

Study of neutrino-nucleus interaction at around 1 GeV using  
cuboid lattice neutrino detector, WAGASCI, muon range  
detectors and magnetized spectrometer, Baby MIND, at  
J-PARC neutrino monitor hall

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### Abstract

We, the WAGASCI collaboration, propose to perform a study of neutrino-nucleus interactions on the B2 floor of the neutrino monitor building with a new-type fine-grained neutrino detector and muon range detectors. The hollow cuboid lattice scintillators filled with water as the neutrino interaction target (known as WAGASCI module) would enable the measurement of cross section on H<sub>2</sub>O. Measurement in wide phase space becomes possible by the combination of the WAGASCI modules, side- and downstream- muon range detectors (MRD's). The downstream-MRD, the so-called Baby MIND detector, also works as a magnet and provides charge identification capability as well as magnetic momentum measurement for high energy muons. The nominal experimental setup has two WAGASCI modules. Most of the detectors have been constructed and have been commissioned in the J-PARC T59 experiment and the CERN neutrino platform. Therefore, the collaboration will be ready to collect physics data by January 2019. The experiment can run parasitically with T2K, without dedicated beam time. With one-year data taking ( $\sim 5 \times 10^{20}$  POT) in neutrino-mode and another one-year in antineutrino mode, expected numbers of charged-current interaction event are 5,400 and 2,240 for one WAGASCI module respectively. We will provide inclusive and exclusive differential cross sections of the charged current neutrino and antineutrino interactions with water and hydrocarbon with a slightly higher neutrino energy and with wider angler acceptance than T2K ND280. By combining our measurements with those from ND280, model-independent extraction of the cross section for narrow energy spread becomes possible. These measurements would improve the understanding of the neutrino-nucleus interaction at around 1 GeV and also contribute to reducing one of the most significant uncertainties source of the T2K experiment.

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## 1 Introduction

The understanding of neutrino-nucleus interactions in the 1 GeV energy region is critical for the success of accelerator-based neutrino oscillation experiments such as the T2K experiment. Complicated multi-body effects of nuclei render this understanding difficult. The T2K near detectors have been measuring these and significant progress has been achieved. However, the understanding is still limited. One of the big factors preventing a complete understanding is the non-monochromatic neutrino beam spectrum. Measurements with distinct but partially overlapping beam spectra would be a great benefit in resolving the contribution from different neutrino energies. We, the WAGASCI collaboration, proposes to study the neutrino-nucleus interaction at the B2 floor of the neutrino monitor building, where different neutrino spectra from the T2K off-axis near detector (ND280) can be obtained due to the different off-axis position. Our experimental setup contains two hollow cuboid lattice detectors filled with water as the neutrino interaction target (known as WAGASCI modules), two side- and one downstream- muon range detectors(MRD's). We will have two types of the WAGASCI modules, a water-in module and a water-out module. The water-in WAGASCI module has water the hollow cuboid lattice, and the water-out WAGASCI module doesn't have water inside the lattice. The hollow cuboid lattice and side-MRD's allow a measurement of wider-angle scattering than ND280. High water to scintillator material ratio enables the measurement of the neutrino interaction with water, which is highly desired for the T2K experiment because it's far detector, Super-Kamiokande, is composed of water. The MRD's consist of plastic scintillators and iron plates. The downstream-MRD, so called the Baby MIND detector, also works as a magnet and provides the charge identification capability as well as magnetic momentum measurement for high energy muons. The charge identification is essentially important to select antineutrino events in the antineutrino beam because contamination of the neutrino events is as high as 30%. Most of the detectors have already been constructed. The WAGASCI modules have been commissioned as the J-PARC T59 experiment and the Baby MIND detector was commissioned at the CERN neutrino platform. Therefore, the collaboration will be ready to proceed to the physics data taking by January 2019. We will provide the cross sections of the charged current neutrino and antineutrino interactions on water with slightly higher neutrino energy than T2K ND280 with wide angler acceptance. The requested beam time is one-year in neutrino-mode and another one-year in antineutrino mode assuming that the POT for the fast extraction in each year is more than  $5 \times 10^{20}$  POT. When combined with ND280 measurements, our measurement would greatly improve the understanding of the neutrino interaction at around 1 GeV and contribute to reducing one of the most significant uncertainties of the T2K experiment.

## 2 Experimental Setup

Figure 1 and 2 show a schematic view and a CAD drawing of the entire set of detectors. Central neutrino target detectors consist of two WAGASCI modules and T2K INGRID proton module. Inside the WAGASCI module, plastic scintillator bars are aligned as a hollow cuboid lattice and spaces in the lattice are filled with water for a water-in WAGASCI module. T2K INGRID proton module is a full active neutrino target detector which is composed only with scintillator bars in its tracking region. The central detectors are surrounded by two side- and one downstream- muon range detectors(MRD's) The MRD's are used to select muon tracks from the charged-current (CC) interactions and to reject short tracks caused by neutral particles that originate mainly from neutrino interactions in material surrounding the central detector, like the walls of the detector hall, neutrons and gammas, or neutral-current (NC) interactions. The muon momentum can be reconstructed from its range inside the detector. The MRD's consist of plastic scintillators and iron plates. The downstream-MRD, also known as the Baby MIND detector, additionally has a coil wound around each of the iron plates so it may be magnetized. This provides the charge selection capability.

For all detectors, scintillation light in the scintillator bar is collected and transported to a photodetector with a wavelength shifting fiber (WLS fiber). The light is read out by a photodetector, Multi-Pixel Photon Counter (MPPC), attached to one end of the WLS fiber. The signal from the MPPC is read out by the dedicated electronics developed for the test experiment to enable bunch separation in the beam spill. The readout electronics are triggered using the beam-timing signal from MR to synchronize to the beam. The beam-timing signal is branched from those for T2K, and will not effect T2K data taking.

T2K adopted the off-axis beam method, in which the neutrino beam is intentionally directed 2.5 degrees away from SK producing a narrow band  $\nu_\mu$  beam. The off-axis near detector, ND280, is installed towards the SK direction in the B1 floor of the near detector hall of the J-PARC neutrino beam-line. We propose to install our detector in the B2 floor of the near detector hall, where the off-axis angle of 1.5 degrees is slightly different to the 2.5 degrees of ND280. The candidate detector position in the B2 floor is shown in Figure 3. The expected neutrino energy spectrum at the candidate position is shown in Figure 4.

### 2.1 WAGASCI modules

#### 2.1.1 Detector

The WAGASCI modules are mainly composed of 1280 plastic scintillator bars and a surrounding stainless steel tank as shown in Figure 5. The total number of channels in one WAGASCI module is 1280. The stainless steel tank is constructed by welding stainless steel plates, is sized as 460mm×1250mm×1250 mm, and weighs 0.5 tonne.

One WAGASCI module consists of 16 scintillator tracking planes, where each plane is an array of 80 scintillator bars fixed with ABS frames. The 40 bars, called parallel

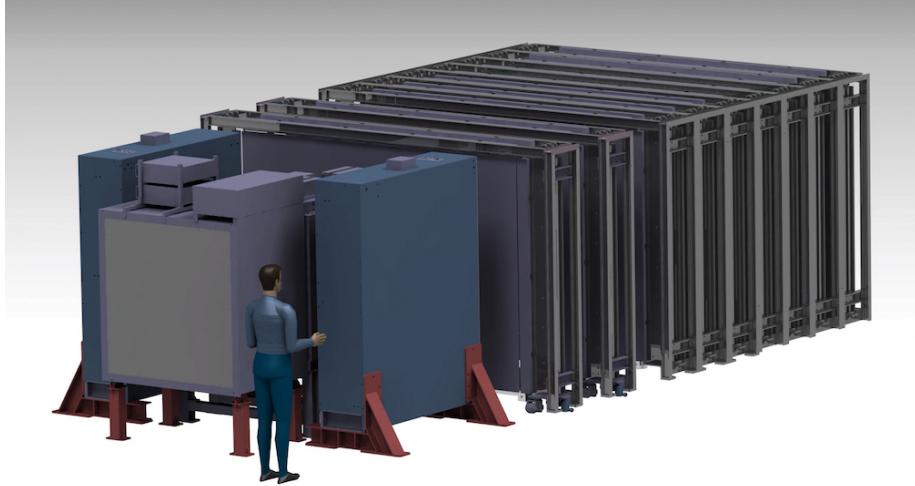


Figure 1: Schematic view of entire sets of detectors.

scintillators, are placed perpendicularly to the beam, and the other 40 bars, called lattice scintillators, are placed in parallel to the beam with hollow cuboid lattice in the tracking plane as shown in Figure 5. Thanks to the hollow cuboid lattice of the scintillator bars, the WAGASCI module has  $4\pi$  angular acceptance for charged particles.

Thin plastic scintillator bars produced at Fermilab by extrusion method, mainly consists of polystyrene and are surrounded by thin reflector including  $\text{TiO}^2$  (3 mm in thickness) are used for the WAGASCI modules to reduce the mass ratio of scintillator bars to water, because neutrino interactions in the scintillator bars are a background for the cross section measurements on  $\text{H}_2\text{O}$ . Each scintillator bar is sized as  $1020\text{mm} \times 25\text{mm} \times 3\text{ mm}$  including the reflector part, and half of all the scintillator bars have 50-mm-interval slits to form the hollow cuboid lattice (Figure 6 ).

We can operate the WAGASCI module with two conditions, water-in and a water-out. The water-in WAGASCI module has water in spaces of the hollow cuboid lattice. The total water mass serving as neutrino targets in the fiducial volume of the module is 188 kg, and the mass ratio of scintillator bars to water is 1 : 4. The water-out WAGASCI module doesn't have water inside the detector. The total CH mass serving as neutrino target in the fiducial volume of the module is 47 kg, and the mass fraction of scintillator bars is 100 %.

