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Production of the quintuplet leptons in future high energy linear e^+e^- colliders

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Abstract

The quintuplet heavy leptons are the typical particles predicted by the TeV scale seesaw model which is proposed as a viable and testable solution to the neutrino masses problem. The observation of these particles might be regarded as a direct evidence of the new model. In this paper, we investigate production and detection prospects of the quintuplet heavy leptons in the processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^+\overline{\Sigma^+})$ and $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^+\overline{\Sigma^+})$ at the ILC. We present the production cross sections and the main kinematic distributions of the various observables. Our numerical results show that the values of cross sections can reach a few hundreds of fb. We also study the possible final state signals of quintuplet heavy leptons and relevant SM backgrounds. Due to high produced rate and small SM backgrounds, the possible signals of quintuplet heavy leptons might be detected via some processes in the future ILC experiments.

1. Introduction

The standard model (SM) of particle physics has been proven to be extremely successful in describing collider experimented data so far. In July 2012, both the ATLAS and the CMS Collaborations announced the discovery of a new scalar particle with a mass of 126 GeV, which is consistent with the predictions of the SM Higgs boson [1,2]. However, this newly discovered scalar particle has been interpreted in various new physics models [3–7], since the SM cannot

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present an explanation for some fundamental problems, such as the hierarchy problem, neutrino masses and dark matter.

The observation of neutrino oscillations has unequivocally established that at least two of the three active neutrinos have nonvanishing mass and that individual lepton flavor is violated [8]. Which can be seen as the typical experimental clue to new physics beyond the SM. Therefore, a precise understanding of the neutrino mass mechanism is an important step in unraveling the nature of new physics.

There have been numerous attempts to build new physics models aiming to explain these puzzles. The seesaw mechanism is one of the most attractive approaches, which can explain the smallness of neutrino mass via introducing the new particles with sufficiently large masses. At the tree level, type-I [9], type-II [10] and type-III [11] seesaw mechanisms proceed via introducing heavy lepton singlet, scalar triplet and lepton triplet, respectively, which also predict the existence of the new scalars particles or gauge bosons.

We here focus on a new TeV scale seesaw model [12], which is proposed as a viable and testable solution to the neutrino masses problem. This new model is proposed for generating small neutrino masses which predicts the relation $m_\nu \sim v^6/M^5$ at tree-level, rather than the conventional three types seesaw formula $m_\nu \sim v^2/M$, where v is the electroweak scale and M is the scale of new physics. This new model introduces a scalar quadruplet Φ and fermion quintuplets Σ_R. The fermion quintuplet contains the doubly charged heavy leptons (Σ^{++} and $\overline{\Sigma^{++}}$), singly charged heavy leptons (Σ^+ and $\overline{\Sigma^+}$) and neutral heavy leptons (Σ^0). The neutral component of the fermion quintuplet is identified as a minimal dark matter candidate.

The fermion quintuplet is provided with outstanding features, which can give the unravel signals of possible scenarios beyond the SM. Thus, the discovery of these exotic fermions at the future high-energy colliders might shed some light on the new physics.

Many works have been done to study of the exotic leptons in various of new physics models [13–16]. Both single production and pair production of exotic leptons have been studied in Refs. [17–20]. Doubly charged leptons also appear in left–right symmetric models [24], in extra dimensional models [21], in string inspired models [22], and in generic lepton triplets minimally coupling to the SM fields [23]. The phenomenology of the exotic leptons has also been analyzed in Refs. [25–27].

The heavy leptons have been searched at the LHC [28,29], which has already posed significant bounds on the masses of the heavy leptons. Furthermore, the LHC Run-2 with higher energy and higher luminosity will certainly extend the horizon to seek for the heavy leptons. Some phenomenological researches of this new seesaw model at the LHC have been fruitfully analyzed in Refs. [12,30]. It is well known that the TeV scale linear colliders with high luminosity, such as the international linear collider (ILC) [31], are the best options to complement and extend the LHC physics program.

In this paper, we will study the direct searches for quintuplet leptons predicted via processes: $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^+\overline{\Sigma^+})$ and $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^+\overline{\Sigma^+})$, and give detailed analysis of the signals and the corresponding SM backgrounds at the ILC in the context of this new model.

2. The TeV scale seesaw model and relevant couplings

The new model we concern here is based on the SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$. Besides usual SM fermions, three generations of hypercharge zero quintuplets $\Sigma_R = (\Sigma_R^{++}, \Sigma_R^{+}, \Sigma_R^{0}, \Sigma_R^{-}, \Sigma_R^{--})$ are introduced transforming as $(1, 5, 0)$ under the gauge group. Besides the SM Higgs doublet $H = (H^+, H^0)$, there is a scalar quadruplet $\Phi = (\Phi^+, \Phi^0, \Phi^-, \Phi^{--})$ transforming as $(1, 4, -1)$.

The renormalizable Lagrangian involving these new fields is given as follows [12]:

$$\mathcal{L} = \overline{\Sigma_R} i\gamma^\mu D_\mu \Sigma_R + (D^\mu\Phi)^\dagger(D_\mu\Phi) - \left(\overline{L_L} Y \Phi \Sigma_R + \frac{1}{2}\overline{(\Sigma_R)^C} M \Sigma_R + \text{H.c.}\right) - V(H,\Phi)\ . \quad (1)$$

Where, Y is the Yukawa-coupling matrix, D_μ is the gauge covariant derivative and M is the mass matrix of the heavy leptons. Here, the matrix of heavy leptons is diagonal and real.

