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Introduction

This thesis delves into the impact of nonstandard interaction (NSI) on various measures of quantum correlation within the context of neutrino oscillations. The NSI can influence neutrino oscillation at a subleading level, making them a valuable tool for investigating physics beyond the Standard Model (SM). Quantum correlation is employed to explore the inherent quantumness of a system, a complex concept within quantum mechanics. Measures of quantum correlation are utilized to analyze the connections between different subsystems of a composite system through nonlocality, entanglement steering, and discord. In recent times, quantum correlations have garnered attention in high-energy physics systems due to advancements in various experimental techniques. Specifically, the expected precision in future neutrino experiments motivates an examination of subleading effects, such as NSI, on various measures of quantum correlations in neutrino oscillation within the context of different reactor and accelerator experimental setups.

In the middle of the 20th century, the discovery of various fundamental particles, including neutrinos, prompted the need for a comprehensive theory to comprehend their properties and interactions. This led to the development of the SM of particle physics, which integrates the electromagnetic, weak, and strong forces [1]. The SM fundamental building blocks are fermions, which include quarks and leptons. These particles interact through the exchange of different gauge bosons, depending on the type of interaction. The electromagnetic interaction is mediated by the exchange of photons, the strong interaction by the exchange of gluons, and the weak interaction by the exchange of massive vector bosons. The particle spectrum of the Standard Model is illustrated in figure 1.1.

SM is the most successful theory of particle physics till date. The modern SM was established through the unification of the electromagnetic and weak forces by Sheldon Glashow

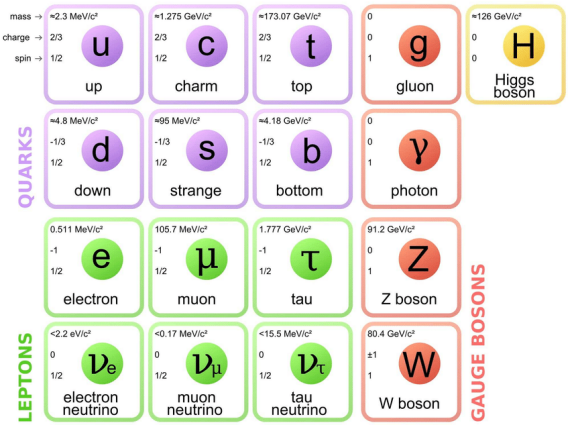

Figure 1.1.: Elementary particle spectrum of the Standard Model [2]

[3], combined with the Higgs mechanism developed by Steven Weinberg and Abdus Salam, culminating in the electroweak unification formalism [4–10]. The SM was refined, with its current formulation solidified in the 1970s. The SM is mathematically described as a non-abelian gauge theory that Yang Chen-Ning and Robert Mills developed in 1954 [11]. SM is invariant under the symmetry group $G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. The SM gauge group G_{SM} is a twelve-dimensional Lie group, with each of its twelve generators corresponding to a particle that mediates the SM interaction. The $SU(3)_C$ gauge group generates eight massless gluons, which are the carriers of the color force in strong interactions between quarks. The unified electroweak group $SU(2)_L \otimes U(1)_Y$ has four mediators, where in the $SU(2)_L$, there are three mediators, the massive vector bosons $W^{\pm}$ and Z^0, responsible for weak interactions, and in the $U(1)_Y$, the massless photon is the mediator of electromagnetic interactions. The Yang-Mills lagrangian density is expressed by

$$\mathcal{L}_{\text{YM}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + G^i_{\mu\nu} G^{i\mu\nu} + H^j_{\mu\nu} H^{j\mu\nu}, \tag{1.1}$$

where $F_{\mu\nu}$, $G^i_{\mu\nu}$, and $H^j_{\mu\nu}$ are the field strength tensors that can be written in terms of Yang-Mills potentials B_μ, W^i_μ and V^j_μ for the symmetry groups $U(1)_Y$, $SU(2)_L$, and $SU(3)_C$, respectively, where $i \in \{1, 2, 3\}$ and $j \in \{1, \ldots, 8\}$. Due to the non-Abelian nature of the gauge structure, the Yang-Mills Lagrangian density also includes self-interaction terms. Fermions are another part of SM particle content. For a massless fermion ψ, the kinetic term in the Lagrangian density is expressed by

$$\mathcal{L}_\psi = i\overline{\psi}\ \not{\partial}_\mu \psi. \tag{1.2}$$

If ψ is a set of fermions that transforms as a multiplet under the SM gauge group, then the Lagrangian density is not invariant under gauge transformations. A minimal coupling scheme can be used to ensure gauge invariance, where the differential operator $\not{\partial}$ is replaced by the covariant derivative $\not{D}$ according to

$$\not{\partial} \to \not{D} = \partial - ig'\ \not{B}\left(\frac{Y}{2}\right) - ig\ \not{W}^i \tau^i - ig''\ \not{V}^j \rho^j. \tag{1.3}$$

