R&D towards ND280++ a new near detector for the Hyper-K precision phase era

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on behalf of the D_RD_41 project

Joint Workshop of TYL/FJPPN and FKPPN

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Outline

- Neutrino oscillation
- Hyper-Kamiokande experiment
- Overview of ND280++
- Development of 3D-segmented water-based liquid scintillator detector

Neutrino oscillation

- Flavor of neutrino $(\nu_e, \nu_\mu, \nu_\tau)$ changes periodically as it propagates.
- Described by mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$, mass squared differences $\Delta m^2_{21}, \Delta m^2_{32}$, and a CP phase δ_{CP}.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

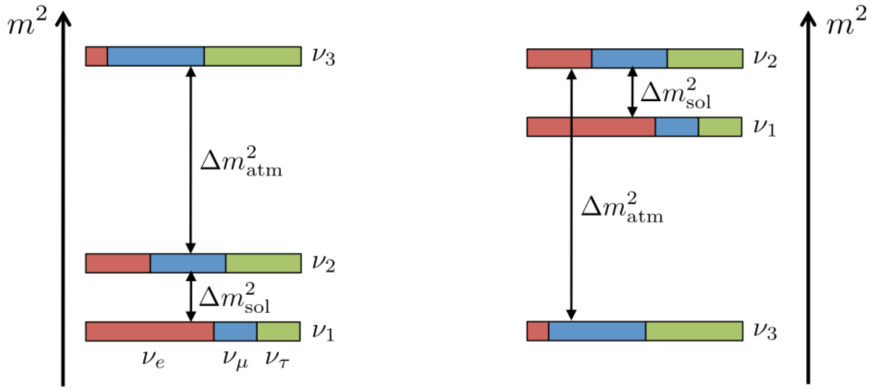
Flavor eigenstates

Pontecorvo–Maki–Nakagawa–Sakata matrix

Mass eigenstates

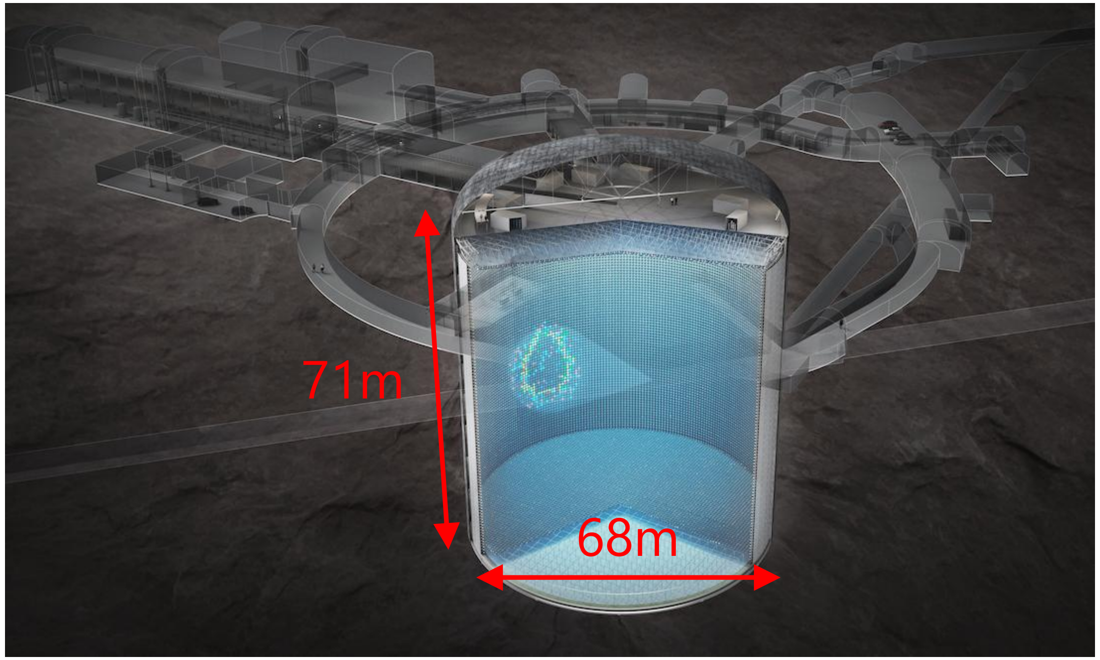
- Remaining questions.
  - Is $\sin\delta_{CP}$ non-zero? (CP violation in lepton?)
  - Is θ_{23} 45°? (maximal mixing? octant?)
  - Normal ordering ($m_3 > m_2 > m_1$) or inverted ordering ($m_2 > m_1 > m_3$)?

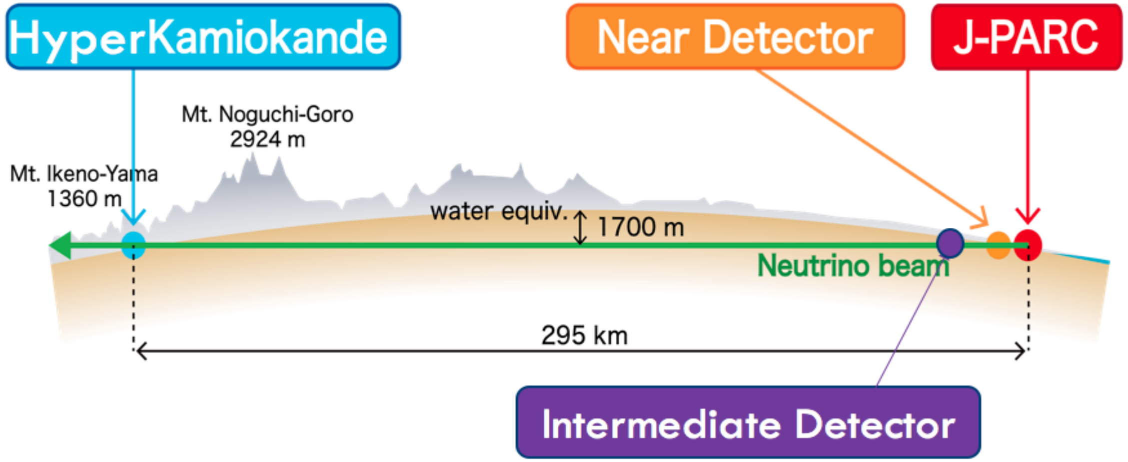
Normal Ordering (NO) **Inverted Ordering (IO)**



Hyper-Kamiokande experiment

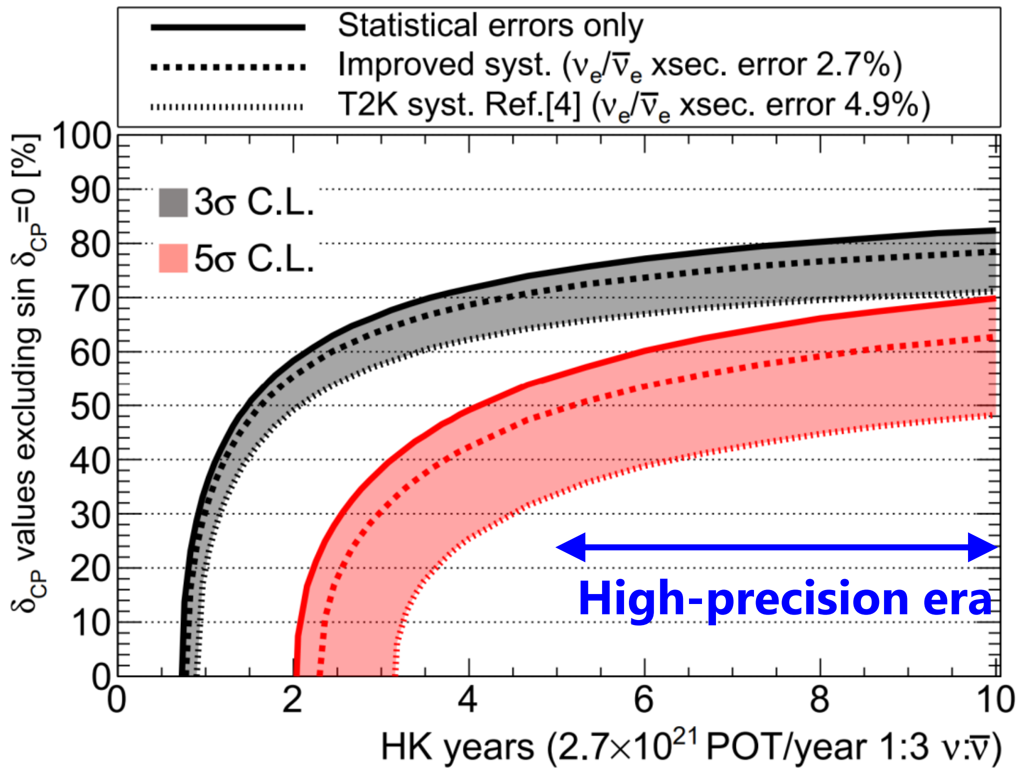
- Hyper-Kamiokande detector
  - 600m underground at Kamioka
  - Fiducial volume: 188 kton (×~8 SK)
  - 20,000 PMTs with 50cm diameter
  - ~800 multi-PMT modules
- J-PARC neutrino beam with upgraded power (1.3 MW).
- Near detectors (INGRID and ND280) at 280m inherited from T2K.
- Intermediate water Cherenkov detector at 1km.

