BERTHA: BettER Timing precision for Hyper-kAmiokande

Project Coordinator: Mathieu Guigue

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2.1 Scientific context

The presence of more matter than antimatter in the visible Universe is one of the most puzzling problems in our current understanding of the Universe. This matter-antimatter asymmetry is usually expressed in terms of the baryon asymmetry.This baryon asymmetry appears to be rather small with one extra baryon for every billion pairs of baryon-antibaryon [1, 2]. It was proposed by Sakharov [?] that such asymmetry could arise from a perfectly symmetric Universe if three conditions are satisfied. One of them is the existence of CP (charge conjugaison and parity transformation) violation processes. In the quark section,

Say clever things about CP violation in the quark sector

In the leptonic sector, CP violation sources are being actively searched for in the neutrino and antineutrino oscillations phenomenon. Neutrino flavor oscillations were first discovered by the Super-Kamiokande (SK) experiment in Japan [3] and in the SNO experiment in Canada [4] by observing the electron neutrino flux coming from the Sun. For these discoveries, the 2015 Nobel Prize in Physics was awarded to T. Kajita and A. B. McDonald. This phenomenon can be explained by assuming that the neutrinos have non-zero but small masses, leading to non-degenerate neutrinos mass states and the possible presence of mass and flavor eigenstates mixings.

From these breakthrough, a broad international program has been initiated to measure the parameters needed to describe the oscillation patterns, i.e. three mixing angles θ_{13}, θ_{23} and θ_{13} and two mass squared differences Δm^2_{21} and Δm^2_{31} along with a CP violation phase δ_{CP}. In this PMNS (for Pontecorvo-Masaka-Nakagawa-Sakata) framework, the neutrinos change flavor as they travel in space. Let's consider the probability for muon neutrinos to oscillate into muon neutrinos, called ν_μ *disappearance probability*:

$$\begin{aligned} P\left(\nu_\mu \rightarrow \nu_\mu\right) &= 1 - \left(\cos^2\theta_{13}\sin^2 2\theta_{23} + \sin^4\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\tfrac{\Delta m^2_{31}L}{4E}\right) \\ &\simeq 1 - \sin^2 2\theta_{23}\sin^2\left(\tfrac{\Delta m^2_{31}L}{4E}\right). \end{aligned} \tag{1}$$

Equation (1) shows that it is possible to enhance the oscillatory pattern by tuning the neutrino energy E and the oscillation length L in order to determine the value of Δm^2_{31}. This makes accelerator long-baseline neutrino (LBL-ν) oscillation experiments excellent places to measure such oscillation pattern and extract constraints on the mixing angles and mass square differences. Let us point out here that this oscillation probability is identical in the case of muon antineutrinos.

Now the probability for muon neutrino to oscillate into electron neutrinos, called ν_e *appearance probability*, can be written as:

Maybe rewrite the oscillation probability with only the main CP-conservin term and the CP violating term...

$$\begin{aligned} P\left(\nu_\mu \rightarrow \nu_e\right) &= \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2\left[(A-1)\Delta_{31}\right] \\ &- \alpha\frac{\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin\left(A\Delta_{31}\right)\sin\left[(1-A)\Delta_{31}\right] \\ &+ \alpha\frac{\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin\left(A\Delta_{31}\right)\sin\left[(1-A)\Delta_{31}\right] \\ &+ \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2\left(A\Delta_{31}\right), \end{aligned} \tag{2}$$

with $\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 0.03$, $\Delta_{31} = \Delta m^2_{31}L/4E$. The term $A = 2\sqrt{2}G_F n_e E/\Delta m^2_{31}$ (where n_e is the electron density) is related to the matter effect induced when neutrinos are crossing the Earth. This oscillation probability pattern is interesting for two reasons. First it allows to measure the θ_{13} parameter which turned out to be non-zero as measured by T2K [5], RENO [6] and Daya Bay [7] experiments. Secondly this term depends on whether we are considering neutrinos or antineutrinos; indeed this would change the sign of both $\sin\delta_{CP}$ and A, leading to a change of the third term sign and therefore in the oscillation probability by about ∓ 30 % if δ_{CP} is close to $\pm\frac{\pi}{2}$. By looking at the differences between the oscillation patterns for neutrino and antineutrinos as a function of the neutrinos energy, the δ_{CP} phase can be determined.

Long-baseline neutrino oscillations experiments are therefore unique experimental techniques because of their capabilities to precisely determine various oscillations parameters such as θ_{23}, δm^2_{32}. They could also observe CP violation in the leptonic sector by comparing the electron neutrino and antineutrinos appearance probabilities.

Currently, two LBL-ν experiments are taking data: NOνA (for NuMI Off-axis ν_e Appearance) in the Unites States and T2K (Tokai To Kamioka) in Japan. These two experiments are taking data for about a decade and will continue providing the most precise measurments of the neutrino mixing parameters for the next decade, until the next generation experiments (DUNE and Hyper-Kamiokande) will start taking data.

The T2K experiment is a long-baseline neutrino oscillation experiment running across Japan that aims at constraining mixing parameters by looking at muon neutrino beam flavor oscillations. The experimental setup is as follows: a muon neutrino beam is produced by shooting $30-\text{GeV}$ protons onto a graphite target at the J-PARC complex on the East Coast of Japan. These hadrons, mostly

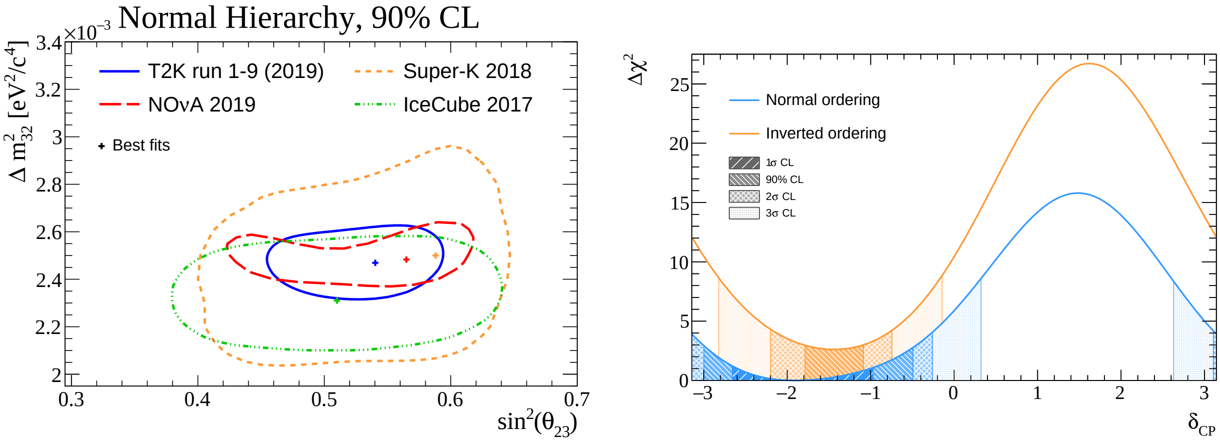

Figure 1: Results of the T2K recent oscillation analysis. Measurements of θ_{23} and Δm^2_{32} by T2K, NOνA and Minos (left) and constraints on the CP violation phase δ_{CP} from the 2021 oscillation analysis (right).

