extensions of the SM is to include an $U(1)'$ gauge symmetry. After the $U(1)'$ symmetry breaking, there could remain a residual discrete symmetry as emphasized in Ref. [6], and this would cause the lightest new fermion to be stable. The discrete symmetry for the new model could protect new heavy fermions from the SM fermions to explain Z boson width measurement at LEP. The model could provide a stable particle for dark matter candidate, a new source of CP violation, baryon$-$lepton number conservation. The particle spectrum of the model [6] will include, in addition to the SM particles, an extra heavy fermion family, an extra Higgs doublet, a Higgs singlet as well as an extra gauge boson (Z'). Since the SM fermions have vanishing $U(1)'$ charges, the new gauge boson Z' cannot form a dilepton or dijet signal besides the $Z - Z'$ mixing effects which is constrained to be tiny by the precise Z measurements at LEP [7]. Recently, the most stringent limits on a heavy neutral gauge boson Z'_S with the same universal couplings to fermions as the Z boson (sequential model) have been set using measurements from ATLAS [8] and CMS [9],

translated to a lower bound on the mass $m_{Z'} > 2.79$ TeV and 2.96 TeV, respectively.

In this work, we use the new heavy fermion model accompanied by an $U(1)'$ symmetry under which only the heavy fermions have nonzero charge. The heavy charged lepton pair production at Linear Colliders (LC) through the process $e^+e^- \to l'^+l'^-$ and subsequent decay of $l'^- \to \nu' W^-$ ending up with a stable heavy neutrino have been examined at linear collider energies $\sqrt{s} = 0.5$ TeV for the International Linear Collider (ILC) [10], 1 TeV for its upgrade and 3 TeV for Compact Linear Collider (CLIC) [11].

II. HEAVY LEPTONS

The interactions of new heavy leptons (l',ν') can be described by the following Lagrangian

$$\begin{aligned} L' \;=\; & -g_e \bar{l'}\gamma^\mu l' A_\mu - \frac{g_z}{2}\bar{l'}\gamma^\mu(c_V^{l'} - c_A^{l'}\gamma^5) l' Z_\mu - \frac{g_z}{2}\bar{\nu'}\gamma^\mu(c_V^{\nu'} - c_A^{\nu'}\gamma^5)\nu' Z_\mu \\ & \frac{g_z}{2}\bar{l'}\gamma^\mu(c'^{l'}_V - c'^{l'}_A\gamma^5) l' Z'_\mu - \frac{g_z}{2}\bar{\nu'}\gamma^\mu(c'^{\nu'}_V - c'^{\nu'}_A\gamma^5)\nu' Z'_\mu \\ & -\frac{g_w}{2\sqrt{2}} U_{\nu' l'}\bar{l'}\gamma^\mu(1-\gamma^5)\nu' W_\mu + H.c. \end{aligned}$$

where g_e, g_W and g_Z are the electromagnetic, weak-charged and weak-neutral coupling constants, respectively. The A_μ, W_μ and Z_μ are the fields for photon, W boson and Z boson, respectively. The field Z'_μ is for the new Z' boson. The $U_{\nu' l'}$ is the mixing element for the charged current coupling of heavy leptons. Here, we consider a long-lived neutrino with unit mixing element. The c_V and c_A are vector and axial-vector couplings with the Z boson. The c'_V and c'_A are vector and axial-vector couplings with the new Z' boson. These couplings can be expressed as $c_V = \mathcal{Q}_L + \mathcal{Q}_R$ and $c_A = \mathcal{Q}_L - \mathcal{Q}_R$ with the left and right handed fermion gauge charges $\mathcal{Q}_L$ and $\mathcal{Q}_R$, respectively. The $U(1)'$ charge is defined as $\mathcal{Q} = (B-L) + xY$ with the mixing parameter x. In the model, the SM fermions are not charged under the $U(1)'$ while the new fermions have the gauge charges as shown in Table I.