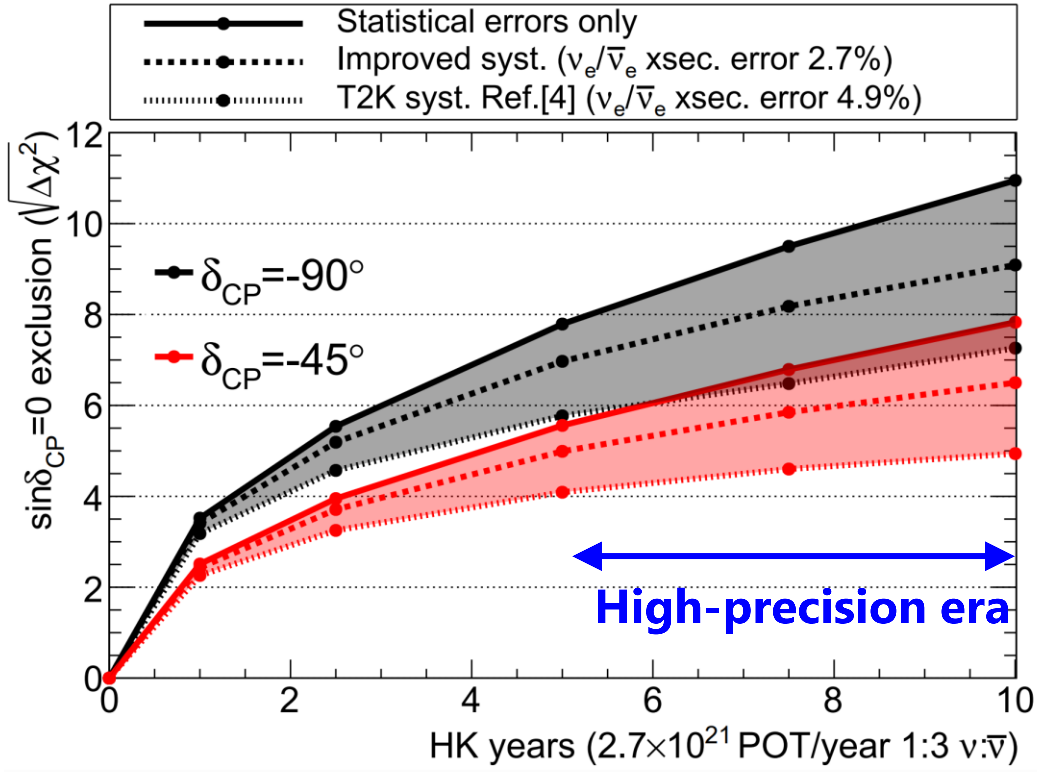




Hyper-Kamiokande oscillation sensitivity

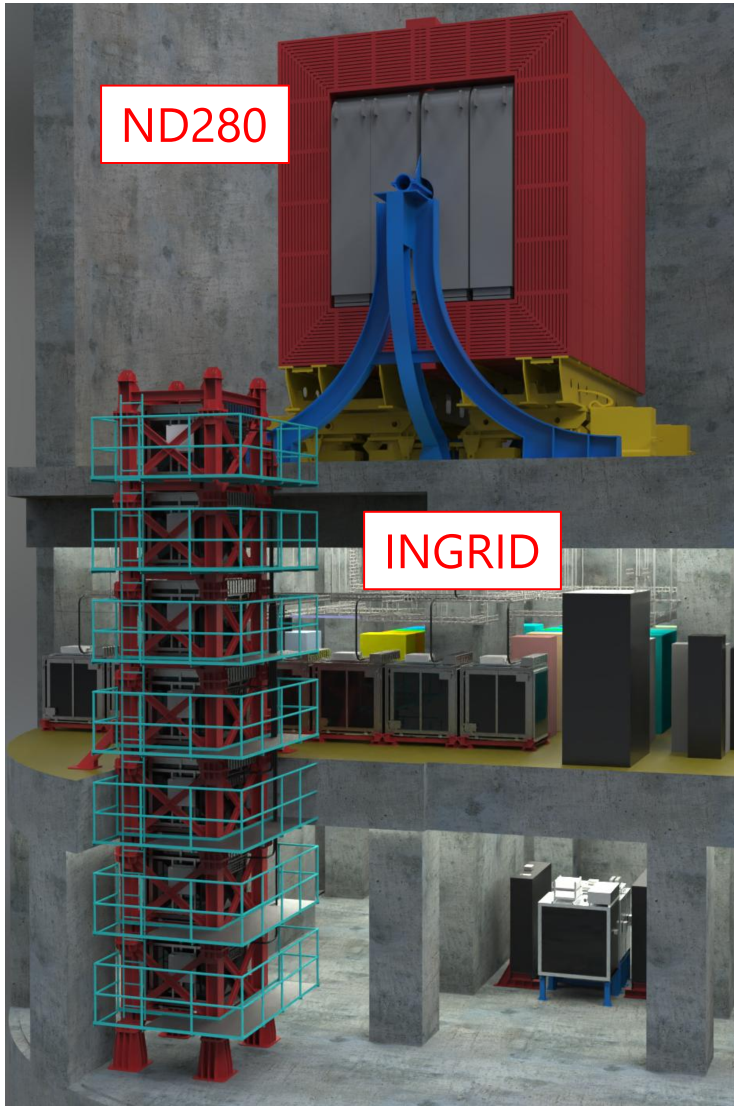
- If CP violation is large ($|\sin\delta_{CP}| > 1/\sqrt{2}$), it may be discovered within 5 years.
- If it is small ($|\sin\delta_{CP}| < 1/\sqrt{2}$), reduction of systematic errors will be a key.
- Goal of our project (ND280++) is ultimate reduction of systematic errors.





Near detectors

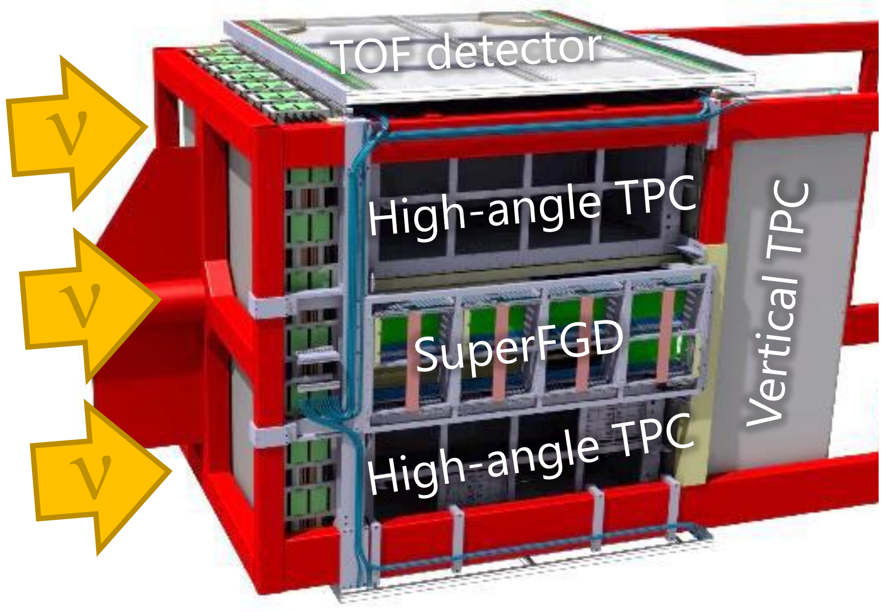
- INGRID (on-axis)
  - 14 identical modules arranged in a cross shape.
  - Measure neutrino beam direction and stability.
- ND280 (2.5° off-axis)
  - Scintillator trackers + TPCs and ECals in 0.2 T magnetic field.
  - Precisely measure neutrino beam spectra before oscillation and neutrino interactions.
  - Upgraded in 2023-2024.
- Will be inherited from T2K and will play a complementary role with IWCD.