pions, then decay producing muons neutrinos inside a 100 m-long decay volume before arriving onto a suite of detectors called ND280. The selection of neutrino or antineutrino beam can then be done by changing the current direction in a set of magnetic focusing elements next to the target; if the current is positive (negative), π^+ (π^-) will be focused and decay into μ^+ and ν_μ (μ^- and $\bar{\nu}_\mu$), leading to a ν ($\bar{\nu}$) beam into ν-mode ($\bar{\nu}$-mode). Due to the very close distance to the production point, the muon neutrinos don't have the time to oscillate before being detected by these near detectors, allowing the monitoring of the muon neutrino flux and electron neutrino contamination. Then 295 km away from J-PARC is the far detector, Super-Kamiokande. This detector consists in a cylindrical tank filled with water equipped with photomultipliers that detect Cherenkov light produced by charged particles created by the interaction of the beam muon and electron neutrinos with the water. The detector can easily distinguish between e and μ using the shape of the Cherenkov ring and suppress background with a high efficiency. The incoming neutrino energy E_ν is reconstructed using the kinematics of the outgoing lepton, namely its energy E_l and the angle θ_l between the lepton and the beam direction:

$$E_\nu = \frac{2M'_n E_l - \left((M'_n)^2 + m_l^2 - M_p^2\right)}{2\left(M'_n - E_l + \sqrt{E_l^2 - m_l^2 \cos\theta_l}\right)}. \tag{3}$$

T2K is the first neutrino experiment to implement the so-called "off-axis technique" that consists in placing the near and far detectors 2.5° away from the beam axis direction, peaking the neutrino energy around 600 MeV and leading to a maximum disappearance probability of the muon neutrinos at the far detector.

Thanks to the total statistics of 3.13×10^{21} protons − on − target (POT) accumulated since 2009, T2K is producing the world leading measurement of some of the mixing parameters. Indeed, by combining all the appearance and disappearance samples collected in neutrino and antineutrino mode, constraints can be placed on θ_{23} and Δm^2_{32} such as shown in figure 1. Recently first hints on the value of the δ_{CP} were published in Nature [8]. As shown in figure 1, a maximum CP violation with $\delta_{\mathrm{CP}} \approx -\frac{\pi}{2}$ seems preferred by the most recent datasets. Moreover, CP conservation corresponding to $\sin\delta_{\mathrm{CP}} = 0$ has been excluded with 95 % C.L. T2K will continue taking data till the start of Hyper-Kamiokande and plans to reach 10×10^{21} POT. If the current measurement $\delta_{\mathrm{CP}} \approx -\frac{\pi}{2}$ corresponds to Nature's choice, CP-conserving values should be excluded at more than 3 σ.

In order to reach a 5 σ discovery of CP violation in the leptonic sector, a new generation of LBL-ν experiments are needed, namely the DUNE and Hyper-Kamiokande experiments. The DUNE experiment will implement an on-axis with a 1300 km long baseline and plans to deploy using a staged aproach four liquid argon TPC as far detector of 40 kt in total. Build-

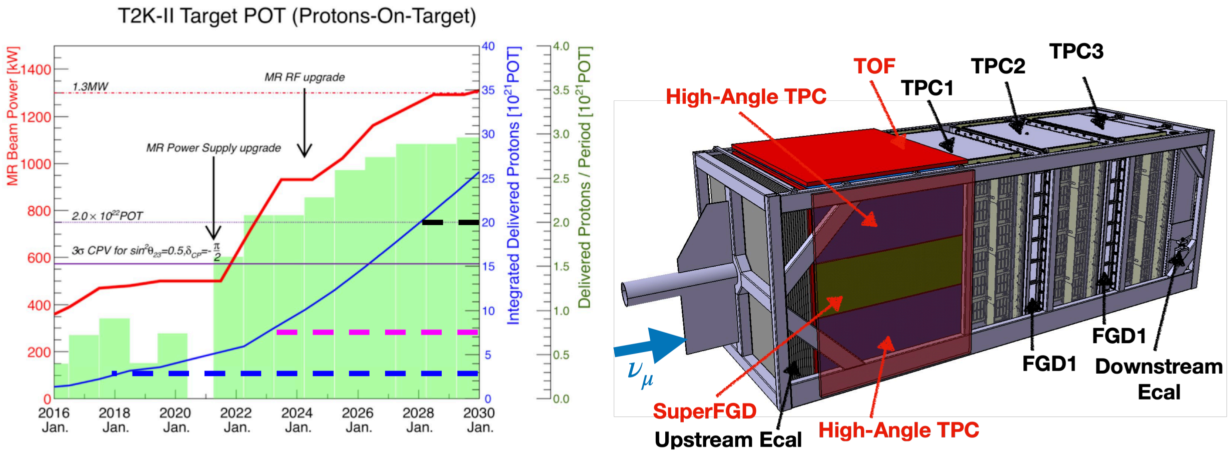

Figure 2: Left: upgrade of the muon neutrinos beam until the start of Hyper-Kamiokande. Right: upgrades to ND280. In red are the new detectors added to the composite detector.

ing upon the expertise gained from the current experiments, the Hyper-Kamiokande experiment is a long-term program initiated in Japan which aims at upgrading the key components of the current T2K experiment and also building new detectors to fully profit from these upgrades.

One key element that is being upgraded is the J-PARC proton main ring used to produce the neutrino beam. This upgrade is twofold: first, the number of pulses per second will be doubled to reach one pulse every 2.5 s. Second, as represented in figure 2, the beam power will be increased from 515 kW to 1.3 MW. These upgrades will triple the number of POT by period, and thus the statistics at the far site.

ND280 is a magnetized composite detector consisting of several Fine Grained Detectors (FGD) and Time Project Chambers (TPC) surounded by calorimeters. Because of the orientation of these detectors, the reconstruction of the outgoing lepton is not very efficient for $\cos\theta_l \geq 0.4$. The upgrade the T2K collaboration is working on aims at better reconstructing particles coming out of the neutrino interaction vertex at high angles with respect to the incoming beam direction. Since the far detector SK has no dependence on the reconstruction efficiency with the lepton angle, it is important that constraints on the neutrino cross-sections are obtained over the entire kinematic phase space in order to reduce the systematic uncertainties at the far detector. Such improvement in the reconstruction acceptance can be achieved by replacing part of ND280 with a new horizontal fully active carbon target (Super-FGC) surrounded by two horizontal TPCs (High-Angle TPC) and six Time-Of-Flight (TOF) planes. This upgrade will be installed in 2022 and fully commissionned before the beginning of Hyper-Kamiokande, so that Hyper-Kamiokande fully benefit its upgraded performances during the beam data taking period. Indeed this upgrade along with better modeling of the neutrino cross sections will help reducing the overall systematics uncertainties on the number of events at the far detector from about 10 % down to 3 %.

