”Whatever Nature has in store for mankind, unpleasant as it may be, men must accept, for ignorance is never better than knowledge.”

Enrico Fermi

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Introduction

Neutrinos have drawn the attention of particle physicists around the world in the last few decades. This elusive particle was proposed much before it was detected to solve some fundamental observations of nuclear physics. In 1914, James Chadwick showed that the beta decay energy spectrum is a continuous one, opposite of what was expected [1]. During that period, electrons and protons are considered to be the basic building blocks of matter and the nucleus is the bound state of both. These assumptions cannot successfully explain the fundamental observation of continuous β decay spectrum along with the problem of spin of some nuclei. β decay is nothing but a process of emission of electrons from a nucleus (A,Z) with the atomic number Z and mass number A in the transition-

$$(A,Z) \longrightarrow (A,Z+1) + e^{-} \tag{1.1}$$

From the theoretical point of view, the released electron should have fixed kinetic energy, approximately equal to the released energy according to the conservation of energy and momentum. But, the β decay spectrum is found to be continuous with endpoint energy equal to the released energy experimentally. Still, physicists were trying to fix the problem of the continuous energy spectrum of β decay by assuming energy loss of electron at the target which was later denied by the Ellis and Wooster experiment in 1927. After this experiment, Pauli was the first to understand that, under energy and momentum conservation, the only way to explain this discrepancy is to consider it to be a three-body decay rather than a two-body decay [2]. He hypothesized a particle to account for this energy difference in theoretical calculation and experimental observation. Three body β decay is represented as-

$$(A,Z) \longrightarrow (A,Z+1) + e^- + \nu \tag{1.2}$$

The released energy is shared by the electron and the new particle, which results in continuous energy spectrum. Pauli also proposed it to be a spin half particle like an electron and proton. This assumption solved another problem that existed at that time, the problem of the spin of some nuclei. In 1934, Enrico fermi called this newly hypothesized particle as **neutrinos** [3]. These particles are electrically neutral and hence cannot be detected through electromagnetic interaction ,and they do not interact through strong interaction. The possibility of neutrino interaction through weak force is also less, which makes it difficult for theorists and experimentalists to detect neutrinos. Around 1946, Burno Ponetcorvo first proposed the idea of experimental detection of neutrinos using the inverse beta decay process. Despite these theoretical and experimental efforts made by Pauli, Fermi, and Pontecorvo, there was very little information about this elusive particle during that time. Frederick Reines and Clyde Cowan successfully detected antineutrinos in an observatory at Savvanah river around 1956 [4]. For this discovery, both Reines and Cowan shared the Nobel prize for Physics in 1995. After this, Ray Devis tried to detect the solar neutrinos with his experimental setup at Brookhaven national laboratory (BNL). In 1968, Devis reported the first detection of solar neutrino, but the amount detected was one-third of the total amount of solar neutrino predicted by the solar model. This led to a great discrepancy between theory and experiment named as, the **solar neutrino problem** [5]. The neutrino observed by this experiment was electron neutrino(ν_e). Later on two more flavors of neutrino, muon neutrino (ν_μ) and tau neutrino (ν_τ) were discoverded in 1962 at BNL [6] and in 2000 by the experiment DONUT at Fermilab [7]. Now the solar neutrino problem was addressed by Pontecorvo by assuming that neutrino changes its flavor to another while propagating, which is quantum mechanically possible [8]. This concept leads to the tiny but significant neutrino mass, and this property is known as neutrino oscillation. The discovery of neutrino mass opened up a lot of unaddressed questions in the field of particle physics. Most importantly, the absolute values of neutrino mass is still unknown as the experiments of neutrino oscillations are not sensitive to it and the hierarchy of the mass. One more important issue is whether neutrinos are four-component Dirac type or two-component Majorana type in nature. This is directly related to the concept of lepton number conservation or violation. As the neutrinos are electrically neutral, they can be a Majorana fermion i.e particle is its antiparticle. Theoretically, right-handed Majorana fermions can generate neutrino mass within beyond standard model (BSM) frameworks, although the true nature of neutrino is not determined yet. Another important topic that should be taken care of is the charge lepton flavor violating process. Neutrino oscillation directly implies lepton flavor violation. As the neutral leptons show lepton flavor violation, it is expected that charge leptons also show such kind of decay. But experimentally this kind of decays are not detected yet. Also, there are no conclusive details on CP(Charge-Parity) violation in the leptonic sector which leads to a better understanding of the baryon asymmetry of the Universe (BAU). There are many ongoing and future-generation experiments designed to address these unsolved questions of the particle physics. These open questions are some important motivations for the current and future research of neutrino physics in both theoretical and experimental aspects.

1.1 Current status of neutrinos:

1.1.1 Theoretical Aspect:

In natural sciences, experimental results do confirm theoretical predictions. In the case of neutrino physics also, the experimental and theoretical aspects go hand in hand. Neutrino oscillation is one of the earliest theoretical concepts of neutrino physics proposed by Pontecorvo in 1957 [9, 10]. The complete formulation of neutrino oscillation was later provided by Girbov and Pontecorvo [11]. Neutrino oscillation is a very crucial phenomenon in both theoretical and experimental consideration as it directly implies the massiveness of neutrinos with finite mixing, unlike massless neutrinos in the SM. This phenomenon is the starting point beyond the SM realm. Takaki Kajita and Arthur McDonald were conferred the Nobel prize in physics in 2015 for the discovery of neutrino oscillation. In neutrino oscillation, the flavor eigenstates of neutrinos are related to mass eigenstates by a 3×3 mixing matrix known as Pontecorvo Maki Nagakawa Sakata (PMNS) matrix [12] for three active neutrino scenario. This mixing matrix can be parametrized by three mixing angles solar(θ_{12}), atmospheric (θ_{23}), reactor(θ_{13}) and one physical CP violating phase δ_{cp}. The reactor mixing angle (θ_{13}) is assumed to be zero earlier, which is proved to be wrong later on. Different neutrino oscillation experiments have proved that the reactor mixing angle has non-zero values [34]. Neutrino physics has entered the precision era. Future generation experiments focuses on the precise measurement of atmospheric mixing angle (θ_{23}), correct mass ordering, and determination of CP violating phase. One important aspect of the neutrino oscillation experiments is that these are not sensitive to the absolute mass of the neutrinos but sensitive to the mass square difference of different flavors. Because of this, it is still impossible to measure the absolute mass scale of neutrinos. The cosmological bound coming from the

Planck satellite data put constraints on the sum of the three neutrino mass as $\sum m_\nu < 0.12$ eV [13]. Although the oscillation experiments can precisely measure the mass square difference of three different flavors, they cannot provide information about whether it follows a normal ordering ($m_1 \ll m_2 < m_3$) or inverted ordering ($m_3 \ll m_1 < m_2$).

Data provided by different experiments directly hints toward the existence of the BSM physics. In a theoretical point of view, it is quite important to explore the BSM realm. Several mixing schemes and BSM frameworks have been proposed to explain the neutrino mass and mixing along with other phenomena which remained unaddressed within the SM. Mixing schemes such as bimaximal mixing (BM), tri-bimaximal mixing (TBM), hexagonal mixing (HM) and golden ratio mixing (GRM) have gained attention as these are consistent with the neutrino oscillation data. With the advancement of the neutrino oscillation experiments, some stronger constraints on the parameters have been put forward for which some mixing patterns are discarded. After the confirmation of non zero reactor mixing angle by RENO [25], the TBM mixing pattern has been ruled out. To make it consistent with data, another mixing pattern known as tri-maximal (TM) mixing, has been proposed which is a perturbation to the previous mixing. The tri-maximal (TM) mixing pattern is consistent with the experimental data at present. There are many BSM frameworks proposed as Seesaw, LRSM, radiative seesaw and many GUT theories which address these problems. These frameworks are not only successful in explaining the small neutrino mass but also account for the explanation of BAU, Dark matter, LFV processes, etc.

1.1.2 Experimental progress

The most significant point of experimental neutrino physics is the discovery of neutrino oscillation. Super-Kamioka Neutrino Detection Experiment (Super-Kamiokande) [15–17] and the Sudbury Neutrino Observatory (SNO) [18] are two instrumental experimental set up which came up with the pieces of evidence of atmospheric and solar neutrino oscillation respectively. After this discovery, neutrino flavor oscillation was confirmed by the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) experiment [19]. There has been fast progress in the experimental sector thereafter as it enters the precision era in the current scenario. Different ongoing and future neutrino oscillation experiments are designed in such a way that it collects information about the properties of the neutrinos. Neutrinos from different sources like the Sun, the Earth's atmosphere, supernova explosions, particle accelerators, and nuclear reactors have been investigated in the last few decades. Solar neutrino experiments are sensitive to Δm^2_{31} and solar mixing angle θ_{12}. Super-K [20], Borexino [21], Sage [22], and SNO [18] are some examples of solar neutrino experiments. Measurement of oscillation parameters Δm^2_{23} and mixing angle θ_{23} are mainly done by atmospheric and astrophysical neutrino experiments such as Super-K, Icecube [23], ANTARES, etc. Reactor-based oscillation experiments includes experiments like Daya Bay [24], RENO [25], Double-Chooz [26], etc. There are many accelerator-based experiments are currently going on such as T2K [27], MINOS [28], NOνA [29], OPERA [30], ICARUS [31], Microboone [32], Miniboone [33], etc, which are sensitive to Δm^2_{23}, mixing angle θ_{23}, CP violating phase (δ_{cp}) and even the elusive sterile neutrino. The next important observation related to neutrino oscillation was proposed by Tokai-to-Kamioka (T2K) [34]. T2K is a long baseline experimental setup that provided the first evidence of a non-zero reactor mixing angle (θ_{13}). Later it was confirmed by the reactor-based experiments like Daya Bay [24], Reactor Experiment for neutrino oscillations (RENO)[25] and Double Chooz [26]. The discovery of $\nu_\mu \longrightarrow \nu_e$ appearance by T2K in 2013 [35], later confirmed by NuMI Off-Axis ν_e Appearance(NOνA) experiment [29, 14], plays a crucial role for future development and opened the way towards probing three-flavor effects. All of these experiments aim at solving different open questions in neutrino physics like the ordering of the neutrino masses, absolute mass scale, their mixing angles, etc. These experiments are successful in providing the oscillation parameters with high accuracy which can be seen in table 1.1.

