"Research Is to See What Everybody Else Has Seen,
and Think What Nobody Has Thought"

– Albert Szent-Gyorgyi

1
INTRODUCTION

Neutrinos, an elusive particle in the Standard Model, holds a unique status as the second most abundant particles in the universe, trailing only behind photons. Due to their neutral nature and interaction solely through the weak force, neutrinos exhibit limited interactions with other particles, making them exceptionally challenging to study. To conduct neutrino experiments with meaningful results, massive detectors are required to achieve significant statistical output. Given the limited knowledge about neutrinos, these experiments play a crucial role in comprehending weak interactions and serve as a vital avenue to explore new physics beyond the standard model. Presently, neutrino physics enters an exciting phase, with ongoing efforts to precisely measure neutrino masses and mixings. This field holds great potential for delving into BSM physics. Numerous present and future experiments aim to provide more accurate insights into the many unanswered questions.

This chapter provides an overview of neutrino history, followed by discussions on neutrino sources, the phenomenology of neutrino mixing and oscillations, the current state of neutrino oscillations, and a brief exploration of new-physics beyond standard oscillations. We then discuss the details of various neutrino experiments. Finally, we provide a concise overview of the outline of the thesis.

1.1 A brief history of neutrinos

In the year 1930, in a desperate attempt to explain the continuous energy spectrum of electrons observed in nuclear beta decay, W. Pauli postulated a new particle [26]. He suggested that the missing energy may be carried out by this hypothesized neutral particle, spin 1/2 particle [27]. Later in the year 1934, Enrico Fermi formulated an effective theory of the β-decay and named this particle as "neutrino" [28–30]. Due to its small interaction cross section with matter ($\sigma \sim 10^{-44}\ cm^2$) initially it was thought that neutrinos would never be detected [31]. However, after a long wait of 26 years the experiment done by F. Reines and C. L. Cowan successfully detected neutrino ($\bar{\nu}_e$) in the year 1956 [32]. They have used the flux of antineutrinos coming from a nuclear reactor and the detection principle was based on inverse beta decay process [32, 33],

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{1.1}$$

After that, Leon Lederman, Mel Schwartz, and Jack Steinberger detected ν_μ at Brookhaven National Accelerator Laboratory in the year 1962 [34]. Finally, the third neutrino was detected by DONuT collaboration in 2000 [35] and completed the three families of neutrinos corresponding to three charged leptons (e, μ, τ) family.

The involvement of neutrinos played a crucial role in uncovering the violation of parity. Experiments using cosmic rays revealed an intriguing phenomenon: the decay of K^+ particles into two distinct modes with opposing parity, commonly known as the $\tau - \theta$ puzzle. This puzzling behavior was later validated through meticulous accelerator experiments. Seeking a solution to this puzzle, Lee and Yang proposed the concept of parity violation within the context of weak interactions [36]. Following their proposition, the violation of parity was further supported by experiments involving neutrinos. An illustrative example is the work of C.S. Wu [37], which showcased parity violation through the forward-backward asymmetry of emitted electrons resulting from the β decay of polarized ^{60}Co. This development paved the way for the formulation of the V – A model of weak interactions in 1958. This model was attributed to the collaborative efforts of R.P. Feynman [38] and M. Gell-Mann, E.C.G. Sudarshan [39] and R.E. Marshak, and J.J. Sakurai [40]. Within this theoretical framework, weak interactions exclusively involve the interaction of left-handed neutrinos and right-handed antineutrinos.

1.2 An overview of neutrinos

Neutrinos constitute a vital component of the Standard Model (SM), the theoretical framework that elucidates our present comprehension of elementary particles and fundamental forces. Initially introduced as massless entities with exclusive left chirality, the quest to elucidate neutrino masses necessitates additional elements, thereby indicating the presence of physics Beyond the Standard Model (BSM). Nevertheless, owing to the minuscule nature of neutrino masses and their subtle impact, all facets of contemporary neutrino physics can be incorporated into the Standard Model through the application of an effective field theory (EFT) approach.

