Operational Status and Timing Performance of the WAGASCI–BabyMIND Detector in the T2K Experiment

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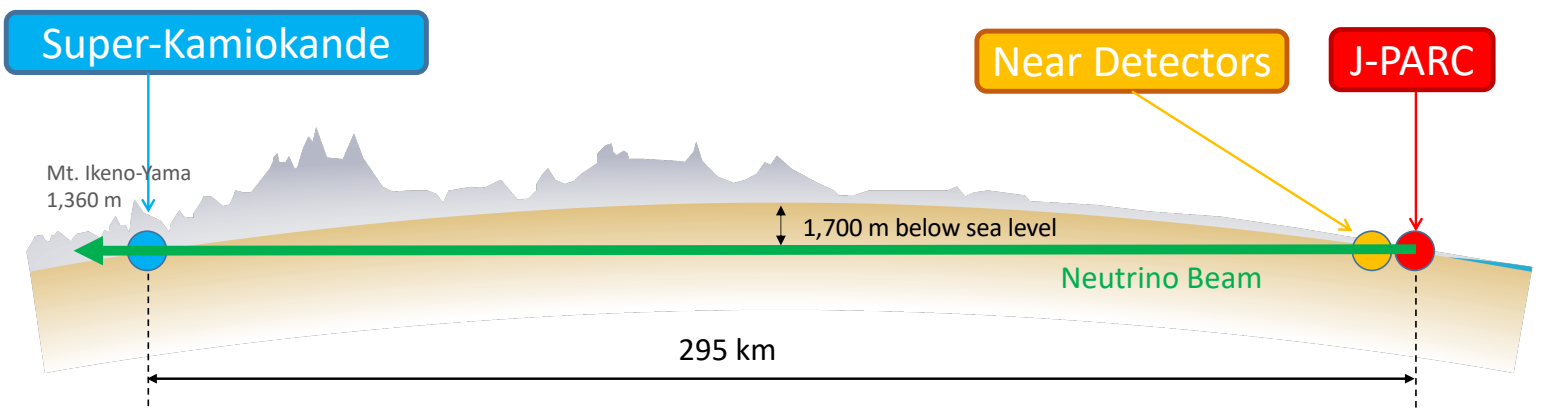
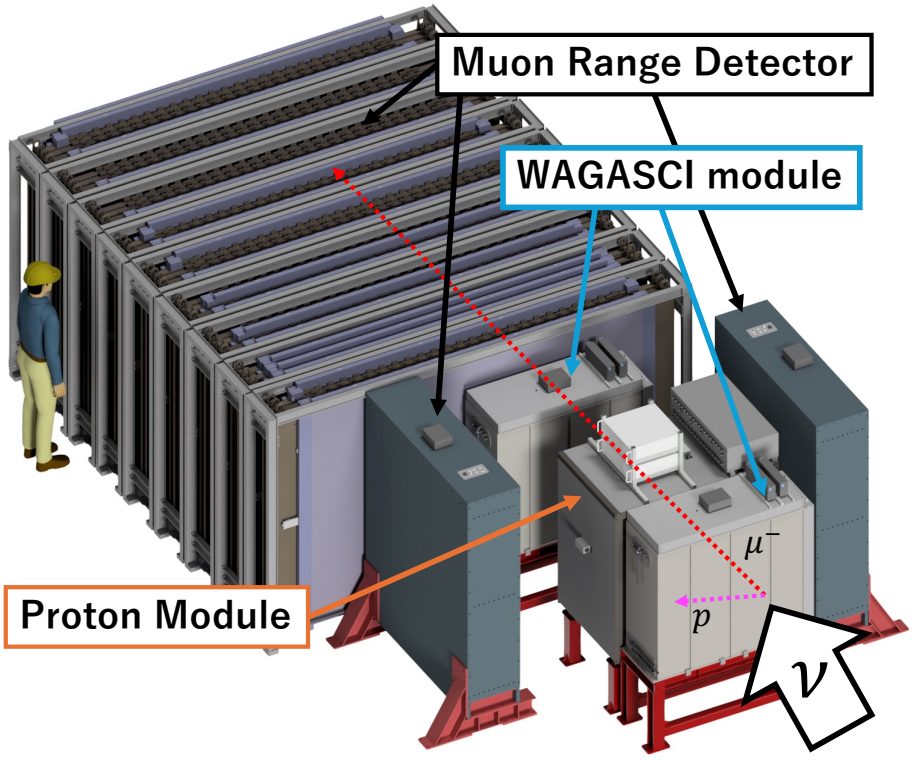
The T2K experiment