This leads to the expression

$$\mathcal{L}_\psi = i\overline{\psi}\ \not{D}\psi, \tag{1.4}$$

where g', g and g'' are the gauge coupling of $U(1)_Y$, $SU(2)_L$, and $SU(3)_C$, respectively. The hypercharge operator is represented by $\frac{Y}{2}$, the $SU(2)_L$ generators are represented by τ_i, and the $SU(3)_C$ generators are represented by ρ_j, all acting on the multiplet ψ. In this model, right-handed fermions are SU(2) singlets, while left-handed fermion fields are SU(2) doublets. Generation of quarks is introduced by having one $SU(2)_L$ doublet and two $SU(2)_L$ singlets, while in the case of leptons, there is one $SU(2)_L$ doublet and one $SU(2)_L$ singlet; the right-handed neutrino field is ν_R not introduced here. It encompasses three generations, each of leptons and quarks given in table 1.1.

In the SM, particles gain mass through the Higgs mechanism. The explanation of masses in the SM involves spontaneous symmetry-breaking, where gauge bosons $W^{\pm}$ and Z^0 acquire mass, while the photon remains massless. A complex scalar weak doublet Φ can be defined as

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \tag{1.5}$$

where ϕ_1, ϕ_2, ϕ_3, and ϕ_4 are real fields. Here Φ is known as the Higgs field, and the Lagrangian density corresponding to this Higgs field can be written as

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(|\Phi|). \tag{1.6}$$

	$\mathbf{SU(2)}_L$ **Doublets**	$\mathbf{SU(2)}_L$ **Singlets**
Quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$	u_R, d_R c_R, s_R t_R, b_R
Leptons	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	e_R μ_R τ_R

Table 1.1.: $\mathrm{SU}(2)_L$ Doublets and Singlets for Quarks and Leptons

This Lagrangian density is symmetric under gauge transformations. Here the symmetry breaking appears from the potential $V(|\Phi|)$ not having its minimum at $|\Phi| = 0$. For $\Phi^\dagger\Phi$, there are infinitely many degenerate solutions. When a specific solution is chosen, the electroweak symmetry is spontaneously broken to

$$SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}. \tag{1.7}$$

After spontaneous symmetry breaking, three real fields of the Higgs doublet Φ become massless Goldstone bosons, which are absorbed by the physical fields $W^\pm$ and Z^0, and the fourth field, associated with the unbroken $U(1)$ symmetry, remain massless, and this one is recognized as the photon field. Before symmetry breaking, the masses of fermions and gauge bosons are zero. After spontaneous symmetry breaking, the Higgs mechanism provides masses to the gauge bosons and fermions. For fermions, the mass term arises from the Yukawa term, i.e. $-y\bar{\psi}_L\psi_R\langle\phi\rangle$, where y is the Yukawa coupling ψ_L and ψ_R are the left-handed and right-handed fermionic fields, respectively, and $\langle\phi\rangle$ is the vacuum expectation value (VEV) of the Higgs field.

One of the fundamental particles in SM is the neutrino, which Wolfgang Pauli proposed to save the laws of energy and momentum conservation [12]. In the SM, the neutrino is a neutral particle that interacts via weak interactions. Neutrino is a left-handed particle, where ν_e, ν_μ, and ν_τ are three different neutrino flavors. Neutrino is the second most abundant particle in the universe after the photon. They were produced abundantly during the Big Bang, known as relic neutrinos, which form the cosmic neutrino background, but detecting them is challenging due to their tiny scattering cross-section. The sun also emits neutrinos during nuclear fusion, and on Earth, particle accelerators and reactors are man-made sources of neutrinos from proton collisions and $\beta-$decay processes, respectively. Atmosphere and supernovas are also the source of neutrinos. There are some other galactic and extra-galactic sources of high-energy neutrinos. In SM, the neutrino is a massless particle. The neutrinos cannot have a gauge-invariant mass term in the SM because there is no suitable right-handed partner. The absence of right-handed neutrinos is due to the observation of parity violation in weak interactions [13]. In the SM, neutrinos are considered massless; however, the experimentally observed phenomenon of neutrino oscillation indicates that neutrinos have mass [14].