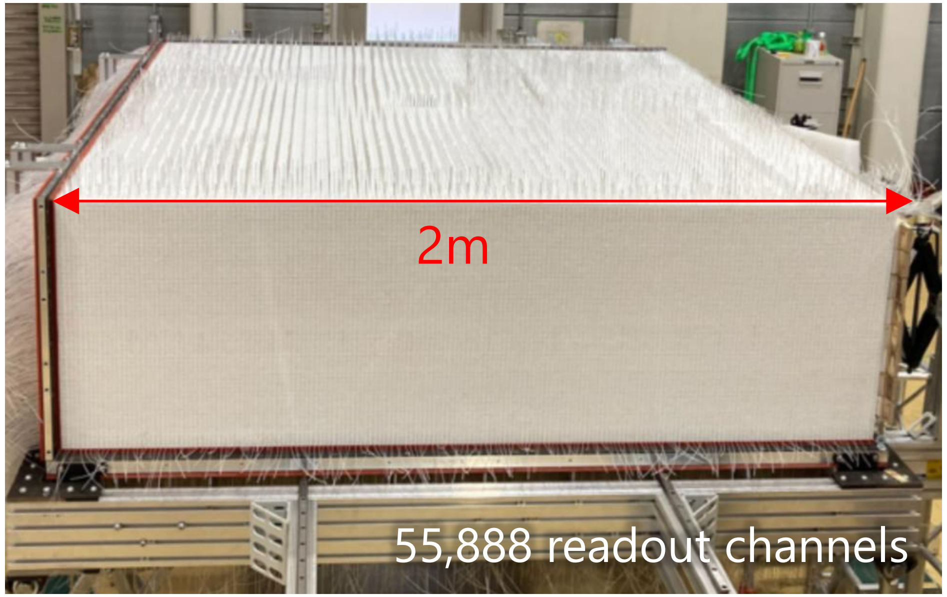
ND280 upgrade in T2K

- Upstream part of ND280 was replaced by new detectors in 2023-2024.
  - SuperFGD: 2 million scintillator cubes with WLS fiber and SiPM readout.
  - High-angle TPCs: Precisely measure high-angle particles from SuperFGD.
  - TOF detectors: Provide 150 ps time resolution.

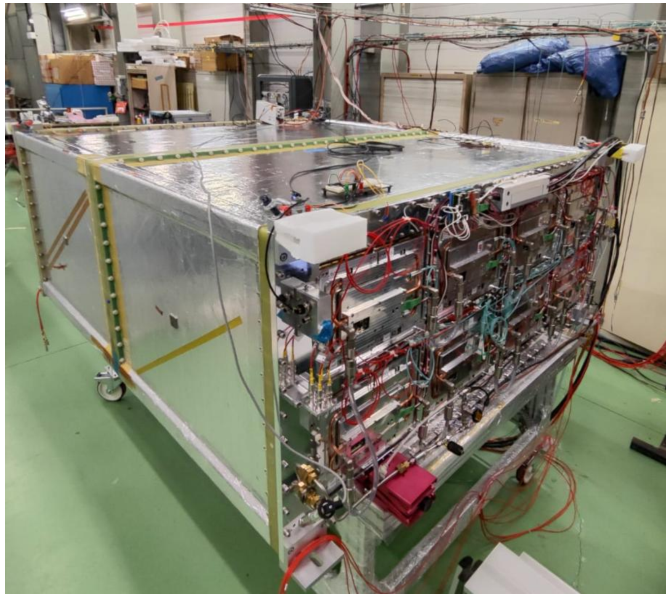
ND280 upgrade



SuperFGD scintillator cubes under assembly



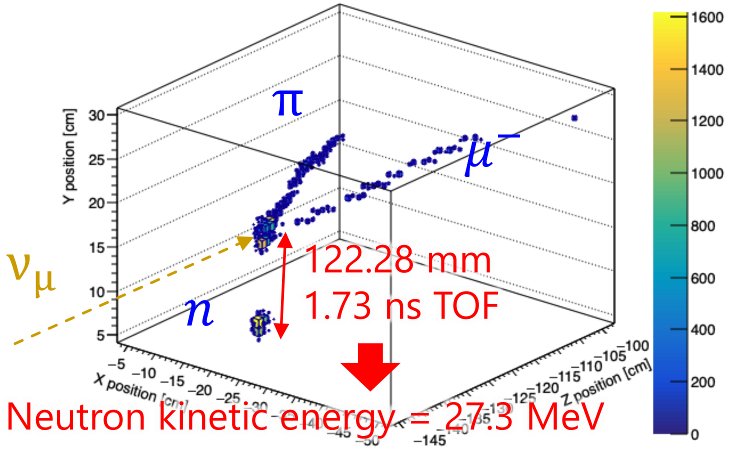
High-angle TPC



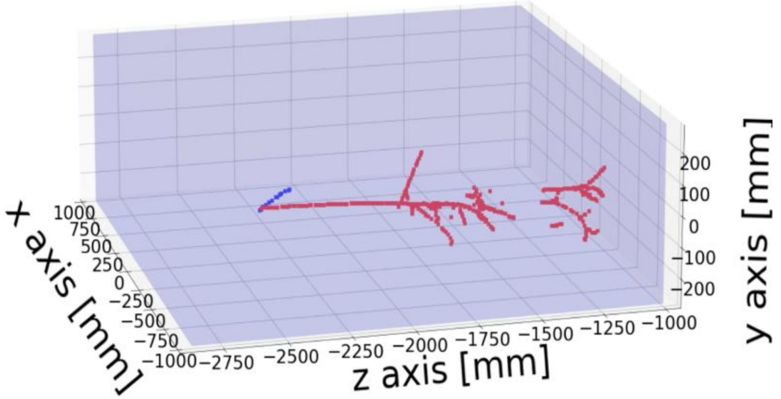
Expected performance of upgraded ND280

- 4π acceptance and sensitive to even neutron or low-momentum protons.
- ν_e can be precisely measured with low background.
- But interaction target is hydrocarbon while HK detector uses water.
- Precise measurement of $\nu_e/\bar{\nu}_e$ cross section with water target with more statistics will be critical in HK high-precision era.

