



# Performance of 3D segmented neutrino detector SuperFGD in the T2K neutrino beam

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> 550 members  
76 institutions  
from 14 countries

# Long-Baseline Neutrino Oscillation Experiment



Super-K

Toyama

Kamioka Mine



JPARC

Tokai

Tokyo

Tokyo/Narita Airport

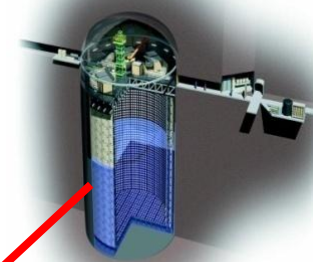
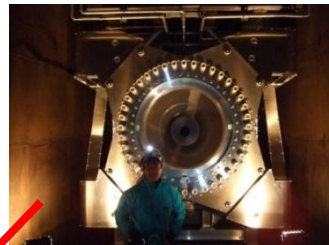
JAPAN



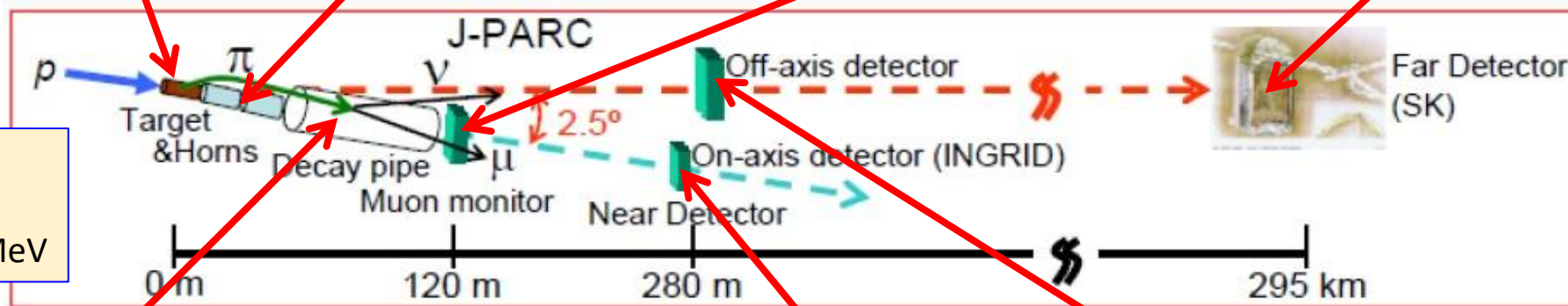


# Experiment T2K

T2K collects data since 2010



Far neutrino detector  
SuperKamiokande

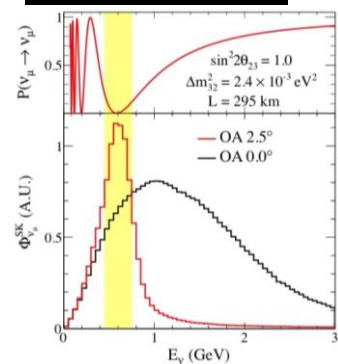


L = 295 km  
Off-axis  $\nu$  beam  
Peak energy 600 MeV

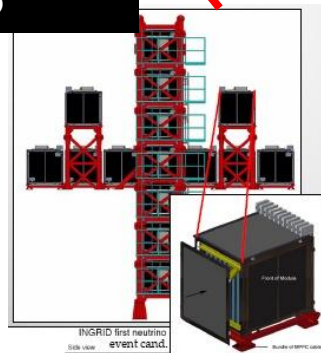
Decay tunnel



Off-axis neutrino beam

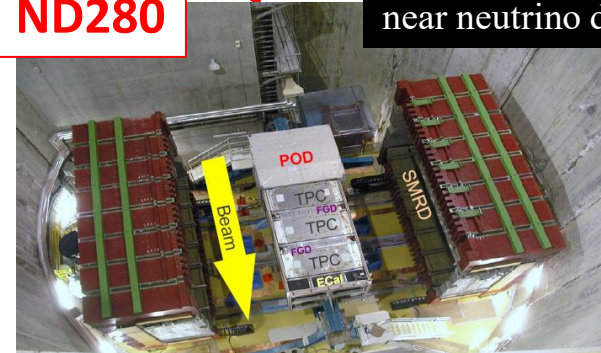


Neutrino monitor INGRID



ND280

Off-axis near neutrino detector

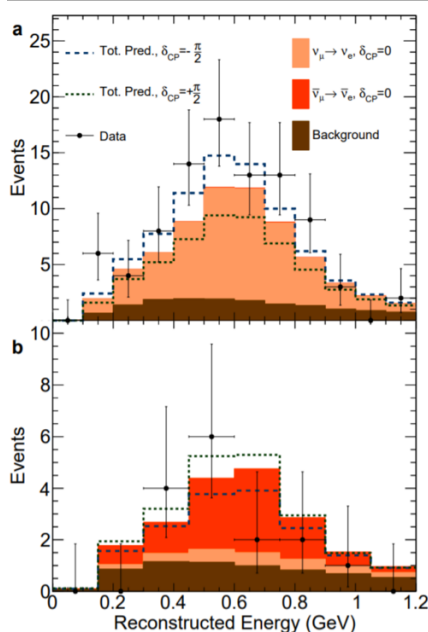




# Main T2K Results

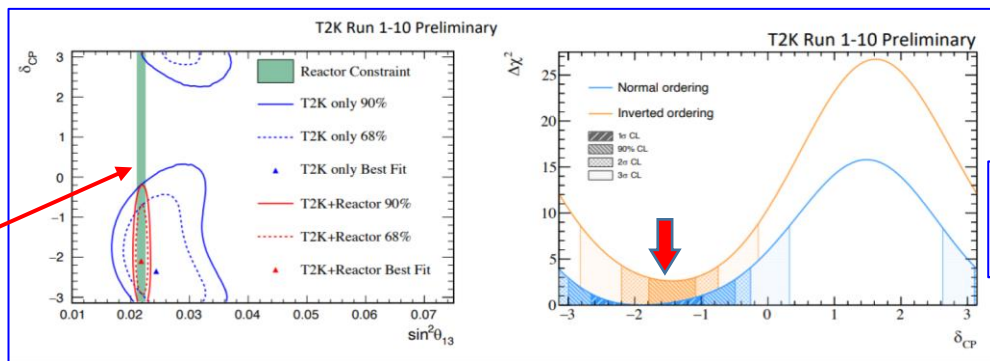


*Discovery*  
of  $\nu_\mu \rightarrow \nu_e$  oscillations



*Constraints on CP violating parameter  $\delta_{CP}$*

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \sim \sin \delta_{CP}$$



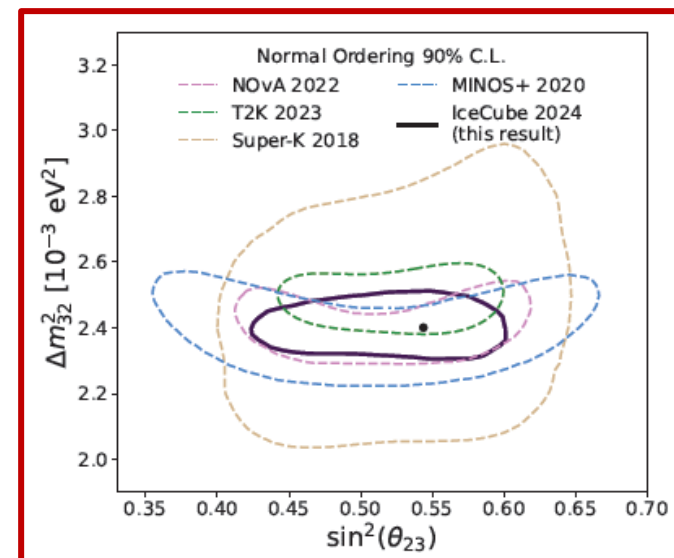
**Constraint on  $\theta_{13}$  from reactor experiments**  
Daya Bay,  
RENO,  
DChooz

**Indication of maximal CP violation in neutrino oscillations  $\delta_{CP} \sim -\pi/2$**

*Measurements of oscillation parameters  $\sin^2(\theta_{23})$  and  $\Delta m^2_{32}$*



arXiv:2405.02163



35% of  $\delta_{CP}$  values excluded at  $3\sigma$  marginalized over hierarchies  
CP conserving values ( $\delta_{CP} = 0, \pi$ ) excluded at  $>90\%$

*Nature* 580 (2020) 7803, 339-344

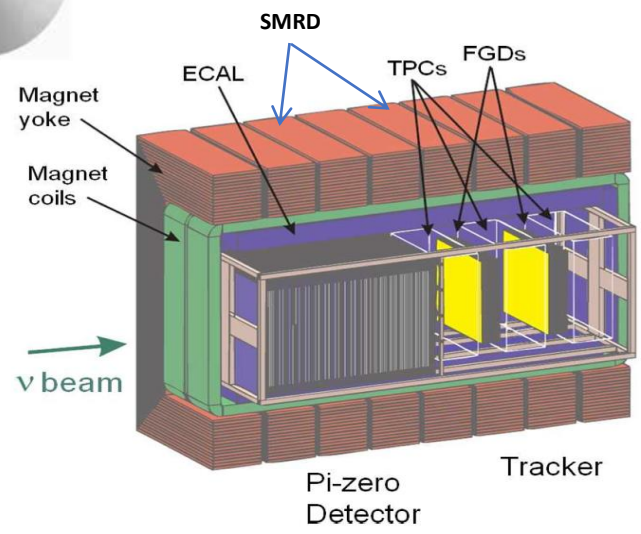
**Normal mass ordering is preferred at 80% CL**



