Towards the discovery of CP violation in the leptonic sector with T2K-II and the Near Detector Upgrade

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T2K is a long-baseline neutrino oscillation experiment (LBL-ν) taking data in Japan [1]. The goal of LBL-ν experiments is to do precise measurements of neutrino oscillation parameters, that depend on the ratio between the neutrino energy (E) and the distance between the production and the detection of neutrinos (L) by producing a neutrino beam in which both, L and E, are optimized.

To produce a neutrino beam, an accelerator is used to accelerate protons that hit a target leading to the emission of hadrons. These hadrons, mostly pions, are selected in charge by a system of magnetic horns and focused on a decay tunnel where they decay after few tenths of meters. Their decay produces a pure beam of muon neutrinos (or antineutrinos) that is observed at a Near Detector and at a Far Detector at a distance of few hundreds of km. In the case of T2K, the Near Detector is ND280 and it is a multipurpose magnetic detector used to predict the neutrino spectra in absence of oscillations, while the Far Detector is Super-Kamiokande, a Water Cherenkov detector at a distance of 295 km from the neutrino production point.

T2K was the first experiment to detect neutrino oscillations in appearance mode by detecting the appearance of electron neutrinos [2, 3] and it is currently searching for CP violation in the leptonic sector by comparing appearance probabilities for electron neutrinos and electron antineutrinos. In 2020 T2K reported first hints of CP violation in the leptonic sector [4]. This measurement, if confirmed by more data, could help explaining one of the deepest mysteries in our understanding of the Universe, the matter-antimatter asymmetry. CP violation in the leptonic sector can only be discovered with long-baseline experiments and it is the goal T2K of and of its successor, Hyper-Kamiokande (HK) [5], a detector that will be 10 times larger than SK. HK is under construction in Japan and will start taking data in 2027.

In order to measure CP violation effects, an exceptional understanding of systematic uncertainties is needed. In particular, a careful modeling of the interactions between neutrinos and the nuclei (neutrino cross-sections) and of the differences between neutrinos and antineutrinos is required. One of the main sources of systematic uncertainties is related to the reconstruction of the neutrino energy from the measured kinematics of the leptons emitted by neutrino interactions. This relationship depends on the type of neutrino interaction with the matter that can be quasi-elastic (the neutrino interacts with a free nucleon) multinucleon (the neutrino interacts with a bound pair of nucleons), pion production (the neutrino excites the nucleon producing a Δ resonance), etc. Each of these interactions lead to a different relationship between neutrino energy and lepton kinematics and it is described by one or more cross-section models that must be tuned on data. In T2K this is done by using the Near Detector, ND280, that is able to select exclusive samples of neutrinos and anti-neutrino interactions.

To scrutinize the hints of CP violation reported in 2020, T2K is finalizing the upgrade of the Near Detector that will lead to the second phase of the experiment, T2K-II. The ND280 Upgrade [6] consists in a new active target (Super-FGD) and two new Time Projection Chambers (HA-TPC) instrumented with Resistive MicroMegas modules (ERAM) that will be installed in J-PARC by the end of 2022 and will start collecting neutrino data in 2023. The analyses of these data is the main goal of the thesis.

The ND280 Upgrade will have three main advantages with respect to the current ND280:

- Better efficiency to reconstruct muons emitted at high angle with respect to the neutrinos.
- Better efficiency to reconstruct the hadronic part, reducing the threshold for the reconstruction of protons and pions as well as the capability to reconstruct neutrons from the time of flight between the neutrino interaction and the neutron re-scattering in the detector [7].
- Better capability to distinguish electron from gammas in order to select a high purity sample of electron neutrino interactions.

The reconstruction of the hadrons will help to better reconstruct the energy of the neutrinos and to improve our knowledge of the nuclear processes on-going when neutrinos interact with nuclei. The capability of selecting a clean sample of electron neutrino and antineutrinos will allow to study differences in the cross-section between electron and muon neutrinos, one of the main systematic uncertainties for future long-baseline experiments. This work will hence be crucial also for Hyper-Kamiokande that will use ND280 as one of its near detectors.

Thesis directors, subject and expected timeline

The supervisors of this thesis are, respectively, the coordinator of the ND280 Upgrade (Claudio Giganti) and the T2K analysis coordinator (Sara Bolognesi) thus ensuring an excellent supervision for both, hardware and analysis related topics.

The T2K LPNHE and IRFU/DPhP groups collaborate since the beginning of T2K. Our groups are leading the sensitivity studies and the preparation of the analyses tools for the Upgrade [8], as well as the production of the ERAM modules and of the HA-TPC electronics, the development of the HA-TPC reconstruction tools and the analysis of test beam data [9, 10].

During the first year of the thesis, the PhD candidate will participate to the commissioning of the ND280 Upgrade in Europe and in Japan. The PhD candidate will also contribute to the data taking in Japan and will work on the development of the reconstruction tools and of the analysis tools in order to exploit the first data of the ND280 Upgrade.

The analyses topics, on which the PhD candidate will concentrate once the first data will be taken, include exploiting the full reconstruction of the final state of Quasi-Elastic muon neutrino or antineutrino interactions (muons plus protons or neutrons) to reduce systematic uncertainties in T2K oscillation analysis and work on the selection electron neutrino interactions to constraint differences between electron and muon neutrino interactions that constitute one of the main systematics in the search for CPV in T2K-II and in future long-baseline experiments.

An additional topic will be the combination of muon and electron neutrino selected to perform an oscillation analysis at ND280 searching for sterile neutrinos. We published a first search of sterile neutrinos at ND280 in [11] and we expect that the upgraded ND280 will have several advantages, including a larger target mass, a lower threshold to reconstruct leptons, better performances in distinguishing electrons from gammas, and the larger exposure that will be collected in T2K-II.

In summary, we should stress that the timing of the proposed PhD thesis matches perfectly with the ND280 Upgrade schedule and provides a possibility to make a significant and highly visible contribution to the T2K-II experiment.

References

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