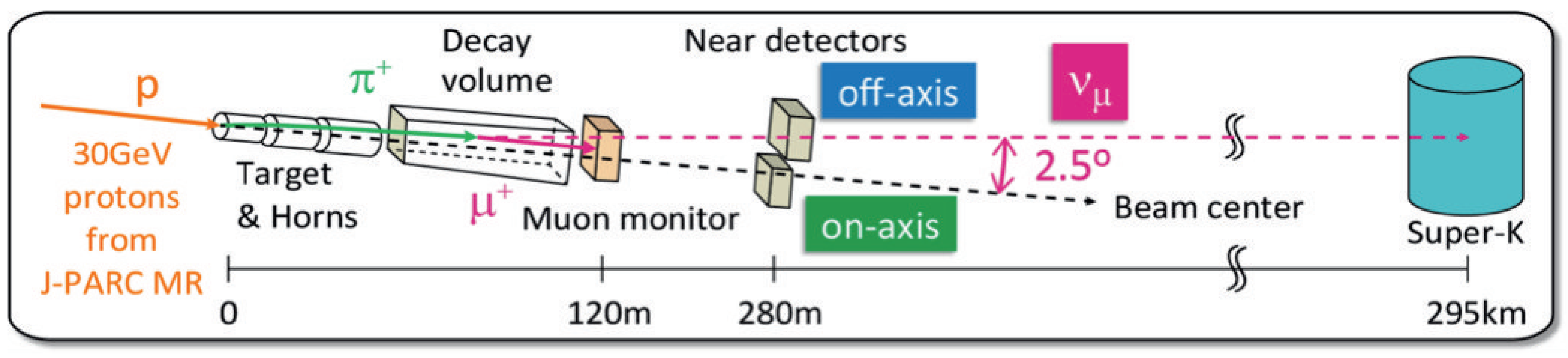
# T2K-WAGASCI: FIRST PHYSICS RUN OF THE WAGASCI-BABYMIND DETECTOR WITH FULL SETUP

**ON BEHALF OF THE WAGASCI COLLABORATION:**
**MR. PINTAUDI GIORGIO**
**(YOKOHAMA NATIONAL UNIVERSITY)**

## Introduction

### T2K EXPERIMENT

T2K (Tokai-to-Kamioka) is a **long-baseline off-axis neutrino oscillation** experiment that focuses on measuring $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ in both $\nu$ and $\bar{\nu}$-modes. A very pure $\nu_\mu$ beam is produced at J-PARC accelerator complex and detected 295 km away at the **Super-Kamiokande (SK) far detector**. T2K uses a set of near detectors in order to reduce the large uncertainties on the oscillation parameters that come from the neutrino fluxes and interaction models.



### MOTIVATIONS FOR AN ADDITIONAL NEAR DETECTOR

The ND280 off-axis detector measures the non-oscillated $\nu_\mu$ spectrum 280m downstream of the beam target, constrains the cross-section models and determines the $\nu_e$ intrinsic contamination in the beam. However, this **systematic uncertainty reduction is limited due to intrinsic detector limitations**:

- differences in most of the target material between **ND280 (80% $C_8H_8$ + 20% $H_2O$)** and SK (pure $H_2O$). This leads to using the cross-section model to cover the difference between $C_8H_8$ and $H_2O$.
- differences in the angular acceptance of **ND280 (mostly foward) and SK (4π)**. The flux and cross-section models are therefore not constrained in the high angle regions.
- inability to reconstruct low momentum protons (< 450 MeV/c) at the near detector. This leads to a large uncertainty on the interaction of the neutrino with bounded states of 2 nucleons (2p-2h) and Final State Interactions (FSI) that affect the far detector differently than ND280 due to the different threshold in proton momentum.

### WAGASCI EXPERIMENT

The new water-scintillator detector (WAGASCI, WAter-Grid-SCIintilator-Detector) is proposed to reduce the T2K systematic error. The main goals of the proposed detector are:

