Study of neutrino-nucleus interaction at around 1 GeV using a 3D grid-structure neutrino detector, WAGASCI at J-PARC neutrino monitor hall

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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 from full understanding is the non-monochromatic neutrino beam spectrum. Measurements with different but some overlapping beam spectra would greatly benefit to resolve 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 can be obtained due to the different off-axis position. Our experimental setup contains 3D grid-structure plastic-scintillator detectors filled with water as the neturino interaction target (Wagasci modules), two side- and one downstream- muon range detectors(MRD's). The 3D grid-structure and side-MRD's allows a measuremen of wider-angle scattering than the T2K off-axis near detector (ND280). High water to scitillator material ratio enables the measurement of the neutrino interaction on water, which is higly 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, is also work as a magnet and provides the charge identification capability. 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 has been already constructed and commissioned as the J-PARC T59 experiment. Therefore, the collaboration will be ready to proceed to the physics data daking for the T2K beam time in 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. When combined with ND280 measurements, our measurement would greatly improve the understanding of the neutrino interaction at around 1 GeV and contribute to reduce the most significant uncertainty of the T2K experiment.

2 Experimental Setup

Figure. 1 shows a schematic view of the entire set of detectors. A central detector, Wagasci modules, consists of 3D grid-structure plastic-scintillator detectors filled with water as the neturino interaction target. They 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. In addition, eaco of the iron plates of the downstream-MRD, so called the Baby MIND detector, is wound by a coil and can be magnetized. It provide 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 is 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 cause any effect on the 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 narrowband ν_μ 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 is similar but slightly different. The candidate detector position in the B2 floor is shown in Fig. 2. The expected neutrino tmp.pdf

Figure 1: Schematic view of entire sets of detectors.

energy spectrum at the candidate position is shown in Fig. 3.

2.1 Wagasci module

The dimension of the central detector is 100cm $\times$ 100cm in the x and y directions and 200cm along the beam direction. The total water and hydrocarbon masses serving as neutrino targets are $\sim$1 ton each. Inside the central detector, plastic scintillator bars are aligned as a 3D grid-like structure, shown in Fig. 4, and spaces in the structure are filled with the neutrino target materials, water and hydrocarbon. When neutrinos interact with hydrogen, oxygen or carbon, in water and hydrocarbon, charged particles are generated. Neutrino interactions are identified by detecting tracks of charged particles through plastic scintillation bars. Thanks to the 3 D grid-like structure of the scintillator bars, the central detector has 4π angular acceptance for charged particles. Furthermore, adopting a 2.5cm grid spacing, short tracks originated from protons and charged pions can be reconstructed with high efficiency. Thin plastic scintillator bars (thickness $\sim$ 0.3cm) will be used for the central detector to reduce the mass ratio of scintillator bars to neutrino target materials, because neutrino interactions in the scintillator bars are a background for the cross section measurements. Scintillator bars whose dimensions are 2.5cm x 0.3cm x 100cm will be used for the central detector. The total number of channels in the central detector is 12880.

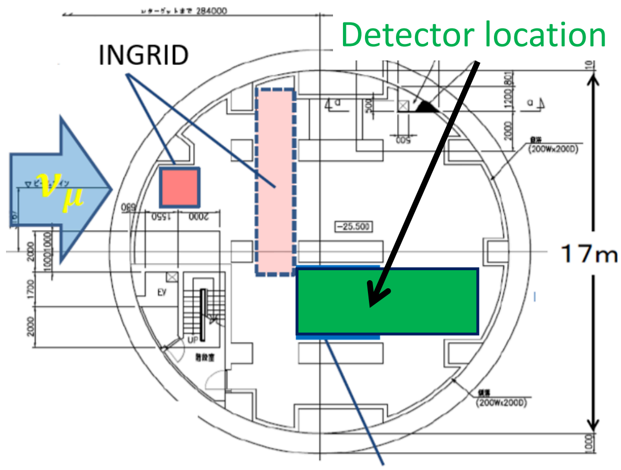

Figure 2: Candidate detector position in the B2 floor of the near detector hall.

2.2 Baby MIND

2.3 Side muon range detector

Two Side-MRD modules will be constructed by the end of January 2018. Each Side-MRD module is composed of iron plates and scintillator bars for tracking secondary particles from neutrino interactions. Support structure of the Side-MRD module mainly consists of 11 steel plates of which dimensions are $1800 \times 1610 \times 30$ mm^3, is sized as $2236 \times 1630 \times 975$ mm^3 as shown in Fig. 5, and weights $\sim$8.5 ton. Scintillator bars were produced by Uniplast company in Vladimir, Russia. Each bar is polystyrene based and made by extrusion technology with scintillating composition of 1.5% PTP and 0.01% POPOP. Then each bar's suface is etched by a cemical agent to form a white diffuse layer. The usage of this method gives almost ideal contact between the scintillator and the reflector which allows us to gain in light yield up to 50% compared to clear scintillator. 80 scintillator bars are installed in one Side-MRD module, and each scintillator bar is sized as $1800 \times 200 \times 7$ mm^3 including reflector part. Scintillation light is collected by wave length shifting fibers, Y-11 (S type) with a diameter of 1.0 mm produced by Kuraray. The fiber is glued by optical cement EJ-500 in a S-shape groove on the surface of the scintillator bar as shown in Fig. 6. Using this technique allows us to uniform light collection over scintillator's sufaces. Two optical connectors as shown in Fig. 7 are attached to either end of the fiber, and scintillation light is lead to two MPPCs, S13081-050CS(X1), produced at Hamamatsu Photonics. Optical connector of such type (so-called Baby-mind type of optical connector) consists of two parts (see Fig. 7): a) a MPPC cover and b) a ferrule. Ferrule b) is fixed in

