Introduction

The perception of the fundamental particles and the interactions among them has emerged into a distinct illustrative picture today. Forces found in nature can be distinguished into four categories according to their observed strength at low energies: strong, electromagnetic, weak, and gravitational. Their strengths are approximately of the following orders of magnitude:

Strong $\sim 10^1$; Electromagnetic $\sim 10^{-2}$; Weak $\sim 10^{-5}$; Gravitational $\sim 10^{-40}$.

The ranges of electromagnetic and gravitational interactions are infinite, whereas the weak and strong interactions have very short range. In Fig. 1.1 we have shown a wide classification of the familiar “elementary” particles. Leptons and nonhadronic bosons undergo only weak and electromagnetic interactions, while baryons and mesons participates in strong and
weak (as well as electromagnetic) interactions. Nonhadronic particles (leptons, $\gamma, W^{\pm}, Z...$) manifest themselves into pointlike structure, while the hadronic particles (baryons and mesons) have finite sizes. There are two sets of basic building blocks of matter: the basic fermions (leptons and quarks, on which weak, electromagnetic, and strong forces act) and the basic elementary bosons such as photon, $W, Z$, colored gluons, which are the mediators of the above forces (except gravity). Baryons and mesons are made up of a more elementary constituent of matter called quarks, which have strong, as well as weak, interactions. Strong, weak and electromagnetic force can be gracefully expressed in terms of mathematical formulation known as gauge field theory which is comprised of group symmetries. Moreover, the entire theory of basic elementary particles and the three forces (except gravity) above, can be formulated into a single symmetrical group structure which is termed as the standard model. The standard model (SM) gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ has three independent gauge couplings $g_1, g_2$ and $g_3$. Grand Unified Theory (GUT) which aims at the unification of strong and electroweak interactions are considered as prime candidates for describing neutrino masses and also ensures the accommodation of all the known fermions of a given generation including the right handed neutrino in a common multiplet of a single gauge group. The SM gauge couplings runs logarithmically from one energy scale to the other leading to an unified coupling, $g_{GUT}$, when the three forces unifies at some high scale say $M_{GUT}$. 

**Fig. 1.1:** Broad classification of elementary particles
The concept of neutrino physics began with Pauli’s “Neutrino Hypothesis”, however the origin of neutrinos can be dated back to radioactivity, where in the late 19th century Becquerel discovered that an unstable atomic nucleus [1] loses its energy by emitting alpha(α), beta(β) and gamma(γ) radiations. In 1930 Wolfgang Pauli proposed the “Neutrino Hypothesis” to save the energy momentum conservation principle in β decay. He said that the continuous spectra might be due to an invisible light neutral particle engrossed in the β – decay. In the three particles process, the electron might possess any momentum from zero to the maximum allowed value with the left out momentum [2] being taken by the other neutral particle. In 1933 Fermi postulated the famous theory of β-decay based on Pauli’s Neutrino hypothesis. At that time the the name neutrino [3] was coined for the Pauli’s invisible particle. All β-decay have the same underlying physics.

\[ n \rightarrow p + e + \bar{\nu} \]  \hspace{1cm} (1.1)

To conserve angular momentum neutrinos must be spin-1/2 particles obeying the Fermi-Dirac Statistics. The existence of neutrino was firmly established in 1953 when Clyde Cowan and Frederick Reines announced about the experimental detection [4, 5] of this weakly interacting particle, where electron type antineutrinos (\(\bar{\nu}_e\)) came out of nuclear reactors. In 1962, Leon M. Lederman, Melvin Schwartz and Jack Steinberger proved that neutrinos have flavor and they named the neutrinos produced in muon decay as the muon neutrino \(\nu_\mu\) [6]. Finally in 2000 the DONUT collaboration at Fermilab [7] detected the tau neutrino (\(\nu_\tau\)) interactions.

For the unification of the electromagnetic, weak, and strong forces, a non-abelian gauge theory known as Standard Model (SM) [8] based on the symmetry group \(U(1)_Y \times SU(2)_L \times SU(3)_C\) was developed in the latter half of 19th century. In SM there are three generations of
SU(3)_C colored quarks:

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}, \quad
\begin{pmatrix}
  c \\
  s
\end{pmatrix}, \quad
\begin{pmatrix}
  t \\
  b
\end{pmatrix}
\]

first generation  second generation  third generation

(1.2)

and three generations of leptonic doublets,

\[
\begin{pmatrix}
  e \\
  \nu_e
\end{pmatrix}, \quad
\begin{pmatrix}
  \mu \\
  \nu_\mu
\end{pmatrix}, \quad
\begin{pmatrix}
  \tau \\
  \nu_\tau
\end{pmatrix}
\]

first generation  second generation  third generation

(1.3)

All the six quarks have three SU(3) color charges: red, green and blue. The weak force is mediated by \(W^\pm\) and \(Z\) bosons. Photon is the mediator of the electromagnetic force and the gluons are the carrier of strong force. Neutrinos, the weakly interacting massive particles interact with the other leptonic fields through the exchange of \(W^\pm\) and \(Z\) bosons which results in charge current (CC) interactions and neutral current (NC) interactions respectively. Though the SM theory is both rigorous and self-consistent model and has a number of desirable features that helps in building theory for experimentally proven facts, there are a certain aspects of its drawbacks. One of them is the neutrino mass. In SM, the fermions and gauge bosons are massless until and unless the symmetry of the gauge group breaks down. After the spontaneous symmetry breaking, the gauge bosons and the fermions acquire mass via Higgs mechanism. The mass term of the fermions comes from the yukawa coupling term

\[-Y \bar{\psi}_L \psi_R < \phi >,\]

where \(Y\) is the yukawa coupling, \(\psi_L\) and \(\psi_R\) are the left handed leptonic doublets and right handed singlets respectively, and \(< \phi >\) is the vacuum expectation value of the Higgs field. Since there are no right handed neutrinos in SM, it is impossible to write a mass term for fermions which remains singlet (invariant) under local and global gauge transformations and thus the neutrinos are massless in SM. Parity is violated in weak interarctions [9] as a result of absence of right handed neutrinos in SM. Parity violation in
weak interactions [10] was first observed in Wu’s experiment where the $^{60}$Co nuclear spins aligned by an external magnetic field, emitted electrons with an asymmetrical distribution in their emitted directions.

$$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \bar{\nu}_e$$  \hspace{1cm} (1.4)

The absence of $\bar{\nu}_L$ and $\nu_R$ in the above decay clearly indicates that parity is violated in weak interactions. The experimental observation of “neutrino oscillation” phenomenon dictates that neutrinos are massive.

