T2K Upgrade
Assembly, Commissioning and Expected Sensitivity

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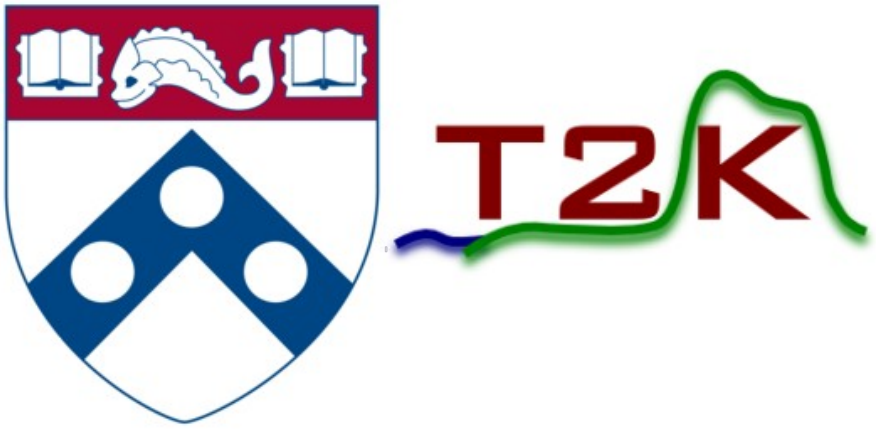
PASCOS 2024, Rencontres du Vietnam

July 10th 2024
Quy Nhon, Vietnam

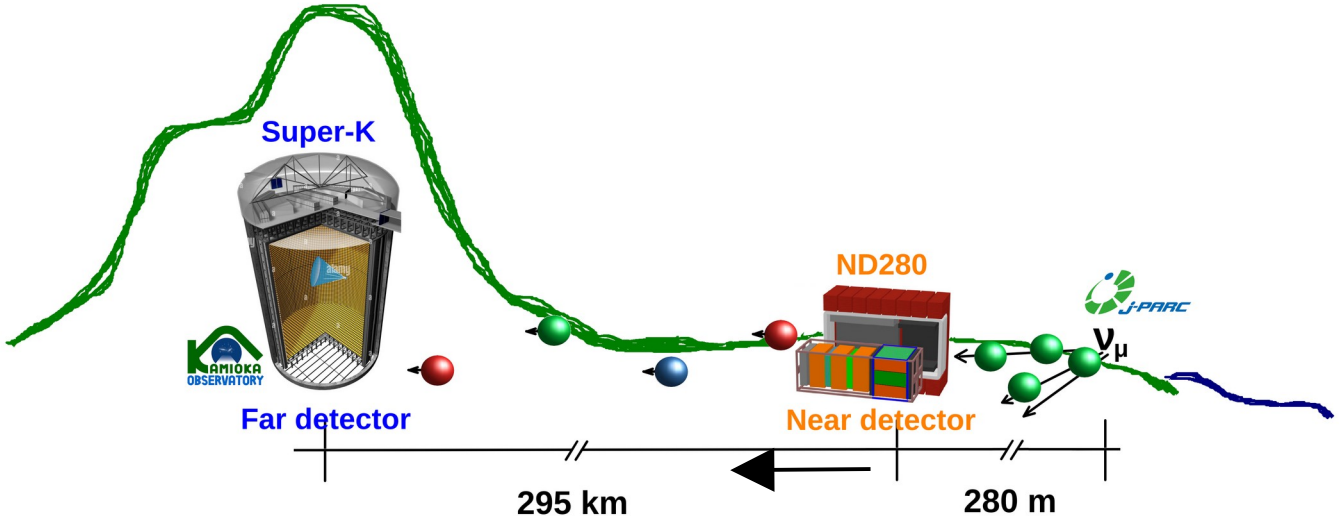


Content

What Is T2K?

Tokai to Kamioka

- Long baseline neutrino **oscillations** and neutrino **interactions** experiment.
- Extraction of cross section and oscillation parameters, for example:
  - Δm^2_{32}, θ_{23} through ν_μ disappearance.
  - δ_{CP}, θ_{13} through ν_e appearance.

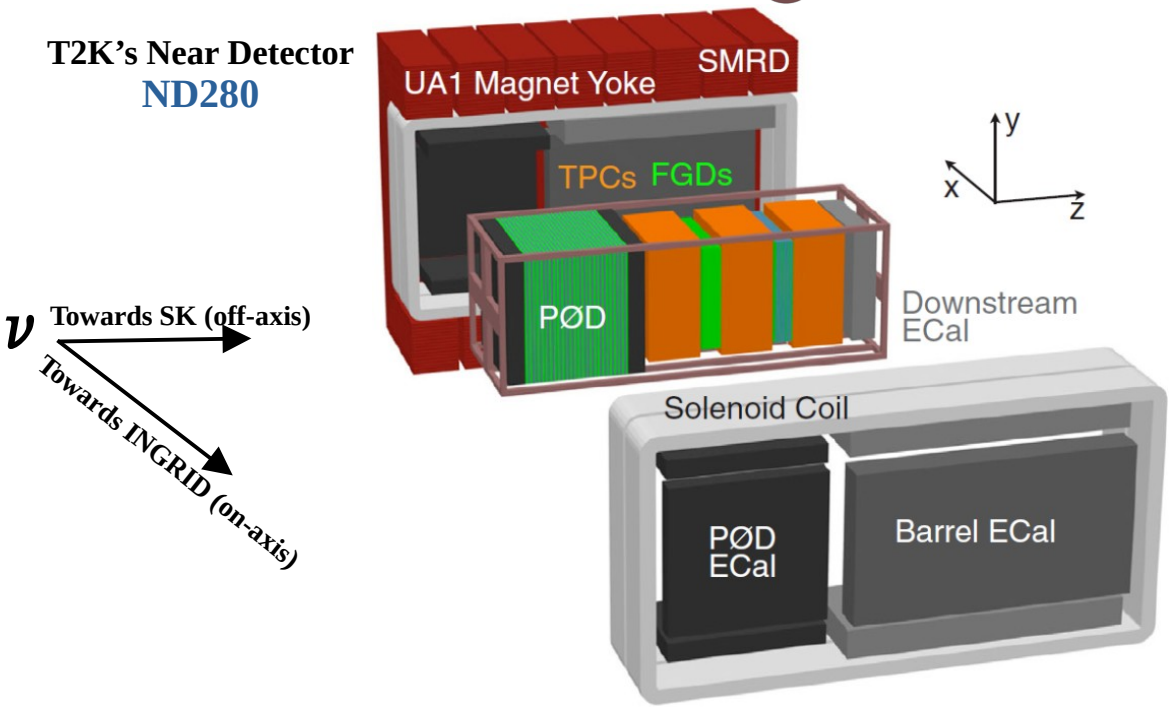


Original Near Detector Complex

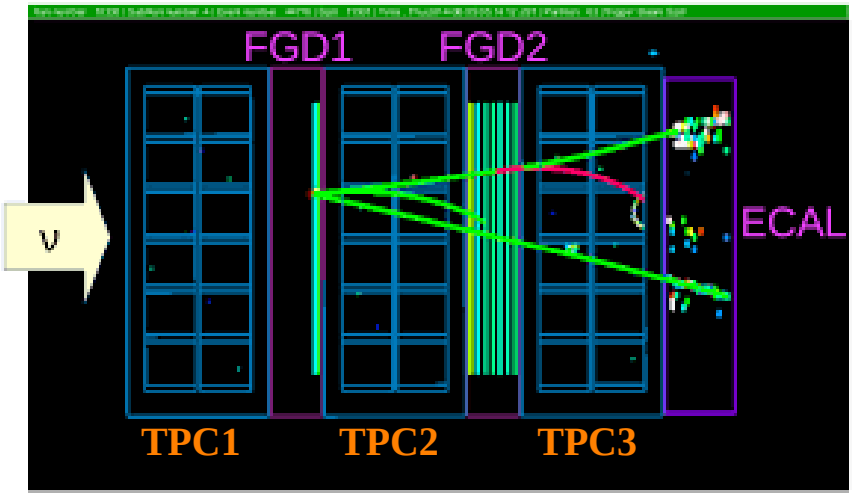
Components

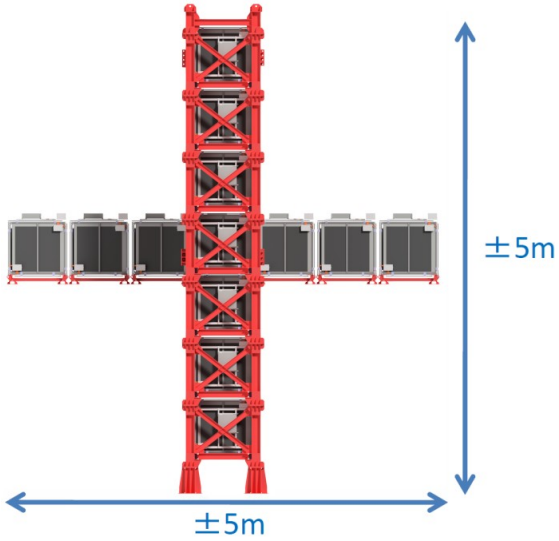
- Neutrino monitor on-axis (INGRID).
- UA1 magnet (0.2 T).
- Outer calorimeters.
- "Basket" with off-axis sub-detectors.
  - π^0 detector (P0Dx1).
  - Fine-Grained Detectors (FGDsx2).
  - Time Projection Chambers (TPCsx3).
  - Inner calorimeters.

T2K's Near Detector
ND280



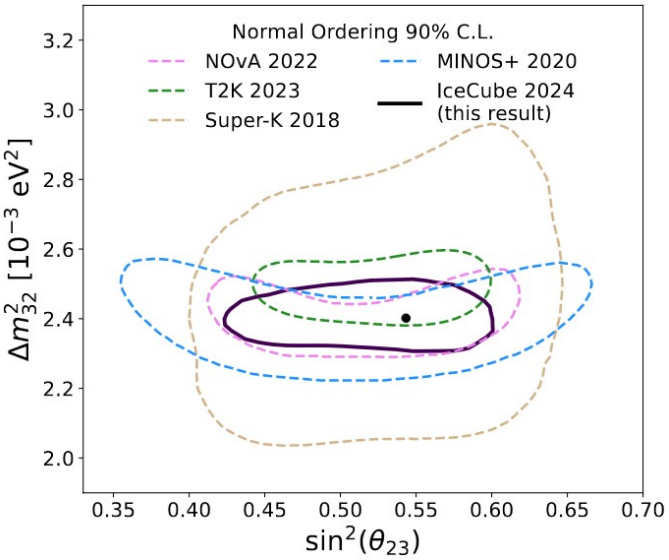
Neutrino candidate in FGD1





INGRID (neutrino monitor)

