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The ND280 Upgrade of the T2K experiment

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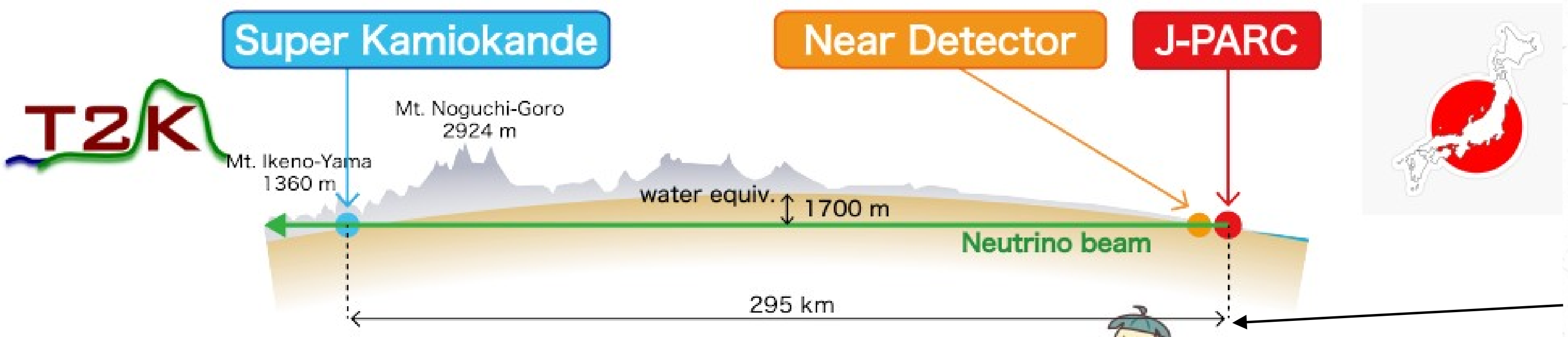
On behalf of the T2K collaboration

Contents

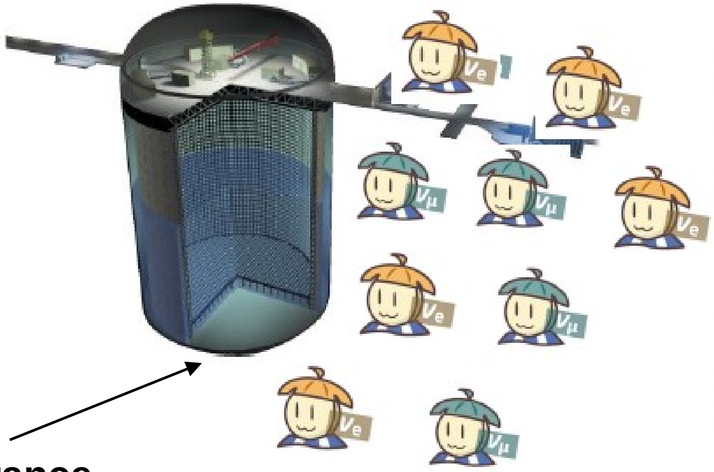
01

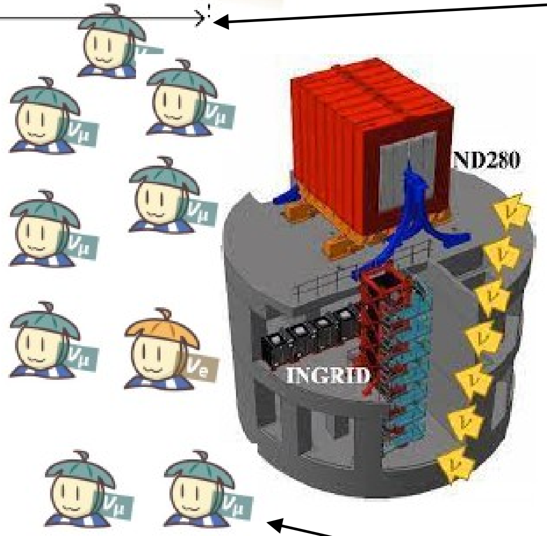
T2K experiment and its near detector- ND280

The T2K experiment: Tokai to Kamioka



Long baseline neutrino oscillation experiment





Measurement of -
- **ν_μ ($\bar{\nu}_\mu$) disappearance**
- **ν_e ($\bar{\nu}_e$) appearance**

ν_μ ($\bar{\nu}$) beam

(p (30 GeV) + graphite ⟶ π ⟶ μ + ν_μ)

Neutrino cartoons by Yuki Akimoto

Purpose of the near detector

Flux model | Neutrino interaction model | Detector model | Oscillation probability

$$N^{ND}_{\nu_\mu}(E_\nu) = \Phi^{ND}_{\nu_\mu}(E_\nu) \times \sigma^{ND}_{\nu_\mu}(E_\nu) \times \epsilon^{ND}(E_\nu)$$

$$N^{FD}_{\nu_e}(E_\nu) = \Phi^{FD}_{\nu_e}(E_\nu) \times \sigma^{FD}_{\nu_e}(E_\nu) \times \epsilon^{FD}(E_\nu) \times P_{\nu_\mu \rightarrow \nu_e}(E_\nu)$$

Constrained by near detector

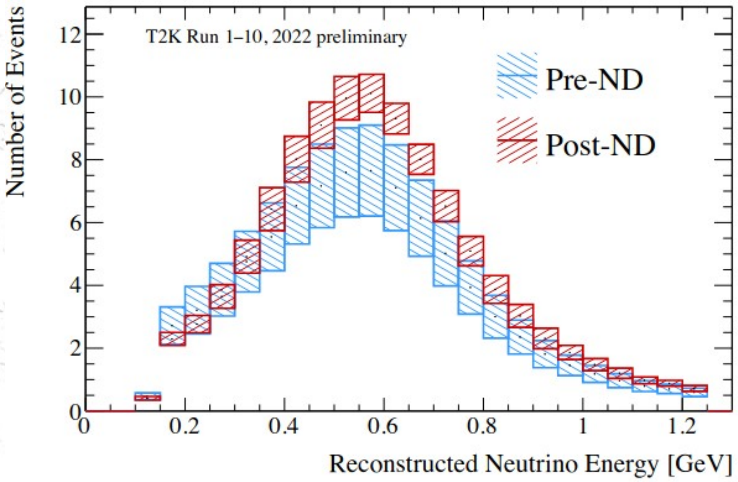
- Near detector (ND) measures beam spectrum and flavor composition <u>before oscillations</u>.
- ND measurements constrain **flux** and **ν-nucleus cross-section model** parameters and propagate to far detector.
- Different **detector systematics** affect far detector (FD) and ND due to different detectors used.

Reduction in SK energy spectra prediction uncertainties

17.3% → **5.2%**

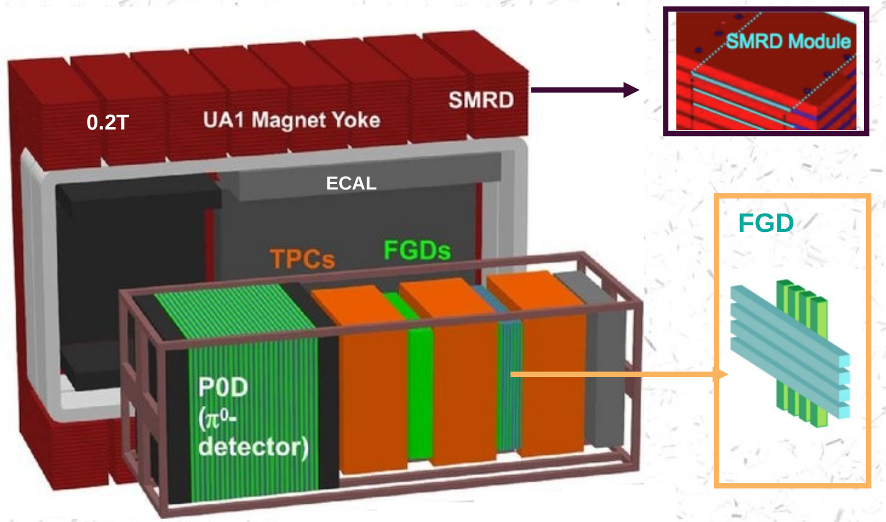
(pre-ND fit) (post-ND fit)

SK single ring e-like sample

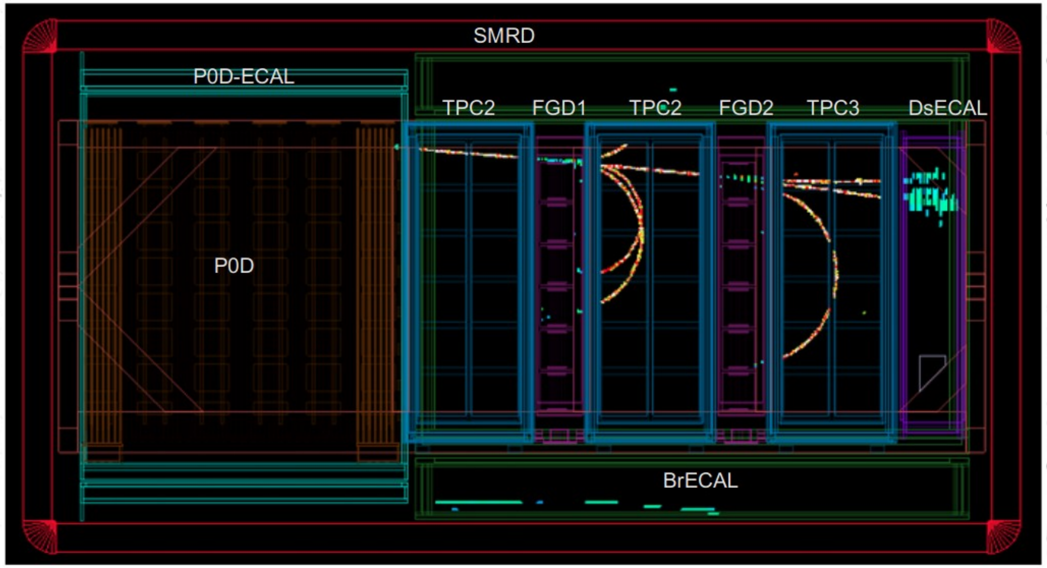


T2K near detector: ND280 (before upgrade)

ND280 (before upgrade)



Event display of ν interaction



Detector installed inside the **UA1/NOMAD magnet (0.2 T)**

- **A detector optimized to measure π^0 (P0D)**
- **An electromagnetic calorimeter to distinguish tracks from showers**

