Participation of IN2P3 physicists in the T2K experiment

LLR and LPNHE neutrino groups

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Contents

Executive Summary

This document describes the participation of the LLR, LPNHE and ILANCE physicists in the ongoing T2K experiment. These contributions had been already evaluated by the IN2P3 Scientific council in 2018 and we refer to that report for more details about the history of the IN2P3 groups contributions to T2K.

In this document we briefly present the updates occurred in the last three years and the prospects for the future in which we will start the phase II of the experiment (T2K-II) that will include an upgrade of the J-PARC accelerator complex and of the off-axis Near Detector (ND280).

We will not describe here the proposed contributions of the LLR, LPNHE and ILANCE groups to the Hyper-Kamiokande experiment for which a dedicated document has been prepared. It should be noted, however, that Hyper-Kamiokande will use the J-PARC beam and the Hyper-Kamiokande near detector complex will include the T2K Near Detectors. In this sense the successful deployment of the ND280 Upgrade will be extremely beneficial also to Hyper-Kamiokande.

The T2K (Tokai-To-Kamioka) experiment is a long-baseline neutrino oscillation experiment, designed to precisely measure neutrino oscillations driven by the so-called atmospheric mass squared difference (Δm^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. 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 and, originally, the main goal was the observation of ν_e appearance in the ν_μ beam that would have implied that the last unknown mixing angle, θ_{13}, was different from zero.

The LLR and LPNHE neutrino groups were heavily involved in the construction and operation of the experiment as well as in the data calibration and analysis.

After first indications from T2K on the $\nu_\mu \to \nu_e$ transition and non-zero value of θ_{13} [1], θ_{13} was measured to be different from zero in 2012 by Daya Bay [2] and RENO [3] with more than 5σ significance. In 2013, T2K definitely established ν_e appearance [4], 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 and seamless program that comprises the T2K experiment, its extension and upgrades (T2K-II), the upgrade of Super-Kamiokande with Gadolinium, 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 [5], by excluding CP conserving values ($\delta_{\rm CP}$ =0 or π) at more than 2σ and favoring $\delta_{\rm CP} \sim$-$\pi/2$, 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 2022 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 2027, will be able to definitely observe CP violation with more than 5σ significance.

1 The T2K experiment

T2K [6] is a long-baseline neutrino oscillation experiment originally intended to measure θ_{13} by observing electron neutrino appearance. A muon neutrino beam is produced at the J-PARC accelerator complex on the East Coast of Japan 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). The undecayed pions and other hadrons, as well as the muons, are stopped by a beam dump, installed 100 m downstream of the target.

Neutrinos are then observed in a set of near detectors, INGRID and ND280, at 280 m from the target, where the effect of the oscillations is negligible, and at the first oscillation peak at the far detector, Super-Kamiokande, 295 km away from J-PARC. The neutrino energy, peaked at 600 MeV, and the distance are chosen to be at the expected maximum of the oscillations in order to maximize the sensitivity to ν_μ and $\overline{\nu}_\mu$ disappearance and to ν_e and $\overline{\nu}_e$ appearance. A schematic view of T2K is shown in Fig. 1.

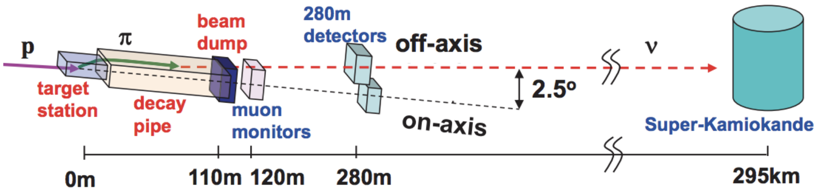

Figure 1: A schematic view of the T2K neutrino beamline and detectors.

The near detector complex comprises an on-axis detector (INGRID) and two off-axis detectors: ND280, at 2.5°, and WAGASCI/BabyMind, at 1.5°.

The INGRID detector (see left panel of Fig. 2) is composed of 14 modules of iron and plastic scintillator spanning the neutrino beam in a transverse section of 10×10 meters. Its goal is to measure, on a day–by–day basis, the neutrino beam direction and profile.

Seven modules are used to build the two branches of the cross-shaped INGRID detector. The overall setup is centered on the beam axis, and two additional modules are used to check the beam central symmetry. A specific module with no iron and narrower scintillator bars, is used to measure the tracks of the recoiling protons created by neutrino interactions. This so-called Proton Module is placed in between the two INGRID branches, on the beam axis.

The off-axis detector, ND280 (see central panel of Fig. 2), consists of several detectors installed in

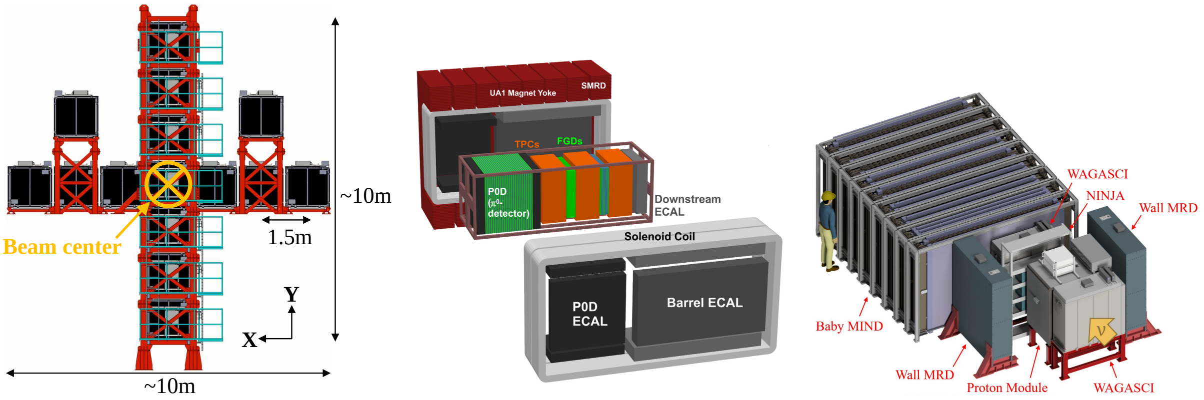

Figure 2: Schematic views of the INGRID detector (left) of the ND280 detector (center) and of the WAGASCI/BabyMind detector (right).

the ex-UA1 magnet, operated at 0.2 T: a π^0 detector (P0D) to measure interactions with π^0 production, an electromagnetic calorimeter (ECAL) and a Side Muon Range Detector (SMRD) embedded in the magnet yokes. Finally a Tracker system is composed of two Fine Grained Detectors (FGD) and three Time Projection Chambers (TPC). Neutrino interactions with different topologies selected in the Tracker system are used as inputs to the T2K oscillation analyses. An important upgrade of the off-axis detector is currently being constructed and will be described in details in Sect. 4.

Since 2017, T2K counts an additional near detector, called WAGASCI (WAter Grid And SCIntillator), and located at 1.5° off-axis with respect to the beam direction (see right panel of Fig. 2). The installation of this detector was completed at the end of 2019 and the first physics data taking happened in spring 2021. Made of 80% of water and thanks to its peculiar structure where a hollow cuboid lattice of scintillators is filled with water, the WAGASCI detector will allow more precise measurements of neutrino cross sections on H_2O, the same target as Super-Kamiokande.

The far detector of T2K is Super-Kamiokande, a 50 kton water Cherenkov detector located at a depth of 2700 meters water equivalent in the Kamioka mine. Super-Kamiokande has a cylindrical shape with two concentric optically separated regions instrumented with Hamamatsu PMTs. Neutrino interactions on water produce Cherenkov light which can be used to distinguish between electron-like and muon-like events by analyzing the sharpness of the Cherenkov ring. A muon makes a sharp edged ring whilst an electron makes a fuzzy one due to electromagnetic showers. The electron/muon misidentification probability, estimated using atmospheric neutrinos, is about 1% for the T2K neutrino energy.

T2K has collected so far 3.6×10^{21} p.o.t., equally shared between ν–mode and $\overline{\nu}$–mode modes.

2 IN2P3 groups contributions to the T2K physics program

The LLR and LPNHE groups contributed to several aspects of the T2K physics program, including the neutrino flux prediction through the NA61/SHINE experiment, the construction and operation of the T2K Near Detectors (INGRID, WAGASCI and off-axis ND280), the analysis of the Near Detector data for the oscillation analysis and for the extraction of neutrino cross-sections, and the operation of Super-Kamiokande.

Currently IN2P3 group members have the following responsibilities within the T2K experiment:

- convener of the NA61/SHINE analysis (Boris Popov);
- co-convener of the T2K Oscillation analysis group (Benjamin Quilain)
- co-convener of the cross-section group (Margherita Buizza Avanzini)
- co-convener of the ND280 reconstruction group (Mathieu Guigue)
- co-convener of the WAGASCI electronics (Thomas Mueller)
- co-convener of the SuperFGD electronics (Olivier Drapier)
- ND280 Upgrade project leader (Claudio Giganti)

Since the beginning of T2K, a total of 10 PhD theses have been defended by students from IN2P3 groups. Currently 4 PhD students are working at LLR and LPNHE. The topics of these theses are cross-section measurements, T2K oscillation analyses, ND280 upgrade sensitivity, and ND280 upgrade reconstruction.

The LPNHE group is also complemented by 2 postdocs, hired with an ANR grant, that are working on the HA-TPCs simulation and reconstruction, on the HA-TPCs DAQ, and on the development of the fitter described in Sect. 4.2.

3 The phase I of T2K

3.1 Latest oscillation analysis results

Using data collected until 2018, the T2K collaboration has published in 2020 its first paper in Nature [5], providing for the first time the 3σ confidence intervals for the CP violating phase in the lepton sector, δ_{CP}, that disfavor almost half of the possible δ_{CP} values. Also, T2K shows a preference for $\delta_{CP} \simeq -90°$, that is a maximal violation of CP (see right panel of Fig. 3). As shown in the left panel of Fig. 3, the T2K publication was chosen to make the Nature cover on April 16th 2020.

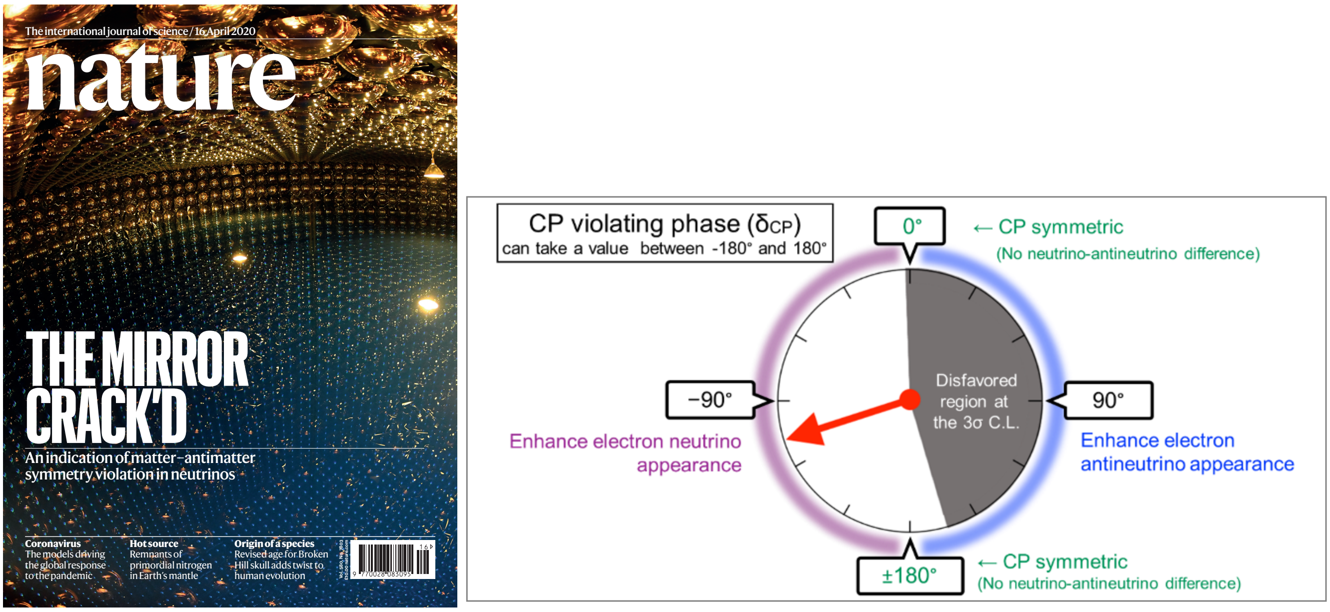

Figure 3: *Left:* T2K makes the cover of Nature in April 16th 2020. *Right*: diagram showing T2K results on δ_{CP}: the arrow indicates the value most compatible with the data. The gray region is disfavored at 99.7% (3σ) confidence level. Nearly half of the possible values are excluded.