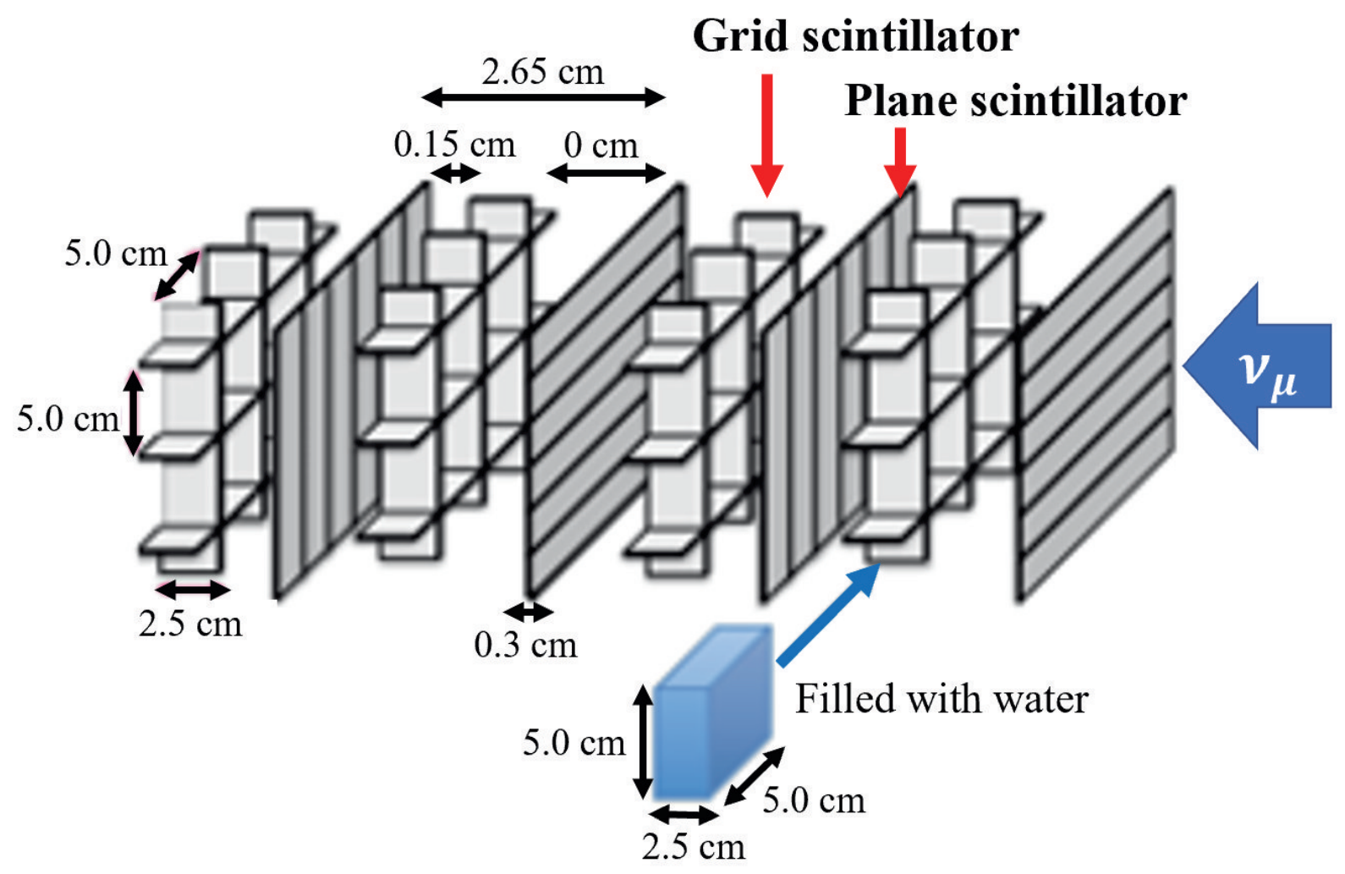
- **measurement of the charge current cross section ratio between water and scintillator targets with 3% accuracy,**
- **measurement of different charged current neutrino interaction channels with high-precision and large acceptance.**

## Commisioning

### WAGASCI DETECTOR

The WAGASCI detector is the main target for the incoming neutrinos. It consists of a grid-like hollow scintillator scheleton filled up with water. Its main features are:

- **main target is pure water (80% $H_2O$ + 20% $C_8H_8$)**
- **4π acceptance thanks to the isotropic grid structure**