The scalar potential $V(H, \Phi)$ is given as follows [12]:

$$\begin{aligned} V(H,\Phi) = &-\mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger\Phi + \lambda_1\left(H^\dagger H\right)^2 + \lambda_2 H^\dagger H \Phi^\dagger \Phi + \lambda_3 H^* H \Phi^* \Phi \\ &+ \left(\lambda_4 H^* H H \Phi + \text{H.c.}\right) + \left(\lambda_5 H H \Phi\Phi + \text{H.c.}\right) + \left(\lambda_6 H \Phi^* \Phi\Phi + \text{H.c.}\right) \\ &+ \lambda_7\left(\Phi^\dagger\Phi\right)^2 + \lambda_8 \Phi^*\Phi\Phi^*\Phi\ . \end{aligned} \quad (2)$$

After diagonalizing the mass matrix for the neutral leptons, the light neutrinos obtain the Majorana mass matrix

$$m_\nu^{tree} = -\frac{1}{2} v_\Phi^2 Y M^{-1} Y^T\ . \quad (3)$$

The electroweak ρ parameter controls a small value for the vacuum expectation value (vev) v_Φ of the scalar quadruplet. And the vev v_Φ is given a constraint $v_\Phi \lesssim 1.9$ GeV by taking the experimental value $\rho = 1.0004^{+0.0003}_{-0.0004}$ [32]. In the basis where the matrix of exotic leptons is diagonal and real, $M = diag(M_1, M_2, M_3)$, m_ν^{tree} can be written as

$$(m_\nu)_{ij}^{tree} = -\frac{1}{2} v_\Phi^2 \sum_k \frac{Y_{ik} Y_{jk}}{M_k}\ . \quad (4)$$

Besides at the tree-level, the light neutrino masses arise also through one-loop level. There are two different contributions, one with heavy charged fields $(\Sigma^+, \Phi^+, \Phi^-)$ and the other with heavy neutral fields (Σ^0, Φ^0) running in the loop. If we neglect the mass splitting within the Σ and Φ multiplets and take $m_\Phi^2 \simeq M_k^2$, the contribution to the light neutrino mass matrix is given by

$$(m_\nu)_{ij}^{loop} = \frac{-5\lambda_5^* v^2}{48\pi^2} \sum_k \frac{Y_{ik} Y_{jk}}{M_k}. \quad (5)$$

Then, the tree-level and the one-loop contributions added together provide the light neutrino mass matrix

$$(m_\nu)_{ij} = \frac{(-\lambda_4^*)^2 v^6}{6\mu_\Phi^4} \sum_k \frac{Y_{ik} Y_{jk}}{M_k} + \frac{-5}{24}\frac{\lambda_5^* v^2}{\pi^2} \sum_k \frac{Y_{ik} Y_{jk} M_k}{m_\Phi^2 - M_k^2}\left[1 - \frac{M_k^2}{m_\Phi^2 - M_k^2}\ln\frac{m_\Phi^2}{M_k^2}\right]. \quad (6)$$

The quintuplet heavy leptons can couple to the SM particles in this new model. In the following, we concentrate on the phenomenology of the heavy leptons and give the relevant Feynman rules of the heavy leptons to the SM particles which are related to our calculations in this paper.

The gauge Lagrangian relevant for the production processes is given by

$$\begin{aligned} \mathcal{L}_{gauge}^{\Sigma\overline{\Sigma}} = &+e(2\overline{\Sigma^{++}}\gamma^\mu\Sigma^{++} + \overline{\Sigma^+}\gamma^\mu\Sigma^+)A_\mu \\ &+ g\cos\theta_W(2\overline{\Sigma^{++}}\gamma^\mu\Sigma^{++} + \overline{\Sigma^+}\gamma^\mu\Sigma^+)Z_\mu + \text{H.c.} \end{aligned} \quad (7)$$

The decay properties of charged leptons Σ^{++} and Σ^{+} strongly depend on the model parameters. A preliminary study in [12] shows that, the most important decay channel of Σ^{++} is l^+W^+. While the Σ^+ can decay to l^+Z and νW^+. The Lagrangian relevant for the decays of the heavy leptons is given by

$$\mathcal{L} = g\Big[\bar{\nu}(-\sqrt{\frac{3}{2}}V^{\dagger}_{PMNS}V\gamma^{\mu}P_L + \frac{-\sqrt{3}}{2\sqrt{2}}V^{T}_{PMNS}V^{*}\gamma^{\mu}P_R)\Sigma^{+} \\ + \bar{l^c}(\sqrt{\frac{3}{2}}V^{*}\gamma^{\mu}P_R)\Sigma^{++}\Big]W^{-}_{\mu} + \bar{l^c}(\frac{\sqrt{3}}{4}V^{*}\gamma^{\mu}P_R)\Sigma^{+}Z_{\mu} + \text{H.c.} \tag{8}$$

Where $V_{l\Sigma}$ represents the mixing matrix of the heavy leptons and the SM leptons, and $P_L(P_R)$ is the left-hand (right-hand) projection operator. V_{PMNS} represents the 3×3 Pontecorvo–Maki–Nakagata–Saki (PMNS) matrix [33].

