A Novel Highly Segmented Neutrino Detector

The Super Fine Grained Detector for the Upgraded T2K Near Detector ND280

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For the T2K Collaboration

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T2K

Outline

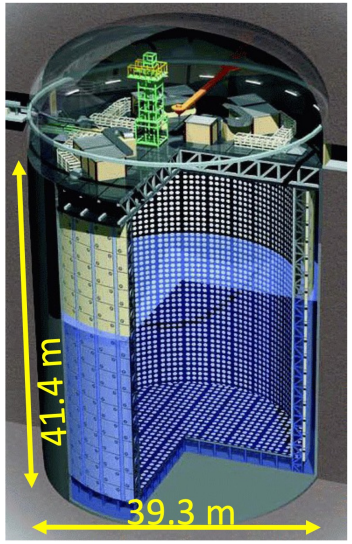
- T2K Experiment and Motivation for SuperFGD
- SuperFGD Hardware Components
- SuperFGD Performance
- Summary/Outlook

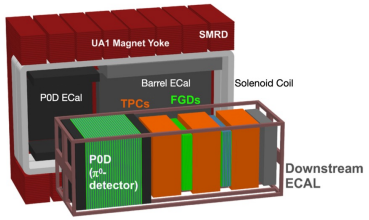
T2K Experiment

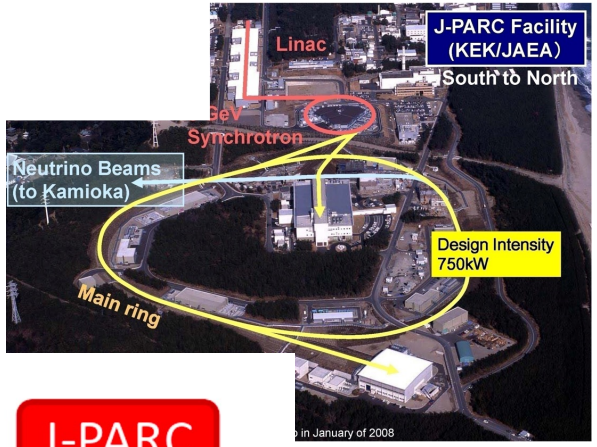
- Tokai to Kamioka (T2K) is a long-baseline neutrino experiment
- high intensity ν_μ ($\overline{\nu}_\mu$) beam
  - Sampled by near detectors and by far detector Super-Kamiokande
- Measure ν_μ ($\overline{\nu}_\mu$) disappearance and ν_e ($\overline{\nu}_e$) appearance

