Report from the LPNHE-neutrino group to the LPNHE Scientific Council

LPNHE Neutrino group

October 23, 2019

Executive Summary

The LPNHE neutrino group joined the Japanese accelerator neutrino program and the T2K experiment in 2006. Originally, the main goal of the T2K project was the measurement of the θ_{13} mixing angle through the observation of ν_e appearance in the ν_μ beam. As this angle turned out to be substantially non-zero, it opened a way to explore the combined charge-parity (CP) symmetry violation in the lepton sector and eventually to measure the CP violating phase δ_{CP}. This is now the primary goal of the second phase of the T2K experiment (T2K-II) currently under preparation as well as of the next generation general-purpose Hyper-Kamiokande (HK) project in Japan.

The group activities have already been reviewed by the LPNHE Scientific Council in May 2018 and by the IN2P3 Scientific Council in June 2018. These councils approved our group's participation in T2K-II and, in particular, our contributions to the near detector (ND280) upgrade. Developments in those activities will be briefly discussed in this document.

A point that was left open after those two meetings was the participation of the LPNHE group, and more generally of IN2P3 physicists, in the Hyper-Kamiokande project. No decisions were taken, mostly due to uncertainties about Japanese funding for Hyper-Kamiokande.

Hyper-Kamiokande is the next generation long-baseline neutrino oscillation experiment based on the well established Water Cherenkov technology to be built in Japan in the next decade.

Contrary to T2K, which had access only to a subset of Super-Kamiokande (SK) data in a small time window around the beam spill, the Hyper-Kamiokande project has a broad physics program covering 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 program.

The detector will have a fiducial mass of 188 kton, 8 times larger than its predecessor Super-Kamiokande. It will be the most sensitive experiment to measure CP violation in the lepton sector, to observe the proton decay and it will also be a gigantic observatory for neutrinos produced in supernovae, in the Sun and in the Earth atmosphere. Clearly, the HK experiment is capable of providing major discoveries in the coming years.

Very recently, in August 2019, the Hyper-Kamiokande project was approved by the Japanese Ministery of Science (MEXT). The construction of Hyper-Kamiokande will begin in April 2020 with a start of data taking expected by 2027. Contributions from the various foreign countries are being discussed now within the collaboration and have to be formalized in the coming months. For this reason, we consider it important to describe in details the Hyper-Kamiokande project and to ask the LPNHE scientific council for an approval of the group's participation in Hyper-Kamiokande experiment.

In this document we present the HK detector, its physics case and discuss the foreseen contributions to the experiment from the LPNHE-neutrino group.

Group members and responsibilities

A list of present and past group members and their responsibilities within the T2K, NA61/SHINE and Hyper-Kamiokande experiments is given below.

Physicists	
Bernard Andrieu	*CNRS-Chargé de Recherche*
Alain Blondel	*CNRS-Directeur de Recherche, started in September 2019*
Jacques Dumarchez	*CNRS-Directeur de Recherche, Group leader till September 2018*
	Magnet and TPC expert; Member of the publication board
Claudio Giganti	*CNRS-Chargé de Recherche*
	TPC expert; Run coordinator;
	Convenor of the T2K oscillation analysis group (until July 2018);
	ND280-upgrade project leader from July 2019
Mathieu Guigue	*SU-Associate Professor, started in September,2018*
	Co-convenor of the ND280 Upgrade Simulation group
Jean-Michel Levy	*CNRS-Chargé de Recherche (benevole)*
Boris Popov	*CNRS-Directeur de Recherche, Group leader from September 2018*
	Magnet and TPC expert; convenor of the T2K-NA61 group
	Co-convenor the T2K-beam group (till February 2018)
	Convenor of the NA61 software and analysis groups
Ciro Riccio	*Invited researcher, during the year of 2019*
Marco Zito	*LPNHE director, started in July 2019*
	ND280-upgrade project leader till July 2019
Viet Nguyen	*PhD student started in October 2019*
???	*New ANR postdoc starting in January 2020*
???	*New "Emergence SU" postdoc starting in 2020*
Previous PhD students	
Laura Zambelli	*PhD student till October 2013*
Pierre Bartet-Friburg	*PhD student till October 2016*
Matej Pavin	*PhD student till October 2017*
Simon Bienstock	*PhD student till October 2018*
Engineers	
Jean-Marc Parraud	*CNRS-Assistant d'ingénieur*
	ND280-upgrade@LPNHE technical coordinator; Design of the FEC board
Eric Pierre	*CNRS-Assistant d'ingénieur*
	CAO for the FEC board
Francois Toussenel	*CNRS-Ingénieur de recherche*
	Verification of the FEC board design and production
Julien Philippe	*CNRS-Ingénieur d'études*
	Mechanics for the new suspension system
Yann Orain	*CNRS-Assistant d'ingénieur*
	Mechanics and cooling for the new FEC boards
Diego Terront	*CNRS-Ingénieur d'études*
	Data acquisition for the new HA-TPCs
Stefano Russo	*CNRS-Ingénieur de recherche*
	Design of the time distribution system for HK

Funding status

Our budget (in k€) obtained from the IN2P3 over the last seven years is summarized in the following table (in parentheses our request for the budget).

year	**T2K+NA61 miss+equip**	**T2K-CF**	**NA61-CF**
2013	33 (60+20)	25	8 (8)
2014	35 (50+10)	22	8 (11)
2015	30 (45+10)	11	10 (10)
2016	36 (50+10)	14	10 (10)
2017	40 (45+10)	17	10 (10)
2018	47 (62+5)	30	10 (10)
2019	40+20 (40+60)	-	15 (15)

Starting from 2019 we are part of JENNIFER-II, an EU funded project to cover scientific trips to Japan from European participants in Japan-based experiments T2K, Hyper-Kamiokande and Belle-II. For LPNHE-neutrino group we obtained 39 k€, corresponding to about 10 months in Japan to be spent during the next 4 years.

Young LPNHE-neutrino group members have also obtained individual grants in 2019. Claudio Giganti obtained an ANR JCJC grant that will allow us to hire a PhD student and a 2-years postdoc with corresponding travel money, while Mathieu Guigue gained an Emergence Sorbonne University grant that will allow to hire a postdoc for 1 year with some money for instrumentation. The ANR project is centered on the analysis of T2K-II data, while the Sorbonne University grant is oriented towards participation in Hyper-Kamiokande.

1 Introduction

After several decades of controversial results, neutrino oscillations, originally proposed by B. Pontecorvo in 1957 [1], were firmly established during the years 1998-2002 by the Super-Kamiokande [2] and the SNO [3] experiments, later confirmed also by KamLAND [4] and K2K [5]. These discoveries have been recognized with the 2015 Nobel Prize in Physics awarded to T. Kajita and A. McDonald.

The discovery of neutrino oscillations started a broad program in which neutrino oscillations have been observed by several experiments using very different neutrino sources and detection techniques [6].

This large variety of experimental results is described within the PMNS framework [7, 8]. The PMNS matrix is a 3×3 unitary mixing matrix, parametrized by three mixing angles, θ_{12}, θ_{23}, θ_{13}, and a CP violating phase, δ_{CP}. The additional parameters governing neutrino oscillations are the squared–mass differences $\Delta m^2_{ij} = m^2_j - m^2_i$, where m_i is the mass of the i-th neutrino mass eigenstate.

The last relevant milestone has been the discovery that also the last unknown mixing angle, θ_{13}, is different from zero. After first indications from T2K in the $\nu_\mu \to \nu_e$ transition [9], θ_{13} was measured to be different from zero in 2012 by Daya Bay [10] and RENO [11]. The T2K experiment has then firmly established the $\nu_\mu \to \nu_e$ appearance in 2013 [12]. This observation can be considered as the beginning of the era of precision measurements of neutrino oscillations with the possibility of investigating sub-leading order effects to determine the neutrino mass ordering (normal vs inverted) and to observe CP violation in the lepton sector, for which measurements in appearance mode are necessary.

In this context, accelerator based long-baseline neutrino experiments play a leading role, thanks to the possibility of tuning the baseline length and the neutrino energy in order to investigate, with maximal precision, the oscillatory behaviour driven by $\Delta \mathrm{m}^2_{32}$, and to the possibility of producing beams predominantly composed of ν or of $\overline{\nu}$ in order to study ν_μ and $\overline{\nu}_\mu$ disappearance and $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance.

The T2K experiment took advantage of a few key elements: the new high intensity proton accelerator at J-PARC (Tokai, Japan), the first use of the off-axis beam technique which allows for a very narrow band neutrino energy spectrum tuned for maximizing the oscillation probability at the far detector, which is the high-performance Super-Kamiokande water Cherenkov detector. A near detector (ND280) was built inside the former UA1/NOMAD magnet in order to precisely measure the beam composition prior to oscillations, to study neutrino interactions and to quantify potential sources of background to the ν_e appearance.

In order to improve the sensitivity of the experiment to δ_{CP}, T2K started anti-neutrino mode data taking in 2014 in order to compare the ν_e and $\bar{\nu}_e$ appearance probabilities. The effect of δ_{CP} is opposite for neutrinos and anti-neutrinos, so that the value of $\delta_{CP} = -\pi/2$ would maximize the ν_e appearance probability and minimize the $\bar{\nu}_e$ appearance probability.

A combined analysis of ν_e and $\bar{\nu}_e$ data has been recently performed by the collaboration. The first direct indication of CP violation in the lepton sector has been obtained with CP-conserving values of $\delta_{CP} = 0$ or π excluded at more than 2σ when T2K data are combined with reactor constraints [13]. Very recently T2K has submitted a paper to Nature in which we reported, for the first time, exclusion of 45% of the possible δ_{CP} values at more than 3σ CL [14].

These results which were obtained with $\sim 40\%$ of T2K approved statistics strengthen the case for a continuation of data taking (T2K-II project) aiming at 20×10^{21} POT in order to establish CP violation at better than 3σ, if the currently favoured value is the true one.

An upgrade of the T2K off-axis near detector ND280 is being prepared and the participation of the LPNHE neutrino group in this activity has been approved in 2018 by both, the LPNHE Scientific Council and the IN2P3 Scientific Council. Following these approval, financial and human ressources have been allocated by the IN2P3 and by the LPNHE directorate to the T2K-II and ND280-upgrade. The upgrade project and progress towards its realization will be described in Sect. 3.2.

1.1 Recommendations from LPNHE and IN2P3 Scientific Council

We recall here the conclusions and the recommandations of the 2018 Scientific Councils [15, 16] and we briefly discuss the actions taken by the group. More details will be given in Sect. 3.

LPNHE Scientific Council : Recommandations

Le conseil félicite le groupe pour l'importance et la qualité de ses contributions et salue sa visibilité dans la collaboration T2K. Il encourage le groupe à poursuivre les projets engagés sur l'upgrade de T2K mais reste vigilant sur l'évolution du calendrier de la future prise de données qui pourrait etre retardée et sur la confirmation du financement d'Hyper-K. Compte tenu de ces aléas, le conseil encourage le groupe à ne pas perdre de vue l'évolution de DUNE.

Concernant HyperK, le conseil encourage le groupe à se rapprocher de l'APC dans le cadre de la fédération APC-LLR-LPNHE en cours de constitution pour explorer la faisabilité d'une contribution sur les tests des modules optiques en immersion. Bien que le groupe soit assisté par deux ITA en électronique pour l'upgrade de T2K, le conseil remarque que ce support est faible compte tenu des tâches envisagées et de la charge existante des ITA concernés. Cependant, le conseil comprend que les contraintes induites pas les développements actuels au laboratoire ne permettent pas une grande augmentation du support local. Il souhaite donc que les activités techniques du groupe puissent être menées en cohérence avec les autres laboratoires de l'IN2P3 et le CEA.

Le conseil se félicite du recrutement du maitre de conférences SU qui viendra renforcer le groupe à l'automne 2018. Puisqu'un autre recrutement en poste permanent dans le groupe n'interviendra pas avant quelques années, le conseil encourage le groupe à rester focalisé sur les activités actuelles et à recruter des postes CDD. Il encourage également le groupe à recruter des doctorants, y compris en recherchant activement des sources de financements en complément de ceux de l'ED STEP'UP.

IN2P3 Scientific Council : Recommandations - T2K

Les groupes francais proposent de participer aux prochaines phases de T2K selon un programme scientifique et technique cohérent et ciblé sur les réductions d'effets systématiques et basé sur l'expertise mise en œuvre dans le projet T2K dès son début avec les détecteurs proches et NA61/Shine. Ce programme de réduction d'effets systématiques, bien que divisé en plusieurs parties propres á chaque laboratoire, est un atout des groupes francais et doit être maintenu et soutenu. Cela serait cependant plus favorable de se mettre sur des participations communes pour plus de visibilité et d'efficacité. Les développements techniques proposés sont adaptés aux expériences des laboratoires impliqués dont les équipes techniques semblent bien dimensionnées. Les améliorations des TPC horizontales, bien qu'ambitieuses, sont relativement bien définies.