As it can be seen from Table I, the key values for the parameter x can be calculated as follows: for quarks $c_V^{t'}(c_V^{b'})$ vanishes when $x = -2/15(2/3)$, respectively; and for leptons $c_V^{l'}(c_V^{\nu'})$ vanishes when $x = -2/9(-2/3)$, which are in the range of $-2/3 < x < 2/3$. A specific value of the mixing parameter $x = 0$ corresponds to a vector-type coupling with the Z boson. Here, we assume that charged heavy lepton decays through the process $l' \to \nu' + W^-$ within a large range of parameters (mixing and mass). If the mass difference between the heavy

Table I: The $U(1)'$ charges of new heavy fermions with a new parity.

Field	$U(1)'$ charge	c_V	c_A
t'_L	$1/3+x$	$2/3+5x$	$-3x$
t'_R	$1/3+4x$		
b'_L	$1/3+x$	$2/3-x$	$3x$
b'_R	$1/3-2x$		
l'_L	$-1-3x$	$-2-9x$	$3x$
l'_R	$-1-6x$		
ν'_L	$-1-3x$	$-2-3x$	$-3x$
ν'_R	-1		

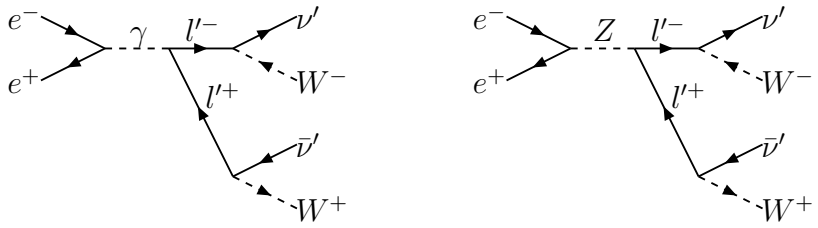


Figure 1: Diagrams contributing to the pair production process at linear colliders.

lepton and neutrino is small enough, then the heavy lepton decay may result in missing transverse energy and off-shell W boson.

III. CROSS SECTIONS

The pair production of heavy charged leptons can be performed through the process $e^+e^- \to l'^+l'^-$ and subsequent decays of $l'^- \to \nu' W^-$ and $l'^+ \to \bar{\nu}' W^+$ ending up with a pair of stable heavy neutrinos and a pair of W bosons. The contributing diagrams for the signal are shown in Figure 1. The calculation of the cross sections for the signal and background is performed using CalcHEP [12] with the implementation of new heavy leptons and their interactions.

At $\sqrt{s} = 0.5$ TeV, the cross sections for the signal of heavy lepton pairs with mass $M_{l'} = 200$ GeV are given as 8.72, 1.38, 0.34, 1.06, 3.52, 7.74 and 21.40 pb for the parameter x values -1.0, -0.5, -0.25, 0.0, 0.25, 0.50 and 1.0, respectively. The e^+e^- collider (ILC)