It was Bruno Pontecorvo, who for the first time in 1950 put forward the idea of neutrino oscillations [11], analogous with $K^0 - \bar{K}^0$ oscillations, where a neutrino produced with a definite flavour ($\nu_e, \nu_\mu, \nu_\tau$) can oscillate to a different lepton flavour [12, 13]. This is possible if neutrinos have masses and mixing [14]. The massive neutrinos are produced in their gauge eigen states ($\nu_\alpha$) which is related to their mass eigen states ($\nu_i$), where the gauge eigen states take part in gauge interactions as

$$|\nu_\alpha > = \sum U^*_{\alpha i} |\nu_i >$$  \hspace{1cm} (1.5)

$U$ is the unitary mixing matrix. $\alpha = e, \mu, \tau$ and $\nu_i$ is the neutrino of definite mass $m_i$. Here, $U$ can be parameterised as (according to PDG format)

$$U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}$$  \hspace{1cm} (1.6)

where, $\theta_{12} = 33^0$, $\theta_{23} = 38^0 - 53^0$, $\theta_{13} = 8^0$ [15–20] are the solar, atmospheric and reactor angles according to the global fits respectively. The Majorana phases $\alpha, \beta$ [21] reside in $P,$
where
\[
P = \text{diag} \left( 1, e^{i\alpha}, e^{i(\beta + \delta)} \right)
\] (1.7)

$U^*P$ is known as the Pontecorvo-Maki-Nakagawa-Sakata $U_{PMNS}$ matrix.

In the recent years, the neutrino oscillation parameters have been gradually measured with increasing precisions. The Super-Kamiokande collaboration [22–24] found that the atmospheric neutrino mass squared splitting is $|\Delta m^2_{23}| \sim O(10^{-3} eV^2)$. The data from SNO [25], Super-Kamiokande and KamLAND experiments established that the solar neutrino mass squared splitting is of the order $|\Delta m^2_{21}| \sim O(10^{-3} eV^2)$. A series of subsequent experiments, utilising reactor and accelerator neutrinos, have brought about the atmospheric and solar neutrino oscillation parameters with a few to several percent accuracy. For the three flavours neutrino oscillation in vacuum, the probability of $\nu_\alpha \to \nu_\beta$ flavor transition is

\[
P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i<j} Re(U_{\alpha i}U_{\beta j}^*U_{\alpha i}^*U_{\beta j}) \sin^2 \left( \frac{\Delta m^2_{ij}L}{4E} \right) + 2 \sum_{i>j} Im(U_{\alpha i}U_{\beta j}^*U_{\alpha i}^*U_{\beta j}) \sin \left( \frac{\Delta m^2_{ij}L}{2E} \right)
\] (1.8)

$\Delta m^2_{ij} = m^2_i - m^2_j$, $i, j = 1$ to 3. Probability of $\nu$ oscillation depends on the two mass squared differences of the neutrinos. Neutrino oscillation is also controlled by the energy of the neutrinos $E$ and the length of the baseline $L$ related with it. The above expression dictates neutrino oscillations in vacuum. For neutrinos propagating in matter, the interaction potential due to matter modifies the neutrino mass matrix which is known as the Mikheyev − Smirnov − Wolfenstein effect [26].

The discoveries of neutrino mass and leptonic mixing have come from the observation of neutrino flavor change, $\nu_\alpha \to \nu_\beta$. CP transformation interchanges every particle in a process by its antiparticle. This CP violation can be produced by the phase $\delta_{CP}$ in $U$. Neutrinos can have two types of mass term in the lagrangian − dirac and Majorana mass terms. To determine whether Majorana masses occur in nature, so that $\bar{\nu}_i = \nu_i$, the favorable approach
to seek is Neutrinoless Double Beta Decay $[0\nu\beta\beta] [27]$. Whatever necessary processes cause $0\nu\beta\beta$, its observation would intend the existence of a Majorana mass term. In the usual unitarity scenario, the three active neutrinos, the flavor eigen states $\nu_e, \nu_\mu, \nu_\tau$ are connected to the mass eigen states $\nu_1, \nu_2, \nu_3$ via $\nu_\alpha = N_{\alpha i} \nu_i$. Here $N$ is the the generalised $\nu$ mixing matrix which could be both unitary and nonunitary [28–30], (see Eq. 1.12 below).

Cosmologists suggest that just after the Big Bang [31], the universe contained equal amounts of matter and antimatter. Today the universe contains matter but almost no antimatter. This change need that matter and antimatter act differently (CP violation). The CP-violating scenario to explain this change is leptogenesis [32]. Leptogenesis is a natural outcome of the See-Saw Mechanism [33]. In the See-Saw picture, we assume that, just as there are 3 light neutrinos $\nu_1, \nu_2, \nu_3$, there are 3 heavy right handed neutrinos $M_1, M_2, M_3$, where $M_R \sim 10^{9–14}$ GeV, $M_R \sim M_1, M_2, M_3$ which were there in the Hot Big Bang. The $M_R$ decays modes are:

$$M \rightarrow l^- + H^+, M \rightarrow l^+ + H^-, M \rightarrow \nu + H^0, M \rightarrow \bar{\nu} + \bar{H}^0$$

(1.9)

where, $l^-$ are $e^-, \mu^-, \tau^-$ and $H^+, H^-, H^0$ are the Higgs fields. CP violation effects in the $M_R$ decays, may result from phases in the decay coupling constants. This leads to unequal numbers of leptons ($l^-$ and $\nu$) and antileptons ($l^+$ and $\bar{\nu}$) in the Universe.

$$\Gamma(M \rightarrow l^+ + H^-) \neq \Gamma(M \rightarrow l^- + H^+)$$

(1.10)

Since unitarity of $\nu$ mixing matrix has not been proved yet, if it is non unitary, then for the $\nu$ mixing matrix $N$ to be non unitary, we have

$$|\nu_\alpha > = \sum N_{\alpha i} |\nu_i >$$

(1.11)
fusing the flavor and mass states. The non-unitary matrix $N$ can be defined as

$$N = (1 + \eta)U_0$$

(1.12)

where, $U_0 = U \ast P$. In leptogenesis, CP violating decays of heavy Majorana neutrinos creates a lepton – antilepton symmetry [32] and then B+L violating sphaleron processes [34] at and above the electroweak symmetry breaking scale converts part of this asymmetry into the observed baryon-antibaryon asymmetry of the Universe (BAU). The heavy neutrinos are seesaw partners of the observed light ones.

For unflavored leptogenesis [30], valid for $M_1 \geq 10^{11}$ GeV, the flavor of the final state leptons plays no role. It can be shown that for lower values of $M_1$, lepton – antilepton symmetry depends on the flavor of the final state leptons, and hence is called flavored leptogenesis [35, 36].

Neutrino oscillation can only probe the mass squared differences of the neutrinos but not their absolute masses. The cosmological constraints of the sum of the $\nu$ masses bound is $\sum_i m(\nu_i) < 0.23$ eV from CMB, Planck 2015 data (CMB15+ LRG+ lensing + $H_0$) [37]. Also Tritium beta decay experiments measures the absolute mass of neutrinos. Bounds on sum of the absolute $\nu$ mass is $\sum_i m(\nu_i) < 2$ eV [37] from tritium beta decay.

The observation of non-zero neutrino mass via neutrino oscillations indicates physics beyond Standard Model. A neutrino mass model needs to explain how neutrinos become massive as well as why the $\nu$ masses are so tiny. The most effective way to generate small neutrino mass naturally is the See-Saw mechanism which associates the smallness of neutrino masses to beyond SM physics at TeV (Tera electronvolt) scale. In Type I [38–40] See-Saw, SM is extended by heavy right-handed Majorana neutrinos which are singlet. In Type II [41–44] and Type III [45] See-Saw, scalar triplets and fermion triplets are added to the gauge invariant lagrangian of the SM respectively. In Type I See-Saw after the spontaneous symmetry breaking (SSB) of the gauge invariant Lagrangian, the neutral component of
the Higgs doublet acquires a vacuum expectation value (VEV) $\nu$ and the smallness of the neutrino mass is hence explained.

$$m_\nu = \frac{\nu^2}{M_R}$$  \hspace{1cm} (1.13)

To have neutrino mass $\sim 0.1$ eV, $M_R$ should be around $10^{14}$ GeV without fine tuning of the neutrino Yukawa couplings. This is quite close to the scale of the Grand Unified Theories (GUT). See-Saw mechanism predicts that neutrinos can be of Majorana nature which implies that the neutrinos are their own antiparticles. In this mechanism lepton number is violated by two units.