3. Numerical results and discussions

The SM input parameters relevant to our study are taken as $M_W = 80.4$ GeV, $M_Z = 91.2$ GeV and $S^2_W = 0.231$ from [32]. In the study of the heavy lepton productions and decays, the mixing matrix $V_{l\Sigma}$ mainly contributes to the decay widths of the heavy leptons. Its square $|V_{l\Sigma}|^2$ is proportional to the decay widths of the heavy leptons. From the experimental point of view, the mixing matrix $V_{l\Sigma}$ decides the contributions to the lepton flavor violating (LFV) processes. Thus, the experiment upper bounds on the branching ratios (BRs) of the radiative LFV decays, for instance, BR$(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [34] and BR$(\mu \to 3e) < 1.0 \times 10^{-12}$ [35] can give constraints on $V_{l\Sigma}$. We take a typical value $V_{l\Sigma} = 3.5 \times 10^{-7}$ in this paper. The searches on exotic leptons at LHC could depend strongly on the model structure. The Ref. [36] has given that the current lower bound for the mass of a generic charged leptons is 100.8 GeV. The stronger bounds on the masses of the exotic leptons are provided from the generic searches for lepton-rich final state at 8 TeV [37,38]. In the following analysis, we will consider these constraints on the mass range of the signals. We ignore the mass differences between the doubly charged and singly charged heavy leptons in the new model, and define $M_{\Sigma^{++}}(M_{\overline{\Sigma^{++}}}) = M_{\Sigma^{+}}(M_{\overline{\Sigma^{+}}}) = M_{\Sigma}$ in our study.

3.1. The production cross sections of $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^{+}\overline{\Sigma^{+}})$

The production channels of the quintuplet leptons in proton–proton collisions are dominated by the quark–antiquark annihilation via neutral and charged gauge bosons. At the ILC, it is obvious that the doubly charged (singly charged) leptons also can be pair produced by the s-channel γ exchange and Z exchange via e^+e^- collisions. The scattering amplitudes of the process $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^{+}\overline{\Sigma^{+}})$ only depend on the heavy lepton mass M_Σ.

Fig. 1 shows the cross sections of the process $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^{+}\overline{\Sigma^{+}})$ varying with respect to the heavy lepton mass M_Σ for $\sqrt{s}1.5$ (2.0) TeV. From Fig. 1, we find that the production rates decrease with the increasing M_Σ, due to phase space suppression. On the other hand, the cross sections for the process $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}$ are larger than that for the process $e^+e^- \to \Sigma^{+}\overline{\Sigma^{+}}$. This is because the strength of coupling $\gamma(Z)\Sigma^{++}\overline{\Sigma^{++}}$ is about twice that of $\gamma(Z)\Sigma^{+}\overline{\Sigma^{+}}$, and thus the total cross sections for process $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}$ are almost four times than that for the process $e^+e^- \to \Sigma^{+}\overline{\Sigma^{+}}$. The production rates for $\Sigma^{++}\overline{\Sigma^{++}}$ decrease with the increasing M_Σ, which are in the range of 357.6 fb $\sim$ 181.3 fb (201.5 fb $\sim$ 178.1 fb), for

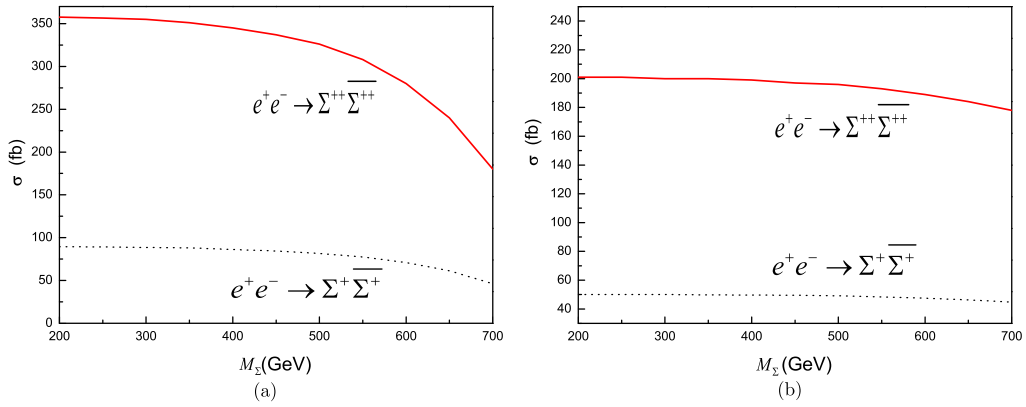


Fig. 1. The cross sections for two processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^+\overline{\Sigma^+})$ as a function of the heavy quintuplet mass M_Σ at the ILC with (a) $\sqrt{s} = 1.5$ TeV, (b) $\sqrt{s} = 2.0$ TeV and $|V_{l\Sigma}| = 3.5 \cdot 10^{-7}$.

