IN2P3 contributions to the Japanese neutrino program: T2K, T2K-II, Super-K and Hyper-K

LLR and LPNHE neutrino groups

Prepared for the IN2P3 Scientific Council – June 2018

Contents

1 Executive Summary

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] framework. The PMNS matrix is a 3×3 unitary mixing matrix and it is parametrized by three mixing angles, θ_{12}, θ_{23}, θ_{13}, and a CP violating phase, $\delta_{\rm CP}$. 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 original discovery of neutrino oscillations and the first measurements of the corresponding mixing angles (θ_{12} and θ_{23}) and mass squared differences from Super-Kamiokande [2], SNO [3], and KamLAND [4] started a broad program in which neutrino oscillations have been observed by several experiments using very different neutrino sources and detection techniques. Among these techniques, neutrinos produced at accelerators are particularly appealing thanks to the possibility of tuning their energy and the distance between neutrinos production point and the detector to the desired values in order to perform precise measurements of different oscillation parameters.

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 ($\Delta \mathrm{m}^2_{32}$). 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. 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 off-axis, 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 operation of the experiment and 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} [5], θ_{13} was measured to be different from zero in 2012 by Daya Bay [6] and RENO [7] with more than 5σ significance. In 2013, T2K definitely established ν_e appearance [8], 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), 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, 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 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.

The Super-Kamiokande detector which serves as the far detector of T2K, provides rich physics beyond T2K. By using atmospheric neutrinos, Super-Kamiokande offers the possibility of an independent measurement of θ_{23}, eventually probing the octant of $\sin^2\theta_{23}$. Super-Kamiokande functions also as an astrophysical neutrino observatory providing indications of supernova burst and supernova relic neutrinos. It provides also the best limits on the proton decay and dark matter candidates can be searched for by looking, for instance, for WIMPs annihilating in the Sun.

In this document we review the IN2P3 contributions to T2K, discuss the proposed contributions to T2K-II and to Super-Kamiokande and present the physics case of Hyper-Kamiokande.

2 IN2P3 groups members and responsibilities

The composition of the LLR neutrino group:

Physicists	
Margherita Buizza Avanzini	*CNRS-Chargé de Recherche*
	Co-convenor of CC0π cross section group in T2K
Olivier Drapier	*CNRS-Directeur de Recherche*
	PI of the (proposed) electronics for SuperFGD
Michel Gonin	*CNRS-Directeur de Recherche*
	Group leader; Convenor INGRID, PI Proton Module;
	Member of the Tank Open Work Country Board;
	PI WAGASCI IN2P3-X; Hyper-Kamiokande representative
Thomas Mueller	*CNRS-Chargé de Recherche*
	Convenor of electronics/DAQ and mechanical engineering for WAGASCI
Pascal Paganini	*CNRS-Directeur de Recherche*
	Super-Kamiokande from November 2017
Stephen Dolan	*Postdoc T2K*
	Co-convenor of CC0π cross section group in T2K
Sonia El Hedri	*Postdoc Super-Kamiokande from September 2018*
Matthieu Licciardi	*T2K-WAGASCI PhD student until September 2018*
Olivier Volcy	*T2K-WAGASCI PhD student until September 2019*
Alice Coffani	*Super-Kamiokande PhD student from Spetember 2018*
	Recipient of the X excellence scholarship
Engineers	
Oscar Ferreira	*Mechanical engineer for INGRID, Proton Module and WAGASCI*
Alain Bonnemaison	*Mechanical engineer for WAGASCI*
Frank Gastaldi	*Electronics engineer for WAGASCI*
Frederic Magniette	*Software/pseudo-online/online engineer for WAGASCI*
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*

The composition of the LPNHE neutrino group:

Physicists	
Bernard Andrieu	*CNRS-Chargé de Recherche*
Jacques Dumarchez	*CNRS-Directeur de Recherche* *Group leader; 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* *co-convenor of the ND280* ν_e *and exotics group (till Oct. 2016)*
Luca Scotto Lavina	*CNRS-Chargé de Recherche*
Jean-Michel Levy	*CNRS-Chargé de Recherche (benevole)*
Boris Popov	*CNRS-Directeur de Recherche* *Magnet and TPC expert; convenor of the T2K-NA61 group;* *co-convenor the T2K-beam group (till Feb,2018)*; *convenor of the NA61 software and analysis groups*
Assistant professor	*Sorbonne Université-Assistant Professor* *starting from September,2018*
Simon Bienstock	*PhD student till October,2018*
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*
William Ceria	*CNRS-assistant d'ingénieur;* *mechanics for the Horizontal TPCs*
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*

Total number of permanent physicists involved in the projects described in this document:

	T2K	NA61	WAGASCI	SK	T2K-II	HK
LLR	4	0	3	4	4	5
LPNHE	3	2	0	0	5	5

3 The T2K experiment and recent results

T2K [9] 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.

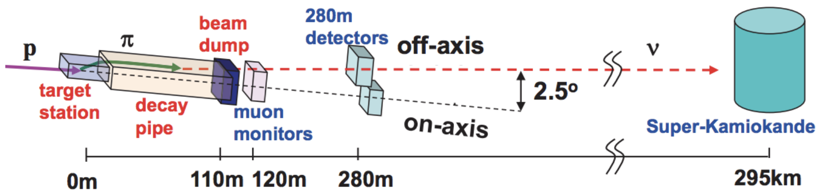


Figure 1: A schematic view of the T2K neutrino beamline and detectors.

The INGRID detector (see 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.

Each INGRID module is made of eleven scintillator tracking planes interleaved with nine iron target planes (see Figure 2). Each tracking plane is composed of twenty-four (1.20 m long, 5 cm wide and 1 cm thick) scintillator bars in both vertical and horizontal directions, read by wavelength shifting fibers and MPPCs. The iron layers have the same transverse dimensions as the tracking planes (120 × 120 cm^3), but a thickness of 6.5 cm. As can be seen from Fig. 2 (left), two 10 m long alignments of 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 (see Figure 2).

The off-axis detector, ND280 (see Fig. 3), consists of several detectors installed in 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.

Each FGD has a mass of ~ 1 ton and acts as active target for neutrino interactions. The first FGD is a fully active detector, while in the second FGD scintillator layers are interleaved with inactive water layers, allowing to select neutrino interactions on carbon and on oxygen. The three TPCs are used to do a 3D tracking of the charged particles produced in interactions in one of the FGDs, and to measure their charge and momentum from the curvature induced by the magnetic field. The particle identification is performed based on the measurement of the ionization.

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 (see Fig. 3). Super-Kamiokande has a cylindrical

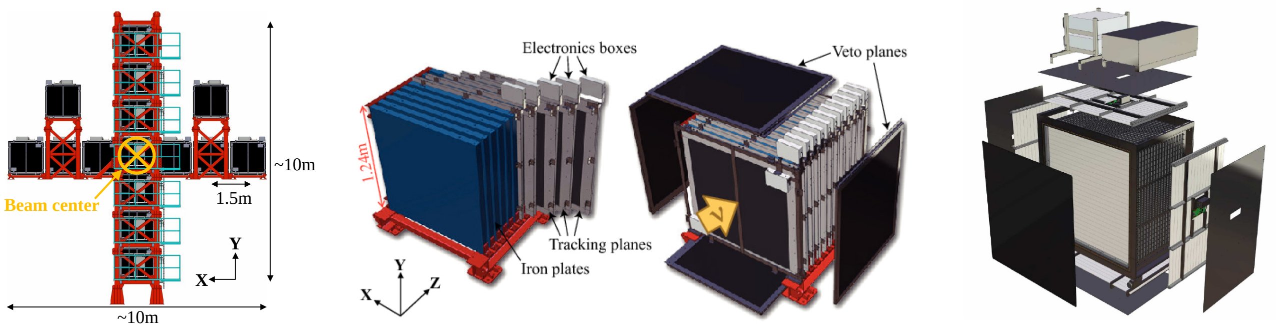


Figure 2: Schematic views of the INGRID detector (left) and of the corresponding individual modules, including the Proton Module (right).

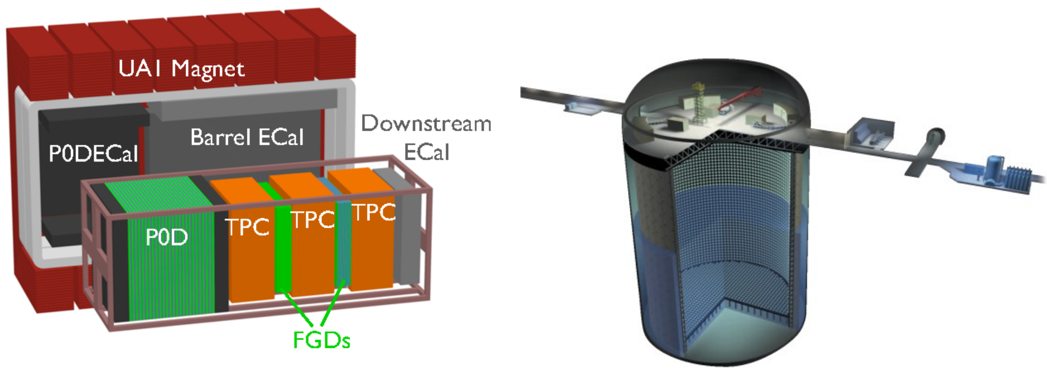


Figure 3: A schematic view of ND280 (left) and Super-Kamiokande (right).

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 was originally approved to collect 7.8×10^{21} p.o.t. (protons on target). We have recently reached 3.0×10^{21} p.o.t. while for the most recent oscillation results, that will be described in the following of this section, the analysed data correspond to 2.2×10^{21} p.o.t. In the next section we will describe in more details the role of the IN2P3 groups in the T2K experiment and their main contributions to the obtained results. In summary we have contributed to the neutrino flux prediction through the ancillary NA61/SHINE experiment, to the ND280 selections and its constraints, to SK calibration and selections and to the oscillation analysis, one of us being a convener of the oscillation analysis group and one of us being responsible for the ND280 fit and extrapolation to SK.

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 [10].

The flux modelling is based on the NA61/SHINE hadroproduction measurements [11]. It allows 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 [12] 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 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), leading to a total of 14 different samples. Examples of these distributions as a function of outgoing muon momentum are shown in Fig. 4.

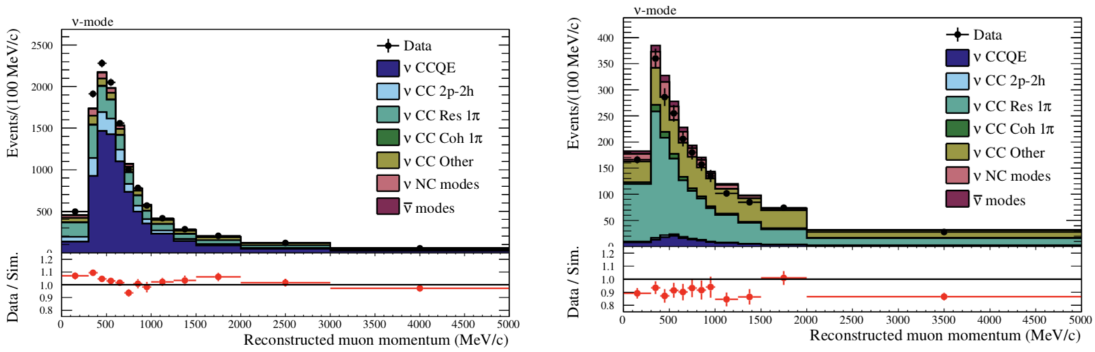


Figure 4: Momentum distribution of outgoing muons for ν_μ CC-0π^+ (left) and CC-1π^+ (right) samples at ND280.

The 14 event samples, selected in data and Monte Carlo, are binned in p_μ and $\cos\theta_\mu$ (where θ is the angle between the neutrino beam and the lepton candidate track) and fitted with a likelihood method. The likelihood assumes that the observed number of events in each bin follows a Poisson distribution, with an expectation calculated according to the flux, cross-section and detector systematic parameters. The fitted neutrino cross-section and unoscillated SK flux parameters are passed to the oscillation analysis, using a covariance matrix to describe their uncertainties. A systematic uncertainty on the number of expected events at Super-Kamiokande in the range of ∼4–7% is obtained as a result of this fit.

A major improvement of the new T2K oscillation analysis with respect to previous analyses is that a new reconstruction algorithm is used for the Super-Kamiokande event selection. This algorithm combines time and charge likelihood for a given ring hypothesis. The better performance of this algorithm allows for a new definition of the Fiducial Volume in which not only the distance of the vertex from the wall but also the direction of the lepton candidate with respect to the wall is used.

This new Super-Kamiokande selection and the new definition of the fiducial volume allow to increase by 30% the efficiency in selecting e–like samples while keeping the same purity of ∼ 80%. For the μ–like sample the new selection allows to increase the purity in selecting charged–current interactions without pions in the final state from 70% to 80%.

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. The number of events selected at Super-Kamiokande in the 5 samples are presented in Tab. 1 and compared with the expected numbers of events for different values of $\delta_{\rm CP}$. The corresponding energy spectra are shown in Fig. 5.

