# Assembly, Test and Analysis Development of the T2K Near Detector Upgrade

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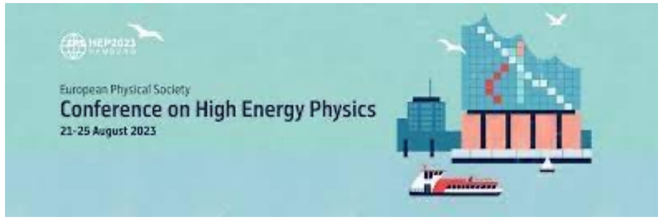
On behalf of the T2K collaboration

EPS-HEP, Hamburg, August 21-25, 2023



# Outline

1. Introduction

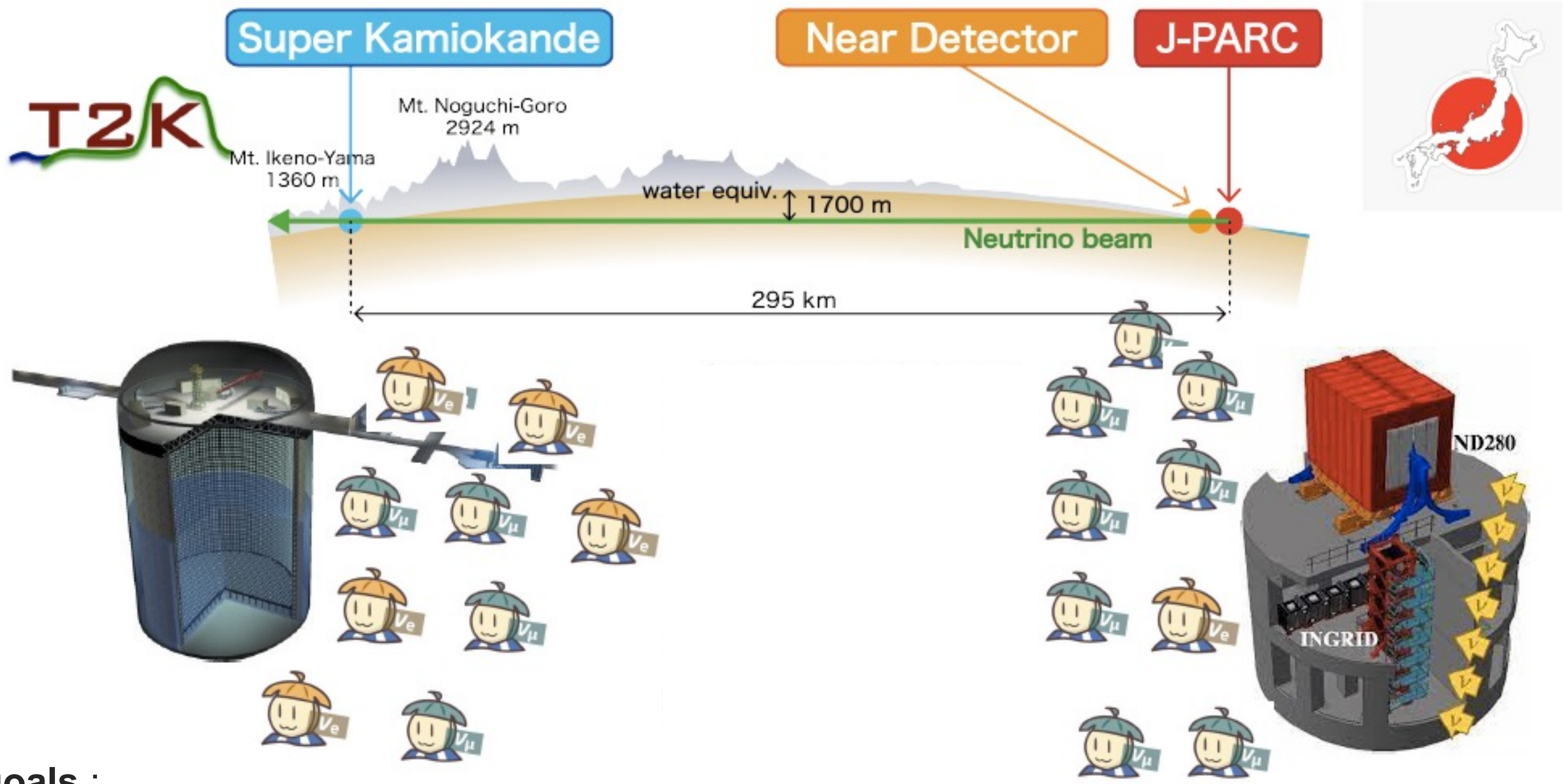
2. T2K Near Detector Upgrade
    1. 3D Fine-Grained scintillator
    2. High Angle Time Projection Chambers
    3. Time of Flight detector

3. Physics with the Near Detector Upgrade

4. Summary

# 1. Introduction

# The T2K experiment: Tokai to Kamioka

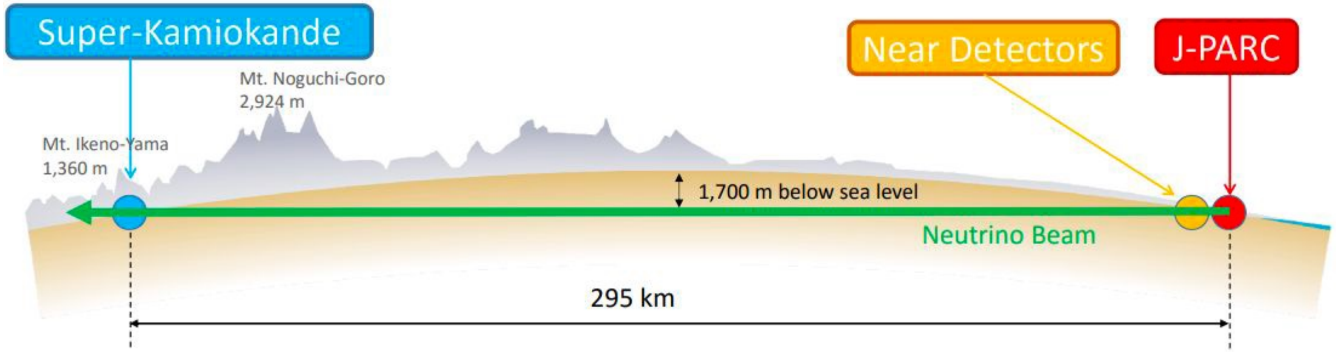



- **Main goals** :
  - Measure $\nu_e / \overline{\nu}_e$ appearance : sensitive to ($\theta_{13}$, $\delta_{CP}$)
  - Measure $\nu_\mu / \overline{\nu}_\mu$ disappearance : sensitive to ($\theta_{23}$, $\Delta m^2_{32}$)

*see talks by Yashwanth Prabhu & David Hadley*

- **First hint of CP violation in the lepton sector** : indication of maximal CP violation in neutrino oscillations $\delta_{CP} \sim -\pi/2$
- T2K aims to determine CPV at the $3\sigma$ level in the coming years

# The role of the Near Detector




Neutrino flux | Detector response | Interaction models

$$N_{\nu_\alpha}^{ND}(E_\nu) = \Phi_{\nu_\alpha}^{ND}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma_{\nu_\alpha}^{ND}(E_\nu)$$

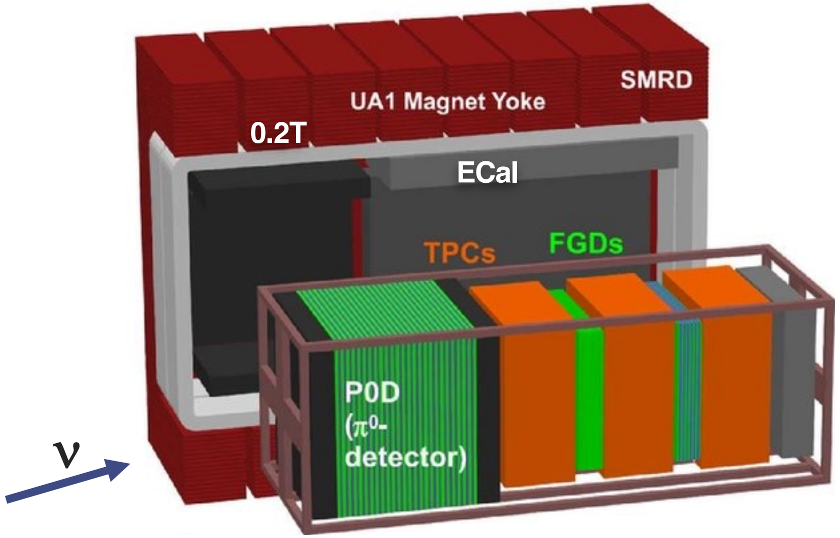
$$N_{\nu_\beta}^{FD}(E_\nu) = \Phi_{\nu_\beta}^{FD}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma_{\nu_\beta}^{FD}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

