The Hyper-Kamiokande experiment

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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 the KamLAND experiment [4]. These discoveries have been recognized with the 2015 Nobel Prize in Physics awarded to T. Kajita and A. McDonald.

The original discovery of neutrino oscillations and the first measurements of the corresponding mixing angles (θ_{12} and θ_{23}) and mass squared differences, started a broad program in which neutrino oscillations have been observed by several experiments using very different neutrino sources and detection techniques.

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 [5], θ_{13} was measured to be different from zero in 2012 by Daya Bay [6] and RENO [7]. The T2K experiment has then firmly established the $\nu_\mu \to \nu_e$ appearance [8]. 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.

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 $|\Delta \mathrm{m}^2|$, 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 ν_e and $\overline{\nu}_e$ appearance. T2K has recently published first hints of CP violation in the lepton sector, by excluding CP conserving values at more than 2σ C.L. [9].

Hyper-Kamiokande (HK) is a next generation long-baseline neutrino oscillation experiment that will be built in Japan. The main physics goal of the experiment is the discovery of CP violation in the lepton sector. HK has been recently approved in Japan by the MEXT (Japanese Ministry of Education, Culture, Sports, Science and Technology) and the construction will start in April 2020. The start of the data taking is foreseen for 2027.

The experiment will exploit the same experimental technique (Water Cherenkov detector), neutrino energy ($E_\nu \sim 600$ MeV) and baseline (295 km) as the existing T2K experiment to which IN2P3 and IRFU/DPhP physicists have been participating for more than 15 years.

This well-proven technology has already led to two Nobel prizes in physics with the previous detectors of the Kamiokande 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 δ_{CP} and will be a fundamental experiment to bring neutrino oscillation physics into the era of high 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.

The participation of the LLR and LPNHE neutrino groups to the Hyper-Kamiokande project is built upon the human and financial investments made along the years in T2K and T2K-II, which allowed the French groups to acquire a deep expertise and a primary role in the collaboration, thus ensuring a large return in terms of visibility and responsibility even in the very competitive environment of such large international collaborations.

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. In this document we will introduce the HK detector and its physics case and we will then present our foreseen contributions to the experiment. Another document, describing our contributions to the second phase of the T2K experiment (T2K-II) has also been submitted.

This input to the IN2P3 perspectives has been discussed with the IRFU Neutrino Accelerator group and a clear path for collaborating on the HK experiment and on the topics described in the rest of this document has been commonly defined by the IN2P3 and IRFU/DPhP physicists.

2 Hyper-Kamiokande experiment

HK consists of an underground water Cherenkov detector that will be located about 8 km south of the Super-Kamiokande in the Tochibora mine with an overburden of 1750 m.w.e. The detector will be cylindrical (60 m high and 74 m in diameter) and will have a fiducial (total) mass of 187 (260) 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 [10], soon afterwards is actively being explored.

HK will use at least 20,000 photomultiplier tubes (PMTs), providing a 20 % photocoverage as SK, and 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. As a result, this new model offers better timing resolution and twice the detection efficiency due to improvements in both quantum efficiency and collection efficiency.

To complement the 20” PMTs and increase the photocoverage, particularly important for the low-energy physics, the option to add few thousands multi-PMT modules (mPMTs) to the far detector is being actively discussed.

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 with a beam energy of 30 GeV from the J-PARC Main Ring synchrotron. The proton beam is extracted to the neutrino beam line, 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 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. Hyper-K collaboration plans a suite of near and intermediate detectors to address all systematic effects that are critical for the Hyper-K physics program. This will include the existing T2K Near Detectors, INGRID and ND280.

In addition, a new Intermediate Water Cherenkov Detector (IWCD) is proposed for HK. IWCD will be a kiloton scale Water Cherenkov detector instrumented with $\sim$ 500 mPMTs, using the same technology as developed for the HK mPMTs. The detector will be located 750 m from the neutrino production target and, by measuring the neutrino beam at different off-axis angles, will probe the dependence of neutrino interactions on the neutrino energy.