	Data	MC ($\delta_{\rm CP}$ = -$\pi/2$)	MC ($\delta_{\rm CP} = 0$)	MC ($\delta_{\rm CP} = \pi/2$)	MC ($\delta_{\rm CP} = \pi$)
e–like ν–mode	**74**	73.5	61.5	49.9	61.5
e–like + 1π ν–mode	**15**	6.9	6.0	4.9	5.8
e–like $\overline{\nu}$–mode	**7**	7.9	9.0	10.0	8.9
μ–like ν–mode	**240**	267.8	267.4	267.7	268.2
μ–like $\overline{\nu}$–mode	**68**	63.1	62.9	63.1	63.1

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

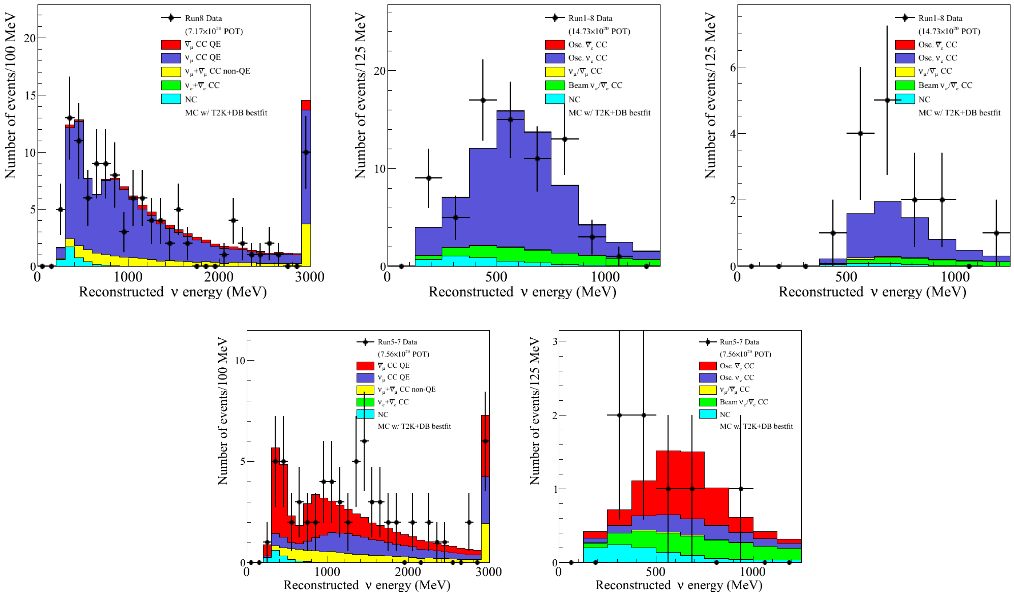


Figure 5: Observed energy spectra for the five SK samples used in the oscillation analyses. Top: μ–like, e-like, e–like+1π in ν–mode. Bottom: μ–like and e–like in $\overline{\nu}$–mode.

As it is clear from Tab. 1, δ_{CP} only affects the e-like samples and values of δ_{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 (7) single-ring e-like events are observed while 62 (9) are expected if $\delta_{\mathrm{CP}} = 0$ or π.

The five samples are then fitted together in order to extract the oscillation parameters θ_{23}, $|\Delta\mathrm{m}^2|$, θ_{13}, δ_{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 precise measurement of the reactor experiments. The two cases are shown in Fig. 6: both fits prefer values of δ_{CP} close to -$\pi/2$ and, when the reactor constraint is included, the CP conserving values 0 and π are excluded at more than 95% CL. θ_{23} and $|\Delta\mathrm{m}^2|$ are also precisely determined by T2K: in particular the value of θ_{23} is compatible with maximal mixing as shown in Fig. 7. It should be noted that in Fig. 7 some tensions are observed between T2K and the first published NOνA results for θ_{23} [13]. In a recent update of the oscillation analysis of NOνA, θ_{23} is found to be compatible with maximal mixing and currently there is no tension between T2K and NOνA results.

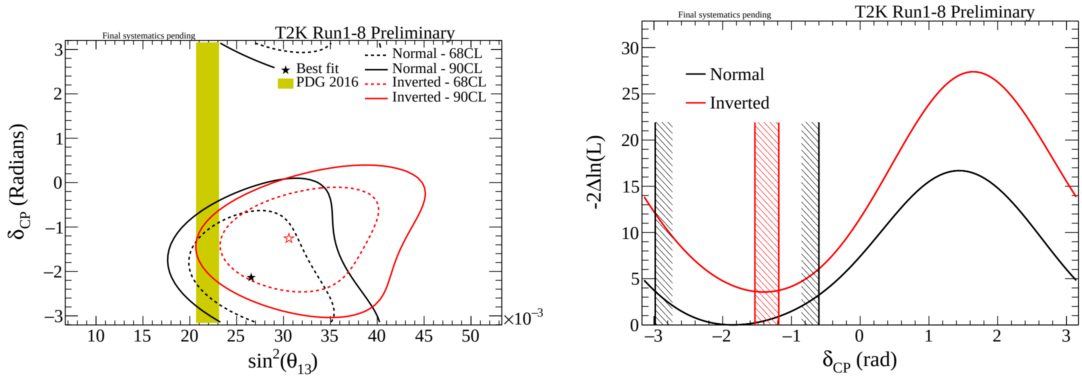


Figure 6: Measurement of the oscillation parameters θ_{13} and δ_{CP} without reactor constraint (left) and measurement of δ_{CP} with reactor constraints (right). The bands on the right plot represent the 95% CL allowed regions for the two mass ordering hypotheses.

In October 2017 T2K has restarted the data taking in $\overline{\nu}$–mode. The beam can run steadily at 485 kW

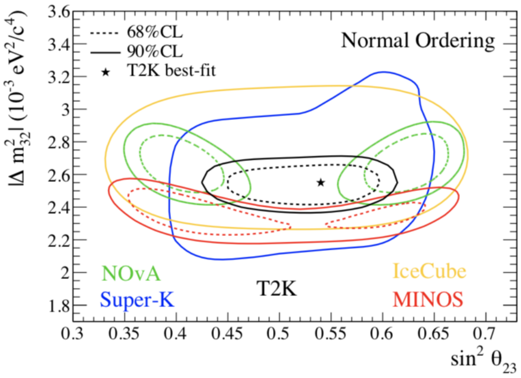


Figure 7: Measurement of the oscillation parameters θ_{23} and $|\Delta m^2|$ from T2K compared to other experiments.

and we expect to double the $\overline{\nu}$–mode statistics with data taken until May 2018. Updated oscillation results will be released during Summer 2018.

4 IN2P3 contributions to the T2K physics program

The IN2P3 groups of LLR and LPNHE contributed to several aspects of the T2K physics program.

The LPNHE group had a leading role in the NA61/SHINE experiment at CERN, an experiment designed to measure hadron-production cross-sections in order to reduce uncertainties on the neutrino fluxes. As it will be detailed in the following, the group also 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. One of the members of the group is currently one of the conveners of the T2K oscillation analysis group that produced the results described in Sect. 3. LPNHE members have also been responsibles of 4 paper committees (2 for T2K and 2 for NA61/SHINE), and members of 14 paper committees (7 for T2K and 7 for NA61/SHINE)

The LLR group mainly contributed to the INGRID and WAGASCI detectors and to the calibration of Super-Kamiokande. The LLR group has been responsible for the design and the mechanical construction of the INGRID detector and the Proton Module. This is illustrated by Figure 8, showing the mechanical calculations in case of an earthquake that have been performed at LLR, and the construction phase of the detector. More recently, the LLR group was responsible for the mechanical design of the WAGASCI water modules (see Sect. 4.4), 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. Presently, two members of the group are co-conveners of the cross-section group for measuring neutrino interactions without pions in the final state (see Sect. 4.3). The group also recently joined the Super-Kamiokande collaboration as it will be detailed in Sect. 6.

4.1 NA61/SHINE

One of the main systematic uncertainties in a neutrino long-baseline experiment is the uncertainty on the (anti-)neutrino fluxes. A small fraction of the T2K collaboration (essentially 1 japanese group - KEK - and 4 european groups, including LPNHE) has decided in 2006 to measure the production of charged pions and kaons in proton interactions at 31 GeV/c with a replica of the T2K Carbon target in the framework of the **NA61/SHINE experiment** at CERN SPS. The NA61/SHINE spectrometer [14] also used by an on-going heavy ion experiment, has been refurbished with the help of the T2K groups and data have been taken with a thin (4% λ_{int}) carbon target and with a T2K replica target in 2007 first, and then in 2009 and 2010.

In the NA61/SHINE project we have two important responsibilities: **software coordinator** (for

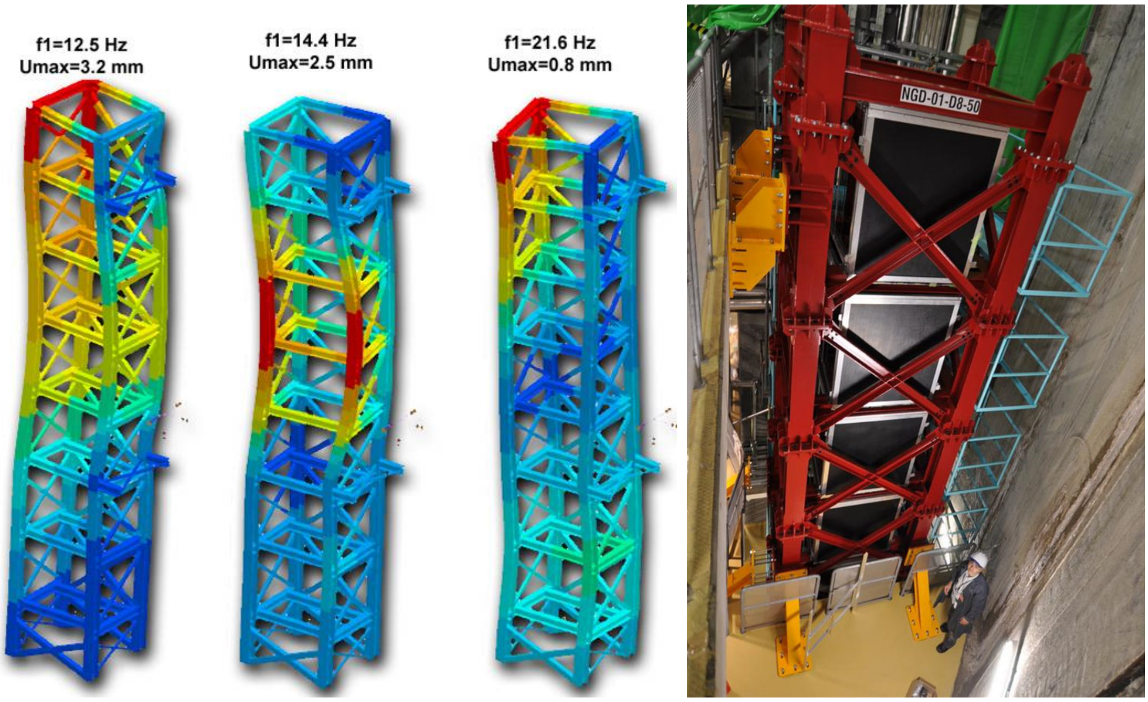


Figure 8: Left : the INGRID detector has been designed at LLR, taking into account the constrains in case of severe earthquakes. Right : the LLR engineer responsible for the project, during the construction phase.

the legacy software) and **analysis coordinator for Neutrino (T2K) and Cosmic Ray (CR) experiments**.

The group members were responsible for the first NA61/SHINE physics papers devoted to the interaction cross sections and charged pion spectra measurements in p+C interactions at 31 GeV/c (analysis of 2007 and 2009 data taken with the thin carbon target) [15, 16]. These data together with a more recent publication on the measurement of the production properties of positively charged kaons have been **used in the first T2K oscillation results to improve predictions of the initial neutrino fluxes for the T2K experiment**.

Later, the NA61/SHINE thin-target hadroproduction results have been complemented with measurements of neutral strange particle (K^0_S and Λ) yields [17].

A combined paper on the new better-precision measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton–carbon interactions at 31 GeV/c using a graphite target with a thickness of 4% of a nuclear interaction length has been finalized and published under the supervision of the LPNHE group [11].

Predicting the neutrino flux and energy spectrum is an important component of analyses in accelerator neutrino experiments. In 2013 a detailed paper on the T2K neutrino flux prediction, including the NA61/SHINE input, has been prepared with our active participation [18]. The results of hadronic interactions modeling is re-weighted using thin-target hadron production data from NA61/SHINE. For the first T2K analyses the uncertainties on the flux prediction were evaluated to be below 15% near the flux peak. They are now reduced down to $\sim$ 10% thanks to the new NA61/SHINE thin-target measurements. The uncertainty on the ratio of the flux predictions at the far and near detectors is less than 2% near the flux peak.

Special efforts have also been invested into the **first full-scale analysis of the long – T2K replica – target data** collected by NA61/SHINE. Long-target data are more difficult to reconstruct and analyse but they provide much more directly the information needed for predicting the neutrino flux. As a result of this important activity, in close cooperation with the T2K beam group, we prepared an article which presents details of the experiment, data taking, data analysis method and results from the 2007 pilot run [19].

A detailed analysis of a larger sample of 2009 T2K replica-target data has recently been finalized and published [20]. These measurements are currently being used for improved predictions of (anti-)neutrino fluxes in T2K, see below.

An ultimate analysis of the high-statistics 2010 replica-target data has been performed by the LPNHE group [21]. Yields of charged kaons and protons have been measured for the first time, while the precision and the phase-space coverage for $\pi^{\pm}$ measurements has been improved.

