ABSTRACT

The first part of this thesis focuses on the search for magnetic monopoles, which remain among the most intriguing and elusive phenomena in modern physics. Although they are strongly motivated by theory and have been the subject of intensive experimental investigations for many decades, no particle with an isolated magnetic charge has yet been detected. Magnetic monopoles emerge naturally in various extensions of the Standard Model, particularly in grand unified theories (GUTs). The Monopoles predicted by GUTs are expected to be extremely massive, with typical masses around 10^{16} GeV, placing them far beyond the production capabilities of any foreseeable particle accelerator. Such particles could, however, have been generated in the early Universe and might persist today as relics within the cosmic-ray flux, which strongly motivates experimental searches for magnetic monopoles in cosmic radiation.

The NOvA Far Detector (FD), though primarily designed for neutrino oscillation studies, offers remarkable sensitivity for magnetic monopoles. In this thesis, we present a search for highly ionizing magnetic monopoles in the cosmic-ray flux using a 2,713-day dataset collected between 2015 and 2025 with the NOvA FD, a 14-kiloton segmented detector situated at the Earth's surface in Minnesota, United States. This analysis is sensitive to monopoles in a wide range of speeds $7 \times 10^{-4} < \beta < 0.995$, and can probe monopole masses up to 2×10^5 GeV for the fastest monopoles. No monopole signal is observed. Due to the large geometric acceptance of the detector and the minimal overburden, we obtained the most stringent flux limits to date in several regions of monopole speed and mass. For heavy monopoles with masses exceeding 10^{13} GeV that can reach the detector either from above or by traversing the Earth from below, We set a 90% confidence level upper limit on the flux of $\phi_{90\%} < 2 \times 10^{-16}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ for monopole velocities in the range $0.005 < \beta < 0.8$. Over the same velocity interval, we also obtain a limit of $\phi_{90\%} < 8 \times 10^{-16}\,\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ for lighter monopoles with masses above 10^8 GeV that can reach the detector from above.

The second part of this thesis investigates the phenomenon of scalar non-standard interactions (NSI) in the context of the P2SO experiment and compares its sensitivity with that of DUNE. In particular, we examine the ability of these two experiments to constrain the

diagonal scalar NSI parameters, namely η_{ee}, $\eta_{\mu\mu}$, and $\eta_{\tau\tau}$, and analyze the impact of these parameters on the determination of the neutrino mass ordering, the octant of θ_{23}, and the CP violating phase δ_{CP}.

Our analysis reveals that the parameter Δm^2_{31} plays a nontrivial role when estimating bounds on $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ under the assumption that scalar NSI are absent in nature. We find that the sensitivities of P2SO and DUNE to constraining $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ are comparable, while DUNE exhibits a slightly better sensitivity to η_{ee}. Assuming the presence of scalar NSI in nature, we observe that the sensitivities to the neutrino mass ordering and to CP violation are predominantly affected by η_{ee}, whereas the octant sensitivity is primarily influenced by $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$. These sensitivities can be either enhanced or degraded relative to the standard three-flavor oscillation scenario, depending on the relative signs of the scalar NSI parameters. With regard to the precision of the atmospheric mixing parameters, we find that the precision in the measurement of θ_{23} is significantly deteriorated in the presence of $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$.