After this impressive result, a first analysis update was published in [7]. In the following, we will focus on 2020 oscillation analysis (OA2020) results, as presented at the Neutrino2020 conference. For this analysis several improvements were implemented:

1. additional statistics at the far detector (from $3.1\text{x}10^{21}$ to $3.6\text{x}10^{21}$ p.o.t.);
2. the ND280 statistics in neutrino and antineutrino mode used for the oscillation analysis has been doubled;
3. the reference nuclear model used to describe the nucleus for CCQE neutrino interactions has been upgraded from a simplistic relativistic Fermi gas, to a more sophisticated and (in principle) more accurate model, called Spectral Function (SF);
4. as a consequence, the systematics parameters describing our uncertainties on neutrino interactions have been updated;
5. at the near detector, the event selection for the samples in the anti-neutrino mode have been improved in order to reflect the ones used in the neutrino mode and now 18 near detector samples are used;
6. the T2K flux prediction includes NA61/SHINE data from the T2K replica target [8], thus reducing the flux uncertainty from $\sim 10\%$ down to $\sim 5\%$ (see Fig. 21 later).

The flow of the T2K oscillation analysis (OA) has been already deeply described in our previous document [9]. As a reminder, the T2K OA extracts the neutrino oscillation parameters by performing a fit to the oscillated data at the far detector Super-Kamiokande. In practice, this involves estimating the event rate at Super-Kamiokande in absence of oscillations. To do this, T2K uses the data from ND280 to constrain the systematics related to the flux and cross section, thus reducing the uncertainties on the rate estimation at the far detector. This procedure is depicted in Fig. 4.

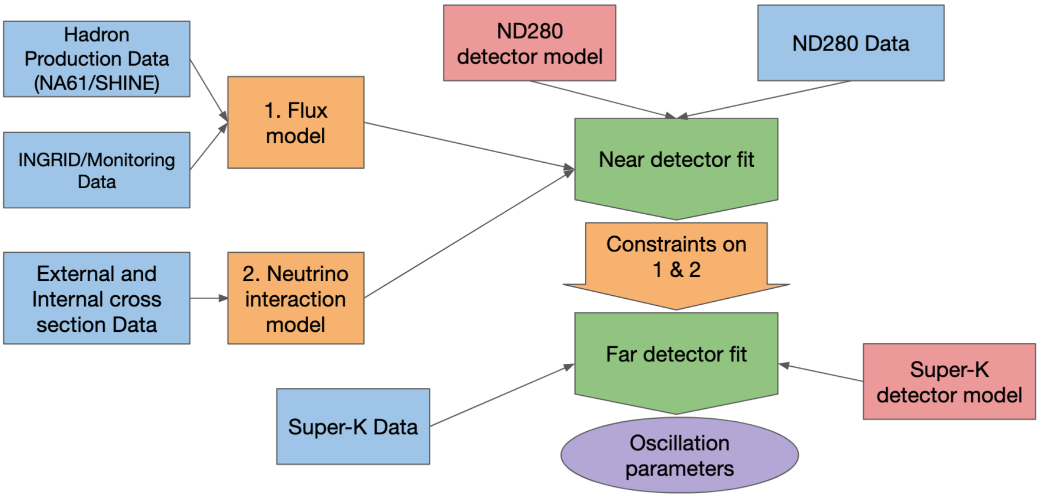

Figure 4: The T2K oscillation analysis strategy. The flux model is developed using external hadron production measurements from NA61/SHINE experiment and internal data from INGRID. The neutrino interaction model is developed using internal and external cross section measurements. The detector model is based on Geant4 and on detector calibrations. These three models are source of uncertainties and are parametrized in the near detector fit by three sets of parameters, referred to as nuisance parameters, that are fit to the ND280 data. The constrained flux and cross section parameters are then propagated via their post-fit covariance matrix to the far detector, where they are used as input to the far detector fit, in addition to the Super-Kamiokande detector model and data. At this stage, it is possible to finally extract the neutrino oscillation parameters.

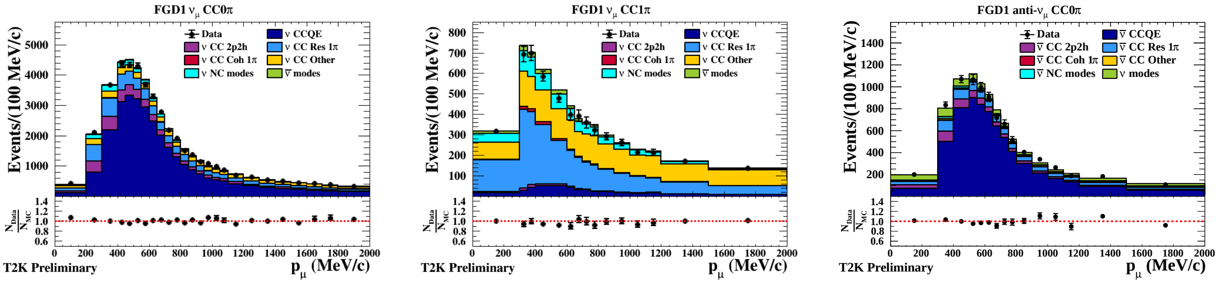

Figure 5: Momentum distribution of outgoing muons for ν_μ CC-0π (left) and CC-$1\pi^+$ (middle) samples in neutrino mode and for $\overline{\nu}_\mu$ CC-0π (right) sample in anti-neutrino mode. Data (dots) are compared with simulations (filled distribution), split by true neutrino interactions, after the fit adjustment, as in 2020 oscillation analysis.

For OA2020, 18 event samples are used for the fit at the near detector, depending on the detector in which the vertex was reconstructed, to the charge of the muon, to the beam configuration (neutrino or antineutrino mode) and to the number of pions observed in the final state (0, 1, more than 1). Examples of post-fit distributions at ND280 are showed in Fig. 5. The ND280 data allow to reduce the uncertainties on flux and cross-section from ~13% (~11%) down to ~2% (2.3%) for the ν_e ($\overline{\nu}_e$) e–like appearance while the total systematics, including also Super-Kamiokande detector systematics and cross-section parameters not included in the ND280 fit is of ~5% (~6%). This represent a sizeable improvement with respect to the Nature paper in which the total systematics errors were 9% and 7% for ν_e and $\overline{\nu}_e$.

At the far detector, 5 event samples are selected; the corresponding number of events are presented in Tab. 1 and compared with the expected numbers of events for different values of δ_{CP}. The corresponding energy spectra are shown in Fig. 6.

	Data	MC ($\delta_{\rm CP}$ = -$\pi/2$)	MC ($\delta_{\rm CP}$ = 0)	MC ($\delta_{\rm CP}$ = $\pi/2$)	MC ($\delta_{\rm CP}$ = π)
e–like ν–mode	**94**	96.6	81.6	66.9	81.6
e–like + 1π ν–mode	**14**	9.3	8.1	6.6	7.8
e–like $\overline{\nu}$–mode	**16**	16.6	18.8	20.8	18.5
μ–like ν–mode	**318**	346.6	345.9	346.6	347.4
μ–like $\overline{\nu}$–mode	**137**	135.8	135.4	135.8	136.2

Table 1: Observed and expected numbers of events at SK for different values of $\delta_{\rm CP}$.

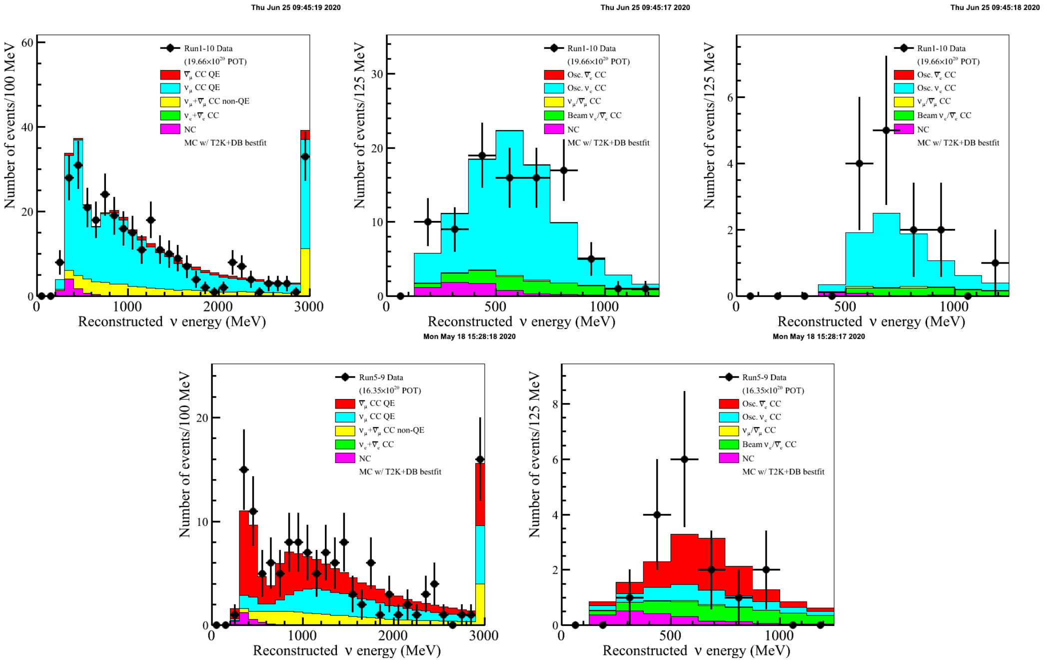

Figure 6: Observed energy spectra for the five SK samples used in the 2020 oscillation analyses. Top: μ–like, e-like, e–like+1π in ν–mode. Bottom: μ–like and e–like in $\overline{\nu}$–mode.

As it is clear from Tab. 1, $\delta_{\rm CP}$ 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 94 (16) single-ring e-like events are observed while 81.6 (18.8) are expected if $\delta_{\rm CP} = 0$ or π.

The five 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. The value of θ_{13} can either be a free parameter in the fit or it can be constrained to the value precisely measured by the reactor experiments. The two cases are shown in Fig. 7: both fits prefer values of $\delta_{\rm CP}$ close to -$\pi/2$ and, when the reactor constraint is included, the CP conserving values 0 and π are excluded at more than 90% CL. θ_{23} and $|\Delta {\rm m}^2|$ are also precisely determined by T2K, that presents indeed the world leading measurement of "atmospheric" ν oscillation parameters, with slight preference of non-maximal sin2θ_{23}, as shown in Fig. 8.

The T2K collaboration, with strong participation from IN2P3 members, is now working on the OA2021, where further improvements will be provided, namely: a better justified parameterisation of the neutrino interaction systematics, a more sophisticated sample definition at both the near and the far detector, a further improved flux prediction from the NA61/SHINE measurements with T2K replica target and the use of Run 11 data, the first taken with Super-Kamiokande loaded with Gadolinium (0.01%). Updated oscillation results are expected at the end of 2021.

