Projet scientifique à 5 ans du groupe Neutrino du LPNHE

Groupe Neutrino du LPNHE

Juillet 2020

1 Introduction

The discovery of neutrino oscillations and the first measurements of the corresponding mixing angles (θ_{12} and θ_{23}) and mass squared differences (Δm^2_{12} and $\Delta \mathrm{m}^2_{32}$), started a broad program in which neutrino oscillations have been observed by several experiments using very different neutrino sources and detection techniques [1]. The LPNHE-neutrino group has been taking part in this research activities for more than 35 years now.

This large variety of experimental results is described within the PMNS framework [2, 3]. 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 mass squared 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 [4], θ_{13} was measured to be different from zero in 2012 by Daya Bay [5] and RENO [6]. The T2K experiment has then firmly established the $\nu_\mu \to \nu_e$ appearance in 2013 [7]. This observation can be considered as the beginning of the new 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 as well as $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ appearance. Let us stress that T2K has recently published in "Nature" important results on the study of CP violation in the lepton sector, by excluding some region of δ_{CP} values at 3σ C.L. [8].

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. This upgraded near detector will also play a key role in the next generation experiment, Hyper-Kamiokande, that will take over in the late 2020's.

Hyper-Kamiokande (HK) [9] is a next generation long-baseline neutrino oscillation experiment that will be built in Japan. One of its main physics goals is the discovery of CP violation in the lepton sector, but Hyper-Kamiokande will also be the most sensitive detector to proton decay and an observatory for neutrinos from astrophysical sources, such as supernovae neutrinos. HK has been recently approved in Japan and the construction was launched in April,2020 with a start of data taking foreseen for 2027.

HK constitutes a natural extension of the on-going activities of our group that will allow most prominent physics outputs. 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.

The advantage of such a staged path from T2K to Hyper-Kamiokande is that, while getting full experience with a precision neutrino oscillation experiment, like T2K and T2K-II, we will invest in beam design studies, required hadron production measurements, detector R&D's and physics potential studies for Hyper-Kamiokande. This strategy was endorsed by the LPNHE Scientific Council in November,2019.

Let us stress that in 5 years from now the T2K upgrade will be finished, commissioned, taking data and producing physics results, while the HK experiment after a successful R&D program will be at the final construction phase.

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.

The group expects a new CR CNRS position in the coming couple of years.

Physicists	
Alain Blondel	*CNRS-Directeur de Recherche, started in September 2019* *member of the Hyper-Kamiokande Steering Committee*
Jacques Dumarchez	*CNRS-Directeur de Recherche, Group leader till September 2018* *Magnet and TPC expert@ND280; Member of the publication board*
Claudio Giganti	*CNRS-Chargé de Recherche, HDR* *TPC expert@ND280; 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 Reconstruction & Software group*
Jean-Michel Levy	*CNRS-Chargé de Recherche (benevole)*
Boris Popov	*CNRS-Directeur de Recherche, Group leader from September 2018* *Magnet and TPC expert@ND280; convenor of the T2K-NA61 group* *Co-convenor the T2K-beam group (till February 2018)* *Convenor of the NA61 software and analysis groups* *External reviewer for Spanish and Polish national funding agencies*
Ciro Riccio	*Invited researcher, during the year of 2019*
Marco Zito	*LPNHE director, started in July 2019* *TPC expert@ND280; ND280-upgrade project leader till July 2019* *neutrino section convener in Physics Briefing Book (ESPP Update 2020)*
Viet Nguyen	*PhD student from October 2019*
Adrien Blanchet	*SU/ANR postdoc from January 2020*
Marco Martini	*Associated researcher starting from September 2020*
Lucile Mellet	*New PhD student starting from October 2020*
Sergey Suvorov	*New ANR postdoc starting from October 2020*
Uladzislava Yevarouskaya	*New PhD student starting from November 2020*

Previous PhD students

Laura Zambelli	*PhD student till October 2013* [JSPS postdoc, CR CNRS at LAPP now	
Pierre Bartet-Friburg	*PhD student till October 2016* [Data scientist at Withings now]	
Matej Pavin	*PhD student till October 2017* [postdoc at TRIUMF now]	
Simon Bienstock	*PhD student till October 2018* [Ministère des Armées now]	

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 eight 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)
2020	40+50 (50+100)	26 (for 7 authors)	15 (15)
2021	(50+60)	(for 8 authors)	(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 allowed us to hire two postdocs with corresponding travel money, while Mathieu Guigue gained an Emergence Sorbonne University grant that allowed to pay a postdoc for 1 year and to use some money for instrumentation. The ANR project is centered on the analysis of T2K-II data and ND280-upgrade, while the Sorbonne University grant is oriented towards participation in Hyper-Kamiokande.