Scintillation light is collected by wave length shifting fibers, Y-11 (non-S type with a diameter of 1.0 mm produced by Kuraray). A fiber is glued by optical cement in a groove on surface of a scintillator bar. 32 fibers are gathered together by a fiber bundle at edge of the module, and lead scintillation light to a 32-channel arrayed MPPC. Since crosstalk

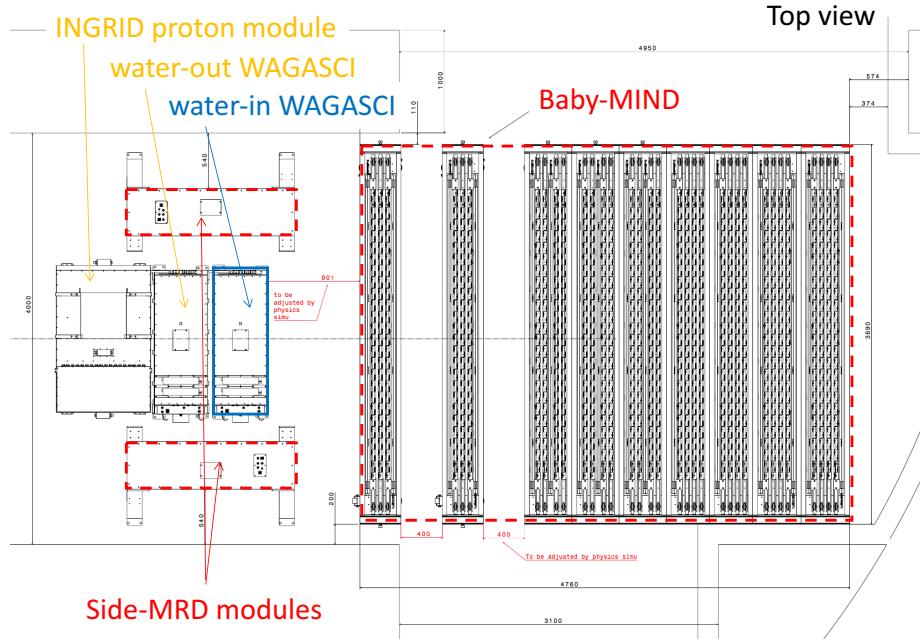


Figure 2: Top view of entire sets of detectors.

of light yield due to reflection on the inner surface of each cell has been observed, all the scintillator bars are painted black by aqueous color spray. It is confirmed by measurements with cosmic rays that black painting on the surface of the scintillator bars suppresses this crosstalk so that no significant crosstalk effect is observed within uncertainty.

32-channel arrayed MPPCs, as shown in the Figure 7, are used for the modules. The surface of the fiber bundle is polished and directly attached onto the 32-channel arrayed MPPCs. The positions of 32 fibers on the bundle are aligned to fit the channels of MPPCs. The MPPC is a product of Hamamatsu Photonics, S13660(ES1), with suppressed noise rate of  $\sim 6$  kHz per channel at 0.5 p.e. threshold. For each MPPC channel, 716 pixels of APD are aligned in a shape of circle.

### 2.1.2 Electronics

As front-end electronics of this detector, a Silicon PM Integrated Read-Out Chip (SPIROC) [13] is adopted. SPIROC is a 36-channel auto-triggered front-end ASIC, and is produced by OMEGA/ IN2P3. It not only contains an analog signal processing part such as amplification and shaping of the waveform, but contains a digital signal processing parts such as auto-trigger and timing measurement. Charge of MPPC signal is sampled by track-and-

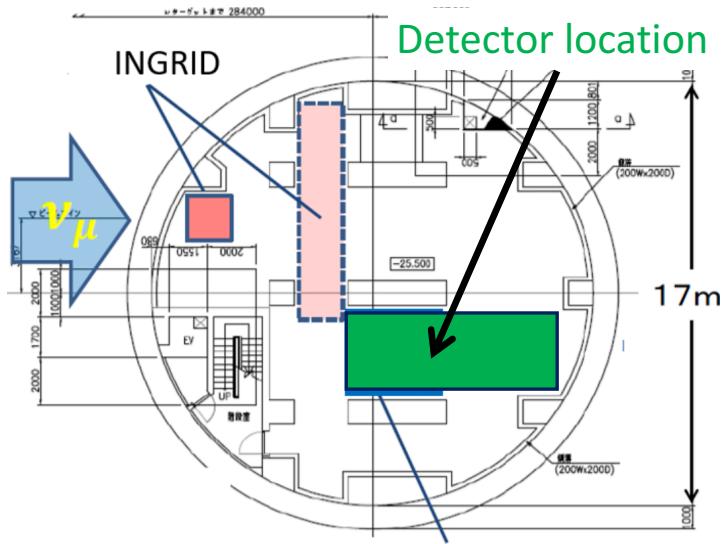


Figure 3: Candidate detector position on the B2 floor of the near detector hall.

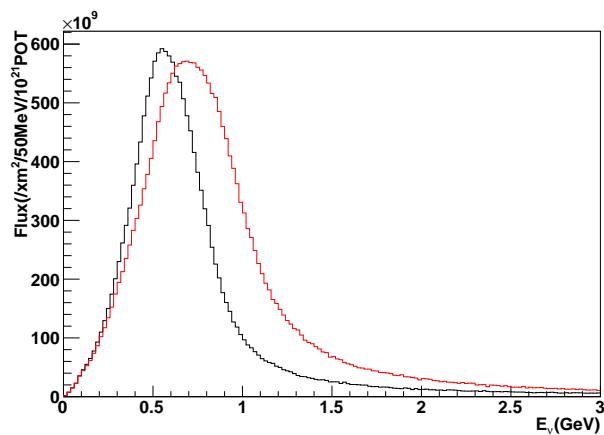


Figure 4: Neutrino energy spectrum at the candidate detector position (red, off-axis 1.5 degree). The spectrum at the ND280 site (black, off-axis 2.5 degree) is also shown.

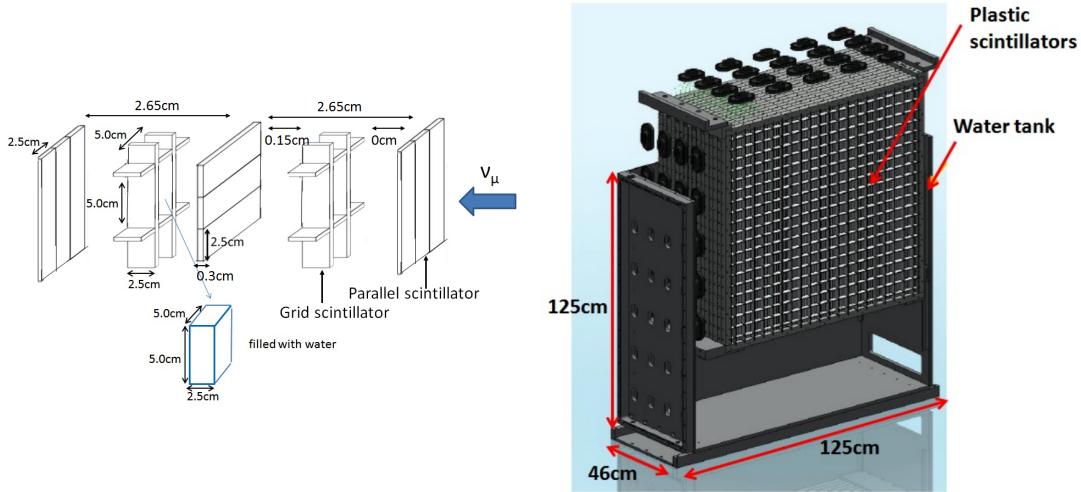


Figure 5: Schematic views of hollow cuboid lattice of plastic scintillator bars (left) and WAGASCI module (right).

hold circuit. A Front-end electronics board, Active Sensor Unit (ASU), has been developed with the SPIROC2D chip, which is the latest version of SPIROC. Each readout board is designed to control a 32-channel arrayed MPPC, and 40 of the ASU boards are aligned on the module surface. The data acquisition system used for this detector, including back-end boards, has been developed for prototypes of ultra-granular calorimeters for the International Linear Collider (ILC) [6], and independent of the T2K DAQ system. To synchronize the DAQ system to J- PARC neutrino beam, pre-beam trigger and beam trigger are sent to the clock control card. The beam trigger signals are converted from optical signals to NIM signals at NIM module on the B2 floor. In addition, the information of spill number are delivered with 16-bit ECL level signals, and converted to an Ethernet frame by an FPGA evaluation board to be directly sent to the DAQ PC. The electronics readout scheme is shown in Figure 8.

### 2.1.3 Water system

Pure water is filled to the water tank of the water-in WAGASCI module as follows. First, the water storage tank located at the B2 floor of the NM pit is filled with water delivered from a water tap on the ground level through a long hose. Second, the water is pumped to the other water storage tank though a water filler to produce pure water. Third, a compound preservative called Germall plus, which is the same preservative used in one of the sub-detectors of T2K ND280, FGD2, is put into the water to keep water from being bad. Then, the water is poured to the water-in WAGASCI module, and it is kept in the

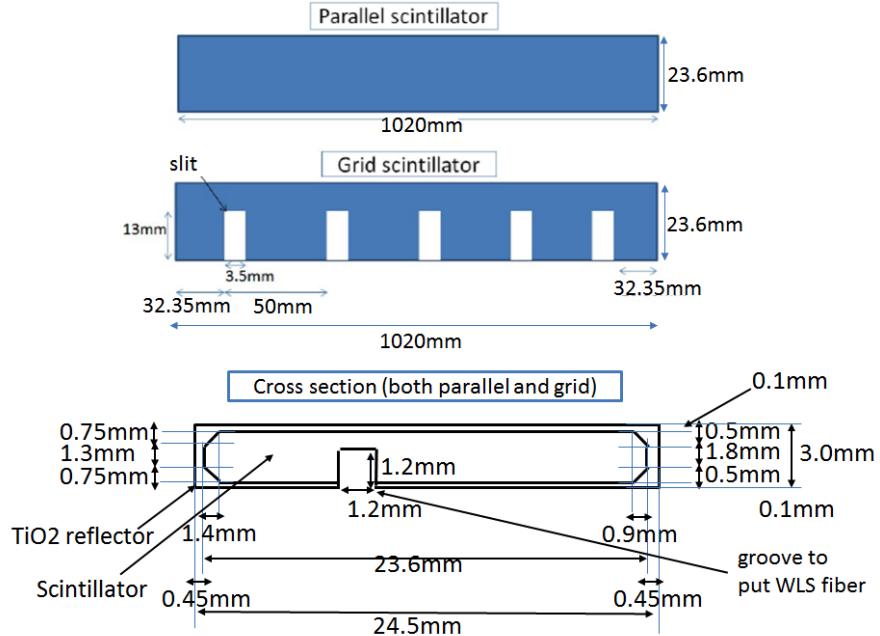


Figure 6: Geometry of scintillators used for WAGASCI modules.

module during the neutrino beam operation and not to be circulated.

