3D сегментированный детектор нейтрино СуперFGD

Юрий Куденко

ИЯИ РАН

Сессия-конференция
«Физика фундаментальных взаимодействий»,
посвященную 70-летию В. А. Рубакова
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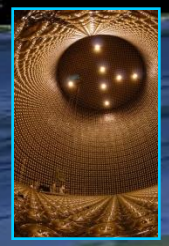
Supported by the RSF grant # 24-12-00271

Long-Baseline Neutrino Oscillation Experiment

> 550 members
76 institutions
from 14 countries
Russai: INR, JINR



Super-K

Toyama

Kamioka Mine

JPARC

Tokai

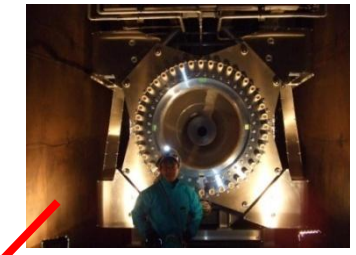
Tokyo

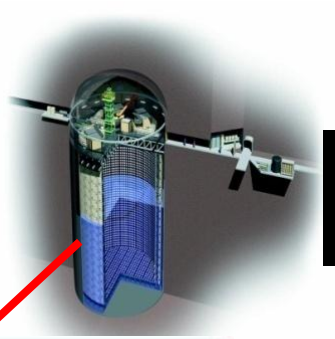
Tokyo/Narita Airport

JAPAN

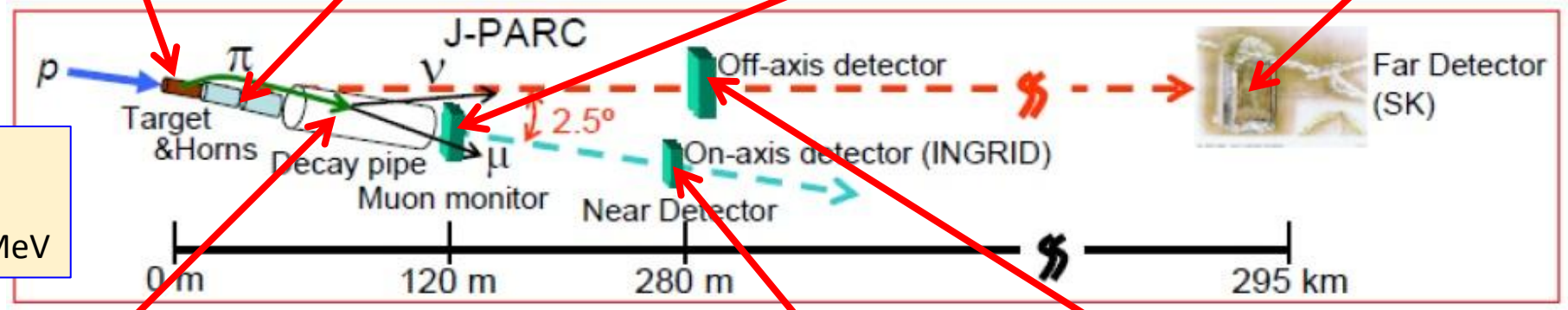
Experiment T2K

T2K collects data since 2010





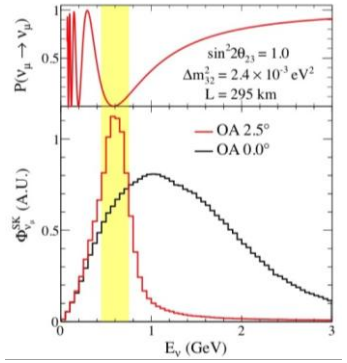
Far neutrino detector SuperKamiokande



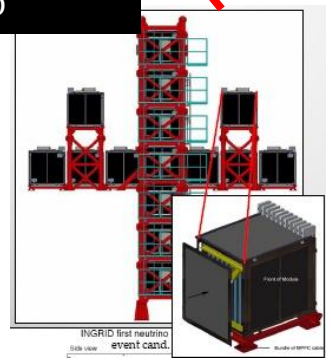
L = 295 km
Off-axis ν beam
Peak energy 600 MeV

Decay tunnel

Off-axis neutrino beam

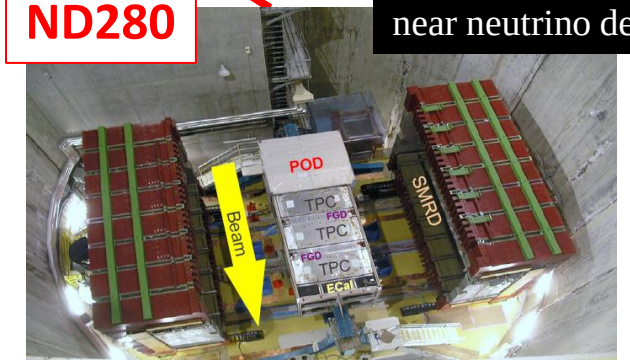


Neutrino monitor INGRID



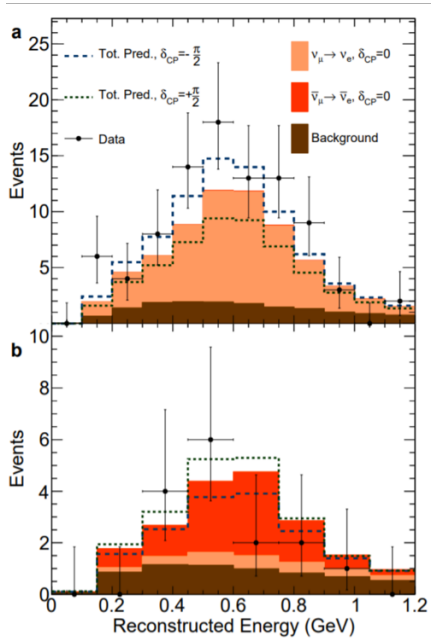
ND280

Off-axis near neutrino detector



Main T2K Results

Discovery of $\nu_\mu \to \nu_e$ oscillations

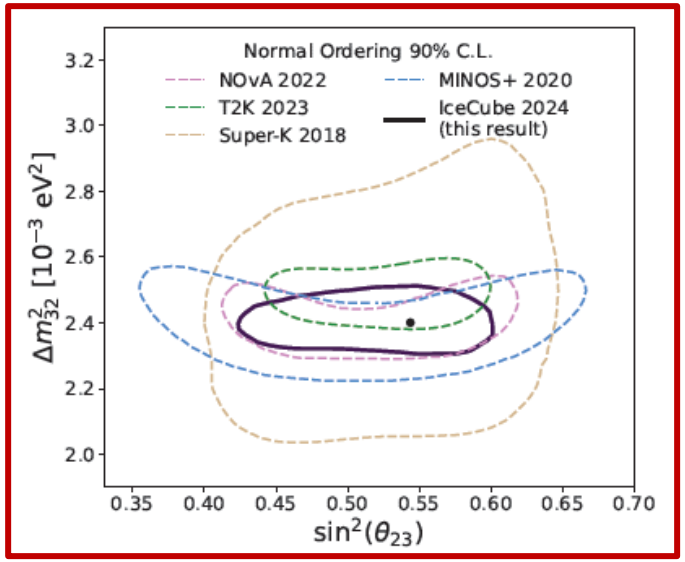


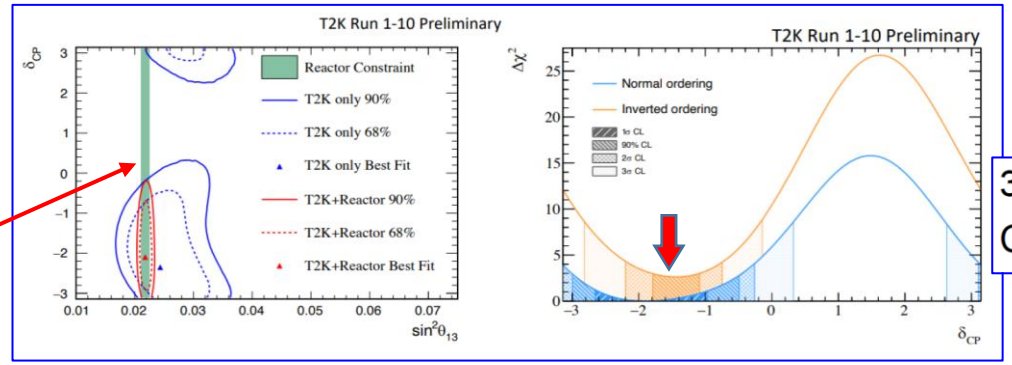
Constraints on CP violating parameter δ_{CP}

$$A_{CP} = \frac{P(\nu\mu \to \nu e) - P(\bar{\nu}\mu \to \bar{\nu} e)}{P(\nu\mu \to \nu e) + P(\bar{\nu}\mu \to \bar{\nu} e)} \sim \sin\delta_{CP}$$