One of the major components of this program is the construction of a new large-scale water Cherenkov neutrino detector in the Kamioka mines. As depicted in figure 3, this new far detector called Hyper-Kamiokande of 250 ktons of pure water will have a fiducial volume 8 times larger than the current SK detector and will be instrumented with about 20,000 20-inch photomultiplier tubes (PMTs) from Hamamatsu (R12860HQE). These newly-developped PMTs have improved quantum efficiency of 24 % with a photon timing resolution reduced to 1.5 ns and the detector photocoverage should reach 20 %. An outer water Cherenkov detector surrounding the inner detector and equipped with 8,000 3-inch PMTs will be used to detect charged particles entering the detector from the outside.

Contrary to the SK design, the frontend electronics collecting the signals from the PMTs will be located under water. This novel design allows to reduce the length of the analog cables between the digitizers and the PMT, but requires the electronics cases to be water-tight. In the current design, there will be 24 photosensors connected to a water-tight case.

Add details about the front-end electronics in

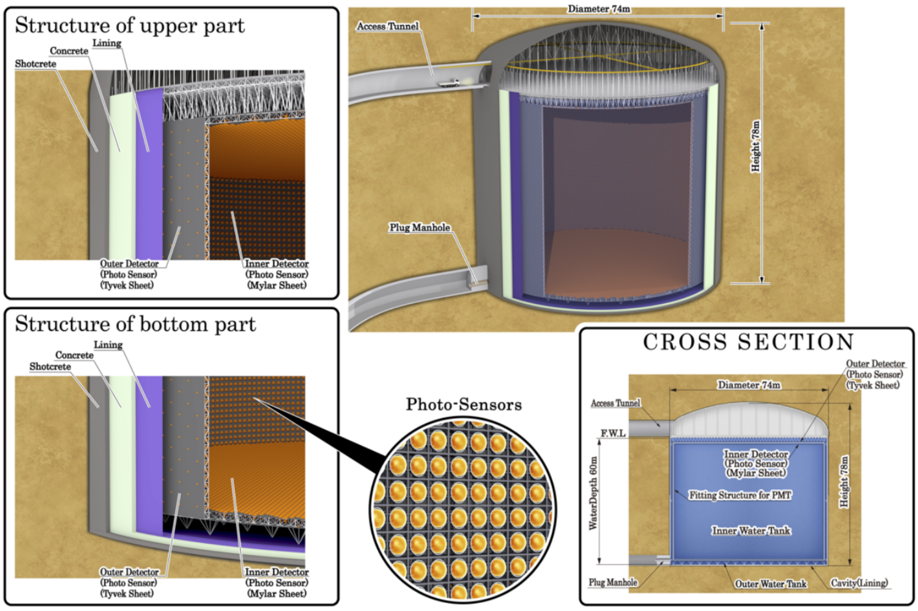

Figure 3: Scheme of the Hyper-Kamiokande far detector.

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Scheme of the electronics

Figure **??** shows a scheme of the front-end electronics. All the systems required to monitor and control the electronics, including digitization, low- and high-voltage, clock and counter, must then be distributed to each case. This last item consists in a stable reference clock at 125 MHz frequency used to drive the internal frequency of the digitizers and a time base at 1 Hz (1 Pulse Per Second or PPS) that serves to determine the time. These signals will be sent via optical fibers from a clock and PPS generation system and distributed as uniformly as possible to all the front-ends cases.

Several R&D on the key elements of the experiment are in progress and should be completed in the next couple of years. The construction and exclavation work has started in April 2020 and this new detector should start taking data in 2027. After 10 years of data taking, this far detector should register about 4,200 ν_e events and about 23,000 ν_μ events from J-PARC, thus increasing statistics by a factor 40 compared with T2K.

Thanks to this very large statistics and the constraints on the systematic parameters (cross-sections and flux) obtained with the near and intermediate detectors, a combined analysis using disappearance and appearance samples will provide exquisite sentivity to the δ_{CP} phase. Indeed, as depicted in figure 4, depending on the value of δ_{CP}, Hyper-Kamiokande will obtain a measurement with an error between 10° and 23°.

Any more clever comments on δ_{CP} and the other oscillation

2.2 Originality and relevance in relation to the state of the art

The rich Hyper-Kamiokande physics program goes well beyond the measurements of neutrino oscillation parameters and neutrino cross-sections measurements. For example, thanks to its gigantic mass of purified water, the Hyper-Kamiokande far detector is an excellent setup for testing models predicting

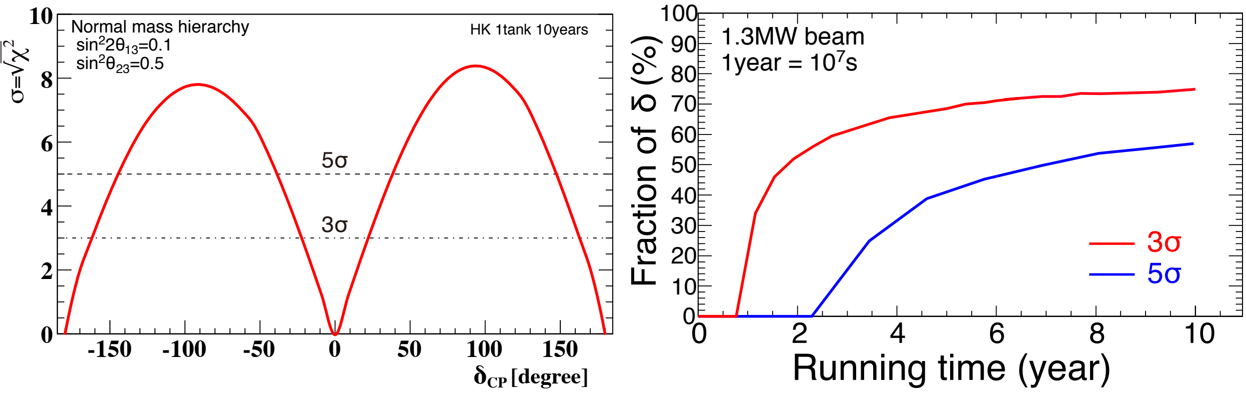

Figure 4: Left: Hyper-Kamiokande sensitivity on the exclusion of CP conservation after 10 years of data taking. Right: precision on the δ_{CP} measurement as a function of time for $\delta_{\mathrm{CP}} = 0$ (blue) and $\delta_{\mathrm{CP}} = \pi/2$ (red).

the proton decay. In particular, the decay of the proton into a positron and a neutral pion is of great interest for testing Grand Unified Theories (GUT) and can be searched by Hyper-Kamiokande as their signature in the detector would be three electronmagnetic showers: one coming from the pion decay and one from the positron appearing in the opposite direction. Since there are no invisible particles or hadronic scattering, the initial particle properties can be reconstructed precisely and especially the momentum depending on which we can determine whether the proton comes from an atom of oxygen or hydrogen. After 20 years of datataking (similar to SK's overall period), Hyper-Kamiokande should be able to put a proton lifetime limit on decau into this mode to 10^{35} years, which is 10 times better than the current limit from SK.