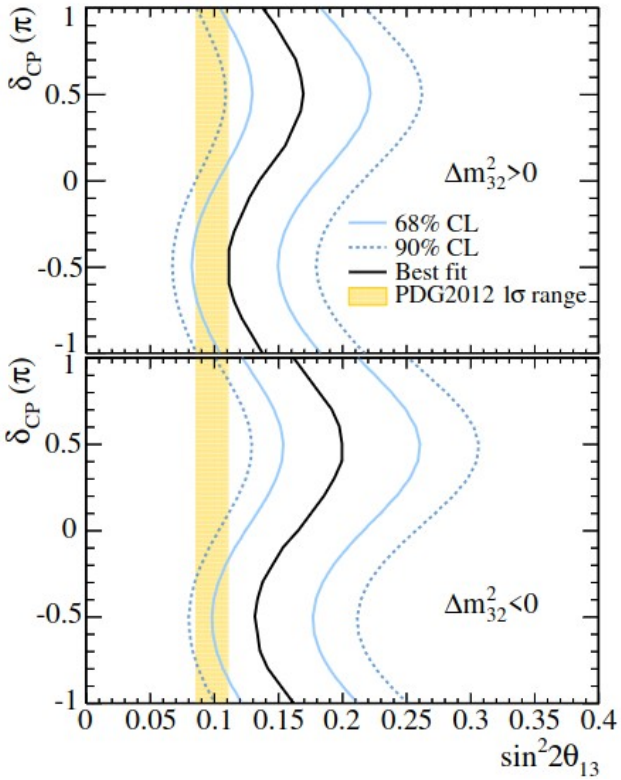
Outstanding Results



$\nu_\mu \rightarrow \nu_\mu$ Disappearance

- **θ_{23}-Δm^2_{32} constraint.**
- **Consistent with both octants.**

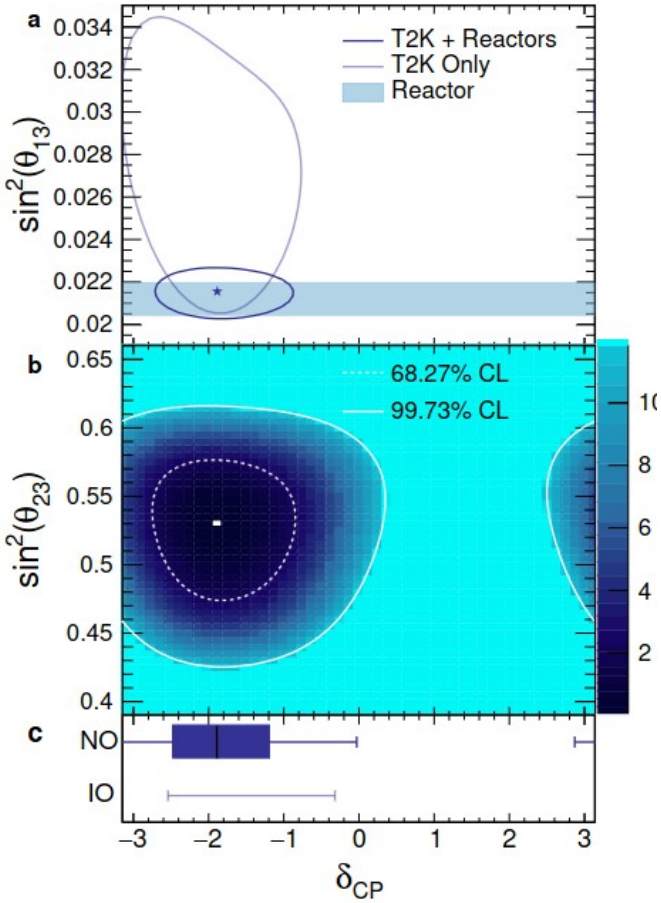
K. Abe et al. (T2K), Eur. Phys. J. C 83 782 (2023)



$\nu_\mu \rightarrow \nu_e$ Appearance

- **θ_{13}-constraint.**
- **Consistent with stronger reactor constraint!**

Phys. Rev. Lett. 112, 061802 (2014)



δ CP constraint

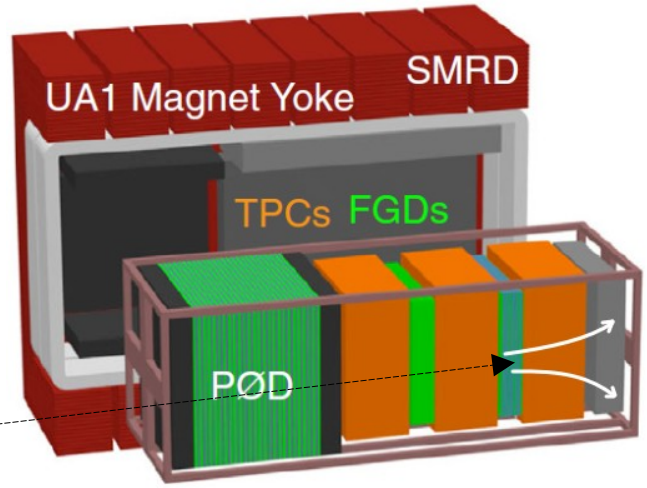
- **{0, π} excluded at 90%.**
- **Best fit close to maximal CP violation!**

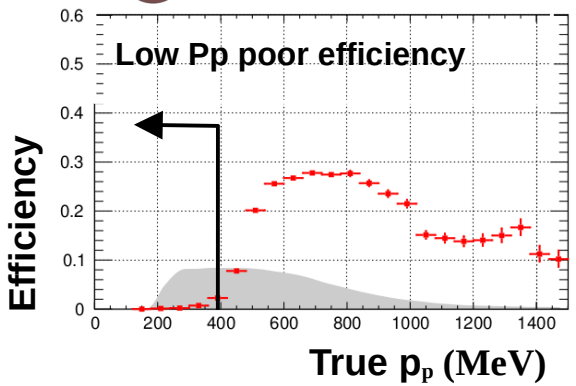
Nature 580, 339–344 (2020)

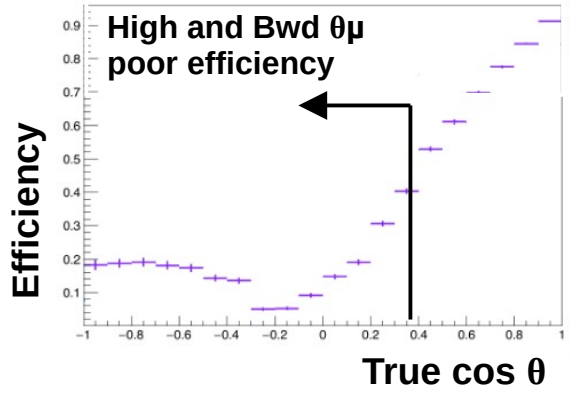
ND280 Upgrade

Limitations

- Limited angle acceptance.
- High hadron momentum threshold.
- No neutron detection capabilities.
- Poor efficiency for $E\nu_e < 1$ GeV (limited statistics for a good flux constraint).
- Eν estimator based on muon variables only!



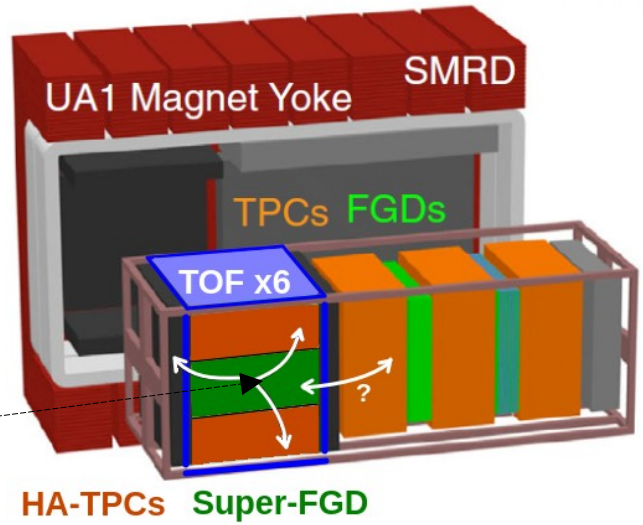




Expected Capabilities

- Lower hadron momentum threshold
- 4π angular acceptance.
- Event-by-event neutron reconstruction.
- Eν estimator based on muon+hadron kinematics

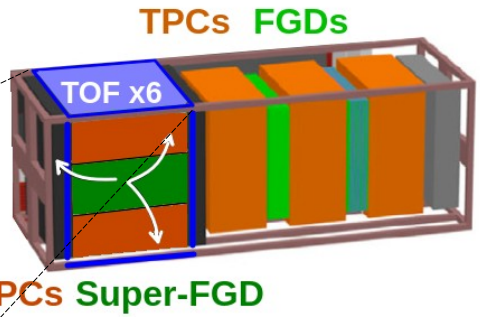
- Better e/γ and μ/e PID.
- Increased total tracker mass (x2).
- Veto of incoming particles.