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

arXiv:2405.02163





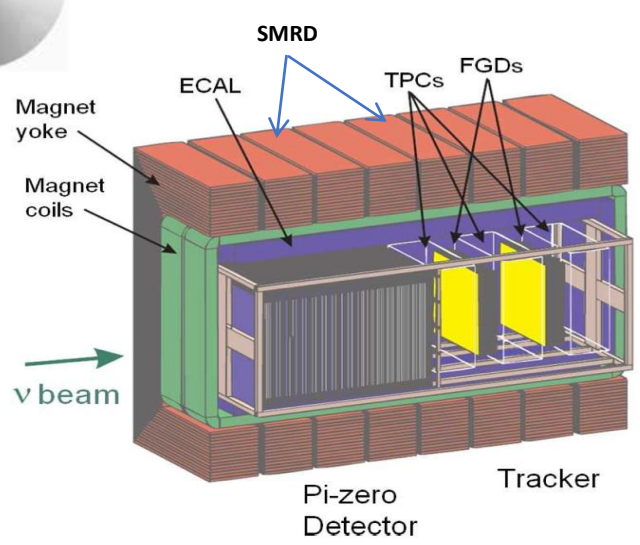
Constraint on θ_{13} from reactor experiments Daya Bay, RENO, DChooz

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

Normal mass ordering is preferred at 80% CL

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

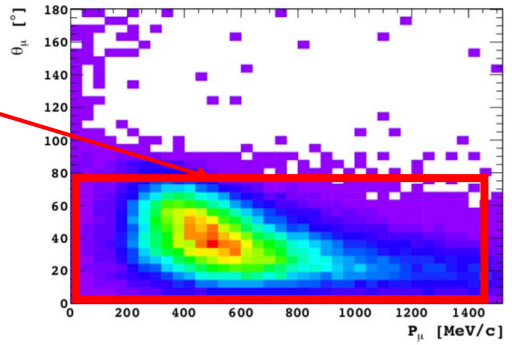
T2K Near Detector ND280



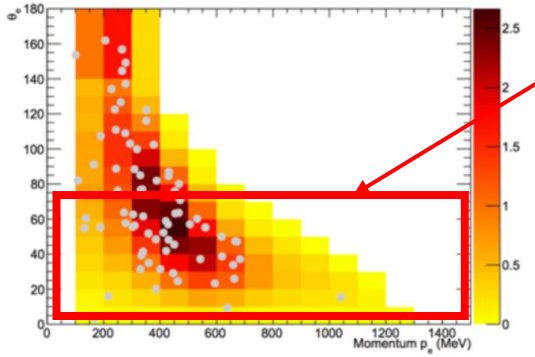
- Placed at 280 m from the target
- Measures the flux, flavor content, energy spectrum of the neutrino beam, studies neutrino-nucleus interactions

Muons in ND280:
- forward direction

ND280

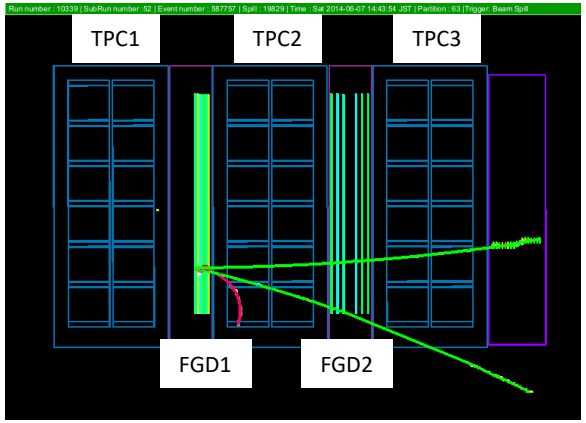


ν_e detection in SuperK:
- 4π acceptance



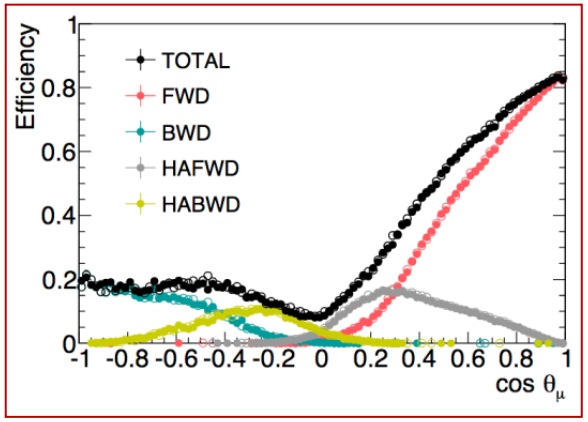
ND280

ν interaction in ND280



Current ND280

- **Momentum threshold for protons 450 MeV/c (100 MeV kinetic energy);**
- **Non-CCQE interaction (2p2h, FSI) observed as CCQE;**
- **Acceptance for tracks in forward direction, SuperKamiokande - 4π acceptance;**
- **Larger oscillation systematic uncertainties due to tracks not measured by TPCs**
- **No capability to detect neutrons**

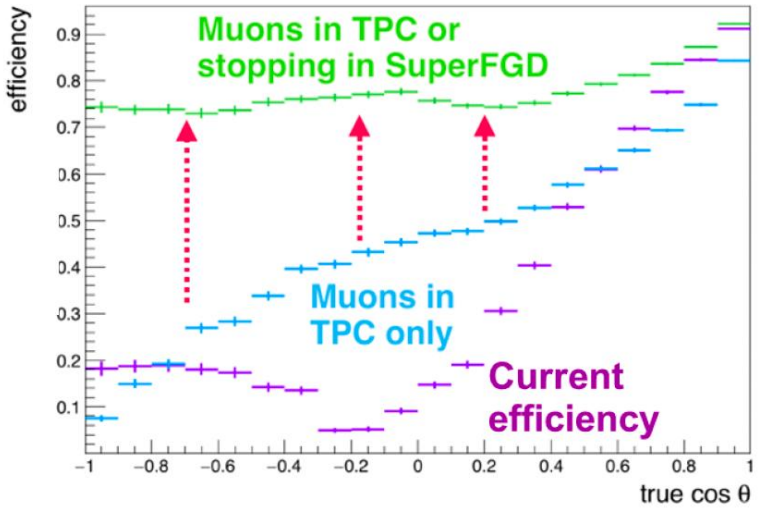


Features of upgraded ND280

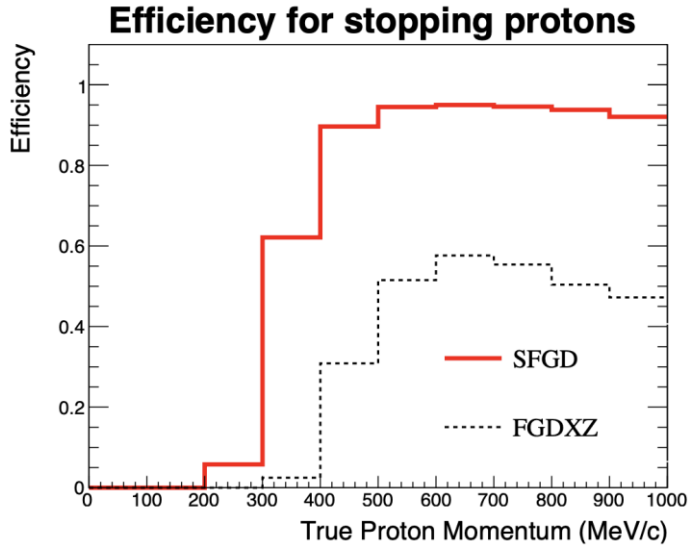
Current ND280 ⇒ ***Upgraded ND280***

- **SuperFGD and HA-TPC improve 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 provides reconstruction of the neutrino energy by time-of-flight**
- **TOF Detector separates background from outside SuperFGD and HA-TPC**