## 2.2 INGRID Proton module

INGRID Proton module is a neutrino detector of the T2K experiment. It is a fully-active tracking detector which consists of only scintillator strips. The purpose of this Proton Module is to separate the neutrino interaction types by detecting the protons and pions together with the muons from the neutrino interactions, and to measure the neutrino cross section for each interaction type. It consists of 36 tracking planes surrounded by veto planes (Figure 9), where each tracking plane is an array of two types of scintillator strips. The 16 strips in the inner region have dimensions of  $25\text{mm} \times 13\text{mm} \times 1200\text{mm}$ , while the 16 strips in the outer region have dimensions of  $50\text{mm} \times 10\text{mm} \times 1200\text{mm}$ , making a plane of  $1200\text{mm} \times 1200\text{mm}$  in the horizontal and vertical directions. The former is the scintillator produced for the K2K SciBar detector [4] and the latter was produced for INGRID. The tracking planes are placed perpendicular to the beam axis at 23mm intervals. Since the strips are aligned in one direction, each tracking plane is sensitive to either the horizontal or vertical position of the tracks. The tracking planes are therefore placed alternating in the horizontal and vertical directions so that three-dimensional tracks can be reconstructed. The tracking planes also serve as the neutrino interaction target. As with the WAGASCI

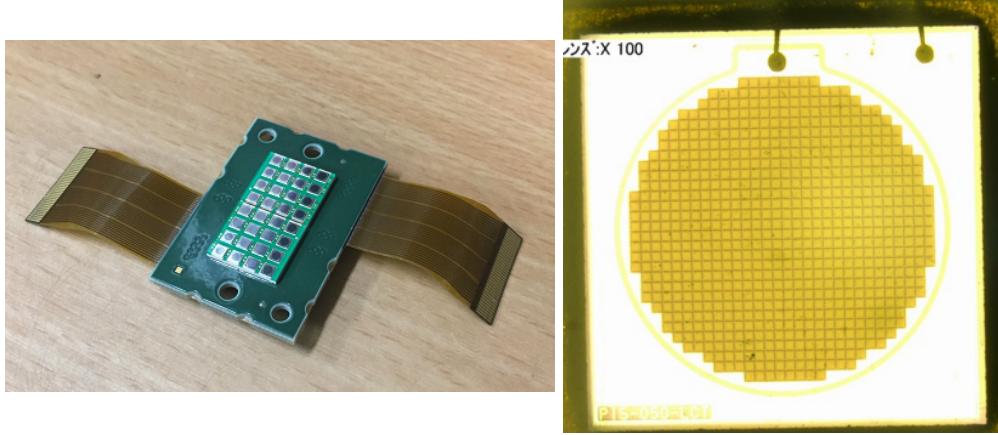


Figure 7: 32-channel arrayed MPPC (left) and an enlarged view of one MPPC channel (right).

modules, scintillation light is read out by a WLS fiber and MPPC.

It was installed on the neutrino beam axis on the SS floor of the T2K near detector hall in 2010, and had been used for neutrino cross section measurements. In August 2017, it was moved to the B2 floor of the T2K near detector hall by J-PARC T59 after getting the approval from T2K to use them. J-PARC T59 is performing a neutrino beam measurement using the detector from October 2017, and the measurement will continue until May 2018 as we will discuss in Sec. 4.

We will operate the INGRID Proton module using the T2K near detector electronics/DAQ system in the same way as J-PARC T59. A proposal to use the module and its electronics for our project will be submitted to the T2K collaboration.

### 2.3 Baby MIND

The Baby MIND is the downstream Muon Range Detector. It also works as a magnet and provides the charge identification capability as well as magnetic momentum measurement for high energy muons.

The Baby MIND collaboration<sup>1</sup> submitted a proposal to the SPSC at CERN, SPSC-P-353. The project was approved by the CERN research board as Neutrino Platform project NP05 and constructed. The detector consists of 33 magnet modules, each 3500 mm × 2000 mm × 50 mm (30 mm steel) with a mass of approximately 2 tonnes. Of these magnet modules, 18 are instrumented with plastic scintillator modules.

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<sup>1</sup>Contact person: E. Noah, Spokesperson: A. Blondel, Deputy spokesperson: Y. Kudenko

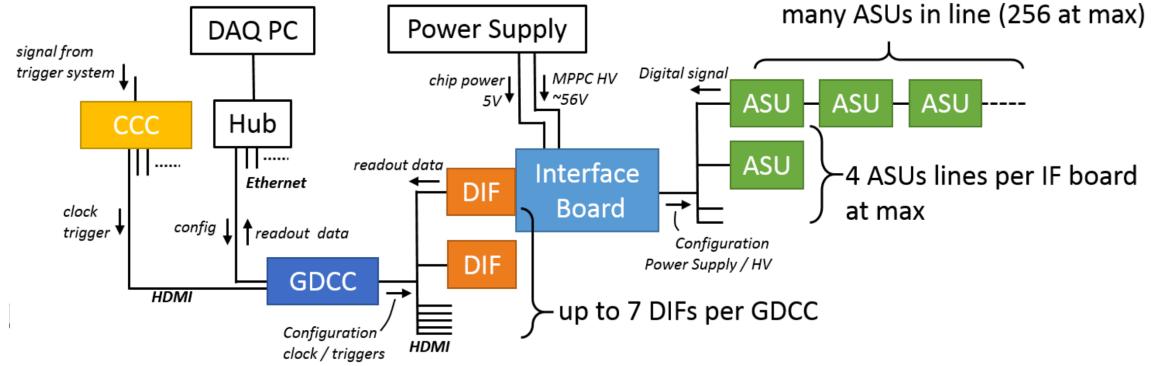


Figure 8: WAGASCI electronics readout scheme.

### 2.3.1 Magnet modules

Traditional layouts for magnetized iron neutrino detectors (e.g. MINOS) tend to be monolithic blocks with a unique pitch between consecutive steel segments and large conductor coils threaded around the whole magnet volume. The Baby MIND detector, like traditional designs, is built from sheets of iron interleaved with scintillator detector modules. However Baby MIND is novel in that the iron segments are all individually magnetized as shown in Figure 10, allowing for far greater flexibility in the setting of the pitch between segments, and in the allowable geometries that these detectors can take.

The key design outcome is a highly optimized magnetic field map. A double-slit configuration for coil winding was adopted to increase the area over which the magnetic flux lines are homogeneous in  $B_x$  across the central tracking region. Simulations show the magnet field map to be very uniform over this central tracking region covering an area of  $2800 \times 2000 \text{ mm}^2$ , Figure 11. The  $B_x$  component dominates in this region, with negligible  $B_y$  and  $B_z$ . This was confirmed by measuring the field with 9 pick-up coils wound around the first module. Subsequent modules were equipped with one pick-up coil. Test results on the 33 modules show all achieve the required field of 1.5 T for a current of 140 A, with a total power consumption of 11.5 kW. The polarity of the field map shown in Figure 11 (middle) can be reversed by changing the power supply configuration.

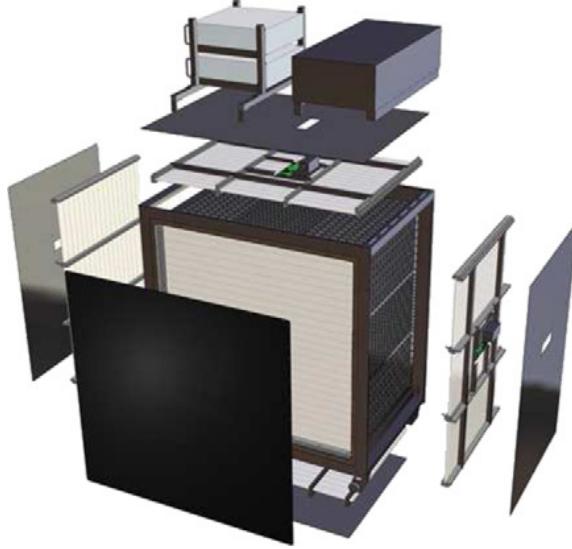


Figure 9: Schematic view of INGRID Proton module.

### 2.3.2 Scintillator modules

Each of the 18 scintillator modules is constructed from 2 planes of horizontal counters (95 counters in total) and 2 planes of vertical counters (16 counters in total) [3], arranged with an overlap between planes to achieve close to 100% hit efficiency for minimum ionizing muons. The arrangement of planes within a module is vertical-horizontal-horizontal-vertical. This arrangement was the result of an assembly approach whereby each plane was built from 2 half-planes, with each half plane consisting of a horizontal plane and a vertical plane. The scintillator bars are held in place using structural ladders that align and maintain the counters, Figure 12. No glue is used in the process, so counters can be replaced. Aluminum sheets front and back provide light tightness.

The plastic scintillator counters were made from 220 mm-wide slabs, consisting of extruded polystyrene doped with 1.5% paraterphenyl (PTP) and 0.01% POPOP. They were cut to size then covered with a 30-100  $\mu\text{m}$  thick diffuse reflector resulting from etching of the surface with a chemical agent [10, 11]. The horizontal counter size is  $2880 \times 31 \times 7.5 \text{ mm}^3$ , with one groove along the length of the bar in which sits a wavelength shifting fiber from Kuraray. The vertical counter size is  $1950 \times 210 \times 7.5 \text{ mm}^3$ , with one U-shaped groove along the bar. On each counter, two custom connectors house silicon photomultipliers, MPPC type S12571-025C from Hamamatsu, either side of the horizontal counter, and both connectors at the top for the vertical counter. This geometrical configuration for vertical counters was chosen for ease of connectivity to the electronics, and maintenance operations.

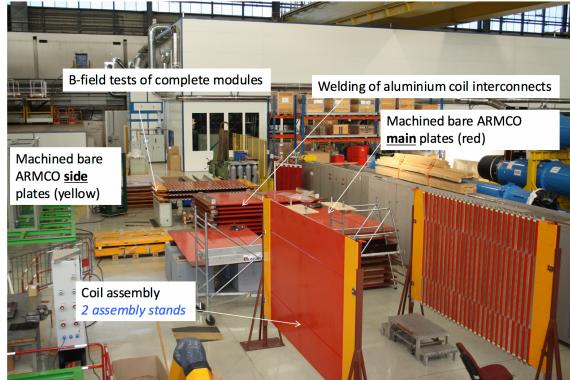


Figure 10: Magnet assembly zone at CERN.

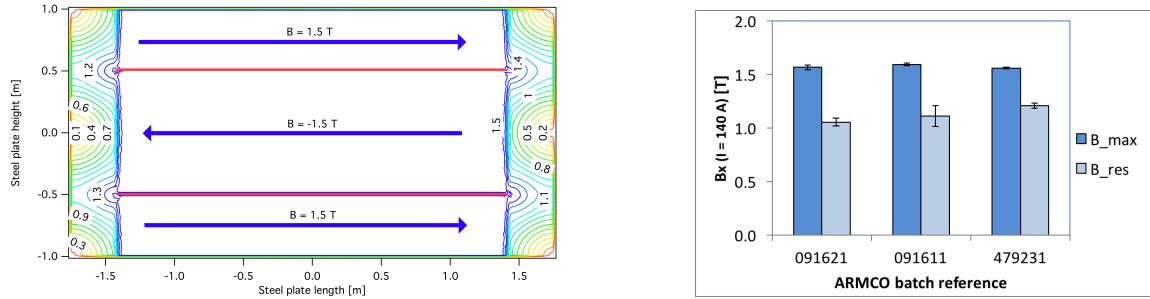


Figure 11: Left) Magnetic field map with a coil along 2800 mm of the length of the plate. Right) Measured B field for 33 modules.



Figure 12: Scintillator modules assembly. Left) top of front half-module showing vertical counters, and the spacer-ladders that set the pitch between horizontal counters and hold them in place. Middle) rear half-module showing horizontal counters on their ladders. Right) Assembled rear half-module, the front half-module can be seen in the background.

A total of 1744 horizontal counters and 315 vertical counters (including spares) were produced at the Uniplast company (Vladimir, Russia).