Oscillation parameters	bfp$\pm$ 1σ	3σ(NO)	bfp $\pm$ 1σ	3σ(IO)
$\Delta m^2_{21}[10^{-5}eV^2]$	$7.42^{+0.21}_{-0.20}$	6.82 - 8.04	$7.42^{+0.21}_{-0.20}$	6.82 - 8.04
$\Delta m^2_{31}[10^{-3}eV^2]$	$2.515^{+0.028}_{-0.026}$	2.435 - 2.598	$-2.498^{+0.028}_{-0.028}$	-2.584- -2.413
$sin^2\theta_{12}/10^{-1}$	$3.04^{+0.013}_{-0.012}$	2.69 - 3.43	$3.04^{+0.013}_{-0.012}$	2.69 - 3.43
$sin^2\theta_{23}/10^{-1}$	$5.73^{+0.018}_{-0.023}$	4.05 - 6.20	$5.78^{+0.017}_{-0.021}$	4.10 - 6.23
$sin^2\theta_{13}/10^{-2}$	$2.220^{+0.062}_{-0.063}$	2.032 - 2.41	$2.238^{+0.00064}_{-0.00062}$	2.053 - 2.434
$\delta_{CP}/^0$	194^{-25}_{+52}	105 - 405	287^{-32}_{+27}	192- 361

Table 1.1 Latest Global fit neutrino oscillation Data [36].

Whether neutrinos are four-component Dirac particles possessing a conserved lepton number or two-component lepton number violating Majorana particles is still an open question in neutrino physics. The neutrinoless double beta decay (NDBD/$0\nu\beta\beta$) [37, 38] is one such fundamental process that arises in the beyond SM framework. In this slow and radioactive process, a nuclide of atomic number Z transforms into its isobar with the atomic number $Z+2$,

$$N(A,Z) \longrightarrow N(A,Z+2) + e^- + e^- \tag{1.3}$$

The experiments running for the search of the NDBD process are sensitive to the effective Majorana neutrino mass, which is a combination of the neutrino mass eigenstates and neutrino mixing matrix terms. Although, there is no significant result from these experiments exists to date. But new generation of experiments are already running or about to run to explore effective neutrino mass along with decay rates of the NDBD process. In addition to the lifetime of NDBD combined with sufficient knowledge of the nuclear matrix elements (NME), one can set a constraint on the effective neutrino mass. The experiments that have improved the lower bound of the half-life of the decay process include KamLANDZen [39] and GERDA [40] which use Xenon-136 and Germanium-76 nuclei respectively. Incorporating the results from the first and second phases of the experiment, KamLAND-Zen imposes the best lower limit on the decay half-life using Xe-136 as $T^{0\nu}_{1/2}> 1.07 \times 10^{26}$ yr at 90 percent CL and the corresponding upper limit of effective Majorana mass in the range $(0.06-0.165)$ eV. In SM the decay rates of Lepton flavor violating decays are suppressed by the tiny neutrino mass, which is well below the current experimental limits and near-future sensitivity. No experiment so far has observed a flavor-violating process involving charged leptons. However, many experiments are currently going on to set strong limits on the most relevant LFV observables that will constrain the parameter space of many new physics models. The most stringent bounds on LFV come from the MEG experiment [41]. The limit on branching ratio for the decay of $\mu \to e\gamma$ from this experiment is obtained to be Br($\mu \to e\gamma$)$< 4.2 \times 10^{-13}$. In the case of $l_\alpha \to 3l_\beta$ decay constrain comes from the SINDRUM experiment [42] is set to be $\mathrm{BR}(\mathrm{l}_\alpha \to 3\mathrm{l}_\beta) < 10^{-12}$.

The number of active neutrinos is restricted to three according to LEP data. However, there is no restriction on the existence of the fourth flavor of neutrino which is known as sterile neutrino that does not couple with W and Z Boson. A hint towards the extra generation of neutrino is given by LSND [43, 44] and MiniBooNE [33]. In the confusing results of these two experiment revives the hypothetical existence of fourth state of neutrino by calculation of production rate of $\bar{\nu}_e$ in the nuclear reactors, that yields 3 % higher flux of $\bar{\nu}_e$ than previously predicted by experiments. This calculation then implies that the measured event rates for all reactor $\bar{\nu}_e$ experiments within 100 meters of the reactor are about 6% too low. The deficit can be explained by an hypothetical fourth massive ν separated from the three others by a new $\Delta m^2 > 0.1\ eV^2$. This is known as reactor anomaly. Cosmological observations [45] (mainly CMB or SDSS) are also in favor of the existence of sterile neutrinos. This additional flavor of neutrino in SM will generate new mixing. Sterile fermion is still a hypothesis as the experiments dedicated to detect sterile neutrinos are unable give significant results to date. Though Standard Model (SM) provides a coherent and successful framework to account for a wide range of experimental data in particle physics, it fails to explain many issues in the neutrino sector as well as cosmology. It indicates that there may be some new physics beyond SM that are responsible for generating neutrino masses, mixing, and other related issues. To explain neutrino masses and mixing, many extensions of the SM require the introduction of sterile fermions. We discuss the Standard Model and its drawbacks in the later sections.

1.2 The Standard Model of particle physics

Glashow-Weinberg-Salam initially proposed the SM of particle physics. It is a relativistic quantum field theory with the application of local gauge theory [46–48]. The SM is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. These groups represent three of the four fundamental forces which are strong nuclear force, weak nuclear force, and electromagnetic force respectively except gravitational force. Here, the $SU(3)$ group is used to describe strong force where C stands for the color charge of the quarks and gluons, which are the mediators of the strong force. Electro-weak force is represented by the group $SU(2) \times U(1)$. In this case, L stands for left-handed chirality and Y stands for weak hypercharge. The discovery of the Higgs boson [49, 50] in the Large Hadron Collider (LHC) in 2012 has made the SM one of the successful theories of particle physics.

Particles of the SM can be categorized into three different sections namely fermions, Gauge Bosons, and scalars. Three flavors of quarks and leptons come under the fermion sector. Quarks having the color charges transforms as triplets and leptons being color neutral transforms as singlet under Gauge group $SU(3)_C$. One of the important assumptions of the SM is that the left-handed fermions field transforms as doublet and right-handed fermions as singlet under $SU(2)_L$. All the fermions are charged under $U(1)_Y$. In the Gauge Boson sector, for mediation of strong interaction, there are eight massless vector fields known as gluons which are electrically neutral and charged under $SU(3)_C$. Similarly, a photon (γ) is responsible for the mediation of the electromagnetic force which is massless and electrically neutral. For weak interaction, $W^\pm$ and Z Boson is the mediator, where $W^\pm$ Boson are massive charged particles and Z Boson is a neutral massive particle. In SM, masses of fermions and Gauge Bosons except neutrinos are generated through the Higgs mechanism where Higgs

Boson plays an important role. Higgs Boson is a scalar particle which is a singlet under $SU(3)_C$ and doublet under $SU(2)_L$. Particle content and their charge assignment under gauge group is given in 1.2.

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
lepton doublets	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	1	2	-1
lepton singlets	e_R	1	1	-2
quark doublet	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	3	2	$1/3$
quark singlets	u_R	$\bar{3}$	1	$4/3$
	d_R	$\bar{3}$	1	$-2/3$
Higgs doublet	$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1	2	1

Table 1.2 Charge assignments of leptons, quarks and Higgs field under the standard model gauge group

1.2.1 The Electroweak sector

The electroweak part of the SM describes all the electromagnetic and weak interactions by gauge group $SU(2)_L \times U(1)_Y$. The most important principles of the SM are local gauge symmetry, spontaneous symmetry breaking, and the Higgs mechanism. The gauge theory relies on the study of Lagrangian density which contains all the information on interactions and dynamics of different fields of the theory. The SM Lagrangian is invariant under a local gauge transformation, which is given by-

$$\bar{\Psi}'_L = e^{(ig\frac{\tau}{2}\theta(x)+ig'\frac{Y}{2}\Theta(x))}\bar{\Psi}_L, \bar{\Psi}'_R = e^{ig'\frac{Y}{2}\Theta(x)}\bar{\Psi}_R \tag{1.4}$$

In the local gauge transformation, we have to change the ordinary derivative to a covariant derivative given as,

$$D_\mu = \partial_\mu + i\frac{g}{2}\tau_a W^a_\mu + i\frac{g'}{2} Y B_\mu \tag{1.5}$$

With the introduction of two gauge fields W_μ^a and B_μ, the symmetry groups $SU(2)$ and $U(1)$ are gauged respectively. τ_a and Y are generator of these gauge groups with $a = 1,2,3$ which represents three different generations of leptons. g and g' are the coupling constants of electromagnetic and weak interactions respectively. The gauge term containing pure gauge interactions can be written as,

$$\mathcal{L}_{gauge} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \tag{1.6}$$

where,

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g\varepsilon^{abc}W^b_\mu W^c_\nu,\ \ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \tag{1.7}$$

Where ε^{abc} is the structure constant for $SU(2)$ group. The Lagrangian for fermion sector is given as-

$$\mathcal{L}_{fermion} = \bar{L}\gamma^\mu(i\partial_\mu - g\frac{\tau}{2}W_\mu - g'\frac{Y}{2}B_\mu)L + \bar{R}\gamma^\mu(i\partial_\mu - g'\frac{Y}{2}B_\mu)R \tag{1.8}$$

The Lagrangian for the Higgs field is given by-

$$\mathcal{L}_{Higgs} = [(i\partial_\mu - g\frac{\tau}{2}W_\mu - g'\frac{Y}{2}B_\mu)\phi]^2 - V(\phi) \tag{1.9}$$

The Yukawa Lagrangian for the quark and leptons are given as-

$$\mathcal{L}_y = -Y_d[\bar{Q_L}\phi d_R] - Y_u[\bar{Q_L}\tilde{\phi}u_R] - Y_l[\bar{l_L}\phi l_R] + h.c \tag{1.10}$$

The electroweak Lagrangian in SM can be written as,

$$\mathcal{L}_{EW} = \mathcal{L}_{gauge} + \mathcal{L}_{fermion} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \tag{1.11}$$

It is clear from the Lagrangian that scalar potential and the Higgs field will explain fermion and gauge Boson mass through spontaneous symmetry breaking (SSB) and the Higgs mechanism which will be discussed in the next section. The Yukawa Lagrangian implies that due to the absence of right-handed (RH) neutrino, the mass term for neutrino does not arise within the framework of the SM.