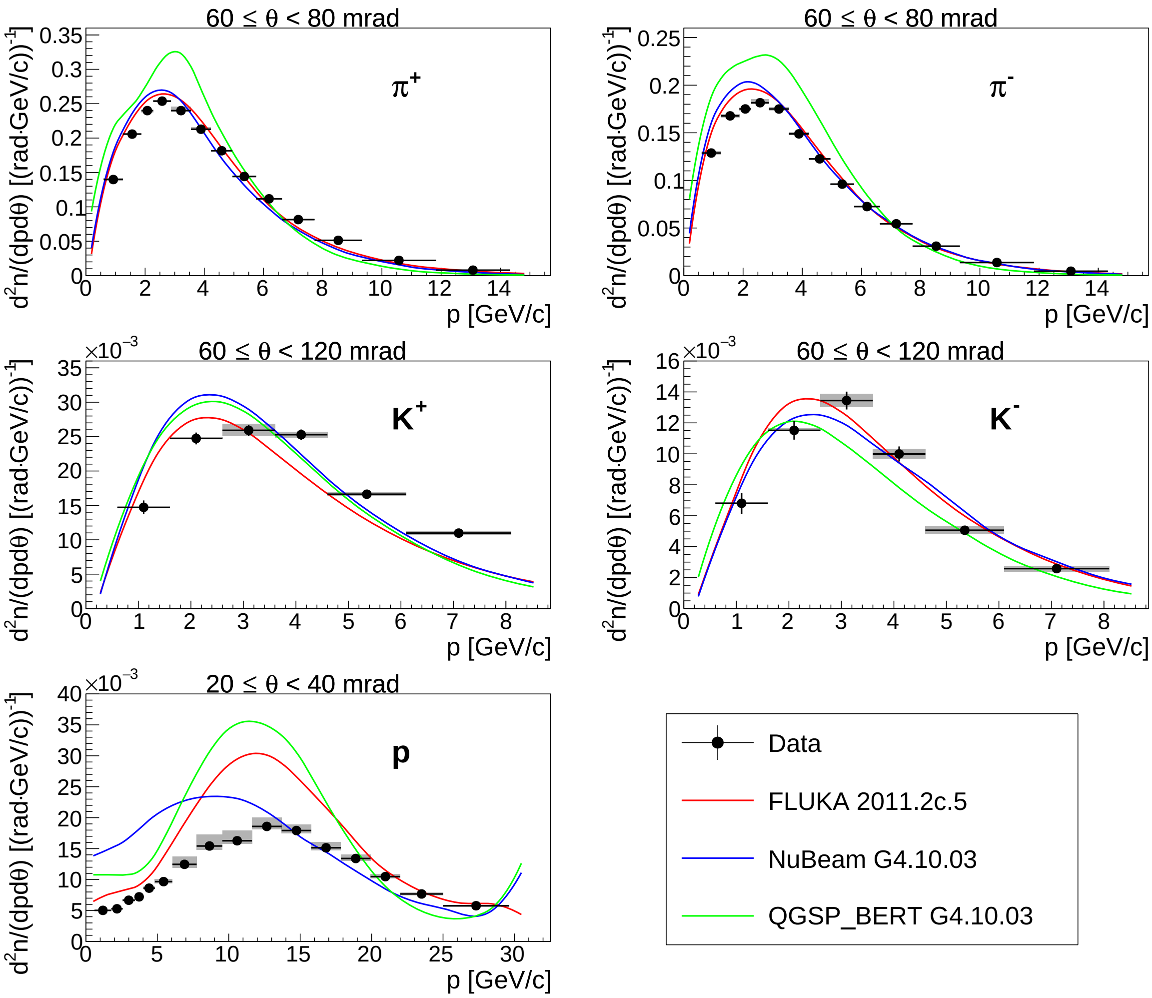


Figure 9: Double differential $\pi^{\pm}$, $K^{\pm}$ and proton yields coming from the second longitudinal target bin and one selected polar angle interval. Vertical error bars represent statistical uncertainties, while shaded regions are systematic uncertainties. Lines represent predictions of different MC models: FLUKA2011.2c.5 (red), NuBeam (blue) and QGSP_BERT (green) physics lists of GEANT4.10.

The analysis was performed by using a joint energy-loss and time-of-flight particle identification procedure as described in the previous publications devoted to replica target measurements [19, 20]. In contrast to other NA61/SHINE measurements, replica-target measurements are performed by extrapolating TPC tracks towards the target surface instead of reconstructing the main interaction vertex. This was done because the T2K neutrino flux actually depends on the longitudinal position of emitted hadrons along the target surface. Therefore, the $\pi^{\pm}$, $K^{\pm}$ and proton results are presented as triple differential yields normalized by the total number of incoming beam protons hitting the target, in bins of momentum, polar angle and longitudinal position along the target surface. The target was subdivided into five longitudinal sections 18 cm in size and the downstream target face. Polar angle and momentum binning is defined for each particle species separately since the size of the bins depends on the available statistics. Extracted yields were fully corrected for various inefficiencies by using multiplicative corrections based on the data and simulations.

Detailed comparisons of the $\pi^{\pm}$, $K^{\pm}$ and proton yields with the FLUKA2011.2c.5 model [22] as well as with the NuBeam and QGSP_BERT physics lists of GEANT4.10 [23, 24, 25] have also been performed.

An example can be seen in Fig. 9 which shows hadrons emitted from the second longitudinal target bin in just one selected polar angle interval. Both the FLUKA2011.2c.5 and NuBeam GEANT4.10 physics lists predict pion yields within ±30%, whereas QGSP_BERT GEANT4.10 shows larger differences. While all selected models provide reasonable predictions for charged kaon yields, they all fail to predict proton yields. The differences can be larger than a factor of two. A full set of comparisons can be found in Ref. [21].

These new results represent a major milestone for the neutrino-related programme of NA61/SHINE. Reduction of systematic uncertainties on the (anti-)neutrino fluxes down to 5% and below is one of the priorities for the on-going and future neutrino experiments. Publication of these results is in preparation.

Indeed, future neutrino oscillation experiments at accelerators would require a precision of about 2-3% on the predicted absolute neutrino fluxes. The so-called USNA61 part of the NA61/SHINE scientific programme – an extension of the NA61/SHINE physics program utilizing hadron production measurements for Fermilab neutrino beams – is now officially approved. The physics data-taking period started in October, 2015 and continues till now. Future extension of this program towards T2K-II and T2HK is being prepared and will be discussed in Sect. 5.4.

4.2 INGRID

The main goal of the INGRID detector is the measurement of the stability and the direction of the neutrino beam, as shown in Figure 10 (Left). However, INGRID data have also been used for extracting interesting cross section measurements and to test a possible violation of the Lorentz invariance in the neutrino sector, as detailed below.

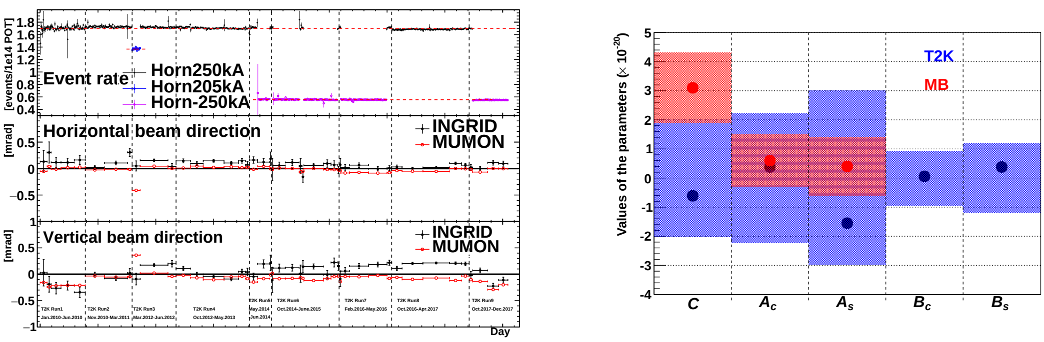


Figure 10: Left : beam intensity and direction as a function of time measured with INGRID. Right : Some of the Standard Model Extension parameters, as measured by T2K and MiniBooNE [57].

The LLR group joined the T2K collaboration in 2007 to participate in the INGRID construction. The group was responsible for the mechanical structure design. LLR was also in charge of testing a considerable amount of Multi Pixel Photon Counter (MPPC) used for the light detection. Moreover, the INGRID installation in Tokai (2008-2009) has been coordinated by an LLR engineer. The detector calibration has also been performed by LLR group members.

A second detector, called Proton Module (PM), has been added in the center of the INGRID cross in 2010. Entirely designed at LLR, the PM is made of plastic scintillator only, thus making it possible to detect low momentum protons ejected after a neutrino interaction.

Recently, one of the WAGASCI modules (see Sec. 4.4), called Water Module (WM) has replaced the Proton Module in the center of INGRID, thus allowing the measurement of water over scintillator cross section ratio on axis. Two analyses are currently on-going, aiming at the measurement of the CC0π and CC1π cross sections on water and on water/carbon. The two analyses are developed in parallel by a PhD student at LLR and a post-doc in Japan (previously PhD student at LLR) and share the same data selection and the same strategy for the cross section extraction. In particular, the unfolding framework, based on D'Agostini method [31], developed for these analyses, is one of the reference methods accepted by the T2K collaboration (together with the Likelihood fitter based, as described

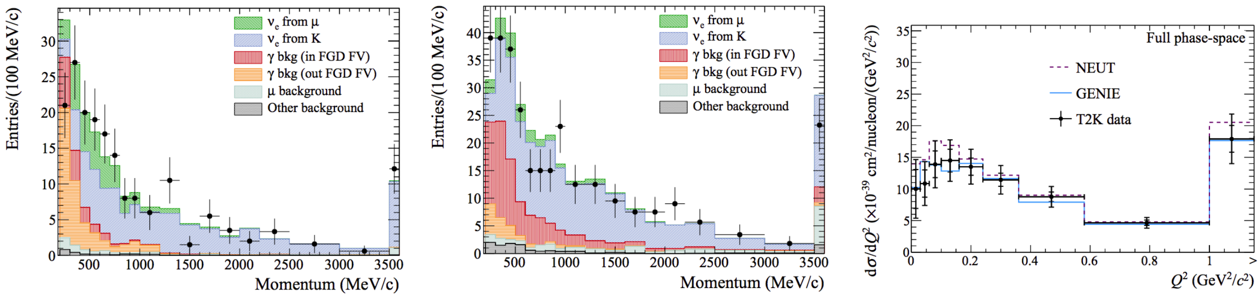


Figure 11: ND280 ν_e candidates with 1 reconstructed track (left), more than 1 reconstructed track (center) and ν_e cross-section on carbon as a function of the transferred momentum to the nucleus (right).

in Sec. 4.3). Particularly interesting here is the fact that each analysis uses alternatively the CC0π and CC1π samples as signal or as a control sample for background. Results will be probably published together in the same paper. These analyses represent a first step towards a more sophisticated analysis aiming at simultaneously extract the CC0π and CC1π cross sections that could in principle show a nice sensitivity to Final State Interactions through a measurement of the migration of CC-resonant events from CC0π to CC1π samples and vice-versa.

In addition, within the cross section group led by LLR members, a first attempt to combine INGRID and ND280 data to simultaneously extract the CC0π cross section on Carbon on- and off-axis is on-going. This represents a first step to probe the interest of measuring cross sections at different angles w.r.t. the beam direction (that means at different neutrino energies), that is the primary goal of proposed detectors like nuPRISM [30]. As a further step we will include a new off-axis point at 1.5°, by exploiting data of the Water Module + Proton Module off-axis (see Sec. 4.4).

Finally, INGRID data has been used also to study the possible violation of the Lorentz invariance in neutrino sector [32]. The upper limits obtained with INGRID on the corresponding parameters can be competitive as compared to those published by other experiments, as is shown in Figure 10 (Right). The upper limits obtained with INGRID on the corresponding parameters can be competitive as compared to those published by other experiments, as is shown in Figure 10 (Right).

In summary, the LLR contribution to the construction and to the data analysis of the INGRID detector has been remarkable. INGRID data have been exploited for three PhD theses (defended respectively in 2009, 2011 and 2014) and a fourth thesis is currently on-going. INGRID (and WAGASCI) data will be still object of publication in a short term and more sophisticated analyses combining on- and off-axis detectors are foreseen.

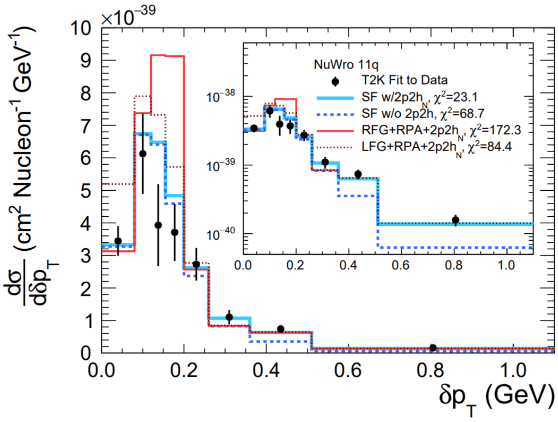
4.3 ND280 off-axis

ND280 is the T2K off-axis near detector that has two crucial roles: contribute to the T2K oscillation analyses by constraining flux and cross-section parameters (as discussed in Sect. 3) and perform various inclusive and exclusive cross-section measurements, taking advantage of the high statistics and the good quality of reconstructed tracks.

During the construction, the IN2P3 groups were responsible for the UA1/NOMAD magnet power supply and for the back–end electronics of the TPCs. Besides the required shift quota, the groups contribute to the operations of ND280 being on-call expert for the magnet and for the TPCs. During some of the data-taking periods the **run coordinator** responsibility has also been assured by members of the IN2P3 groups.

The LPNHE and LLR group members also contributed to the ND280 analyses. One member of the LPNHE has been convener of the ν_e and exotics working groups while two of the members of LLR are currently conveners of the cross-section group for measuring neutrino interactions without pions in the final state.

The ν_e and exotics groups produced a measurement of the electron neutrino contamination in the



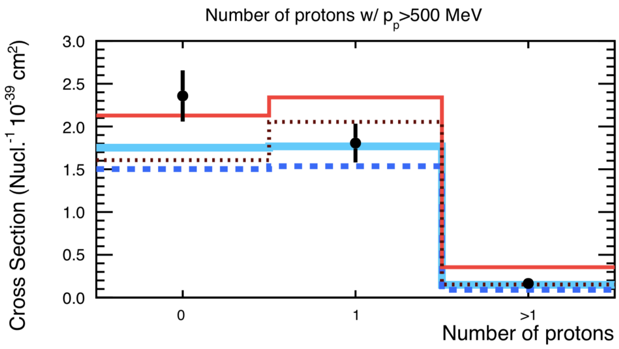


Figure 12: Left: the ND280 cross-section measurement of the momentum imbalance between the outgoing lepton and highest momentum proton (δp_T) compared to a variety of different nuclear models (SF, RFG+RPA, LFG+RPA) with and without a 2p2h contributon. The bulk of the distribution can be seen to be sensitive to the former whilst the tail show sensitivity to the latter. The inlay shows the same plot on a logorithmic scale. Right: cross section as a function of the number of protons compared to different neutrino generators: NEUT [40, 41] (red), NuWRO [42] without 2p2h (dotted blue), NuWRO SF+2p2h (light blues), NuWRO LFG+2p2h (dotted brown).

muon neutrino beam [29], that is the main background to the ν_e appearance searches in T2K, the first measurement of ν_e cross-section since Gargamelle in 1978 [33], and a search for sterile neutrinos leading to ν_e disappearance at ND280 [34]. A summary of these results is shown in Fig. 11. These measurements are important because the intrinsic ν_e contamination in the beam is the main background to ν_e appearance signal in the oscillation analyses and measurements of ν_e cross-section and particularly of possible differences between ν_e and $\overline{\nu}_e$ cross-sections are vital in order to search for CP violation by comparing ν_e and $\overline{\nu}_e$ appearance probabilities. Future developments of these analyses, with more statistics and a more efficient Near Detector, will be fundamental in order to fully exploit the T2K oscillation measurements.