### 2.3.3 Electronics

The Baby MIND electronic readout scheme includes several custom-designed boards [12]. The revised version is shown in Figure 13. At the heart of the system is the electronics Front End Board (FEB), developed by the University of Geneva. The readout system includes two ancillary boards, the Backplane, and the Master Clock Board (MCB) whose development has been managed by INRNE (Bulgarian Academy of Sciences) collaborators.

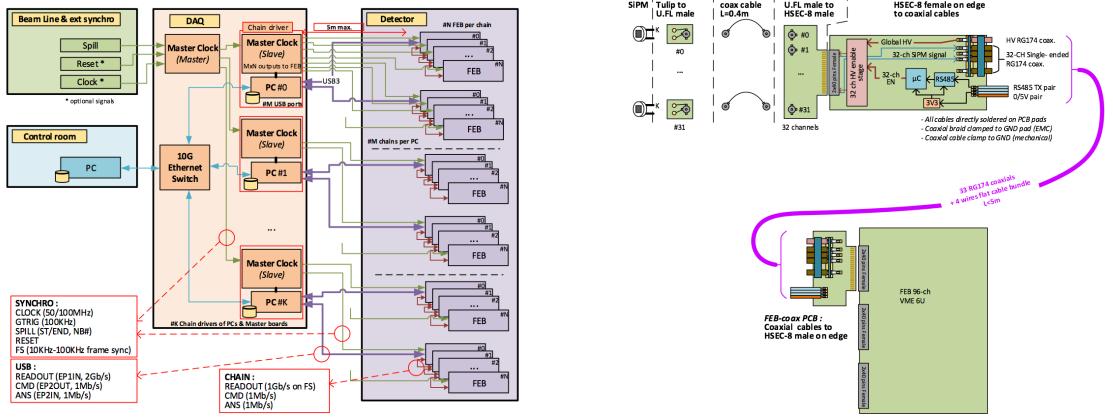


Figure 13: Left) Baby MIND electronics readout scheme. Right) SiPM-to-FEB connectivity.

The FEBv2 hosts 3 CITIROC chips that can each read in signals from 32 SiPMs [7]. Each signal input is processed by a high gain (HG), and a separate low gain (LG), signal path. The outputs from the slow shapers can be sampled using one of two modes: a mode with an externally applied delay, and a peak detector mode. A faster shaper can be switched to either HG or LG paths, followed by discriminators with adjustable thresholds providing 32 individual trigger outputs and one OR32 trigger output. An Altera ARIA5 FPGA on the FEBv2 samples these trigger outputs at 400 MHz, recording rising and falling times for the individual triggers and assigning time stamps to these. Time-over-threshold, the difference between falling and rising times, gives some measure of signal amplitude. This is used in addition to charge information and proves useful if there is more than one hit per bar within the  $\sim 9 \mu\text{s}$  deadtime due to the readout of the multiplexed charge output. The ARIA5 also manages the digitization of the sampled CITIROC multiplexed HG and LG outputs via a 12-bit 8-ch ADC.

The internal 400 MHz clock on the FEBv2 can be synchronized to a common 100 MHz clock. The synchronization subsystem combines input signals from the beam line into

a digital synchronization signal (SYNC) and produces a common detector clock (CLK) which can eventually be synchronised to an external experiment clock. Both SYNC and CLK signals are distributed to the FEBs. Tests show the FEB-to-FEB CLK(SYNC) delay difference to be 50 ps (70 ps). Signals from the beam line at WAGASCI include two separate timing signals, arriving 100 ms and 30  $\mu$ s before the neutrino beam at the near detectors. The spill number is available as a 16-bit signal.

### 2.3.4 Performance check

All counters were measured at INR Moscow with a cosmic ray setup using the same type S12571-025C MPPCs and a CAEN DT5742 digitizer. The average light yield (sum from both ends) was measured to be 37.5 photo-electrons (p.e.) per minimum ionizing particle (MIP) and 65 p.e./MIP for vertical and horizontal counters, respectively. After shipment to CERN, all counters were individually re-tested with an LED. 0.1% of counters failed the LED tests and were therefore not used during the assembly of modules. The assembly of modules was completed in June 2017, and it was then tested in June and July 2017 at the Proton Synchrotron experimental hall at CERN with a mixed particle beam comprising mostly muons whose momenta could be selected between 0.5 and 5 GeV/c. Muon tracks from the summer 2017 beam tests are shown in Figure 14 for different muon momentum beam settings and for both muon polarities.

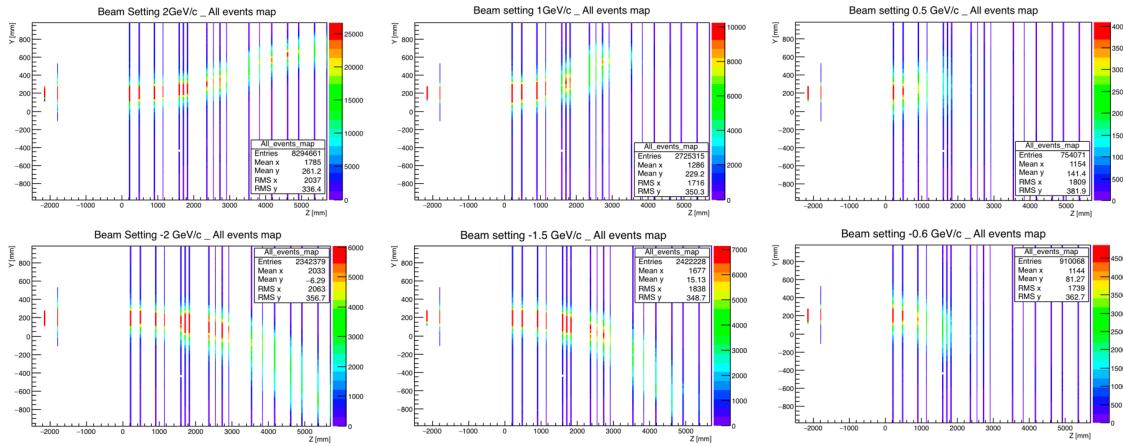


Figure 14: Y-Z hit profiles in Baby MIND detector modules for positive (upper row) and negative (lower row) muon beam settings during the summer 2017 beam tests at the CERN-PS facility. Muon momentum settings for the beam shown here are 2 GeV/c, 1.5 GeV/c and 0.5 GeV/c for left, middle and right plots respectively.

## 2.4 Side muon range detector

Two Side-MRD modules for tracking secondary particles from neutrino interactions will be installed in 2018. Each Side-MRD module is composed of 11 steel plates and 80 scintillator slabs. The slabs are arranged as 10 layers installed in the 13 mm gaps between the 30 mm thick plates. Each steel plate size is 30 mm  $\times$  1610 mm  $\times$  1800 mm. Total module size is 2236 mm  $\times$  1630 mm  $\times$  975 mm as shown in Figure 15 (left), weight is  $\sim$ 8.5 tonne.

Scintillator bars were manufactured by Uniplast company in Vladimir, Russia. Polystyrene based scintillators were extruded with thickness of 7 mm, then cut to the size of 7  $\times$  200  $\times$  1800 mm<sup>3</sup>. Dopant composition is 1.5% PTP and 0.01% POPOP. Scintillator surface was etched by a chemical agent to form a white diffuse layer with excellent reflective performance. Ideal contact between the scintillator and the reflector raises the light yield up to 50% comparing to an uncovered scintillator. A sinusoidal groove was milled along the scintillator to provide uniform light collection over the whole scintillator surface. WLS Y11 Kuraray fiber of 1 mm diameter was glued with an optical cement EJ-500 in the S-shape groove as shown in Figure 15(right). A minimum bending radius of 30 mm was used to ensure the the Kuraray S-type fibers remained within specification. Both ends of the fiber were glued into optical connectors which were themselves attached to the scintillator and provide an interface to SiPMs, Hamamatsu MPPC S13081-050CS(X1).

Scintillators for the Side-MRD modules were assembled at INR in Russia, and shipped to Japan in July 2017. The light yield for each scintillator was measured with cosmic rays at INR and at YNU in Japan after delivery.  $LY_1$  and  $LY_2$  are light yields measured at both ends of the counter. The light yield asymmetry between the ends calculated as  $100\% \times \frac{LY_1 - LY_2}{LY_1 + LY_2}$ . After tests at INR we selected 324 counters from measured 332 ones with the mean light yield of 45 p.e./MIP ( $LY_1 + LY_2$ ) and the asymmetry value less than 10 %. The measurements at YNU yielded the average total light yield of about 40 p.e./MIP which varies in range from 32 to 50 p.e./MIP (Figure 16 (left)). Only two counters showed relatively high asymmetry close to 25 % as shown in Figure 16 (right). Using the results of the quality assurance test we selected 320 scintillator counters for the Side-MRD modules.

We also measured the time resolution for a combination of four counters piled one upon another. The average result for four counters is  $\sigma_T = 1.04$  ns. The resolution of combination of 2, 3, 4 counters is measured to be 0.79 ns, 0.66 ns and 0.58 ns, respectively.

Construction of the Side-MRD modules is scheduled from November 2017 at Yokohama National University. They will then be transported to J-PARC for installation on the B2 floor of the T2K near detector hall.

Same electronics as the WAGASCI modules (see Sec. 2.1.2) are used for the Side-MRD modules.

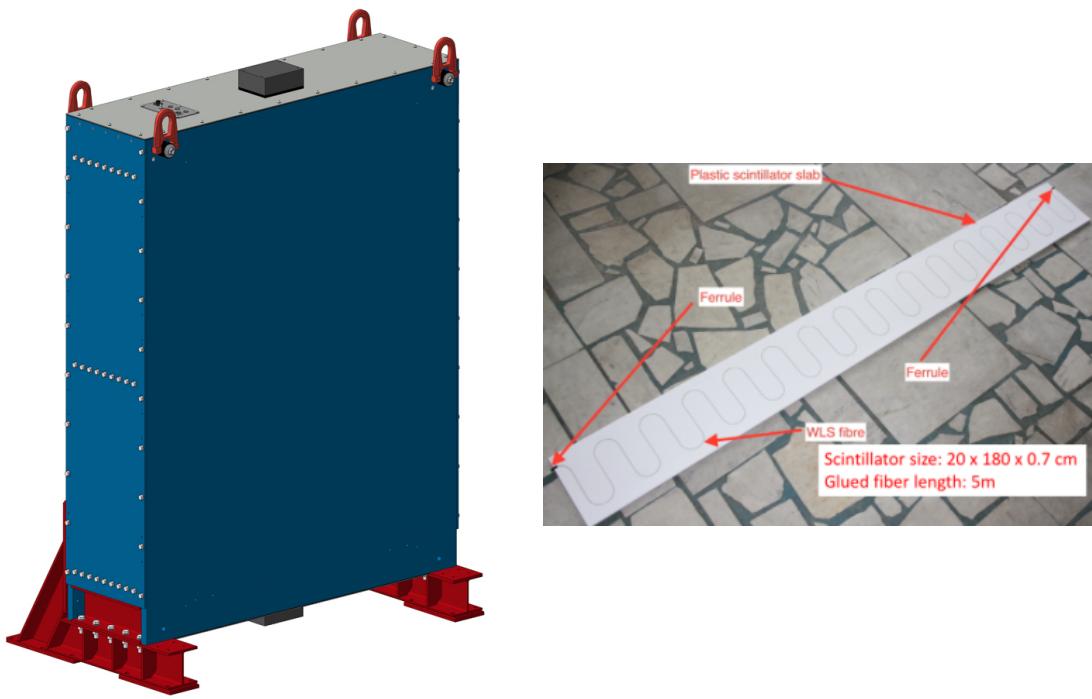


Figure 15: Left :Side-MRD module. Right: Scintillator bar of the Side-MRD modules.