Since in the SM, neutrinos are massless, one is bound to go beyond the SM. A Grand Unified Theory (GUT), which aims to unify all the three forces together with a single gauge coupling constant [46] is basically based on a single gauge group [45, 47]. It also unifies quarks and leptons in the same multiplet of the underlying gauge group [45]. SO(10) [48] is one such GUT group where all the known fermions of a given generation including the right handed neutrino are present in a single sixteen dimensional spinorial representation of the group. It has the correct quantum numbers to accommodate all fermions (including the right-handed neutrino) of one generation. These theories require running masses and mixings of quarks and charged leptons at GUT scales for calculating neutrino masses. Since GUTs aims to unify quarks and leptons in the single spinorial irreducible representation of the same gauge group it has received much attention from this perspective. The issue of neutrino masses and mixing in the context of SO(10) GUTs will be discussed in the chapter 2 where we present a possible scenario to generate neutrino masses and mixings in a specific SO(10) model.

The quadratic divergences to the radiative corrections of the Higgs scalar masses can have dangerous contributions to Higgs mass. To solve this issue one of the most attractive physics is supersymmetry (SUSY) which is a implementation of symmetry between fermions and bosons [49], and is a unique extension of the Poincare group. SUSY is incorporated
into a beyond Standard Model (BSM) theory by the introduction of the superpartners of the standard model sfermions for fermions, gauginos and higgsinos for gauge bosons and Higgs. A supersymmetrical transformation turns a bosonic state into a fermionic state, and vice versa. In supersymmetry the radiative correction to the Higgs mass gets contribution from the superpartner loops, and this motivates to cancel the quadratic divergences in the Higgs mass sector [50].

Since SUSY particles are not detected yet at Large Hadron Collider, it implies that SUSY must be broken at some high energy scale. Supersymmetry can be broken spontaneously in a hidden sector and is then communicated to the Minimal Supersymmetric Standard Model (MSSM) [51, 52] sector through the ‘messenger sector’ which could be either gauge interactions or gravitational interactions. This leads to soft supersymmetry breaking terms in the MSSM. Such supersymmetry breaking models are (i) minimal Supergravity (mSUGRA) [53–56] (ii) Gauge Mediated Supersymmetry Breaking (GMSB) (iii) Anomaly Mediated Supersymmetry Breaking (AMSB) etc. In Grand Unified Theories, it has been prescribed that the strictly universal feature of the soft masses might break and in fact some amount of non-universalities can enter in a model-dependent way in Non universal gaugino mass models (NUGM) [57], non universal scalar mass models (NUSM) [58], non universal Higgs mass models (NUHM) [59] which will be discussed briefly in chapter 3 in the context of charged lepton flavor violating decay, $\mu \rightarrow e\gamma$, in $\mu - \tau$ symmetric [?] SO(10) model.

This is precision era for Neutrino physics. With the precise measurement of reactor mixing angle $\theta_{13}$ [19, 60, 62–64] by reactor experiments, the unknown quantities left behind to be measured in neutrino sector are – leptonic CP violating phase [65–70]; octant of atmospheric angle $\theta_{23}$ [71–76]; mass hierarchy; nature of neutrino (i.e., Dirac or Majorana); the mechanism of generation of neutrino masses and explanation of their smallness; non standard interaction (NSI) of the neutrinos; non-unitary neutrino mixing and CPT violation in neutrino oscillation etc. Long baseline neutrino experiments (LBNE [77, 78], NOvA
[79], T2K [80], MINOS [81], LBNO [82] etc) may be very promising, in measuring many of these sensitive parameters. Measuring leptonic CP violation (CPV) is one of the most demanding tasks in future neutrino experiments [83]. The relatively large value of the reactor mixing angle $\theta_{13}$ measured with a high precision in neutrino experiments has opened up a wide range of possibilities to examine CP violation in the lepton sector. The leptonic CPV phase can be induced by a Dirac type CP violating phase [17, 18, 20, 84–86] and two extra Majorana phases if neutrinos are Majorana particles. In this connection, possible size of leptonic CP violation detectable through neutrino oscillations can be predicted in the context of entanglement of octant of $\theta_{23}$ ($\theta_{23} < 45^0$ or $\theta_{23} > 45^0$) and quadrant of leptonic CP violating phase, which we will discuss in detail in chapter 4.

Precise determination of the CP violating phase $\delta_{CP}$ indicates towards understanding of the present matter–antimatter asymmetry of the universe. The lepton asymmetry of the universe can be explained by the process of baryogenesis [87] via leptogenesis in which out of equilibrium decay of lightest of the heavy right handed Majorana neutrinos can create lepton asymmetry and a part of which may be converted to baryon asymmetry. Different studies show that under certain assumtions, it is possible to connect the leptonic CP phase $\delta_{CP}$ to leptogenesis.

Grand unified theories are very important for building models of fermion masses and hence examine neutrino masses and mixings. In this thesis we have discussed about the neutrino mass generation in an SO(10) model at GUT scales, using updated values of running quark and lepton masses in SO(10) Grand unified theory using type II seesaw mechanism. We have studied charged lepton flavor violation decay $\mu \rightarrow e\gamma$ in mSUGRA, NUGM, NUSM in which we have predicted some values of masses of new supersymmetric particles that may be detected at next run of LHC. We have also resolved entanglement of the quadrant of leptonic CPV phase and octant of atmospheric mixing angle $\theta_{23}$, at Long Baseline Neutrino Experiments in the light of baryon asymmetry of the universe through the mechanism of
leptogenesis and have showed how possible values of the leptonic CP violating phase can be predicted in this context. The effects of non-unitary lepton mixing matrix on lepton flavor violation, neutrino oscillation and leptogenesis in flavored and unflavored regime have been explored here and in this connection the constraints developed on the absolute value of the lightest neutrino mass is also discussed. Outline of the Thesis is discussed in the Section 1.6.

1.1 Neutrino Mass In SO(10) Theory And Type II Seesaw Mechanism

The standard model is a successful theory at low scale ($\sim 100\text{GeV}$). The Grand unified group $G$ contains the SM group $SU(2)_L \times U(1)_Y \times SU(3)_C$ as a subgroup. In GUT, all the fermions are contained in the same multiplet of the GUT gauge group, $G$. Thus all the fermions of one generation are present in a single spinorial representation of $G$.

Grand unified theory have a larger symmetry than the standard model. The gauge bosons of GUT acquire masses once the underlying GUT symmetry is broken at very high scale which is the unification scale. These gauge bosons causes proton decay [88]. The probability of SO(10) as a grand unification group of the standard Model $SU(2)_L \times U(1)_Y \times SU(3)_C$ was first observed by Georgi [89] and Fritzsch and Minkowski [89]. SO(10) is a group of rank 5 which has the extra diagonal $B-L$ generator as in the left-right symmetric groups, thus making parity a part of continuous symmetry. The advantages of SO(10) are:

1) SO(10) has all the correct quantum numbers to accommodate all fermions (including the right-handed neutrino) of one generation in a single 16 dimensional spinorial representation.