LLR and LPNHE groups also participated in the developments of new ν_μ selections at ND280 and in the ν_μ cross-section analyses. One of the most important cross-section analyses performed up to now at ND280 is the measurement of muon neutrino charged-current interactions on carbon without pions in the final state [35]. For the first time the measurement is reported as a flux-integrated, double-differential cross-section in muon kinematic variables ($\cos\theta_\mu$, p_μ), without correcting for events where a pion is produced and then absorbed by final state interactions. The measurements compare favorably with recent models which include nucleon-nucleon correlations but, given the present precision, these measurements do not solve the degeneracy between different models. The data also agree with Monte Carlo simulations which use effective parameters that are tuned to external data to describe the nuclear effects.

Extensions of this analysis to include also measurements of neutrino cross-sections on Oxygen, Lead as well as $\overline{\nu}_\mu$ cross-section are being currently performed within the working group lead by LLR members.

The LPNHE group developed a new selection to improve the angular acceptance of the Near Detector and to perform a measurement of charged current muon neutrino cross sections with 0, 1, or 2 protons in the final state. In parallel, one of the LLR members used events with one reconstructed muon and at least one reconstructed proton to measure their kinematic imbalance in the plane transverse to the incoming neutrino [36]. These measurements are particularly sensitive to distinguishing different cross-section models, specifically in characterising the initial state of the nucleus and in separating the quasi–elastic and 2p2h contributions, as is demonstrated in Fig. 12. This is important as these nuclear-medium effects are currently poorly understood and plausible variations of them can significantly alter the estimation of the neutrino energy in the oscillation analyses [37], thereby making them responsible for some of the dominant systematic uncertainties.

These measurements require tracking of fairly low-momentum protons in multi-particle final states

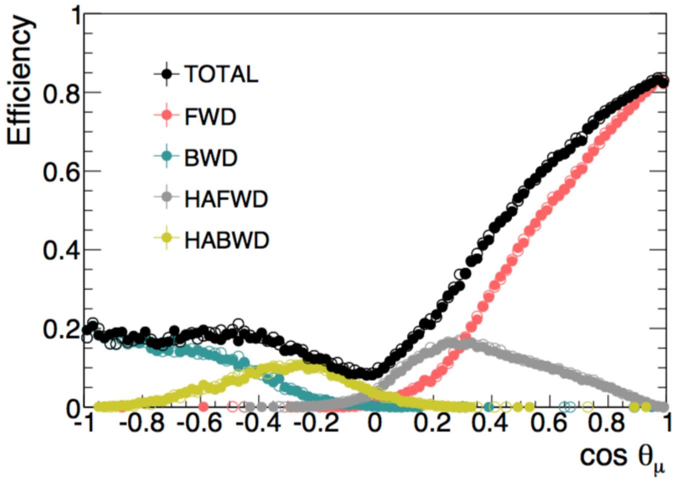


Figure 13: Efficiency of the ND selection as a function of $cos(\theta)$ when the high angle (HAFWD and HABWD) and backward (BWD) selections are added to the forward (FWD) selection.

and are therefore only possible thanks to the capabilities of the T2K Near Detector. Thanks to its fine granularity, high-resolution tracking and the presence of a magnetic field, it allows for a detailed measurement of the protons emitted in neutrino interactions. These two analyses developed by LLR and LPNHE group members have been recently combined and submitted for publication [38]. A further analysis of these results by an LLR member in collaboration with leading neutrino interaction theorists has allowed the validation and clarification of a theory of 2p2h interactions [39], thereby taking important steps toward better understanding of the effect responsible for key systematics in oscillation analysis.

It is also worth noting that the cross-section measurements developed by LLR and LPNHE have employed novel cross-section extraction methods to minimise bias from the input simulations and thereby maximise the usefulness and longevity of the result to the community. This includes the first use of a likelihood-fitter to extract an unregularised cross section in a neutrino scattering analysis [35] followed by the first employment of a data-driven regularisation [38]. Since their development, these techniques have become the standard for almost all T2K cross-section analyses.

An important point to stress is that the new selections developed by IN2P3 physicists allowed to increase the ND280 angular acceptance, by exploiting the identification of tracks going at high angles and backward with respect to the neutrino direction, mainly by using Time-Of-Flight (ToF) information. The efficiency as a function of the angle with respect to the beam is shown in Fig. 13. The importance of this work is witnessed by the on-going ND280 upgrade project that will be discussed later and that is mainly motivated by the improvement of the angular acceptance of ND280.

4.4 WAGASCI

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. 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. However in the T2K experiment near and far detectors have different target materials and angular acceptance : ND280 target is mainly made of hydrocarbon (plastic scintillators) with a small fraction of water and has a mainly forward angular acceptance (as shown in Fig. 13), whereas SK is a water Cherenkov detector with a 4π-acceptance. For these reasons the extrapolation from near to far detector could be biased.

In order to reduce this systematic error, the LLR group has been involved since 2015 in the WAGASCI (WAter Grid And SCIntillator) experiment. The goal of this experiment is the measurement

Figure 14: Left panel shows the assembly of the 3D scintillator grid. Right panel shows the DAQ chain developped at LLR for MPPC readout.

of exclusive neutrino cross-sections on water and on plastic scintillators as well as their ratio. The WAGASCI detector is based on an innovative design of plastic scintillators assembled to form a tri-dimensional grid (see left panel of Figure 14). The hollow cuboid lattice of scintillators is filled with water as the neutrino interaction target and will allow the measurement of cross sections on H_2O. The removal of water is possible allowing for a pure-CH target measurement with a very low momentum threshold for outgoing hadrons. Measurements over a wide phase space of muon momentum and opening angle are possible by combining those 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.

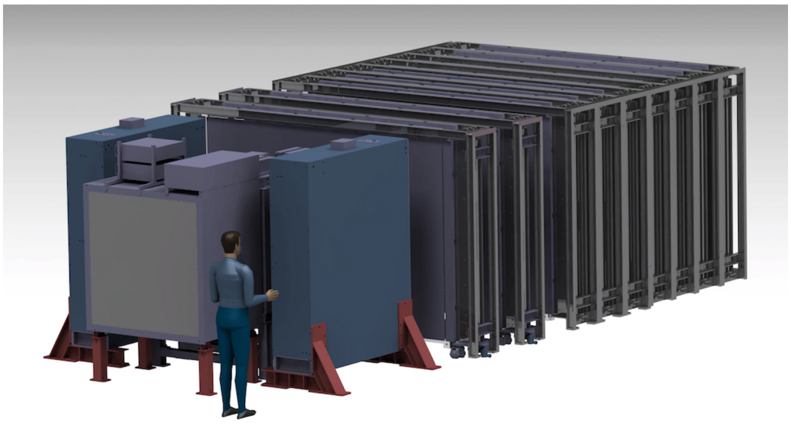


Figure 15: Schematic view of the entire set of detectors for the 4π measurement of the WAGASCI experiment.

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 14) 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**. For this work, the LLR group has received a financial support of 50 k€ from École polytechnique. The first WAGASCI module – so-called WaterModule (WM) and already mentioned in Sec. 4.2 – has been successfully installed on the axis of the J-PARC neutrino beam during autumn 2016 and is taking data since its installation. The first off-axis measurement (at 1.6° from the neutrino beam) has started in October 2017, using a second WAGASCI module associated with the Proton Module as a hydrocarbon target and with one INGRID module as muon calorimeter. Baby-MIND has been successfully installed in May 2018 and the full configuration (2 WAGASCI modules, Baby-MIND and 2 additional side-MRDs, see Figure 15) will be ready by summer 2018 for the 4π measurement. In 2018, the WAGASCI experiment has been included in the T2K experiment.

The LLR group is also actively participating to the analyses of WAGASCI data. In addition to the analysis using the Water Module, already described in Sect. 4.2, another analysis using first WAGASCI off-axis data is being pursued by one PhD student at LLR. The goal of this analysis is to extract CC cross sections (with or without an additional charged pion in the final state) on water, hydrocarbon as well as their ratio. Neutrino cross-sections analyses performed by IN2P3 members (including those done using FGD1+FGD2) will allow a better understanding of the underlying physics across various off-axis angles *i.e.* various neutrino energy spectra.

5 The phase II of T2K

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

The most recent results of T2K show intriguing hints that CP symmetry might be violated in the lepton sector. These results are obtained with statistics of 2.2×10^{21} p.o.t., corresponding to about 30% 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.

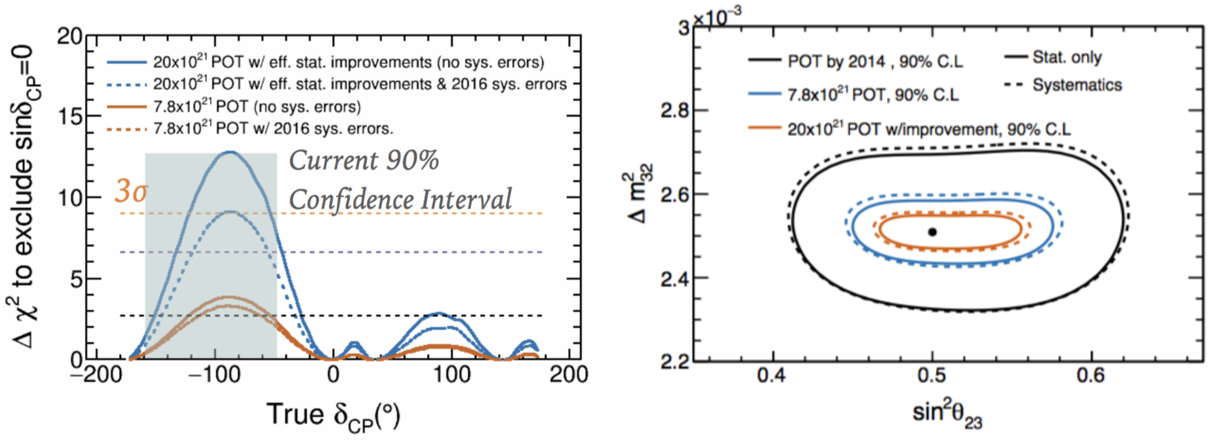


Figure 16: Left: Expected T2K-II sensitivity to $\delta_{\rm CP}$ assuming the mass ordering is not known. Right: Expected T2K-II sensitivity to θ_{23} and Δm^2_{32}.

These goals can be achieved by T2K (and NOνA) before the next generation of experiments will be operational if the following conditions are satisfied:

1. more statistics have to be collected by the two experiments;
2. better understanding of flux and cross-sections systematic uncertainties;
3. combination of the T2K and NOνA oscillation analyses.

Conditions #1 and #3 are related since both involve adding statistics to the oscillation analyses. The T2K and NOνA collaborations plan to perform a combined oscillation analysis by 2021. This combination will provide the best possible constraint on the mass ordering and on CP violation. T2K and NOνA, while being sensitive to the same oscillation parameters, have different baselines (295 versus 810 km) and different neutrino energies (600 MeV versus 2 GeV). A proper combination of the two experiments is then mandatory to obtain reliable measurements of these fundamental parameters of the neutrino mixing. This will require a large amount of work in order to unify the neutrino flux prediction, to define a common model for the neutrino cross-section, able to describe neutrino cross-sections in the

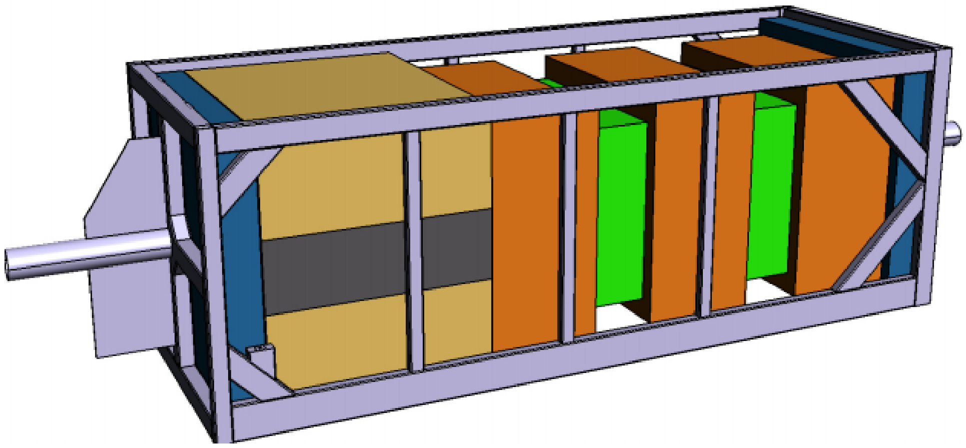


Figure 17: Sketch of the ND280 upgrade project. In the upstream part of the detector (on the left in the drawing) two horizontal TPCs with a scintillator module in the middle will be installed. In the downstream part, the tracker system composed by three TPCs (orange) and the two FGDs (green) will remain unchanged.

whole energy range of interest, from 300 MeV to 3–4 GeV and finally to identify a common way to propagate the constraints from the near detectors to the far detectors. In T2K several near detector samples are used to constraint the flux and cross-section model while in the case of NOνA they have identical detectors and they directly use the reconstructed energy spectra at the near detector to obtain the predicted energy spectra at the far detector. The two approaches have strengths and weaknesses and a common way of propagating uncertainties will have to be developed in order to combine the oscillation analyses. Common working groups are being established between the two collaboration and the IN2P3 groups participating to T2K plan to be involved in this effort.

In order to fulfill the condition #1, 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 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 [43]. Such statistics will be collected thanks to a program of accelerator upgrades that is the highest priority of KEK and J-PARC [44] and that will allow to reach a power of 800 kW in 2020 and 1.3 MW a few years later (to be compared with 485 kW currently achieved).