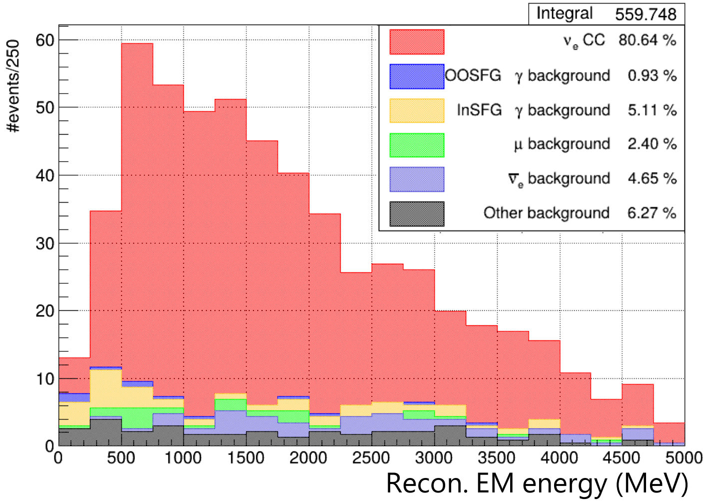
Candidate of ν_μ CC event with one neutron in beam data



Candidate of ν_e CC event with EM-shower in beam data



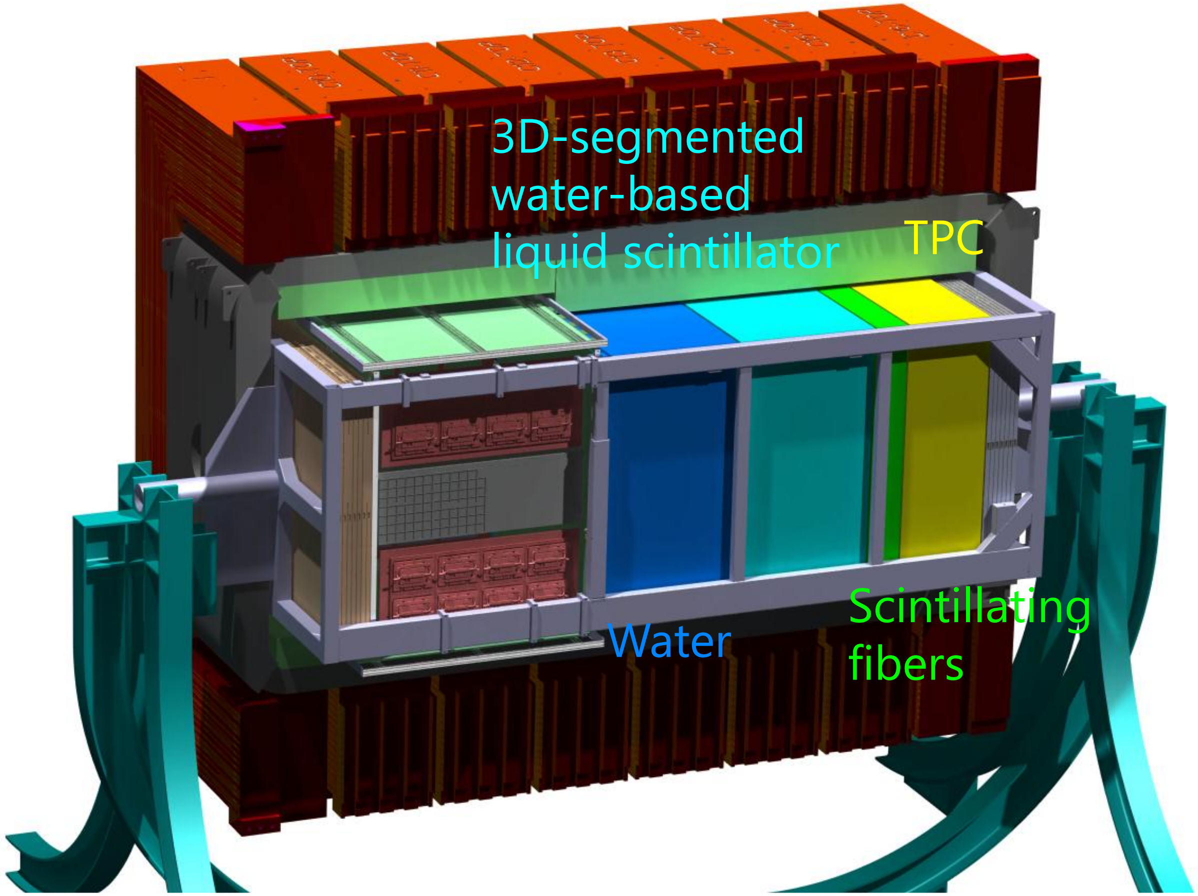
Reconstructed EM energy for ν_e CC sample with EM-shower PID



ND280++ project

- Replace the downstream part of ND280 to several-tonne water-target detectors for the HK high-precision era after 2030.
- Current reference design includes:
  - ~ 4.5 tons of 3D-segmented water-based liquid scintillator detector
  - ~ 4.5 tons of inactive water
  - ~ 1 ton of scintillating fibers
  - 1 TPC
- R&D is actively ongoing.

Reference design of ND280++

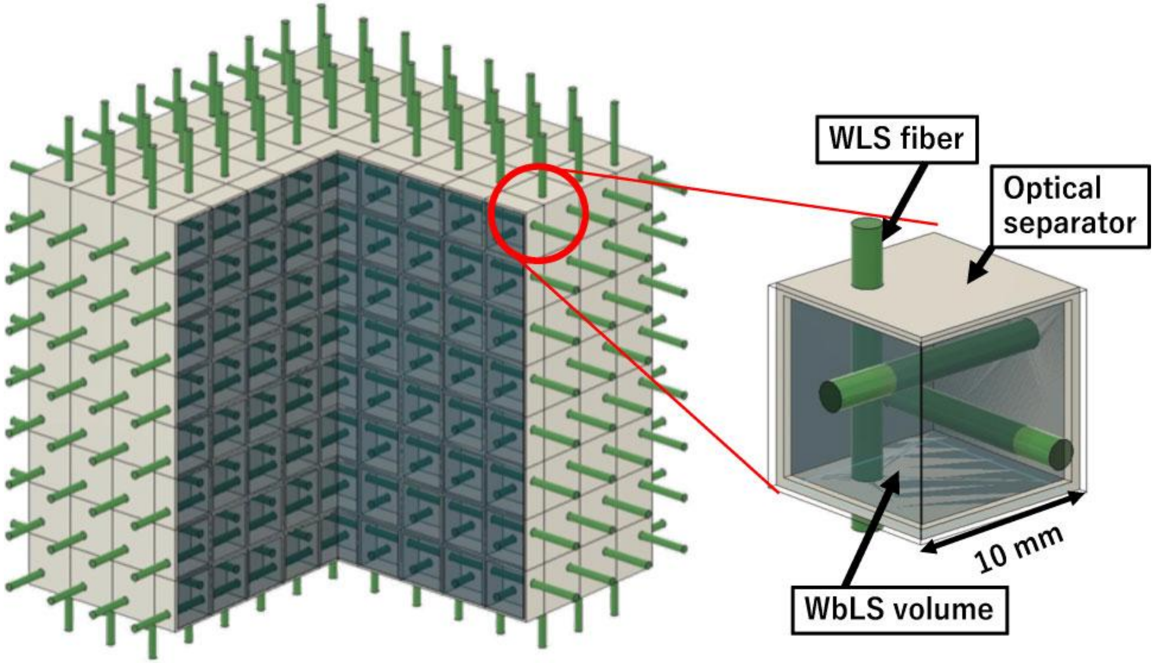


3D-segmented water-based liquid scintillator detector

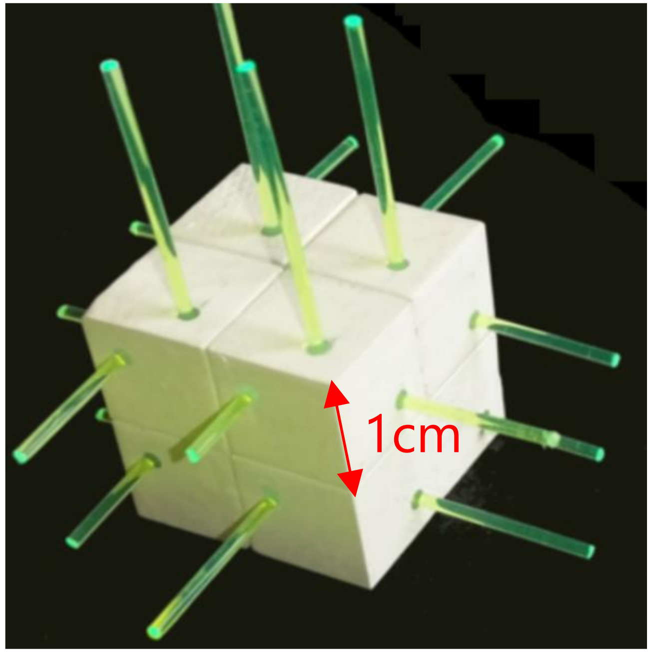
- Optically separate water-based liquid scintillator (WbLS) to $1cm^3$ cells by 3D-grid reflector and read out light in 3D by WLS fibers and SiPMs.
- Enables precise measurements of particles from neutrino interactions, as in SuperFGD, while using water as the main target.