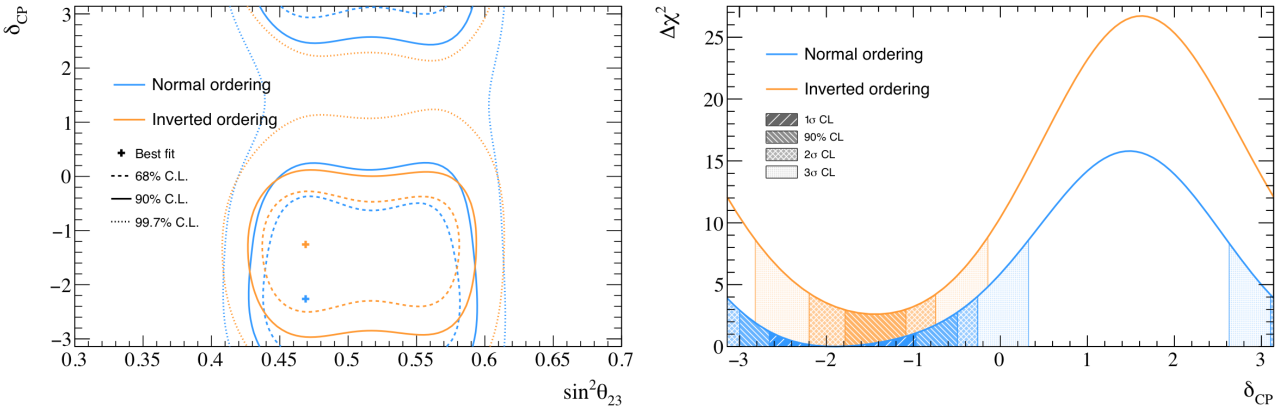

Figure 7: Measurement of the oscillation parameters θ_{13} and δ_{CP} without reactor constraint (left) and measurement of δ_{CP} with reactor constraints (right) assuming the normal (light blue) or the inverted (orange) mass ordering. The bands on the right plot represent different level of confidence, from 1 to 3 σ.

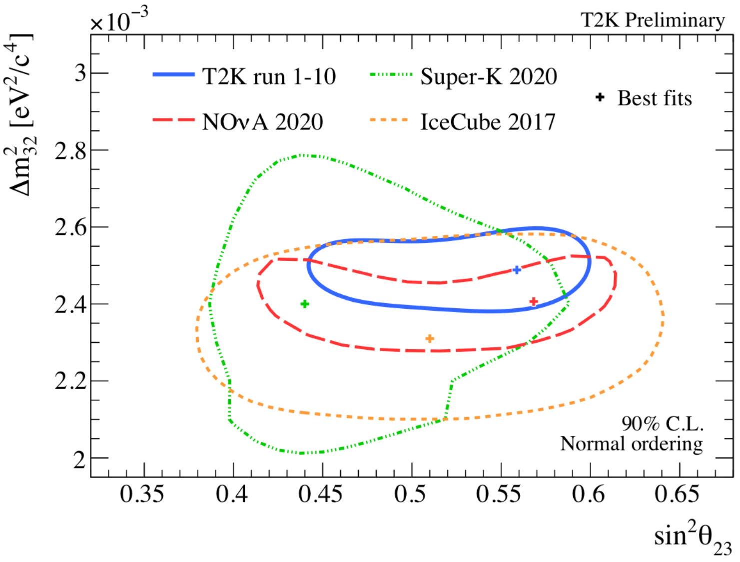

Figure 8: T2K measurement of the oscillation parameters θ_{23} and $|\Delta m^2|$ from T2K compared to other experiments.

3.2 Latest cross-section measurements

One of the main sources of systematic error in the T2K experiment – and in other similar accelerator-based experiments – is due to the limited knowledge of neutrino-nucleus interaction cross sections. As an example, in our Nature paper [5], for a total systematic uncertainty of about 9% in the ν_e appearance channel, 7% was due to one of the neutrino cross section parameters (the uncertainty on the nuclear binding energy).

Indeed, even if the computation of the Charged-Current Quasi-Elastic (CCQE) cross section of neutrinos on a free nucleon is relatively simple, it is much more complicated to take all nuclear effects into account (correlations between nucleons, final state interactions...). Cross sections are a key ingredient to correctly estimate the expected number of events at the far detector from measurements at the near detector complex. The only way to reduce those systematics uncertainties consists in a better understanding of the neutrino nucleus interactions, via more precise measurements and more sophisticated theoretical models. The T2K collaboration is very active in this sense and, from one side, is continuing to provide new and more accurate neutrino cross section measurements (as it will be explained in present section and in Sec. 3.3) and, from the other side, is preparing the upgrade of the ND280 near detector, as described in Sec. 4.2.

The T2K cross section group has been extremely productive in last years providing, since 2018, $\sim$ 10 cross section related publications. Considering that IN2P3 counts among its members a **cross section convener**, the IN2P3 contribution to the overall cross section results is extremely important and we were involved in all the publications either as main analyser, and/or as main reviewer, and/or as member of the paper committee. Anyway, in this section, we will only mention some of the published results, where our contribution was more relevant.
The main axes that guided recent cross section analyses were the following:

1. **Promote combined measurements**: a simultaneous measurement has the advantage of allowing to provide the correlation between more measured cross sections thus making possible to extract further information (cross section ratio, asymmetry, sum, difference,...) to be obtained through a proper combination of the different measurements, often reducing common systematics uncertainties. This technique has been adopted for many recent cross section publications: 1. the first $\overline{\nu}_\mu$ CC0π cross section measurement on water [10]; 2. the simultaneous oxygen and carbon measurement for the ν_μ CC0π channel [11], 3. the first simultaneous measurement of ν_μ and $\overline{\nu}_\mu$ CC0π cross section on hydrocarbon [12]. Each of these analyses has exploited the potential of a joint measurement either to elegantly subtract an intrinsic background (for instance the non-water interactions as in [10]), or to extract at the same time two different cross sections with additional interesting combinations (as in [11] and [12]).

2. **Explore nuclear effects**: as already mentioned, the present poor knowledge of the nuclear effect remains the main source of systematics uncertainty in the OA. By looking at the combination (sum, difference and asymmetry) of the ν_μ and $\overline{\nu}_\mu$ CC0π cross sections it is possible to shed light on the so-called multi-nucleon effects (a.k.a. 2p2h or npnh); this is what we have done in [12], while in [13], we report the first measurement of the transverse kinematic imbalance (TKI) in the CC1π channel. Looking at TKI is a way to access the initial state of the nucleons in the nucleus and several comparisons with available nuclear models are provided in the paper.

3. **Provide new measurements on water target**: this is a key point for T2K, since our far detector is made of water. In addition to the already mentioned papers [10] and [11], that exploit the ND280 detector, in [14] we report the first measurement realized using one of the WAGASCI module, placed at 1.5° off-axis and thus exposed to a slightly different neutrino beam with respect to ND280.

In Fig. 9 we report some of the data/model comparisons that we provided in [11], while in Fig. 10 we do the same for paper [12]. Looking at the χ^2 reported in the legend, we notice a preference for CCQE models based on a relatively simple Local Fermi-gas nuclear ground state ("LFG" in the plots), as opposed to more sophisticated Spectral Function or mean-field predictions ("SF" or "SuSa v2" in the plots) or even GiBUU. With current statistical uncertainties, the strength of this preference is dominated by the most forward angular slice, the so-called "low momentum transfer (Q^2) region", where the nuclear physics governing low energy and low momentum transfer interactions becomes most important. This is also where relatively poorly understood 2p2h interactions and Final State Interactions (FSI)[1] are larger relative to the CCQE prediction. It therefore remains possible that the more sophisticated CCQE models are correct but are undermined by the more simple FSI models or the inappropriate 2p2h predictions.

It is interesting to now look at Fig. 11, where we report some of the results published in [13]. In this case, data seems to prefer more sophisticated models like GiBUU and to disfavor LFG based model. This makes us thinking that more sophisticated nuclear model are able to correctly describe the data at higher Q^2, when we use variables more sensitive to the nuclear effects (as in [13]), but simpler nuclear models (as LFG) are enough to match the data when we look at the muon kinematics only (as in [11, 12]).

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[1] Interactions affecting outgoing hadrons before they exit the nucleus.

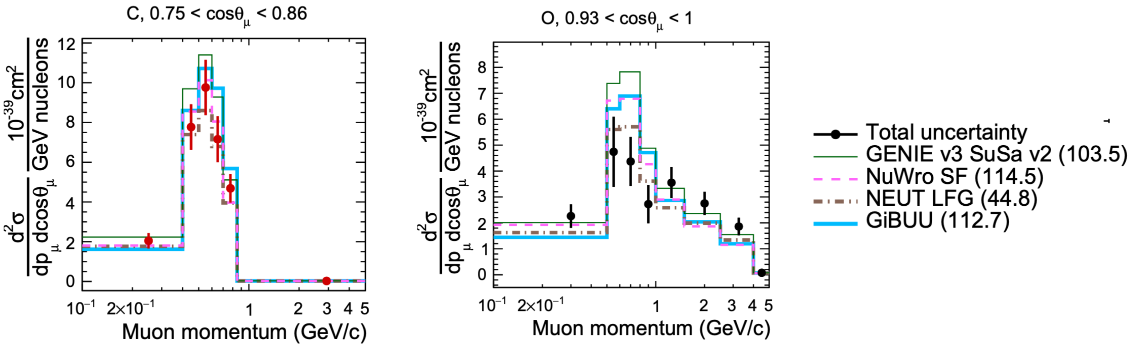


Figure 9: Carbon (left) and oxygen (right) double differential ν_μ CC0π cross section (unfolded from the detector effects) in one of the muon angular bins, compared with several generators and models. The parenthesis in the legend report the values of the χ^2 between the data and the model for the full measurement (oxygen + carbon), taking into account all the correlations, for a total of 58 dof.

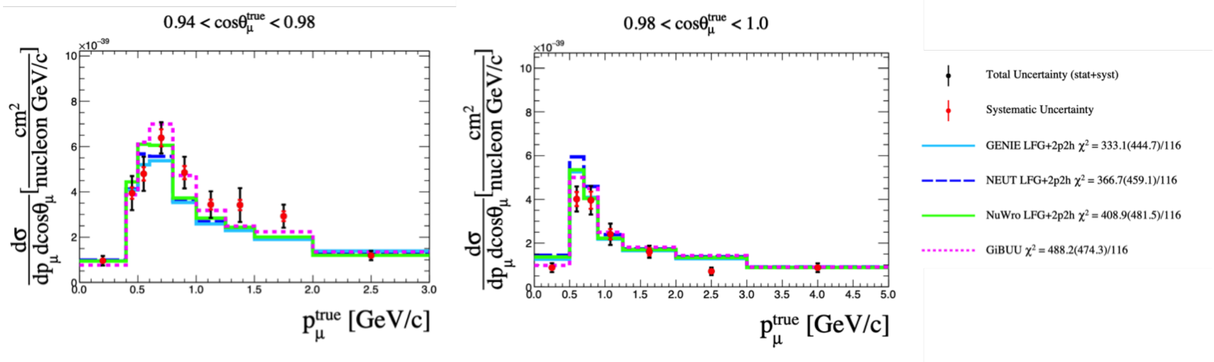


Figure 10: ν_μ (left) and $\overline{\nu}_\mu$ (right) CC0π double differential cross section (unfolded from the detector effects) in one of the muon angular bin, compared with several generators and models. In the legend report the values of the χ^2 and of the shape-only χ^2 (in parenthesis) between the data and the model for the full measurement ($\nu_\mu + \overline{\nu}_\mu$), taking into account all the correlations, for a total of 116 dof.

