Neutrino and Collider Implications of a Left-Right Extended Zee Model

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We study a simple left-right symmetric (LRS) extension of the Zee model for neutrino mass generation. An extra \( SU(2)_L \times SU(2)_R \) singlet charged scalar helps in generating a loop-induced Majorana mass of the neutrinos. This scenario is quite distinct from other LRS models as the right-handed neutrinos are very light of the order of a few eV to a few MeV. We study the collider signature of the charged scalar at \( e^+e^- \) collider, where a huge enhancement in the production cross-section is possible, resulting in a much stronger signal at the ILC or CLIC experiments.

Introduction: The observation of neutrino oscillation leading to the realization that neutrinos are massive is one of the biggest motivations of physics beyond the Standard Model (SM). A large number of models have been suggested to explain neutrino masses and mixings either by the seesaw mechanism [1] or through loop induced processes [2]. The Zee model [3] is one of the simplest such scenarios where neutrino masses are generated at one–loop by extending the SM scalar sector with an extra doublet and a charged singlet scalar field. The charged singlet scalar can mix with other charged scalars while also having non-zero flavor violating couplings with leptons, giving rise to neutrino masses at one–loop. Unfortunately the simplest form of the Zee model was shown to be ruled out by experimental neutrino data [4] however its extensions might still be viable. In this work we study an extended Zee model in a left-right symmetric (LRS) framework [5] to examine its viability from neutrino oscillation data as well as to analyse the possible collider implications for the charged singlet Higgs.

It is quite natural to extend the Zee model in a simple LRS framework to generate the neutrino masses and mixings. LRS models can help explain the origin of parity violation as a spontaneously broken mechanism. It can possibly solve the strong CP problem [6] while also being able to generate the light neutrino masses through seesaw mechanism. Yet the minimal scalar sector in a LRS framework consisting of two doublet and a bidoublet scalar fields can only generate a Dirac mass term for the neutrinos. Inclusion of an extra charged singlet scalar is thus the most economical way to generate neutrino Majorana masses in such a scenario.

The singlet charged scalar can give rise to rich collider phenomenology at lepton colliders. Even though the Large Hadron Collider (LHC) has a very limited capability of observing them, the upcoming lepton colliders will be able to copiously produce these charged particles owing to their large couplings with the leptons. The same coupling also contributes to SM neutrino masses. A detailed study of the pair production and decay of these charged scalars in the upcoming International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments have been performed in this letter, taking into account neutrino masses and mixings. The final state of two opposite sign leptons and missing energy can be measured quite significantly over the SM background resulting in a possibility to observe such a process even with a very low luminosity at these experiments.

Model and Spectrum: LRS models are simple gauge extensions of the SM with the gauge group being \( SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_B−L \). The charge of a particle is defined as \( Q = I_{L} + I_{R} + (B − L)/2 \). The quarks and leptons consist of left–handed and right–handed doublet fields and hence the right-handed neutrinos are naturally present in this framework.

The minimal Higgs sector consists of

\[
H_{R}(1,1,2,1) = \begin{pmatrix} H_{R}^{+} \left[ H_{R}^{0} \right] \end{pmatrix}, \quad H_{L}(1,2,1,1) = \begin{pmatrix} H_{L}^{+} \left[ H_{L}^{0} \right] \end{pmatrix},
\]

\[
\Phi(1,2,2,0) = \begin{pmatrix} \phi_{1}^{0} \phi_{2}^{0} \phi_{1}^{+} \phi_{2}^{+} \end{pmatrix}, \quad \delta(1,1,1,2) = \delta^{+},
\]

where the numbers in the brackets denote the quantum numbers under \( SU(3)_C, SU(2)_L, SU(2)_R, U(1)_{B−L} \) gauge groups. The model has been proposed in [7], and studied in detail for the LHC and low energy phenomenology.