In the SM, neutrinos interact weakly with other leptonic fields through the $W^\pm$ and Z^0 bosons. Charge current (CC) interactions are mediated by the $W^\pm$ boson, while neutral current (NC) interactions are mediated by the Z^0 boson. To determine the number of light neutrino species, we can examine the Z^0 boson decay properties [15]. The Z^0 boson decays invisibly into neutrino-antineutrino pairs and visibly into quarks and charged leptons. The invisible decay width is the difference between the Z^0 boson total decay width and its visible decay width. By subtracting the visible decay width of the Z^0 boson from the total Z^0 width, the decay rate to neutrino pairs can be calculated. Using the decay rate of a single neutrino pair, the number of active neutrino species with a mass less than half the Z^0 mass can be determined. The LEP experiment has provided a precise measurement for the number of neutrino species: $N_\nu = 2.994 \pm 0.012$ species [16].

The SM is considered one of the most reliable models in particle physics and has been validated in the majority of high-energy physics experiments. The SM of particle physics, despite its remarkable success in precisely describing all observed particle interactions, has notable shortcomings. Firstly, it does not account for gravity. Secondly, the SM fails to provide a viable dark matter (DM) candidate despite overwhelming astronomical and cosmological evidence for its existence [17, 18]. Evidence for dark matter comes from gravitational lensing, cosmic microwave background observations, and the evolution of galaxies and clusters. Dark energy, comprising about 68% of the universe total energy density, remains a mystery beyond the reach of the SM. Dark energy drives the universe accelerated expansion. Its nature can be explored by analyzing the universe at large-scale structures and the redshift of universal objects. Additionally, the SM cannot adequately explain the baryon asymmetry of the universe, a phenomenon well-supported by experimental data. In 1967, Sakharov proposed three conditions for generating baryon asymmetry: baryon number violation, violation of C and CP symmetry, and deviation from thermal equilibrium [19]. While the SM includes CP violation via a phase in the quark mixing matrix, its magnitude is insufficient to account for the observed asymmetry. Furthermore, a neutrino is a massless particle in the SM, while neutrino mass is essential for explaining neutrino oscillations, which is explained in great detail in chapter 2. Therefore, while the SM has been extraordinarily successful, it is not the be-all and end-all; it must be extended to align with these significant observations.
Neutrino was first discovered in 1956 by Reines and Cowan via the inverse beta decay process from the reactor neutrino [20]. In the 1960s, Raymond Davis was trying to measure the solar neutrinos [21]. But the solar neutrinos captured by Ray Davis were one-third of what was predicted. This mismatch emerges as a solar neutrino anomaly. Later, in atmospheric neutrino measurement, it was detected that neutrino flux changed based on the zenith angle, and sub-GeV muon-like events were fewer than expected. Neutrino oscillation, a simple quantum mechanical process where a neutrino's flavor changes during travel, was introduced by Pontecorvo as a solution for solar and atmospheric anomalies. Neutrino oscillation was confirmed by atmospheric neutrino flux drop in Super-Kamiokande (SK). The Sudbury Neutrino Observatory (SNO) experiment showed that a solar neutrino transforms into another type of active neutrino. In 2015, Takaaki Kajita from SK and Arthur B. McDonald from SNO won the Nobel Prize for the groundbreaking discovery of neutrino oscillation.

All flavor states are unitary linear combinations of all mass eigenstates. The result of mixing between flavor and mass neutrino states is neutrino oscillation, which shows that the neutrinos must have some mass [22], which is now recognized as a well-established phenomenon, i.e., neutrino oscillation from different experimental setups [14, 23–25]. Although the mechanism of neutrino mass is not known, it is confirmed from neutrino oscillation experiments that neutrinos have mass. Due to a nontrivial neutrino mass matrix, neutrino oscillation was once postulated to occur in vacuum [26].

