Higgs Phenomenology of Minimal Left-Right Symmetric Model and Neutrinos Masses in Beyond Standard Models

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Certificate of Examination

This is to certify that the dissertation titled **"Higgs Phenomenology of Minimal Left-Right Symmetric Model and Neutrinos Masses in Beyond Standard Models"** submitted by **Mr. Manvendra Singh** (Reg. No. MS11044) for the partial fulfilment of BS-MS dual degree programme of the Institute, has been examined by the thesis committee duly appointed by the Institute. The committee finds the work done by the candidate satisfactory and recommends the report be accepted.

Professor C.S. Aulakh	Dr. H.K. Jassal	Dr. Manimala Mitra (Supervisor)

Dated: April 22, 2016

Declaration

The work presented in this dissertation has been carried out by me under the guidance of Dr. Manimala Mitra at the Indian Institute of Science Education and Research Mohali.

This work has not been submitted in part or in full for a degree, a diploma, or a fellowship to any other university or institute. Whenever contributions of others are involved every effort is made to indicate this clearly with due acknowledgement of collaborative research and discussions. This thesis is a bonafide record of original work done by me and all sources listed within have been detailed in the bibliography.

Manvendra Singh
(Candidate)
Dated: April 22, 2016

In my capacity as the supervisor of the candidate's project work, I certify that the above statements by the candidate are true to the best of my knowledge.

Dr. Manimala Mitra
(Supervisor)

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Manvendra Singh

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Abstract

Standard Model has been very successfull theory in explaining subatomic phenomena. The existence of building blocks of universe such as quarks, leptons (Fermions) and bosons and laws they follow has been understood very well under the Standard Model. But some major shortcomings is integral part of the Standard Model i.e., (a) It does not consider Gravity, it unifies only electromagnetic force, weak force and includes also strong force, (b) It does not explain the existence of dark matter and dark energy, (c) It does not explain the fact Neutrinos change Flavor which is best explained by the fact that Neutrinos have non-zero mass. So we need Physics Beyond the Standard Model to explain such facts of nature. With this motivation, in this final year research thesis project I study B-L Model and Minimal Left-Right Symmetric Model(MLRSM) which explain the fact that Neutrinos are massive through 'See-saw Mechanism'. I explore the gauge sector and Higgs sector of MLRSM. The main focus of my project is on the Higgs Phenomenology of the MLRSM.

We study the production of Doubly Charged Higgs at 14 TeV at LHC using MadGraph5 and FeynRules-2.3.3. Further, We study different-2 decay channels of Doubly Charged Higgs(dilepton Channel, double W-boson Channel etc.) and Singly Charged Higgs decay channels using MadGraph5.

Contents

Chapter 1

Introduction

Standard Model has been very successfull theory in explaining subatomic phenomena. The existence of building blocks of universe such as quarks, leptons(Fermions) and bosons and fundamental laws they follow has been understood very well under Standard Model. But there are some major shortcoming is integral part of the Standard Model i.e.

- Standard Model(SM) does not consider gravity, it unifies electromagnetic force, weak force and includes also strong force. The Guage symmetry group of SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$. Eletro-Weak theory is based on the gauge symmetry group $SU(2)_L \times U(1)_Y$ of left-handed isospin and hypercharge. The Quantum Chromo-Dynamics (QCD) is based on the symmetry group $SU(3)_C$. These two theories combined construct Standard Model of Particle Physics which has been consistent in explaining almost all experiments done at all the particle detectors such as LHC, Fermilab etc.
- It does not explain the existence of dark matter and dark energy. From Cosmological observation, we know that universe is made of only 4 percent of visible matter, 25 percent of DarK matter(No known interaction with visual matter, only interact gravitationally) and 71 percent of Dark Energy.
- The SM Higgs is not stable under radiative corrections.
- There is no right handed neutrino in SM and no Dirac mass term for neutrinos in SM. It can not explain flavor change of neutrinos (given by PMNS matrix),

flavor change of neutrinos is best explained by the fact that neutrinos have non-zero mass.

The probability that neutrino changes flavor is (considering only two generations):-

$$|\nu_\alpha\rangle = \Sigma_i U^*_{\alpha i}|\nu_i\rangle, \quad |\nu_i\rangle = \Sigma_\alpha U_{\alpha i}|\nu_\alpha\rangle$$

here $|\nu_\alpha\rangle$ are flavor states and $|\nu_i\rangle$ are mass eigenstates (with $\alpha, i = 1, 2$).U is the PMNS lepton mixing matrix given by :-

$$U = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix}$$

Then, the probability,

$$P_{\alpha\to\beta,\alpha\neq\beta} = sin^2(2\theta)sin^2\left(\frac{\Delta m^2 L}{4E}\right), (in\ natural\ units) \tag{1.1}$$

Where Δm^2 is the mass square difference of 1st and 2nd generation neutrinos masses(in the mass eigenstates) and θ is the mixing angle of lepton mixing matrix.

Due to all these inconsitencies of Standard Model, we need Physics Beyond the Standard Model to explain such facts of nature. There are two approaches to achieve this goal, one is 'Top to Bottom approaches', for e.g. Grand Unified theories(GUTs), Qunatum Gravity etc. Other is 'Bottom to Top approaches'. Good Candidates in the second approaches are 'B-L Model' and 'Left-Right Symmetric models' which explain neutrino mass generation through 'See-saw mechanism' and consider the existence of Right handed neutrinos.

1.0.1 B-L Model

The conservation of lepton number(L) and baryon number(B) in Standard Model is global symmetry at tree level only, not at loop level or quantum level. As we know that $B-L$ is the global symmetry of Standard model both at classical and quantum level. In $B-L$ model, this global symmetry is gauged to become local symmetry and thus gauge group of standard model is extended to get a new model, $B-L$ model:-

$$SU(3)_C \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}.$$

This model is minimal in gauge sector (adds one extra neutral gauge boson), fermion(adds one new right-handed heavy neutrino per generation) and scalar sector(adds one new neutral complex Higgs, singlet under SM gauge group, has only B-L charge to break the B-L symmetry).
B-L symmetry breaking takes place at the TeV or even higher energy scale and gives masses to new gauge boson and right handed neutrino.
The Quantum consistency(anomaly cancellation) of the theory is satisfied by extending the fermion content with the right handed neutrino (singlet under SM group) for each generation.
This simple extention of SM satisfy the phenomenological requirement of having a renormalisable theory that provides a mechanism for giving mass to light Neutrinos as well as a good candidate for Dark matter in the form of heavy Right-handed Neutrinos. Apart from this, it is important to notice that $B-L$ symmetry breaking takes place at the TeV energy scale or even higher energy scale and leave the open possibility of being part of the Grand Unified Theories and giving rise to new and interesting TeV scale phenomenology.

1.0.2 Left-Right Symmetric Models

Left-right symmetric model(LRSM) provide an interesting extension of the standard model(SM). Left-right symmetric models are extensions of the Standard Model (SM) based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Parity is the exact symmetry of this model and right-handed fermions are the $SU(2)_R$ doublets. $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$ is broken spontaneously to SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ by the non-zero VEV of v_R.
This model consists the full quark-lepton symmetry of the weak interactions. LRSM give the U(1) generator of the electroweak symmetry group a definite meaning in terms of the B-L quantum number. Hypercharge Y, an assigned quantum number in the SM model, is defined in LRSM with the combination $Y = T_{3,R} + (B-L)/2$, where $T_{3,R}$ is the third component of the right-handed isospin. Finally, for appropriately chosen Higgs fields (left and right Triplet Higgs fields and a Bidoublet Higgs field), this model leads to a natural explanation of the smallness of neutrino masses, by relating to the observed suppression of $V + A$ currents. This model contains two W

bosons W_L and W_R and two neutral gauge bosons Z_1 and Z_2. The W_L and Z_1 are those already discovered and contained in standard model. In the Fermion sector, LRSM contains the usual SM quarks and charged leptons, along with three light neutrino mass eigenstates $\nu_k(k = 1, 2, 3)$ and three heavy neutrino mass eigenstates $N_K(k = 1, 2, 3)$. Light neutrinos(ν_k) mostly couple to the W_L(standard model's gauge boson), while the heavy neutrino(N_K) mainly couple to W_R.

Chapter 2

B-L Model

2.1 Introduction

The conservation of lepton number and baryon number in Standard Model is accidental symmetry(global symmetry) at tree level only, not at loop level. Chiral anomalies violate this conservation law such that the current associated with baryon and lepton number has non-zero divergences:

$$\partial_\mu J_\mu^{B,L} = cG_{\mu\nu}\tilde{G^{\mu\nu}} \neq 0. \tag{2.1}$$

Here, $G_{\mu\nu}$ is the electroweak field strength and $J_\mu^B = \Sigma\bar{q}_i\gamma_\mu q_i, J_\mu^L = \Sigma\bar{l_i}\gamma_\mu l_i$. We know that $B-L$ is the global symmetry of Standard model both at classical and quantum level. In $B-L$ model, this global symmetry is gauged to become local symmetry and thus gauge group of the SM is extended to get a new model, $B-L$ model.

2.2 Gauge Group and Representation

Gauge group of $B-L$ model is:-

$$G_{B-L} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \tag{2.2}$$

The Lagrangian of $B-L$ model is invariant under this gauge group. Some key features of Minimal '$B-L$' model with respect to the standard model, are:-

- It is minimal in gauge sector, adds one extra neutral gauge boson corresponding to extra $U(1)_{B-L}$ part of the gauge group.

- It is minimal in fermion sector, adds one new right handed heavy neutrino per generation, because the quantum consistency(anomaly cancellation) of the theory is satisfied by extending the fermion content with the right handed neutrino(which is singlet under SM gauge group) for each generation.
- It is also minimal in scalar sector, adds one new neutral complex higgs, which is singlet under standard model gauge group and has only $B-L$ charge to break the $B-L$ gauge symmetry.
- The $B-L$ gauge symmetry breaking takes place the TeV scale or even higher scale and gives masses to the new gauge boson and the right handed neutrinos.

2.3 Lagrangian

Total Lagrangian of this model is :-

$$L_{B-L} = L_{YM} + L_f + L_Y + L_S \tag{2.3}$$

where L_{YM} is Yang-Mills part, L_f is fermionic part, L_Y is Yukawa part and L_S is scalar/Higgs part of the Lagrangian.

2.3.1 The Yang-mills sector

As in the Standard model, gauge fields are uniquely determined by the choice of the gauge group and by the transformation in their adjoint representation.

$$L_{YM} = -\frac{1}{4}(G_{\mu\nu})_\alpha (G^{\mu\nu})^\alpha - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} \tag{2.4}$$

where,

$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad F'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$$

$$G^\alpha_{\mu\nu} = \partial_\mu A^\alpha_\nu - \partial_\nu A^\alpha_\mu + g f^{\alpha\beta\gamma} A^\beta_\mu A^\gamma_\nu, \quad (\alpha, \beta, \gamma = 1, 2...8)$$

$$W^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu, \quad (a, b, c = 1..3)$$

here, B_ν and B'_ν are gauge fields associated with $U(1)_Y$ and $U(1)_{B-L}$. A^α_μ are 8 gluons corresponding to $SU(3)_C$ generators and A^α_μ are 3 gauge bosons corresponding to $SU(2)_L$ generators.

2.3.2 Fermion Sector

Fermion sector is the same as in the standard model, except the addition of RH neutrino ν_R (singlet under SM gauge group) for each generation of leptons. This addition is essential for anomaly cancellation and preserving gauge invariance.The covariant derivative is given by:-

$$D_\mu = \partial_\mu + ig_s T^\alpha G^\alpha_\mu + ig\tau^\alpha W^a_\mu + ig_1 Y B_\mu + ig'_1 Y_{B-L} B'_\mu \tag{2.5}$$

And fermionic Lagrangian,

$$L_F = i\bar{q}_{kL}\gamma^\mu D_\mu q_{kL} + i\bar{u}_{kR}\gamma^\mu D_\mu u_{kR} + i\bar{d}_{kR}\gamma^\mu D_\mu q_{kR} + i\bar{l}_{kL}\gamma^\mu D_\mu l_{kL} + i\bar{e}_{kR}\gamma^\mu D_\mu e_{kR} + i\bar{\nu}_{kR}\gamma^\mu D_\mu \nu_{kR} \tag{2.6}$$

Where charges of the fields are usual standard model ones plus the $B-L$ charge, such that, $Y_{B-L} = \frac{1}{3}$ for all quarks and $Y_{B-L} = -1$ for all leptons.

Representations of fermion fields:

$$Quarks: \quad q_{kL} = (2, \frac{1}{6}, \frac{1}{3}), \quad u_{kR} = (1, \frac{2}{3}, \frac{1}{3}), \quad d_{kR} = (1, -\frac{1}{3}, \frac{1}{3})$$

$$Leptons: \quad l_{kL} = (2, -\frac{1}{2}, -1), \quad e_{kR} = (1, -1, -1), \quad \nu_{kR} = (1, 0, -1)$$

2.3.3 Scalar Sector

The choice is essential to preserve the gauge invariance of the model. Here,the $B-L$ charge of the two scalar fields:-

$$Y^H_{B-L} = 0 \quad ; \quad Y^\chi_{B-L} = +2$$

Then the most general and gauge invariant scalar Lagrangian is given by:-

$$L_S = D^\mu H^\dagger D_\mu H + D^\mu \chi^\dagger D_\mu \chi - V(H, \chi) \tag{2.7}$$

With the scalar potential :-

$$V(H,\chi) = -m^2 H^\dagger H - \mu^2|\chi|^2 + (H^\dagger H \quad |\chi|^2)\begin{pmatrix} \lambda_1 & \frac{\lambda_3}{2} \\ \frac{\lambda_3}{2} & \lambda_2 \end{pmatrix}\begin{pmatrix} H^\dagger H \\ |\chi|^2 \end{pmatrix}$$

$$= -m^2 H^\dagger H - \mu^2|\chi|^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 |\chi|^4 + \lambda_3 H^\dagger H |\chi|^2 \tag{2.8}$$

Here, all the parameters are taken positive and λ's are dimension-less and m and μ have mass dimension.

2.3.4 Yukawa Sector

In this model, we have two new types of Yukawa interactions involving right-handed neutrinos. Yakawa part of the Lagrangian is given by:-

$$L_Y = -y^d_{jk}\bar{q}_{Lj}Hd_{Rk} - y^u_{jk}\bar{q}_{Lj}\tilde{H}u_{Rk} - y^e_{jk}\bar{l}_{Lj}He_{Rk} - y^\nu_{jk}\bar{l}_{Lj}\tilde{H}\nu_{Rk} - y^M_{jk}(\bar{\nu^c}_R)_j\nu_{Rk}\chi + h.c. \tag{2.9}$$

Higgs particles Representation:

$$H = (2, \frac{1}{2}, 0) \quad ; \quad \chi = (1, 1, 2)$$

One can check that every term in the L_Y has zero charge under the whole gauge group. In other words that L_Y is constructed in a way that it is singlet under the gauge group.

Here, notice that Yukawa interaction can generate both Dirac type and Majorana type mass terms for the Right handed neutrinos, [Pruna 11], which is responsible for the 'see-saw mechanism' for giving masses to the neutrinos such that 3 neutrinos have light masses and other 3 neutrinos have heavy masses, will be discussed in next section.

2.4 Spontaneous Symmetry Breaking $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

We generalise the SM discussion of spontaneous Electro-weak symmetry breaking(EWSB) to the more complicated case represented by the potential of Eqn(2.8). To determine the condition for $V(H, \chi)$ to be bounded from below, the matrix in Eqn(2.8) has to be positive-definite which gives the conditions :-

$$4\lambda_1\lambda_2 - \lambda_3^2 > 0, \tag{2.10}$$

and,

$$\lambda_1,\ \lambda_2 > 0. \tag{2.11}$$

If the above conditions are satisfied, the choice of parameters is consistent with a well- defined potential, hence we can proceed to the minimisation of V as a function of constant Vacuum Expectation Values (VEVs) for the two Higgs fields. Now, we make the particular choice of gauge, since minimization is not affected by the gauge choice :-

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \quad , \quad \langle \chi \rangle = \frac{x}{\sqrt{2}} \tag{2.12}$$

Where, v and x are real and non-negative. Now, when we put these VEVs in the potential, Eqn(2.8), and take first derivative of $V(v,x)$ with respect to v and x, we get the set of differential equations :-

$$\frac{\partial V}{\partial v}(v,x) = v(m^2\lambda_1 v^2 + \frac{\lambda_3^2 x^2}{2}) = 0 \tag{2.13}$$

$$\frac{\partial V}{\partial x}(v,x) = x(\mu^2\lambda_2 x^2 + \frac{\lambda_3^2 v^2}{2}) = 0 \tag{2.14}$$

The physically allowed solutions are for the case v, $x > 0$:-

$$v^2 = \frac{-\lambda_2 m^2 + \frac{\lambda_3^2\mu^2}{2}}{\lambda_1\lambda_2 - \frac{\lambda_3^2\mu^2}{4}} \tag{2.15}$$

$$x^2 = \frac{-\lambda_1 \mu^2 + \frac{\lambda_3^2 m^2}{2}}{\lambda_1\lambda_2 - \frac{\lambda_3^2\mu^2}{4}} \tag{2.16}$$

The denominator is positive, Eqn(2.10), then numerator is forced to be positive or non-negative too, since the VEVs(v, x) are real and non-negative.

2.5 See-saw Mechanism and Neutrino Masses

The minimal $B - L$ model provides a nice solution to generate neutrino masses.The presence of right-handed neutrinos and Majorana mass terms in the Yukawa Lagrangian (Eqn(2.9)) gives raise to the so-called 'see-saw' mechanism.

After the spontaneously broken of gauge Symmetry, we put the VEVs of the Higgs fileds in Yukawa part of the Lagrangian, Eqn(2.9), we get the mass matrix for the three Dirac and six Majorana mass eigenstates, [Pruna 11] :-

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_m \end{pmatrix} \tag{2.17}$$

Where m_D and M_m are respectively the Dirac and Majorana mass matrices, defined by :-

$$m_D = \frac{(y^\nu)^*}{\sqrt{2}}v, \qquad M_m = \sqrt{2}y^M x \tag{2.18}$$

Once the hierarchy $\Lambda_D << \Lambda_M$(Λ is energy scale) is assumed to be true, the diagonalization of the mass matrix gives us the 'see-saw' results for the neutrinos masses. After this diagonalization, we get three light Majorana neutrinos and three heavy neutrinos, whose 3×3 mass matrces(M_l and M_h respectively) are given by :-

$$M_l = m_D M^{-1} m_D^T \simeq \frac{1}{2\sqrt{2}} y^\nu (y^M)^{-1} (y^\nu)^T \frac{v^2}{x} \tag{2.19}$$

$$M_h \simeq M_m = \sqrt{2} y^M x \tag{2.20}$$

From these equation see the 'See-saw' effect in the sense that, the greater is M, the smaller is M_l.