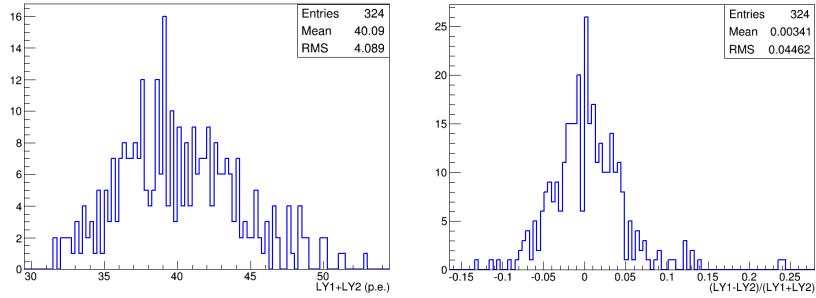


Figure 16: Total light yield distribution (left) and light yield assymetry (right) measured at YNU.

### 3 Physics goals

We will measure the differential cross section for the charged-current (CC) interaction on H<sub>2</sub>O and Hydrocarbon(CH). The water-scintillator mass ratio of the WAGASCI module is as high as 4:1 and the high purity measurement of the cross section on H<sub>2</sub>O is possible. One experimental option is to remove water from one of the two WAGASCI modules. The water-out WAGASCI module will allow to measure pure-CH target interactions with very low momentum-threshold for protons. This will also allow this CH interaction background to be subtracted from the water-in target measurement. Another option is to add the T2K proton module which is fully made of plastic scintillators. It will allow a high statistics comparison of cross section between H<sub>2</sub>O and CH and also comparison with ND280 measurements. The actual configuration will be optimized with detailed MC simulation by 2018 Summer.

Our setup allows the measurements of inclusive and also exclusive channels such as 1 $\mu$ , 1 $\mu$ 1 $p$ , 1 $\mu$ 1 $\pi^{\pm}$ np samples, the first two of which are mainly caused by the quasi-elastic and 2p2h interaction and the latter is mainly caused by resonant or coherent pion production and deep elastic scattering. In general, an accelerator produced neutrino beam spectrum is wide and the energy reconstruction depends upon the neutrino interaction model. Therefore, recent neutrino cross section measurements including those from T2K are given as a flux-integrated cross section rather than cross sections as a function of the neutrino energy to avoid model dependence. We can provide the flux-integrated cross section. In addition, by combining our measurements with those from ND280, model-independent extraction of the cross section for narrow energy spread becomes possible. This method was demonstrated in [1] and also proposed by E61 (NUPRISM) experiment.

### 3.1 Expected number of events

The expected number of CC neutrino events remaining after the event selections was evaluated with simulation. Details are described in Sec. 5. In neutrino-mode, 5,400, 1,100 and 3,800 events are expected for the water-in WAGASCI module, the water-out WAGASCI module and the INGRID proton module, respectively, with  $5 \times 10^{20}$  POT. Among 5,400 events for the water-in WAGASCI module, 78 % are interactions on H<sub>2</sub>O. In the antineutrino-mode, 2,240, 400 and 1,500 CC antineutrino events are expected for the water-in WAGASCI module, the water-out WAGASCI module and the INGRID proton module, respectively, with  $5 \times 10^{20}$  POT. Among the 2,240 events observed in the water-in WAGASCI module, 74% are interactions on H<sub>2</sub>O. The wrong-sign interactions in antineutrino-mode is 561 events, but will be removed with 90 % or higher efficiency by Baby MIND.

### 3.2 Pseudo-monochromatic beam by using different off-axis fluxes

The off-axis method gives narrower neutrino spectrum, and the peak energy is lower for larger off-axis angle. There still remains a high energy tail mainly due to neutrinos from Kaon decay. The off-axis angle of the WAGASCI location is 1.5 degrees as opposed to 2.5 degrees for ND280. The top two plots of Figure 17 show the energy spectra of fluxes and neutrino interactions at these two different locations. The Bottom two plots of Figure 17 show the energy spectra of fluxes and neutrino interaction events obtained by subtraction of fluxes at ND280 and WAGASCI. We can effectively get two fluxes, from 0.2 GeV to 0.9 GeV and 0.6 GeV and 2 GeV and measure flux-integrated cross section for these two fluxes. It should be noted that even though the statistical errors are drawn for each energy bin for the bottom right plot of Fig. 17, measurement results will be given as an integration across energies.

### 3.3 Extraction of Cross sections

The flux-integrated CC inclusive cross sections on H<sub>2</sub>O and CH are calculated from the number of selected events with background subtraction and efficiency correction

$$\sigma_{CC} = \frac{N_{sel} - N_{BG}}{\phi T \epsilon},$$

where  $N_{sel}$  is the number of selected events from the real data,  $N_{BG}$  is the number of background events contaminating the selected sample,  $\phi$  is the integrated  $\nu_\mu$  flux,  $T$  is the number of target nucleons, and  $\epsilon$  is the detection efficiency for signal estimated by MC simulation. The number of main background events is estimated from sideband samples. The CH interaction background for the H<sub>2</sub>O measurement is estimated from the measurement of the Water-out WAGASCI module and/or the proton module. The neutrino interaction background for the antineutrino measurement is estimated from the opposite-sign interactions selected by Baby MIND. The dominant error for the inclusive total cross section

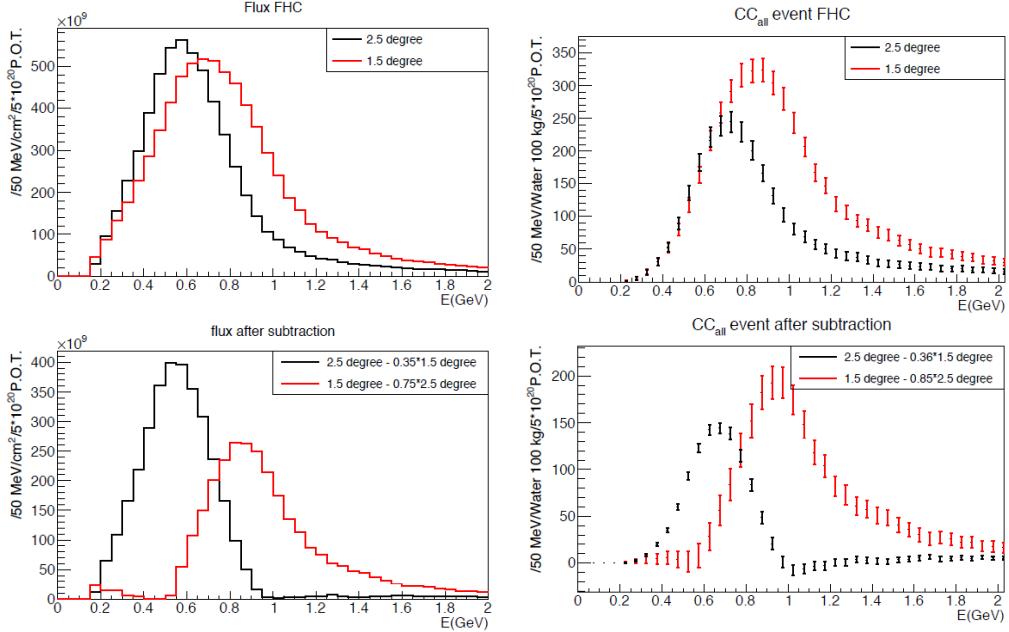


Figure 17: Energy spectra obtained by using different off-axis angle fluxes. Top two plots show the energy distribution of the fluxes (left) and interactions (right) for ND280 (off-axis 2.5 degree) and WAGASCI (off-axis 1.5 degree). Bottom two plots show the fluxes (left) and spectra of interaction events (right) obtained by subtraction of fluxes at ND280 and WAGASCI. The error bars represent the statistical error and those in the bottom right plot assume the statistical error for ND280 measurements are much smaller than those of the WAGASCI experiment.

measurement is the uncertainty of the neutrino flux, which is  $\sim 9\%$  now and is expected to be reduced to  $\sim 6\%$ . Since the flux error is dominated by normalization uncertainties that are correlated across measurements on the different target materials and locations, the flux error can be significantly reduced for the relative comparison of the H<sub>2</sub>O and CH cross sections and the relative comparison of the ND280 and WAGASCI measurements. For example, T2K INGRID succeeded to determine the cross section ratio for CH and Fe with 3% precision[5]. For the exclusive and/or differential cross section measurements, statistical error would be dominant, the size of which depends on the binning.

### 3.4 Subjects to which WAGASCI can contribute

Recent accelerator neutrino experiments use nuclear target e.g. organic scintillator, water and iron. So the interactions are significantly affected by nuclear effects such as Fermi motion, correlated pairs of nucleons in nucleus (two particles-two holes, 2p2h), collective nuclear effects and final state interactions (FSI) of secondary particles in the nuclei after the initial neutrino interactions.

The main interaction type at the T2K energy (sub GeV) is the CC quasi-elastic (CCQE) interaction with nucleons inside nucleus. The energy is reconstructed from the lepton momentum assuming CCQE kinematics in T2K, which is biased in the case of other interaction channels. Figure 18 shows how the reconstructed energy is affected. The 2p2h interactions mainly happen through the interaction with a correlated nucleons pair and also through the  $\Delta$  resonance interaction followed by pion-less decay. The 2p2h interactions are observed in electron scattering experiments [8] where the 2p2h events were observed in the gap between the quasi-elastic and pion-production regions. Neutrino experiments have attempted to measure the 2p2h interactions, but so far there are only indicative results. This is because the transferred momentum ( $p$ ) and energy ( $\omega$ ) cannot be determined in the neutrino experiments due to the wide energy spectrum of the neutrino beam. Our measurements, when combined with ND280 measurement, will give the cross section values for narrow energy-spread fluxes and give insight for such interactions. Another efficient way to investigate the 2p2h interaction is direct measurement of proton tracks with low momentum threshold and wide acceptance. Figure 19 left plot shows proton multiplicities for the CCQE events and 2p2h events. Figure 19 right plot shows the opening angles between the protons in events with two outgoing protons. The water-out WAGASCI can provide good sample for the 2p2h interaction search because its low density medium enables the detection of low momentum protons at wide angles.