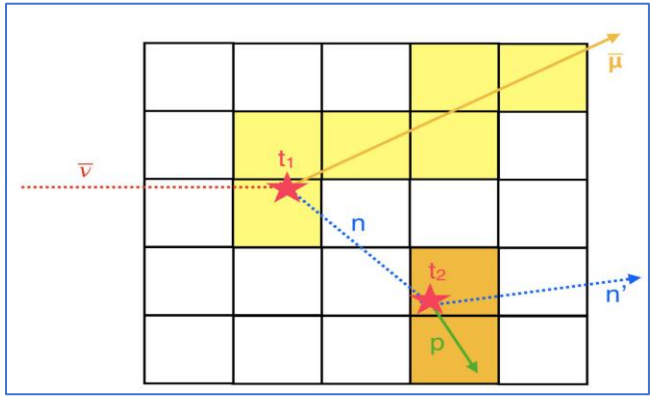
High angle acceptance



Efficiency for stopping protons



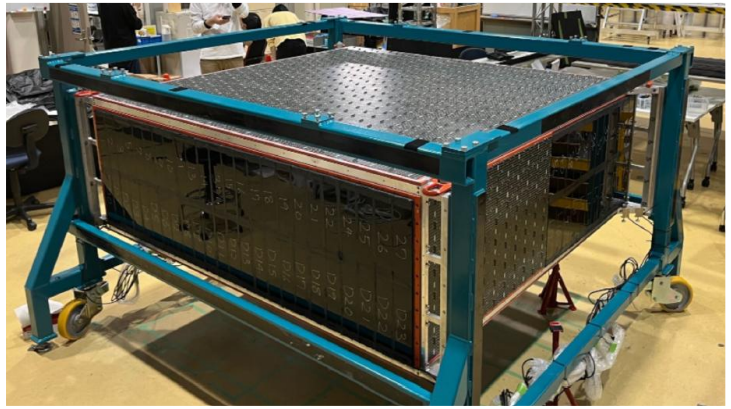
Neutron detection by SuperFGD using time-of-flight



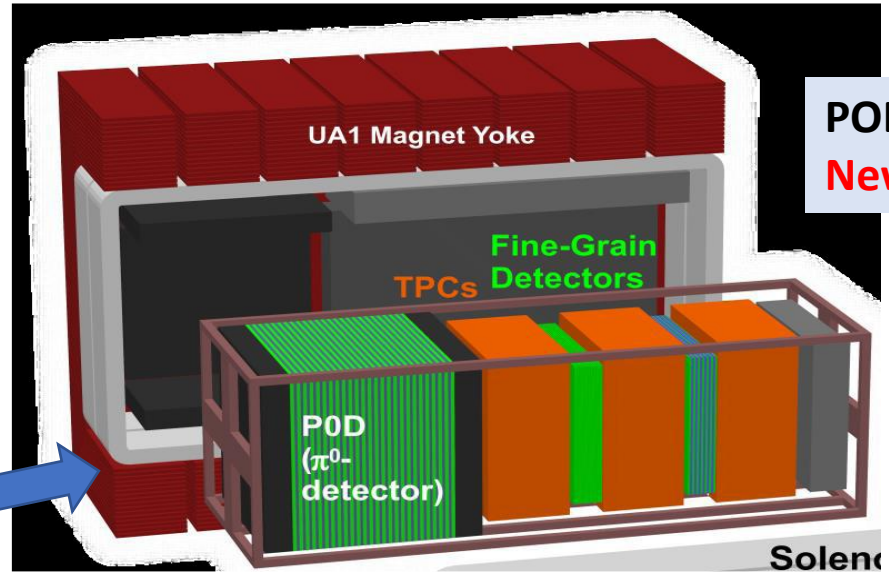
ND280 upgrade

arXiv:1901.03750

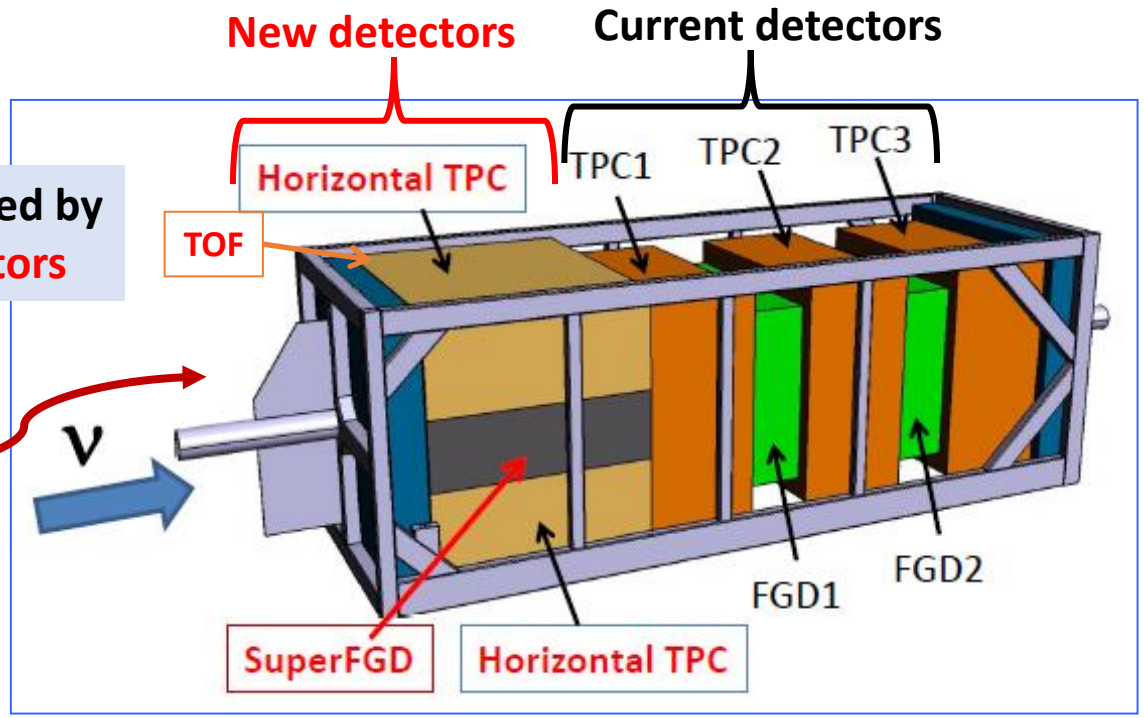
New upstream detectors
- **3D fine-grained scintillator target/detector SuperFGD**
- **Two Horizontal TPCs**
- **TOF system around new tracker**



Current ND280 complex



POD replaced by New Detectors



SuperFGD

- Volume ~192 x 184 x 56 cm^3
- ~2 x 10^6 scintillator cubes , each 1 x 1 x 1 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

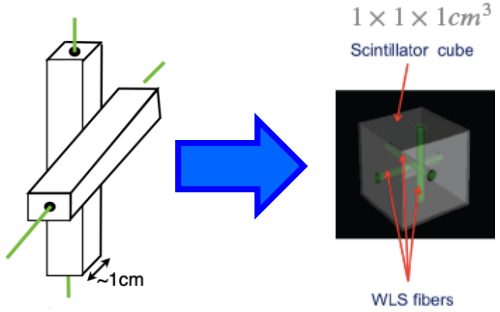
Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout - proposed at INR in 2017

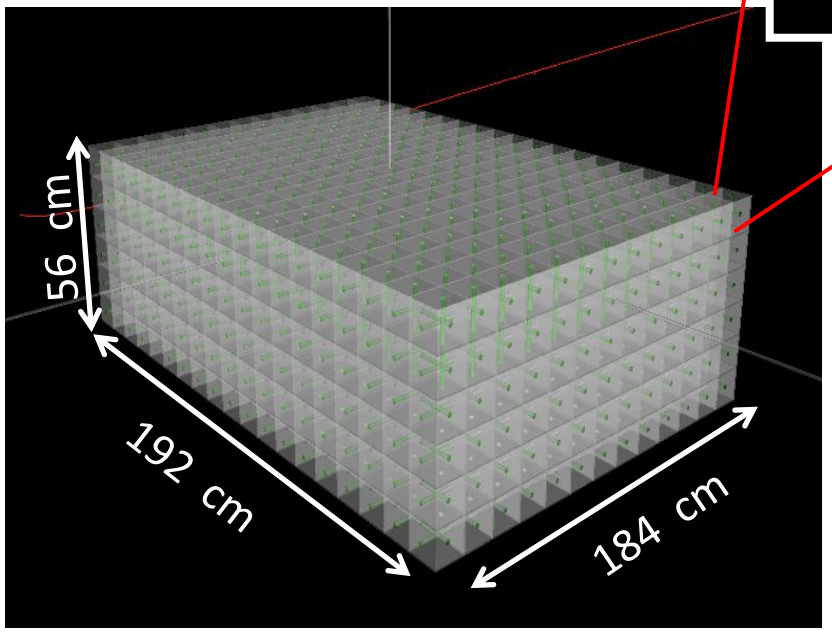
JINST 13 (2018) 02006

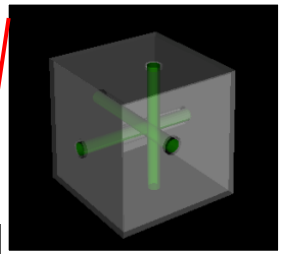
- Cubes produced by injection molding at OOO Uniplast, Vladimir
- Covered by chemical reflector
-Tolerance (each side) about 30 microns