IN2P3 Scientific Council : Recommandations - HK

L'expérience HK a des objectifs scientifiques bien établis, de premier ordre, sur le même plan et avec des performances similaires á DUNE, mais avec une technologie différente et un programme différent. La complémentarité des projets est claire et c'est un atout. Le LLR et le LPNHE manifestent un intérêt pour rejoindre HK. Le projet n'est pas actuellement approuvé au Japon et il n'y a pas suffisamment d'informations quant á l'organisation du projet pour envisager et discuter des participations directes á HK. Les pistes de contributions techniques proposées par le LLR et le LPNHE concernent les photomultiplicateurs et leur électronique de lecture. Bien que la *discussion sur HK soit trop prématurée, le projet de regarder les multi-PMTs comme alternative aux PMTs simples est très intéressant en tant que projet R&D, en particulier par la cohérence avec les développements effectués á l'IN2P3 dans le cadre de KM3Net. Le conseil suggère de continuer á suivre l'évolution du projet et aux groupes concernés d'être attentifs á la structuration du projet, relativement floue pour un programme qui prévoit de démarrer rapidement.*

In summary, both councils approved our participation in the T2K-II experiment and in the ND280 upgrade. Following these approvals, LPNHE group members have taken important roles in the ND280 upgrade project. Claudio Giganti has recently been nominated by the collaboration as a coordinator of the ND280-upgrade project replacing Marco Zito who has become the new LPNHE director and a member of the LPNHE-neutrino group. Mathieu Guigue, is now one of the conveners of the software and reconstruction group for the ND280-upgrade. The group has also attracted the well-known physicist Alain Blondel, former professor of Geneva University and our close collaborator in both T2K and NA61/SHINE.

We would like to thank the LPNHE directorate for allocating to this project the engineers needed for our technical involvements in the ND280-upgrade.

Concerning the human ressources, a new PhD student has started his thesis in October,2019 and we recently obtained an ANR JCJC grant, which will allow us to hire a 2-years postdoc and a PhD student in 2020. In addition, we obtained a Sorbonne University Emergence grant for development and tests of multi-PMT modules (mPMTs) for HK that will also allow to hire one postdoc for one year. In order to fully profit from this opportunity it would be very important that the IN2P3 or the LPNHE could complement this funding to transform it into a 2-years postdoc.

We would like to stress that these non-permanent positions do not reduce our need for at least one additional permanent researcher, that should be hired by CNRS to contribute to the ambitious project we describe in this document.

Concerning Hyper-Kamiokande, both councils expressed their scientific interest for the project, asking for further evaluation of the LPNHE and IN2P3 contributions when the financial situation will be clarified by the Japanese government. This clarification arrived in August 2019, when the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) submitted its budget request to the Ministry of Finance (MoF) explicitly including the Hyper-Kamiokande experiment. The released document states: **In addition to the ongoing 13 large-scale projects, the next-generation neutrino research project Hyper-Kamiokande, will be newly launched in FY2020.**

Following this approval, the University of Tokyo, that will be the responsible host laboratory for the construction of Hyper-Kamiokande, has started negotiations with the different funding agencies in order to define possible foreign contributions to the experiment. The IN2P3 directorate will have a meeting with them, to discuss HK, in November 2019 and we believe it is now a good time to ask the LPNHE Scientific Council to approve the neutrino group participation in Hyper-Kamiokande experiment. The foreseen contributions of our group to Hyper-Kamiokande will be detailed in Sect. 3.3.

Let us first present the Hyper-Kamiokande experiment and its physics goals.

2 The Hyper-Kamiokande project

Hyper-Kamiokande [17] is a next generation long-baseline neutrino oscillation experiment that will be built in Japan. One of the main physics goals of the experiment is the discovery of CP violation in the lepton sector, but Hyper-Kamiokande will also be the most sensitive detector to proton decay and will be an observatory for neutrinos from astrophysical sources, such as supernovae neutrinos. As mentioned above, HK has been recently approved in Japan by the

MEXT and the construction will be launched in April 2020. The start of the data taking is foreseen for 2027.

The experiment will exploit the same experimental technique (Water Cherenkov detector) as Super-Kamiokande and, for its long baseline program, it will use the same beamline and hence the same neutrino energy ($E_\nu \sim 600$ MeV) and baseline (295 km) as the T2K experiment, to which IN2P3 and IRFU/DPhP physicists have been participating for more than 15 years. For Hyper-Kamiokande, the accelerator complex will be upgraded to deliver a 1.3 MW beam, more than twice the intensity currently available for T2K.

The well-proven Water Cherenkov technology has already led to two Nobel prizes in physics with the previous detectors of the Kamioka saga. Thanks to its larger size, HK has a sensitivity to measure CP violation at more than 5σ (3σ) for 50% (75%) of the values of CP-violating phase $\delta_{\rm CP}$ and will be a fundamental experiment to bring neutrino oscillation physics into the era of precision measurements. Besides measurements of neutrino oscillations with accelerator, atmospheric and solar neutrinos, the large fiducial volume of HK makes it the most sensitive experiment to rare events such as proton decay or neutrinos from supernovae explosions.

HK constitutes a natural extension of the on-going activities of our groups that will allow most prominent physics outputs, notably a timely discovery of CP violation in the lepton sector and a search for rare events, such as proton decay, with unprecedented sensitivities. As it will be shown in this section, the physics goals of Hyper-Kamiokande are much wider than the ones of T2K, that is limited to measurements within the long-baseline neutrino oscillations program.

Full participation in the Hyper-Kamiokande experiment will then open the possibility to enlarge our 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.

2.1 The Hyper-Kamiokande detector

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, shown in Fig. 1, will be cylindrical (72 m high and 68 m in diameter) and will have a fiducial (total) mass of 188.4 (257.8) kton, making it more than 8 (5) times as large as its predecessor. The option to add a second Water Cherenkov detector, possibly in Korea [18], soon afterwards is actively being explored.

HK will use at least 20,000 photomultiplier tubes (PMTs), providing a 20 % photocoverage as the SK-II configuration, and will benefit from newly designed high-efficiency 20" PMTs, the Hamamatsu R12860-HQE, developed for HK. The design is based on Hamamatsu R3600 PMT used in SK, but includes a box-and-line dynode and several other improvements. This new model offers better timing resolution and twice the detection efficiency due to improvements in both quantum efficiency and collection efficiency.

To complement the 20" PMTs and increase the photocoverage, particularly important for the low-energy physics, the option to add a few thousands of multi-PMT modules (mPMTs) is being actively exploited. The final expected photocoverage in the HK is 40 %, as in the current SK-IV configuration.

The HK experiment will use the (anti)neutrino beam from the J-PARC accelerator complex, which will be upgraded with respect to the T2K beam and will be able to provide a 1.3 MW power proton beam accelerated to 30 GeV by the J-PARC Main Ring synchrotron. The proton beam is extracted to the neutrino beam line where it strikes a graphite target, producing charged hadrons (mostly pions) that are focused and selected in charge by a system of magnetic horns. The hadrons enter a decay-tunnel producing a muon neutrino or antineutrino beam that is sent towards HK. As in the case of Super-Kamiokande, HK will be shifted by 2.5° with respect to the

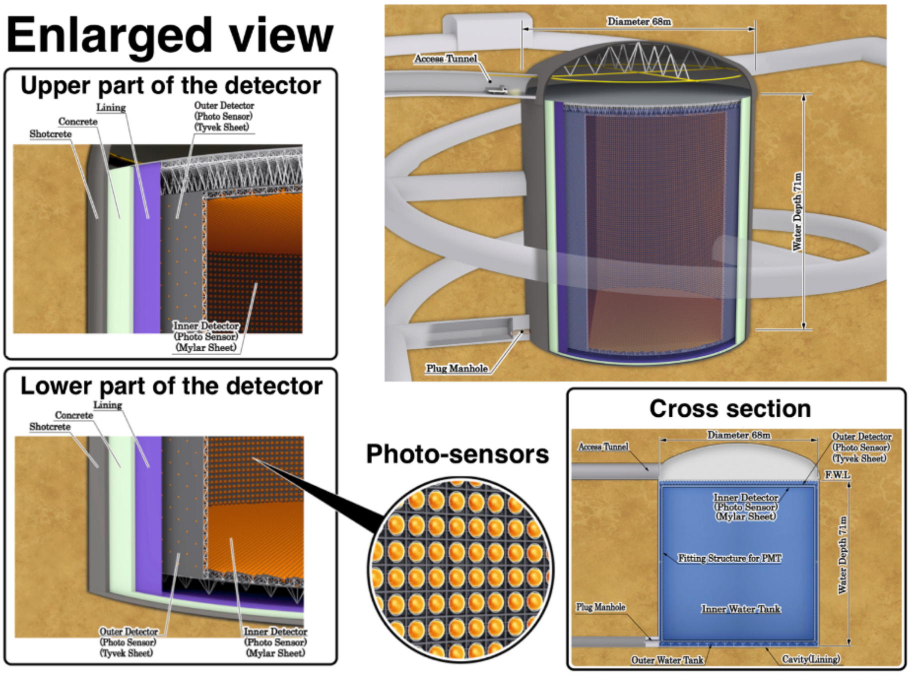

Figure 1: Schematic view of the HK detector.

axis of the neutrino beam.

After the neutrino beam is produced, the neutrino fluxes and interaction cross sections must be measured with near and intermediate detectors. The collaboration plans to use a suite of near detectors to address all systematic effects that are critical for the Hyper-Kamiokande physics program. One of them is the magnetized ND280 off-axis detector that plays the crucial role of reducing flux and cross-section systematic uncertainties for the T2K experiment and is currently being upgraded for the T2K-II phase. It is foreseen that ND280, in its upgraded configuration, will still be running at the beginning of the Hyper-Kamiokande experiment and further upgrades will be considered for a later phase, if it will be required by the Hyper-Kamiokande physics program.

In addition, a new Intermediate Water Cherenkov Detector (IWCD) is proposed for HK. IWCD will be a kiloton scale Water Cherenkov detector (10 m diameter, 8 m height) instrumented with $\sim$ 500 mPMTs. The detector will be located 750 m from the neutrino production target and its elevation in the pit can be varied by controlling the water level of the pit, allowing measurements to be made at varying angles relative to the average neutrino direction, measuring neutrino cross-section at different energies.

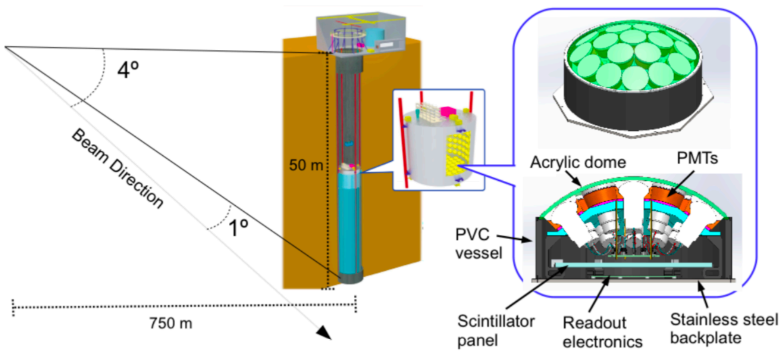

Figure 2: Schematic overview of the IWCD detector.