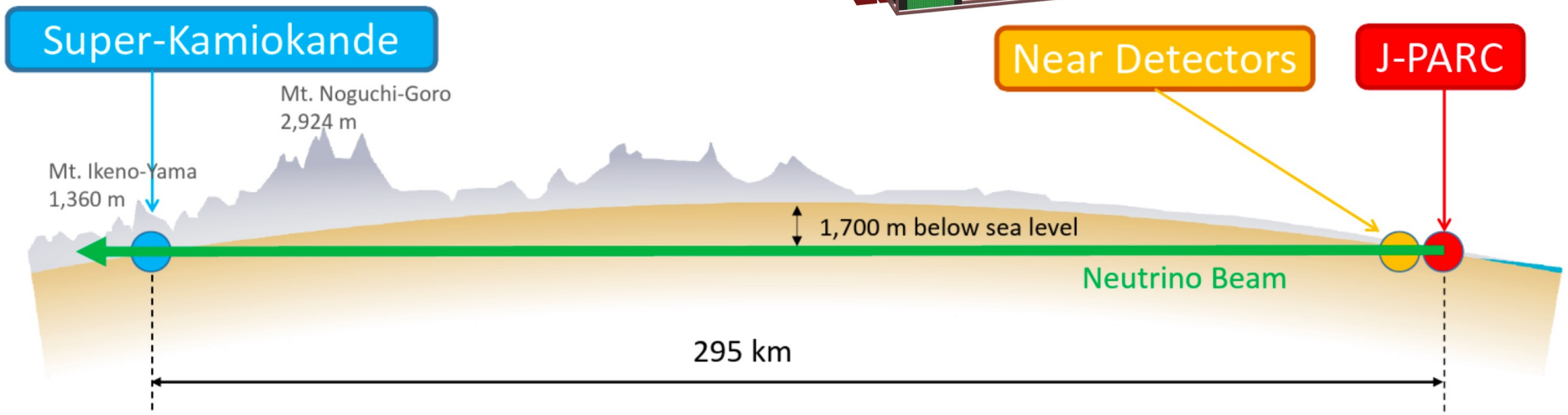
  → extract oscillation parameters

  → search for CP violation



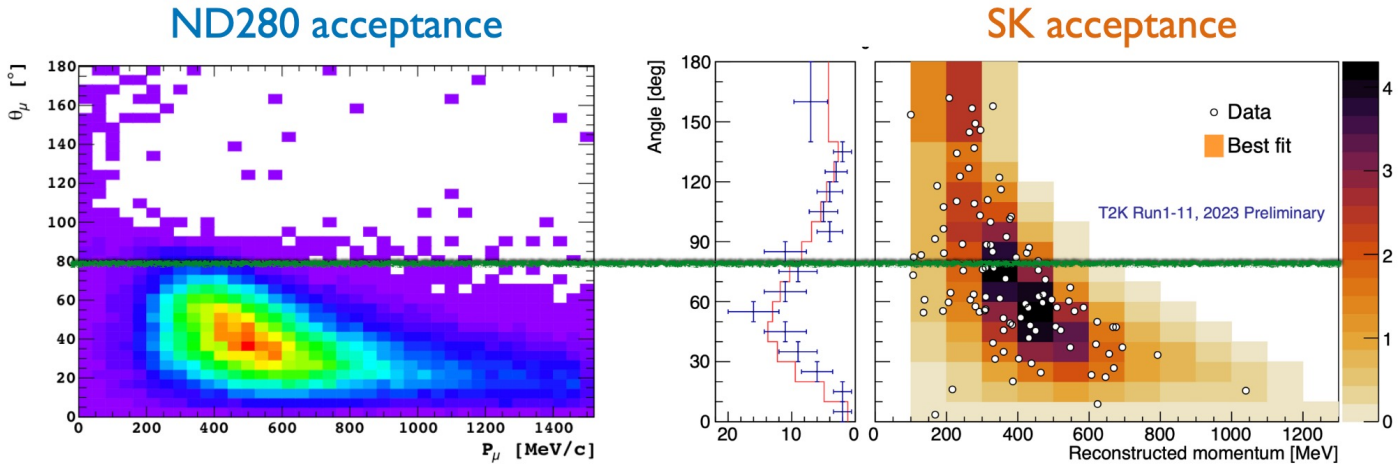


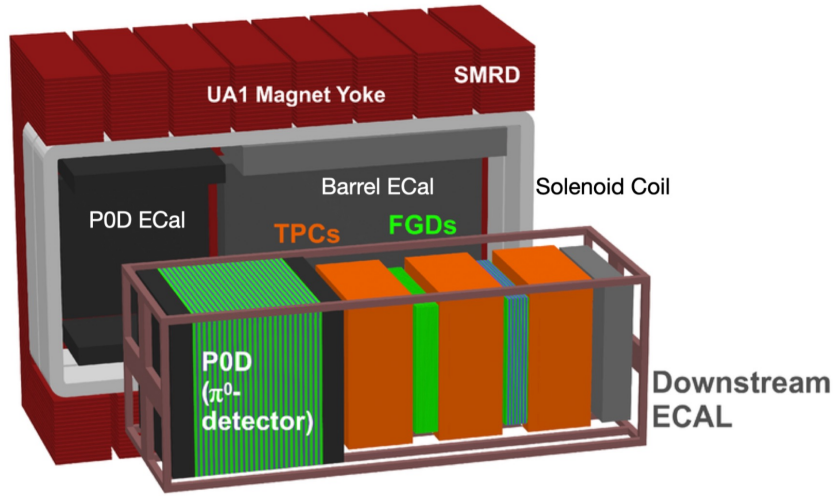




T2K ND280 “Classic” Limitations

- Predominantly forward angular acceptance

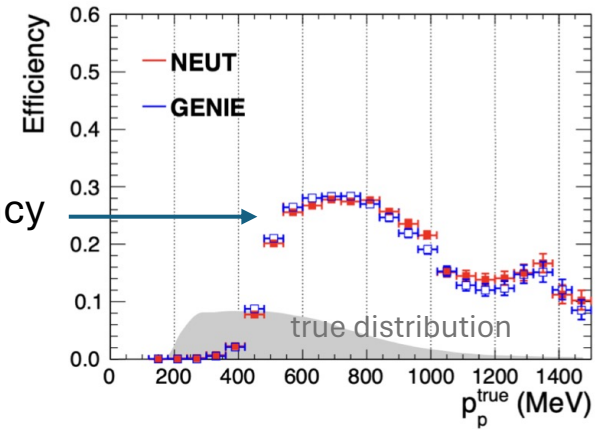




- Relatively high proton momentum reconstruction threshold

ND280 proton reconstruction efficiency

MC simulation

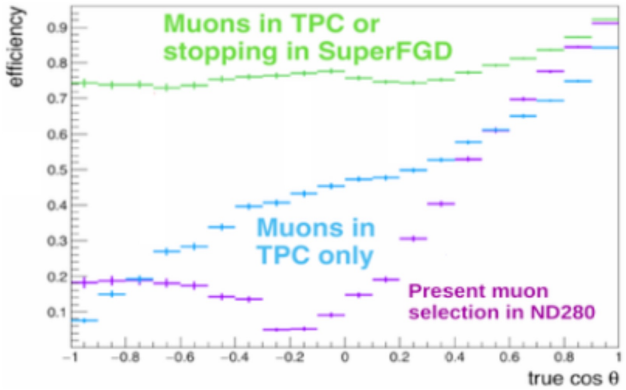


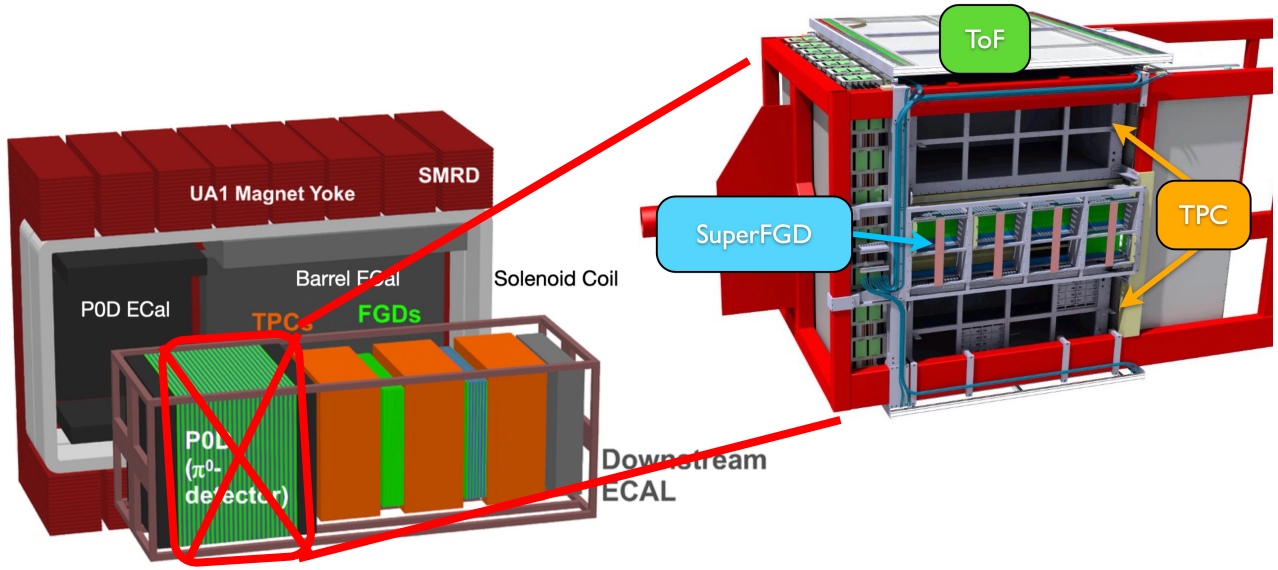
- No neutron detection capabilities

→Limitations impact systematic uncertainties

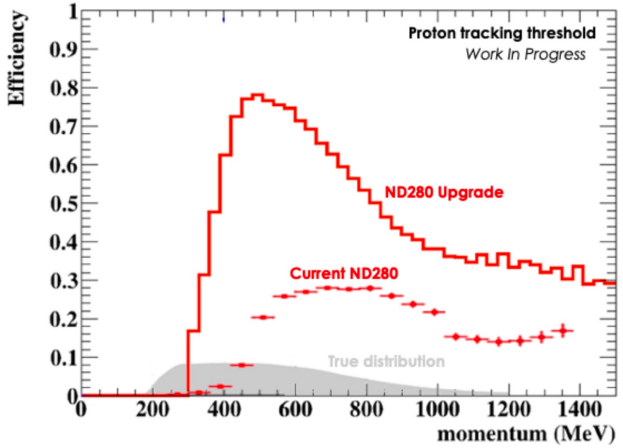
T2K ND280 Upgrade

- High angle muon acceptance

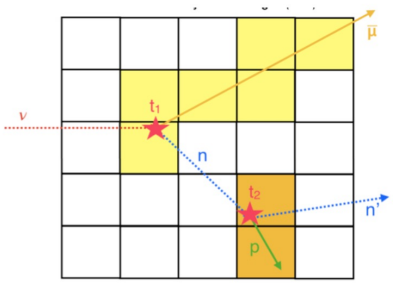




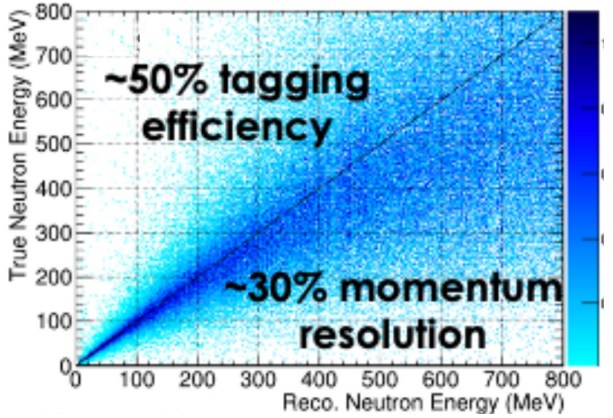
- Lower proton reconstruction threshold



- Neutron detection capabilities

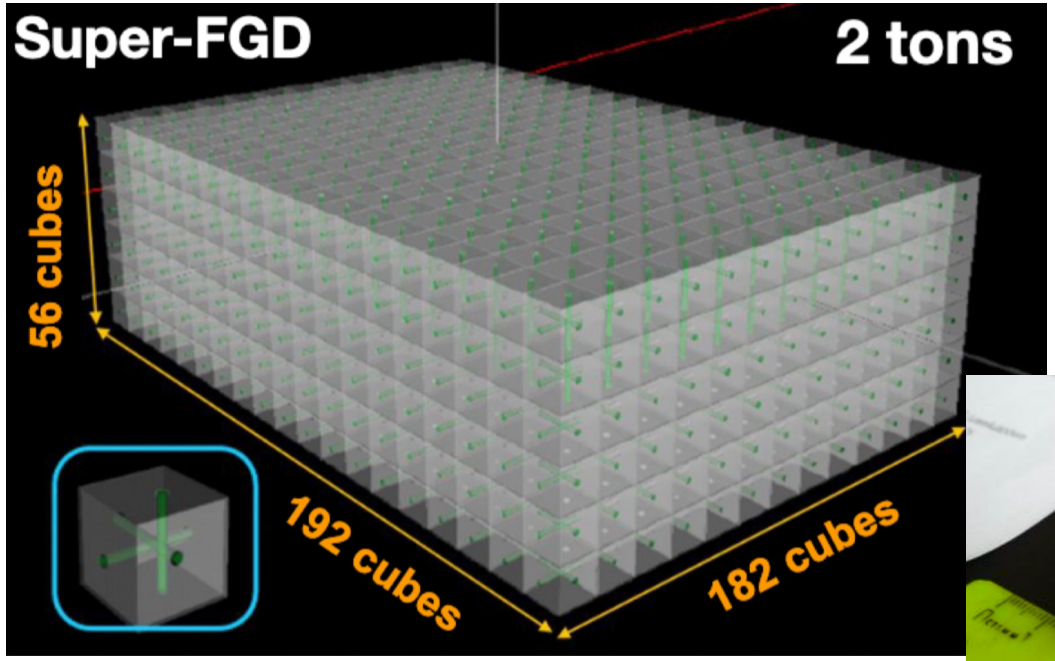