Chapter 3

Minimal Left-Right Symmetric Model (MLRSM)

3.1 Introduction

Left-right symmetric model(LRSM) provide an interesting extension of the standard model(SM). In this model, the parity is considered as exact symmetry of the Lagrangian and it is broken spontaneously when Higgs fields get non-zero VEV. This model consists the full quark-lepton symmetry of the weak interactions and give the U(1) generator of the electroweak symmetry group a definite meaning in terms of the B-L quantum number. Finally, for appropriately chosen Higgs fields this model leads to a natural explanation of the smallness of neutrino masses, by relating to the observed suppression of $V + A$ currents.This model contains two W bosons W_L and W_R and two neutral gauge bosons Z_1 and Z_2. The W_L and Z_1 are those already discovered and contained in standard model. In the Fermion sector, LRSM contains the usual quarks and charged leptons, along with the three light neutrino mass eigenstates $\nu_k(k = 1, 2, 3)$ and three heavy neutrino mass eigenstates $N_K(k = 1, 2, 3)$. Light neutrinos(ν_k) mostly couple to the W_L(standard model's gauge boson), while the heavy neutrino(N_K) mainly couple to W_R.

3.2 Gauge Group and Representation

The Lagrangian of LRSM is invariant under the gauge-group:-

$$G = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \tag{3.1}$$

The representation of G is characterized by triplet(d_C, d_L, d_R, Y), where d_L, d_R denote the dimension of $SU(2)_L$ and $SU(2)_R$, respectively and Y is the Hypercharge. Relation between Electric charge and $B-L$ hypercharge is given by:-

$$Q = T_{3L} + T_{3R} + \frac{Y}{2} \tag{3.2}$$

Here we have $Y = B - L$.

3.2.1 Fermion Doublet and Higgs Fields of MLRSM

$$Quarks :: Q_L(3, 2, 1, \frac{1}{3}), Q_R(3, 1, 2, \frac{1}{3}) \tag{3.3}$$

$$Leptons :: \Psi_L(1, 2, 1, -1), \Psi_R(1, 1, 2, -1) \tag{3.4}$$

And,

$$\psi_L^j = \begin{pmatrix} \nu_j \\ e_j \end{pmatrix}_L, \psi_R^j = \begin{pmatrix} \nu_j \\ e_j \end{pmatrix}_R ; j = e, \mu, \tau$$

Their antiparticles are given by:-

$$\hat{\psi_R} = \gamma_0 C \epsilon \psi_L^* : (1, 2, 1, 1) \tag{3.5}$$

$$\hat{\psi_L} = \gamma_0 C \epsilon \psi_R^* : (1, 1, 2, 1) \tag{3.6}$$

Where $\epsilon = i\tau_2$ with τ's are Pauli matrices and $C = i\gamma^2\gamma^0$ is the charge conjugation matrix. Now we can obtain fermion bilinears which have net (B-L) quantum number :-

$$\bar{\psi_L}\hat{\psi_R} \quad or \quad \psi_L^T C^{-1} \psi_L \sim (2, 1, 1) \bigotimes (2, 1, 1) = (1, 1, 2) \bigoplus (3, 1, 2)$$

$$\bar{\psi_R}\hat{\psi_L} \quad or \quad \psi_R^T C^{-1} \psi_R \sim (1, 2, 1) \bigotimes (1, 2, 1) = (1, 1, 2) \bigoplus (1, 3, 2)$$

These bilinears will construct Majorana type mass terms in Yukawa part of the Lagrangian.

$$\bar{\psi_L}\psi_R \sim (2, 1, 1) \bigotimes (1, 2, -1) = (2, 2, 0)$$

This bilinear will construct Dirac type mass terms in Yukawa part of the Lagrangian. To make these fermionic bilinears singlet of our gauge group 'G', we introduce three kind of **Higgs Fields**:-

$$\Phi(2,2,0), \quad \Delta_L(3,1,2), \quad \Delta_R(1,3,2) \tag{3.7}$$

with the representation as :-

$$\Delta_{L,R} = \begin{pmatrix} \frac{\delta^+_{L,R}}{\sqrt{2}} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\frac{\delta^+_{L,R}}{\sqrt{2}} \end{pmatrix}; \quad \phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix}$$

Electric Charges(Q) on the matrix components of the Higgs fields(Bidoublet, Left and Right Triplet Higgs Fields) can found by:-

$$Q_\phi = [T_{3L} + T_{3R},\ \phi], \quad Q_{\Delta_L} = [T_{3L} + \frac{Y}{2},\ \Delta_L], \quad Q_{\Delta_R} = [T_{3R} + \frac{Y}{2},\ \Delta_R]$$

Under the gauge transformations, the **Higgs Fields transformation** is given as :-

$$\phi \longrightarrow U_L \phi U_R^{-1}, \quad \tilde{\phi} \longrightarrow U_L \tilde{\phi} U_R^{-1}, \quad \Delta_L \longrightarrow U_L \Delta_L U_L^{-1}, \quad \Delta_R \longrightarrow U_R \Delta_R U_R^{-1} \tag{3.8}$$

Where $U_{L,R} = e^{-i\epsilon_\alpha \frac{\tau_\alpha}{2}}$ and $U^{-1}_{L,R} = e^{i\epsilon_\alpha \frac{\tau_\alpha}{2}}$.

So that 'Covariant Derivatives' are given by :-

$$D_\mu \phi = \partial_\mu \phi - i(g_L \frac{1}{2}\tau_\alpha W^\alpha_{\mu,L}\phi - g_R \phi \frac{1}{2}\tau_\alpha W^\alpha_{\mu,R}) \tag{3.9}$$

$$D_\mu \Delta_L = \partial_\mu \Delta_L - i\frac{1}{2} g_1 Y_\Delta B_\mu \Delta_L - i g_L (\frac{1}{2}\tau_\alpha W^\alpha_{\mu,L}\Delta_L - \Delta_L \frac{1}{2}\tau_\alpha W^\alpha_{\mu,L}) \tag{3.10}$$

$$D_\mu \Delta_R = \partial_\mu \Delta_R - i\frac{1}{2} g_1 Y_\Delta B_\mu \Delta_R - i g_R (\frac{1}{2}\tau_\alpha W^\alpha_{\mu,R}\Delta_R - \Delta_R \frac{1}{2}\tau_\alpha W^\alpha_{\mu,R}) \tag{3.11}$$

Where $Y_\phi = 0$, $Y_\Delta = +2$, and $Y_F = -1$.

3.3 Largrangian Of MLRSM

We consider only the leptonic part of the Lagrangian(similart part will be for the quarks), which will be necessary for the calculations for the Neutrino's masses('See-saw Mechanism') and calculations of Gauge Boson's masses.

So, let's consider only the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ part of our gauge group 'G':-

$$L = L_F + L_Y + L_B \tag{3.12}$$

With the kinetic part Fermions:-

$$L_F = i\bar{\psi}_L^j\gamma^\mu(\partial_\mu - i\frac{1}{2}g_1 Y_F B_\mu - ig_L\frac{1}{2}\tau_\alpha(W_\mu^\alpha)_L)\psi_L^j + i\bar{\psi}_R^j\gamma^\mu(\partial_\mu - i\frac{1}{2}g_1 Y_F B_\mu - ig_R\frac{1}{2}\tau_\alpha(W_\mu^\alpha)_R)\psi_R^j \tag{3.13}$$

And Yukawa Part given as:-

$$L_Y = -\bar{\psi}_L^i(f_{ij}\phi + \tilde{f}_{ij}\tilde{\phi})\psi_R^j + h.c. - \psi_L^{Ti}Ci\tau_2 h_{ij}^L\Delta_L\psi_L^j + h.c. - \psi_R^{Ti}Ci\tau_2 h_{ij}^R\Delta_R\psi_R^j + h.c. \tag{3.14}$$

Bosonic and Scalar part:-

$$L_B = Tr|D_\mu\Delta_L|^2 + Tr|D_\mu\Delta_R|^2 + Tr|D_\mu\phi|^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}(G_{\mu\nu})_\alpha(G^{\mu\nu})^\alpha - V(\phi, \Delta_L, \Delta_R) \tag{3.15}$$

Where α runs from 1 to 3, is a $SU(2)_{L,R}$ index and V is the Higgs potential of ϕ, Δ_L and Δ_R . Here, the **notation** is as follow:-

$$\psi_L^j = \begin{pmatrix} \nu_j \\ e_j \end{pmatrix}_L, \psi_R^j = \begin{pmatrix} \nu_j \\ e_j \end{pmatrix}_R ; j = e, \mu, \tau$$

And $\tilde{\phi} = \tau_2\phi^*\tau_2$. We also have $\bar{\psi_L^c} = (\frac{1-\gamma_5}{2}\psi^c)^\dagger\gamma^0 = \psi_R^T C$ and $\bar{\psi_R^c} = \psi_L^T C$, where $C = \iota\gamma^2\gamma^0$ is the Charge Conjugation matrix(and here we have used the property of this matric :- $C^{-1}\gamma_\mu C = -\gamma_\mu^T$).

3.3.1 Spontaneous symmetry breaking

Spontaneously broken gauge symmetry of the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is realized by 'Vacuum Expectation values (VEVS)' of the Higgs fields. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge group is broken to $SU(2)_L \times U(1)_Y$ due to non-zero vacuum expectation value of Δ_R, and further, $SU(2)_L \times U(1)_Y$ is broken to $U(1)_Q$ due to non-zero VEVs of Δ_L and ϕ .

VEVs of Higgs fields are given by :-

$$\langle\Delta_{L,R}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}; \quad \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}$$

With the **assumptions** :-

$$|v_L| << |k_{1,2}| << |v_R| \tag{3.16}$$

The minimization of Higgs potential leads to hierarchy between VEVs, v_L and v_R , will be discussed explicitly in section(3.7) :-

$$v_L = \gamma \frac{k_+^2}{v_R} \tag{3.17}$$

It is clear from this relation that If v_R has very large value than V_L will have very small value same as above stated assumption in Eqn(3.16).

3.4 Yukawa Part of The Lagrangian And Neutrino Masses

We put the VEVs of the Higgs Fields in the Yuawa part of the Lagrangian, Eqn(3.14), then we will get the lepton masses in terms of Yukawa couplings and the VEVs of Higgs fields :-

$$-L_Y = \bar{\psi}_L^i (f_{ij} \langle \phi \rangle + \tilde{f}_{ij} \langle \tilde{\phi} \rangle) \psi_R^j + h.c. + \psi_L^{Ti} C i \tau_2 h_{ij}^L \langle \Delta_L \rangle \psi_L^j + h.c. + \psi_R^{Ti} C i \tau_2 h_{ij}^R \langle \Delta_R \rangle \psi_R^j + h.c. \tag{3.18}$$

Now using the notation introduced in the section(3.2), we have:-

$$\begin{aligned} -L_Y = (\bar{\nu_L}^i \quad \bar{e_L}^i) \left(f_{ij} \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix} + \tilde{f}_{ij} \frac{1}{\sqrt{2}} \begin{pmatrix} k_2 & 0 \\ 0 & k_1 \end{pmatrix} \right) \begin{pmatrix} \nu_R^j \\ e_R^j \end{pmatrix} + h.c. \\ + (\bar{\nu_R^c}^i \quad \bar{e_R^c}^i) \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} h_{ij}^L \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix} \begin{pmatrix} \nu_L^j \\ e_L^j \end{pmatrix} + h.c. \\ + (\bar{\nu_L^c}^i \quad \bar{e_L^c}^i) \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} h_{ij}^R \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix} \begin{pmatrix} \nu_R^j \\ e_R^j \end{pmatrix} + h.c. \end{aligned}$$

After a little bit calculation, we get :-

$$-L_Y = \bar{\nu}_L^i (m_D)_{ij} \nu_R^j + \frac{1}{2} \bar{\nu_L^c}^i (m_L)_{ij} \nu_L^j + \frac{1}{2} \bar{\nu_R^c}^i (m_R)_{ij} \nu_R^j + \bar{e}_L^i (m'_D)_{ij} e_R^j + h.c. \tag{3.19}$$

Where,

$$(m_D)_{ij} = \frac{f_{ij} k_1 + \tilde{f}_{ij} k_2}{\sqrt{2}}, \quad (m_R)_{ij} = \sqrt{2} v_R h_{ij}^R$$

$$(m'_D)_{ij} = \frac{f_{ij} k_2 + \tilde{f}_{ij} k_1}{\sqrt{2}}, \quad (m_L)_{ij} = \sqrt{2} v_L h_{ij}^L$$

We need to take every parameter $(f_{ij}, \tilde{f}_{ij}, h^R_{ij}, h^L_{ij})$ real. We assume that m_D and m'_D take values of the order of leptonic masses m_l,

$$m_D \approx m'_D \approx m_l$$

By the use of Eqn(3.16) we have:-

$$|(m_L)_{ij}| << |(m_D)_{ij}| << |(m_R)_{ij}| \tag{3.20}$$

Furthermore, Considering Hermitian conjugate parts also, we get :-

$$L_Y = \bar{\nu} m_D N + \bar{N} m_D \nu + \bar{\nu} m_L \nu + \bar{N} m_R N$$

In another form :-

$$(L_Y)_{\nu,N} = (\bar{\nu} \quad \bar{N}) \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \tag{3.21}$$

where

$$\nu = \frac{\nu_L + (\nu_L)^C}{\sqrt{2}} = \frac{\nu_L + \nu_R^C}{\sqrt{2}}; \quad N = \frac{\nu_R + (\nu_R)^C}{\sqrt{2}} = \frac{\nu_R + \nu_L^C}{\sqrt{2}}$$

After diagonalizing the mass matrix, we have the 'See-saw' result for each ij :-

$$|m_{ail}| \simeq |\frac{(m_{Dij})^2}{m_{Rij}}|, and \quad |m_{bij}| \simeq |m_{Rij}| \tag{3.22}$$

With the eigenstates :-

$$\nu_{aj} \simeq \nu_j - \frac{m_{Dij}}{m_{Rij}} N_j, and \quad N_{bj} \simeq N_j + \frac{m_{Dij}}{m_{Rij}} \nu_j \tag{3.23}$$

Then the Eqn(3.20) can be re-written in these new mass-eigenstates as :-

$$L_Y = \bar{\nu_{ai}} m_{aij} \nu_{aj} + \bar{N_{bj}} m_{bij} N_{bj} \tag{3.24}$$

Here, each term is diagonal for the three generations; $i, j = 1, 2, 3$. Due to our assumption in Eqn(3.16), v_R is very heavy than v_L, so the mass of RH neutrino(N) is heavy and LH neutrino(ν) mass is small due to 'See-saw' suppression, as evident from the Eqn(3.22), [Kokado 15].

3.5 Masses of Charged Guage Boson

After the gauge symmetry is spontaneously broken due to VEVs of the Higgs fields $(\langle\phi\rangle, \langle\Delta_R\rangle, \langle\Delta_R\rangle)$, the trace part of the Bosonic Lagrangian(L_B) are as follow, [Kokado 15] :-

$$Tr|D_\mu\Delta_L|^2 = \frac{1}{2}\left(|g_L W^+_{\mu L}|^2 + (g_1 B_\mu - g_L W^3_{\mu L})^2\right) v_L^2 \tag{3.25}$$

$$Tr|D_\mu\Delta_R|^2 = \frac{1}{2}\left(|g_R W^+_{\mu R}|^2 + (g_1 B_\mu - g_R W^3_{\mu R})^2\right) v_R^2 \tag{3.26}$$

$$Tr|D_\mu\phi|^2 = \frac{1}{8}\left((g_L W^3_{\mu L} - g_R W^3_{\mu R})^2\right)(k_1^2 + k_2^2) + 2|k_1 g_L W^+_{\mu L} - k_2 g_R W^+_{\mu R}|^2 + 2|k_2 g_L W^+_{\mu L} - k_1 g_R W^+_{\mu R}|^2 \tag{3.27}$$

Where $W^{\pm}_{L,R} = \frac{(W^1 \mp \iota W^2)_{L,R}}{\sqrt{2}}$.

Calculation:

From the use of covariant derivatives as given in Eqns(3.9,3.10,3.11) and putting the higgs VEVs, we get :-

$$\langle\Delta_{L,R}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}; \quad \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}$$

In the bosonic part of the Lagrangian we get,

$$(L_{mass})_{\Delta_R} = tr|D_\mu\Delta_R|^2$$

$$= \frac{1}{2} tr\left[g_1 B_\mu \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} + g_R\left(\begin{pmatrix} \frac{W^3_\mu}{2} & \frac{W^+_\mu}{\sqrt{2}} \\ \frac{W^-_\mu}{\sqrt{2}} & -\frac{W^3_\mu}{2} \end{pmatrix}\begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} - \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}\begin{pmatrix} \frac{W^3_\mu}{2} & \frac{W^+_\mu}{\sqrt{2}} \\ \frac{W^-_\mu}{\sqrt{2}} & -\frac{W^3_\mu}{2} \end{pmatrix}\right)\right]$$

After doing the further calculation for the diagonal terms and leaving the off-diagonal terms(as they are not needed in trace calculation), we get :-

$$(L_{mass})_{\Delta_R} = \frac{1}{2}\begin{bmatrix} \frac{g_R^2 v_R^2 |W^+_{\mu,R}|^2}{2} & (...) \\ (...) & \frac{g_R^2 v_R^2 |W^+_{\mu,R}|^2 + (g_1 B_\mu - g_R W^3_{\mu,R})^2 v_R^2}{2} \end{bmatrix}$$

$$= \frac{1}{2}\left(g_R^2 |W^+_{\mu,R}|^2 + (g_1 B_\mu - g_R W^3_{\mu,R})^2\right) v_R^2 \tag{3.28}$$

By similar kind of calculations, for Δ_L and ϕ we get:-

$$(L_{mass})_{\Delta_L} = tr|D_\mu\Delta_L|^2 = \frac{1}{2}\left(g_L^2 |W^+_{\mu,L}|^2 + (g_1 B_\mu - g_L W^3_{\mu,L})^2\right) v_L^2 \tag{3.29}$$

And,

$$
\begin{aligned}
(L_{mass})_\phi &= tr|D_\mu \phi|^2 \\
&= \frac{1}{4}\left[|k_1 g_L W^+_{\mu,L} - k_2 g_R W^+_{\mu,R}|^2 + |k_2 g_L W^+_{\mu,L} - k_1 g_R W^+_{\mu,R}|^2\right] \\
&\qquad + \frac{1}{8}(g_L W^3_{\mu,L} - g_R W^3_{\mu,R})^2 (k_1^2 + k_2^2) \quad (3.30)
\end{aligned}
$$

Now, collecting the mass terms corresponding to the charged bosons($W^+_{\mu,R}$ and $W^+_{\mu,L}$) from equations(2.27,2.28,2.29) we get:-

$$
X = \frac{1}{2}|g_L W^+_{\mu,L}|^2 v_L^2 + \frac{1}{2}|g_R W^+_{\mu,R}|^2 v_R^2 + \frac{1}{4}|k_1 g_L W^+_{\mu,L} - k_2 g_R W^+_{\mu,R}|^2 + \frac{1}{4}|k_2 g_L W^+_{\mu,L} - k_1 g_R W^+_{\mu,R}|^2
$$

After squaring 3rd and 4th term and rearranging the all terms, we get :-

$$
\begin{aligned}
X = \frac{1}{2}|W^+_{\mu,L}|^2 \left(g_L^2 v_L^2 + \frac{1}{2}(k_1^2 + k_2^2) g_L^2\right) + \frac{1}{2}|W^+_{\mu,R}|^2 \left(g_R^2 v_R^2 + \frac{1}{2}(k_1^2 + k_2^2) g_R^2\right) \\
- \frac{1}{2} k_1 k_2 g_L g_R [W^+_{\mu,L} W^-_{\mu,R} + W^+_{\mu,R} W^-_{\mu,L}] \quad (3.31)
\end{aligned}
$$

In the matrix form (in $W_L - W_R$ basis) this relation can be written nicely :-

$$
M^2_{W^\pm} = \frac{1}{2}\begin{pmatrix} (v_L^2 + \frac{1}{2}(k_1^2 + k_2^2)) & -\frac{1}{2}k_1 k_2 g_L g_R \\ -\frac{1}{2}k_1 k_2 g_L g_R & g_R^2(v_R^2 + \frac{1}{2}(k_1^2 + k_2^2)) \end{pmatrix} \quad (3.32)
$$

Here, $M^2_{W^\pm}$ is the squared mass matrix of the charged gauge bosons(flavor states). It needs to be diagonalized to get mass eigenstates.