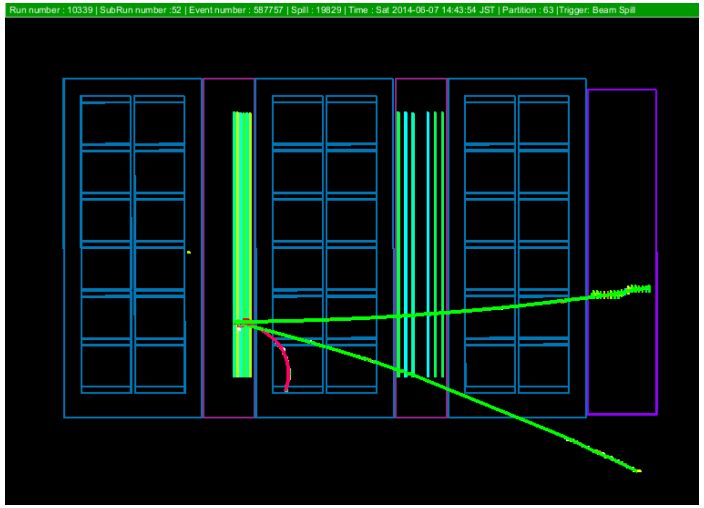
Oscillation Probability

- The role of the Near Detector is to constrain the flux and cross-section systematics model by measuring neutrino interactions before the oscillations.
- T2K’s approach is to propagate the constraints on the flux and the neutrino interaction models from the Near Detector to the Far Detector.
- The Near Detector has delivered quality measurements for T2K results, but as statistics increase, its limitations on flux and neutrino interaction model uncertainties are starting to emerge in the analyses.

# Current Near Detector : ND280

*NIM A 659 (2011) 106–135*



**ND280 :**

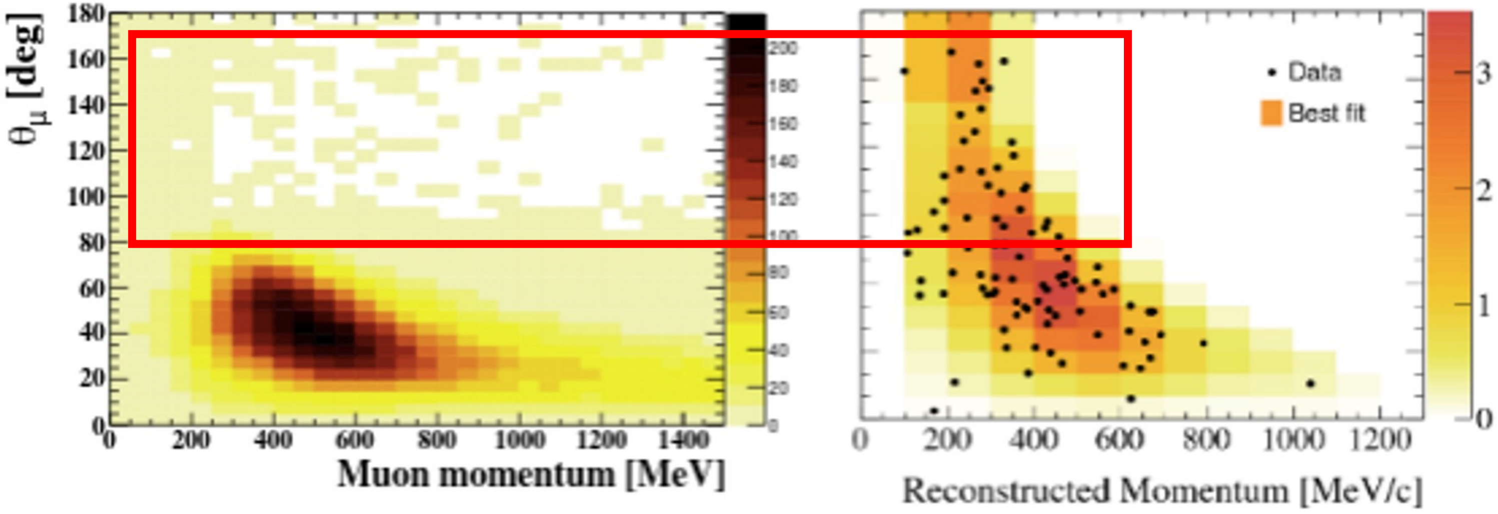
- Used on its own for neutrino cross section measurements
- Used in the oscillation analysis to constrain systematic parameters related to the neutrino flux and neutrino interactions

- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- A detector optimized to measure $\pi^0$ (P0D)
- An electromagnetic calorimeter to distinguish tracks from showers
- **A tracker system composed by**:
  - **Two Fine-Grain-Detectors (FGD) as neutrino active target**
    - **FGD1 (scintillator)**
    - **FGD2 (scintillator: water)**
    - **1.6 tons fiducial mass for analysis**
  - **Three vertical Time Projection Chambers:**
    - **Instrumented with bulk MicroMegas**
    - **8% dE/dx resolution, 9% momentum resolution@1GeV/c**

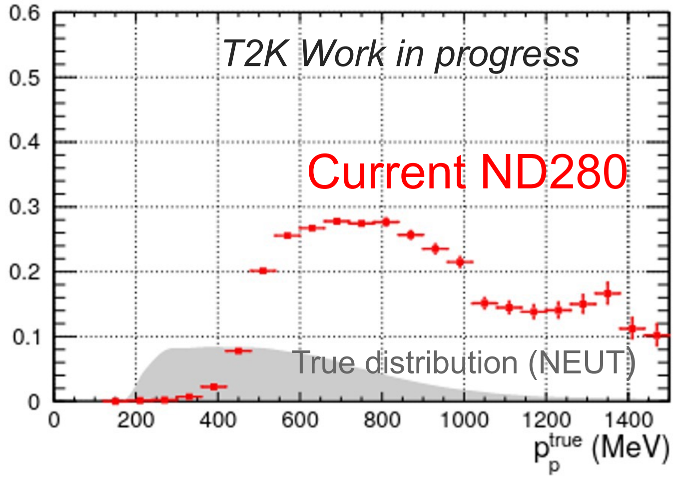
# Limitations of current ND280

**Muons at ND280**
Forward region

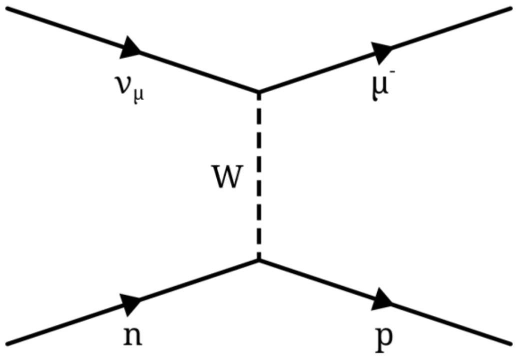
**Electrons at Super-K**
$4\pi$ acceptance




**Proton Detection Efficiency**




CCQE (1p1h)
*(Quasi-elastic Scattering)*




- Lack phase space coverage for high angle particles (unlike Super-k, $4\pi$ acceptance).
- Only lepton kinematics are used in energy reconstruction.
- High momentum proton threshold (~ 450 MeV/c).
- No capability to detect neutrons.

**T2K is currently upgrading ND280 to address and overcome these limitations.**

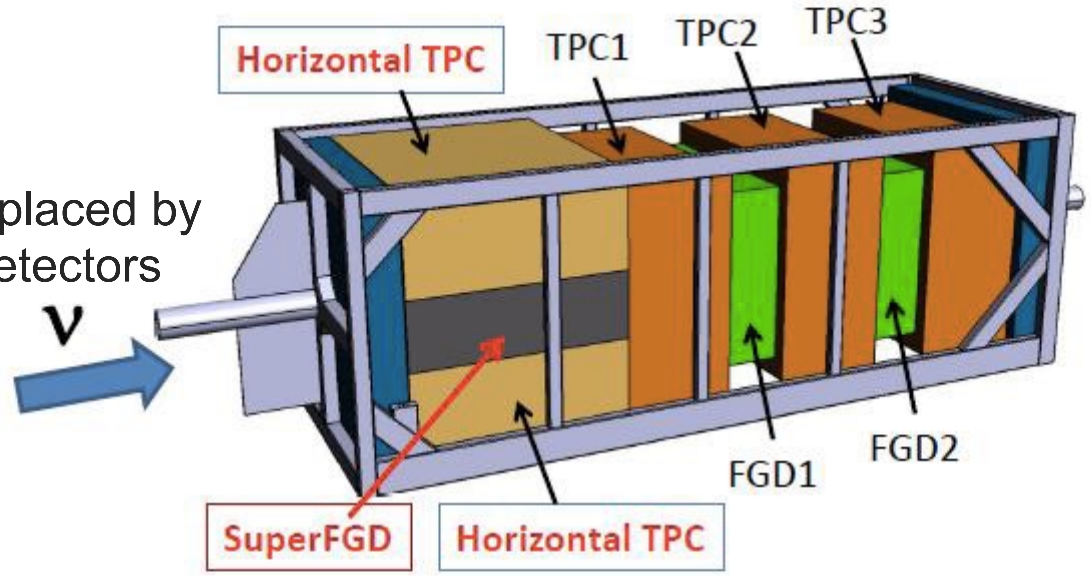
# 2. T2K Near Detector Upgrade

# ND280 Upgrade Overview

ND280 upgrade group :
120 participants, 29 institutions,
11 countries including CERN