- Long-baseline neutrino oscillation experiment
  - Generate neutrino at J-PARC and detect them at Near Detectors and Super-Kamiokande.
- Search CP violation by measuring the difference between
  - $P(\nu_\mu \rightarrow \nu_e)$
  - $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$
- Main systematic uncertainty: neutrino interaction uncertainties



WAGASCI-BabyMIND detector

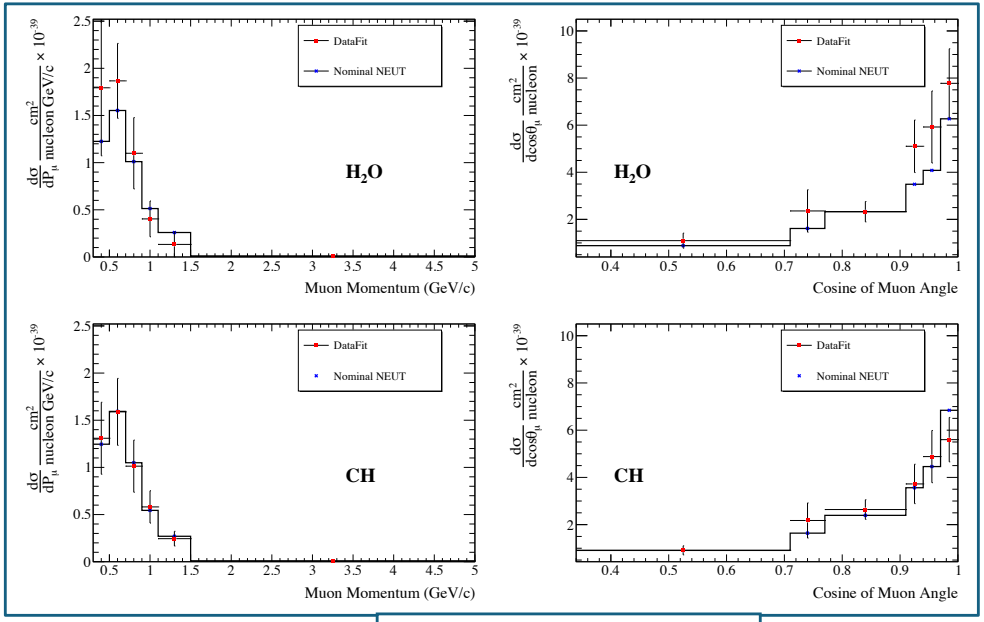
- One of near neutrino detector
- **Goal**: Precise measurement of neutrino interactions on water target
- WAGASCI module
  - Target: Water
  - Water-to-CH mass ratio: 4:1
- Proton module
  - Target: CH
  - Measure neutrino interaction on CH target to extract this from WAGASCI measurement.
- Muon Range Detector
  - Iron–scintillator sandwich structure
  - Measures muon momentum and angle.