2) The gauge interactions of SO(10) conserve parity thus making parity a part of a continuous symmetry.

3) Non zero $\nu$ masses, the see-saw scale and a high $B$-$L$ scale fits naturally in a grand unified model group based on the gauge group SO(10).
4) SO(10) model contains the L-R symmetric unification group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$ which provides the origin of parity violation in nature.

5) It is the simple GUT group which does not require mirror fermions.

The right handed Majorana neutrinos owe its origin to the breaking of local $B-L$ symmetry which indicates that $M_R \simeq M_{B-L}$. Local $B-L$ [90] symmetry thus provides a natural process to perceive the smallness of the RH neutrino mass compared to $M_{\text{Planck}}$. Now SO(10) group also contains the local $B-L$ as a subgroup. $B-L$ symmetry of SUSY SO(10) can be broken by an 126 dimensional Higgs which automatically leaves R-parity unbroken and hence explains, why neutralino is a stable dark matter [91, 92]. The submultiplet of 126 that breaks $B-L$ have $B-L = 2$. Therefore R-parity (defined by $R_P = (-1)^{(B-L)+2S}$) have quantum number of this field as even and hence it leaves R-parity as an exact symmetry.

In the type II seesaw mechanism, an induced triplet vev is added to the usual type I seesaw formula which arises due to the heavy Majorana RH neutrino scale. In SO(10) models, type II seesaw dominates if both parity and $B-L$ symmetry are broken at the same scale. The neutrino mass matrix is given by the type II seesaw formula, with contributions from the heavy right handed Majorana neutrino intermediate scale and from an induced triplet vev. As shown in [93] when the induced triplet vev term dominates the neutrino mass matrix we have

$$M_\nu = a(M_l - M_d)$$

(1.14)

where $l$ and $d$ denotes the charged leptons and down quarks. This equation is the key to the work of neutrino masses and mixings, in chapter 2.

The invariant Superpotential of $SO(10)$ that gives the Yukawa Couplings of the 16 dimensional matter spinor $\psi_i$ with the Higgs fields $H_{10} = 10$ and $\Delta = \overline{126}$ is [94]

$$W_Y = h_{ij} \psi_i \psi_j H_{10} + f_{ij} \psi_i \psi_j \Delta$$

(1.15)
where $h$ and $f$ are symmetric Yukawa coupling matrices under SO(10) invariance. In the type I seesaw mechanism the neutrino mass matrix is given by

$$M_\nu = -M_D^\nu M_R^{-1}M^{TD}_\nu$$  (1.16)

where $M_R = f\nu_{B-L}$ and $\nu_{B-L}$ is the seesaw scale. In SO(10), the seesaw formula has a second term which appears from an induced $SU(2)_L$ triplet vev. The type II seesaw mechanism has the following expression [94]

$$M_\nu = f\sigma_L - M_D^\nu M_R^{-1}M^{TD}_\nu$$  (1.17)

$$\sigma_L = \lambda \frac{v^2}{\nu_{B-L}}$$  (1.18)

$v$ is the $SU(2)_L$ breaking scale. $\lambda$ is a combination of parameters in Higgs potential. There are two VEVs $\sigma_L$ and $\nu_{B-L}$ instead of one in the type I case. The decomposition of $126$ under the group $SU(2)_L \times SU(2)_R \times SU(4)_C$ is

$$126 = (1,1,6) + (2,2,15) + (3,1,\overline{10}) + (1,3,10)$$  (1.19)

$\Delta_L = (3,1,\overline{10})$ couples to the left handed multiplet $\psi_L = (2,1,4)$ of the 16 dimensional SO(10) model containing the spinorial matter representation i.e $\psi_L\psi_L \Delta_L$. The mass of the right handed neutrino originates owing to coupling of $\Delta_R = (1,3,10)$ submultiplet of $126$ to right handed fermion irreducible multiplet $\psi_R^C = (1,2,4)$ i.e $\psi_R^C\psi_R^C \Delta_R$. $\Delta_R$ breaks the $B-L$ gauge symmetry and in this process the RH neutrinos acquire mass that produces the second term in the type II seesaw formula. The sumrule Eq. 1.14 holds in the domain of the parameter space, where triplet vev contribution to the neutrino mass matrix dominates in the type II seesaw mechanism.
In this connection, neutrino oscillation parameters can be calculated using the updated values of running quark and lepton masses from [95] using Eq. 1.14 and a consistency can be made between the results obtained by this process and global fit data of neutrino oscillation parameters described below. More analysis will be presented in detail in chapter 2. The global fit values [15–20] of neutrino oscillation parameters are

\[
\Delta m^2_{21}[10^{-5}eV^2] = 7.60^{+0.19}_{-0.18}
\]

\[
|\Delta m^2_{31}|[10^{-3}eV^2] = 2.48^{+0.05}_{-0.07}(2.38^{+0.05}_{-0.06})
\]

\[
\sin^2\theta_{12} = 0.323\pm0.016
\]

\[
\sin^2\theta_{23} = 0.567^{+0.032}_{-0.124}(0.573^{+0.025}_{-0.039})
\]

\[
\sin^2\theta_{13} = 0.0226\pm0.0012(0.0229\pm0.0012)
\]

(1.20)

For \(\Delta m^2_{31}, \sin^2\theta_{23}, \sin^2\theta_{13}\), the quantities inside the bracket corresponds to inverted neutrino mass hierarchy and those outside the bracket corresponds to normal mass hierarchy. The errors are within the 1\(\sigma\) range of the \(\nu\) oscillation parameters.

The SUSY SO(10) theory naturally incorporates the seesaw mechanism. The presence of heavy RH neutrinos at an intermediate scale leads to the running and generates flavor violating entries in the left-handed slepton mass matrix at the weak scale. In this connection charged lepton flavor violating decays (cLFV) like \(\mu \rightarrow e\gamma\) can be studied in various universal and non-universal SUSY SO(10) models which will be discussed elaborately in chapter 3, where we will predict the possibility of detection of new supersymmetric particles at next run of LHC.
1.2 Charged Lepton Flavor Violating Decays

There are sound reasons to believe that the Standard Model is an incomplete theory, and one should expect New Physics (NP) around the TeV scale for explaining dark matter, baryon asymmetry of the universe, hierarchy problem etc. Flavour physics observables are sensitive to new particles (through their couplings to fermions) and are thus complementary to direct searches at colliders. Flavor physics gives information about the flavour structure of new physics (couplings and mixing patterns of new particles which may be produced some day in a collider in future) and is sensitive to BSM physics scales or bounds on regions of new physics parameter space that may not be accessible at the LHC.