The need for the condition #2 is also clear from Fig. 16. 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 the 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 T2K collaboration has launched an upgrade project for the Near Detector [45], aimed at overcoming the known limitations of the current design of ND280. The ND280 upgrade group consists of 218 physicists from 45 laboratories (mostly European and Japanese groups already involved in the construction and operation of ND280).

As shown in Sect. 3, ND280 has been extremely useful to select clean sample of ν_μ and $\overline{\nu}_\mu$ interactions thanks to the presence of the magnetic field and to the TPCs capable of reconstructing the momentum and the charge of the lepton produced in neutrino interactions. The analysis of the data collected so far also showed some limitations of the current ND280 design that mainly concern the reduced angular acceptance of the detector.

Super-Kamiokande, thanks to its cylindrical shape and large size, in fact, has an efficiency in selecting neutrino interactions that is independent on the lepton direction. The geometrical configuration of the ND280 tracker (see Fig. 17) with TPCs installed downstream the FGD, instead, allows to select with excellent efficiency tracks emitted parallel to the beam direction but this efficiency rapidly drops with

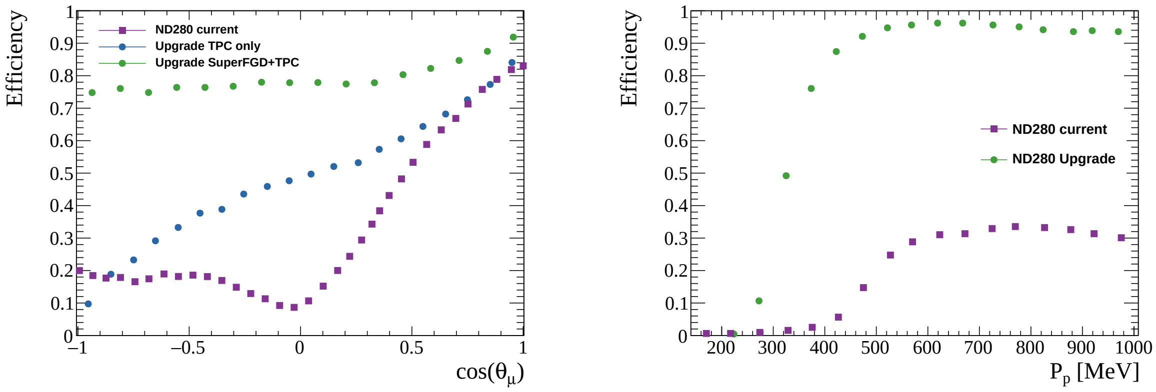


Figure 18: Left: Muon selection efficiency as a function of $\cos\theta$ for the current ND280 detector and for the upgraded Near Detector. Blue points show the efficiency by requiring the muon to enter the TPC while for the green points only the SuperFGD is used for the track reconstruction and particle identification. Right: efficiency to reconstruct protons as a function of outgoing proton momentum for the current and the upgraded ND280.

the angle with respect to the beam, being close to zero for $\cos\theta \leq 0.4$ (where θ is the angle between the emitted lepton and the beam). This means that, when ND280 data are used to constrain flux and cross section uncertainties in the oscillation analysis, the data driven constraints obtained in the forward region are extrapolated to the high angle and backward regions by using cross section models, naturally bringing additional sources of uncertainties to the oscillation analyses.

Other important limitations of ND280, also briefly discussed in Sect. 4.3, are its low efficiency in selecting electron neutrinos with energies below 1 GeV coupled with the relatively small mass of the tracker system, and the low efficiency in reconstructing low momenta protons. To overcome these limitations, an upgrade of ND280 is proposed. The baseline proposal (see Fig. 17), which achieves 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 favoured option for this detector is the Super-FGD concept, consisting of small scintillator cubes each read-out by three WLS fibers. Two new TPCs cover the large angles and measure charge, momenta and deposited energy of charged particles, and time-of-flight detectors allow rejection of out of fiducial volume events.

As shown in Fig. 18, 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 ($\sim$ 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 IN2P3 groups are currently participating in the optimization of the design for the Near Detector upgrade. In particular we are performing the studies to investigate the impact of such upgrade on the T2K oscillation analysis. A comparison between the capability of constraining flux and cross-section systematics between the current ND280 design and its upgraded version is shown in Fig. 19. According to these studies the uncertainty on the event rates at Super-Kamiokande will be reduced by $\sim$ 30% after the upgrade.

In addition to the better efficiency in reconstructing charged particles, the high granularity of the SuperFGD will allow for a detailed reconstruction of the hadronic part of the neutrino interaction. Several studies are also on-going to address the capability of the upgrade to distinguish between different cross-section models. This includes a simulation of the measure of imbalances in the plane transverse to the incoming neutrino [36] using the ND280 upgrade. This study reveals that the SuperFGD's low proton momentum threshold and high angular acceptance will facilitate an unprecedented probe of the aspects of neutrino-nucleus interactions most pertinent to long-baseline neutrino oscillation analysis,

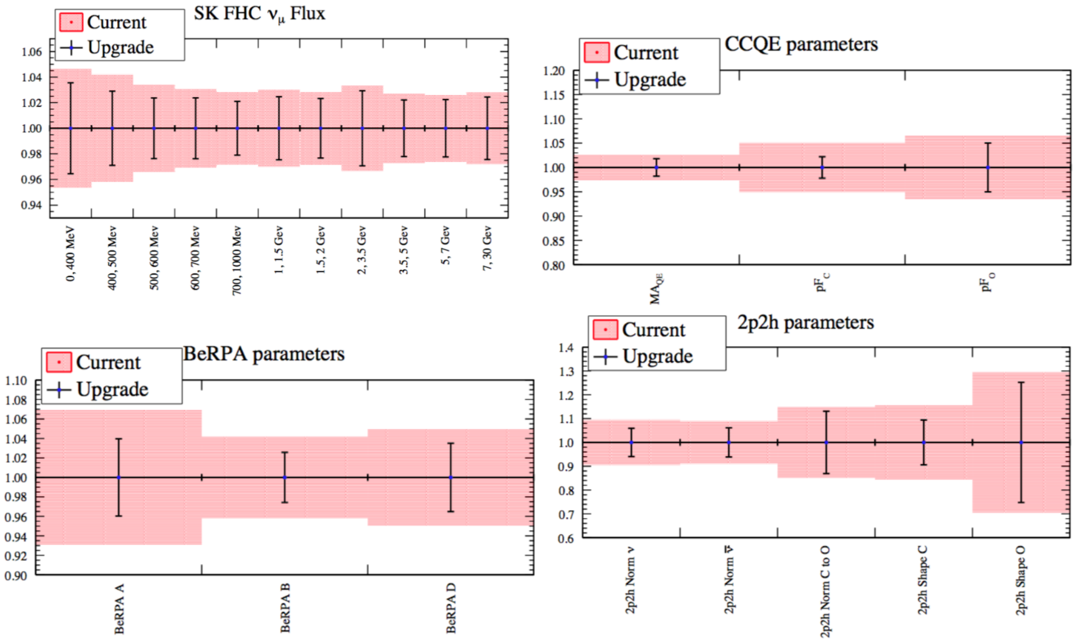


Figure 19: Errors after the ND280 fit on flux and cross-section parameters for the current ND280 configuration (red bars) and the upgraded one (blue dots). The number of POT assumed for the two simulations is the same.

such as Fermi motion, 2p2h and final state hadronic re-interactions (FSI). This is demonstrated in Fig. 20, which shows the ability of the SuperFGD (and HATPCs) to perform such a measurement. Of particular interest is the ability of the observable $\delta\alpha_T$, which describes the direction of the transverse imbalance, to clearly distinguish the impact of FSI in the SuperFGD, whereas this would be much less clear in the ND280 FGD design with only two readout planes. The studies suggest that a high statistics multi-differential SuperFGD measurement of $\delta\alpha_T$ and δp_T (the momentum imbalance between the outgoing lepton and highest momentum proton) could allow a novel distinction of 2p2h and FSI effects, thereby allowing a more direct probe of the effects responsible for some of the largest systematics in the oscillation analyses. These studies will continue to develop with a view to further exploring the physics potential of the ND280 upgrade.

As described in Sect. 5.2 and 5.3 we also propose to participate to the construction of the SuperFGD and of the new horizontal TPCs.

5.2 Super–FGD and its electronics

The Super–FGD (Super–Fine Grained Detector) will act as the target for the neutrino interaction as well as the detector to reconstruct the tracks around the interaction vertex. It needs to have a sufficiently large mass to provide a high number of neutrino interactions, comparable to the 2000 kg total mass of the current FGD. Its acceptance must account for charged leptons (muons and electrons) from charged current interactions that match the surrounding TPCs. In addition, it must allow to reconstruct and identify short tracks of low energy hadrons around the interaction vertex. The dimensions of the detector under consideration is approximately 1.8 m(W) $\times$ 2.0m(L) $\times$ 0.6m(H), corresponding to about two tons of target mass for neutrino interactions.

The detector will be based on plastic scintillators read out via wavelength shifting fibers, which is a technology commonly used for the existing INGRID and ND280 detectors. Considering the importance of the target mass and the detection of low energy hadrons, the preferable detector design is based on a fully active scintillator target. Recently, a novel idea of a fine grained fully-active plastic scintillator detector made of many optically independent cubes was proposed by members of the collaboration [51]. The detector design, called Super-FGD, consists of $1 \times 1 \times 1$ cm^3 cubes of extruded scintillator read

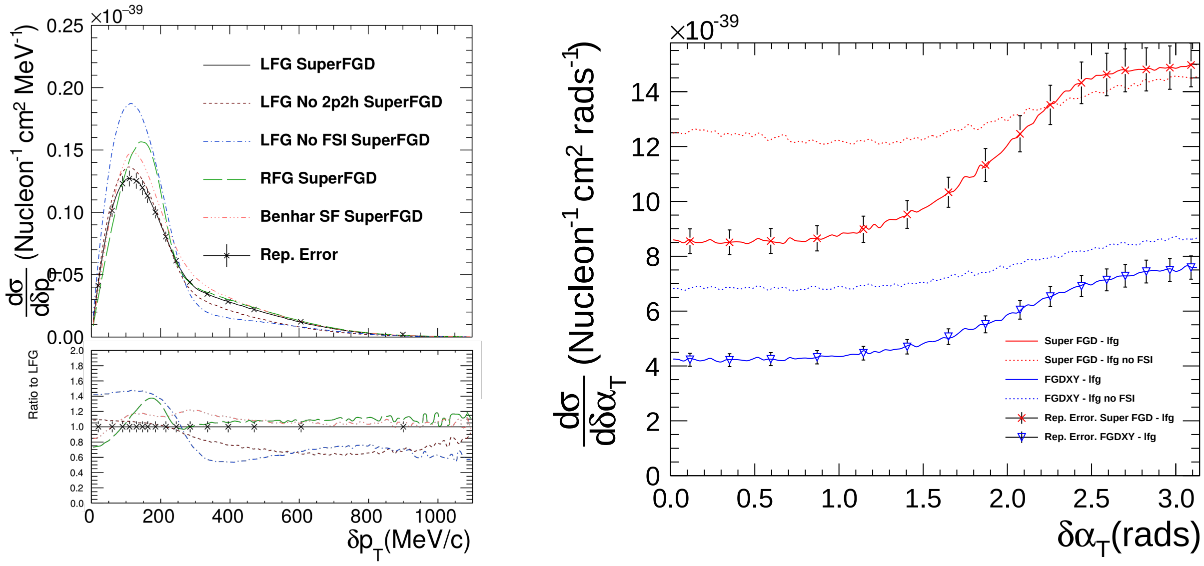


Figure 20: Left: the data points show a simulation of the ability of the ND280 upgrade to measure the momentum imbalance between the outgoing lepton and highest momentum proton (δp_T) under realistic assumptions of the tracking thresholds, resolution and available statistics. The lines show a variety of different nuclear models from the NEUT 5.4.0 simulation. The plot below shows the same information but as a ratio to the LFG model. Right: a comparison of a the sensitivity a measurement of $\delta\alpha_T$ (related to the direction of the transverse imbalance, see [36] for a complete definition) would have to FSI processes in the SuperFGD and for an FGD with only two readout planes (FGDXY). A much greater shape difference can be seen in the former case.

out along three orthogonal directions by wavelength shifting (WLS) fibers. A schematic view of this concept is displayed in Figure 21. The candidate scintillator is a composition of a polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP. The cubes produced by Uniplast, a company in Vladimir, Russia, are covered by a 50 μm thick chemical reflector. Each cube has three orthogonal cylindrical holes of 1.5 mm diameter drilled along X, Y and Z axes. Three 1.0 mm diameter WLS fibers are inserted through these holes. Tests of this design have been performed by the Russian team, and pictures of small assemblies of cubes are shown in Figure 22.

Kuraray Y11(200) wavelength shifting (WLS) fiber will be used to collect light from the scintillator cubes, as it is widely used in recent neutrino detectors, and its performance is well established as a standard. One end of each fiber can be mirrored to increase the photon yield, if necessary. As a photosensor for scintillation light detection, we plan to use Multi-Pixel Photon Counters (MPPC) produced by Hamamatsu Photonics, as they have been successfully used in all of scintillator based detectors in the current ND280. The preferred version is the new surface-mounted S13360-1325PE, which has a 1.3×1.3 mm^2 active area made of 2668 pixels, and presents a very low dark noise rate (typically 70 kHz for a 1/2 photoelectron threshold). Two proposals have been made for the readout electronics of this detector. The first one is based on the Baby-Mind detector presently running as a part of the WAGASCI detector, and has been developed by the T2K team at the University of Geneva. The second one is **an alternative solution, proposed by the LLR team**, which is based on the readout and acquisition system that has been developed for ILC/CALICE that was already adapted by LLR for the water module of WAGASCI. This alternative proposal will be detailed hereafter.