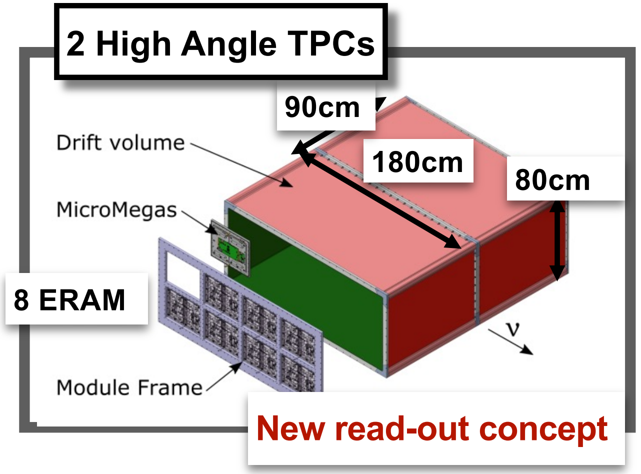
*arXiv:1901.03750*

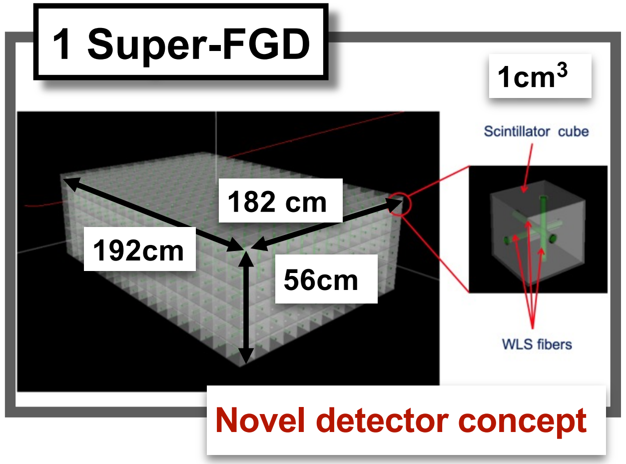
P0D replaced by
New Detectors

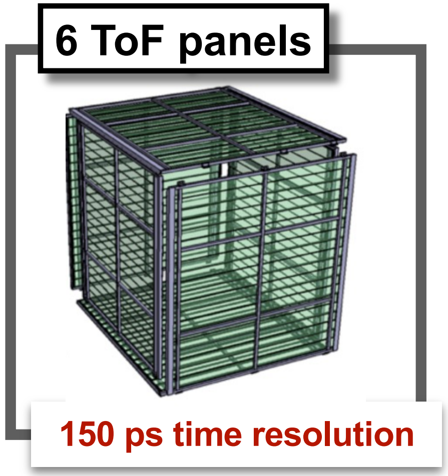



- The goal is to reduce the ND280 systematics with :
  - Fully active detector
  - $4\pi$ acceptance for charged particles
  - Detection of low energy protons and pions
  - Detection of neutrons
  - Electron/gamma separation

## Three novel technologies in ND280

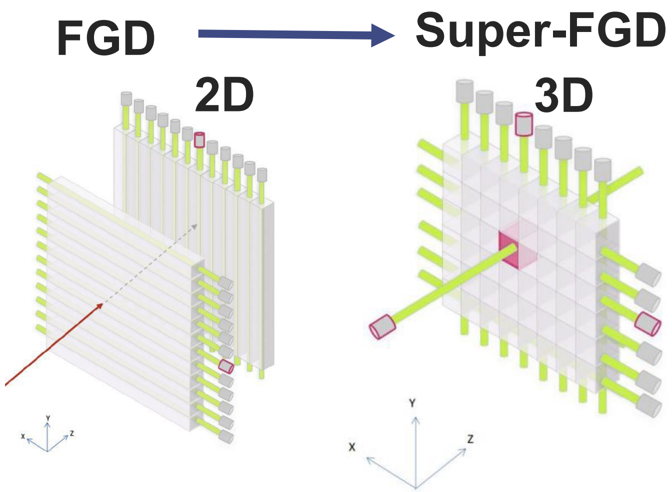


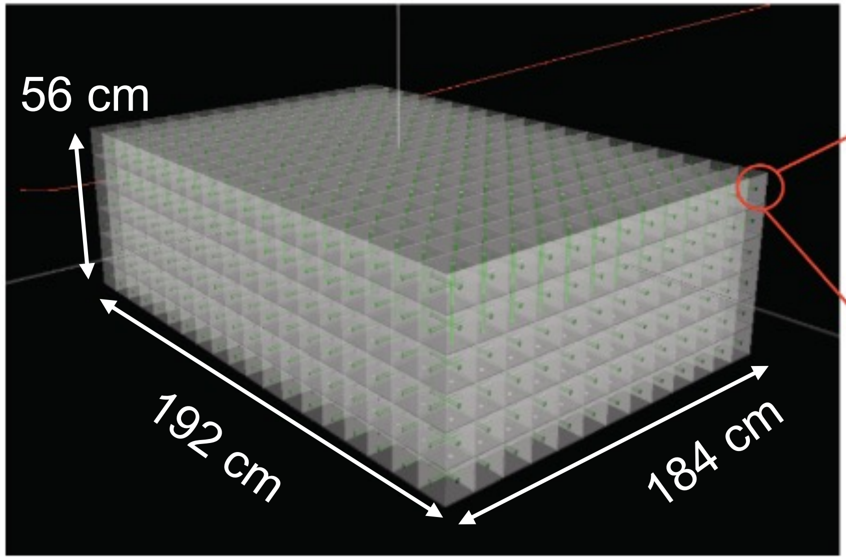



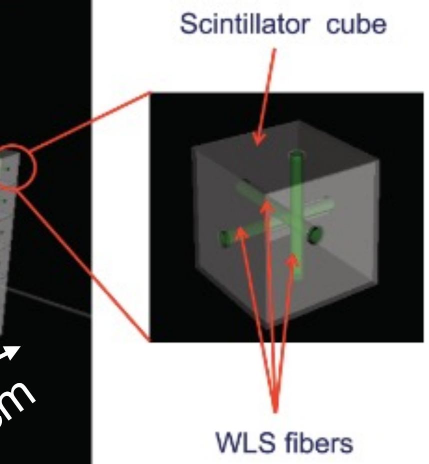



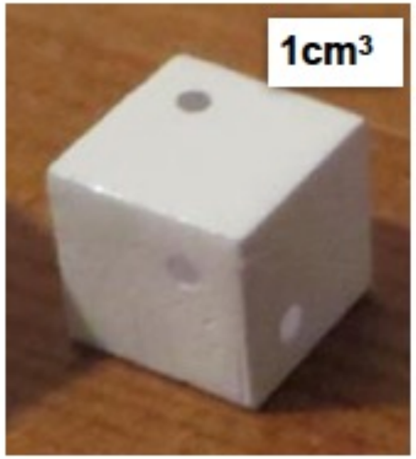
# Super-Fine Grain Detector (Super-FGD)