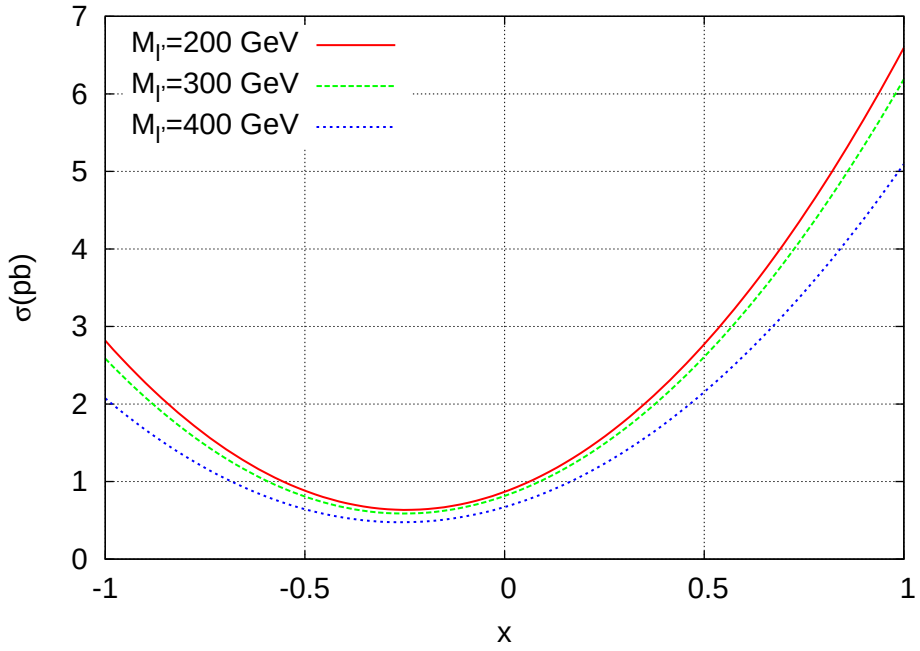


Figure 2: The pair production cross sections for the process $e^+e^- \to l'^+l'^-$ depending on the parameter x for different mass values of $M_{l'} = 200$, 300 and 400 GeV at the center of mass energy $\sqrt{s} = 1$ TeV.

with $\sqrt{s} = 0.5$ TeV, has the potential up to the kinematical range ($m_{l',\nu'} \leq 250$ GeV) for the direct production of new heavy lepton pairs. However, the CLIC with multi-TeV extends the mass range for the new heavy leptons. At the center of mass energies of the linear colliders with $\sqrt{s} = 1$ TeV and $\sqrt{s} = 3$ TeV, the cross sections for the signal are shown in Figure 2 and Figure 3 , respectively. It is clear from Figures 2 and 3, the cross section has a minimum around $x = -0.25$. At the center of mass energy $\sqrt{s} = 1$ (3) TeV, we calculate the change in the cross sections as $\Delta\sigma \simeq 0.5$ (0.05) pb for a change in mixing parameter $|\Delta x| = 0.25$ around the minimum. The signal cross sections depending on the heavy lepton mass and mixing parameter are given in Table II for $\sqrt{s} = 1$ TeV and in Table III for $\sqrt{s} = 3$ TeV.

The cross sections for the background processes contributing to the lepton+dijet and missing transverse energy (MET) in the the final state are given in Table IV. The cross sections for the processes can be multiplied by the corresponding branching ratios, such as $BR(W^+ \to l^+\nu) = 0.22$, $BR(W^+ \to 2j) = 0.68$, $BR(Z \to \nu\bar{\nu}) = 0.20$ and $BR(h \to ZZ^*) = 0.016$ to obtain the cross sections for the interested final state.

Table II: Cross sections (pb) for the signal process $e^+e^- \to l'^+l'^-$ at $\sqrt{s} = 1$ TeV depending on the heavy lepton mass $M_{l'}$ and the parameter x.

	x						
$M_{l'}(GeV)$	-1.0	-0.5	-0.25	0.0	0.25	0.5	1.0
200	2.82	4.71×10^{-1}	1.21×10^{-1}	3.19×10^{-1}	1.07	2.36	6.59
300	2.59	4.24×10^{-1}	1.09×10^{-1}	3.04×10^{-1}	1.01	2.23	6.19
400	2.07	3.32×10^{-1}	8.55×10^{-2}	2.55×10^{-1}	0.84	1.84	5.10

Table III: Cross sections (pb) for the signal process $e^+e^- \to l'^+l'^-$ at $\sqrt{s} = 3$ TeV depending on the heavy lepton mass $M_{l'}$ and the parameter x.

	x						
$M_{l'}(GeV)$	-1.0	-0.5	-0.25	0.0	0.25	0.5	1.0
200	3.21×10^{-1}	5.47×10^{-2}	1.42×10^{-2}	3.55×10^{-2}	1.19×10^{-1}	2.64×10^{-1}	7.39×10^{-1}
300	3.20×10^{-1}	5.43×10^{-2}	1.40×10^{-2}	3.54×10^{-2}	1.19×10^{-1}	2.63×10^{-1}	7.37×10^{-1}
400	3.17×10^{-1}	5.37×10^{-2}	1.39×10^{-2}	3.54×10^{-2}	1.18×10^{-1}	2.62×10^{-1}	7.34×10^{-1}
500	3.13×10^{-1}	5.28×10^{-2}	1.37×10^{-2}	3.53×10^{-2}	1.18×10^{-1}	2.61×10^{-1}	7.29×10^{-1}
600	3.09×10^{-1}	5.18×10^{-2}	1.34×10^{-2}	3.51×10^{-2}	1.17×10^{-1}	2.59×10^{-1}	7.22×10^{-1}
700	3.02×10^{-1}	5.04×10^{-2}	1.31×10^{-2}	3.48×10^{-2}	1.16×10^{-1}	2.55×10^{-1}	7.12×10^{-1}
800	2.94×10^{-1}	4.87×10^{-2}	1.26×10^{-2}	3.43×10^{-2}	1.14×10^{-1}	2.51×10^{-1}	6.98×10^{-1}

Table IV: Cross sections (pb) for the dominant background contributing to the final state $l^\pm + 2j +$ MET.