1.2.1 Standard Model and The Neutrino

The Glashow–Weinberg–Salam Standard Model (SM) of Particle Physics, which delineates the elementary particles and fundamental forces of nature (excluding gravitational force), was formulated in 1967 by S. Weinberg and A. Salam [41, 42]. This model is based on an SU(2) $\times$ U(1) gauge model by S.L. Glashow, predicting the existence of weak neutral currents and the Z–boson [43, 44]. The incorporation of the Higgs Mechanism into Glashow's formulation allows the originally massless gauge bosons in the local gauge group model to acquire mass. The validation of the Standard Model was demonstrated by the Gargamelle experiment at CERN, which discovered neutral-current neutrino interactions in 1973 and was subsequently confirmed at Fermilab. The intrinsic constituents of the universe consist of 12 spin– 1/2 fermions (6 leptons and 6 quarks) and their antiparticles, interacting through 4 spin–1 gauge bosons, referred to as force carriers. The fermions and W and Z gauge bosons acquire mass through interactions with the Higgs field, with the associated particle known as the Higgs boson, predicted to be a massive and scalar particle. Experimental confirmations include the recent discovery of a Higgs–like boson at the LHC experiments at CERN. The precise measurement of the invisible decay width of the Z boson by the LEP experiments at CERN constrains the number of active neutrino species, with a mass less than half the mass of Z, to three. Now after the latest discovery of Higgs boson [43, 44] which gives masses to SM particles through Higgs Mechanism makes the SM complete. The SM contains a total of 12 spin 1/2 fermions and its antiparticle and four gauge bosons with spin 1 which carries the fundamental forces of nature (except gravitational force).

1.2.2 Neutrino Interactions

The study of neutrino interaction has been instrumental in validating the theory of weak interactions and electroweak unification. Presently, however, the exploration of neutrino interactions assumes a subordinate position to investigations into the inherent properties of neutrinos, including aspects such as neutrino masses and mixing. Understanding neutrino interactions stands as a crucial factor in achieving precision measurements of neutrino oscillation parameters at accelerator experiments. According to SM neutrinos can interact only through weak interactions viz. charge current (CC) and neutral current (NC) interactions mediated by W and Z bosons respectively. The Feynman diagram for these interactions is shown in figure 1.1. The SM V-A model of weak interactions by R.P. Feynman and M. Gell-Mann [38], E.C.G. Sudarshan [39] and R.E. Marshak, and J.J. Sakurai [40] infers that all neutrinos are left-handed and antineutrinos are right-handed. Also, within the SM neutrinos are massless fermions and can couple through weak interactions only. This makes the detection of neutrinos very hard in the neutrino experiments. However, the experimental observations of the phenomena of neutrino oscillations have proven that neutrinos are massive. To explain the phenomena of neutrino oscillations in which neutrinos change its flavour while traveling, needs an extension of the SM despite its unprecedented success. This was the first clear experimental hint of physics beyond SM (BSM). In the following section, we discuss the detailed formalism of neutrino oscillations in vacuum as well as in matter.

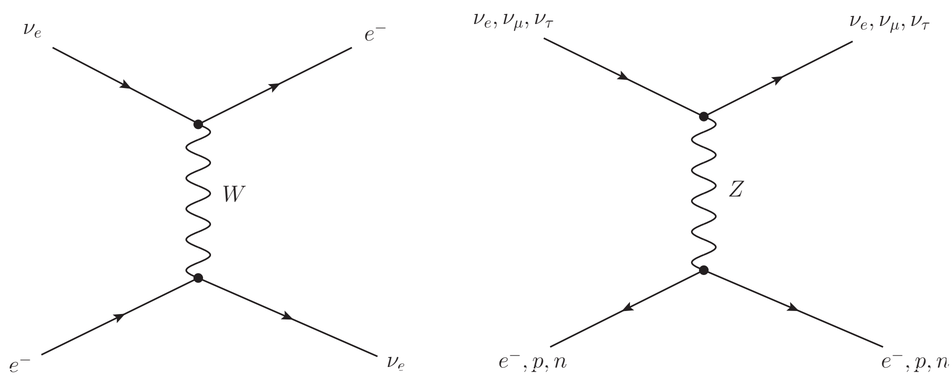

FIGURE 1.1: Feynman diagram for CC and NC interactions of neutrinos.

1.2.3 Neutrino Oscillations

The idea of neutrino oscillations was originally proposed by B. Pontecorvo in the 1950's [45]. It is a quantum mechanical phenomenon in which a neutrino with a flavour may change into another flavour after some time. This happens due to the mixing of neutrinos. The neutrino flavour eigenstates can be written as a linear superposition of mass eigenstates through a mixing matrix called Pontecorvo, Maki, Nakagawa and Sakata (PMNS) matrix [46]. This mixing may be represented as follows,

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle, \tag{1.2}$$

with $\alpha = e, \mu, \tau$ and i = 1, 2, 3. U is the PMNS matrix that governs the neutrino mixing. It can be parametrized by three mixing angles : θ_{12}, θ_{23} and θ_{13} and one Dirac type phase, δ_{CP} as follows,

$$\begin{aligned} U &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}, \end{aligned} \tag{1.3}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

As the neutrino travels through space, its constituent mass eigenstates move at different velocities and become out of phase with each other. Consequently, a neutrino initially in a specific flavor α at t = 0 can transform into another flavor β with a certain probability. This transformation probability is influenced by factors such as the distance the neutrino travels, its energy, and the properties of the medium it passes through. This phenomenon is only possible if neutrinos possess mass and have distinct mass eigenstates.