The Yukawa lagrangian is given as:

\[
L_{Y} = Y_{ij}^{q} \overline{Q}_{Li} \Phi Q_{Rj} + Y_{ij}^{e} \overline{L}_{Li} \Phi \tilde{e} Q_{Rj} + Y_{ij}^{t} \overline{t}_{Li} \Phi l_{Rj} + \lambda_{Li} \overline{t}_{Li} \overline{t}_{Li} l_{Rj} \delta^{+} + \lambda_{Rj} \overline{l}_{Rj} \overline{l}_{Rj} l_{Rj} \delta^{+} + H.C.
\]

where \( Y \) and \( \lambda \) are the Yukawa couplings and

\[
\tilde{\Phi} = \tau_{2} \Phi^{*} \tau_{2}. \tag{3}
\]

The structure of \( \lambda_{Li}/\lambda_{Rj} \) term is such that the only terms that will survive are the ones with \( i \neq j \). This is exactly the same that happens in the Zee mechanism of neutrino mass generation. If we expand out any one of the terms involving \( \delta \) in the Yukawa Lagrangian we will obtain:

\[
\mathcal{L} \supset \sum_{i,j} \nu_{i} e_{j} \lambda'_{i,j}, \tag{4}
\]
where $\nu_i$ and $e_j$ are in flavor basis and $\lambda_{ij} = \lambda_{ij} - \lambda_{ji}$.

The Vacuum expectation values (VEV) of the Higgs fields are given as:

$$\langle \phi^0_i \rangle = v_1, \quad \langle \phi^0_2 \rangle = v_2, \quad \langle H^0_R \rangle = v_R, \quad \langle H^0_L \rangle = v_L,$$

(5)

with the effective electroweak VEV given as $v_{EW} = \sqrt{v_1^2 + v_2^2 + v_R^2}$. Without loss of generality, one of the bidoublet VEVs can be chosen to be small. Also since $v_2$ does not contribute to the top mass, a large $v_L$ would automatically require a large top Yukawa coupling resulting in the theory being non-perturbative at quite low scales. The hierarchy in the VEVs thus has been chosen such that

$$v_R >> v_1 > v_2, v_L.$$  (6)

The $\delta$ field is responsible for producing the Majorana mass terms in the neutrino mass matrix which are given as [7]:

$$(M^L_\nu)^{ij} = \frac{1}{4\pi^2} \lambda^{\alpha \beta}_{L} \frac{m_{e\beta}}{m_{e\alpha}} \sum_{i=1}^{3} \log \frac{M_{h_i}^2}{m_{e\alpha}^2} \times V_{3i} \left[ (Y^\nu_L)^{\gamma \beta} V_{2i}^* - (\tilde{Y}^\nu_L)^{\gamma \beta} V_{1i}^* \right] \quad \alpha \leftrightarrow \gamma,$$

$$(M^R_\nu)^{ij} = \frac{1}{4\pi^2} \lambda^{\alpha \beta}_{R} \frac{m_{e\beta}}{m_{e\alpha}} \sum_{i=1}^{3} \log \frac{M_{h_i}^2}{m_{e\alpha}^2} \times V_{3i} \left[ (Y^\nu_R)^{\gamma \beta} V_{2i}^* - (\tilde{Y}^\nu_R)^{\gamma \beta} V_{1i}^* \right] \quad \alpha \leftrightarrow \gamma.$$  (7)

Here $V_{ij}$ are the charged Higgs boson mixing elements. The neutrino mass matrix would thus be a $6 \times 6$ matrix given as:

$$M_\nu = \begin{pmatrix} M^L_\nu & M^D_\nu \\ (M^D_\nu)^T & M^R_\nu \end{pmatrix},$$

(8)

where $M^L_\nu$ and $M^R_\nu$ are generated at one-loop. A simple rotation of the bidoublet fields is performed such that only one of the new fields get a non-zero vev. This along with a redefinition of the couplings gives

$$M_{\alpha} = Y^q v_1, \quad M_{d} = \tilde{Y}^q v_1, \quad M_{l} = \tilde{Y}^l v_1, \quad M_{\nu}^D = Y^l v_1.$$  (9)

