The Super-FGD detector as part of the T2K ND280 upgrade

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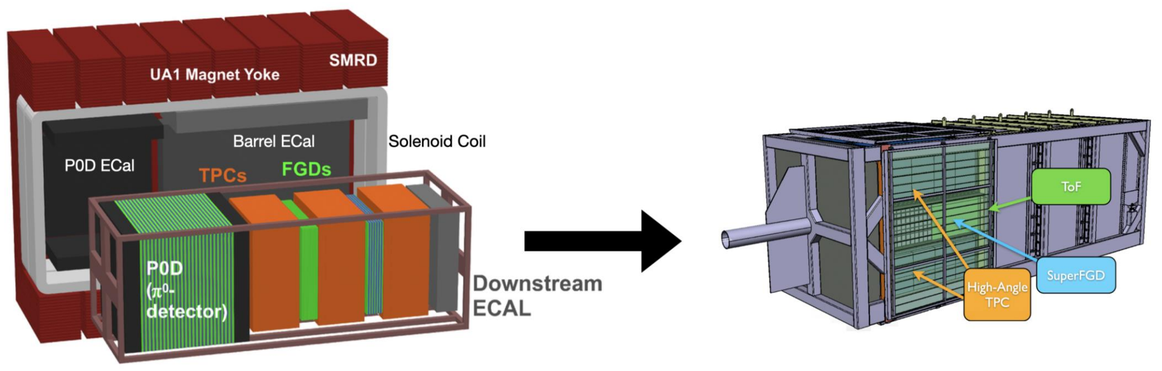
1. The T2K experiment

- The T2K (Tokai-to-Kamioka) is a long-baseline neutrino experiment based in Japan
- ν_μ or $\bar{\nu}_\mu$ beam produced at J-PARC, characterized by near detectors and detected at Super-Kamiokande
- Measures the fundamental parameters of neutrinos, including their mass hierarchy, oscillation angles and degree of Charge-Parity violation [1].

2. Near detector (ND280) upgrade



Pre-Upgrade ND280

Upgraded ND280 Tracker

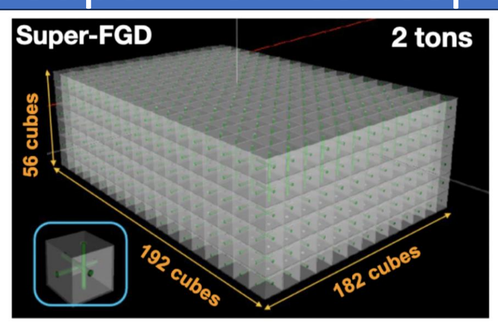
Replace π^0 detector with three new sub-detectors:

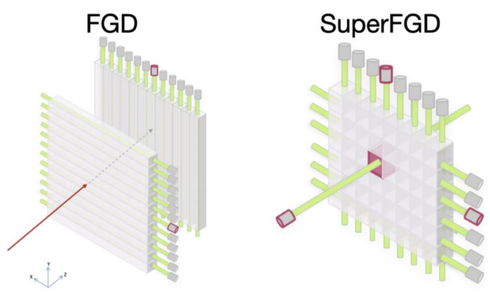
- Super Fine-Grained Detector (Super-FGD): highly segmented target material with ability to reconstruct neutrons and lower momentum protons
- High-Angle Time Projection Chambers (HATPCs):measure momentum, charge and particle ID with better angular acceptance than before
- Time-of-Flight (ToF): precise timing information to reject backgrounds and improve reconstruction

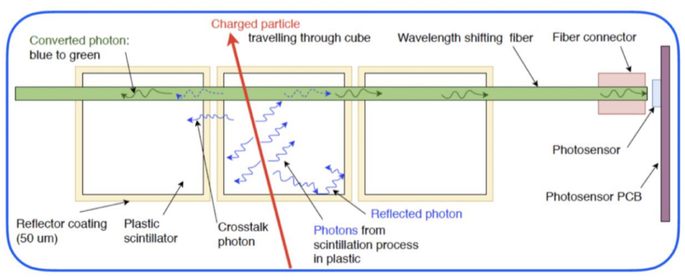
Goals:

- Reduce systematic uncertainties from 6% to ~ 3% [2]
- Achieve 4π detection for all particles
- Reduce the proton momentum threshold to below 500 MeV/c
- Neutron detection