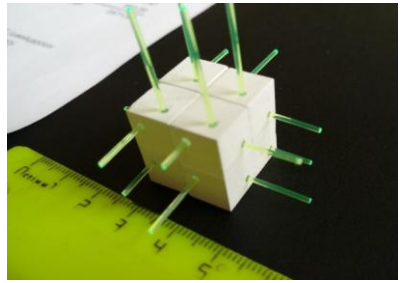
SuperFGD project: about 100 participants from 6 countries
Russia: INR, JINR, LPI

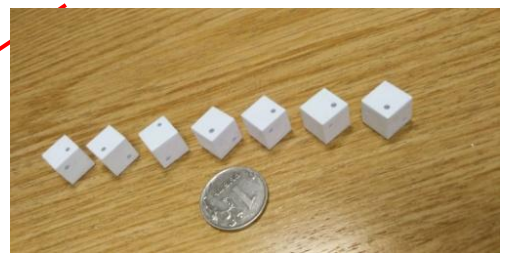
ND280 FGD → SuperFGD

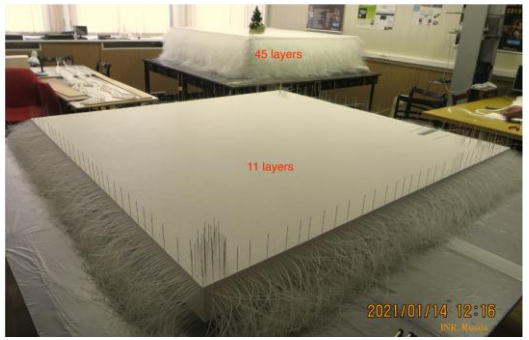


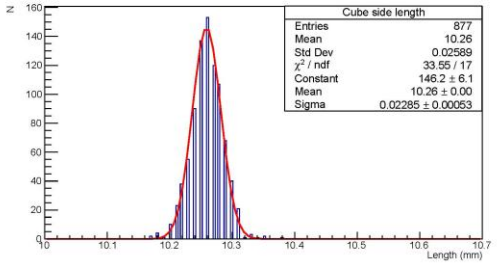








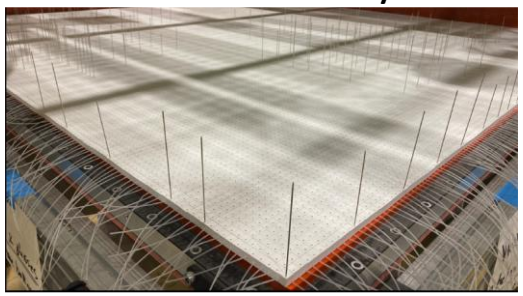




- 2000000 cubes produced in 2019-2021
- 56 planes assembled at INR using fishing lines in 2021-2022
- SFGD delivered to J-PARC in 2022

Assembly of SuperFGD at J-PARC

Installation of cube layers

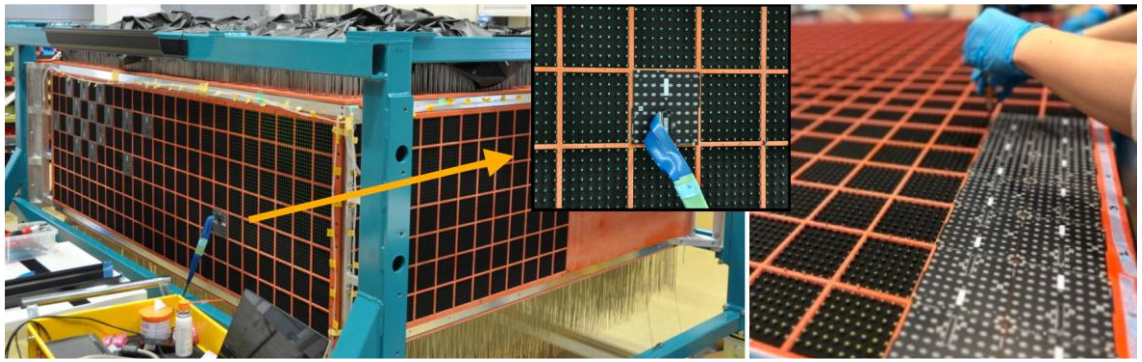


Installation of soft foam

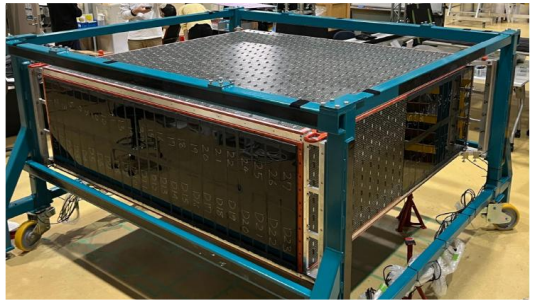
Transfer to new support frame

Fishing lines → WLS fibers

Installation of MPPC-PCB



Installation of LED calibration system



Cabling

About 6 months
to assembly SFGD:
from installation of 1st layer
to finish cable connection

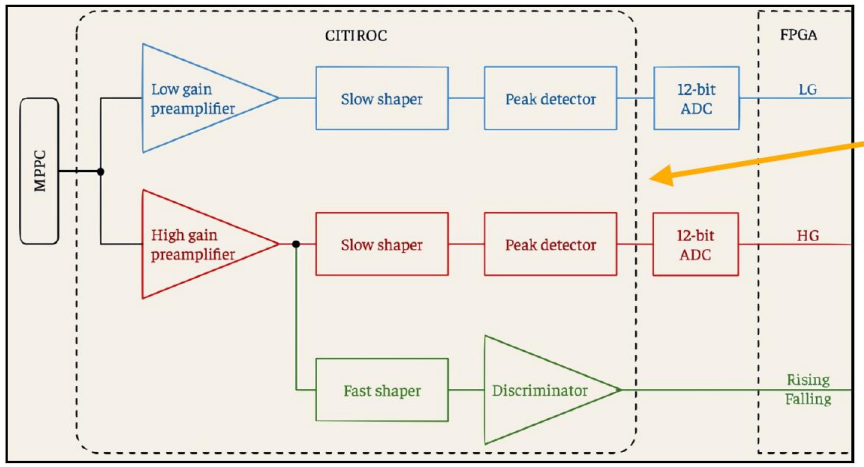
SuperFGD Electronics

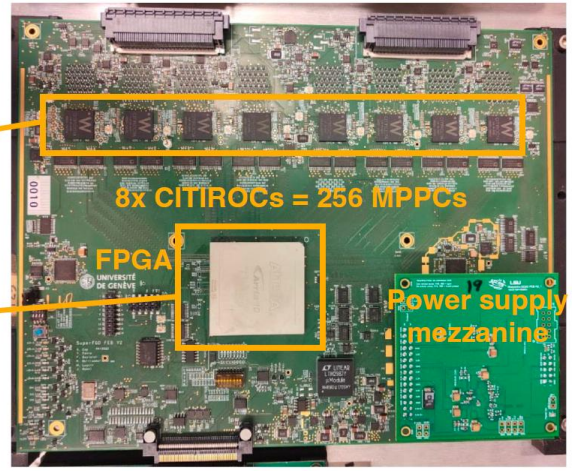
- MPPC analogue signal digitised by CITIROC (Omega lab. Ecole Polytechnique)
- Peak detector, Low-gain and High-gain signals (2x 12-bit ADCs)
- Constant threshold discriminator → rising edge and falling edge timestamps