$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$



Super FGD Overview

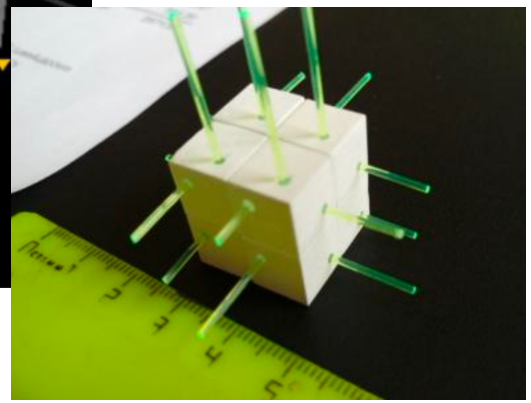
- Volume: 192×182×56 cm^3 ; total active weight of ~2 tons
- ~2M scintillator cubes (1×1×1 cm^3 each, optically isolated) with 3 orthogonal fiber holes
  → 3D WLS fiber readout
- ~56k SiPMs and electronics channels

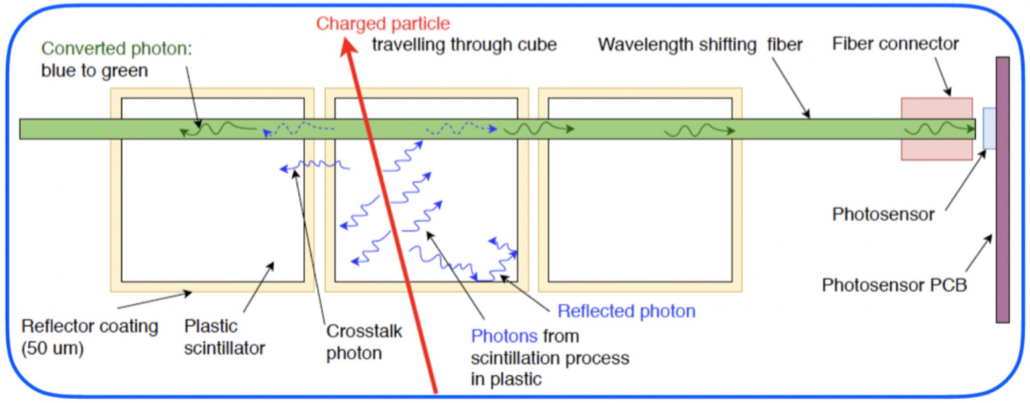


- Large, fully active volume with high granularity

→low threshold

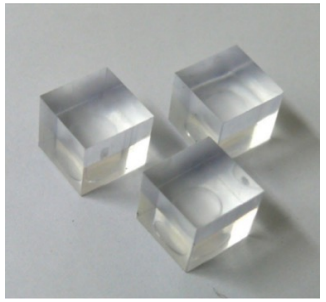
→4π response

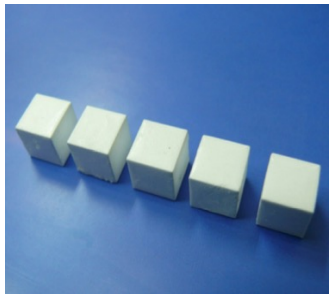


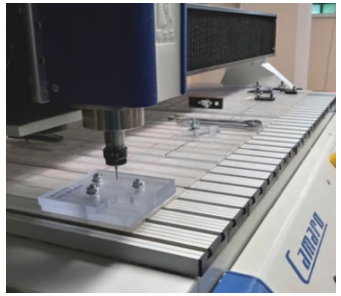


Super FGD Assembly and Enclosure

- From individual cubes to a large volume detector inside a carbon fiber box

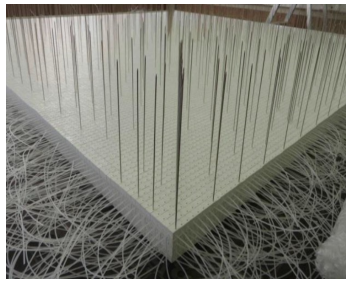

Injection molded

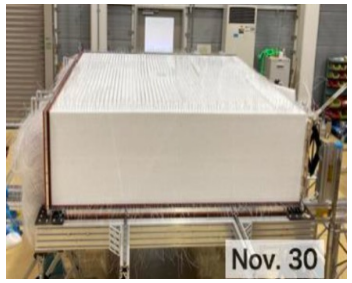

Chemical reflector
Size tolerance: 30μm


Hole drilling
tolerance: 50-70μm


Cube stringed
by fishing lines


Cube planes
(fishing lines)