- **Oscillation in vacuum:** The likelihood of neutrino oscillation can be derived by computing the amplitude of probability through the temporal evolution of flavor eigenstates (utilizing equation 1.2). When considering neutrinos traversing through a vacuum, the probability of neutrino oscillation (for a two-flavor mixture) from flavor α to flavor β is expressed as follows:

$$P(\nu_\alpha \to \nu_\beta) = sin^2 2\theta sin^2(\frac{\Delta m^2 L}{4E}) \tag{1.4}$$

here, E represents the energy and L signifies the distance covered by the neutrino. For the scenario involving the mixture of three flavors, the oscillation probability can be formulated as follows:

$$\begin{aligned} P_{\alpha\beta} = \delta_{\alpha\beta} \quad &- \quad 4\sum_{i<j} \mathrm{Re}\big(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\big) \sin^2\{\Delta_{ij}L/4E\} \\ &+ \quad 2\sum_{i>j} \mathrm{Im}\big(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\big) \sin\{2\Delta_{ij}L/4E\}, \end{aligned} \tag{1.5}$$

where $\Delta_{ij} = m_i^2 - m_j^2$ and i, j runs from 1 to 3 [see appendix A for details].

- **Oscillation in matter:** However, when matter is present, the oscillation probability exhibits substantial deviations from the probabilities observed in a vacuum. The equation governing the evolution of a neutrino propagating through matter is influenced by effective potentials arising from coherent interactions with the surrounding medium, primarily through coherent forward elastic weak charge-current (CC) and neutral-current (NC) scatterings. Negligible input comes from incoherent scatterings and can be disregarded. All three neutrino flavors engage with the passing matter through the NC mode, while ν_e also partakes in CC interactions with electrons. The NC interactions contribute terms that aren't pertinent to oscillation probabilities, thus matter effects primarily originate from CC interactions. In the simplified scenario of two-flavor mixing, the oscillation probability retains the same structure as Equation (1.6), albeit with the mass eigenstates and mixing angle substituted by their effective values in the presence of matter:

$$P(\nu_\alpha \to \nu_\beta) = sin^2 2\theta_m sin^2(\frac{\Delta m_m^2 L}{4E}) \tag{1.6}$$

The quantities Δm_m^2 and θ_m are contingent upon the effective matter potential A, as well as the mass eigenstates and vacuum mixing angle. When A equals $\Delta m^2 cos^2\theta$, the mixing reaches its maximum extent ($\theta_m = \pi/4$), even if the vacuum mixing angle is infinitesimal. This phenomenon is referred to as the Mikheyev–Smirnov–Wolfenstein (MSW) resonance effect [12, 47].

For three-flavor mixing scenarios, the expressions describing oscillation probabilities in the presence of matter become intricate, and obtaining precise solutions for the neutrino's evolution equation generally requires numerical methods. The extent of neutrino oscillations is influenced by the three mixing angles, while the frequency is controlled by the differences in squared masses, denoted as $\Delta m_i^2 j = m_i^2 - m_j^2$. Additionally, the probability is contingent on factors such as the Dirac phase (δ), the distance between the source and detector (L), neutrino energy (E), and the density of matter encountered during propagation. These attributes—distance, neutrino energy, and matter density-are specific to each experiment and define the experiment's sensitivity.

Oscillation experiments yield insights into mixing angles and mass-squared differences. Δm_{21}^2 and θ_{12} can be approximated from solar neutrino experiments, often referred to as Δm_{sol}^2 and θ_{sol}, respectively. Similarly, atmospheric neutrino experiments offer measurements for Δm_{32}^2 and θ_{23}, denoted as Δm_{atm}^2 and θ_{atm}. While the magnitude and sign of Δm_{21}^2 are established, for Δm_{31}^2 (or Δm_{32}^2), only the magnitude is known. The unknown sign of Δm_{31}^2 results in two potential arrangements of neutrino mass eigenstates. The normal hierarchy (NH) entails the order $m_1 < m_2 < m_3$, whereas the inverted hierarchy (IH) involves the order $m_3 < m_1 < m_2$. Confirming the hierarchy of neutrino mass eigenstates hinges upon determining the sign of Δm_{31}^2, presenting a captivating challenge within the realm of neutrino oscillations.