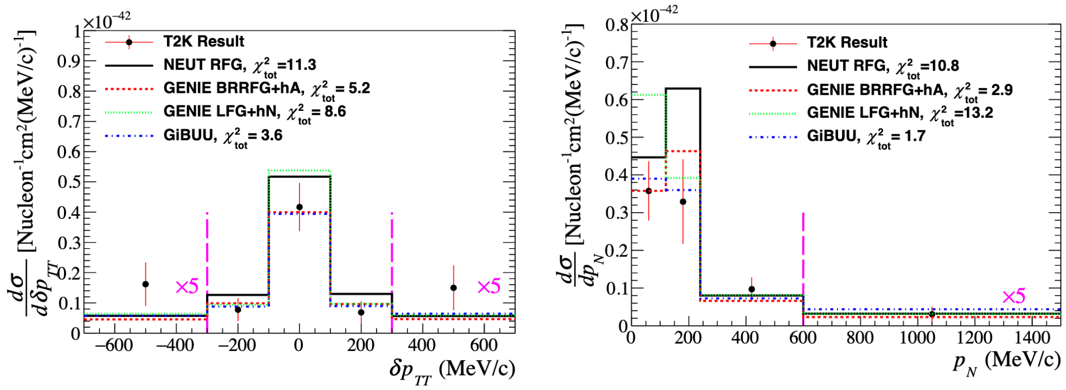


Figure 11: ν_μ CC1π double differential cross section (unfolded from the detector effects) as a function of the imbalance in the transverse momentum, δp_{TT} (left) and of the initial nucleon momentum, p_N (right), compared with several generators and models. In the legend we report the values of the χ^2 between the data and the model for the full measurement ($\nu_\mu + \overline{\nu}_\mu$), taking into account all the correlations; ndof is 5 for δp_{TT} and 4 for p_N.

A general conclusion that we can draw from the recent cross section measurements is that we need to go further in a deeper understanding of neutrino interactions. Comparisons with models often give ambiguous interpretations: some models reproduce well certain parts of the phase space, but are pretty bad in others, other models correctly reproduce the data in muon kinematics, but loose this capability when looking at protons or pion kinematics. Those are clear sign that we need not only to work more closely with theoreticians, in order to deeply understand the subtleties of the models, but also to use more sophisticated detectors, able to characterize the lepton, as well as the outgoing hadrons from a neutrino interaction. This last point is the main goal of the upgrade of the ND280 near detector, as better described in Sec. 4.2.

In the meanwhile, the T2K cross section group is pursuing its effort to provide new and more accurate measurements with presently available data and detectors. In particular, the acquired expertise in performing joint analyses (O+C or $\nu_\mu + \overline{\nu}_\mu$) has opened the door to more complex analyses implying the simultaneous use of detectors placed at different off-axis angles. This approach is particularly interesting since it allows to analyse at the same time interactions involving different neutrino fluxes, as shown in Fig. 12. It is thus possible to study the cross section dependence on E_ν, and a reduction of the flux systematics, as well as of the interaction model systematics, on the final results is expected.
The first joint ND280+INGRID (Proton Module) ν_μ CC0π analysis will be released soon and an update of this analysis, including also the anti-neutrino sample, is already ongoing. In the near future, the plan is to also try to include WAGASCI samples in these joint fits.
Other ongoing efforts involve: 1. the development of new variables (like the so called "available energy"), allowing to better characterise the activity around the interaction vertex and thus to access nuclear effects and low momentum hadrons; 2. improved (more statistics, better selection and reconstruction) measurements of the CC1π channel, where we currently see important data/model disagreements. Several publications are thus expected in upcoming years.

To conclude, we should mention that, within the cross section group, IN2P3 members have contributed since years to the development of a likelihood fitter, that is now a reference tool in T2K. It has been used for almost all the already mentioned papers [10, 11, 12, 13]. Thanks to its versatility, recently, we have introduced several improvements and modifications to this fitter, in order to make it a suitable tool for the near detector fit in the oscillation analysis, able to include new samples that will be available with the ND280 upgrade (for more details, see Sec. 4.2).

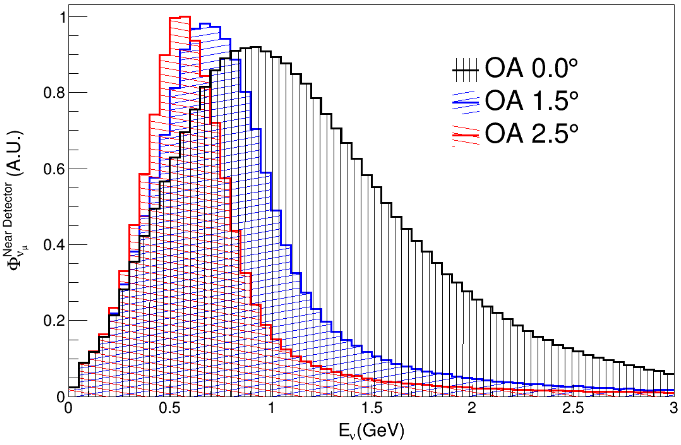


Figure 12: Incoming neutrino fluxes at the three T2K near detectors: INGRID on-axis (black), WAGASCI 1.5° off-axis(blue) and ND280 2.5° off-axis (red).

3.3 Electronics and mechanics for the new WAGASCI detector

Since 2015 the LLR group has been involved in the construction of the WAGASCI (WAter Grid And SCIntillator) detector. The goal of WAGASCI is the measurement of exclusive neutrino cross-sections on water and on plastic scintillators as well as their ratio. The detector is based on an innovative design of plastic scintillators assembled to form a tri-dimensional grid (see left panel of Figure 13). The

Figure 13: Left panel shows the assembly of the 3D scintillator grid. Right panel shows the DAQ of one WAGASCI module, developed at LLR starting from the SiWEcal acquisition system, with 20 ASU cards treating the signal from 32 MPPC.

hollow cuboid lattice of scintillators is filled with water, that acts as the neutrino interaction target, and allows the measurement of cross sections on H_2O. Measurements over a wide phase space of muon momentum and opening angle are possible by combining the two WAGASCI modules with side and downstream Muon Range Detectors (MRDs). The downstream-MRD (so-called Baby-MIND detector) includes magnetized iron modules and provides charge identification capability as well as momentum measurement for high energy muons.

The LLR group has taken the full responsibility of the Monte-Carlo physics study, of the mechanical conception and design, as well as all installation procedures of both the WAGASCI modules and the two side-MRDs. The development of the complete DAQ chain (see right panel of Figure 13) has also been made at LLR based on a system that had been built for other experiments. Therefore one member of LLR is **convener of electronics/DAQ and mechanical engineering**. The first off-axis measurement (at 1.5° from the neutrino beam) with one of the WAGASCI module (water target), the Proton Module (hydrocarbon target) and one INGRID module (as muon calorimeter) has started in October 2017. Data collected at that time have been used for two analyses: 1. the O. Volcy PhD thesis (defended at the end of 2019) and 2. the analysis published in the already mentioned paper [14].
After that, Baby-MIND has been successfully installed in May 2018 and the full configuration (2 WAGASCI modules, the Proton Module, Baby-MIND and 2 additional side-MRDs) was ready by the end of 2019 and took first physics data in Spring 2021. As already mentioned in Sec. 3.2, an effort is already ongoing (with an obvious participation from IN2P3 members) to analyse this new data and start considering its integration in a "multi-detector" approach, not only for cross section analyses but eventually also for the T2K OA.

4 The phase II of T2K

In this section we will briefly remind the physics case for T2K-II and we will describe the contributions of IN2P3 groups to the ND280 Upgrade. In addition to what is described here, IN2P3 is also contributing to the computing of T2K-II being one of the Tier 2 centers. Full details on this contribution are given in the document we submitted to this Scientific Council for Hyper-Kamiokande.

4.1 Physics case for T2K-II and for the ND280 upgrade

The recent results of T2K show intriguing hints that CP symmetry might be violated in the lepton sector. These results are obtained with statistics of 3.6×10^{21} p.o.t. and, as shown in Table 1, are based on less than 100 ν_e candidates and 15 $\overline{\nu}_e$ candidates. These hints, together with the approval of the Hyper-Kamiokande experiment that will start its data taking in 2027, pushed the T2K collaboration to propose a phase II of the experiment, the so-called T2K-II project.

T2K-II has been approved by the J-PARC PAC and by all the involved funding agencies and consists in two main hardware projects:

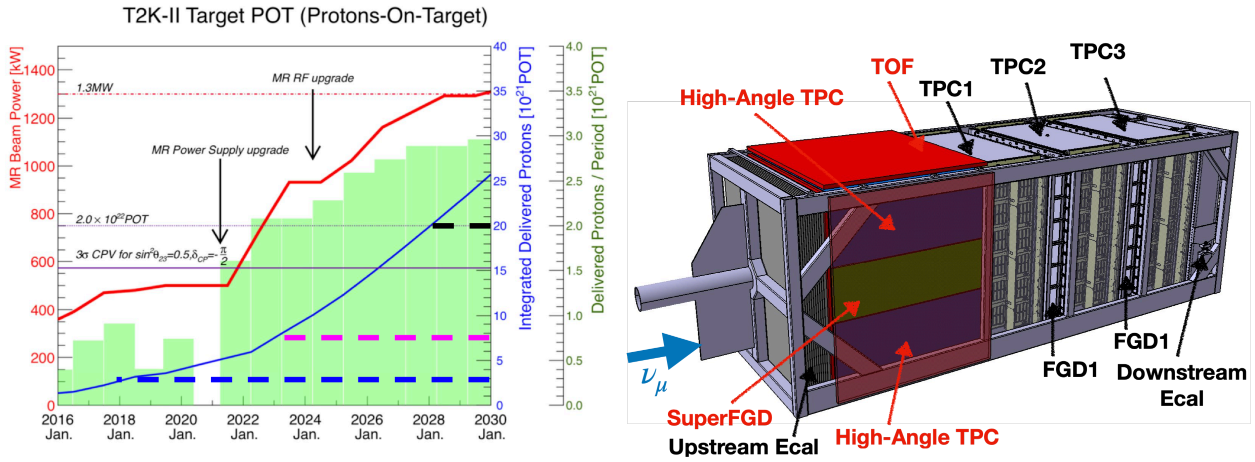


Figure 14: Left: upgrade of the muon neutrinos beam until the start of Hyper-Kamiokande. Right: upgrades to ND280. In red are the new detectors added to the existing detector.

- The upgrade of the proton beamline, including the replacement of the power supplies that will allow to double the frequency at which protons are extracted;
- The upgrade of the off-axis Near Detector ND280.

It should be noted that these two upgrades will benefit not only T2K-II but also the upcoming Hyper-Kamiokande experiment. In particular the beamline upgrade will allow to reach the Hyper-Kamiokande design beam power of 1.3 MW (currently T2K is running at 500 kW) while the ND280 upgrade is expected to reduce the flux and cross-section systematics in the oscillation analysis.

These upgrades are currently on-going and are expected to be completed by the end of 2022 in order to start T2K-II and take few months of data during the Japanese Fiscal Year 2022. This program has been endorsed by the J-PARC PAC, that granted stage-2 approval to T2K-II and to the ND280 upgrade in 2020, and by the KEK directorate that committed to provide ~4 months of neutrino data to T2K-II until the beginning of Hyper-Kamiokande. As shown in Fig. 14, this will allow to collect more than 10×10^{21} p.o.t. with a sensitivity to CP violation of more than 3σ for the most favorable case of δ_{CP}.

The ND280 Upgrade is being carried out by participating institutes since 2015. It started with some physics studies for the optimization of the detector design and culminated in the TDR that was published in 2019 [15]. Since then the groups are working for the construction of the new detectors. The ND280 Upgrade has also been approved by the CERN SPSC and it is part of the CERN Neutrino Platform, under the name NP-07.

The IN2P3 groups are deeply involved in the construction of the upgrade of ND280 and count among their members the **ND280 Upgrade project leader**. In the early phases we contributed to the conceptual design and to the optimization of the upgrade. At the end of the optimization work we decided to replace one of the ND280 sub-detectors, the P0D, with a new tracker system, composed by a fully active scintillator detector (Super-FGD), two new TPCs (HA-TPCs) and six Time-Of-Flight planes as shown in Fig. 14. Such tracker system will be oriented in the direction parallel to the neutrino beam in order to enhance ND280 capabilities to reconstruct leptons emitted at any angle.