Now let's introducing the mass eigenstates$(W_\mu, W'_\mu)_{L,R}$:-

$$
\begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = U \begin{pmatrix} W^\pm \\ W'^\pm \end{pmatrix}, \quad U = \begin{pmatrix} cos\alpha & sin\alpha \\ -sin\alpha & cos\alpha \end{pmatrix}
$$

Putting this into equation(2.30), will turns out to be of the form :-

$$
X = |W|^2 M_W^2 + |W'|^2 M_{W'}^2 + (W^\dagger W' + W'^\dagger W)\lambda \quad (3.33)
$$

Where,

$$
M_W^2 = G_L U_{11}^2 + G_R U_{21}^2 - k_1 k_2 g_L g_R U_{11} U_{21}, \quad M_{W'}^2 = G_L U_{12}^2 + G_R U_{22}^2 - k_1 k_2 g_L g_R U_{12} U_{22}
$$

$$
\lambda = U_{11} U_{12} G_L + U_{21} U_{22} G_R - \frac{1}{2} k_1 k_2 g_L g_R (U_{12} U_{21} + U_{22} U_{11})
$$

Where U_{ij}'s are the matrix components of U and $G_L = \frac{1}{2}g_L^2 v_L^2 + \frac{1}{4}g_L^2(k_1^2+k_2^2)$,$G_R = \frac{1}{2}g_R^2 v_R^2 + \frac{1}{4}g_R^2(k_1^2+k_2^2)$. Now,*due to fact that W and W' are the mass eigenstates, the vanishing condition for the cross term is:-*

$$\lambda = U_{11}U_{12}G_L + U_{21}U_{22}G_R - \frac{1}{2}k_1k_2g_Lg_R(U_{12}U_{21}+U_{22}U_{11}) = 0.$$

$$\Rightarrow U_{11}U_{12}G_L + U_{21}U_{22}G_R = \frac{1}{2}k_1k_2g_Lg_R(U_{12}U_{21}+U_{22}U_{11})$$

$$\Rightarrow cos\alpha sin\alpha G_L - sin\alpha cos\alpha G_R = \frac{1}{2}k_1k_2g_Lg_R(-sin^2\alpha + cos^2\alpha)$$

$$\Rightarrow tan(2\alpha) = \frac{k_1k_2g_Lg_R}{G_L - G_R} = \frac{k_1k_2g_Lg_R}{\frac{1}{2}(g_L^2v_L^2 - g_R^2v_R^2) + \frac{1}{4}(g_L^2-g_R^2)(k_1^2+k_2^2)}$$

Because of the condition $g_Lv_L << g_Rv_R$ and $k_1, k_2 << v_R$,

$$tan(2\alpha) \simeq -\frac{k_1k_2(g_L/g_R)}{\frac{v_R^2}{2} + \frac{(k_1^2+k_2^2)}{4}} \simeq -\frac{2k_1k_2\epsilon}{v_R^2} \simeq 2\alpha$$

Where $\epsilon = \frac{g_L}{g_R}$, we get :-

$$|\frac{\alpha}{\epsilon}| = |\frac{k_1k_2}{v_R^2}| << 1. \tag{3.34}$$

So,we see that the mixing angle($W_L - W_R$) is very small(In our MadGraph model file ,$k_1 = 227.9$ GeV ,$k_2 = 92.5$ GeV,and $v_R = 2543.2$ GeV, so we get $\alpha \approx 3\times 10^{-3}$ is quite small). Finally, the charged gauge Boson masses(with approximation $v_L << k_1, k_2 << v_R$, $sin\alpha \approx \alpha$ and $cos\alpha \approx 1 - \frac{\alpha^2}{2}$) are,from Eqn(3.33) :-

$$M_W^2 = g_L^2\frac{(k_1^2+k_2^2)}{4} + \frac{1}{2}g_L^2k_1k_2(\frac{\alpha}{\epsilon}) \simeq g_L^2\frac{(k_1^2+k_2^2)}{4} \tag{3.35}$$

$$M_{W'}^2 = \frac{1}{2}g_R^2v_R^2 - g_L^2k_1k_2(\frac{\alpha}{\epsilon}) \simeq \frac{1}{2}g_R^2v_R^2 \tag{3.36}$$

So, the mass ratio of W and W' :-

$$\left(\frac{M_W}{M_{W'}}\right)^2 = 2\left(\frac{g_L}{g_R}\right)^2\frac{(k_1^2+k_2^2)}{4v_R^2} = 2\epsilon^2\delta, \quad \delta = \frac{(k_1^2+k_2^2)}{4v_R^2} << 1, \quad \epsilon < 1$$

From this it is clear seen that mass of W boson is quite small with respect to W' boson.

3.6 Masses of Neutral Gauge Bosons

Let's collect the all the mass terms corresponding to neutral gauge bosons form Eqns(3.28,3.29,3.30), we get :-

$$X' = \frac{1}{2}\left[(g_1B_\mu - g_LW_{\mu,L}^3)^2v_L^2 + (g_1B_\mu - g_RW_{\mu,L}^3)^2v_R^2 + \frac{1}{8}(g_LW_{\mu,L}^3 - g_RW_{\mu,R}^3)^2(k_1^2+k_2^2)\right] \tag{3.37}$$

Let us introduce mass eigenstates(A, Z, Z') :-

$$\begin{pmatrix} B \\ W_L^3 \\ W_R^3 \end{pmatrix} = T \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix} \tag{3.38}$$

Where T matrix,(a unitary matrix) is generally given by the three mixing angles :-

$$T = \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & -s_{13} \\ 0 & 1 & 0 \\ s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{13} \\ 0 & s_{13} & c_{23} \end{pmatrix} \tag{3.39}$$

$$= \begin{pmatrix} c_{12}c_{13} & -s_{12}c_{23} - c_{12}s_{23}s_{13} & s_{12}s_{23} - c_{12}c_{23}s_{13} \\ s_{12}c_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} \\ s_{13} & s_{23}c_{13} & c_{23}c_{13} \end{pmatrix}$$

From electromagnetic interaction term in fermionic part of the Lagrangian(L_F), we can get constraints, [Kokado 15] :-

$$tan\theta_{23} = \frac{g_1}{g_L}, \quad sin\theta_{13} = \frac{e_0}{g_R}, \quad g_1 cos\theta = \frac{e_0}{c_{13}}, \quad g_L sin\theta = \frac{e_0}{c_{13}}, \quad \theta = \theta_{12} \tag{3.40}$$

$$\frac{1}{e_0^2} = \frac{1}{g_1^2} + \frac{1}{g_L^2} + \frac{1}{g_R^2} \tag{3.41}$$

By the use of equations(2.36) and (2.37), we get mass term(X') in terms of the mass eigenstates(A, Z, Z') :-

$$X' = \frac{1}{2} Z^2 M_Z^2 + \frac{1}{2} Z'^2 M_{Z'}^2 + \mu Z Z' \tag{3.42}$$

Where,

$$M_Z^2 = (g_1 T_{12-g_L T_{22}})^2 v_L^2 + (g_1 T_{12} - g_R T_{32})^2 v_R^2 + \frac{k_1^2 + k_2^2}{4} (g_L T_{22} - g_R T_{32})^2, \tag{3.43}$$

$$M_{Z'}^2 = (g_1 T_{13-g_L T_{23}})^2 v_L^2 + (g_1 T_{13} - g_R T_{33})^2 v_R^2 + \frac{k_1^2 + k_2^2}{4} (g_L T_{23} - g_R T_{33})^2, \tag{3.44}$$

And the cross term μ is :-

$$\mu = (g_1 T_{12-g_L T_{22}})(g_1 T_{13-g_L T_{23}}) v_L^2 + (g_1 T_{12} - g_R T_{32})(g_1 T_{13} - g_R T_{33}) v_R^2$$
$$+ (g_L T_{22} - g_R T_{32})(g_L T_{23} - g_R T_{33}) \frac{k_1^2 + k_2^2}{4}.$$

Since the mass term must be diagonal in mass eigenstates, from this cross term should be zero, $\mu = 0$. From this vanishing condition of the cross term one can get the solution to θ_{23}, [Kokado 15],

$$tan\theta_{23} = -\frac{g_1 s}{l} + O(\delta) \tag{3.45}$$

Where, $\delta = \frac{k_1^2+k_2^2}{4v_R^2} << 1$ and $l = \sqrt{g_R^2 + g_1^2 c^2}$. Then, the Z boson mass is given by Eq.[3.43] :-

$$M_Z^2 = v_R^2 (g_1 s\, c_{23} + l\, s_{23})^2 + \frac{k_1^2 + k_2^2}{4} (g_L c\, c_{23} - l\, s_{23})^2, \tag{3.46}$$

After substituting the solution in Eq.[3.45] into the first bracket of v_R^2 term, we get :-

$$v_R^2 (g_1 s\ c_{23} + l\, s_{23})^2 = v_R^2 c_{23}^2 (g_1 s + l\, tan_{\theta 23})^2 = v_R^2 c_{23}^2 l^2 O(\delta^2) \sim \frac{1}{v_R^2}$$

. And From the second bracket term gives,

$$(g_L c c_{23} - l\, s_{23}) = c_{23}(g_L c - l\, tan\theta 23) = c_{23}(g_L c + g_1 s - O(ls)) = c_{23}\sqrt{g_L^2 + g_1^2} - O(l c_{23} \delta)$$

Neglecting the $O(\delta)$ term one can get the final result,

$$M_Z^2 = \frac{k_1^2 + k_2^2}{4} (g_L^2 + g_1^2) c_{23}^2. \tag{3.47}$$

In the same way One can get,

$$M_{Z'}^2 = c_{23}^2 (l + \frac{g_1 s^2}{l})^2 v_R^2 + c_{23}^2 \frac{k_1^2 + k_2^2}{4} \left(l - \frac{g_L g_1 s\, c}{l}\right)^2 \tag{3.48}$$

$$\rightarrow M_{Z'} \simeq l\, c_{23} (l + \frac{g_1 s^2}{l^2}) v_R = g_R v_R \frac{1}{c_{23}\, c_{13}}. \tag{3.49}$$

3.7 Higgs Sector of MLRSM

The Higgs field of the LRSM are :-

$$\Phi(2,2,0), \qquad \Delta_L(3,1,2), \qquad \Delta_R(1,3,2)$$

Where $SU(2)_L$, $SU2)_R$ and $B - L$ dimensions are given in the parentheses. In the case of the Δ_R,the $B - L$ has been chosen so as to realize the 'seesaw mechanism' for explaining small left-handed Neutrino masses. A proper representation of the fields is given by 2×2 matrices :-

$$\Delta_{L,R} = \begin{pmatrix} \frac{\delta_{L,R}^+}{\sqrt{2}} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\frac{\delta_{L,R}^+}{\sqrt{2}} \end{pmatrix} ; \quad \phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$$

Where a neutral field ϕ^0 is written in terms of correctly normalized real and imaginary components as $\phi^0 = \frac{1}{\sqrt{2}}(\phi^{0r} + \iota\phi^{0i})$.

Now let's discuss the form of the scalar field potential. The most general scalar potential, which is invariant under the left-right symmetry($\delta_L \leftrightarrow \delta_R$ and $\phi \leftrightarrow \phi^\dagger$) of the Higgs multiplets is given by :-

$$V(\phi, \Delta_R, \Delta_L) = -\mu_1^2 Tr(\phi^\dagger\phi) - \mu_2^2[Tr(\tilde{\phi}\phi^\dagger) + Tr(\tilde{\phi}^\dagger\phi)] - \mu_3^2[Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R\Delta_R^\dagger)]$$

$$+\lambda_1[Tr(\phi\phi^\dagger)]^2 + \lambda_2\left([Tr(\tilde{\phi}\phi^\dagger)]^2 + [Tr(\tilde{\phi}^\dagger\phi)]^2\right)$$

$$+\lambda_3[Tr(\tilde{\phi}\phi^\dagger)Tr(\tilde{\phi}^\dagger\phi)] + \lambda_4\left(Tr(\phi\phi^\dagger)[Tr(\tilde{\phi}\phi^\dagger) + Tr(\tilde{\phi}^\dagger\phi)]\right)$$

$$+\rho_1\left([Tr(\Delta_L\Delta_L^\dagger)]^2 + [Tr(\Delta_R\Delta_R^\dagger)]^2\right) + \rho_2[Tr(\Delta_L\Delta_L)Tr(\Delta_L^\dagger\Delta_L^\dagger) + Tr(\Delta_R\Delta_R)Tr(\Delta_R^\dagger\Delta_R^\dagger)]$$

$$+\rho_3[Tr(\Delta_L\Delta_L^\dagger)Tr(\Delta_R\Delta_R^\dagger)] + \rho_4[Tr(\Delta_L\Delta_L)Tr(\Delta_R^\dagger\Delta_R^\dagger) + Tr(\Delta_L^\dagger\Delta_L^\dagger)Tr(\Delta_R\Delta_R)]$$

$$+\alpha_1\left(Tr(\phi\phi^\dagger)[Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R\Delta_R^\dagger)]\right) + \alpha_2[Tr(\phi\tilde{\phi}^\dagger) + Tr(\phi^\dagger\tilde{\phi})][Tr(\Delta_R\Delta_R^\dagger) + Tr(\Delta_L\Delta_L^\dagger)]$$

$$+\alpha_3[Tr(\phi\phi^\dagger\Delta_L\Delta_L^\dagger) + Tr(\phi^\dagger\phi\Delta_R\Delta_R^\dagger)] + \beta_1[Tr(\phi\Delta_R\phi^\dagger\Delta_L^\dagger) + Tr(\phi^\dagger\Delta_L\phi\Delta_R^\dagger)]$$

$$+\beta_2[Tr(\tilde{\phi}\Delta_R\phi^\dagger\Delta_L^\dagger) + Tr(\tilde{\phi}^\dagger\Delta_L\phi\Delta_R^\dagger)] + \beta_3[Tr(\phi\Delta_R\tilde{\phi}^\dagger\Delta_L^\dagger) + Tr(\phi^\dagger\Delta_L\tilde{\phi}\Delta_R^\dagger)]$$

Here λ_i's , ρ_i's ,α_i's β_i's are dimensionless couplings and μ_i's are the mass parameters. All the parameters in the above Higgs potential are real due to CP invariance of the potential. Because of the fact that the potential has minimum, the mass parameters(μ_i's) can be expressed in terms of λ_i's , ρ_i's ,α_i's ,β_i's and Higgs VEVs as follow :-

$$\mu_1^2 \approx v_R^2\left(\frac{\alpha_1}{2} - \frac{\alpha_3 k_2^2}{2k_-^2}\right), \quad \mu_2^2 \approx v_R^2\left(\frac{\alpha_2}{2} + \frac{\alpha_3 k_1 k_2}{4(k_1^2 - k_2^2)}\right), \quad \mu_3^2 \approx \rho_1 v_R^2 \tag{3.50}$$

As discussed in [Deshpande 91], the CP invariant potential and minimization conditions on the potential impose a set of constraints on the model parameters. First constraint is that the VEVs of Higgs bidoublet k_1 and k_2 must be real. Another constraint emerge from two minimization conditions($\frac{\partial V}{\partial v_R} = 0$ and $\frac{\partial V}{\partial v_L} = 0$), which leads to some very interesting relation between different VEVs. Insert in the Higgs potential the VEVs of the Higgs Fields :-

$$\langle\Delta_{L,R}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}; \quad \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}$$

Which gives,

$$\tilde{V}(v_L, v_R, k_1, k_2) = -\mu_1^2(k_1^2 + k_2^2) - 4\mu_2^2 k_1 k_2 - \mu_2^2(v_L^2 + v_R^2)$$

$$+\lambda_1(k_1^2 + k_2^2)^2 + (8\lambda_2 + 4\lambda_3)k_1^2 k_2^2 + 4\lambda_4 k_1 k_2(k_1^2 + k_2^2)$$

$$+\rho_1(v_L^4 + v_R^4) + \rho_3 v_L^2 v_R^2$$

$$+\left[\alpha_1(k_1^2 + k_2^2) + 4\alpha_2 k_1 k_2 + \alpha_3 k_2^2\right](v_L^2 + v_R^2)$$

$$+2\left[\beta_1 k_1 k_2 + \beta_2 k_1^2 + \beta_3 k_2^2\right] v_L v_R$$

A kind of 'See-saw relation' between the VEVs can be found by simply computing the $v_R\frac{\partial\tilde{V}}{\partial v_L} - v_L\frac{\partial\tilde{V}}{\partial v_R} = 0$, Which gives:-

$$\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2 = (2\rho_1 - \rho_3)v_L v_R \tag{3.51}$$

or,

$$v_L = \gamma\frac{k_1^2 + k_2^2}{v_R} \tag{3.52}$$

Where,

$$\gamma = \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)(k_1^2 + k_2^2)} \tag{3.53}$$

First consider the case that β_i's and ρ_i's are order of unity(such that not too large to preserve unitarity, and not too small to avoid fine tuning) implies that $\gamma \sim 1$. As we know the fact the light neutrinos masses (proportional to v_L via Yukawa coupling) are bounded to be less than order of 1 eV, then using 'VEVs Seesaw relation' v_R has to be at least as large as order of 10^8 GeV. So, this case leads to the unobservably large masses for the additional Gauge bosons and Higgs states(masses of the order of 10^8 GeV).Now, consider the second case,in which β_i's are fine-tuned to reduce γ to about 10^{-6} and leads v_R to be small enough, i.e, $v_R \sim$ order of 10^3 GeV. In this case, the additional gauge bosons and new Higgs particles are become accessible at the LHC(see the Mass Formulas in Appendix(B)). Now, The case in which, we want to avoid the fine-tuning of the Higgs couplings by eliminating completely the 'Seesaw Relation Of VEVs' by setting β_i's parameters to zero.This may be a possible consequence of some higher level exact symmetry(e.g. GUT or SUSY), which lies beyond the context of the LRSM, [Deshpande 91]. The VEV seesaw relation with (β_i's=0) can be satisfied by setting The VEV of the left-handed triplet, $v_L = 0$. Now, Let's summarize the above discussion, the imposed constraints on the Higgs potential parameters and the

Higgs VEVs are, [Roitgrund 14], [Deshpande 91]:-

1. The VEVs of Higgs bidoublet k_1 and k_2 are real.
2. The parameters β_i's are set to zero.
3. The Left-triplet Higgs VEV v_L is set to zero.