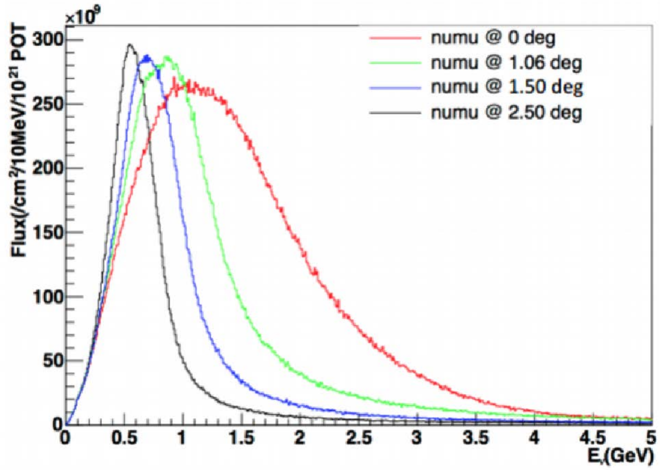

Figure 3: Neutrino energy spectrum at the candidate detector position(red). The spectrum at the ND280 site (black) is also shown.

scitillator by glue with glued fiber in it, cut by mill and polished to form an optical contact between the fiber end and the MPPC. Cover a) is clicked into place on ferrule b) and used to fix MPPC in optical contact. To ensure the tightness of the contact between the MPPC window and the fiber's end in ferrule a special spring made of sponge rubber is used (Fig. 8). For each MPPC, 667 pixels of APD are aligned in a shape of square 1.3 mm on a side.

Construction of scintillator bars of the Side-MRD modules had been completed in Russia, and they were transported to Japan in July 2017. Construction of Side-MRD modules will be done from November 2017 to January 2018 at Yokohama National University, then they will be transported to J-PARC and will be installed to the B2 floor of the T2K near detector hall before staring the T2K beam in March 2018.

3 Physics goals

We will measure the differential cross section for the charged current interaction on H_2O and/or CH. The water-scntillator mass ratio of the Wagasci module is as high as 5:1 and the high purity measurement of the cross section on H_2O is possible. One experimental option is to replace one of the two Wagasci module with the T2K proton module which is fully made with plastic scintillators. It will alow the precise comparison of cross section between H_2O and CH and also comparison of cross sections with ND280 Our setup would allow the measuemrents of inclusive and also exclusive channles such as 1-μ, 1-$\mu 1p$, 1-$\mu 1\pi \pm np$ samples, former two of which are mainly caused by the quasi-elastic and 2p2h interaction

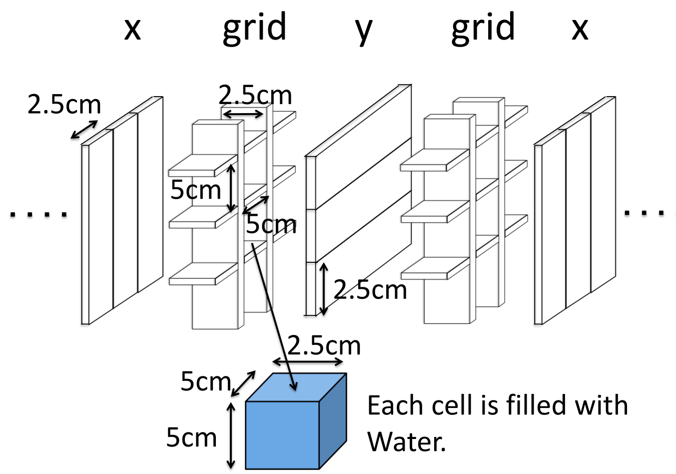

Figure 4: Schematic view of 3D grid-like structure of plastic scintillator bars inside the central detector.

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 somehow rely on the neutrino interaction model. Therefore, recent neutrino cross section measurement results including T2K are given as a flux-integrated cross section rather than cross sections as a function of the neutrino energy to avoid the model dependency. We can provide the flux-averaged cross section. In addition, by combining our measurements with those at ND280, model-independent extraction of the cross section for narrow energy region becomes possible. This method was demonstrated in **??** and also proposed by P** (NUPRISM). add Yasutome plot here or later.