Together with our Japanese colleagues we have also obtained some additional resources via projects approved within the "Toshiko Yuasa" France Japan Particle Physics Laboratory (TYL-FJPPL). Moreover, we are also part of the new International Research Laboratory (IRL) recently established between the CNRS and the University of Tokyo. We do have within our group researches interested in long stays in Japan in the framework of this IRL for both ND280-upgrade and HK.

In 2020 the group obtained an international PhD grant from CNRS to work on the ND280-upgrade project.

2 T2K results and T2K-II

The LPNHE-neutrino group participates in the T2K long-baseline neutrino oscillation experiment in Japan since 2006.

The T2K strategy to measure neutrino 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 [10].

The flux modelling is currently based on the NA61/SHINE hadroproduction thin-target measurements [11]. 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 [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 of the ND280 off-axis detector.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.

At Super-Kamiokande five samples are selected and 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.

The Super-Kamiokande samples are then fitted together in order to extract the oscillation parameters θ_{23}, Δm^2_{32}, θ_{13}, δ_{CP} and the mass ordering. A set of corresponding results is presented in Fig. 1 (from [13]).

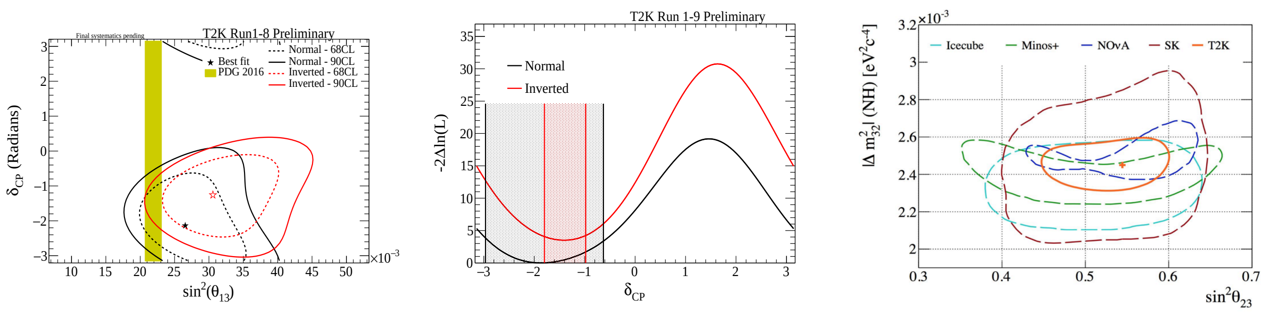

Figure 1: Left: T2K measurement of θ_{13} and δ_{CP} without reactor constraint, represented as a yellow band. Center: Measurement of δ_{CP} including the reactor constraint. The bands represent the 95% CL allowed regions for the two mass ordering hypotheses. Right: Measurement of θ_{23} and Δm^2_{32} 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 2.2×10^{21} p.o.t., corresponding to about 30% of the total T2K approved statistics. Updated results have recently been published in "Nature" excluding for the first time some region of δ_{CP} values at 3σ C.L. [8]. If the currently favoured T2K best-fit region contains the true δ_{CP}, 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.

The T2K collaboration has proposed an extension of 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

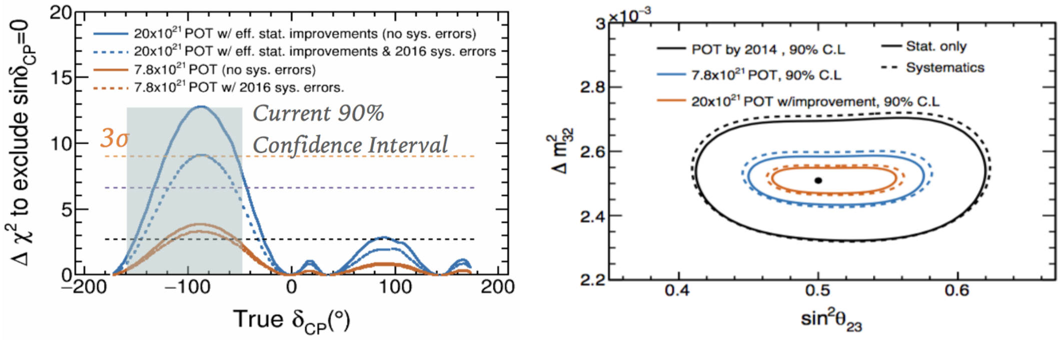

Figure 2: Left: Expected T2K-II sensitivity to $\delta_{\rm CP}$ assuming the mass ordering is not known. Right: Expected T2K-II sensitivity to θ_{23} and $\Delta {\rm m}^2_{32}$.

time until 2026, before the beginning of Hyper-Kamiokande, and to collect a statistics of up to 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 [14]. A program of accelerator upgrades has been approved by KEK and J-PARC and will be performed in 2021 [15]. 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 500 kW currently achieved). Recently the KEK directorate issued the following statement: "KEK will make its best effort to provide approximately four months of T2K beam operations per year until the start of HK".