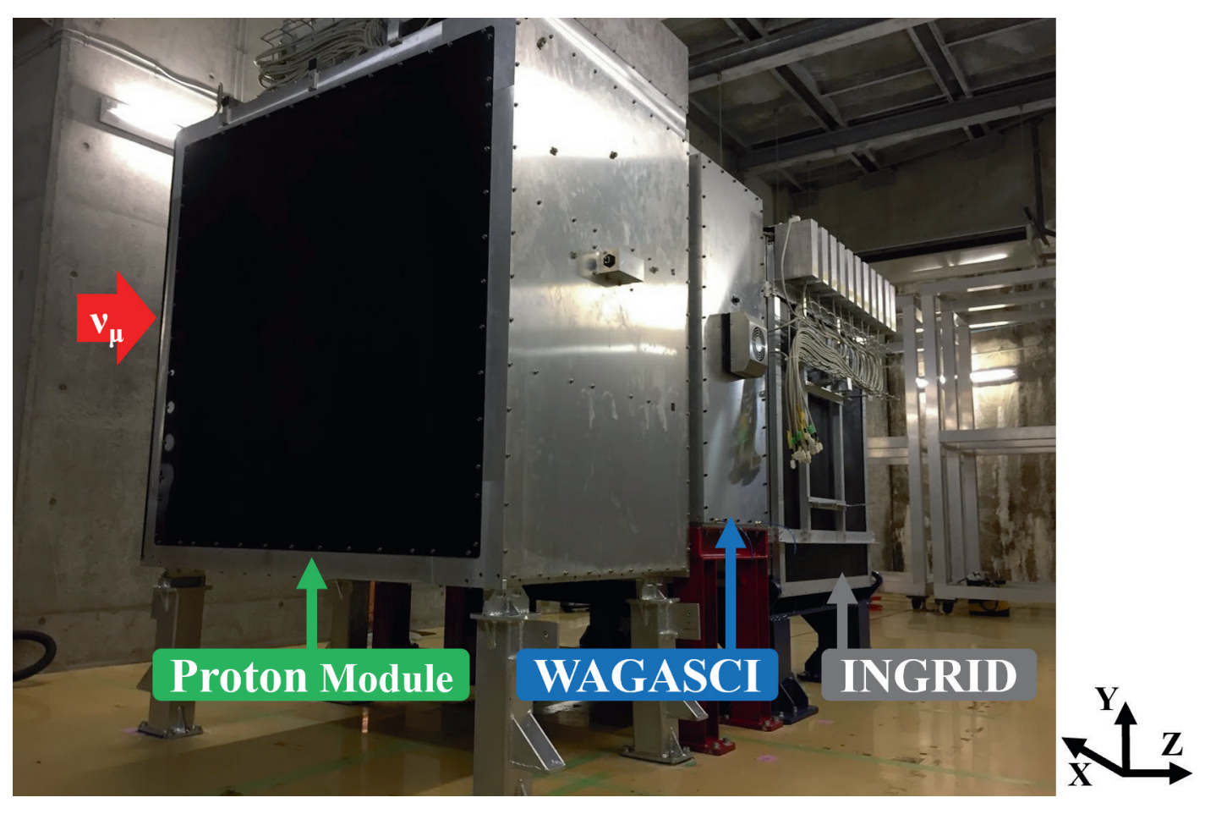
### PROTON AND INGRID MODULES

The **proton module** is a more conventional neutrino detector completely filled with bar-shaped scintillators and acts as a **hydrocarbon target**. The $\nu$-$C_8H_8$ cross-section eximated using the proton module is used to subtract the background events in the WAGASCI module where the neutrino interacts with the WAGASCI scintillators and not with water.

The **INGRID module** was used during the commissioning as a forward-going muon spectrometer. It consists of planes of scintillator bars interleaved with iron slabs.

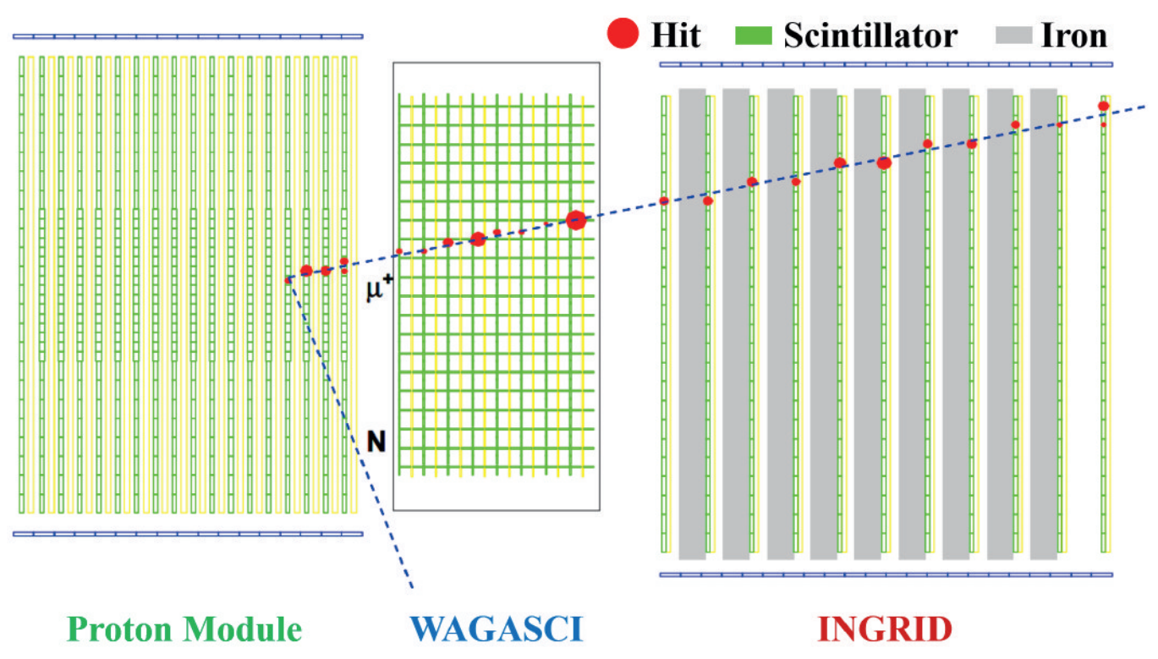
### COMMISSIONING RUN

The WAGASCI detector was commissioned last year during the RUN9 of T2K, from October 2017 to May 2018 (**$8.2 \times 10^{20}$ acquired POT**). Only the WAGASCI, proton and INGRID modules were used, aligned at an offaxis angle of 1.5°.