Cross sections (pb)	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 1$ TeV	$\sqrt{s} = 3$ TeV
$e^+e^- \to W^+W^-Z$	4.39×10^{-2}	6.52×10^{-2}	3.82×10^{-2}
$e^+e^- \to W^+W^-h$	5.85×10^{-3}	4.21×10^{-3}	1.25×10^{-3}
$e^+e^- \to W^+W^-$	7.68×10^{0}	2.87×10^{0}	4.98×10^{-1}
$e^+e^- \to W^+W^-\nu\bar{\nu}$	1.09×10^{-2}	3.38×10^{-2}	1.47×10^{-1}
$l^\pm + 2j +$ MET	1.15×10^{0}	4.36×10^{-1}	9.76×10^{-2}

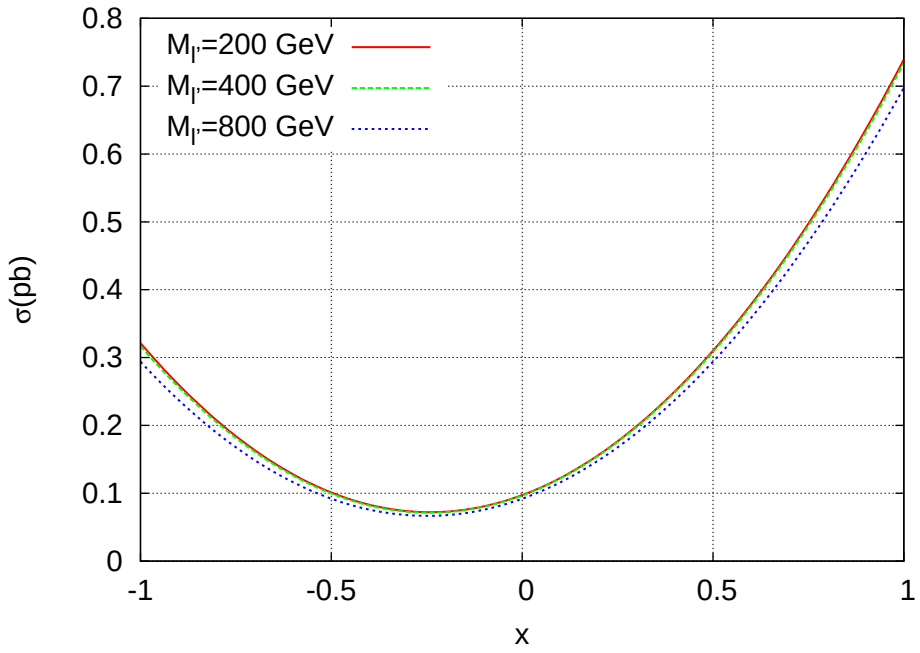


Figure 3: The same as Fig. 2, but for the mass values of $M_{l'} = 200$, 400 and 800 GeV at $\sqrt{s} = 3$ TeV.

