"As we reach the conclusion of this journey,
we find not an endpoint but a gateway to new questions,
beckoning further exploration."

– Albert Einstein

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Conclusion and Future Prospects

In this chapter, we have summarized the key findings of our phenomenological studies. We then provide a future scope of this thesis work.

7.1 Conclusion

In the following, we provide a concise summary of the significant conclusions drawn from each of the last four chapters.

- **Chapter 3**: In the precision era of neutrino physics, it is essential to discern subdominant effects such as Non-Standard Interactions in neutrino experiments and evaluate their impact on the physics potential of these experiments. In this chapter, the study primarily focuses on DUNE as a Long Baseline (LBL) candidate to investigate the effects of scalar NSI. The impact of diagonal elements of the scalar NSI matrix on the experiment is explored through a χ^2 analysis. The experiment exhibits similar sensitivity to $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ with slightly better performance for $\eta_{\mu\mu}$, while sensitivity towards constraining η_{ee} is marginally lower. A CP-violation sensitivity study at DUNE in the presence of scalar NSI elements reveals significant impacts. For instance, a negative value of η_{ee}, like -0.10, leads to DUNE's CP sensitivity falling below the 3σ confidence level. Conversely, positive non-zero values of η_{ee} generally enhance DUNE's CP sensitivity compared to the scenario without scalar NSI. Our study on CP precision demonstrates that DUNE's ability to constrain the CP phase is significantly affected by scalar NSI. Positive $\eta_{\alpha\beta}$ elements enhance the experiment's capability to measure the δ_{CP}, whereas negative $\eta_{\alpha\beta}$ elements diminish DUNE's ability to constrain δ_{CP} values. Constraints on these scalar NSI parameters are crucial for accurately interpreting data from various neutrino experiments. Furthermore, probing scalar NSI provides insights into various neutrino mass models, as it directly influences the mass term in the neutrino Hamiltonian.

- **Chapter 4**: In this chapter we have primarily investigated the influence of scalar NSI on the sensitivity of CP measurements in three forthcoming Long Baseline experiments, DUNE, T2HK, and T2HKK, adopting a model-independent approach. Additionally, we have explored the benefits of sensitivity measurements through combined analyses involving DUNE + T2HK and DUNE + T2HKK. If scalar NSI is allowed by nature, its impact on CP violation sensitivity is observed to be significant. Negative values of NSI parameters lead to a degradation in CP measurement sensitivities. Conversely, certain positive values of $\eta_{\alpha\beta}$ exhibit an overlap between standard and non-standard CPV sensitivities at DUNE and T2HKK, rendering the experiments insensitive to spurious CP effects from scalar NSI in those regions. However, this limitation is mitigated through a joint sensitivity analysis of DUNE + T2HK and/or DUNE + T2HKK, primarily due to an expanded parameter space. T2HK demonstrates superior capabilities in constraining NSI parameters compared to DUNE or T2HKK, attributed to its substantial detector size (approximately 374 kton fiducial mass). The synergy between two experiments (DUNE + T2HK or DUNE + T2HKK) facilitates the accumulation of extensive statistics across an enlarged parameter space, resulting in improved overall sensitivities for all non-zero NSI parameters. Notably, for positive (negative) $\eta_{\alpha\beta}$ values, a combined analysis involving all three experiments exhibits a substantial enhancement (deterioration) in CPV sensitivities. The element η_{ee} is identified to have the highest sensitivity to CPV for all considered NSI parameters.

- **Chapter 5**: Scalar Non-Standard Interactions present an intriguing avenue for investigating the absolute masses of neutrinos through neutrino oscillations. The primary objective of the study in this chapter is to demonstrate the potential for constraining the lightest neutrino mass using oscillation data in the presence of scalar NSI. In this communication, we have derived constraints on the lightest neutrino mass while considering the cosmological limit on the sum of neutrino masses. Our findings indicate that the scalar NSI parameter $\eta_{\alpha\beta}$ can impose a significant constraint on the absolute mass of neutrinos. Notably, the presence of $\eta_{\tau\tau}$ or $\eta_{\mu\mu}$ enhances the constraining capability, making it marginally superior to that of η_{ee} for the lightest neutrino mass, regardless of the mass hierarchy. The constraint on the neutrino mass is pivotal for gaining insights into the mechanisms governing neutrino mass generation, representing a potential breakthrough in our comprehension of the universe and its underlying physics.