✓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

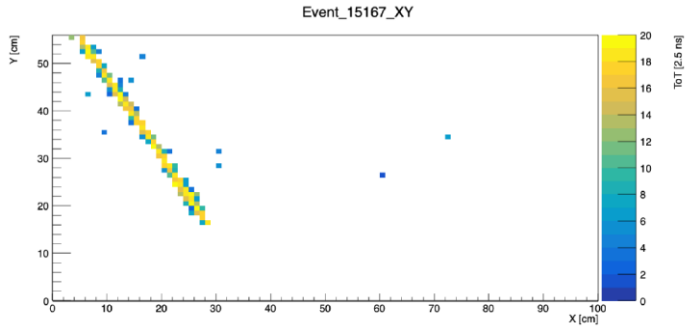


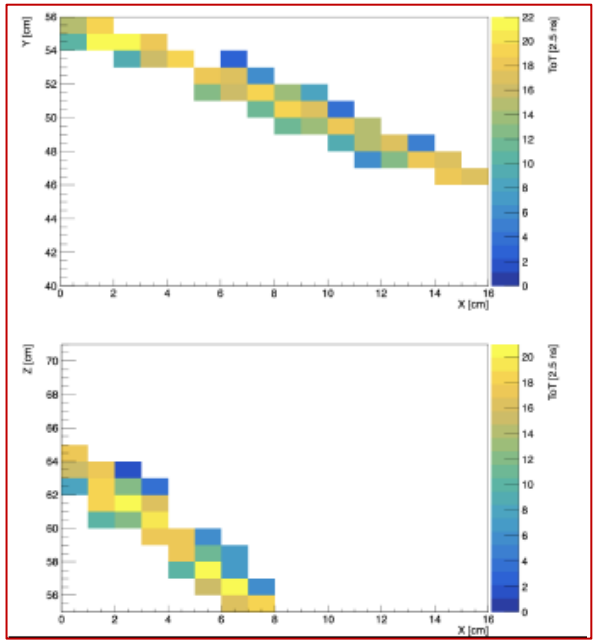


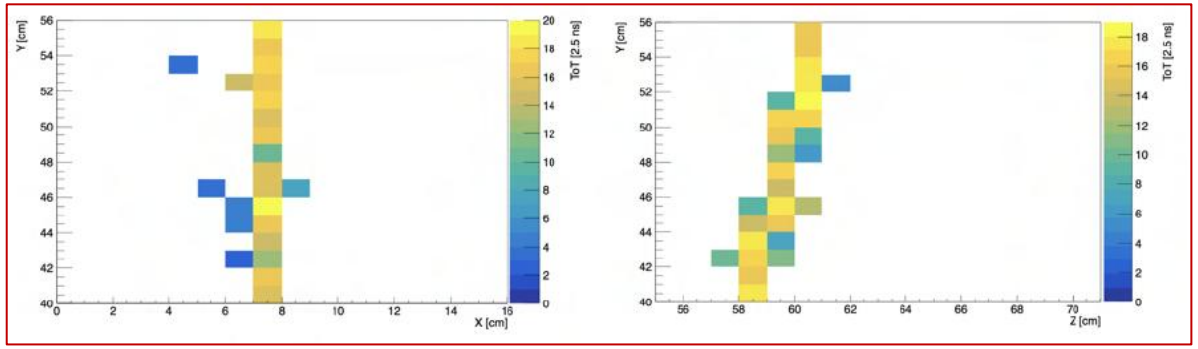
Calibration of SuperFGD

μ

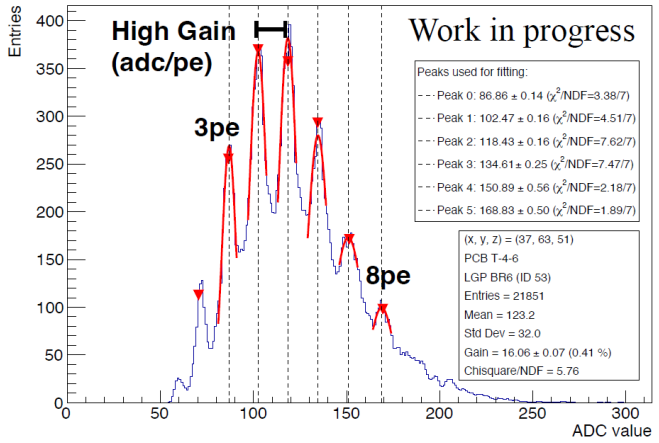
Cosmic events: muon tracks



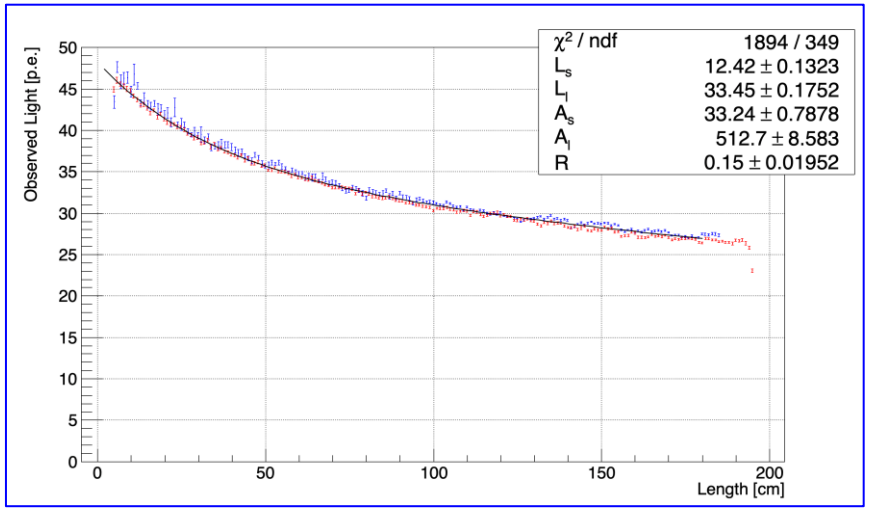




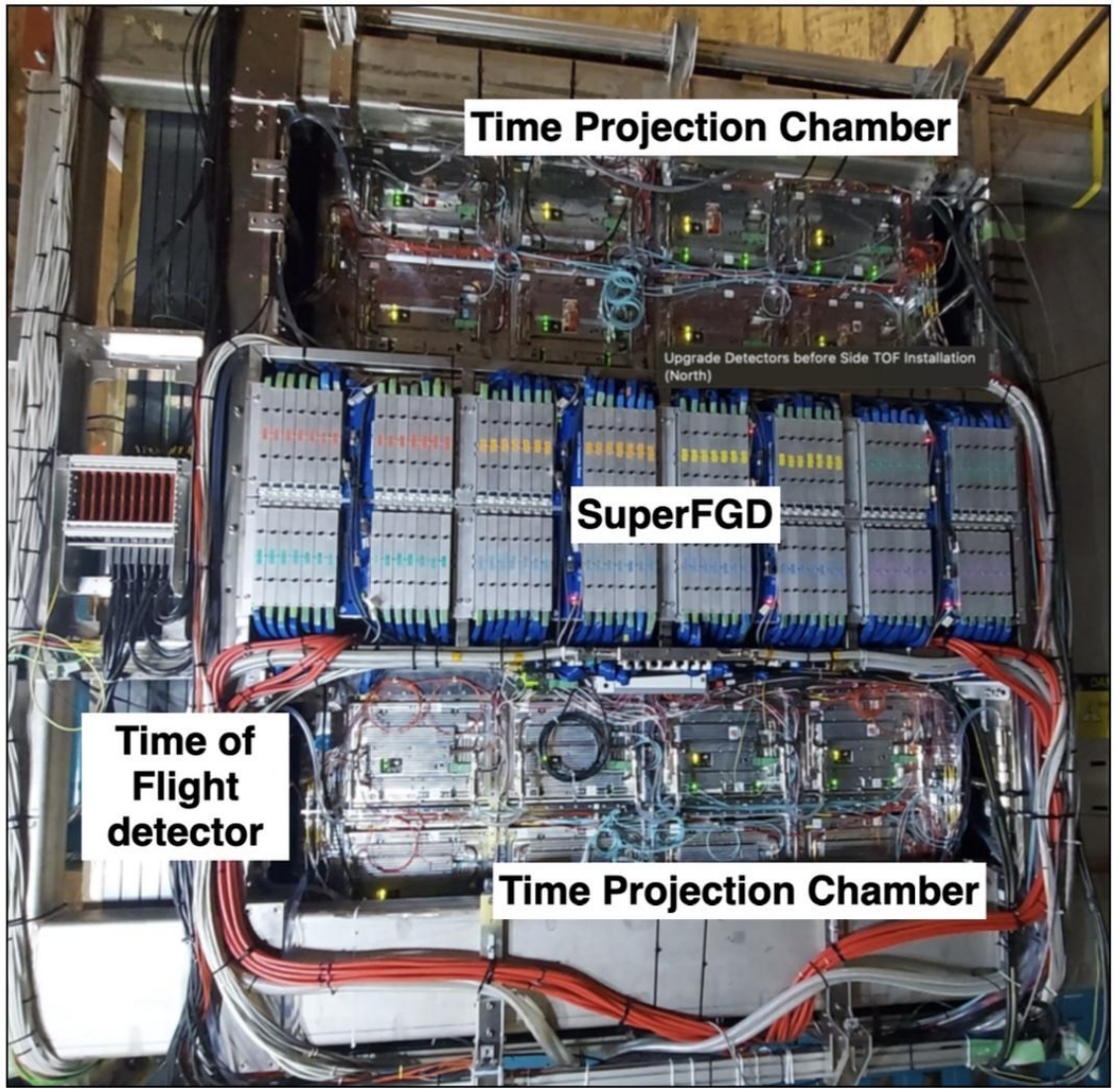
LED calibration in photoelectrons



LY per MIP and attenuation of WLS fibers



New ND280 detectors in ND280 magnet



Installation of all detectors (SuperFGD, HA-TPC, TOF) into ND280 magnet completed in May 2024