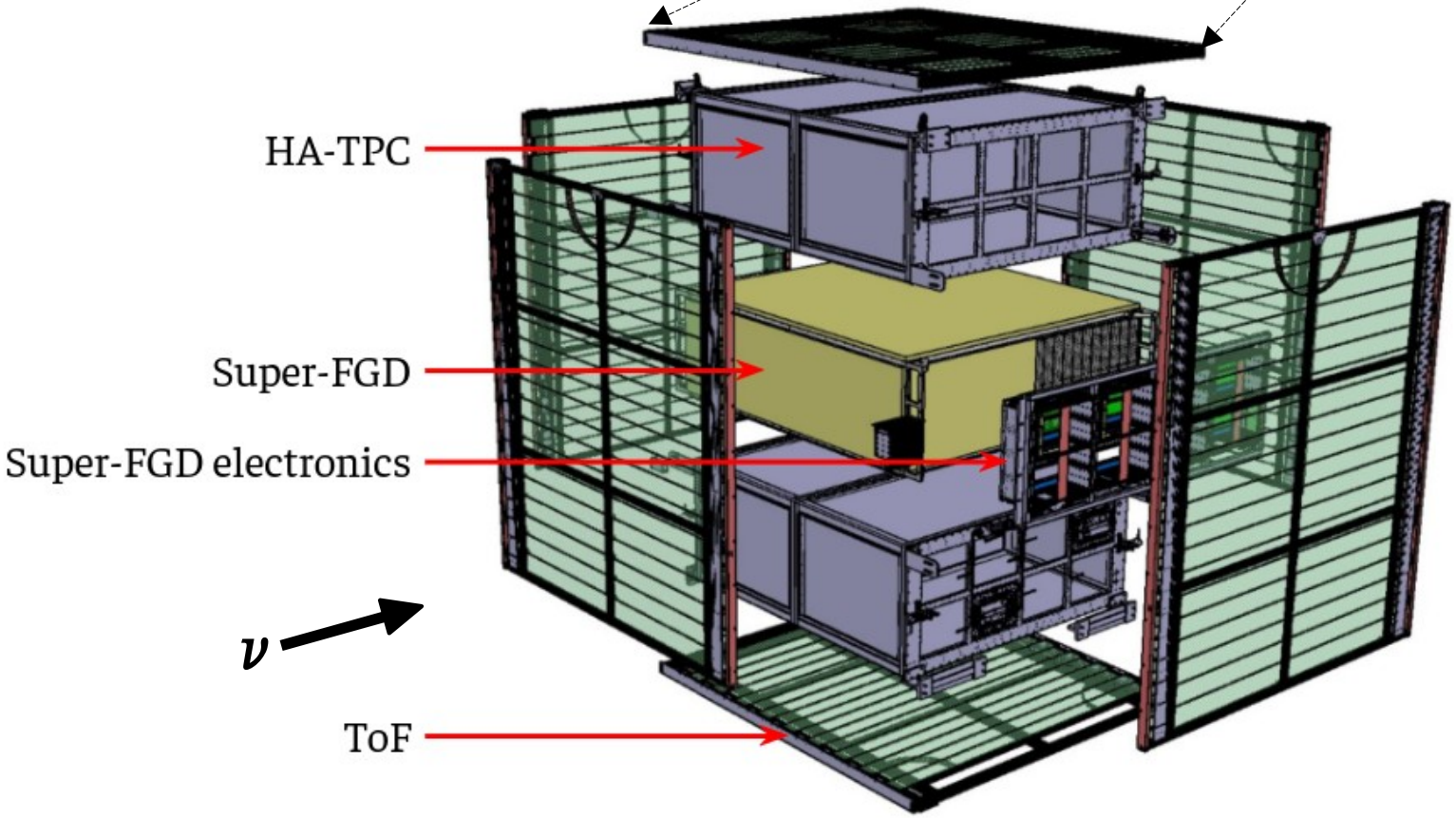


ND280 Upgrade

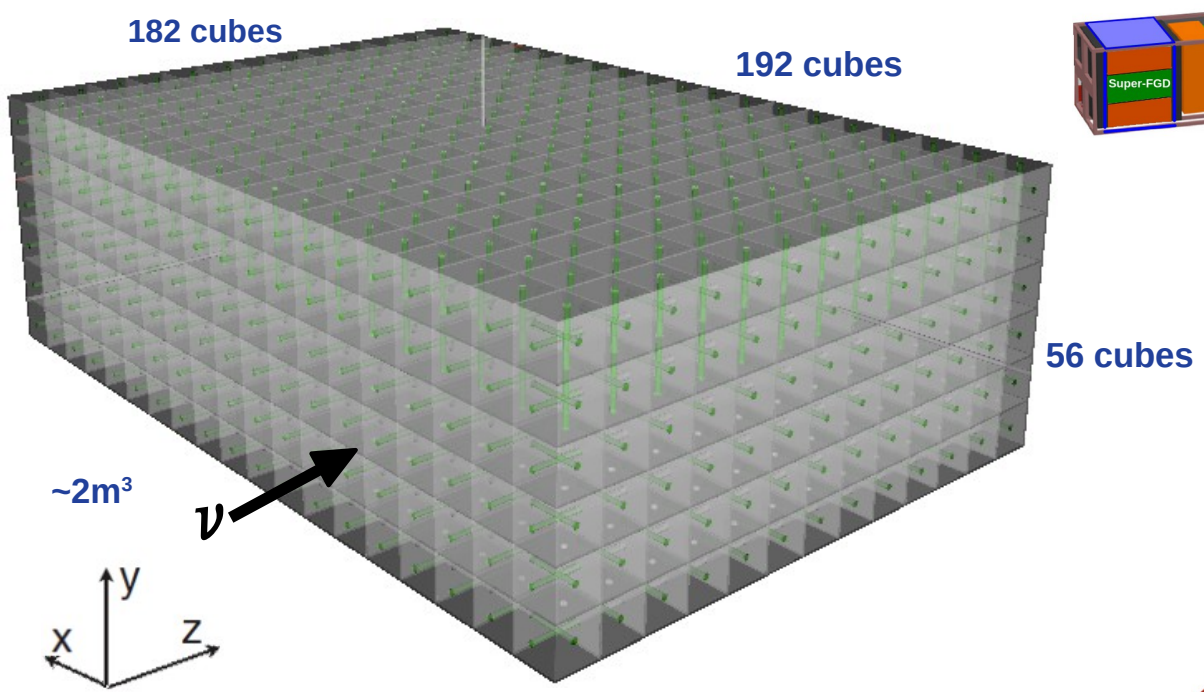
New Sub-Detectors

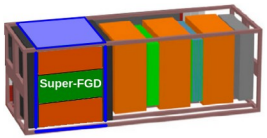
- 1 “Super” fine-grained detector tracker (Super-FGD).
- 2 High-angle TPCs (HAT).
- 6 Time-of-flight modules (TOF).

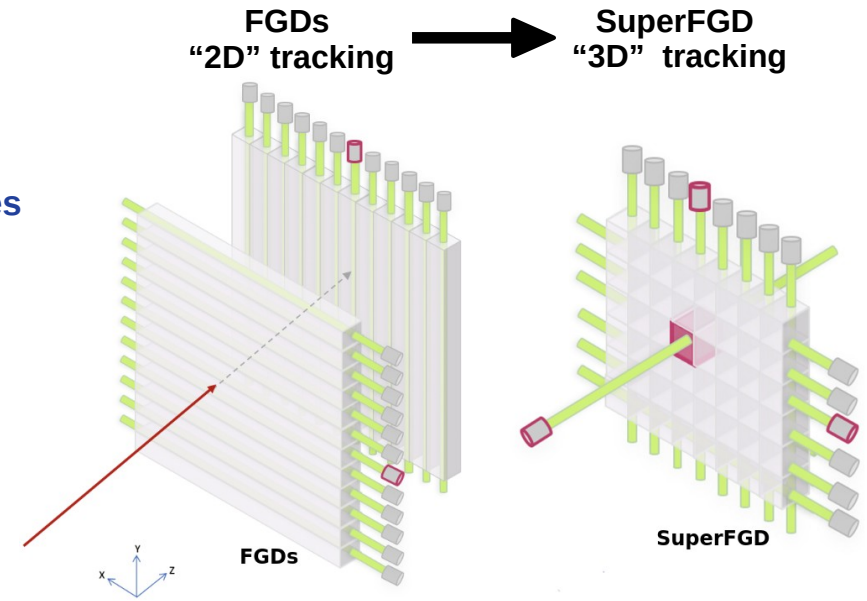




SuperFGD







Characteristics

~2x10⁶ 1-cm³, plastic scintillator, optically isolated cubes (~2 tons).

3 orthogonal WLS fibers per cube, ~56x10³ in total, 1 readout channel per fiber.

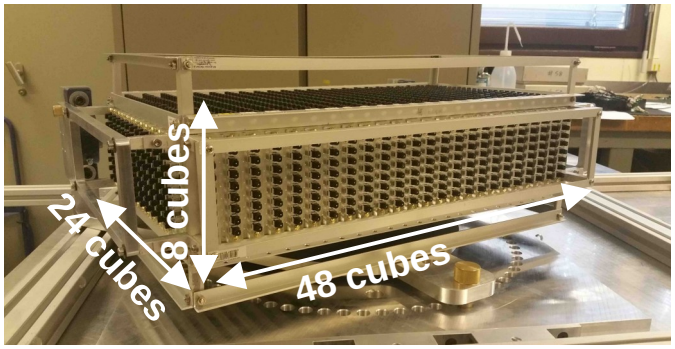
3 1.5-mm Φ holes to insert the fibers.

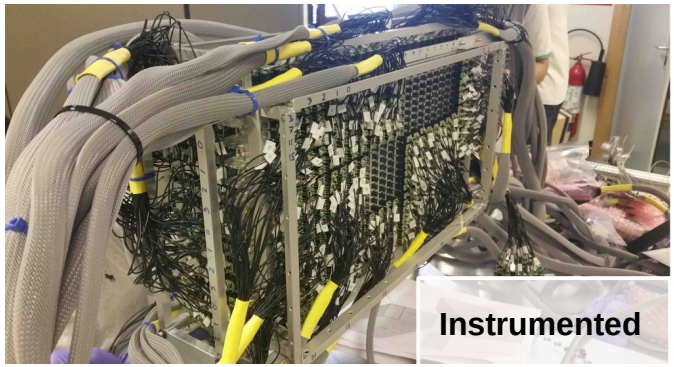
Improvements

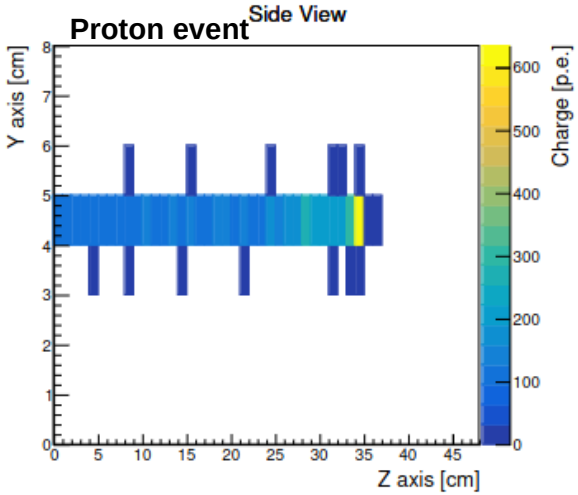
- **2D -> 3D tracking.**
- **Full polar angle coverage.**
- **Lower momentum threshold.**
- **Better timing resolution.**

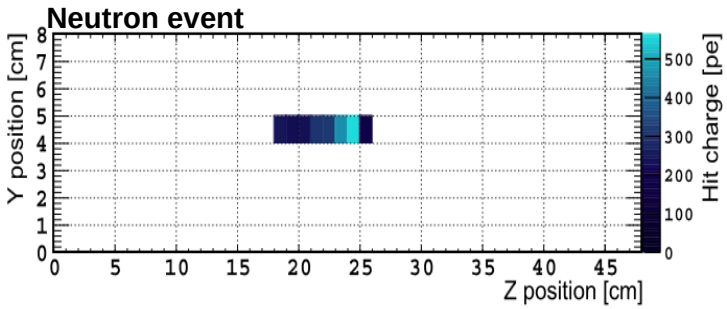
SuperFGD Prototypes

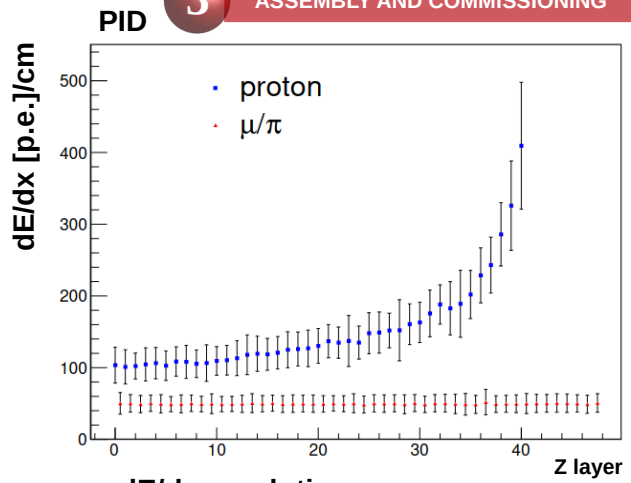
- Tested with charged particles at CERN and neutrons at LANL.
  JINST 15 (2020) 12, P12003
- Same photosensors and similar electronics as in the final SuperFGD.
- Total neutron cross section extracted!
  Physics Letters B, 840 0370-2693 (2023)