In 1978, Wolfenstein detected the matter potential that neutrinos encounter as they travel through a medium composed of matter [27]. When neutrinos move through matter, the weak interaction couples them to matter, and there is a scattering of neutrinos with matter particles they encounter along the path. Normal matter is formed of protons, neutrons, and electrons, but no muons or tau-leptons exist. Neutrinos of all three flavors interact with electrons, protons, and neutrons via NC interactions mediated by Z bosons, and because these contributions are equal for neutrinos of all three flavors, these interactions have no effect on neutrino oscillation probability. Significantly, electron neutrinos contribute more because of their CC interactions, which are mediated by the W boson. The presence of matter can affect neutrino oscillation, and this phenomenon can be affected drastically by resonance. The parameters that contribute to this change are matter density and energy of neutrinos. Even this MSW (Mikheyev-Smirnov-Wolfenstein) effect can be satisfactorily explained by the observed solar neutrino fluxes [28, 29] Our understanding of neutrino oscillations has been strongly affected by matter effects.

Some neutrino oscillation parameters are known with high accuracy, but others, such as the mass ordering, the value of the CP phase, and the absolute neutrino mass, remain unknown. Of course, the road must be altered to incorporate neutrino masses and mixing, resulting in new physics outside the SM. Despite extensive research on neutrino mass discrepancies and mixing, their origin remains a mystery. To incorporate such neutrino features, the SM must be extended. Beyond Standard Model (BSM) physics [30] suggests that neutrinos might engage in new interactions not covered by the SM. These interactions are often described by higher-dimensional operators involving SM fields, which introduce new physics through NSI. Various model-independent and model-dependent research has been conducted for NSI [31–41]. NSI can impact neutrino oscillations, allowing them to be utilized to search for physics beyond the SM.

The electromagnetic properties of neutrinos represent another BSM concept. In the SM, neutrinos are massless and do not interact electromagnetically. However, with small non-zero masses, neutrinos can acquire a magnetic moment, leading to a number of possible consequences in particle physics, astrophysics, astroparticle physics and cosmology, see for e.g., [42–52]. In the minimal extension of the SM, Dirac neutrinos develop a tiny magnetic moment, whereas Majorana neutrinos exhibit an even smaller off-diagonal magnetic moment. These values can be enhanced in a number of new physics models. Another BSM scenario in the neutrino sector involves the decay of a neutrino mass state (ν_i) into another neutrino (ν_j) and a new particle (ϕ) [53–58]. Neutrino decay can be either visible or invisible. Invisible decay results in undetectable final products, such as a light sterile neutrino or a low-energy active neutrino, causing fewer observed events than predicted. Visible decay produces detectable active neutrinos with lower energy, leading to more observed events. The decay rate depends on the neutrino mass, lifetime, distance traveled, and energy. Constraints from astrophysical and experimental data set bounds on decay rates. From a phenomenological standpoint, studying these BSM phenomena is intriguing as it helps uncover new physics.

In this thesis, we focus solely on NSI among various BSM phenomena. Wolfenstein introduced non-standard interactions that can affect neutrino oscillation subdominantly [59]. This opens up the prospect of using neutrino oscillation to investigate additional new physics beyond the SM [31, 60–65]. These probable interactions appear as four-fermion components in the effective Lagrangian, providing a model-independent method of parameterizing novel physics. The non-renormalizable components, including dimensional operators $d > 4$, can be added to the SM effective Lagrangian to include the NSI effects in a model-independent manner within the framework of effective field theory, while dimensional operators are $d \leq 4$ in SM Lagrangian. We have examined the impact of the dimension-6 four-fermion operator. NSI is classified into two categories. One is a nonstandard neutral current interaction, and the other is a nonstandard charged current interaction. Because the neutral current NSI influences neutrino propagation via the matter effect, experiments with a long baseline, such as atmospheric neutrino and long baseline (LBL) experiments, are likely to be sensitive to it. The charged current NSI, on the other hand, produces zero distance effects in neutrino oscillations. If NSI exists, they are intriguing from a phenomenological perspective since they explicitly refer to the existence of some new physics.The NSI can manifest its effect in neutrino oscillation phenomena at the sub-leading level, and it is possible to see it in a variety of recent and prospective neutrino experimental data. The bounds on NSI parameters are extracted from global analysis of the data obtained from different oscillation and non-oscillation experiments [66–68]. Recently, the concept of scalar NSI has gained a lot of interest. Scalar NSI introduces a coupling between neutrinos and scalar fields, affecting the neutrino mass term [69–76]. Recent Borexino data prefer nonzero scalar NSI $\eta_{ee} = 0.16$ [77]. Bounds on diagonal and off-diagonal scalar NSI parameters are also coming from various experiments. Current experiments are not that much sensitive to detect various subdominant effects in neutrino oscillations. Future experiments, on the other hand, may be able to identify these impacts with more accuracy.