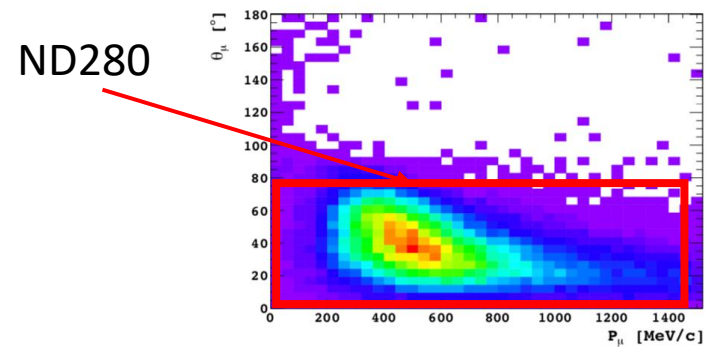
# Original T2K Near Detector ND280



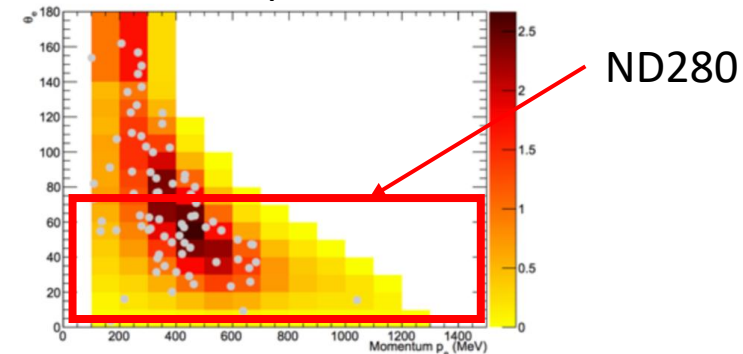
- Placed at 280 m from the target
- Measures the flux, flavor content, energy spectrum of the neutrino beam, studies neutrino-nucleus interactions



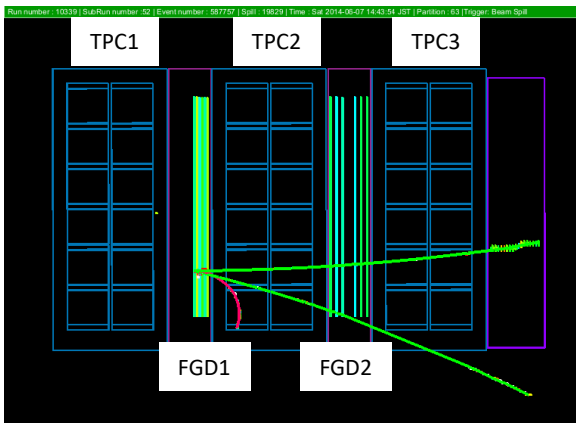
Muons in ND280:  
- forward direction



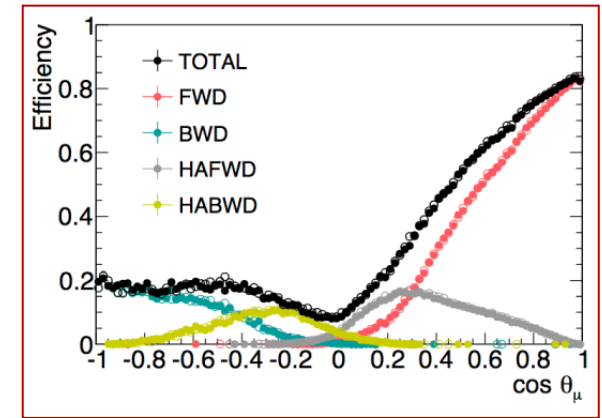
$\nu_e$  detection in SuperK:  
-  $4\pi$  acceptance



$\nu$  interaction  
in ND280



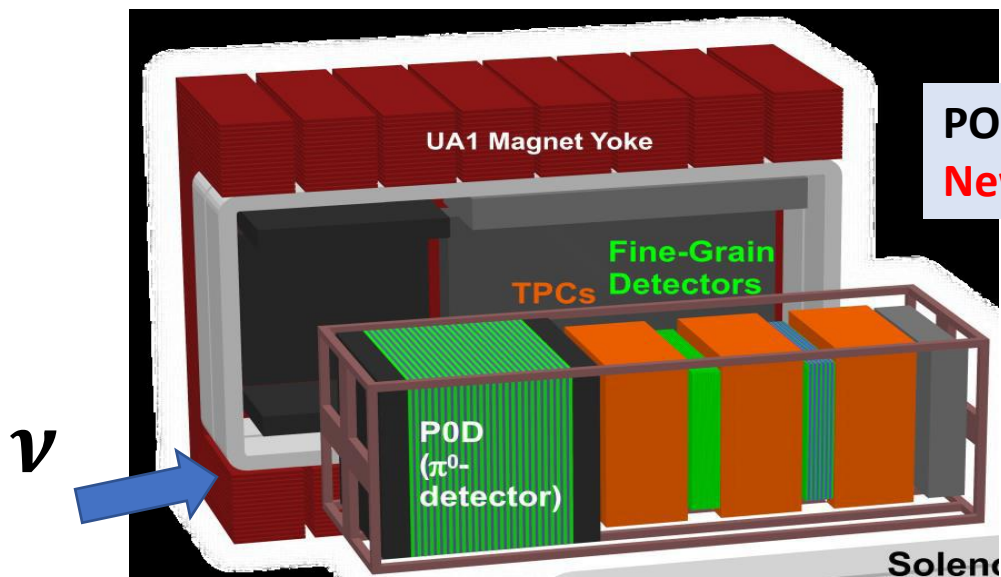
- ### Limitations
- Momentum threshold for protons 450 MeV/c (100 MeV kinetic energy);
  - Non-CCQE interaction (2p2h, FSI) observed as CCQE;
  - Low high-angle acceptance, Super-Kamiokande -  $4\pi$  acceptance;
  - No capability to detect neutrons



- New upstream detectors**
- 3D fine-grained scintillator target/detector **SuperFGD**
  - Two Horizontal TPCs
  - TOF system around new tracker