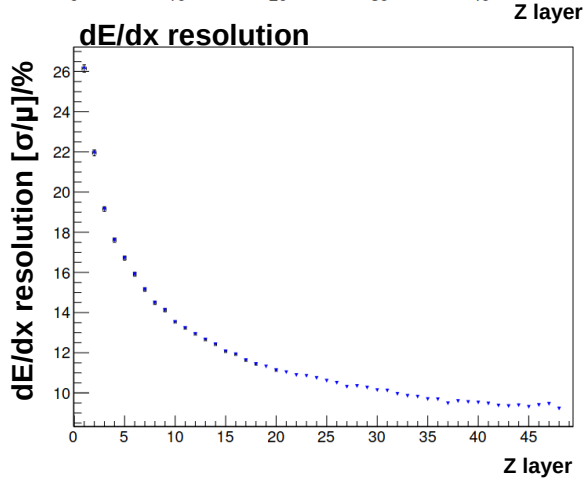


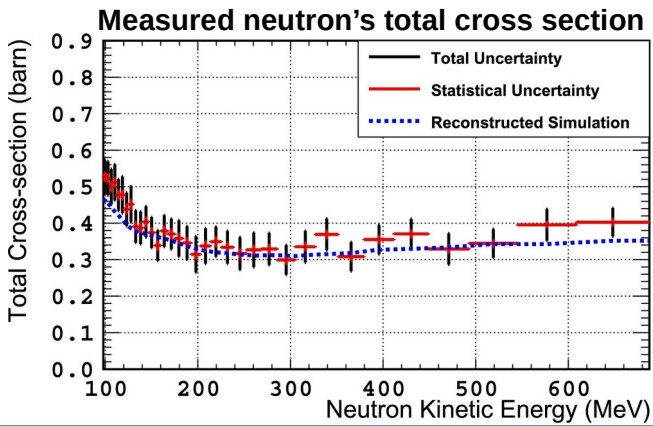






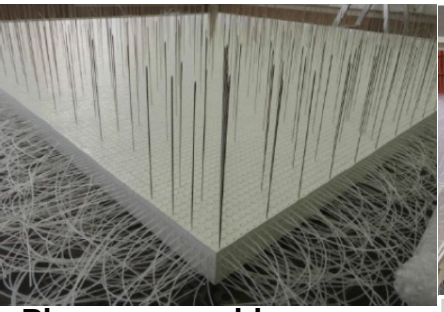






SuperFGD Assembly & Commissioning

Assembly

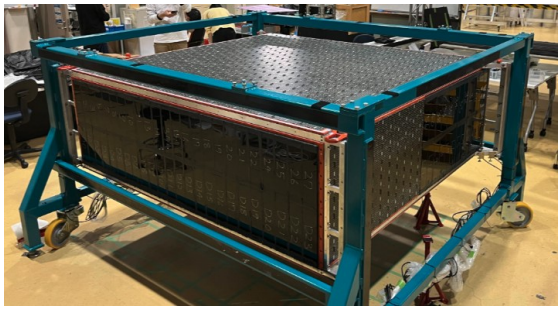


Planes assembly

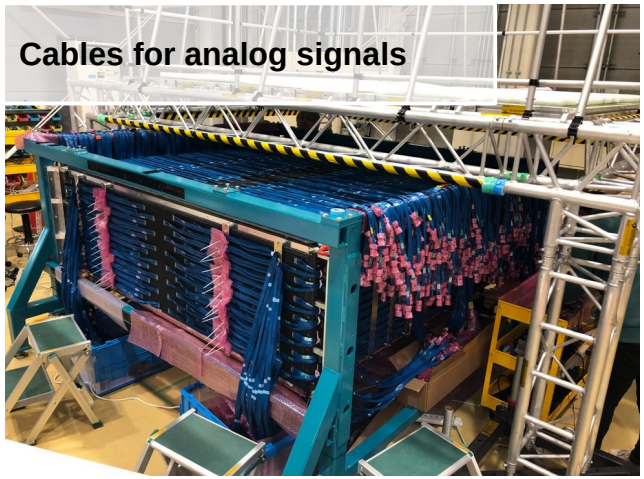
Cube stacking & alignment

Box complete

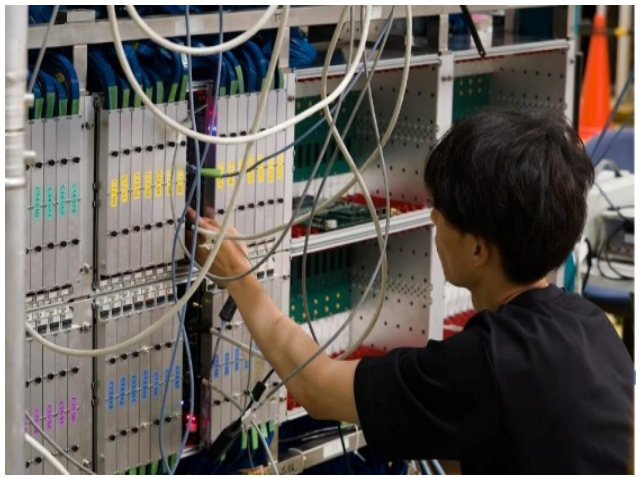
Light collection & light injection interfaces



Commissioning



Cables for analog signals

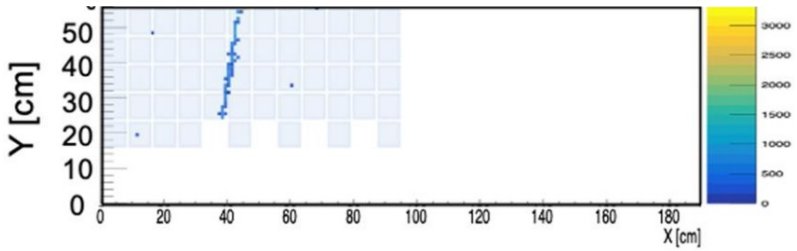


First few (out of 16) crates with FE boards

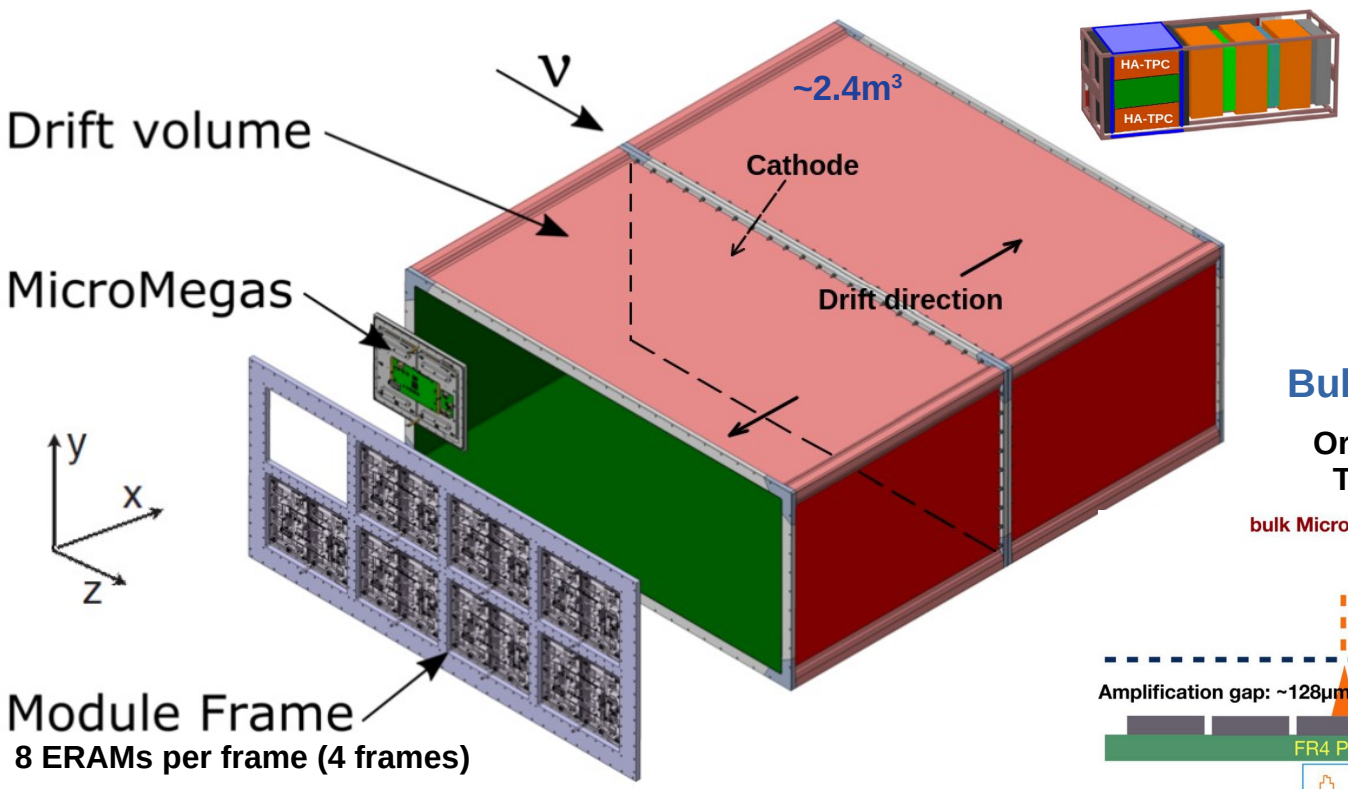
Checks on-site

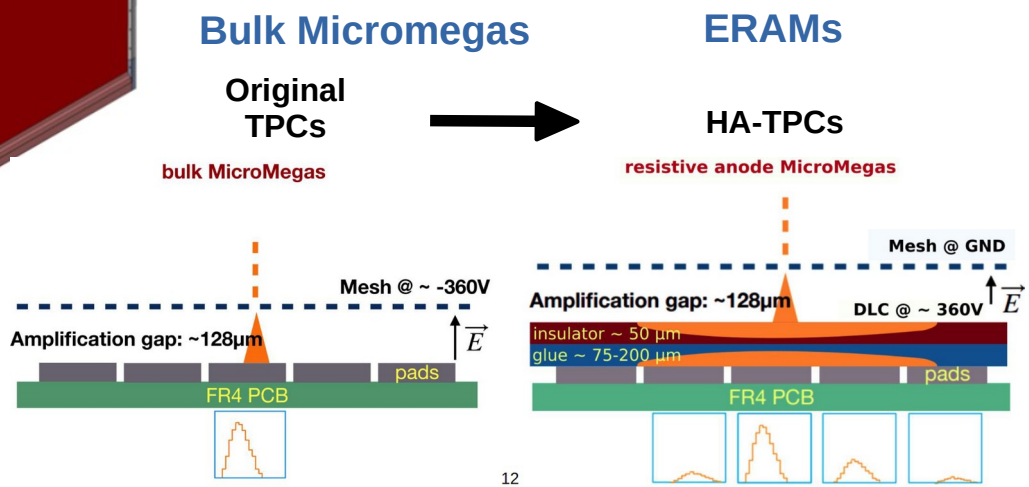
- Cooling system
- Electronics
- DAQ and Slow Control

First cosmic event recorded (on the surface)



HA-TPC





Characteristics

1 Field cage per TPC (200x180x80 cm)

32 ERAMs detectors (Micromegas)

1152 pads per ERAM. ~37k channels, 1 per pad.

"T2K gas": Ar+CF_4+iC_4H10 (95:3:2).

E_{field} = 275 V/cm.

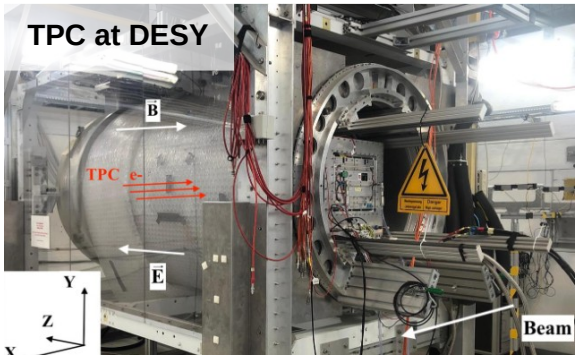
Drift length = 90 cm.