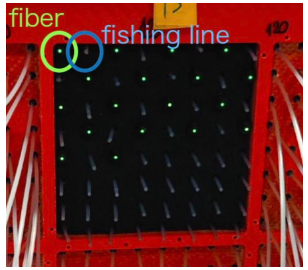

Stacked cube planes
(fishing lines + rods)

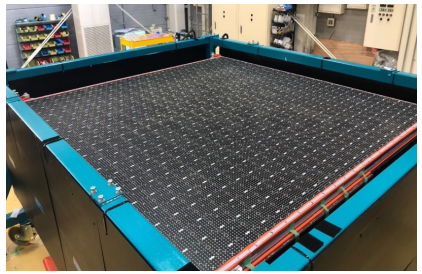


Stacked cube planes
Within carbon fiber box

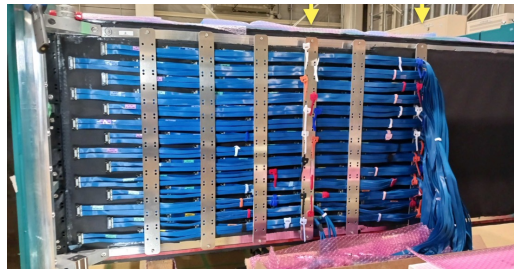

Closed box

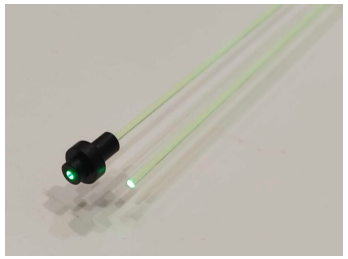

Fishing line extraction + WLS fiber insertion

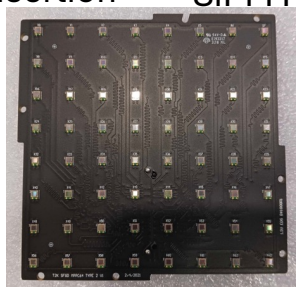



SiPM PCB mounting


Light barrier


cabling

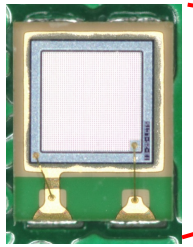

WLS fiber + ferrule


8x8 SiPM array PCB

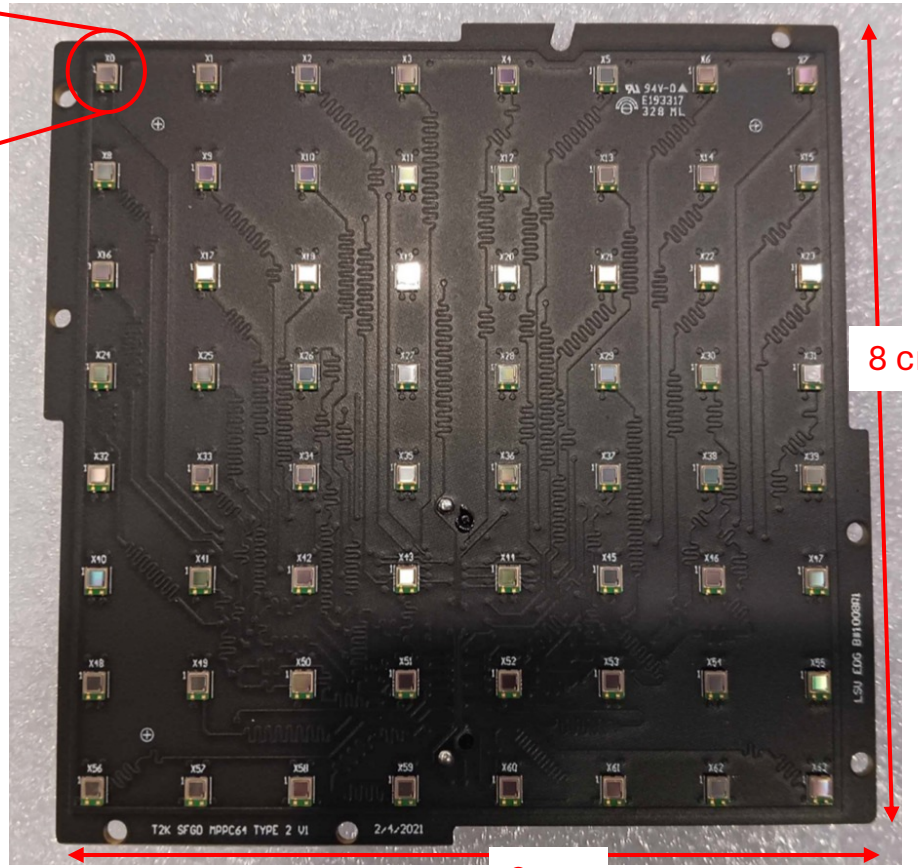
Quality control of all components and checks at all integration steps

Super FGD Photosensors

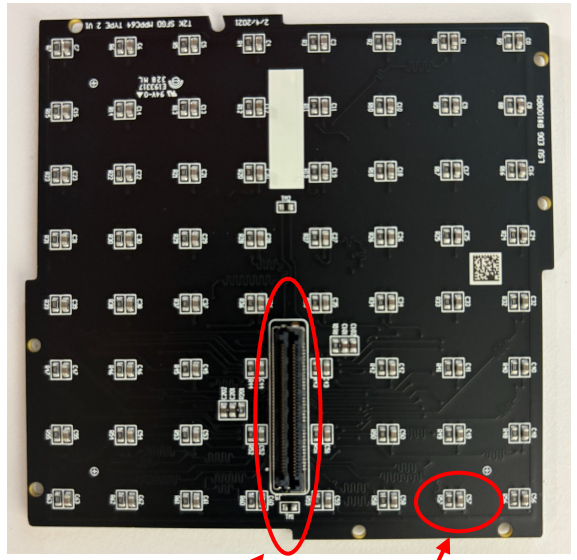
- Hamamatsu S13360-1325PE Multi Pixel Photon Counters (MPPC)
- Arranged in a 8x8 array PCB with RC filters, length equalized traces and grouped V_{bias}



Front side



Back side



Item	Specification
Effective photosensitive area	1.3 mm x 1.3 mm
Pixel pitch	25 μm
Number of pixels	2668 pixels
Fill factor	47%
Package type	Surface mount
Breakdown voltage (V_{BR})	53 $\pm$ 5 V
Peak sensitivity wavelength	450 nm
Photo detection efficiency	25%
Gain	7.0 x 10^5
Dark count	70 kcps (typ.)
Crosstalk probability	1%

Super FGD Electronics

- Sub-ns timing resolution → neutron reconstruction
- Large dynamic range: ~0.5 – 1500 p.e. → stopping protons