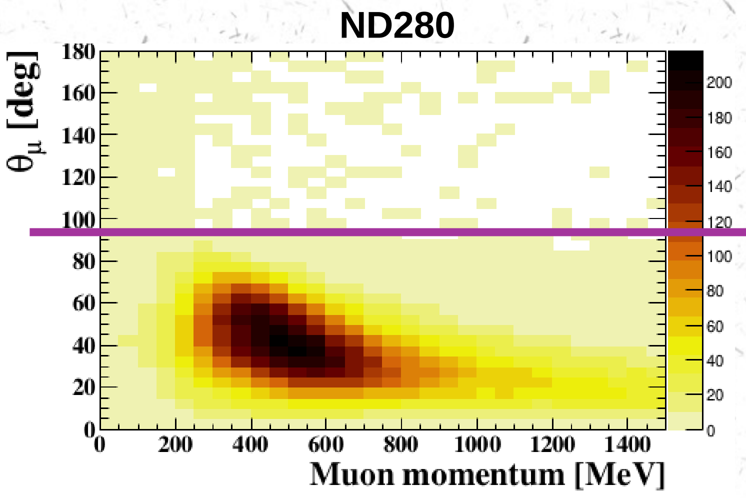
A target-tracker system composed of:

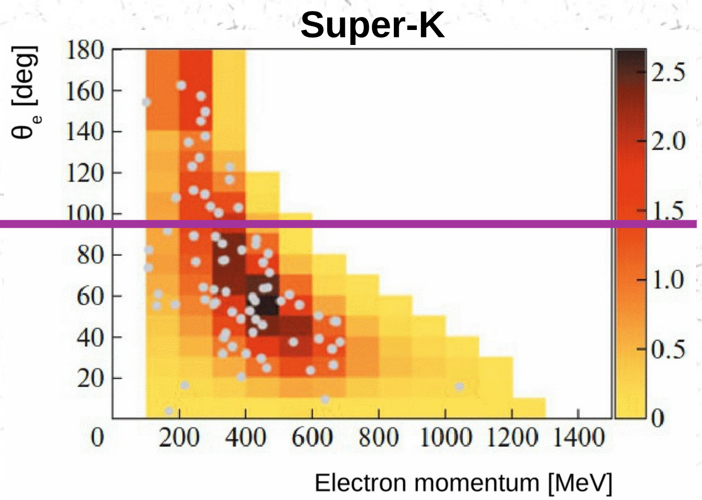
- **2 Fine Grained Detectors (target for ν interactions).**
  - **FGD1 is pure scintillator,**
  - **FGD2 has water layers interleaved with scintillators**
- **3 vertical Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization**

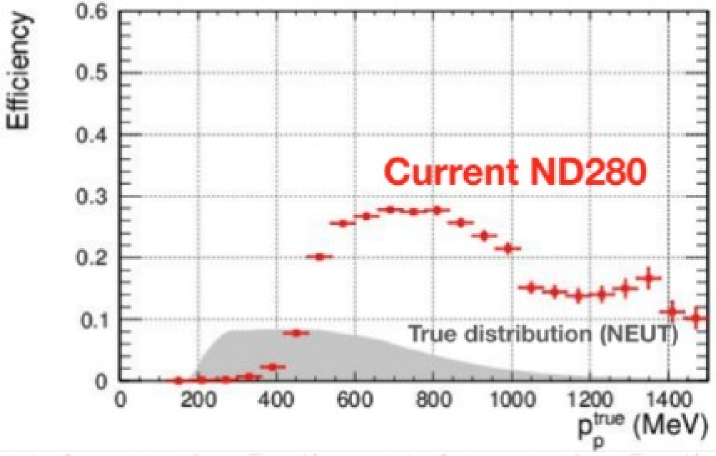
02

ND280 upgrade: motive and components

Limitations of original ND280 design





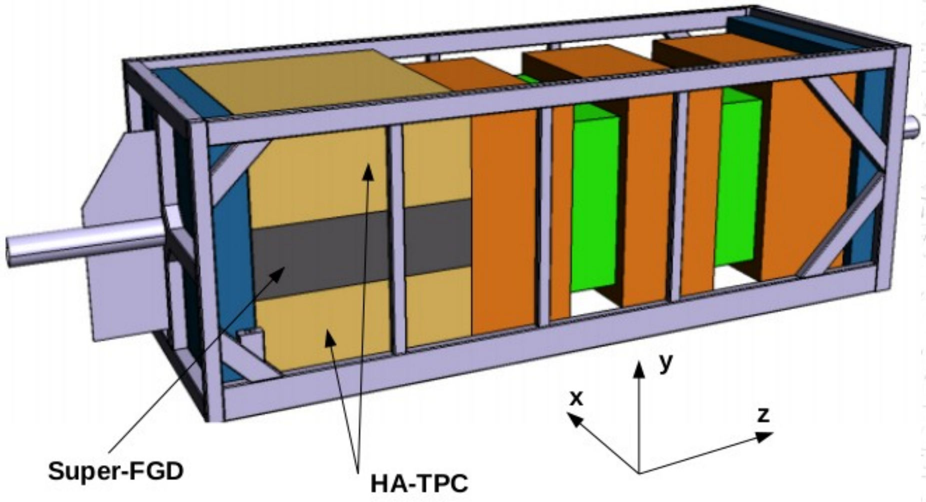


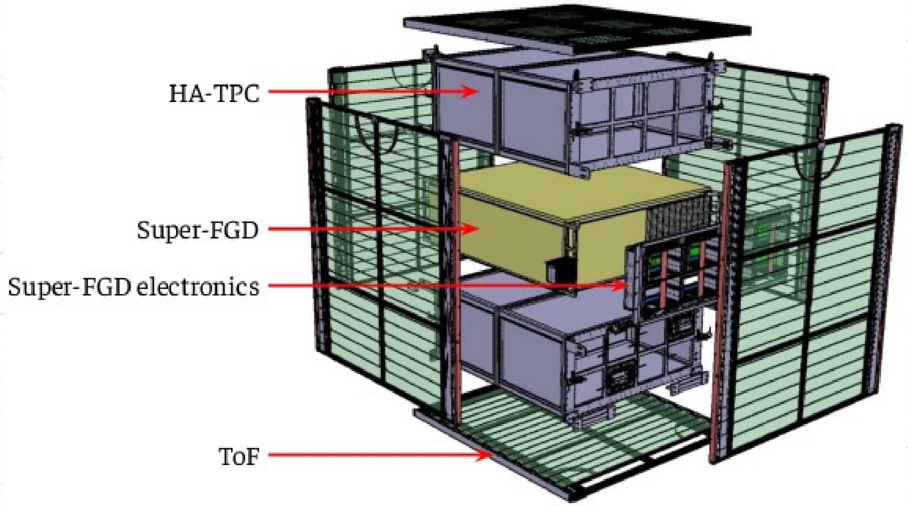
- Low angular acceptance (as opposed to 4π coverage at Super-K) ⟶ Mostly reconstruct forward going tracks entering the TPCs.
- Low efficiency to track low momentum protons ⟶ Have to use lepton kinematics only for E_ν reconstruction.
- No capability to detect/reconstruct neutrons.
- Limited ToF information resulting in out-of-fiducial-volume (OOFV) background.
- Insufficient ν_e background estimation.

$$E_{\text{rec}} = \frac{m_p^2 - (m_n - E_b)^2 + m_l + 2\,(m_n - E_b)\,E_l}{2\,(m_n - E_b - E_l + p_l \cos\theta_l)}$$

ND280 upgrade

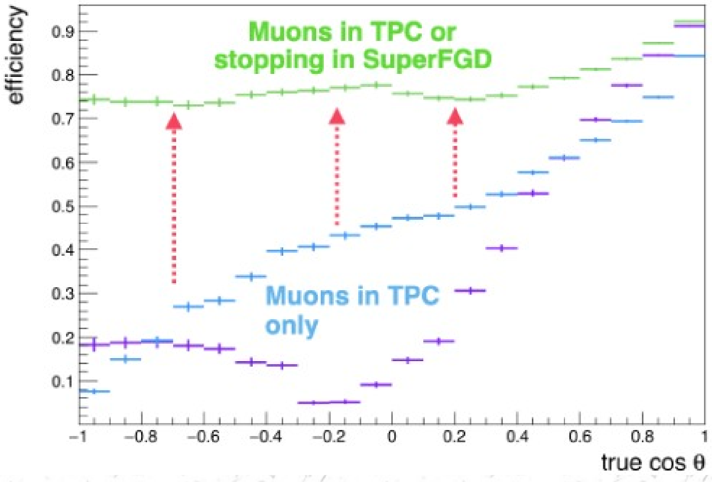
P0D replaced with a new scintillator target (Super-FGD), two High-Angle TPCs and six Time-of-Flight planes.



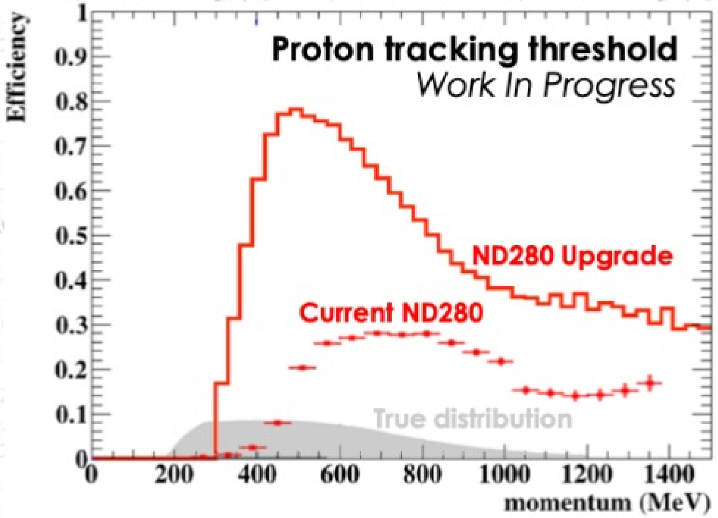


- Super-FGD allow to fully reconstruct tracks in 3D → lower threshold and excellent resolution to reconstruct protons at any angle.
  - Neutrons will also be reconstructed via proton recoil.
- High-Angle TPCs (x 2) allow to reconstruct muons at any angle with respect to beam.
  - Readout using resistive Micromegas.
- ToF planes (x 6) allow to veto particles originating from outside the ND280 fiducial volume.

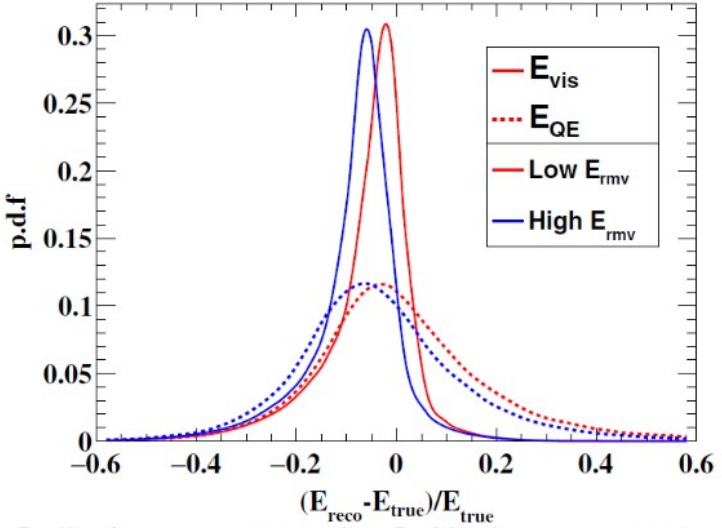
Improvements with ND280 upgrade



➔ 4π acceptance for outgoing muons thanks to high angle detection by HATPC.