In the quark sector, the data collected by K physics experiments ($K^0 - \bar{K}^0$ oscillations) and B ($B_d - \bar{B}_d$ mixing) factories do not show any clear signal of deviation from the Standard Model, and put strong constraints on the flavour structure of its extensions. The lepton sector is distinct from the quark sector in many folds. Since so far lepton flavour violation (LFV) has been detected only in the neutrino sector (\(\nu_e \leftrightarrow \nu_\mu\) which violates both \(L_e\) and \(L_\mu\)), the SM predicts no observable flavour violation in the charged lepton sector. The observation of any cLFV decay, e.g. $\mu \rightarrow e + \gamma$, would be an unambiguous indication of new physics beyond the SM. This makes charged lepton flavour violation a good probe for new physics beyond the Standard Model (and of the mechanism of neutrino mass generation). Such experimental searches, and theoretical studies on cLFV can help us constrain the new physics or BSM theories, that could be present just above the electroweak scale, or within the reach of next run of LHC. It is worth mentioning that in the next run of LHC, the center of mass energies are expected to go to 14 TeV [96, 97].

In the Standard Model, the violation of lepton flavour by the charged current does not signify large CLFV rates as a result of the GIM mechanism [98]. For cLFV decay, $\mu \rightarrow e + \gamma$, the branching ratio (BR) is (where branching ratio for a given mode is defined as $BR = \ldots$)
\[ BR(\mu \rightarrow e + \gamma) = 3 \frac{\alpha}{2\pi} |\sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu i}^2}{M_W^2}|^2 \] (1.21)

The \( m_{\nu i} \) independent piece in the loop integral, \( \frac{m_{\nu i}^2}{M_W^2} \), drops due to the unitarity of the PMNS matrix. \( \sum_i U_{\mu i}^* U_{ei} = 0 \). Similar mechanism exists for hadronic flavor changing neutral currents, but \( \frac{m_{\nu i}^2}{M_W^2} \) is much smaller than \( \frac{m_c^2}{M_W^2} \), where \( m_c \) is the mass of the charm quark. Using known neutrino oscillation parameters one gets \( BR(\mu \rightarrow e + \gamma) \lesssim 10^{-54} \) which is inaccessible to experiments at LHC. The present experimental status of different cLFV process have been discussed in chapter 3 and 5.

Improvements for \( \mu \rightarrow e\gamma \) decay of MEG experiment has presently reached \( BR(\mu \rightarrow e + \gamma) \leq 4.2 \times 10^{-13} \) [99, 100]. SUSY GUTs naturally give rise to tiny neutrino masses via see saw mechanisms in which significant contributions to cLFVs could come from flavor violations among heavy sleptons. The lepton flavor violation effects could become significant due to radiative corrections to Dirac Neutrino Yukawa Couplings (DNY), which might arise if the see saw scale is slightly lower than the GUT scale.

Supersymmetric version of the seesaw mechanism extends the Minimal Supersymmetric Standard Model by adding right handed neutrinos. The transformation properties of the MSSM + right handed neutrinos, under the gauge group

\[ G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \]

is given as

\[ L : (1, 2, -\frac{1}{2}); e^c : (1, 1, +1); \nu^c : (1, 1, 0) \] (1.22)

\[ Q : (3, 2, +\frac{1}{6}); u^c : (\bar{3}, 1, -\frac{2}{3}); d^c : (\bar{3}, 1, \frac{1}{3}) \] (1.23)
1.2 Charged Lepton Flavor Violating Decays

\[ H_u : \left(1, 2, +\frac{1}{2}\right); H_d : \left(1, 2, -\frac{1}{2}\right) \]  

(1.24)

where \( Q \) and \( L \) denotes the \( SU(2)_L \) doublet quarks and leptons, \( u^c, d^c, e^c \) and \( \nu^c \) are the \( SU(2)_L \) singlet quarks and leptons and \( H_u, H_d \) are the two Higgs doublet chiral superfields.

The soft supersymmetry-breaking terms in the Lagrangian of a general SUSY theory consisting of the mass terms of the gauginos, mass square terms for the scalar fields and also the bilinear and trilinear contributions of \((scalar)^3\) couplings is

\[
L_{soft} = \frac{1}{2} (M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g}) + m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2 + m^2_{L_{ij}} \tilde{L}_i \tilde{L}_j 
+ m^2_{\tilde{e}_{ij}} \tilde{e}_{i}^{*} \tilde{e}_{j} + m^2_{\tilde{\nu}_{ij}} \tilde{\nu}_{i}^{*} \tilde{\nu}_{j} + B_{\mu} H_u H_d + B_{M_{ij}} \tilde{\nu}_{i} \tilde{\nu}_{j} + h.c
+ \frac{1}{6} A^{ijk} \phi_i \phi_j \phi_k + h.c
\]

(1.25)

where,

\[
\frac{1}{6} A^{ijk} \phi_i \phi_j \phi_k = A^u_{ij} \tilde{Q}_i \tilde{u}_j H_u + A^d_{ij} \tilde{Q}_i \tilde{d}_j H_d + A^c_{ij} \tilde{L}_i \tilde{e}_j H_d + A^{\tilde{\nu}}_{ij} \tilde{\nu}_i \tilde{\nu}_j H_u 
\]

(1.26)

where, \( \tilde{B}, \tilde{W}, \tilde{g} \) stands for Bino, Wino, Gluino. It is well known that SUSY can be broken by soft terms of type \(-A_0, m_0, M_{1/2}\), where \( A_0 \) is the universal trilinear coupling, \( m_0 \) is the universal scalar mass, and \( M_{1/2} \) is the universal gaugino mass. Strict universality between Higgs and matter fields of mSUGRA model can be relaxed in NUHM (Non Universal Higgs Mass Models).

The lepton flavour violating entries in the SO(10) SUSY GUT framework can be understood in terms of the low energy parameters. These entries in the leading log approximation in mSUGRA are [101]

\[
(m^2_{L})_{i \neq j} = -\frac{3m^2_0 + A_0^2}{8\pi^2} \sum_k (Y^*_\nu)^{ik} (Y_{\nu})^{jk} \log \left( \frac{M_X}{M_{R_k}} \right)
\]

(1.27)

Here \( M_X \) is the GUT scale, \( M_{R_k} \) is the scale of the \( k^{th} \) heavy RH Majorana neutrino, \( m_0 \) and \( A_0 \) are universal soft mass and trilinear terms at the high scale. \( Y_{\nu} \) are the Dirac neutrino...
1.2 Charged Lepton Flavor Violating Decays

Yukawa couplings. The flavour violation is parameterized in terms of the quantity $\delta_{ij} = \frac{\Delta_{ij}}{m_i}$. Here $m_i = \sqrt{m_{\tilde{l}_i} m_{\tilde{l}_j}}$ is the geometric mean of the slepton squared masses [102], and $\Delta_{i \neq j}$ are flavour non diagonal entries of the slepton mass matrix induced at the weak scale due to RG evolution.

The branching ratio of a charged LFV decay $l_i \rightarrow l_j$ is [103]

$$\text{BR} (l_i \rightarrow l_j + \gamma) \approx \alpha^3 \frac{|\delta_{ij}^{LL}|^2}{G_F M^4_{\text{SUSY}}} \tan^2 \beta \text{BR} (l_i \rightarrow l_j \nu_i \tilde{\nu}_j)$$

(1.28)

where $M_{\text{SUSY}}$ is the SUSY breaking scale. In NUHM models, the term $(-3m_o^2 + A_o^2)$ of mSUGRA models in Eq. 1.23 is replaced by $(-2m_o^2 + A_o^2 + m_{H_u}^2)$. Here, $m_{H_u}$ is the soft mass terms of the up type Higgs at the high scale. We consider the NUHM1 case (at the GUT scale)

$$m_{H_u} = m_{H_d}$$

(1.29)

Moreover, there can be a relative sign difference between the universal mass terms for the matter fields and the Higgs mass terms at the GUT scale. This can clearly either lead to cancellation or enhancement compared to mSUGRA in the flavor violating entries at the weak scale. Cancellations for

$$m_{H_u}^2 \approx -2m_0^2$$

(1.30)

Or enhancements for

$$m_{H_u}^2 \geq m_0^2$$

(1.31)

Further discussions on this topic shall be presented in chapter 3.