### CC0π0p CROSS SECTION

Using the commissioning setup the charge current events, with **no detected proton or pion and an escaping muon with a momentum of more than 400MeV/c and an angle with respect to the beam of less than 30°**, were selected.



$$
\begin{aligned}
\sigma^{\overline{\nu}_\mu}_{\mathrm{H_2O}} &= [1.082 \pm 0.068(\mathrm{stat.})^{+0.145}_{-0.128}(\mathrm{syst.})] \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleon},\\
\sigma^{\overline{\nu}_\mu}_{\mathrm{CH}} &= [1.096 \pm 0.054(\mathrm{stat.})^{+0.132}_{-0.117}(\mathrm{syst.})] \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleon},\\
\sigma^{\overline{\nu}_\mu}_{\mathrm{H_2O}}/\sigma^{\overline{\nu}_\mu}_{\mathrm{CH}} &= 0.987 \pm 0.078(\mathrm{stat.})^{+0.093}_{-0.090}(\mathrm{syst.}),\\
\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}} &= [1.155 \pm 0.064(\mathrm{stat.})^{+0.148}_{-0.129}(\mathrm{syst.})] \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleon},\\
\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} &= [1.159 \pm 0.049(\mathrm{stat.})^{+0.129}_{-0.115}(\mathrm{syst.})] \times 10^{-39}\mathrm{cm}^2/\mathrm{nucleon},\\
\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{H_2O}}/\sigma^{\overline{\nu}_\mu+\nu_\mu}_{\mathrm{CH}} &= 0.996 \pm 0.069(\mathrm{stat.})^{+0.083}_{-0.078}(\mathrm{syst.}),
\end{aligned}
$$