1.2.2 Origin of gauge boson and and fermion mass:

The electroweak theory is a nonabelian theory of gauge group $SU(2)_L \times U(1)_Y$. In this theory one has to generate masses of three gauge Boson of weak interaction $W^{\pm}$ and Z boson, however, the gauge boson of electromagnetic interaction i.e photon (γ) remains massless and QED must be an exact symmetry so that electric charge is a conserved quantity. Spontaneous symmetry breaking is the process where the Lagrangian of a system possesses some symmetry i.e it remains invariant under that symmetry but the ground state does not have that symmetry. The Higgs mechanism is the process by which masses of the fermions and the gauge Bosons of the SM are generated by spontaneous symmetry breaking (SSB). A complex scalar field which is a $SU(2)_L$ doublet known as the Higgs field is required to break the symmetry spontaneously. The Higgs field is given by-

$$\phi = \begin{bmatrix} \phi^+ \\ \phi^- \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix} \tag{1.12}$$

where, ϕ^+ and ϕ^- are component of the Higgs field. Transformation of the Higgs field under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ is given as- $(1,2,1)$. The interaction of scalars is described by the Lagrangian-

$$\mathcal{L}_{Higgs} = (D_\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \tag{1.13}$$

where D_μ is the covariant derivative. The scalar potential $V(\phi)$ can be written as-

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \;\; \phi^\dagger \phi = \frac{1}{2}[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2] \tag{1.14}$$

To generate masses of the gauge Bosons and the fermions, the Higgs field must acquire non-zero VEV. This is possible only when the Higgs potential is minimized for the coefficients

$\lambda > 0$ and $\mu^2 < 0$. On minimization of the scalar potential, the vacuum needs to be charge-neutral, that is why, the neutral component of the Higgs field acquires VEV v [51–53].

$$< \phi_0 >= \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v \end{bmatrix}; \quad v = \sqrt{\frac{-\mu^2}{\lambda}}; \quad [\phi_1 = \phi_2 = \phi_4 = 0, \phi_3 = v] \tag{1.15}$$

The VEV v is responsible for breaking the gauge symmetry $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$. One can parameterize the fluctuations around ϕ_0 with the help of four fields θ_1,θ_2,θ_3 and $h(x)$ as,

$$< \phi(x) >= \begin{bmatrix} \theta_1 + i\theta_2 \\ \frac{1}{\sqrt{2}}(v+h(x)) - i\theta_3 \end{bmatrix} = e^{\frac{i\theta_a \tau_a}{v}} \begin{bmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h(x)) \end{bmatrix} \tag{1.16}$$

where $h(x)$ represents the physical Higgs field. After considering a $SU(2)_L$ gauge transformation on this field we will have,

$$< \phi(x) >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix} \tag{1.17}$$

The three field θ_1,θ_2 and θ_3 are the three Goldstone Boson which are responsible for giving mass to the three gauge Boson of weak interaction $W^a_\mu(x), a = 1,2,3$. The mass term can be derived from the Lagrangian-

$$\mathcal{L}_{Higgs} = M_W^2 W_\mu^+ W_\mu^- + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_h^2 h \tag{1.18}$$

where,

$$\begin{aligned} W^+ &= \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}, \\ W^- &= \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}}, \\ Z_\mu &= cos\theta_W W_\mu^3 - sin\theta_W B_W. \end{aligned} \tag{1.19}$$

and,

$$M_W = \frac{gv}{2} \quad \text{and} \quad M_Z = \frac{gv}{2cos\theta_W} \quad M_H = 2v\sqrt{\lambda} \tag{1.20}$$

where Weinberg angle θ_W [54] can be given as,

$$tan\theta_W = \frac{g}{g'}; \quad \rho = \frac{M_W^2}{M_Z^2 cos^2\theta_W} \tag{1.21}$$

ρ is a parameter with a value of 1. This mechanism has given an accurate prediction of masses of the gauge bosons which is related to the VEV of the complex scalar field. The masses of the gauge bosons are found to be, $M_Z = 91.1875 \pm 0.0021$ GeV, $M_W = 80.399 \pm 0.023$ GeV. The photon field A_μ is an orthogonal combination of W_μ^3 and B_μ given by,

$$A_\mu = cos\theta_W W_\mu^3 + sin\theta_W B_\mu \tag{1.22}$$

There exists a massless gauge boson (the photon) associated conservation of electric charge as the U$(1)_Q$ symmetry is preserved in the whole process. $SU(2)_L$ and $U(1)_Y$ gauge symmetry is broken spontaneously but ϕ_0 is chosen in such a way that U$(1)_Q$ symmetry remains unbroken. This is why the photon remains massless in the SM ($m_A = 0$).

The Higgs mechanism is also responsible for the generation of fermion masses. The dynamics of the interaction between gauge field and fermions which is the origin of fermion mass are determined by local gauge invariance. This kind of interaction is known as the Yukawa interaction. The Yukawa Lagrangian can be written as-

$$\mathcal{L}_y = -Y_d[\bar{Q_L}\phi d_R] - Y_u[\bar{Q_L}\tilde{\phi} u_R] - Y_l[\bar{l_L}\phi l_R] + h.c \tag{1.23}$$

where, $\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \tilde{\phi} = i\tau_2\phi^\dagger$. After the scalar field acquires VEV , the masses of quarks and charged leptons are generated, given as

$$M_u = \frac{Y_u v}{\sqrt{2}}; \quad M_d = \frac{Y_d v}{\sqrt{2}}; \quad M_l = \frac{Y_l v}{\sqrt{2}} \tag{1.24}$$

Y_d, Y_u, and Y_l are the Yukawa couplings corresponding to down type quark, up type quark, and charged lepton respectively. For neutral lepton i.e neutrino does not have a right handed counter part within the SM, so the mass of neutrinos can't be generated by the Higgs mechanism.

1.3 Drawbacks of the Standard Model

Although the SM is one of the most successful theories of particle physics that can explain almost all the experimental results, it is found to be an incomplete theory as various issues and phenomena remained unaddressed within its framework. Some shortcomings of the SM are listed below:

- Gravitational interaction is one of the four fundamental interactions of the nature. It is one of the weakest interaction of the nature. The SM cannot explain and incorporate gravitational interaction without which a theory remains incomplete.

- The SM contains many free parameters such as quark and charged lepton masses, gauge coupling constants, parameters of the scalar potential, mixing angles, CP-violating phase, etc. The model cannot predict the values of these free parameters as these are experimentally measured quantities. For this reason, the SM cannot be considered as a complete theory.

- The strength of fundamental interactions has a very huge difference in magnitude. It is one of the aspects of the hierarchy problem. The range of the masses of the SM fermions extends from sub-eV (for neutrinos) to over a hundred GeV (for top quark). The SM cannot explain the fermion mass hierarchy puzzle. The SM is also unable to explain the quark mixing pattern.

- The quantum chromodynamics (QCD) lagrangian implies strong CP symmetry. But there is no experimental evidence of CP symmetry in strong interaction to date. The strong CP problem is nothing but the reason why QCD does not seems to break CP symmetry. As we know, there is no specific reason for which QCD conserves CP symmetry, it can be taken as an unnatural fine-tuning.

- The SM cannot explain whether the gauge couplings unify at a high energy scale like the grand unification theory (GUT). So, the SM can be called an effective low energy theory which has a corresponding theory at a high energy scale.

- The small neutrino mass which is confirmed by different neutrino oscillation experiments cannot be addressed within the SM as there are no right-handed neutrinos in SM.

- Tree level values of different parameters of the SM must be stable. In the renormalization procedure, the inclusion of higher order terms leads to the modification of gauge couplings and masses known as a radiative correction. However, the mass of the Higgs is not stable corresponding to any radiative correction. This is one of the drawbacks of SM.

- One of the most important and open questions of high energy physics and cosmology is dark matter and its property. Cosmological and astrophysical measurements ensure that almost 27% of the universe is made up of nonbaryonic and non luminous matter called dark matter. These can interact through gravitational interaction unlike baryonic matter. Similarly, 68% of our universe is composed of dark energy. The SM does not have any viable particle content to explain the dark sector. It is quite evident that the SM does not have any explanation of the dominant contribution to our universe i.e the dark sector.

- Another unsolved problem of particle physics is the concept of matter-antimatter asymmetry known as baryon asymmetry of the universe(BAU) which is an excess of baryons over anti-baryons. This phenomenon does not have a proper explanation within the framework of SM.

- The nature of the neutrino, whether they are four-component Dirac particles or two-component Majorana particles can not be explained in the SM.

1.4 Beyond Standard Model(BSM) Framework

1.4.1 Neutrino mass

Various BSM frameworks have been proposed to address different unsolved problems within the SM. The mass of the neutrino is one of the focuses of these frameworks. The existence of neutrino mass is experimentally established by detecting the neutrino oscillation. Although the absolute scale of neutrino mass is not determined yet. In this section, we will briefly discuss the phenomenon i.e. neutrino oscillation which confirmed the existence of BSM realm.

1.4.2 Neutrino flavor oscillation in vacuum

Neutrino oscillation implies that neutrinos are massive and was first proposed by Bruno Pontecorvo in 1957 [10]. Three different types of neutrinos and antineutrinos (electron, muon, and tau) take part in the charge current(CC) and neutral current(NC) weak interaction [55]. These three types of neutrino change their flavor during propagation, which is termed neutrino oscillation. The experimental data provided by solar, atmospheric, and long baseline experiments are well supported by three neutrino scenarios. Neutrinos are produced at the source as a flavor eigenstate and propagate as the superposition of mass eigenstates [8]. Neutrino oscillation in the vacuum demands non-degenerate neutrino mass and finite lepton flavor mixing.

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle \tag{1.25}$$

Where ν_α represents flavor eigenstate with α = e,μ,τ and ν_i with i=1,2,3 are mass eigenstates. The flavor eigenstates and mass eigenstates are co-related by 3×3 rotation matrix which is a unitary matrix denotes as U.

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \end{pmatrix} = (U_{PMNS}) \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \end{pmatrix}; \quad U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{e1} & U_{e2} & U_{e3} \\ U_{e1} & U_{e2} & U_{e3} \end{pmatrix} \tag{1.26}$$

U_{PMNS} is a mixing matrix known as the Pontecorvo Maki Nagakawa Sakata matrix which is similar to CKM matrix of quark mixing parameterized by three mixing angles solar (θ_{12}), atmospheric (θ_{23}), reactor (θ_{13}) and one physical CP-violating phase δ_{CP}. PMNS matrix is written as,

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} U_{\text{Maj}} \tag{1.27}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and δ is the leptonic Dirac CP phase. The diagonal matrix $U_{\text{Maj}} = \text{diag}(1, e^{i\alpha}, e^{i(\beta)})$ contains the Majorana CP phases α, β. Again, this mixing matrix can be expressed as $U_{PMNS} = U_l^\dagger U_\nu$, where U_l and U_ν are the diagonalizing matrix of charged lepton mass matrix and neutrino mass matrix respectively. During propagation suppose neutrino changes its flavor from electron neutrino(ν_e) to muon neutrino (ν_μ) in two flavor case. In this case, one can obtain the probability amplitude of observing a certain flavor of neutrino after a certain distance L is given by [56],

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{ij}) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) \tag{1.28}$$

where $\Delta m_{ij}^2 = m_j^2 - m_i^2$ represents the mass squared difference of the neutrinos.