arXiv:1901.03750

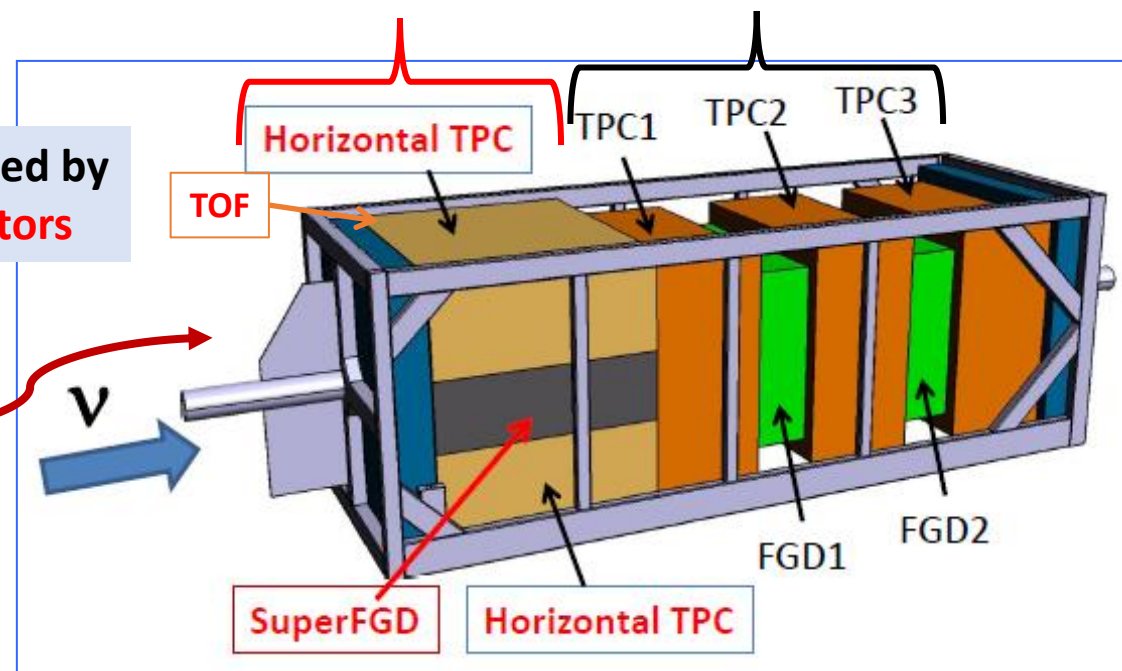
Original ND280 complex



POD replaced by **New Detectors**

**New detectors**

**Old detectors**





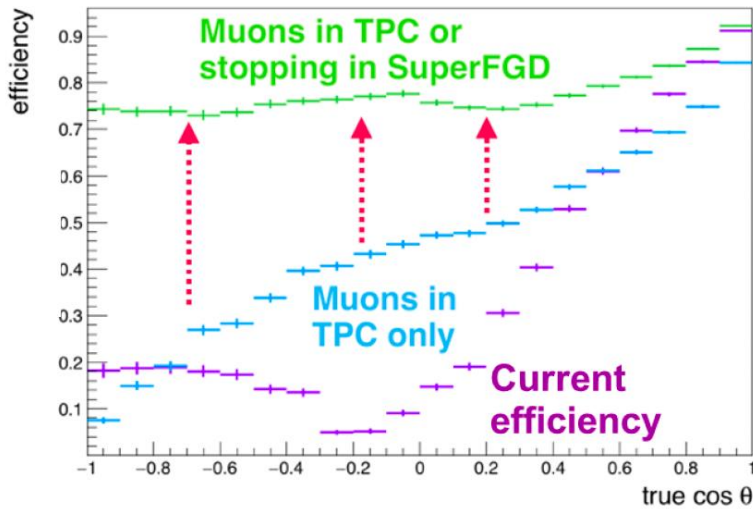
# Features of upgraded ND280



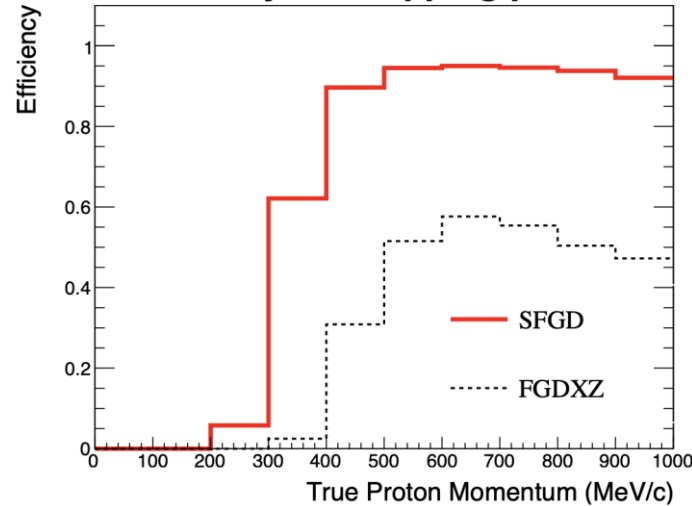
- SuperFGD improves acceptance for high angle and backward tracks
- SuperFGD provides a high precision probe of the nuclear effects responsible for some of the dominant systematics in neutrino oscillation analyses → reduced systematics
- High granularity of SuperFGD → detection of short proton tracks which is very important for T2K analysis
- SuperFGD measures the neutrino energy by time-of-flight



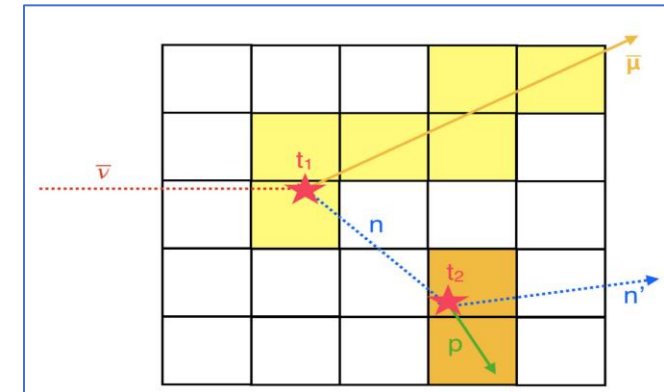
### High angle acceptance



### Efficiency for stopping protons



### Neutron detection by SuperFGD using time-of-flight





# SuperFGD



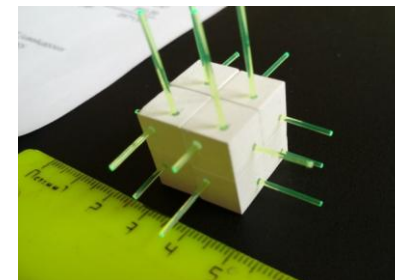
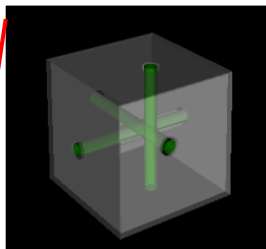
JINST 13 (2018) 02006

- Volume  $\sim 192 \times 184 \times 56 \text{ cm}^3$
- $\sim 2 \times 10^6$  scintillator cubes, each  $1 \times 1 \times 1 \text{ cm}^3$
- Each cube has 3 orthogonal holes of 1.5 mm diameter
- 3D (x,y,z) WLS readout
- About 60000 readout WLS/MPPC channels
- Total active weight about 2t

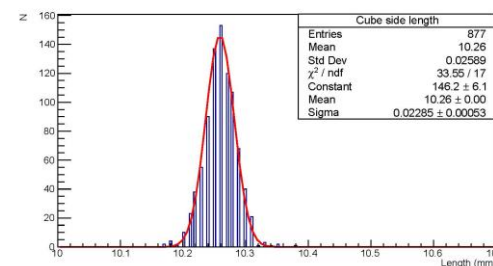
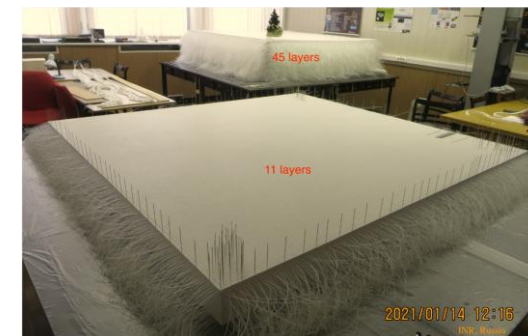
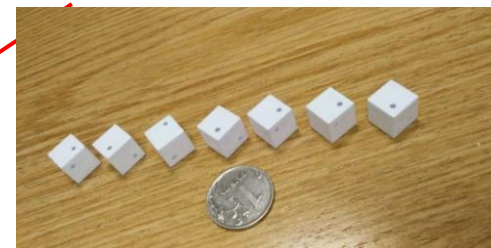
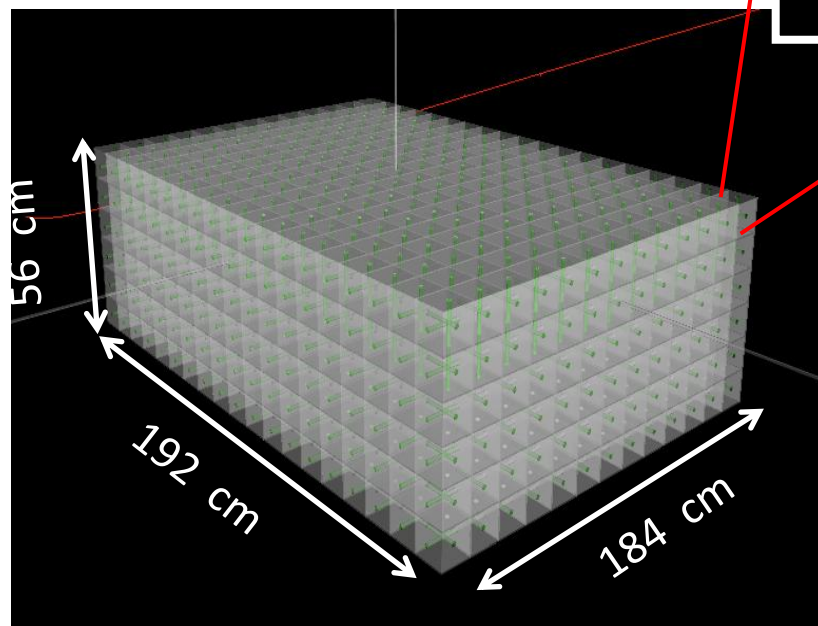
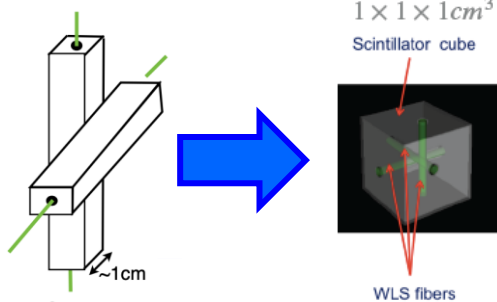
Fully active, highly granular,  
 $4\pi$  scintillator neutrino detector  
 with 3D WLS/MPPC readout

- Cubes produced by injection molding
- Covered by chemical reflector
- Tolerance (each side) about 30 microns

SuperFGD project: about 100 participants from France, Japan, Russia, Spain, Switzerland, UK, USA and CERN