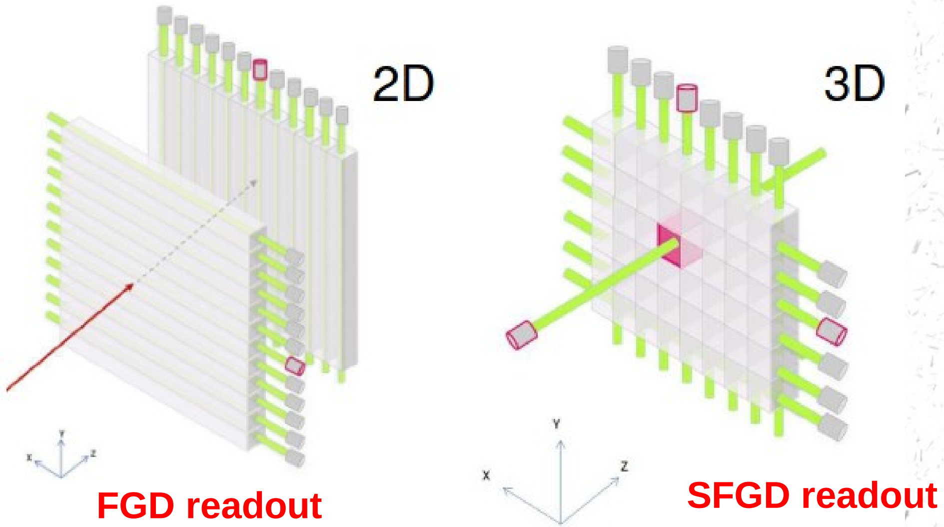
➔ Decrease in proton detection threshold and improved efficiency over entire momentum range.

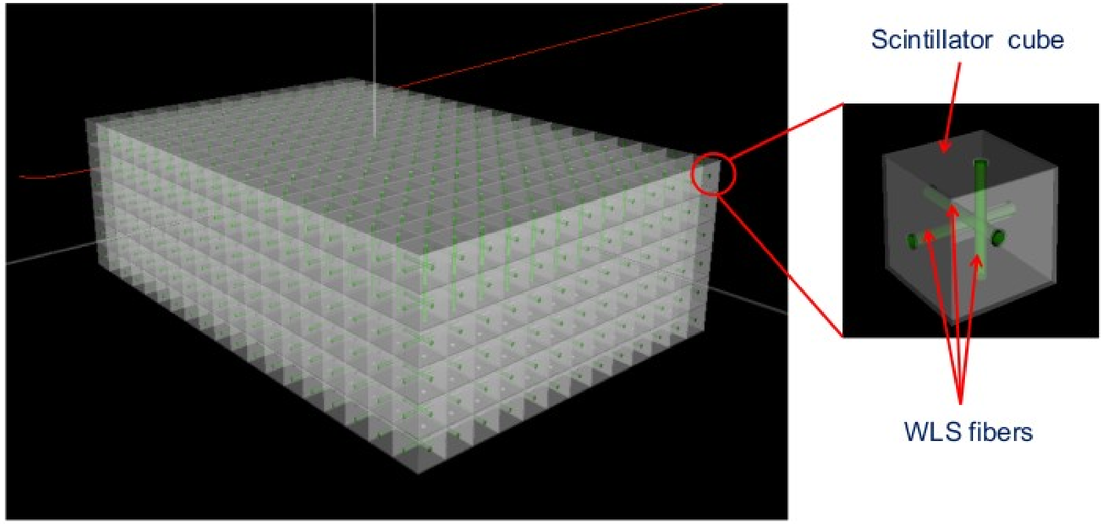


➔ Better estimation of E_ν^{true} using E_{vis}, which utilizes lepton and hadron kinematics. $E_{\text{vis}} = E_\mu + T_N$

➔ Made possible due to improved proton and neutron detection.

Super-Fine Grained Detector (SFGD)





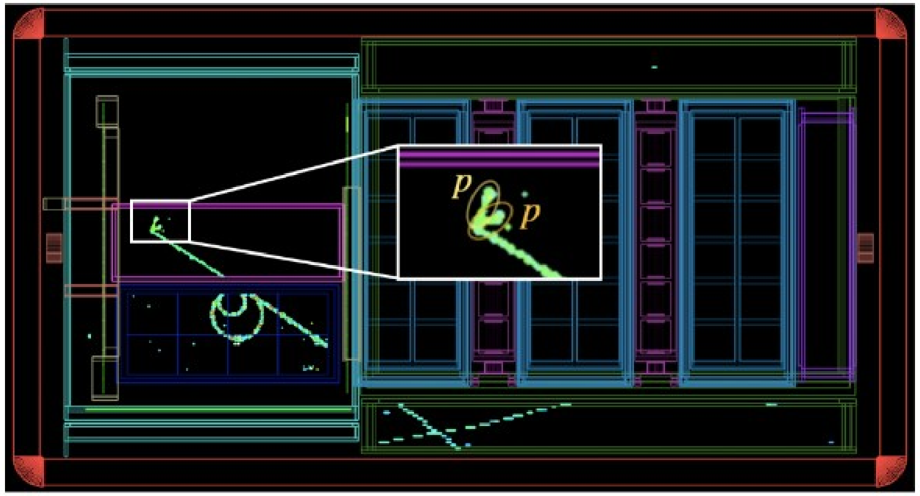
- A fully active high granularity scintillator target/detector.
  - Total volume ≈ 192 × 182 × 56 cm^3
  - Fiducial mass ≈ 2 tons
- <u>Composition</u>- 2 million optically isolated cubes with 3 orthogonal 1.5 mm diameter holes each.
  - Dimensions ≈ 1 × 1 × 1 cm^3
- <u>Readout</u>- 55000 WLS fibers with MPPCs at one end.
- <u>Characteristics</u>- 3D track reconstruction, 4π acceptance, improved hadron reconstruction, PID.

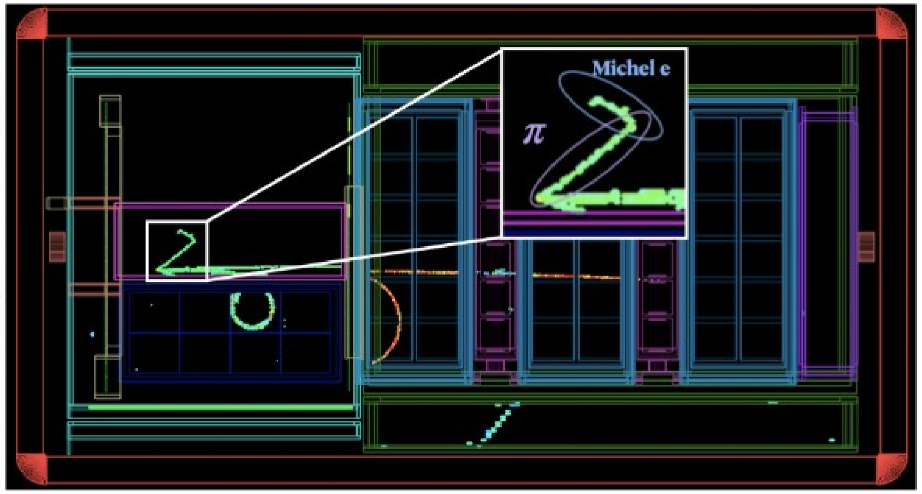
SFGD installation

SFGD installed in the ND280 pit in October 2023

Expected performance from SFGD

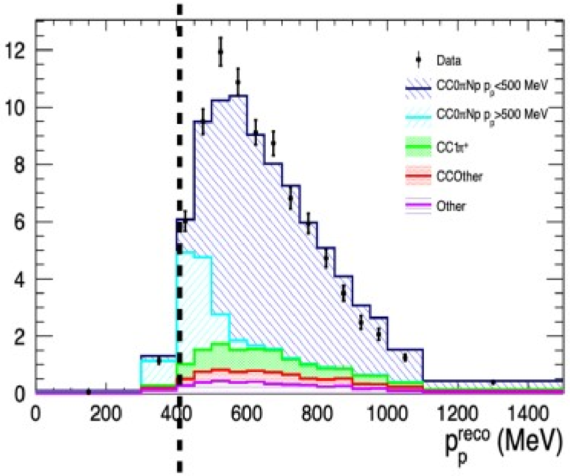
First neutrino interactions recorded in SFGD!



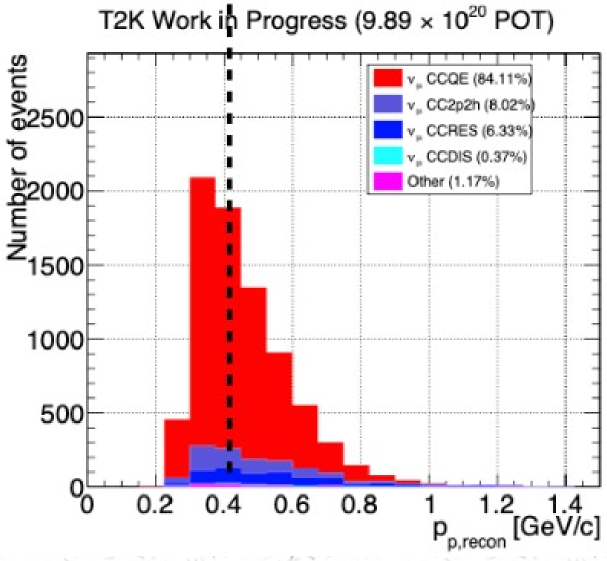


➔ Lower proton detection threshold and better CCQE purity expected.