WAGASCI-BabyMIND detector

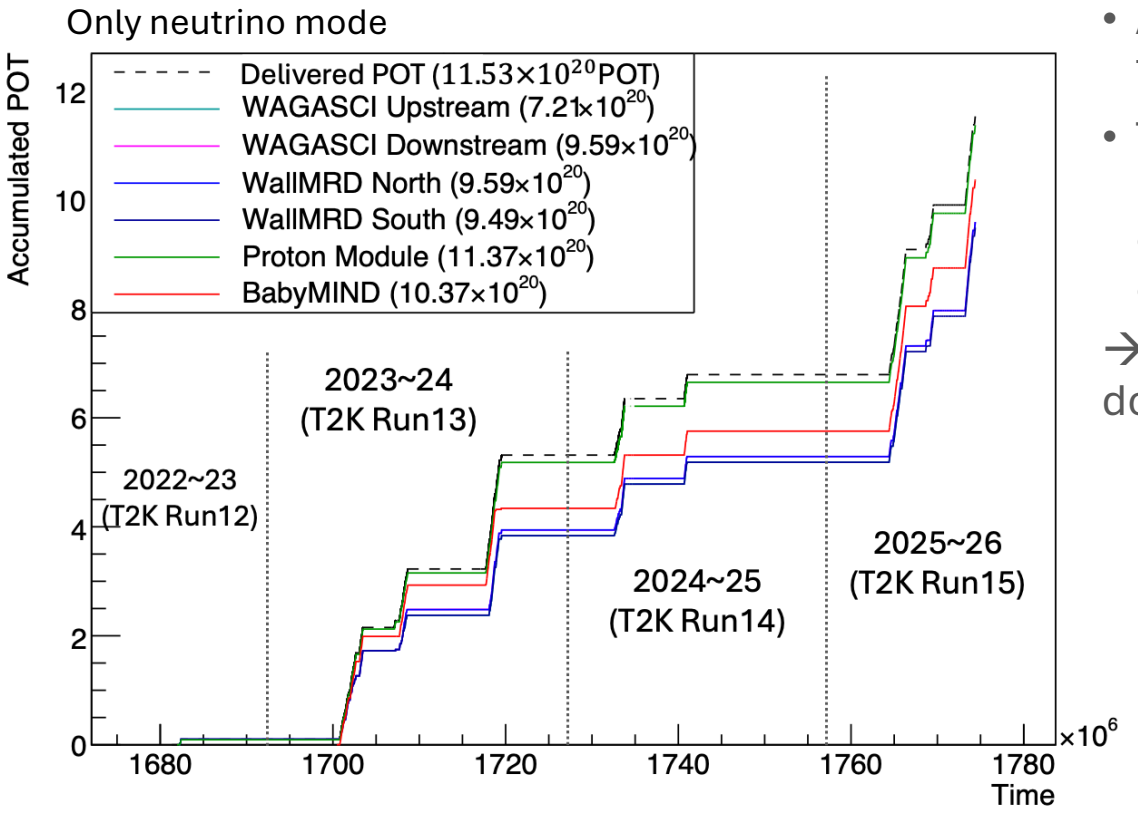
- Data taking started in 2019.
- ν_μCC0π cross section on water and hydrocarbon target was measured. (Phys. Rev. D **112**, 112020)
- Used 2019~2021 data, 2.96×10^{20} POT.
- **Stat. error was dominant.**

- Data acquisition has been ongoing to date.
- Aim to measure cross section more precisely using a larger number of statistics.



Phys. Rev. D **112**, 112020

2022-2026 operation status



- Acquired neutrino beam data from 2022 to 2026.
- The amount of data to be newly added to the physics analysis is expected to be approximately 9.0×10^{20}POT

→ Next measurement will be done using ~12×10^{20} POT

- WAGASCI's DAQ experienced a long period of instability, resulting in low data acquisition efficiency.
- In recent years, stable operation has been achieved.