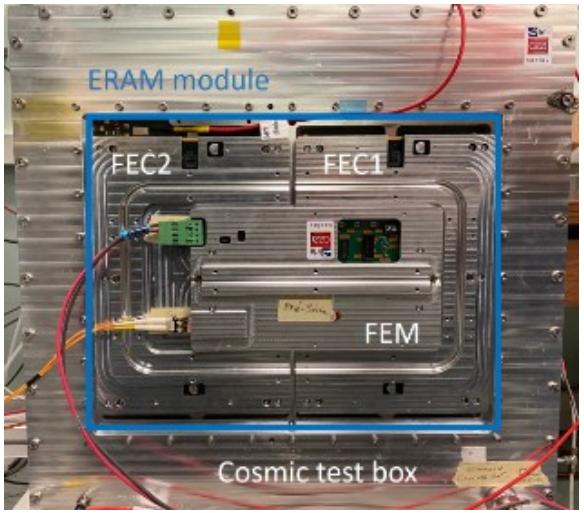
Improvements

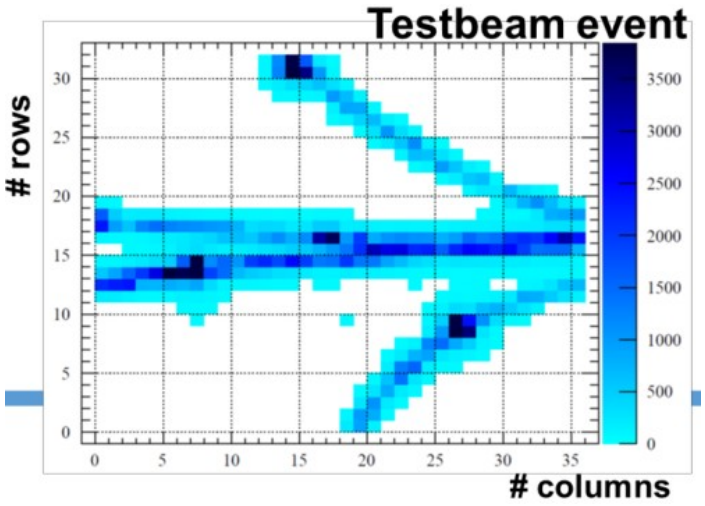
- **Maximized tracking volume.**
- **Intrinsic spark protection.**
- **Better e/μ separation**
- **Better spatial resolution**

HA-TPC Prototypes

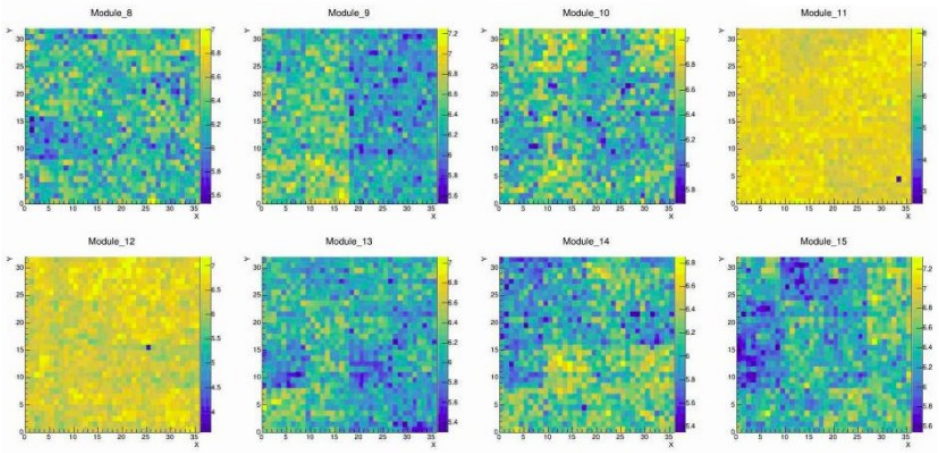
- Tested with electrons at DESY, and with electrons/pions/muons/protons at CERN.
- Same drift length as the final HA-TPCs
- First version of Micromegas. Response tested with different particles, at different momenta, drift distances, voltage bias and sampling time.
  Nucl.Instrum.Meth.A 1052 (2023) 168248

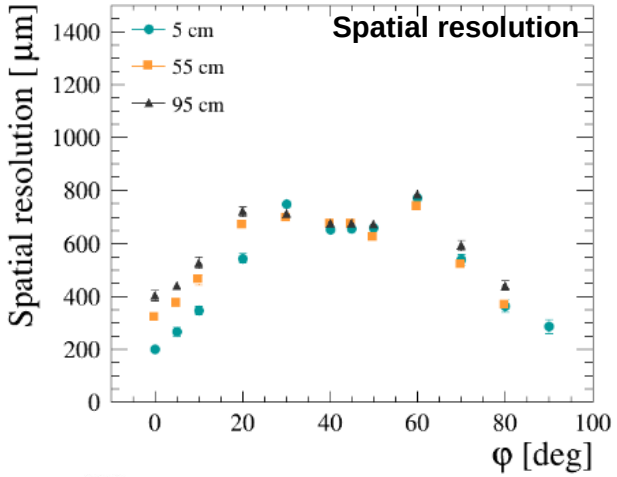


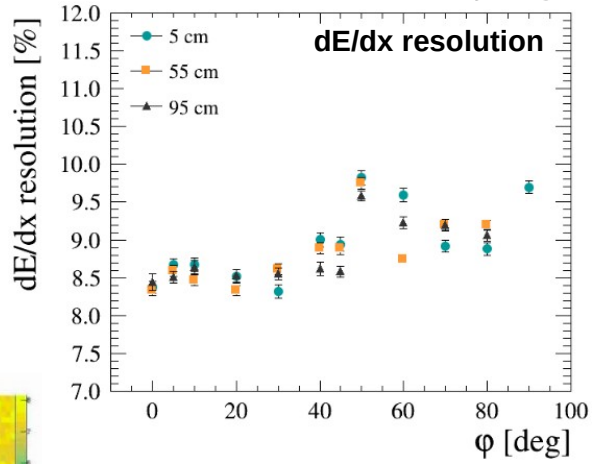




ERAMs gain



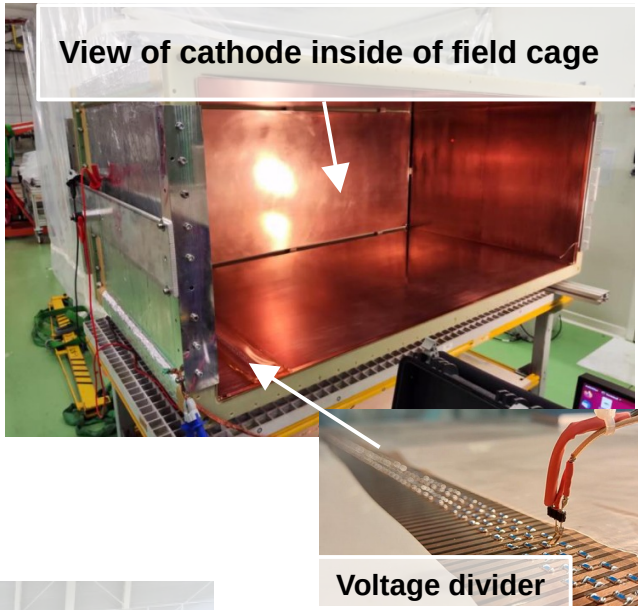




Assembly & Commissioning

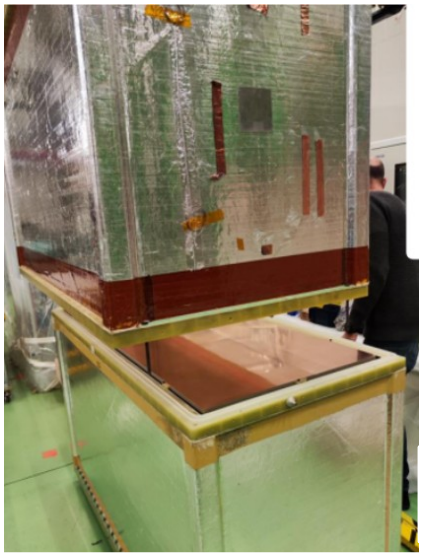
TPCs fully pre-assembled at CERN

Field cage assembly

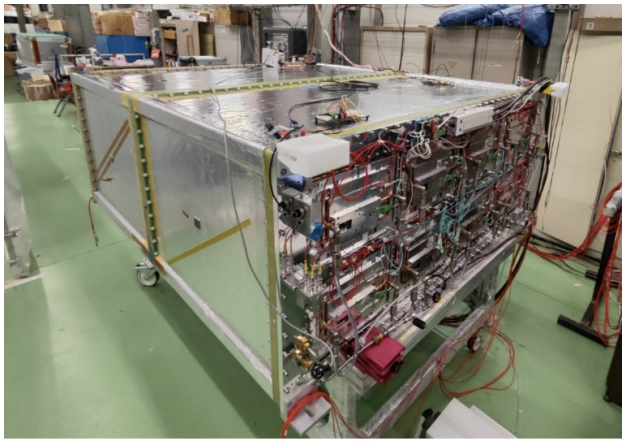


View of cathode inside of field cage

Voltage divider



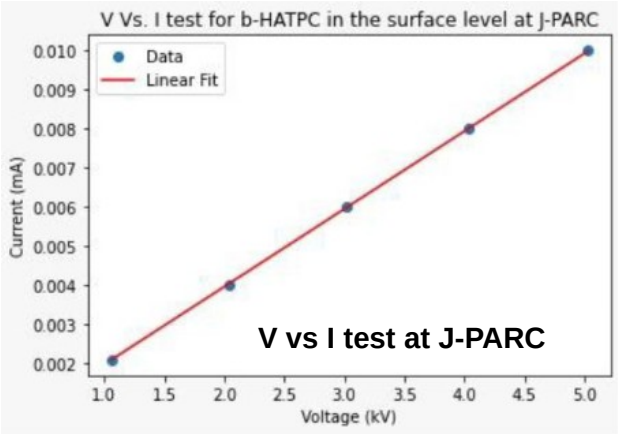
Union of cages



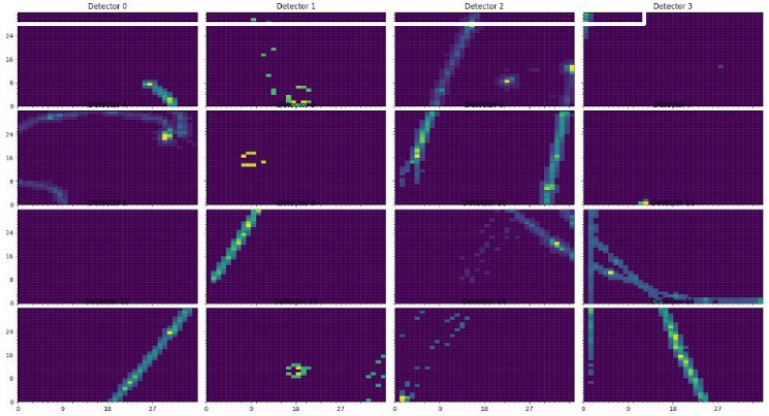
Bottom TPC, including ERAM modules

Minimal tests on-site

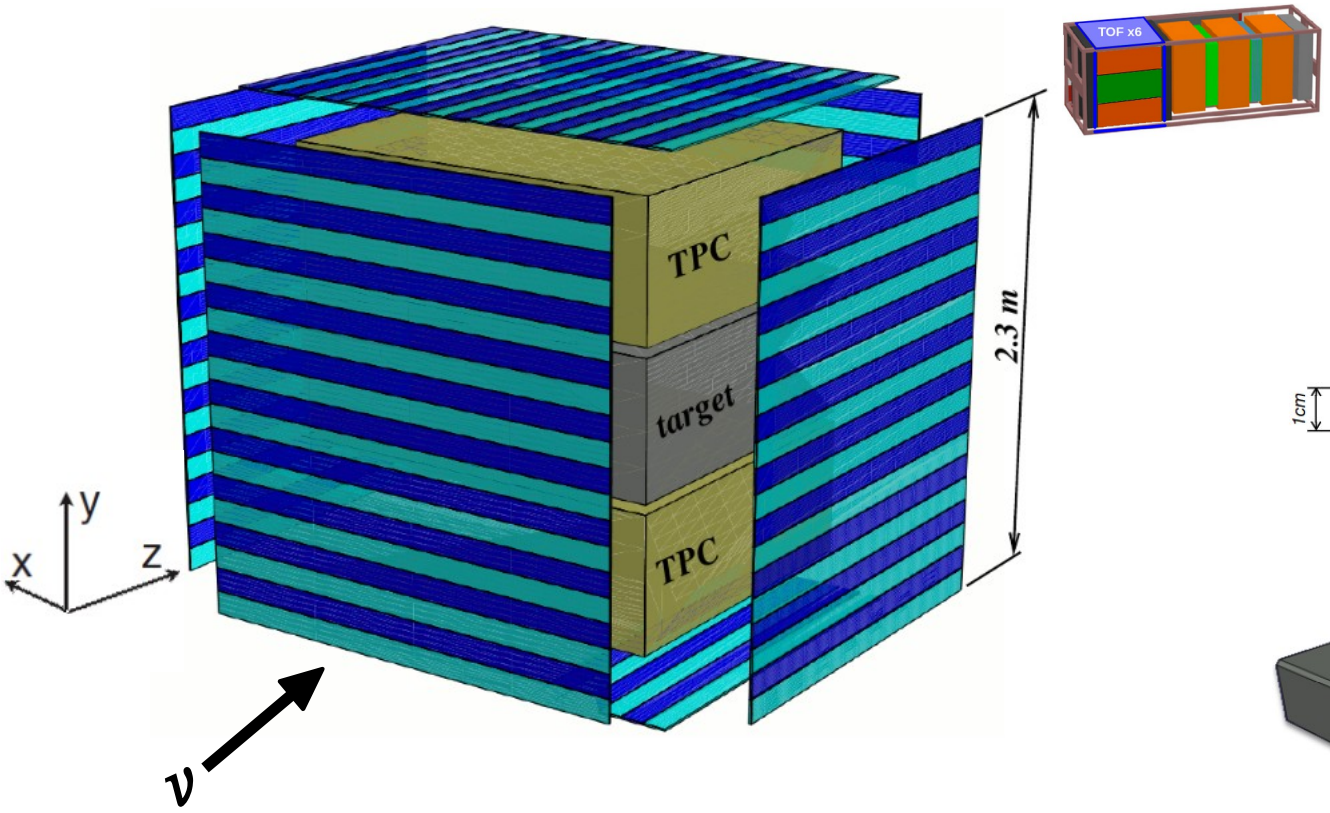
Checks on-site
- Cooling
- Gas system
- LV and HV
- DAQ and Slow Control