1.4.3 Neutrino flavor oscillation in matter

The neutrino oscillation in the matter is affected by many factors which leads to a special kind of resonant oscillation. This phenomenon known as the MSW effect was first observed and explained by Mikheyev, Smirnov, and Wolfenstein (MSW). In this effect, the potential of different flavors of neutrinos are modified by charged-current interaction and the effective potential is proportional to the number densities of electrons, protons, and neutrons. The difference in potential between the different flavors of neutrino is the relevant physical quantity that drives the neutrino oscillation in the matter. This is proportional to the number density of electrons in the medium (N_e) and can be written as,

$$V = \sqrt{2}G_F N_e \tag{1.29}$$

where G_F stands for the Fermi constant. The neutrino mass eigenstates and eigenvectors get modified by the effective potential which further affects the flavor evolution on neutrino propagation in matter. The effective mass can be written as,

$$m_{\nu e}^2 \to m_{\nu e}^2 + A = m_{\nu e}^2 + \sqrt{2}G_F N_e E \tag{1.30}$$

The light neutrino mass is,

$$M_\nu^2 \equiv O^T M_\nu^{Diag} O + \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \tag{1.31}$$

where O is an orthogonal matrix, can be represented as,

$$O = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \tag{1.32}$$

From this, we can arrive at the mass squared matrix given by,

$$O = \frac{m_0}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{1}{2}\begin{pmatrix} A - \Delta m_{12} cos2\theta & \Delta m_{12} sin2\theta \\ \Delta m_{12} sin2\theta & -A + \Delta m_{12} cos2\theta \end{pmatrix} \tag{1.33}$$

where, $\Delta m_{12} = |m_2^2 - m_1^2|$ and $m_0 = m_1^2 m_2^2 - A$. The modified mass eigenvalues are,

$$m_{\nu_{1,2}} = \frac{m_0}{2} \pm \frac{1}{2}\sqrt{(\Delta m_{12} cos2\theta - A)^2 + \Delta m_{12}^2 sin^2 2\theta} \tag{1.34}$$

The modified mixing angle can be given as,

$$tan2\theta = \frac{\Delta m_{12} sin2\theta}{\Delta m_{12} cos2\theta - A} \tag{1.35}$$

Thus, in presence of matter, the mass eigenvalues and mixing angle gets modified depending on the number density of electrons.

It is quite clear from the Eq1.28 that the expression of the probability depends on the mixing angle θ, the mass square difference, propagation distance L, and neutrino energy E. So, neutrino oscillation is possible only if the mass squared difference is non zero and there should be a finite mixing among different flavors corresponding to a non-zero mixing angle. Oscillation parameters are determined by different experiments up to some accuracy, although the absolute scale of neutrino mass is not known. Also, the mass ordering problem of neutrinos is not solved yet. Different oscillation experiments have confirmed that solar mass square difference Δm_{12}^2 is always positive i.e. $m_2 > m_1$. However, the sign of atmospheric mass square difference Δm_{13}^2 is not known to us. Because of this reason, there are two possible neutrino mass ordering or hierarchies depending on the sign of Δm_{13}^2.

(a) Normal mass hierarchy : $m_3 > m_2 > m_1$

(b) Inverted mass hierarchy :$m_2 > m_1 > m_3$

These two mass ordering are represnted in the fig 1.1

1.4.4 Type of neutrino mass: Dirac and Majorana

From the Lagrangian of the SM, it is clear that the mass and mixing are determined by a mass term that arises due to coupling between both LH and RH components of the field. As there is no RH neutrino in the SM, the mass of the neutrino could not be generated. It

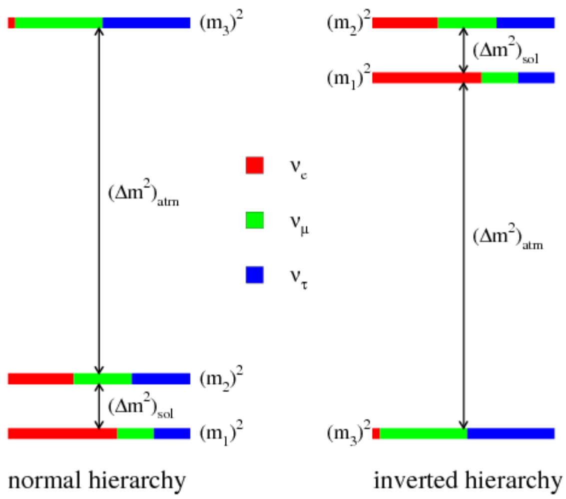

Fig. 1.1 Mass splitting and two possible neutrino mass ordering: Normal mass hierarchy and inverted mass hierarchy

is theoretically possible to add RH neutrino in SM. In such a case, two distinct types of neutrino mass terms are possible in the electroweak Lagrangian. These are namely Dirac and Majorana mass terms. In the case of the Dirac mass term lepton number is a conserved quantity and for Majorana mass term lepton number is violated by two units. The Dirac mass term arises from the coupling of RH neutrino with active lepton after the Higgs field acquires VEV of 174 GeV. Now, one can write the Dirac Lagrangian as-

$$-\mathcal{L}_{Dirac} = \sum_{i,j} \bar{\nu}_{iL} M_D \nu_{jR} + h.c \tag{1.36}$$

where M_D is the 3×3 mass matrix. M_D can be written as $M_D = Y_\nu m_\nu$. Y_ν is the Yukawa coupling. To obtain the neutrino mass in sub eV scale the Yukawa coupling has to be around $(\sim)10^{-12}$ which does not have any natural explanation. This requires a fine tuning of the theory. Dirac particles are represented by four component Dirac spinors.

As the SM has only the LH neutrino, Ettore Majorana proposed that the mass term can be written if we consider $\nu_L^C = C\bar{\nu}_L^T$, where C is the charge conjugation matrix. A particle is called Majorana when the particle is its antiparticle. Neutrinos are only neutral particles in the SM that can be considred as Majorana fermions. The Majorana Lagrangian can be written as-

$$-\mathcal{L}_{Majorana} = -\frac{1}{2} M_R \nu_L \nu_L^C \tag{1.37}$$

As the hermitian conjugate for the Majorana particles is identical, the factor $\frac{1}{2}$ appears in the Lagrangian. This mass term is not allowed within the SM as it violates the lepton number by $\Delta_L = \pm 2$. To address the neutrino mass we have to go beyond SM. In the next part of this thesis, we will discuss some of the BSM frameworks which can successfully generate neutrino mass.

1.4.5 Mechanisms of neutrino mass generation

Experimental observations of neutrino oscillation implies that neutrino mass and leptonic mixing lead to new and exciting BSM physics. Theoretical physicists have proposed many frameworks to address the neutrino mass and mixing. Formulation of the seesaw mechanism is the most significant progress in the BSM scenario. Seesaw mechanisms are classified into different types such as type-I [57–62], type-II [63–65, 58, 66, 67], type-III [68, 69], inverse seesaw(ISS) [70–72], and radiative seesaw [73–77]. Another important BSM framework where type-I and type-II seesaw arises naturally is the left-right symmetric model(LRSM) [78–82]. LRSM is a simple extension of the SM gauge group by $SU(2)_R$, which treats LH and RH particles on equal footing. Extended LRSM is also an interesting BSM framework where neutrino mass can be studied with the natural realization of different seesaw mechanisms. Grand unified theory (GUT) [83, 84] is also an important extension of SM which leads to the explaination of neutrino mass and different phenomenologies.

Type-I Seesaw: The type-I [58, 85, 86] seesaw mechanism is the simplest extension of SM to realize the tiny neutrino mass through the dimension five operators. In this seesaw mechanism, SM is extended with gauge singlet fermion, which generates the neutrino mass via Yukawa interaction with lepton doublets and scalar Higgs particle. The Majorana mass term can be written as,

$$-\mathcal{L}_{\text{TypeI}} = Y_\nu \bar{N}_R \tilde{\phi}^\dagger L + \frac{1}{2} M_R \bar{N}_R N_R^C + h.c. \tag{1.38}$$

M_R is the RH neutrino mass matrix and Y_ν is the nonsymmetric and non-hermitian Yukawa matrix. After electroweak symmetry breaking, the Higgs particle acquires VEV and gives the Dirac neutrino mass $M_D = Y_\nu v$, where v is the VEV of the Higgs particle. The mass scale M_R is much higher than M_D, because the gauge singlet ν_R is decoupled from the electroweak scale allowing them to be at the high energy scale. The light neutrino mass matrix can be obtained from Eq. 1.38

$$\mathcal{L}_{mass} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^C & \bar{N}_R \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix} \tag{1.39}$$

We can write the light neutrino mass after block diagonalization as $M_{light} = M_D^T M_R^{-1} M_D$ and $M_{heavy} = M_R$. M_R is the right-handed neutrino mass matrix and m_ν is the light neutrino mass matrix. From the expression of mass matrices, it is evident that the heavier the M_R lighter will be the M_ν, this is why it is called the seesaw mechanism.

Type-II Seesaw: In the type-II [65, 66, 87] seesaw mechanism, the scalar $SU(2)$ triplet is added to the SM. This scalar triplet is responsible for the generation of neutrino mass in a type-II seesaw. The transformation of Higgs triplet $\Delta = (\delta_1, \delta_2, \delta_3)$ under SM gauge group is $(1, 3, +1)$. The matrix representation of the triplet Higgs is given as,

$$\Delta = \frac{1}{\sqrt{2}} \sum_i \sigma^i \Delta_i = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} \tag{1.40}$$

where, σ_i are the Pauli matrices and $\Delta^0 = \frac{\delta_1 + i\delta_2}{\sqrt{2}}$, $\Delta^+ = \delta_3$, $\Delta^{++} = \frac{\delta_1 - i\delta_2}{\sqrt{2}}$ are three complex scalar. The Lagrangian for type-II seesaw is given as,

$$-\mathcal{L}_{\text{TypeII}} = Y_\Delta L^T C i \sigma_2 \Delta L + M_\Delta^2 Tr[\Delta^+ \Delta] + \frac{1}{2} (\lambda_\Delta M_\Delta \tilde{\phi}^\dagger \Delta^+ \phi) + h.c \tag{1.41}$$

In Eq. (1.41) M_Δ is the mass of triplet Higgs and Y_Δ is the Yukawa coupling. The neutrino mass is gnererated when neutral component of the triplet Higgs acquires VEV by electroweak symmetry breaking. The VEV is given by $<\Delta>= v_\Delta = \frac{\lambda_\Delta v^2}{M_\Delta}$.