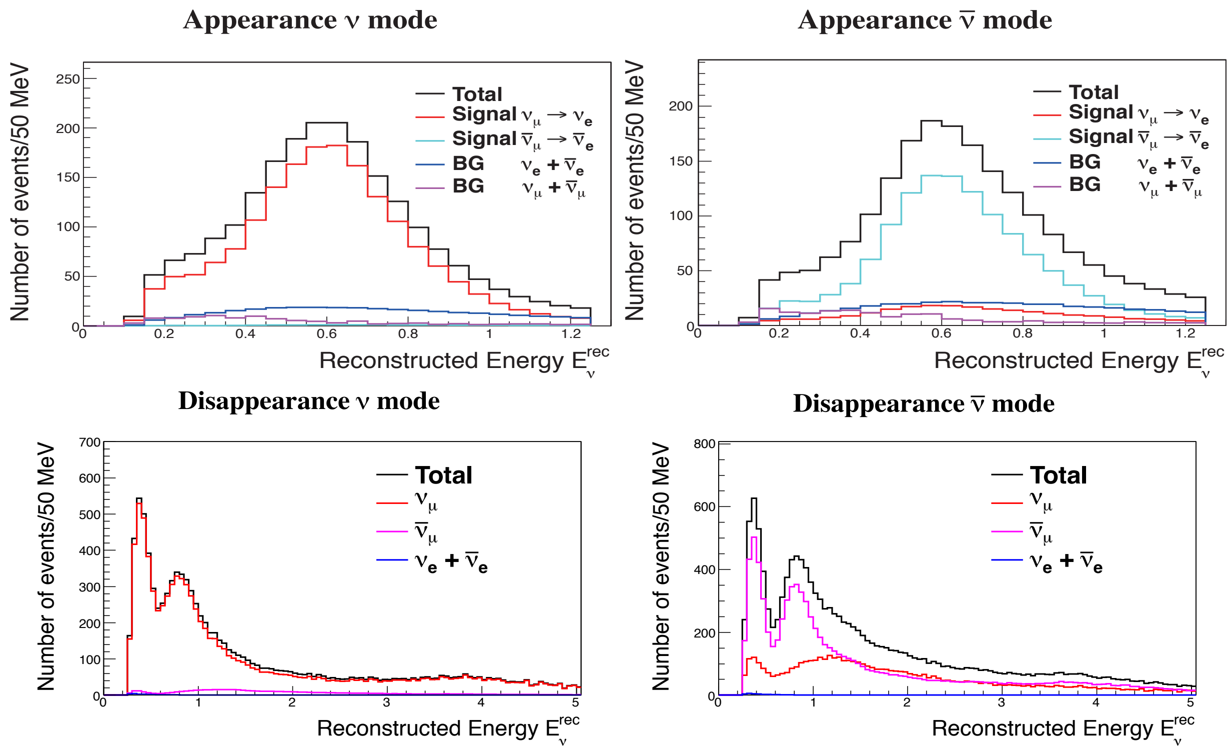

Figure 3: Reconstructed neutrino energy distribution of the ν_e (top) and ν_μ (bottom) candidate events in neutrino beam mode (left) and antineutrino beam mode (right) for 2.7×10^{22} protons on target.

2.2 Neutrino oscillations with Hyper-Kamiokande

The long-baseline neutrino oscillation analysis is one of the main motivation of Hyper-Kamiokande and, based on the T2K experience, is performed by combined fits of the ν_e appearance and ν_μ disappearance channels in ν–mode and $\overline{\nu}$–mode. The main goal of this program is the discovery of CP violation in the lepton sector, that would result in $\delta_{\rm CP}$ being different from 0 or π.

The $\nu_\mu \rightarrow \nu_e$ oscillation channel is the most sensitive to the oscillation parameters $\sin^2\theta_{13}$, nowadays determined with large precision from reactor experiments, and $\delta_{\rm CP}$, although other parameters also contribute to the oscillation probability.

The other main question in neutrino oscillations is whether $\sin^2\theta_{23}$ is maximal or not, and if not, whether θ_{23} is less or greater than $\pi/4$, as it could constrain models of neutrino mass generation and quark-lepton unification [19, 20, 21]. The ν_μ survival probability $P(\nu_\mu \rightarrow \nu_\mu)$ is proportional to $\sin^2 2\theta_{23}$ to first order leading to an octant ambiguity, since for each value of $\theta_{23} \leq 45^\circ$ (in the first octant), there is a value in the second octant ($\theta_{23} > 45^\circ$) that leads to the same oscillation probability. This degeneracy is broken by the measurements in appearance mode, since the amplitude is, in first approximation, proportional to ($\sin^2\theta_{23} \times \sin^2 2\theta_{13}$).

The evaluation of the physics potential of HK is based on the well-known performances of SK and T2K. An integrated beam power of 13 MW$\times 10^7$ sec is assumed, corresponding to 2.7×10^{22} protons on target with 30 GeV J-PARC beam ($\sim$10 years at 1.3 MW). Various ν–mode and $\overline{\nu}$–mode beam running time ratio scenarios have been studied, and a ν:$\overline{\nu}$ ratio of 1:3 is considered here. This will allow to collect $\sim$2000 e–like candidates in ν–mode and in $\overline{\nu}$–mode as shown in Tab. 1. The expected spectra for the appearance and disappearance channels are presented in Fig. 3.

The CP violation effects at Hyper-Kamiokande emerge as up to $\sim$ 30% variations in small ($\sim$ 5%) $\nu_\mu \rightarrow \nu_{\rm e}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities. In order to maximize the benefit of the high statistics neutrino data and enhance the physics capabilities of Hyper-Kamiokande, systematic

Table 1: The expected number of $\nu_e/\overline{\nu}_e$ candidate events for 2.7×10^{22} protons on target and efficiencies with respect to fully-contained fiducial volume (FCFV) events. Background is categorized by the flavor before oscillation.

		signal		BG	Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$		
ν mode	Events	1643	15	400	2058
	Eff.(%)	63.6	47.3	1.6	—
$\bar{\nu}$ mode	Events	206	1183	517	1906
	Eff. (%)	45.0	70.8	1.6	—

uncertainties of the measurement must be suppressed down to a few percent (3 – 4% or below). This includes the interaction model uncertainties, which are the dominant systematic contribution in the existing T2K analysis. In addition to the rate measurement, spectral information will also be important for the precise measurement of oscillation parameters, including δ_{CP}, Δm^2_{32} and $\sin^2\theta_{23}$. For example, as shown in Fig. 4, $\delta_{CP} = 0°$ and 180° can be distinguished from the observed neutrino energy spectrum in the appearance mode. Energy calibration in the Hyper-Kamiokande detector and correct modelling of particle kinematics in neutrino interactions, especially the contribution from non-quasi elastic (non-QE) and multi-nucleon processes, are relevant systematic error sources to the energy scale.

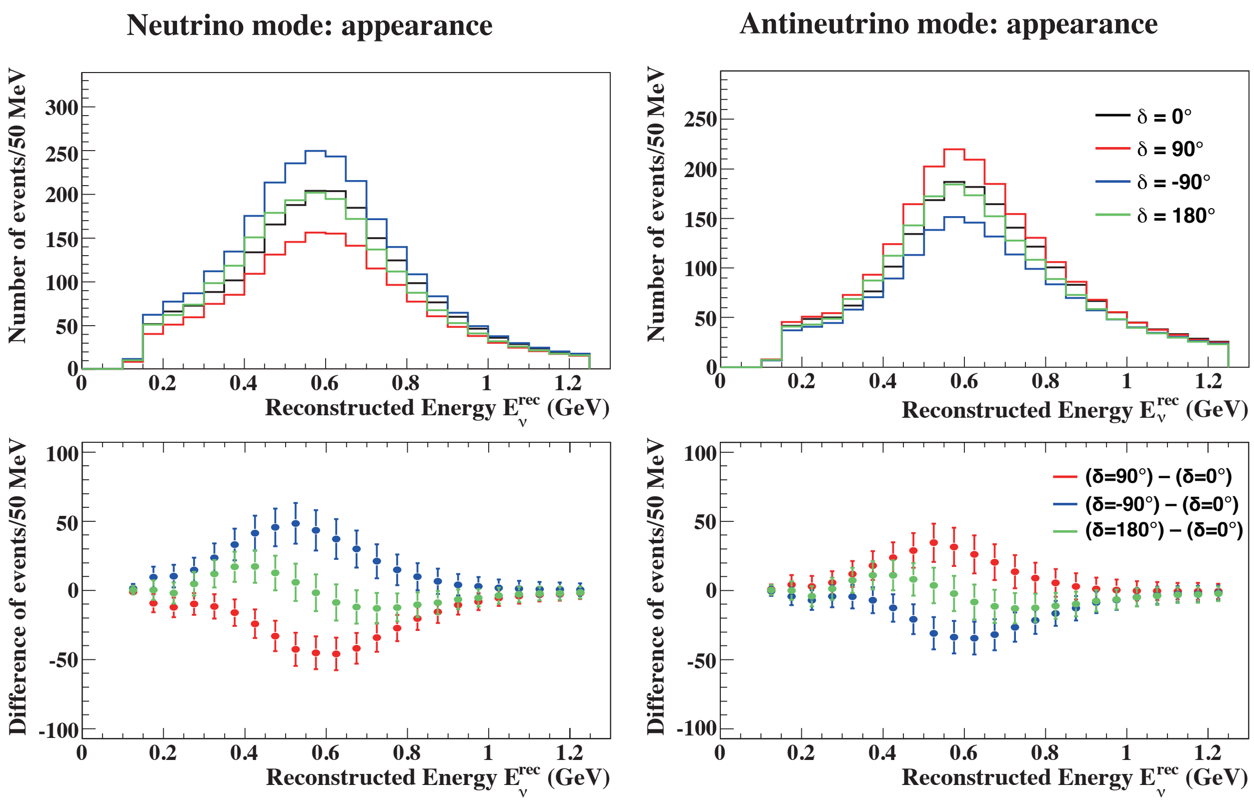

Figure 4: Top: Reconstructed neutrino energy distribution for several values of δ_{CP}. $\sin^2 2\theta_{13} = 0.1$ and normal hierarchy is assumed. Bottom: Difference of the reconstructed neutrino energy distribution from the case with $\delta_{\mathrm{CP}} = 0°$. The error bars represent the statistical uncertainties of each bin.

Based on the experience of T2K, we plan to use a suite of Near Detectors in order to control the systematics uncertainties affecting the measurement of oscillation parameters. As mentioned above, we plan to use the existing magnetized Near Detector (ND280) and a newly built Intermediate Water Cherenkov Detector (IWCD).

The ND280 will be used to measure the beam composition, including the interactions of ν_μ in the $\overline{\nu}$–mode (expected to be ~30% of the total interaction rate), by reconstructing the charge of the lepton emitted in neutrino interactions. In addition, thanks to the excellent segmentation after the Near Detector upgrade, it will be able to reconstruct low momentum particles and to carefully study and characterize the hadronic part of the neutrino interactions.

The IWCD will complement the ND280 measurements, by studying neutrino interactions on water, the same target as Hyper-Kamiokande. Thanks to its large size it will be able to constraint the ν_e/ν_μ cross-section ratio and it will also characterize the neutrino flux at different off-axis angles, from 1 to 4 degrees, in order to probe the relationship between neutrino energy and final state particle multiplicities and kinematics.

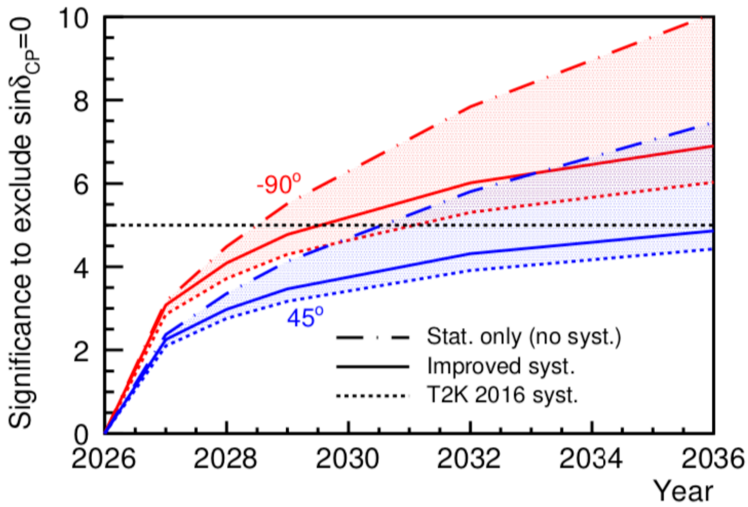

Figure 5: Hyper-Kamiokande sensitivity to CP violation as a function of operation time with the systematic uncertainties from T2K analysis in 2016 (dashed), with the systematic error suppression assumed in the HK Design Report (solid), and without systematic uncertainties (statistical error only, dash-dotted). The cases of $\delta_{CP} = -90°$ (red) and $\delta_{CP} = 45°$ (blue) are presented.

Thanks to this combination of Near Detector measurements a reduction of the systematics uncertainties with respect to T2K analysis is expected (from ~6% to ~ 4%, see [17] for more details). The impact of the systematics uncertainties on the discovery of CP violation is shown in Fig. 5. An improvement of the systematic uncertainties from ~6% to ~ 4% could anticipate the discovery of CP violation by ~1.5 years.

2.3 Proton decay with Hyper-Kamiokande

Grand Unified Theories (GUT) predict proton and bound nucleon decays, both of which are processes that violate baryon number. Such processes have been searched for a long time and Super-Kamiokande has set the strongest limit on the proton-decay with a half-life larger than 10^{34} years [22]. The huge size of Hyper-Kamiokande will make it the most sensitive experiment in the search for the proton decay, surpassing the Super-Kamiokande sensitivity after less than one year of data taking.