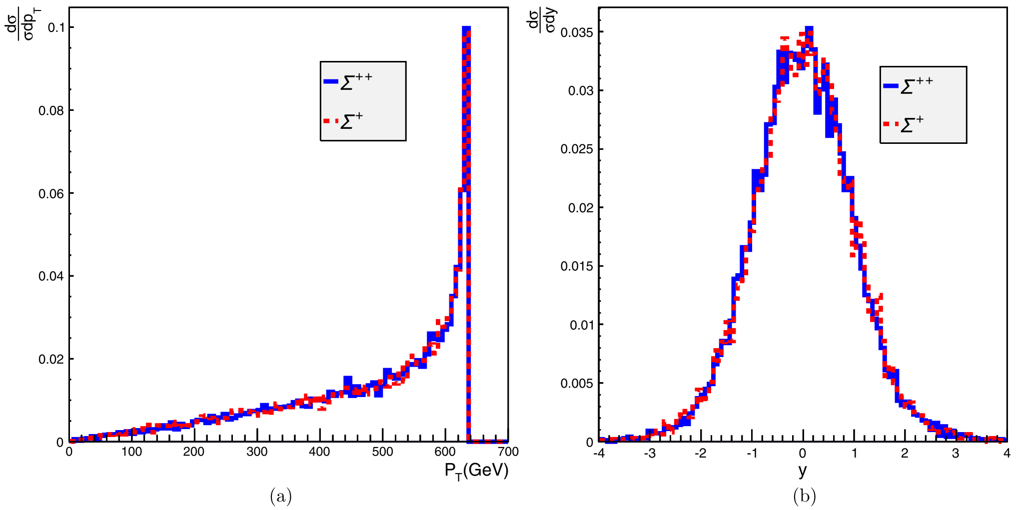
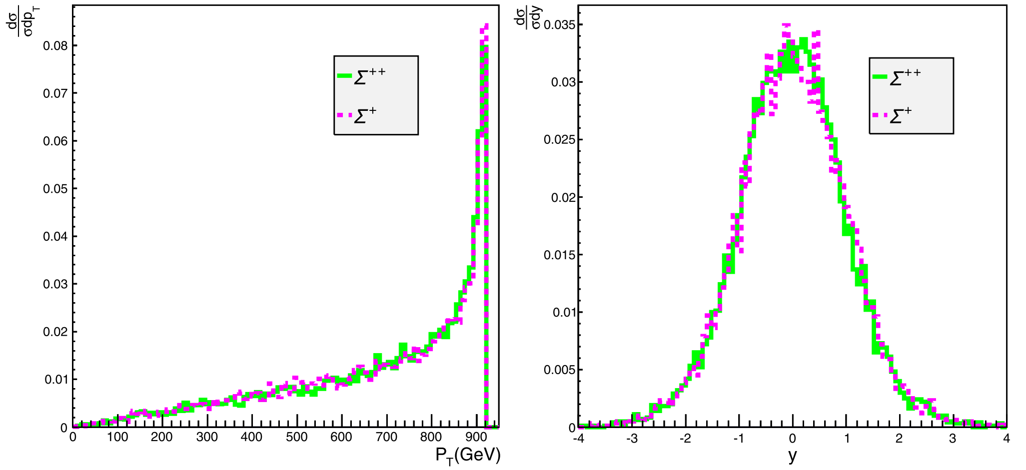


Fig. 2. (a) Normalized transverse momenta distribution, as well as (b) normalized rapidity distribution of Σ^{++} and Σ^+ with $\sqrt{s} = 1.5$ TeV and $M_\Sigma = 400$ GeV.

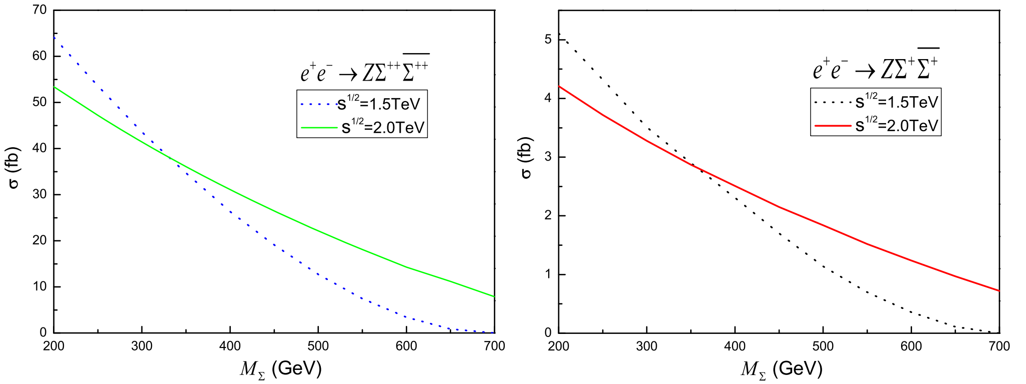
200 GeV $\leq M_\Sigma \leq$ 700 GeV with $\sqrt{s} = 1.5$ (2.0) TeV. When M_Σ is small, the curve of cross section changes gently. While, the production rates for $\Sigma^+\overline{\Sigma^+}$ also decrease with the increasing M_Σ, which are in the range of 89.3 fb $\sim$ 46.1 fb (50.1 fb $\sim$ 44.8 fb), for 200 GeV $\leq M_\Sigma \leq$ 700 GeV with $\sqrt{s} = 1.5$ (2.0) TeV. For $M_\Sigma = 500$ GeV, there will be 3.26×10^4 (1.95×10^4) $\Sigma^{++}\overline{\Sigma^{++}}$ events to be generated at the ILC with $\sqrt{s} = 1.5$ (2.0) TeV and the yearly integrated luminosity of 100 fb^{-1} [31,39,40].

In Fig. 2 and Fig. 3, we provide the distributions of transverse momenta and rapidity of Σ^{++} and Σ^+ for two processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^+\overline{\Sigma^+})$ with $M_\Sigma = 400$ GeV for $\sqrt{s} = 1.5$ (2.0) TeV. The signal and background curves are normalized by their individual cross sections. We find that the peak values of differential cross sections are obtained for high p_T values. The signal distributions for the exotic leptons peak around 620 $\sim$ 640 GeV for $\sqrt{s} = 1.5$ TeV, while



(a) (b)

Fig. 3. (a) Normalized transverse momenta distribution, as well as (b) normalized rapidity distribution of Σ^{++} and Σ^{+} with $\sqrt{s} = 2.0$ TeV and $M_\Sigma = 400$ GeV.



(a) (b)

Fig. 4. The production cross sections (a) $\sigma(Z\Sigma^{++}\overline{\Sigma^{++}})$ and (b) $\sigma(Z\Sigma^{+}\overline{\Sigma^{+}})$ as function of the heavy quintuplet mass M_Σ at the ILC for $\sqrt{s} = 1.5$ (2.0) TeV and $|V_{l\Sigma}| = 3.5 \cdot 10^{-7}$.

peak around 900 ∼ 920 GeV for $\sqrt{s} = 2.0$ TeV. And, an interesting tendency is that the charged leptons and doubly charged leptons are all likely to be produced in the central region for two different c.m. energy. This is because the produced exotic leptons pair prefer to go out almost back to back.