3.1 Expected number of events

4 Status of J-PARC T59 experiment

We had submitted a proposal of a test experiment to test a new detector with a water target, WAGASCI, at the T2K near detector hall to J-PARC PAC on April 2014, and the proposal was approved as J-PARC T59. There are several updates on the project after three years from then. Fist, the start time of neutrino beam measurement is changed from December 2015 to October 2017, and the requested neutrino beam is changed from 1×10^{21} POT of ν beam to 0.8×10^{21}POT of anti-ν beam. Second, the detector configuration is changed. In the original proposal, central neutrino detector are expected to be surrounded by newly developed muon-range detectors (MRDs), but we will use spare neutrino detectors

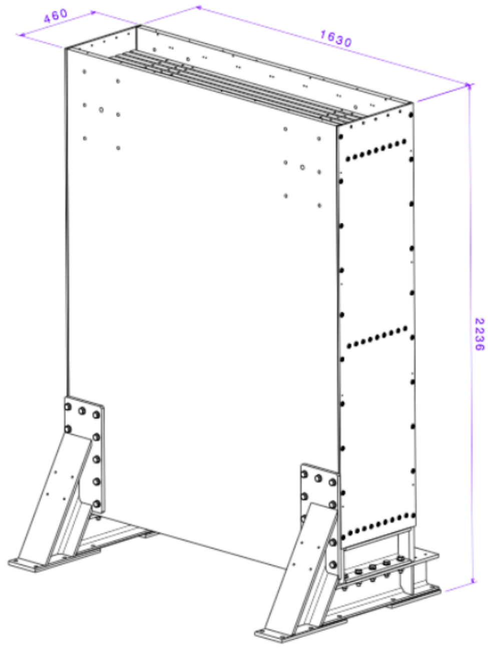

Figure 5: Support structure of the Side-MRD module.

of the T2K experiment instead of them during neutrino beam measurement from October to December 2017. Construction of the newly developed MRDs, Baby-MIND and Side-MRD, is in progress, and they will be installed to the both sides and the downstream of the central neutrino detector from January to March 2018. Then, we will resume neutrino beam measurements from March 2018 and will take the neutrino beam data until May 2018.

4.1 On-axis beam measurement with Prototype detector

Add INGRID water module measurement here.

4.2 Plans from October 2017 to May 2018

J-PARC MR will extract its proton beam to T2K neutrino beam-line from October to December 2017, and, from March to May 2018. T2K experiment will produce anti-neutrino beam and will accumulate $\sim 8 \times 10^{20}$ POT data during the above period.

J-PARC T59 will perform neutrino beam measurements on the B2 floor of the T2K near neutrino detector hall during the above period to test basic performances of the

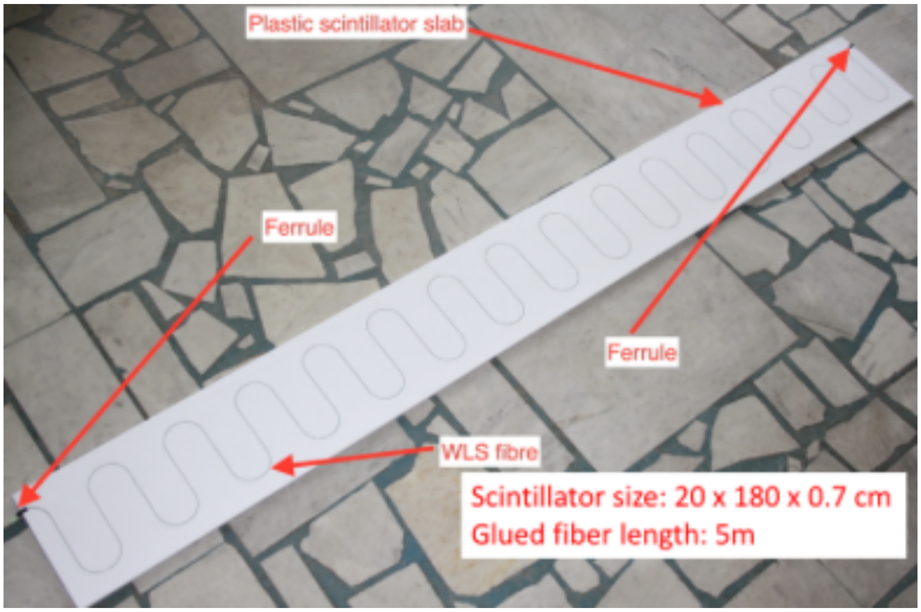

Figure 6: Scintillator bar of the Side-MRD modules.

WAGASCI detector and new electronics. During the beam measurements from October to December 2017, one WAGASCI module will be placed between spare neutrino detectors of the T2K experiment, INGRID Proton module and INGRID standard module. Here, the INGRID Proton module is used as a charged particle VETO detector and, the INGRID standard module is used as a downstream muon detector. We had submitted a proposal to use these spare neutrino detectors for the T59 neutrino beam measurements to the T2K collaboration, and we got an approval from T2K.

During the beam measurements from March to May 2018, Baby-MIND and two side muon-range detector (Side-MRD) modules will be installed on the downstream and the both sides of the WAGASCI detector, as shown in Fig. 9, to increase angular acceptance for secondary charged particles from neutrino interactions. Add Baby-MIND commissioning items here!!!