Therefore, the neutrino mass generated in type-II seesaw mechanism is ,

$$M_\nu = (Y_\Delta v_\Delta)/\sqrt{2} \tag{1.42}$$

Type-III Seesaw: In type-III seesaw SM is extended with three additional hypercharge-less color singlet fermion triplets to generate the neutrino mass [88, 89]. The triplet $\Sigma = (\eta_1, \eta_2, \eta_3)$ has a $SU(2)$ representation given as,

$$\Sigma = \frac{1}{\sqrt{2}} \sum_i \sigma^i \Delta_i = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix} \tag{1.43}$$

where, $\Sigma^0 = \eta_3$ and $\Sigma^\pm = \frac{\eta_1 \pm i\eta_2}{\sqrt{2}}$. The type-III Lagrangian for neutrino mass generation is given by,

$$-\mathcal{L}_{\text{TypeIII}} = Y_\Sigma \tilde{\phi}^\dagger \Sigma^a L + \frac{1}{2} M_\Sigma Tr[\Sigma^a \Sigma^b] + h.c \tag{1.44}$$

In Eq. (1.44) M_Σ is the mass of triplet fermion and Y_Σ is the dimensionless Yukawa coupling matrix. The light neutrino mass in this framework is given by,

$$-m_\nu = m_D M_\Sigma m_D^T \tag{1.45}$$

where $m_D = \frac{Y_\Sigma v}{\sqrt{2}}$. The mass of triplet fermion can reach up to the cut-off scale of the theory as it does not process any kind of symmetry.

Inverse seesaw: The SM is extended by one or more generations of RH neutrino (ν_R) and singlet fermion (S) [90, 91]. The relevant Lagrangian for the ISS is given as,

$$L = -\frac{1}{2} n_L^T C M n_L + h.c \tag{1.46}$$

The Lagrangian leads to the following mass matrix:

$$M = \begin{pmatrix} 0 & M_d & 0 \\ {M_d}^T & 0 & M_R \\ 0 & M_R^T & \mu \end{pmatrix} \tag{1.47}$$

where M_d, M_N and μ are complex matrices. After block diagonalization of this 9×9 matrix with the condition $\mu < M_D < M_R$, we will get the final light neutrino mass as,

$$M_\nu \approx M_d^T (M_R^T)^{-1} \mu M_R^{-1} M_d \tag{1.48}$$

From Eq (1.48) it is seen that the neutrino mass in this seesaw arises by double suppression of RH neutrino mass, which is not the case for another seesaw. Because of this, ISS is known as a low scale seesaw. In this kind of seesaw origin of neutrino mass can be explained very elegantly.

Radiative Seesaw: Radiative seesaw model is nothing but a simple extension of SM with an inert Higgs and three neutral fermions [73, 92]. The inert Higgs field is $SU(2)_L$ doublet with hypercharge $Y = 1$. This framework has a built-in Z_2 symmetry. The role of the inert Higgs is to accommodate the dark matter in the model with stability taken care of by Z_2 symmetry. Three neutral singlets fermion N_i with $i = 1,2,3$ having oddly charged under Z_2 symmetry are responsible for the generation of neutrino mass. In this model mass of the neutrino is generated in one or two loop levels, unlike other seesaws where mass is generated at tree level.

The new leptonic and scalar particle content can thereafter be represented as follows under the group of symmetries $SU(2) \times U(1)_Y \times Z_2$:

$$\begin{pmatrix} \nu_\alpha \\ l_\alpha \end{pmatrix}_L \sim (2, -\frac{1}{2}, +),\ l_\alpha^c \sim (1,1,+),\ \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (2, \frac{1}{2}, +),$$

$$N_i \sim (1,1,-),\ \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} \sim (2, 1/2, -). \tag{1.49}$$

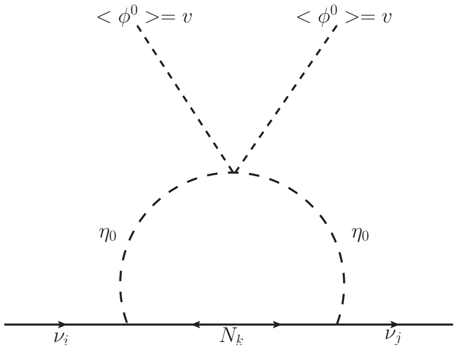

Fig. 1.2 One-loop contribution of neutrino mass generation with the exchange of right-handed neutrino N_i and the scalar η_0.

The scalar doublets are written as follows :

$$\eta = \begin{pmatrix} \eta^{\pm} \\ \frac{1}{\sqrt{2}}(\eta_R^0 + i\eta_I^0) \end{pmatrix}, \quad \phi = \begin{pmatrix} \phi^{+} \\ \frac{1}{\sqrt{2}}(h + i\xi) \end{pmatrix}. \tag{1.50}$$

The lagrangian involving the newly added field is :

$$\mathcal{L} \supset \frac{1}{2}(M_N)_{ij} N_i N_j + Y_{ij} \bar{L} \tilde{\eta} N_j + h.c \tag{1.51}$$

where, the 1^{st} term is the Majorana mass term for the neutrino singlet and the 2^{nd} term is the Yukawa interactions of the lepton. The neutrino mass matrix arising from the radiative mass model is given by :

$$\begin{aligned} M_{ij}^{\nu} =& \sum_k \frac{Y_{ik}Y_{jk}}{16\pi^2} M_{N_k} \left[\frac{m^2_{\eta_R^0}}{m^2_{\eta_R^0} - M^2_{N_k}} ln \frac{m^2_{\eta_R^0}}{M^2_{N_k}} - \frac{m^2_{\eta_I^0}}{m^2_{\eta_I^0} - M_{N_k}}^2 ln \frac{m^2_{\eta_I^0}}{M_{N_k}}^2 \right] \\ \equiv& \sum_k \frac{Y_{ik}Y_{jk}}{16\pi^2} M_{N_k} [L_k(m^2_{\eta_R^0}) - L_k(m^2_{\eta_I^0})], \end{aligned} \tag{1.52}$$

where M_k represents the mass eigenvalue of the mass eigenstate N_k of the neutral singlet fermion N_k in the internal line with indices j=1,2,3 running over the three neutrino generation with three copies of N_k and Y is the Yukawa coupling matrix. The function $L_k(m^2)$ used in Eq. (1.52) is given by:

$$L_k(m^2) = \frac{m^2}{m^2 - M^2_{N_k}} \ln \frac{m^2}{M^2_{N_k}} \tag{1.53}$$

Left-right symmetric model(LRSM): LRSM is a very simple extension of the standard model gauge group where parity restoration is obtained at a high energy scale and the fermions are assigned to the gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which can be tested in present-day experiments [82, 93, 94]. The usual type-I and-II seesaw arises naturally in LRSM. Several other problems like parity violation of weak interaction, massless neutrinos, CP problems, hierarchy problems, etc can also be addressed in the framework of LRSM. The seesaw scale is identified as the breaking of the $SU(2)_R$ symmetry. In this model, the electric charge generator is given by, $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$ [60], where T_{3L} and T_{3R} are the generators of $SU(2)_L$ and $SU(2)_R$ and B-L being the baryon minus lepton number charge operator.

The Quarks and leptons (LH and RH) that transform in the Left-Right symmetric gauge group are given by,

$$Q_L = \begin{bmatrix} u \\ d \end{bmatrix}_L, Q_R = \begin{bmatrix} u \\ d \end{bmatrix}_R, \Psi_L = \begin{bmatrix} \nu_l \\ l \end{bmatrix}_L, \Psi_R = \begin{bmatrix} \nu_l \\ l \end{bmatrix}_R. \tag{1.54}$$

where the Quarks are assigned with quantum numbers $(3,2,1,1/3)$ and $(3,1,2,1/3)$ and leptons with $(1,2,1,-1)$ and $(1,1,2,-1)$ respectively under $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The Higgs sector in LRSM consists of a bi-doublet with quantum number $\phi(1,2,2,0)$ and the $SU(2)_{L,R}$ triplets, $\Delta_L(1,2,1,-1)$, $\Delta_R(1,1,2,-1)$. The Yukawa lagrangian in the lepton sector is given by,

$$\mathcal{L} = h_{ij}\overline{\Psi}_{L,i}\phi\Psi_{R,j} + \widetilde{h_{ij}}\overline{\Psi}_{L,i}\widetilde{\phi}\Psi_{R,j} + f_{L,ij}{\Psi_{L,i}}^T Ci\sigma_2\Delta_L\Psi_{L,j} + f_{R,ij}{\Psi_{R,i}}^T Ci\sigma_2\Delta_R\Psi_{R,j} + h.c. \tag{1.55}$$

where the family indices i, j are summed over, the indices $i, j = 1,2,3$ represent the three generations of fermions. $C = i\gamma_2\gamma_0$ is the charge conjugation operator, $\widetilde{\phi} = \tau_2\phi^*\tau_2$ and γ_μ are the Dirac matrices. Considering discrete parity symmetry, the Majorana Yukawa couplings $f_L = f_R$ (for left-right symmetry) gives rises to Majorana neutrino mass after electroweak symmetry breaking when the scalar triplets Δ_L and Δ_R acquires non zero vev leads to 6×6 neutrino mass matrix which is given as-

$$M_\nu = \begin{bmatrix} M_{LL} & M_D \\ {M_D}^T & M_{RR} \end{bmatrix}, \tag{1.56}$$

where

$$M_D = \frac{1}{\sqrt{2}}(k_1 h + k_2 \widetilde{h}), M_{LL} = \sqrt{2} v_L f_L, M_{RR} = \sqrt{2} v_R f_R, \tag{1.57}$$

where M_D, M_{LL} and M_{RR} are the Dirac neutrino mass matrix, left-handed and right-handed mass matrix respectively. Assuming $M_L \ll M_D \ll M_R$, the light neutrino mass, generated within a type I+II seesaw can be written as,

$$M_\nu = {M_\nu}^I + {M_\nu}^{II}, \tag{1.58}$$

$$M_\nu = M_{LL} + M_D {M_{RR}}^{-1} {M_D}^T = \sqrt{2} v_L f_L + \frac{k^2}{\sqrt{2} v_R} h_D {f_R}^{-1} {h_D}^T, \tag{1.59}$$

where the first and second term in equation (1.59) corresponds to type-II seesaw and type-I seesaw mediated by RH neutrino respectively. Here,

$$h_D = \frac{(k_1 h + k_2 \widetilde{h})}{\sqrt{2} k}, k = \sqrt{|k_1|^2 + |k_2|^2}. \tag{1.60}$$

In the context of LRSM both type I and type II seesaw terms can be written in terms of M_{RR} which arises naturally at a high energy scale as a result of spontaneous parity breaking. In LRSM the Majorana Yukawa couplings f_L and f_R are the same (i.e, $f_L = f_R$) and the vev for left-handed triplet v_L can be written as,

$$v_L = \frac{\gamma {M_W}^2}{v_R}. \tag{1.61}$$

Thus equation (1.59) can be written as ,

$$M_\nu = \gamma(\frac{M_W}{v_R})^2 M_{RR} + M_D {M_{RR}}^{-1} {M_D}^T . \tag{1.62}$$

The dimensionless parameter γ can be written as [95]

$$\gamma = \frac{\beta_1 k_1 k_2 + \beta_2 {k_1}^2 + \beta_3 {k_2}^2}{(2\rho_1 - \rho_3) k^2}. \tag{1.63}$$

Here the terms β, ρ are the dimensionless parameters that appear in the expression of the Higgs potential.