The Higgs mass is then determined as follow :-

$$\frac{\partial^2 V}{\partial\phi_i \partial\phi_j}|_{\phi_i=\phi_j=0} = m^2_{i,j} \tag{3.54}$$

By using, first the minimization conditions of the potential and then the three above stated constraints, one can calculate the physical Higgs masses. The expressions for the masses of Higgs in terms of free adjustable parameters, are given in the Appendix(B)(For the case of $k_1, k_2 << v_R$ and $v_L = 0$).

Chapter 4

Higgs Phenomenology Of MLRSM

4.1 Introduction

We will focus mainly to left handed and right handed triplet Higgs Fields because their phenomenology is very interesting and amenable to the systematic study. They have interesting experimental signatures for e.g. because they have $B - L = 2$, the doubly charged triplet members can decay to two same sign leptons. It will be useful at this point to review a few general features of their couplings to leptons and gauge bosons. The fermion couplings of the triplet Higgs are given by the Yukawa part Lagrangian(Eqn[3.14]) :-

$$L_Y = i\psi_L^{Ti} C\tau_2 h_{ij}^L \Delta_L \psi_L^j + i\psi_R^{Ti} C\tau_2 h_{ij}^R \Delta_R \psi_R^j + h.c.$$

Where the notation has same meaning as in Eqn(3.14). A discussion of the magnitude and role of the Majorana Yukawa couplings h^M is being discussed in section(3.4). Mass spectrum of Higgs and dependence of masses of Higgs on the parameters of the potential is also an essential part to figure out, before going towards the decays of different Higgs via various channels. Production of the Doubly charged Higgs is discussed in the next section at LHC(at 14 TeV E.O.M. energy).

4.2 Doubly Charged Higgs Phenomenology

Why First Doubly charged Higgs phenomenology?,the reasons are as follow:-

- We do not have any Doubly charge Higgs in other model such as SM, so it phenomenological signature only for MLRSM.
- In decay processes such as, Doubly Charged Higgs decays to two like-sign lepton, decay rates are as follow :-

$$\Gamma(\delta_R^{\pm\pm} \longrightarrow l_R l_R) \sim |h_{\Delta_R}|^2$$

$$\Gamma(\delta_L^{\pm\pm} \longrightarrow l_L l_L) \sim |h_{\Delta_L}|^2 \propto |m_\nu|^2$$

$$pp \longrightarrow \delta_L^{++}\delta_L^{--} \longrightarrow e^+e^+e^-e^- \sim |h_L|^4 \sim (Um_{ee}U^T)^4$$

  Since we know the PMNS lepton mixing matrix(U), then we can estimate the decay rates for such leptonic decay signatures from Doubly charged Higgs. This is an interesting connection between collider physics and neutrino oscillations.

4.2.1 Production of $\delta_R^{\pm\pm}$ using Madgraph5/FeynRules2.3 at 14 TeV at LHC

There were 24 different processes/diagrams to generate $\delta_R^{++} + \delta_R^{--}$ out of the proton-proton collision. Some sample Feynman Diagrams generated through MadGraph5 are as follow:-

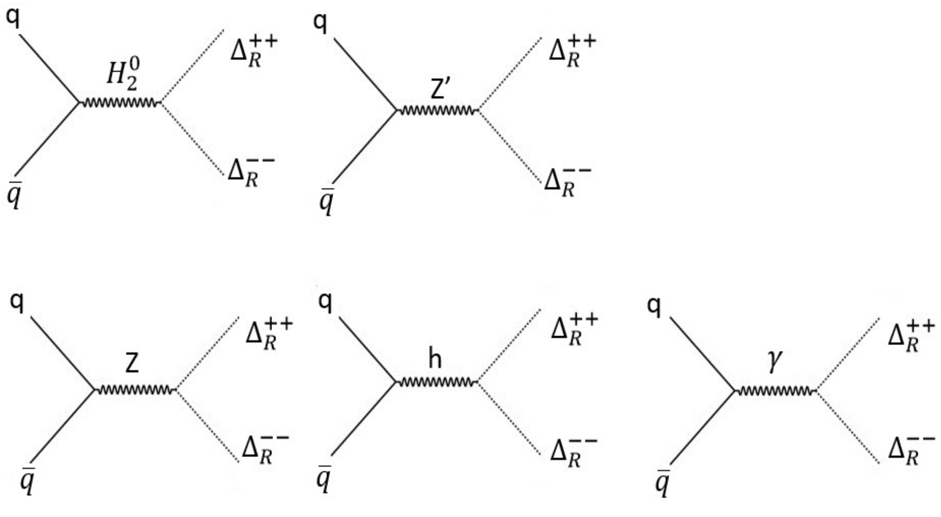

Figure 4.1: Feynman Diagrams for Doubly Charged Higgs production

Variation of Cross-section(In pb) with Doubly charged Higgs mass(In GeV) :-

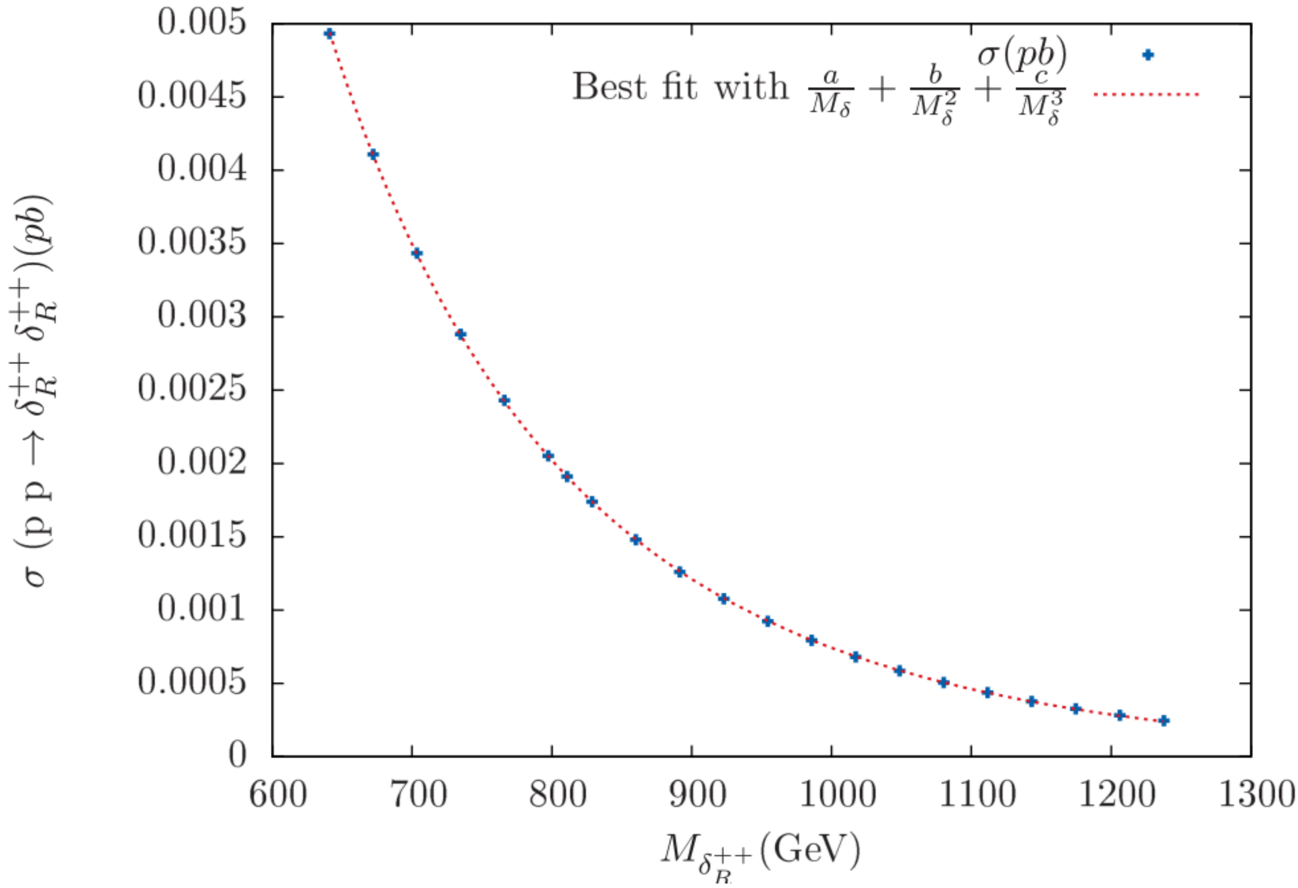

Figure 4.2: Cross-section(In Pb) Vs. Mass(In GeV) of Doubly Charged Higgs

Now let's discuss the 'Reaction Rate' for this process (p + p $\longrightarrow \delta_R^{++} + \delta_R^{--}$).Reaction rate is defined as number of scattering events per unit time(in collider experiments) and given by the formula :-

$$R(s) = \sigma(s)L \tag{4.1}$$

Where 's' stands for the square of center of mass energy(In our case $\sqrt{s} = 14$ TeV), $\sigma(s)$ is the total scattering cross-section (in our case varying from 0.0005 pb to 0.005 pb, $pb = picobarn = 10^{-24}cm^2$) and L is 'Luminosity' of the detector (LHC luminosity in next run of LHC will be 100 fb^{-1}/year).

Given all this information, For the process(p + p $\longrightarrow \delta_R^{++} + \delta_R^{--}$), the reaction rate will be '50 to 500' event per year in the next run of the LHC at 14 TeV.

4.2.2 Analytic Estimation of p + p $\longrightarrow H_2^0 \longrightarrow \delta_R^{++} + \delta_R^{--}$

Let us consider a process out of those 24 processes to generate $\delta_R^{++} + \delta_R^{--}$ from the proton-proton collision.

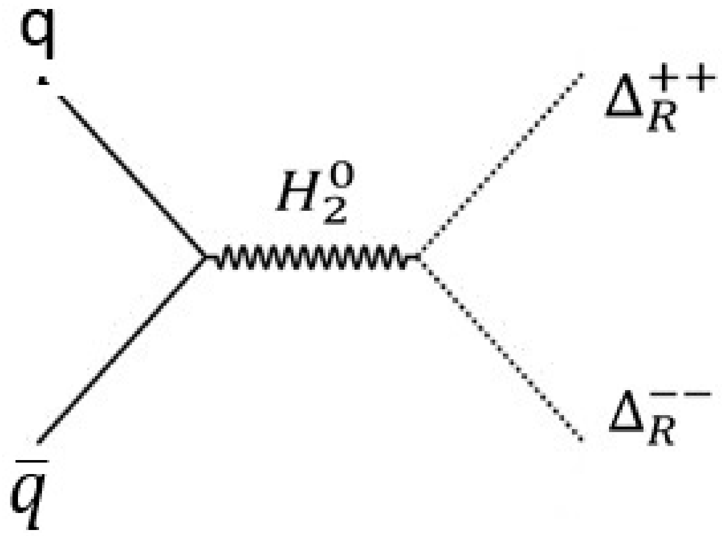

Figure 4.3: A Feynman diagram for Doubly charged Higgs Production involing H_2^0 as intermediate particle

4-momentum$(q_1, q_2) \rightarrow (p_1, p_2)$ for this process.
Amplitude of this process :-

$$iM = \bar{v}^{s'}(q_2)\left(-i\frac{gm_q}{2m_w}\right)u^s(q_1)\frac{i}{(q_1+q_2)^2 - m_{h2}^2}(-2i\rho_1 - 4\iota\rho_2)v_R \tag{4.2}$$

Vertex(H_2^0, δ_R^{++} , δ_R^{--}) can be simplified as follow :-

$$(-2i\rho_1 - 4i\rho_2)v_R\frac{v_R}{v_R} \approx i\frac{g_R M_\delta^2}{m_{W'}} \tag{4.3}$$

Here we have used $M^2_{\delta_R^{\pm\pm}} = \frac{1}{2}(\alpha_3 k_-^2 + 4v_R^2\rho_2)$ and $m_{W'} \approx \frac{1}{\sqrt{2}} g_R v_R$ to simplify the vertex term. Now, the square of the amplitude can be written as :-

$$|M|^2 \approx g^4\frac{m_q^2 m_\delta^4}{m_W^2 m_{W'}^2}\frac{1}{[(q_1+q_2)^2 - m_{h2}^2]^2}\frac{1}{4}tr[(\gamma^\mu q_{2\mu} - m_q)(\gamma^\nu q_{1\nu} + m_q)]$$

$$= g^4\frac{m_q^2 m_\delta^4}{m_W^2 m_{W'}^2}\frac{1}{[(q_1+q_2)^2 - m_{h2}^2]^2}\frac{1}{4}(q_2.q_1 - m_q^2)$$

In *Center of Mass frame:-* We have $q_1 = (E_q, \vec{q})$,$q_1 = (E_q, -\vec{q})$ and $p_1 = (E_p, \vec{p})$,$p_2 = (E_p, -\vec{p})$. After putting these in the above expression, the square amplitude can be written as :-

$$|M|^2 = g^4 \frac{m_q^2 m_\delta^4}{4m_W^2 m_{W'}^2} \frac{(E_q^2 + |\vec{q}|^2 - m_q^2)}{(4E_\delta^2 - m_{h2}^2)^2} \tag{4.4}$$

And the two-body Lorentz invariant phase space(*LIPS*) for our process is :-

$$LIPS = \frac{|\vec{p}|}{8\pi\sqrt{|\vec{p}|^2 + m_\delta^2}}$$

Then the Total Cross-section is:-

$$\sigma = \frac{1}{8E_q^2}|M|^2(LIPS) \sim \frac{1}{m_\delta} \tag{4.5}$$

Similarly we get for $\sigma(pp \longrightarrow h \longrightarrow \delta_R^{++}\delta_R^{--}) \sim \frac{1}{m_\delta}$.

Further, if we can calculate all the 24 diagrams cross-sections then the sum-up effect or the results will probably match the computational result which we got from curve fitting of Cross-section Vs. Mass curve for Right-handed Doubly Charged Higgs :-

$$\sigma(TotalCross-section) = \frac{0.5782}{m_\delta} - \frac{2502.8}{m_\delta^2} + \frac{2.66781 \times 10^6}{m_\delta^3} \tag{4.6}$$

4.3 Mass Spectrum of Higgs Sector Of MLRSM

There are total 20 degree of freedom(6 degrees of freedom from each Higgs Triplet and 8 degrees of freedom from Higgs Bi-doublet) of Higgs particle states in minimal left-right symmetric model, *Out of these 20 degrees of freedom 6 are absorbed in giving masses to the 6 left and right handed gauge bosons, so there remains only 14 physical degrees of freedom.* The expressions are given in Appendix(B) for the masses of all the physical states of Higgs. Here, we study the dependence of the Higgs masses on the parameters of the Higgs potential(As given in section(3.7)).

Standard values of the parameters of Higgs potential as used in MadGraph5 model file to create all the processes of MLRSM :-

$$\lambda_1 = 0.118, \quad \lambda_1 = 0.2, \quad \lambda_3 = -0.234, \quad \lambda_4 = 0$$

$$\rho_1 = 0.5, \quad \rho_2 = 0.05, \quad \rho_3 = 1.25, \rho_4 = 0.125$$

$$\alpha_1 = 0.5, \quad \alpha_2 = 0.5, \quad \alpha_3 = 0.5$$

LRSM symbols	Symbols in Madgraph model files
$W_L^+,\ W_R^+, Z_1, Z_2$	w+, w2+, z, z2
$h(SMHiggs),\ \delta_L^{++}, \delta_R^{++}$	h, hl++, hr++
$\delta_L^0, \delta_R^0(H_1^0,H_2^0), \delta_L^+, \delta_R^+()$	h03, h2, h02, h+, hp2
$\rho_{1..4},\ \alpha_{1..3},\ \rho_{diff.} = \rho_3 - 2\rho_1$	rho1..4, alpha1..3, rhodifference
Couplings	e, g, g', g_s

Table 4.1: The MLRSM parameters and their corresponding symbols in MadGraph model file.

$$v = 246\ GeV, \quad k_1 = 227.91\ GeV, \quad k_2 = 92.7\ GeV, \quad v_R = 2543.2\ GeV, \quad v_L = 0$$

By varying these parameters, we study the variation of the Higgs masses and the variation of the difference in different-2 Higgs Masses. The motivation of this analysis is phenomenological for e.g. the decay mode $\delta_L^{++} \to \delta_L^+ W_L^+$ is forbidden for the standard values of the parameters as stated above, But this decay mode is possible for the some range of the parameters($\rho_{diff.} = (\rho_3 - 2\rho_1) \leq 0.01$) if we vary them, [Gunion 89].

MadGraph5 Notation and notation used in plotting these curves are given in Table(4.1).