In general, GUTs provide interactions that can induce transitions between quarks and leptons and thereby predict a variety of potential nucleon decay modes. The two favorite modes from

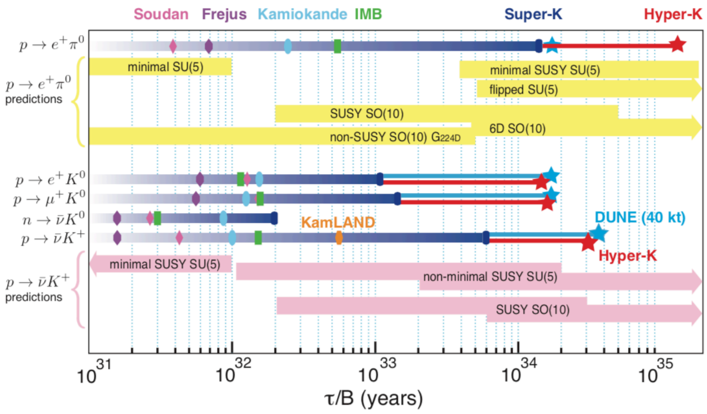

Figure 6: A comparison of historical experimental limits on the rate of nucleon decay for several key modes to indicative ranges of theoretical prediction. Included in the figure are projected limits for Hyper-Kamiokande and DUNE based on 10 years of exposure.

two dominant classes of GUT models are the $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$, but the experiment will have world-leading sensitivity to several other channels, as shown in Fig. 6.

The $p \to e^+\pi^0$ decay has a very clean event topology, with no invisible particles in the final state. As a result, it is possible to fully reconstruct the proton's mass from its decay products.

We require events with an invariant mass close to the one of the proton ($800 < m_{inv} < 1050$ GeV/c^2) and with a low total momentum from the sum of all visible particles. As Hyper-Kamiokande's target material - water - contains both eight protons bound in the oxygen nucleus and two free protons from its hydrogen atoms, separate total momentum cuts are applied to enrich the signal sample. Free protons are expected to decay nearly at rest and as a result the total momentum is required to be $p_{tot} < 100$ MeV/c, whereas bound protons may have non-zero momenta due the Fermi motion and correlated nucleon effects so the threshold is $100 < p_{tot} < 250$ MeV/c.

The primary background to this and all nucleon decay searches is atmospheric neutrinos. Indeed, charged current single-pion production processes such as $\nu_e + n \to e^- + \pi^0 + p$, where the proton is below the Cherenkov threshold, can in principle have the same event topology as the signal.

Table 2 shows the expected signal efficiency and background rates for the $p \to e^+\pi^0$ search together with their systematic uncertainties. The expected invariant mass distribution after 10 years of data taking and for a proton lifetime of 1.7×10^{34} years is shown in Fig. 7.

$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

Table 2: Signal efficiency and background rates as well as estimated systematic uncertainties for the $p \to e^+\pi^0$ analysis at Hyper-K.

Figure 8 shows the 3σ discovery potential for observing a $p \to e^+\pi^0$ signal based on these estimates. Projections from other experiments, including DUNE and Super-K, as well as the expectation for two Hyper-K tanks, the second one starting six years after the first, are shown for comparison. A proton decay signal can be observed at 3σ if the proton lifetime is less than 10^{35} years with a 20 year exposure, surpassing other experiments by nearly an order of magnitude.

The other main decay mode, predicted by supersymmetric GUT models, is the $p \to \bar{\nu}K^+$. Unlike the search for $e^+\pi^0$ events it is not possible to fully reconstruct the initial proton kinematics

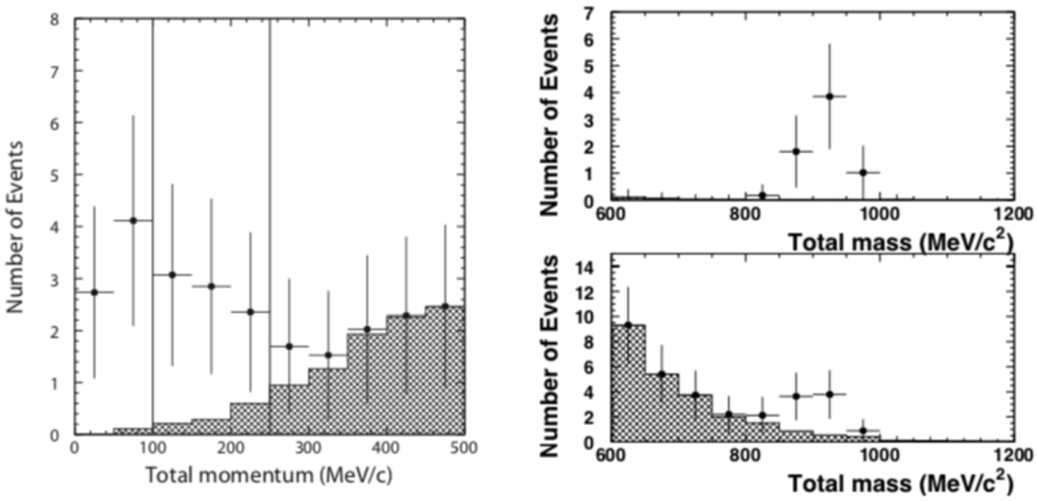

Figure 7: Left: Total momentum distribution for events selected in the $p \to e^+\pi^0$ sample. Right: Invariant mass distribution in two bins of total momentum, $p_{tot} < 100$ MeV/c (top) and $100 < p_{tot} < 250$ MeV/c (bottom). The hatched histograms show the expected atmospheric neutrino beackground while for the signal a proton lifetime of 1.7×10^{34} is assumed.

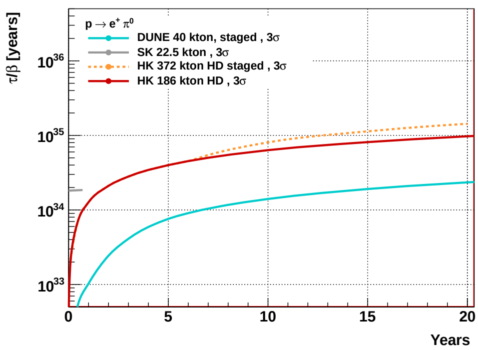

Figure 8: Comparison of the 3σ $p \to e^+\pi^0$ discovery potential as a function of year Hyper-K (red solid) assuming a single tank as well as that of the 40 kton liquid argon detector DUNE (cyan solid) following [23]. In the orange dashed line an additional Hyper-K tank is assumed to come online six years after the start of the experiment. Super-K's discovery potential in 2026 assuming 23 years of data is also shown.

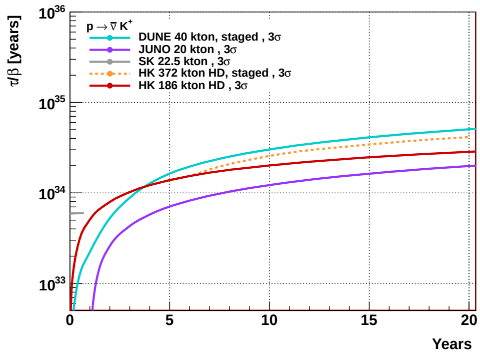

Figure 9: Comparison of the 3σ $p \to \bar{\nu}K^+$ discovery potential as a function of year for the Hyper-K as well as that of the 40 kton DUNE detector (cyan solid) based on [23] and the 20 kton JUNO detector based on [24]. The red line denotes a single Hyper-K tank, while the orange line shows the expectation when a second tank comes online after six years. The expected discovery potential for Super-K by 2026 assuming 23 years of data is also shown.

since the neutrino is essentially invisible to Hyper-K. Further, the kaon is emitted with momentum of 340 MeV/c, which is well below its Cherenkov threshold in water. Searching for this decay mode in Hyper-K is performed based on identifying a monochromatic kaon with the appropriate momentum by reconstructing its decay particles, that can be either a 236 MeV/c muon from the $K^+ \to \nu + \mu^+$ decay mode (64% branching fraction) or the π^0 from the $K^+ \to \pi^+\pi^0$ decay (21%).

Figure 9 shows the 3σ discovery potential as a function of running time for the $p \to \bar{\nu}K^+$ search. This figure compares Hyper-K with other future experiments. Though Hyper-K has a larger total volume its relatively low signal efficiency places its sensitivity between that of DUNE and JUNO experiments. If the proton lifetime is near the current Super-K limit of $\sim 7 \times 10^{34}$ years, Hyper-K would expect to see a signal at 3σ significance in its first three years of running.

2.4 Hyper-Kamiokande as an astrophysical neutrino observatory

Right from the start of their history, the gigantic Water Cherenkov detectors have been particularly successful in detecting neutrinos from astrophysical sources. Back in 1987, Kamiokande detected few neutrinos issued by the famous 1987A Supernova explosion, while in 1998 Super-Kamiokande observed for the first time oscillations of neutrinos produced in the atmosphere and in the Sun. Super-Kamiokande is currently being filled with Gadolinium in order to improve its capability of detecting neutrons with the goal of observing neutrinos from the Supernova remnants.

2.4.1 Neutrinos from Supernova

Hyper-Kamiokande, thanks to its large mass, will detect thousands of $\overline{\nu}_e$ (via inverse β-decay) and ν_e (via elastic scattering) from SN bursts in the galactic center (see Fig. 10). Thanks to the elastic scattering events it will be possible to reconstruct the direction towards a Supernova at a distance of 10 kpc with an accuracy of about 1 degree. The events observed in Hyper-Kamiokande will allow to provide detailed information about the time profile and the energy spectrum for inspecting Supernova explosion mechanism.

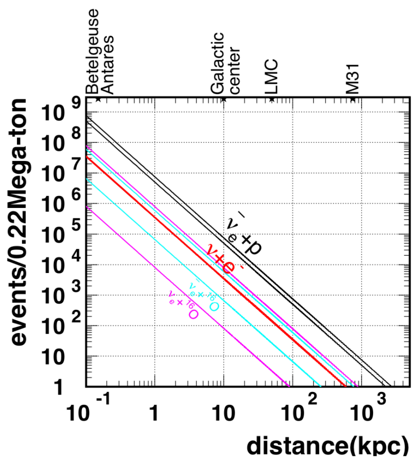

Figure 10: Expected number of supernova burst events for each interaction as a function of the distance to a supernova.

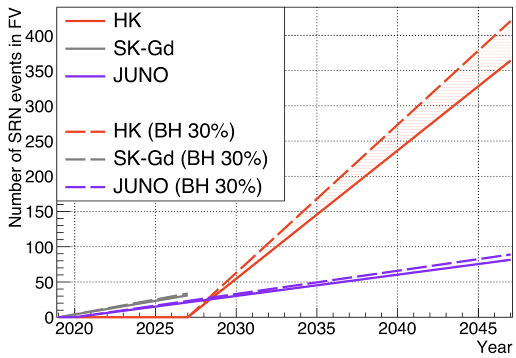

Figure 11: Expected number of inverse beta decay reactions due to supernova relic neutrinos in several experiments as a function of year. The neutrino temperature is assumed to be 6 MeV. Solid line corresponds to the case, in which all the core-collapse supernovae emit neutrinos with the particular energy. Dashed line corresponds to the case, in which 30% of the supernovae form black holes and emit higher energy neutrinos corresponding to the neutrino temperature of 8 MeV.

In addition, it will be possible to detect neutrinos also from extra-galactic Supernova explosions. Even for distances of 4 Mpc, we will observe few tenths of neutrinos in Hyper-Kamiokande and, at such distances, one Supernova is expected every three years.

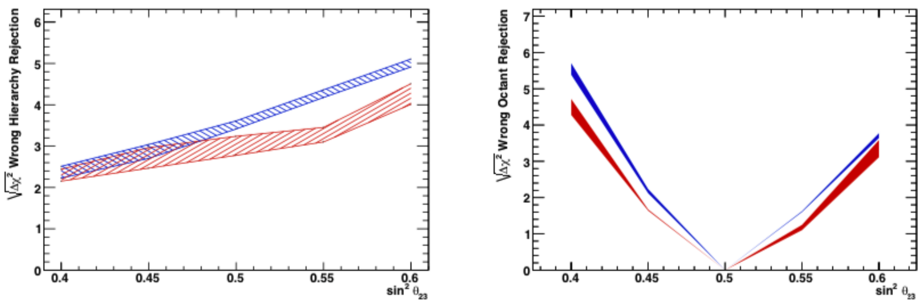

Figure 12: Neutrino mass hierarchy sensitivity (left) and octant sensitivity (right) as a function of the true value of $\sin^2\theta_{23}$. In both figures the blue (red) band denotes the normal (inverted) hierarchy and the uncertainty from $\delta_{\rm CP}$ is shown by the width of the band.

Hyper-Kamiokande will also be able to detect the Supernova relic neutrinos (SRN) that are neutrinos produced by all Supernova explosions since the beginning of the universe. Such neutrinos fill the present universe and have a flux of few tens/cm^2/sec. The observation of SRN would allow to understand how heavy elements have been synthesized in stellar formation and it is the main goal of the SK-Gd project [25].