3.2. *The production cross sections of* $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^{+}\overline{\Sigma^{+}})$

The doubly charged (charged) lepton pair also can be produced associated with the Z boson via the processes $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^{+}\overline{\Sigma^{+}})$. In Fig. 4(a), we plot the cross sections $\sigma(Z\Sigma^{++}\overline{\Sigma^{++}})$ as function of the heavy lepton mass M_Σ for two values of $\sqrt{s}$. The plots show that their cross sections values decrease as M_Σ increases, which are in the ranges of 64.1 fb ∼ 0.3 fb (53.1 fb ∼ 7.86 fb), for 200 GeV $\leq M_\Sigma \leq$ 700 GeV and $\sqrt{s} = 1.5$ (2.0) TeV.

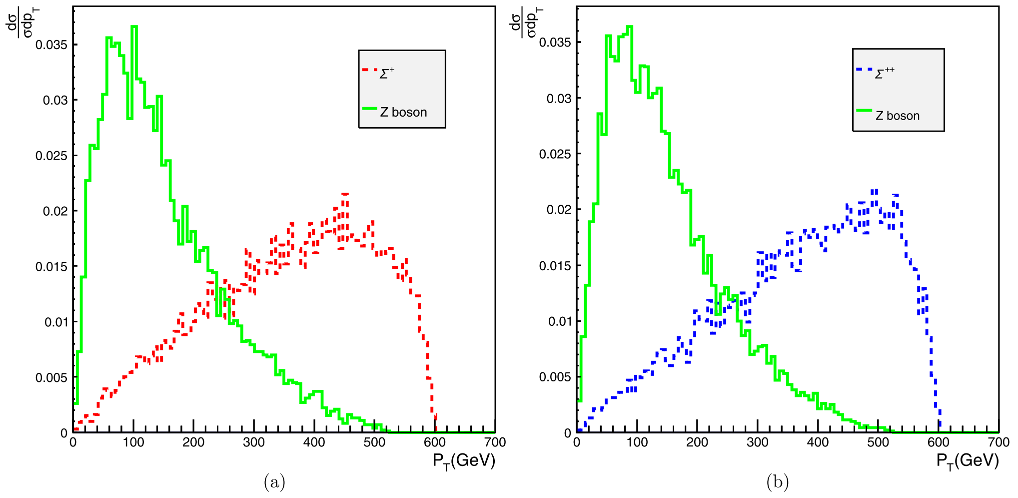


Fig. 5. Normalized transverse momenta distribution of (a) Σ^+ and Z, as well as (b) Σ^{++} and Z with $\sqrt{s} = 1.5$ TeV and $M_\Sigma = 400$ GeV.

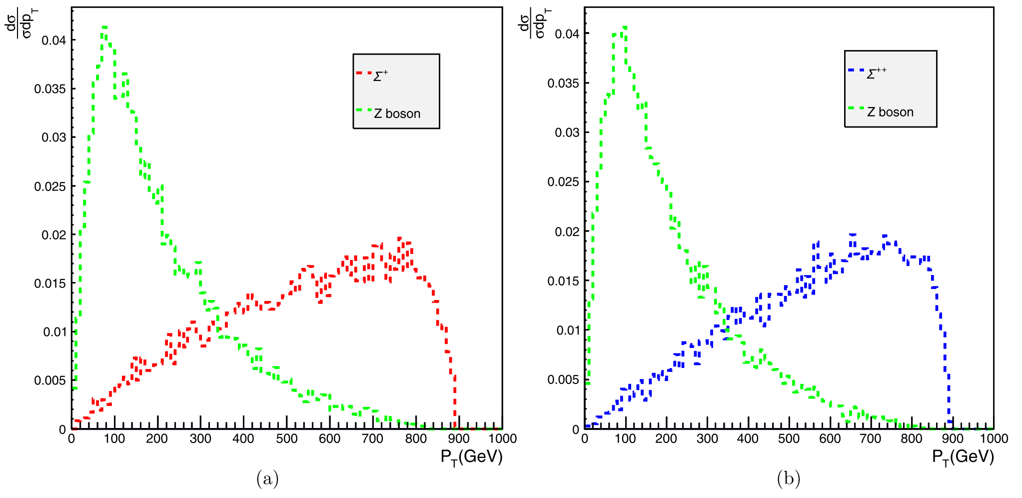


Fig. 6. Normalized transverse momenta distribution of (a) Σ^+ and Z, as well as (b) Σ^{++} and Z with $\sqrt{s} = 2.0$ TeV and $M_\Sigma = 400$ GeV.

Meanwhile, Fig. 4(b) shows the cross sections $\sigma(Z\Sigma^+\overline{\Sigma^+})$ varying with the heavy lepton mass M_Σ. We find that the production rates decrease with the increasing M_Σ, which are in the range of 5.11 fb $\sim$ 0.07 fb (4.21 fb $\sim$ 0.72 fb), for 200 GeV $\leq M_\Sigma \leq$ 700 GeV and $\sqrt{s} = 1.5$ (2.0) TeV. For $M_\Sigma = 500$ GeV, there will be 3.11×10^3 $Z\Sigma^{++}\overline{\Sigma^{++}}$ (2.51×10^2 $Z\Sigma^+\overline{\Sigma^+}$) events to be generated at the ILC with $\sqrt{s} = 2.0$ TeV and the yearly integrated luminosity of 100 fb^{-1} [31, 39,40].