*Flux integrated cross sections (0-30°). Still to be published.*

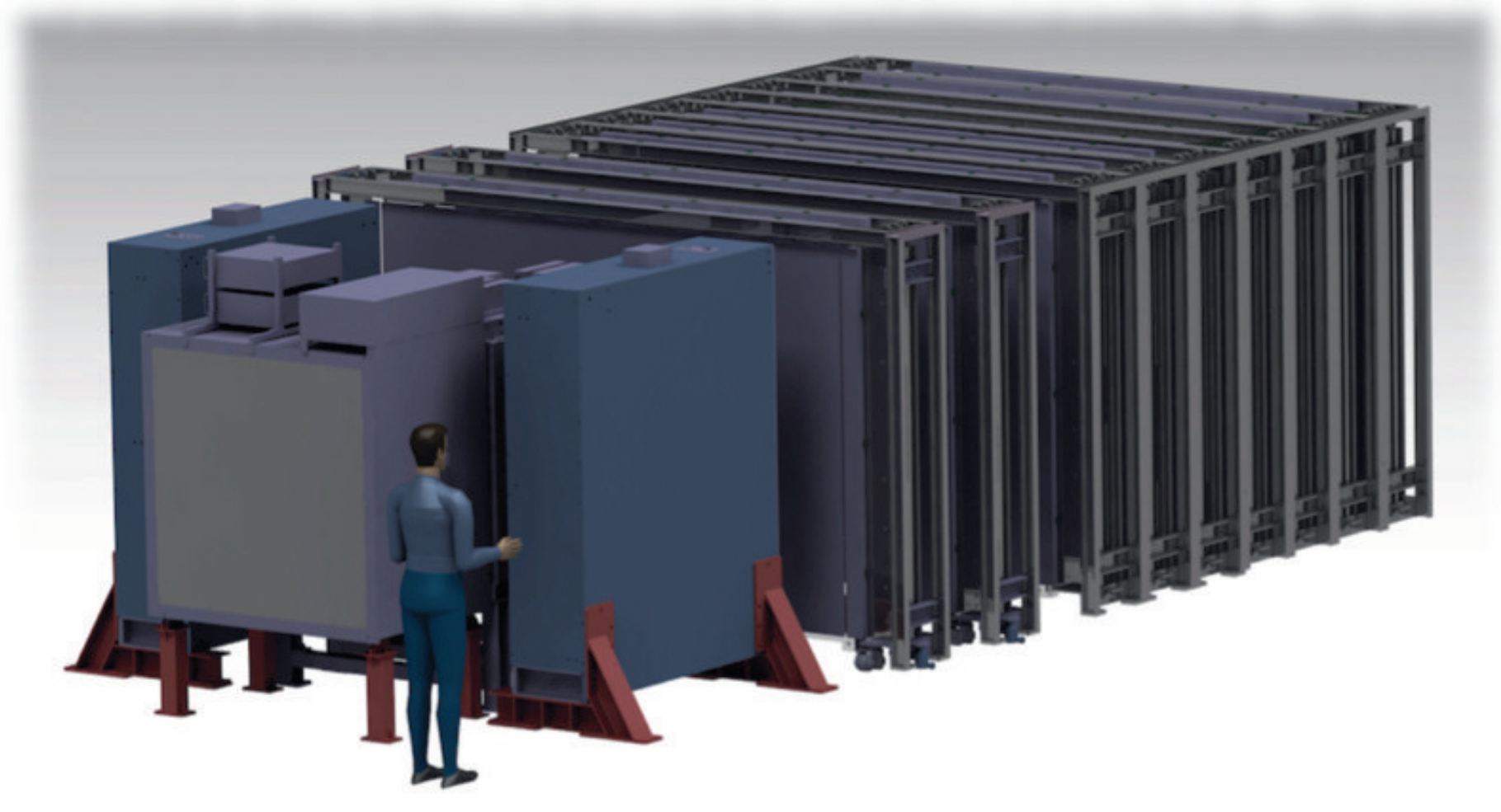
## Final Setup

### BABYMIND

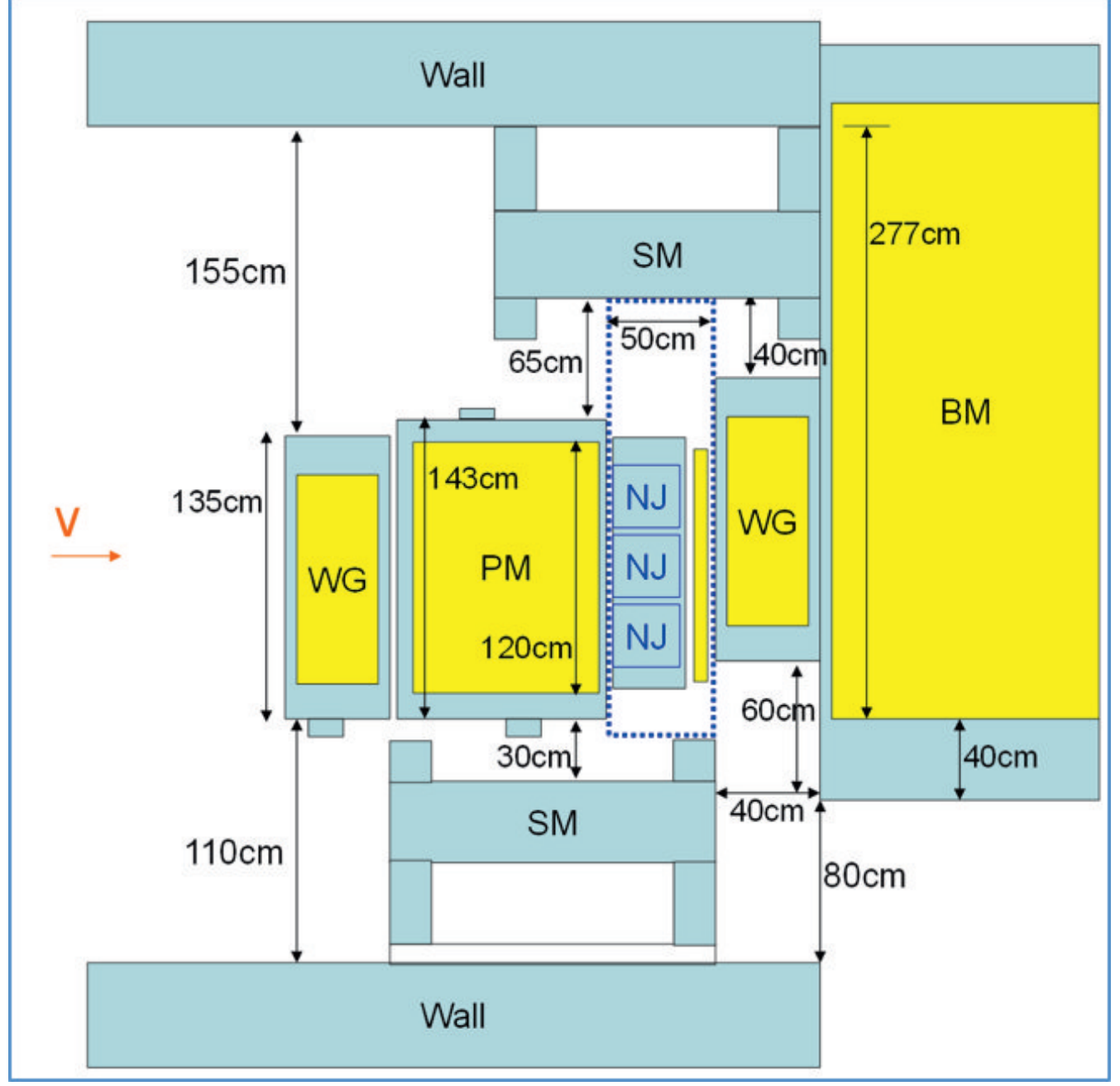
A magnetized iron neutrino detector (Baby MIND) will be used to **measure momentum and charge identification** of the outgoing muons from charged current interactions. The Baby MIND modules are composed of magnetized iron plates and long plastic scintillator bars read out at the both ends with wavelength shifting fibers and silicon photomultipliers.

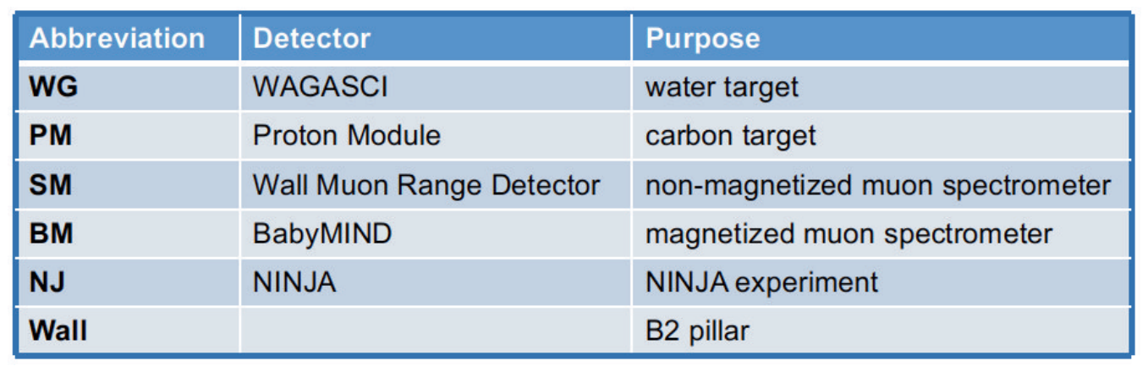
### FINAL CONFIGURATION

After the commissioning, an additional WAGASCI detector, two Wall Muon Range Detectors (Wall-MRD) and the BabyMIND detector were added to improved statistics and gain access to a larger phase-space for the outgoing muon.