ND280 FGD  $\rightarrow$  SuperFGD





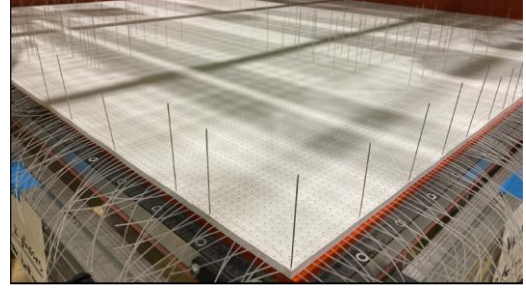
# Assembly of SuperFGD at J-PARC



Installation of cube layers



Transfer to new support frame



Fishing lines → WLS fibers

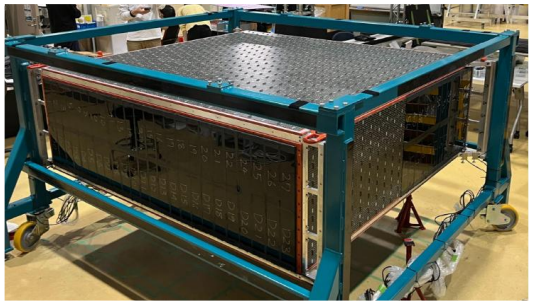


Installation of MPPC-PCB

Installation of soft foam



Installation of LED calibration system



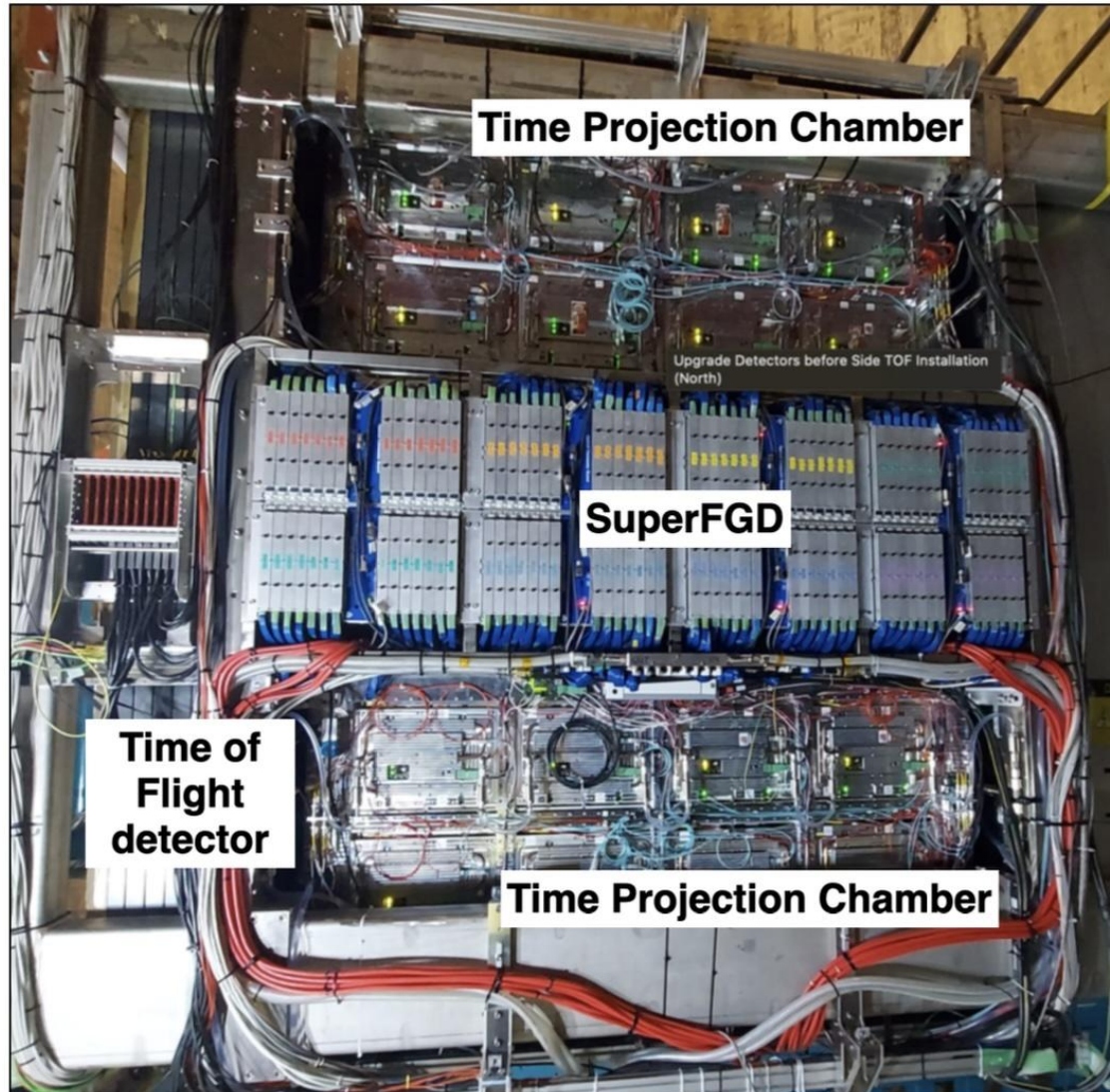
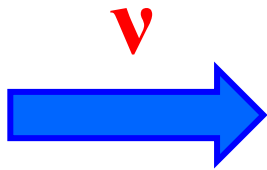
Cabling



- 200000 cubes produced  
in 2019-2021  
Detector assembly at J-PARC  
in 2022-2023



# New detectors in ND280 magnet



- Installation of all detectors (SuperFGD, HA-TPC, TOF) into ND280 magnet completed in Spring 2024
- Data taking with beam neutrinos begun in May 2024



# Calibration of SuperFGD

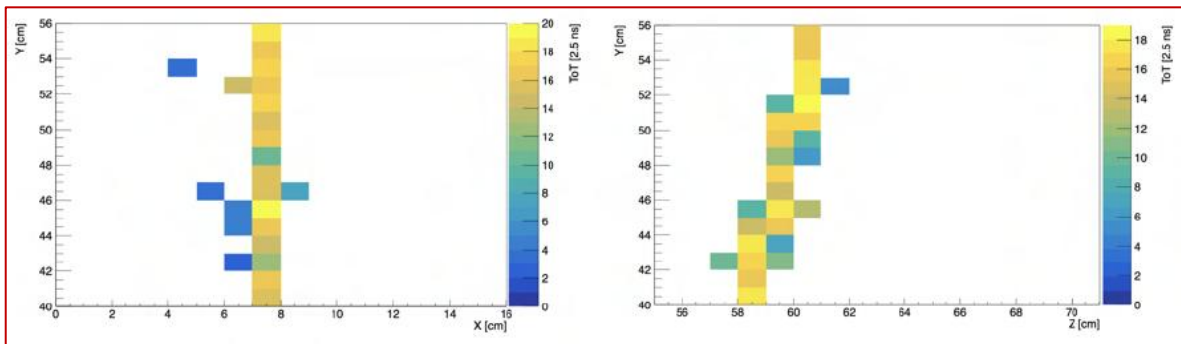
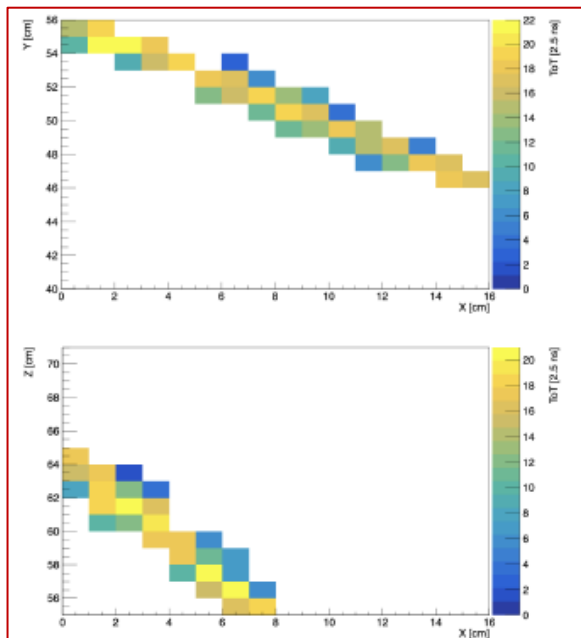
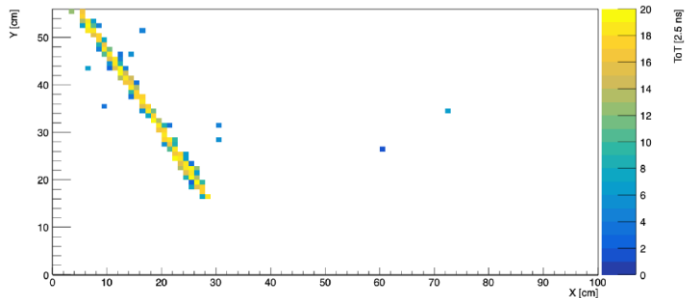