FGD data (before upgrade)

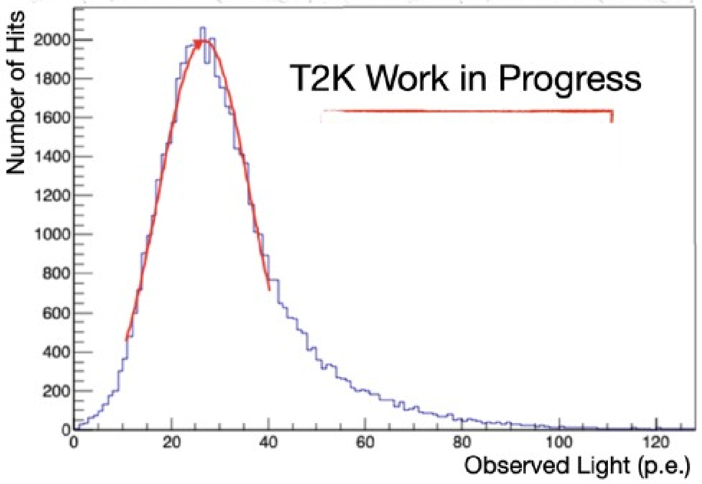


SFGD MC (after upgrade)



SFGD cosmics data results

new SFGD data

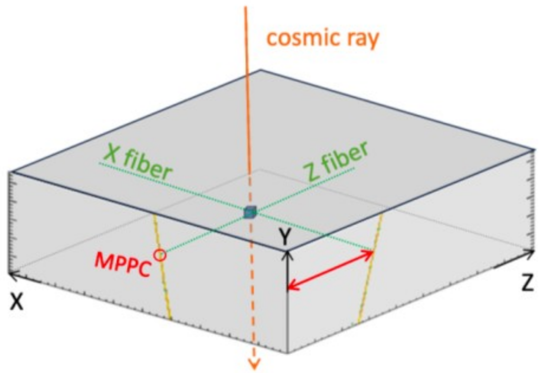


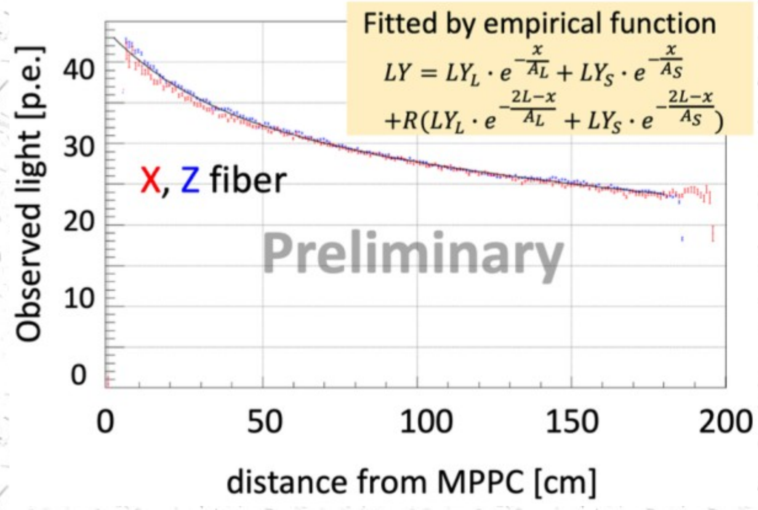
- Observed light (p.e) recorded as a function of distance from MPPC to characterize attenuation length.
- Information from orthogonal fibers allow for a more reliable characterization.
- Measured attenuation length consistent with WLS fibers specifications.

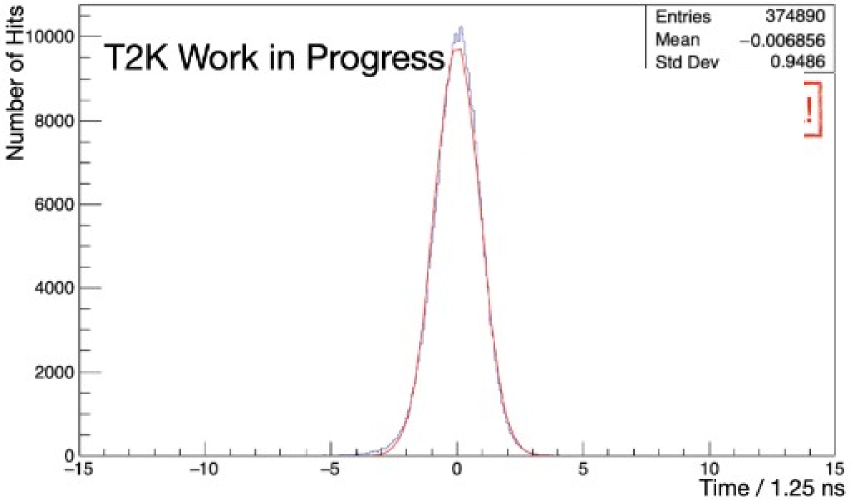
- Select hits with LY > 40 p.e. in all three directions.
- Compare mean time of hit with mean time of event.
- **Time resolution ≈ 1.2 ns**.

Time resolultion

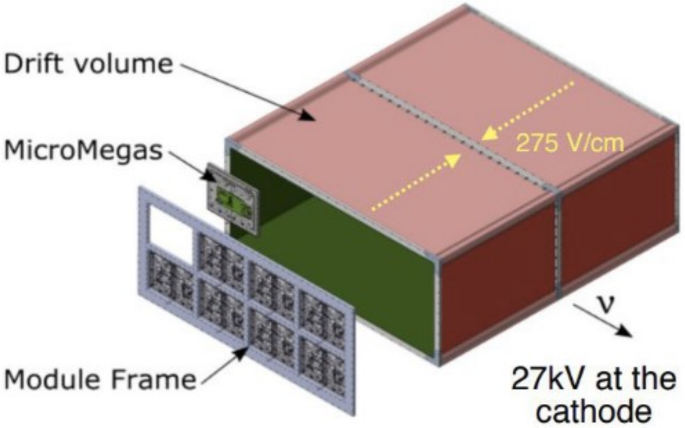
Light yield



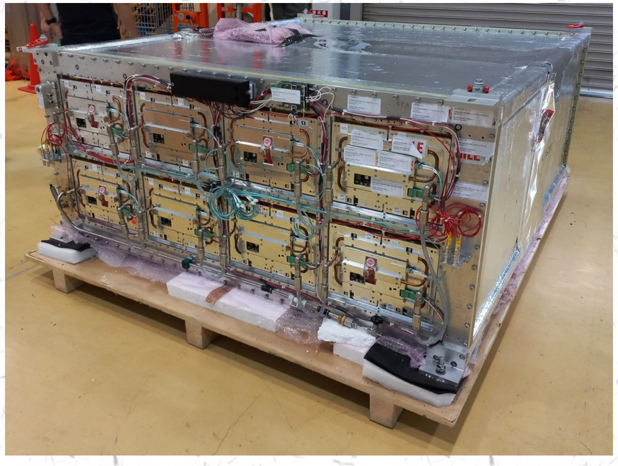




High Angle TPC (HATPC)

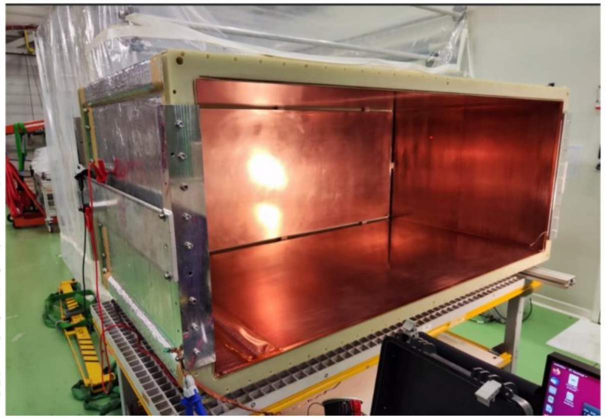


HATPC instrumented with 16 ERAMs

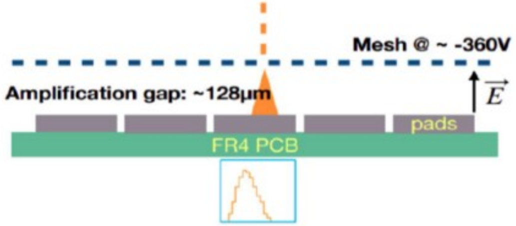


- Two field cages joined at the central cathode plane.
- Each anode plane instrumented with 8 Encapsulated Resistive Anode Micromegas (ERAM). [16 ERAMs per HATPC]
- Purpose- 3D track reconstruction, PID, tracking high angle and backward-going particles.

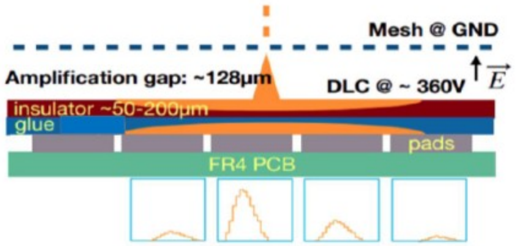
➔ New field cage design with thin walls to minimize dead space and maximize tracking volume. (Total width ≈ 4 cm / 2% X_0)



➔ Readout using ERAM instead of standard bulk Micromegas.
- Charge spreading over multiple pads → Good spatial resolution with fewer and larger pads.
- Suppression of sparks.
- Better E-field uniformity.

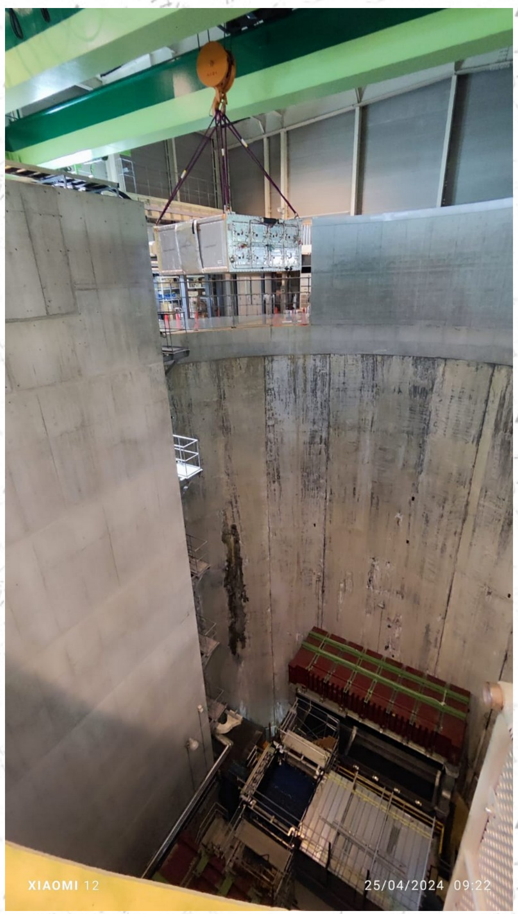


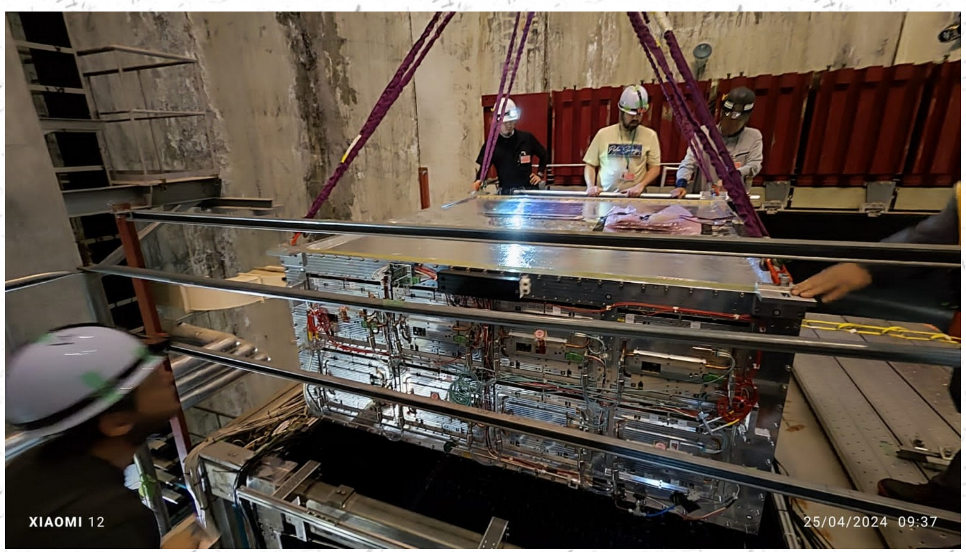
bulk Micromegas (used in v-TPC)



resistive Micromegas (used in HATPC)