1.2.4 Present status of the neutrino oscillation parameters

Neutrino oscillations have played a crucial role in our understanding of various properties of neutrinos. Several experiments have probed neutrino oscillations of neutrinos from different sources with varied baselines and energies to constrain its oscillation parameters. The present global analyses of the existing neutrino data have been able to constrain these parameters tremendously. The results of these analyses are listed in table 1.1.

Currently, neutrino experiments are focused to address the three main unknowns of neutrinos,

- **The hierarchy of neutrino masses:** Neutrinos have 3 mass eigenstates (say,ν_1, ν_2 and ν_3). So far only the absolute value of the mass squared difference Δm_{31}^2 has not been determined but not its sign. So there exist two possibilities in which the mass eigenstates are arranged: a) $m_3 > m_2 > m_1$ [called normal hierarchy or NH] or b) $m_2 > m_1 > m_3$ [called inverted hierarchy or IH]. These are schematically shown in figure 1.2. The non-zero value of θ_{13} will enhance the matter effect

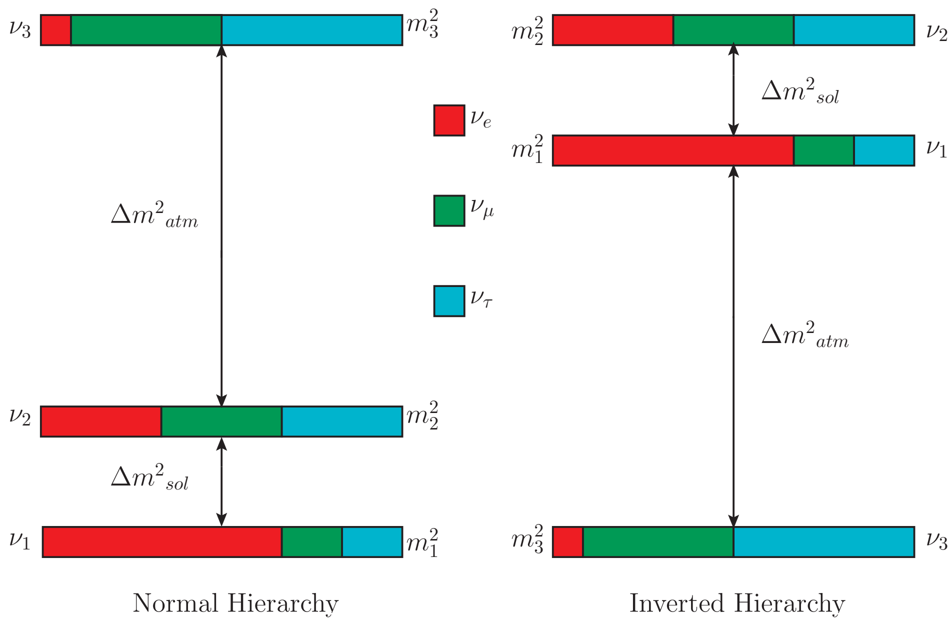

FIGURE 1.2: The two possible arrangements of neutrino mass eigenstates, *Left:* Normal Hierarchy, *Right:* Inverted Hierarchy.

when neutrinos pass through matter. Because of the enhanced matter effect, the different interactions that neutrinos and antineutrinos undergo while passing through the earth's matter will be more detectable. This will help to resolve the mass hierarchy.

- **Measurement of CP violation in leptonic sector:** As of now, CP Violation has only been observed in the quark sector of the Standard Model (SM). However, determining whether CP is also violated in the leptonic sector (i.e., CP $\neq$ 0 or π) holds fundamental importance, as it can offer insights into the observed baryonic asymmetry of the universe through a natural process called leptogenesis. In 1967, Sakharov first proposed the three necessary conditions that could dynamically generate the currently observed baryon asymmetry in the universe through baryogenesis: i) Baryon number violation, ii) C and CP violation, and iii) departure from thermal equilibrium.

- **Octant of θ_{23}:** Examining the interference term in the expression for neutrino oscillation reveals that it includes the term $sin^2\theta_{23}$, which is the same for θ_{23} and $\pi/2$ - θ_{23}. Consequently, there exists an ambiguity regarding which octant the angle θ_{23} belongs to. Atmospheric neutrino experiments such as SK have measured the value of $sin^2\theta_{23}$, yet it remains to be determined whether θ_{23} lies in the higher octant ($\pi/4 < \theta_{23} < \pi/2$) or the lower octant ($0 < \theta_{23} < \pi/4$).