In addition, Hyper-Kamiokande will detect thousands of electron antineutrinos (via inverse beta-decay) and electron neutrinos (via elastic scattering) from SN bursts in the galactic center. Using the elastic scattering events, it will be possible to reconstruct the direction towards a SN 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 to further inspect SN explosion mechanism. In addition, it will be possible to detect neutrinos also from extra-galactic SN explosions. Even for distances of 4 Mpc, we will observe few tenths of neutrinos in Hyper-Kamiokande and, at such distances, one SN is expected every three years. Hyper-Kamiokande will also be able to detect the SN relic neutrinos (SRN) that are neutrinos produced by all SN explosions since the beginning of the universe. Such neutrinos fill the present universe and have a flux of few tens/cm^2/s. The observation of SRN would allow understanding how heavy elements have been synthesized in stellar formation.

On top of that, Hyper-Kamiokande will collect a large sample of atmospheric high-energy neutrinos. Such measurements will complement the long-baseline program since joint analyses between beam and atmospheric neutrinos can improve the sensitivity to neutrino mass ordering and thus to CP violation in neutrino oscillations. Indeed, the matter effects are rather small for the 295 km baseline of Tokai to Hyper-Kamiokande making the sensitivity to the mass ordering limited, while atmospheric neutrinos emitted on the other side of the Earth and measured at the Hyper-Kamiokande detector have crossed the Earth's core and experienced strong matter effects. Therefore, the Hyper-Kamiokande detector as part of the Japanese long-baseline neutrino program will be extremely useful to further constrain neutrino oscillation parameters.

The success of this experiment relies on the excellent reconstruction of incoming neutrino energies and directions using the PMTs. The detection of SN events strongly depends on the reconstruction of the associated low-energy events and on the synchronisation of Hyper-Kamiokande PMTs and other experiments around the world. Moreover, reconstruction of neutrino interaction vertices in the detector requires an accurate timing determination of the event occurrence. It is therefore essential that an excellent distribution system is built for distributing clocks among all the detectors. Preliminary studies indicate that the timing precision should be lower than 1 ns with a maximum jitter of 100 ps rms along with the capability of sending slow control data using this link thanks to a sufficient bandwidth.

World-wide, several detectors currently running or nearing completion are sensitive to a core-collapse supernova neutrino signal in the Milky Way using the so-called SNEWS (SuperNova Early Warning System) network. The neutrino burst signal emerges promptly from a supernova's core, whereas it may take hours for the first photons to be visible. Therefore, the detection of the neutrino burst from the next Galactic supernova can provide an early warning for astronomers. Requiring a coincident signal from several detectors will provide the astronomical community with a very high confidence early warning of the supernova's occurrence. Being able to properly time with respect to UTC an neutrino event in the Hyper-Kamiokande detector is essential when studying time profile of these astrophical events or when comparing with other experiments in the context of multimessenger studies.

Need to study the Cherenkov light profile, pion scattering in water and secondary neutron production. Given the expected statistical sensitivity of the entire Hyper-Kamiokande data taking campaign, the reduction of systematics uncertainties will be at the heart of the experimental setup and the physics analysis program. As we already mentionned, Hyper-Kamiokande comes with upgrades of the neutrino beam and the near detector suite, in order to reduce the systematics uncertainties related to the flux and neutrino cross-sections. Another set of systematics are related to the understanding of Cherenkov detectors, the far detector modeling and the interaction of charged particles with water. These error sources contribute to an overall systematic uncertainty of 5.87 % for the ν_e and $\bar{\nu_e}$ samples. In particular, the nuclear binding energy of the outgoing nucleons after a neutrino interaction represents an uncertainty of 3.74 %. In order to better constraint this dominant systematic, it is necessary to build a neutrino detector that have an energy scale determination down to 1 %. In addition, the uncertainties on the modeling of the pion production reinteractions in water represents another large source of uncertainty that could be improved by utilizing neutrino event samples with and without pions in the final states.

For these reasons, a new Intermediate Water Cherenkov Detector (IWCD) will be built 1 km away from the J-PARC neutrino source. It will consist in a 10-m diameter by 8-m tall cylindrical water Cherenkov detector operated in a 50 m deep shaft. The detector will be equipped with mPMTs and its elevation could be varied in order to move the detector to various angles with respect to the neutrino beam direction: the various neutrino spectrum shapes will allow to probe different neutrino energies. Such technique will also allow the study of the energy dependence of the neutrino interactions. To reach the expected 1 % precision on the neutrino energy scale, it is necessary to calibrate the reconstruction of the final states topologies and kinematic properties in order to correctly obtain the neutrino energy. This requires to be able to reconstruct the final stats pions that may undergo hadronic interactions in the detector and could bias the energy scale. In addition, the vertex reconstruction uncertainty needs to be under 1 cm in order to have an exquisite control on the detector fiducial mass. In a second phase, IWCD will be loaded with Gadolinium to enhance the neutron radiative capture cross-section and better reconstruct neutron capture events. These measurements are important for SK and Hyper-Kamiokande that will use the neutron multiplicity measurements to reject background events.

To test the detector design and constraint the charged particles interaction with water, a scaled-down version of IWCD composed also of 128 mPMTs will be placed under a charged particle beam at CERN. The goal of the experiment is to measure the properties of charged particles such as $\pi^\pm$, p, $e^\pm$, $\mu^\pm$ and $K^\pm$ with momenta ranging from 200 MeV/c to 1200 MeV/c transversing the detector and evaluate the important physics processes that are necessary for the accurate modeling of the final detector. It will also be used to in-situ calibrate the mPMT design that will be used at IWCD.

Need to define the computing tools

2.3 Work packages and deliverables

Here we present the different work packages and associated deliverables that will be produced by the BERTHA project.