There are various models which describe the collective nuclear effects [9]. The wide acceptance of the WAGASCI experiment will provide information complementary to ND280 and will play an important role to select and tune models.

T2K is starting to use  $\nu_e$  CC1 $\pi$  samples at the far detector to increase statistics. One of the biggest uncertainty of the CC1 $\pi$  sample comes from the final state interactions of pions in the nuclei after the initial neutrino interactions because they change the multi-

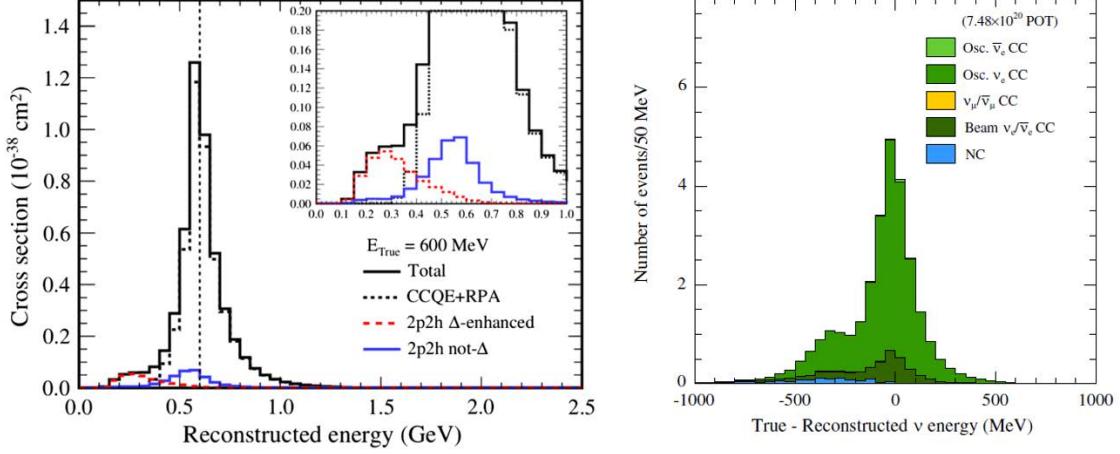


Figure 18: Left: reconstructed neutrino energy for CCQE and 2p2h interactions of simulated 600 MeV muon neutrinos on  $^{12}\text{C}$ . Right: difference between true and reconstructed energy of the  $\nu_e$  CCQE-like sample. The energy is reconstructed from the lepton momentum assuming the kinematics of the CCQE interaction. Both plots from [2]

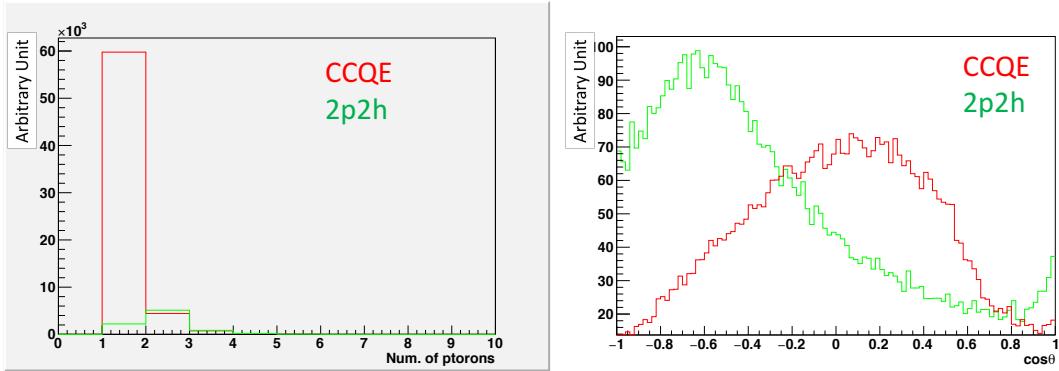


Figure 19: Proton multiplicities (left) and opening angles between two proton tracks (right) for CCQE events and 2p2h events. The final-state interaction is taking into account.

plicity, charge and kinematics of the pions. Multi pion production events can migrate into the CC1pi sample due to FSI and become background. The WAGASCI module has the capability to distinguish the pion track and proton track by  $dE/dx$ , so WAGASCI can provide the  $CC1\pi$  cross section with low momentum threshold and wide acceptance for pion tracks.

## 4 Status of J-PARC T59 experiment

We had submitted a proposal of a test experiment to J-PARC in April 2014 to test a new detector with a water target, WAGASCI, at the neutrino monitor hall, and the proposal was approved as J-PARC T59. The project contains the side and downstream muon range detectors as well.

The first WAGASCI module has been constructed in 2016 and installed at the on-axis position in front of the T2K INGRID detector for the commissioning and the first cross section measurement as a part of the T2K experiment. The INGRID electronics boards are used to read the signal. The light yield measured with muons produced by the interaction of neutrinos in the hall wall, shown in Figure 20, is sufficiently high to get a good hit efficiency. A track search algorithm based on the cellular automaton has been developed

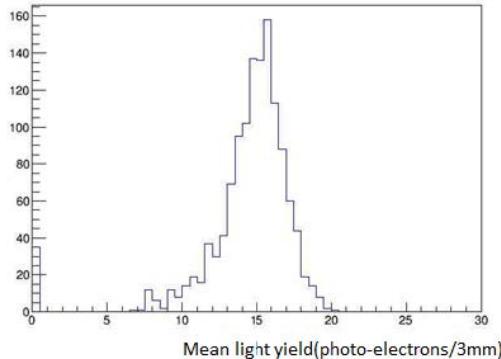


Figure 20: Light yield for muons produced by the interaction of neutrinos in the hall wall. Average light yields for each channel are plotted.

using the software tools from T2K INGRID. Examples of observed events are shown in Figure 21. The tracking efficiency in a 2-dimensional projected plane was evaluated by comparing the reconstructed track in the WAGASCI module and the INGRID module, and is shown in Figure 22. Note that the tracking efficiency for high angle ( $> 70$  deg) is not evaluated because of the acceptance of the INGRID module, not because of the limitation of the WAGASCI module.

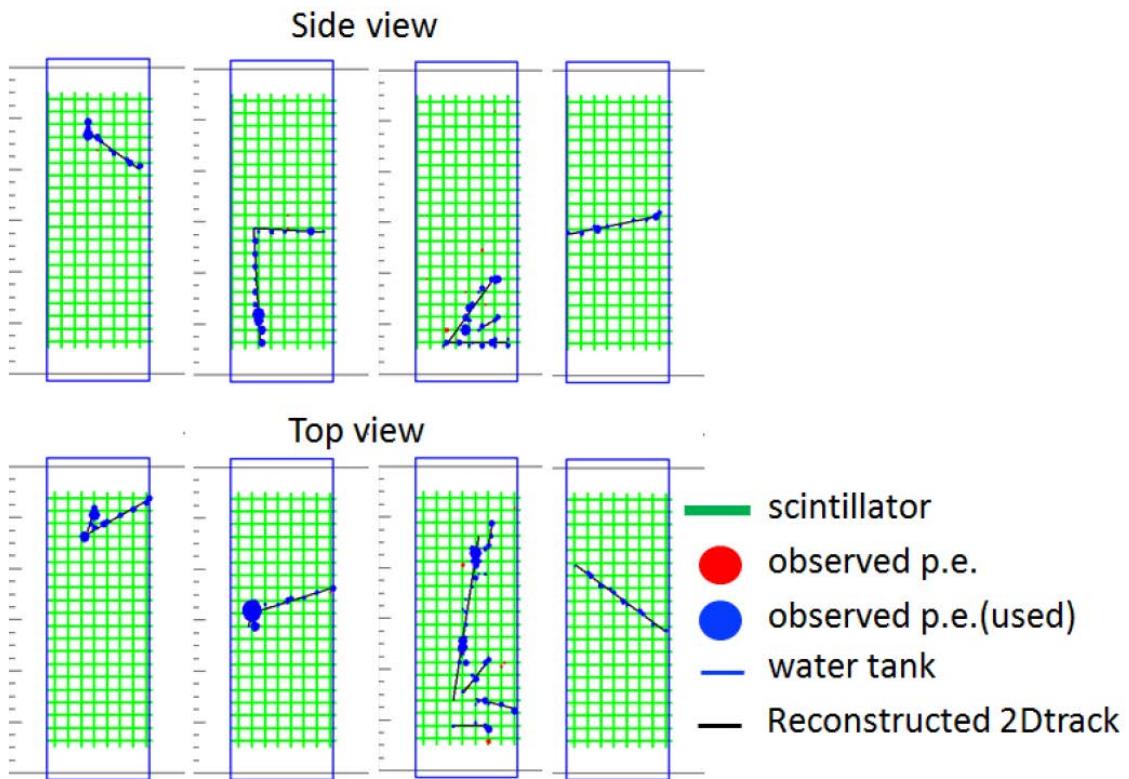


Figure 21: Example event displays of the WAGASCI module at on-axis. The reconstructed tracks are overlaid.

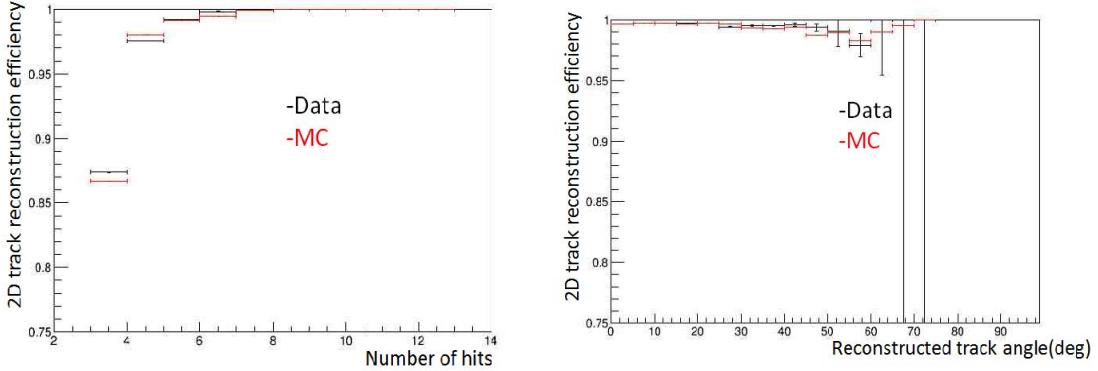


Figure 22: 2D track reconstruction efficiency as a function of number of hits (left) and track angle (right). Here the track angle is the one reconstructed by the INGRID module.

In 2017 Autumn, the construction of the second WAGASCI module and the dedicated electronics board were completed. The module and the electronics were install on the B2 floor together with the T2K proton module and the INGRID module as shown in Figure 23. The proton module is to be used as the entering muon veto and also for the comparison of interaction between CH and Water. The INGRID module will act as the muon detector for this period but due to its limited acceptance angle this is only a temporary measure. The detector was commissioned and since October has been in operation taking data with the T2K antineutrino beam.