LRSM with extended seesaw with type-II dominance: In this framework, the LRSM is extended with a neutral sterile fermion per generation along with quark and leptons.Scalar sector of this extension consist of Higgs bidoublet Φ, two scalar triplets Δ_L, Δ_R and two doublets H_L,H_R. The B-L charge of Higgs bidoublet, scalar triplets and doublets are 0,2 and -1 respectively. This kind of extension of LRSM is known as extended LR model and naturally arising seesaw from it is called the extended seesaw mechanism [96–99]. Quarks are assigned with quantum numbers $(3,2,1,1/3)$ and $(3,1,2,1/3)$ and leptons with $(1,2,1,-1)$ and $(1,1,2,-1)$ respectively under $\mathrm{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$. The sterile fermion transformation under the relevant Gauge group is given as $S_L(1,1,1,0)$ The scalar sector in this extension of LRSM consists of a bi-doublet with quantum number $\Phi(1,2,2,0)$, the $SU(2)_{L,R}$ triplets, $\Delta_L(1,3,1,2)$, $\Delta_R(1,1,3,2)$ and two $SU(2)_{L,R}$ doublets, $H_L(1,2,1,-1)$, $H_R(1,1,2,-1)$.

A natural type-II dominance in such a case can be realized with the following Yukawa interaction-

$$-\mathcal{L_Y} = \bar{l_L}[Y_1\Phi + Y_2\tilde{\Phi}]l_R + f[\bar{l_L}^c l_L \Delta_L + \bar{l_R}^c l_R \Delta_R] + F(\bar{l_R}) H_R S_L^c + h.c \tag{1.64}$$

In terms of mass matrices, we can write Eq(1.64) as-

$$-\mathcal{L}_{\mathcal{Y}} \supset M_D \bar{\nu_L} N_R + M_L \bar{\nu_L}^c \nu_L + M_R \bar{\nu_R}^c \nu_R + M \bar{N_R} S_L + h.c \tag{1.65}$$

where, $M_D = Y < \Phi >$ is the Dirac neutrino mass matrix which measures the light and heavy neutrino mixing and Y stands for Yukawa coupling, $M_R = f < \Delta_R >= f v_R$ ($M_L = f < \Delta_L >= f v_L$) is the Majorana mass term for heavy(Light) neutrinos and f is the Majorana left right symmetric coupling along with v_R, v_L corresponding to the vacuum expectation values(VEV) of scalar triplets, finally $M = F < H_R >$ stands for heavy neutrino-sterile mixing matrix. We have assumed the induced vev of $< H_L >$ to be zero. Now in flavor basis the complete 9×9 mass matrix for neutral fermions can be represented as [97]-

$$\mathcal{M} = \begin{pmatrix} M_L & 0 & M_D \\ 0 & 0 & M \\ M_D^T & M^T & M_R \end{pmatrix} \tag{1.66}$$

After complete block diagonalization which is extensively discussed in various literature, we can write left-handed neutrino, heavy right-handed neutrino, and sterile neutrino mass matrices as-

$$\begin{aligned} m_\nu &= M_L \\ M_R &= \frac{v_R}{v_L} M_L \\ M_S &= -M M_R^{-1} M^T \end{aligned} \tag{1.67}$$

Again these mass matrices can be diagonalised by using respective 3×3 unitary matrices as follows-

$$\begin{aligned} m_\nu^{diag} &= U_\nu^\dagger m_\nu U_\nu^* = diag(m_1, m_2, m_3) \\ M_N^{diag} &= U_N^\dagger M_N U_N^* = diag(M_{N_1}, M_{N_2}, M_{N_3}) \\ M_S^{diag} &= U_S^\dagger M_S U_S^* = diag(M_{S_1}, M_{S_2}, M_{S_3}) \end{aligned} \tag{1.68}$$

Complete block diagonalization results-

$$\begin{aligned}\mathcal{M}_{diag} &= V_{9\times9}^{\dagger}\mathcal{M}V_{9\times9}^{*}\\ &= (\mathcal{W}.\mathcal{U})^{\dagger}\mathcal{M}(\mathcal{W}.\mathcal{U})\\ &= diag(m_1.m_2,m_3,M_{S_1},M_{S_2},M_{S_3},M_{N_1},M_{N_2},M_{N_3})\end{aligned} \tag{1.69}$$

where, $\mathcal{W}$ is the block diagonalizing mixing matrix and $\mathcal{U}$ is the unitary mixing matrix. Thus the complete 9×9 unitary mixing matrix can be written as-

$$V = \mathcal{W}.\mathcal{U} = \begin{pmatrix} U_\nu & M_D M^{-1} U_S & M_D M_R^{-1} U_N \\ (M_D M^{-1})^{\dagger} U_\nu & U_S & M M_R^{-1} U_N \\ \mathcal{O} & (M M_R^{-1})^{\dagger} U_S & U_N \end{pmatrix} \tag{1.70}$$

1.4.6 Lepton number violation: neutrinoless double beta decay:

The intrinsic nature of the neutrino is still unknown, whether they are Dirac or Majorana particles. Majorana particle is its antiparticle which violates lepton number symmetry whereas, in the case of Dirac particle lepton number is a conserved quantity. This problem cannot be solved by neutrino oscillation experiments as they are not sensitive to Majorana parameters. To detect lepton number violation(LNV) alternative and more sensitive experiments are required. The most prominent way to establish the lepton number violation is the neutrinoless double beta decay(NDBD) experiment. The NDBD [100–102] is a very slow radioactive process of second order, first considered by Wendell H Furry in 1939 and is characterized by,

$$N(A,Z) \rightarrow N(A,Z+2) + 2e^{-} \tag{1.71}$$

This can be taken as two simultaneous beta decay and can only be possible for even-even nuclei. In this process, nuclei of proton number Z and mass number A by emitting two electrons and two antineutrino decays to a nucleus of proton number $Z+2$ and proton number A. Observation of NDBD will certainly confirm that lepton number violation and neutrino are Majorana type in nature. The amplitude of these processes can be written as-

$$A_i \propto m_i {U_{ei}}^2 M^{0\nu\beta\beta}(m_i) \tag{1.72}$$

where $M^{0\nu\beta\beta}$ is the nuclear matrix element(NME), which is the characteristics of a particular decay. The matrix element is given by,

$$M^{0\nu\beta\beta} = \lambda g_{\mu\lambda} \sum_i \frac{U_{ei}^2 m_i}{< p^2 >} \bar{e_L}(P_1) C \bar{e_L}^T(P_2) \tag{1.73}$$

where, C is the charge conjugation matrix, λ is the phase, $< p^2 >$ is momentum exchange with numerical value around $(125MeV)^2$. The expression of the decay width of the NDBD process mediated by light neutrino can be written as,

$$\Gamma^\nu = \frac{1}{T^\nu_{\frac{1}{2}}} = G^\nu(Q,Z) \mid M^{0\nu\beta\beta} \mid^2 \frac{\mid m_{\beta\beta} \mid^2}{m_e^2} \tag{1.74}$$

where, $G^\nu(Q,Z)$, $M^{0\nu\beta\beta}$ and m_e are the phase factor, NME and electron mass respectively. $T^\nu_{\frac{1}{2}}$ represents the half-life of the decay. NME is directly dependent on the isotope of the particular nucleus under consideration. $m_{\beta\beta}$ is the effective Majorana mass which is nothing but a combination of neutrino mass eigenstates and the first row of the mixing matrix.

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} {U_{ei}}^2 m_i \right|, \quad i = e, \mu, \tau \tag{1.75}$$

After parametrization the effective mass can be given by,

$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta} \tag{1.76}$$

with $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ are respective oscillation angle and α and β are the Majorana phase.

The NDBD process is not observed experimentally to date. Different experiments like KamLAND-Zen [19], GERDA[40], NEMO-3 [103], EXO-3 [104], CUORE-3 [105], Legend-

1K [106] and MAJORANA [107] etc, are dedicated to detect this decay and they provide limits on the half life of the NDBD process and effective mass.

$$T_{\frac{1}{2}}(^{76}Ge) \geq 1.88 \times 10^{21}y; T_{\frac{1}{2}}(^{100}Mo) \geq 7.06 \times 10^{18}y \tag{1.77}$$

The experimentally allowed range of the effective Majorana neutrino mass.

$$m_{\beta\beta} < 0.061 - 0.165eV \tag{1.78}$$

The NDBD process has a great implication on theoretical and experimental BSM physics. Although detection of the decay is still far from reality, lepton number violating NDBD process is one of the prime motivation of BSM physics. In near future, experiments like KATRIN are expected to measure the mass of neutrino, which would be an impressive result.

1.4.7 Baryon Asymmetry of the Universe(BAU)

Matter-antimatter asymmetry also known as baryon asymmetry of the Universe (BAU) is one of the sought-after topics in particle physics. The abundance of matter over antimatter also hints towards the existence of BSM physics. After the big bang, the universe was so hot and dense that can create particle-antiparticle pairs through a sea of radiation. But it was observed otherwise, that there must be an abundance of particles over antiparticles for the very existence of the universe. This asymmetry remains one of the important astrophysical puzzles to date. From the data of baryon acoustic oscillation and WMAP(Wilkinson Microscopy Anisotropy Probe) along with Plack data, the baryon to photon ratio of number density is found to be [108]-

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.1 \pm 0.18) \times 10^{-10} \tag{1.79}$$

where n_B, $n_{\bar{B}}$ and n_γ are the baryon number density, anti baryon number density and photon density. In terms of entropy above expression can be written as,

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11} \tag{1.80}$$

These results are well supported by big bang nucleosynthesis (BBN). There are many hypotheses that neutrino can be an important link to explaining this asymmetry. The most essential condition for BAU has been postulated by Sakharov long ago [109],

- **Baryon number violation**: The baryon number B must be trivially violated as BAU cannot be generated with conserved baryon number.
- **Charge(C) and Charge-parity(CP) violation**: The C and CP symmetry must be violated to generate the BAU. The number of left-handed particles generated should not be equal to the number of right-handed antiparticles (CP conjugated state of the left-handed particle) generated in any process. CP violation ensures this requirement. C violation is required so that generation of right-handed particles does not compensate for the generation of left-handed particle.
- **Departure from thermal equilibrium**: This departure from the thermal equilibrium is realized only when the rate of the baryon number violating process is slower than the expansion of the universe. In other words, as heavy particle decays into sub-products, these products will move apart before they could take part in the inverse decay of the same process. It is an essential condition to generate the BAU.