3 Physics potential

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$10 years at 1.3 MW). Various neutrino mode and antineutrino mode beam running time ratio scenarios have been studied, and a ν:$\overline{\nu}$ ratio of 1:3 is considered here. The expected numbers of events in appearance channel are shown in Table 1 and the spectra expected in

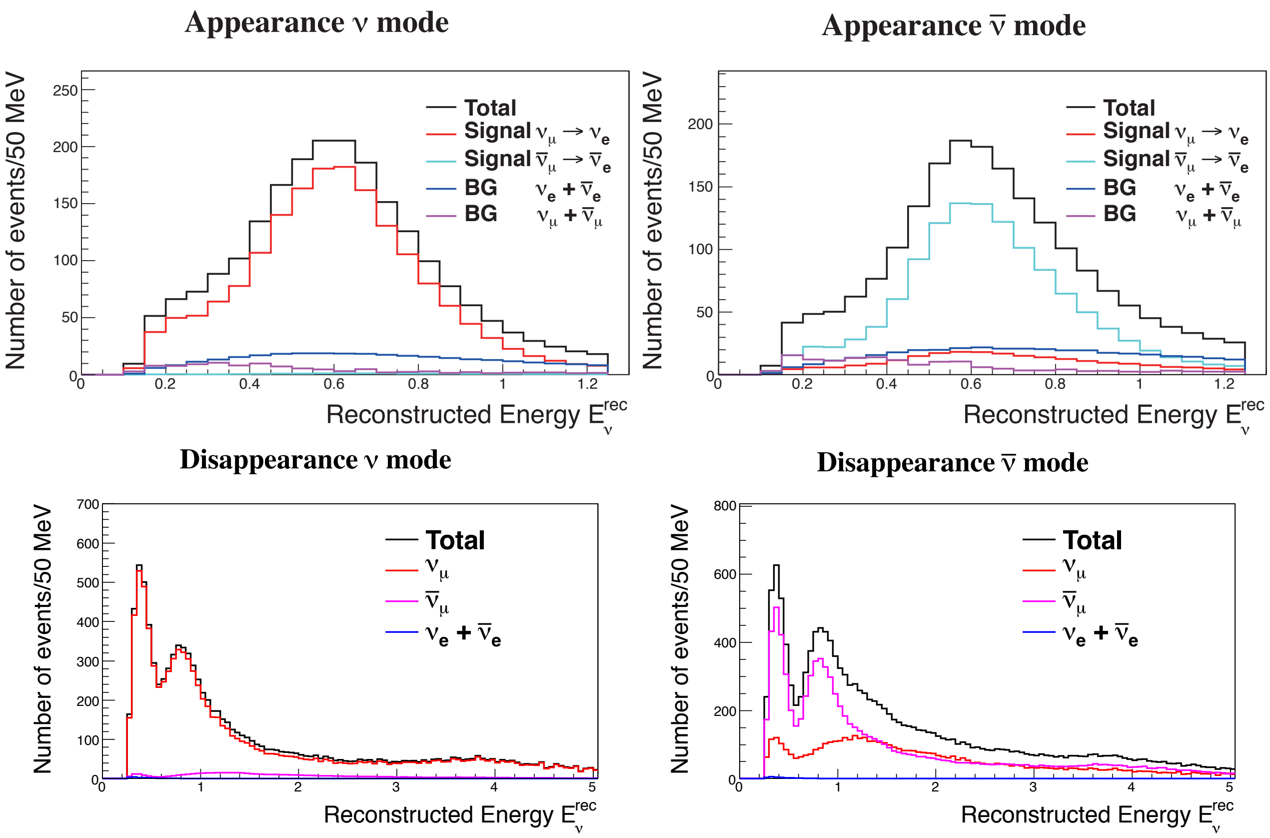

Figure 1: Reconstructed neutrino energy distribution of the ν_e (top) and ν_μ (bottom) candidate events in neutrino beam mode (left) and antineutrino beam mode (right).