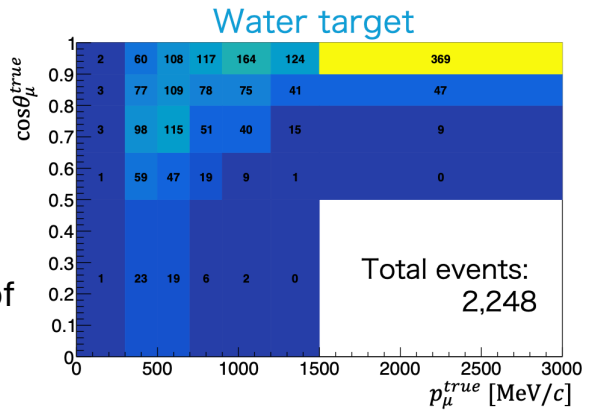
Prospects

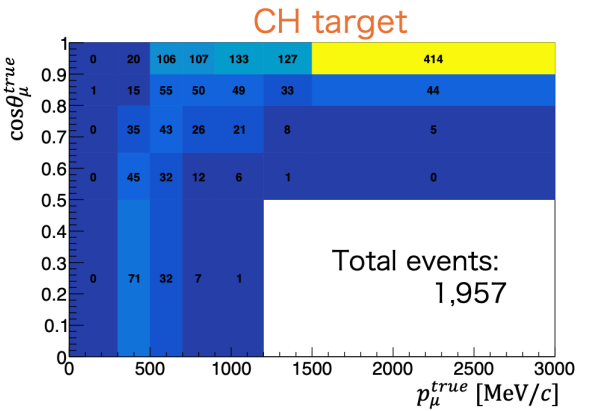
- Approximately 12×10^{20} POTs data are available for physics analysis. This is about **4 times larger** than previous measurement.
- This will likely allow for the measurement of **the ν_μCC0π double differential cross-section**.

$$\frac{d^2\sigma}{dp_\mu d\theta_\mu}$$

- **First measurement of ν_μCC1π** on H_2O and CH target is also planned.
- Enough signal events for measurement is predicted.

Predicted number of CC1π events



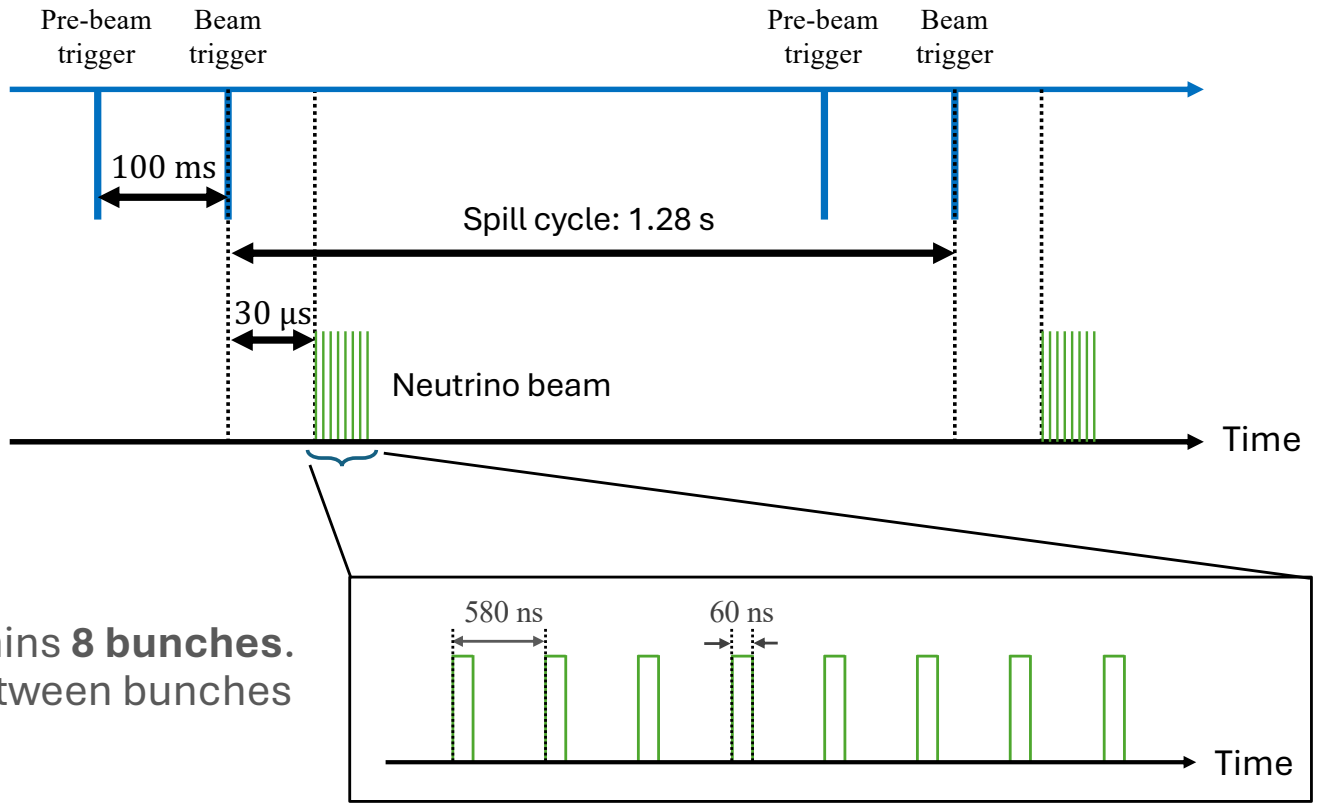


WAGASCI timing calibration using laser

J-PARC neutrino beam

- One spill is delivered every **1.28 s**
- A **beam trigger** is issued **30 μs before** the neutrino beam and distributed to each detector