The impact of NSI can be observed in various contexts. In this thesis, our aim was to analyze how NSI affects different quantum correlation measures. Since neutrino oscillation is a quantum phenomenon, it inherently involves quantumness. By studying quantum correlations, we can explore and analyze this embedded quantumness. Quantum correlations, which are grounded on the principles of locality and realism, provide a platform for testing and analyzing theories of local hidden variables. Schrödinger pioneered the concept of quantum correlation [78]. Albert Einstein, Boris Podolsky, and Nathan Rosen proposed a thought experiment that argues that quantum mechanics provides an incomplete description of physical reality [79]. Later, in 1964, John Bell mathematically formulated the concepts of locality and realism and demonstrated that if the classical picture is sufficient to describe the correlation existing between the outcomes of two specific spatially separated systems, then they support Einstein local hidden variable theory, and the correlation is required to obey a specific type of inequality known as the Bell-CHSH inequality [80]. Violation of this inequality demonstrates the nonlocal character of correlations shared by two subsystems, implying their quantum nature. Thus, quantum correlations can be thought of as great tools for determining whether a system behaves classically or quantum mechanically.
Correlations can exist between subsystems in a composite system whether they are separated by space or time. Some well-known measures of spatial quantum correlations are flavor entropy [81], entanglement [82], quantum discord [83], steering [84, 85], nonlocality along with the well known Bell-CHSH inequality [86], while the temporal correlations encompass the Leggett-Garg inequality (LGI) [87] and Leggett-Garg type inequalities (LGtI) [88]. For such a study, neutrino is an especially good candidate. By treating the neutrino as a three-mode system and mapping its state to that of a three-qubit system, it is possible to study three-flavor neutrino oscillations [89, 90]. To further investigate the quantum nature of neutrino oscillations, some promising research have been done [81, 90–102]. It was demonstrated that the multi-mode entanglement of single-particle states is connected to neutrino oscillation. Due to this characteristic, numerous studies on quantum correlation measures have been conducted within the neutrino oscillation sector. These studies typically focus on various measures such as nonlocality, entanglement, coherence, and steering. While much of this research has been conducted in vacuum, some studies have also considered standard matter effects [89, 96–100, 102–111, 111–120]. Our goal is to investigate the influence of NSI, both scalar and vector type on several temporal and spatial quantum correlation measures.

1.1 Layout of the thesis

This thesis is dedicated to the study of quantum correlation measures in neutrino oscillation with NSI. Nonlocal quantum correlations such as the nonlocal advantage of quantum coherence (NAQC) [119, 121, 122], which is considered as a stronger measure than other nonlocal quantum correlation measures [109] and one of them is Bell's inequality measure, which is a very famous measure to study nonlocality in neutrino oscillations. In this work, we analyze the effects of NSI on these measures in the context of two flavor neutrino oscillations for different experimental setups [123–131] i.e., DUNE, MINOS, T2K, KamLAND, JUNO, and Daya Bay for two flavors neutrino oscillation scenario.

Quantum correlations in quantum mechanics are complex and cannot be fully described by a single measure. One key aspect is entanglement, which is crucial for tasks like quantum teleportation and quantum cryptography. There are various ways to quantify entanglement, such as Entanglement of Formation (EOF) [132, 133], Concurrence [134, 135], and Negativity [136, 137]. We analyze the influence of NSI on these measures across various experimental setups involving both reactors and accelerators for three flavor neutrino oscillations.

Recent anomalies observed in the NOνA and T2K experiments within the standard three-flavor neutrino oscillation framework could potentially indicate physics beyond the SM. To address these anomalies, we explore NSI parameters, focusing on violating LGtI in the context of three-flavor neutrino oscillations. Specifically, our analysis examines LGtI violations in scenarios involving complex NSI with either $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$ couplings in DUNE, considering both normal and inverted mass ordering.