Table 1: The expected number of $\nu_e/\overline{\nu}_e$ candidate events 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	—

appearance and disappearance channels are presented in Fig. 1. The expected significance to exclude CP conservation is shown in Fig. 2. Regions of $\delta_{\rm CP}$ which can be excluded at 3σ and 5σ are presented as well as the corresponding fractions as a function of the running time.

In addition, HK, thanks to his huge mass, will improve the SK measurements of solar and atmospheric neutrinos, will have unprecedented sensitivity to the proton-decay through the $p \to e^+\pi^0$ and $p \to \nu + K^+$ channells, and will observe neutrinos from SuperNovae explosions through inverse β decay and elastic scattering.

4 IN2P3 contributions to Hyper-Kamiokande

We are working on the definition of our contributions to the Hyper-Kamiokande experiment. Currently we have identified four different areas:

- Reduction of flux and cross-section systematics with NA61/SHINE and ND280 based on our experience accumulated within T2K

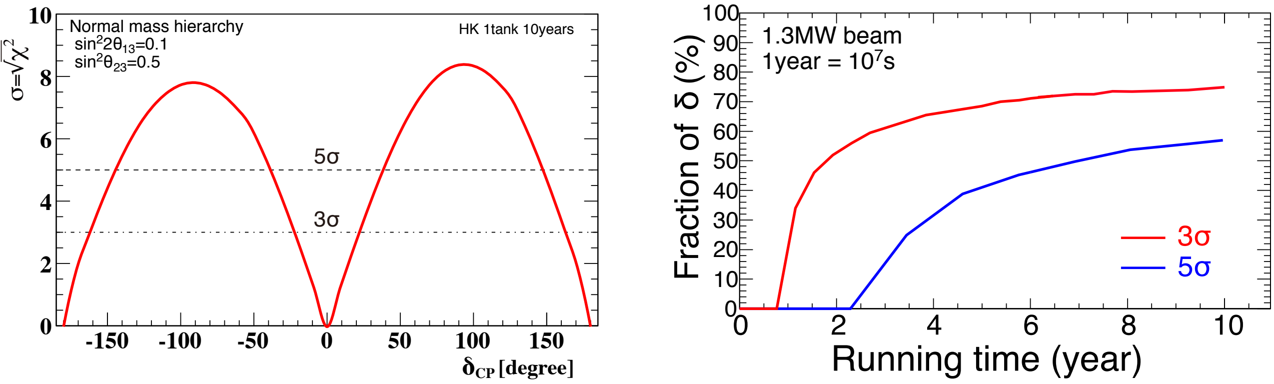

Figure 2: Left : expected significance to exclude $\sin\delta_{\rm CP} = 0$ plotted as a function of true $\delta_{\rm CP}$. Right : fraction of $\delta_{\rm CP}$ for which $\sin\delta_{\rm CP} = 0$ can be excluded with more than $3\,\sigma$ (red) and $5\,\sigma$ (blue) significance as a function of the running time.

- Clock distribution and time synchronization for the 20" PMTs
- Further study, development and tests of multi-PMT option for IWCD and HK
- Software and computing.

4.1 NA61/SHINE

Long-baseline experiments measure rate and spectra of neutrino interactions in their detectors. These rates and spectra are the convolution of neutrino flux, $\phi(E_\nu)$, neutrino cross-section $\sigma(E_\nu)$, and the detector efficiency. $\phi(E_\nu)$ and $\sigma(E_\nu)$ are then the main sources of systematic uncertainties and need to be well controlled with ancillary dedicated experiments and near detectors.

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 [11, 12].

The IN2P3 physicists have played a leading role in obtaining the NA61/SHINE results with both a thin carbon target [13] and a T2K replica target [14]. There 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 for the HK experiment.