IV. ANALYSIS

We take into account the final state containing $l^{\pm}+2j+$MET. The transverse momentum and pseudo-rapidity distributions of the final state lepton from the signal and background process are given in Fig. 4 and 5, respectively. It is seen from Fig. 4 that a transverse momentum cut $p_T > 15$ GeV on the lepton will be required for the acceptance. However, higher p_T cut will not improve the signal to background ratio in the analysis. Furthermore, the lepton pseudo-rapidity cut of $-1.5 < \eta < 1.5$ can be used to suppress the relevant background as seen from Fig. 5. The difference between the pseudo-rapidity distributions for the signal and background is more pronounced at higher center of mass energies such as $\sqrt{s} = 1$ TeV and 3 TeV. The cross section for the main background process $e^+e^- \to W^+W^-$ with $W^{\pm} \to l^{\pm}\bar{\nu}_l$ and $W^{\mp} \to q\bar{q}'$ will be reduced by 60%, 75% and 90%, after applying these cuts, depending on the center of mass energies $\sqrt{s} = 0.5$, 1 and 3 TeV, respectively. Moreover, the other background process $e^+e^- \to W^+W^-Z$ (where $W^{\pm} \to l^{\pm}\bar{\nu}_l$, $W^{\mp} \to q\bar{q}'$ and $Z \to \nu_l\bar{\nu}_l$) will give contribution with a reduction in cross section by 50% after the cuts.

In order to present the potential of the linear colliders to search for heavy lepton signal,

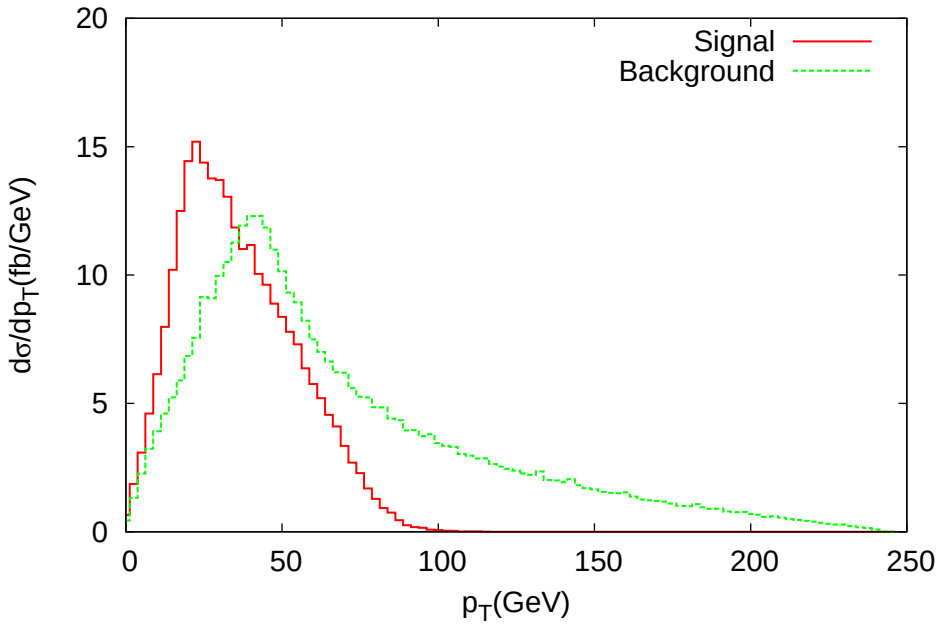


Figure 4: The transverse momentum distribution of the final state muon (μ^-) from the signal process $e^+e^- \to W^+\mu^-\bar{\nu}_\mu\nu'\bar{\nu}'$ with the parameters $x = 1$ and $M_{l'} = 200$ GeV, and from the background process $e^+e^- \to W^+\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 500$ GeV.

we use a brief statistical significance analysis with $S/\sqrt{B}$. We find accessible ranges of the mixing parameter and the mass of heavy leptons depending on the integrated luminosity at different center of mass energies. We present the exclusion plot (95% C.L.) for the heavy lepton mass $M_{l'}$ and mixing parameter x at $\sqrt{s} = 1$ TeV and $L_{int} = 20$, 100, 1000 pb^{-1} and 10 fb^{-1} in Fig. 6. Fig. 7 presents the integrated luminosity needed to exclude (95% C.L.) the ranges of the parameter x at $\sqrt{s} = 1$ TeV depending on the heavy lepton masses of 350, 375, 400 and 450 GeV.

In Fig. 8, we present the exclusion plot (95% C.L.) for the heavy lepton mass $M_{l'}$ and mixing parameter x at $\sqrt{s} = 3$ TeV and $L_{int} = 5$, 10, 30 and 100 fb^{-1}. Fig. 9 presents the integrated luminosity needed to exclude (95% C.L.) the ranges of the parameter x at $\sqrt{s} = 3$ TeV depending on the heavy lepton masses of 200, 400, 500 and 600 GeV.