Parameters	bfp $\pm 1\sigma$	3σ (NH)	bfp $\pm 1\sigma$	3σ (IH)
$\Delta m^2_{21}[10^{-5}eV^2]$	$7.41^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.03$
$\Delta m^2_{31}[10^{-3}eV^2]$	$2.507^{+0.026}_{-0.027}$	$2.427 \rightarrow 2.590$	$-2.486^{+0.025}_{-0.028}$	-2.570 $\rightarrow$ -2.406
$sin^2\theta_{12}/10^{-1}$	$3.03^{+0.12}_{-0.12}$	$2.70 \rightarrow 3.41$	$3.03^{+0.12}_{-0.11}$	$2.70 \rightarrow 3.41$
$sin^2\theta_{13}/10^{-2}$	$2.225^{+0.056}_{-0.059}$	$2.052 \rightarrow 2.398$	$2.223^{+0.058}_{-0.058}$	$2.048 \rightarrow 2.416$
$sin^2\theta_{23}/10^{-1}$	$4.51^{+0.19}_{-0.16}$	$4.08 \rightarrow 6.03$	$5.69^{+0.16}_{-0.21}$	$4.12 \rightarrow 6.13$
$\delta_{CP}/\circ$	232^{+36}_{-26}	$144 \rightarrow 350$	276^{+22}_{-29}	$194 \rightarrow 344$

TABLE 1.1: Recent NuFIT (2022) results for active neutrino oscillation parameters with best-fit and the latest global fit 3σ range for normal and inverted ordering [24].

1.3 Sources of neutrinos

Neutrinos are the second most abundant ($\sim 330/cm^3$) particle in the universe, photon ($\sim 400/cm^3$) being the first. Neutrinos are found in wide ranges of energies from a variety of sources both natural and man-made. Neutrinos, being the most abundant matter particles in the universe, are primarily generated through weak interactions, such as beta decay in atomic nuclei. Their sheer quantity surpasses that of ordinary matter constituents (electrons, protons, neutrons) by an astonishing factor of ten billion. To investigate neutrino oscillations and the characteristics of neutrino sources, we have leveraged neutrinos from diverse origins with varying energy ranges. Essentially, we can categorize neutrino sources into two main groups: Natural sources and Artificial/Man-made sources.

1.3.1 Natural sources

- **Solar Neutrinos:** In accordance with the Standard Solar Model (SSM), the Sun's energy emission occurs through the exothermal thermonuclear fusion of hydrogen into helium [48]. This fusion process can be represented as:

$$4p \rightarrow^4 He + 2e^+ + 2\nu_e + 26.7MeV. \qquad (1.7)$$

The majority of the energy released during this fusion is emitted as thermal energy, while a small fraction (approximately 2%) is transferred to neutrinos. The energy production mechanism inside the Sun involves two cycles: (i) the Proton-Proton (PP) cycle and (ii) the Carbon-Nitrogen-Oxygen (CNO) cycle. The total solar neutrino flux reaching the Earth, with energy in the range of a few MeVs, is approximately $6 \times 10^{10} cm^{-2} s^{-1}$.

- **Atmospheric Neutrinos:** Earth's atmosphere serves as another significant source of electron and muon neutrinos, as well as their antiparticles, which are produced in hadronic showers initiated by primary cosmic rays. The detection of atmospheric neutrinos dates back to the 1960s when the Kolar Gold Field experiment in India and underground experiments in South Africa first observed them. Neutrinos in the atmosphere are created through interactions of cosmic rays with atmospheric nuclei. Primary cosmic rays, primarily composed of protons, collide with atmospheric nuclei, giving rise to secondary cosmic rays, which consist of pions and kaons. These pions subsequently decay, producing muons and muon neutrinos.

  The energy of the neutrinos generated in the processes mentioned above ranges from a few hundred of MeV to 8 GeV. Due to the varying positions of detectors and the production points of neutrinos, the oscillation length can span from 15 km to 13,000 km. The broad energy spectrum and long baselines of atmospheric neutrinos provide ample opportunities for studying neutrino oscillations.

- **Supernova Neutrinos:** The life of a star often concludes with a massive explosion known as a Supernova, which can outshine an entire galaxy. However, only a small fraction of the total released energy is emitted as visible light. Approximately 99% of the energy is released in the form of neutrinos with energies ranging from 10-30 MeV. During this process, around 6×10^{58} neutrinos and antineutrinos of all flavors are emitted over a time interval of about ten seconds.

  The neutrino luminosity of a gravitational collapse-driven supernova is typically 100 times greater than its optical luminosity. Consequently, the neutrino signal emerges promptly from the core of the star after the core collapse, while the photon signal may take hours or days to emerge from the stellar envelope. This enables the neutrino signal to provide valuable information about the very early stages of core collapse, which remains inaccessible to other forms of astronomy.