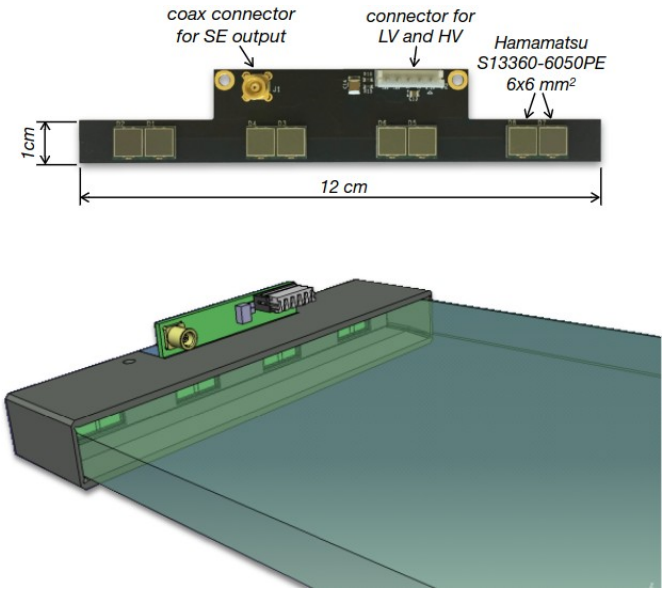


First events recorded on-site!



TOF





Characteristics

- 6 planes, 2.0 x 2.3 m
- 20 or 18 scintillator bars per plane.
- 236 readout channels.

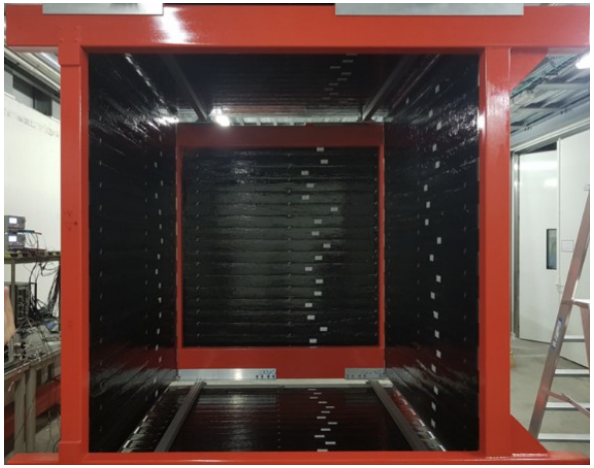
Distinctive Qualities

- Veto for incoming particles
- PID
- Cosmic trigger for HA-TPC and Super-FGD
- ~150 ps timing resolution

Assembly & Commissioning

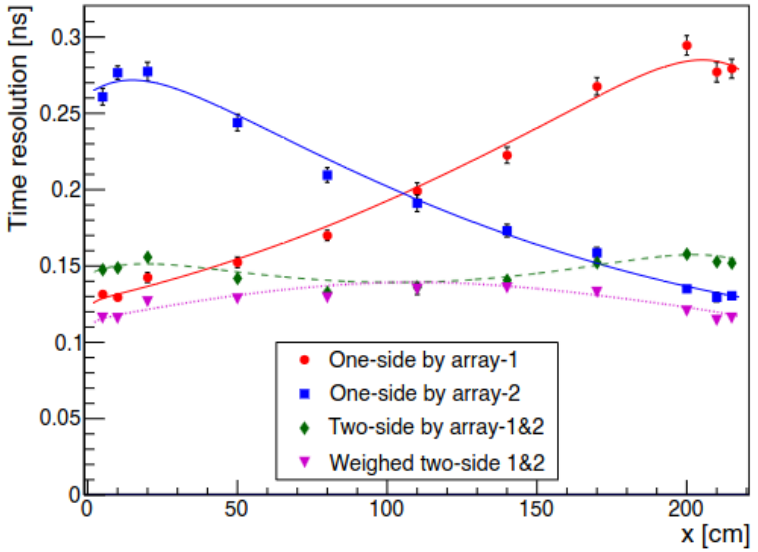
- Tested at CERN with cosmic muons, using the same planes to be installed in the T2K's near detector.
  JINST 17 (2022) 01, P01016, JINST 17 (2022) 01