It can be seen from the contour plots Fig. 6 and Fig. 8, the accessible range of the parameters are defined outside of the contour lines depending on the luminosity of the collider. For example, at $\sqrt{s} = 1$ TeV and $L_{int} = 100$ fb^{-1} the search can be performed beyond the range of mixing parameter $-0.4 < x < 0.1$ for given $M_{l'} = 400$ GeV, while at

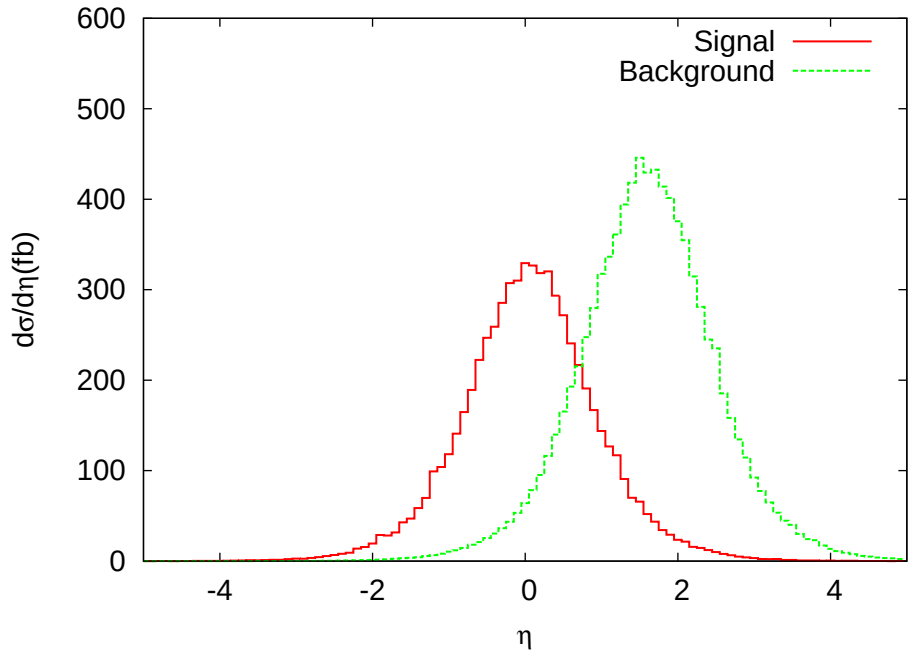


Figure 5: The pseudo-rapidty distribution of the final state muon (μ^-) from the signal process $e^+e^- \to W^+\mu^-\bar{\nu}_\mu\nu'\bar{\nu}'$ with the parameters $x = 1$ and $M_{l'} = 200$ GeV and from background process $e^+e^- \to W^+\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 500$ GeV.

$\sqrt{s} = 3$ TeV and $L_{int} = 10$ fb^{-1} the inaccessible range becomes only $-0.3 < x < -0.1$ for given $M_{l'} = 600$ GeV. We find the ranges of parameters which can be accessed beyond $-0.4 < x < 0.1$ and $-0.25 < x < -0.2$ for $M_{l'} = 400$ GeV at the center of mass energies $\sqrt{s} = 1$ TeV and 3 TeV at $L_{int} = 10$ fb^{-1}, respectively. However, the whole region of interest of the parameter x can be accessed for $M_{l'} < 800$ GeV at $\sqrt{s} = 3$ TeV and $L_{int} = 100$ fb^{-1}.

