# Abstract

The Standard Model (SM) of particle physics has been tremendously successful in explaining fundamental particles and their interactions. Except for gravity, it can explain three of the four basic interactions in nature, namely the electromagnetic interaction, the weak nuclear interaction, and the strong nuclear interaction. In 2012, the discovery of the 125 GeV neutral boson at the Large Hadron Collider (LHC) must be one of the most important events of this decade in the area of Particle Physics. This significant discovery declares (confirms) the SM as the most effective theory to date in terms of the number of experimental evidence that supports its predictions.

However, the SM is not a complete (fully developed) theory. In spite of its impressive success, there are still many things that SM cannot explain, like the small neutrino mass, the baryon asymmetry of the universe (BAU), lepton flavor violation, dark matter, etc. Other fundamental theoretical problems in SM exist, such as the hierarchy problem, the flavor puzzle, the gauge coupling unification, and the strong-CP problem, etc., remain unsolved. As a result of these unsolved problems, it provides enough motivation to look for beyond the SM (BSM). Also, there are reasons to assume physics beyond the Standard Model (BSM) based on experimental data on neutrino masses and mixing from several neutrino oscillation experiments as well as cosmology, astrophysics, and other related fields. The construction of BSM scenarios often involves extending with the extension of SM particle sector, scalar, and/or fermions.

Various neutrino oscillation experiments have confirmed the massive nature of the neutrinos. The neutrino oscillation parameters have been precisely calculated by these experiments. Numerous BSM frameworks have been proposed to explain the neutrino mixing patterns and the origin of neutrino masses. Various phenomena like Lepton Flavour Violation (LFV) , Lepton Number Violation (LNV) and Baryon Asymmetry of the Universe (BAU) can also be explained using the BSM physics.

Whether the neutrinos are two-component Majorana fermions or four-component Dirac fermions is one of the most significant topics in particle physics. The lepton number conservation directly relates to this query.

There are various process that arises in BSM frameworks. One such process that appears in several BSM frameworks is neutrinoless double beta decay (NDBD/$0\nu\beta\beta$). It is a hypothetical decay mode of certain atomic nuclei in which two neutrons simultaneously transform into two protons inside the nucleus, emitting only electrons and no neutrinos in the process, which violates

the lepton number(LN) conservation. The main goal of the search for $0\nu\beta\beta$ decay is to measure the effective Majorana neutrino mass, which is a mixture of the neutrino mass eigenstates and the neutrino mixing matrix terms. If this phenomenon were to be observed, it would have significant implications for our understanding of the fundamental characteristics (properties) of neutrinos, the nature of matter-antimatter asymmetry in the universe, and the fundamental principles of particle physics beyond the Standard Model. No experimental evidence for the NDBD has yet been discovered.

However, a number of modern generations of experiments are currently underway or will soon start in order to explore the effective neutrino mass along with decay rates of the NDBD phenomenology. The KamLAND-Zen experiment which is an extension of the original KamLAND experiment uses the isotope xenon-136 and the GERDA experiment uses the isotope germanium-76 to study neutrinoless double beta decay. In order to protect the detectors from cosmic rays and other types of background radiation that can interfere with the observations, these experiments are often carried out deep underground.

The baryon asymmetry of the Universe (BAU) is another cosmological observation that necessitates the extension of the Standard Model. It refers to the puzzling and fundamental imbalance between baryonic matter and antibaryonic matter in the observable universe. The observed universe is dominated by matter and this matter-antimatter asymmetry can be generated by a process known as baryogenesis. One of the well-motivated and simplest scenarios is leptogenesis where the asymmetry comes from the out-of-equilibrium decays of the heavy neutrinos. Leptogenesis establishes a significant and intricate connection between two distinct observations: the absence of primordial antimatter in the observable Universe, and the characteristics of neutrinos, specifically their mass and mixing properties. There exist multiple forms of leptogenesis, including thermal, resonant, and vanilla leptogenesis, which are widely used to produce the observed BAU. The fundamental symmetries and dynamics of particle physics and cosmology are closely related to the baryon asymmetry of the universe. Understanding its origin may shed light on the laws governing the early universe, the behavior of matter, and antimatter and perhaps even reveal novel physics outside the boundaries of the Standard Model.