WbLS and water exposed to UV

3D-segmented WbLS detector



SuperFGD scintillator and fiber



LPNHE and Kyoto joint development

- Development of 3D-segmented WbLS detector is ongoing as a joint project between LPNHE-Paris and Kyoto University.
- LPNHE-Paris (France): C. Giganti, D. Ferlewicz, R. Gaior, E. Hily, M. Antonelli
- Kyoto University (Japan): T. Kikawa, T. Nakaya, J. McKean, K. Hayashi
- So far, work at LPNHE has been supported by an ANR PRCI grant in collaboration with ETH Zurich, while Kyoto University has been supported by MEXT KAKENHI Number JP22K14058, JP24K00644.

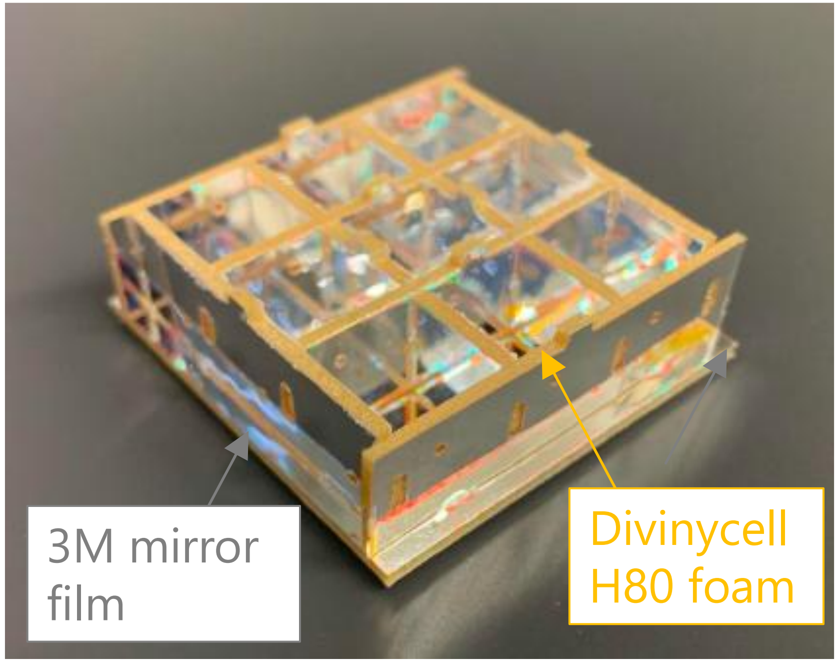
LPNHE PARIS

KYOTO UNIVERSITY

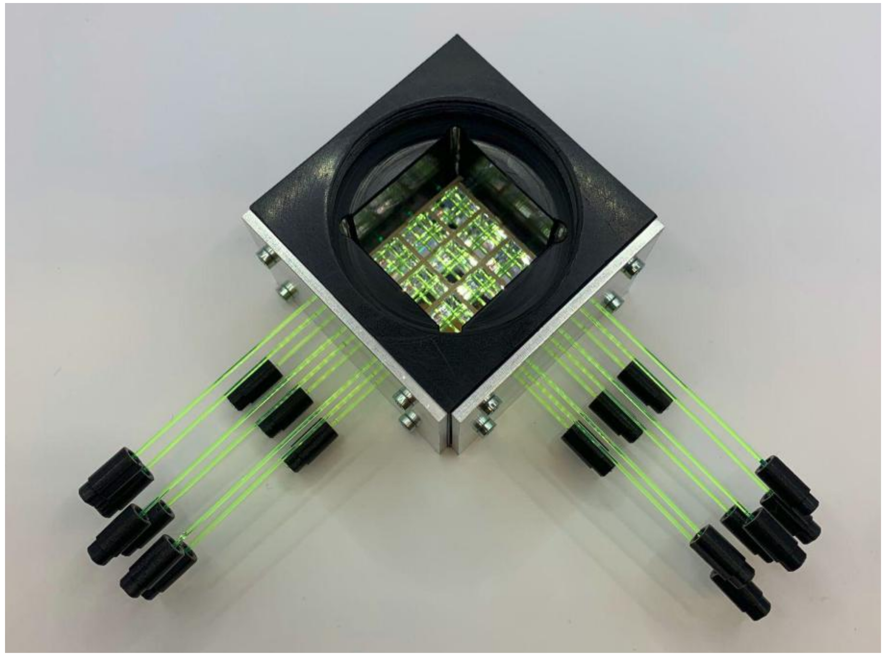
Development in LPNHE in collaboration with ETH Zurich

- Using WbLS invented by M.Yeh (BNL) with base composition of 90% water, 10% LS (LAB+PPO+MSB) by weight.
- Lightweight and high reflectivity optical reflector was developed with a sandwich structure of 3M mirror films and Divinycell H80 foam.

