The T2K-II project: the second phase of the T2K experiment

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1 Introduction

A large variety of experimental results using neutrinos from very different sources has contributed to establish the phenomenon of neutrino oscillations that are described within the PMNS [1, 2] framework. The PMNS matrix is a 3×3 unitary mixing matrix, parametrized by three mixing angles, θ_{12}, θ_{23}, θ_{13}, and a CP violating phase, δ_{CP}. The additional parameters governing neutrino oscillations are the squared–mass differences $\Delta m^2_{ij} = m^2_j - m^2_i$, where m_i is the mass of the i-th neutrino mass eigenstate.

The T2K (Tokai-To-Kamioka) experiment is a long-baseline neutrino oscillation experiment, designed to accurately measure neutrino oscillations driven by the so-called atmospheric mass squared difference ($\Delta \mathrm{m}^2_{32}$). A neutrino beam is produced at the J-PARC accelerator complex by striking a 30 GeV proton beam onto a 90 cm long carbon target. The produced hadrons are focused and charge-selected by a system of magnetic horns and are directed towards a decay tunnel. By changing the direction of the current in the magnetic horns it is possible to select hadrons of opposite charge. If positively charged pions are focused they decay into μ^+ and ν_μ (ν–mode) while if negatively charged pions are focused they decay into μ^- and $\overline{\nu}_\mu$ ($\overline{\nu}$–mode).

A set of near detectors has been constructed 280 m from the target with a significant contribution of IN2P3 groups: an on-axis detector, INGRID, is crucial for the neutrino beam monitoring, while a magnetized off-axis detector, ND280, is used to precisely measure the beam composition prior to oscillations and to quantify potential sources of background. The high-performance Super-Kamiokande water Cherenkov detector is used as a far detector.

T2K started taking data in 2010 with the main goal of observing ν_e appearance in the ν_μ beam that would have implied that the last unknown mixing angle, θ_{13}, was different from zero. After first indications from T2K on the $\nu_\mu \to \nu_e$ transition and non-zero value of θ_{13} [3], θ_{13} was measured to be different from zero in 2012 by Daya Bay [4] and RENO [5] with more than 5σ significance. In 2013, T2K definitely established ν_e appearance [6], and, more generally, the existence of neutrino oscillations in appearance mode with a statistical significance larger than 7σ.

The relatively large value of θ_{13} opened the possibility of observing CP violation in the lepton sector with long-baseline experiments using conventional neutrino beams and comparing the ν_e and $\overline{\nu}_e$ appearance probabilities. This strategy is pursued in Japan with a staged program that comprises the T2K experiment, its extension and upgrades (T2K phase II or T2K-II), and the future Hyper-Kamiokande detector, a water Cherenkov detector with a fiducial volume roughly 8 times larger than the existing Super-Kamiokande.

As a first step towards this goal, since 2014 T2K is taking data in both ν–mode and in $\overline{\nu}$–mode and has recently reported first hints of CP violation, by excluding CP conserving values (δ_{CP} =0 or π) at more than 2σ and favoring δ_{CP} ∼-$\pi/2$, the value that maximizes the $\nu_\mu \to \nu_e$ appearance probability while minimizing the $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance probability. If these hints are confirmed, the phase II of T2K (from 2021 to 2026) that will consist in upgrades of the beamline and of the ND280, will be able to observe CP violation with a significance of more than 3σ and Hyper-Kamiokande, starting in 2026, will be able to definitely observe CP violation with more than 5σ significance.

Since the beginning of T2K, the LLR and LPNHE neutrino groups in close collaboration with IRFU/DPhP colleagues were heavily involved in the construction and operation of the experiment as well as in the data calibration and analysis. The LPNHE group had a leading role in the NA61/SHINE experiment at CERN, an experiment designed to measure hadron-production cross-sections, contributed to the ND280 off-axis detector construction and operation (for the TPCs and the magnet), to the ND280 analyses and to the T2K oscillation analysis. The LLR group has been responsible for the design and the mechanical construction of the INGRID detector and the Proton Module. More recently, the LLR group was responsible for the mechanical design of the WAGASCI water modules, and for the readout and DAQ system of both the water modules and the side Muon Range Detectors, which are part of the WAGASCI setup. During last years, the group has also contributed to the cross section measurements at ND280. Both groups are currently involved in the upgrade of the T2K Near Detector for the phase II of T2K as it will be discussed in Sect. 4.