3. Super-FGD concept and construction

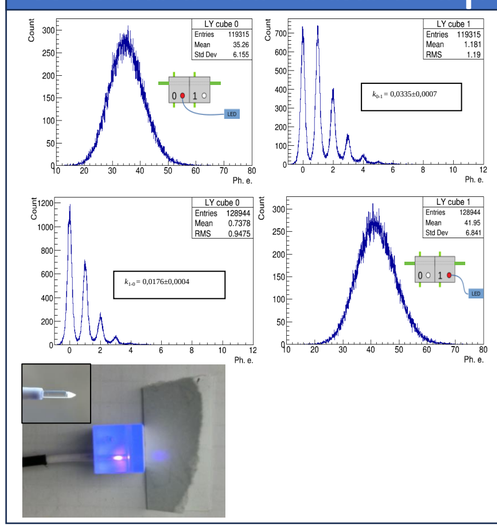


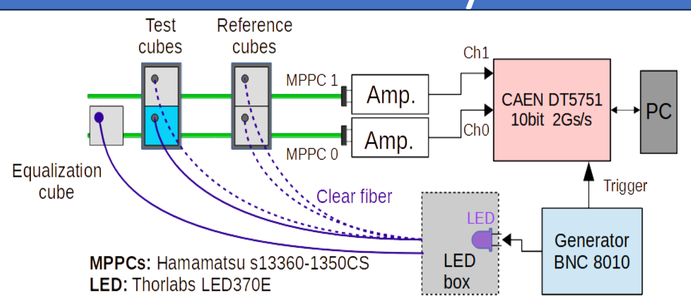




- 1 956 864 reflector-coated 1x1x1 cm plastic scintillator cubes [3]
- 55888 WLS-fibers, each coupled to a Hamamatsu S13360-1325PE MPPC, three orthogonal fibers per cube
- Concept proven in charged particle [4] and neutron beam tests [5]
- Detector assembly at J-PARC October 2022 – April 2023:
  - Assembly platform designed and manufactured by JINR
  - Cube layers installed with fishing lines
  - Vertical alignment using welding rods
  - Fishing lines replaced with WLS-fibers
  - MPPCs and LED calibration system installed
- Super-FGD installed in October 2023

4. Cube-to-cube optical crosstalk study



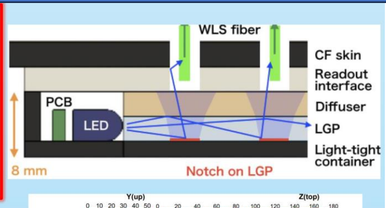


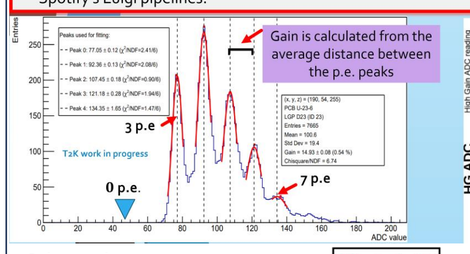
LED light injection into channel:	K_{0-1}	K_{1-0}	<k>
Optically isolated cubes (black paper separator)	≈ 0	≈ 0	0
No coommon fiber, hole is open	0,053±0,001	0,0287±0,0006	0,041
Common fiber hole is closed with plug	0,0327±0,0007	0,0187±0,0004	0,026
Common WLS fiber inserted	0,0335±0,0007	0,0176±0,004	0,026

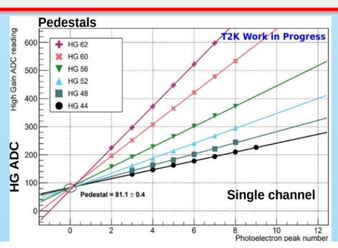
5. Calibration system

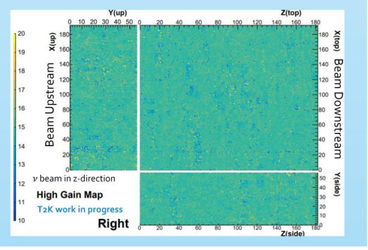
SFGD LED Calibration system

- LED panels surround the detector (see right plot), and flash at different intensities.
- Finger plots show electronics readout from LED flashes, peaks correspond to a different photoelectron peaks.
- Gaussian fits for the position of peaks used to determine gain (below left).
- 0p.e. point (pedestal, below middle) is determined by extrapolating peak positions from different gain voltage settings.
- An analysis pipeline system, b2luigi [4], is used to process and measure the gain in all channels, adapted from Spotify's Luigi pipelines.