Expected number of neutrino events in the WAGASCI detector during the above beam period is evaluated with 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. The neutrino flux at the detector location, 1.5 degrees away from the J-PARC neutrino beam axis, is shown in Figure 3, and

Figure 7: Optical connector for the Side-MRD scintillator. a) MPPC cover. b) Ferrule.

Figure 8: Scheme of the MPPC placement in optical connector. a) MPPC cover. b) Ferrule. c) Spring (sponge rubber). d) MPPC.

its mean neutrino energy is around 0.68 GeV. An event display of the GEANT4-based detector simulation is shown in Figure 12.

To perform the detector performance test, the following event selections are applied to the data. First, track reconstructions are performed in the WAGASCI detector, and the reconstructed vertex is required to be inside a defined fiducial volume, $80 \times 80 \times 32$ cm^3 region at the center of the detector, to reduce contamination from external backgrounds. Second, at least one charged particle is required to reach to INGRID standard module or Side-MRD modules, and it makes more than two hits in these sub-detectors. With the event selection, expected numbers of the neutrino-candidate events during the beam period are summarized in Table 1. Using the data, we will test the detector performance with $\sim 3\%$ statistical uncertainties.

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Figure 9: J-PARC T59 detector configuration with Baby-MIND and two Side-MRD modules from Mar. to May 2018. (Need to prepare the figure.)

5 Detector performance

5.1 Wagasci module

To demonstrate the performance of the Wagasci module and also to study the neutrino interaction, the first Wagasci module was installed at the on-axis position, in front of the T2K INGRID horizontal center module in 2016. The INGRID module is made of iron plates and segmented plastic scintillator bars. It's cross sectional size viewed from the beam direction is 1 m$\times$1 m. The charged current interactions in the Wagasci module are selected by requiring a muon track candidate in the INGRIRD modules. Here, we describe the performance of the Wagasci module evaluated at this T2K on-axis measurement. Figure 10 shows the light yeild of channels for muons produced by the interaction of neutrinos in the hall wall. The light yield is sufficiently hgih to get good hit efficieincy. A track search algorithm based on the celluar automaton has been developed using the software tools by the T2K INGRID. The tracking efficiency in 2-dimentional projected plane was evalualted by comparing the reconstructed track in the Wagasci module and the INGRID module and shown in Fig.11. Note that that the tracking efficinecy for high angle ($> 70\,$deg) is not evaluated because of the acceptance of the INGRID module, not because of the limitation of the Wagasci module.

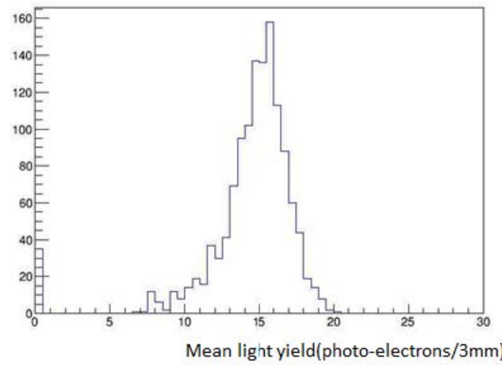


Figure 10: Light yield of channels for muons produced by the interaction of neutrinos in the hall wall.

5.2 Baby MIND

5.3 Side muon range detector

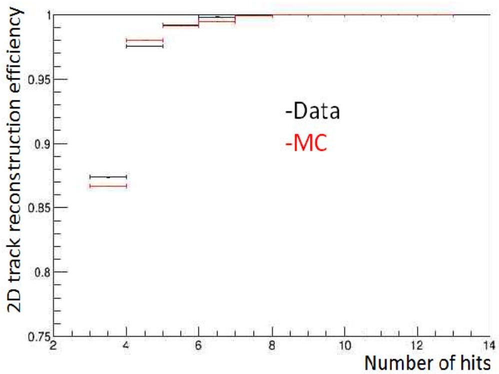
6 MC studies

6.1 Detector simulation

Expected number of neutrino events in the WAGASCI detector is evaluated with 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. The neutrino flux at the detector location, 1.5 degrees away from the J-PARC neutrino beam axis, is shown in Figure 3, and its mean neutrino energy is around 0.68 GeV.