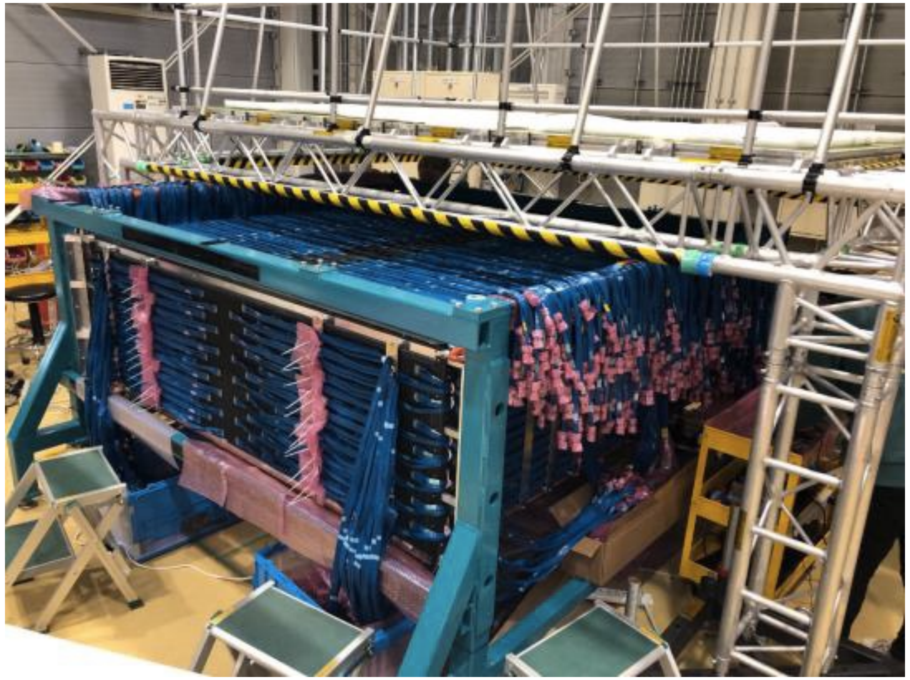
*JINST 13 P02006 (2018)*



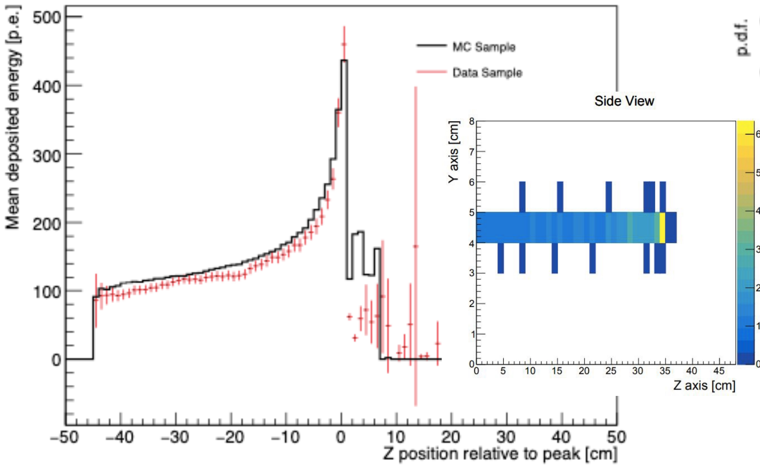



- **Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout**
  - Volume ~192 x 184 x 56 $cm^3$
  - Total active weight about 2 tons of target
  - 2 million of optically isolated cubes, each 1 x 1 x 1 $cm^3$
  - Each cube has 3 orthogonal holes of 1.5 mm diameter
  - Cubes covered by reflector will be read out with 3 orthogonal WLS fibers each with MPPC on one end
    → total of ~ 60000 fibers

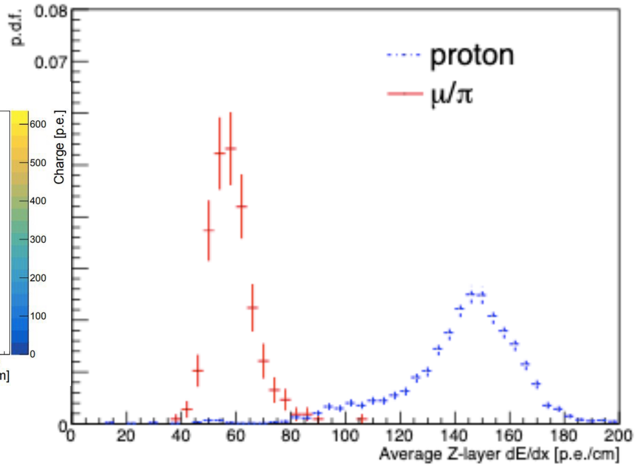
# Super-FGD prototypes Performance

- Multiple beam tests using prototypes have been conducted :
  - **<u>At CERN with charged particles</u>**: *NIMA 936 (2018), JINST 15, 12 (2020), JINST 18 (2023)  P01012*

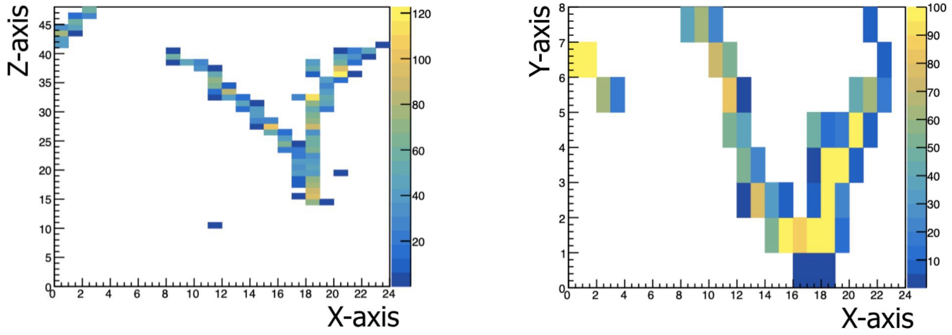
**Bragg peak from a stopping proton**




**dE/dx for different particles**

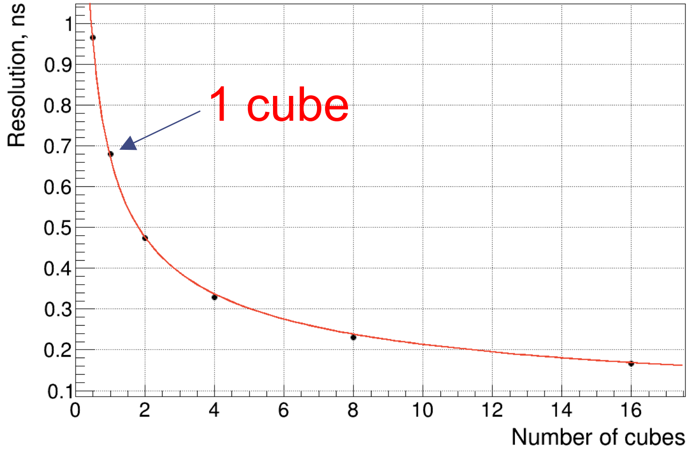



**e / γ separation**




Super-FGD prototype (8x24x48 cm)

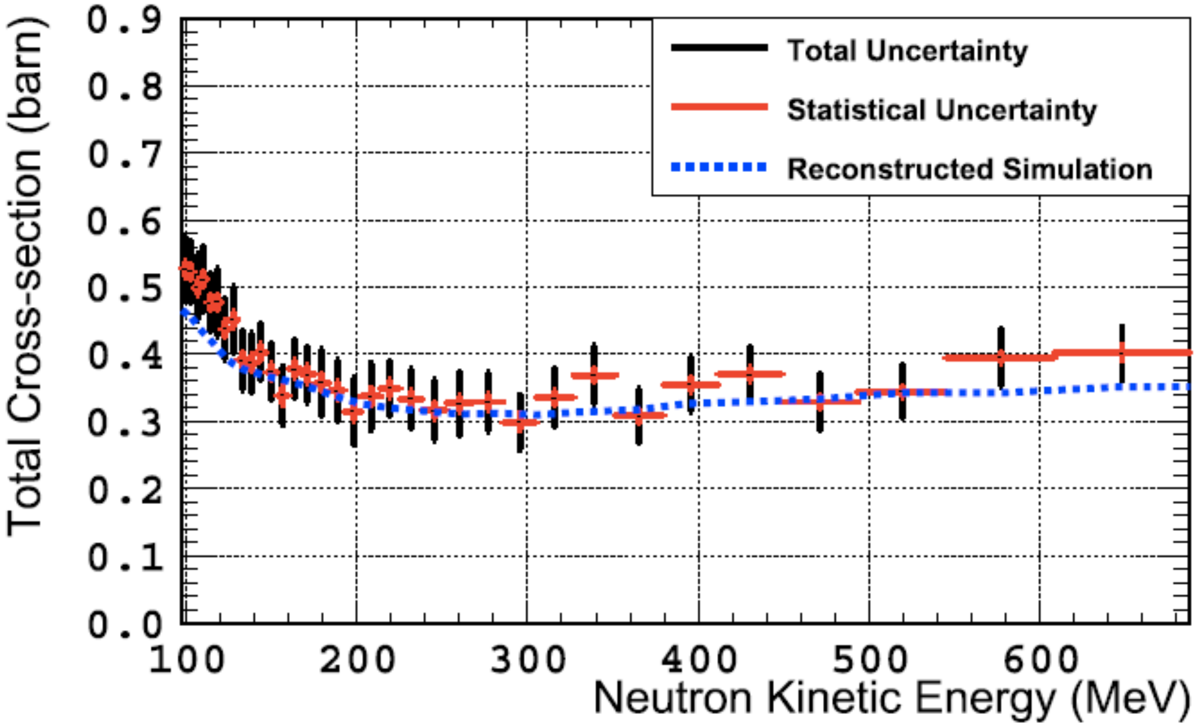
**Time resolution for a MIP → Neutron energy**