$\mu$

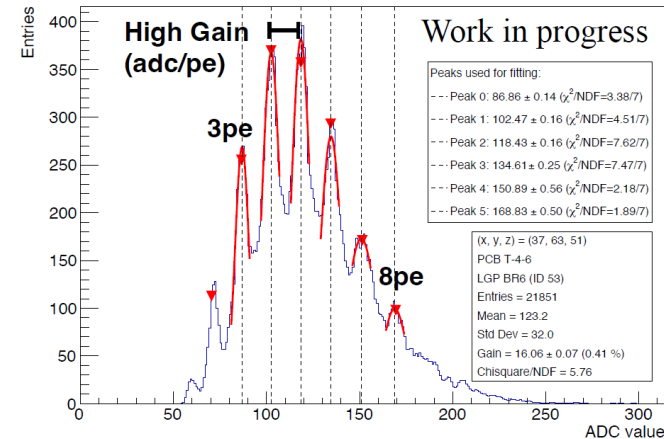
Cosmic events: muon tracks



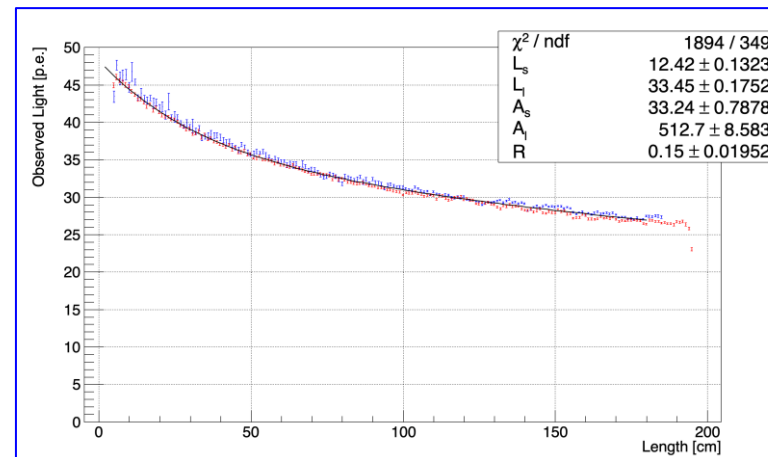
Event\_15167\_XY



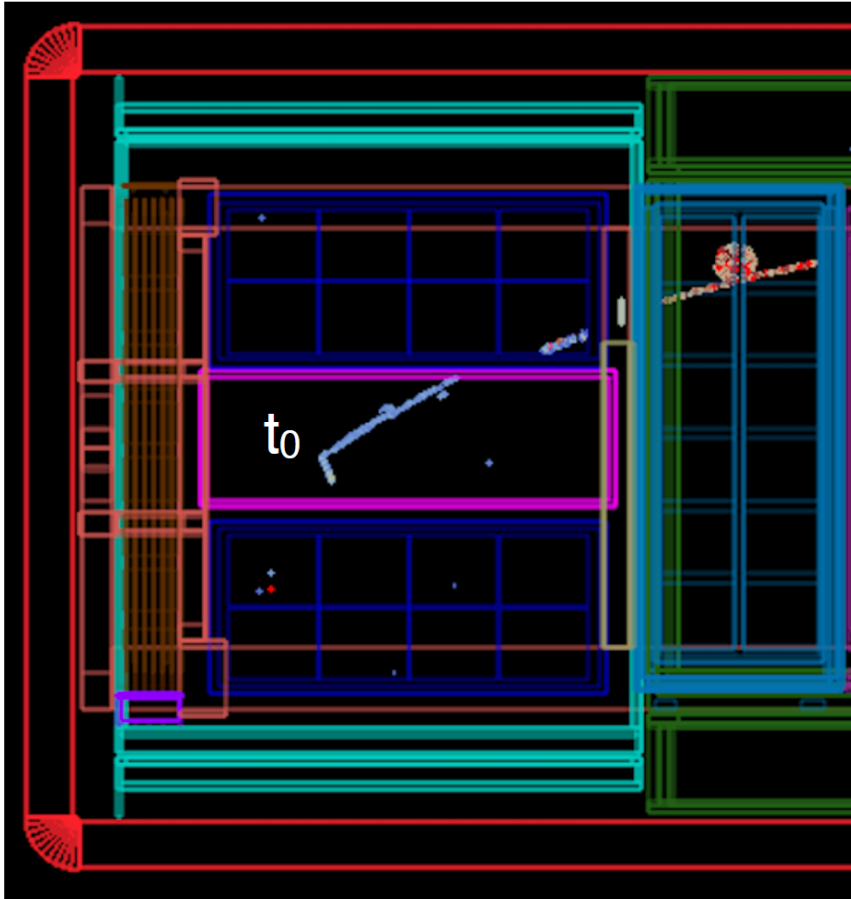
## LED calibration in photoelectrons



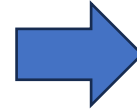
## Light Yield per MIP and attenuation of WLS fibers



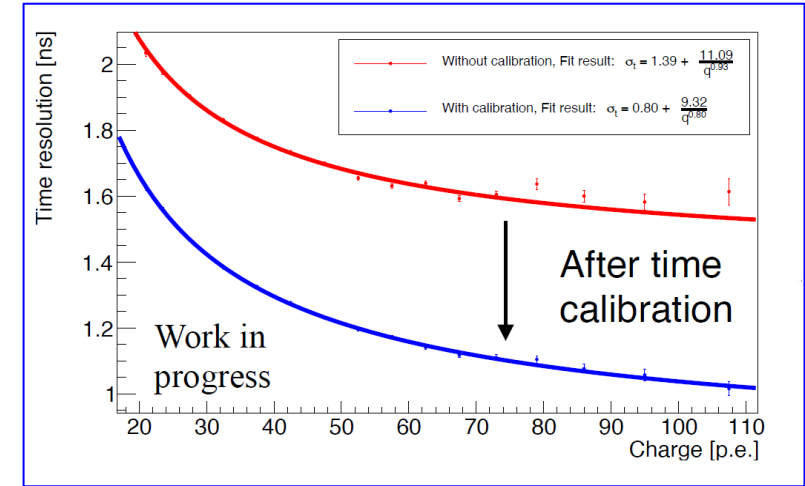
# Time resolution



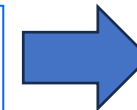
**Time resolution of a single cube**



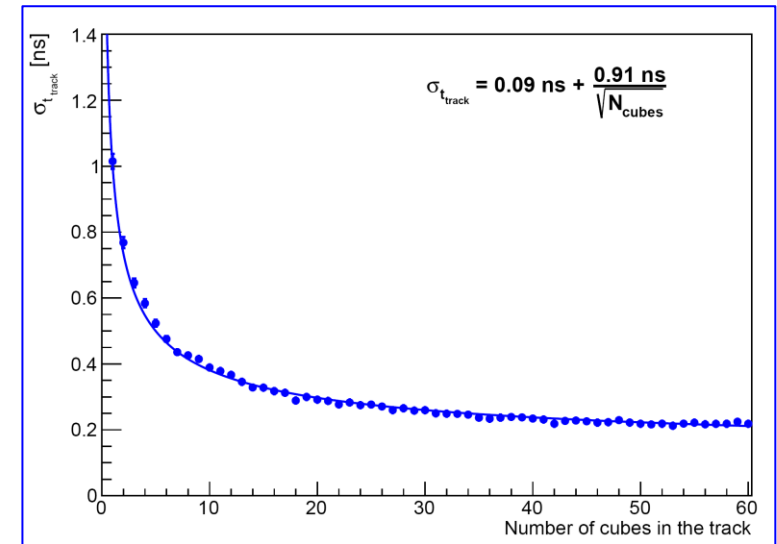
$\sigma(t)_{\text{single channel}} \sim 1.3\text{-}1.4 \text{ ns}$   
at 1 m distance from MPPC