Even if the observation of SRN is performed at Super-Kamiokande, a mega-ton size experiment such as Hyper-Kamiokande will allow to collect a large statistics of SRN in the energy region between 16 and 30 MeV, the region where the background from spallation products is negligible. The number of expected events detected in Super-Kamiokande, JUNO and Hyper-Kamiokande as a function of time is shown in Fig. 11.

2.4.2 Atmospheric Neutrinos

Hyper-Kamiokande will also collect a large sample of atmospheric neutrinos. Such measurements will complement the long-baseline program and joint analyses between beam and atmospheric neutrinos are planned in order to improve the sensitivity to the mass ordering. The matter effects are, in fact, rather small for the 295 km baseline of Tokai to Hyper-Kamiokande and the experiment will have limited sensitivity to the mass ordering.

Several experiments, running and planned, are trying to determine the mass ordering so we expect that it will be determined before the beginning of Hyper-Kamiokande operation. In case it will not, the combination of atmospheric and beam neutrinos will allow to determine the ordering with the sensitivity shown in Fig. 12. Such combination will also improve the sensitivity to the octant of $\sin^2\theta_{23}$.

2.4.3 Solar Neutrinos

As in the case of Super-Kamiokande, Hyper-Kamiokande will detect solar neutrinos from the ^{8}B with an energy threshold of few MeV. The main output of the Hyper-Kamiokande solar neutrino program will be the observation of the spectrum upturn, that could clarify the 2σ tension currently observed in the determination of Δm^2_{12} between solar and reactor experiments shown in Fig. 13.

In order to observe the solar upturn it will be necessary to decrease as much as possible the energy threshold. The impact of the threshold at 3.5 MeV or at 4.5 MeV on the significance of detecting the upturn is shown in Fig. 14. The addition of few thousands of multi-PMTs in the Hyper-Kamiokande detector will be extremely beneficial in order to reduce the energy threshold, thanks to their better vertex resolution that allows to explore the region below 5 MeV.

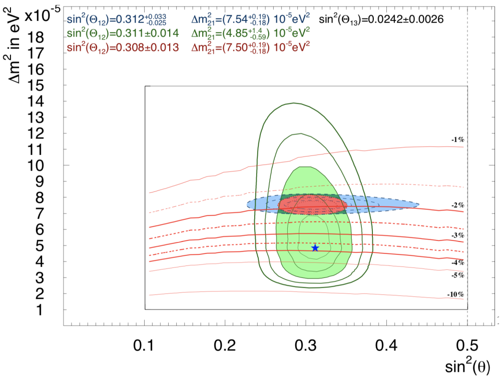

Figure 13: Allowed neutrino oscillation parameter region from all the solar neutrino experiments (green), reactor neutrino from KamLAND (blue) and combined (red).

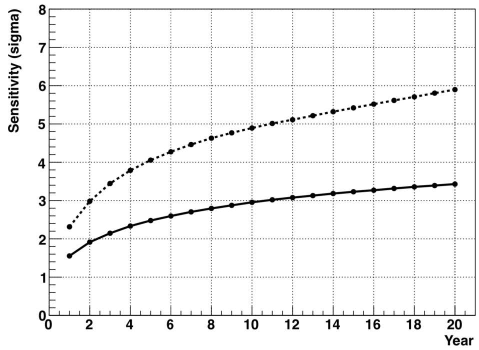

Figure 14: Spectrum upturn discovery sensitivity as a function of observation time. The solid line shows the sensitivity assuming an energy threshold of 4.5 MeV, while the dotted line shows the sensitivity with a 3.5 MeV threshold.

3 LPNHE activities and foreseen contributions to Hyper-Kamiokande

The major news since the discussions we had during the LPNHE Scientific Council in May,2018 is the approval of the Hyper-Kamiokande project by the MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology). In this section we briefly summarize the developments with respect to the May 2018 Scientific Council of our activities in T2K and present the contributions we identified up to now for the Hyper-Kamiokande experiment.

It should be noted that 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 Hyper-Kamiokande.

Full participation in the Hyper-Kamiokande experiment will open the possibility to enlarge our 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 studies at each stage.

Our past and on-going contributions to T2K, T2K-II and NA61/SHINE are presented in [15]. A nearly full list of our scientific publications can be also found there.

3.1 T2K results and T2K-II

The T2K strategy to measure oscillation parameters is to predict the expected event rates and spectra at Super-Kamiokande based on a model of neutrino fluxes and of neutrino cross-sections and on measurements of neutrino interactions at ND280. More details on the oscillation analyses are given in [26].

The flux modelling is currently based on the NA61/SHINE hadroproduction thin-target measurements [27]. It allows the reduction of the uncertainties on the T2K fluxes below 10%. Thanks to the data taken with the T2K replica target a further reduction, down to the level of 5%, has been reached. The neutrino cross-section model is based on external measurements from different experiments (mostly MiniBooNE and Minerva, see [28] 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 of the ND280 off-axis detector and most notably of its tracker system, composed of two Fine Grained Detectors (FGDs), acting as a target for neutrino interactions, and three Time Projection Chambers (TPCs) where the momentum, charge and particle type of the charged particles emitted in neutrino interactions are measured. The ND280 samples are separated according to the detector in which the interaction vertex was reconstructed, to the charge of the muon, and to the number of pions observed in the final state (0, 1, more than 1) and are fitted to predict the expected spectra at Super-Kamiokande without oscillations. Examples of these distributions as a function of outgoing muon momentum are shown in Fig. 15.

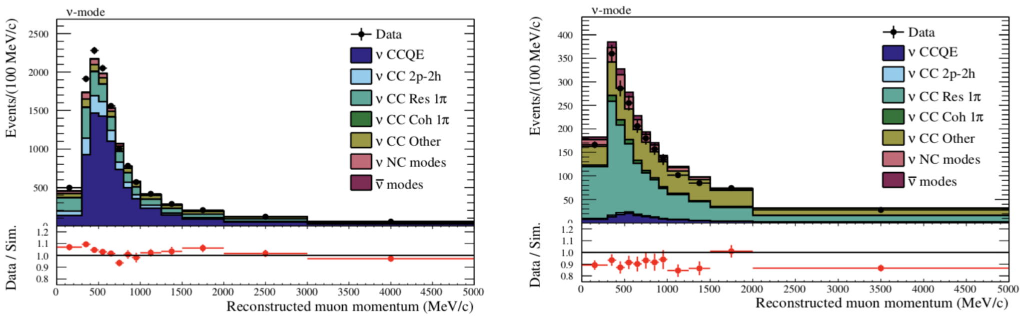

Figure 15: Muon momentum distribution for ν_μ CC–$0\pi^+$ (left) and CC–$1\pi^+$ (right) samples at ND280.

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

As shown in Fig. 16, $\delta_{\rm CP}$ only affects the e–like samples and values of $\delta_{\rm CP}$ close to $-\pi/2$ tend to increase the ν_e appearance probability, while decreasing the $\overline{\nu}_e$ probability. This is exactly what is observed in the data in ν–mode ($\overline{\nu}$–mode), where 74 (15) single–ring e–like events are observed while 62 (19) are expected if $\delta_{\rm CP} = 0$ or π.

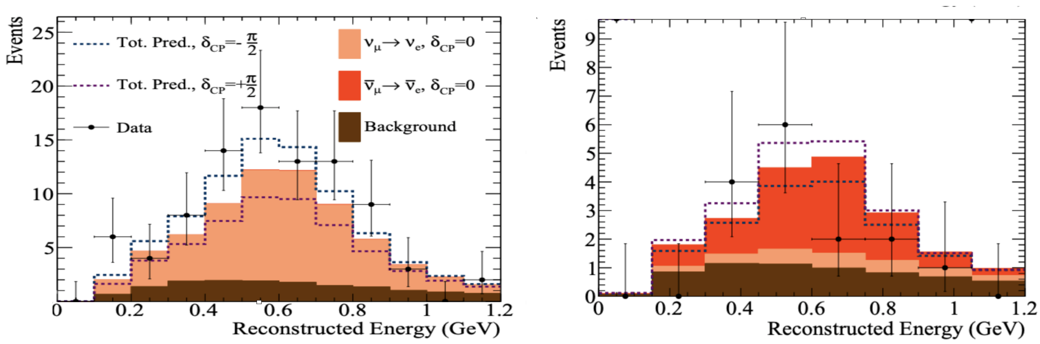

Figure 16: Observed energy spectra for the e–like samples in ν–mode (left) and $\overline{\nu}$–mode (right) compared to the prediction for different values of $\delta_{\rm CP}$.

The Super-Kamiokande samples are then fitted together in order to extract the oscillation parameters θ_{23}, Δm^2_{32}, θ_{13}, $\delta_{\rm CP}$ and the mass ordering, and the results are presented in Fig. 17 (from [13]).

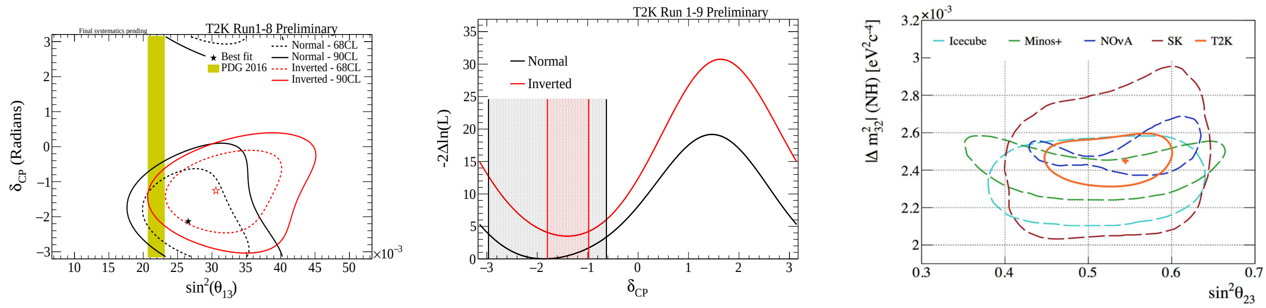

Figure 17: Left: T2K measurement of θ_{13} and δ_{CP} without reactor constraint, represented as a yellow band. Center: Measurement of δ_{CP} including the reactor constraint. The bands represent the 95% CL allowed regions for the two mass ordering hypotheses. Right: Measurement of θ_{23} and $\Delta\mathrm{m}^2_{32}$ by different experiments.

These results, described in more details in [13] show intriguing hints that CP symmetry might be violated in the lepton sector. They have been obtained with statistics of $2.2{\times}10^{21}$ p.o.t., corresponding to about 30% of the total T2K approved statistics. 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.

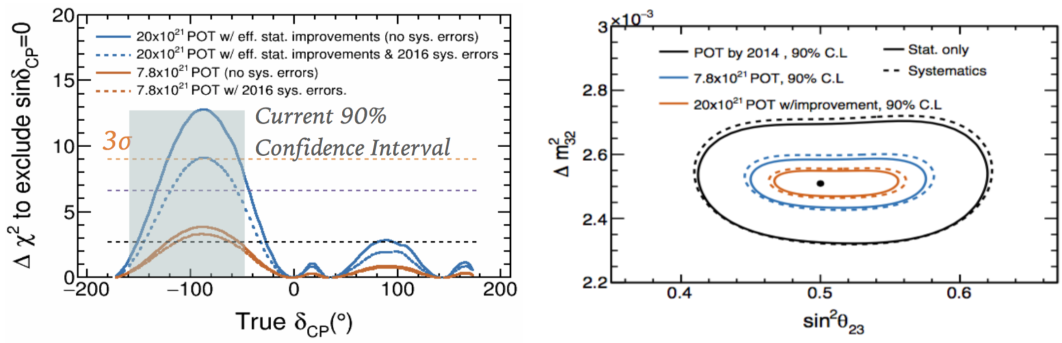

Figure 18: Left: Expected T2K-II sensitivity to δ_{CP} assuming the mass ordering is not known. Right: Expected T2K-II sensitivity to θ_{23} and $\Delta\mathrm{m}^2_{32}$.

The T2K collaboration has proposed an extension of the currently approved T2K statistics ($7.8{\times}10^{21}$ p.o.t.). This program, known as T2K-II, will allow to extend the T2K running time until 2026, before the beginning of Hyper-Kamiokande, and to collect a statistics of up to $20{\times}10^{21}$ 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 [29]. Such statistics can be collected thanks to a program of accelerator upgrades that is approved by KEK and J-PARC and will be performed in 2021. This upgrade will allow to reach a power of 800 kW in 2022 and 1.3 MW a few years later (to be compared with 485 kW currently achieved), see Fig. 19.