6.1.1 Detector geometry

The detector geometry in the GEANT4-based simulation is slightly different from the actual detector as shown in Fig. 14. The active neutrino target region consists of four WAGASCI modules, and each WAGASCI detector has the dimension with 100 cm $\times$ 100 cm in the x and y directions and 50 cm along the beam direction. An event display of a MC event in the WAGASCI detectors is shown in Figure **??**. Two Side-MRD modules is installed at both sides of the WAGASCI modules, and each Side-MRD module consists of ten iron plates whose dimension is 3 cm (thickness) $\times$ 180 cm (height) $\times$ 320 cm (width). The distance between the Side-MRD modules and WAGASCI modules is 60 cm. The



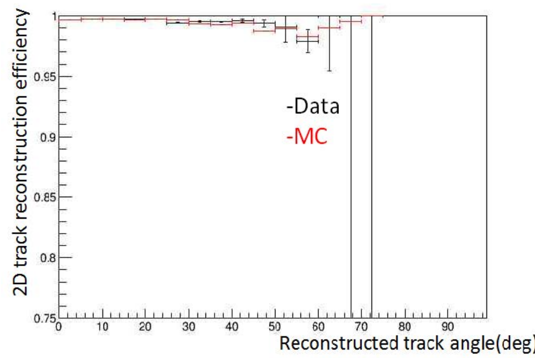


Figure 11: 2D track reconstruction efficiency as a function of number of hits (left) and track angle (right). Here the track angle is the one reconstructed by the INGRID module.

downstream-MRD equivalent to the Baby-MIND is installed at the downstream of the WAGASCI modules. The downstream-MRD consists of ten iron plates whose dimension is 3 cm (thickness) $\times$ 180 cm (height) $\times$ 320 cm (width) and another ten iron plates whose dimension is 6 cm (thickness) $\times$ 180 cm (height) $\times$ 320 cm (width). The distance between the downstream-MRD modules and WAGASCI modules is 60 cm.

In order to estimate backgrounds from neutrino interactions in the wall and floor of the experimental hall, the geometry of the experimental hall is implemented in the GEANT4-based detector simulation.

6.1.2 Response of detector components

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.

6.2 Track reconstruction

To select neutrino interaction from the hit patterns, a track reconstruction algorithm is developed. The flow of the track reconstruction is as follows.

1. Two-dimensional track reconstruction in each sub-detectors
2. Track matching among the sub-detectors
3. Three -dimensional track reconstruction

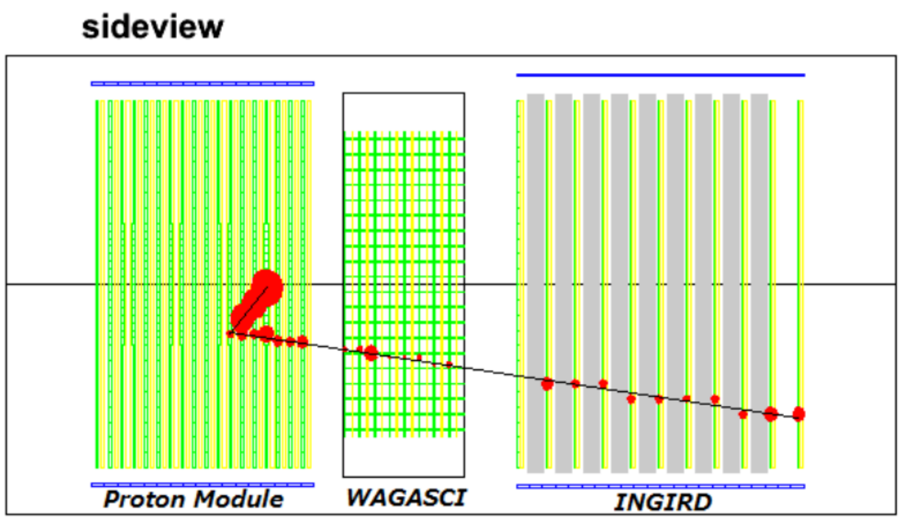


Figure 12: J-PARC T59 event display of a neutrino event in the GENAT4-based detector simulation.

Add explanation about two-dim reco, track matching and three-dim reco here.

6.3 Event selection

The events with the track which starts in 5 cm from the wall of the WAGASCI module are rejected to remove the background from the outside as shown in Fig. 15.

To reject backgrounds from NC and neutral particles, the longest tracks are required to penetrate more than one (five) iron plates in Side-MRD modules (Baby-MIND) as shown in Figure 16. In order to measure muon momentum, the longest tracks are required to stop in MRDs (Side-MRD modules and Baby-MIND) or penetrate all iron plates.

6.4 Selected events

Table 1 shows numbers of the selected events after each event election. 2.41×10^3 CC events are expected with 1×10^{20} POT in neutrino-mode, and the purity is 75.5 %. The main background is the neutrino interaction in the scintillators inside the WAGASCI detector.

Figure 17 shows the reconstructed angles of the longest tracks in the selected events.