HATPC installation



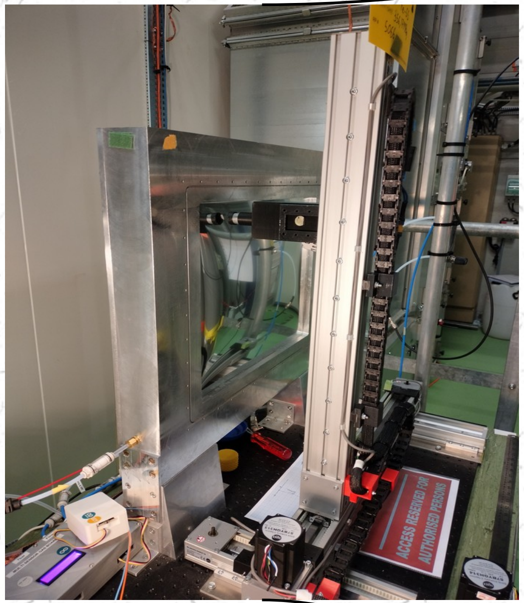


bottom HATPC installed in Sept. 2023

top HATPC installed in April 2024

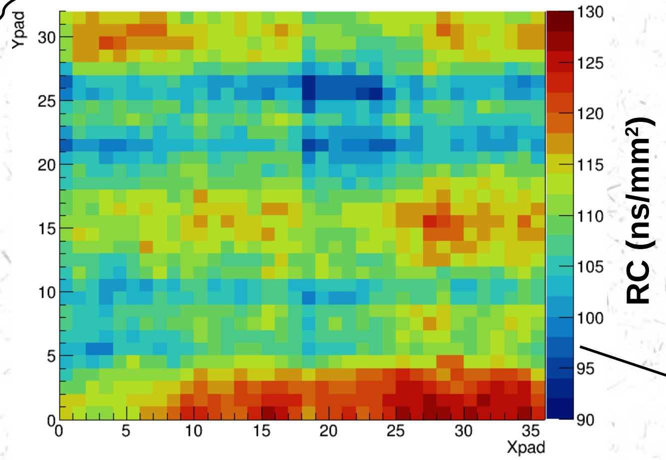
ERAM characterization

X-ray test bench at CERN

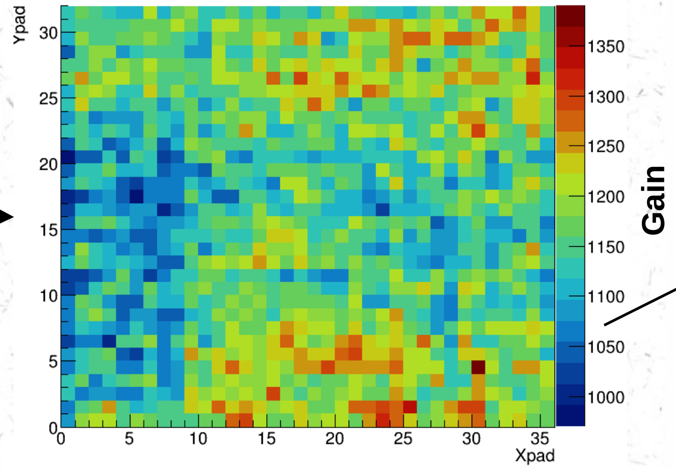


RC map of ERAM-28

(RC characterizes charge spreading in ERAM)

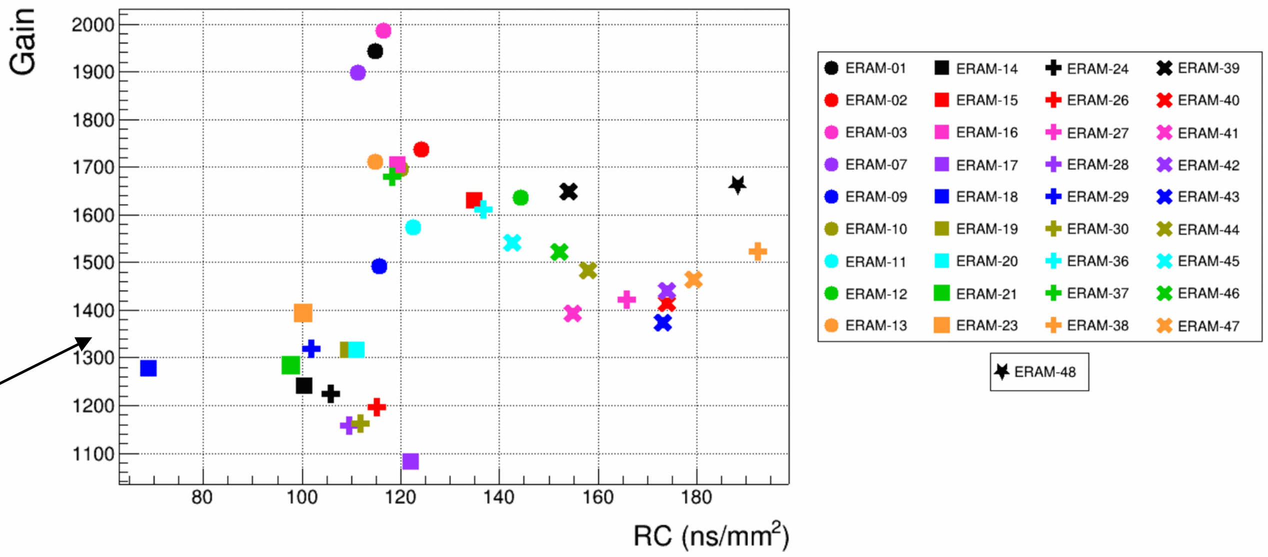


Gain map of ERAM-28



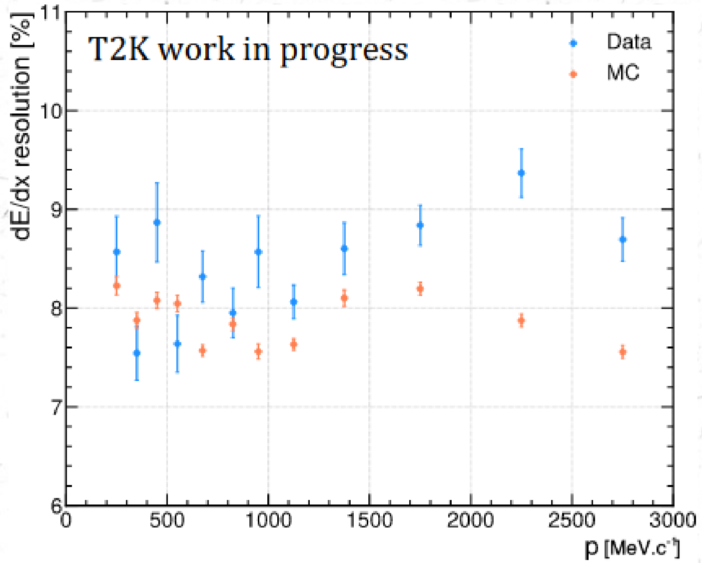
- ERAMs are characterized using X-ray test bench at CERN.
- Detailed physical model developed for simultaneous extraction of RC and gain of ERAM. (https://doi.org/10.1016/j.nima.2023.168534)
- Pad-by-pad RC, gain and energy resolution is obtained for all ERAMs.

37 ERAMs produced and characterized

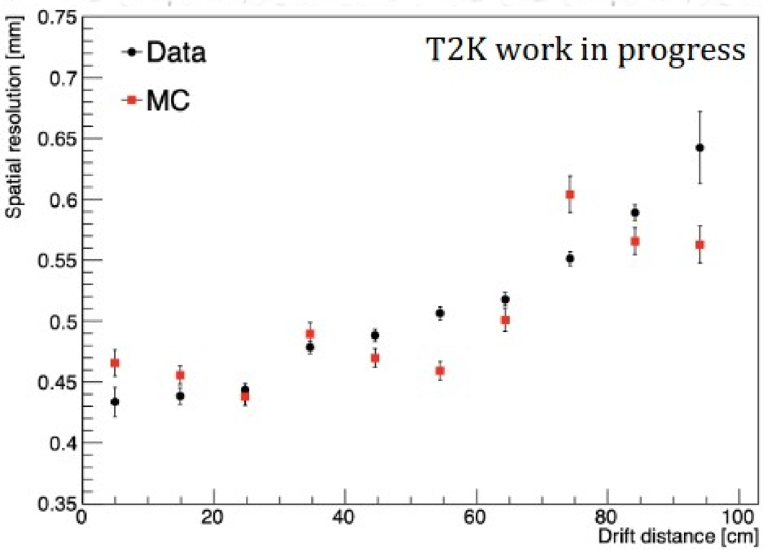


HATPC cosmics data results

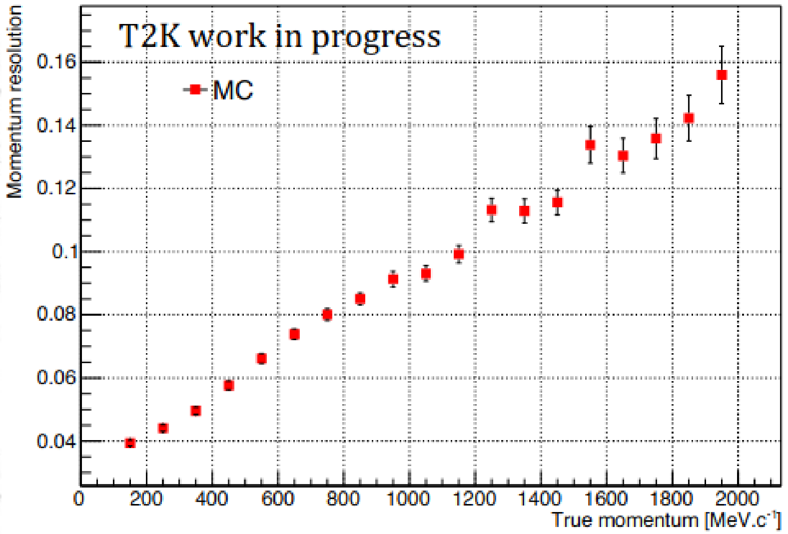
dE/dx resolution



Spatial resolution



Momentum resolution

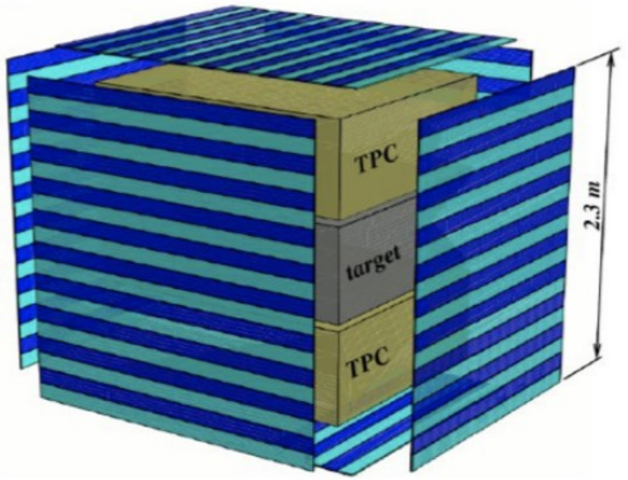


- dE/dx resolution **better than 10 %**.
- Behaves as expected.