In order to fully profit of the foreseen additional statistics, a better understanding of systematic uncertainties and in particular the ones related to flux and cross-section systematic uncertainties is crucial. This need motivates the upgrade of the T2K Near Detector [30], planned to be installed in 2021 and to which the LPNHE group is contributing with coordination roles and by designing and producing the Front-End Cards (FEC) for the electronics of the new TPCs, as well as with contributions to the new detector suspension system and upgraded DAQ.

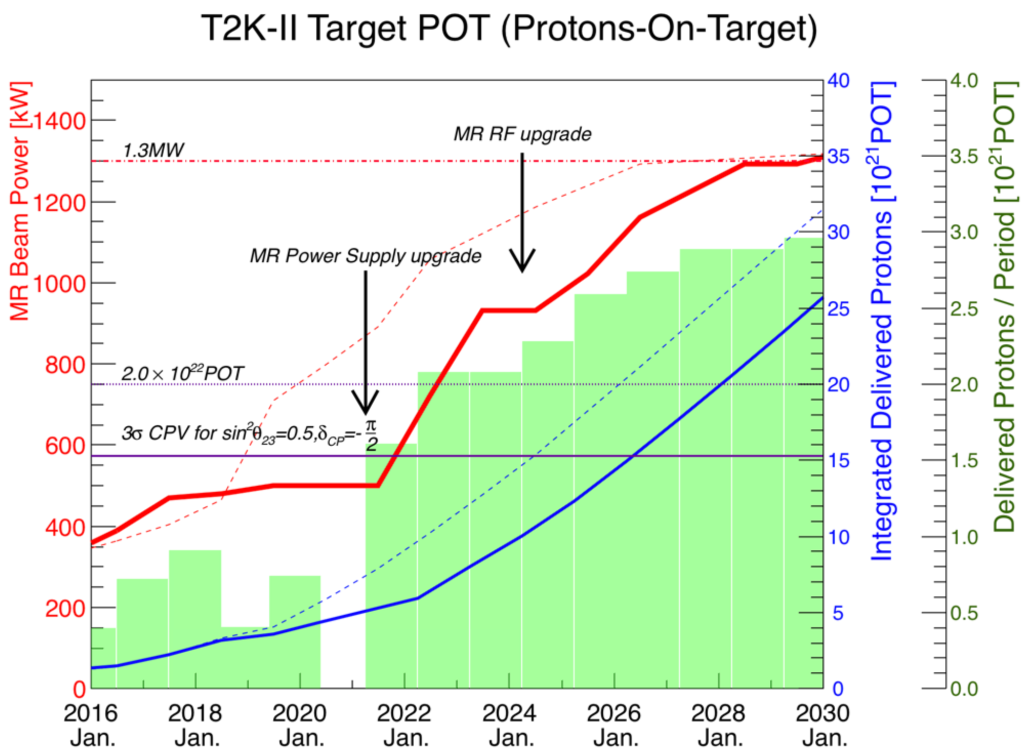

Figure 19: The expected target MR beam power and accumulated POT as a function of Japanese Fiscal Year (JFY). The solid lines are the target MR beam power (red) and accumulated POT (blue) where six months of the MR operation with the fast-extraction mode each year and the running time efficiency of 90% are assumed. In this case, the MR main power supply installation is assumed to be performed from July 2020 to September 2021. The dashed lines are the target MR beam power (red) and accumulated POT (blue) shown in T2K-II proposal [29] where the MR main power supply installation was scheduled in 2019.

It is important to mention that thanks to a successfull refurbishment of the SK tank completed in 2019, starting from 2020 SK will be running in a new configuration, with Gd dissolved in pure water. This will improve the efficiency of neutron tagging. The exact schedule will be decided in close coordination with T2K-II.

Moreover, in addition, T2K is planning to perform combined oscillation analyses with Super-Kamiokande and with NOνA and such combinations are one of the goals of the SUNCORE project, that was financed by the ANR in 2019.

The combination of atmospheric and accelerator neutrinos collected in Super-Kamiokande is a first important step to combine different experiments, with the advantage that the data are collected using the same detector, thus reducing the detector-related systematic uncertainties. A first demonstration of the potential of the combination between T2K and Super-Kamiokande is shown in [31]. A MoU between T2K and Super-Kamiokande management has been signed in order to perform official combinations of the two data sets.

The expected sensitivity of the combination is shown in Fig. 20: the combination will improve the sensitivity of Super-Kamiokande to the mass ordering, while Super-Kamiokande data will help to break the degeneracies between $\delta_{\rm CP}$ and mass ordering and will improve the sensitivity of T2K, especially for values of $\delta_{\rm CP}$ larger than 0.

The results shown in Fig. 20 are obtained from a statistical combination of the two experiments, but even better results are expected if the T2K Near Detector data are used to constrain the cross-section model also for the atmospheric neutrino samples.

Concerning T2K and NOνA, the collaborations have recently agreed to produce a first joint

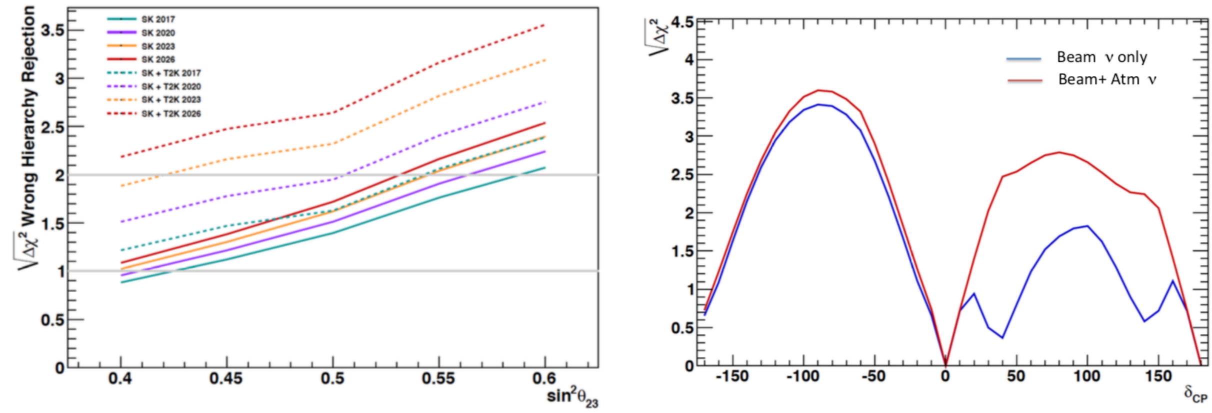

Figure 20: Left: Expected mass ordering sensitivity of Super-Kamiokande only and of the combination of T2K and Super-Kamiokande. Right: δ_{CP} sensitivity of T2K only and of the combination of T2K and Super-Kamiokande.

oscillation analysis by 2022. 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, that goes beyond the simple sum of the likelihoods done by global fits [32], is then mandatory to obtain reliable measurements of these fundamental parameters of the neutrino mixing and will be pursued by the two collaborations in the coming years.

3.2 ND280 upgrade

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

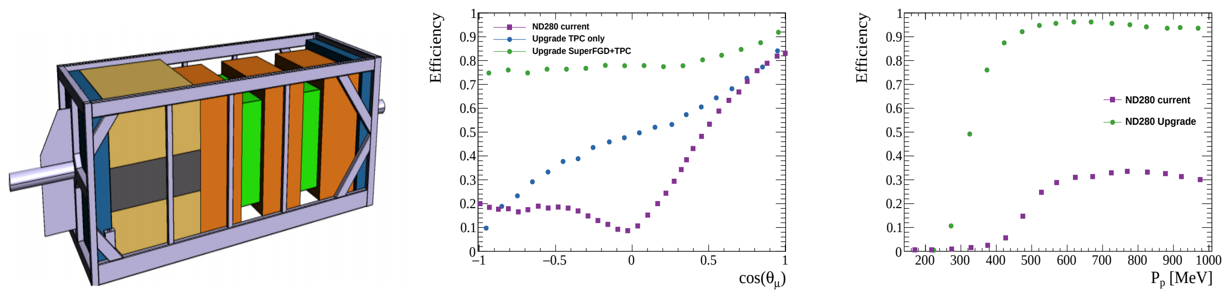

Figure 21: Left: Sketch of the ND280 upgrade project. In the upstream part of the detector two horizontal TPCs (yellow) and the SuperFGD (grey) will be installed. Center: Muon selection efficiency as a function of $\cos\theta$ for the current ND280 detector and for the upgraded Near Detector. Blue points show the efficiency by requiring the muon to enter the TPC while stopping tracks in the SuperFGD are also included for the green points. Right: efficiency to reconstruct protons as a function of outgoing proton momentum for the current and the upgraded ND280.

The aim of the ND280 upgrade is to overcome the two main limitations of the current ND280 design: the different angular acceptance between ND280 (mostly forward) and Super-Kamiokande (4π efficiency) and the relatively large threshold to reconstruct charged hadrons produced in neutrino interactions.

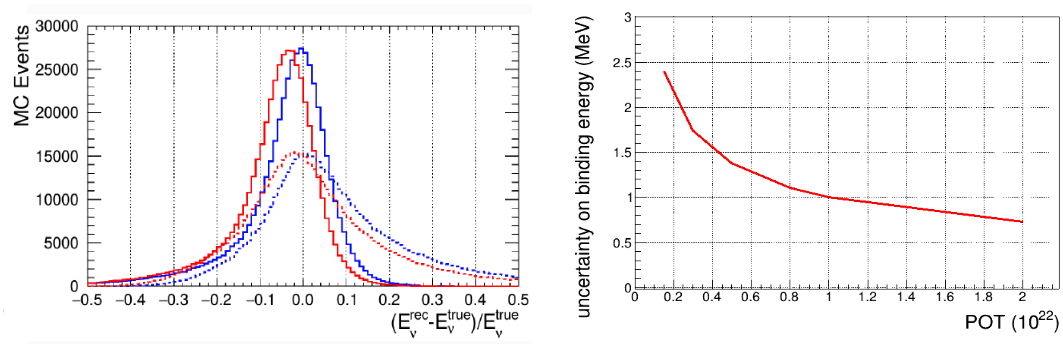

Figure 22: Left: Comparison of neutrino energy reconstruction in QE events using the new variable $E_{had} = E_p + E_\mu$ (solid lines) or E_{rec}, based only on muon kinematics (dashed lines) for two different values of the binding energy (blue and red curves). Right: Expected precision on the ND280 upgrade to measure the binding energy as a function of the p.o.t.

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

As shown in Fig. 21, 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 high efficiency in reconstructing the hadronic part of the interaction will allow to reconstruct the neutrino energy in a calorimetric way, by combining the information of the leptonic and of the hadronic part of the neutrino interaction (E_{had}). In Fig. 22 the expected performances of this new variable is compared with the reconstructed energy used today in T2K based on the reconstruction of the lepton kinematics and assuming a Quasi-Elastic interaction. E_{had} is clearly a more precise estimator of the true neutrino energy and therefore a more powerful variable to estimate the binding energy, that is the dominant source of systematic uncertainties in most recent T2K publications [13]. A precision on binding energy of about 1 MeV can be obtained with 10^{22} p.o.t.

The successful completion of the ND280 Upgrade project is also mandatory for the Hyper-Kamiokande physics program. It is foreseen that, in the second half of the 2020s the Hyper-Kamiokande collaboration will propose futher upgrades to ND280 but the upgraded version of ND280 will still be running at the beginning of the Hyper-Kamiokande era, in order to control changes in the neutrino fluxes between T2K and Hyper-Kamiokande.

Within the ND280 upgrade project the LPNHE-neutrino group is responsible for the development of a part of the readout electronics for the new High Angle TPCs (HA-TPCs). We are also involved in the development of the new DAQ system and in the design and production of a new detector suspension system.

As physicists we participate in the development of the software and reconstruction tools for the Upgrade and we are studying the expected performances of this detector in constraining flux and cross-section models.

These projects were described in great details in the document prepared for the LPNHE Scientific Council of May 2018 and such description can be found here [15].

3.2.1 TPCs electronics

The new TPCs will be instrumented with resistive MicroMegas that are readout by the AFTER chip [33], designed for T2K and used in the current TPCs and FGDs. The AFTER chips are mounted on a Front End Card (FEC), for which the LPNHE has the responsibility of the design, construction and installation in the new HA-TPCs.

The AFTER chips 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. Since the resistive Micromegas detectors are used, the number of channels per detector module is reduced compared to the current TPCs (e.g. from 1728 pads to 1152 pads) and the anti-spark protection circuit currently used on every channel is no longer needed. We note that the corresponding reduction in channel count and board area for passive components allows 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 doubled 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.