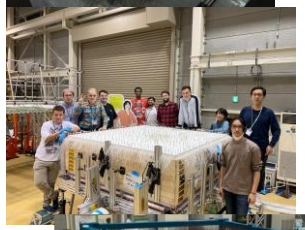
- SuperFGD begun collecting neutrino data in November 2023
- Now SuperFGD taking statistics with all detectors installed into marnet

Milestones of SuperFGD

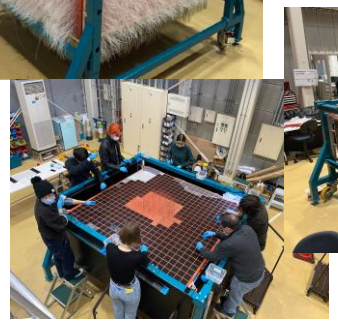
Start
INR 2017

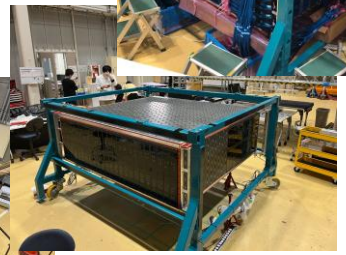
CERN 2018

INR 2020-2021



J-PARC 2022





J-PARC 2022

J-PARC 2023

J-PARC 2024

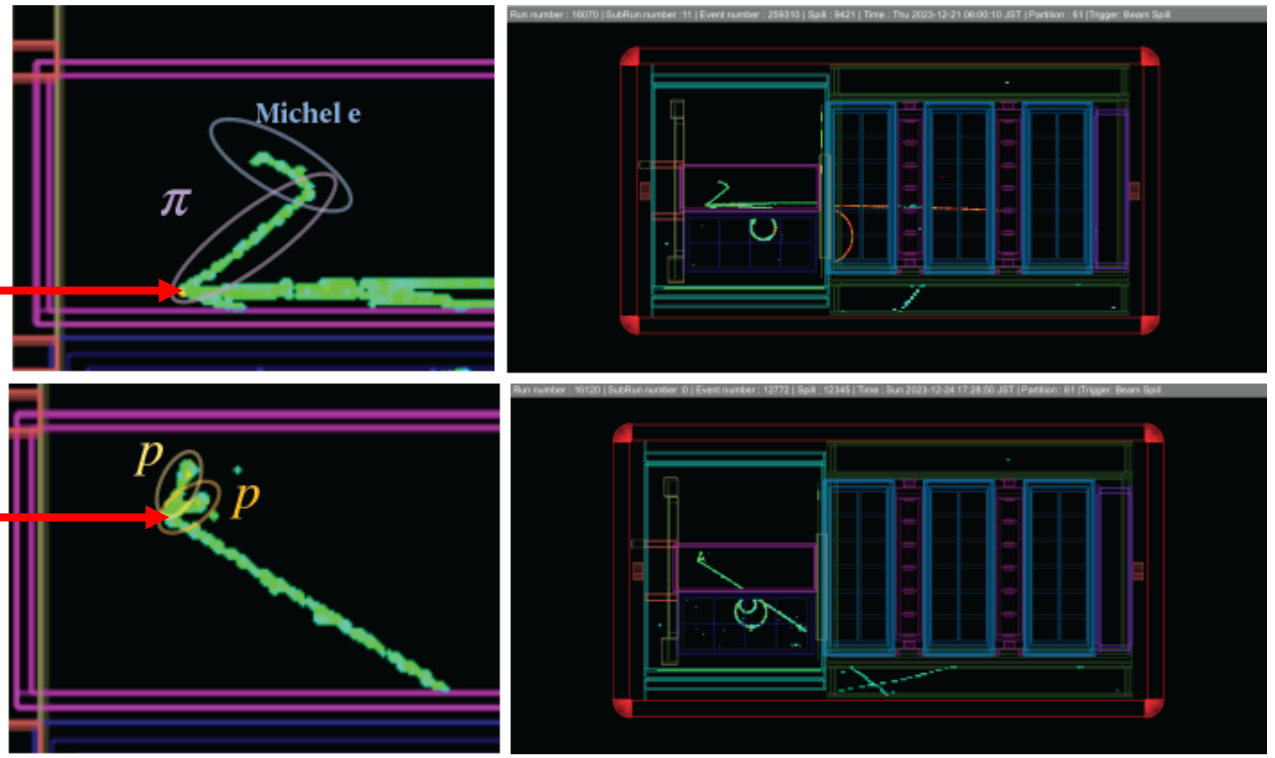
ν event 2024

Neutrino interactions in SuperFGD

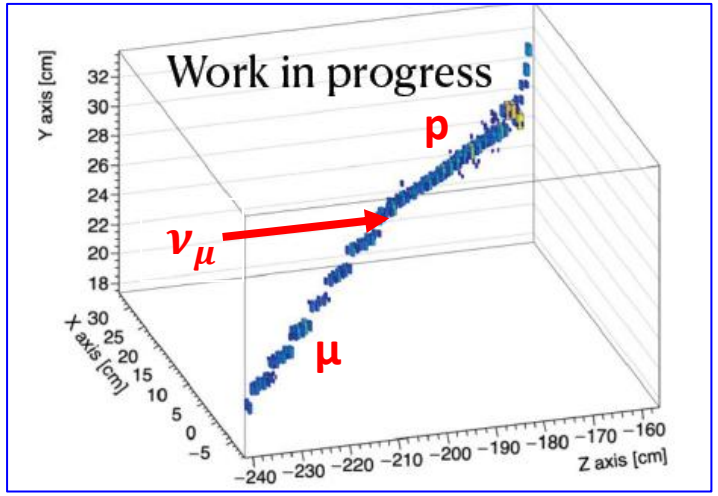
SuperFGD

ND280

First run with neutrinos
November 2023



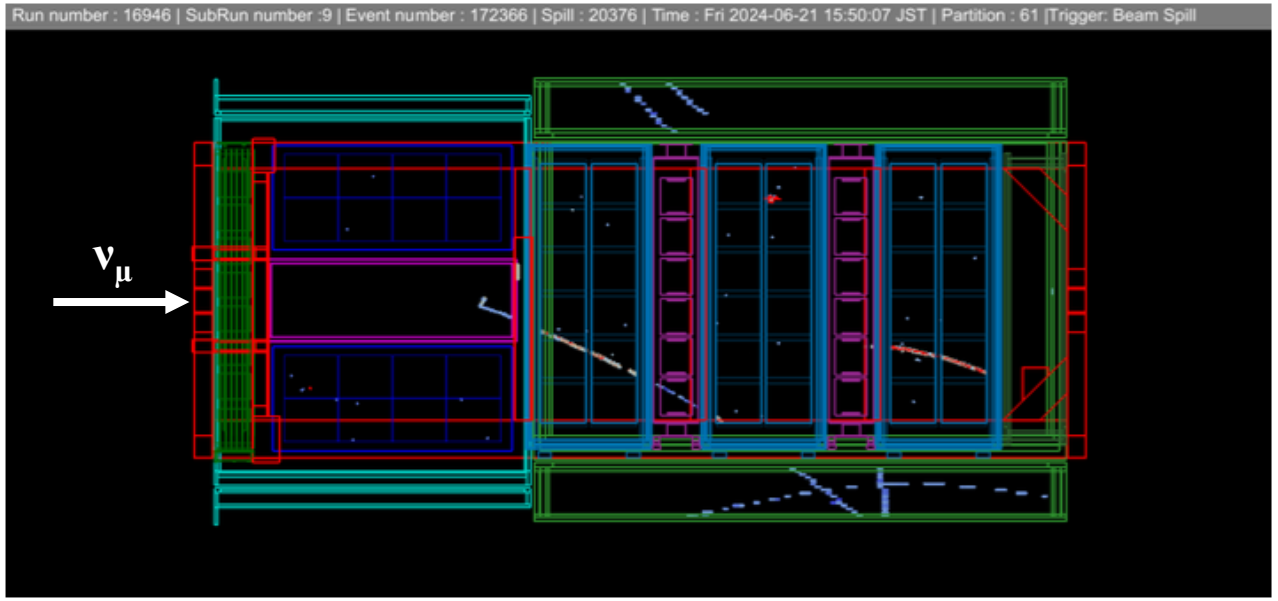
3D reconstructed tracks



T2K muon neutrino beam, CC events

Neutrino interactions in SuperFGD

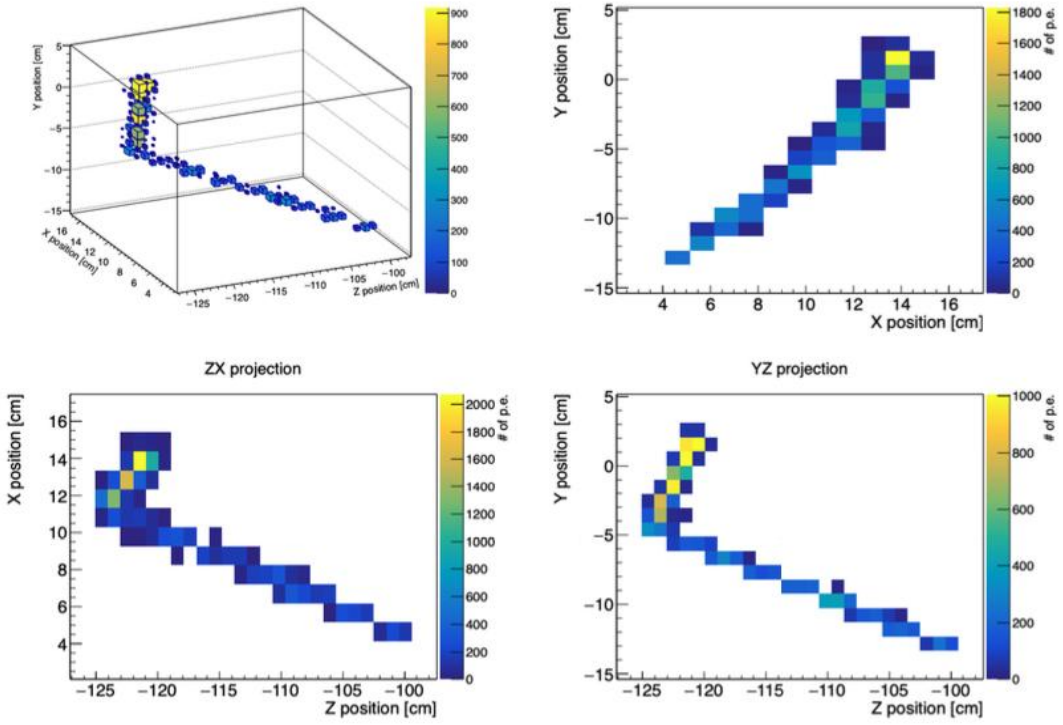
ν_μ CC interaction event



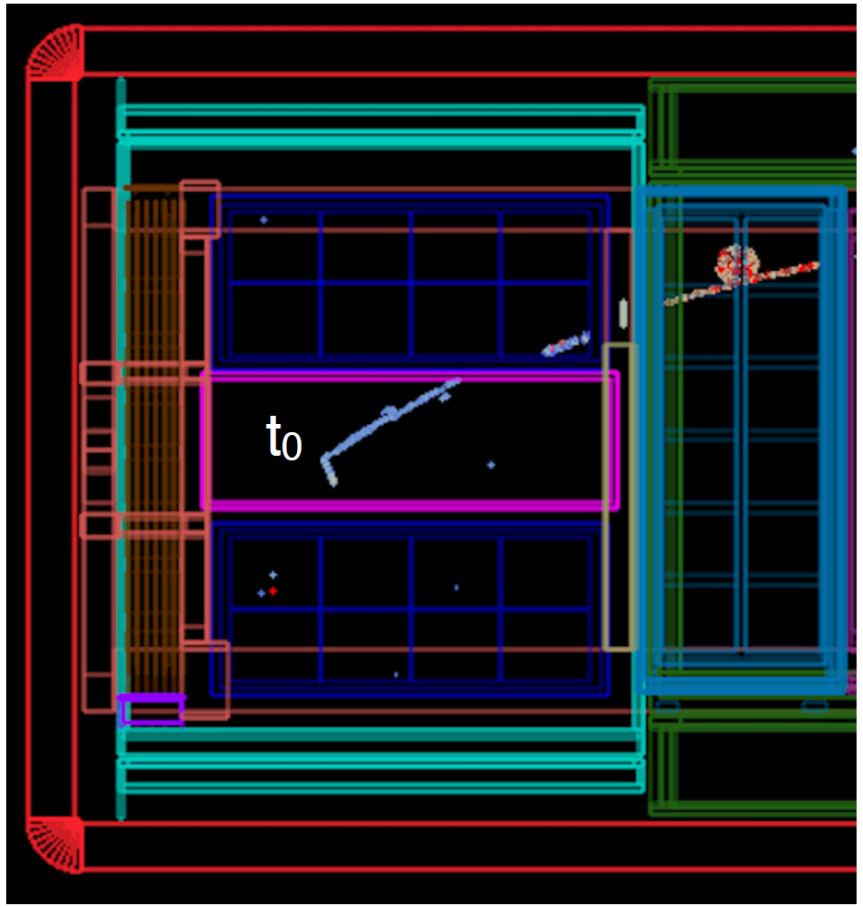