For the construction of the upgrade, the IN2P3 groups took the responsibility of the conception and production of the Front-End-Cards for the new HA-TPCs (LPNHE) and of the Front-End electronics for the Super-FGD (LLR together with University of Geneva). The HA-TPCs FECs use the AFTER chip, already employed for the electronics of the existing ND280 TPCs, while the Super-FGD FE cards are based on the CITIROC chip produced by the OMEGA lab. In the following subsection we will describe the expected performances of the ND280 Upgrade and we will give some details on the status of each sub-detector and the installation plans.

Obviously the project has been impacted by the current COVID-19 pandemic that induced several delays. In a certain sense, we have been lucky so far because the pandemic occurred before the integration of the detectors in a common place and it was possible to advance for most of the aspects without the need for travelling. As we will show in the next sections we are now entering the critical phase of the ND280 Upgrade in which the assembly of the detectors will take place at CERN for the HA-TPCs and at J-PARC for the Super-FGD. In order to keep the schedule and install the detectors in the pit by the end of 2022 we hope that the international situation will allow us to do regular trips to CERN, starting from October 2021, and to J-PARC, starting from March 2022.

4.2 ND280 Upgrade expected performances

The T2K off-axis Near Detector has been operated for more than 10 years and its inputs have been crucial for all the T2K oscillation results. The main strength of ND280 is the presence of a magnetic field that, coupled with the TPCs, allows to reconstruct the charge and the momentum of the leptons emitted in neutrino interactions. This allows to distinguish ν from $\overline{\nu}$ and to precisely characterize the neutrino beam by exploiting the muon kinematics.

Nevertheless, the T2K physics runs have shown some limitations in the current design of ND280, that are:

- low efficiency to reconstruct tracks emitted with high angle with respect to the neutrino beam due to the geometrical configuration of the existing ND280 Tracker system, that is oriented perpendicular to the neutrino beam;
- low efficiency to reconstruct the hadronic part of the interactions and, in particular, low momentum protons that are stopped within the FGDs, that have limited tracking performances.

The ND280 Upgrade aims to address these two limitations. The combination of the new HA-TPCs and the existing vertical TPCs surrounding the Super-FGD will allow to reconstruct leptons emitted at any angle with respect to the neutrino beam, thus matching the 4π acceptance of Super-Kamiokande. In addition, the 3D readout and fine segmentation of the Super-FGD allows for an excellent hadron reconstruction with very low thresholds in a hydrocarbon material. Within the ND280 Upgrade group we have also studied the capabilities of the Super-FGD to reconstruct neutrons through time of flight between the neutrino interaction vertex and the neutron scattering off protons as described in [16].

The expected performances of the ND280 Upgrade to reconstruct muons, protons and neutrons are shown in Fig. 15.

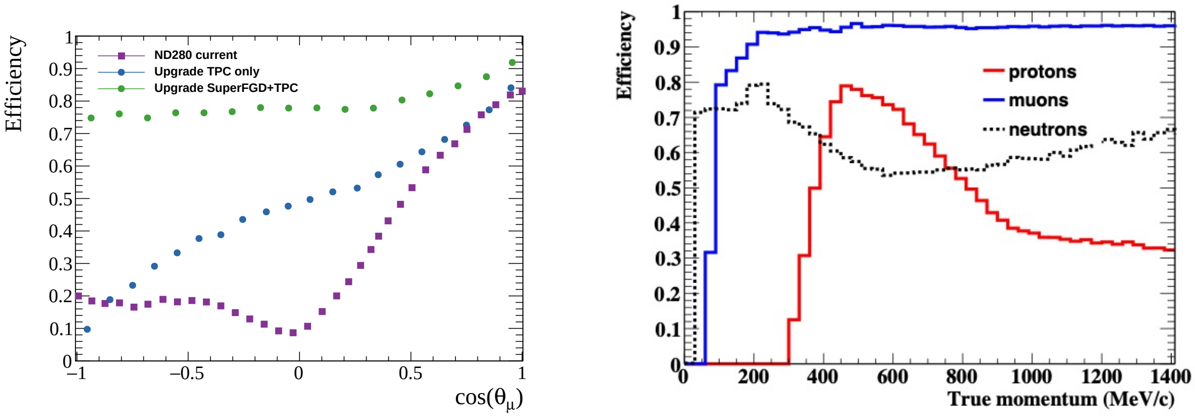


Figure 15: Left: Muon selection efficiency as a function of $\cos\theta$ for the current ND280 detector and for the upgraded Near Detector. Blue points show the efficiency by requiring the muon to enter the TPC while for the green points only the Super-FGD is used for the track reconstruction and particle identification. Right: efficiency to detect protons, muons and neutrons as a function of the particle momentum.

These efficiencies will allow to better understand the nuclear effects which can alter the final state topology and kinematics of neutrino interactions, inducing possible biases in neutrino energy reconstruction. In a recent paper [17] we evaluated the sensitivity of the upgrade to nuclear effects by fitting kinematic variables including lepton and hadron kinematics (protons and neutrons for the CC0π channel) which better exploits the performance assets of the Super-FGD. Some of the results are shown in Fig. 16: the ND280 upgrade will be able to constraint to better than 1 MeV the removal energy, that, as already mentioned in Sec. 3.2, is one of the main sources of systematics in the Nature paper; in addition, the 1p1h (i.e. CCQE) normalization can be constrained to better than 1% (2%), and the npnh normalization to better than 5% (8%) for neutrinos (antineutrinos). It should be noted that these performances extend to an amount of p.o.t. that is well beyond the ones expected for T2K-II but will be obtained during Hyper-Kamiokande, showing the importance of running ND280 and its upgrades also during the Hyper-Kamiokande era.

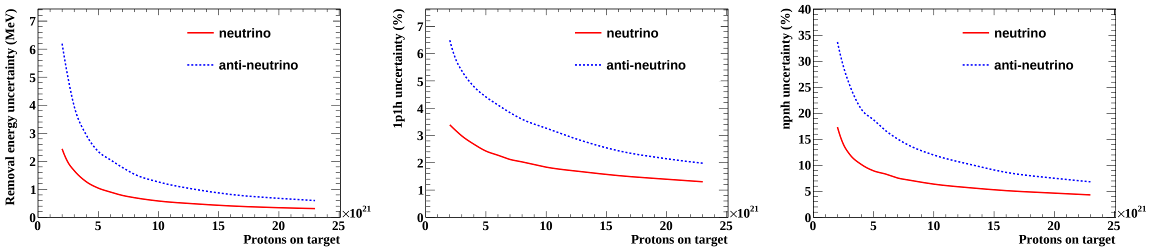


Figure 16: The 1σ sensitivity to the removal energy (left), 1p1h (center) and npnh (right) cross-section normalisations as a function of POT for neutrino and anti-neutrino interactions [17].

The Upgrade is also expected to reach better purities and efficiencies with respect to the ND280 tracker in the measurement of ν_e interactions [18], that will be one of the leading uncertainties in high statistics measurement of CP violation. This can be done thanks to the larger granularity and the 3D readout of the Super-FGD that will allow to better separate electrons track emitted in neutrino interactions from γ conversions in which the electron/positron pair is not separated and that constitute the dominant background in the current ND280 measurements.

Based on these extremely encouraging results, the IN2P3 groups are already working to prepare the oscillation analysis framework for the Upgrade era. As already mentioned in Sec. 3.2, a new version of the cross section fitter is under development. Much faster and user friendly, this tool will allow to include in the near detector fit the new samples from the Upgrade and to perform more accurate fits, by exploiting at the same time the muon kinematic information (as currently done in the OA, see Sec. 3.1) and some more sophisticated observables, described in [17], that include the hadron kinematic information. This fitter framework is going to be validated against the already collected ND280 data and is supposed to be ready by the end of 2022.

In the following section we will describe the status of the construction and the observed performances of the Super-FGD and the HA-TPCs towards the installation foreseen at J-PARC for the Fall 2022.

4.3 The Super-FGD

The Super-FGD is being built by T2K groups from France (LLR), Japan, Russia, Switzerland, and US, and CERN. The contribution from LLR is centered on the conception and construction of the front-end electronics cards that is based on the CITIROC chip from OMEGA.

The design of the Super-FGD is described in the ND280 Upgrade TDR [15]. It is composed of 2 millions 1 cm^3 plastic scintillators optically independent cubes readout by wavelength shifting fibers (3 fibers per cube in x, y, z). The light is transported by the fibers to a Multi-Pixel Photon Counters (MPPC). The total number of MPPCs and the corresponding electronic channels is $\sim 60k$.

Currently all the cubes have been produced and assembled in $x - y$ layers with fishing lines at INR (Russia). The design of the box that will host the cubes has been finalized and procurement of the box is on-going. The delivery is expected in March 2022 and the assembly of the cubes in the box will start at J-PARC in April 2022. Each of the six box plates consists of a carbon-fiber sandwich with a core of rigid foam (divinycell), for a total thickness of $\sim$ 30 mm. On the two sides of the sandwich a $\sim$ 9 mm G10/Fr4 layer is glued to act as an interface to guide the WLS fibers and to improve the rigidity of the object. This design ensures a maximum sagging on the bottom plate of $\sim$ 3.2 mm, increased up to $\sim$ 5.5 mm in case of earthquake.

After installation of the cubes in the box, we will replace the fishing lines with the WLS fibers and then install the MPPC that are mounted on a PCB in groups of 64. For the fibers, 75 km of WLS fibers have been received at KEK and have been coupled with the optical connectors. Also 63k MPPCs have been received and tested and are being mounted on the PCB with mass production of the board on-going.

A calibration system has also been designed based on Light Guide Plate (LGP). The calibration system will be mounted on the opposite side with respect to the MPPCs and will be used to equalize the gain of each MPPCs by sending light to the MPPCs via a LED system. The installation of the cubes, fibers, MPPCs, and calibration system is expected to be completed by Summer 2022.

Major components for the SuperFGD electronics are the front-end board (FEB), backplane, optical concentrator board, master clock board and power systems. The electronics engineers from LLR, U. Geneva and US groups (U. Pennsylvania, U. Pittsburgh and LSU) are working on those.

A first FEB prototype hosting 8 CITIROC chips has been delivered just before summer and functional tests are ongoing (see Fig. 17). The needed CITIROC chips (2000 chips, 32 channels each) were already delivered and, upon completion of the tests with the FEB prototypes, the mass production will be started and we plan to deliver all the Super-FGD FEB to J-PARC by Summer 2022 for the integration on the detector. Possible consequences on this timescale due to the worldwide shortage of electronics component are currently being evaluated.

The mechanical design for the electronics crates and its fixation to the ND280 basket has also been finalized.