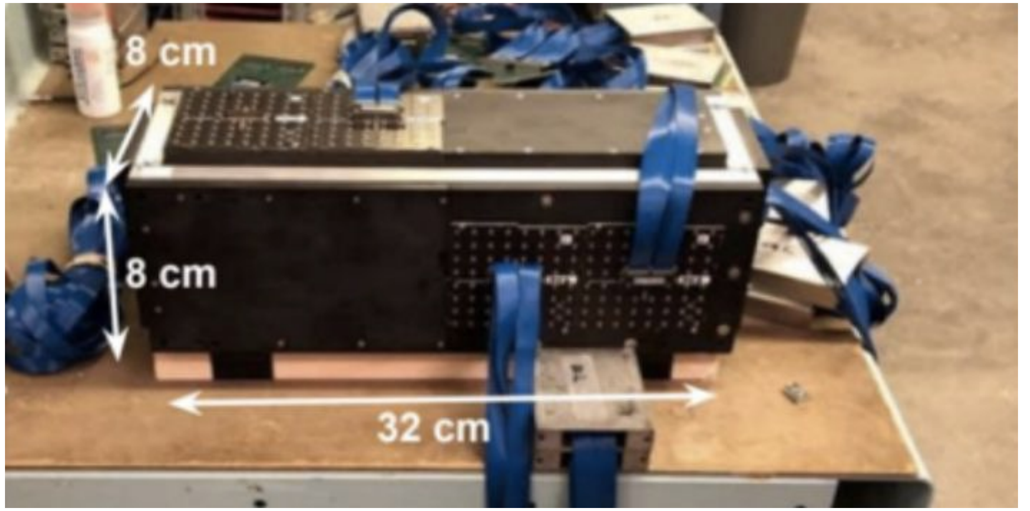

**Fulfills the requirements**

# Super-FGD prototypes Performance

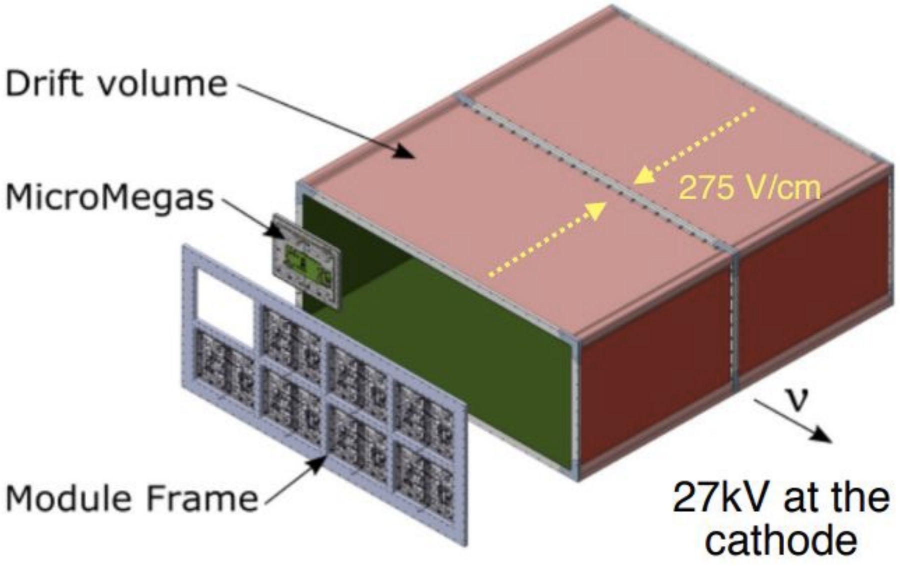
- Multiple beam tests using prototypes have been conducted :
  - **<u>At LANL with neutrons</u> :** *Physics Letters B 840 (2023) 137843*
    - Measurement of the total neutron-CH cross section as a function of the neutron kinetic energy using event rate depletion along the beam axis.



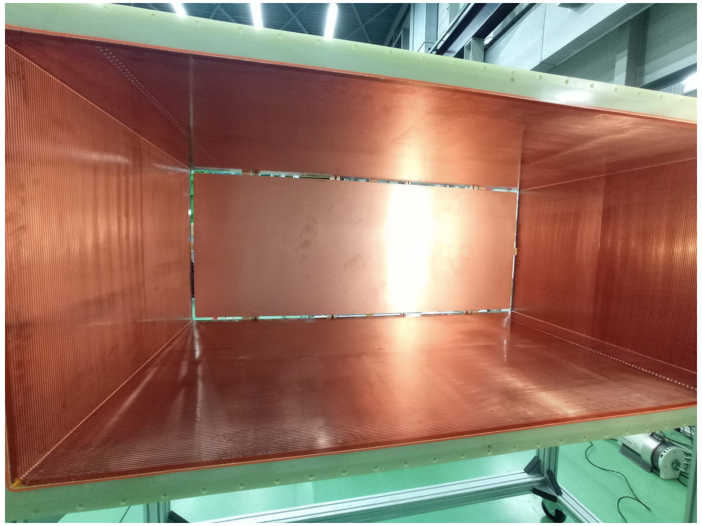

US-Japan prototype (8x8x32 cm)



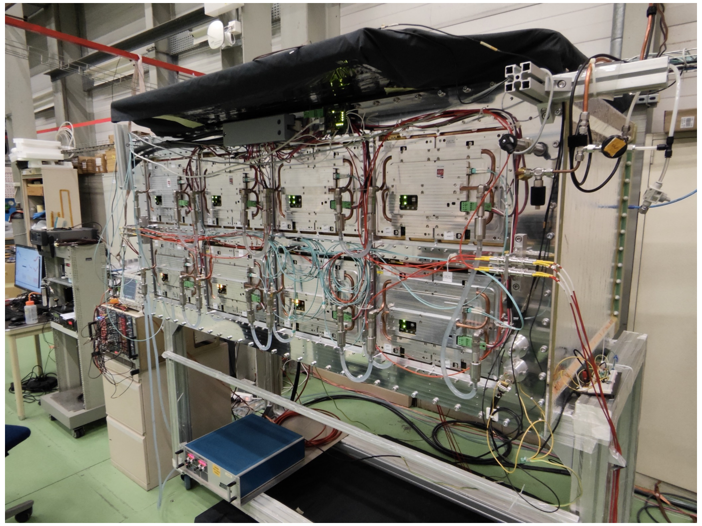
# High-Angle Time Projection Chambers (HA-TPC)




**Cathode**

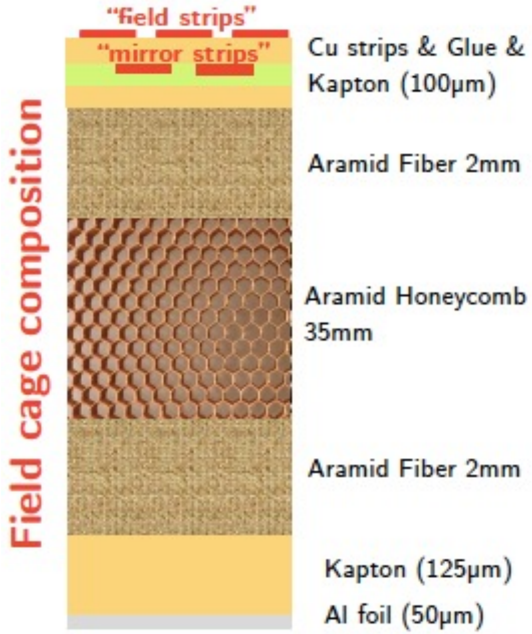


**Anode plane with 8 ERAMs**

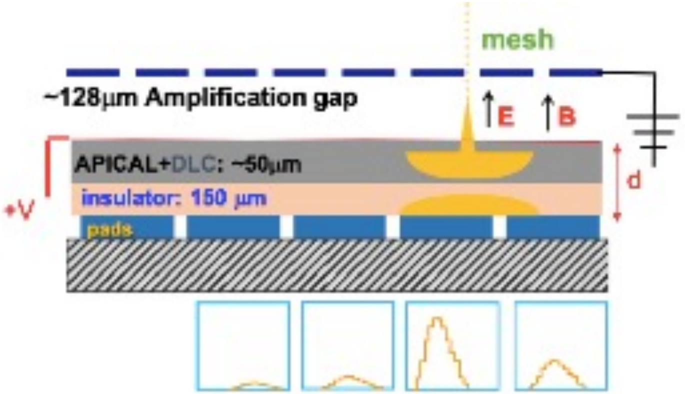


- Two Field Cages joined at the central cathode plane.
- Each Field Cage is 175 x 84 cm² in size with a drift length of 99 cm.
- 16 Encapsulated Resistive Anode Micromegas (ERAM) modules read out the device at the two opposite Anodes.

- **The HA-TPC features :**
  - New field cage design to minimize dead space and maximize tracking volume.
  - Replacement of standard bulk-MicroMegas with new resistive MicroMegas →improved spatial resolution using fewer pads.