1.2.1 Universal mSUGRA Models

In mSUGRA, SUSY is broken in the hidden sector, and is communicated to the visible sector MSSM fields via gravitational interactions. The property universal refers to the flavor space
1.2 Charged Lepton Flavor Violating Decays

i.e. all the soft terms take the same value irrespective of the flavor at the mediation scale. Generation of gaugino masses [104, 105] in mSUGRA (N=1 supergravity, where N is the number of gravitino of a supergravity theory), involves two scales — spontaneous SUGRA breaking scale in the hidden sector through the singlet chiral superfield and the other one is GUT breaking scale through the non singlet chiral superfield [53–56, 106–109]. In principle these two scales can be different. But in a minimalistic viewpoint, they are usually assumed to be the same [53–56, 106–109]. At the unification scale, $M_{GUT}$ the gaugino masses are universal to a value $M_{1/2}$, i.e.

$$M_1 = M_2 = M_3 = M_{1/2}$$  \hspace{1cm} (1.32)

The scalar and the Higgs masses are given by the universal soft mass parameter $m_0$ at $M_{GUT}$

$$m^2_{\tilde{Q}_i} = m^2_{\tilde{U}_R} = m^2_{\tilde{D}_R} = m^2_{\tilde{L}_i} = m^2_{\tilde{E}_i} = m^2_{\tilde{\nu}_i} = m^2_{0} \mathbb{1}$$  \hspace{1cm} (1.33)

$$m^2_{\tilde{H}_u} = m^2_{\tilde{H}_d} = m^2_{0}$$  \hspace{1cm} (1.34)

where, $\mathbb{1}$ is the identity matrix. The trilinear couplings are given by the parameter $A_0$ at $M_{GUT}$. The vacuum expectation values (vevs) of the two Higgs fields, is related by,

$$\tan\beta = \frac{\nu_u}{\nu_d}$$

where the sign of $\mu$ or the Higgsino mass parameter is needed to specify the spectrum at the weak scale.

### 1.2.2 Non Universal Models

In Grand Unified theories (GUTs) like SO(10), all the matter may be accomodated in a single representation while the Higgs gets represented in different representation, the universality of
the soft masses need not incorporate Higgs, especially when supersymmetry breaking scale is close to the GUT scale. Strict universality between Higgs and matter fields of mSUGRA models can be relaxed in NUHM (Non Universal Higgs Mass [59] Models). Therefore the Higgs boundary conditions at the high scale, $M_{GUT}$ are

$$m^2_{\tilde{Q}_i} = m^2_{\tilde{u}_i} = m^2_{\tilde{d}_i} = m^2_{\tilde{L}_i} = m^2_{\tilde{e}_i} = m^2_0 \mathbb{1}$$

(1.35)

where, $\mathbb{1}$ is the identity matrix.

$$m^2_{\tilde{H}_u} = m^2_{10}; \ m^2_{\tilde{H}_d} = m^2_{20}$$

(1.36)

$m_{10}$ and $m_{20}$ are used for the Higgs mass parameters in the non universal Higgs mass model. The non universal gaugino mass scenario in NUGM (Non Universal Gaugino Mass Models) is

$$M_1(M_{GUT}) \neq M_2(M_{GUT}) \neq M_3(M_{GUT})$$

(1.37)

In fact the non-universality of the gaugino masses is by no means a peculiar phenomenon, rather it is realized in various scenarios, including some approaches to grand unification [110].

The parameters of NUSM (Non Universal Scalar Mass Models) model is given by [111] $\tan \beta, M_{1/2}, A_0$, $\text{sgn}(\mu)$, and $m_0$. The parameters play exactly the same role to those in mSUGRA except for a significant difference in the scalar sector. Masses of the first two generations of scalars (squarks and sleptons) and the third generations of sleptons are designated as $m_0$ at the GUT scale. Here $m_0$ is allowed to span upto a very large value upto tens of TeVs. However the Higgs scalars and the third family of squarks are assumed to have vanishing mass values at $M_{GUT}$. In chapter 3, the mass parameters for the third generation of squarks and Higgs scalars will be set to zero and we will limit ourselves to a vanishing $A_0$ in our analysis [58].
1.3 CP Violation And Octant Degeneracy

Determination of CP violating phase in PMNS matrix gives a hint towards understanding of the present matter—asymmetry of the universe. CP symmetry is a composite of C and P symmetries, where C stands for charge conjugation symmetry and where P is the parity operation. C operation transforms a particle into its antiparticle or vice versa, and parity transforms everything into its mirror image so left becomes right and vice versa. The combined CP operation is invariant under the strong and electromagnetic interactions, while this symmetry is violated under weak interactions. If we take both the mirror and charge conjugation of a left handed neutrino, we get a right handed antineutrino, which exists.

The parameter that describes CP violation in $\nu$ sector is the angle $\delta_{CP}$. The value of $\delta_{CP}$ signifies to what extent CP is violated in $\nu$ sector and affects the $\nu$ oscillation which takes place between the three $\nu$ flavor states.

It is known that observed baryon asymmetry of the Universe (BAU) can be explained via leptogenesis. In leptogenesis, the lepton-antilepton asymmetry can be explained, if there are complex Yukawa couplings or complex fermion mass matrices. This in turn arises due to complex leptonic CPV phases, $\delta_{CP}$, in fermion mass matrices. If all other parameters except leptonic $\delta_{CP}$ phase in the formula for lepton-antilepton asymmetry are fixed, for example, then observed value of BAU from experimental observation can be used to constrain quadrant of $\delta_{CP}$. An experimental signature of CP violation associated to the Dirac CP phase $\delta_{CP}$, in PMNS matrix, can in principle be obtained, by searching for CP asymmetry in neutrino flavor oscillation. To elucidate this proposal, we will consider type I seesaw mechanism in non-SUSY SO(10) model, in which BAU arises due to leptogenesis, and this lepton-antilepton asymmetry is generated by the out of equilibrium decay of the right handed, heavy Majorana neutrinos, which form an integral part of seesaw mechanism for neutrino masses and mixings.