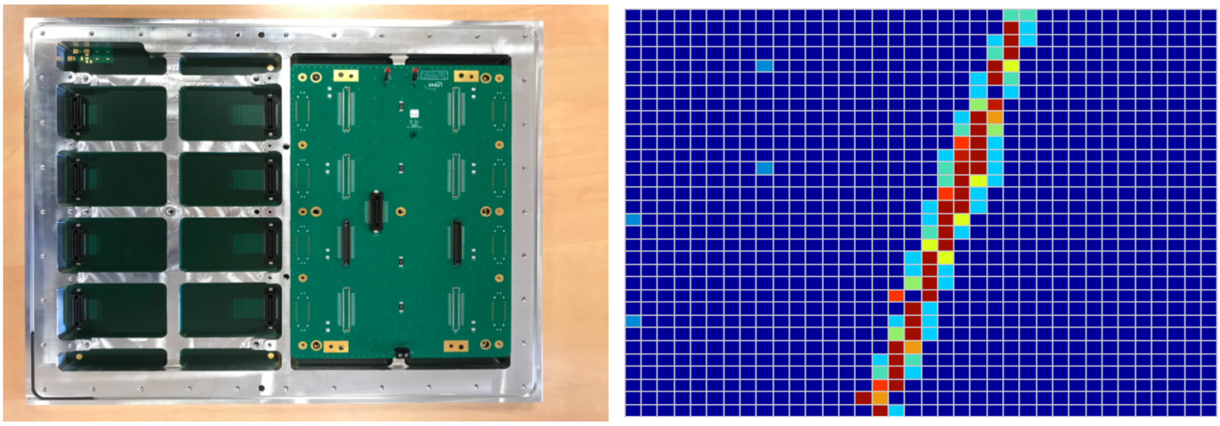

Figure 23: One FEC-mockup board mounted on the MicroMegas prototype detector (left). A cosmic ray track observed with this setup (right).

Initially, a FEC-mockup without active components has been designed and produced in early 2019. This mockup was used for two main purposes: firstly, to validate the type of connectors ("floating" connectors) chosen to interface FEC boards with MicroMegas detector, and to interface FEC with FEM boards. Secondly, two mockups were used for beam tests at DESY-Hamburg in June 2019 in order to validate the first MicroMegas prototype equipped with a data acquisition system composed of 2 FEC-mockups from LPNHE / 4 ARC boards from IRFU / 1 TDCM board from IRFU, see Fig. 23.

Following the positive outcome of this step, the first FEC prototype is currently under development: the design has recently been finalized, while the routing is in progress, as shown in Fig. 24. The PCB will be made of FR4-HTG material, stacked-up of 8 or 10 Cu layers. We plan to produce 8 PCB prototypes before the end of 2019, but only 2 will be fully equipped by the end of January 2020. These boards will then be tested at IRFU and connected to the FEM prototype board developed by IRFU engineers.

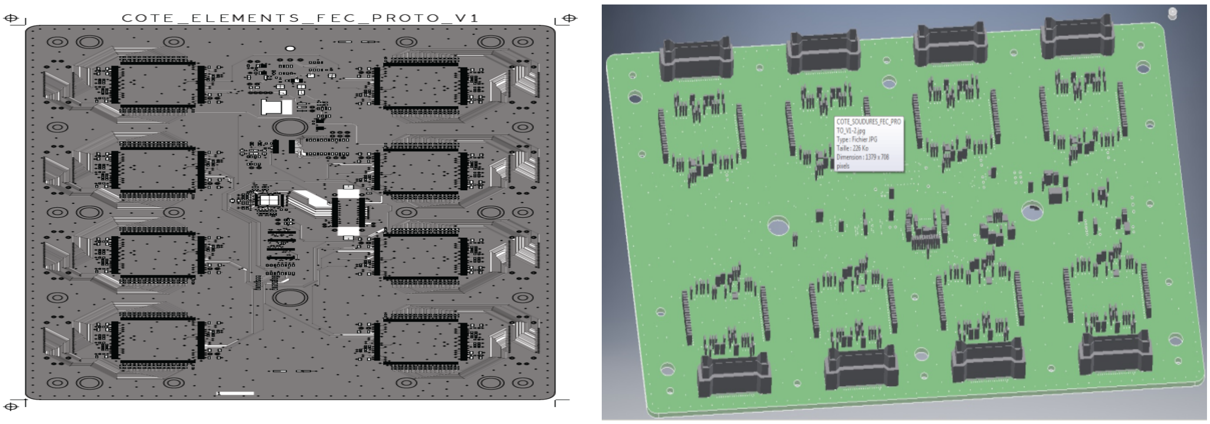

Figure 24: First full FEC prototype: top view (left) and 3D bottom view (right).

The FEC board should be equipped with a cooling shield in order to keep the components at a reasonable temperature during the operation. This shielding plate, which is currently under study in collaboration with IRFU engineers, will be designed at LPNHE, see Fig. 25.

After producing 8 FEC prototypes which will provide boards for future test benches in different collaborating laboratories, the next aim is to produce the first series of production FEC boards (quantity: 16, which are meant to be the pre-prod boards). These 16 FEC boards should equip the first TPC, and planned to be possibly delivered by the end of June 2020.

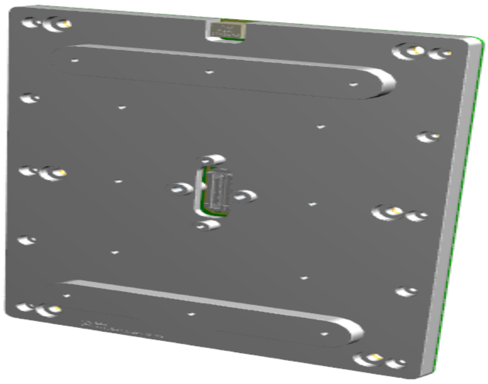

Figure 25: A cooling plate prototype for the FEC board.

3.2.2 DAQ

For the ND280-upgrade we will integrate in the DAQ chain a TDCM board powered by a FPGA module, the Mercury ZX1 from Enclustra [34]. This module includes a Xilinx Zynq FPGA that provides two soft ARM embedded processors, bringing the possibility to have in one CPU a bare metal system as it was already implemented, running the basis of a program servicing a command server. This command server processes commands related to configuration, monitoring and DAQ, received from a remote DAQ PC over an ethernet connection and returning results in the same way.

Eventually, and this is what we expect to accomplish, we can perform a secondary bare metal system or an embedded Linux system in the other CPU, separating the communication functionalities of the command server from the specific frontend and TDCM functionalities. This would bring atomicity and concentrate our team expertise in specific activities related to advanced DAQ features, like for example the zero suppression in data contents and incorporating an embedded MIDAS frontend.

In both cases we should provide the required services to control the readout from the frontend and bring a stable throughput to the MIDAS DAQ.

We plan to test and compare different scenarios having both CPU's available to the system. It could be a double bare metal or a single bare metal plus a single CPU embedded Linux or a double CPU embedded Linux.

We believe it would be a step forward to bring the power of Linux at this level, reducing the complexity of construction of a system compared to a bare metal system and simplifying the code development and the integration of low level devices, memories and the data transfer protocols, such as TCP/IP.

Moreover, the huge amount of tools and documentation available within the Linux community to support the integration, tuning and monitoring of this kind of system is a major asset in this course of actions.

3.2.3 Mechanics

The installation of the new detectors (HA-TPCs, SuperFGD and TOFs) inside the existing ND280 basket will require a careful management of the mechanical design and construction. The coordination is under the responsability of the University of Geneva, and the LPNHE mechanics group will contribute to this activity via:

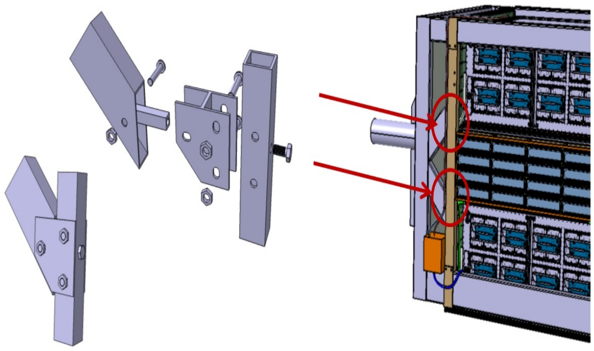

Figure 26: An example of possible basket modification and suspension system's elements for the new detectors.

- designing the basket modifications including finite element analysis and seismic analysis of the modified basket;
- global detector envelopes and service volume definitions;
- design and production of the suspension system's elements for the new detectors inside the basket, see Fig. 26;
- designing the "baby-basket" (a mockup version of the ND280 basket restricted to the new detector area) to be constructed at CERN for testing purposes and for checking the installation procedures.

3.3 Hyper-Kamiokande

Discussions with IN2P3 (LLR and Omega laboratories) and CEA physicists are still on-going in order to define common French contributions to the Hyper-Kamiokande project.

Up to now we have identified the following area where the LPNHE-neutrino group could make important and visible contributions.

3.3.1 Clock distribution and PMTs synchronization

One of our foreseen contributions to the Hyper-Kamiokande experiment is related to the communication block and, in particular, to the time synchronization and clock distribution for both the large PMTs and mPMTs since it represents a critical part of the experiment and we do have, in our electronic groups, experts on this kind of technology.

The experiment's TDCs or FADCs timing synchronization is crucial for precise measurements of photon arrival and the actual requirement is set to have timing resolution of the photo-sensors at the level of 1 ns with a maximum jitter of 100 ps RMS. To accomplish this task the experiment requires the distribution of a clock signal, synchronous with the GPS and a local atomic clock, to all Front-End (FE) nodes plus some signals to align FE's local counters. These needs call for a system structured as a data exchange protocol. The bandwidth not occupied by the timing information could be used to move data between the DAQ and the FEs, like physics related information or slow control. For this reason, there is an interest to have its bandwidth as large as possible while still keeping the total cost to produce and deploy it at a reasonable level. Several solutions are under consideration at present, but two of them seem to be the most promising. One is based on the CERN White Rabbit (WR) protocol and the other on a custom solution.

White Rabbit solution

The White Rabbit protocol [35] implements a fully deterministic gigabit ethernet-based network for general purpose data transfer and sub-nanosecond accuracy time transfer. The link, from the timing distribution point of view, is structured as single-master-many-slaves. The master receives the temporal information from an external reference (the GPS and the atomic clock, in our case) builds a clock and distributes it to all the slaves embedded in the data stream. Each slave reconstructs this clock with an almost zero phase delay compensating for the medium's propagation delay. The phase alignment is continuously monitored and adjusted thanks to a series of data packets exchanged between the master and the slaves. The amount of data needed for the timing synchronization is less than 400 Bps meaning that almost all the gigabit ethernet bandwidth is available for the user's data. Special 18 ports' networks switches have been designed by CERN to connect different nodes allowing the transfer of time synchronization information. Any switch can receive the GPS signal and become the system's master. A White Rabbit node can be also connected inside a standard ethernet network and, while the synchronization's mechanism does not work, all the standard data packets are distributed normally.

A possible architecture for the experiment could be constituted by a series of switches. The one defined as master receives the GPSs signal and distributes the clock to all the others via a daisy chain connection. Each switch of the chain can be connected to a maximum of 8 FEs and the other ports are used as a link to the data acquisition system. From this description it is clear that the White Rabbit represents a very attractive solution for the experiment also considering that the protocol is developed and maintained by CERN and the firmware and the hardware designs are distributed freely.

Custom solution

Another architecture that could match the experiment's needs in terms of time distribution is based on a custom design that takes advantage from a very specific configuration mode present in almost all the high speed serializer-deserializer ('serdes') embedded in modern FPGAs. This mode allows the realization of a high-speed point-to-point connection between two nodes where one of them, the master, can send its clock embedded into the data and the other, the slave, can recover it from the data stream and always lock its reconstructed clock to the same phase with respect to the master's. This mechanism, therefore, guarantees a clock distribution with a fix phase delay that is proportional to the medium's length that connects the two nodes. The phases delay, however, could change if the medium's characteristics, like e.g. temperature, change. This aspect should not represent a problem for the Hyper-Kamiokande's needs because the cables' temperature is not expected to change very much for the entire duration of the data taking so the difference's range can be of the order of hundreds of picoseconds. In these conditions the phase difference can also be measured and compensated at the deployment's time but, judging from the actual requirements, this procedure seems not needed. Modern FPGA's 'serdes' can have bandwidth up to tens of gigabits per second so the link's width can be tailored on the experiment's needs.

A possible architecture based on this kind of custom solution could be implemented designing a custom distribution board connected on one side to the data acquisition system and on the other to the FEs. The link to the FEs would be designed using the synchronous technique described above while the DAQ side would be based on a standard protocol like the 10 Gbps ethernet. The number of links and the number of the custom boards needed in our case depends essentially on the desired bandwidth but, to make the comparison easier, we could consider having a 1 Gbps to all the FEs. In this case the custom board could have 8 FE's connections and one 10 Gbps ethernet link to the data acquisition system. Each distribution board could receive the GPS signal and build its own clock or one master clock could be sent to all the distribution boards by means of a fanout. The main advantage of this solution is the possibility of designing a system tailored on the experiment's needs.