4.2 Near Detector (ND280)

The biggest challenge for the Hyper-Kamiokande experiment will be the control of systematic uncertainties at the unprecedented level of about 3%. The Hyper-Kamiokande strategy is based on the successful experience of T2K, where the near detector (ND280) has a crucial role to constrain such systematic uncertainties. The French group had a primary role in the construction, maintenance and data exploitation of **INGRID**, **WAGASCI** and **ND280** and we have today a leading role in the upgrade of the ND280 detector in preparation of the higher statistics expected after the J-PARC beam upgrade.

ND280 is a magnetized detector with outstanding tracking performances. It allows a precise measurement of the wrong sign background (measurement of neutrino background in the antineutrino beam), which is compulsory for the discovery of leptonic CP-violation. The upgrade of ND280 includes a new concept of 3D finely-segmented scintillator detector (superFGD) capable of exclusive measurements of the hadronic final states in neutrino-nucleus interactions. The superFGD enables the reconstruction of the neutrino energy with a calorimetric approach, also in presence of neutrons, thus validating the neutrino energy reconstruction based only on muon kinematics which is a large source of systematic uncertainty in the Hyper-Kamiokande water Cherenkov detector.

ND280 is a modular detector which can be further upgraded, on the basis of the results obtained with larger statistics, in order to match the challenges which the Hyper-Kamiokande experiment will certainly face in the run to the ultimate precision in neutrino oscillation measurements.

4.3 Clock distribution and time synchronization of PMTs

One of the most interesting challenges in HK will be to distribute the clock and to synchronise thousands of PMTs at the 1 ns level. We plan to develop a system that will be applied to both, the 20" PMTs and the mPMTs.

TDCs or FADCs timing synchronization is crucial for precise measurements of photon arrival and, to achieve this goal, we are planning to distribute the common system clock and the reference counters to all the modules. In Hyper-Kamiokande, timing resolution of the photo-sensor is expected to be largely improved with respect to SK, at the level of 1 ns; therefore, we have to be careful with the synchronization of the modules and the clock jitter.

Clock distribution methods for Hyper-K, will be based on serial links with clock reconstruction. Many different options are under consideration, like SK and Belle-II schemes, as well as the CERN White Rabbit technology [15] or a possible custom solution.

The implemented synchronization channel could be also used to perform sensitive slow control tasks as the FPGAs remote upload while mesh topology and multiple connections schemes will be developed in order to avoid single point failures. The chosen time synchronization system could be tested on a smaller scale on test beam at CERN and could also be used for the IWCD.

4.4 Multi–PMTs option for HK

R&D on an alternative photosensor option based on multi-PMT (mPMT) modules is actively being carried on by several countries (mostly Canada, Italy, UK) with the goal of providing half of the photo–cathode coverage for Hyper-Kamiokande. The multi-PMTs are also the baseline photosensor option for the Intermediate Water Cherenkov Detector (IWCD).

The performances of a hybrid design for HK with a combination of large PMTs and multi-PMTs are being studied. Preliminary study 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 of the small PMTs for JUNO, and from the presence of the Memphyno water tank [16] at APC for performing 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 Memphyno.

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 Hyper-Kamiokande collaboration. This design corresponds to a downscaled version of the Intermediate Water Cherenkov Detector (IWCD). This experiment aims at testing the technological choices for IWCD and Hyper-K and plans to demonstrate that the response of the detector can be calibrated at the 1% level necessary for IWCD. Our contribution to this test beam experiment 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 extraction of the detector performances.

4.5 Software and Computing

The very performant IN2P3 Computing Centre at Lyon will allow us to play a leading role in the Hyper-K software and computing group.

As physicists we plan to develop new reconstruction tools for Water Cherenkov detectors based on Machine Learning techniques while on the computing side we can contribute to the Hyper-K needs by providing storage elements and working on the distributed computing for which DIRAC [17] is planned to be used.

This will also allow us to exploit synergies with Belle-II groups in the context of the already-funded JENNIFER-II European project.

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