ABSTRACT

Precision measurements in long-baseline neutrino oscillation experiments require a detailed understanding of both detector-related backgrounds and neutrino–nucleus interaction physics. In experiments such as NOvA, systematic uncertainties arising from cosmic-ray induced backgrounds and nuclear modeling directly impact neutrino energy reconstruction and, consequently, the determination of oscillation parameters. Neutrino detectors such as NOvA also provide opportunities to study cosmic-ray properties and search for particles like dark matter, magnetic monopoles, etc.

This thesis presents two studies based on the data collected by the NOvA Near Detector (ND). The first study investigates the seasonal variation of cosmic ray-induced multiple-muon events observed in the ND. While the seasonal modulation of single-muon events is characterized by a summer maximum and winter minimum and is well understood, previous measurements by the MINOS experiment reported an unexpected inverted seasonal behavior for multiple-muon events, with a winter maximum, for which no conclusive explanation was established. Using nearly four years of NOvA ND data, this work confirms the inverted seasonal behavior of multiple-muon events with high statistical significance. A robust event-rate extraction technique based on Erlang probability distributions is employed to mitigate detector and data-acquisition effects. The observed multiple-muon rate is found to be strongly anti-correlated with the effective atmospheric temperature. To explain this behavior, detailed CORSIKA simulations incorporating realistic atmospheric profiles and detector geometry are performed. The results demonstrate that the interplay between seasonal atmospheric density variations, high-energy air-shower development, and the finite geometry of the detector leads to the observed phase reversal. This study provides the first comprehensive, simulation-backed explanation of the long-standing multiple-muon seasonal anomaly.

The second part of the thesis focuses on neutrino–nucleus interaction modeling, specifically charged-current quasi-elastic (CCQE) interactions, which play a central role in NOvA oscillation analyses. An advanced nuclear model based on the Hartree-Fock Continuum Random Phase Approximation (HF-CRPA) framework is studied and implemented to assess its impact on oscillation measurements. By incorporating realistic nuclear ground-state

descriptions and long-range nuclear correlations, HF-CRPA provides an improved treatment of CCQE interactions compared to traditional models. This work evaluates the effects of HF-CRPA on CCQE kinematics, reconstructed neutrino energy distributions, and oscillation sensitivities within the NOvA analysis framework, demonstrating that nuclear modeling uncertainties constitute a non-negligible systematic effect.

Together, these studies enhance the understanding of both atmospheric backgrounds and neutrino interaction systematics in NOvA, contributing to improved precision in current and future neutrino oscillation measurements.