**Time resolution of a long muon track**

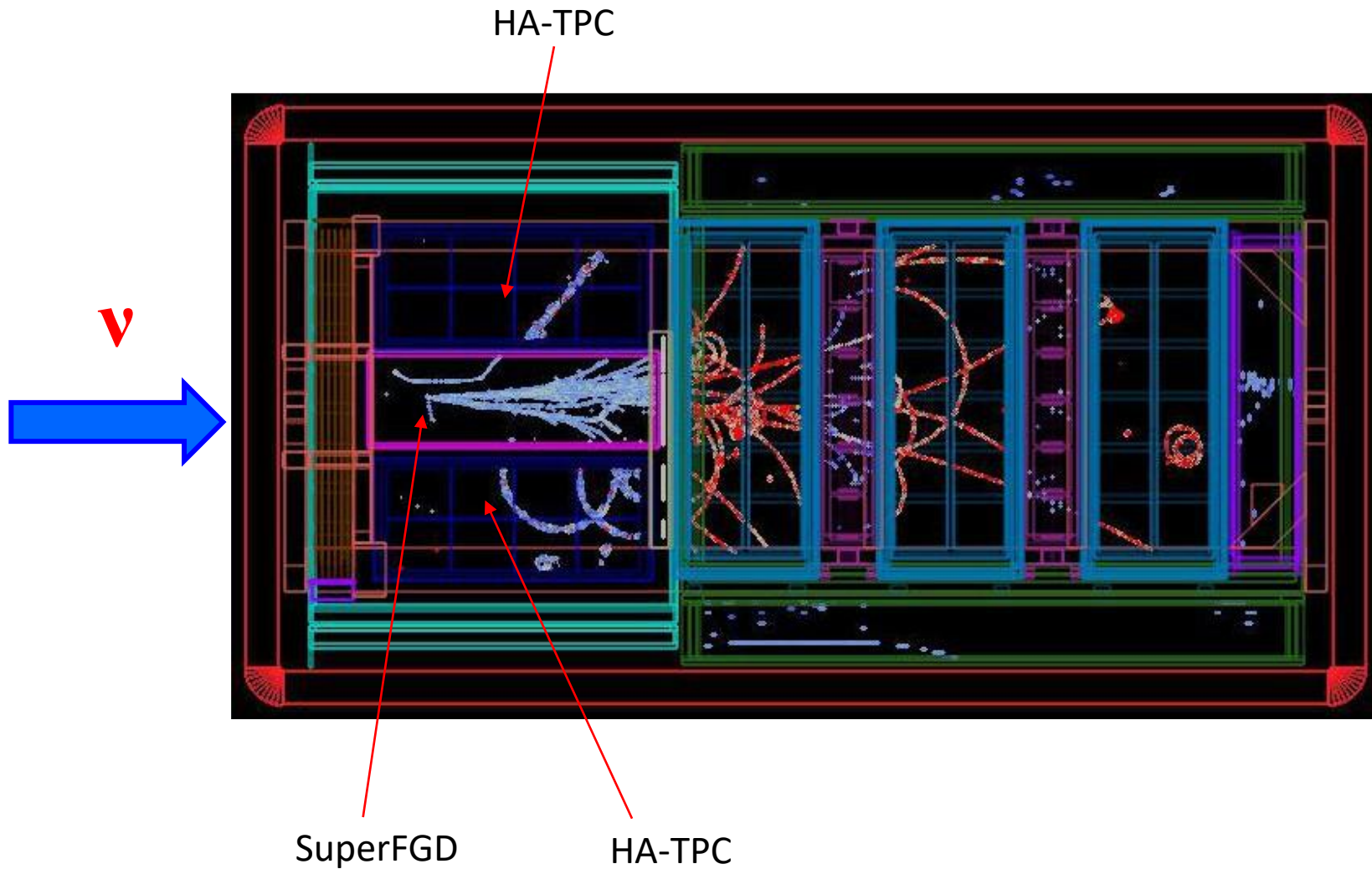


Precise time calibration and determination of the time of event  $t_0$





# Neutrino event in SuperFGD



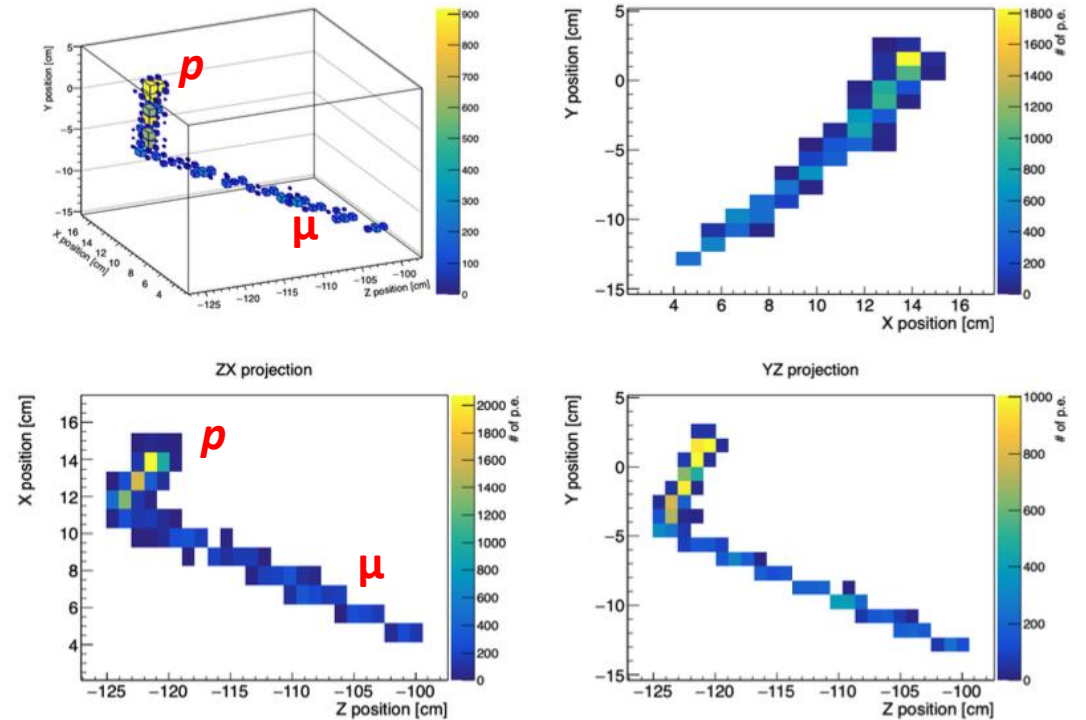
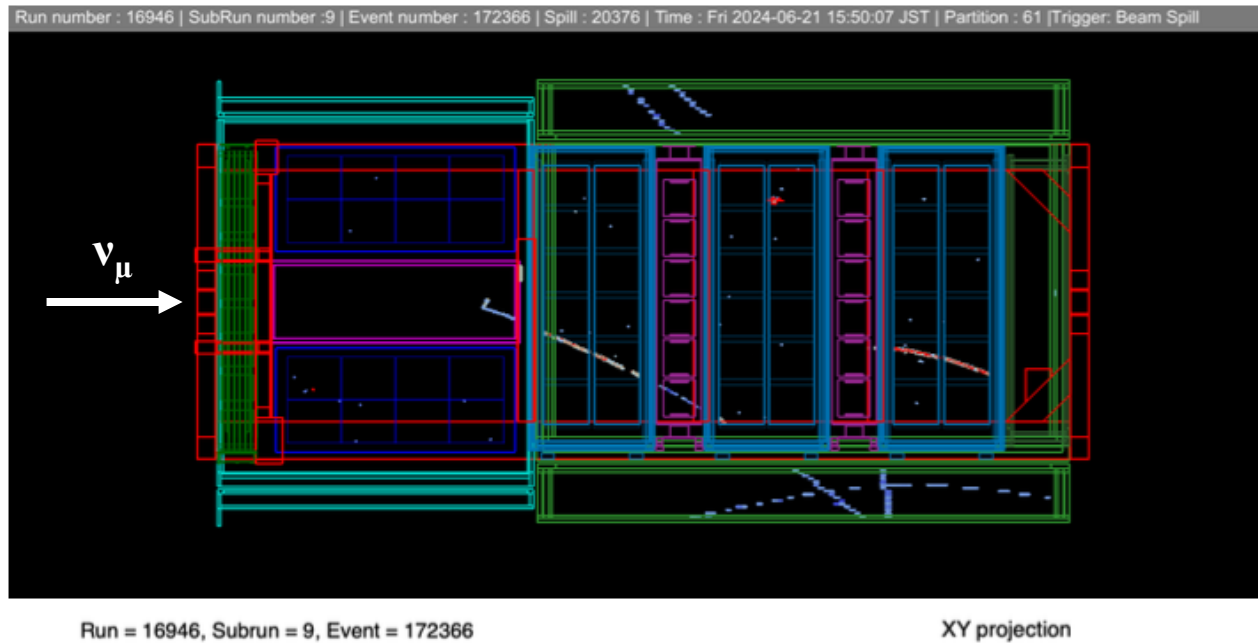
Display one of the first neutrino events in SuperFGD



# Neutrino interactions in SuperFGD (I)



$\nu_\mu$  CC interaction in SuperFGD





# Neutrino interactions in SuperFGD (II)

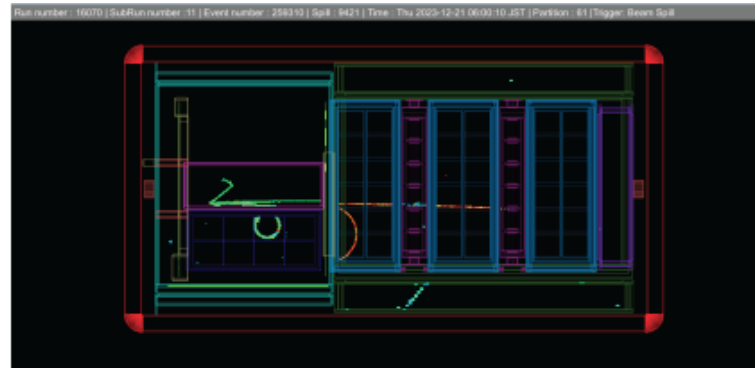
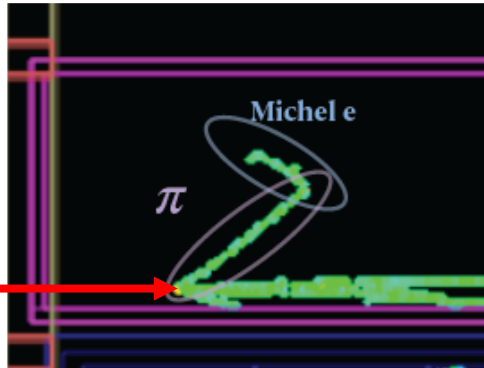