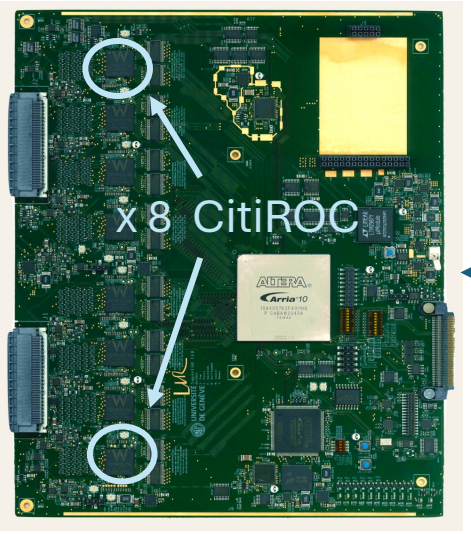
Readout based on CitiROC chip (32 channels) and 12 bit ADCs

256 channels per Front End Board (FEB) → total of 222 FEBs

FEBs (14 per crate) connected via backplane to Optical Concentrator Board (OCB): Z-Turn

OCB connects to Data Acquisition and Master Clock Board (MCB) which provides timing and triggering

FEB (x 222)

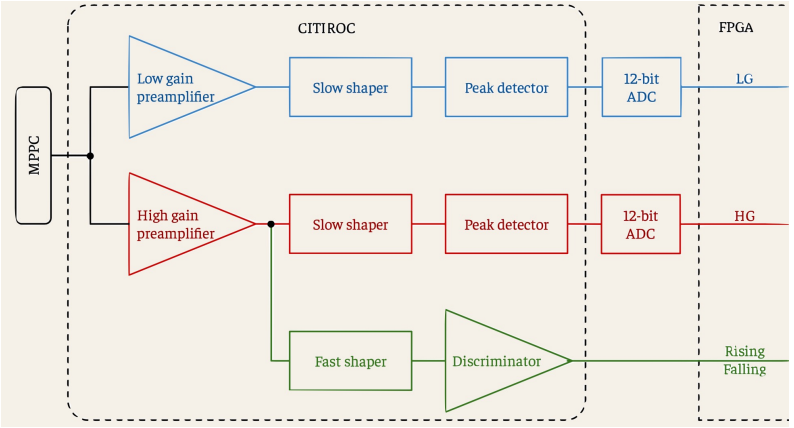


OCB (x16)

MCB (x1)

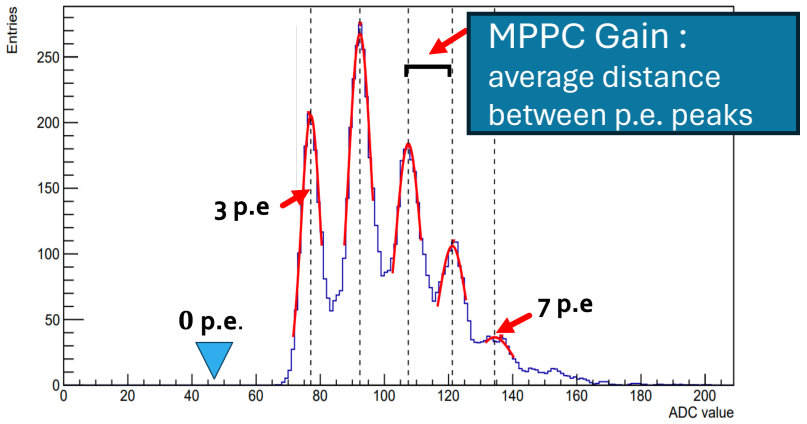
DAQ

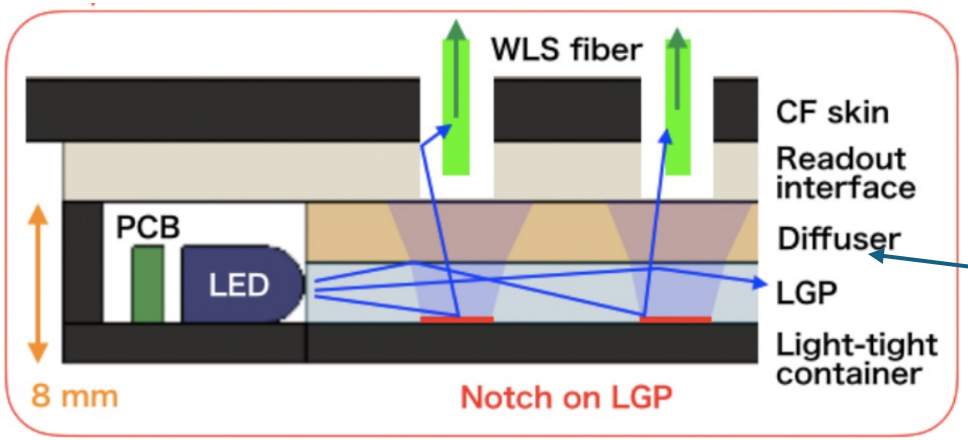
Readout channel (x 56k)



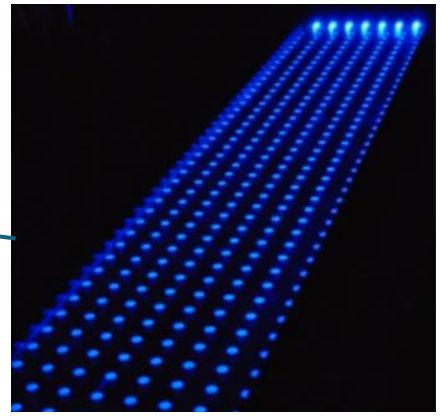
Super FGD DAQ and Calibration

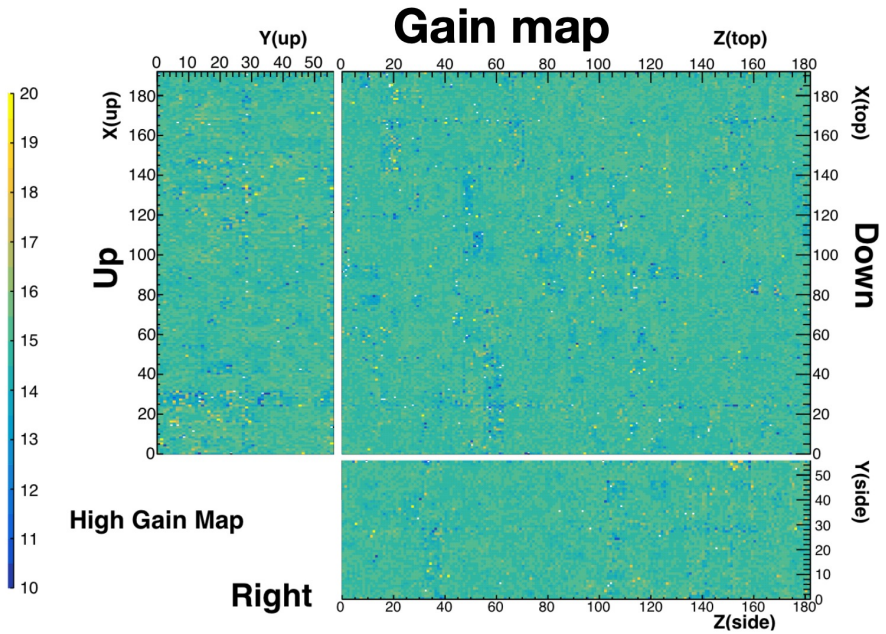
- MIDAS frontend based DAQ
  - Configuration control and event building
- Channel calibration
  - MPPC gain tuning and stability monitoring