- **Chapter 6**: This study provides a succinct exploration of energy spectrum analysis across different quantities of statistical data points. The primary finding suggests that, with an increasing number of statistical data points, the ratio tends to approach unity. In simpler terms, this implies a high level of agreement between our simulated results and the input data information. It's crucial to emphasize that this analysis is specifically showcased for the Si29 isotope, but similar evaluations have been carried out for other isotopes, yielding consistent outcomes. Essentially, augmenting the number of statistical data points leads to a consistent enhancement in the alignment between our results and the actual data.

  The characteristics such as the ν_e burst and the rise of $\bar{\nu}_e$ offer distinct insights into the challenge of determining the mass ordering of neutrinos. In this chapter, we conducted an investigation into these aspects of supernova (SN) neutrino emission using several forthcoming detectors, including Hyper-Kamiokande (HK), the Deep Underground Neutrino Experiment (DUNE), and Jiangmen Underground Neutrino Observatory (JUNO). Our analysis indicates that the mass ordering scenarios are more clearly distinguishable in HK compared to JUNO.

  For the successful operation of an experiment, each RPC must operate without displaying significant signs of aging during its operational period. Consequently, various tests, including a thorough leak test, are conducted during and after production. The conventional methods of leak rate calculation using a manometer are applicable only when both the volume of the test subject and ambient pressure remain constant. However, these quantities for an RPC gas gap vary with ambient pressure and temperature. Precise quantitative estimation of the leak rate cannot be obtained from such pressure measurements. Monitoring the absolute pressures both outside and inside an RPC, along with the temperature, allows for the estimation of its leakage rate. Additionally, during the test period, it is essential to detect any detachment of supporting button spacers inside an RPC that may occur due to manufacturing defects.

7.2 Future Prospects

The research conducted in this thesis opens the door to various potential extensions and further exploration. There are numerous avenues in which the findings and methodologies employed here can be expanded upon, leading to additional investigations and advancements in the field. To work done in the thesis provides a foundation to delve deeper into related topics and broaden the scope of inquiry. The potential future directions for the thesis are outlined below:

- The future plans involve delving deeper into the exploration of scalar Non-Standard Interactions to comprehensively investigate their influence on neutrino experiments. A collaborative initiative, incorporating data from solar, atmospheric, reactor, and other experiments, will be pivotal in gaining a holistic understanding of the ramifications of these non-standard interactions. Furthermore, emphasis will be placed on strengthening constraints on scalar NSI parameters to refine our understanding and contribute to the advancement of neutrino physics.

- In simple terms, determining the neutrino oscillation parameters requires a careful examination of correlations and degeneracies resulting from extra parameters introduced by NSI, in addition to the standard three parameters in neutrino physics. In the standard model, the only source of CP violation is the Dirac CP phase. Therefore, to attribute any findings on the CP phase solely to the standard three-neutrino framework, it's essential to eliminate or limit the impact of new physics scenarios that could also influence the observed signal.

- Neutrinos serve as a particularly intriguing channel for studying supernovae due to their unique ability to provide a direct observation of the stellar core precisely at the moment of the explosion. This distinct characteristic makes neutrinos invaluable in offering insights into the dynamics and inner workings of supernovae, presenting researchers with a direct observational tool to explore the intricate details of these celestial events. While Hyper-Kamiokande stands out due to its distinctive features of a large detection volume and the capability to accurately reconstruct individual events, it's essential to recognize that other neutrino detectors might exhibit greater sensitivity to specific aspects of the neutrino signal. Different detectors may excel in capturing particular nuances or characteristics of neutrino interactions, contributing to a comprehensive understanding of neutrino behavior and properties. Hence a synergy study combining various experiments can help understand as well as resolve various current puzzles of neutrinos.

- We have effectively fabricated and conducted a series of tests on the Resistive Plate Chamber (RPC), as detailed in Chapter 6. The forthcoming strategy for advancing this research involves simulating the RPC with the aim of enhancing both its detector sensitivity and overall characteristics while identifying potential issues. Given the substantial deployment of RPCs in the INO-ICAL detector, comprehending and optimizing their characteristics holds paramount importance. These investigations not only contribute to our understanding of the detector physics associated with these devices but also promise to facilitate the efficient and cost-effective operation of the ICAL detector in the future.