The mechanics and integration will be a challenge, as the Super–FGD detector consists of about two millions of plastic scintillator cubes, which we do not plan to glue to each other in order to avoid possible damages to the coating. Furthermore, given the very large number of cubes, gluing all of them would increase the assembly time by a non-negligible amount. A box that contains all the cubes is needed. It must be strong enough to keep the cubes in place, and support about 2 tons. It must also resist to the mechanical stresses during the shipment or due to earthquakes. The current design of the box is based

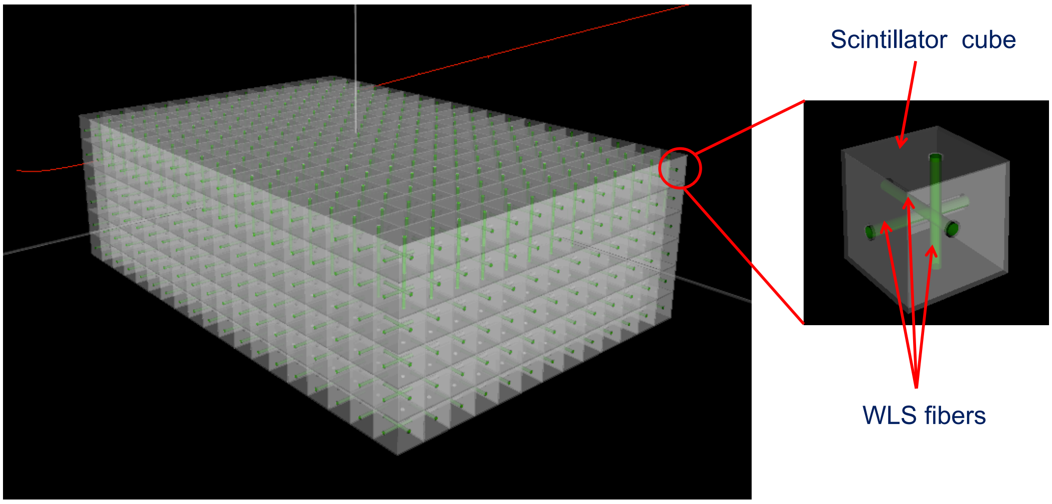


Figure 21: Schematic of the super-FGD structure.

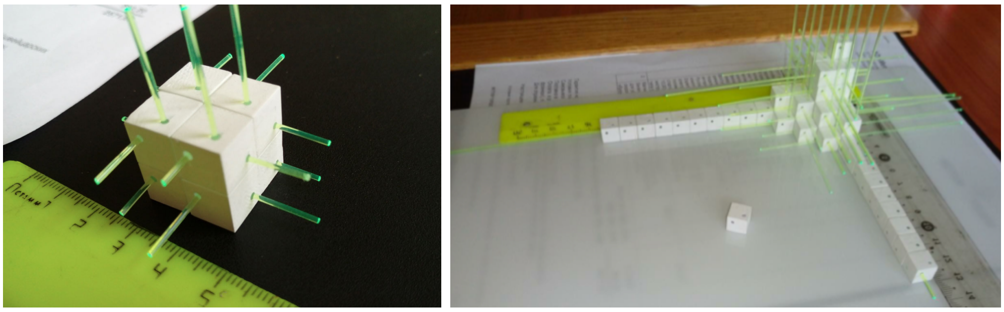


Figure 22: Picture of a small Super-FGD prototype . Several cubes of extruded plastic scintillator with three fibers inserted in the three holes are assembled. The size of each cube is $1 \times 1 \times 1$ cm^3.

on panels consisting of a 30 mm thick AIREX layer sandwiched between two 2 mm thick carbon-fiber skins. From preliminary finite element analysis simulation studies, we expect a maximum deformation of 1.7 mm in the middle of the bottom panel. The AIREX material has a very low density (about 60 kg/m^3), and provides a good rigidity combined with a very low material budget, which is needed in order to minimize particle multiple scattering in between the Super–FGD and the surrounding TPCs. Inside the box, a soft foam material will be used to fill the remaining empty space and keep the cubes in place. The readout system will be placed outside the box, and in all panels except the bottom one that supports the structure, holes will be drilled in order to let the WLS fibers exit the box and bring the light to the corresponding MPPC. This principle design still needs a full mechanics and integration study, which has been started at CERN and University of Geneva, and **for which the expertise of the LLR mechanics team in carbon fiber structures could indeed be very useful. The exact needs and the possibilities for LLR to participate in these studies have not been precisely evaluated at the time this report is being written. These elements will be detailed during the presentation to the IN2P3 scientific council**.

The readout system proposed by the LLR team is based on the Omega SPIROC(2E) chip, used together with the generic readout and DAQ system that has been developed for the ultra-granular calorimetry part of the ILD/ILC project (CALICE)[52], and which is shown in Figure 23. This design, which is scalable to a huge number of channels, comprises the very front-end electronics that can in principle be made of up to ~ 200 chained readout chips, each chain being read out by "DIF" boards. Up to 7 DIF boards are read out by "GDCC" boards which directly communicate with the DAQ computer. For the very front-end electronics, the 36 channel SPIROC readout chip combines high precision time measurement and dual-gain charge measurement with power pulsing capabilities, and is therefore well adapted to the T2K beam time structure (one beam spill made of 8 bunches spaced by 580 ns, with a

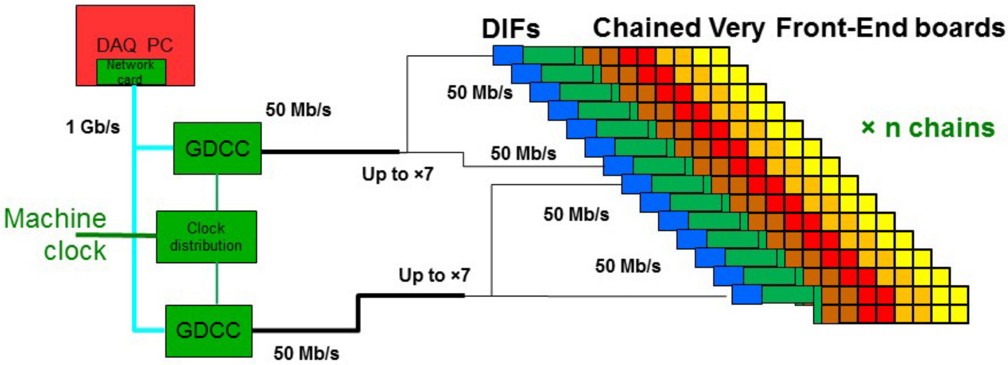


Figure 23: Schematic view of the readout and DAQ system developed for the ultra-granular calorimetry at the future International Linear Collider (adapted from [52]). For the proposed Super–FGD detector, the original silicon slabs will be replaced by chains of about 20 boards hosting 4 SPIROC(2E) chips, each chain corresponding to the readout of $\sim$ 3000 MPPCs.

repetition cycle of 2.5 s). In our proposal, electronic boards, each comprising 144 MPPCs and 4 SPIROC chips (low profile BGA) and covering a surface of 12×12 cm^2, will be used to cover the complete surface of the top and side panels of the Super–FGD box. Each chain of $\sim$ 20 of these boards will be read out by one DIF board, located on the side of the detector to avoid increasing the material budget. The DIF board signals will be conveyed by standard HDMI cables to the GDCC boards, located out of the UA1 magnet. This feature is important, as the GDCC is where the main FPGA chip resides, and a failing board will be easier to replace if it is not enclosed inside the magnet. Furthermore, the GDCC board has not been designed to be compatible with the 0.2 T magnetic field. The SPIROC chip stores the signal in a 16 column analog memory array, each column comprising 2×36 cells for the charge (one for each gain) and 36 cells for the time measurement, also stored as a charge by means of a dedicated internal voltage ramp. A column is used every time one of the 36 channels presents a signal above a given programmable threshold during a cycle of the master clock. We propose to adapt the master clock frequency to synchronize it with the beam bunch spacing of 580 ns. This way, each one of the 8 beam bunch fills at maximum one column, and several columns are left available to record signal arising in the few microseconds after the beam, allowing therefore to record tracks form the so-called “Michel electrons” created by muon decay. The signals are then digitized and sent to the DIF boards in between beam spills. The total time needed to read the data might vary from a few milliseconds to a few tenths of a seconds, depending on the detector occupancy, and therefore on the exact value we choose for the programmable chip threshold. Due to the very low interaction rate, only a few tracks are present in the whole detector during the entire beam spill, and the signal pile-up is therefore very unlikely, given the very high granularity of this detector. Of course, the probability of having two particles giving a signal in the same fiber during a clock cycle and the overall detector occupancy are expected to be very small, but the exact corresponding numbers are still being studied by simulations. The basic design comprises about 60000 channels, more than 400 boards and 1600 chips. Splitting the detector in four parts is preferable to be able to access to the boards if needed, but introduces more mechanical integration complexity and possibly dead zones. If this option is finally preferred, the number of channels is increased to about 80000 channels, 600 boards and 2400 SPIROC chips, depending on the exact dimensions of the detector. Figure 24 shows a possible arrangement of the very front-end boards around the (four quarters) detector, which minimizes the material budget by deporting the DIF boards on both sides and the GDCCs outside the magnet. For this number of channels, only 7 DIF and one GDCC boards are needed for each quarter. The total power dissipation does not exceed 700 W spread over the 8 m^2 of the entire detector with no use of the power-pulsing capability of the chips, which allows air cooling and therefore matches the low material budget constrain.

We presently consider that our proposed design is preferable as compared to the design proposed by the team at the University of Geneva, which is based on the CITIROC chip, as the latter has no

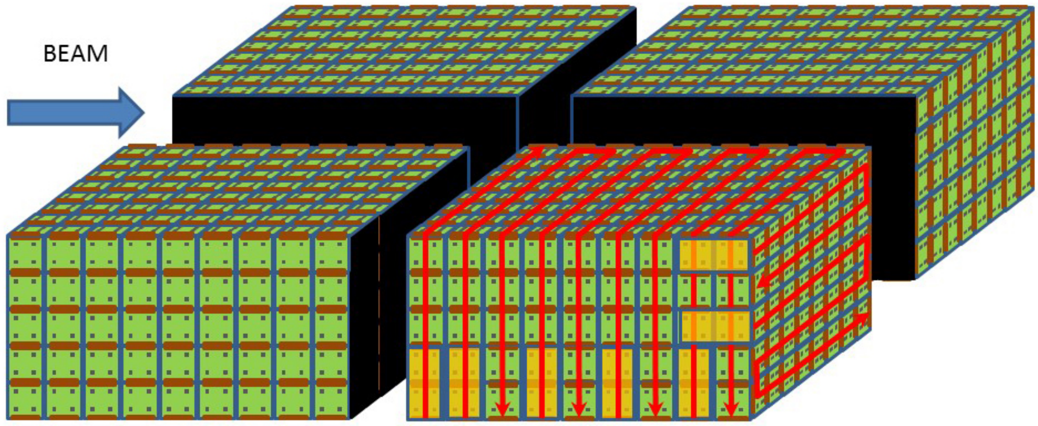


Figure 24: Schematic view of the proposed arrangement for the very front-end boards. Each quarter of the detector is read out on the top and external side panels. For each quadrant, the 7 chains of ~ 20 boards are connected to 7 DIF boards (represented in yellow on the lower right quadrant), which are in turn connected to one GDCC board (located outside of the magnet) by means of standard HDMI cables (not shown).

built-in time measurement and the TDC capability has therefore to be implemented in external FPGAs, as it has been done for Baby-Mind. The presence of a FPGA for ~4 chips on the very front-end boards is not favored, as it increases both the material budget and the power dissipation by a huge factor, and is difficult to make compatible with the magnetic field. A way to cope with these constrains is to extract the analog signal of the MPPCs on a ~10-15m distance and place all the electronics outside the magnet, which would necessitate to use thin flex cables and very dense connectors to ensure a good signal integrity for all 80000 channels, together with low material budget.

Both options are still being studied by a dedicated task force within the collaboration, and a decision is expected before the convening of the IN2P3 scientific council.

5.3 Horizontal TPCs and their electronics

The existing ND280 TPCs [46] have been extremely useful in providing crucial information for the event reconstruction and the analysis:

- track reconstruction in 3D. All other detectors have coarser granularity and projected position information (mostly in the x or y directions). Therefore TPC tracks are used as pivot in the reconstruction.
- momentum and charge measurement through the curvature in the magnetic field;
- particle identification by combining dE/dx with momentum measurement.

The performance obtained with the existing TPC has been completely satisfactory and no substantial improvement is needed. The requirement on the momentum resolution is rather loose, 10% at 1 GeV/c. This translates into a space point resolution around 800 μm for a magnetic field of 0.2 T, 72 space points and a track length of 72 cm in the forward region. The requirement on the momentum resolution is easily satisfied in the high angle and backward direction, where tracks have lower momenta, around 500 MeV/c and down to 200 MeV/c.

Another important requirement is related to the separation of electrons from muons for the measurement of the ν_e cross-section. Since the ν_e flux represents only approximately 1 % of the total neutrino flux, an excellent e-μ separation is needed and the TPC particle identification is crucial for this task. We have achieved, in the existing TPC, a resolution of 8% on minimum ionizing particles for the dE/dx measurement and this performance is sufficient for the ν_e studies [29], providing approximately 4 σ separation between electrons and muons. As the resolution on dE/dx is largely driven by the track

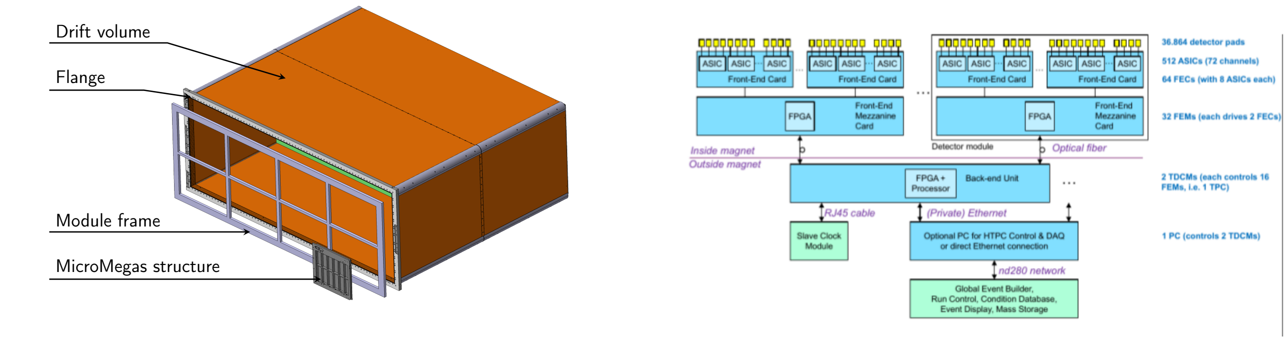


Figure 25: Left: Schematic view of the High-Angle TPC. Right: architecture of the readout system of the TPC.

length L (the dependence is roughly $\sigma \propto 1/\sqrt{L}$), we conclude that we also need a measured track length of approximately 70 cm in the vertical direction.