- Spatial resolution **≈ 500 μm**.
- In reasonable agreement with MC.

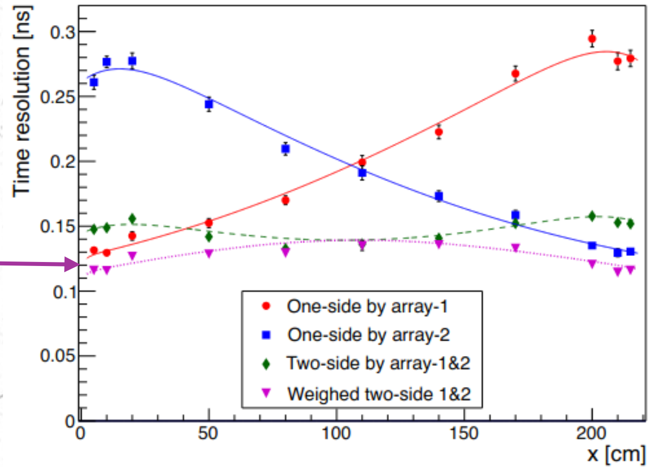
- Momentum resolution **better than 10%** for vertical muons with momenta < 1.2 GeV/c and L > 600 mm.

Time-of-Flight (ToF) detector

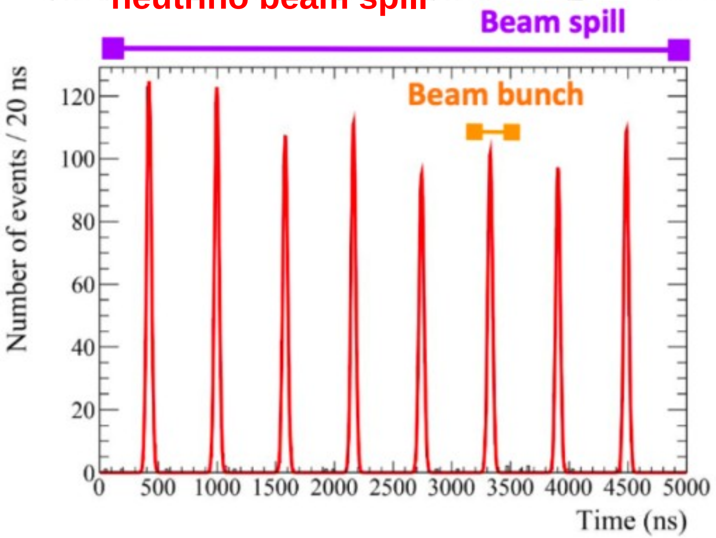


- 6 ToF planes completely enclose b-HATPC + SFGD + t-HATPC.
- Composition- 20 cast plastic scintillator bars (EJ-200), each with dimensions 12 × 1 × 230 cm^3.
- Readout- 8 SiPM at each end of scintillator bar.
- Purpose-
  - Veto inward-going background.
  - Particle identification through timing information.
  - Provide cosmic trigger for SFGD and HATPCs.
  - Measure crossing time of charged particles.

Timing resolution v/s particle incidence position

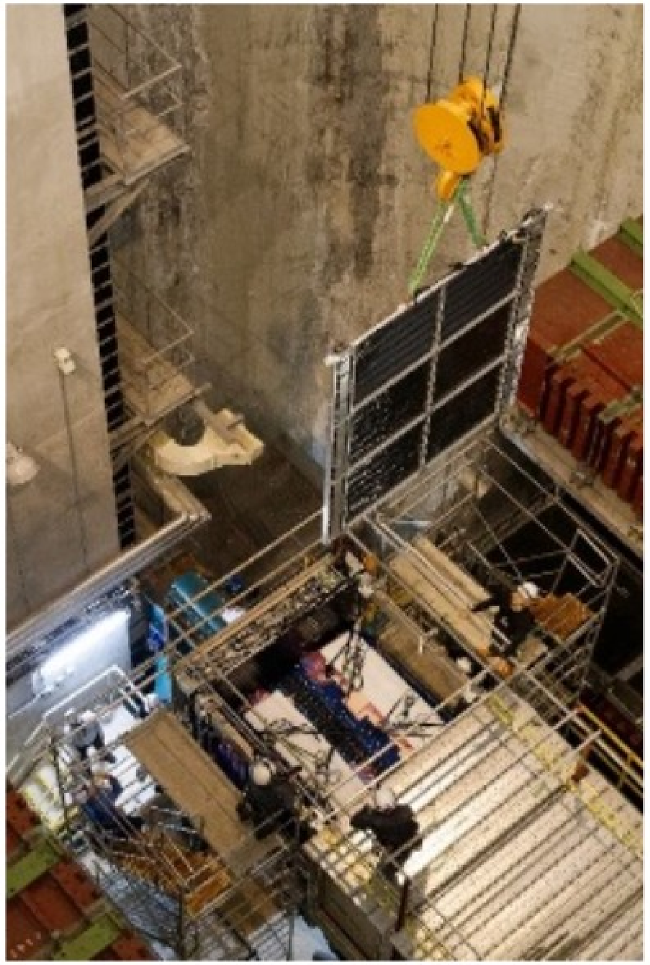


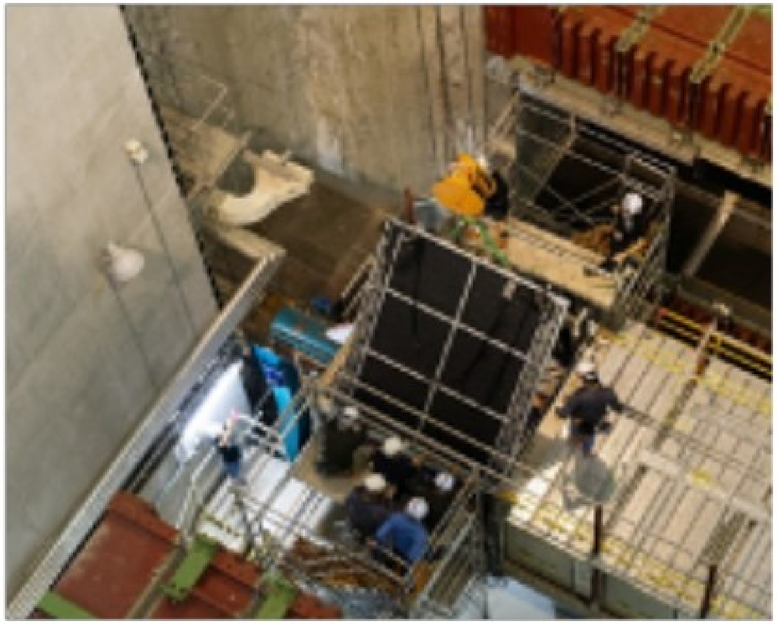
ToF measurement of neutrino beam spill

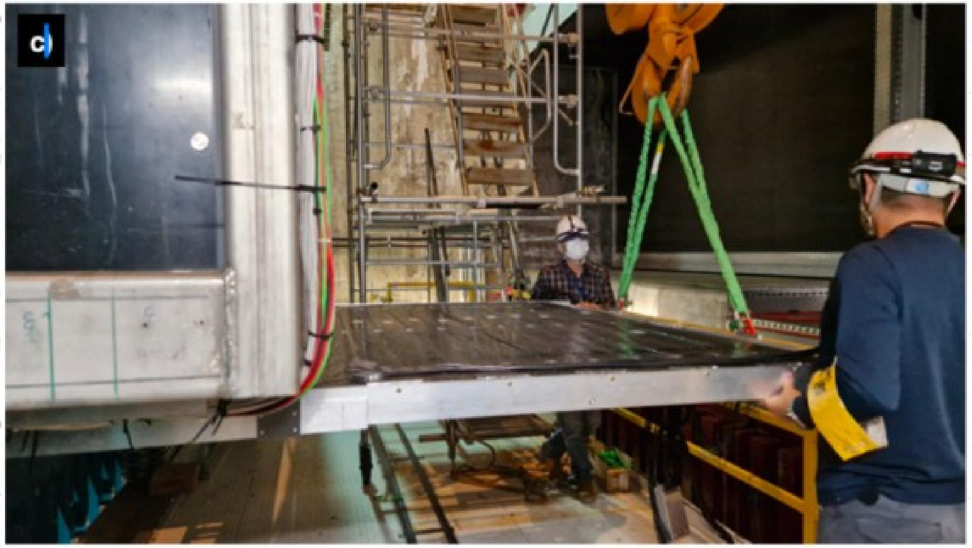


- Timing resolution of a scintillator bar tested using cosmic test bench.
  (A. Korzenev et al 2022 JINST 17 P01016)
- Timing resolution ≈ **140 ps** from any particle incidence position.
- ToF can clearly resolve individual bunches in a neutrino beam spill.

ToF installation







03

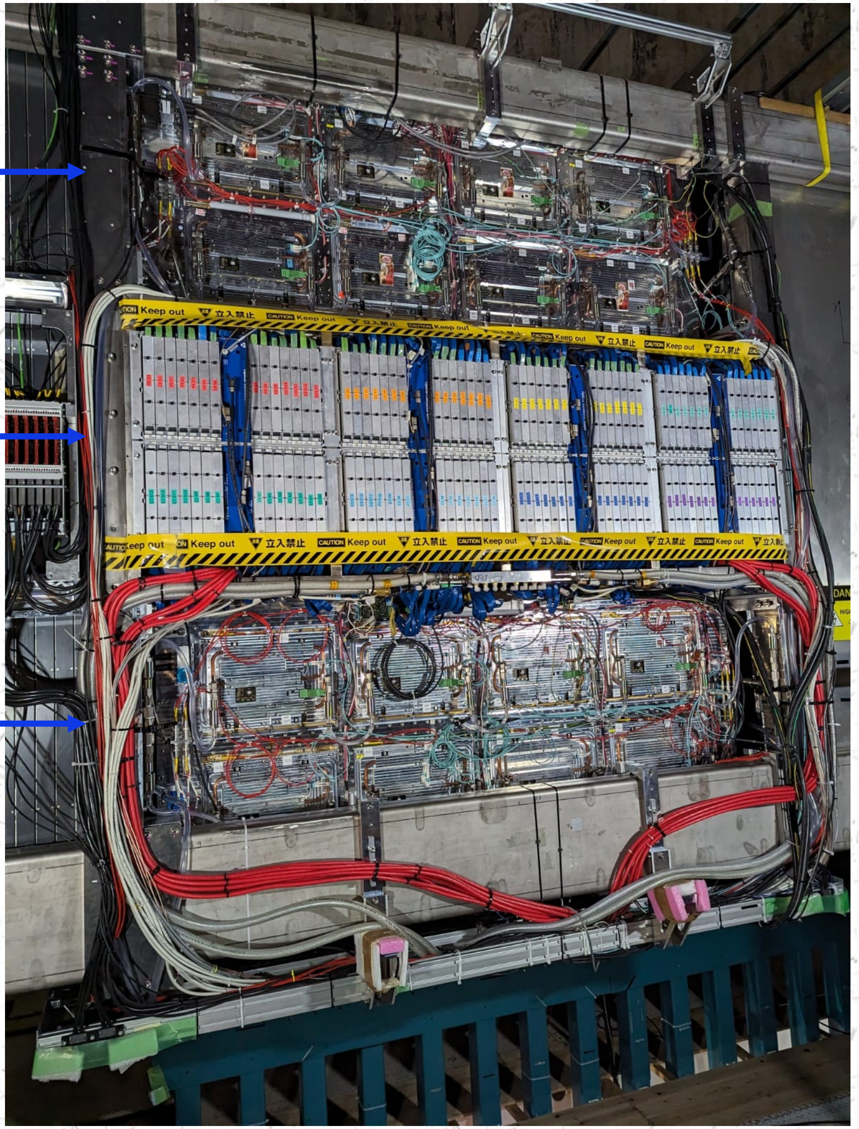
ND280 upgrade: current status

ND280 upgrade status: Completed!