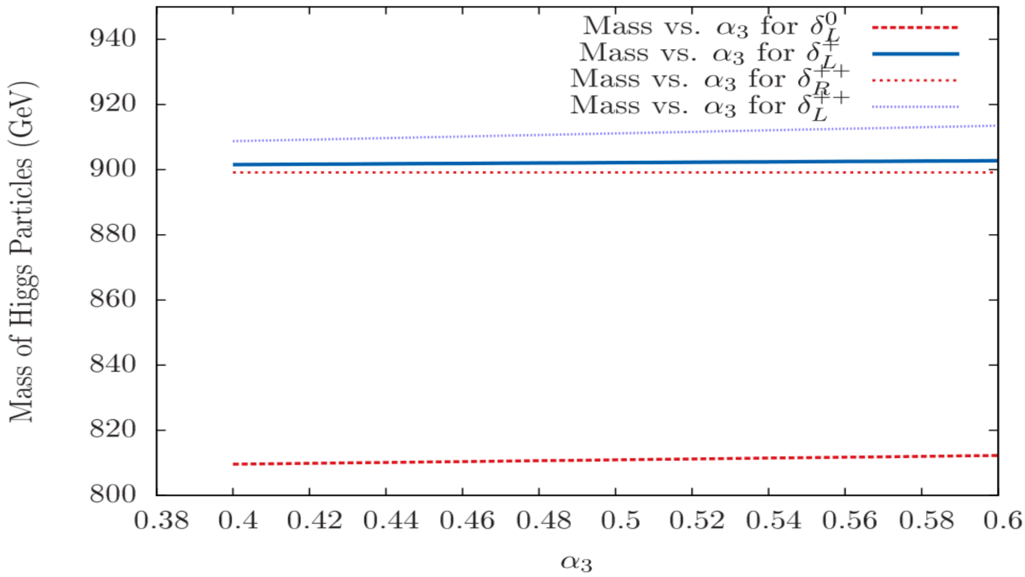

Figure 4.4: Dependence of Left-handed Triplet Higgs masses on α_3

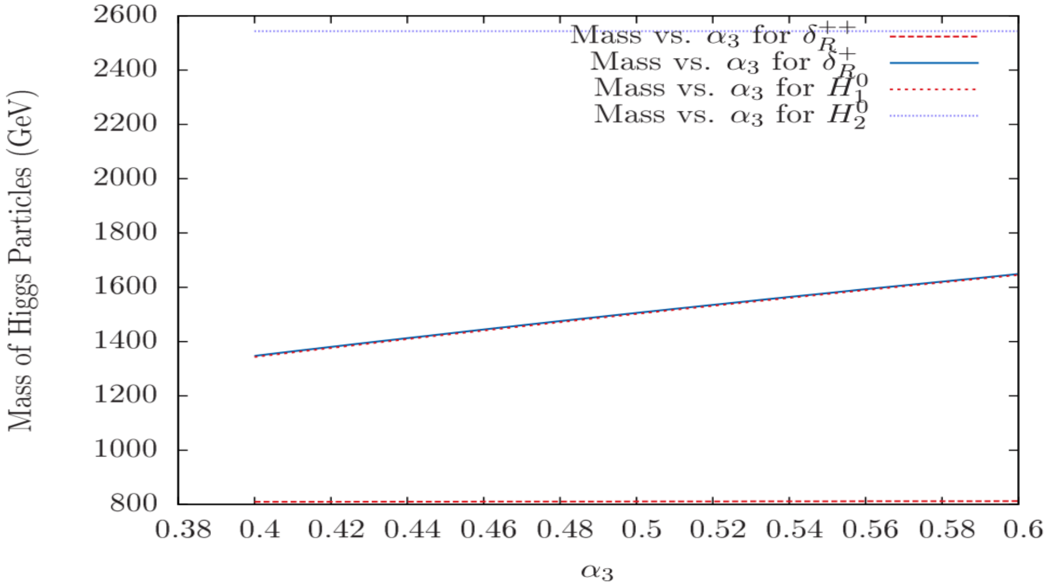

Figure 4.5: Dependence of Right-handed triplet Higgs masses on α_3

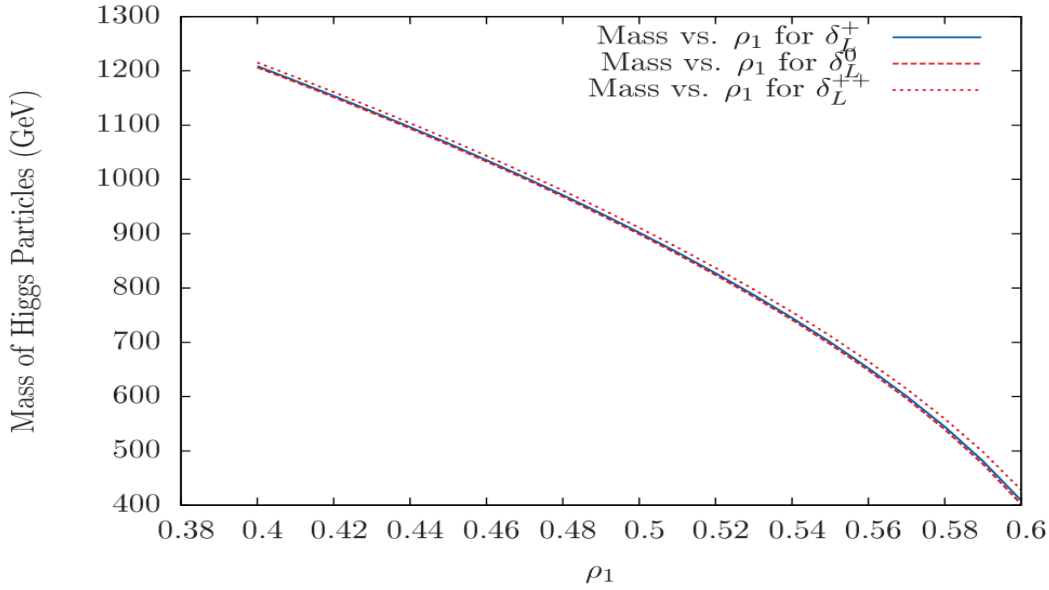

Figure 4.6: Dependence of Leftt-handed triplet Higgs masses on ρ_1

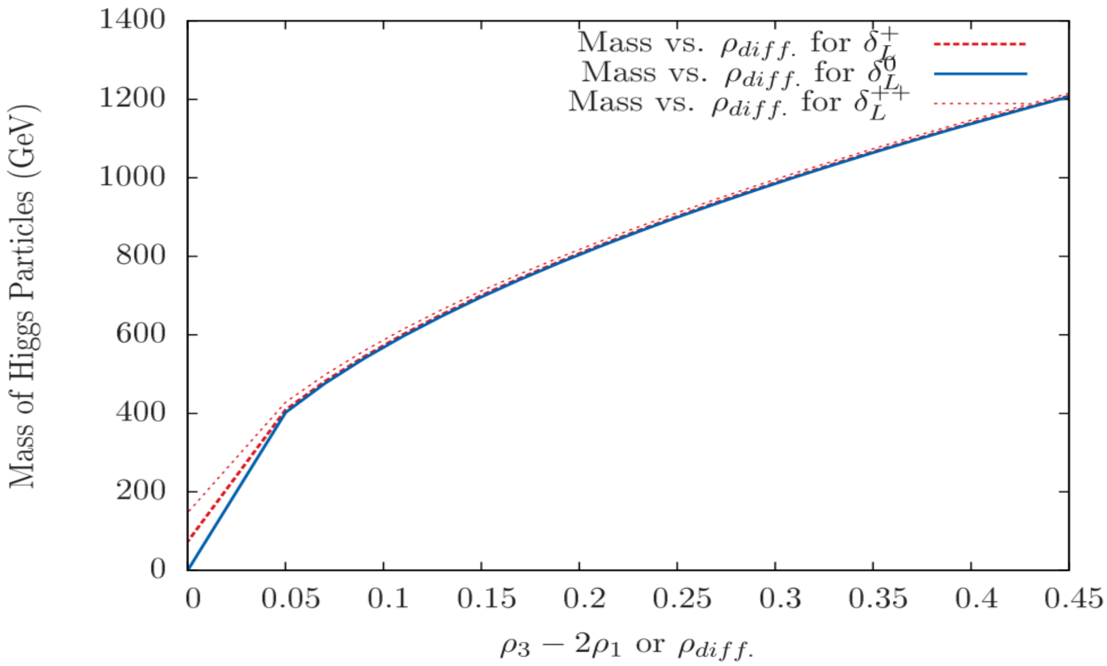

Figure 4.7: Dependence of Left-handed triplet Higgs masses on $\rho_{Difference}$ or $(\rho_3 - 2\rho_1)$

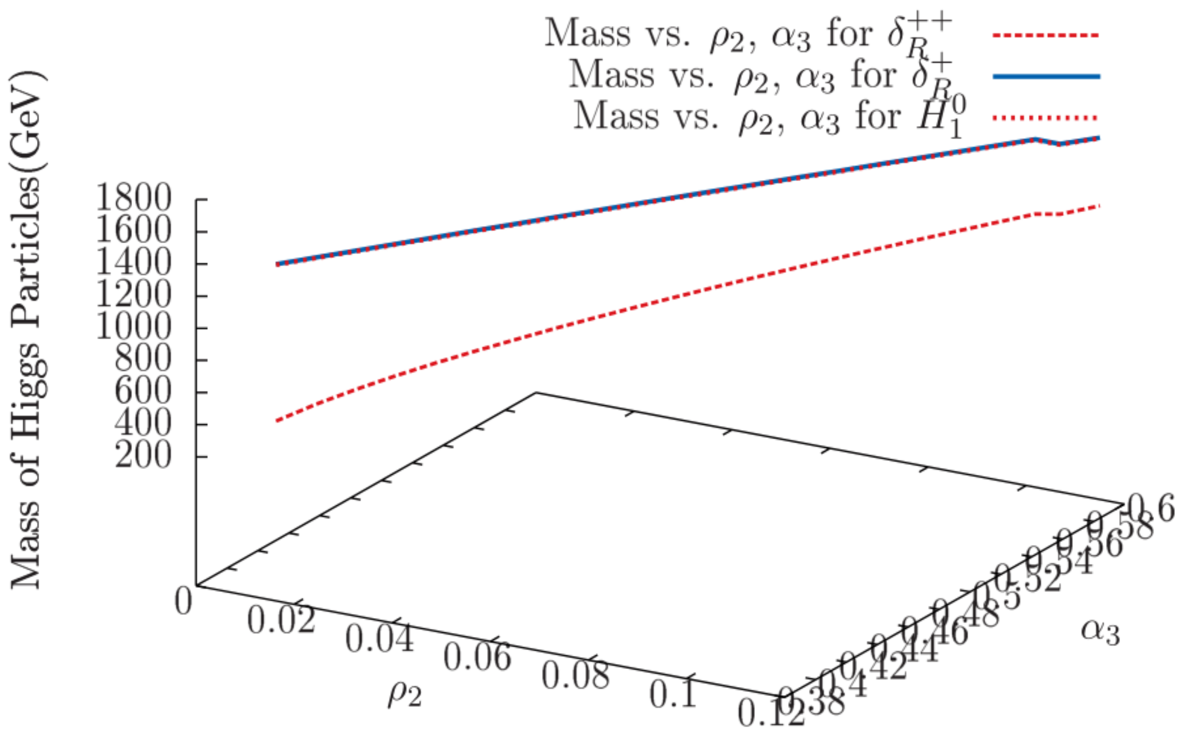

Figure 4.8: Dependence of Rightt-handed triplet Higgs masses on ρ_2 and α_3

4.4 Decays Modes of Doubly and Singly Charged Higgs Using Madgraph5

Here we have divided this section into two parts Discussions and Results.

4.4.1 Discussion

Coupling of the Δ_L triplet Higgs bosons to W_L are of phenomenological significance. Let's first consider vertices involving one Δ_L member and two gauge bosons, these are all proportional to v_L(without of i factor):-

$$\delta_L^{++}W_L^-W_L^- : -\sqrt{2}g^2 v_L, \quad \delta_L^{0r}W_L^+W_L^- : g^2 v_L, \quad \delta_L^{++}W_L^-Z_1 : -\frac{g^2 v_L}{\sqrt{2}cos\theta_W} \tag{4.7}$$

As discussed in [Gunion 89], we know that the potential couplings involving the photon are absent at the tree level, which is a common feature of extended Higgs sector.

$$\delta_L^+ W_L^- \gamma = 0, \quad \delta_L^{0r} Z_1 \gamma = 0. \tag{4.8}$$

The second type of coupling in which we are interested are those in which one Higgs couples with other higgs and a gauge boson :-

$$\delta_L^{++}\delta_L^{--}W_L^- : g, \quad \delta_L^{0r}\delta_L^+ W_L^- : \frac{g}{\sqrt{2}}, \quad \delta_L^{0i}\delta_L^+ W_L^- : -i\frac{g}{\sqrt{2}} \tag{4.9}$$

Furthermore, there are couplings involving three Higgs bosons. The $\delta_L^{++}\delta_L^-\delta_L^-$ coupling is proportional to $(\rho_1 + \rho_2)v_L$ and vanishes when $v_L = 0$ is considered, still $\delta_L^{++}\delta_L^-\delta_L^-$ two body on-shell mode is not possible at because of the fact that mass of two δ_L^- is more than mass of the δ_L^{++}, in our case and couplings of the δ_L^0 to $\delta_L^+\delta_L^-$ or $\delta_L^{++}\delta_L^{--}$ are not relevant for δ_L^0 decays due to mass argument. Now there remains just couplings of the type, $\delta_L^{0r,i}h^0h^0$, $\delta_L^{0r,i}h^0H^0$ etc., which are all proportional to v_L, thus are suppressed or zero in case of $v_L = 0$.

Now, let's discuss about a straightforward estimation of $v_{R,L}$ and $k_+^2 = k_1^2 + k_2^2$. By this estimation a value is found for Dirac and Majorana type Yukawa couplings(f and h respectively). The hierarchy between VEVs plays an important role in this argument as given by :-

$$v_L = \gamma\frac{k_1^2 + k_2^2}{v_R}, \quad with \quad \gamma = \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)(k_1^2 + k_2^2)}$$

Where γ will be the free parameters on which the quantities of our interest will depend. We will use the mass formulas for Neutrinos and electron :-

$$m_\nu = 2hv_L - \frac{(f_1k_1 + f_2k_2)^2}{2hv_R} \tag{4.10}$$

$$m_e = f_1k_2 + f_2k_1 \tag{4.11}$$

Due to the motivation that leptons(electron and LH neutrinos) masses are order of dirac mass,$m_l \simeq m_D$, we made assumptions :- 1. $k_2/k_1 << 1$; 2. $f := f_1 \approx f_2$; 3. the two terms in m_ν are more or less equal to m_ν. As we know from Eqn(3.35) that $m_W \approx \frac{1}{2}gk_+$ and experimental value of W boson mass $\approx$ 80 GeV, this gives us $k \approx k_+ \approx 246$ GeV. Another experimental input is $m_e = 0.5$ MeV and lastly we estimate $m_\nu \approx 1$ eV(experimental), so in the following calculation both terms in m_ν

γ	v_R(In GeV)	v_L(In eV)	h
1	1×10^8	4×10^5	1×10^{-6}
10^{-1}	3×10^7	1×10^5	4×10^{-6}
10^{-2}	1×10^7	4×10^4	1×10^{-5}
10^{-4}	1×10^6	4×10^3	1×10^{-4}
10^{-6}	1×10^5	4×10^2	1×10^{-3}
10^{-8}	1×10^4	4×10^1	1×10^{-2}

Table 4.2: The values of some key parameters depending on γ

expression can be taken of the order of 1 eV.

Now, Using the assumptions 1st and 2nd we get: $f_1k_1 + f_2k_2 \approx f_1k_2 + f_2k_1 \approx fk_+(\approx m_e)$, which gives, $f = m_e/k_+ \approx 3 \times 10^{-6}$. Furthermore, when we set the two terms in $m_\nu \sim 1$ eV, then the 3rd assumption makes possible to express all the unknowns in terms of k_+,m_e,m_ν and γ :-

$$v_L = \frac{m_\nu k_+}{m_e}\sqrt{\gamma} \approx 4\sqrt{\gamma} \times 10^{-4}\ GeV$$

$$v_R = \frac{m_e k_+}{m_\nu}\sqrt{\gamma} \approx 4\sqrt{\gamma} \times 10^{8}\ GeV$$

$$f = 2h\sqrt{\gamma} \approx \frac{m_e}{k_+} \approx 3 \times 10^{-6}$$

$$m_N = 2hv_R = \frac{m_e^2}{m_\nu} \approx 3 \times 10^{2}\ GeV$$

The following table shows the values of v_L,v_R and h for some values of gamma :-
From the right handed gauge boson formula($m_{W_R} \approx \frac{1}{2}gv_R$), that v_R set the mass sale of RH gauge bosons. Direct experimental searches for these heavy extra gauge bosons has resulted in lower bound of $m_{W_R} > 720$ GeV, [Eidelman 04]. A second lower bound was obtained by considering the $K_L - K_R$ mass splitting, resulting in $M_{W_R} > 1.6$ TeV. These lower bound has been satisfied with the value of v_R in our above discussion.The value of v_L is small enough not to disturb the value of $\rho_{ew} = m_{W_L}^2/(M_Z cos\theta_W)^2 = (k_+^2 + 2v_L^2)/(k_+^2 + 4v_L^2)$. It should be within one percent of the unity, implying $v_L < 14$ GeV(this is our roughly estimated bound on v_L's value, its value is bounded from above from electroweak precision tests $v_L < 10$ GeV), [Deshpande 91], [Duka 00] and [Gunion 89].

The limits listed in the Table(4.2) are important in examining the decays of the different Δ_L scalar Higgs bosons. If all the h^M's are as small as given by $h^M < 1 \times 10^{-4}$, then widths for $\delta_L^{++} \to e^+e^+$ and $\delta_L^+ \to e^+v_e$ and for many others are very small, and any other open channel (e.g. $\delta_L^{++} \to W^+W^+$, if $v_L \neq 0$) would dominate over these interesting leptonic signatures, although we can check that the lifetimes($\Gamma \sim 10^{-4} - 10^{-5}$ GeV) are short enough that these decays will be contained in the typical detectors. Now, let's consider these alternative possibilities for $v_L \neq 0$ scenario. For e.g. consider whether the following decays are kinematically allowed and if so which one will dominate :-

1. $\delta_L^{++} \to W_L^+ W_L^+$
2. $\delta_L^{++} \to W_L^+ \delta_L^+$
3. $\delta_L^{++} \to \delta_L^+ \delta_L^+$
4. $\delta_L^{++} \to W_L^+ W_L^+ \delta_L^0$
5. $\delta_L^{++} \to \delta_L^+ \delta_L^+ \delta_L^0$

- It is clear that 3rd and 4th are not possible due to fact that the total of masses of the final states are more than mass of the initial state. The 2nd and 4th modes are possible or not that depends on the value chosen for $m_{\delta_L^+}$.

- In the range $m_{\delta_L^+} < 200$ GeV allowed by $\rho_{diff.}$ limits (as shown in Figure 4.7), $m_{\delta_L^{++}} - m_{\delta_L^+} \leq 80$ GeV, the 2nd decay mode is not possible. Although, 1st and 4th modes are possible once $m_{\delta_L^{++}} = \sqrt{2} m_{\delta_L^+}$ is larger than $2m_{W_L}$. For the $\delta_L^{++} \to W_L^+ W_L^+$ mode, the coupling is of the order of $g^2 v_L$ (as in Eqn[4.7]). we if $v_L \neq 0$ and large(order of a few GeV) but less than maximum allowed bound,then the $W_L^+ W_L^+$ mode will dominate the dilepton decay mode($\delta_L^{++} \to e^+e^+$).

- 4th decay mode $\delta_L^{++} \to W_L^+ W_L^+ \delta_L^0$ will be less significant compared to two body mode due to the three body phase space. but it could be important if v_L is small and its signature will be quite similar to two body mode when δ_L^0 is appeared approximately massless and invisible(coupling, $\delta_L^{++} \to W_L^+ W_L^+ \delta_L^0 : -2g^2$).

- Notice though, in $W_L^+ W_L^+$ decay mode the leptons need not to be of the same generation, whereas, to the extent that h^M is almost diagonal in generation space, the directly produced leptons would tends to be from the same generation.