SuperFGD

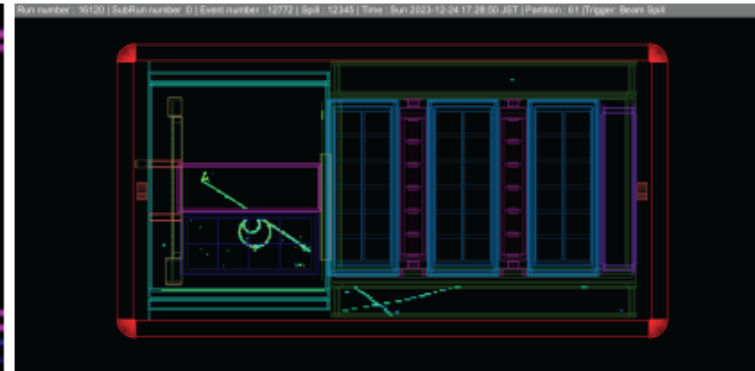
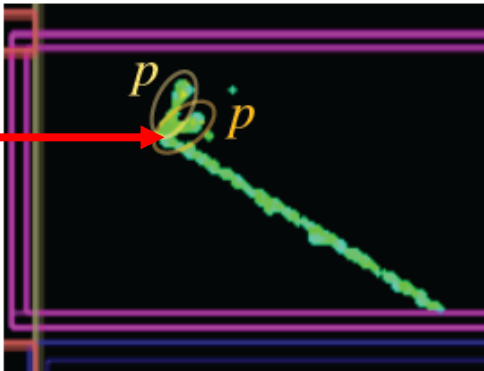
ND280



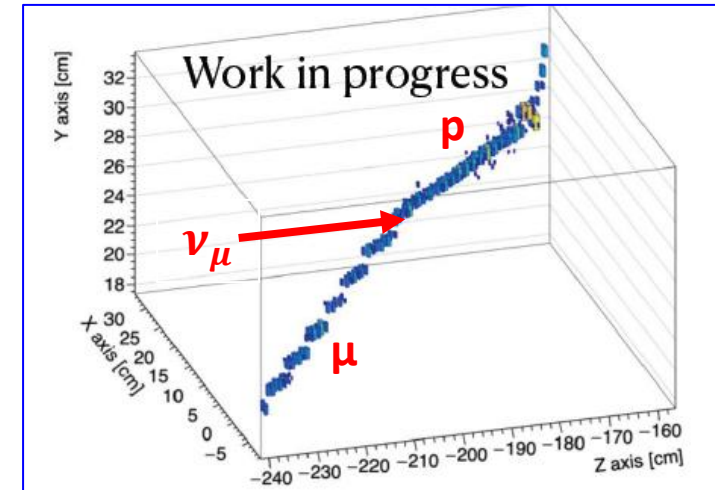
$\nu_\mu$



$\nu_\mu$



3D reconstructed tracks



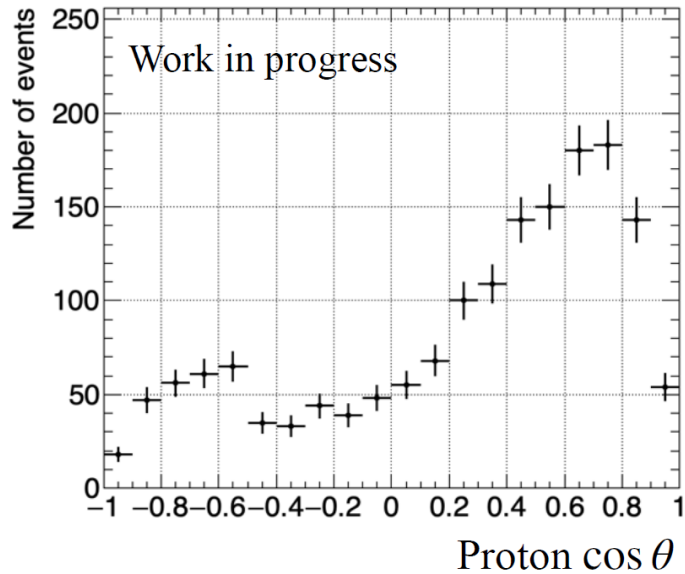
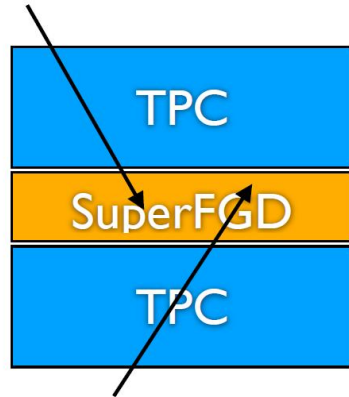
T2K muon neutrino beam, charged current events