Cosmic tests at CERN



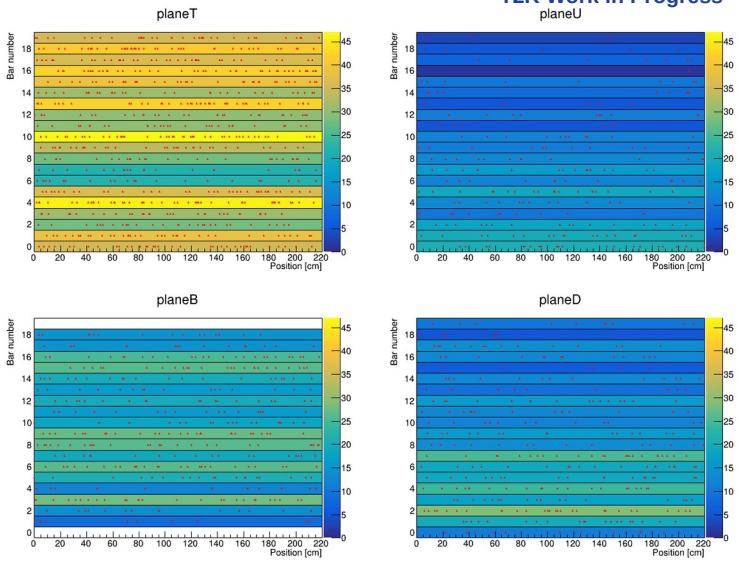
Preparations on-site

Time resolution



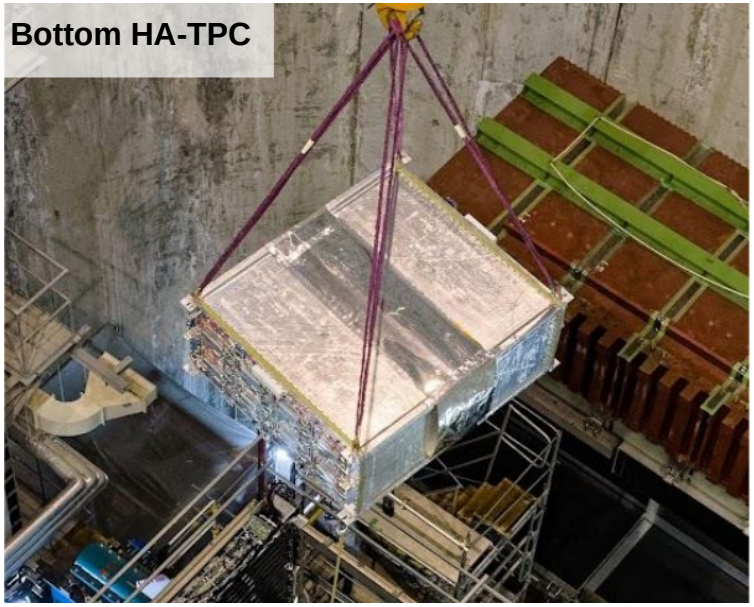
First cosmic events on site

T2K Work in Progress



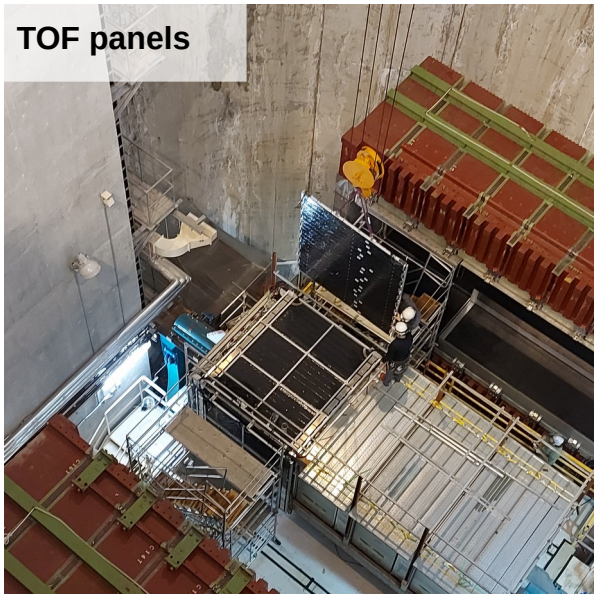
Sub-detectors Installation at ND280

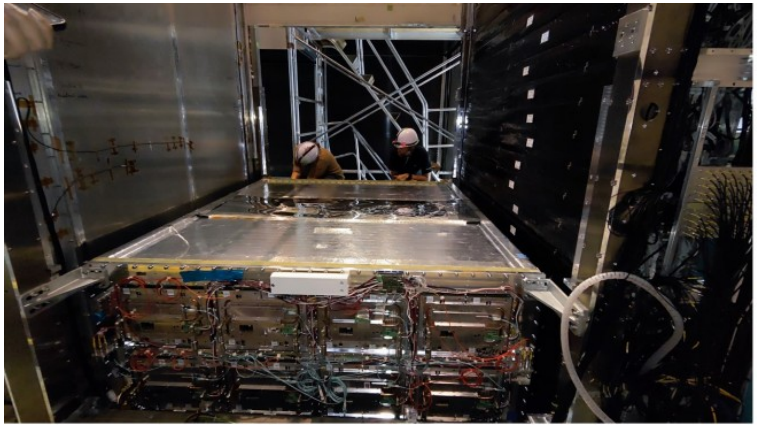
Bottom HA-TPC

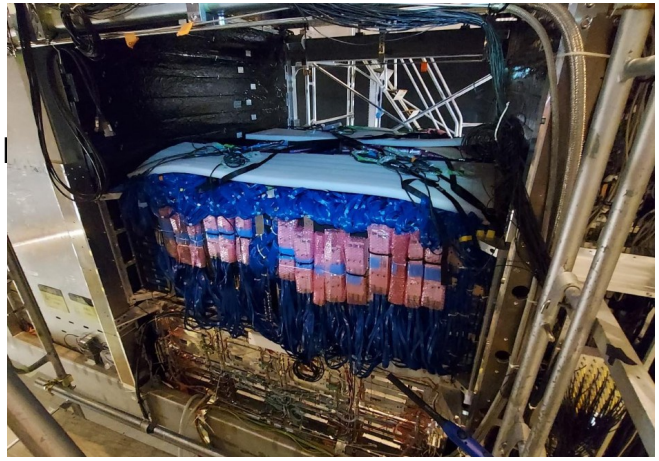


Super-FGD

TOF panels





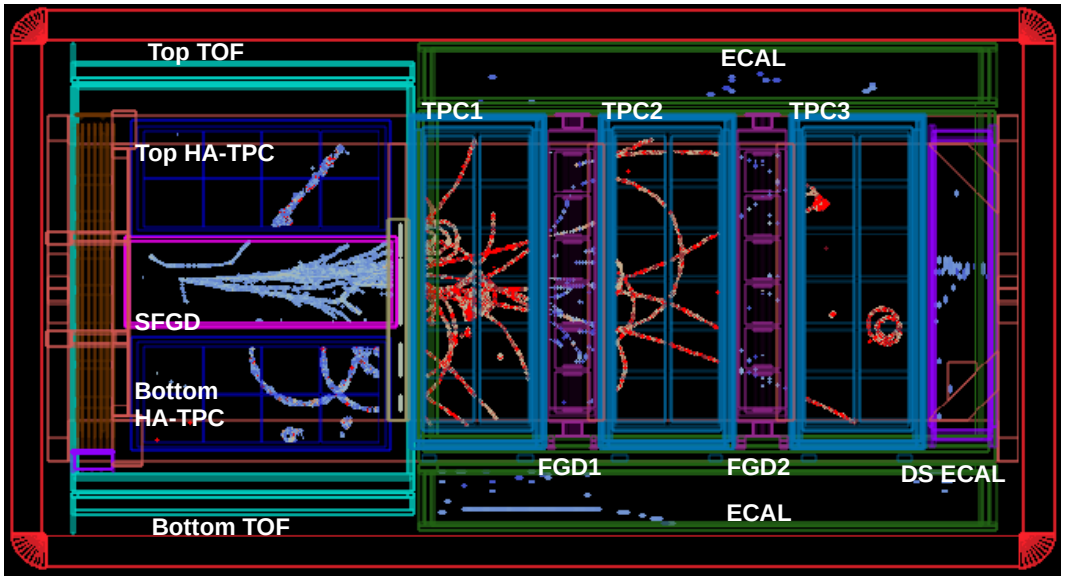


Full Upgrade Near Detector Operations

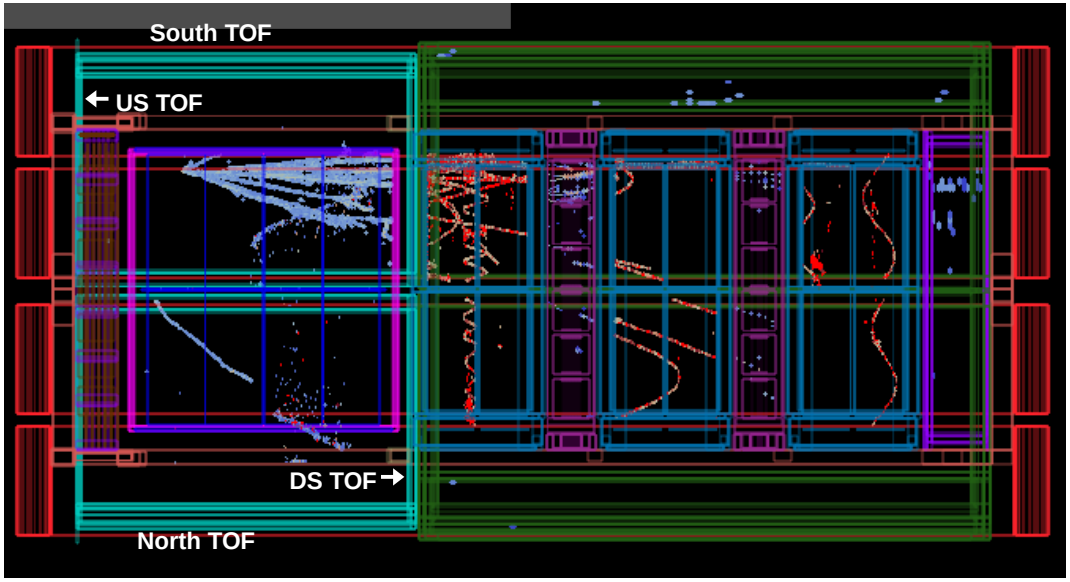
- Full integration finished!
  - Super-FGD.
  - Bottom and Top HA-TPCs.
  - Six TOF panels.
- First neutrino event with new sub-detectors on November 2023.
- First simultaneous neutrino event using all sub-detectors, on June 6th 2024!
- First successful run, June 6th to June 28th!

ν →

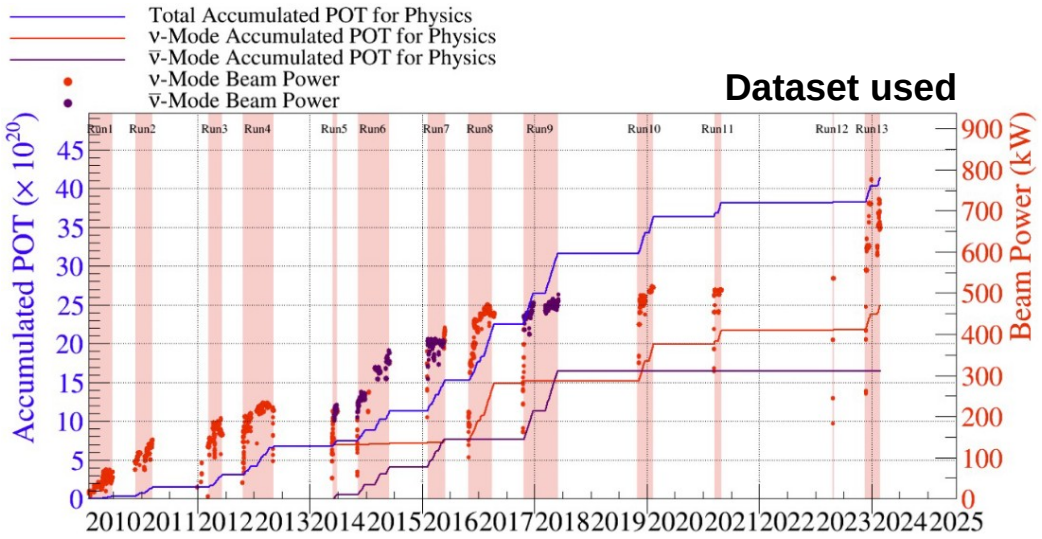
Side view (Y-Z plane)



Top view (X-Z plane)