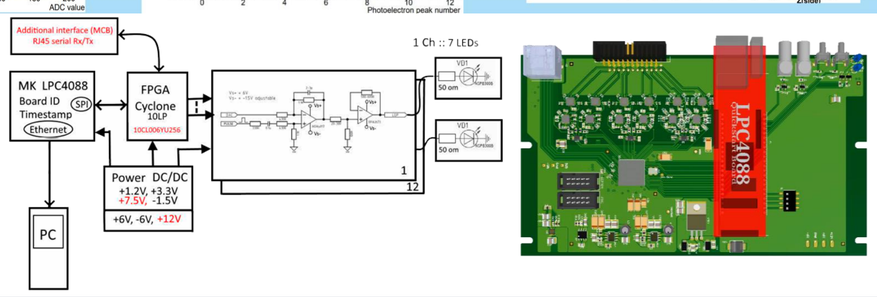




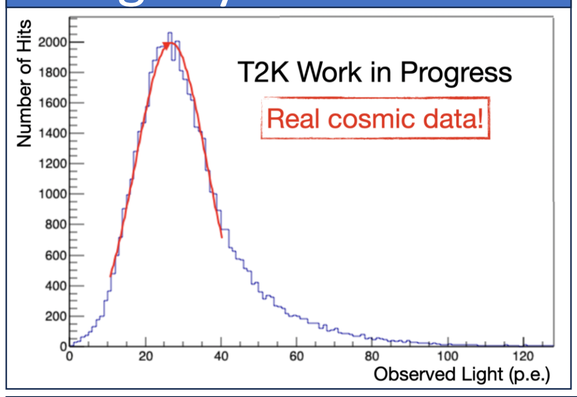




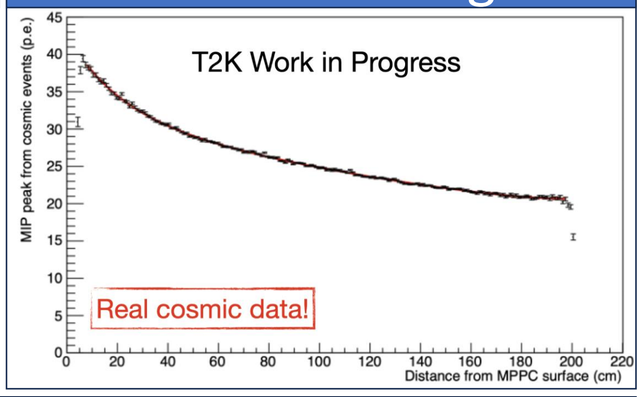
- 8 boards
- Number of channels - 12
- NIM standard board
- Interface - RJ45 – Ethernet UDP
- Additional interface (MCB) - RJ45 serial Rx/Tx
- Pulse width - 5ns – 600ns
- Amplitude - 0 – 6.5V