2 T2K oscillation analyses and results

In order to measure oscillation parameters, the expected event rates and spectra at Super-Kamiokande are predicted based on a model of neutrino fluxes and of neutrino cross-sections and measurements of neutrino interactions at ND280. More details on the oscillation analyses are given in [7].

The flux modelling is currently based on the NA61/SHINE hadroproduction thin-target measurements [8]. It allows the reduction of the uncertainties on the T2K fluxes below 10%. The neutrino cross-section model is based on external measurements from different experiments (mostly MiniBooNE and Minerva, see [9] for details). Uncertainties on event rates and spectra of the order of 15% would be expected if only those data were available.

Crucial inputs to the T2K oscillation analyses are then the measurements at the Near Detectors. The INGRID detector is used continuously during the data-taking to monitor the (anti-)neutrino beam profile and its stability. In the ND280 tracker ν_μ and $\overline{\nu}_\mu$ charged current (CC) interactions are selected in the FGD1 and in the FGD2 with charge and momentum of the muons precisely measured by the TPCs. The samples are separated according to the detector in which the interaction vertex was reconstructed, to the charge of the muon, and to the number of pions observed in the final state (0, 1, more than 1) and are fitted to predict the expected spectra at Super-Kamiokande without oscillations. Examples of these distributions as a function of outgoing muon momentum are shown in Fig. 1 .

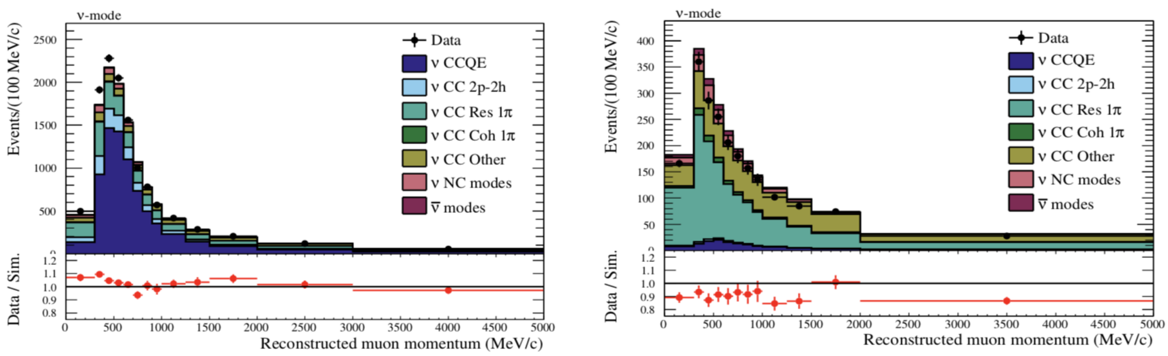


Figure 1: Momentum distribution of outgoing muons for ν_μ CC-$0\pi^+$ (left) and CC-$1\pi^+$ (right) samples at ND280.

Five samples are selected at Super-Kamiokande and are used in the oscillation analyses: single–ring μ–like events selected in ν–mode and in $\overline{\nu}$–mode, single–ring e–like events selected in ν–mode and in $\overline{\nu}$–mode, and a fifth sample, selected only in ν–mode, where the e–like ring is accompanied by the presence of a delayed electron, due to the decay of a pion produced in the neutrino interaction.

As shown in Fig. 2, $\delta_{\rm CP}$ only affects the e-like samples and values of $\delta_{\rm CP}$ close to -$\pi/2$ tend to increase the ν_e appearance probability, while decreasing the $\overline{\nu}_e$ probability. This is exactly what is observed in the data in ν–mode ($\overline{\nu}$–mode), where 74 (15) single-ring e-like events are observed while 62 (19) are expected if $\delta_{\rm CP} = 0$ or π.