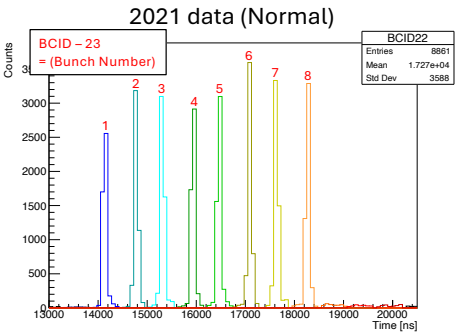
→ Neutrino detector acquires data for one spill per one trigger

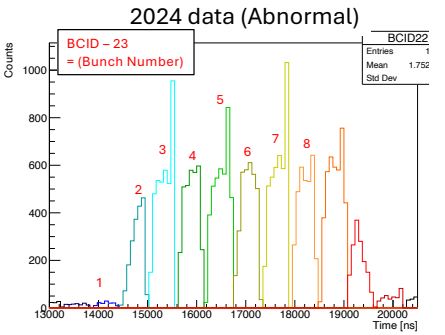


- One spill contains **8 bunches**. The interval between bunches is **580 ns.**

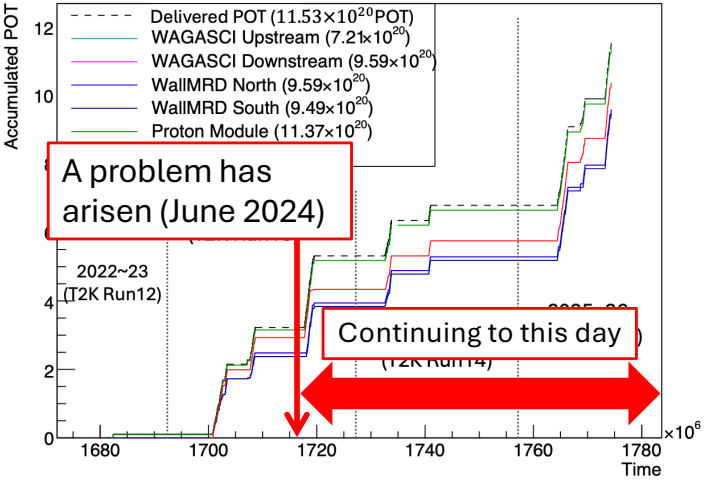
WAGASCI timing issue

- When the detector receives a beam trigger, a signal is issued within the detector to begin data acquisition.
- This signal fluctuates **about 1 μs** event-by-event.
- 8-bunch structure is smeared by this fluctuation.