In the above-mentioned work, we analyzed vector NSI. In our further research, we also considered scalar NSI. To examine the effects of scalar NSI, we used the strongest quantum correlation measures, such as nonlocality. We analyzed scalar NSI using both temporal and spatial measures of nonlocality.

In this thesis, the chapters are compiled in such a way that someone can first become acquainted with the concepts related to neutrinos, neutrino oscillations, NSI, and quantum correlations. Following that, we will discuss fresh findings from refs. [138–141]. In this chapter, we provide information on SM in the context of neutrinos. The following is an overview of the thesis:

- In chapter 2, we mention many aspects of neutrino physics. We will first go through the history of the neutrinos, including brief introductions to solar and atmospheric neutrino anomalies. Then, we discuss neutrino oscillation in vacuum for two-flavor and three-flavor scenarios. Then, we provide a brief overview of the neutrino oscillation in matter and briefly discuss the nonstandard interactions. Following that, we analyze the formalism of NSI with neutrino oscillations.

- In chapter 3, we first provide a brief history of quantum correlations. Next, we discuss some important aspects of quantum correlations. Following this, we delve into various quantum correlation measures and their significance in detail. Building on our understanding of quantum correlations and neutrino oscillations, we delve into the formalism of neutrinos within the context of quantum correlations. We begin by exploring quantum correlations, specifically in the neutrino sector, and then examine how these correlations can be expressed in terms of neutrino survival and oscillation probabilities. Additionally, we introduce and explain some of the mathematical terminology used in these quantum correlation measures.

- Chapter 4 delves into the significance of nonlocality within the realm of quantum correlations. It examines nonlocal quantum correlation measures, including the NAQC, which is considered a robust measure, along with Bell's inequality. These measures are applied to the system of two-flavor neutrino oscillations in the vacuum, as well as within the matter effect and NSI, across multiple experimental setups. The analysis within this chapter aims to provide a comprehensive understanding of nonlocal quantum correlations and their implications within the context of neutrino oscillations and beyond.

- In chapter 5, we explore how new physics affects various measures of tripartite entanglement in the realm of three-flavor neutrino oscillations. Entanglement, a fundamental aspect of quantum correlations, serves as the focal point of our investigation. We scrutinize the impact of NSI on different measures of entanglement, including concurrence, entanglement of formation, and negativity. This analysis spans diverse experimental configurations involving reactors and accelerators. By examining these measures within different experimental setups, we aim to discern the influence of NSI on the intricate nature of entanglement in neutrino oscillations.

- In chapter 6, we delve into how NSI affects temporal correlation measure. The recent anomalies observed in NOνA and T2K experiments within the standard three-flavor neu-

trino oscillation framework could indicate physics beyond the SM. For the NSI parameters that can accommodate this anomaly, we explore the violation of LGtI. Our analysis centers on scenarios involving complex NSI with $\epsilon_{e\mu}$ or $\epsilon_{e\tau}$ coupling in DUNE, prioritizing normal ordering.

- In chapter 7, we examine the impact of scalar NSI on nonlocality measures, spatial as well temporal. Recently, there have been improvements in the bounds of scalar NSI as well. In light of these developments, we aim to examine the impact of scalar NSI on quantum correlation measures.

Finally, in chapter 8, collective conclusions are provided.

The central theme and objective of the thesis are to explore how quantum correlations behave in neutrino oscillations when NSI is present. Although different chapters use different types of quantum correlation measures, such as Bell's inequality, NAQC, LGtI, and entanglement (via concurrence, entanglement of formation, and negativity), they are all connected by one central goal, i.e., to understand whether quantum correlations can act as sensitive tools to detect new physics beyond the Standard Model. The chapters are organized to follow a clear progression. We begin with simpler systems and gradually build toward more complex ones. First, we study two-flavor neutrino oscillations with spatial quantum correlations like NAQC and Bell's inequality. Then, we move to three-flavor neutrino systems and analyze entanglement using different measures. Later, we explore temporal correlations such as LGtI to see how NSI affects temporal quantum behavior. Finally, we study the impact of scalar NSI, extending the investigation beyond the commonly used vector NSI. This structure allows for a systematic investigation of how various types of quantum correlations respond to different kinds of NSI. Overall, the thesis aims to show that quantum correlations are not just theoretical tools but could play a role in revealing new features of neutrinos and uncovering signs of new physics.