Long-baseline neutrino experiments are sensitive to $\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations. The dominant term of survival probability $P(\nu_\mu \rightarrow \nu_\mu)$ in vacuum is mainly sensitive to $sin^2 2\theta_{23}$. 
Many experimental results indicate that \( \theta_{23} \) is not maximal. A collective property that has appeared from all the global fits of the world neutrino data is that we now have evidence for non-maximal \( \theta_{23} \) [112]. Thus, we have the two degenerate solutions: either \( \theta_{23} \) belongs to the LO \( (\sin^2 \theta_{23} \sim 0.4) \) or it lies in the HO \( (\sin^2 \theta_{23} \sim 0.6) \). This degeneracy, in convention, can be broken with the help of \( \nu_\mu \leftrightarrow \nu_e \) oscillation data. If \( \sin^2 2\theta_{23} \) differs from 1 as indicated by the recent neutrino experiments, then we get two solutions for \( \theta_{23} \). Here 1 indicates maximal value of \( 2\theta_{23} \) ie, \( \theta_{23} \) is equal to 45 degree. If the quantity \( (0.5 - \sin^2 \theta_{23}) \) is positive (negative) then \( \theta_{23} \) belongs to lower octant (higher octant). This is known as the octant degeneracy of \( \theta_{23} \) [71]. Dominant term of \( P_{\mu\mu}^{\text{m}} \) survival probability is also sensitive to \( \sin^2 \theta_{23} \). For a given value of the survival probability \( P_{\mu\mu}^{\text{m}} \), we have two fold solutions for \( \theta_{23} \), i.e

\[
P(\theta_{23}) = P\left(\frac{\pi}{2} - \theta_{23}\right)
\]

when a measurement is made, it can not differentiate between

\[
\frac{\pi}{2} - \theta_{23} \text{ and } \theta_{23}.
\]

The main aim of beam based long baseline experiments T2K, NO\( \nu \)A is to measure the leptonic CPV phase \( \delta_{CP} \). The experiments LBNE and LBNO experiments are proposed to measure neutrino mass hierarchy, octant of \( \theta_{23} \) and CP violation in the leptonic sector with significant confidence level. The \( DA\!E\!S\!L\!U\!S \) experiment [113] aims to substitute the antineutrinos of the superbeam experiments by the low energy antineutrinos from muon decay at rest or by using Gd-doped water Cerenkov detector.

The aim of the atmospheric \( \nu \) experiments ICAL@INO [114], the Hyperkamiokande [115], PINGU [116], is to determine the \( \nu \) mass hierarchy. The primary focus of the medium baseline reactor neutrino experiments JUNO [117] and RENO-50 [118] is to determine the mass hierarchy utlising liquid scintillator detector.
In general, leptogenesis and CP violation in the light neutrino sector imply each other. If the CP violation phase $\delta_{CP}$ proves to be large, it could give a proper understanding of almost the entire Baryon–Antibaryon asymmetry by itself. Probing CP violation in light neutrino oscillation is now a major international aim. The search will implement accelerator neutrino beams to compare two CP-mirror-image processes. We have CP violation, provided these two CP-mirror-image processes have different rates. The upcoming CP violation experiments are today’s version of comparing of the decay processes, $\Gamma(M \rightarrow l^+ + H^-)$ with $\Gamma(M \rightarrow l^- + H^+)$.

Inspite of several experimental verifications of neutrino oscillations and precise measurements of two mass squared differences and the three mixing angles, the unitarity of the leptonic mixing matrix is not yet established, leaving room for the presence of small non-unitarity effects. Deriving the bounds on these non-unitarity parameters from existing experimental constraints, on cLFV decays such as, $\mu \rightarrow e\gamma$, $\mu \rightarrow \tau\gamma$, $\tau \rightarrow e\gamma$, we will study their effects on generation of baryon asymmetry through leptogenesis and neutrino oscillation probabilities in chapter 5 where we will predict values of lightest neutrino mass, and Dirac and Majorana CP violating phase $\delta_{CP}$, $\alpha$ and $\beta$, for normal hierarchy and inverted hierarchy for one, two and three flavor leptogenesis regimes. It is worth mentioning that all these four quantities are unknown yet, and future experiments will be measuring them.

1.4 Flavored And Unflavored Leptogenesis

Leptogenesis [32] is one of the most aspiring and well inspired framework which can produce baryon asymmetry of the Universe through B + L violating electroweak sphaleron process [34]. As directed by Sakharov’s condition the three basic requirements that produces baryon asymmetry in this Universe are [119]

(i) Baryon number violation,

(ii) C and CP violation and
(iii) Out of equilibrium decay

Matter–Antimatter could be generated by out of equilibrium decay of heavy right handed Majorana neutrinos into Higgs and lepton in the framework of type I seesaw mechanism. In a hierarchical pattern of heavy Majorana neutrinos $M_{2,3} > M_1$, the lepton asymmetry created by the decay of $M_1$, the lightest of three heavy right handed neutrinos is [36] (for both flavored and unflavored leptogenesis)

$$
\varepsilon_1^\alpha = \frac{1}{8\pi v^2} \frac{1}{(m_D^a m_D^b)_{11}} \left[ \sum_{2,3} \text{Im}[(m_D^a)_{a1}(m_D^b m_D)_{1j}(m_D^b)_{aj}] g(x_j) \right]
$$

$$
+ \sum_{2,3} \text{Im}[(m_D^a)_{a1}(m_D^b m_D)_{j1}(m_D^b)_{aj}] \frac{1}{1-x_j}
$$

where, $v = 174$ GeV, the Higgs bidoublets vev which breaks the electroweak symmetry

$$
g(x) = \sqrt{x}(1 + \frac{1}{1-x} - (1+x)\ln \frac{1+x}{x}), x_j = \frac{M_j^2}{M_1^2}
$$

$m_D$ is the Dirac neutrino mass matrix. At temperatures, $T \geq 10^{12}$ GeV all charged lepton flavors come out of equilibrium and thus all of them behave in the same way which results in the one flavor regime (unflavored leptogenesis). At moderate temperatures $T < 10^{12}$ GeV ($T < 10^9$ GeV), tau (muon) yukawa coupling interactions come into equilibrium and hence flavor effects play an important role in the calculation of lepton asymmetry [120–127]. The region of temperatures belonging to $10^9 < T/GeV < 10^{12}$ and $T/GeV < 10^9$ are respectively denoted as two and three flavor regimes of leptogenesis. $Y_B$ in the two and three flavor regimes are designated as [36]

$$
Y_B^{2/\text{flavor}} = \frac{-12}{37 g^*} [\varepsilon_2 \rho(\frac{417}{589} \tilde{n}_\tau) + \varepsilon_1 \rho(\frac{390}{589} \tilde{n}_\tau)]
$$
1.5 Rationale for the work done in this Thesis

In this section, we discuss the Rationale for the work done in this thesis. We have focussed on some of the open challenges that the field of high energy physics faces today. Future
experiments are very important in the sense that they can probably answer several important questions. Some of them are:

Is the physics of the dynamics of neutrino mass generation different from that behind the masses of all other known particles. Are neutrinos their own antiparticles. What is the absolute scale of the masses of neutrinos. What is the exact nature of the neutrinos (i.e., Dirac or Majorana). Do neutrino interactions violate CP, which is the basis for understanding the matter—antimatter asymmetry of the universe. Is the neutrino spectrum normal or inverted hierarchical in nature. Do we and all matter have descended from heavy neutrinos. Does non standard interaction (NSI) of the neutrinos exist. Does eV scale sterile neutrinos exist in nature. Does neutrinos and the universe are related to each other which will answer one of the fundamental questions, "Where have all the antimatter gone which were created in the hot Big Bang?"