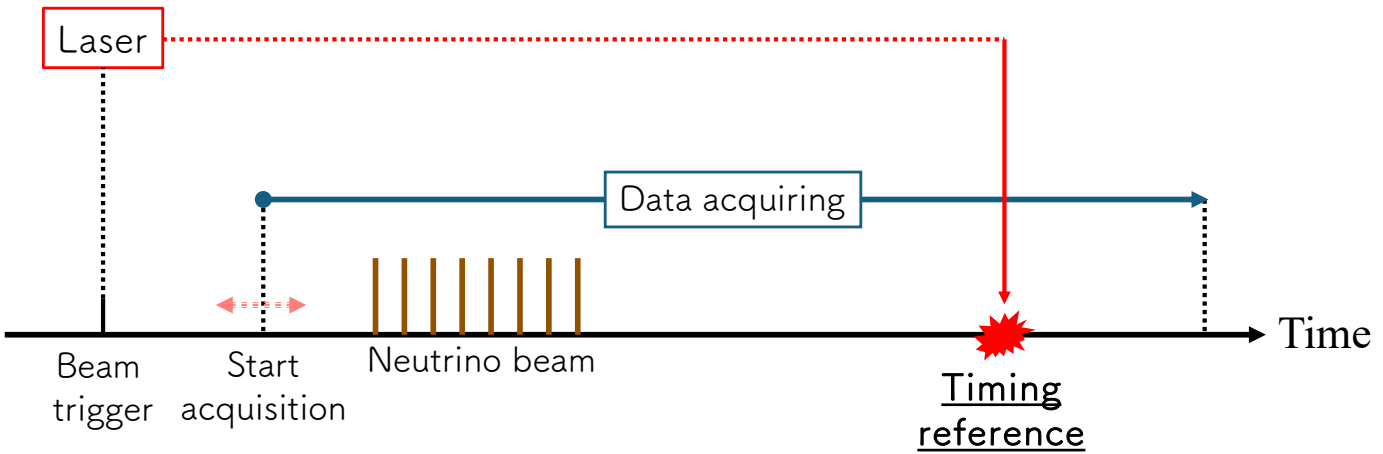


- This issue started with data from June 2024.
- A fundamental solution has yet to be found.
- **Physics analysis is possible**, but the probability of incorrect connection of tracks between each sub-detectors increases.



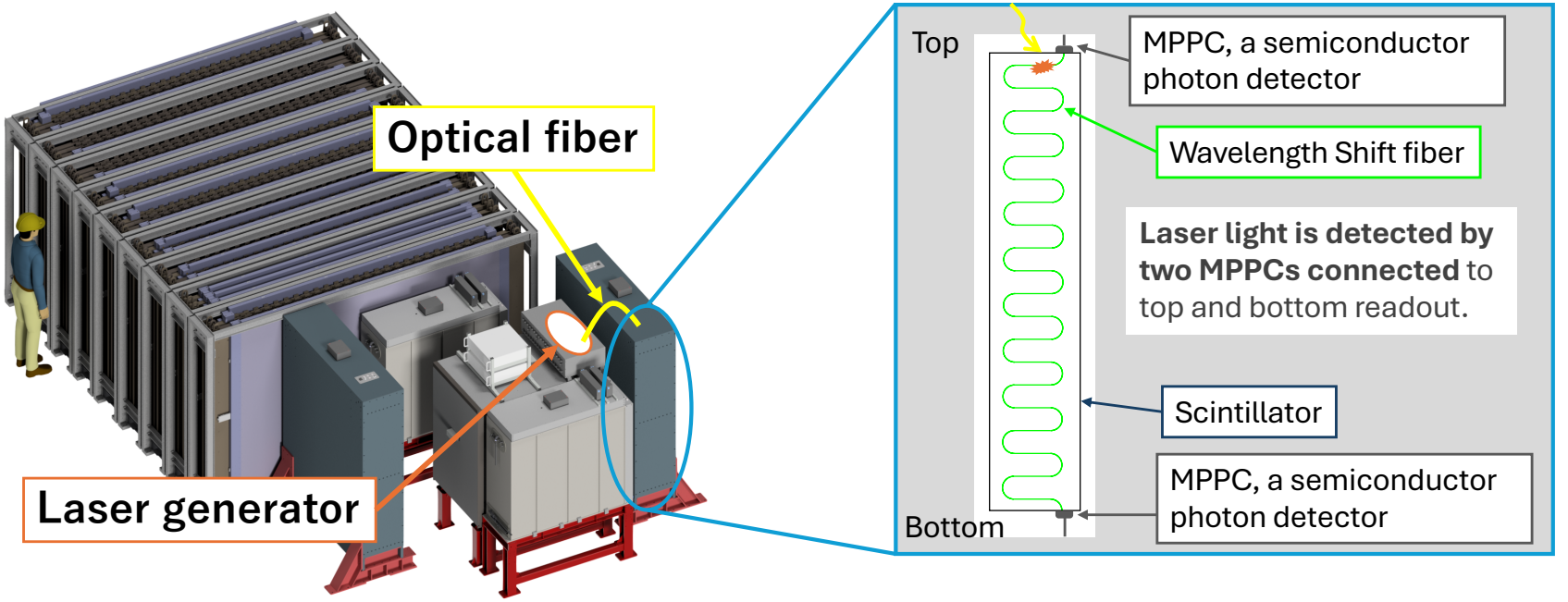
Laser-based timing calibration

- A countermeasure for timing issue is proposed.
- Install a picosecond pulse laser and emit lights in synchronization with the beam trigger so that the laser beam can be detected by the detector.
- The detection time of the laser pulse is used as the reference for the time information in each spill.