Detectors size as compared to a human figure





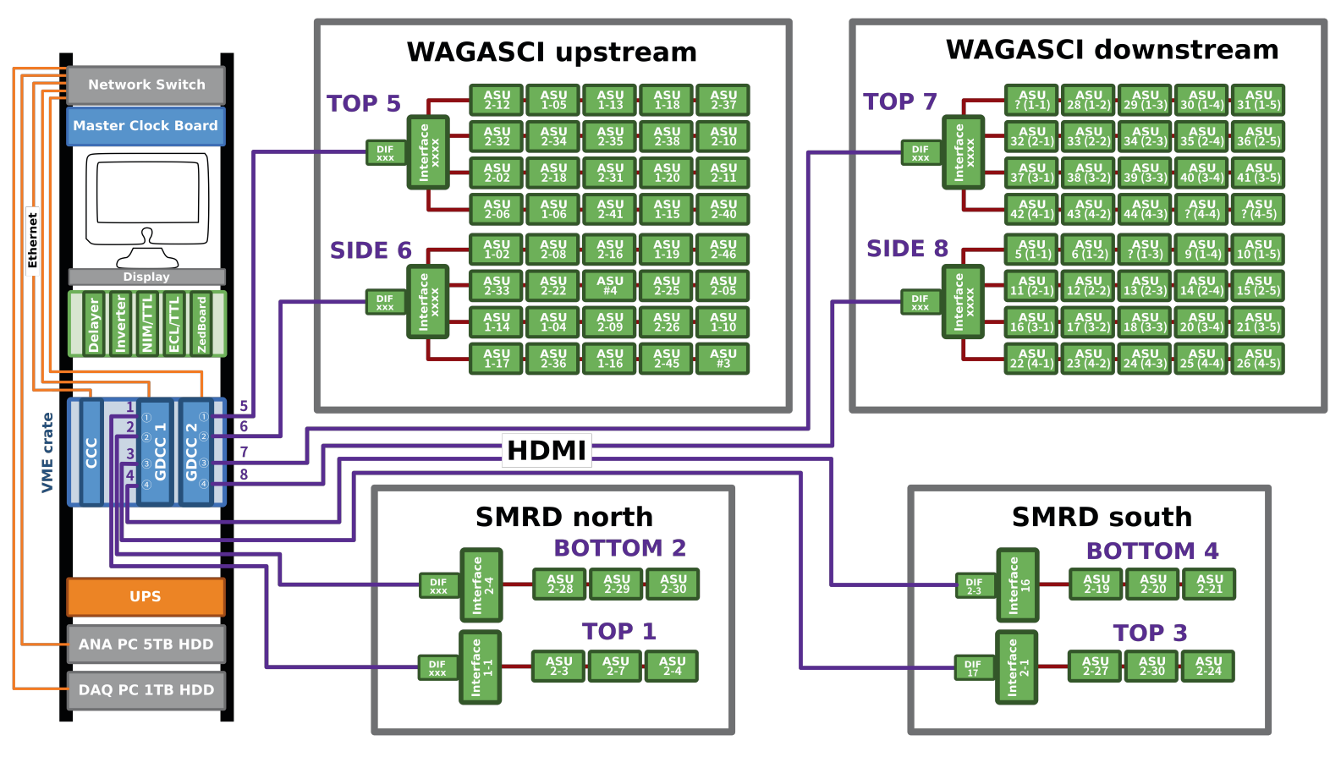
| Abbreviation | Detector | Purpose |
|---|---|---|
| WG | WAGASCI | water target |
| PM | Proton Module | carbon target |
| SM | Wall Muon Range Detector | non-magnetized muon spectrometer |
| BM | BabyMIND | magnetized muon spectrometer |
| NJ | NINJA | NINJA experiment |
| Wall | | B2 pillar |

### ELECTRONICS

The frontend chip for the WAGASCI and Wall-MRD detectors is called **SPIROC2D** and it was developed at the Omega laboratories at L'Ecole Polytechnique. It has been developed to match the requirements of **large dynamic range, low noise, low consumption, high precision and large number of readout channels needed**. SPIROC is an auto-triggered, bi-gain, 36-channel ASIC which can measure the charge from one to 2000 PEU (Photo Equivalent Unit) and the time with a 100ps accurate TDC.

### DAQ SOFTWARE : PYRAME

Pyrame is a fast prototyping framework for online systems. It provides basic blocks (called **modules**) for control-command or data acquisition. These blocks can be assembled together like LEGO to quickly obtain complete systems for testbenches and small experiments. The framework is **very flexible** and provides **lots of options**.