In the case of the δ_L^+ we should consider the competing modes

$$\delta_L^+ \to Z_1 W_L^+, \quad \delta_L^+ \to Z_1 W_L^+ \delta_L^0, \quad \delta_L^+ \to \delta_L^0 W_L^+ \tag{4.12}$$

We can ignore the first mode of Eqn(4.12), since the third has a much larger coupling(Eqn[4.7]), the same cubic dependence on $m_{\delta_L^+}$ and is always allowed when the first is allowed. The second mode has the three body phase space, hence it is suppressed compared to third mode. Note also that, the $\delta_L^+ \to \delta_L^0 W_L^+$ decay mode can produce a final state same as to the mode $\delta_L^+ \to l^+ v_l$, since the δ_L^0 decays invisibly and the W_L^+ can decay to $l^+ \nu_L$, [Gunion 89].

4.4.2 Results

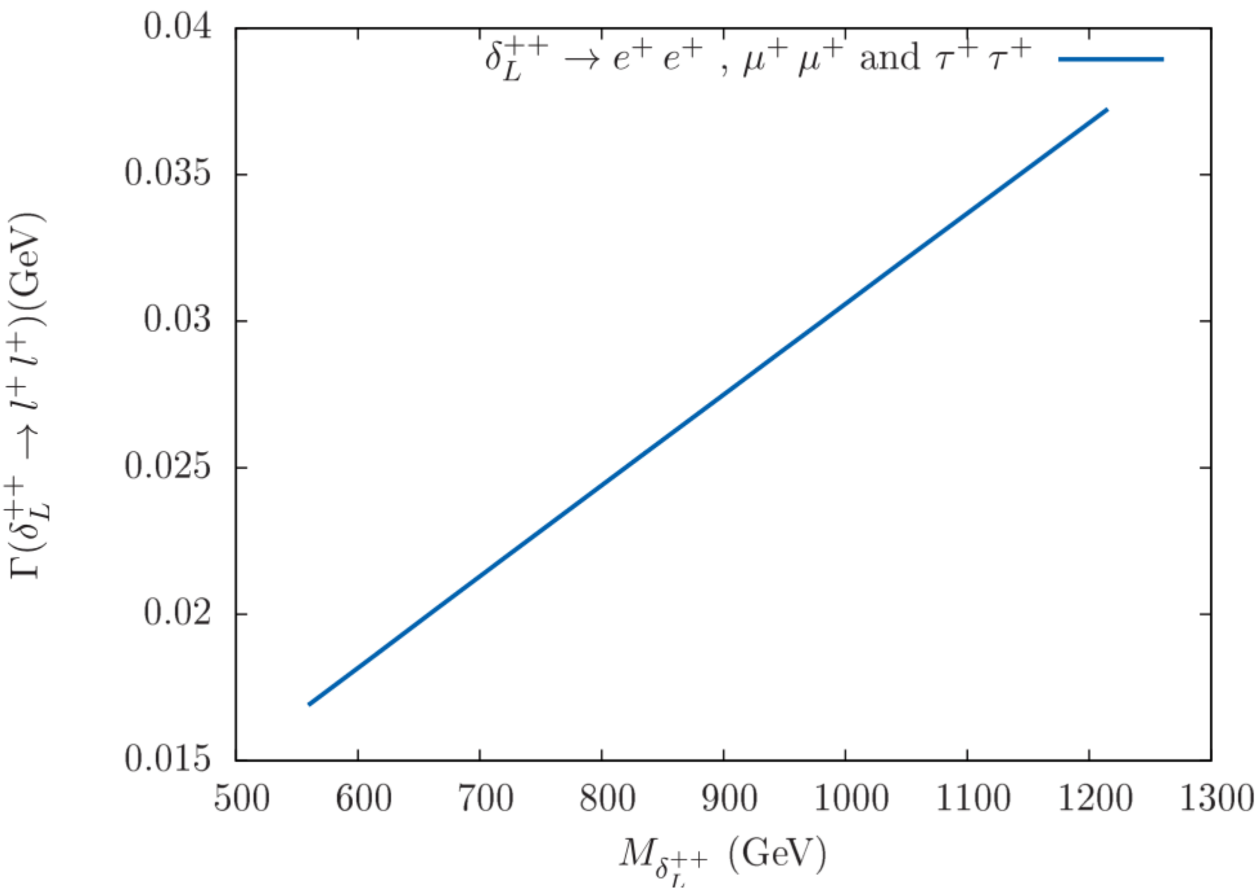

Figure 4.9: Decay Width dependence on the mass of Higgs for the process $\delta_L^{++} \to l^+ \ l^+$

Figure no.	Process	Value of adjusted parameters
4.2	p p $\rightarrow \delta_R^{++}\ \delta_R^{--}$	v_R is adjusted to give the relevant $M_{\delta_R^{++}}$. $v_L = 0$,$M_{N_{e,\mu,\tau}} = 100\, GeV$
4.9	$\delta_L^{++} \rightarrow l^+\ l^+\ (l = e, \mu, \tau)$	ρ_1 is adjusted to give the relevant $M_{\delta_L^{++}}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu,\tau}} = 100\, GeV$
4.10	$\delta_L^{++} \rightarrow l^+\ l^+\ (l = e, \mu, \tau)$	ρ_1 is adjusted to give the relevant $M_{\delta_L^{++}}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu}} = 100\, GeV$,$M_{N_\tau} = 1600\, GeV$
4.11	$\delta_L^{++} \rightarrow W_L^+\ W_L^+$	ρ_1 is adjusted to give the relevant $M_{\delta_L^{++}}$. $v_R = 2543.2$ GeV, $M_{N_{e,\mu,\tau}} = 100\, GeV$ $v_L = (2\, GeV, 5\, GeV, 8\, GeV)$,If $v_L = 0$ then, $\Gamma\ (\Delta_L^{++} \rightarrow W_L^+ W_L^+) = 0$
4.12	$\delta_R^{++} \rightarrow l^+\ l^+\ (l = e, \mu, \tau)$	ρ_2 is adjusted to give the relevant $M_{\delta_R^{++}}$. $v_R = 2543.2GeV$,$v_L = 0$,$M_{N_{e,\mu,\tau}} = 100GeV$
4.13	$\delta_R^{++} \rightarrow l^+\ l^+\ (l = e, \mu, \tau)$	ρ_2 is adjusted to give the relevant $M_{\delta_R^{++}}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu}} = 100\, GeV$,$M_{N_\tau} = 1600\, GeV$
4.14	$\delta_L^+ \rightarrow l^+\ \nu_l\ (l = e, \mu, \tau)$	ρ_1 is adjusted to give the relevant $M_{\delta_L^+}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu,\tau}} = 100\, GeV$
4.15	$\delta_l^+ \rightarrow l^+\ \nu_l\ (l = e, \mu, \tau)$	ρ_1 is adjusted to give the relevant $M_{\delta_L^+}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu}} = 100\, GeV$,$M_{N_\tau} = 1600\, GeV$
4.16	$\delta_R^+ \rightarrow l^+\ \nu_l\ (l = e, \mu, \tau)$	α_3 is adjusted to give the relevant $M_{\delta_L^+}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu,\tau}} = 100\, GeV$
4.17	$\delta_R^+ \rightarrow l^+\ \nu_l\ (l = e, \mu, \tau)$	ρ_1 is adjusted to give the relevant $M_{\delta_R^+}$. $v_R = 2543.2\, GeV$,$v_L = 0$,$M_{N_{e,\mu}} = 100\, GeV$,$M_{N_\tau} = 1600\, GeV$

Table 4.3: Adjusted values of parameters which were used in the validation processes in MadGraph5-aMC@NLO.

Here, for the three decay modes($\delta_L^{++} \to l^+ \, l^+; l = e, \mu, \tau$) we consider same masses(100 GeV) of the three heavy Neutrinos(N_e, N_μ, N_τ) corresponding to three lepton generations, that is why we get same decay width due to decay width formula:-

$$\Gamma(\delta_L^{++} \to l^+ l^+) = \frac{h_{ll}^M}{8\pi} m_{\delta_L^{++}} \tag{4.13}$$

Where the Yukawa couplings are given in terms of the Neutrino's mass by the expression, $(h_R)_{ij} = \frac{m_{ij}^R}{\sqrt{2} v_R}$ (as discussed in section 3.4). So if the mass of the right handed neutrinos is same for all generations than the Yukawa couplings h^M are also same for all the three generations.

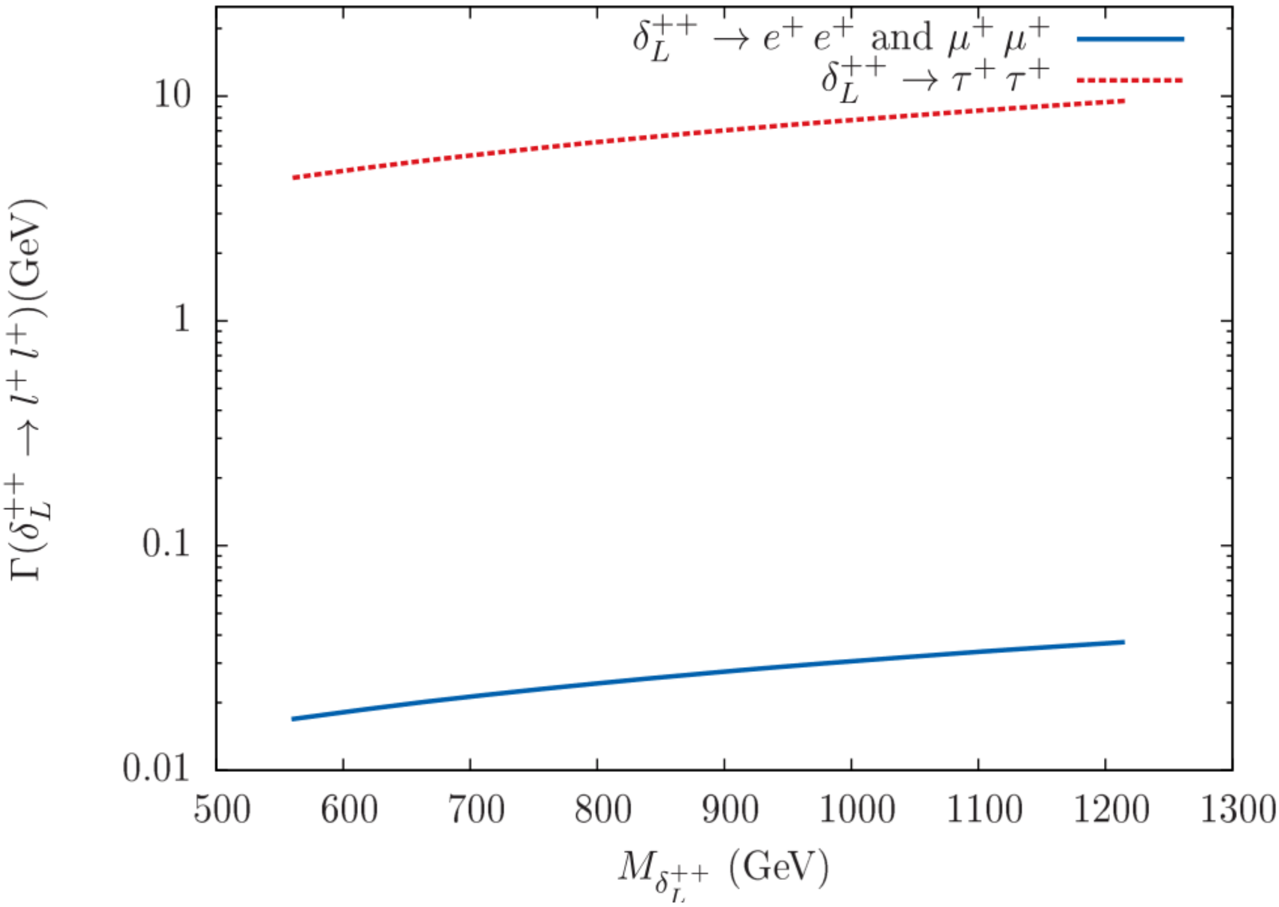

Figure 4.10: Decay Width dependence on the mass of Higgs for the process $\delta_L^{++} \to l^+ \, l^+$ with different Neutrino masses.

Here, for the decay modes($\delta_L^{++} \to l^+ \, l^+ ; l = e, \mu, \tau$) we consider same masses(100 GeV) of the two heavy neutrinos(N_e, N_μ) corresponding to e^+, μ^+ generation and 1600

GeV mass of the third generation Neutrino(N_τ). Due to this fact we get same decay width for the two modes($\delta_L^{++} \to l^+ \ l^+ \ ;l = e, \mu$) and large decay width(compared to former two modes) for the mode($\delta_L^{++} \to \tau^+ \ \tau^+$) since $M_{N_\tau} = 1600$ GeV, is quite large than $M_{N_e} = M_{N_\mu} = 100$ GeV.

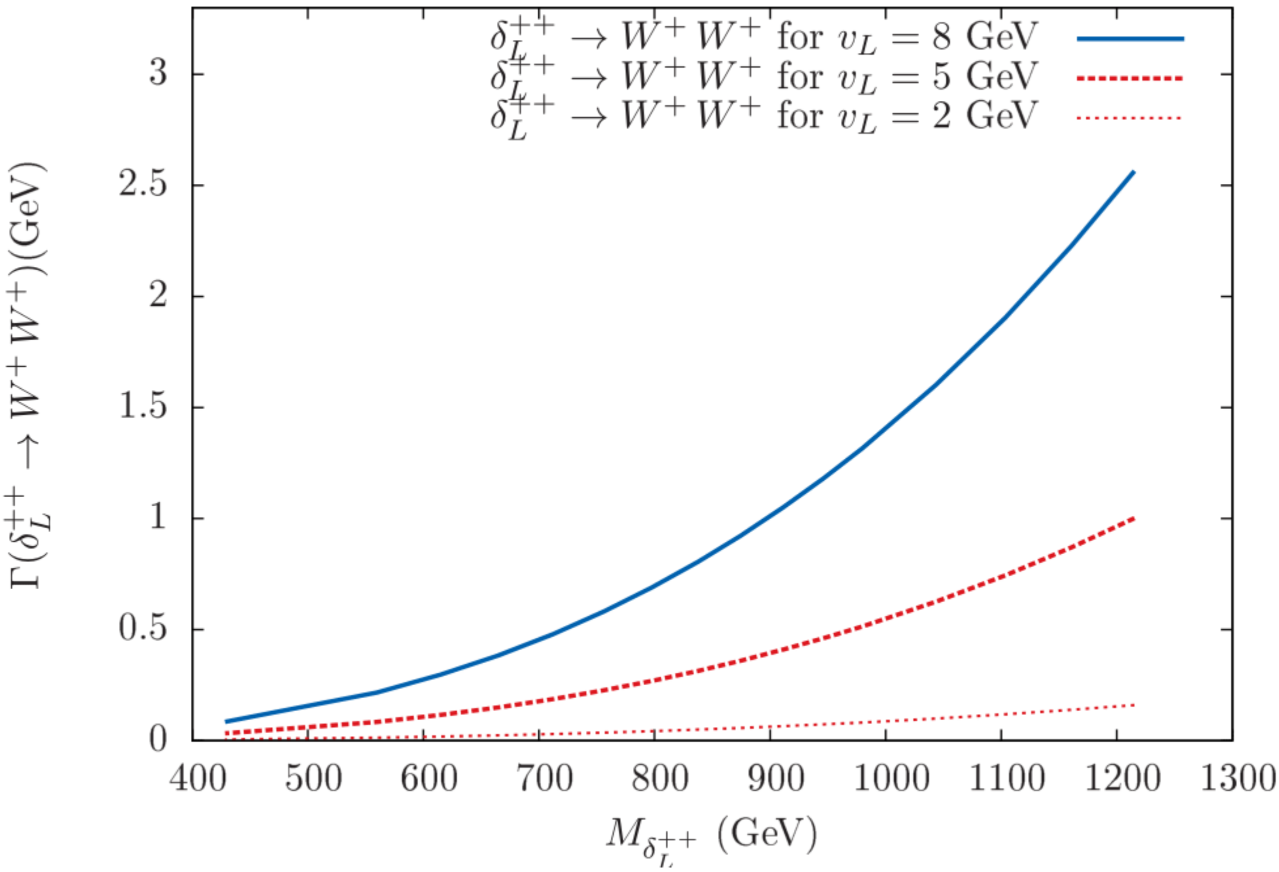

Figure 4.11: Decay Width dependence on the mass of Higgs for the process $\Delta_L^{++} \to W^+ \ W^+$.

Here, We take three scenarios of non-zero VEV of left-handed triplet, $v_L = (2 \ GeV, 5 \ GeV, 8 \ GeV)$ and get results as shown in Figure[4.11], for the decay width of the mode($\delta_L^{++} \to W_L^+ \ W_L^+$). In the case of $v_L = 0$, the direct couplings to two gauge bosons vanish(because the Coupling is proportional to v_L), therefore, we get zero decay width for this mode. The analytic formula of decay rate for this decay mode is given by, [Melfo 12] :-

$$\Gamma(\delta^{++} \to W^+W^+) = \frac{g^4 v_L^2}{8\pi m_{\delta^{++}}} \left(1 - \frac{4m_W^2}{m_{\delta^{++}}^2}\right)^{\frac{1}{2}} \left[2 + (\frac{m_{\delta^{++}}^2}{2m_W^2} - 1)^2\right] \tag{4.14}$$

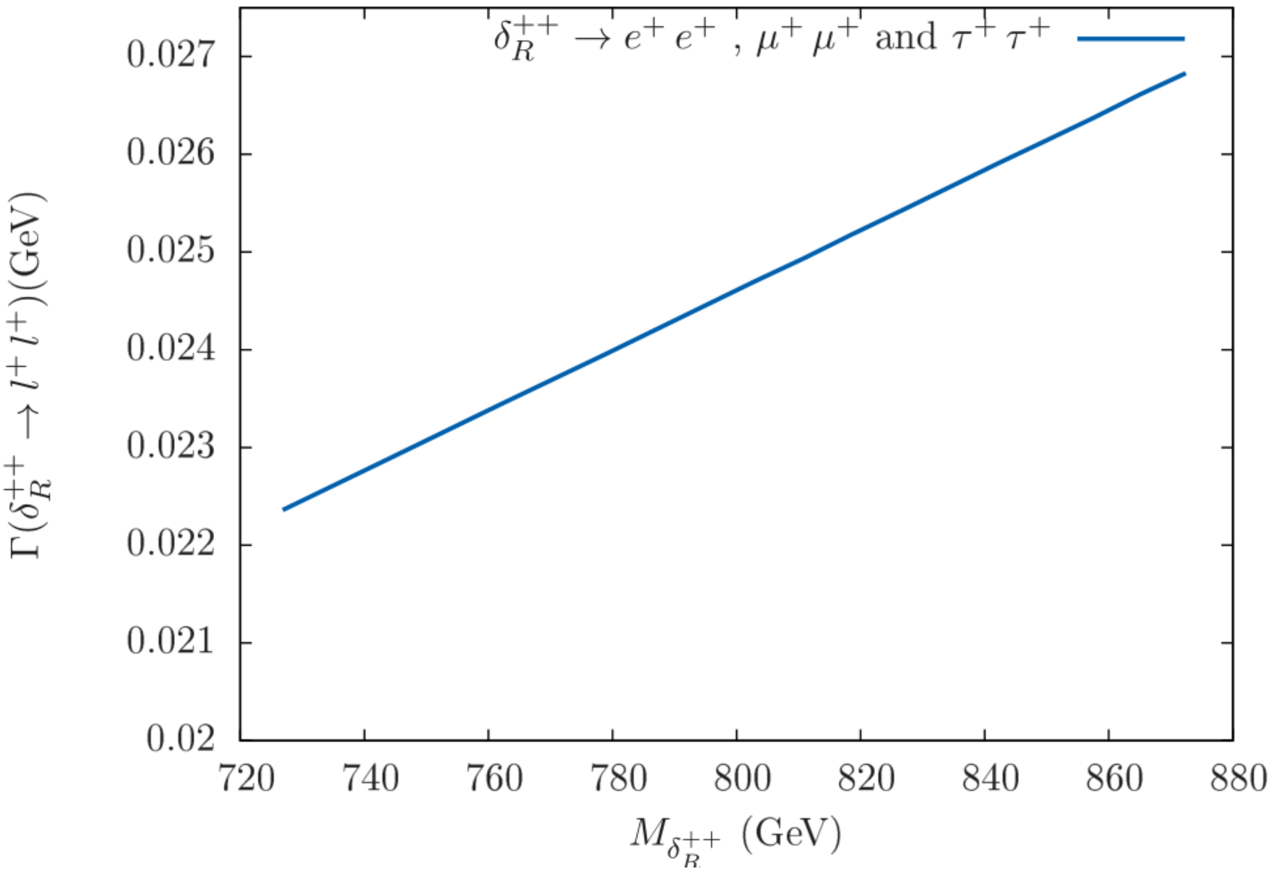

Figure 4.12: Decay Width dependence on the mass of Higgs for the process $\Delta_R^{++} \to l^+ \; l^+$ with same Right-handed Neutrino masses.