2.3.1 Work package 1: Project coordination and outreach

Task responsible: Mathieu Guigue

The BERTHA project will be coordinated by Mathieu Guigue. This responsibility includes the definition and tracking of the various work packages, their schedule and all the actions required for producing the associated deliverables. The coordinator will also oversee the hiring process of the postdoc. He will organize bi-weekly meetings with the project members to follow on the evolution of the work packages and coordinate the common efforts between tasks 2, 3 and 4. Given the international nature of the project, regular workshops involving people of interest (in IN2P3 and internationnally) in the work packages will be organized. The responsability also includes the writing of reviews and reports both for the internal project and for the Hyper-Kamiokande collaboration and the overseeing of the papers publication and data release process. Finally, he will make sure that all the members of the team gain in visibility inside and outside the Hyper-Kamiokande collaboration by attending to collaboration meetings and workshops and at international conferences.

Deliverables: project organization, project and collaboration reviews and reports.

2.3.2 Work package 2: Development and characterisation of clock distribution and time synchronisation system for Hyper-Kamiokande

Task responsible: Stefano Russo

The reconstruction of Cherenkov events relies on the accurate timing of the photon arrival at each detector's PMT and have to be correlated to the absolute time on Earth. When looking at the reconstruction of a single event, any timing bias between subsets of PMTs will lead to misreconstruction of the vertex position. A physical event is defined as a set of charges collected on various PMTs that occur on a specified time window large about 10 μs. Any signal outside this time window not in coincidence with another set of PMTs will be discarded as background noise. From this collection, the event reconstruction algorithm, named fiTQun, currently used in SK and that will serve as a starting point for the Hyper-Kamiokande reconstruction, relies on building the event's likelihood characteristics such as the vertex position or the energy starting from the PMTs charge and the timing information [9]. In particular, it includes the probability for getting a certain amount of charge at a certain time, given a set of event parameters from which fiTQun will try to determine the best values by maximising the tracks parameters with respect to the likelihood. The use of timing is new compared with the previous reconstruction algorithm called APFit which used the timing only during the initial step to find the initial vertex candidate. Such method is still used in fiTQun but only as a fast pre-fitting technique to get a rough estimation of the vertex location before using the likelihood minimisation method.

From the above description is evident that measuring the light arrival time on each PMT (time tagging) is crucial for the event's reconstruction and all the timing uncertainties have to be analysed and, if possible, controlled.

A first goal of the BERTHA project is to evaluate the impact of the timing on the detector capabilities and in consequence on the physics performances of the detector, such as the impact on the oscillation parameters extraction.

The most important contribution to the total time uncertainty is the so-called Transit Time Spread or TTS which is a statistical effect related to the photon to electron conversion that happens in the detector. Since photoelectrons have a broad range of velocities and emission angles and the electron multiplication by the dynodes is a random phenomenon, a spread on the PMT output signals rise time is observed. For the Hyper-Kamiokande 20-inch PMTs, the TTS has been measured to be 5 ns, while for mPMT is about 1.5 ns. Due to its randomness nature this effect depends on the number of photoelectrons produced on the photocathode, so it is usually expressed for one single photoelectron.

Time Synchronization Experimental Constraints	
Total Jitter	$\leq$ 100 ps
Board to Board skew	fixed over any reset and power cycle
Accuracy to UTC	$\leq$ 50 ns
Critical Slow Control Data bandwidth	$\geq$ 100 Mbps

Table 1: Experimental constraints for the time distribution and synchronisation system.

The TTS depends mostly on the intrinsic detector construction's characteristics and can vary from PMT to PMT but on Hyper-Kamiokande the detectors have been selected to have a time fluctuations between them smaller than 100 ps.

Another possible source of timing uncertainty could reside in the front-end electronics that collects the waveforms. The signal's digital conversion is based on a 125 MHz clock which is generated by an atomic clock and distributed to all the front-end electronics. Any clock instability induced by the electronics itself or by the clock distribution architecture will lead to time misestimations and potentially errors in events reconstruction. This is the reason why the clock distribution architecture is a critical part of the far detector and has to be designed properly in order to give a negligible contribution to the time reconstruction.

In order to minimise this uncertainty contribution a time distribution jitter smaller then 100 ps RMS and the clock skew between front-end boards constant over any power-up and reset are required.

The time tag of each particle interaction needs to be in a format that allows its correlation with data collected by other experiments; for this reason the generated local time base has to be associated with the Coordinated Universal Time (UTC) with an accuracy of 50 ns or smaller. This absolute time tagging will be also used to identify the events generated in the detector by the particles sent from the J-PARC accelerator. Along with the time synchronisation some "critical information" like remote firmware FPGA updating stream and slow control data have to be transmitted by this subsystem hence a 100 Mbps or greater bandwidth bidirectional data channel has to be provided.

The basic experimental requirements relative to the time distribution system, as defined at this time, are summarised in Table 1 while the the conceptual block scheme is depicted in Fig .

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Oversimplified scheme of the clock generation and distribution system plus the slow control

To guarantee the most stable and precise reference, the local time base originates in an atomic clock and a GNSS (Global Navigation Satellite System) working together to generate a Pulse Per Second (PPS) and a 10 MHz signals which are synthesised in the master clock generator (MCLK Gen) to produce a 125 MHz output. This frequency is then distributed over different branches and delivered to more than 1,000 electronic front-ends modules that "read" 40,000 20-inch PMTs and about 5,000 mPMTs The PPS and the 10 MHz signal, along with satellite information, reach also a computer infrastructure to form the UTC time synchronous with the local time base and, from there, propagated to all the elements in form of data packets.

Several clock distributions solutions have been considered, but two are the most promising: one is based on a custom solution and the other on the CERN White Rabbit (WR) protocol.

The custom solution relies on the Clock and Data Recovery (CDR) technology which is the process of extracting time information (clock) and data from a single serial stream. The CDR is implemented by means of a specific serializer-deserializer (ser-des) couple to be used on both sides of the link. The simplicity, reliability and the convenience of this technique has fuelled its use in many different fields so that all the modern FPGAs have CDR compliant ser-des already embedded on the silicon. This represents a further advantage for the experiment because it is possible to send slow control data and distribute the system clock using one single fibre.

A time distribution scheme based on the CDR requires that one entity (called master) receives the precise clock (the master clock), generated as described above, and distributes it to the different nodes (called slaves). This implies that the master has a CDR compliant link to each slave. The number of slaves, i.e. the front ends, in the HK case, doesn't allow the implementation of all the master's functionalities on a single electronics board hence they have to be divided upon different cards.This diffused architecture requires that the base clock must be fan-out to all the different distributors also called Time Distribution Module (TDM).

In order to guarantee the time performances required by the experiment, extreme care must be devoted to the ser-des configuration to achieve low jitter and a fixed phase relation between the transmitter's and receiver's clock. This last aspect is particularly critical since, in the standard configuration, the FPGA's ser-des locks on a random phase after each reboot or reset.