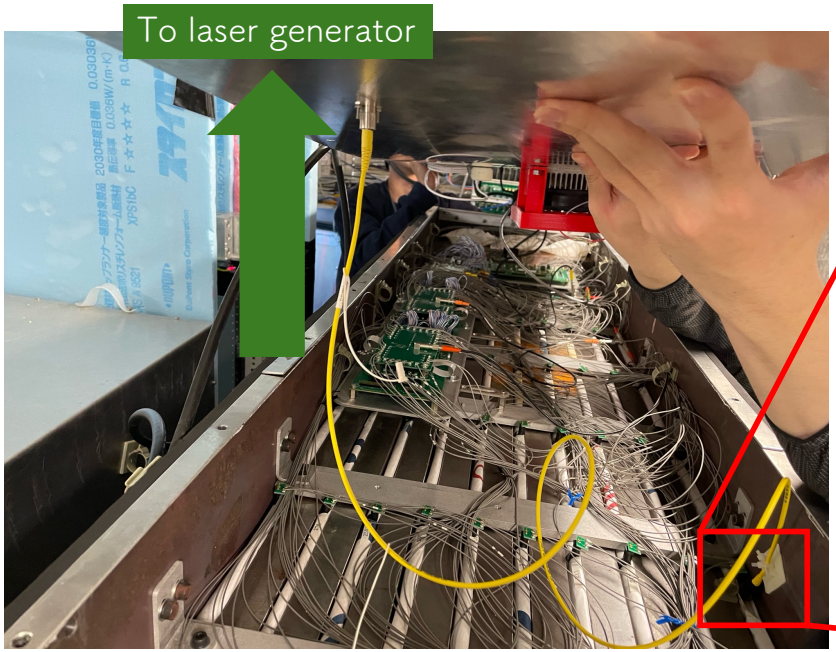
Laser installation

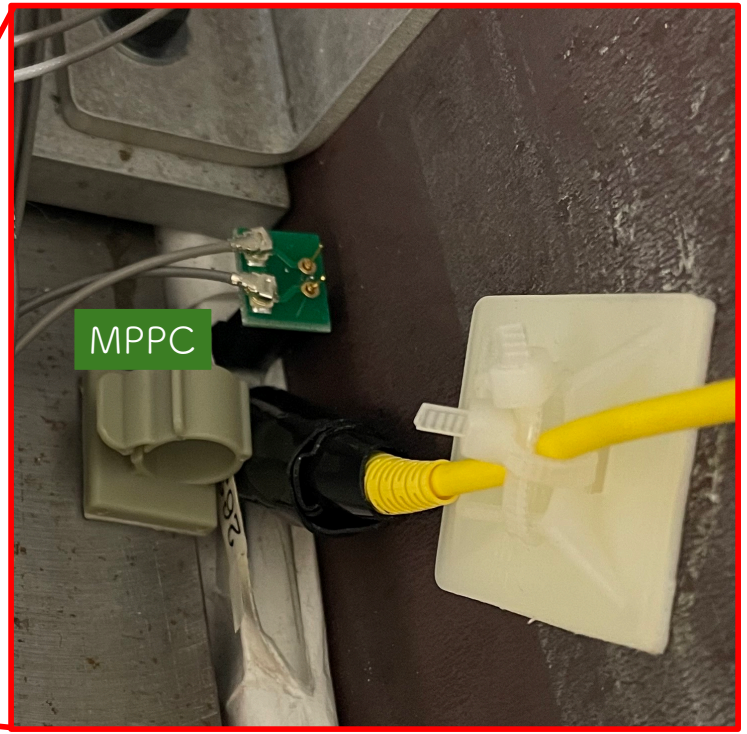
- As a commissioning test, laser light was injected only into the north Wall MRD
- The end of an optical fiber guiding the laser was installed inside the top electronics box
- Laser light was directed toward wavelength-shifting fibers embedded in the scintillator
- The signal was detected by two MPPCs located at the top and bottom



Laser installation

<View inside the electronics box at the top of WallMRD>
The tip of optical fiber is close to MPPC (light detector.)