Fig. 5 shows the transverse momenta distributions of exotic lepton $\Sigma^{++}(\Sigma^+)$ and gauge boson Z for two processes $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^+\overline{\Sigma^+})$ with $\sqrt{s} = 1.5$ TeV and $M_\Sigma =$ 400 GeV. From Fig. 5, we find that there exist peaks at different conditions, and there are different significant regions of P_T for exotic lepton $\Sigma^{++}(\Sigma^+)$ and gauge boson Z in two processes. The signal of the exotic leptons peaks at high transverse momentum area while the gauge boson Z peaks at low transverse momentum area. In Fig. 6, we provide the transverse momenta distributions of exotic lepton Σ^{++} (Σ^+) and gauge boson Z for two processes $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^+\overline{\Sigma^+})$ with $M_\Sigma = 400$ GeV and $\sqrt{s} = 2.0$ TeV. We can see that two figures in Fig. 6 show similar characteristics as that in Fig. 5.

3.3. Analysis of SM backgrounds

To see whether the exotic leptons can be observed at the ILC, we consider the possible decay modes of the exotic leptons. In this new model, the doubly charged heavy leptons Σ^{++} mainly decays to a SM charged lepton with a same-sign W boson $\Sigma^{++} \to l^+W^+$. While, the charged heavy leptons Σ^+ can decay to l^+Z and νW^+. The detailed formulas for all of these decay channels are listed in Ref. [12].

3.3.1. The processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^+\overline{\Sigma^+})$

In this new model, the doubly charged heavy lepton $\Sigma^{++}(\overline{\Sigma^{++}})$ can only decay to a SM charged lepton with a same-sign W boson $\Sigma^{++}(\overline{\Sigma^{++}}) \to l^+W^+(l^-W^-)$. While, the decay channel of $\Sigma^+(\overline{\Sigma^+})$ is $l^+Z(l^-Z)$ and $\nu W^+(\nu W^-)$. In the following, we detailed discuss the signal and relevant SM backgrounds of processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^+\overline{\Sigma^+})$.

In our study, MadGraph/MadEvent [41] is employed to generate both the distinctive signal and SM background events. The basic acceptance cuts, referred to as basic cuts, are applied for the signal and background events,

$$\begin{aligned} &p_{Tj} \geq 25 \text{ GeV}, \qquad p_{Tl} \geq 25 \text{ GeV}, \qquad \not{E}_T \geq 25 \text{ GeV}, \\ &|\eta_j| \leq 2.5, \qquad |\eta_l| \leq 2.5, \qquad \sqrt{(\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2} \geq 0.4. \end{aligned} \tag{9}$$

Here, $\eta_i(\phi_i)$ denotes the rapidity (azimuthal angle) of the related lepton (jet). For the SM leptons, the lepton-tagging efficiency is taken as $\epsilon_l = 90\%$. The light jet j means light quarks or gluons. p_{Tl} is the lepton transverse momentum, p_{Tj} is the jet transverse momentum, and $\not{E}_T$ is the missing transverse momentum from the invisible neutrino in the final state. We smear the energies of the final lepton and jet according to the assumed Gaussian resolution parametrization

$$\delta(E)/E = \frac{a}{E} \oplus b. \tag{10}$$

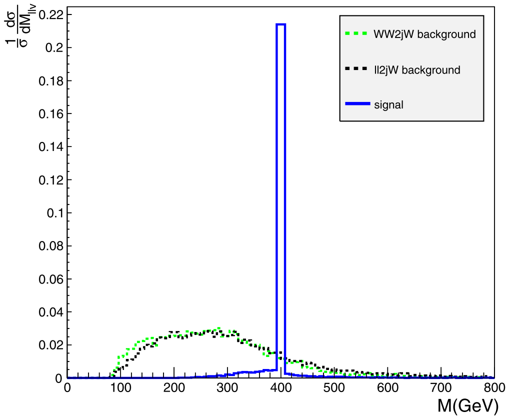
Here, we take $a = 5\%$ $(a = 100\%)$ and $b = 0.55\%$ $(b = 5\%)$ for leptons (jets) [42].

• Case I: for the process $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}$, two opposite sign W bosons and two opposite sign leptons are generated by the two heavy leptons Σ^{++} and $\overline{\Sigma^{++}}$ decaying. We demand that one of the W bosons decays hadronically and the other one decays leptonically. Thus, the final state contains two leptons with same charge, one lepton with opposite charge, two light jets plus one neutrino,

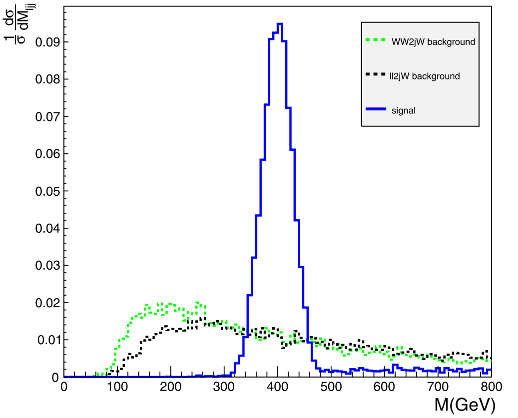
$$e^+e^- \to \overline{\Sigma^{++}}\Sigma^{++} \to l^-W^-l^+W^+ \to l^-l^+jjl^+\nu(l^-\bar{\nu}). \tag{11}$$

The corresponding characteristic backgrounds are $l^+l^-2jW^\pm$ and $W^+W^-2jW^\pm$, where W decays leptonically.