White Rabbit (WR) [10] is the name of a collaborative project including CERN, GSI Helmholtz Centre for Heavy Ion Research and other partners from universities and industry to develop a fully deterministic Ethernet-based network for general purpose data transfer and sub-nanosecond accuracy time transfer. Its initial use was as a timing distribution network for control and data acquisition of the accelerator sites at CERN as well as in GSI's Facility for Antiproton and Ion Research (FAIR) project. The hardware designs and the source code are publicly available [11].

This protocol is based on the clock and data recovery so, also in this case, one optical fibre can be used to distribute the master clock and for a bi-directional communication link between each front end and the data acquisition system.

White Rabbit uses Synchronous Ethernet (SyncE) to achieve sub nanosecond synchronisation and IEEE 1588 Precision Time Protocol (PTP) to communicate time. The phase difference between the master reference clock and the local clock is measured using a specific module based on phase frequency detectors [12]. A two-way exchange of the Precision Time Protocol synchronisation messages allows precise adjustment of clock phase and offset. The link delay is known precisely via accurate hardware timestamps and the calculation of delay asymmetry. The measurements results are computed to align the master and the slave clocks and remove skew due to the cabling and thermal effects. This feature is certainly useful but not fundamental in the Hyper-Kamiokande due to the fact that the fibres and the electronics are in a caver where the temperature excursions are very limited.

Distributing the clock using this infrastructure means building an Ethernet network where each front end is a network endpoint and the connections can be routed trough a special network switch. Each node, including the switch, can act as a master or slave meaning that it can receive the master clock base (called grand master clock in the WR language) and distribute it to all the other endpoints trough a network that can have even multiple layers. Each White Rabbit compliant endpoint that receive the data stream, can reconstruct the master clock and compensate the phase differences as explained before. If a node is not WR compliant all the time information is filtered following the standard Ethernet rules but the data content is preserved. This feature is particularly useful in the HK case because the time synchronisation network can be included in the data acquisition infrastructure.

Through the BERTHA project, we plan to evaluate each solution's performances and propose a clock distribution system that could be used for the clock distribution and slow control in both the Hyper-Kamiokande inner and outer detectors and IWCD. In particular, the prototypes built during the duration of the BERTHA project will be tested at LPNHE but also on the WCTE experiment at CERN. WCTE will be composed of 128 mPMTs and 6 mPMT Concentrator Cards (MCC) will be used outside of the tank to collect data digitised by 24 mPMTs. These MCC will also be used at the Hyper-Kamiokande far detector and the IWCD, so developing and testing a prototype for Hyper-Kamiokande detector on WCTE is highly valuable in the R&D process. Despite the small size of the experiment, the clock distribution prototype will have the same technology as the final Hyper-Kamiokande far detector but a scaled architecture composed on a single custom clock distributor (TDM) or a White Rabbit switch.

From this in-situ test and the other tests made at LPNHE, we plan on producing a design report for the clock distribution system that will be shared with the Hyper-Kamiokande electronics working group before approval by the Hyper-Kamiokande management. Given the intrinsic modularity and flexibility of the proposed distribution architecture the system under study could be extended to accomodate the larger number of mPMTs of the IWCD; this way the far and intermediate detectors will have similar clock distribution system with well-studied characteristics.

One of the BERTHA project goals is to develop a time base generation system that can be deployed at Hyper-Kamiokande. Given the duration of the Hyper-Kamiokande experiment and the randomness nature of the collected events, the system needs to be stable over very long periods of time and be able to recover in case of failure. The time generation system therefore needs to include some redundancy in order to cope with long-term issues. For that purpose, we plan on using the running SK detector to test the long term stability of the time generation system. We will install and monitor a prototype of this system against the running SK one over the duration of the BERTHA project. This long-term test will provide insights about the performances and robustness of our design.

Finally, the data channel implemented as part of the clock distribution will be used to collect all the environmental parameters that monitor the status of the detector. Given the large number of nodes, this information have to be distributed across several machines of a back-end farm that can process the shifter requests and store these data locally and on a remote storage element.

Given the broad scope of such system and the potential interest from other large-scale experiments, the source code will be made available using code sharing platforms such as GitHub and presented in peer-reviewed papers.

The postdoc of BERTHA will contribute during the first half of the project to this Work Package both on the determination of the timing impacts and on the development, characterization and deployment of a time synchronization and clock distribution system. The postdoc will also present the results during collaboration meetings and international workshops and conferences.

deliverables: Simulation for studying impacts of timing on reconstruction capabilities and physics studies; prototype for the slow control system; design report for Hyper-Kamiokande time synchronisation and clock distribution system; time generation system deployable at Hyper-Kamiokande far detector; peer-reviewed paper on the clock generation and distribution system.

2.3.3 Work package 3: Cherenkov light studies with Water Cherenkov Test Experiment

Task responsible: Boris Popov

Water Cherenkov Test Experiment is a IWCD scaled-down setup designed to understand the performance of new detector technologies such as mPMTs in the context of Hyper-Kamiokande intermediate and far Cherenkov detectors, especially when exposed to known particles fluxes and with dedicated calibration systems that will be deployed in Hyper-Kamiokande. This will allow to construct accurate modelling of the detectors that will be built. In addition, important processes for the water Cherenkov detector response will be measured and constrained, in particular the high-angle Cherenkov light production, pion scattering and absorption, and secondary neutron production in hadron scattering. This ambitious program will take place at the CERN East Area beam line T9 as depicted in Figure 5. The T9 consists in a 24 GeV/c primary proton beam that interacts with a target to produce secondary particles like electrons, muons and protons (secondary beam configuration). By placing a secondary target on this beam line and slightly moving the detector, it is possible to obtain low momentum pions and protons (tertiary beam configuration). electrons produced by interaction of secondary beam particles on a secondary target. The WCTE detector will be placed on the charged particle beam including $\pi^{\pm}$, p, $e^{\pm}$ and $\mu^{\pm}$. The target is placed less than 5 m away from the detector in order to provide pions with momenta as as low as 140 MeV/c. To be able to have both low momenta muons and pions, it is necessary to have two experimental configurations: one where the beam line is short allowing the short-lived pions to reach the detector without decaying and one with a longer baseline where the pions have the time to decay into muons.