**Resistive Micromegas**

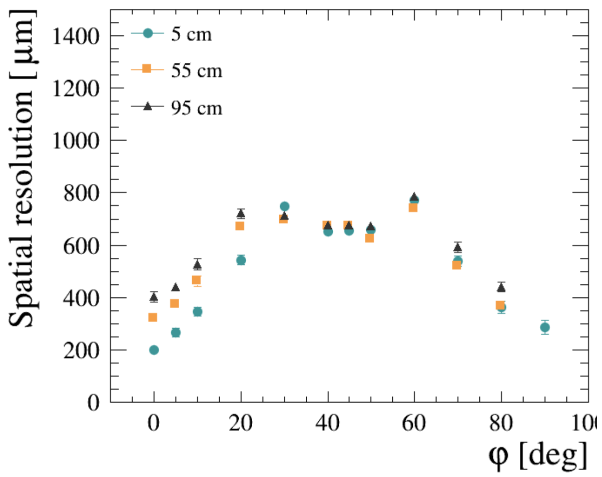


# High-Angle Time Projection Chambers (HA-TPC)

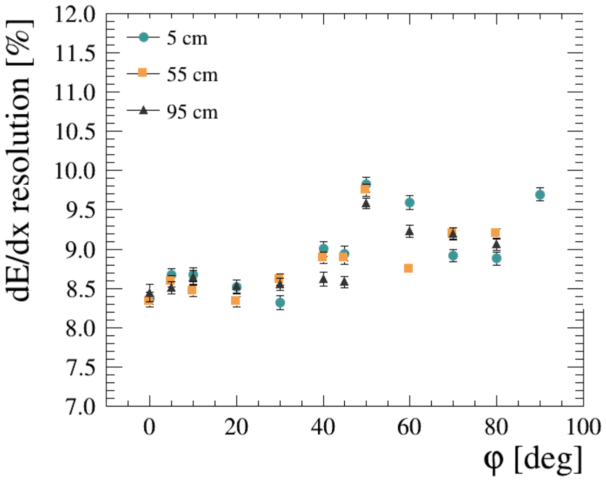
- **Characterization of charge spreading (RC) and gain of ERAMs using X-ray at CERN .**
  - Developed a detailed physical model enabling simultaneous extraction of gain and RC information of the ERAMs. *e-Print: 2303.04481, https://doi.org/10.1016/j.nima.2023.168534*
- **Measurement of spatial and energy resolution through several test beam campaigns at CERN and DESY.**
  - Achieved spatial resolution better than 800 μm and dE/dx resolution better than 10%.

    *NIMA* 957 (2020) 163286, *NIMA* 1025 (2022) 166109 , *NIMA* 1052 (2023) 168248

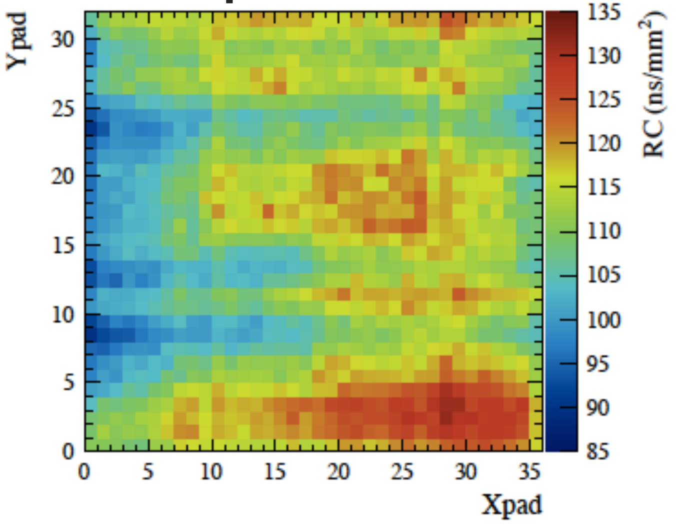
**Spatial Resolution**



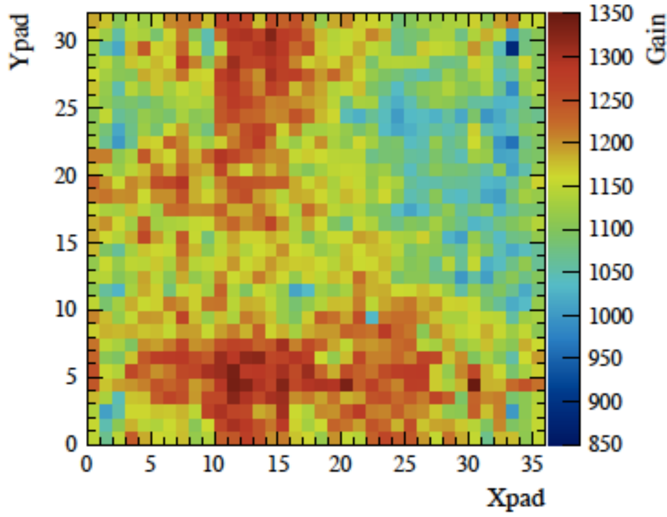

**dEdx Resolution**




**RC map of ERAM-30**



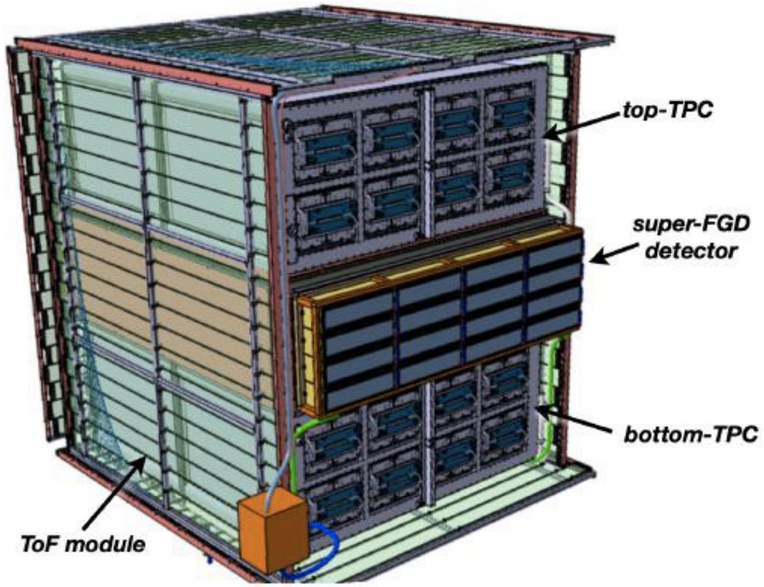

**Gain map of ERAM-30**




**Fulfills the requirements.**

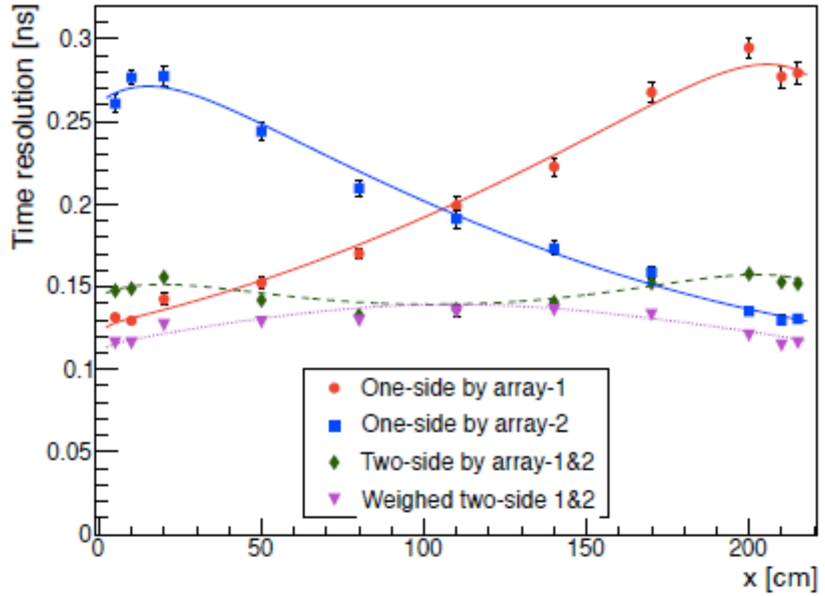
# Time-of-Flight (ToF) Detector

*JINST 17 (2022) 01, P01016*




- 6 ToF planes will fully cover 2 HA-TPC and Super-FGD.
- Each plane consists of 20 scintillator bars (EJ200) of $12 \times 1 \times 230$ cm$^3$ size.
- Readout of 16 MPPC at both ends of each bar.