The SM contains above mentioned Sakharov conditions, but not in a sufficient way to explain the observed BAU. So, we require new physics beyond SM to address the observed BAU. Many mechanisms have been proposed to explain the BAU, like GUT baryogenesis, electroweak baryogenesis, leptogenesis, Affleck-Dine mechanism, etc. In this thesis, we have studied leptogenesis in the radiative seesaw framework.

1.4.7.1 Leptogenesis

Many interesting theoretical models have been put forward by physicists to address the observed asymmetry of matter over antimatter. Leptogenesis is one of the popular mechanisms by which we can explain this asymmetry. In this mechanism, lepton asymmetry is created before the electroweak phase transition. After that, the Lepton asymmetry is converted into BAU through the sphaleron process which is a B+L violating process. The sphaleron process converts any primordial lepton asymmetry or B-L asymmetry into a baryon asymmetry. The origin of the baryon asymmetry can be connected to leptons including neutrino. Heavy right-handed neutrino i.e the counterpart of light neutrino which was postulated earlier to explain neutrino mass is assumed to be present at the time of the early universe. The decay of this heavy neutrino could produce more matter than antimatter. Fukugita and Yanagida first proposed this kind of realization of leptogenesis by the out of the equilibrium decay of heavy neutrino with Majorana mass at larger than critical temperature $T_c = 100-200$ GeV. This kind of decay satisfies all the required conditions for BAU given by Sakharov. The superposition of tree level and one loop level diagram prides the essential CP asymmetry. The Yukawa interactions are very slow and occur at a temperature above the electroweak scale which leads to departure from thermal equilibrium. Heavy neutrino decays into a lepton and a Higgs doublet ($N_i \to L+\phi^c$) and its CP conjugated process $N_i \to L^c+\phi$ also occurs at both tree level and loop level, which responsible for lepton number violation. So the origin of CP asymmetry parameter ε_{CP} is the interference between the tree level and loop level amplitude of the decay with self-correction and given as,

$$\varepsilon_{CP} = \frac{\Gamma(N_i \to L+\phi^c) - \Gamma(N_i \to L^c+\phi)}{\Gamma(N_i \to L+\phi^c) + \Gamma(N_i \to L^c+\phi)} \tag{1.81}$$

The RH neutrino mass range is different for the framework under consideration. It is in the TeV scale for the left-right symmetric model, in around the GeV scale for radiative seesaw, and for certain GUT theories, it is up to 10^{16} GeV. There are many types of leptogenesis such as thermal leptogenesis, resonant leptogenesis, vanilla leptogenesis, etc, which can produce observed baryon asymmetry. In this thesis, we have studied vanilla leptogenesis in the framework of the radiative seesaw. In case of, hierarchical mass of RHN, i.e $M_{N_1} << M_{N_2}, M_{N_3}$, the leptogenesis produced by the decay of N_2 and N_3 are suppressed due to the strong washout effects produced by N_1 or N_2 and N_3 mediated interactions [110]. Thereby, the lepton asymmetry is produced only by the virtue of N_1 decay and this is further converted into the baryon asymmetry of the Universe(BAU) by the electro-weak sphaleron phase transitions [111]. This kind of leptogenesis is known as vanilla leptogenesis. Now for the generation of BAU, we solve the simultaneous Boltzmann equations for N_1 decay and formation of N_{B-L}.

1.4.8 Lepton flavor violation

Charged lepton flavor violation (CLFV) directly implies the existence of new physic beyond SM. Charged lepton muons are discovered in early 1940, and since then the search for CLFV is going on to date. In this precision era of experiments, motivation for the search for CLFV is still going on as it can be the pathway to BSM physics. The experimental evidence of neutrino oscillation has provided proof of lepton flavor violation during propagation of neutrino, which further confirms the massiveness of neutrino. Because of this reason, lepton flavor violation is also expected in the charged lepton sector. As the mechanism of LFV is not known, although this sector of study has been linked with neutrino mass, CP violation, and new physics BSM. There are many present and future generation experiments are dedicated to search for lepton flavor violating processes such as two body decay($l_\alpha \to l_\beta \gamma$) [112] and three body decay such as ($l_\alpha \to 3l_\beta$) [113]. The muon decay channels like $\mu - e, N$, $\mu \longrightarrow eee$, $\mu \longrightarrow e\gamma$ and $\mu^- e^- \longrightarrow e^- e^-$ are thoroughly analyzed as muon decay experiments are most prominent [114–116]. Tau decays are also very important decay to be analyzed as it contains many channels of CLFV. There are many tau decay channel are present in the nature, out of these $\tau \longrightarrow e\gamma$, $\tau \longrightarrow \mu\gamma$, $\tau \longrightarrow 3e$ and $\tau \longrightarrow 3\mu$ are significant [117, 118]. This decay leads to many decay channels to hadrons such as $\tau \longrightarrow l\pi^+\pi^-$. The present and future bounds on CLFV processes are given in the following table 1.3,

cLFV Process	Present Bound	Future sensitivity
$\mu \longrightarrow eee$	1.0×10^{-12}	$\sim 10^{-16}$
$\mu \longrightarrow e\gamma$	5.7×10^{-13}	6.0×10^{-14}
$\tau \longrightarrow e\gamma$	3.3×10^{-8}	$\sim 3 \times 10^{-9}$
$\tau \longrightarrow \mu\gamma$	4.4×10^{-8}	$\sim 10^{-9}$
$\tau \longrightarrow eee$	2.7×10^{-8}	$\sim 10^{-9}$

Table 1.3 Current experimental bounds and future sensitivities for different cLFV processes.

For $\mu \longrightarrow e$ conversion considering Au nucleus the exprimental bound is 7×10^{-13} and considering Al nucleus it is found to be 3×10^{-12}. The neutrinoless $\mu - e$ conversion of the muonic atom is the most interesting development regarding the LFV processes [119]. Many experiments will aim for the positive signal running with different targets like Titanium (Ti), Lead (Pb), Gold (Au) Aluminum (Al), and give different bounds. DeeMe [120], Mu2e [121], COMET [122] and PRIME [123] are such experiments primarily focusing on $\mu - e$ conversion of a muonic atom. The sensitivity of these experiments will range from 10^{-14} to 10^{-18}. The current limits on τ observables are less stringent, but will also get improved shortly by the LHC collaboration, as well as by B-factories such as Belle II [124]. The MEG collaboration [41] has been able to set the impressive bound on muon decay $\mathrm{BR}(\mathrm{l}_\alpha \to \mathrm{l}_\beta \gamma) < 4.2 \times 10^{-13}$. This is expected to improve as the experiment is upgraded to MEG II. In case of $l_\alpha \to 3l_\beta$ decay, constraints comes from SINDRUM experiment [42] to be $\mathrm{BR}(\mathrm{l}_\alpha \to 3\mathrm{l}_\beta) < 10^{-12}$ which is set long ago. The future Mu3e experiment announces a sensitivity of 10^{-16}, which would imply 4 orders of magnitude improvement on the current bound.

Tau leptons also have many lepton flavor-violating decay channels. Experimental detection of such decay is very challenging. Different theoretical models predict LFV in the tau sector which are successful in predicting muon decays. Experiments like BaBar and

Belle provide limits to cLFV decays involving tau leptons. In this thesis, we have studied muon decays and muon conversion in the framework of the radiative seesaw and left-right symmetric model.

1.4.9 Dark matter

The nature and origin of the dark matter and matter-antimatter asymmetry are the two major questions of modern cosmology that remain unanswered in the SM. The existence of dark matter is completely an experimentally observed fact that directly hints toward the BSM realm. The concept of dark matter was first proposed in 1933 by Fritz Zwicky [125]. After that, there are many observational confirmations of very mysterious, nonbaryonic, and nonluminous matter known as dark matter.

Galaxy Cluster: These are very massive objects which contain a large amount of gas in the intergalactic medium. The first observational indication of DM comes from the measurement of velocity dispersion of the coma cluster [126]. With the luminous matter, the velocity dispersion of this cluster is expected to be 80 km/sec however, it is found to be about 2000 km/sec. This huge discrepancy in the velocity dispersion hints toward non-luminous matter.

Galaxy rotation curve: One of the most striking and significant observations of unusual gravitational effects of DM comes from rotational curves of spiral galaxies [127]. In these types of galaxies, almost all the visible mass is concentrated in the budge and the disc. From classical theory, one can obtain the rotational velocity v the galaxies at a distance R from the center of the galaxy under gravitational force as,

$$v(R) = \sqrt{\frac{G_N M(R)}{R}} \tag{1.82}$$

where $M(R)$ is the amount of mass contained within the galaxy of radius R. G_N is the gravitational constant. From the above expression, it is clear that rotational velocity is inversely proportional to the radius of the galaxy. The study of certain galaxies showed a constant value of rotational velocity ($v = 200 km/sec$) in the outer luminosity region. This can only be explained if we assume $M(R) \propto R$ in the outer luminosity region which indicates the presence of DM.

Gravitational lensing: Gravitational lensing [128] is one of the indirect detection techniques of DM. The light from a distant source will bend in presence of a massive object according to the theory of relativity. This massive gravitational body behaves like a lens. Analysis of different lensing patterns of different gravitational objects confirmed the presence of DM. The matter distribution of the bullet cluster which is nothing but a subcluster of two merging galaxies measured through lensing confirmed the existence of DM. Weak lensing of mass profile of the process of merger of two galaxies confirms the presence of collisionless particles which indirectly implies the existence of DM.