After a compact spectrometer and a set of magnets, the narrow beam of charged particles enters in the water Cherenkov detector and produce Cherenkov rings that are detected by the 128 mPMTs

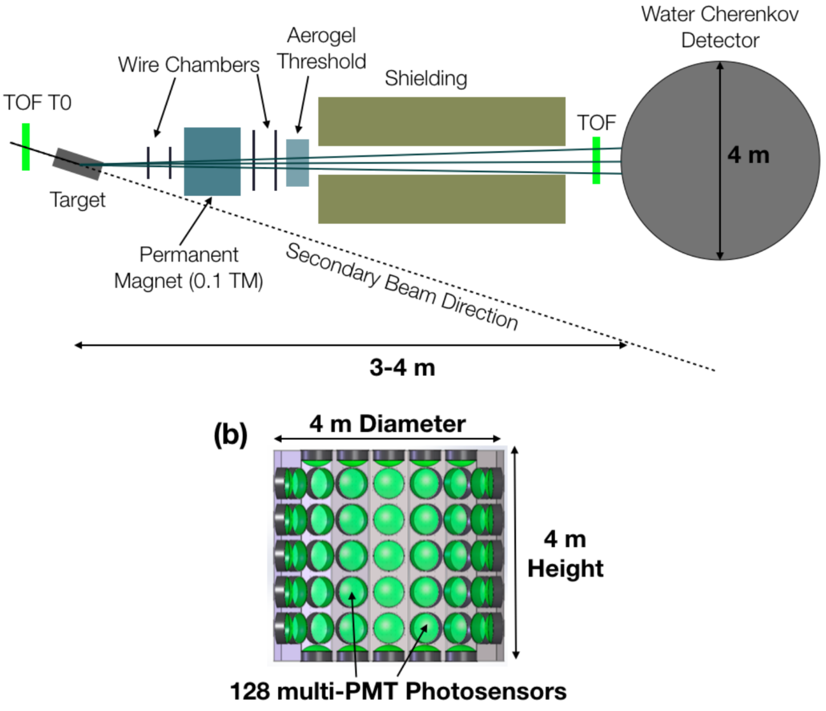


Figure 5: Top: schematics of the WCTE in the secondary beam line. Bottom: WCTE detector with the 128 mPMTs (green).

covering the inside of the detector. From the collected light, the vertex, momentum and type of the initial particle are reconstructed. The water Cherenkov detector has been simulated and optimized so that the reconstruction performances (vertex and momentum resolutions) will be simular to IWCD.

During the first phase of the experiment, the detector will be filled with ultra-pure water in order to match as closely as possible the IWCD configuration and evaluate the important physics processes that are necessary for the accurate modeling of the final detector. In particular, the production of Cherenkov light at large angles relative to the particle propagation due to delta rays will be studied. The angular distribution of Cherenkov photons is a critical input to water Cherenkov detectors, as it can biais the reconstructed momentum and particle vertex along the particle direction. Thanks to the exquisite timing resolution of the mPMT along with the precise clock distributed between the modules that will be installed on this experiment as part of the Work Package 2), it will be possible to separate the light from delta rays or pions scattering from reflections in the detector and study the properties of pion scattering in the detector or partial Cherenkov rings due to pions with momentum right above the Cherenkov threshold. In this case, the simulations using GEANT3 and GEANT4 particles propagation modeling display clear discrepancies on the outer edge of the Cherenkov ring, leading to discrepencies in the results produced by the SK and Hyper-Kamiokande simulations software. In addition, the reconstruction performances of electrons, muons and protons will be studied in this configuration. By changing the beam configuration to produce pions (tertiary beam configuration), it will be possible to study pion scattering which is usually challenging in T2K, SK and Hyper-Kamiokande since the samples are statistically limited. Being able to directly measure the water Cherenkov detector response to pions in Water Cherenkov Test Experiment will be highly valuable to these experiments.

During the second phase of the experiment, the water Cherenkov detector will be loaded with $Gd_2(SO_4)_3$. This doping, recently made on the SK far detector, will enhance the detection and reconstruction of neutrons by capture on the gadolinium which will rapidly decay by emitting a gamma that can be detected by the mPMTs. With this loading it will be possible to study the multiplicity of neutrons produced by second interactions on charged particles in the water, which is not well constrained by data leading to discrepencies in the simulation tools used by SK and Hyper-

Kamiokande.

The Water Cherenkov Test Experiment operations will start in 2023 and should last up to 26 weeks during which the hired postdoc will contribute to the data taking campaign, the analysis of the collected data and the production of the physics results.

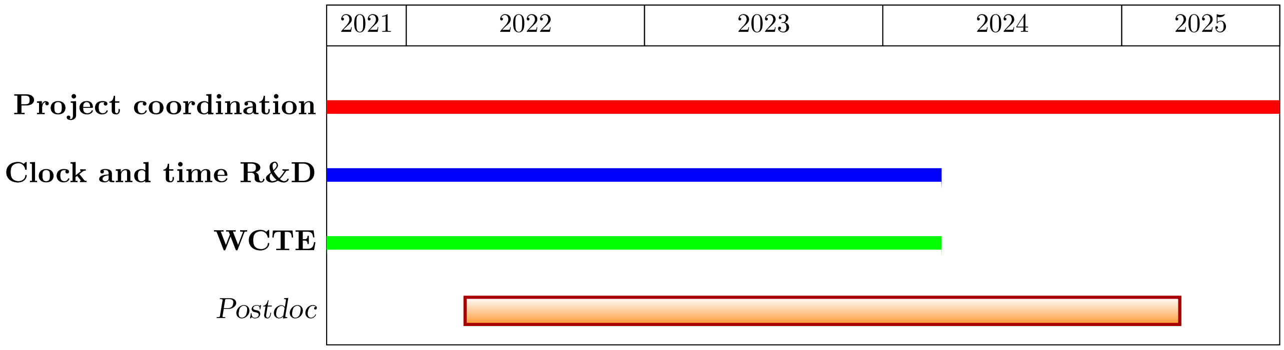
Deliberables: installation of clock distribution system for the detector mPMTs; constraint on the Cherenkov angular distribution for low momentum hadrons, pion scattering modeling and secondary neutron production; peer-reviewed papers presenting the results obtained by WCTE.

2.3.4 Work package 4: Computing developments and integration

Task responsible: Mathieu Guigue

Deliberables: Global computing model; tools for productions; data management plan.

2.4 Project schedule



2.5 Risks management

Liste des risques à propos du projet

1. Project funding
2. Scientific challenges of Hyper-Kamiokande
3. Covid
4. Need for clock distribution system
5. Technological challenges of clock distribution
6. Technological challenges of mPMT and WCTE

3 Organisation and implementation of the project

The BERTHA project is structured around three tasks with a responsible designated in the permanent members of the LPNHE Neutrino group. The whole team, including the hired postdoc, will contribute to the tasks 2, 3 and 4, while the first one, concerning the project coordination, will be managed by the project leader.

3.1 Scientific coordinator and team

The project will include Mathieu Guigue, Jacques Dumarchez, Claudio Giganti, Boris Popov, Stefano Russo and Marco Zito, permanent staff in the neutrino group at LPNHE, and Lucile Mellet, Sorbonne Université PhD student working on the Hyper-Kamiokande experiment, as summarized in Table 2.