top-HATPC

Super-FGD

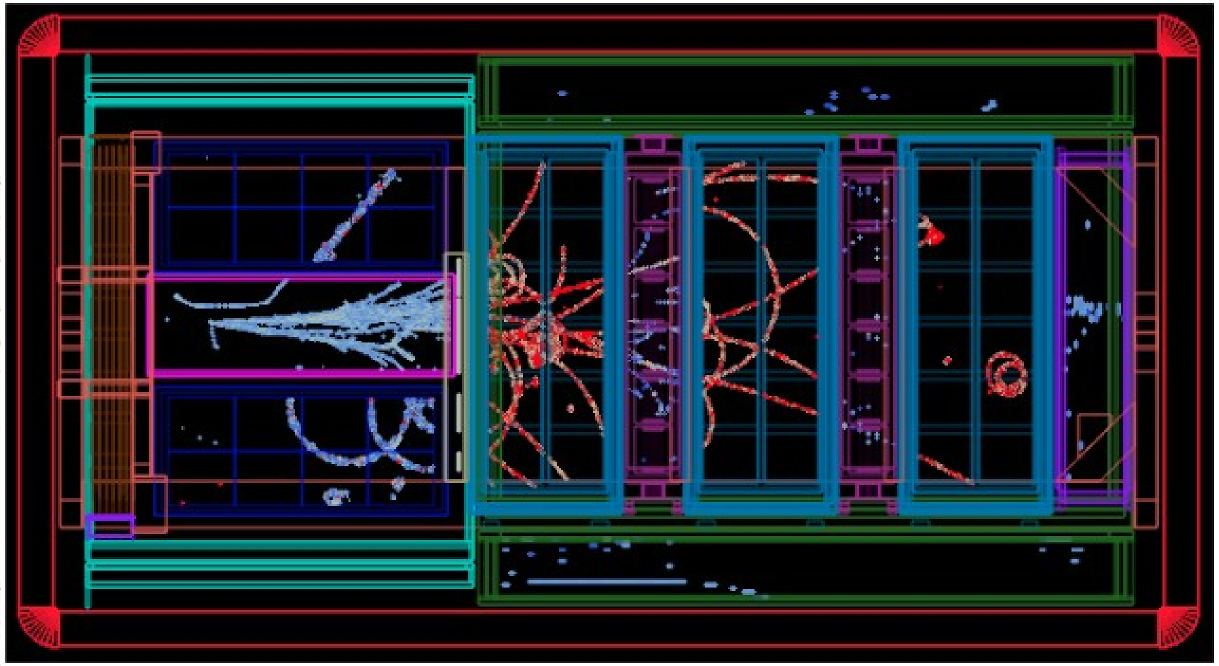
bottom-HATPC

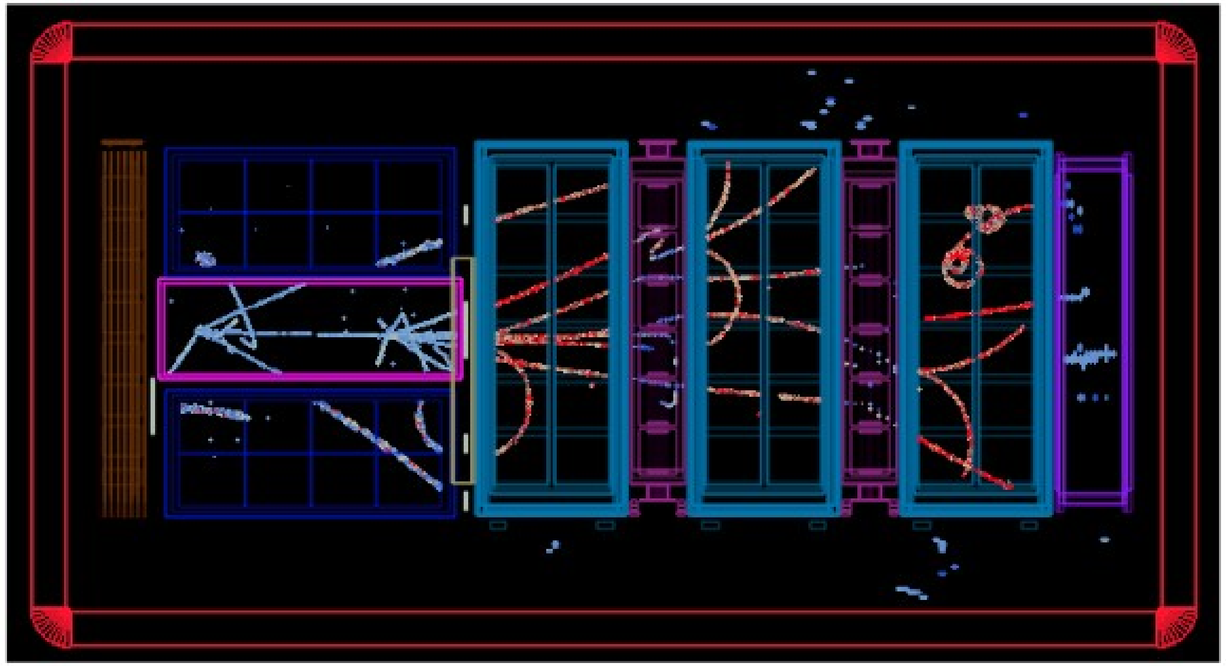


Installation of upgrade detectors was completed in May 2024

First neutrino interactions with full ND280 upgrade!

June 2024

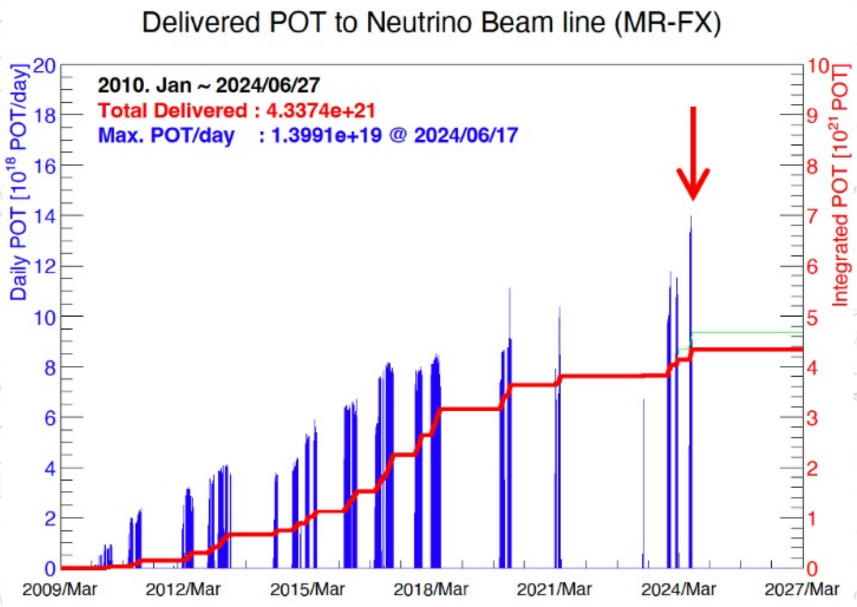




Conclusion

- Upgrade of ND280 has been successfully completed in May 2024!
- First neutrino interactions with fully upgraded ND280 were recorded last month.
- First physics run with full ND280 upgrade and increased beam power (800 kW) completed last month.
- All the upgrade detectors are working well.
- Physics analysis with full suite of upgrade detectors and increased beam power is currently ongoing!

POT- Protons on Target



Thank you for your attention!

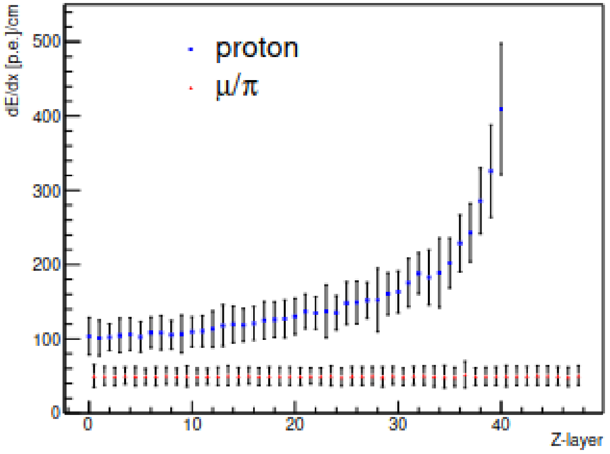
Back-up

SFGD: Tests and Prototypes

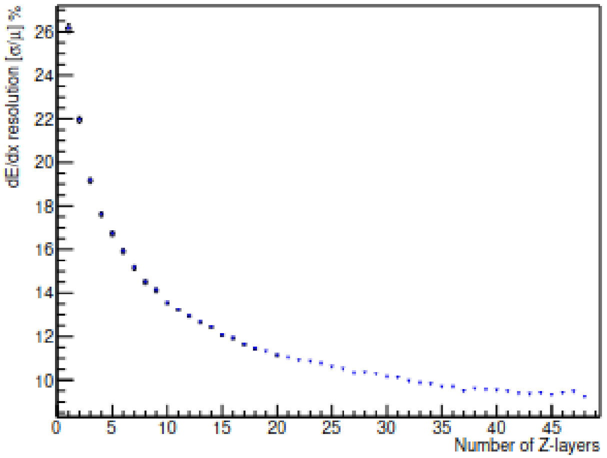
24 × 8 × 48 cubes

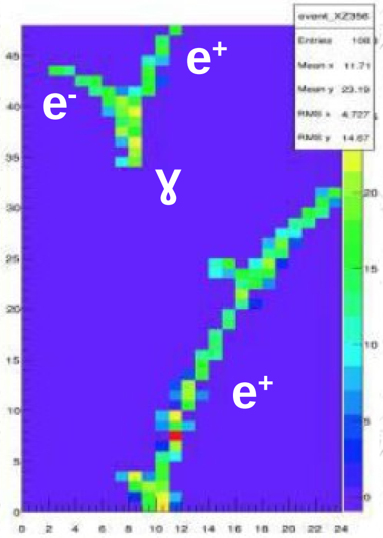
- SFGD prototype comprising 9216 cubes arranged in 24 × 8 × 48 array tested using CERN-PS T9 beamline with 0.2 T magnetic field.
- <u>Key findings</u>- (A. Blondel et al 2020 JINST 15 P12003)
  - Optical cross-talk between adjacent cubes ≈ **3% per cube side**.
  - Timing resolution for 1 readout channel ≈ **0.97 ns**.
  - dE/dx resolution **better than 10%** obtained when information from more than 40 cubes is used.
- Ability to differentiate between $e^{-/+}$ and ɣ.