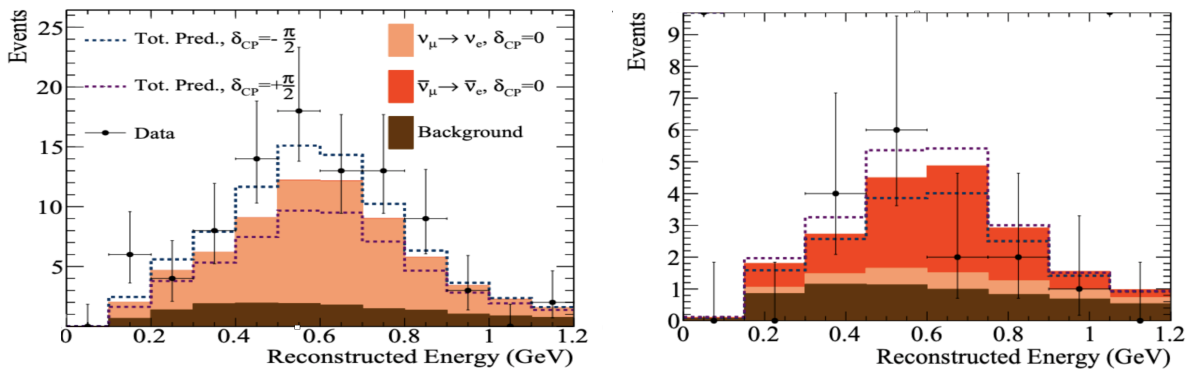


Figure 2: Observed energy spectra for the e-like samples in ν–mode (left) and $\overline{\nu}$–mode (mode) compared to the prediction for different values of $\delta_{\rm CP}$.

The Super-Kamiokande samples are then fitted together in order to extract the oscillation parameters θ_{23}, $|\Delta {\rm m}^2|$, θ_{13}, $\delta_{\rm CP}$ and the mass ordering, and the results showed in Fig. 3 from [12].

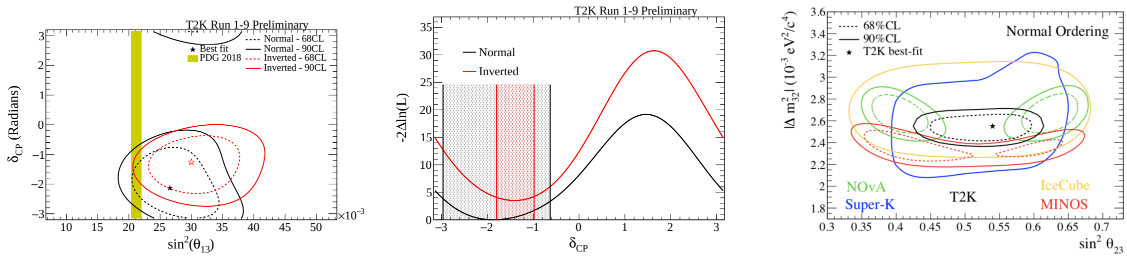


Figure 3: Measurement of the oscillation parameters θ_{13} and $\delta_{\rm CP}$ without reactor constraint (left) and measurement of $\delta_{\rm CP}$ with reactor constraints (center) θ_{23} and $|\Delta {\rm m}^2|$ (right). The bands on the center plot represent the 95% CL allowed regions for the two mass ordering hypotheses.

In addition to the oscillation analysis, the powerful Near Detectors of T2K allow to perform many measurements of neutrino cross-sections for different neutrino types (ν_μ, $\overline{\nu}_\mu$, ν_e), final states (0, 1 or more reconstructed pions, 0 or 1 reconstructed protons) and different targets (iron, carbon, and water). Such measurements are fundamental for the neutrino community since the precision needed by future long-baseline experiments requires to control the systematics uncertainties at the 2–3% level and this will only be possible by developing the existing neutrino interactions models, informed by precise data for different final states.

3 T2K-II physics case

The most recent results of T2K [12] show intriguing hints that CP symmetry might be violated in the lepton sector. These results are obtained with statistics of $3.2{\times}10^{21}$ p.o.t., corresponding to about 40% of the total T2K approved statistics. These results are also supported by the most recent analyses of NOνA and Super-Kamiokande data that also prefer large CP violation ($\delta_{\rm CP}$ $\sim$-$\pi/2$) and a normal mass ordering. If true, those are the most favorable values for early discoveries by long-baseline experiments, with the exclusion of CP conserving values and a determination of the mass ordering that is within reach of T2K and NOνA experiments.

These goals can be achieved by T2K before the next generation of experiments will be operational by collecting more statistics and by reducing the systematic uncertainties, currently dominated by uncertainties on neutrino fluxes and cross-section models.