Timing correction

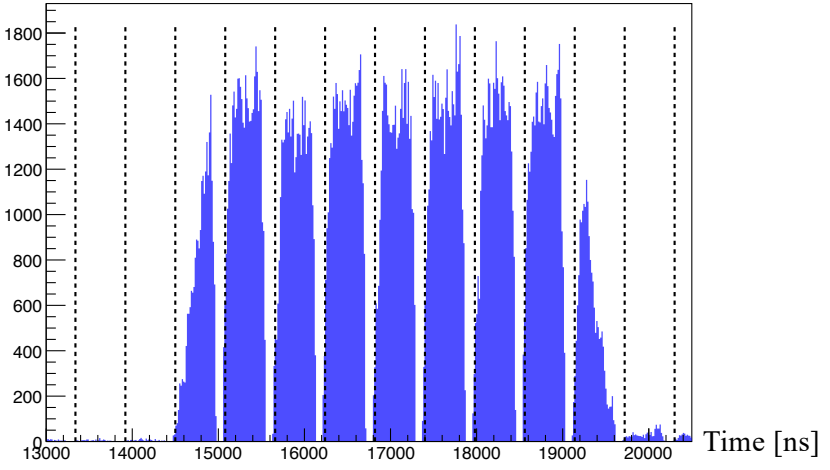
- 8-bunch is restored.

<Problem>

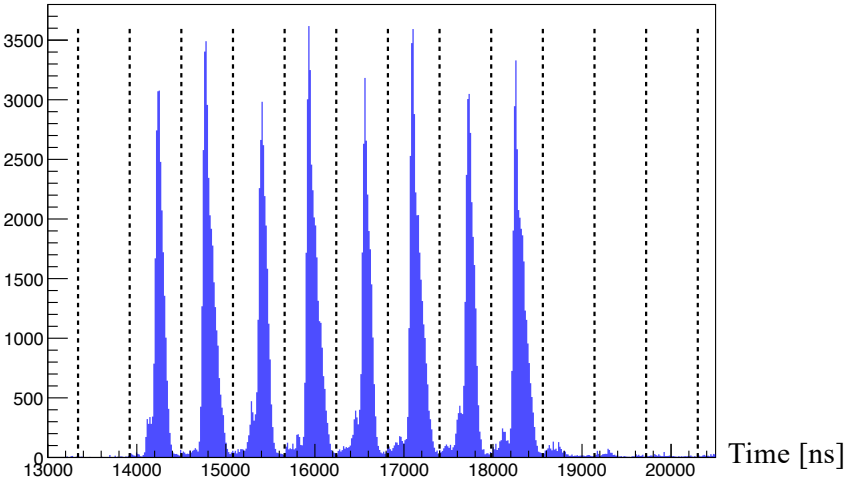
- The WAGASCI DAQ has periodic dead times where the TDC cannot be recorded.
- When the laser signal enters this period, time correction is not possible in that spill.
- As a result, this time calibration is not be applicable to approximately **25%** of spills.

→ Possible countermeasure: Inject the light 3 or 4 times in one spill. It is unlikely that all pulse enter a dead time.

Before correction



After correction



Summary

- WAGASCI-BabyMIND is one of T2K near neutrino detector.
- Goal is precise measurement of cross section on water target.
- The previous measurement lacked sufficient statistics, so we continued to collect data. Acquired approximately 12×10^{20} POT so far.
- Double differential cross section measurement of ν_μ CC0π and ν_μ CC1π is planned.

- A hardware issue that occurred in June 2024 is causing timing jitter, making bunch identification impossible.
- By using laser time information as a reference, 8 bunches could be recovered.
- If the laser hit time could not be recorded, time correction was not possible.

→ Possible countermeasure: Inject the light 3 or 4 times in one spill. It is unlikely that all pulse enter a dead time.