The normalized invariant mass distribution of the two heavy leptons after the basic cuts are shown in Fig. 7. We find that the SM background events mainly distribute in the low invariant mass region while the signal distribution shows a sharp peak at the input value of



(a)



(b)

Fig. 7. Normalized invariant mass distribution of $M_{ll\nu}$ (a) and M_{ljj} (b) in the $2l^{\pm}l^{\mp}2j\not{E}_T$ signal for $M_\Sigma = 400$ GeV at the ILC.

$M_\Sigma = 400$ GeV. The invariant masses of the heavy leptons in the signal events are different from those in the background events.

We employ the invariant mass through various combinations of the final particles to constrain the mediate resonances (cuts II),

$$|M_{l\nu} - M_W| < 10\% M_W \text{ GeV}, \qquad |M_{jj} - M_W| < 10\% M_W \text{ GeV}. \tag{12}$$

After ignoring the mass splitting among the heavy leptons, we require the invariant mass of the reconstructed double charged leptons through various combinations of the final particles to be within the mass window (cuts III),

$$|M_{ll\nu} - M_\Sigma| < 10\% M_\Sigma \text{ GeV}, \qquad |M_{ljj} - M_\Sigma| < 10\% M_\Sigma \text{ GeV}, \tag{13}$$

where M_Σ is taken as 400 GeV.

• Case II: for the process $e^+e^- \to \Sigma^+\overline{\Sigma^+}$, the decay channel $\Sigma^+(\overline{\Sigma^+}) \to l^+Z(l^-Z)$ plays an important role in finding the charged lepton signal. For the pair production channel $\Sigma^+\overline{\Sigma^+}$, one of the Z bosons decays hadronically and the other one decays leptonically. Thus, the final state contains four leptons and two jets,

$$e^+e^- \to \Sigma^+\overline{\Sigma^+} \to l^+Zl^-Z \to l^+l^-l^+l^-jj. \tag{14}$$

The corresponding characteristic SM backgrounds are $2l^{\pm}2l^{\mp}jj$ and l^+l^-jjZ, where Z decays leptonically.

The normalized invariant mass distribution of the two heavy leptons after the basic cuts are shown in Fig. 8. The invariant masses of the heavy leptons in the signal events are larger than those in the background events for $M_\Sigma = 400$ GeV.

We also employ the invariant mass through various combinations of the final particles to constrain the mediate resonances (cuts II),

$$|M_{ll} - M_Z| < 10\% M_Z \text{ GeV}, \qquad |M_{jj} - M_Z| < 10\% M_Z \text{ GeV}. \tag{15}$$

We subsequently reconstruct the mass of the heavy leptons to further suppress the backgrounds. The two jets with one charged lepton in the final state can reconstruct one heavy lepton

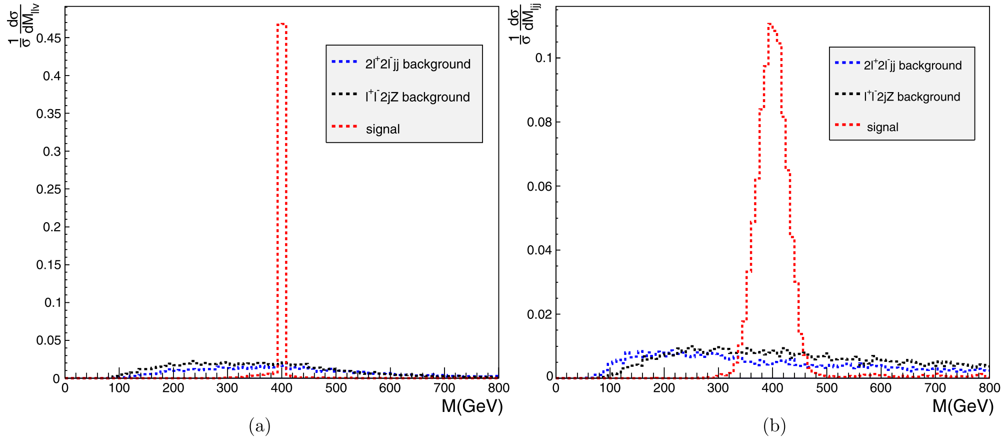


Fig. 8. Normalized invariant mass distribution of $M_{ll\nu}$ (a) and M_{ljj} (b) in the $2l^{\pm}2l^{\mp}2j$ signal for $M_{\Sigma} = 400$ GeV at the ILC.

Table 1
The cross sections (fb) and the event numbers of the signals and the backgrounds for $M_{\Sigma} = 400$ GeV at the ILC with $\sqrt{s} = 1.5$ TeV and $\mathcal{L} = 100\ \text{fb}^{-1}$.

	Basic cuts	Cuts II	Cuts III	Number of events	$S/\sqrt{S+B}$
Signal $2l^{\pm}l^{\mp}2j\not{E}_T$ (Case I)	29.63	28.12	21.54	2154	46.3
Bkg $l^+l^-2jW^{\pm}$	2.33	2.11	0.0441	4.41	
Bkg $W^+W^-2jW^{\pm}$	0.0076	0.0068	0.000012	0.0012	
Signal $2l^{\pm}2l^{\mp}jj$ (Case II)	23.83	22.16	15.16	1516	38.9
Bkg $2l^{\pm}2l^{\mp}jj$	0.015	0.0137	0.0071	0.71	
Bkg l^+l^-2jZ	0.0098	0.0091	0.00031	0.031	

mass M_{ljj}, and the remaining three charged leptons can reconstruct another heavy lepton mass M_{lll}. Similarly, we require the invariant mass of the reconstructed charged leptons to be within the mass window (cuts III),

$$|M_{ljj} - M_{\Sigma}| < 10\% M_{\Sigma}\ \text{GeV}, \qquad |M_{lll} - M_{\Sigma}| < 10\% M_{\Sigma}\ \text{GeV}, \tag{16}$$

where M_{Σ} is taken as 400 GeV.