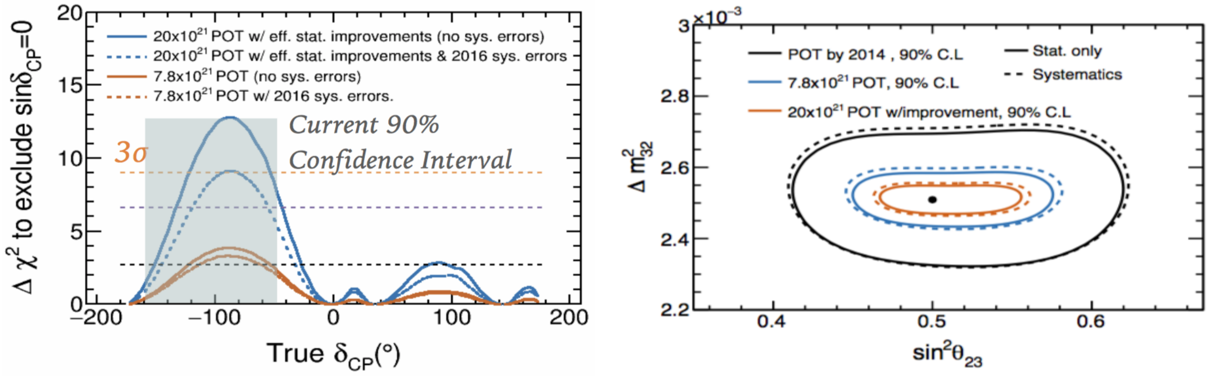


Figure 4: Left: Expected T2K-II sensitivity to $\delta_{\rm CP}$ assuming the mass ordering is not known. Right: Expected T2K-II sensitivity to θ_{23} and $\Delta {\rm m}^2_{32}$.

The T2K collaboration has proposed an extension to the currently approved T2K statistics (7.8×10^{21} p.o.t.). This program, known as T2K-II, will allow to extend the T2K running time until 2026, before the beginning of Hyper-Kamiokande, and to collect a statistics of 20×10^{21} p.o.t., aiming at initial observation of CP violation with 3σ or higher significance for the case of large CP violation and measurements of mixing parameters, θ_{23} and Δm^2_{32}, with a precision of $1.7°$ or better and 1%, respectively [10]. Such statistics will be collected thanks to a program of accelerator upgrades that is approved by KEK and J-PARC and will be performed in 2021. This upgrade will allow to reach a power of 800 kW in 2022 and 1.3 MW a few years later (to be compared with 485 kW currently achieved).

In order to fully profit of the foreseen additional statistics a better understanding on systematic uncertainties and in particular the ones related to flux and cross-section systematic uncertainties. The IN2P3 groups plan to continue their long–lasting activities in order to reduce systematics on the flux (NA61/SHINE replica target data) and cross-section measurements and modelling. In addition the LLR and LPNHE groups are heavily involved in the upgrade of the T2K Near Detector [11].

4 ND280 upgrade project

The ND280 upgrade project has been proposed by collaborators from 45 laboratories, including most of the groups already involved in the construction and operation of ND280. The ND280 Upgrade has been approved as a T2K project in 2017 and has been positively reviewed by the CERN SPSC and the J-PARC PAC in 2019. The goal is to install the new detectors in 2021.

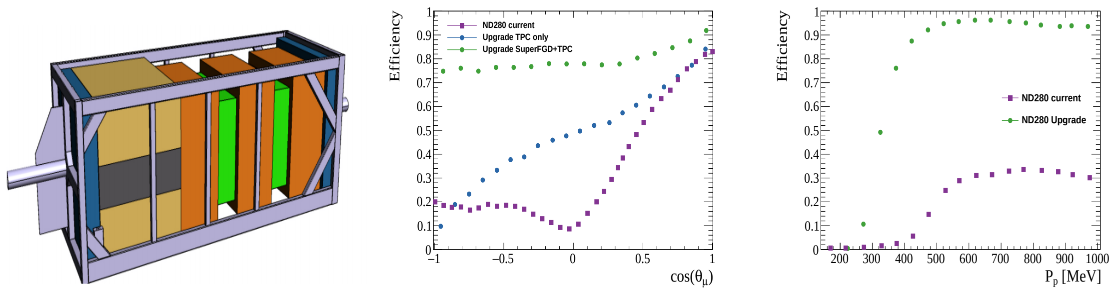
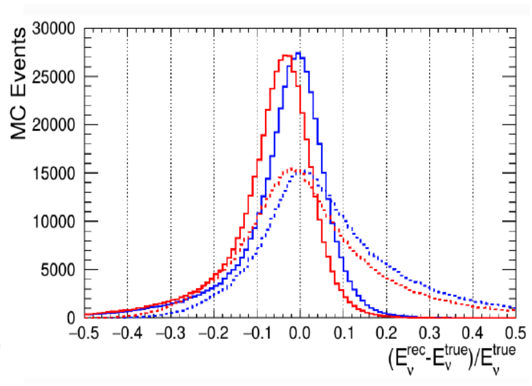
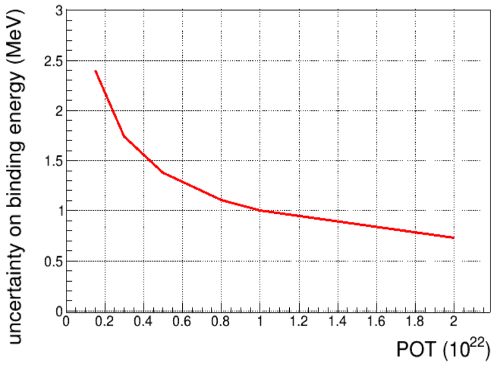