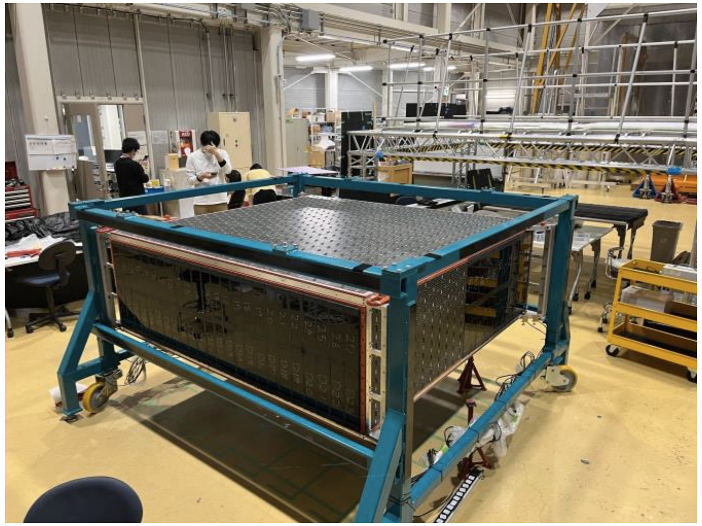
**Single bar test with cosmic rays**
**→140 ns time resolution**

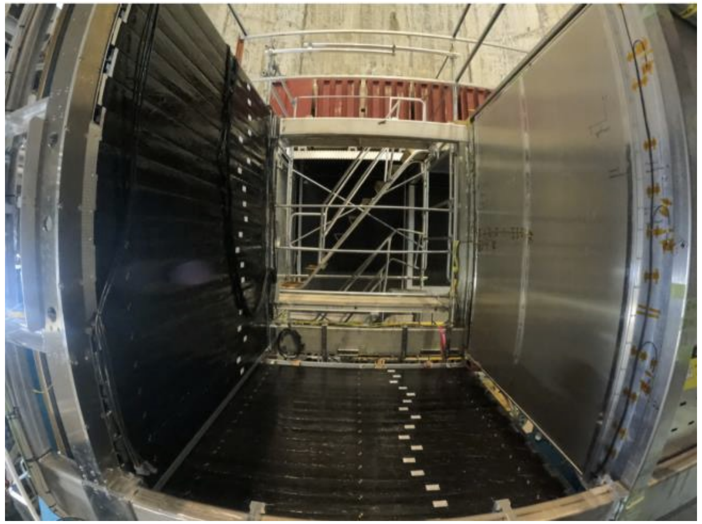



**Goals :**

- Precisely measure the crossing time of charged particles.
- Separate inward-going background from neutrino interaction products within the fiducial volume.
- Serve as a cosmic trigger for Super-FGD and HA-TPC calibration.
- Enhance particle identification through timing information.

# Status of ND280 Upgrade

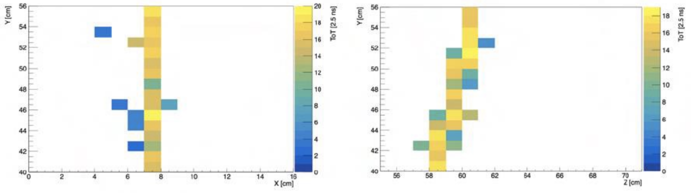




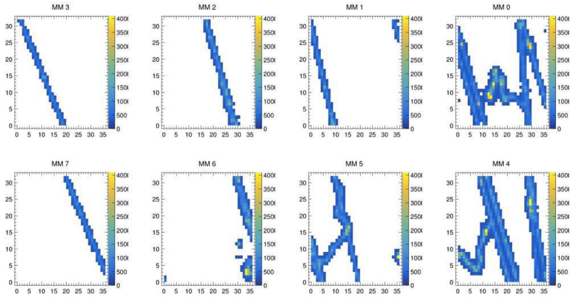
**Super-FGD at J-PARC**. electronics installation, calibration, tests with cosmic  muons on surface

**Bottom HA-TPC** was assembled at CERN and is scheduled for delivery to J-PARC in August 2023

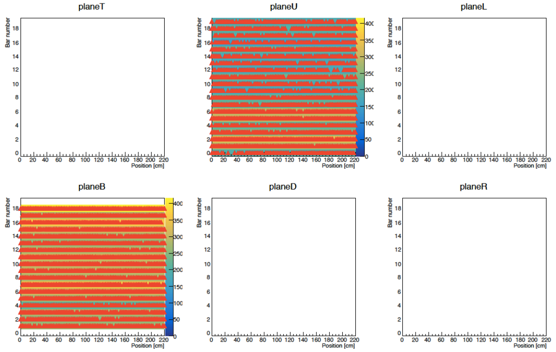
**TOF detector at J-PARC.** 2 modules installed into the Near Detector pit



First cosmics



First cosmics

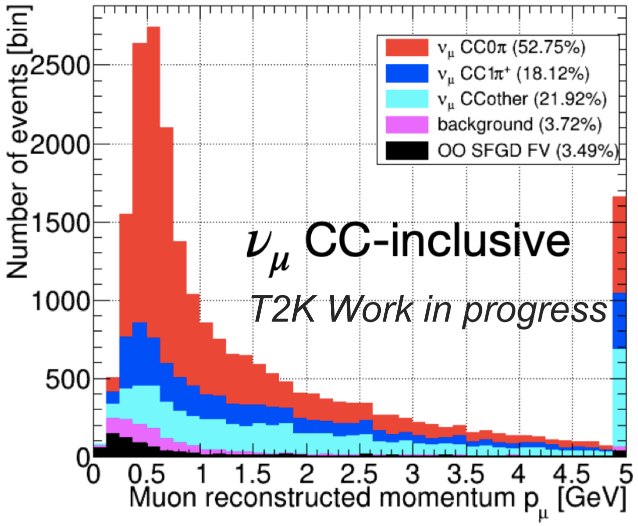


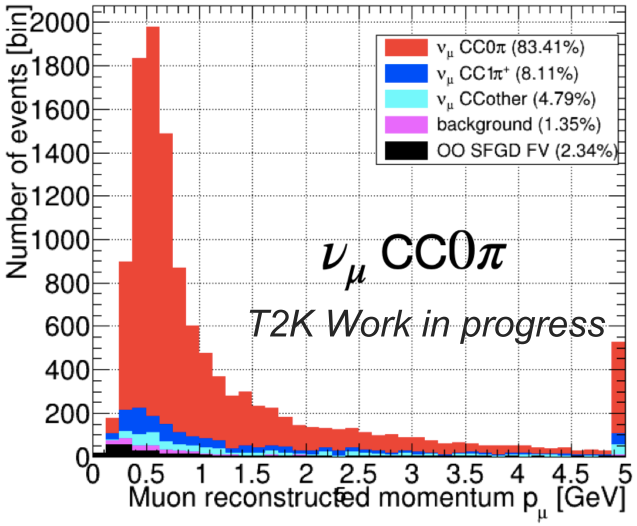
**The upgraded ND280 will start collecting neutrino data in November 2023**

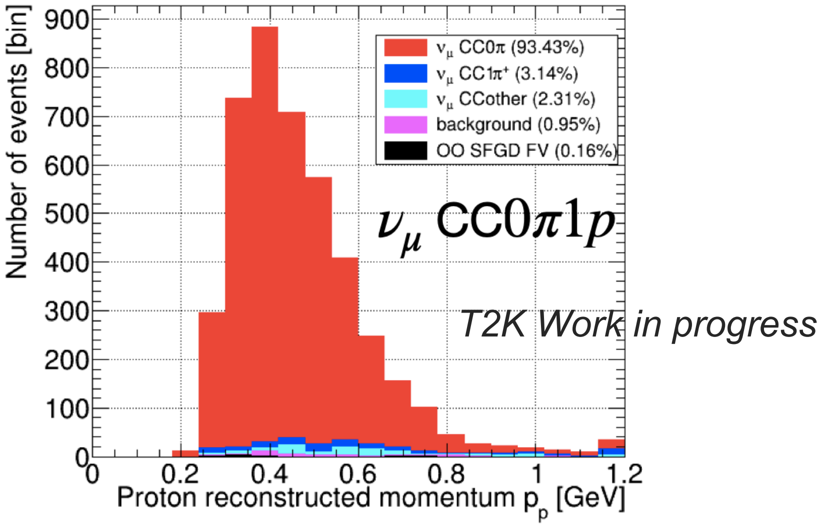
# 3. Physics with the Upgrade

# Reconstruction Performance with ND280 Upgrade

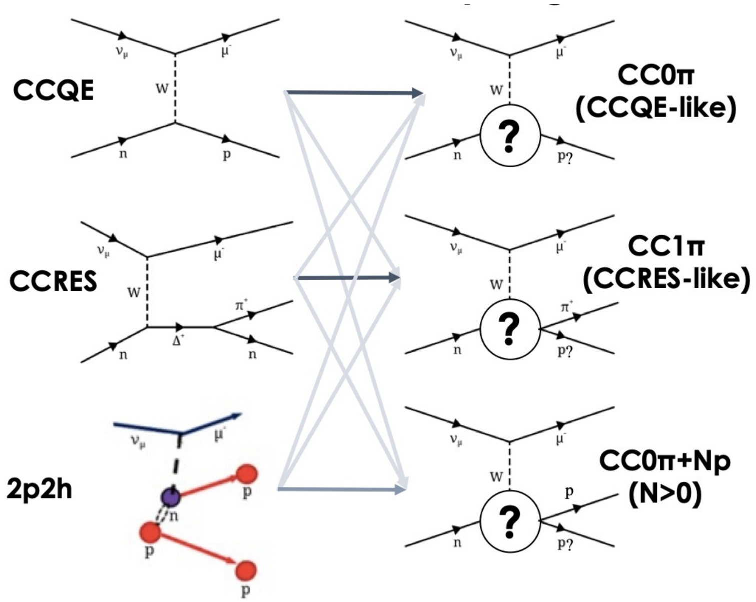
## Selection of $\nu_\mu$ CC Events




- **Selection based on visible topologies (number of protons and pions in the final state).**
- $\nu_\mu$ CC-inclusive : purity 94.6%, efficiency 64.7%
- $\nu_\mu$ CC0π : purity 90.8% and proton selection purity 99.6%
- Developed selection of CC1π with Michel electron tagging, both in the case the pion track is reconstructed as well as without the track (access to pions below 100 MeV/c).