Partner	Name	First name	Current position	Role & responsibilities in the project	Involvment in person.month
Sorbonne Université	Guigue	Mathieu	Maitre de Conférences	Coordinator Responsible of task 1 and 4	24
LPNHE	Russo	Stefano	Ingénieur de Recherche HDR	Responsible of task 2	24
LPNHE	Popov	Boris	Directeur de Recherche HDR	Responsible of task 3	12
LPNHE	Giganti	Claudio	Chargé de Recherche HDR	Scientific partner on task 3	12
LPNHE	Dumarchez	Jacques	Directeur de Recherche HDR	Scientific partner on task 3	6
LPNHE	Postdoc	to be hired	Postdoc	Scientific partner on task 2, 3 and 4	36
LPNHE	Mellet	Lucile	PhD Student	Scientific partner on task 2	18

Table 2: Summary table of persons involved in the project.

Name of the researcher	Person. month	Call, funding agency, grant allocated	Project's title	Name of the scientific coordinator	Start-End
M. Guigue	6	SU Emergence	MULTIPLY	M. Guigue	2019 - 2021
M. Guigue	20	ANR JCJC	SUNCORE	C. Giganti	2019 - 2023

Table 3: Implication of the scientific coordinator in on-going projects.

The funding will cover the postdoc salary and travel expenses to conferences and the Hyper-Kamiokande meetings and workshops related to this project. In addition, the equipment necessary to the success of this project will be funded with this ANR.

The project coordinator Mathieu Guigue earned in 2015 his PhD in particle physics from Université de Grenoble-Alpes and was employed as a Postdoctoral Research Associate by Pacific NorthWest National Laboratory (Washington, USA) from 2016 until 2018. During this period, he had leading roles on the Project 8 experiment at the University of Washington being the Experiment Coordinator and Analysis Convenor from 2016 until 2019 and has been the primary author of two peer-reviewed papers of the collaboration. In addition, he strongly contributed the development of slow control and DAQ system for this experiment in order to produce a reliable monitoring system during all of the Phase II data taking period (2016-2020). He has then been hired by Sorbonne Université in Paris as Maître de Conférences since September 2018 and joined the T2K activities of the Neutrino group at LPNHE. Since 2019 he is co-convenor of the T2K Simulation and Reconstruction working group. As such, he is coordinating the simulation and reconstruction efforts for the upgrade of ND280. He is also contributing to the T2K Oscillation Analysis effort, in particular on the combined analysis with SK atmospheric neutrinos. In addition to his activities in T2K, he is working on the Hyper-Kamiokande experiment, primarly on the test of mPMTs at the Memphyno setup, on the R&D for the clock distribution and time synchronisation system. To that purpose, he was awarded in 2019 with an IdEx "Emergence" from Sorbonne Université in order to explore these technologies before proposing a stronger contribution to these items with this ANR proposal. Finally, he is pushing for a global long-term plan to provide computing and long-term storage resources to both the T2K and Hyper-Kamiokande collaborations which should last at least until the middle of the century. Table 3 summarises the implication of the scientific coordinator in on-going projects. Mathieu Guigue will be responsible of the overall coordination of the BERTHA project (task 1) and of the computing effort (task 4), but he will also contribute to the clock distribution and time synchronisation system (task 2) and the studies at Water Cherenkov Test Experiment (task 3).

Stefano Russo is Fill with great things about Stefano, that he is convenor of the Electronic WG...

Boris Popov is Fill with great things about Boris, that he is convenor for NA61 and leading the upgrade effort for the electronics at LPNHE...

The strength of this project resides in the strong expertise of the group in neutrino physics and in the electronic design in various experiments and the close collaboration established with other groups.

The LPNHE is well integrated in the laboratories network in the Paris area. First of all, LPNHE is part of the "Paris federation" which gathers IN2P3 laboratories, namely AstroPhysique et Cosmologie (APC) and the Laboratoire Leprince Riguet (LLR) on the Ecole Polytechnique campus, along with the Institut de Recherches des lois Fondamentales de l'Univers (IRFU) at CEA Saclay. LLR, IRFU and LPNHE have been collaborating for the last 10 years on the T2K experiment on which the three labs are providing major hardware and software contributions. In particular, the ND280 upgrade design and construction have been led by Marco Zito and are now under the supervision of Claudio Giganti. In collaboration with CEA, the LPNHE has developed and produced the front-end electronics that will equip the High-Angle TPCs in the upgraded ND280 . Such collaboration continues in the development and integration of the detector responses and performances in the T2K official simulation, reconstruction and analysis tools.

Other significant contributions?

Collaboration within the Paris federation are also very active in the context of Hyper-Kamiokande. Indeed the test of the mPMTs is a collaboration between the APC that provides the water tank and overall infrastructure, the LLR that provides scientific context and integration in the Hyper-Kamiokande simulation and the LPNHE that provides the logistic and resources for the tests. This strong collaboration will continue during the construction and exploitation of the WCTE at CERN (task 3). For the development of the time synchronisation system for Hyper-Kamiokande (task 2), the Neutrino group is working closely with the SYstèmes de Référence Temps-Espace (SYRTE) laboratory at the Observatoire de Paris. Indeed Michel Abgrall's team has strong expertise in the design and the characterisation of stable and accurate time references; this project aims at providing the LPNHE group the necessary financial and human resources to complete this R&D and propose a complete solution suitable for the Hyper-Kamiokande experiment. Collaboration with IRFU on the development of a clock distribution system has also emerged recently given their interest in this topic. Moreover, the solution developed by LPNHE will be integrated with the other parts of the far detector front-end electronics for the 20-inch PMTs developped by LLR, Omega and CEA.

The funding of this ANR project would allow the scientific coordinator to secure the LPNHE group contribution to the Hyper-Kamiokande experiment, strengthen his team dedicated to the clock distribution system and improve the group's visibility within the collaboration (see section 4).

3.2 Implemented and requested resources to reach the objectives

4 Impact and benefits of the project

4.1 Positionning LPNHE and IN2P3 in the Hyper-Kamiokande collaboration

Strenghten involvment in WG4

Clock solution will be integrated with LLR/CEA electronics -¿ stronger proposal to the collaboration

4.2 Developing national and international synergies and expertise

Collaborative work with SYRTE

- Development of close relationship with SYRTE
- Knowledge transfer to LPNHE
- Connect with other synchronisation projects (V Voisin?)

Collaborations in Europe

- Colllaboration with INFN colleagues on mpmt
- Collaboration with CERN

Talk about the benefits of a close collaboration of Japan-France

- Collaboration with the UoT (joint PhD programs, exchange progams, joint lab)
- Synergies with Belle-II
- Creation d'une école France-Japon

4.3 Impact on society

Proposition de stages et de thèses

Parler de l'open source et du développement de compétences pour tout le laboratoire

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