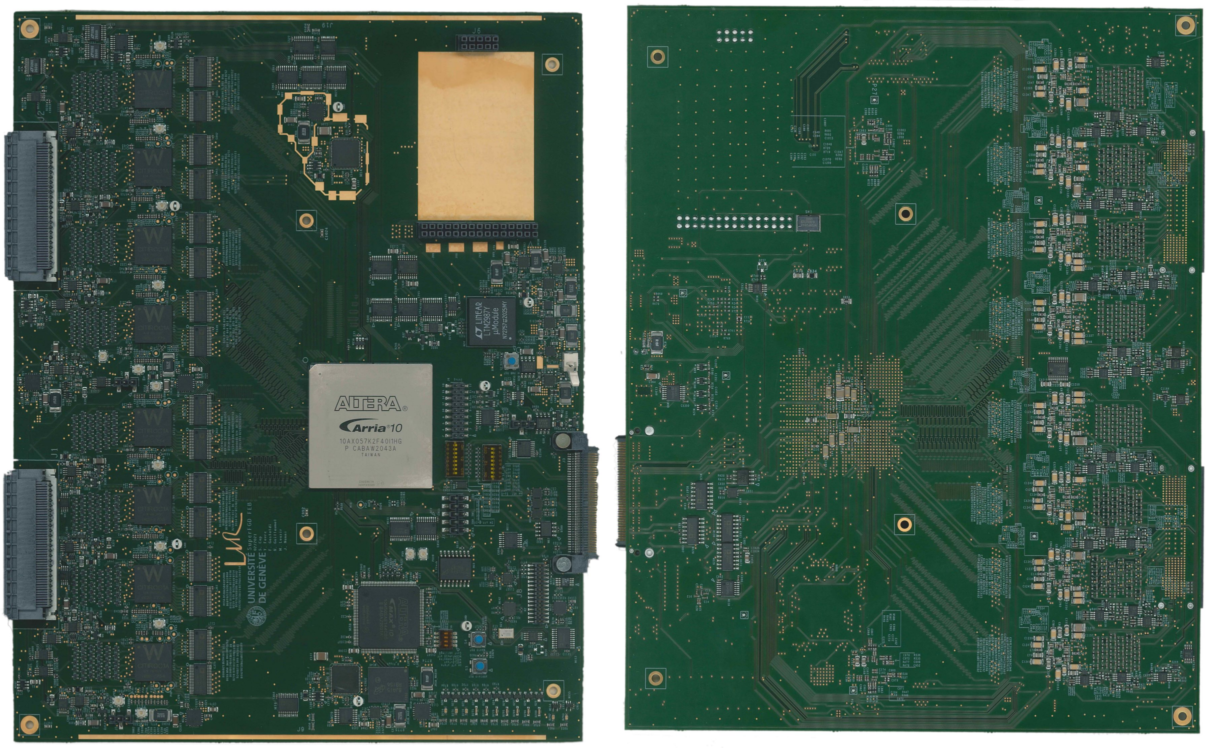


Figure 17: Top (left) and bottom (right) view of the Super-FGD Front-End-Board prototype

Two Super-FGD prototypes have already been constructed and instrumented. The first Super-FGD prototype, assembled at CERN, has 9216 cubes which are read out by 1728 MPPCs. As electronics the one developed for the Baby MIND project was used. It has the same CITIROC chips adopted for the Super-FGD electronics. The second prototype, assembled in the US, has 2048 cubes and 576 channels and is read by MPPCs. Its design already takes into account several of the design concepts considered for the final Super-FGD. For example the MPPCs are mounted on PCB in group of 64, as in the final Super-FGD design. It also uses the Baby MIND electronics for the readout.

The first prototype was exposed in Summer 2018 during two campaigns to a particle beam at the T9 beamline at CERN. A dedicated trigger system was set up by the collaboration allowing to select different particle types. This was used to study the detector response to these particles with and without magnetic field. The results confirmed the excellent time resolution and dE/dx performance and show that the requirement for the T2K Near Detector are reached. Some results are shown in Fig. 18. More details of the beam test results can be found in [19], published in December 2020.

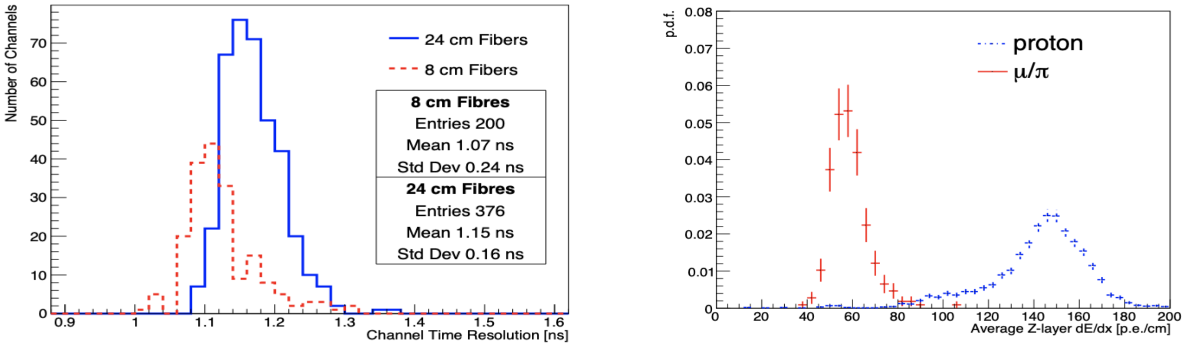


Figure 18: Left: single-channel time resolution obtained with different fiber lengths. Right: Measuerd dE/dx for protons and MIPs from a 0.8 GeV/c beam.

The detector response to neutrons is of special interest to measure anti-neutrino CCQE ($\bar{\nu} + \mathrm{p} \rightarrow \mathrm{l} + \mathrm{n}$) or multinucleon interactions in the detector.

The Super-FGD prototype used in the CERN testbeam and the so-called US-Japan prototype have been exposed, in December 2019 and 2020, to a neutron beam at the Los Alamos National Laboratory (LANCES) facility to study the detector response to neutrons. This is of special interest to measure anti-neutrino CCQE ($\bar{\nu} + \mathrm{p} \rightarrow \mathrm{l} + \mathrm{n}$) or multinucleon interactions in the detector.

The analysis of the data is advancing. An event display from data collected at LANL is shown in Fig. 19. A preliminary understanding of the neutron response including the detection efficiency, neutron-induced particle topology have been performed and the analysis aiming at measuring the total neutron cross section is ongoing. Despite the pandemic, data have been collected also in December 2020 with limited personnel onsite. The beam test was successful in both 2019 and 2020 with more than 10 millions neutron candidates collected in each year.

4.4 High-Angle TPCs

The HA-TPCs are being built by T2K groups from France (LPNHE and IRFU), Germany, Italy, Spain, Poland, and CERN. The LPNHE group has the responsibility of the design and production of the Front-End-Cards, based on the AFTER chip that was developed by the IRFU for the existing ND280 TPCs.

The HA-TPCs, in fact, share many features with the existing ND280 TPCs. The two main innovations with respect to the existing TPCs will be the use of Resistive Micromegas modules, called ERAM (Encapsulated Resistive Anode Micromegas) and the use of a single layer of solid insulator laminated on a composite material for the field cage, while for the current ND280 TPCs, two gas-tight boxes, one inside the other were used.

The ERAM modules, naturally introduce a spread in the charge on the anode plane, allowing for a lower density of readout pads and eliminating the risks of discharges (sparks). This allows to remove the protecting diodes on the front end cards. The new design of the field cage, instead, minimize the dead space and maximizes the tracking volume.

Details on the design of the field cage and of the ERAM detectors are given in [15]. Here we just briefly summarize the design and the status of the production.

The Field Cage (FC) of an HA-TPCs consists of two lightweight and low-Z mechanical structures with an hollow shell shape (box). The boxes are laminated on a Aluminum mold in several layers,

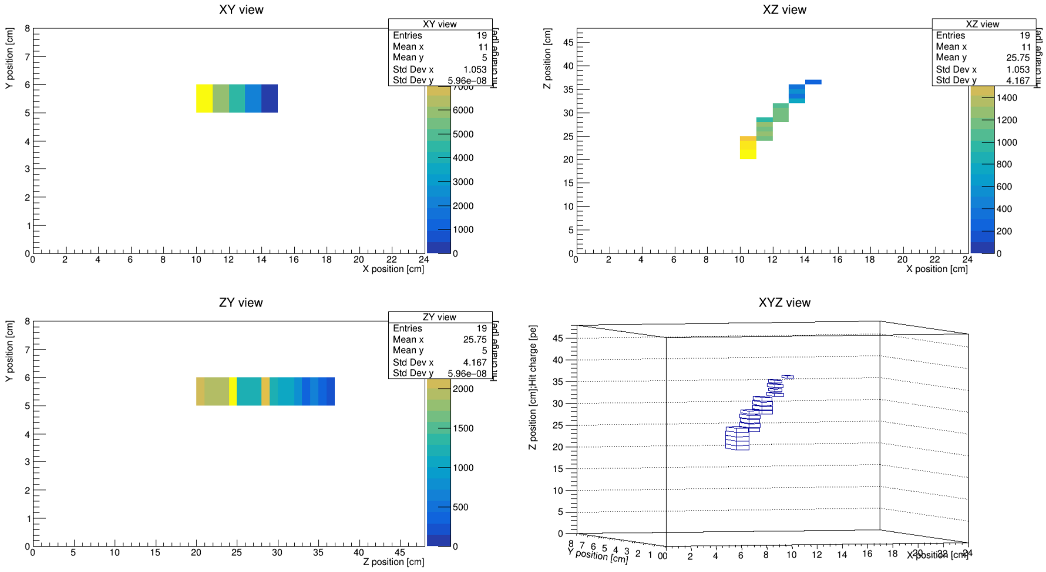


Figure 19: SuperFGD prototupe Event display of an interacting neutron from beam tests at LANL. Both the 2D projectiions (colors show the number of photoelectrons measured by the MPPCs in each channel). The 3D reconstructed track from the three 2D projections is also shown.

namely Kapton sheets, aramide fiber-fabrics peels and honeycomb spacer panels glued together. The FC mechanical strength is enforced by embedding solid material flanges and angular bars along the four longitudinal edges. The two boxes are juxtaposed enclosing the cathode at the center of the HA-TPCs and are closed at the two opposite sides by the two anodes, where the ERAM sensors are located. Each anode hosts 8 ERAM modules. The drift length between the cathode and the anode is of $\sim 1\ m$.

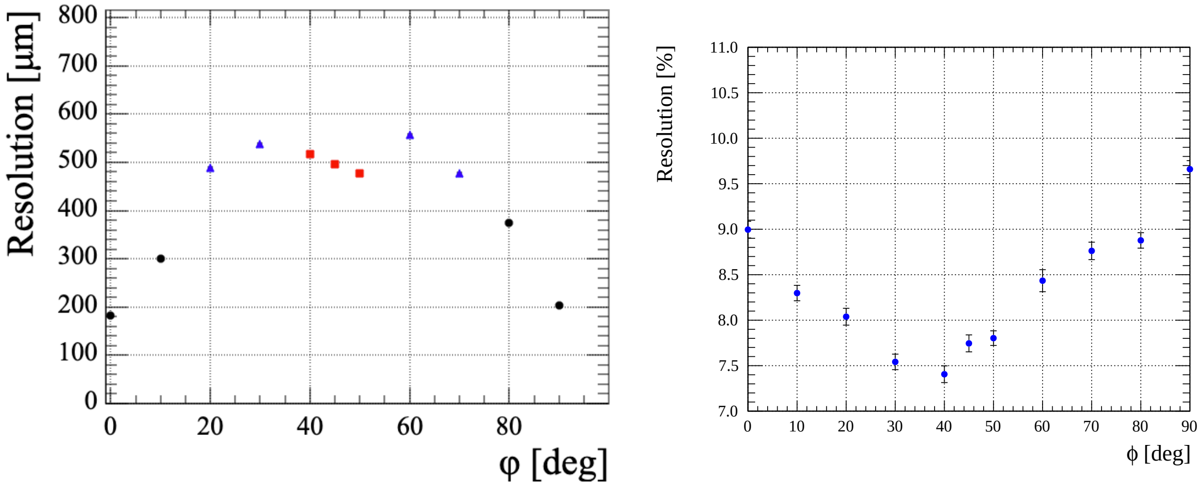
Concerning the ERAM detectors, each module has a size of 420×340 mm^2 with 32×36 rectangular pads of size 10.1×11.2 mm^2. This ERAM module has a resitivity of 200 kOhm/using DLC foils stack on a 75 μm glue layer. The design of the ERAM detectors have been validated using different prototypes exposed to CERN and DESY test beams [20, 21].

The ionization energy resolution and spatial resolution as a function of the angle of the track with respect to the ERAM plane are shown in Figure 20. Spatial resolution better than 600μm is obtained for all the angles using a dedicated clustering algorithm which is adapted to the track angle. Energy resolution better than 9% is obtained for all the angles. The ERAM module performances in terms of deposited energy resolution and spatial resolution fully satisfy the ND280 upgrade requirements.

The TPC electronics will be based on the use of the AFTER chips, that had been designed for the existing ND280 TPCs. The AFTER chip is a 72-channel device that includes preamplifiers and shapers with programmable gain and shaping time coupled to a 511-time bucket switched capacitor array (SCA). 8 AFTER chips will be mounted on the Front-End Cards (FEC), that will be installed parallel to the ERAM modules. Each ERAM module will be readout by two FECs for a total of 64 FECs for the two HA-TPC. The two FECs on each ERAM will be connected to a Front-End Mezzanine (FEM) card that performs the control, synchronization and data aggregation of the two FECs of a detector module. As back-end electronics we will use the TDCM, a generic clock, trigger distributor and data aggregator module designed at IRFU for several projects, including the upgrade of T2K.