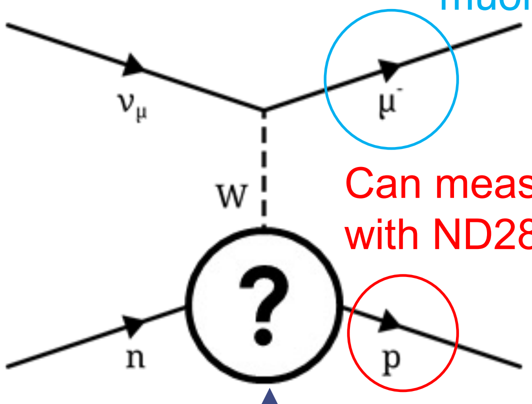


# Improved Observables: Visible Energy

- Currently, only lepton kinematics are used in energy reconstruction.

$$E_{\nu}^{QE} = \frac{m_p^2-(m_n-E_b)^2-m_\mu^2+2(m_n-E_b)E_\mu}{2(m_n-E_b-E_\mu+p_\mu \cos\theta_\mu)}$$

Only use muons currently



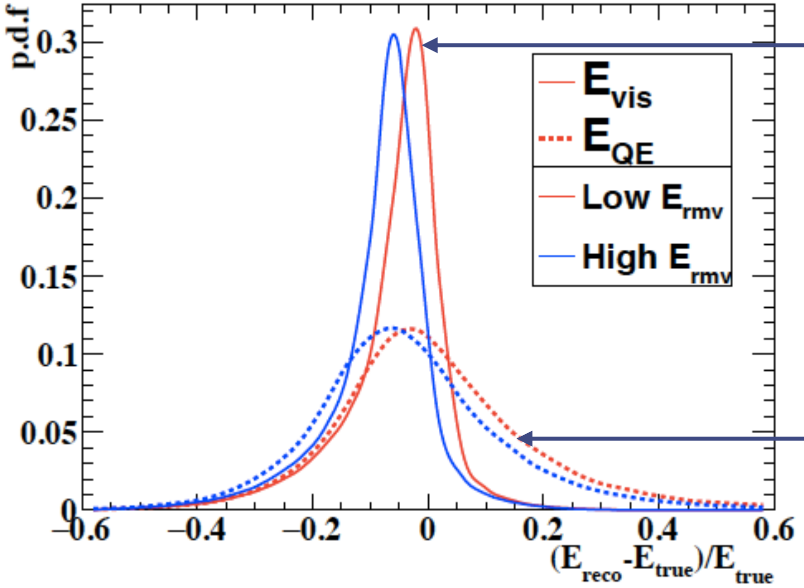

Can measure reliably with ND280 Upgrade

Nuclear effects

- Control of nuclear effects relies on inclusive model predictions.
- By reconstructing the proton as well, the visible energy provides a more accurate estimation of the neutrino energy.

$$E_{\text{vis}} = E_\mu + T_p$$

*Phys. Rev. D 105,032010*



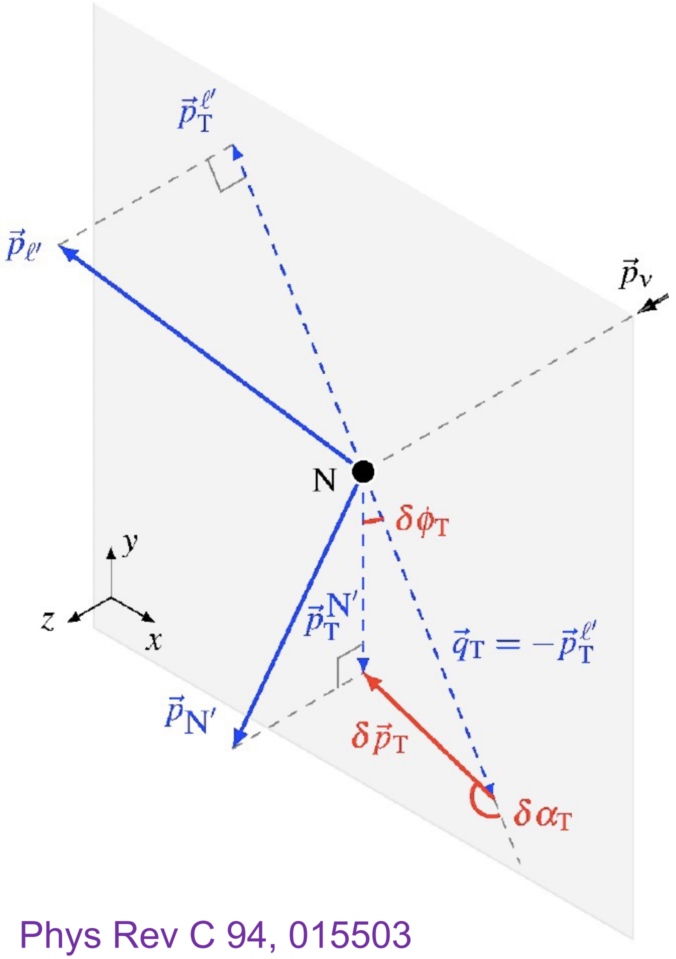

Using proton & lepton information

Using lepton information only

# Improved Observables: Transverse Kinematic Imbalance

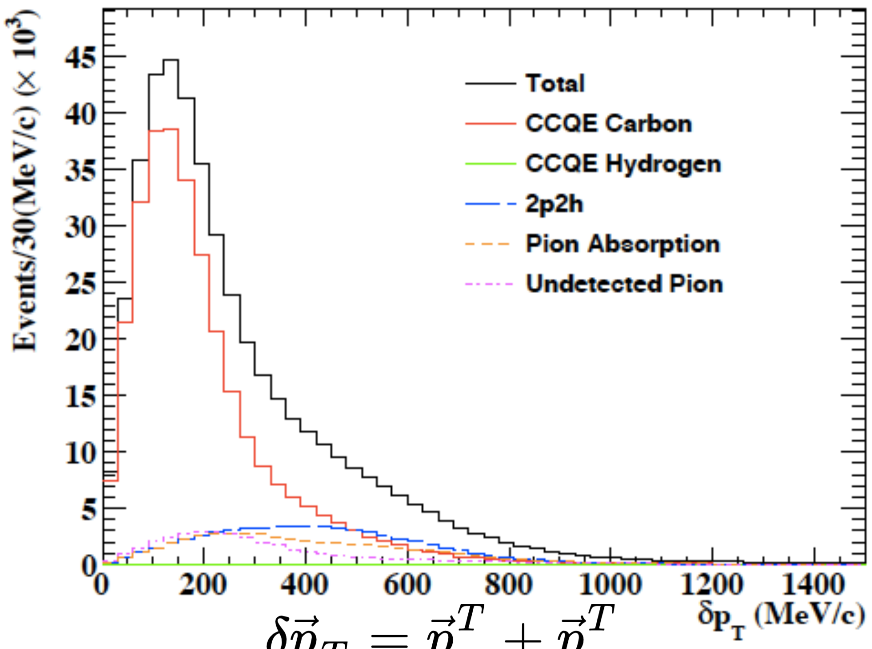
**Transverse Kinematic Imbalance Variables**

→Any deviation from $\delta p_T$=0 and $\delta\phi_T$=0 is indicative of nuclear effects



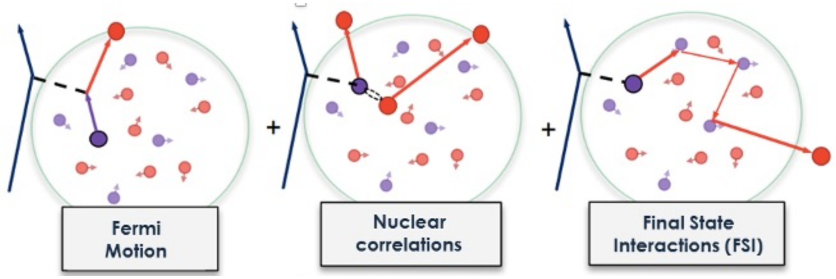

Phys Rev C 94, 015503

**Neutrino mode** *Phys. Rev. D 105,032010*




$$\delta\vec{p}_T = \vec{p}_\mu^{\,T} + \vec{p}_p^{\,T}$$

- The bulk probes Fermi motion
- The tail probes FSI and multi-nucleon processes



# Summary

- T2K's near detector ND280 is undergoing an ambitious upgrade.
- The installation of the Upgraded ND280 detector is currently underway this summer and is anticipated to start collecting neutrino data in November 2023.
- ND280 Upgrade's low detection thresholds and full polar angle coverage will enable T2K to probe the complete final state of neutrino-nucleus interactions.
- The performances of the ND280 Upgrade are expected to open the door to precisely probe nuclear effects at an unprecedented level, in both current and next-generation experiments.