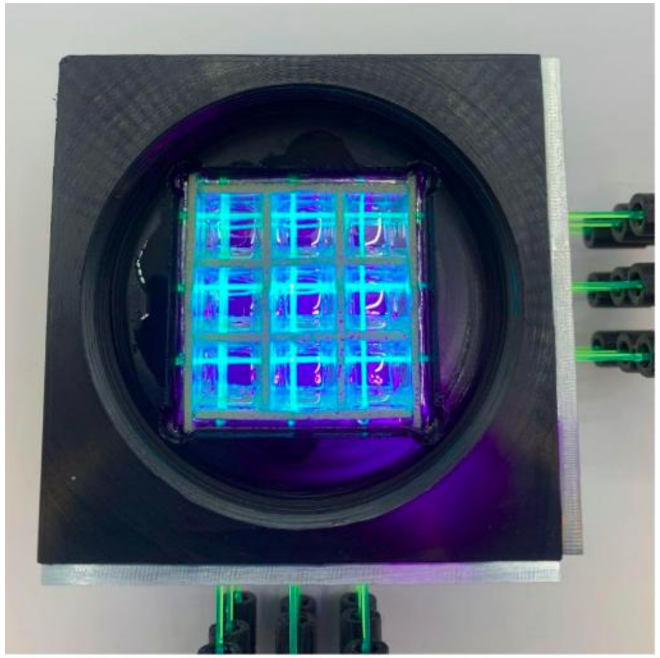
Lightweight optical reflector



Sealed dark box with one layer of WbLS



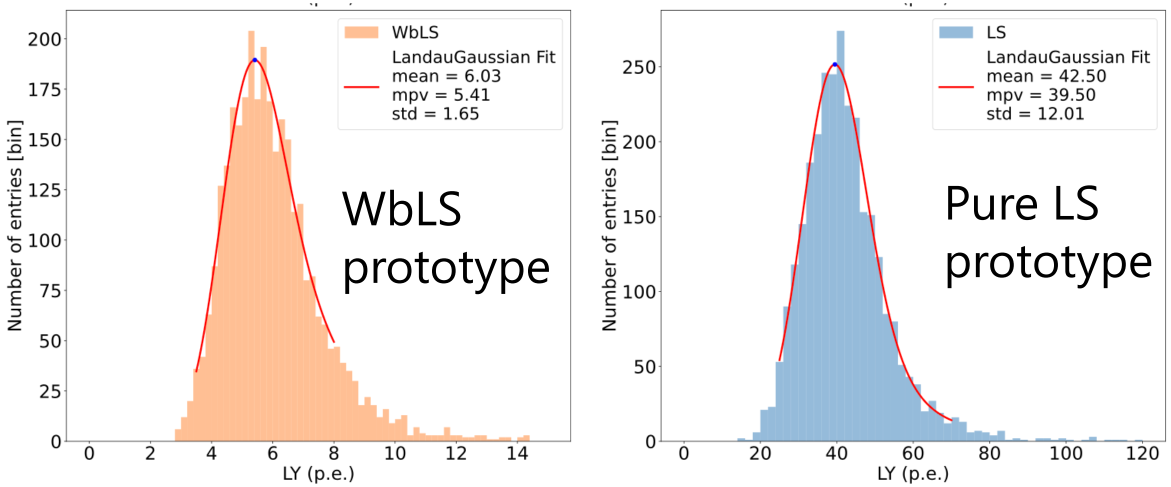
Completed prototype



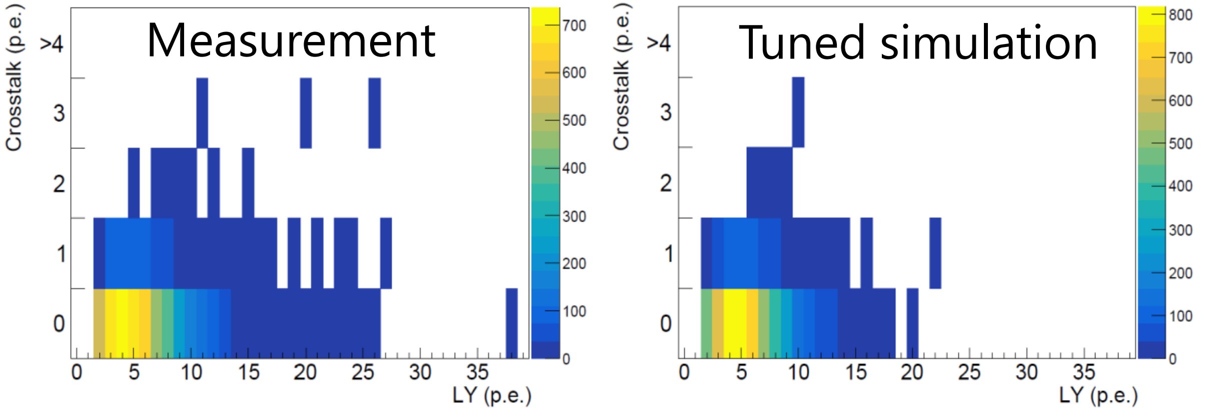
Development in LPNHE in collaboration with ETH Zurich

- Light yield was lower than pure LS but consistent with expectation from LS density.
- Optical crosstalk was small enough.
- Precisely modeled with GEANT4-based simulation.
- Results published in JINST 21 P01012 (2026).

Light yield distribution for the prototypes



Comparison between measurement and simulation



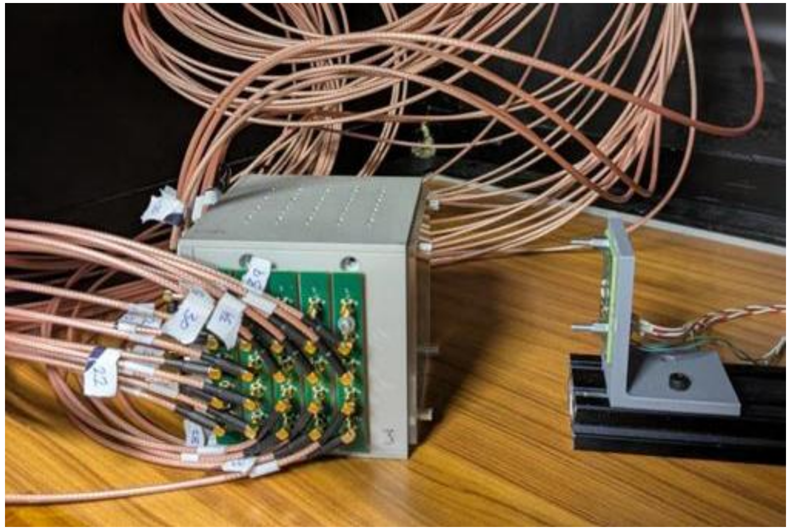
Average light yield and crosstalk for prototypes

	WbLS prototype	Pure LS prototype
Light yield (p.e./channel/MIP)	6.0	42.5
Optical crosstalk	2.29%	1.90%

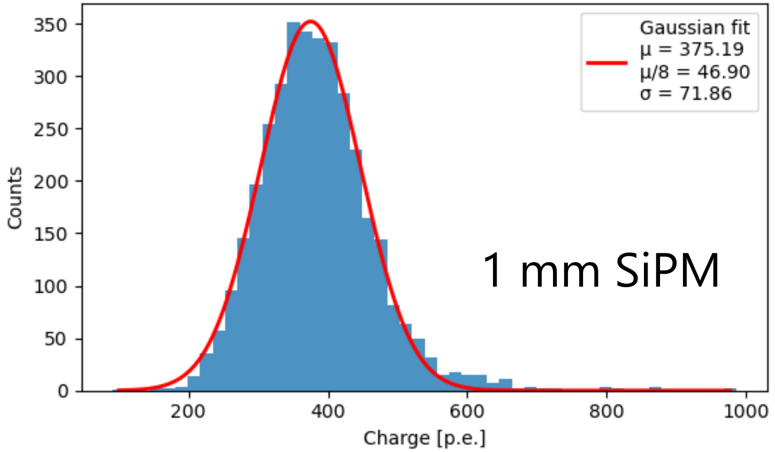
Development in LPNHE in collaboration with ETH Zurich

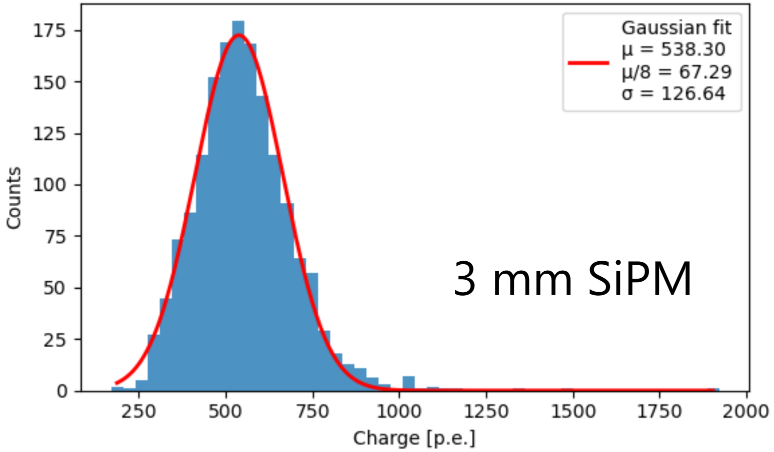
- Used plastic scintillator setup to test possible light yield increase.
- 3 mm SiPMs show a light-yield increase of about 1.5 compared to 1 mm SiPMs.
- Adding a reflector at the fiber end increases the light yield by about 10–20%.