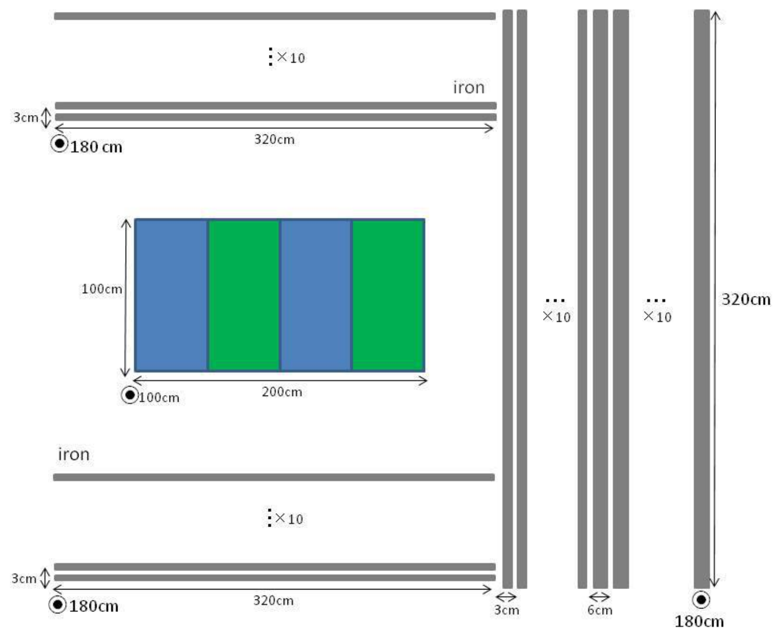


Figure 13: Geometry of the detectors in the Monte Carlo simulation.

Figure 18 shows differences between true angles and the reconstructed angles of the longest tracks in the selected events, and the angle resolution is ∼3 degrees.

Figure 19 shows the iron plane numbers corresponding to the end points of the longest tracks in the selected events.

Table 2 shows particles which produce the longest tracks in the selected events, and the fraction of muons is 85.6%.

Figure 20 shows detection efficiencies of muon tracks in the selected events as a function of muon's true angle and true momentum. The efficiency in the large angle region is low because Side-MRD modules only cover sides of the WAGASCI modules. The efficiency in the low momentum region is also low because more than two hits are required to reconstruct the track in the WAGASCI detector.

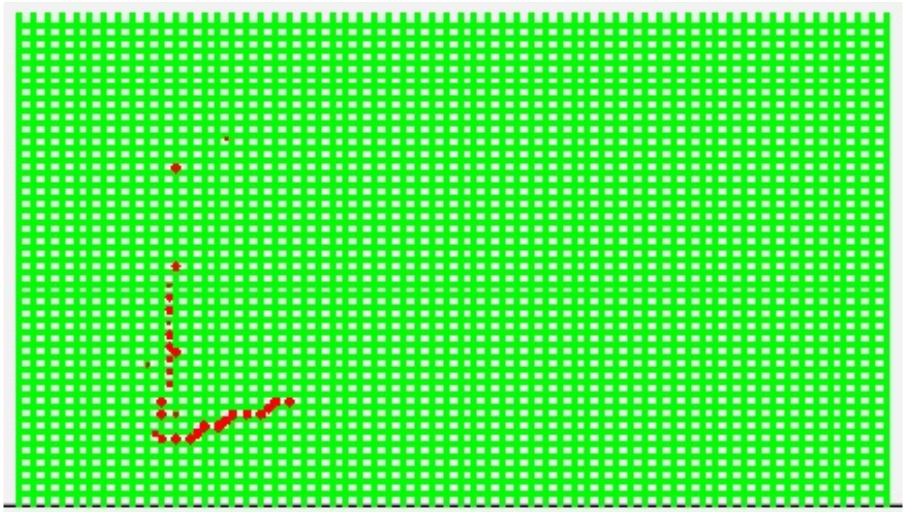


Figure 14: An event display of MC event in WAGASCI detectors. Green lines are scintillators and red circles are the hit channels.

7 Schedule

8 Requests

8.1 Beam condition and beam time

The experiment can run parasitically with T2K, therefore we request no dedicated beam time nor beam condition. We request 1×10^{21} POT neutrino beam data and another 1×10^{21} POT antineutrino data.

Table 1: Expected number of the neutrino-candidate events in two WAGASCI modules after the event selections with $1{\times}10^{20}$ POT in neutrino-mode.

Cut	CC	NC	BG (Scinti.)	BG (outside)	
Track reconst.	6.27×10^4	3.61×10^3	1.62×10^4	1.04×10^6	1.12×10^6
Fiducial	3.95×10^4	1.75×10^3	9.71×10^3	7.32×10^3	5.55×10^4
Penetrated iron	3.02×10^4	9.12×10^2	7.67×10^3	2.04×10^3	4.00×10^4
Stop in MRDs	2.41×10^4	8.65×10^2	6.19×10^3	1.64×10^3	3.19×10^4
after all cuts	75.5 %	2.71 %	19.4 %	5.14 %	100 %