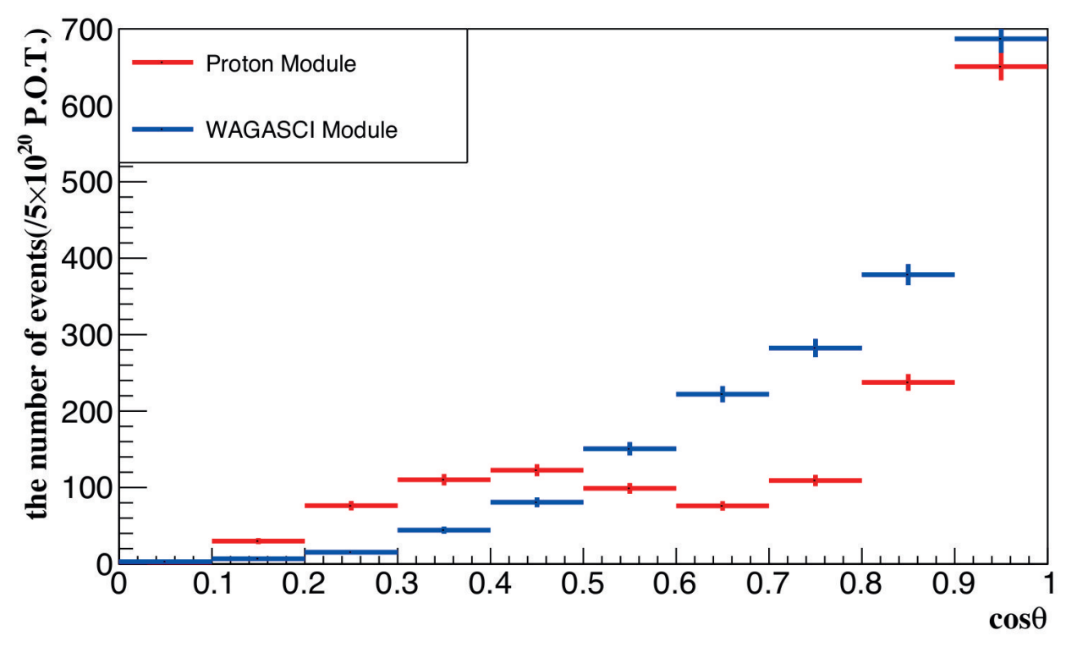
*Electronics and DAQ configuration for WAGASCI and SideMRD*

## Future analysis

### NUMBER OF EXPECTED EVENTS ($5 \times 10^{20}$ POT)

By a very conservative choice of the fiducial volume in the WAGASCI and Proton Module, we estimated the number of neutrino interactions whose escaping muon is **fully contained** in the Wall-MRD or BabyMIND.

We plan to **increase the fiducial volume** roughly by 50%. Moreover, by measuring the muon momentum in BabyMIND not only by range but also by curvature radius, we can lift the fully contained condition.

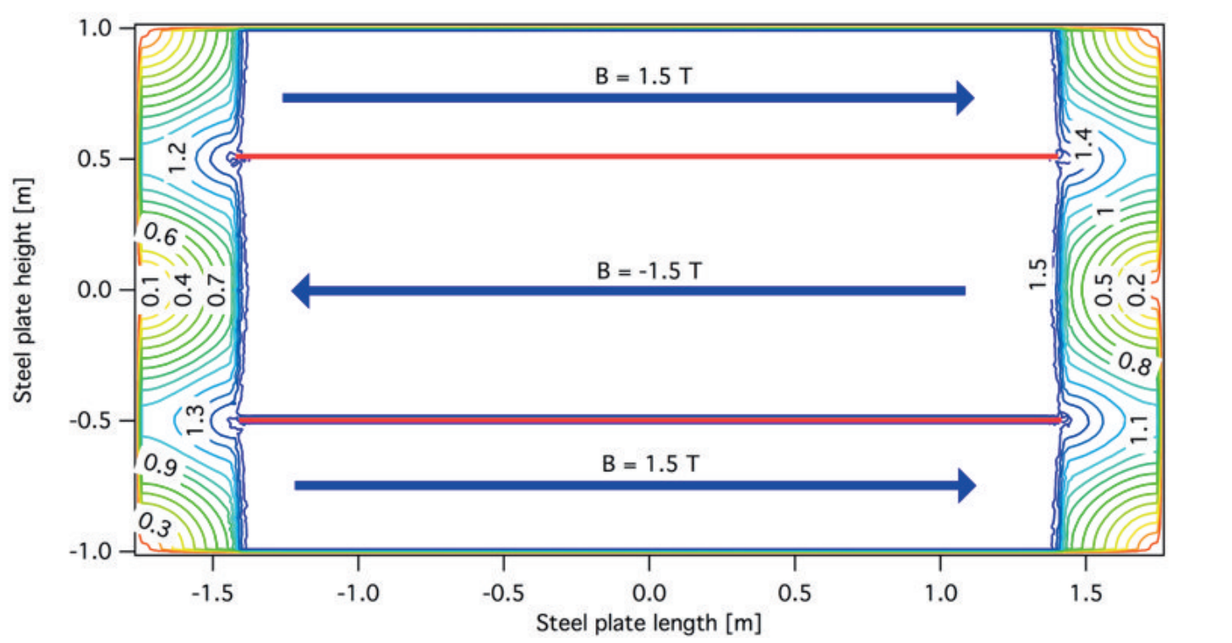


*Differential event rate (muon polar angle)*

### PARTICLE IDENTIFICATION IN BABYMIND

The wrong-sign component in the neutrino beam is significant and, especially in antineutrino mode, is as high as 30%. Therefore, μ charge ID is therefore crucial to control backgrounds.