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 is crucial. This need motivates the upgrade of the T2K Near Detector [16], planned to be installed in 2022 and to which the LPNHE-neutrino group is contributing with coordination roles and by designing and producing the Front-End Cards (FEC) for the electronics of the new high-angle TPCs, as well as with contributions to the new detector suspension system and upgraded DAQ.

It is important to mention that thanks to a successful 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. The process of dissolving Gd actually started on July 14, 2020. This will improve the efficiency of neutron tagging.

Moreover and in addition with the improvements mentioned above, T2K is planning to perform combined oscillation analyses with Super-Kamiokande and with NOνA. The LPNHE-neutrino group is fully involved in these activities since 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 [17]. An MoU between T2K and Super-Kamiokande management has been signed in 2019 in order to perform official combinations of the two data sets.

Concerning T2K and NOνA, the collaborations have recently agreed to produce a first joint 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 [18], 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 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 2022.

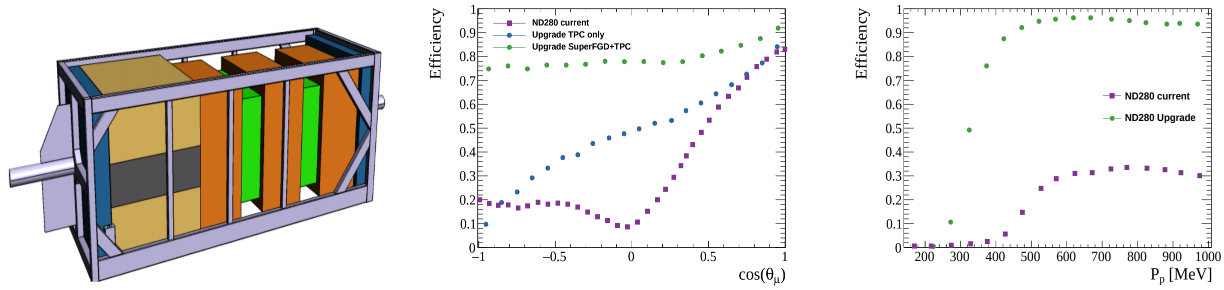

Figure 3: Left: Sketch of the ND280 upgrade project. In the upstream part of the detector two horizontal TPCs (yellow) and the SuperFGD (grey) will be installed. Center: Muon selection efficiency as a function of $\cos\theta$ for the current ND280 detector and for the upgraded Near Detector. Blue points 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.

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. 3, such configuration, combined with the existing tracker system, will allow to select with similar efficiencies outgoing charged leptons emitted in any direction with respect to the beam giving a better handle to distinguish among different neutrino cross-section models and to better constrain the parameters in these models. In addition, the large mass of the detector (~ 2 tons) 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 successful completion of the ND280 Upgrade project is also mandatory for the Hyper-Kamiokande physics program. It is foreseen that after a few years of data-taking the Hyper-Kamiokande collaboration will propose further upgrades to the near detector complex, 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 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.

The new TPCs will be instrumented with resistive MicroMegas that are readout by the AFTER chip [19], 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 production of the corresponding cooling plates is also the responsibility of our group.

Concerning the DAQ chain for the ND280-upgrade detectors, we have started evaluating the possibility to embed a Linux system on both FPGA processors to allow for the command server to process commands related to configuration, monitoring and DAQ, received from a remote DAQ PC over an ethernet connection and returning results in the same way. 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.

4 Hyper-Kamiokande

The next-generation Hyper-Kamiokande experiment 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. 4, 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.

