Every second billions of neutrinos reach the Earth from the Sun, passing human bodies without any physical impact. Indeed, neutrino-matter interactions are so weak that massive detectors containing hundreds of tons of specially prepared materials are needed to detect them.

In the project we will deal with the theory of neutrinos while working on the answer to the fundamental questions arising in the theory of elementary particles: how many types of neutrinos occur in nature? How to discover them? What are their symmetry properties? Are there non-standard neutrino interactions, and how can they change neutrino oscillation experiments and the search for new processes at low and high energies in the future?

Experimental and theoretical premises indicate that the currently known three types of so-called flavors (also named families, generations, species) of neutrinos (electron, muon, and tau) are not everything. The masses of neutrinos known to us are at least a million times lighter than the electron mass, and the addition of heavy neutrino states to the theory matters for instance in cosmology. They influence the rate and the way the universe evolves.

As a part of the project, we will analyze the properties of the matrix responsible for the quantum effects of neutrino mixing. Superposition of neutrino states leads to their oscillation (change of probability to detect a given flavor with a distance over which the neutrino propagates), observed among others for neutrinos traveling from the Sun and neutrinos passing Earth's atmosphere. We will assume that extra neutrino states exist. The existence of additional neutrino states should be manifested in a deviation from the so-called unitarity of the neutrino mixing matrix, which is determined experimentally. The group has developed an original approach to neutrino mixing analysis based on the advanced properties of matrix theory, which has already improved the estimates for models in which one additional type of neutrino appears. This work was published in 2020 in the Journal of High Energy Physics, https://doi.org/10.1007/JHEP03(2020)169.

We will examine the possible quantum effect of neutrino mixing leading to their oscillation, i.e. the conversion of one neutrino state into another, and whether this mixing contains complex elements. Complex phases in the matrix can lead to the effects of breaking the parity (mirror) symmetry 'P' and the charge (asymmetry of particle and antiparticle interactions) symmetry 'C' in models with one, two and three additional neutrinos. We will investigate how complex phases of neutrino matrices and the corresponding new neutrino states can be detected in planned rare processes. Such processes break the lepton number (e.g., muon decay into an electron with photon emission), or high energy accelerators (CLIC, FCC, ILC, CEPC).

We will also inquire about the mechanism that leads to the fact that neutrino masses are so extremely small. One of the possible and exciting mechanisms is the so-called seesaw mechanism in which neutrinos interact with Higgs fields. We are particularly interested in scenarios in which doubly charged Higgs particles exist. We will study their connection with neutrinos and the possibility of their direct production and experimental verification in high energy accelerators.

Our research will determine the possible forms of full neutrino mixing matrices containing known three neutrino states as well as additional, yet undiscovered neutral particles. We will determine for these matrices the possible degree of CP symmetry breaking and will examine the so-called family symmetry. Based on the obtained mixing matrix structures and the restrictions obtained on non-standard mixing of neutrinos, we will calculate the probability of detecting new neutrino states or Higgs particles associated with the mechanism of neutrino mass generation in low and high energy processes. We will introduce new methods of analytical and numerical analysis to neutrino physics related to matrix algebra and quaternion theory (a generalization of complex numbers).

Engagement in this international project of MSc, PhD students, and postdocs will be of great importance for young researchers, it will increase their creativity and will leverage the scientific level of basic research at the University of Silesia. Cooperation with Dr. Patrick Janot (CERN) and prof. Alain Blondel (U. of Geneva), Switzerland, are renowned experts in e^+e^- collider electroweak and neutrino physics. Prof. Joydeep Chakrabortty and Dr. Tripurari Srivastava are Indian scientists, experts in phenomenological studies of non-standard effects beyond the Standard Model of elementary interactions.