Studying the lepton flavor violation (LFV) is another reason to go beyond the Standard Model (BSM). Lepton flavor is conserved in the Standard Model of particle physics, which means that the flavor of a lepton should remain constant throughout its interactions. Nevertheless, there exist some theoretical frameworks that extend beyond the Standard Model, and predict that LFV processes can occur, providing a window into new physics beyond our current understanding. The phenomenon of neutrino oscillation directly implies the lepton flavor violation for neutral leptons. Therefore, one can expect charged lepton decays to follow a similar pattern of lepton flavor-violating decays. For a long time, one of the most promising fields of research has been the theoretical and experimental manifestation of LFV. The most notable low-energy lepton flavor violation (LFV) channels that can be observed in recent experiments are $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$. We still don't know the exact mechanism causing these decays. Numerous contemporary and forthcoming experiments have been devoted to the detection of such decay. The results of the MEG experiment provide the most stringent limitations on LFV. Based on the results of this experiment, the maximum allowable branching ratio for the decay of $\mu \to e\gamma$ is $\text{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$. Our understanding of the fundamental nature of the universe is aided by ongoing experimental efforts to find or constrain LFV phenomena, both at high-energy colliders and low-energy precision experiments.

Dark matter (DM) is also one of the most important questions in particle physics and cosmology that still haven't been answered. It is a fundamental and mysterious component of the universe that does not emit, absorb, or interact with electromagnetic radiation, making it invisible to direct observation. Fritz Zwicky first proposed the concept of it in 1933. Afterward, on, numerous cosmological and astrophysical measurements in various contexts, such as gravitational lensing, the cosmic microwave background, the motion of galaxies within galaxy clusters, etc., provide evidence that the present universe is made up of a mysterious, non-baryonic, non-luminous substance known as dark matter. Despite the fact that its identity is unknown, some intriguing candidates have been proposed like- Weakly Interacting Massive Particles (WIMPs), Axions, MACHOs, and WIMPs, etc. Based on the latest cosmological data obtained from the Planck satellite , it has been determined that approximately 26.8% of the overall energy density in the Universe is composed of dark matter (DM). There are many BSM frameworks that makes an effort to deal with the DM issues.

In particle physics, symmetries play a significant role in explaining different phenomena related to the particles and forces. Gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ explain the Standard Model, where $SU(n)$ and $U(n)$ are non-Abelian continuous symmetry groups. Nevertheless, the SM fails to provide an explanation for the mass of neutrinos and the observed pattern of mixing among the three neutrino flavors. Neutrino mass and mixing can be explained by the extension of SM with a flavor symmetry corresponding to a non-Abelian discrete (finite) group. This is one of the reasons we adopt discrete flavor symmetry in our work with various BSM systems. Therefore, non-Abelian discrete flavor symmetries are important for controlling the flavor structures of the model, and they have numerous applications in particle physics. Several successful models have been proposed that effectively generate correct neutrino mixing. In the context of developing models for particle physics, discrete symmetries like $A_N$, $S_N$, $\Delta_{27}$, and $Z_N$ are widely used. These symmetries have their origins at a certain high-energy scale and are expected to undergo a process of breaking at lower energy levels, resulting in residual symmetries specific to the charged leptons and neutrino sectors. Several models based on discrete flavor symmetries, like $A_4$, $S_4$, $S_3$, $\Delta_{96}$, $\Delta_{54}$, $\Delta_{27}$, etc., have been suggested to get special mixing patterns of the active neutrinos that are consistent with experimental data.

In this thesis work, we have constructed different neutrino mass models using $A_4$, $\Delta_{27}$, $Z_2$ and $Z_3$ discrete flavor symmetries. These models are constructed and used to study the neutrino phenomenology which is consistent with the recent experimental results.

**In chapter 1**, we reviewed the SM and discussed the current status of how neutrino physics is progressing both experimentally and theoretically. Except the neutrino, we address the particle mass generation mechanisms inside SM as well as the shortcomings of SM that necessitate various BSM scenarios. This chapter also includes a brief discussion on the oscillations of neutrinos in vacuum and in matter. We present a comprehensive analysis of several mechanisms employed for the generation of neutrino masses as documented in the existing literature. We briefly discuss different kinds of seesaw mechanisms with the motivation of going beyond the Standard Model to explain light neutrino mass via the inclusion of heavy right-handed neutrinos. These are type-I, type-II, type-III seesaw, inverse seesaw, minimally extended seesaw, radiative seesaw, littlest seesaw, etc. Our works are mainly based on the type-I seesaw framework. Therefore, we emphasize this framework of neutrino mass generation. We also review several works based on the models proposed by Guido Altarelli and Ferruccio Feruglio (AF) along with G Rajasekaran. This chapter also introduces various BSM phenomena such as Lepton Number Violation, Lepton Flavor Violation, Baryon Asymmetry of the Universe (BAU), Neutrinoless Double Beta Decay, and Dark Matter.