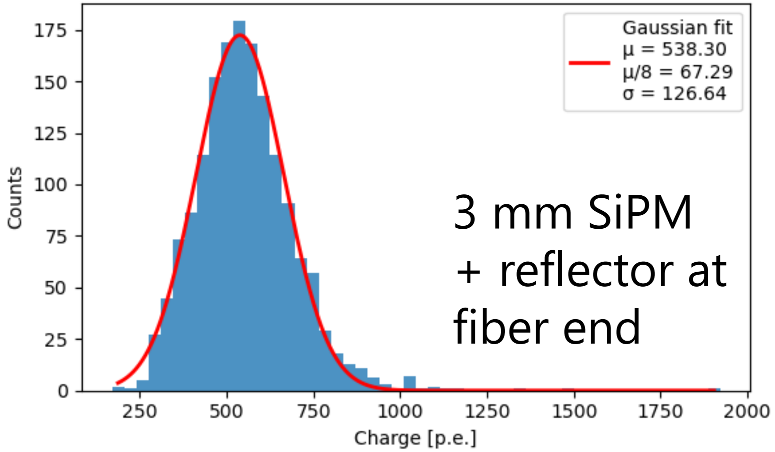
Plastic scintillator setup



Light yield distributions





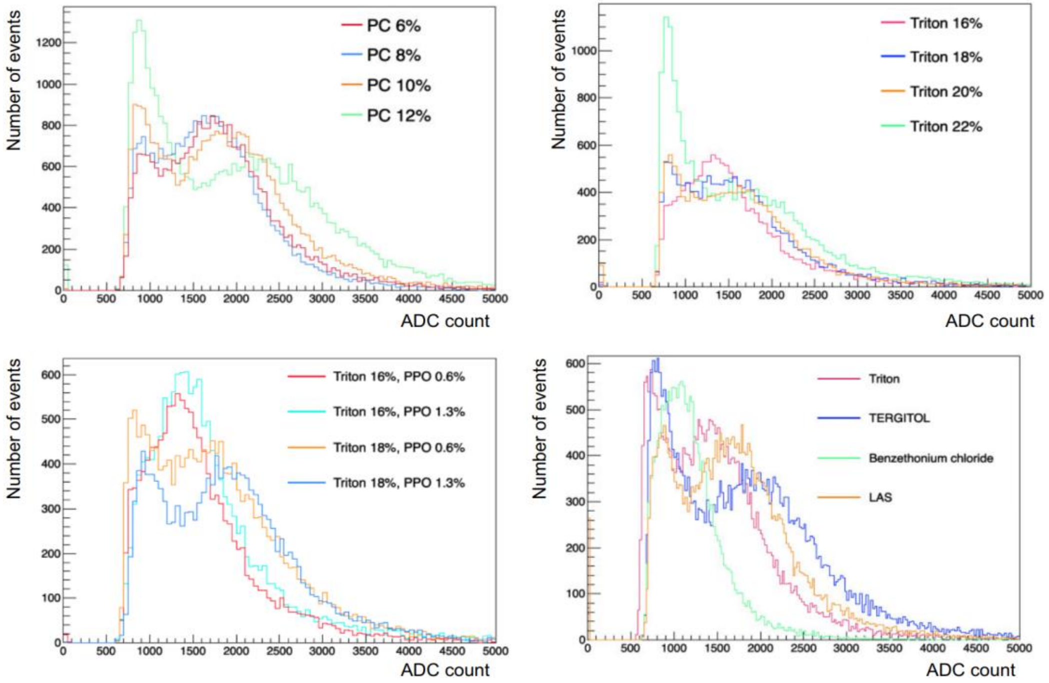


Development in Kyoto University

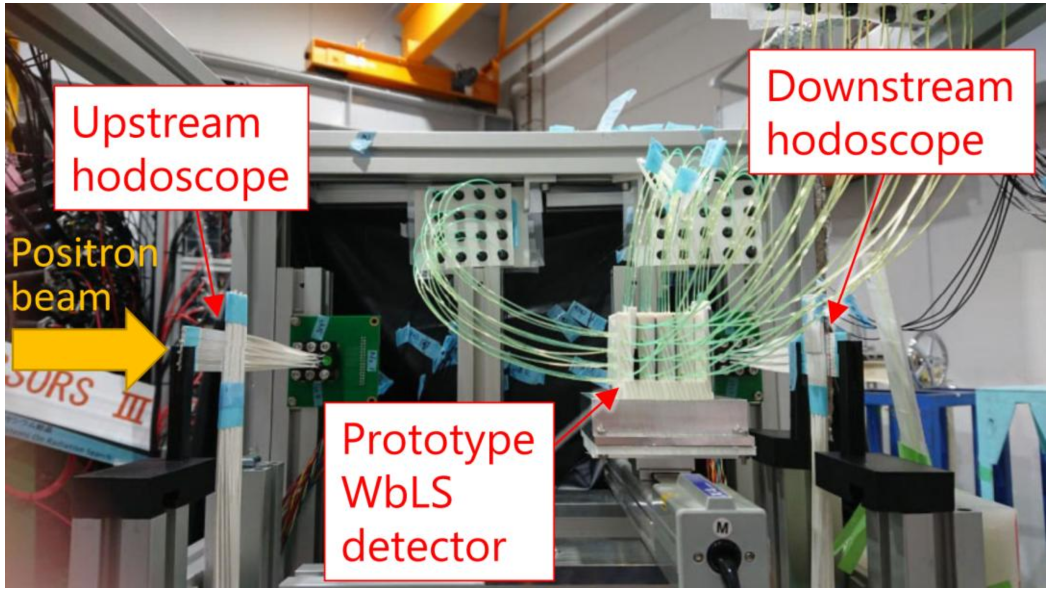
- New WbLS recipe with base composition of 70% water, 10% LS (PC+ PPO+Bis-MSB), 20% surfactant by weight.
- Tested with positron beam but light yield and crosstalk were worse than required.

Production of WbLS

Optimization of composition



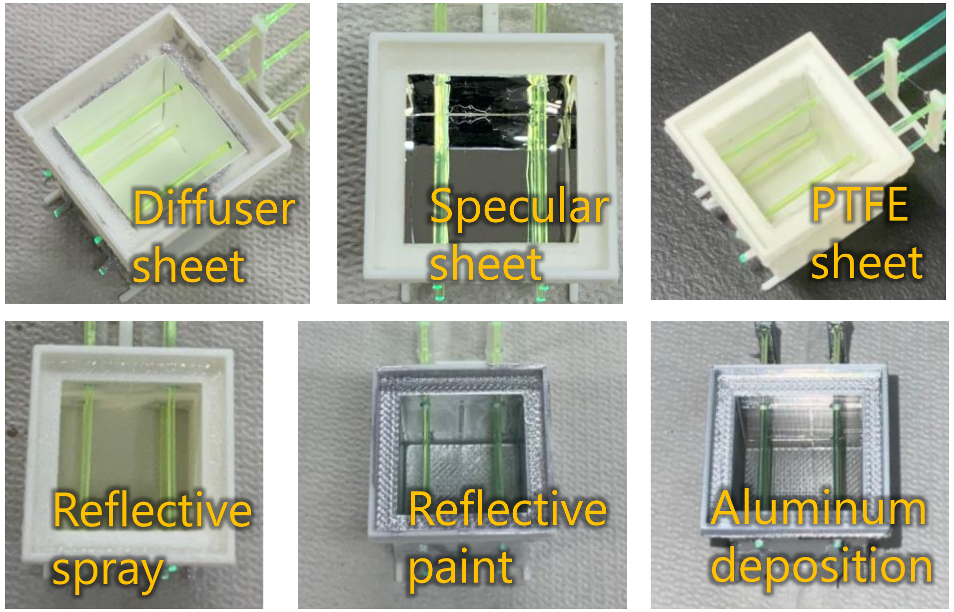
Setup of positron beam test in 2022



Development in Kyoto University

- Various optimizations increased light yield by a factor of 6.2.
- 2nd beam test in 2025 demonstrated high performance.
- Part of results published in PTEP 2025 123H02 (2025).

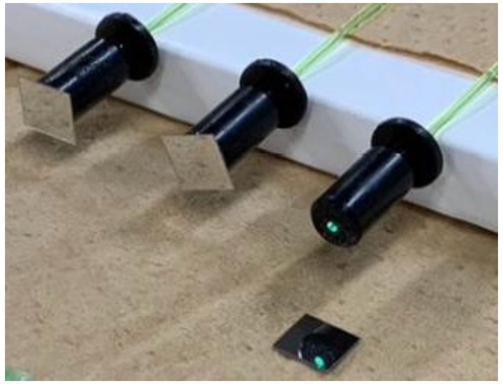
Various reflective coatings on the cell wall



Light yield improvement

Condition	Light yield (p.e./fiber)
(1): Beam test in 2022	3.9
(2): (1)+using new surfactant	5.0
(3): (2)+reflective sheet on cell wall	7.3
(4): (3)+reflective sheet at fiber end	12.0
(5): (4)+using new type of SiPM	24.2