The redefined coupling $\tilde{Y}_i$, which we have chosen to be diagonal, is entirely determined from the charged lepton masses as can be seen from Eq. 9. Similarly $Y^q$ (chosen to be diagonal) and $Y^l$ can be determined from the up and down sector quark masses and CKM mixings. For the neutrino sector we first chose $Y_l$ to be zero and tried to get the light neutrino masses and mixings from $M^D_\nu$ alone. This approach does not work as there are too few free parameters to fit the experimental neutrino data. We then considered the case with $\lambda^L_\nu$ chosen to be zero such that the light neutrino masses arise entirely from $M^D_\nu$ and $M^R_\nu$ similar to type-I seesaw mechanism. This gives us the correct experimentally observed masses and mixings for the light neutrinos and hence this is the approach we follow for the neutrino sector. The right-handed neutrino masses, generated at the loop-level, are proportional to the square of the lepton Yukawa couplings and hence are naturally small ranging from a few eV to a few MeV. This is quite different from other left-right symmetric models where the right-handed neutrino is naturally heavy as its mass is proportional to the right-handed symmetry breaking scale. For our analysis we have chosen $\lambda_R \sim O(1)$ which makes the lightest right-handed neutrino $M_{\nu_1} \sim \text{eV}$, and the other two $M_{\nu_{2,3}} \sim \text{MeV}$. Since we use a type-I seesaw-like structure for the neutrino mass, the Yukawa couplings $Y_l$ are chosen accordingly to satisfy the correct neutrino oscillation parameters. The allowed values for the elements of $M^D_\nu$ obtained by scanning over the allowed parameter space are shown in Fig. 1. Here we have varied the elements of $\lambda^R_\nu$ matrix between 0.5 to 1.0 keeping their values quite close by allowing a spread of only 10% from each other. This is done so that any possible hierarchy due to the experimental neutrino data is clearly visible in the $M^D_\nu$ sector. Since the lightest right-handed neutrino mass is quite small, we also make sure that its mixing with the active neutrinos is small ($\sin \theta \lesssim 10^{-2}$). This makes all of their kinematically allowed decays to occur outside the detector.

The scalar sector of the model consists of four CP-even, two CP-odd and three charged Higgs boson states. Two CP-odd and two charged states are eaten up to give masses to the $Z_R$, $Z$, $W_R$, $W$ gauge bosons respectively. We specifically focus our discussion on the charged Higgs sector, as that is most important for the neutrino masses and the collider analysis of the charged scalar discussed in this letter.

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1 Even if we keep both $Y_l$ and $\lambda^L_\nu$ to be non-zero, the value of the elements of $\lambda^L_\nu$ matrix satisfying the neutrino constraints come out to be very small to have any observable consequences for our study.
FIG. 2: Feynman diagram for the production of $H_1^+ H_1^-$ at $e^+ e^-$ collider.

The charged Higgs mass-squared matrix is $5 \times 5$ which upon diagonalization gives two zero eigenvalues corresponding to the two goldstone bosons absorbed by the $W_R$ and $W$ bosons to give them mass. The goldstone bosons primarily consist of $H^R_1$ and $\phi^\pm_1$ states as their corresponding doublet’s neutral fields get the large non-zero VEVs. The other three eigenstates give the three physical charged Higgses and are linear combinations of $\phi^0_2$, $H^\pm_1$ and $\delta^\pm$. Flavor constraints require the neutral component of the bidoublet field $\phi^0_2$ mass to be heavier than 15 TeV, forcing its charged counterpart to be very heavy as well. So $\delta^\pm$ can primarily mix only with $H^\pm_1$ as $\phi^\pm_1$ is effectively decoupled owing to its large mass. We will consider two scenarios for our analysis. One where the lightest charged Higgs consists almost entirely of the charged singlet field $\delta^\pm$ and another where the lightest physical state is almost equal admixture of $\delta^\pm$ and $H^\pm_L$.

| Mass   | Composition                      |
|--------|----------------------------------|
| 473.32 | $0.002 \phi^+ + 0.999 \delta^+$ |
| 1000.7 | $0.002 \phi^+ + 0.999 \delta^+$ |
| 432.58 | $0.03 \phi^+ - 0.006 \phi^0_2 + 0.72 H^+_L + 0.69 \delta^+$ |
| 1000.9 | $0.03 \phi^+ - 0.006 \phi^0_2 + 0.76 H^+_L + 0.65 \delta^+$ |

TABLE I: Lightest charged Higgs boson $H^\pm_1$.

Experimental limits and Collider signature: In Table I we present a list of the various charged Higgs eigenstates considered in this study. We consider two cases with minimal or zero mixing (consisting entirely of $\delta^\pm$) and two with maximal or half mixing of $\delta^\pm$ with $H^\pm_L$. For these benchmark points we study the pair production of charged Higgs states and their decay to a final state of two opposite sign charged leptons and two neutrinos. The most recent experimental bound on this process is from the ALTAS search [8] of two opposite sign leptons and missing energy. They have put a bound of 500 GeV if the final state is coming from pair production of two sleptons. The production cross-section of the charged Higgs in our model is much lower and even a 430 GeV charged Higgs is safe from the LHC bounds. So the benchmark points we consider are allowed by the experimental observations.

2 For a set of loose cuts denoted by SF1 in [8], a production cross-section for $t^+ l^- E_T$ greater than 2 fb is ruled out while we only get 0.23 fb for $M_{H^\pm} = 450$ GeV with similar cuts.