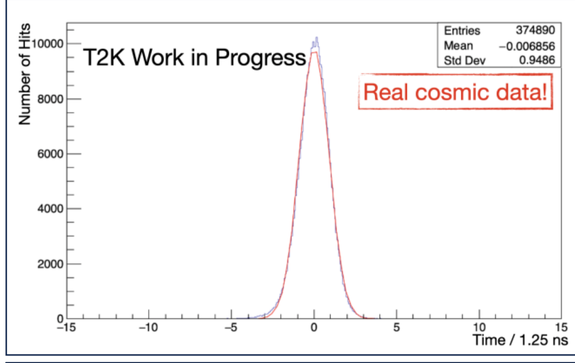
6. Light yield

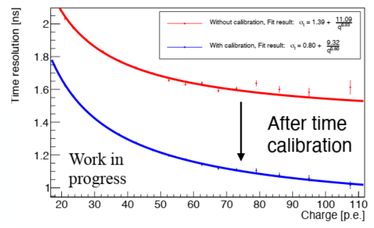


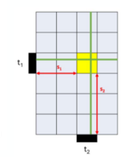
7. Attenuation length



8. Time resolution

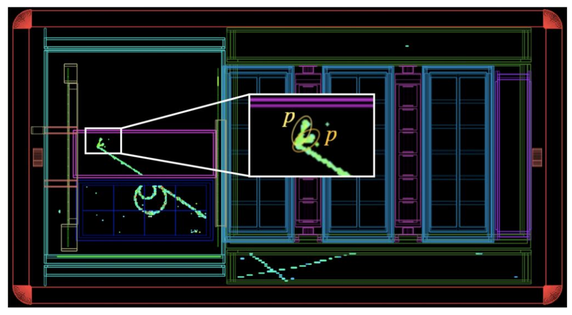




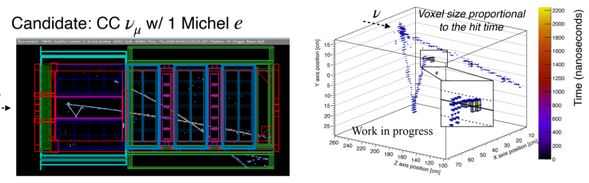


- Select hits > 40 p.e. matched in all three dimensions
- Compare mean time of hit to mean time for event
- Gives ~1,2 ns time resolution (can be improved by electronics firmware update (400 -> 800 MHz)

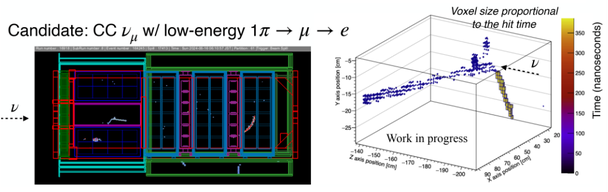
9. Neutrino interactions in the Super-FGD



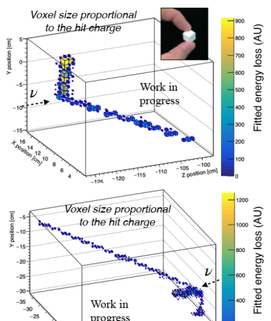
Candidate: CC ν_μ w/ 1 Michel e



Candidate: CC ν_μ w/ low-energy $1\pi \rightarrow \mu \rightarrow e$

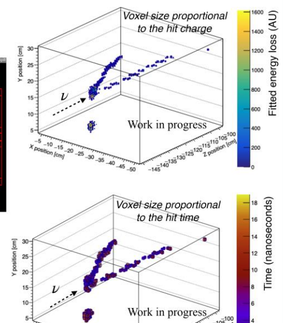


Candidate: CC ν_μ 1 muon 1 protons



Candidate: CC ν_μ 1 muon 2 protons

Candidate: CC ν_μ w/ 1 neutron



Estimated kinematic parameters of the candidate neutron

- ✓ Lever arm = 122.28 mm
- ✓ Time of flight = 1.73 ns
- ✓ Kinetic energy = 27.3 MeV

10. Conclusions

- Super-FGD is currently collecting accelerator neutrino data in J-PARC
- It is the result of a joint effort of 37 research institutes from different countries (CERN, France, Germany, Japan, Russia, Switzerland, UK, USA)
- Owing to 1 cm granularity, calorimetry, sub-nanosecond timing we aim to
  - ✓ 4π tracking of charged particles with O(mm) spatial resolution and proton detection threshold down to ~300 MeV/c
  - ✓ Excellent identification of protons with Bragg peak characterization
  - ✓ High-purity detection of ν_e with rejection of $\gamma \rightarrow e^+e^-$ background
  - ✓ Efficient detection of neutrons with measurement of the time of flight
- The characterization of Super-FGD confirms its performance as by design
- Work in progress on physics analysis with new neutrino data.

[1] K. Abe *et al.* 2011 Nucl. Instr. Meth. A 659, 106
[2] A. Dergacheva *et al.* 2022 Nucl. Instr. Meth. A 1041, 167219
[3] Y. Abreu *et al.* 2017 JINST 12 P04024
[4] A. Blondel *et al.* 2020 JINST 15 P12003
[5] A. Agarwal *et al.* 2023 Phys. Lett. B 840 137843
[6] A. Artikov *et al.* 2022 Phys. of Part. and Nucl. Lett., Vol. 19, No. 6, pp. 784–791
[7] T. Arihara *et al.* 2022 J. Phys.: Conf. Ser. 2374 012118