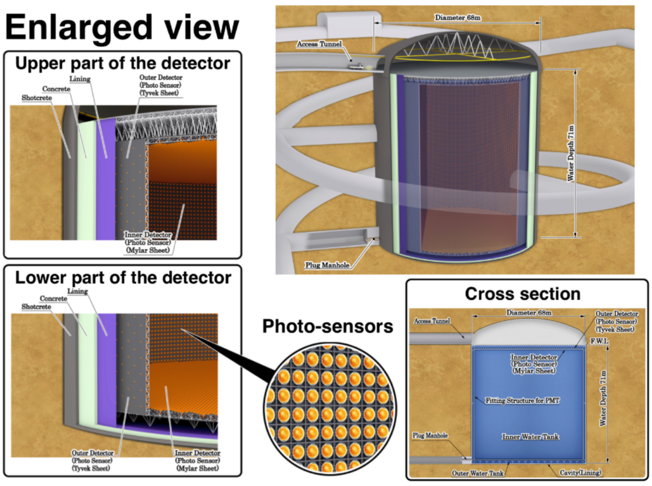

Figure 4: Schematic view of the HK detector.

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.

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.

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 about 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.

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

4.1 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. A close collaboration has been started with the SYRTE laboratory at Observatoire de Paris for a design and R&D program for the next 2 years in order to define the best solution for HK. Within the Hyper-Kamiokande collaboration, the coordination and the R&D work on this item in the electronics work package is under the responsibility of LPNHE. The production stage is planned starting from 2023, and we will prepare a request for the corresponding resources to the IN2P3 directorate. This activity is being closely coordinated with our LLR and IRFU colleagues in order to define a common French contribution to the HK electronics.

4.2 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 Hyper-Kamiokande sensitivity 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.

Participation in the mPMT-related activities 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 [20] at APC to perform underwater tests of the new 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. The 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 participate in 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 in 2019.

4.3 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 [21, 22].

The LPNHE physicists have played a leading role in obtaining the NA61/SHINE results with both a thin carbon target [11] and a T2K replica target [23]. These measurements are currently being used to reduce the (anti)neutrino flux uncertainties in T2K and T2K-II down to about 5%. 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 for T2K-II/HK is being discussed. Motivating the new target is an increase of the neutrino flux while reducing the wrong sign 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 the final inclusion of the NA61/SHINE 2010 replica-target results ([23] and [24]) 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 2022. ND280 in the upgraded configuration will be taking data when Hyper-Kamiokande will start operation in 2027. Obviously, we will keep our responsibilities for the operation of the upgraded near detector.

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.

4.4 Computing for T2K and HK

Given the large amount of data produced by the T2K and HK experiments and the needs in terms of simulation and analysis, dedicating appropriate computing resources is a key element to guarantee the success of these experiments. 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. Indeed, it currently provides 20 millions CPU·hours and some storage for the current T2K needs. These resources benefit also to our IRFU colleagues for common projects, e.g. neutrino cross-section analyses and detector performances studies. Thanks to the already-funded JENNIFER-II European project and expertise on distributed computing models, an effort has been initiated to integrate these resources into the T2K grid system, allowing a more efficient usage of our computing resources. Distributed and CLOUD computing being a challenge common with other experiments at IN2P3, such as Belle-II, we intend to gain expertise on these topics and deploy first prototypes of common solutions within the lifetime of the JENNIFER-II project.

The T2K experiment will continue data taking until 2026 and HK will register its first events around 2027, therefore data will continue to be accumulated over the next two decades. As TRIUMF ramped down as Tier-1 site for T2K, a stronger contribution to the computing effort from the members of the collaboration are highly desired. We believe that CC-IN2P3 could play a leading role for both T2K and HK, by becoming a Tier-1 site for T2K and later on for HK. A proposal to CC-IN2P3 and IN2P3 directorates was recently made and two scenarios are envisaged. The first one consists in making CC-IN2P3 a Tier-1 site for the data produced by ND280 over the lifetime of T2K and HK and provide resources for the Monte-Carlo and analyses productions for these two experiments. The second one includes also the data from the HK far detector onto this site. Such contribution would be highly visible within the T2K and HK collaborations. It is important to note that most of the technologies and investments made for T2K computing are directly transferable to Hyper-Kamiokande.

4.5 Summary and Conclusions

In summary, in the coming years the LPNHE-neutrino group plans to contribute to the next generation of accelerator neutrino experiments with a goal to study the CP-violation in the lepton sector and to measure the neutrino oscillation parameters with unprecedented precision. The projects we would like to participate to are T2K/T2K-II/HK and NA61/SHINE.

The group has recently attracted new researchers and plans to increase even further its visibility in these experiments.

The group is grateful to the IN2P3 directorate for the strong support with the ND280-upgrade project. This activity progresses well.

In the nearest future an additional support from IN2P3 in terms of a permanent position and our involvement in the Hyper-Kamiokande experiment would be required.

Let us stress once again that on a 5-years timescale the T2K upgrade should be finished and in the process of providing physics output, while the R&D towards HK should be fully finalized and the experiment will be in the active construction phase.

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