V. CONCLUSION

The charged $l'^{\pm}$ lepton will have a clear signature at linear colliders. It is shown that the accessible ranges of the parameters of new heavy leptons can be searched through the process $e^+e^- \to l'^+l'^-$ with their subsequent decays $l'^{\pm} \to {}^{(-)}{}'\nu + W^{\pm}$. In this work, the lepton+dijet+missing transverse energy ($l^{\pm}+2j$+MET) final states for the signal and background have been taken into account to find the luminosity required to search for the new heavy lepton mass and mixing parameter. If the LHC find clues about the new physics models, the linear collider at TeV scale can enhance the accessible range of parameter space

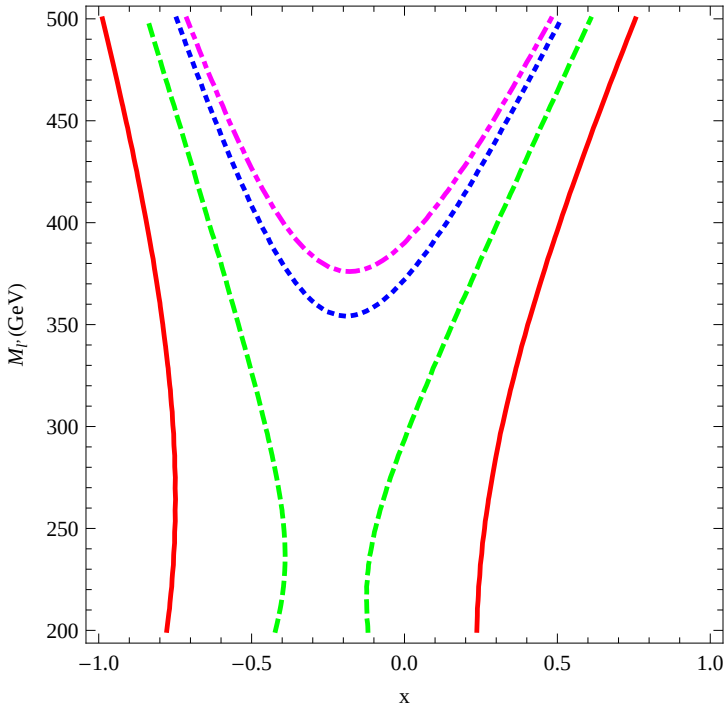


Figure 6: Exclusion plot (95% C.L.) for the heavy lepton mass $M_{l'}$ and mixing parameter x at $\sqrt{s} = 1$ TeV and different integrated luminosities: thick (red) line, dashed (green) line, dotted (blue) line and dot-dashed (magenta) line corresponds to $L_{int} = 20$, 100, 1000 pb^{-1} and 10 fb^{-1}, respectively.

from these models.

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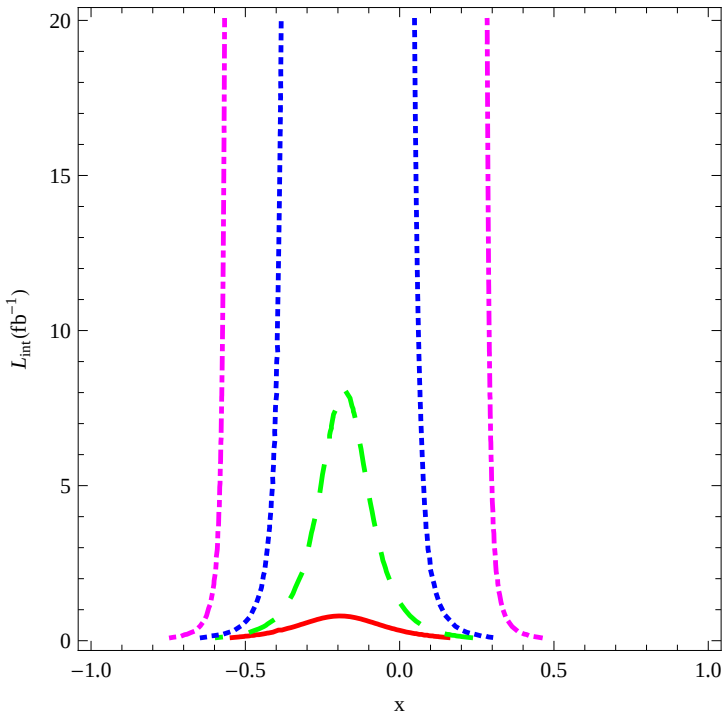


Figure 7: The integrated luminosity needed to exclude (95% C.L.) the ranges of the parameter x at $\sqrt{s} = 1$ TeV depending on the heavy lepton masses: thick (red) line, dashed (green) line, dotted (blue) line and dot-dashed (magenta) line corresponds to the mass values $M_{l'} = 350$, 375, 400 and 450 GeV, respectively.