In 1987, a Supernova occurred in the Large Magellanic Cloud within our galaxy. During this event, approximately 19 neutrinos were observed, confirming our fundamental understanding of the Supernova explosion mechanism [49–51].

- **Geo Neutrinos:** Radioactive isotopes such as ^{238}U, ^{232}Th, and ^{40K}, present in the Earth's crust, emit antineutrinos. The radioactive decay of these isotopes is a significant contributor to the heat generated in the Earth's core. Accurate measurements of the geo-neutrino flux and their spectrum play a crucial role in understanding the composition of the Earth's core and the production of radiogenic heat.

- **Ultra High Energy Astrophysical Neutrinos:** Astrophysical neutrinos can be generated with extraordinarily high energies. Neutrinos originating from the core of an active galaxy can reach Earth with energy levels surpassing anything achievable with terrestrial accelerators. Potential sources of high-energy neutrinos, exceeding 10^{14} eV, include gamma-ray bursts (GRB) and active galactic nuclei (AGN) jets. Detecting such neutrinos might be possible with a telescope having an effective area of about one square kilometer [52–54].

- **Relic Neutrinos:** Relic neutrinos, arising from the Big Bang, rank among the most significant byproducts. Following photons, they are the second most abundant particles in the universe, with a number density of 336 neutrinos per cm^3. Initially, neutrinos were in thermal equilibrium, engaging in weak interactions with other particles. However, they eventually decoupled from matter, offering valuable insights into the early universe. The kinetic energy of relic neutrinos is predicted to be around 10^{-4} eV, resulting in an extremely weak interaction cross-section. As a consequence, the direct detection of relic neutrinos remains an immensely challenging task.

1.3.2 Artificial/Man-made sources

- **Reactor Neutrinos:** Nuclear reactors serve as the primary sources of artificially produced neutrinos. The earliest experimental detection of neutrinos was achieved using reactor neutrinos. Power generation in nuclear reactors occurs through the fission of neutron-rich isotopes, including ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. During this process, a chain of β-decays of the fission products produces electron antineutrinos in the energy range of 0.1 – 10 MeV.

- **Accelerator Neutrinos:** Neutrino beams are produced in particle accelerators through the decays of charged pions and kaons, primarily induced by a proton beam interacting with a target. These beams are predominantly composed of muon neutrinos. Magnetic horns are used to focus the pions and kaons, guiding them into an evacuated decay tunnel where they decay into muons and neutrinos. The muons and the remaining mesons are subsequently absorbed in a beam dump at the end of the tunnel, resulting in the production of a neutrino beam. By focusing positive mesons, a neutrino beam is created, while focusing negative mesons yields an antineutrino beam. Alternatively, when a high-energy proton beam is stopped in a thick target to generate heavy hadrons, semi-leptonic decays of the charmed particles are employed to produce neutrinos. These charmed heavy hadrons decay rapidly, emitting equal fluxes of high-energy electron and muon neutrinos.

Neutrinos coming from these sources lie in a wide range of energies. The fluxes and neutrino energies of neutrinos coming from different sources are shown in figure 1.3.