Cost Analysis

The actual Hyper-Kamiokande topology foresees 8000 large PMTs in the outer detector while, for the inner detector, the baseline is to have 20000 large PMTs. To that number, up to 20000 additional multiPMTs can be added. This cost analysis will be realized by considering the case of 28000 large PMTs and to that 2 possible cases will be added: one with 4000 additional multiPMTs and the other with 20000 multiPMTs. The PMTs data signals are grouped by 25 in a single FE board so the number of nodes served by the timing distribution system has to be: 28000/25=**1120** FE plus 4000/25=**160** or 20000/25=**800** extra FE. 20% contingency and 20% of spares will be added to this cost.

Cost of the White Rabbit solution

Each WR 18 ports' switch costs 3500 euros plus about 100 euros for each laser. The total cost, therefore, sums up to 5300 euros. Considering that each switch can connect 8 FE the total cost is:

- 28000 large PMTs
  (1120/8) x 5300 = 742000 euros

- 4000 multiPMTs
  (160/8) x 5300 = 106000 euros

- 20000 multiPMTs
  (800/8) x 5300 = 530000 euros

Adding the extra 20% contingency plus 20% extra spares switches we have:

Total cost:
Baseline: 1038800 euros
Extra 4000 multiPMTs: 148400 euros
Extra 20000 multiPMTs: 742000 euro

Cost of the custom solution

Each custom distribution board could have an estimated cost of about 4000 euros. If, for simplicity, we consider that each distribution board is connected to 8 FE, the total cost is:

- 28000 large PMTs (1120/8) x 4000 = 560000 euros
- 4000 multiPMTs (160/8) x 4000 = 80000 euros
- 20000 multiPMTs (800/8) x 4000 = 400000 euros

Adding the extra 20% contingency plus 20% extra spares boards we have:
Total cost:
Baseline: 784000 euros
Extra 4000 multiPMTs: 112000 euros
Extra 20000 multiPMTs: 560000 euro

Conclusions
White Rabbit solution:
Pros:
— Very good timing distribution performances.
— Very reliable since it is developed and supported by CERN.
Cons:
— High price.
Custom solution:
Pros:
— Link speed tailored to the experiment's needs.
— Lower price.
Cons:
— Design process is time consuming and prone to delay.

3.3.2 Multi-PMTs for Hyper-Kamiokande and IWCD

R&D on an alternative photosensor option based on mPMTs modules is actively being carried out by several countries (mostly Canada, Italy, UK) with the goal of providing up to a half of the photo–cathode coverage for HK. The multi-PMTs are also the baseline photosensor option for IWCD.

The performances of a hybrid design for HK with a combination of large PMTs and multi-PMTs are being studied. Preliminary studies show that if the dark noise can be kept at the level of 100 Hz, better vertex reconstruction for events close to the wall and a lower energy threshold can be obtained. The better vertex reconstruction will allow to increase the Fiducial Volume while the lower energy threshold will improve performances for low energy events, in particular increasing the sensitivity of HK to the up-turn of the ^{8}B spectrum of solar neutrinos, probing the MSW-LMA prediction in the transition region between vacuum and matter-dominated neutrino oscillations.

This option is particularly appealing for French groups as they could profit from the existing KM3NeT expertise, from the developments and tests of the small PMTs for JUNO, and from the presence of the Memphyno water tank [36] at APC to perform underwater tests of the mPMT modules. Such tests have started and the first mPMT prototype from Italy is currently installed and taking data in water in the Memphyno setup. More mPMTs prototypes are expected to be produced over the next couple of years; this facility will be of great use for a first in-situ characteristisation of their performances.

In addition, a **test beam experiment** to be carried out at CERN with a tank instrumented with ~ 100 mPMTs is being proposed by a part of the HK collaboration. This design corresponds to a downscaled version of IWCD. This experiment aims at testing the technological choices for IWCD and HK and plans to demonstrate that the response of the detector can be calibrated at the 1% level necessary for IWCD. Our contribution will be a continuation of the work carried on the mPMTs studies and DAQ software development for Memphyno. We intend to contribute to the data analysis and the characterization of the detector performances.

For this task we will benefit from the Sorbonne University Emergence grant that was obtained by Mathieu Guigue. This grant lasting for 2 years and covering the salary for only a one-year postdoc, support from the lab and IN2P3 is requested in order to sustain this activity.

3.3.3 NA61/SHINE and Near Detectors

Another natural contribution of our group to the Hyper-Kamiokande experiment will be the continuation of our activities on NA61/SHINE and ND280.

The importance of dedicated hadron production measurements with the **NA61/SHINE** spectrometer at the CERN SPS is now widely recognized within the community, see e.g. documents prepared for the update of European Strategy for Particle Physics [37, 38].

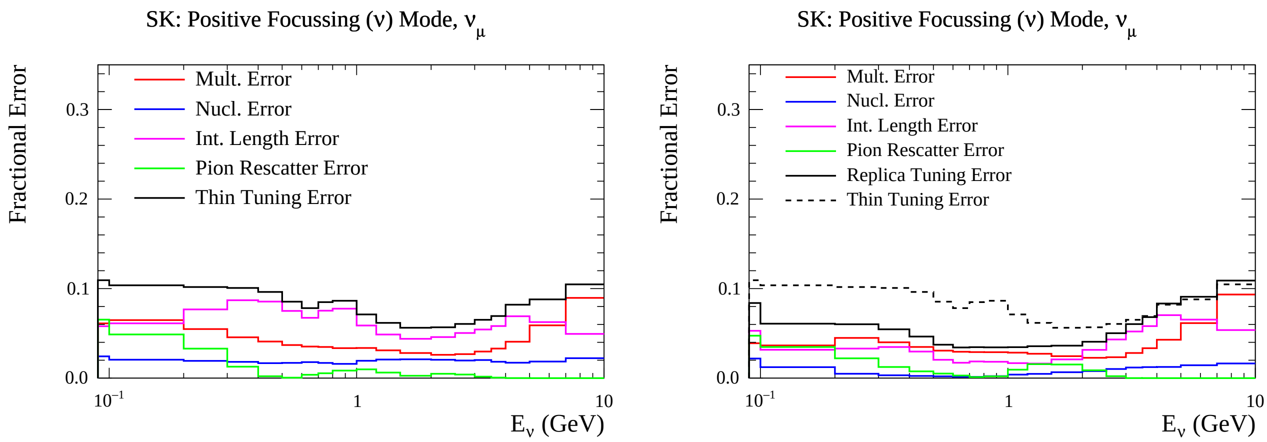

Figure 27: The hadron interaction model uncertainties evaluated on the SK flux prediction. The uncertainties have been calculated for the flux constrained with either purely NA61/SHINE 2009 thin-target data [27] (left side), or using a combination of NA61/SHINE 2009 thin-target and replica-target data [40] (right side, denoted as the replica tuning error). Additional improvement is expected with the NA61/SHINE 2010 replica-target data [39, 41], in particular, the uncertainty in high neutrino energy region because of significant improvement of the knowledge of the kaon yield from the replica target data.

The IN2P3 physicists have played a leading role in obtaining the NA61/SHINE results with both a thin carbon target [27] and a T2K replica target [39]. There measurements are currently being used to reduce the (anti)neutrino flux uncertainties in T2K and T2K-II down to about 5%, see Fig. 27. Similar measurements are planned for the new target to be used in the Hyper-Kamiokande 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-II/HK 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 component 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 the early post-LS2 NA61/SHINE operation. Whether new measurements with the existing T2K replica target are needed will be concluded after introducing the NA61/SHINE 2010 replica-target results ([39] and [41]) 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. First prototype long targets could possibly be available in 2022 and beyond.

Concerning **ND280**, our main goal is to successfully complete the upgrade foreseen for 2021. ND280 in the upgraded configuration will be taking data when Hyper-Kamiokande will start operation in 2027.

Profiting of the modular design of ND280, it will be possible to consider further upgrades, on the basis of the results obtained with larger statistics during T2K-II. This will allow to match the challenges which the Hyper-Kamiokande experiment will certainly face in the run to the ultimate precision in neutrino oscillation measurements.

The experience acquired by our group with Near Detectors in the last 10 years will certainly constitute an important asset to be involved in these further upgrades.

3.4 Computing for T2K and HK

The very performant IN2P3 Computing Centre at Lyon will allow us to play a leading role in the software and computing groups of both T2K and HK.

We plan to contribute on the computing aspects by providing storage elements and computing resources to the T2K and HK collaborations, in addition to expertise on the distributed computing. This effort, currently in motion thanks to the already-funded JENNIFER-II European project, will also allow us to exploit synergies with other IN2P3 groups, including Belle-II.

Currently 20 millions CPU·hours are allocated to the T2K French groups and benefits to our CEA-Saclay colleagues for common projects e.g. neutrino cross-section analyses. However, the usage of these resources varies between each fiscal year because of fluctuations in users' activities leading to either under or over-use of this allocation. Similar issues arise for our allocated 70 TB storage resources. Being able to share these resources with other foreign institutions in need or access additional resources if needed seems therefore highly desirable.

DIRAC[1] [42] is a python-based software framework for distributed computing. In this framework, a data base is used to catalog all the information about each registered file, including its location on each storage element along with extra information about its parents and descendents. It also allows to define submission queues where jobs are distributed across several computing elements depending on their location and their access to the data. Thanks to this system, every computing node has access to the entire data catalog regardless of its location, and can download required files if they are missing on the associated storage elements.

By the end of T2K-II, our allocated computing resources should be entirely shared with the rest of the collaboration using a dedicated job submission queue. The cluster at Lyon would be used to partially store the results of each production, granting convenient access to French contributors along with faster access to other collaborators in Europe. Data sharing and access for job submission should be made easy and transparent thanks to DIRAC.

[1] Available at https://github.com/DIRACGrid/DIRAC

Standard libraries and T2K specific software are shared between computing elements in a top-down approach by using the Cern Virtual Machine File System (CVFMS). Other technologies developped for other collaborations like Belle-II using containerized applications via e.g. Singularity [43] are being investigated. This allows to provide identical computing environment regardless of the computing element architecture.

It is important to note that most of the technologies and investments made for T2K computing are directly transferable to Hyper-Kamiokande. Indeed, since HK will be a new experiment and some aspects of the computing model, data flow and tools are open for discussions, this leaves us a lot of room for developing and implementing innovative solutions. The expertise and collaborative work accumulated over the last years on T2K will be beneficial both to the T2K and HK collaborations but also to other collaborations within the Lab and IN2P3 sharing the same challenges, such as LHCb, Belle-II, CTA. Therefore we suggest to use the expertise within the LPNHE and the Neutrino group to produce these common tools.

For Hyper-Kamiokande, a Tiered computing model based on the LHC model has been developped [44]. Two Tier-0 sites (KEK and Kamioka) will each hold the raw data collected by the Near and Far detector, respectively. Tier-1 sites would store replicas of these raw along with reconstructed data and Monte Carlo results, produced by Tier-2 sites. Since the total storage required to hold a single copy of data collected during 10 years of HK operation would be around 25 PB, it is not expected for each Tier-1 site to have such storage capabilities at the moment. However, partial copies of the production and raw data with sufficient replications on Tier-2 are envisioned as a safety measure. A clear interest in having CC-IN2P3 joining as a Tier-1 site has been expressed at several occasions, given the central place within Europe, the strong expertise developped thanks to work done on LHC and the great resources potential of this cluster. We propose therefore to explore this possibility over the next couple of years in coordination with the CC-IN2P3 and with the Lab support.

4 Conclusions

Hyper-Kamiokande, the third generation of experiments devoted to the study of neutrino oscillations and to the search for nucleon decay, has been recently approved by MEXT. The construction of the detector will start in April 2020 and the beginning of the data taking is foreseen for 2027.

Once built, thanks to its large mass, the very well known Water Cherenkov technology and the increased intensity of the neutrino beam from J-PARC, HK will be the most sensitive experiment for measuring CP violation in the lepton sector and searching for the nucleon decay. HK will also be an exceptional observatory for neutrinos from astrophysical sources.

We have already identified some contributions to the Hyper-Kamiokande project. Our significant involvement in the ND280 upgrade and in the NA61/SHINE hadron production measurements for Hyper-Kamiokande sould also be considered as an important contribution to the Hyper-Kamiokande project.

With this document we request an approval from the LPNHE Scientific Council of the described scientific strategy towards our group's participation in the Hyper-Kamiokande experiment in Japan.

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