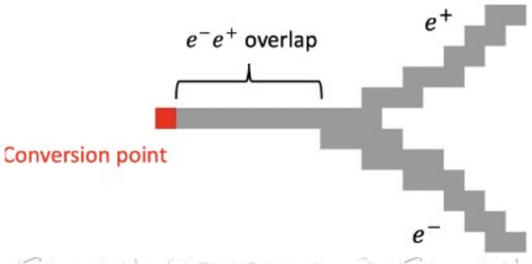
Mean dE/dx v/s no. of cube layers traversed



dE/dx resolution v/s no. of cube layers traversed



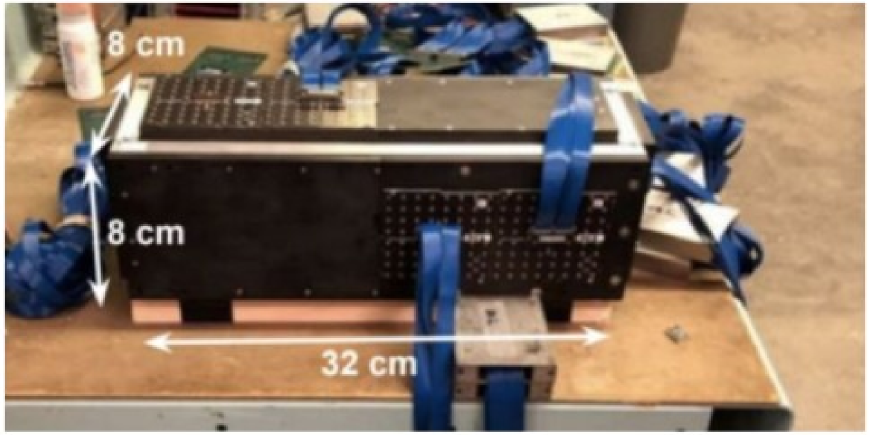




e/ɣ separation

SFGD: Tests and Prototypes

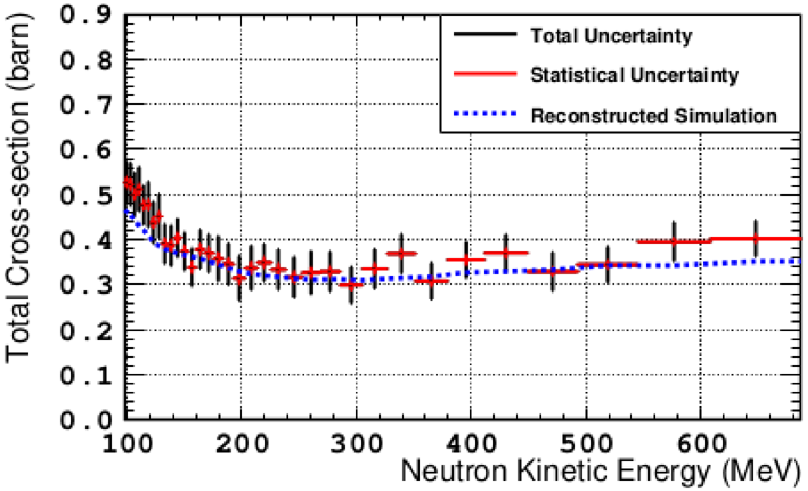
8 × 8 × 32 cubes
(US – Japan prototype)



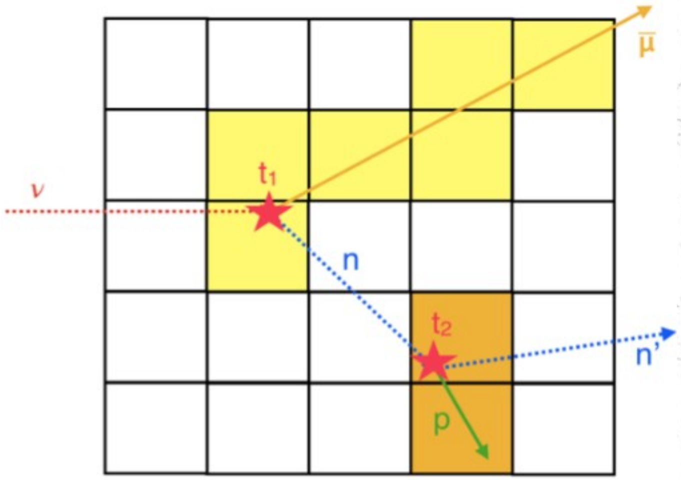
24 × 8 × 48 cubes

- Two SFGD prototypes tested at LANL using neutron beam with energies upto 800 MeV. (Phys. Sci. Forum 2023, 8(1), 29)
- <u>Aim</u>- To measure total neutron cross-section on CH target.
- Neutron detection via proton recoil.
- Cross-section measured using 'extinction method'. $N(z) = N_0 e^{-T\sigma_{tot} z}$
- Total energy-integrated cross-section ≈ **(0.36 ± 0.05) barn**.

Neutron – CH cross-section v/s Kinetic energy

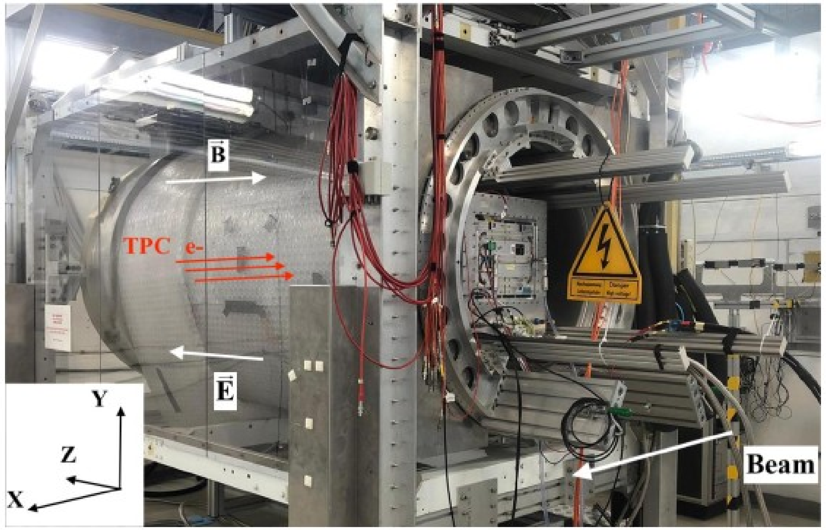


Neutron detection



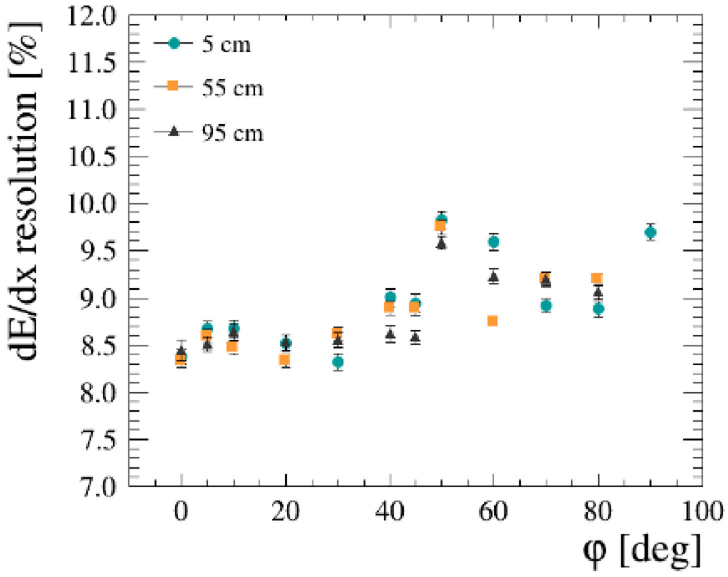
HATPC: Tests and Prototypes

HATPC prototype with ERAM-01

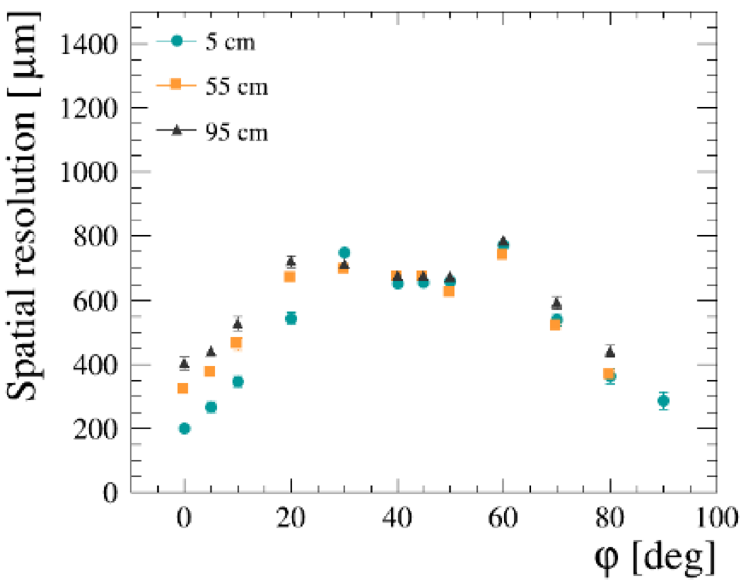


- HATPC performance tested through multiple test beam campaigns at CERN and DESY.
  - CERN 2018- 1 m drift distance HARP field cage with MM0-DLC1 ERAM (NIMA 957 (2020) 163286)
  - DESY 2019- 15 cm drift distance field cage prototype with MM1-DLC1 ERAM (NIMA 1025 (2022) 166109)
  - DESY 2021- 1 m drift distance field cage prototype with ERAM-01 (NIMA 1052 (2023) 168248)

dE/dx resolution v/s track inclination and drift distance



Spatial resolution v/s track inclination and drift distance



➔ Spatial resolution better than 800 μm and dE/dx resolution better than 10% obtained for all the incident angles and drift distances of interest.