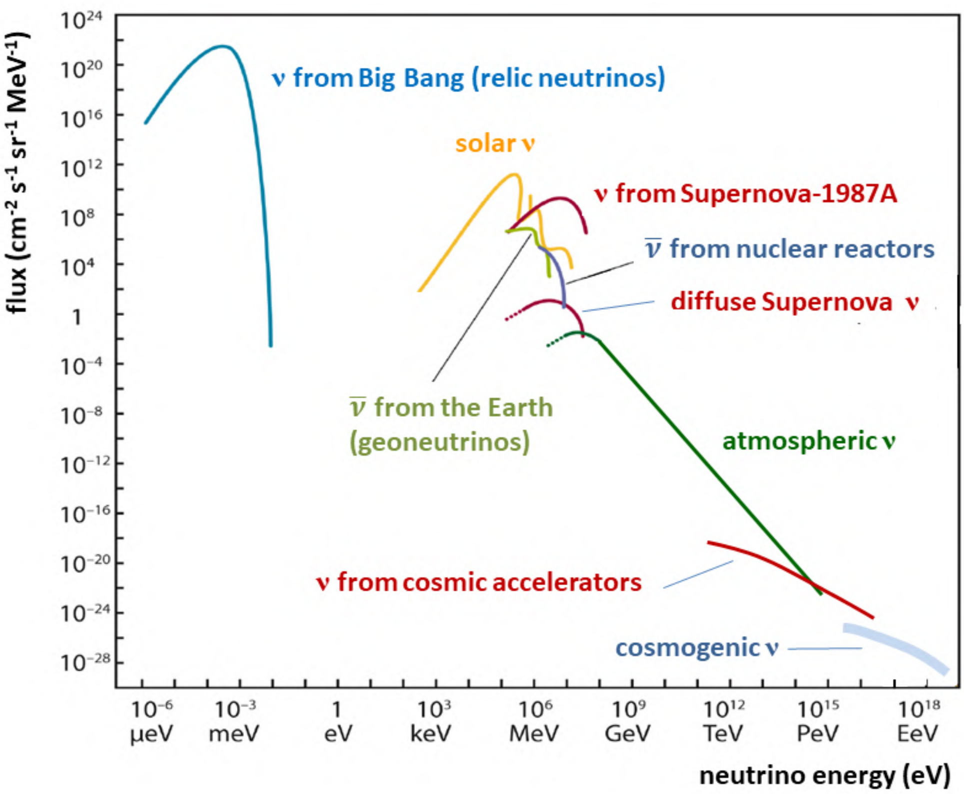

FIGURE 1.3: Fluxes of neutrinos on earth at different energies [19].

1.4 New Physics scenarios in the neutrino sector

Apart from the conventional three neutrino phenomenology, there are experimental observations, though not definitive, and certain theoretical models that suggest the presence of exotic phenomena that extend beyond the standard framework. The following section provides a concise overview of these various possibilities of new physics scenarios in the neutrino sector.

1.4.1 Non Standard Interactions

While neutrino mass and mixing necessitate new physics beyond the minimal Standard Model, most analyses of neutrino oscillations are typically conducted assuming Standard Model neutrino interactions. Nevertheless, in certain scenarios, new physics (referred to as nonstandard interactions [NSIs]) may introduce additional terms to the neutrino interaction Lagrangian. To address this, a common approach is to parameterize these NSIs in terms of dimension-6 operators within an effective Lagrangian [12, 55–58]. These NSIs can have a secondary impact on neutrino oscillation probabilities and lead to noteworthy changes in experimental observations.

Broadly, NSIs can influence neutrino oscillation signals through two types of interactions: (a) Charged Current (CC) interactions, and (b) Neutral Current (NC) interactions. Nonetheless, it is important to note that CC interactions mainly impact processes at either the neutrino source or the detector, making them easily distinguishable when observed at near detectors. Conversely, NC interactions primarily influence the propagation of neutrinos. In principle, nonstandard interactions (NSIs) of neutrinos have the potential to affect the production, propagation, and detection of neutrinos. However, in practice, disentangling these effects from other phenomena, such as neutrino oscillations resulting from neutrino masses and mixing, can pose a challenge. For any future neutrino program, a crucial aspect will be the identification and constraint of these interactions.

1.4.2 Lorentz invariance violation

In local field theories, there exists a close connection between operators that break CPT invariance and those that break Lorentz symmetry. The presence of a CPT-violating term in the Hamiltonian governs the evolution of neutrino flavors. This CPT violation is observable through the asymmetry between the probabilities of neutrinos oscillating to antineutrinos ($P_{\alpha\beta} \neq \bar{P_{\alpha\beta}}$)). However, when neutrinos and antineutrinos propagate through matter, the matter effect introduces artificial CP and CPT-violating effects. These effects must be accounted for correctly when searching for intrinsic CPT violation in neutrino oscillations. The literature has explored various potential origins of CPT violation in the neutrino sector, including within the context of Lorentz violation [59, 60], extra dimensions [61, 62], and nonstandard interactions [63, 64].

1.4.3 Neutrino decay

In the enhanced Standard Model with massive neutrinos, it is postulated that a heavier neutrino has the potential to decay into lighter neutrinos [65]. The lifetimes of these lighter neutrinos are significantly longer compared to the age of the universe. Neutrino decays at a fast rate may occur at the tree level through the mediation of a massless, spinless scalar, denoted as $J : \nu_i \to \bar{\nu_j} + J$, where i and j represent mass eigenstates that could be mixtures of active and sterile flavors. Experimental constraints on the couplings of J to ν_μ and ν_e arise from π and K meson decays [66], although these constraints still allow for the possibility of fast neutrino decays. Some potential candidates for J include a Majoron or a flavor-changing axion. The modification in neutrino oscillation probabilities due to neutrino decay has been addressed in the literature, for example, in [67].