The pair-production of the charged Higgs at LHC is through the s-channel process mediated by $\gamma$, $Z$ and $Z_R$ bosons resulting in a cross-section of a few femtobarns (fb) or less for the mass range considered here. In a lepton collider, there is an additional t-channel process mediated by the neutrinos as shown in Fig. 2. Owing to the large couplings of the charged singlet with the right-handed leptons and the small masses of the right-handed neutrinos in this model, this t-channel process will be the major production channel. We have thus studied the pair production of the charged Higgs at 1 TeV run of the International Linear Collider (ILC) [9] and 3 TeV run by Compact Linear Collider (CLIC) [10]. We include the relevant vertices in FeynRules [11], and use MadGraph[12] for event generation, Pythia[13] for hadronization, and DelPhes[14] for detector simulation. Fig. 3 gives a plot of the pair-production cross-section of the charged singlet Higgs as a function of its mass for four different center-of-mass energies (c.m.energies) at the lepton colliders. The cross-section varies between 0.1-10 pb, for higher c.m.energies. For illustrative purpose, here we consider zero mixing of the singlet scalar and $\lambda_{Rij} \sim 1$. In our analysis, we however consider both the scenarios with and without mixing for four sets of model parameters consistent with neutrino data.

The charged Higgs, once produced, will then decay into a charged lepton and a right-handed neutrino giving a final state of dileptons with opposite charge ($l^+$ and $l^-$) and missing transverse energy (MET). Even the case where the charged Higgs is a mixture of $\delta^\pm$ and $H^\pm_L$, this is the only kinematically allowed 2-body decay channel with its branching into 3-body decays being almost negligible. This is because $H_L$ does not couple to the quarks or leptons and its other physical states (the charged state with $H^\pm_L$ and $\delta^\pm$ orthogonal to the one considered here and the CP-odd and CP-even neutral states coming from $H^0_1$) are much heavier. Schematically, the signal looks like

$$ e^+ e^- \to H^+_1 H^-_1 \to l^+ l^- E_T + X, \quad (10) $$

where $l^\pm$ is either one of $e^\pm$, $\mu^\pm$ and $\tau^\pm$ or a combination of them, and we consider inclusive dilepton+missing energy signature. Inside the detector
τ lepton will decay leptonically or hadronically and a small portion of it will give opposite sign dilepton increasing the signal strength. As τ decays, eventually we get a final state signal which consist of opposite sign electron (e±) or muon (μ±) or di-jet.

For the chosen final state, the dominant SM backgrounds are $e^+e^- \rightarrow l^+l^-Z \rightarrow \nu_l\bar{\nu}_l$ (including both the ZZ and virtual photon contributions), $e^+e^- \rightarrow W^+W^- \rightarrow l^+l^-\nu_l\bar{\nu}_l$, and $e^+e^- \rightarrow t\rightarrow b\ell^+\nu_l\bar{\nu}_l \rightarrow b\ell^-\nu_l$. We do not put any veto on the light jet in our analysis. Various kinematic variables have a clear distinction between signal and the backgrounds, that motivates to implement the following set of cuts.

A0 $p_{T,\ell}^{min} > 10$ GeV and the pseudo-rapidity $|y_\ell| < 2.5$ while generating partonic events.

A1 We select only events which contains two opposite sign lepton.

A2 We use cuts on the $p_T$ of the hardest lepton $p_T^{l_1} > 130$ GeV and relatively softer cut on the second lepton $p_T^{l_2} > 60$ GeV.

A3 To reject background, we implement Z-veto, i.e., we veto events in the di-lepton invariant mass ($m_{ll}$) window with $|m_{ll} - 91.2| < 10$ GeV.

A4 The background ($t\bar{t}$) contains b-jets in the final state. However, the signal doesn’t have any b-jets. Therefore we have used b-veto in the final state to reduce the background without affecting the signal.

A5 We use relatively tight cut on pseudo-rapidity of the leading lepton $|y^{l_1}| > 1$.

A6 To reduce the background we use cut on the missing energy $E_T > 80$ GeV.

Using these cuts we can reduce the background markedly while keeping the signal at a significant level. Table II gives the background cross-section at 1 TeV ILC and 3 TeV CLIC experiments after putting the above-mentioned cuts. It is easy to see that the backgrounds have become quite small ($\sigma \sim 1 - 8$ fb) and in both cases the dominant one arising from $W^+W^-$ final state.