Following these considerations, the design of the new TPCs is mainly based on the design of the existing TPCs with two major changes:

- the Micromegas detector will be constructed with the "resistive bulk" technique, that naturally introduces a spread in the charge on the anode plane, thereby allowing in principle a lower density of readout pads. This technique allows also to eliminate the discharges (sparks) and therefore the protecting diodes on the Front-End Cards are no longer necessary.
- The field cage will be realised with a layer of solid insulator mounted on a composite material. This will minimize the dead space and maximize the tracking volume.

A schematic view of a High-Angle (HA) TPC module is presented in Fig. 25.

The LPNHE group had already contributed to the electronics of the current TPC and will contribute to the new ones, by building the Front End Cards (FECs).

The readout architecture is, in fact, based on the replication of the modular structure used to read out each Micromegas detector module. The front-end electronics is composed of two types of electronic boards: the Front-End Cards (FEC) capture the analog signals of the pads of each detector module and convert the acquired samples in digital format using a fast multi-channel analog to digital converter (ADC). Elementary data processing such as baseline offset correction, zero-suppression and temporary storage is performed by the Front-End Mezzanine card (FEM) which is connected to the number of FECs required to read out one detector module. In order to minimize the degradation of the highly sensitive detector analog signals and avoid the high cost of cables, the FECs and the FEM are directly mounted at the back of detector modules, as it is done for the existing TPCs.

The FECs support the AFTER chips (already used for the existing TPCs) that amplify detector pad signals and sample them in an analog memory (511-bucket switched capacitor array) which is digitized by a commercial 25 MHz 12-bit ADC when a trigger occurs. The resistive Micromegas detectors allows to reduce the number of channels per detector module from 1728 pads to 1152 pads and the anti-spark protection circuit currently used on every channel will no longer be needed. We expect that the corresponding reduction in channel count and board area for passive components will allow a sufficient reduction of the size of the FECs to mount them parallel to the detector sensitive plane instead of the significantly less compact perpendicular orientation used on the existing TPCs. We also plan to double the number of AFTER chips per front-end card from four to eight, so that only two 576-channel FECs per resistive Micromegas detector module will be required instead of the six 288-channel FECs used for the metallic Micromegas detectors of the current TPCs. A total of about 80 FECs, including spares, will have to be built to readout the two new TPCs.

5.4 NA61/SHINE beyond 2020

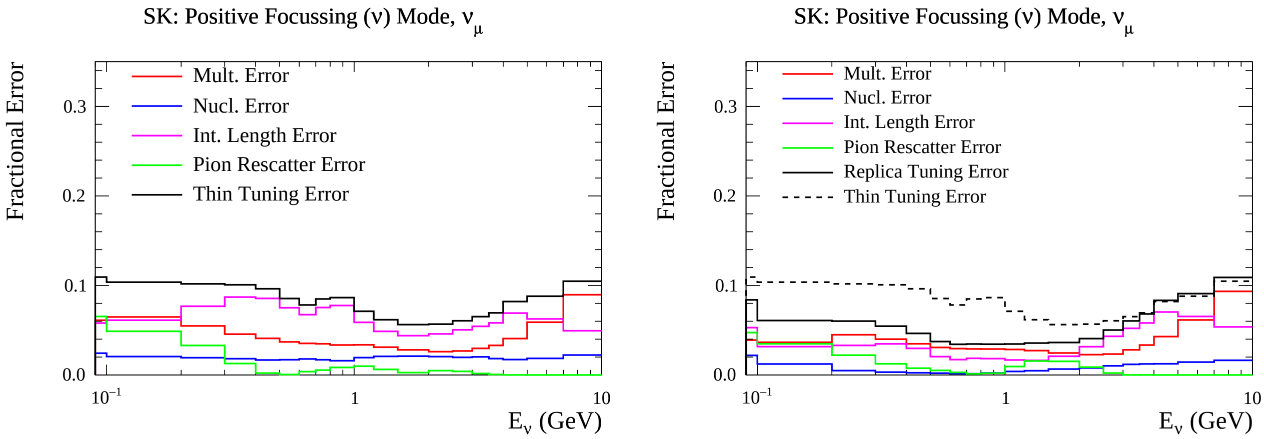


Figure 26: The hadron interaction model uncertainties evaluated on the SK flux prediction. The uncertainties have been calculated for the flux constrained with either purely NA61/SHINE 2009 thin-target data (left side), or using a combination of NA61/SHINE 2009 thin-target and replica-target data (right side, denoted as the replica tuning error).

During the recent 'NA61 beyond 2020' workshop [26] the importance of hadron production measurements for on-going 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 [15, 16, 17, 11] have been crucial for T2K to reduce (anti-)neutrino flux uncertainties down to $\approx$ 10%, and further improvements - by a factor of two (see Fig. 26) - are expected soon [27], as the T2K replica-target results [19, 20] are added to the T2K's flux model. Moreover, additional improvement is expected with the 2010 replica target data [21]. 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.

The SPS beam group has discussed constructing a tertiary hadron beam-line for beams at very low momenta ($<$ 12 GeV/c). Measurements with these low-energy particles could be very important for future high-precision T2K 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 475 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. Whether new measurements with the existing T2K replica target are needed will be concluded after introducing the NA61/SHINE 2010 replica-target results [21] in the T2K beam simulation. The design of new targets for the future high-intensity long-baseline neutrino experiments (DUNE and Hyper-K) is in progress now. Prototype long targets could possibly be available in 2022 and beyond.

Additional tracking detectors will improve the precision of long-target measurements, especially for the very long targets for DUNE. The target could be surrounded by a set of tracking detectors to pinpoint low-angle tracks from the upstream end of the target.

A detailed document with an updated scientific program has been recently submitted by the NA61/SHINE collaboration to the CERN SPS [28] for evaluation and beam request after the LS2.

6 Super-Kamiokande

In February of 1987, the Kamiokande detector (with IMB and Baksan detectors) detected the world's first neutrinos from a supernova burst. Since then, no supernova explosion has occurred in or near our galaxy. Supernova explosions provide a huge source of neutrino flux, neutrinos carrying about 99% of the binding energy released during the collapse of the star. Even if in our galaxy, they may be fairly rare (current estimation is about three per century), it is estimated that about 10^{17} supernova explosions have occurred over the entire history of the universe, yielding about one supernova explosion every second somewhere in the universe. The low energy neutrinos (typically below 100 MeV) emitted from these past and present events have suffused the universe, with a flux estimation of about few tens/cm^2/sec [53]. This so-far unobserved neutrinos flux is usually referred as the Diffuse Supernova Neutrino Background (DSNB), also known as the "relic" supernova neutrinos. Its detection would provide important insights into cosmology, the history of star formation, nucleosynthesis, and stellar evolution. Furthermore, the study of supernova bursts, which produce and disperse elements heavier than Helium, is vital to understand many aspects of the present Universe.

The detection of the supernova relic neutrinos and supernova burst neutrinos constitutes a major challenge for the Super-Kamiokande (SK) experiment. Supernova bursts generate all types of neutrinos, howeverelectron anti-neutrinos are the most copiously detected neutrinos in a water Cherenkov detector like SK. About 88% of the detectable supernova neutrino events are inverse beta decays (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$, ending up with a positron and a neutron in the final state.

SK has previously carried out searches for DSNB from the expected positrons detection (through the emission of the Cherenkov light) without requiring the detection of a delayed neutron and only a integral flux upper limit was set (current best limit) for neutrinos energy threshold $E_{\bar{\nu}_e} > 17.3$ MeV [54]. Since the detector cannot directly differentiate electrons from positrons, these searches suffer from background of electrons and positrons explaining such a large threshold. However, many background channels do not produce neutrons and therefore, the detection of both the positron and the neutron in coincidence, would improve the obtained limit by lowering down the threshold. A recent SK analysis in which the neutron was tagged by its capture on hydrogen thanks to the single 2.2 MeV photon emitted was published [55] but it did not improve the DSNB limit because it suffers from a low tagging efficiency of about 18% leading to poor statistics. Another promising approach first proposed in [56] involves doping the water with a water-soluble chemical compound of Gadolinium ($Gd_2(SO_4)_3$ and referred as Gd below). The neutron capture on Gd benefits from a large cross-section and yields a gamma cascade after the capture reaction with a total energy of about 8 MeV which is much easier to detect (tagging efficiency of about 80% expected). The coincident detection of a positron's Cherenkov light, followed shortly thereafter in roughly the same place by a shower of gamma rays, will serve to positively identify $\bar{\nu}_e$ from IBD in the detector. As shown in Figure 27, the coincident signal from DSNB would be visible on top of the backgrounds in a typical energy range of the positron of the order of 10-20 MeV. In order to achieve such an ambitious goal, a SK-Gd small prototype called EGADS, with a tank volume of 200 m^3, was built in 2013 and tested these last years. The positive results (no loss of water transparency etc.) led the SK collaboration to approve the Gd project in 2015. The schedule of the project includes refurbishment of the SK tank and the progressive Gd-loading up to a 0.2% concentration. The work on the detector starts in June 2018 and LLR who joined the SK collaboration in November 2016 is fully involved in the upgrade work of this phase. LLR members will spend several months working on the detector

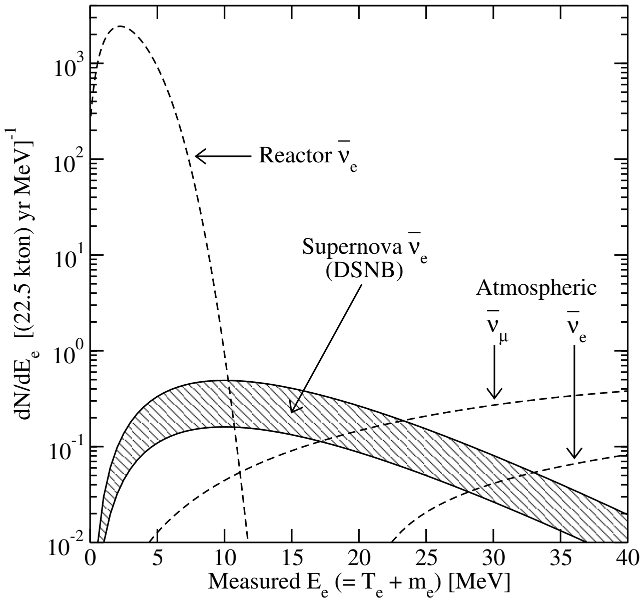


Figure 27: Spectra of low energy $\bar{\nu}_e + p \to e^+ + n$ coincident signals in SK. From [56].

this summer and funding from École polytechnique (for a total amount of 140 000 euros for the two years 2018-2019) is used to contribute to the repair of the detector and various upgrades including the photomultipliers electronics (power supplies etc.). The target for this phase with Gd is to allow the world's first observation of the DSNB within 10 years of data taking.

Even if the observation of the DSNB is the main motivation for Gd-loading, the neutron tagging will lead to other analyses improvements. Still on supernova analysis, during the Si-burning phase massive stars emits $\nu - \bar{\nu}$ pair to balance the energy production. The easier detection of these $\nu - \bar{\nu}$ would allow to predict an incoming supernova event several hours before the neutrino burst. Other analyses would benefit from the possibility to discriminate ν_e from $\bar{\nu}_e$. For instance for long baseline (T2K), a very high statistics measurement of the electron anti-neutrino flux and spectrum from Japan nuclear power reactors, would allow to improve the determination of the mixing parameters connecting the first two generations of neutrinos. Another example, is the reduction of the background of the proton decay events by one order of magnitude.

In order to contribute actively to all these analyses and in particular to the supernova ones, a new PhD student and a new post-doc will join the LLR group this summer. Contributions to multiple-messengers analyses (detection of a burst of neutrinos after a gravitational wave signal) are also envisaged.

7 Hyper-Kamiokande

7.1 Physics case

On the longer term, two next-generation long-baseline neutrino oscillation experiments are planned to start taking data in the second half of 2020s [47]: **DUNE** in the US and **Hyper-Kamiokande** (Hyper-K or HK) in Japan. The two experiments have the common goals of measuring the $\delta_{\rm CP}$ phase and the mass ordering but using different experimental techniques (LAr vs Water Cherenkov), different neutrino energies (E_ν ~2 GeV for DUNE and E_ν ~600 MeV for HK), and different baselines (1300 km for DUNE and 295 km for HK), hence being highly complementary.

DUNE, thanks to its longer baseline, will provide a clean determination of the mass ordering. Both experiments expect to discover CP violation at more than 5σ (3σ) for the 50% (75%) of the values of $\delta_{\rm CP}$ as shown in Fig. 28. An independent comparison of experiments' sensitivities can be found in a recent study [48].

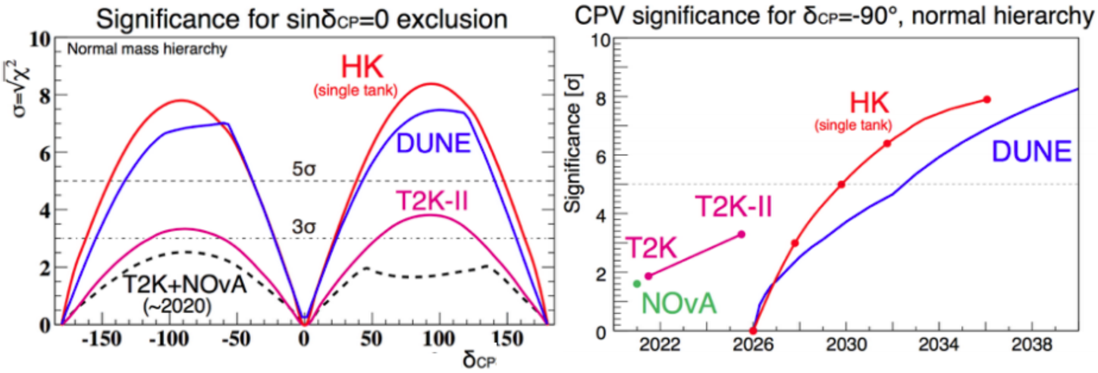


Figure 28: Left: Expected sensitivity to exclude sin$\delta_{\rm CP}$ =0 as a function of the true value of $\delta_{\rm CP}$ for T2K+NOνA, T2K-II, DUNE and Hyper-K after 10 years exposure. Right: Expected sensitivity to exclude sin$\delta_{\rm CP}$ =0 if $\delta_{\rm CP}$ = -$\pi/2$ and the ordering is normal as a function of time.