The production of the components of the side muon range detectors has been completed and now the detectors are being assembled at the Yokohama National University. These detectors will be installed between January and June 2018, when T2K is not running.

The Baby MIND detector was transported from CERN to Japan in December, 2017. It will be installed and commissioned in Jan.-Feb. 2018 and T59 will take the neutrino-induced muon data in April and May.

## 5 MC studies

### 5.1 Simulation setup

The expected number of neutrino events in the water-in Wagasci detector is predicted by Monte Carlo simulations. Neutrino beam flux at the detector location is simulated by T2K neutrino flux generator, JNUBEAM. Neutrino interactions with target materials are simulated by a neutrino interaction simulator, NEUT. Detector responses are simulated using GEANT4-based simulation.

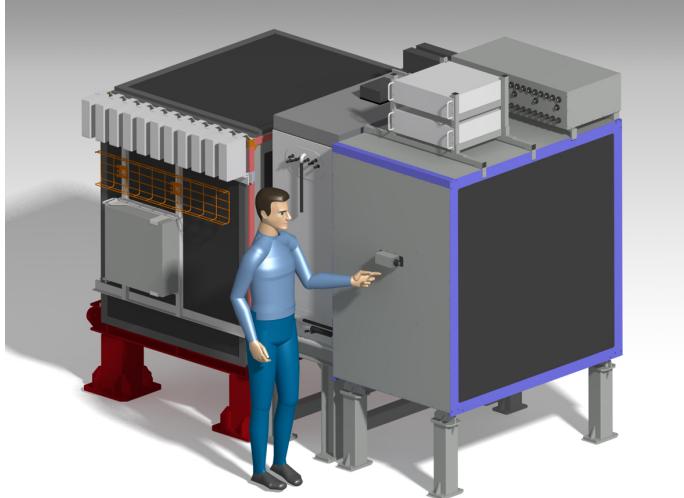


Figure 23: J-PARC T59 detector configuration in October 2017.

The detector geometry in the simulation so far is different from the actual setup as shown in Figure 24. The active neutrino target region consists of four WAGASCI modules. The size of the WAGASCI module is same as the actual one: 1000 mm × 1000 mm in the x and y directions and 500 mm along the beam direction (z-direction). Two Side-MRD modules are installed either side of the Wagasci modules. Each Side-MRD module consists of ten iron plates whose dimension is 30 mm (thickness) × 2000 mm (height) × 3200 mm (width). The distance between the Side-MRD modules and WAGASCI modules is 800 mm. The downstream-MRD is equivalent to the Baby-MIND, but without the magnetic field. It consists of thirty iron plates whose dimension is 30 mm (thickness) × 2000 mm (height) × 4000 mm (width). The distance between the downstream-MRD modules and WAGASCI modules is 800 mm. Update of the study with the actual geometry is now underway.

To simulate the signal, the energy deposit inside the scintillator is converted into the number of photons. The effects of collection and attenuation of the light in the scintillator and the WLS fiber are simulated, and the MPPC response is also taken into account. The light yield is smeared according to statistical fluctuations and electrical noise.

## 5.2 Charged-current event selection

Tracks are reconstructed in two-dimensional planes in each sub-detector. Then, track matching among the sub-detectors and three-dimensional track reconstruction are performed. These analysis tools have been developed from the software tools by the T2K

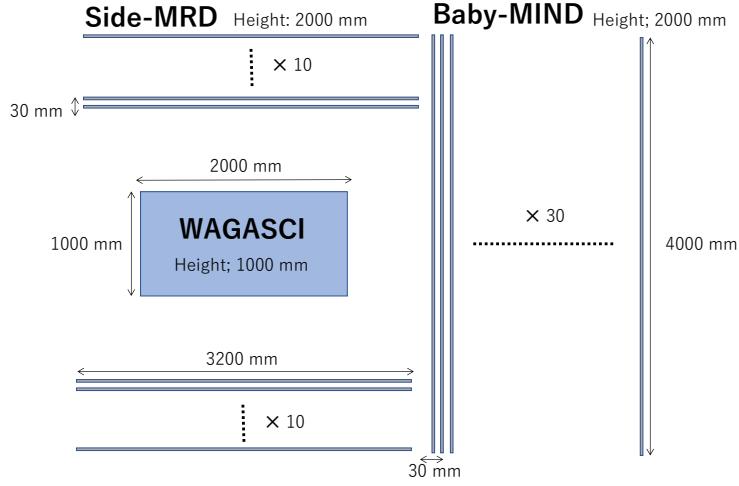


Figure 24: Geometry of the detectors in the Monte Carlo simulation.

INGRID and in mature stage already.

The events are selected as follows. The starting point of the track is required to be 50 mm away from the edge of the WAGASCI module. This is to remove the background from the outside. The longest track has to penetrate more than one (five) iron plates in Side-MRD modules (Baby-MIND). This cut select a muon track and rejects backgrounds from NC and neutral particles. Then, in order to determine the muon momentum, it is required that the longest track stops in MRDs (Side-MRD modules and Baby-MIND) or penetrate all iron plates.

Table 1 shows numbers of the selected events in one water-in WAGASCI module after the event selection. We expect 4,239 (1,666) events from charged-current interaction on H<sub>2</sub>O with  $5 \times 10^{20}$  POT in (anti)neutrino-mode with one water-in WAGASCI module. The purity, when interactions on CH is counted as background, is 78% for the neutrino-mode. There is a significant contamination from the wrong-sign (neutrino) interaction for antineutrino-mode, however, we expect that it will be removed with efficiency higher than 90% by Baby MIND.

Table 2 and 3 summarize contributions classified by the interaction types and final state topologies for the selected charged current-interaction events, respectively.

Figure 25 shows the reconstructed angles of the longest tracks in the selected events in the neutrino-mode and the anti-neutrino mode. Figure 26 shows the iron plane numbers in Side-MRD and Baby-MIND corresponding to the end points of the longest tracks in the selected events in the neutrino-mode and the anti-neutrino mode.

Table 1: Expected number of the selected neutrino-candidate events in one water-in WAGASCI module with  $5 \times 10^{20}$  POT in each of neutrino-mode and antineutrino-mode. Note that the wrong sign component will be reduced by one order by applying the charge selection by Baby MIND.

	CC on H <sub>2</sub> O	NC on H <sub>2</sub> O	Interaction on CH	wrong sign interaction
$\nu$ -mode	4239	107	1087	(negligible)
anti- $\nu$ -mode	1666	14	560	(561)

Table 2: Interaction types for the selected charged-current events.

	CCQE	2p2h	CC resonant $\pi$	CC-DIS
$\nu$ -mode	48.4 %	9.7 %	27.1 %	14.7 %
anti- $\nu$ -mode	57.1 %	8.2 %	17.3 %	17.3 %

Table 3: Final state topologies for the selected charged-current events.

	CC0 $\pi$	CC1 $\pi$	CC2 $\pi$	CCn $\pi$
$\nu$ -mode	67.4 %	20.9 %	3.0 %	8.7 %
anti- $\nu$ -mode	79.5 %	16.3 %	1.2 %	3.0 %

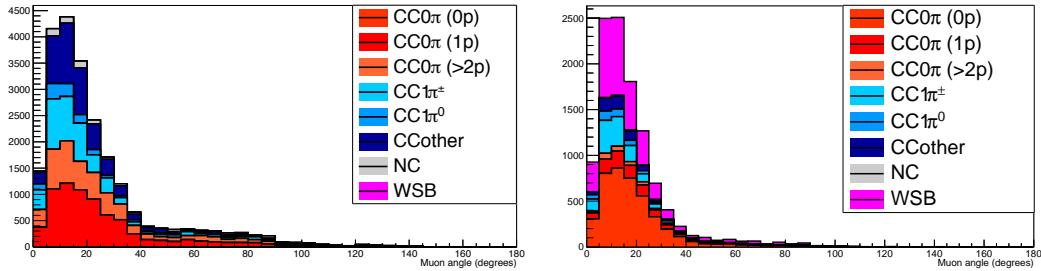


Figure 25: The reconstructed angles of the longest tracks in the selected events in the neutrino-mode (left) and the antineutrino-mode (right).

### 5.3 Standalone WAGASCI-module tracking performance

The previous section has described the inclusive charged-current event selection using the Muon Range detectors. A muon is identified by requiring one track to penetrate multiple planes of the MRD’s. For the WAGASCI configuration described in Sec. 5.1, only 7% of the muons are stopped in one of the WAGASCI modules. This proportion increases to 53% for pions and 73% for protons produced by neutrino interactions. Figure 27 shows the momentum distribution of these daughter particles as well as for the sub-sample stopped in one of the WAGASCI modules. For the measurement of the neutrino interaction final states, tracks of charged pions, protons and low-momentum ( $p_\mu < 300$  MeV/c) muons have to be reconstructed by the WAGASCI module. Therefore, the standalone tracking abilities of the WAGASCI module, especially momentum threshold, is important for the exclusive interaction measurements.

Here we present the result of the study based on an original study done for the T2K ND280 upgrade with some modifications. Though the cell size is similar to the WAGASCI configuration, the external dimensions are different (1864 mm  $\times$  600 mm  $\times$  1300 mm). We present the results which are less affected by the difference of the external dimensions.

A simplified criteria , but representing conditions for the WAGASCI module tracking, are applied to evaluate the reconstruction performance of the WAGASCI module. The fiducial volume is chosen as the inner cube of the module which surfaces are 4  $\times$  scintillator space = 100 mm distant from the module external surfaces. A track is reconstructed if:

- The track is long enough and has at least 2 hits in both of two views (XZ, YZ). In the pure longitudinal or transverse going tracks, it corresponds to the track length of 100 mm.
- The track shall not be superimposed with longer tracks in both of two views. The superposition criterion is estimated with the distance inter-tracks (DIT) which corresponds to the orthogonal distance between two tracks at the ending point of the

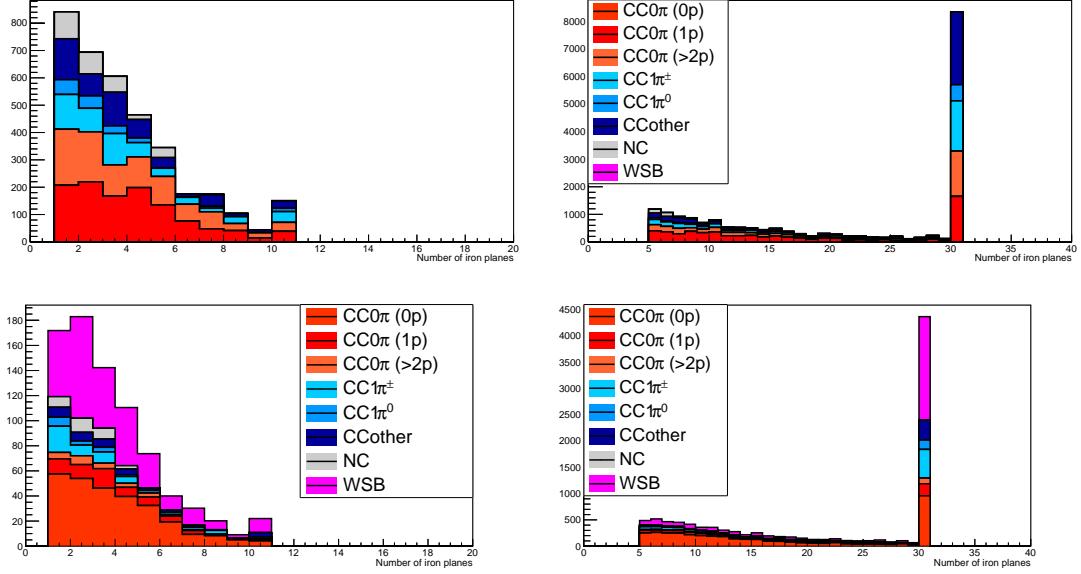


Figure 26: Iron plane numbers in Side-MRD (left) and Baby-MIND (right) corresponding to the end points of the longest tracks in the selected events in the neutrino-mode (top) and the antineutrino-mode (bottom).

shortest one (see Figure 28). The DIT should be higher than  $4 \times$  scintillator width ( $=100$  mm) for the shorter track not to be superimposed with the longer track.