Here also, for the three decay modes($\delta_R^{++} \to l^+ \; l^+$; $l = e, \mu, \tau$) we consider same masses(100 GeV) of the three heavy Neutrinos(N_e, N_μ, N_τ) corresponding to three lepton generations, that is why we get same decay width because the coupling depends on Neutrinos masses.

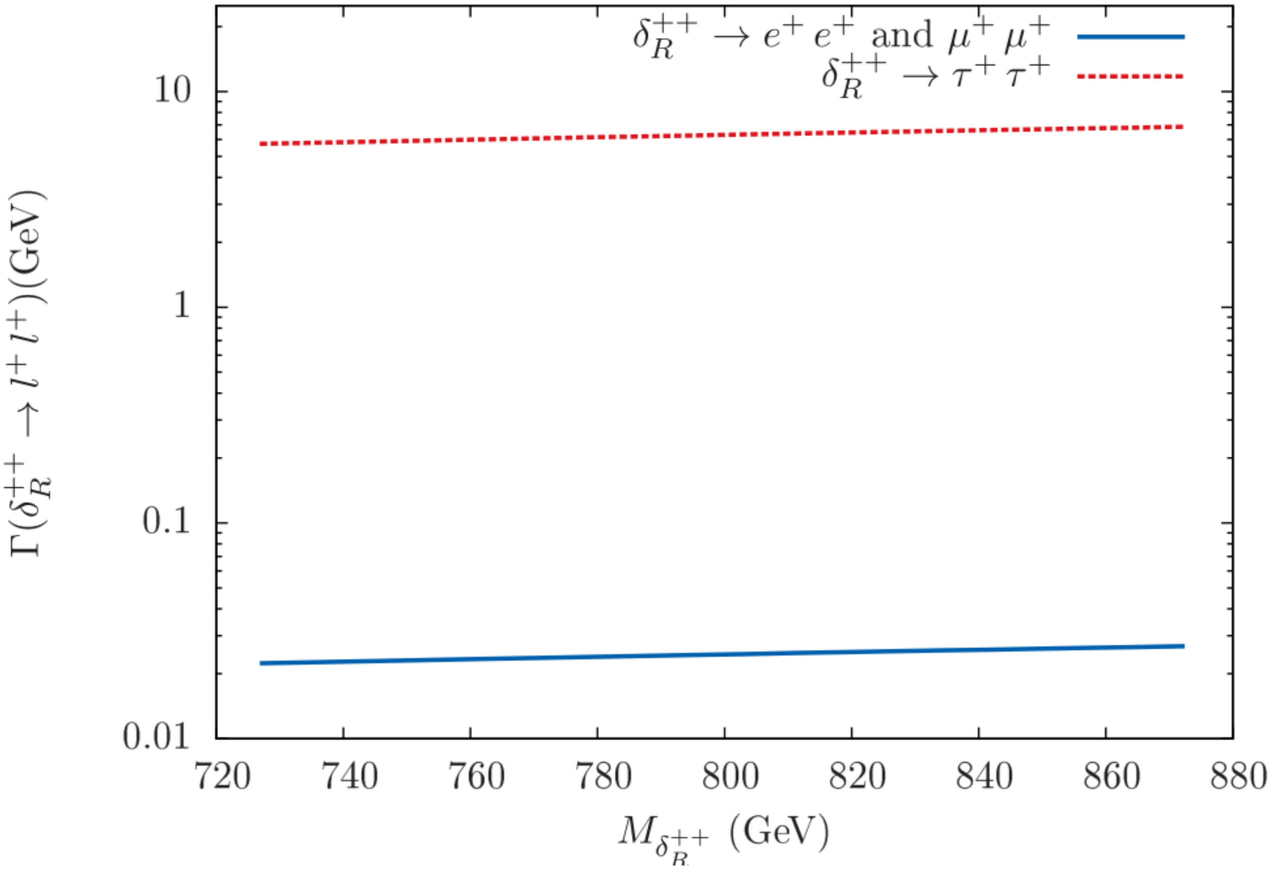

Figure 4.13: Decay Width dependence on the mass of Higgs for the process $\delta_R^{++} \rightarrow l^+\, l^+$ with different Right-handed Neutrino masses.

Here also, for the decay modes($\delta_R^{++} \rightarrow l^+\, l^+\ ;\ l = e, \mu, \tau$) we consider same masses(100 GeV) of the two heavy neutrinos(N_e, N_μ) corresponding to e^+, μ^+ generation and 1600 GeV mass of the third generation Neutrino(N_τ). Due to this fact we get same decay width for the two modes($\delta_R^{++} \rightarrow l^+\, l^+\ ; l = e, \mu$) and large decay width(compared to former two modes) for the mode($\delta_R^{++} \rightarrow \tau^+\, \tau^+$) since $M_{N_\tau} = 1600$ GeV, is quite large than $M_{N_e} = M_{N_\mu} = 100$ GeV.

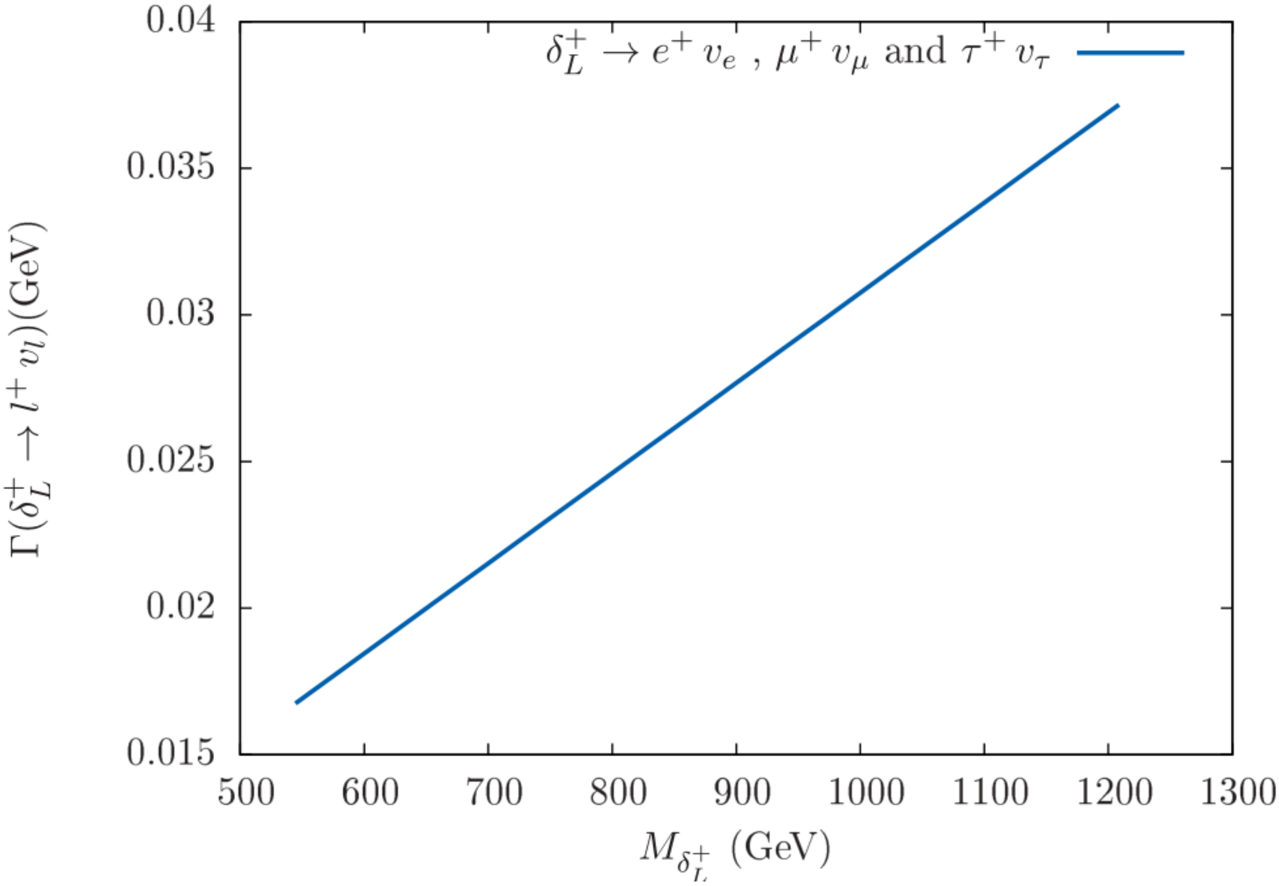

Figure 4.14: Decay Width dependence on the mass of Higgs for the process $\delta_L^+ \to l^+$ ν_l with same Right-handed Neutrino masses.

Here, for the three decay modes($\delta_L^+ \to l^+ \ \nu_l;\ l = e, \mu, \tau$) we consider same masses(100 GeV) of the three heavy Neutrinos(N_e, N_μ, N_τ) corresponding to three lepton generations, that is why we get same decay width due to decay width formula because the coupling depends on Neutrinos masses.

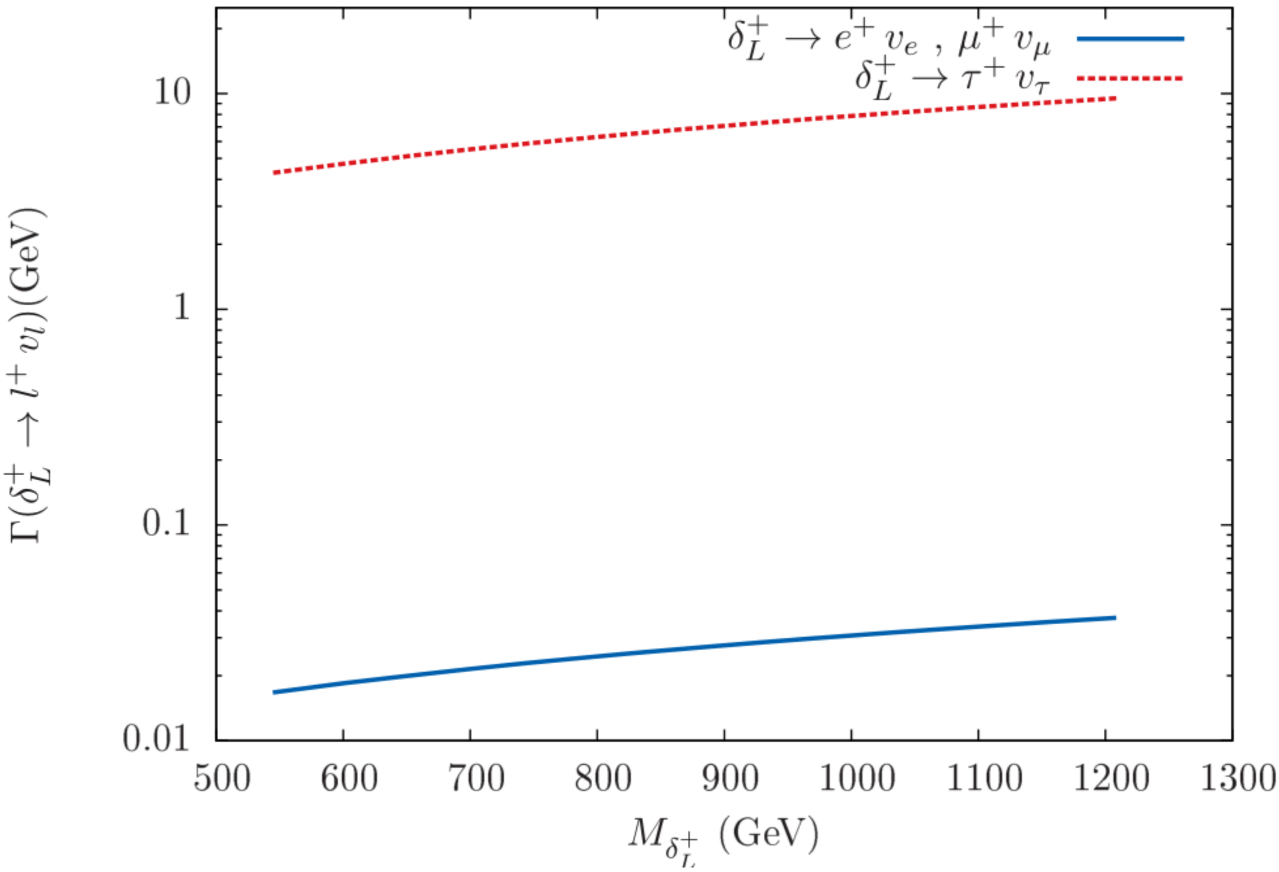

Figure 4.15: Decay Width dependence on the mass of Higgs for the process $\delta_L^+ \to l^+ \nu_l$ with different Right-handed Neutrino masses.

Here, for the decay modes($\delta_L^+ \to l^+ \nu_l; l = e, \mu$) we consider same masses(100 GeV) of the two heavy neutrinos(N_e, N_μ) corresponding to e^+, μ^+ generation and 1600 GeV mass of the third generation Neutrino(N_τ). Due to this fact we get same decay width for the two modes($\delta_L^+ \to l^+ \nu_l; l = e, \mu$) and large decay width(compared to former two modes) for the mode($\Delta_L^{++} \to \tau^+ \tau^+$) since $M_{N_\tau} = 1600$ GeV, is quite large than $M_{N_e} = M_{N_\mu} = 100$ GeV.

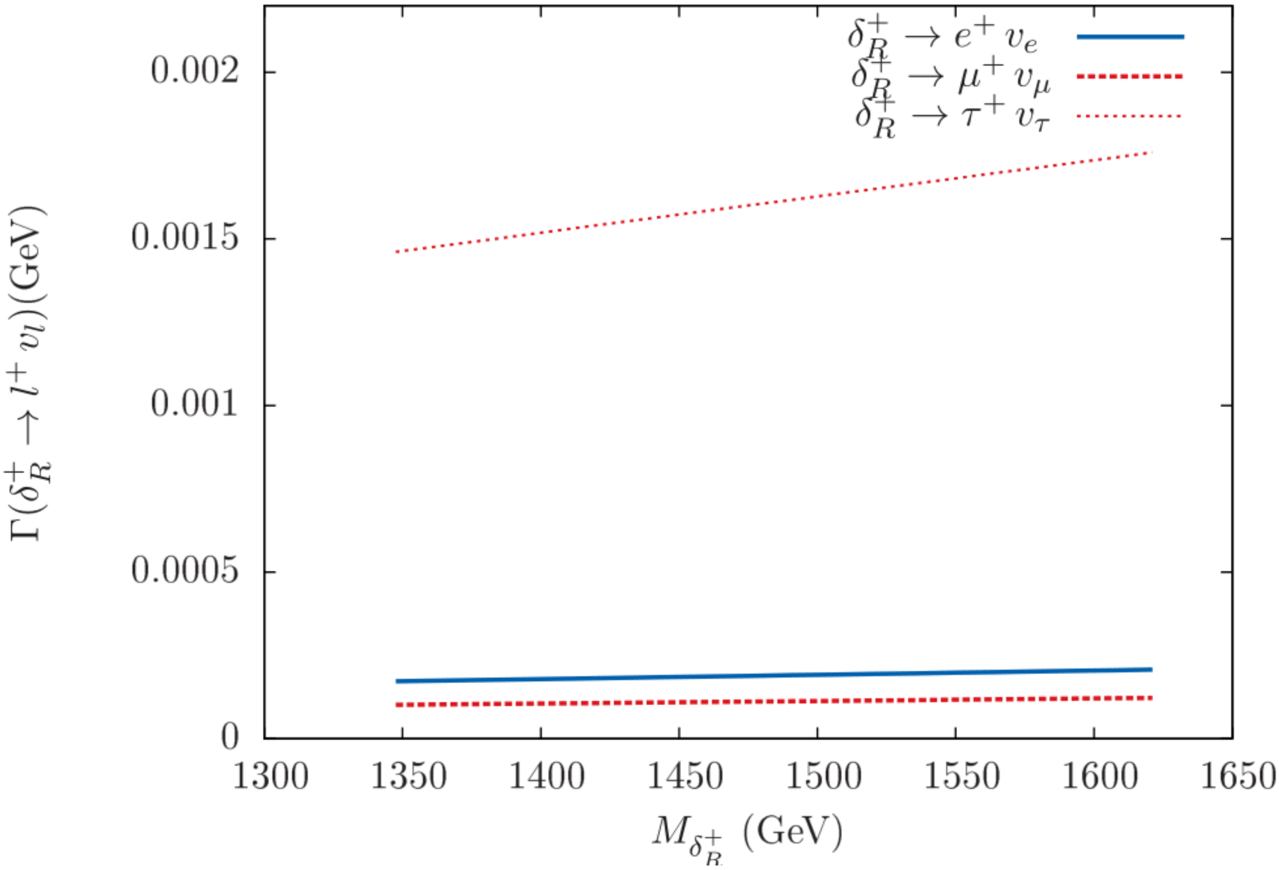

Figure 4.16: Decay Width dependence on the mass of Higgs for the process $\delta_R^+ \to l^+$ ν_l with same Right-handed Neutrino masses.

Here, for the three decay modes($\delta_R^+ \to l^+ \ \nu_l; \ l = e, \mu, \tau$) we consider same masses(100 GeV) of the three heavy Neutrinos(N_e, N_μ, N_τ) corresponding to three lepton generations and we get different-2 decay rates for different-2 generations.