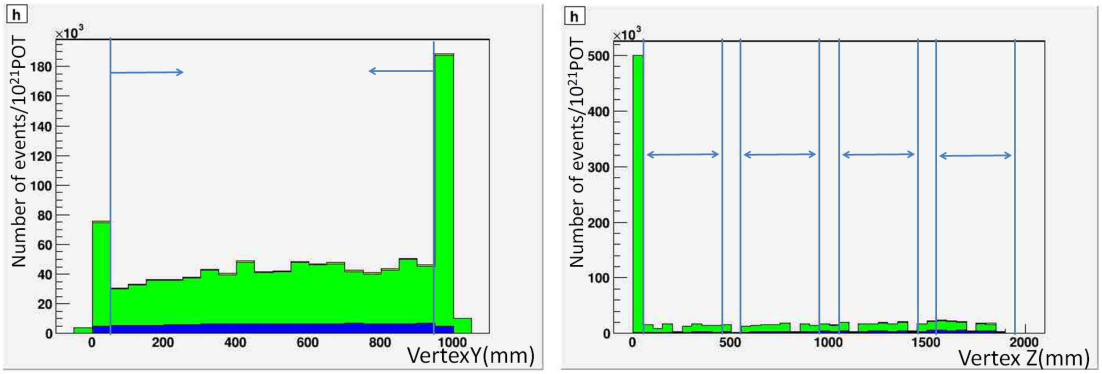


Figure 15: Event selection with the vertex of the track. Blue hist. are events from the WAGASCI modules, green hist. are events from the experimental hall, and yellow hist. are events from the Side-MRD modules and the downstream-MRD.

Table 2: Particles which produce the longest tracks in the selected events.

particles	fraction
μ	85.6%
π^+, π^-	4.8%
p	4.3%
e^+, e^-	4.5%

8.2 Request of equipment

- Site in the B2 floor of the near detector hall (Fig. 2)
- Electricity (∼10kW) for the electronics and water circulation system
- Beam timing signal and spill information
- Network connection

9 Conclusion

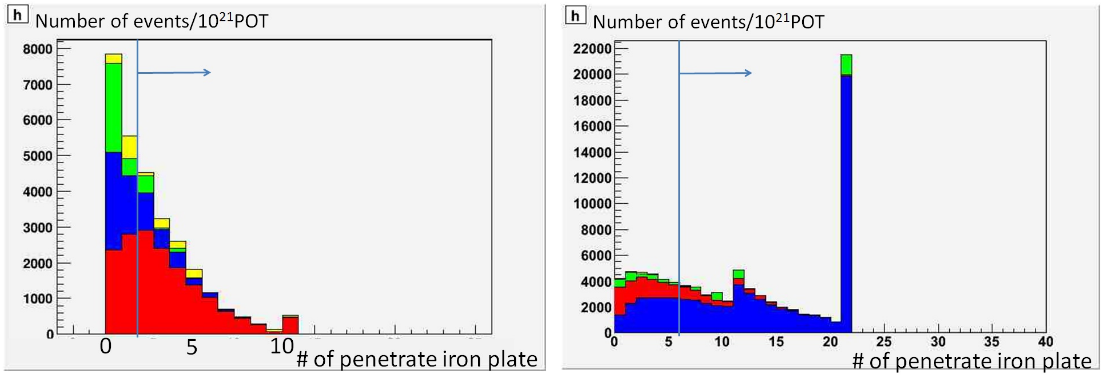


Figure 16: Event selection with the number of the penetrated iron plates in the Side-MRD modules (left) and the Baby-MIIND (right). Blue and red hist. are events from the WAGASCI modules, green hist. are events from the experimental hall, and yellow hist. are events from the Side-MRD modules and the Baby-MIND.

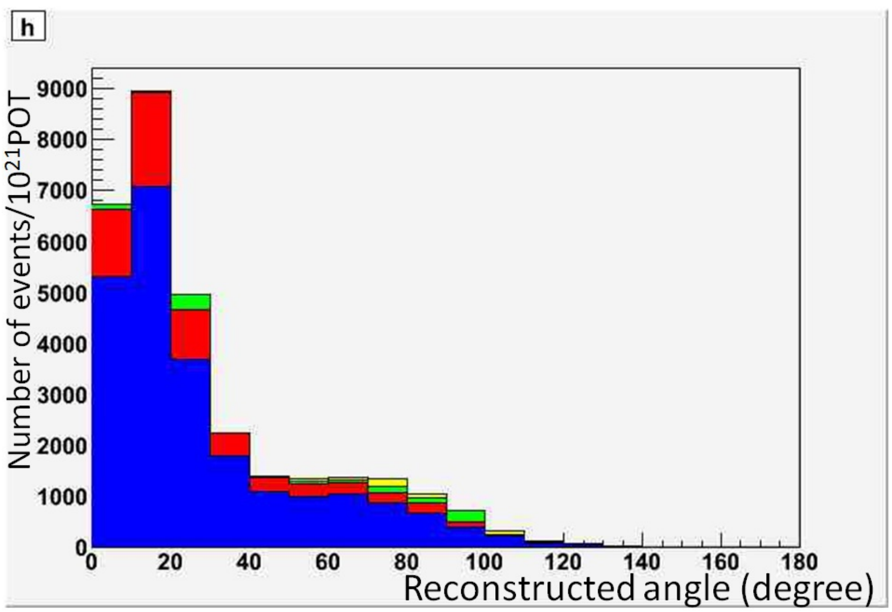


Figure 17: The reconstructed angles of the longest tracks in the selected events. Blue and red hist. are events from water and scintillators in the WAGASCI modules, green hist. are events from the experimental hall, and yellow hist. are events from the Side-MRD modules and the Baby-MIND.