In this Thesis we will focuss on areas of current research related to lepton masses, mixings and flavor violation in SUSY theories, leptonic CPV phase and baryogenesis (via leptogenesis), and non-unitarity in $U_{PMNS}$. First we will concentrate on model buildings relevant to neutrino masses and mixings in SO(10) theories using updated values of running quark and lepton masses in a framework of type II seesaw mechanism. Type II Seesaw mechanism mediates through induced scalar triplet vev and can generate neutrino masses in SO(10) model. Our model is quite predictive in the sense that it uses 126 dimensional Higgs vev which relates masses of the Majorana neutrinos to both the Dirac mass as well as charged fermion masses. Our analysis in this work provides a benchmark for future works connected to model building in neutrino physics with a purpose to conceive the dynamical origin of neutrino mass and mixing.

Next we will explore cLFV processes constrained by the recent MEG experiment to test New Physics BSM theories and hence have predicted the masses of new supersymmetric particles, scalars, gauginos, sfermions that could be present at next LHC’s run. It is worth
mentioning that detection of new particles at the second run of LHC will help immensely in the construction of beyond Standard Model theories.

Then, in the middle part of the Thesis, we will evaluate favored values of leptonic CP violation phase $\delta_{CP}$ in neutrino sector, determined the nature of octant of $\theta_{23}$ and neutrino mass hierarchy in non SUSY SO(10) theory in the context of resolving the entanglement of quadrant of leptonic CPV phase and octant of $\theta_{23}$ at Long Baseline Neutrino Experiments. It may be noted that the above three values (i.e neutrino mass hierarchy, octant of $\theta_{23}$ and leptonic CPV phase $\delta_{CP}$) are still unknown in neutrino sector which needs to be answered. In this regard we will calculate the baryon asymmetry of the Universe via leptogenesis in one flavor regime and predict the favored values of $\delta_{CP}$ consistent with the current BAU of the universe, $5.7 \times 10^{-10} < Y_B < 6.7 \times 10^{-10}$ (BBN).

Unitarity in $U_{PMNS}$ matrix is not yet established, and hence it has left scope for testing non unitarity in the leptonic sector which will result in various implications of New Physics theories in predicting the values of leptonic CPV phase, $\delta_{CP}$, Majorana phases, $\alpha, \beta$ and the absolute value of the neutrino masses. The interesting feature of our work is that we will evaluate the absolute value of lightest neutrino mass which is found to be consistent with the cosmological constraints on the sum of the neutrino mass bound, $\sum_i m(\nu_i) < 0.23$ eV from CMB, Planck 2015 data (CMB15+ LRG+ lensing + $H_0$) [37]. We note that absolute value of lightest neutrino mass is also not known so far, and hence our prediction made here may be tested in future when experiments (including neutrinoless double beta decay experiments) will determine its value in future.

1.6 Outline Of The Thesis

The thesis has been organised as follows.

In chapter 2, we will calculate neutrino masses and mixings at GUT scale, with updated val-
ues of running quark and lepton masses in minimal SO(10) Grand Unified Theory using type II Seesaw mechanism. We find that our calculated values of neutrino oscillation parameters agree with latest global fit values of these parameters.


In chapter 3, we will study the rare cLFV decay $\mu \rightarrow e\gamma$ in $\mu-\tau$ symmetric SUSY SO(10) theories, using type I see saw mechanism, in mSUGRA, NUHM and NUGM models. We have used the value of Higgs mass as measured at LHC, latest global data on the reactor mixing angle $\theta_{13}$ for neutrinos, and latest constraints of $\text{BR}(\mu \rightarrow e\gamma)$ as projected by MEG. We find that in our work mSUGRA very heavy $M_{1/2}$ region is allowed by future MEG bound of $\text{BR}(\mu \rightarrow e\gamma)$, though in NUHM case a low $M_{1/2}$ is also allowed. Hence we further studied the non universal gaugino mass model (NUGM). In mSUGRA, the $m_0$ values as allowed by MEG 2013 bound, shifts toward heavier spectrum, as compared to allowed $m_0$ of (which was allowed by a less stringent bound of MEG 2011). As compared to mSUGRA, in NUHM, a wider parameter range is allowed. For Higgs mass central value 125.4 GeV, our analysis allows a slightly lower value of $m_0$, both in mSUGRA and NUHM. We find that NUGM allows in general, a wider parameter space, as compared to both mSUGRA and NUHM. Here $\text{BR}(\mu \rightarrow e\gamma)$ is found to increase with increase in $m_0$ which could be due to particular ratios of gaugino masses. In NUGM, we find that allowed values of $|A|$ are shifted towards heavier side (compared to mSUGRA and NUHM). Hence any observation of heavy particles at next run of LHC, could help us understand to discriminate among these models, in reference to constraints put by cLFV decays. This in turn could contribute towards a better understanding of theories beyond standard model (BSM).

In Chapter 4, we will discuss how the study of CP violation discovery potential can be improved at long baseline neutrino experiments (LBNE/DUNE), by combining with its ND (near detector) and reactor experiments can be further analysed to resolve entanglement of the quadrant of leptonic CPV phase and Octant of atmospheric mixing angle $\theta_{23}$, at LBNEs. The study will be done for both NH (Normal hierarchy) and IH (Inverted hierarchy), HO (Higher Octant) and LO (Lower Octant). We show how baryogenesis can enhance the effect of resolving this entanglement, and how possible values of the leptonic CP-violating phase $\delta_{CP}$ can be predicted in this context. With respect to the latest global fit data of neutrino mixing angles, we predict the values of for different cases. In this context we present favored values of $\delta_{CP}$ ($\delta_{CP}$ range at $> 2\sigma$) constrained by the latest updated BAU range and also confront our predictions of $\delta_{CP}$ with an up-to-date global analysis of neutrino oscillation data. We find that some region of the favored $\delta_{CP}$ parameter space lies within the best fit values around $\delta_{CP} \sim 1.3\pi - 1.4\pi$. A detailed analytic and numerical study of baryogenesis through leptogenesis is performed in this framework within the nonsupersymmetric S0(10) models. (Ref: Kalpana Bora, Gayatri Ghosh, Debajyoti Dutta, Adv. High Energy Phys. 2016 9496758 (2016), arXiv: 1606.00554, (2015 Impact Factor: 1.839), talk presented at Simplicity II, Fermilab Theory Workshop, Fermilab USA, Sep 6–9, 2016.)

In Chapter 5, we will study the effects of non-unitarity parameters from existing experimental constraints, on cLFV decays such as, $\mu \rightarrow e\gamma$, $\mu \rightarrow \tau\gamma$, $\tau \rightarrow e\gamma$. We also study their effects on generation of baryon asymmetry through leptogenesis and neutrino oscillation probabilities. Considering flavor effects in leptogenesis, we do a parameter scan of a minimal seesaw model in a type I Seesaw framework satisfying Planck data on baryon to photon ratio of the Universe, which lies in the interval, $5.8 \times 10^{-10} < Y_B < 6.6 \times 10^{-10}$ (BBN). We predict values of lightest neutrino mass, and Dirac and Majorana CP violating phase $\delta_{CP}$, $\alpha$ and $\beta$, for normal hierarchy and inverted hierarchy for one, two and three flavor leptogenesis regimes. It is worth mentioning that all these four quantities are unknown yet, and future
experiments will be measuring them.

(Ref: Gayatri Ghosh, Kalpana Bora, arXiv: 1612.09047 [hep-ph], (is in private communication).)

Summary of the work done, new results presented in the Thesis and their significance, will be presented in last chapter (Chapter 6, Conclusions: Present Aspects and Future Prospects).