Light guide plate (LGP) with notches at fiber locations

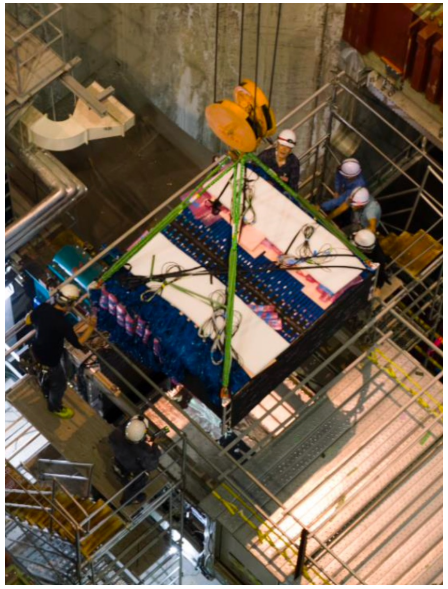




Good level of uniformity

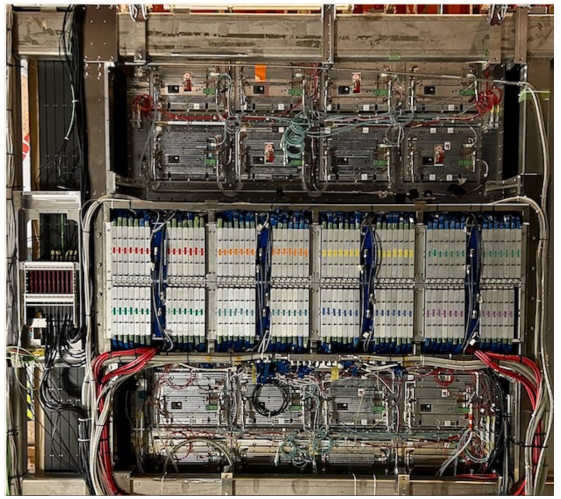
Super FGD Installation/Integration

Surface lab



Detector pit

SFGD electronics

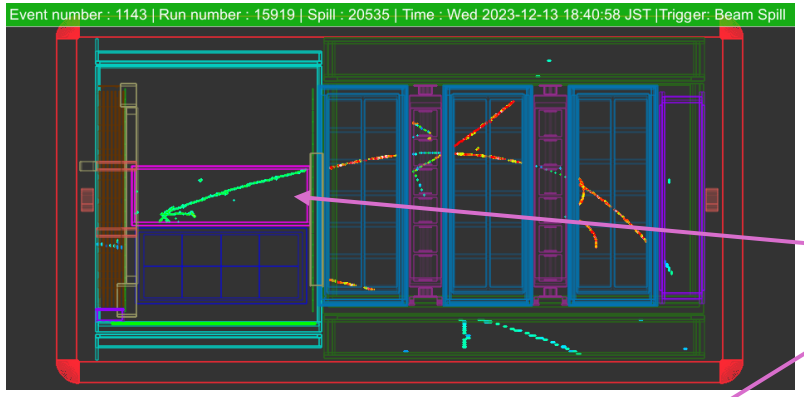


Fully installed
In ND280

Super FGD/ND280 Neutrino Candidate Events

Data taking in neutrino beam : technical run (Nov. 2023) physics data taking (May/June 2024)