After all these cuts applied, the cross sections of these signals and backgrounds are listed in Table 1. It is obvious that the sets of cuts can significantly suppress the backgrounds while keeping most of the signals. We define the statistical significance as $S/\sqrt{(S+B)}$, where S and B represent the number of signal and background events, respectively. For Case I and Case II, the statistical significance can reach 46.3 and 38.9 for $M_{\Sigma} = 400$ GeV with an integrated luminosity of 100 fb^{-1} at $\sqrt{s} = 1.5$ TeV. Therefore, we may discriminate the exotic lepton signals from the backgrounds from these two typical processes at the ILC.

3.3.2. The processes $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^{+}\overline{\Sigma^{+}})$

In the following, we discuss the signals and relevant SM backgrounds of the processes $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^{+}\overline{\Sigma^{+}})$.

(i) for the process $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}$, two opposite sign W bosons and two opposite sign leptons are generated by the two heavy leptons Σ^{++} and $\overline{\Sigma^{++}}$ decaying. The possible signatures of the process $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}$ are $5l2j\not{E}_T$, with the Z boson and one W boson decay leptonically, and the other one W boson decays hadronically. Its SM backgrounds mainly come from the $ZZWW$ with Z bosons and one W boson decay leptonically, and the other one W boson decays hadronically. At the ILC experiment, we recalculate the cross section and find that the value is about 0.0212 fb with $\sqrt{s} = 2.0$ TeV. However, the cross section of the signal $5l2j\not{E}_T$ is larger than 0.17 fb in most of the parameter space of the new model with $\sqrt{s} = 2.0$ TeV. The cross section of the background is much smaller than that of the signal in most of parameters space. Thus, it is possible to extract the signals from the background.

The other signature of the process $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}$ is $3l4j\not{E}_T$, with the Z boson and one W boson decay hadronically, and the other one W boson decays leptonically. Its SM backgrounds mainly come from the $t\bar{t}Z$ with $t \to Wb$, the Z boson and one W boson decay hadronically, and the other one W boson decays leptonically. We recalculate their cross section and find that their value is about 0.017 fb after basic cuts with $\sqrt{s} = 2.0$ TeV. While, the cross section of the signal $3l4j\not{E}_T$ is larger than 0.255 fb in most of the parameter space of the new model with $\sqrt{s} = 2.0$ TeV. Furthermore, there are large kinematic differences between the signals and backgrounds. Thus, it is possible to extract the exotic lepton signals in the reasonable parameters space from the backgrounds.

(ii) for the process $e^+e^- \to Z\Sigma^{+}\overline{\Sigma^{+}} \to Zl^+l^-ZZ$, the production rate of the Zl^+l^-ZZ final state can be easily estimated by $\sigma^s = \sigma \times Br(\Sigma^+ \to l^+Z) \times Br(\overline{\Sigma^+} \to l^-Z)$. For $M_\Sigma =$ 700 GeV, the total production rate of the Zl^+l^-ZZ is estimated to be about 0.026 fb with $\sqrt{s} =$ 2.0 TeV. Unfortunately, the $Z \to ll$ branching ratio is very small, and too few final events are left for an effective measurement. The main SM background comes from the process $e^+e^- \to ZZZZ$. We recalculate their cross section and find that their value is about 0.000341 fb at the ILC experiment with $\sqrt{s} = 2.0$ TeV. Based on the small $Z \to ll$ branching ratio, the cross section of the SM background is so tiny that it might hardly be detected in practice.

4. Conclusions

The observation of exotic particles would be an unambiguous signals for the existence of new physics beyond SM. Therefore, it is important to study the related phenomena both in theory and experiments. In this paper, we study an attractive new physics model, which predicts the existence of quintuplet heavy leptons. The impressive experiments at the LHC have taken us to the energy and luminosity frontier for discovering of new particles. The new exotic leptons might produce observable signatures in future high energy collider experiments. In the context of this new model, some literatures have been done to study the potential discovery of the exotic leptons at the LHC.

In the present work, we investigate production and detection prospects of the quintuplet heavy leptons. We first calculate the cross sections and the distributions of the various observables for processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^{+}\overline{\Sigma^{+}})$ and $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}(Z\Sigma^{+}\overline{\Sigma^{+}})$ at the ILC. By considering the representative decay modes of the heavy leptons, we further study the exclusive signals and SM backgrounds. We carry out a full simulation for the signals from processes $e^+e^- \to \Sigma^{++}\overline{\Sigma^{++}}(\Sigma^{+}\overline{\Sigma^{+}})$ and the relevant SM backgrounds. It is found that the backgrounds can be significantly suppressed by applying suitable kinematic cuts, and the signals have relatively large statistical significances. Thus, the future ILC experiments might detect the possible signals of the heavy leptons via these two processes. For the process $e^+e^- \to Z\Sigma^{++}\overline{\Sigma^{++}}$, the production rate of the SM background is much smaller than that generated by the signal process, then the distinct signal should be easily separated from the SM backgrounds. However, the final events from $e^+e^- \to Z\Sigma^+\overline{\Sigma^+}$ and relevant backgrounds are so tiny that they might hardly be detected in practice.

In a word, as long as the heavy lepton masses are not too heavy, their possible signal might be detected via some of these processes. We expect that these production processes can be used to detect the exotic leptons predicted by this new model in the future ILC experiments.

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