Cosmic microwave background(CMB): CMB is nothing but information on the state of the universe at the time of the Big Bang [129]. CMB provides important evidence of DM's existence. CMB can measure the total matter density of the universe and it is also sensitive to the relative abundance of baryonic matter density to nonbaryonic matter density. In recent experimental data from the Planck collaboration, it is found that 26.8 % of the energy density in the universe is composed of DM and the relic density is represented as:

$$\Omega_m h^2 = 0.1187 \pm 0.0017 \tag{1.83}$$

Despite these observational pieces of evidence, the nature and interaction of DM remain a big question in the particle physics sector. The conditions which have to be obeyed by any particle to be a DM candidates are discussed in many works of literature [130]. The SM does not contain any viable DM candidate as neutrinos are not that massive to satisfy the DM abundance. Because of this reason, there are many BSM frameworks proposed to study the DM. In this thesis, we have studied sterile neutrino as a fermionic dark matter in the framework of extended LRSM.

1.4.9.1 Sterile neutrino: A viable dark matter candidate

Numerous DM candidate has been proposed to explain the observational evidence in different BSM frameworks. One of the important extensions of SM by a gauge singlet sterile fermion is an interesting scenario for the explanation of DM candidate and neutrino phenomenology. The sterile neutrino can be produced from active-sterile oscillation by Dodelson-Widrow (DW) mechanism [131].

There are many cosmological and astrophysical constraints on sterile neutrino dark matter [28, 132–134]. Sterile neutrinos can be produced from Standard model plasma through their mixing with active neutrinos in the early universe. Since sterile neutrino is a fermionic dark matter candidate, lower bounds exist on its mass known as Tremaine-Gunn bound. Again, the upper limit on mass can be obtained from X-ray constraints. Direct and indirect detection of dark matter also impose significant bounds on sterile neutrinos which can be seen in [135–138].

Any stable neutrino state with a non-vanishing mixing to the active neutrinos will be produced through active-sterile neutrino conversion. Thus the abundance is generated through the mixing of sterile and active neutrinos. The mechanism of nonresonant production of sterile neutrinos is known as Dodelson-Widrow (DW) mechanism. The resulting relic abundance can be expressed as:

$$\Omega_{DM}h^2 = 1.1\times 10^7 \sum C_\alpha(m_s)|\varepsilon_{\alpha s}|^2\left(\frac{m_s}{keV}\right)^2, \alpha = e,\mu,\tau \tag{1.84}$$

where $sin^2 2\theta = 4\sum|\varepsilon_{\alpha s}|^2$ with $|\varepsilon_{\alpha s}|$is the active-sterile leptonic mixing matrix element and m_s represents the mass of the lightest sterile fermion.

The nonobservation of X-ray lines from clusters provides upper limits to the active-sterile mixing angle as well as the sterile-neutrino mass. We have implemented the bounds from the X-ray in our analysis. An important constraint on sterile neutrino dark matter is Ly-α bound. This bound provides stronger bounds on the velocity distribution of the DM particles from the effect of their free streaming on the large-scale structure formation. This constraint can be converted into a bound for the mass of the DM particle which can be seen in [132]. The constraint is strongly model dependent and the bounds are governed by the production mechanism of the DM candidate. In this thesis, We have adopted the bounds considering $XQ - 100$ Ly-α data [137].

1.4.10 Discrete flavor symmetry in particle physics:

In particle physics, symmetry plays a very important role in explaining particle interaction and fundamental forces. Noether's theory of particle physics is one example where one can see symmetry as the origin of associated conservation laws. In some cases, broken symmetry also plays an important role. The spontaneous electroweak symmetry breaking and associated Higgs mechanism as discussed earlier is one such case. Many phenomena that occur in strong, weak, and electromagnetic interaction can be understood with the help of continuous symmetries such as Lorentz, Poincare, and gauge symmetry. Charge conjugation(C), Parity(P), and Time reversal (T) are some discrete symmetries essential for a proper description of particle physics. Mathematically symmetry can be realized with the help of group theory. The properties of a particular group are maintained by a set of symmetry transformations, which is known as a symmetry group. These symmetry groups also known as lie groups such as $SU(n)$, $U(n)$, and $O(n)$ are extensively used in theoretical particle physics.

In the previous section, we have studied the SM where the mass generation mechanism of elementary particles is explained with the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. These groups are non abelian ($SU(3)_C, SU(2)_L$) and abelian ($U(1)_Y$) continuous group. We know that neutrino mass and mixing can not be described within the SM. With the experimental confirmation of neutrino mass and mixing the importance of the study of flavor symmetry has increased. It is observed that the lepton sector is relatively less hierarchical and has large mixing as compared to the quark sector. The use of flavor symmetry in extended SM to a corresponding nonabelian finite discrete group can explain the neutrino mass and observed mixing. The flavor structure of a particular model can be controlled by discrete flavor symmetry [139, 140]. Because of this reason discrete flavor symmetry has extensive application in particle physics. A_N, S_N,Z_N are some discrete symmetries that are being used to model building purposes to explain different neutrino phenomenologies along with neutrino mass and mixing. The main motivation for using additional discrete symmetry is to study the flavor structure of any theory extensively and it will enhance the predictability of the model. The origin of this symmetry is supposed to be at some high energy scale which will break at a low energy scale to symmetries of charged lepton and quark through flavors. Flavors are scalar particles introduced in a model which play a crucial role in breaking the discrete symmetry. There are a large number of models proposed using flavor symmetries such as A_4, S_4 Z_2, etc [141–149] to obtain the observed neutrino mixing corresponding to experimental data.

In this thesis, we have used A_4 discrete flavor symmetry extensively in the context of the radiative seesaw, LRSM, and extended LRSM. In the following subsection, we will discuss the properties of the A_4 group.

1.4.10.1 Properties of A_4 group

A_4 is discrete group of even permutation of four objects whose order is equal to 12. The generators S and T of A_4 satisfy the following condition,

$$T^3 = S^2 = (ST)^3 = e \tag{1.85}$$

All of the A_4 elements can be written as products of these two generators.

The character table for A_4 is given below in 1.4

A_4	h	χ_1	$\chi_{1'}$	$\chi_{1''}$	χ_3
C_1	1	1	1	1	3
C_3	2	1	1	1	-1
C_4	3	1	ω	ω^2	0
$C_{4'}$	3	1	ω^2	ω	0

Table 1.4 Character table of A_4 group.

It has three inequivalent one dimensional representation 1, $1'$ and$1''$ a irreducible three dimensional representation 3. Product of the singlets and triplets are given by-

$$
\begin{aligned}
1 \otimes 1 &= 1 \\
1' \otimes 1' &= 1'' \\
1' \otimes 1'' &= 1 \\
1'' \otimes 1'' &= 1' \\
3 \otimes 3 &= 1 \oplus 1' \oplus 1'' \oplus 3_A \oplus 3_S
\end{aligned} \tag{1.86}
$$

where subscripts A and S stands for “asymmetric” and “symmetric” respectively. If we have two triplets (a_1, a_2, a_3) and (b_1, b_2, b_3), their products are given by

$$
\begin{aligned}
1 &\approx a_1 b_1 + a_2 b_3 + a_3 b_2 \\
1' &\approx a_3 b_3 + a_1 b_2 + a_2 b_1 \\
1'' &\approx a_2 b_2 + a_3 b_1 + a_1 b_3 \\
3_S &\approx \begin{pmatrix} 2a_1 b_1 - a_2 b_3 - a_3 b_2 \\ 2a_3 b_3 - a_1 b_2 - a_2 b_1 \\ 2a_2 b_2 - a_1 b_3 - a_3 b_1 \end{pmatrix}
\end{aligned}
$$

$$3_A \approx \begin{pmatrix} a_2b_3 - a_3b_2 \\ a_1b_2 - a_2b_1 \\ a_3b_1 - a_1b_3 \end{pmatrix}$$

The tensor product of 3×3 can be decompsed as in case of A_4

$$(A)_3 \times (B)_3 = (A \cdot B)_1 + (A \cdot \Sigma \cdot B)_{1'} + (A \cdot \Sigma^* \cdot B)_{1''} + \begin{pmatrix} \{A_yB_z\} \\ \{A_zB_x\} \\ \{A_xB_y\} \end{pmatrix}_{3_S} + \begin{pmatrix} [A_yB_z] \\ [A_zB_x] \\ [A_xB_y] \end{pmatrix}_{3_A} . \tag{1.87}$$

where the products are given as,

$$A \cdot B = A_xB_x + A_yB_y + A_zB_z \tag{1.88}$$

$$\{A_iB_j\} = A_iB_j + B_jA_i \tag{1.89}$$

$$\left[A_iB_j\right] = A_iB_j - A_jB_j \tag{1.90}$$

$$A \cdot \Sigma \cdot B = A_xB_x + \omega A_yB_y + \omega^2 A_zB_z \tag{1.91}$$

$$A \cdot \Sigma^* \cdot B = A_xB_x + \omega^2 A_yB_y + \omega A_zB_z. \tag{1.92}$$

1.5 Thesis outline

The thesis is organised as follows:

In **chapter 1**, we present the advancement of theoretical and experimental research in neutrino physics. We discuss the Standard Model of particle physics and also the drawbacks of the model that call for the extension of the Standard Model. After that, we discuss neutrino flavor oscillation in vacuum as well as in matter. We review different mechanisms of generating neutrino masses focusing on the LRSM, extended LRSM and radiative seesaw framework as the thesis work is based on these three frameworks. Two important cosmological issues that call for BSM frameworks : dark matter and baryon asymmetry of universe have also been discussed in this chapter. In this context, we introduce the sterile neutrino and its importance in generating neutrino mass along with dark matter and BAU. We discuss some low energy processes lepton number violation and lepton flavor violation . The chapter is concluded with the discussion on the importance of discrete flavor symmetry in particle physics. We mainly discuss the properties of A_4 flavor symmetry based on which we have constructed different models in this thesis.

In **chapter 2**, we construct a left-right symmetric model (LRSM) with A_4 flavor symmetry to explain neutrino mass generation. We study the neutrinoless double beta decay (NDBD) and charged lepton flavor violation(CLFV) in a generic flavor symmetric LRSM in this chapter.

Chapter 3 is the phenomenological study of NDBD and dark matter in extended LRSM. We have considered possible extension of LRSM with a sterile fermion per generation and studied the dark matter phenomenology. We also study the implications of flavor symmetry on low energy phenomena like neutrinoless double beta decay (NDBD). Different new physics contributions to the NDBD process in the framework are also studied in this chapter.

The motivation of **chapter 4** is to connect neutrino mass, lepton flavor violation and baryon asymmetry of universe within A_4 flavor symmetric radiative seesaw framework. Considering different lepton flavor violating(LFV) processes such as $l_\alpha \longrightarrow l_\beta \gamma$ and $l_\alpha \longrightarrow 3l_\beta$, their impact on neutrino phenomenology is studied. We have also analysed $0\nu\beta\beta$ and baryon asymmetry of the Universe(BAU) in this work.

Finally, we present the conclusion of the thesis work and the future scope of the thesis in **chapter 5**.