ν beam



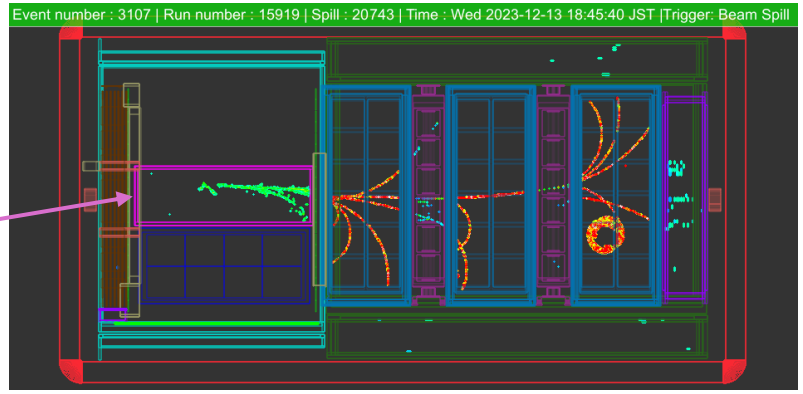
ND280 upgrade

HATPC

SFGD

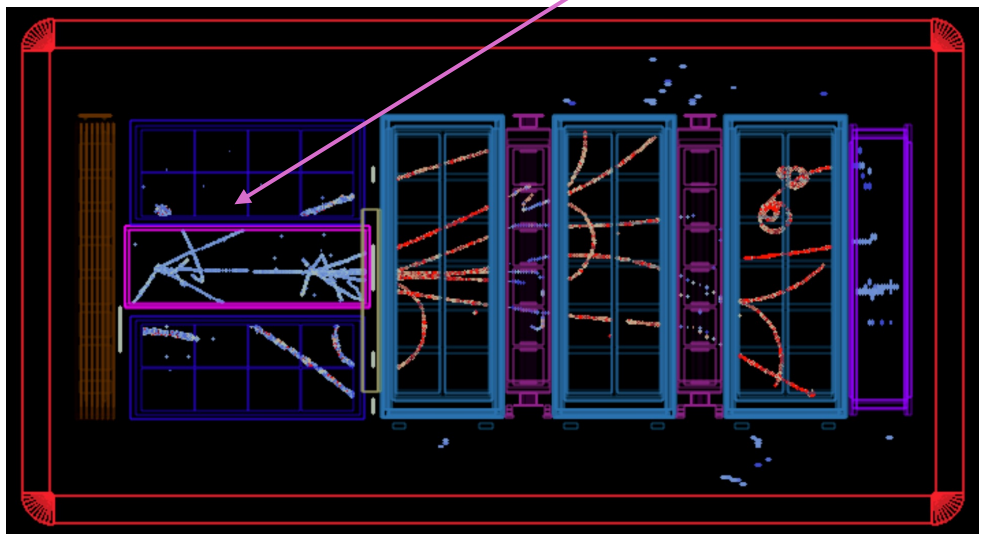
HATPC

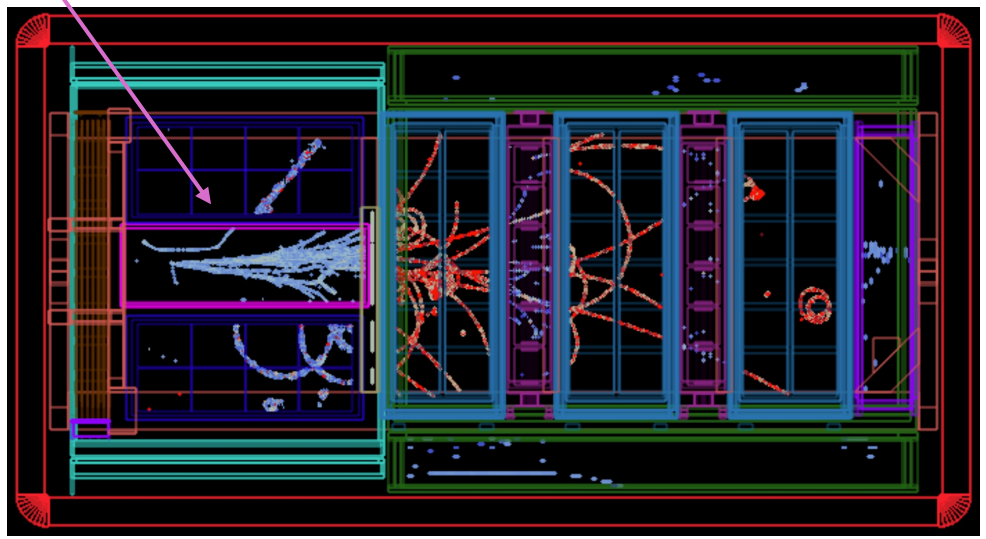
TOF



ND280 classic

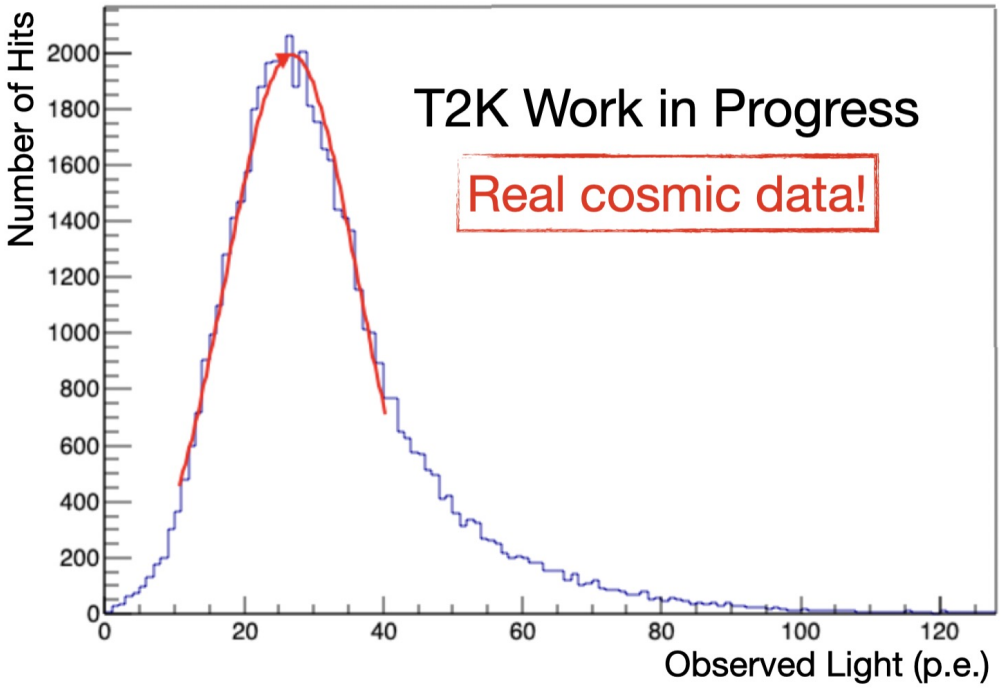
ν beam





Super FGD Performance: Light Yield

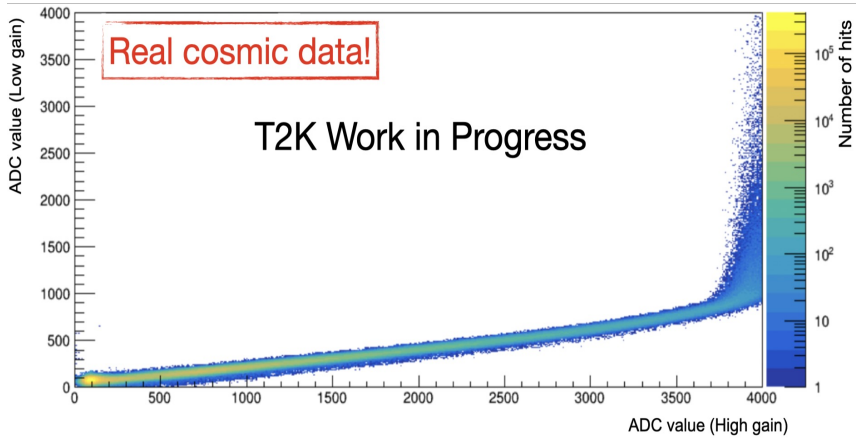
- MIP mean light yield of ~25 p.e. (single cube and single fiber)