While we believe that the successful construction and exploitation of both experiments is mandatory for the neutrino community, it has recently become clear to the members of the LPNHE and LLR neutrino groups that the Hyper-Kamiokande project is the most attractive option in order to pursue their scientific activities.

The already proven water Cherenkov technology represents a realistic approach. The larger size of HK makes it the most sensitive experiment to rare events such as the proton decay or neutrinos from supernova explosion. Finally, our past, on-going and future contributions to the T2K and T2K-II projects are important investments and make it rather natural to continue with HK.

The HK project is well advanced and has good chances to be approved by the Japanese government in the nearest future. Full participation in the HK experiment will also open the possibility to enlarge the group experience by studying also solar, atmospheric, supernovae neutrinos and by performing combined analyses of accelerator neutrino and anti-neutrino data with measurements of (anti-)neutrinos from natural sources.

The advantage of such staged and incremental proposal, is that, while getting full experience with a precision neutrino oscillation experiment like T2K and T2K-II, they allow us to work on beam design studies, detector R&D's and physics potential at each stage.

Hyper-Kamiokande [49] is a proposed next-generation general purpose neutrino detection experiment whose broad physics programme covers many areas of particle and astroparticle physics. Based on the proven technology of (Super-)Kamiokande, its much larger detector volume and additional improvements in key areas like photosensors and near/intermediate detectors make HK a straightforward yet powerful extension of the very successful Japan-based neutrino programme.

HK consists of an underground water Cherenkov detector that will be located about 8 km south of the Super-Kamiokande in the Tochibora mine with an overburden of 1750 m.w.e. The detector will be cylindrical (60 m high and 74 m in diameter) and have a fiducial (total) mass of 187 (260) kton, making it more than 8 (5) times as large as its predecessor. HK will use 40,000 photomultiplier tubes (PMTs), thus reaching the same 40 % photocoverage as SK, and benefit from newly designed high-efficiency PMTs.

Construction is expected to take eight years, with start of operations planned for 2026. The option to add a second detector soon afterwards is actively being explored.

While the second detector could be located in Japan at the same site as the first one, the alternative possibility of building the second tank in Korea was explored in a white paper published recently [50]. In addition to sensitivity improvements for the long-baseline experiment, the Korean candidate sites offer a higher overburden (and thus lower spallation backgrounds) than the Japanese HK site, which would increase sensitivity to low-energy rare events like for instance supernova relic neutrinos.

A new 50 cm PMT model, the Hamamatsu R12860-HQE, was developed for HK. It is based on Hamamatsus R3600 PMT used in SK, but includes a box-and-line dynode and several other improvements. As a result, this new model offers better timing resolution and twice the detection efficiency due to improvements in both quantum efficiency and collection efficiency. Work to reduce the dark noise rate and design new PMT covers for pressure resistance is currently on-going.

We are currently investigating possible contributions to the HK project that will be described in the next section. These discussions also involve our colleagues from CEA (Saclay) in order to define a common french hardware contribution. Let us stress once again that a significant involvement in the ND280 upgrade can be considered as a hardware contribution to the future HK project.

7.2 Possible Contributions for 20-inch PMT electronics

7.2.1 Introduction

The front-end electronics modules for the detectors are required to digitize all signals from photo-sensors that are above a certain threshold, i.e. the acquisition needs to be self-triggered. The digitized information is then either recorded or discarded, depending on the decision of the detector-wide trigger system.

The photo-sensor for the inner detector of HK is newly developed. In the baseline option, around 20,000 20-inch PMT R12860-HQE are used. The R12860-HQE PMT has better timing and charge resolution compared to the same diameter PMT (R3600), which has been used in SK. The dark (noise) rate is required not to exceed 4 kHz, which is a similar requirement to the R3600PMT. Based on this information, we have estimated the total data rate and concluded that it is possible to design the data acquisition system, which is similar to the concept of the SK-IV DAQ.

If we locate the front-end electronics modules on the top of the detector, it is necessary to run the cable from the PMT to the roof and the detector structure has to support the weight of the cables, which is expected to be 800 tons. Thus, it would be possible to simplify the detector structure if we can reduce the weight of the cables. Also, the maximum length of the cable is ∼30% longer than in the SK case. This not only reduces the signal amplitude, but also degrades the quality of the signal – the leading edge is smoothed out due to higher attenuation of the cable in the high frequency region. Therefore, we plan to place the modules with the front-end electronics and power supplies for the photo-sensors in the water, close to the photo-sensors.

7.2.2 Current design

The current baseline design of the front-end module is prepared considering these requirements. The schematic diagram of the front-end module is shown in Figure 29.

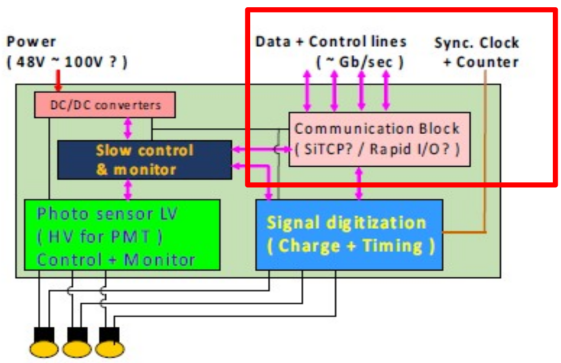


Figure 29: Schematic diagram of the front-end module with the possible contribution from IN2P3 highlighted by the red rectangle.

There are 4 main function blocks in the front-end board. The signal digitization block, the photo-sensor power supply block, the slow control block and the communication block. In the current baseline design, one module accepts signals from 24 photo-sensors, digitizes them and sends out the data.

The signal digitization block accepts the signals from the photo-sensors and converts them to the digital timing and charge data. One possible way to satisfy the requirements is to employ charge-to-time conversion (QTC) chips. The QTC chip receives the signal from the photo-sensor and produces a digital

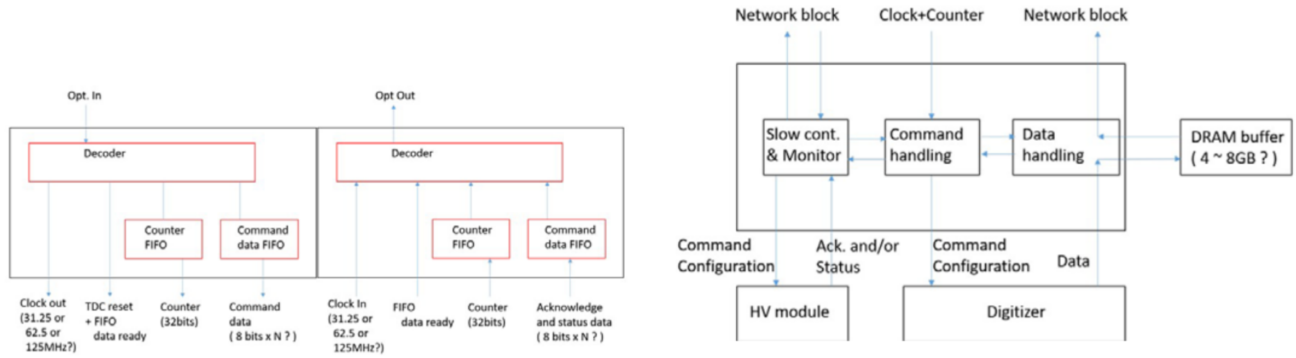


Figure 30: Possible diagrams of the clock and counter modules (left) and simplified schematic of the communication module (right).

signal, whose width is linearly dependent on the amount of the input charge. The leading edge of the output digital signal corresponds to the time when the input signal exceeded the pre-defined threshold to produce the output digital signal. The output signal from the QTC is read out by a TDC. The QTC chips (CLC101) used in the front-end module of SK-IV, called the QBEE, are a good reference and satisfy all the requirements.

Even though the current baseline design is to use the QTC-TDC approach, we are also investigating the possibility of adopting Flash-ADC (FADC) type digitization. In this case, the FADC chip would run all the time and digitize the input signal. Afterwards, FPGA-based on-the-fly digital signal processing would be utilized to find the PMT pulse and determine its charge and time of arrival. An advantage of this approach is that it is completely dead-time free – we would be able to detect photons both from prompt muons and from decay electrons, even if this occurs only 100 ns after the initial interaction. We may also be able to distinguish photons from direct and reflected light. The disadvantage is potentially larger power consumption and higher cost.

7.2.3 Contributions from IN2P3

Our foreseen contributions could be the parts in the red rectangle shown in Figure 29. We do have in our electronic group experts regarding these parts.

The main components are trimming synchronization, data handling and communication.

Synchronization of the timing of each TDC or FADC is crucial for precise measurement of the timing of photon arrival. In Hyper-Kamiokande, timing resolution of the photo-sensor is expected to be largely improved. Therefore, we have to be careful with the synchronization of the modules – the design should minimize the clock jitter, so that the timing resolution of the whole system is as good as possible. We are planning to distribute the common system clock and the reference counter to all the modules.

Possible diagrams of the clock and counter modules are shown in Figure 30.

Regarding the communication block, in order to reduce the amount of cables, we are planning to connect the modules in a mesh topology, with each module connected to its neighbours. Only the top modules would be connected to the readout computers. Each module will have several communication ports, so that a single point of failure would be avoided. In case of failure of one of the modules, the data would simply be re-routed to one of the neighbours, thus ensuring that communication path will be secured.

The communication module is expected to have the following functionalities:

- receive the commands from the DAQ system and control the digitizer,
- return the status of the request from the DAQ system,
- receive the data from digitizer, keep them in the local DRAM buffer, and transmit to the DAQ system,

- receive the commands from the slow control/monitor system and control or monitor the slow control
- return the status of the request from the slow control/monitor system.

A simplified schematic diagram of the communication module is shown in Figure 30.

7.2.4 Schedule

Current plan from the finalization of the design to the completion of the production and tests is shown in Tab. 2.

Spring 2020	Final design review of the system
Autumn 2020	Start the design of the system based on the design review
Autumn 2021	Start bidding procedure
Autumn 2022	Start mass production
Autumn 2023	Start final system test
Autumn 2024	Complete mass production
Autumn 2025	Complete system test and get ready for install

Table 2: Schedule for design and production of Front–end modules for 20-inch PMT electronics

7.3 Possible contributions for multi–PMTs

In addition to this baseline design, R&D on alternative photosensor options like hybrid photo-detectors, LAPPDs and multi-PMT modules is actively being carried on by several countries (mostly Canada, Italy, UK) with the goal of providing half of the photo–cathode coverage for Hyper-Kamiokande.

In particular the multi–PMTs option, based on design developed for Km3Net is particularly appealing, with the possible design of having the half sphere looking at the outer detector equipped with 6 3" PMTs and the half sphere looking at the inner detector equipped with 19 3" PMTs.

In this context there is some interest in using the existing Memphyno water tank [58] at APC for performing underwater tests of the multi-PMT modules developed in Europe. There is also a possibility of contributing to the development of electronics for the multi–PMTs readout based on a chip designed by the Omega laboratory.

8 Summary and requests to IN2P3

This document briefly describes the past, on-going and potential future contributions of the IN2P3 (LLR and LPNHE) groups to the Japanese neutrino programme. World-leading measurements of neutrino oscillation parameters in the T2K and SK experiments will be further reinforced after the planned near detector ND280 upgrade. Conclusive measurements of CP violation in the lepton sector could be performed within the T2K-II project first, and with the planned Hyper-Kamiokande detector in the future.

With this document we request an approval from the IN2P3 Scientific Council of the described scientific strategy. The LPNHE Scientific Council has positively reviewed this project in its session of May 2018 and first conclusions are expected to be available by the time of the IN2P3 Scientific Council in June 2018. The LLR Scientific Council will also review this project in June 2018, before the IN2P3 Scientific Council.

Concerning the resources requested from the IN2P3 a summary is shown in Tab. 3. This is an addition to the regular resources needed for our participation to the T2K and SK experiments (common funds, shifts, meetings, etc).

No request for the Super-Kamiokande experiment is presented. The upgrade for detection of supernovas relic neutrinos will be finished by the end of this year. École Polytechnique is supporting this upgrades with a budget of 140 k€ for equipment as detailed in Sect. 6.

Project	Cost
T2K-II TPCs	200 k€
T2K-II Super–FGD	600 k€
NA61++	15 k€(per year)
Hyper–K R&D	40 k€

Table 3: Estimated resources needed for the projects described in this document.

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).

Concerning the ND280 upgrade, the estimated cost of the project to develop and construct the new Front-End-Cards for the horizontal TPCs within the ND280 upgrade project is about 200 k€. This include also the mechanics and cooling system of the Front-End electronics.

If the LLR option for the Super–FGD electronics is choosen by the collaboration, the total cost of the project is estimated to 600 k€.

Finally for the proposed R&D project for Hyper-Kamiokande the LLR and LPNHE groups will need ∼40 k€ to start buying components and producing cards for prototype activities. An evaluation of the full costs of the project for the Hyper-Kamiokande experiment is not done within this proposal.

If the LLR option for the Super–FGD electronics is choosen by the collaboration, a full time electronics research engineer position will be necessary during three years to adapt the CALICE electronics to the new detector configuration. This person will then develop the electronics for the Hyper-Kamiokande experiment that has been detailed in the previous section. Thus, a permanent position would be preferable. In addition, if it appears that a contribution from LLR is needed for the mechanical structure of the Super–FGD detector, a two years mechanics research engineer position would be required.

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