Figure 5: Left: Sketch of the ND280 upgrade project. In the upstream part of the detector two horizontal TPCs (yellow) and the SuperFGD (grey) will be installed. Center: Muon selection efficiency as a function of $\cos\theta$ for the current ND280 detector and for the upgraded Near Detector. Blue points show the efficiency by requiring the muon to enter the TPC while for the green points stopping tracks in the SuperFGD are also included. Right: efficiency to reconstruct protons as a function of outgoing proton momentum for the current and the upgraded ND280.

The goal of the ND280 upgrade is to overcome the two main limitations of the current ND280 design:



(a)



(b)

Figure 6: a) Comparison of neutrino energy reconstruction in QE events using the new variable $E_{had} = E_p + E_\mu$ (solid lines) or E_{rec}, based only on muon kinematics (dashed lines) for two different values of the binding energy. b) Expected precision on the ND280 Upgrade to measure the binding energy as a function of the p.o.t.

the different angular acceptance between ND280 (mostly forward) and Super-Kamiokande (4π efficiency) and the relatively large threshold to reconstruct charged hadrons produced in neutrino interactions.

The ND280 Upgrade will achieve a much better uniformity of acceptance as a function of polar angle, by reconfiguring the geometry with a fully active scintillator detector acting as neutrino target, disposed along the plane including both the beam direction and the magnetic field. The scintillator detector, called Super-FGD, consist of $\sim 2 \times 10^6$ scintillator cubes of 1 cm^3 each read-out by three WLS fibers thus allowing a 3D reconstruction with excellent granularity. On the top and on the bottom of the Super-FGD, two new TPCs will measure charge, momenta and deposited energy of charged particles existing the scintillator detector. In addition 6 planes of time-of-flight (ToF) will surround the new Tracker system, allowing to reject events entering from outside of fiducial volume.

As shown in Fig. 5, such configuration, combined with the existing tracker system, will allow to select with similar efficiencies outgoing charged leptons emitted in any direction with respect to the beam giving a better handle to distinguish among different neutrino cross-section models and to better constrain the parameters in these models. In addition, the large mass of the detector (~ 2 ton) and the improved reconstruction efficiency will allow to select clean samples of ν_e interactions and of final state ν_μ interactions in which most of the emitted particles will be fully reconstructed.

The high efficiency in reconstructing the hadronic part of the interaction will allow to reconstruct the neutrino energy in a calorimetric way, by combining the information of the leptonic and of the hadronic part of the neutrino interaction (E_{had}). In Fig. 6a the expected performances of this new variable is compared with the reconstructed energy used today in T2K based on the reconstruction of the lepton and assuming a Quasi-Elastic interaction. E_{had} is clearly a more precise estimator of the true neutrino energy and therefore a more powerful variable to estimate the binding energy, that is the dominant source of systematic uncertainties in most recent T2K publications [12]. In Fig. 6b the expected precision in measuring the binding energy with the ND280 upgrade is shown as a function of the statistics available. A precision on binding energy of about 1 MeV can be obtained with 10^{22} p.o.t. It is important to stress that a better understanding of neutrino cross-sections will benefit T2K but also the other long-baseline neutrino oscillations experiments (NOνA, DUNE, and Hyper-Kamiokande).

The LLR and the LPNHE groups, in collaboration with IRFU/DPhP physicists, are involved in the ND280 upgrade, contributing to the electronics of the Super-FGD (LLR) that will be based on the CITIROC chips to provide charge and time informations of the hits in the cubes, and to the Front-End electronics of the TPCs (LPNHE) based on the AFTER chips, developed for the existing ND280 TPCs. The groups are also contributing to the physics sensitivity studies and to the development of the simulation and reconstruction tools and to their inclusion in the framework of the existing ND280 software. Such work, together with the analysis of the data that will be collected during T2K-II will prepare the road for a strong French involvement in the Hyper-Kamiokande project, discussed in a separately submitted document.

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