At the end of the chapter, we discuss the significance of discrete flavor symmetry in particle physics. we discuss different neutrino mass models based on various discrete flavor symmetries like $A_4$ , $S_4$, $\Delta(54)$ , $\Delta(96)$, $\Delta(27)$ etc. We give a comparative analysis of different neutrino mass models and their significance on BSM.

In this thesis work, we have studied two discrete flavor symmetric groups $A_4$ and $\Delta(27)$, on the basis of which different models have been constructed.

**In chapter 2**, we study the modification of the Altarelli-Feruglio $A_4$ flavor symmetry model by adding three singlet flavons $\xi'$, $\xi''$ and $\rho$ and the model is augmented with extra cyclic symmetry $Z_2 \times Z_3$ to prevent the unwanted terms in our study. The addition of these three flavors leads to two higher order corrections in the form of two perturbation parameters $\epsilon$ and $\epsilon'$. These corrections yield the deviation from the exact tri-bimaximal (TBM) neutrino mixing pattern by producing a non-zero $\theta_{13}$ and other neutrino oscillation parameters which are consistent with the latest experimental data. In both the corrections, the neutrino masses are generated via Weinberg operator. The analysis of the perturbation parameters $\epsilon$ and $\epsilon'$, shows that normal hierarchy (NH) and inverted hierarchy (IH) for $\epsilon$ does not change much. However, as the values of $\epsilon'$ increase, $\theta_{23}$ occupies the lower octant for NH case. We further investigate the neutrinoless double beta decay parameter $m_{\beta\beta}$ using the parameter space of the model for both normal and inverted hierarchies of neutrino masses.

**In chapter 3**, we study a neutrino mass model with $A_4$ discrete flavor symmetry using a type-I seesaw mechanism. The inclusion of extra flavons in our model leads to deviations from the exact tribimaximal mixing pattern resulting in a nonzero $\theta_{13}$ consistent with the recent experimental results and a sum rule for light neutrino masses is also obtained. In this framework, a connection is established among the neutrino mixing angles- reactor mixing angle($\theta_{13}$), solar mixing angle($\theta_{12}$), and atmospheric mixing angle ($\theta_{23}$). This model also allows us a predict of Dirac CP-phase and Jarlskog parameter $J$. The octant of the atmospheric mixing angle $\theta_{23}$ occupies the lower octant. Our model prefers normal hierarchy (NH) to inverted hierarchy (IH). We use the parameter space of our model of neutrino masses to study the neutrinoless double beta decay parameter $m_{ee}$.

**In chapter 4**, we present a neutrino mixing model based on the discrete flavor symmetry group $\Delta(27)$ and supplemented by other cyclic symmetries along with the seesaw mechanism to explain the observation of a non-zero reactor mixing angle $\theta_{13}$. This kind of mass matrix easily produces mixing patterns that realistically deviate from tribimaximal mixing, including mixing patterns with non-zero $\theta_{13}$. It explains the hierarchies of the charged leptons. Our model allows us to determine the Dirac CP violation phase  as a function of the mixing angles $\theta_{12}$, $\theta_{23}$, $\theta_{13}$. Both the normal ordering and the inverse ordering of the neutrino masses are quite close to the global fits of the experimental data.

Finally, **chapter 5** presents the summary and conclusion of the thesis work. We have also discussed about the future scope of the thesis in this chapter.

**Keyword**: The Standard Model(SM), Beyond Standard Model (BSM), Discrete Flavor Symmetry, Neutrino Oscillation, Tri-bi maximal mixing (TBM), Lepton Number Violation (LNV), Lepton Flavor Violation (LFV), Baryon Asymmetry of the Universe (BAU), Dark Matter (DM), Neutrinoless Double Beta Decay (NDBD).