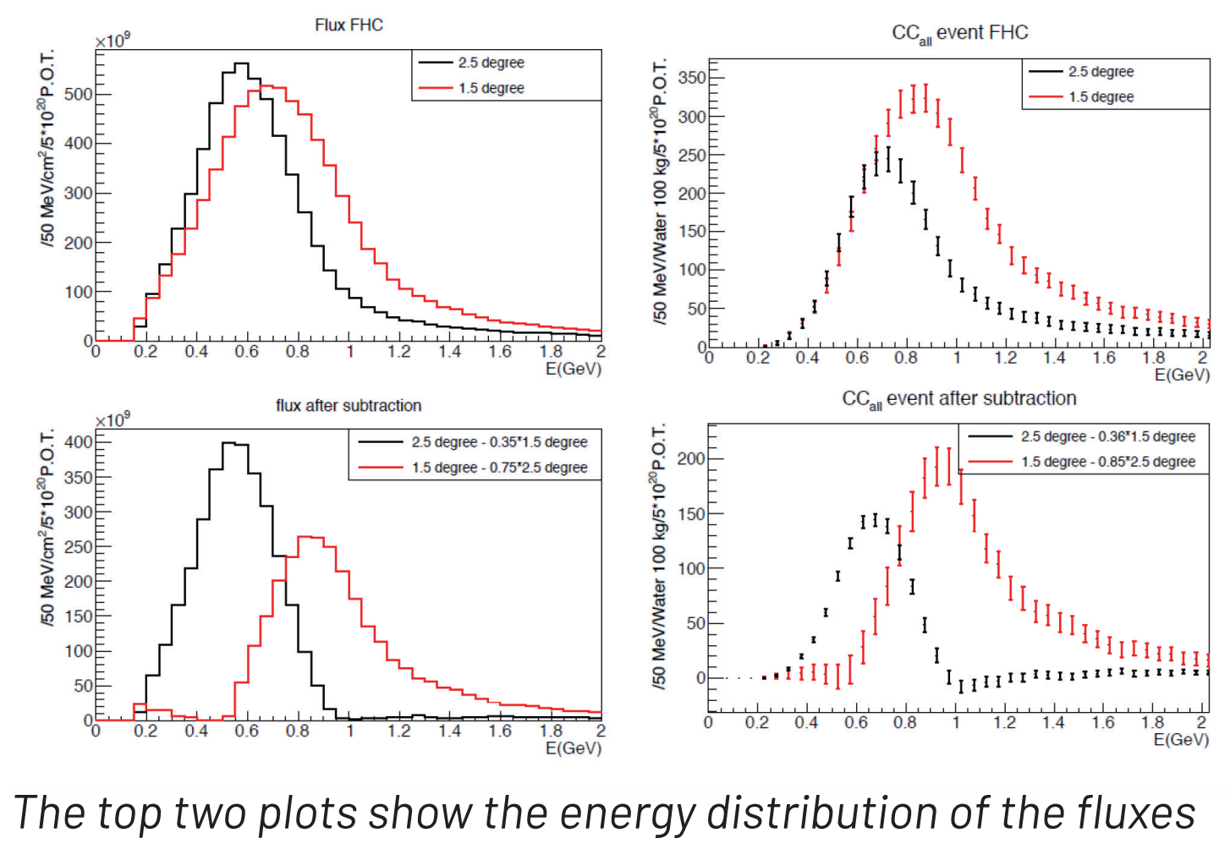
The magnetic field inside of BabyMIND is **not uniform nor continuous** so a precise measurement of the muon momentum is still an open problem. We are presently studying a **Kalman filter algorithm** to reliably reconstruct the muon momentum.



*Magnetic field contour map*

### MULTI-DETECTOR ANALYSIS

The off-axis method gives a **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° as opposed to 2.5° for ND280. The figure on the bottom-left shows the energy spectra of fluxes and neutrino interactions at these two locations and their difference. 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 sections for these two fluxes.



*The 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). The 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.*

**CREDITS:**
**BabyMIND** : Noah E., Favre Y., Parsa S. (Geneva U.) and Yasutome K.
**Commissioning** : Chikuma N. (Tokyo U.) and Kin K. (Osaka City U.)
**Conveners:** Minamino A. (YNU), Kikawa T. (Kyoto U.), Noah E. (U. Geneva)
**DAQ, calibration and analysis software** : Pintaudi G. (YNU) and Eguchi A. (Tokyo U.)
**Detector location and construction** : Asada Yuki (YNU)
**Electronics development** : Omega lab. (Ecole Polytechnique)
**Electronics testing** : Matsushita Kohei (Tokyo U.)
**Pyrame** : LLR lab. (Ecole Polytechnique)
**Simulations** : Kikawa T. and Yasutome K. (Kyoto U.)