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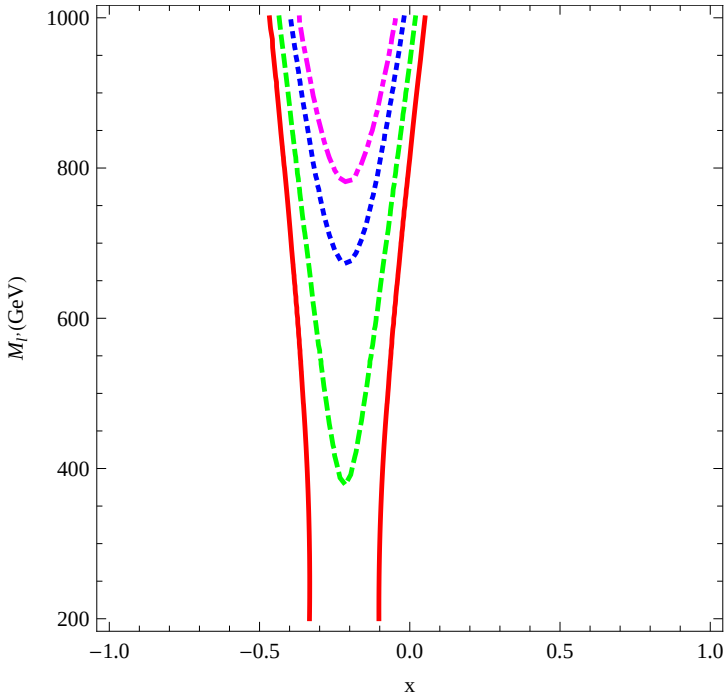


Figure 8: Exclusion plot (95% C.L.) for the heavy lepton mass $M_{l'}$ and mixing parameter x at $\sqrt{s} = 3$ TeV and different integrated luminosities: thick (red) line, dashed (green) line, dotted (blue) line and dot-dashed (magenta) line corresponds to $L_{int} = 5$, 10, 30 and 100 fb^{-1}, respectively.

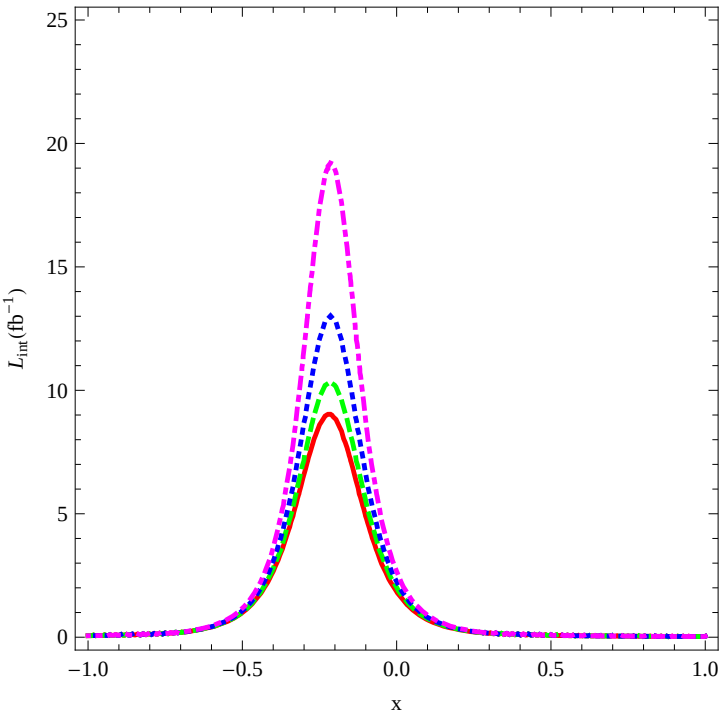


Figure 9: The integrated luminosity needed to exclude (95% C.L.) the ranges of the parameter x at $\sqrt{s} = 3$ TeV depending on the heavy lepton masses: thick (red) line, dashed (green) line, dotted (blue) line and dot-dashed (magenta) line corresponds to $M_{l'} = 200$, 400, 500 and 600 GeV, respectively.