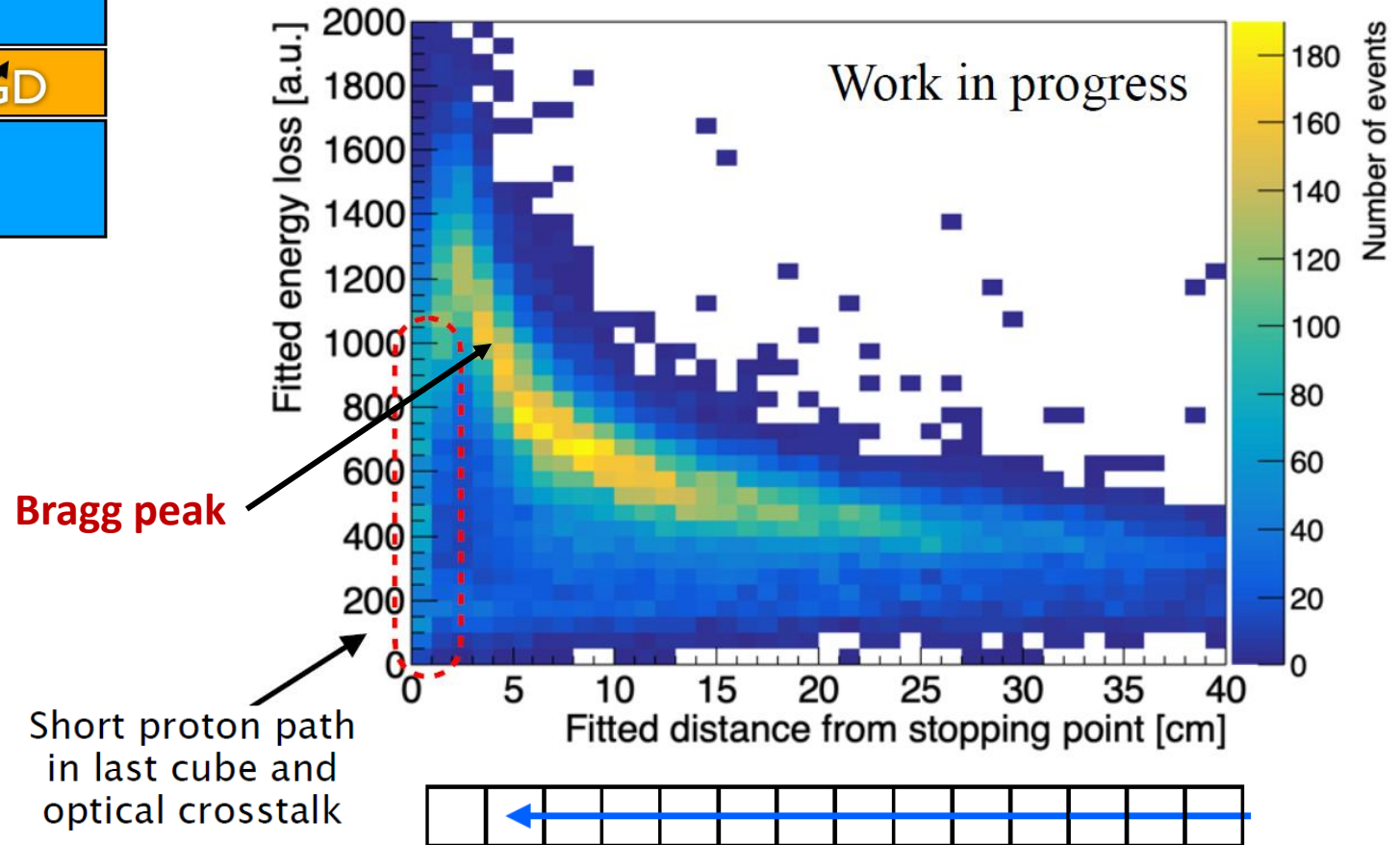
# Detection of stopped protons



Protons from TPC  
stopped in SuperFGD



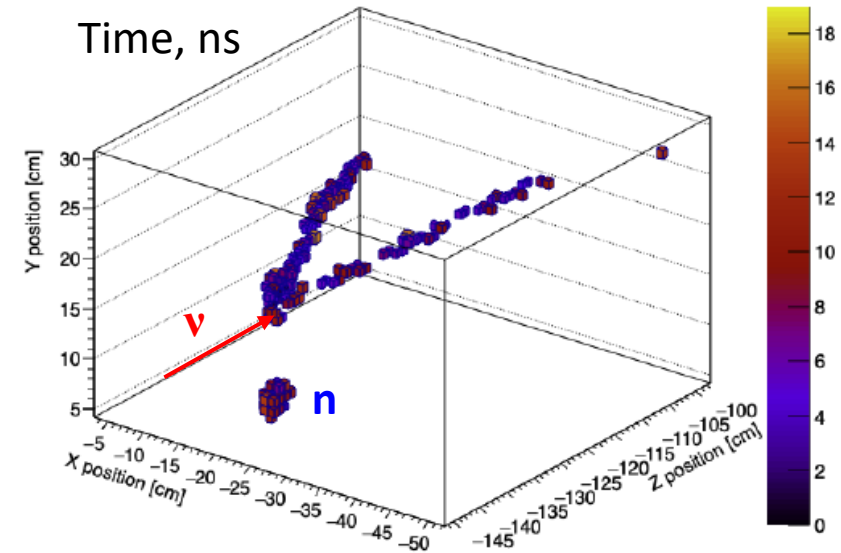
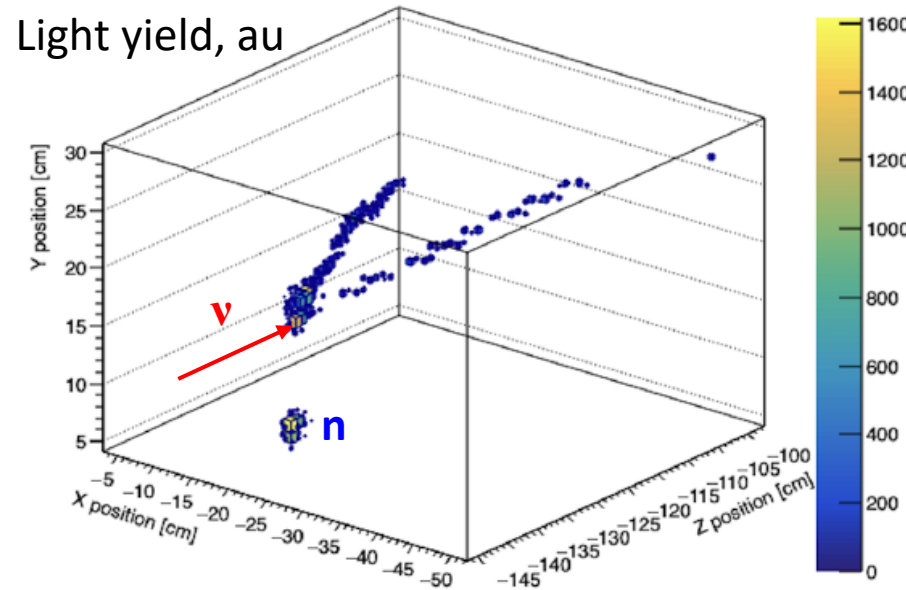
Fitted energy loss per cube of  
protons stopping in SuperFGD



# Detection of neutrons

Charged current neutrino interaction in SuperFGD with a neutron in the final state

## 3D event



Neutrons deposit an energy in the form of a track or a cluster away from the neutrino interaction vertex



# Conclusion



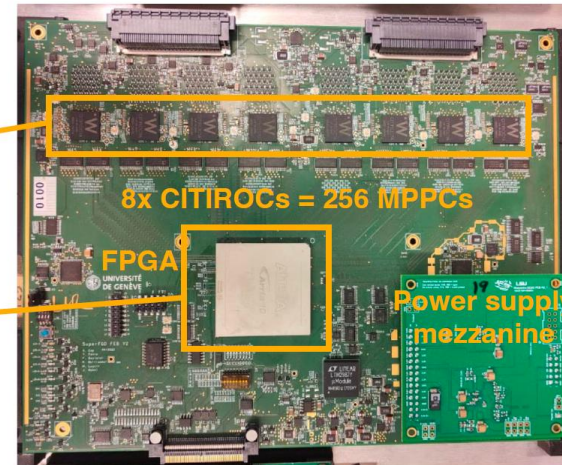
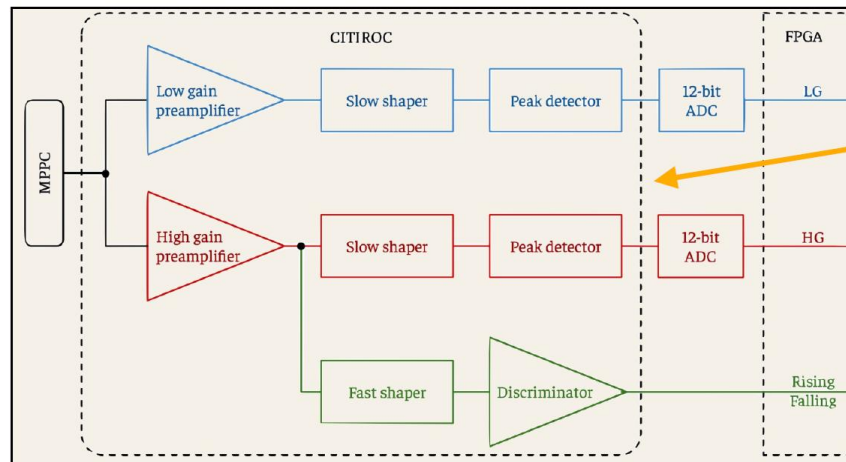
- ❑ Upgraded T2K near detector ND280 with a new neutrino target-detector SuperFGD – crucial for CP-violation search and oscillation measurements in T2K and HyperK
- ❑ Main features of SuperFGD: high segmentation; 3D readout;  $4\pi$  solid angle; good time resolution; excellent identification of  $e$ ,  $\gamma$ ,  $p$ ; low proton threshold  $\sim 300$  MeV/c, neutron detection by ToF
- ❑ SuperFGD should greatly improve T2K's ability to constrain neutrino interaction models
- ❑ SuperFGD is now taking data with T2K neutrino beam

**Thank you for your attention**

# Backup slides

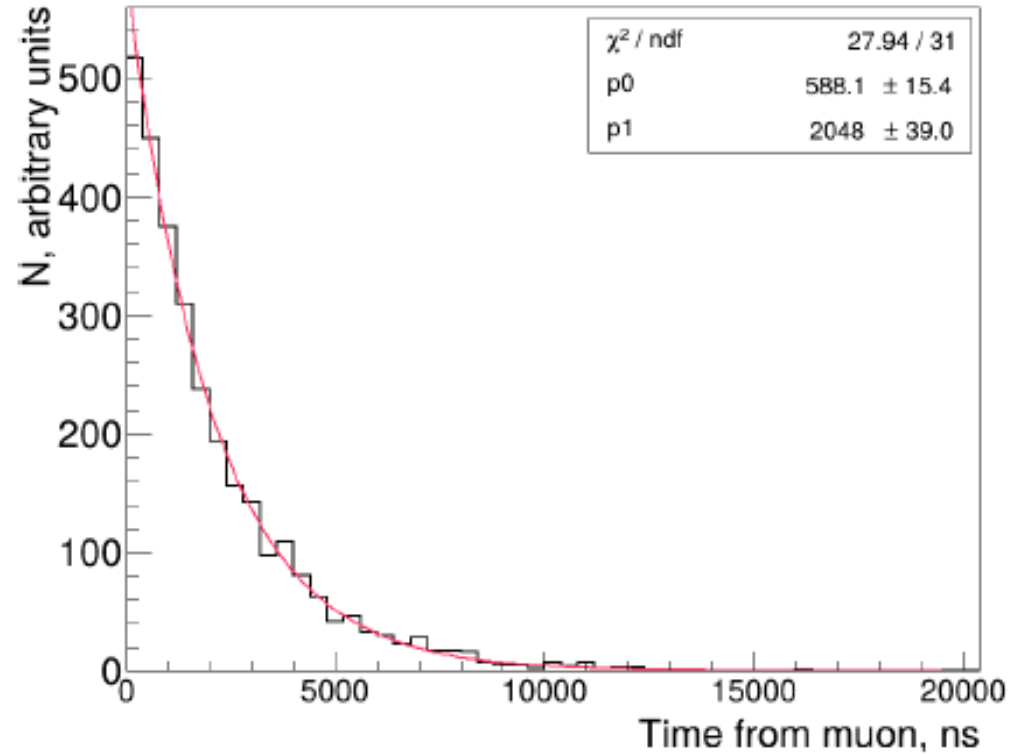
# SuperFGD Electronics

- MPPC analogue signal digitised by CITIROC (Omega lab. Ecole Polytechnique)
- Peak detector, Low-gain and High-gain signals (2x 12-bit ADCs)
- Constant threshold discriminator → rising edge and falling edge timestamps
  - ✓ Complementary measurement of charge from time-over-threshold
  - ✓ FPGA at 400 MHz sampling (single channel 0.7 ns resolution)
    - measure the neutron time of flight
  - ✓ Firmware upgrade will provide 800 MHz, sampling on clock rising/falling edges





# Decay of stopped muons



- Time distribution of Michel electrons events from stopped positive and negative cosmic muons
- Decay time is 2.05  $\mu\text{s}$
- Slightly lower 2.2  $\mu\text{s}$ , due to capture of a fraction of  $\mu^-$ -before decay