### 5.3.1 Expected performance of the water-in WAGASCI module

Figures 29 shows the expected track reconstruction efficiency obtained with the criteria above. Table 4 summarizes the reconstruction efficiencies and the reconstruction momentum thresholds. This threshold is defined as the momentum under which the reconstruction efficiency falls under 30%. The thresholds for muon and pion are 150 MeV/c. The lower

Table 4: Reconstruction efficiency and momentum threshold for muons, pions and protons. The threshold is defined as the momentum under which the reconstruction efficiency falls under 30%.

	$\mu$	$\pi$	p
Reconstruction Efficiency	79%	52%	26%
Momentum threshold	150 MeV/c	150 MeV/c	550 MeV/c

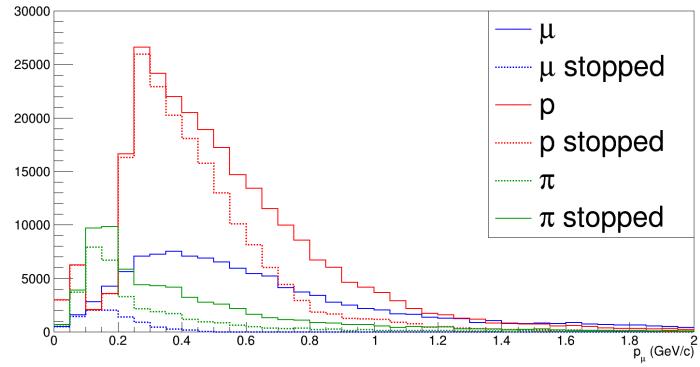


Figure 27: Momentum distribution of particles in WAGASCI (plain) and corresponding distributions only for particles stopping in the WAGASCI module (dashed).

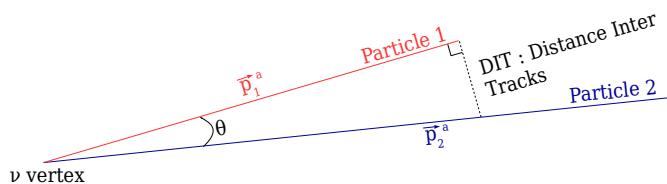


Figure 28: Definition of the distance inter tracks.

pion and proton efficiencies (respectively 52% and 26%) are due to lower momentum and also due to the secondary interaction. Efficiencies of each particle type tend to decrease in the backward region due to lower particle momenta. However, for a fixed momentum value, the reconstruction efficiency do not strongly depend on the angle thanks to the WAGASCI cuboid lattice.

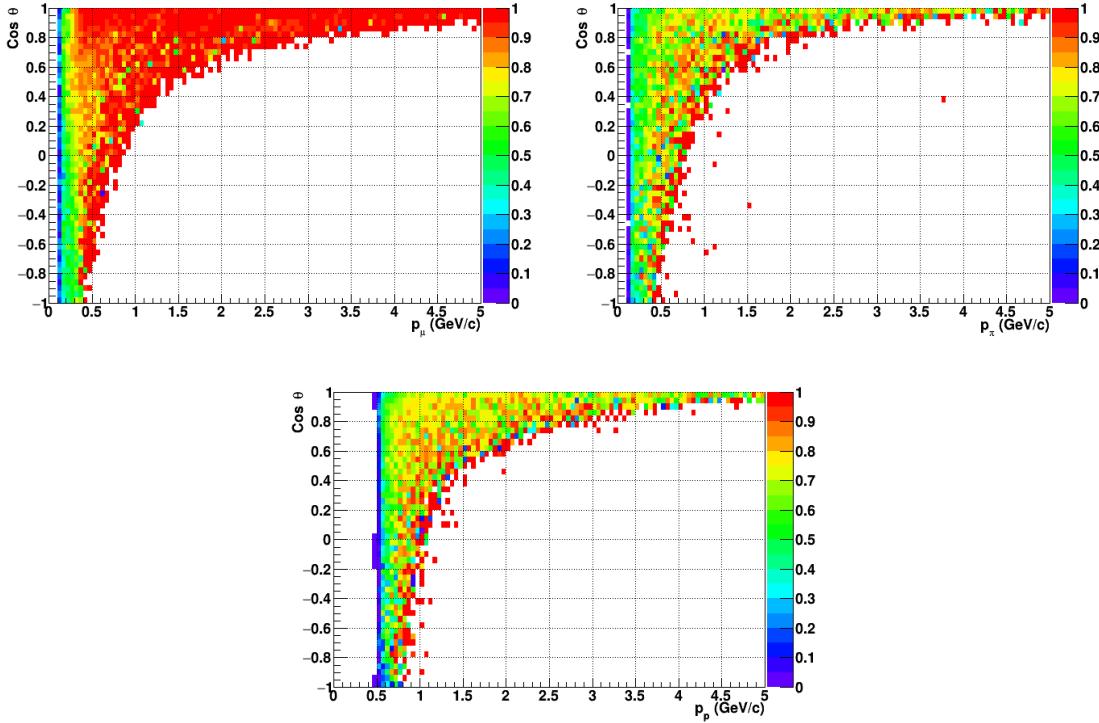


Figure 29: Reconstruction efficiency of muons (left), charged pions (right) and protons (bottom) in the WAGASCI water-module as a function of the particles momenta and angles.

### 5.3.2 Expected performance of the water-out WAGASCI module

One experimental option is to remove water from one of the two WAGASCI modules. The detector is fully active and has a 3 mm spatial resolution (scintillator thickness) which create an ideal detector to reconstruct and identify hadrons, and study 2p2h interaction. The same reconstruction criteria as in Sec. 5.3.1 are applied for the water-out module. Figure 30 shows the comparison between the water-in and the water-out reconstruction efficiencies for muon, pions and protons. 90% of the muons and 87% of the pions are reconstructed, while 70% of the protons are even reconstructed. It allows to low down the

proton threshold to 250 MeV/c (see Table 5). The water-out module offers interesting

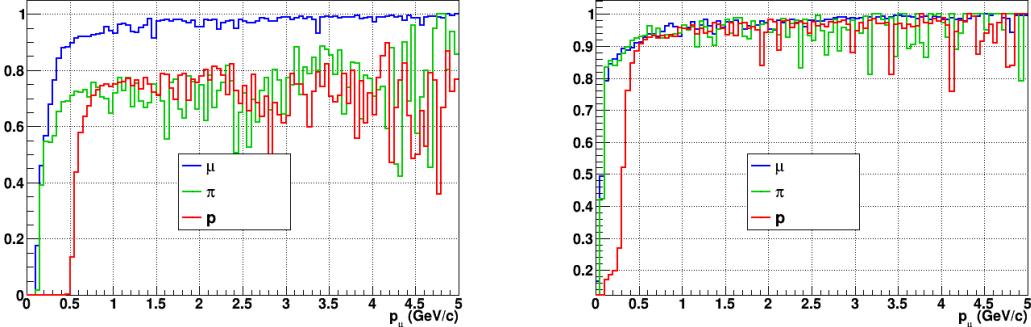


Figure 30: Reconstruction efficiency for muons, pions and protons in the water-in (left) and water-out (right) modules.

Table 5: Reconstruction efficiency, proportions of  $\mu$ -like and non  $\mu$ -like and momentum threshold for muons, pions and protons for the water-out module. The threshold is defined as the momentum under which the reconstruction efficiency falls under 30%.

	$\mu$	$\pi$	p
Reconstruction Efficiency	90%	87%	70%
Momentum threshold	50 MeV/c	50 MeV/c	250 MeV/c

possibilities to study 2p2h interaction since 70% of the protons are reconstructed.

## 6 Schedule

We would like to start physics data-taking with T2K beam after the summer shutdown in 2018. By then, we expect the commissioning and testing of the detectors in J-PARC T59 to be complete. The experiment can run parasitically with T2K, therefore we request no dedicated beam time nor beam conditions as discussed in the following section.

## 7 Requests

### 7.1 Neutrino beam

The experiment can run parasitically with T2K, therefore we request no dedicated beam time nor beam condition. T2K has been requesting  $9 \times 10^{20}$  POT/year and actually

accumulating about  $7 \times 10^{20}$  POT/year in recent years. For each year, starting from the Autumn, T2K is running predominantly in the neutrino mode or in the antineutrino mode. Our request is to have one-year neutrino-mode data and another one-year antineutrino mode data assuming that the POT for the fast extraction in each year is more than  $5 \times 10^{20}$  POT.

## 7.2 Equipment request including power line

We request the following in terms of equipment on the B2 floor:

- Site for the WAGASCI modules, Side-MRD modules and BabyMIND and their electronics system on the B2 floor of the near detector hall (Figure 2 and 3).
- Anchor points (holes) on the B2 floor to secure the WAGASCI modules, Side-MRD module and Baby-MIND. Detailed floor plans to be communicated in a separate document.
- Power line for the magnets in Baby-MIND: 400 V tri-phase 48-to-62 Hz, capable of delivering 12 kW. We request the magnet power line to be installed and available to us by beginning of March 2018.
- Electricity for electronics and water circulation system. We request a total of 3 kW of power in standard Japanese electrical sockets for the following items:
  1. Online PCs: 2.1 kW
  2. Electronics: 0.7 kW
  3. Water sensors: 1 kW
- Air conditioner for cooling heat generation at Baby-MIND magnets, online PCs and electronics
- Beam timing signal and spill information
- Network connection

The infrastructure for much of the above exists already. Exceptions are the power line for the magnet and the electronics and holes in the B2 floor to anchor the detector support structures.

After this WAGASCI experiment, Baby MIND and Side-MRD's will remain if approved by J-PARC, and be used as common platforms of future neutrino experiments using the J-PARC neutrino beam.

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