Neutrinos are the lightest and most abundant known elementary particles of matter. They have no electric charge and come in three species called flavors, each in a ‘neutrino’ and an ‘antineutrino’ or antimatter variant. Their existence was postulated by Wolfgang Pauli in the 1930s to explain the shape of the spectrum of electrons in beta decay. The existence was demonstrated experimentally only 20 years later. It took so long because neutrinos interact very rarely through the weak nuclear force. Their interaction probability is tiny, and neutrinos and their characteristics are extremely difficult to study experimentally. Even if neutrinos interact so weakly, some natural neutrino sources are abundant enough to allow for their detection. Raymond Davis and Masatoshi Koshiba received the 2002 Nobel prize for the measurement of neutrinos reaching the Earth from the Sun and a distant supernova explosion. Today, rich neutrino beams are produced in many laboratories around the world. The fact that neutrinos are so elusive is used in astrophysics in the investigation of objects at distances of billions of light-years away.

Neutrinos have an intriguing property: they change flavor while traveling, a phenomenon known as neutrino oscillations. Neutrino oscillations provide a beautiful illustration of how the basic principles of quantum mechanics operate and open the possibility to investigate some of the most critical remaining questions about the universe. The experimental confirmation of neutrino oscillations was awarded by the Nobel Prize in Physics in 2015 for the measurements done at the Super-Kamiokande laboratory in Japan and the Sudbery Neutrino Laboratory in Canada.

In experimental investigation of neutrino properties a major obstacle arises from the fact that neutrinos cannot be produced in a mono-energetic flux, and neutrino interactions in the detector occur on atomic nuclei. As the pattern of neutrino oscillations is rapidly changing as a function of the neutrino energy, it is critical to develop tools to precisely reconstruct the value of the energy of the interacting neutrino. In can be done only by measuring the particles knocked-out from a nucleus due to neutrino interaction. Prerequisite is the detail understanding of neutrino scattering off a free nucleon. On top of that, one needs reliable modeling of effects of the nuclear medium. The current lack of precise knowledge in this respect is a major source of systematic uncertainties in neutrino oscillation experiments. It makes them more expensive in every dimension, scientific, budgetary, and even environmental. The only way to reduce the overall uncertainty is to run experiments for a very long time to limit the statistical uncertainty to the extreme.

In this decade, investigation of neutrino properties enter a new phase. Two huge experimental facilities are under construction: DUNE in the USA and Hyper-Kamiokande in Japan. Both should start collecting data in 2027. They will perform measurements that should clarify the role played by neutrinos in explaining a fundamental yet poorly understood mechanism that determines why the universe we live in consists almost entirely of matter with a negligible amount of antimatter. A possible explanation called ‘leptogenesis’ comes from a violation of the symmetry of laws of nature under a combined matter-antimatter transformation (‘C’ for a charge) and mirror inversion (‘P’ for parity) in neutrino interactions with matter. Experimentally, a violation of CP symmetry for neutrinos could be seen as a tiny difference in neutrino and antineutrino oscillation patterns. As such, it requires an enormous experimental effort to achieve the accuracy needed to investigate this effect.

A critical tool in the inspection of the experimental data are Monte Carlo (MC) event generators. They are indispensable in every step of the analysis. They enable analyzers to map the signal observed in the detector on the underlying physical mechanisms using a probabilistic approach in a computationally efficient way. An improvement of MC generators has become the primary concern of theorists and experimentalists alike.

The goal of this project is to improve the description of neutrino-nucleus interactions and reduce systematic uncertainties in measurements done in neutrino oscillation experiments. The novelty and originality of the project lie in the combination of theoretical and phenomenological investigation leading to better understanding of nuclear effects and improvement of Monte Carlo simulation tools using machine learning methods. The obtained results and developed techniques will be applied in computational tools like NuWro, GENIE, NEUT and contribute to increased sensitivity of neutrino oscillation experiments.