After validating various design concepts the final electronics has been prototyped and tested with several ERAM detectors in a cosmic ray test bench. The Production Readiness Reviews for the electronics and the ERAM detector took place at the end of 2020. Following positive outcomes, industrial partners were selected and the relevant contracts were established. The production of the front-end electronics, FECs and FEMs, has started and already more than half of the needed cards have been received. Concerning back-end electronics, all TDCMs have now been produced.

Recently, in July 2021, we tested at DESY a full length prototype of the field cage instrumented with one ERAM module and the final HA-TPCs electronics chain, including 2 FECs and 1 FEM. The analysis is ongoing but preliminary results show good performances and allow to validate the design of



a

b

Figure 20: Spatial resolution (a) and dE/dx resolution resolution (b) versus the angle with respect to pad plane. Different symbols on the left plot represent different clustering algorithm adapted to the angle. Data used a peaking time of 412 ns, with a magnetic field of 0.2T applied to the TPC prototype.

the field cage and of the ERAM modules.

The next milestone for the project is the production of the first half of field cage that is ongoing and will be delivered to CERN in October 2021. The remaining 3 halves of field cages will be produced immediately after and one module will be delivered at CERN every two months. The production of the ERAM modules has also started at CERN and they will be continously produced in the next months with a production rate of 1 module per week. 32 modules in total will be needed to equip the two HA-TPCs.

The TPCs will be instrumented and commissioned at CERN and will be shipped to J-PARC for installation in the ND280 basket. The first HA-TPCs will be shipped in April 2022 and the second in July 2022.

4.5 NA61/SHINE beyond 2020

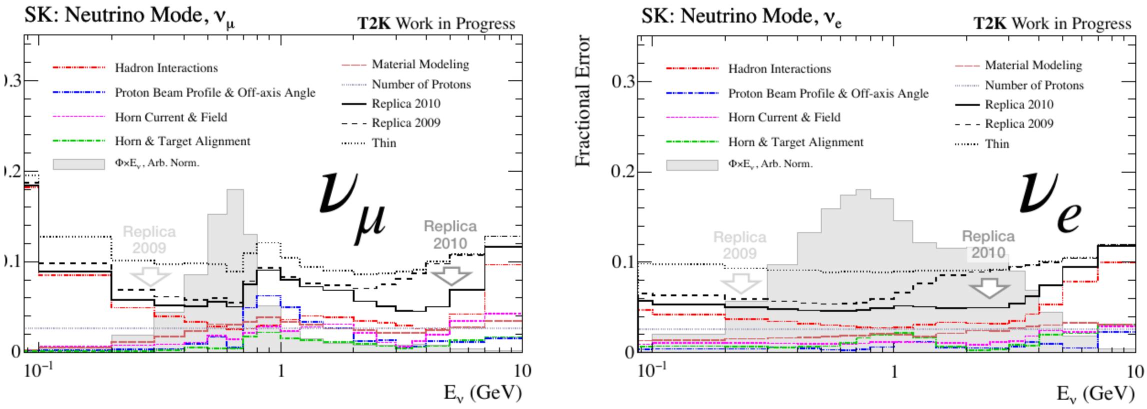


Figure 21: Uncertainty on the ν_μ (left) and ν_e (right) flux at Super-Kamiokande by using NA61/SHINE thin target data (dotted line), 2009 replica target data (dashed line) and 2010 replica target data (continous line). 2009 replica-target data allow to reduce the uncertainty to 5% at the peak of the neutrino flux while the 2010 data reduce the uncertainty for higher energy neutrinos.

At the NA61 beyond 2020 workshop the importance of hadron production measurements for ongoing and future neutrino experiments was strongly emphasized by all neutrino physics speakers. Many accelerator and atmospheric neutrino experiments expressed interest in new additional thin-target measurements. These range from very low beam momenta up to 120 GeV/c.

Published NA61/SHINE thin-target measurements [22, 23, 24, 25] have been crucial for T2K to reduce (anti-)neutrino flux uncertainties down to $\approx 10\%$, and further improvements are made now as the T2K replica-target results [26, 27] are added to the T2K's flux model (see Fig. 21). Additional improvement is expected with the 2010 replica target data [28]. In particular, the uncertainty in high neutrino energy region should be lower because of significant improvement of the knowledge of the kaon yield from the replica target data.

In close collaboration with the SPS beam group, a LoI for a tertiary hadron beam-line for beams at very low momenta (< 12 GeV/c) has been pepared. Measurements with these low-energy particles could be very important for future high-precision T2K-II and Hyper-Kamiokande physics. The low momentum (less than 12 GeV/c) hadron production data are also useful for improvement of the atmospheric neutrino flux prediction for future neutrino experiments, such as Hyper-K and DUNE.

The J-PARC Main Ring beam power is planned to be increased from the current 515 kW to 1.3 MW and some upgrades of the neutrino beam facility are also planned. The neutrino production target will be upgraded by enhancing the cooling capability by increasing the pressure of the cooling helium gas and re-optimization of its titanium window geometry while the shape of core graphite target part will not be changed. The same J-PARC neutrino beam-line will also be utilized for the Hyper-K experiment.

For T2K-II and Hyper-K a reduction of the total flux uncertainty down to 3–4 % is desired. The major uncertainty in the replica target tuning is still hadron production. Further improvement of the hadron production data can be expected from the following measurements:

- Improved measurement of hadron production with the T2K replica target,
- Hadron production with low momentum beams.

Moreover, a new design of the neutrino production target is being discussed. Motivating the new target is an increase of the neutrino flux while reducing the wrong sign neutrino flux for better significance of neutrino CP violation measurements.

T2K is considering hybrid and alternative target materials – e.g. Super-Sialon ($Si_3N_4Al_2O_3$), which has a density of 3.2 g/cm^3, 1.8 times larger than the current graphite target – for high-power operation in the T2K-II/Hyper-K era. Hadron production measurements with these new target materials are a priority for NA61/SHINE, after the CERN LS2. The design of new targets for the future high-intensity long-baseline neutrino experiments (DUNE and Hyper-K) is in progress now.

A detailed document with an updated scientific program has been submitted by the NA61/SHINE collaboration to the CERN SPS [29] for evaluation and beam request after the LS2.

5 Combined analyses

As shown in previous sections, T2K has now excluded CP conservation at 2σ and provided the world-leading constraints on the θ_{23} and Δm^2_{32} parameters. In order to surpass these measurements in a relatively short period of time, T2K is now exploring combined analysis together with the Super-Kamiokande atmospheric (section 5.1) and NOνA beam neutrinos (section 5.2).

5.1 The T2K-Super-Kamiokande analysis

The Super-Kamiokande experiment uses atmospheric neutrinos to simultaneously constrain θ_{23}, Δm^2_{32}, δ_{CP} and the neutrino mass ordering through similar oscillation channels as T2K: the μ-like disappearance and the e-like appearance channels. In particular, the Sub-GeV appearance channels are very sensitive to the δ_{CP} parameter, while the multi-GeV ones are mostly sensitive to the neutrino mass ordering. It should be noted that this sensitivity to mass ordering is essentially possible due to $\nu_e/\bar{\nu}_e$-like separation in the multi-GeV channels. Due to considerably larger oscillation distances through the Earth (up to $\sim$ 13000 kms), the atmospheric neutrinos oscillations are more sensitive to mass ordering than T2K accelerator neutrinos. However, this sensitivity is largely correlated to the θ_{23} parameter, as shown in Figure 23. On the other hand, the T2K experiment has the world leading sensitivity to θ_{23} and δ_{CP} parameters, as shown in Figure 22. But, the measurement of these parameters is highly degenerated with the neutrino mass ordering, for which T2K has little sensitivity. Hence, a combined

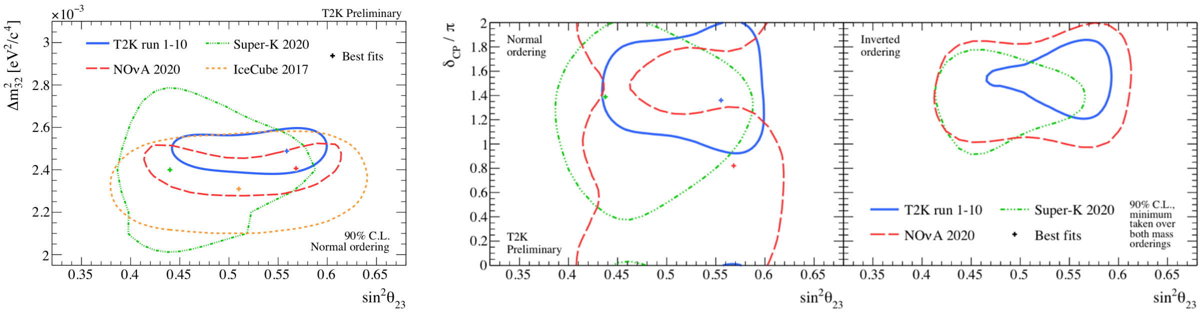


Figure 22: *Left:* T2K measurement of the oscillation parameters θ_{23} and $|\Delta m^2|$ from T2K compared to other experiments. *Right*: T2K measurement of δ_{CP} and θ_{23} assuming the normal ordering (left) and the inverted ordering (right), compared with other experimental results.

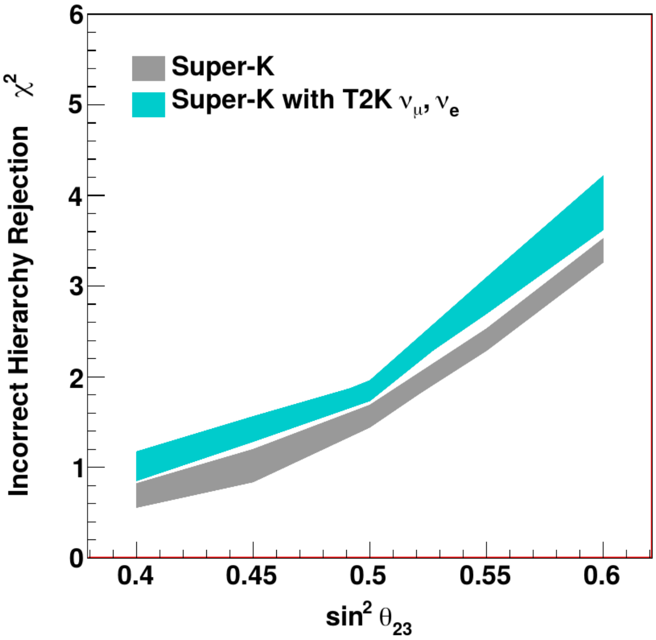


Figure 23: Sentivity to mass hierarchy with respect to $\sin^2\theta_{23}$ [30].

analysis between T2K beam and Super-Kamiokande atmospheric neutrinos is a powerful combination which allow to reduce this degeneracy puzzle, each experiment strengths corresponding to the other one limitations. Moreover, the T2K and Super-Kamiokande experiments are sharing the exact same far detector, the same underlying interaction model as well as a similar neutrino flux, both inherited from hadron disintegration. A combined analysis is therefore the ideal tool to minimize the experiment systematic uncertainties by taking these correlations into account. The combined analysis is currently going-on and aims for an official result in 2022, and should produce the new world leading constraints on atmospheric parameters, neutrino mass-ordering and δ_{CP}. A first idea of the possible outcome is shown in Figure 24. This study will serves as a flagship analysis and be regularly updated with the ultimate goal to provide the very first 3σ exclusion of CP conservation together with the second phase of the T2K experiment. It should be highlighted that in the incoming years, the statistical uncertainties will reach the systematic uncertainties, and the combined analysis with complete correlations will provide its full potential. Moreover, this analysis will provide the complete framework for the future Hyper-Kamiokande experiment in which the atmospheric and beam samples will be combined from the start. It will finally allow to do the most stringent tests of the PMNS framework until the next generation of experiments (Hyper-Kamiokande and DUNE) comes into play.