1.4.4 Sterile neutrinos

Another intriguing aspect of the current neutrino oscillation picture is the potential existence of light sterile neutrinos. The standard three-flavor neutrino oscillation framework has been well-established through various experiments. However, the observations of $\bar{\nu_\mu} \to \bar{\nu_e}$ oscillations in the LSND experiment [68–71], and the subsequent confirmation by the MiniBooNE experiment [72–74], with an oscillation frequency governed by a mass-squared difference around 1 eV^2, cannot be explained within the three-flavor framework. These findings have motivated the consideration of at least one additional neutrino with a mass on the order of eV to account for the three independent mass scales governing solar, atmospheric, and LSND oscillations. While data from the LEP measurements on the Z-line shape suggest that there can only be three light neutrinos with standard weak interactions, the possibility of a fourth light neutrino remains. If it exists, this fourth neutrino must be a Standard Model singlet or sterile. Recent support for this hypothesis comes from (i) the disappearance of electron antineutrinos in reactor experiments with recalculated fluxes and (ii) the deficit of electron neutrinos measured in the GALLEX [75] and SAGE [76] solar neutrino detectors using radioactive sources. The results from the ICARUS experiment [77], however, did not find evidence for the

LSND oscillations, but this does not completely rule out the LSND parameter space, and small active-sterile mixing is still allowed. Recent combined data from Planck, WMAP polarization, and high multipole results give N_{eff} = 3.36 +0.68/-0.64 at 95% confidence level, indicating that the existence of a fourth neutrino species is not entirely ruled out.

1.4.5 Neutrino decoherence

A more precise description of neutrino states involves using wave packets with both momentum and spatial uncertainty. As different mass eigenstates propagate with varying group velocities, their wave packets may eventually cease to overlap, leading to a loss of coherence. The extent of coherence depends on factors such as the sizes of production and detection regions. The investigation of potential decoherence effects and constraints on decoherence-related parameters in a reactor neutrino experiment has been explored in [78]. Another form of decoherence can arise from quantum gravity effects, where initially pure states may evolve into mixed states over time [79]. Numerous studies have examined the possibility of neutrino decoherence effects in various contexts, including solar neutrinos [80], atmospheric neutrinos, long-baseline neutrino experiments, and in a more general context as well.

1.5 Scope of this thesis

Inspired by the aforementioned considerations, the following objectives have been established to address the goals of this thesis:

- To study the theoretical and phenomenological signatures of scalar non standard interactions in both neutrino oscillations & interactions and development of a framework to probe its effects in neutrino oscillation probabilities.

- To explore the possible impact of scalar non standard effects on the sensitivities of the neutrino experiments, primarily long baseline neutrino experiments and perform a synergy analysis combining different long baseline experiments.

- To simulate detector response for neutrino experiments viz. Hyper Kamiokande and associated detector instrumentation.

In alignment with the defined objectives, this thesis is organized into seven chapters, each addressing specific aspects of neutrino physics and its implications. The following provides a concise overview of each chapter:

- **Chapter 1:** Offers a brief overview of neutrino physics, covering its discovery, various neutrino sources, the formalism of ν-oscillations, an update on oscillation parameters, and discussions on potential new physics scenarios within the field. Various neutrino experiments considered in the analysis are thoroughly detailed.

- **Chapter 2:** Explores the framework of scalar Non-Standard Interactions (NSI), discussing its impact on oscillation probabilities using analytical expressions derived within this framework. The chapter introduces the GLoBES statistical χ^2 framework, extensively used in subsequent chapters.

- **Chapter 3:** Examines the effect of scalar NSI on CP-measurement sensitivities in long baseline experiments, using DUNE as a case study. Scalar NSI terms significantly impact both probability and sensitivity levels, introducing a degeneracy in the measurement of the δ_{CP} phase.

- **Chapter 4:** Investigates the impact of scalar NSI through the synergy of various long baseline experiments, such as DUNE, T2HK, and T2HKK. The collaboration across different energies and baselines enhances parameter sensitivities and mitigates degeneracies induced by scalar NSI in δ_{CP} measurements.

- **Chapter 5:** Probes scalar NSI to constrain the absolute neutrino mass. Scalar NSI provides a unique avenue for exploring neutrino mass measurements, introducing a direct dependence of absolute mass on neutrino oscillation probabilities. DUNE data is utilized to tightly bound neutrino masses through certain scalar NSI parameters.

- **Chapter 6:** Focuses on detector simulation and instrumentation work. It includes background simulation for the Hyper-Kamiokande detector, incorporating gamma-ray information for enhanced sensitivity. The chapter also explores supernova model simulation at Hyper-Kamiokande, investigating various signatures of supernova neutrino emission to discern the neutrino mass hierarchy. Additionally, the work on Resistive Plate Chamber (RPC) detector testing as part of the instrumentation process is discussed.

- **Chapter 7:** Provides a comprehensive overview of the final insights and summarizes the findings of the research conducted in this thesis. It outlines a prospective agenda for future endeavors.