Large dynamic range

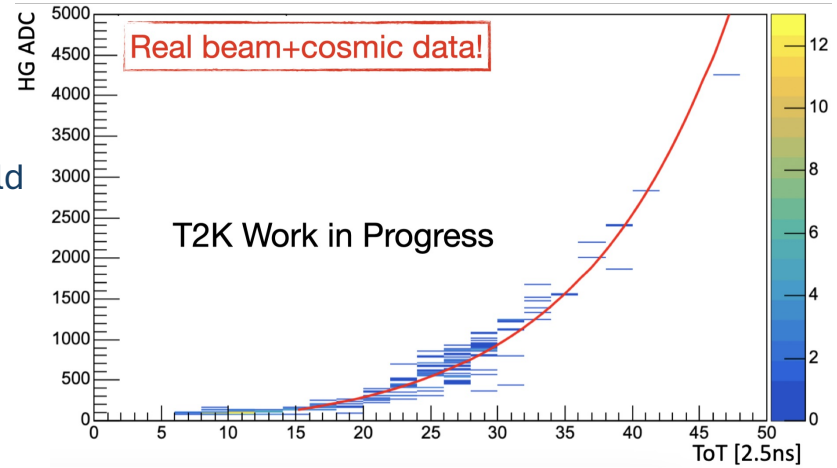
low gain vs high gain

→ linear



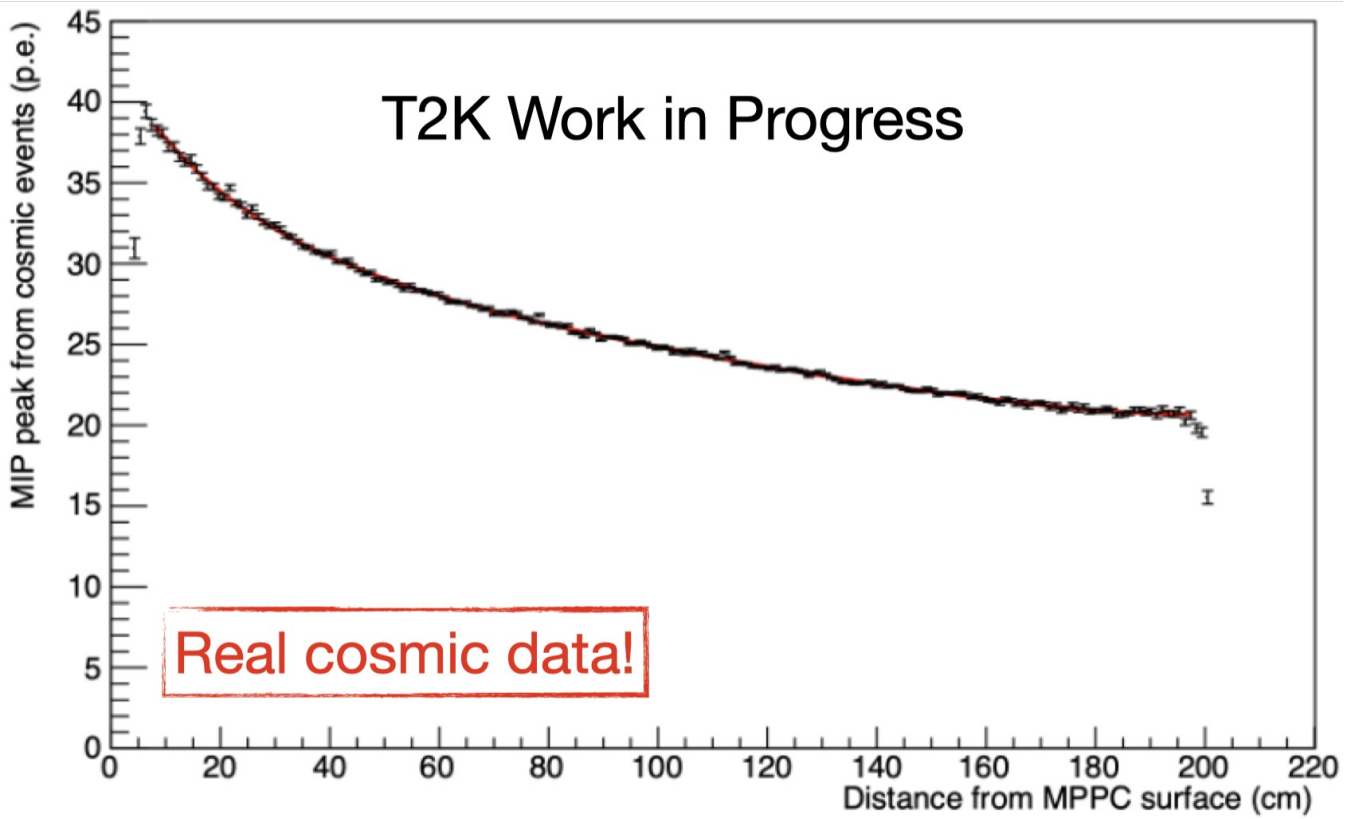
high gain vs Time over threshold (ToT)

→ exponential



Super FGD WLS Fiber Attenuation Length

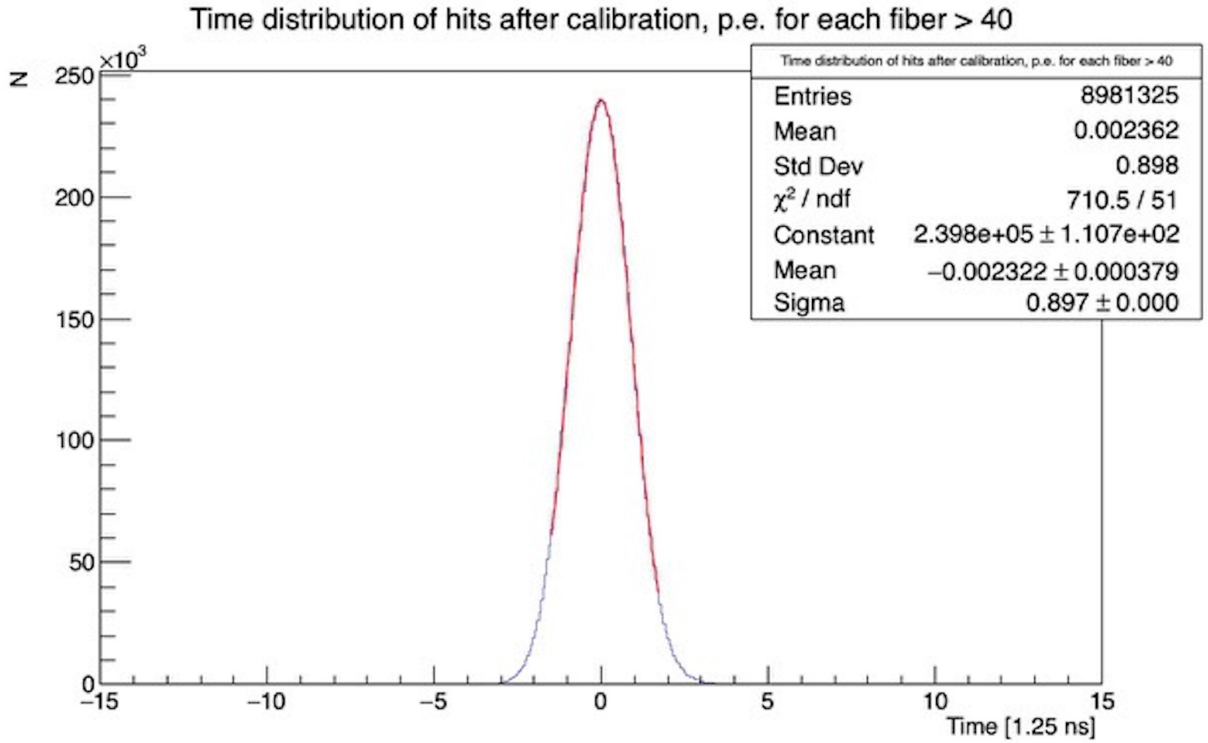
- 3D position information provides light yield and distance from MPPC
- Fit exponential function to extract attenuation length (long and short component)



→ Measurement consistent with WLS fiber specifications

Super FGD Performance: Time Resolution

- MIP signal in single cube in 2 horizontal WLS fibers (> 40 p.e. each)
- Preliminary time resolution: ~ 1.1 ns



Time = (mean time of single cube hits – mean time for event)

Summary and Outlook

- More sensitive measurements of neutrino oscillation parameters with the T2K experiment require reduced systematic uncertainties

- Highly granular Super FGD/ND280 upgrade detector provides
  - full phase space coverage
  - Lower energy threshold
  - Neutron detection capabilities

- Super FGD commissioned and started to take cosmic muon and neutrino beam data in Nov. 2023 and May/June 2024

- Quantitative Super FGD performance characterization in progress
  - Light yield, linearity of response, WLS fiber attenuation, timing resolution
  - Next: dE/dx measurements (use Bragg peak for proton identification), electron/gamma separation, neutron studies, …