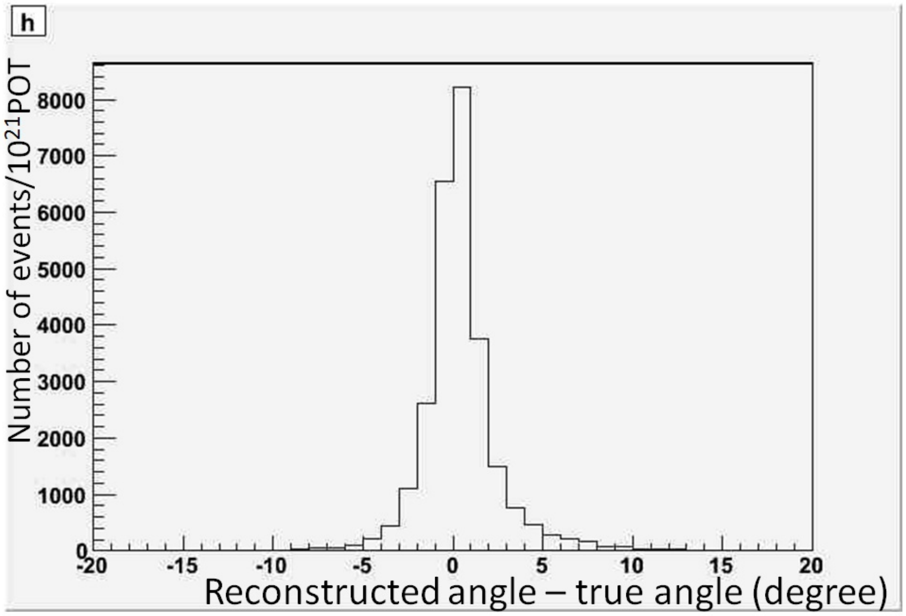


Figure 18: Differences between true angles and the reconstructed angles of the longest tracks in the selected events.

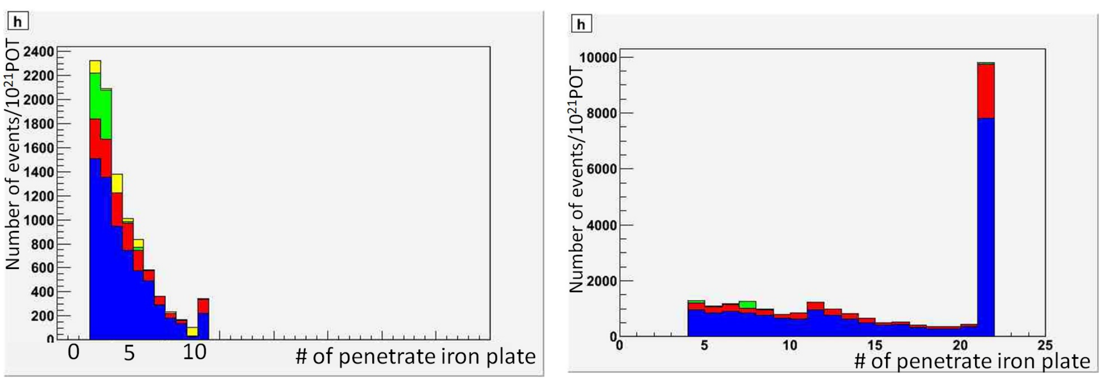


Figure 19: Iron plane numbers in Side-MRD (left) and Baby-MIND (right) corresponding to the end points of the longest tracks in the selected events. Blue and red hist. are events from water and scintillators in the WAGASCI modules, green hist. are events from the experimental hall, and yellow hist. are events from the Side-MRD modules and the Baby-MIND.

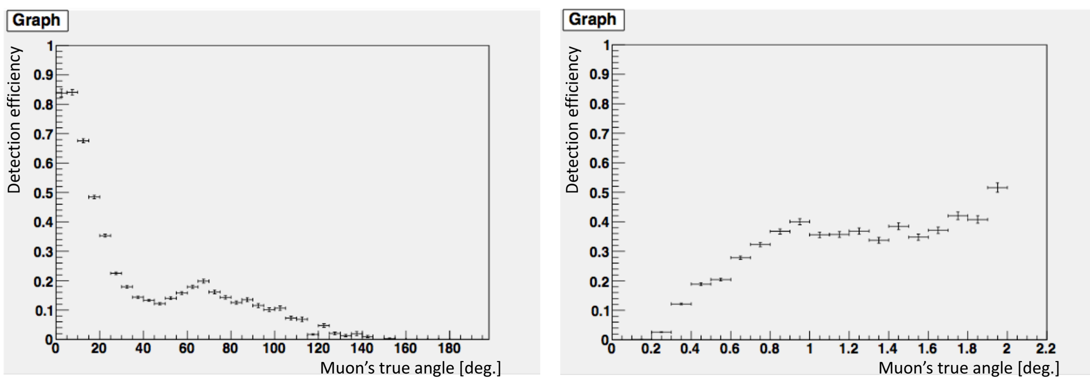


Figure 20: Detection efficiencies of muon tracks in the selected events as a function of muon's true angle (left) and true momentum (right).