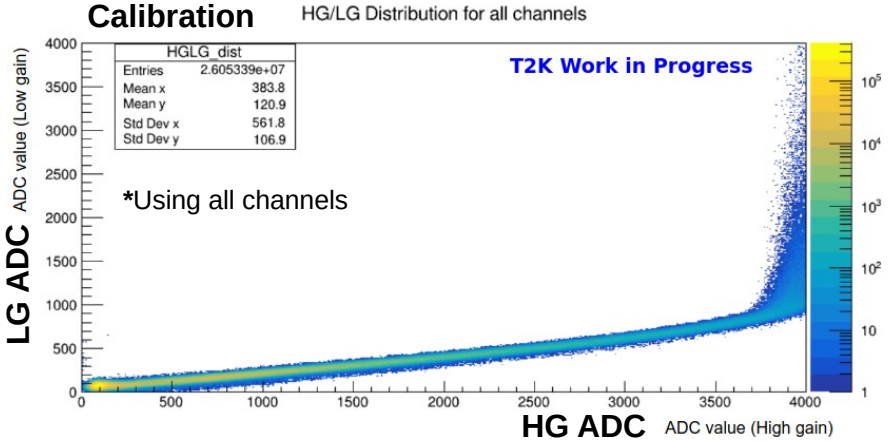


Dataset used

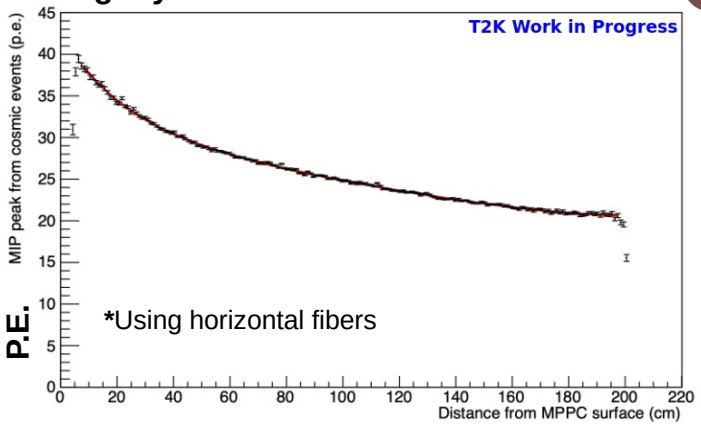


Performance – At ND280

High Gain (HG) and Low Gain (LG) Calibration

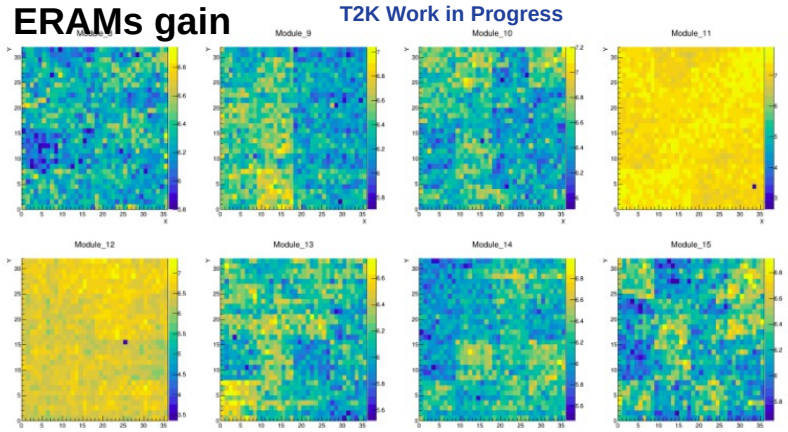


Light yield and attenuation

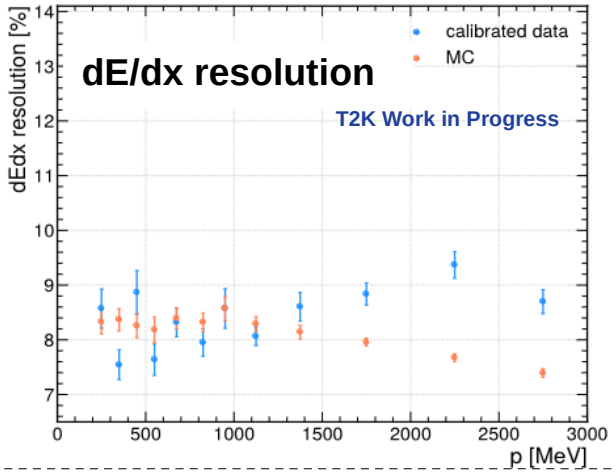


Super-FGD

ERAMs gain

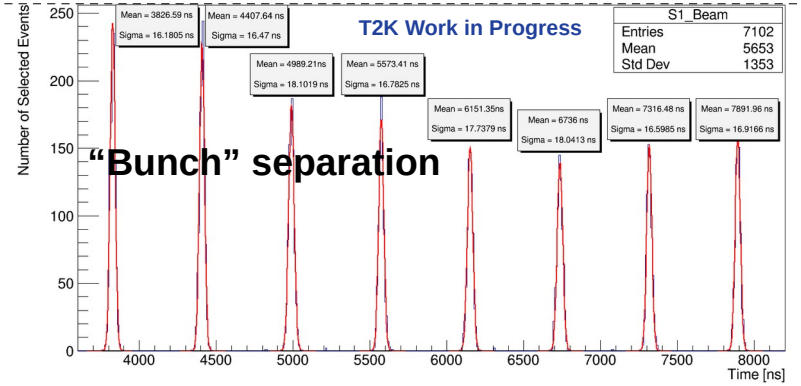


dE/dx resolution

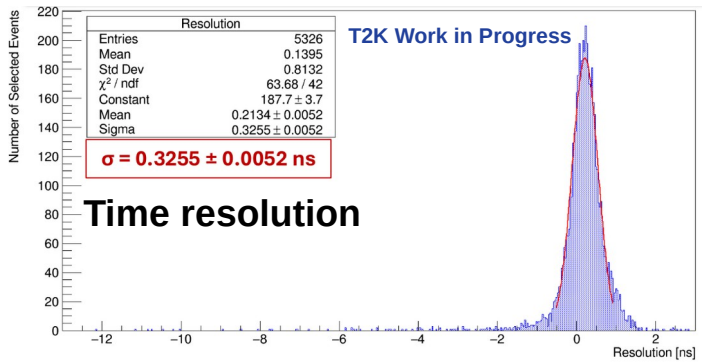


HA-TPC

"Bunch" separation

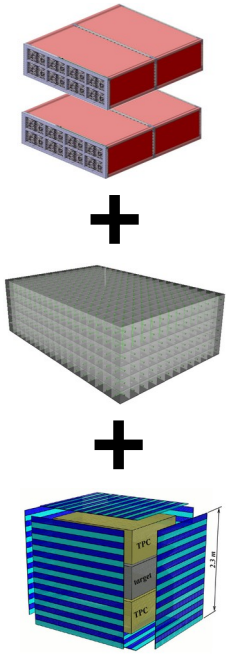


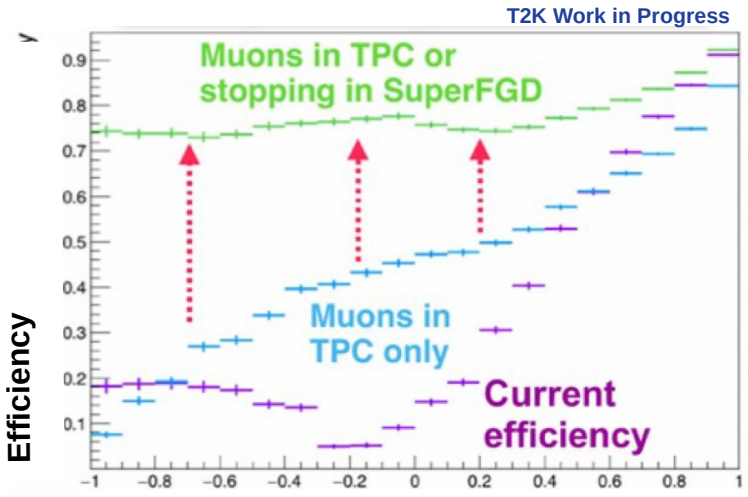
Time resolution



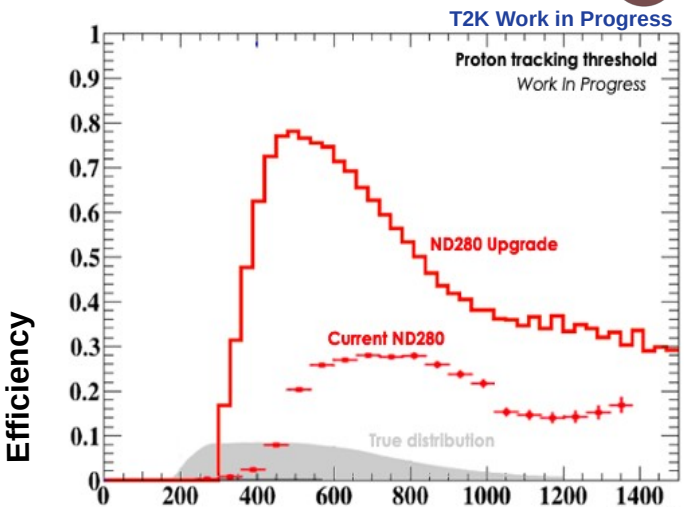
TOF

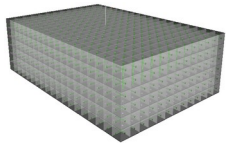
Expected Improvements



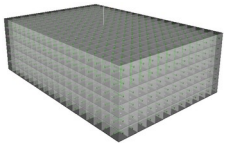


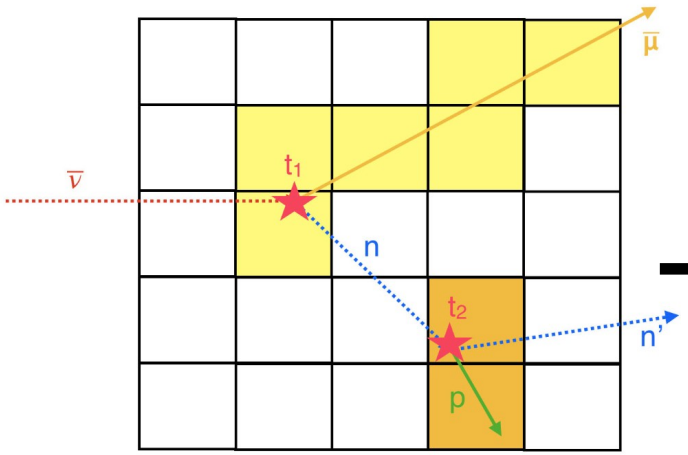
Improved acceptance at high and backward angles



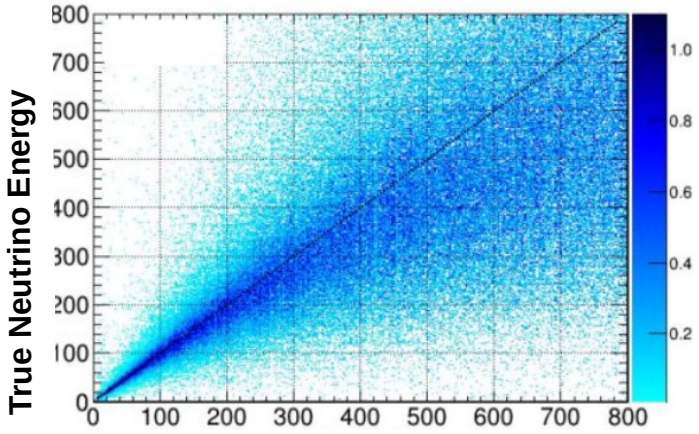


Improved acceptance at low proton momentum





Finer granularity + lower proton momentum



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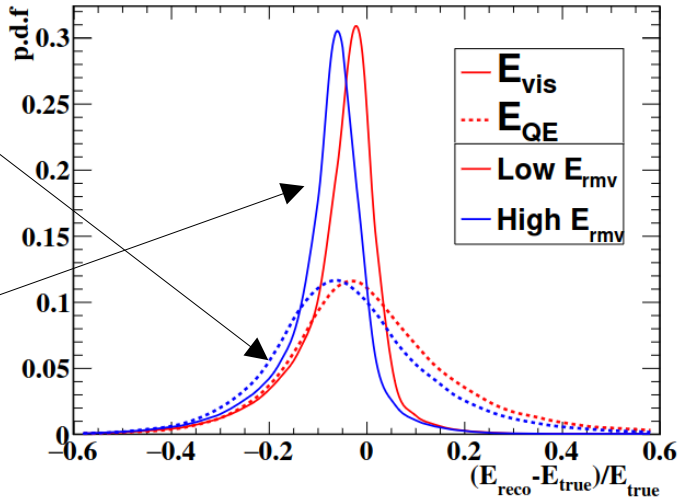
Expected Sensitivity

- Current **Ev** hypothesis is based on muon kinematics only.

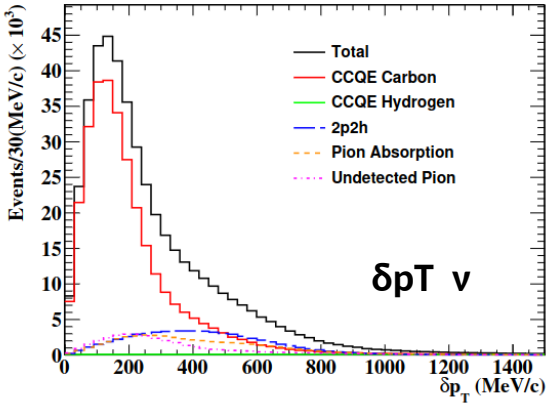
$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$

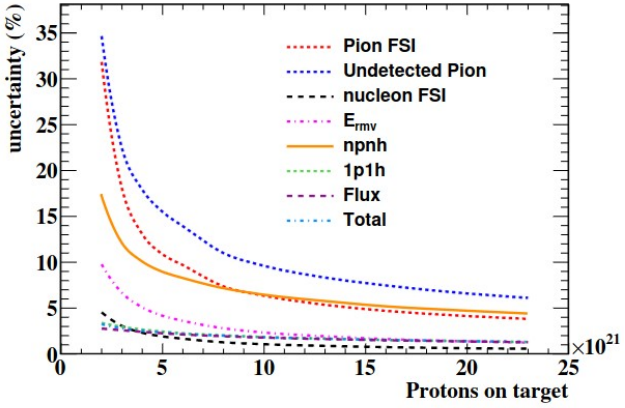
- It's crucial to understand the nuclear effects affecting the "final state" of the neutrino-nucleus interaction, so a better **Eν** hypothesis can be used.

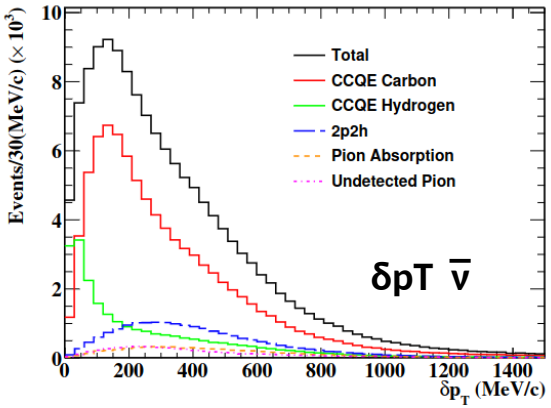
$$E_{vis} = E_\mu + T_N$$

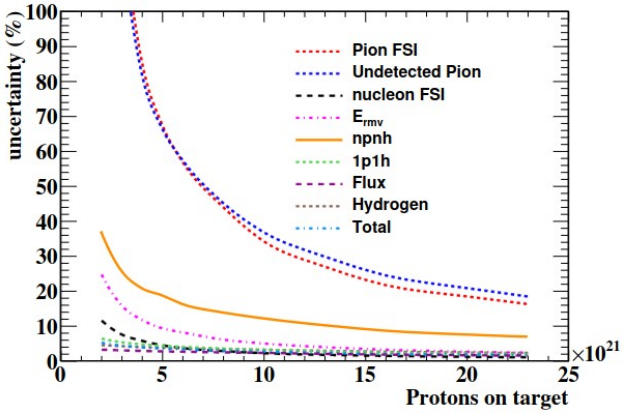


Neutrino energy resolution for the E_{QE} and E_{vis} hypotheses









Sensitivity to systematics parameters as a function of POT

Fit to CCπ0 reconstructed data in bins of δpT and Evis

In Summary

1. T2K envisioned a plan to upgrade its Near detector to reduce the key uncertainties in the measurement of oscillation parameters.

2. It designed, built and commissioned 3 new sub-detectors now installed in the “Off-axis” Near detector!

3. The new sub-detectors allow a full solid angle coverage, enabling the study of high-angle and low momentum particles.

4. The 3 new detectors will allow the exploration of physics until now inaccessible to T2K’s near detector, specially at low energies. With the final goal of having a better constraint of oscillations parameters.

Upgrade Detectors In the Pit!

All new sub-detectors installed