The signal cross-sections ($\sigma \sim 5 - 53$ fb after cut) and their statistical significance ($S$) over the background are given in Tab. III. The later has been computed using the following expression,

$$ S = \sqrt{2 \times \left[(s + b)\ln(1 + \frac{s}{b}) - s\right]}.$$  \hspace{1cm} (11)

Clearly the case with no mixing in the Higgs state gives a much larger cross-section, that results in a much better significance of signal over background boosting its chances to be discovered even in the early run of the upcoming lepton colliders operating with higher c.m. energy. This is because $\delta^2 l^2R^2$ vertex is primarily responsible for the charged Higgs pair-production. The mixing of $\delta^2$ with $H_3^\pm$ will only introduce an extra factor of $\cos^2\theta$, where $\theta$ is the scalar mixing angle, resulting in a decrease of the cross-section. In particular, we show that only 1 fb$^{-1}$ luminosity is required for zero-mixing to discover the charged Higgs $H_3^\pm$ with mass range 473 GeV - 1 TeV. For the relatively less optimistic scenario of half-mixing, 3 fb$^{-1}$ will be required to claim discovery.

| Channels | SM Backgrounds | Cross-section (fb) | Effective Cross section after applying cuts (fb) |
|----------|----------------|-------------------|-----------------------------------------------|
| $l^+l^-Z \rightarrow \nu_l\bar{\nu}_l$ | 18.68 | 10.79 5.99 5.54 | 5.54 2.30 1.67 |
| $W^+(\rightarrow l^+\nu_l)W^-\rightarrow l^-\nu_l$ | 126.88 | 52.72 32.15 32.15 | 32.15 12.44 7.05 |
| $t\rightarrow b\ell^+\nu_l\bar{\nu}_l \rightarrow b\ell^-\nu_l$ | 13.96 | 3.10 0.78 0.78 | 0.1 0.68 0.05 |
| Total Backgrounds | | | 8.77 |
| $l^+l^-Z \rightarrow \nu_l\bar{\nu}_l$ | 6.33 | 3.0 2.89 2.86 | 2.86 0.54 0.44 |
| $W^+(\rightarrow l^+\nu_l)W^-\rightarrow l^-\nu_l$ | 13.85 | 5.45 5.1 | 5.1 1.34 1.13 |
| $t\rightarrow b\ell^+\nu_l\bar{\nu}_l \rightarrow b\ell^-\nu_l$ | 1.76 | 0.05 0.02 0.02 | 0.005 0.002 0.002 |
| Total Backgrounds | | | 1.57 |

**TABLE II:** Cut-flow table for the obtained cross-sections corresponding to the SM backgrounds.

**Conclusion:** In this work, we have studied a left-right symmetric extension of Zee model that has quite unique characteristics. The model consists of light right–handed neutrinos of mass from MeV down to eV scale, and an additional charged scalar that can be copiously produced at lepton colliders. The light neutrino mass is generated via a combination of loop-induced processes and seesaw mechanism. We fit the neutrino masses and the observed mixing in this model, and extensively analyse the charged Higgs phenomenology at 1 TeV ILC and 3 TeV CLIC experiments. Owing to the extra interaction of the charged Higgs with the right–handed neutrinos and for moderately large Yukawas, the cross-section at $e^+e^-$ collider is enormous compared to the LHC. We show that discovery of the charged Higgs with mass between 432–1000 GeV in the di-lepton...
| Experiment | Collider | Effective Cross section after cuts (fb) | Stat Significance ($\mathcal{L}$) |
|------------|----------|----------------------------------------|---------------------------------|
| 1 TeV ILC  |          |                                        |                                 |
|            |          | A0+A1                                  | 11.73                           |
|            |          | A2                                     | 20.32                           |
|            |          | A3                                     | 53.63                           |
|            |          | A4                                     | 110.70                          |
|            |          | A5                                     | 62.02                           |
|            |          | A6                                     | 4.99                            |
| 3 TeV CLIC |          |                                        |                                 |
|            |          | L = 1 fb $^{-1}$                       | 10.78                           |
|            |          | L = 3 fb $^{-1}$                       | 18.67                           |

TABLE III: Cut-flow table of signal cross section at 1 TeV ILC and 3 TeV CLIC.

+ MET will require only 1-3 fb $^{-1}$ integrated luminosity. Therefore, this model can most economically be tested at the very early run of CLIC or ILC experiments at higher c.m. energies.

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