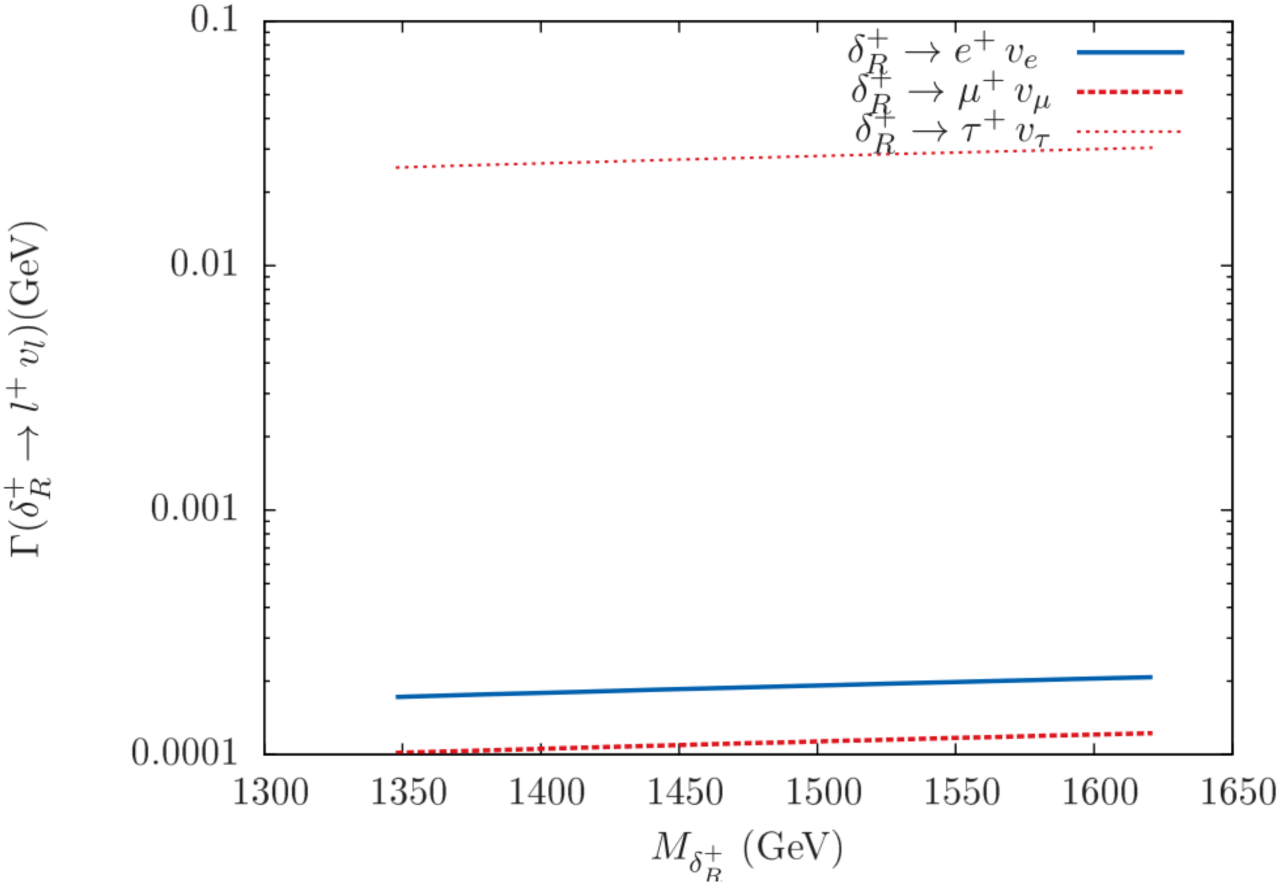

Figure 4.17: Decay Width dependence on the mass of Higgs for the process $\delta_R^+ \to l^+ \, \nu_l$ with different Right-handed Neutrino masses.

Here, for the decay modes($\delta_R^+ \to l^+ \, \nu_l; \, l = e, \mu$) we consider same masses(100 GeV) of the two heavy neutrinos(N_e, N_μ) corresponding to e^+, μ^+ generation and 1600 GeV mass of the third generation Neutrino(N_τ).

$M_{\delta^{++}}$ (In GeV)	Cross-section(In pb),σ	Branching Ratios (B.R.)	$\sigma\times$B.R.(In pb)
1043.5	0.00003079	(a) 0.007753 (for e^+e^++$\mu^+\mu^+$ modes) . (b) 0.992247 (for $\tau^+\tau^+$)	(a)2.387149 $\times$ 10^{-7} (for e^+e^+ + $\mu^+\mu^+$ modes) (b) 3.055129 $\times$ 10^{-5} (for $\tau^+\tau^+$)
911.13	0.0002871	(a) 0.007741 (for e^+e^++$\mu^+\mu^+$ modes) . (b)0.992259 (for $\tau^+\tau^+$)	(a) 2.222441 $\times$ 10^{-6} (for e^+e^++$\mu^+\mu^+$ modes) (b) 2.2669396 $\times10^{-4}$(for $\tau^+\tau^+$)
664.9	0.002287	(a) 0.007753 (for e^+e^++$\mu^+\mu^+$ modes) . (b) 0.992247 (for $\tau^+\tau^+$)	(a) 1.773111 $\times$ 10^{-5} (for e^+e^++$\mu^+\mu^+$ modes) (b) 2.269269 $\times10^{-3}$(for $\tau^+\tau^+$)
428.23	0.00711	(a) 0.007754 (for e^+e^++$\mu^+\mu^+$ modes) . (b) 0.992246 (for $\tau^+\tau^+$)	(a)5.513094 $\times$ 10^{-5} (for e^+e^++$\mu^+\mu^+$ modes) (b) 7.054869 $\times10^{-3}$(for $\tau^+\tau^+$)

Table 4.4: $Cross-section\times$ Brancing Ratios for $\delta_L^{++}\rightarrow e^+e^+$,$\mu^+\mu^+,\tau^+\tau^+$ when $M_{N_1}=M_{N_2}=100$ GeV and $M_{N_3}=1600$ GeV.

Chapter 5

Conclusion

We have seen through the study of the $B - L$ model and Left-Right Symmetric Models(LRSM), that these models resovle the neutrino mass problem and smallness of the left-handed neutrinos because of the 'See-saw Mechanism' as discussed in section(2.4 and 3.4). Both of these models gives rise to interesting TeV scale Phenomenology which includes extra gauge bosons(Z', W') and other Higgs fields searches at next generation colliders and upgraded LHC(at 14 TeV). In LRSM, there are 14 physical Higgs, these give rise to rich and interesting higgs phenomenology. In this project, we study mainly the higgs phenomenology of LRSM. First, we studied the production of the Right-handed Doubly charged Higgs at LHC at 14 TeV, which gave quite interesting results about the dependence of the cross-section on the mass of the Doubly Charged Higgs:-

$$\sigma(pp \to \delta_R^{++}\delta_R^{--}) = \frac{0.5782}{m_\delta} - \frac{2502.8}{m_\delta^2} + \frac{2.66781 \times 10^6}{m_\delta^3} \tag{5.1}$$

Later, I studied the decays of Doubly charged Higgs into interesting decay modes of two like-sign leptons($l^+ \ l^+$) and two charged gauge bosons($W^+ \ W^+$) using MadGraph. Further, we studied the singly charged Higgs decay into a lepton plus neutrino($l \ v_l$) mode.The results have been plotted in section(4.4), which shows the dependence of the decay width on the masses of Higgs. We have also studied the dependence of the Higgs masses on the parameters of the Higgs potential in the section(4.3), which is a important thing to explore before studying the decays of Higgs.

At last, I want to make some concluding remarks on the importance of Higgs Triplet Fields phenomenology of MLRSM, [Melfo 12] :-

- **Probing the Flavor Structure :** The Doubly Charged Higgs decaying to two like-sign charged leptons probe the neutrino masses and mixings. The decay rate is given by :-

$$\Gamma(\delta^{++} \to l_i l_j) = \frac{m_{\delta^{++}}}{8\pi(1+\delta_{ij})} |\frac{(U^* m_\nu U^\dagger)_{ij}}{v_L}|^2 \tag{5.2}$$

  This makes an interesting connection between the collider physics and the low energy processes. If this were the only mode, then one could probe the Yukawa flavor structure through the branching ratios to the different flavor modes. In addition, the deacy modes of Singly Charged Higgs,$\delta^+ \to l_i \nu_l$ may also be important to probe Yukawa flavor structure.

- **Probing the Neutrino Mass Scale :** The probing of flavor structure as above gives the information about ratios of the neutrino masses and by using the neutrino oscillations data one might get the absolute neutrino mass scale.There is also a chance of directly measuring the scale at LHC. The other decay mode, $\delta^{++} \to W^+W^+$ open up for non-zero v_L.

$$\Gamma(\delta^{++} \to W^+W^+) = \frac{g^4 v_L^2}{8\pi m_{\delta^{++}}} \left(1 - \frac{4m_W^2}{m_{\delta^{++}}^2}\right)^{\frac{1}{2}} \left[2 + (\frac{m_{\delta^{++}}^2}{2m_W^2} - 1)^2\right] \tag{5.3}$$

  If this channel is large enough, it would determine the v_L. The critical value is obtained for $\Gamma(\delta^{++} \to l_i l_j) = \Gamma(\delta^{++} \to W^+W^+)$, which give us $v_L = 10^{-4}$ to 10^{-3}.

Appendix A

Notation and Adjustable Parameters as used in FeynRules and Madgraph

The input parameters of MLRSM and their symbols in the model file are collected in Table A.1. The list of adjustable parameters in the model file is given in Table A.1. We can also adjust other dependent parameters in the file,but the consistency must be kept, e.g., we can set numerical value of M_{W_2} instead of v_R, but then the consistency of the model require that $v_R = \frac{M_{W_2}}{M_W}\sqrt{(k_1^2 + k_2^2)/2}$. The model file of FeynRules uses the unitary gauge, so that all the Goldstone modes are omitted in the Feynman rules calculations, [Duka 00].

Category	LRSM symbols	FeynRules model symbols
Fermion doublet(rotated-unphysical)	$Q_{iL},\ Q_{iR},\ L_{iL},\ L_{iR},\ (L^c)_{iL},\ (L^c)_{iR}$ (i=1,2,3)	QL, QR, LL, LR, LCL, LCR
Gauge boson fields(rotated-unphysical)	W_{iL}, W_{iR},B (i=1,2,3)	Wi, WRi, B
Particle names(physical states)	W,Z,A,g (SM Gauge bosons) W_2, Z_2 (Extra SM gauge bosons) u, c, t (Up type quarks) d, s, b (Down type quarks) e, μ, τ (Charged leptons) ν_e, ν_μ, ν_τ (Light neutrinos) N_e, N_μ, N_τ (Heavy neutrinos) H_0^0,H_1^0,H_2^0,H_3^0(Neutral higgs scalars) A_1^0,A_2^0(Neutral higgs pseudoscalars) $H_1^\pm$,$H_2^\pm$(Singly charged Higgs) $\delta_L^{\pm\pm}$,$\delta_R^{\pm\pm}$(Doubly charged Higgs) $\tilde{G}_1^0$,$\tilde{G}_2^0$(Neutral Goldstone bosons) $G_L^\pm$,$G_R^\pm$(Charged Goldstone bosons)	W,Z,A,G W2,Z2 u, c, t (class name: uq) d, s, b (class name: dq) e, mu, ta (class name: 1) NeL,NmL,NtL NeH,NmH,NtH (class name: N1) H,H01,H02,H03 A01,A02 HP1,HP2 HPPL,HPPR G01,G02 GPL,GPR
Particle masses	$M_{RelevantParticle}$	the letter M + Particle name
Decay widths	$\Gamma_{RelevantParticle}$	Either zero or the letter W + Particle name
Mixing matrices	U_L^{CKM},U_R^{CKM},K_L,K_R	CKML, CKMR, KL, KR
Quasi manifest matrices	W^l,W^U,W^D	Wl, WU, WD
Mixing angles	$sin\theta_W$,$cos\theta_W$,$sin\xi$,$cos\xi$,$sin\phi$,$cos\phi$	sw,cw,sxi,cxi,sphi,cphi
Higgs VEVs	k_1,k_2,v_L,v_R	k1,k2,nuL,nuR
Higgs multiplets	ϕ,$\tilde{\phi}$,Δ_L,Δ_R	BD,BDtilde,LT,RT
Higgs multiplets field components	$\phi_{1,2}^0$,$\phi_{1,2}^\pm$,$\delta_{L,R}^0$,$\delta_{L,R}^\pm$,$\delta_L^{\pm\pm}$,$\delta_R^{\pm\pm}$	Phi01,Phi02,PhiP1,PhiP2, H0L,H0R,HPL,HPR,HDPL,HDPR

Table A.1: The MLRSM parameters and their corresponding symbols in the Feyn-

Appendix B

Parameters,Masses and Mixing Angles of MLRSM

The non-adjustable parameters of the model file(FeynRules/Madgraph model file) are defined by the expressions given in this appendix. These expressions consist both adjustable and non-adjustable parameters which are listed in Table A.1, Here, for these expressions, we considered the phenomenological motivated constraints and approximations $k_1, k_2 << v_R$ and $v_L = 0$, Expressions are as follow,[Duka 00], [Roitgrund 14]:-

$$M_{Z_1}^2 \approx \frac{g^2 k_+^2}{4cos^2\theta_W}, \quad M_{Z_2}^2 \approx \frac{g^2 v_R^2 cos^2\theta_W}{cos2\theta_W}, \quad Mixing \quad Angle, sin2\phi = -\frac{k_+^2 (cos2\theta_W)^{\frac{3}{2}}}{2v_R^2 cos^4\theta_W}$$

$$M_{W_1}^2 \approx \frac{g^2 k_+^2}{4}, \quad M_{W_2}^2 \approx \frac{g^2 v_R^2}{2}, \quad Mixing \quad Angle, tan2\xi = -\frac{2k_1 k_2}{v_R^2}$$

$$M_{H_0^0}^2 \approx 2k_+^2 \left(\lambda_1 + \frac{4k_1^2 k_2^2}{k_+^4 (2\lambda_1 + \lambda_3)} + 2\lambda_4 \frac{2K_1 K_2}{K_+^2} \right), \quad M_{H_1^0}^2 \approx \frac{\alpha_3 v_R^2 k_+^2}{2k_-^2},$$

$$M_{H_2^0}^2 \approx 2\rho_1 v_R^2, \quad M_{H_3^0}^2 \approx \frac{1}{2} v_R^2 (\rho_3 - 2\rho_1)$$

,

$$M_{A_1^0}^2 = \frac{\alpha_3 v_R^2 k_+^2}{2k_-^2}, \quad M_{A_2^0}^2 = \frac{1}{2} v_R^2 (\rho_3 - 2\rho_1) \quad ,$$

$$M_{H_1^\pm}^2 = \frac{1}{4}\alpha_3 k_-^2 + \frac{1}{2} v_R^2 (\rho_3 - 2\rho_1), \quad M_{H_1^\pm}^2 = \frac{1}{4}\alpha_3 \left(k_-^2 + 2\frac{k_+^2}{k_-^2} v_R^2 \right),$$

$$M_{\delta_L^{\pm\pm}}^2 = \frac{1}{2}(\alpha_3 k_-^2 + v_R^2(\rho_3 - 2\rho_1)), \quad M_{\delta_R^{\pm\pm}}^2 = \frac{1}{2}(\alpha_3 k_-^2 + 4v_R^2 \rho_2),$$

$$\mu_1^2 \approx v_R^2 \left(\frac{\alpha_1}{2} - \frac{\alpha_3 k_2^2}{2k_-^2} \right), \quad \mu_2^2 \approx v_R^2 \left(\frac{\alpha_2}{2} + \frac{\alpha_3 k_1 k_2}{4(k_1^2 - k_2^2)} \right), \quad \mu_3^2 \approx \rho_1 v_R^2$$

Where $k_\pm = \sqrt{k_1^2 \pm k_2^2}$ and λ_i,ρ_i and α_i are the couplings in the Higgs potential.

Bibliography

[Aad 12] Georges Aad*et al.* *Search for doubly-charged Higgs bosons in like-sign dilepton final states at $\sqrt{s} = 7$ TeV with the ATLAS detector.* Eur. Phys. J., vol. C72, page 2244, 2012.

[Deshpande 91] N. G. Deshpande, J. F. Gunion, B. Kayser & Fredrick Olness. *Left-right-symmetric electroweak models with triplet Higgs field.* Phys. Rev. D, vol. 44, pages 837–858, Aug 1991.

[Duka 00] P. Duka, J. Gluza & M. Zralek. *Quantization and renormalization of the manifest left-right symmetric model of electroweak interactions.* Annals Phys., vol. 280, pages 336–408, 2000.

[Eidelman 04] S. Eidelman*et al.* *Review of particle physics. Particle Data Group.* Phys. Lett., vol. B592, pages 1–1109, 2004.

[Gunion 89] J. F. Gunion, J. Grifols, A. Mendez, B. Kayser & F. Olness. *Higgs bosons in left-right-symmetric models.* Phys. Rev. D, vol. 40, pages 1546–1561, Sep 1989.

[Han 05] Tao Han. *Collider phenomenology: Basic knowledge and techniques.* In Physics in D ¿= 4. Proceedings, Theoretical Advanced Study Institute in elementary particle physics, TASI 2004, Boulder, USA, June 6-July 2, 2004, pages 407–454, 2005.

[Kokado 15] Akira Kokado & Takesi Saito. *New Mixing Angles in the Left-Right Symmetric Model.* Phys. Rev., vol. D92, page 125008, 2015.

[Lahiri 05] A. Lahiri & P.B. Pal. A first book of quantum field theory. Alpha Science International, 2005.

[Melfo 12] Alejandra Melfo, Miha Nemevsek, Fabrizio Nesti, Goran Senjanovic & Yue Zhang. *Type II Seesaw at LHC: The Roadmap*. Phys. Rev., vol. D85, page 055018, 2012.

[Mohapatra 91] R.N. Mohapatra & P.B. Pal. Massive neutrinos in physics and astrophysics. Lecture Notes in Physics Series. World Scientific, 1991.

[Peskin 95] M.E. Peskin & D.V. Schroeder. An introduction to quantum field theory. Advanced book classics. Addison-Wesley Publishing Company, 1995.

[Pruna 11] Giovanni Marco Pruna. *Phenomenology of the minimal $B-L$ Model: the Higgs sector at the Large Hadron Collider and future Linear Colliders*. PhD thesis, Southampton U., 2011.

[Roitgrund 14] Aviad Roitgrund, Gad Eilam & Shaouly Bar-Shalom. *Implementation of the left-right symmetric model in FeynRules/CalcHep*. 2014.

[Tello 12] Vladimir Tello. *Connections between the high and low energy violation of Lepton and Flavor numbers in the minimal left-right symmetric model*. PhD thesis, SISSA, Trieste, 2012.