Run = 16946, Subrun = 9, Event = 172366

XY projection

Muon neutrino
November 2024 Run

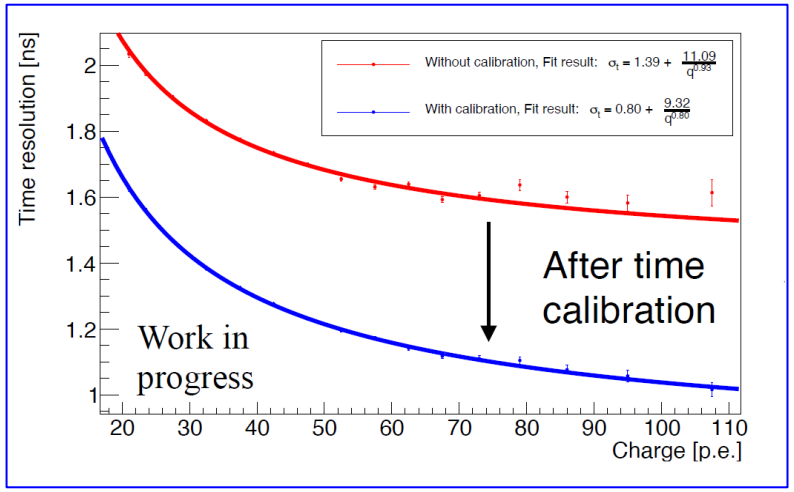


Time resolution



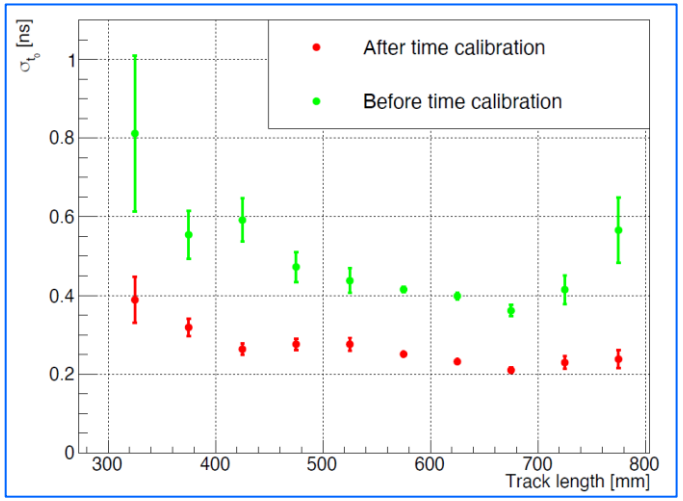
Time resolution of a single cube

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



Time resolution of a long muon track

Precise time calibration and determination of the time of event t_0



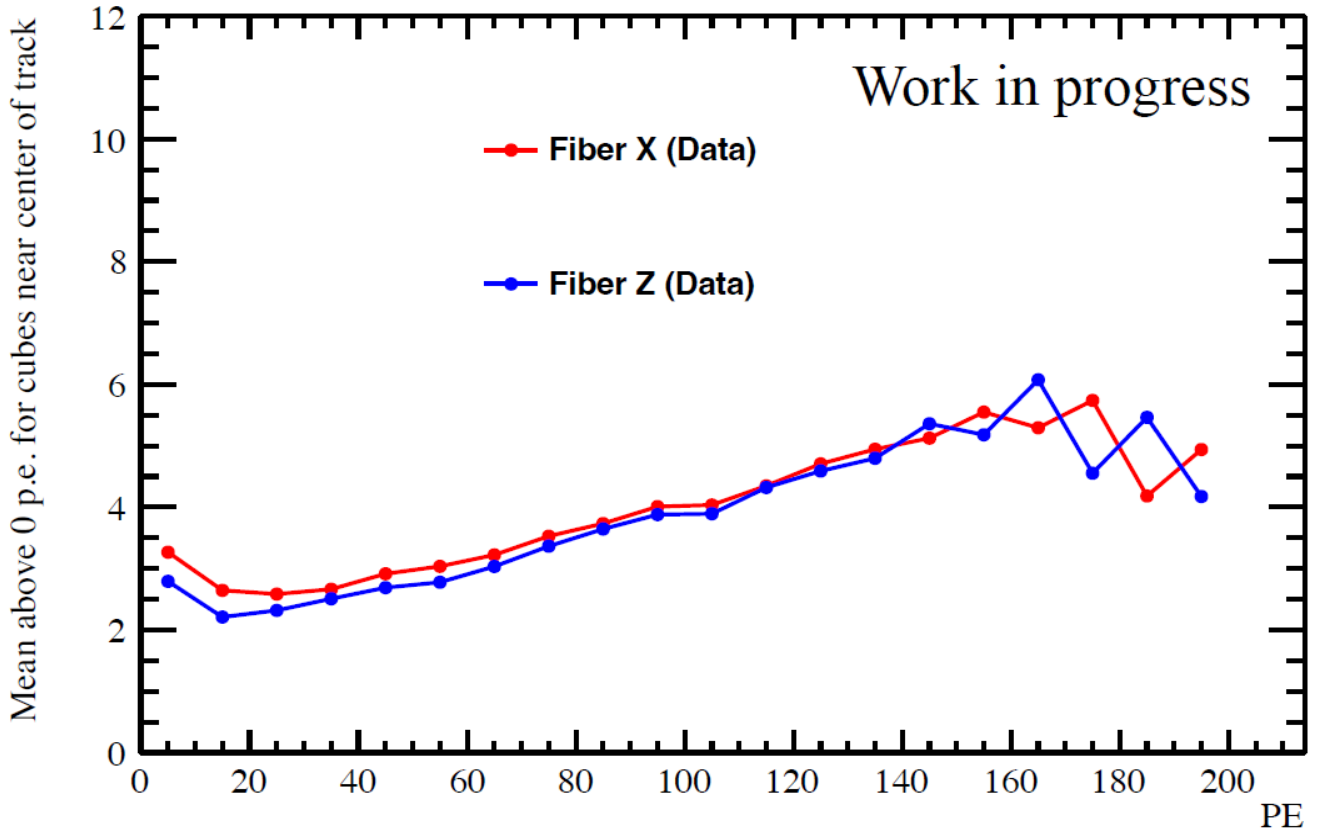
Optical cross-talk

Cube-to-cube optical cross-talk

Data and MC agrees well
→ about 3% cross-talk

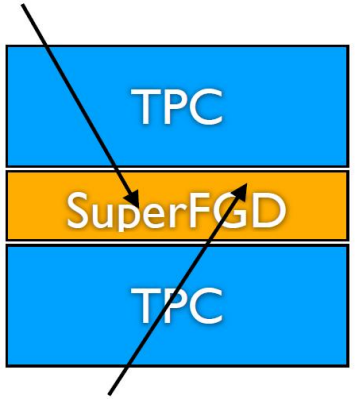
Results are consistent with measurements of detector Prototypes

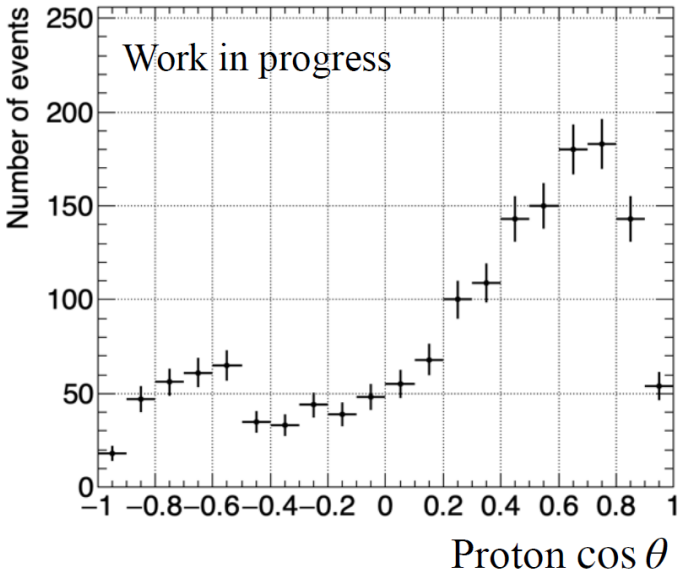
Possible cross-talk between Electronics channels is under study



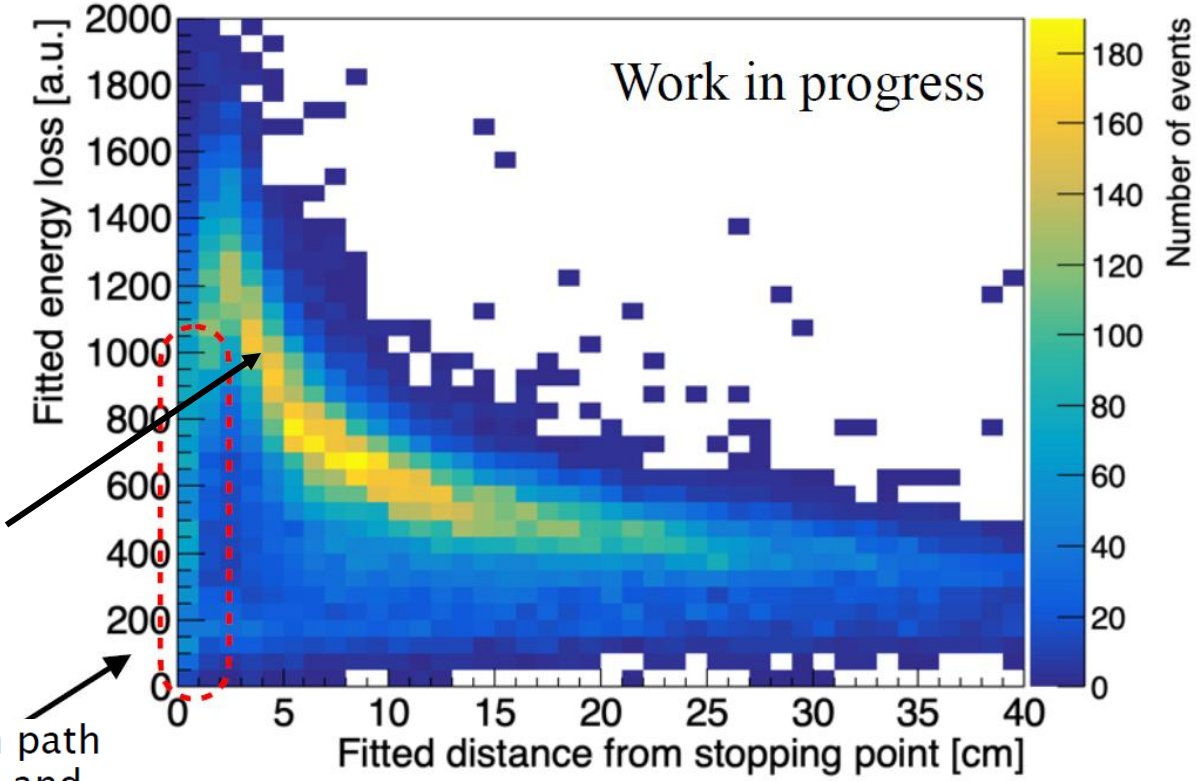
Detection of stopped protons

Protons from TPC stopped in SuperFGD





Fitted energy loss per cube of protons stopping in SuperFGD



Bragg peak

Short proton path in last cube and optical crosstalk

Conclusion

- Reduction of systematic uncertainties – crucial for CP-violation search and oscillation measurements in T2K and HyperK
- Upgrade of T2K near detector ND280 with a new neutrino target-detector SuperFGD is completed
- SuperFGD will be a central near neutrino detector in T2K and HyperK experiments
- SuperFGD begun to accumulate data in T2K neutrino beam in 2024 with 810 kW proton beam
- Main feature of SuperFGDs: 4π solid angle; good time resolution; excellent identification of e, γ, p; low proton threshold ~300 MeV/c, neutron detection by ToF

Thank you very much for your attention