Reflective sheet at fiber end

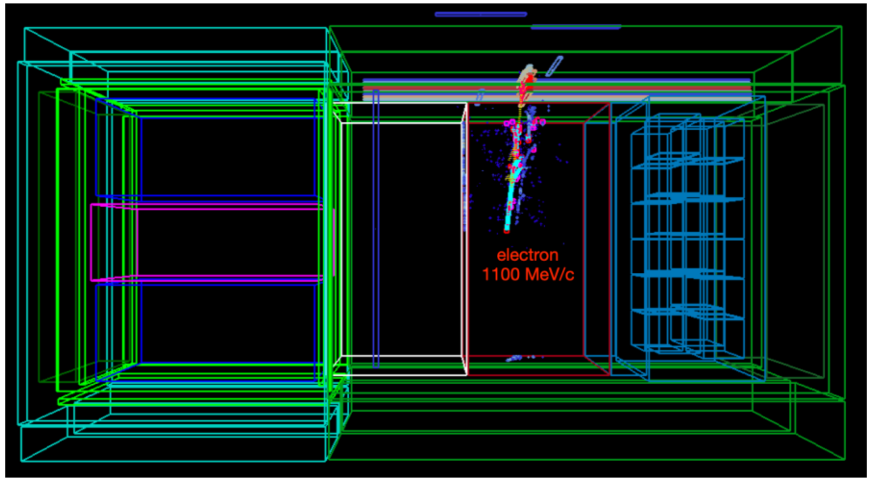


New type of SiPM

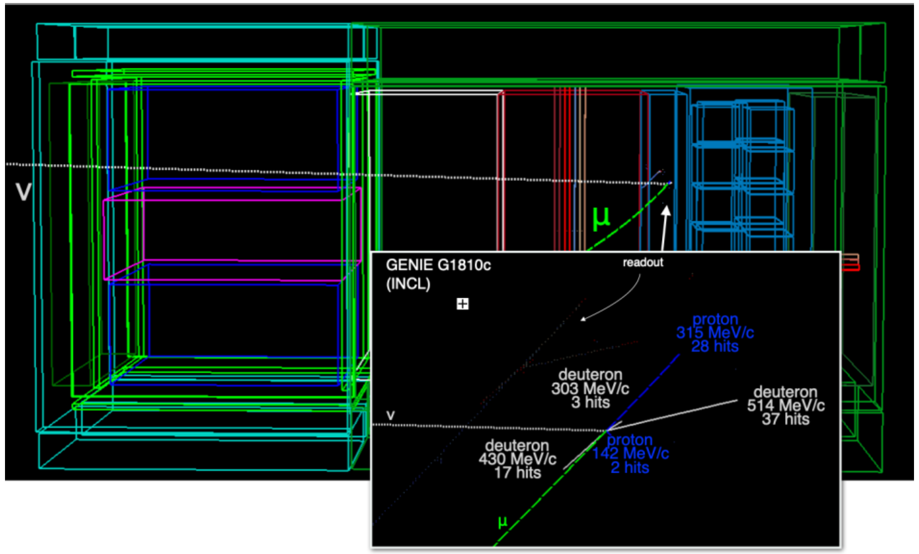
Simulation and physics studies

- Full detector simulation and reconstruction, selection studies are ongoing as a joint collaboration.

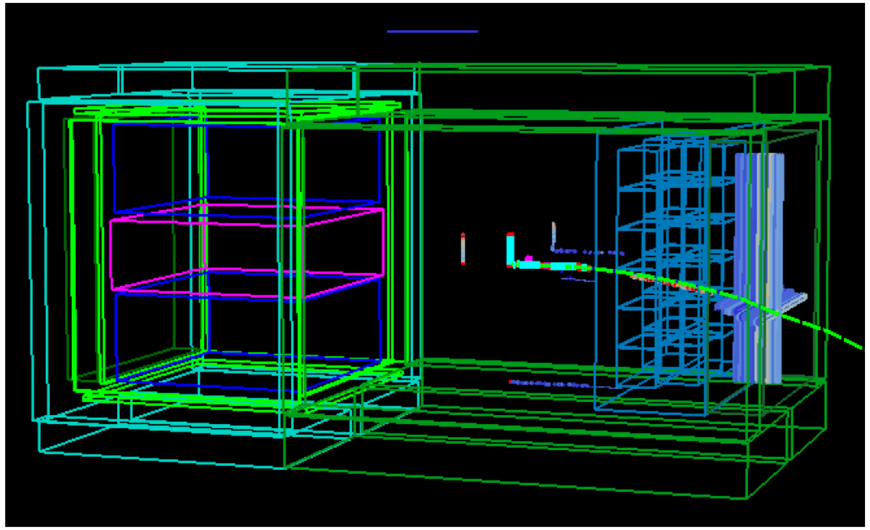
ν_e interaction in water-based liquid scintillator



ν_μ interaction in inactive water



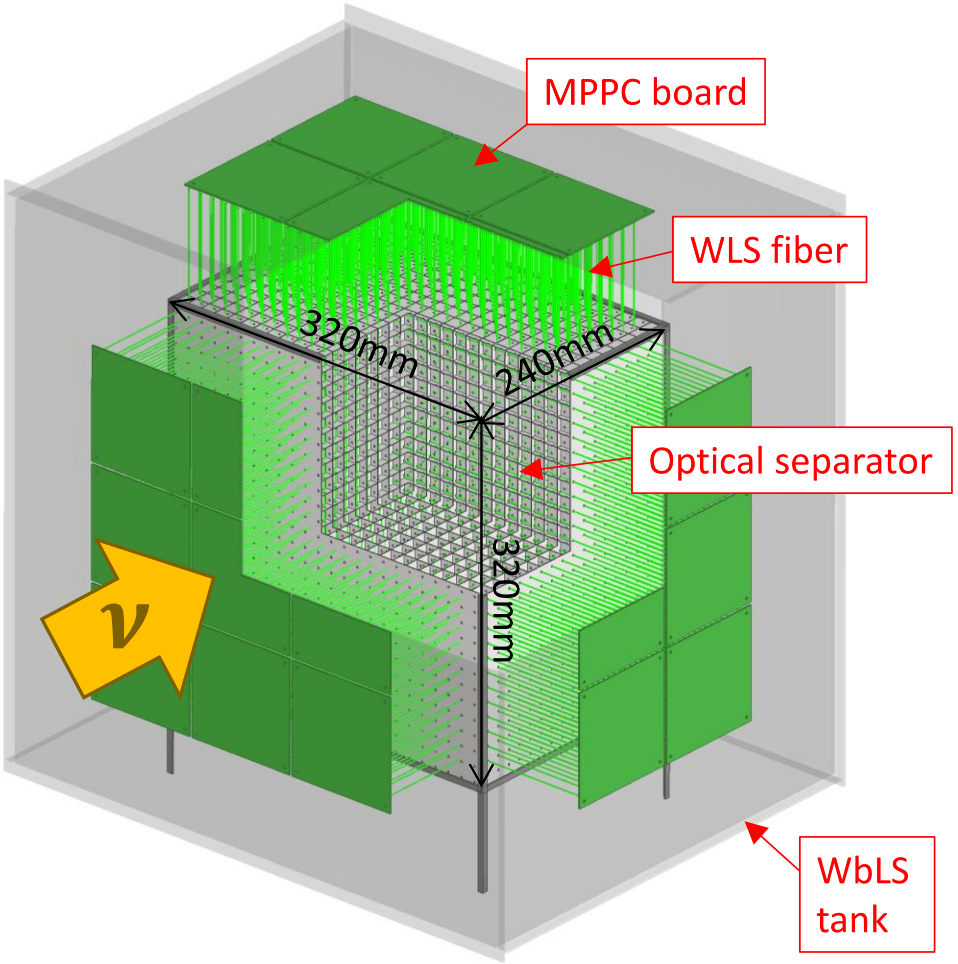
ν_μ interaction in SciFi w/ deuterons



Future research plan as D_RD_41 project

- FY2026: Further improve light yield by integrating the developments of LPNHE and Kyoto University, optimizing WbLS composition, enhancing reflector performance, and improving fiber/SiPM coupling.
- FY2026: Scalable mechanical solutions for tonne-scale water-tight detectors.
- FY2026-2027: Construct a 30cm-scale prototype to be exposed to electron and hadron beams, and ultimately with J-PARC neutrino beam.

Design of prototype detector



Summary

- Hyper-K will require further reduction of systematic uncertainties in the high-precision era.
- ND280++ aims to measure neutrino interactions with a several-tonne water-target detector.
- 3D-segmented WbLS detector is being developed for precise tracking with water as the main target.
- LPNHE and Kyoto are jointly developing key technologies: WbLS, optical reflectors, and fiber/SiPM readout.
- Recent R&D shows improved light yield, small optical crosstalk, and good agreement with simulations.
- Next steps are design optimization and construction of a larger prototype for tests with J-PARC neutrino beam.