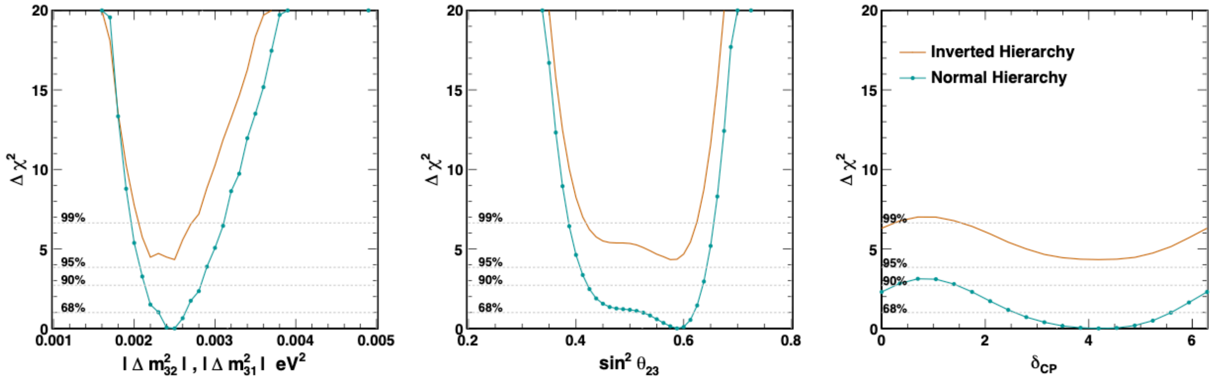


Figure 24: Constraints on the PMNS parameters from Super-Kamiokande atmospheric measurements (deep blue and orange) and a of a first joint fit between Super-Kamiokande and T2K (pale blue and orange). Figures are extracted from [30]. Note that the joint fit has assumed some crude correlations between the atmospheric and beam samples, and this result will be modified when the joint fit will be available next year.

5.2 The T2K-NOνA analysis

The NOνA experiment also provides excellent constraints on the δ_{CP}, θ_{23} and Δm^2_{32} parameters, and have an increased sensitivity to mass ordering, due to its longer baseline, compared to T2K. It should be noted that in last two panels of Fig. 22 some tensions are observed between T2K and NOνA 2020 results for δ_{CP} in the case of normal hierarchy. This motivates the two collaborations to work together with the aim, in some years from now, to provide joint T2K+NOνA results.

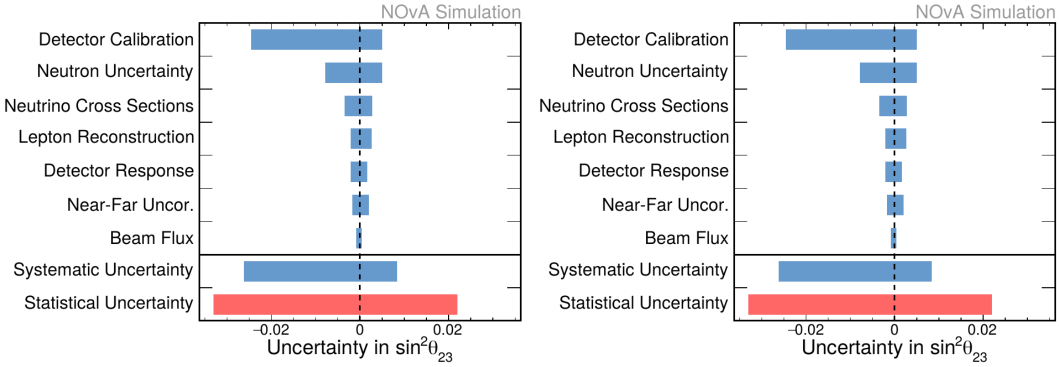


Figure 25: NOνA uncertainties on the $\sin^2\theta_{23}$ (left) and δ_{CP} (right) measurements.

Compared to the T2K-Super-Kamiokande combined analysis, the T2K-NOνA one suffers from the fact that the far detectors are different between the two experiments. As shown in Figure 25, the far detector uncertainties is currently the dominant systematics in the NOνA results. Once that the two experiment results will be systematics dominated, this aspect could limit the interest of a joint fit with T2K. However, since the interpolation from the near to far detector is completely different between T2K and NOνA, this joint fit allows not only to test potential bias which may arise in constraints from a sole detector (Super-Kamiokande), but it will also provide an excellent test of both these interpolation methods, which are central in the systematic uncertainty reduction from relative measurements. This analysis, though having slightly less priority compared to the Super-Kamiokande one, also aims for very first results in 2022.

6 Summary and requests to IN2P3

This document briefly describes the past, on-going and future contributions of the IN2P3 (LLR and LPNHE) groups to the T2K experiment. In the last 10 years T2K has provided world-leading measurements of neutrino oscillation parameters, notably the discovery of neutrino oscillations in appearance mode and the first hints of CP violation in the leptonic sector.

These measurements, coupled with a long list of neutrino-nucleus cross-section measurements, will be further reinforced after the T2K Near Detector upgrade will be installed and will start taking data during the T2K-II phase.

This program will set the stage for the next generation of long-baseline experiments that will use the Hyper-Kamiokande detector to perform conclusive measurements of CP violation in the lepton sector.

Project	Cost
T2K-II TPCs	200 k€
T2K-II Super–FGD	450 k€

Table 2: Resources invested by IN2P3 for the ND280 Upgrade.

The resources invested by the IN2P3 in the ND280 Upgrade are shown in Tab. 2. External resources have been obtained by group members through an ANR project (SUNCORE) that allowed to hire 2 postdocs working on the ND280 Upgrade and on the Combined Oscillation Analyses, and through a P2IO Labex project (BSMnu) that allowed to hire a PhD student to work on the ND280 Upgrade. In addition we are part of the JENNIFER-2 and SK2HK RISE projects founded by European Union that cover scientific trips to Japan. JENNIFER-2 has been paused due to the pandemics but it will restart as soon as travels to Japan will be possible again. SK2HK has just been restarted.

The coming years will be critical for the successful exploitation of the ND280 Upgrade. We ask IN2P3 to continue its long standing support to the T2K experiment covering funds needed for common funds, shifts, meetings, etc. In 2022 no shifts and few meetings in Japan are foreseen, but we will need resources for traveling for the assembly of the detectors at CERN and J-PARC and their commissioning. A support of the order of 150k€ per year will be needed for T2K common funds and participation to T2K shifts and meetings until the beginning of Hyper-Kamiokande.

The request for NA61++ would allow the LPNHE group to continue its participation in the NA61 physics program, with the goal of reducing uncertainties on the neutrino fluxes for T2K-II and future LBL experiments (DUNE and Hyper-Kamiokande). A support of $\sim$ 15 k€ per year will be needed for this part of the programme.

Finally, concerning human ressources, the LPNHE group has recently benefited from the hiring of Mathieu Guigue from Sorbonne Université in 2018 and is currently benefiting of two CDDs hired with the ANR. No new CNRS researchers have been hired in the last 8 years. In order to exploit the ND280 Upgrade during the T2K-II phase, at least one CNRS Chargé de Recherche is desired in the coming years.

The LLR group has recently benefit from the hiring of Benjamin Quilain, but has also lost its Neutrino group founder, Michel Gonin, who took in charge the head of the newly created IRL ILANCE. While waiting for the replacement of this last via a CNRS Chargé de Recherche recruitment, the group urgently needs funds for a post doc, that would help during the transition phase towards the ND280 upgrade physics. As a reminder, the last LLR T2K post-doc financed by IN2P3 ended his contract in 2017.

The activities of the new CRs, as well as the rest of the groups, are expected to transition from T2K-II to Hyper-Kamiokande and decisively contribute to the discovery of CP violation in the leptonic sector.

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A IN2P3 groups members and responsibilities

The composition of the LLR (and *ILANCE) neutrino group:

Physicists	
Margherita Buizza Avanzini	*CNRS-Chargée de Recherche,* *Group leader, Co-convenor of T2K cross section group*
Olivier Drapier	*CNRS-Directeur de Recherche* *Co-convenor of electronics for SuperFGD*
Michel Gonin*	*CNRS-Directeur de Recherche,* **Director of ILANCE since April 2021,* *Convenor INGRID, PI Proton Module*
Thomas Mueller	*CNRS-Chargé de Recherche* *Convenor of electronics/DAQ and mechanical engineering for WAGASCI*
Benjamin Quilain	*CNRS-Chargé de Recherche* *Co-convenor of T2K oscillation analysis*
Jaafar Chakrani	*PhD student till October 2023*
Engineers	
Lorenzo Bernardi	*Electronics engineer for SuperFGD*
Alain Bonnemaison	*Mechanical engineer for WAGASCI*
Oscar Ferreira	*Mechanical engineer for INGRID, Proton Module and WAGASCI*
Frank Gastaldi	*Electronics engineer for WAGASCI and SuperFGD*
Marc Louzir	*Electronics engineer for SuperFGD*
Frederic Magniette	*Software/pseudo-online/online engineer for WAGASCI and SuperFGD*
Jérome Nanni	*Electronics engineer for SuperFGD*
Former PhD student / Postdoc	
Phuong Dinh Tran	*PhD student on T2K until 2009*
Magali Besnier	*Postdoc on T2K until 2011*
Christophe Bronner	*PhD student on T2K until 2011*
Joao Pedro Athayde Marconde de André	*PhD student on T2K until 2012*
Benjamin Quilain	*PhD student on T2K until 2014*
James Imber	*Postdoc on T2K and SK until 2017*
Matthieu Licciardi	*T2K PhD student until September 2018*
Stephen Dolan	*T2K Postdoc until Mai 2019*
Guillermo Megìas	*T2K Postdoc until July 2019*
Olivier Volcy	*T2K PhD student until September 2019*

The composition of the LPNHE neutrino group:

Physicists

Pierre Billoir	*Professeur (emerite), TPC reconstruction expert*
Alain Blondel	*CNRS-Directeur de Recherche (emerite)*
Jacques Dumarchez	*CNRS-Directeur de Recherche (emerite)* *Magnet and TPC expert;* *member of the publication board*
Claudio Giganti	*CNRS-Chargé de Recherche* *TPC expert; Run coordinator;* *co-convenor of the T2K oscillation analysis group (until Oct. 2018)* *ND280-upgrade project leader*
Mathieu Guigue	Sorbonne Université-Assistant Professor *co-convenor of the ND280 reconstruction group*
Jean-Michel Levy	*CNRS-Chargé de Recherche (benevole)*
Marco Martini	*Professor at IPSA and Associate Researcher with SU* *Neutrino cross-section expert*
Boris Popov	*CNRS-Directeur de Recherche* *Group leader; Magnet and TPC expert;* *convenor of the T2K-NA61 group;* *convenor of the NA61 software and analysis groups*
Marco Zito	*LPNHE Director* *ND280-upgrade project leader (until 2019)*
Adrien Blanchet	*Postdoc till December,2022*
Sergey Suvorov	*Postdoc till October,2022*
Quoc Viet Nguyen	*PhD student till October,2022*
Lucile Mellet	*PhD student till October,2023*
Uladzsilava Yevarouskaya	*PhD student till October,2023*

Engineers

Jean-Marc Parraud	*CNRS-assistant d'ingénieur;* *design of the Horizontal TPC FEC board*
Francois Toussenel	*CNRS-ingénieur de recherche;* *design of the Horizontal TPC FEC board*
Yann Orain	*CNRS-assistant d'ingénieur;* *mechanics and cooling for the Horizontal TPC FEC*
Diego Terront	*CNRS-ingénieur d'études;* *data acquisition for the Horizontal TPCs*

Former PhD student / Postdoc

Laura Zambelli	*PhD student till October,2013*
Pierre Bartet-Friburg	*PhD student till October,2016*
Matej Pavin	*PhD student till October,2017*
Simon Bienstock	*PhD student till October,2018*