The T2K ND280 Detector Upgrade

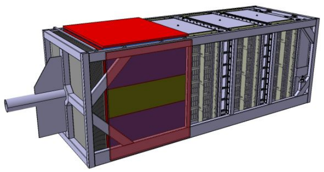
EPS-HEP 2025

11/Jul/25

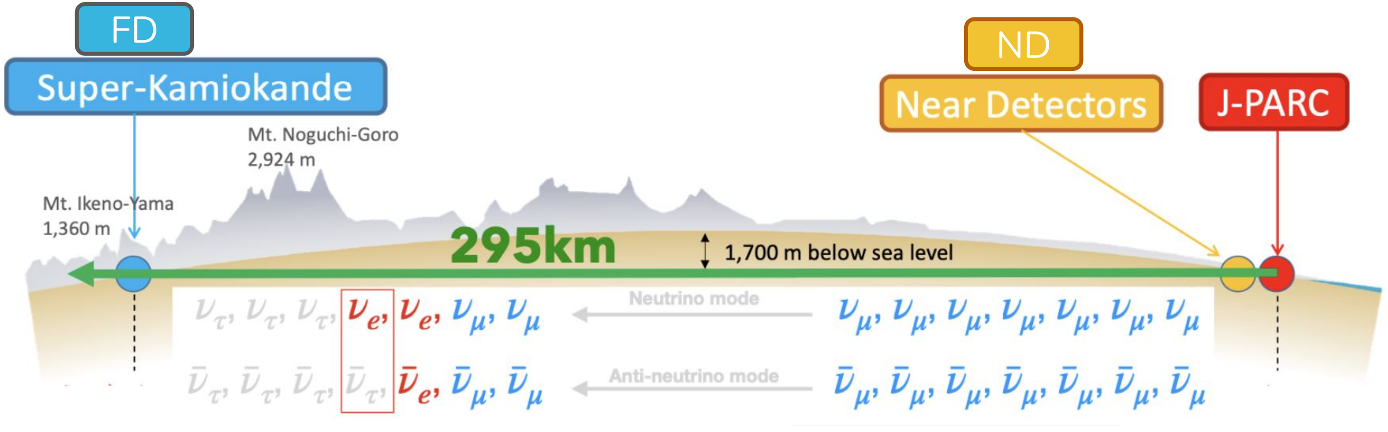
William Saenz
on behalf of the T2K collaboration

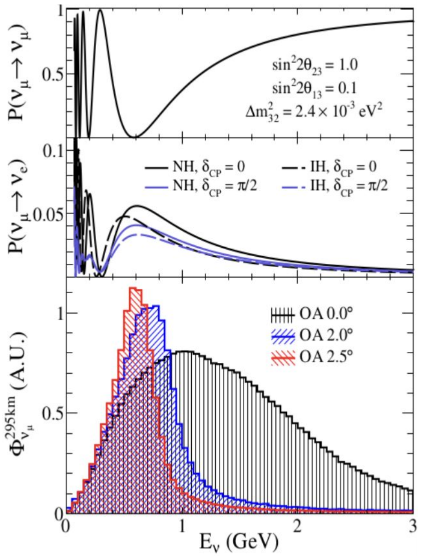
LPNHE PARIS

T2K



Neutrino oscillation - T2K project





- T2K → Tokai to Kamiola: A long baseline experiment
- Computation of **mixing parameters** (δ_{CP}, θ_{13}, θ_{23} and Δm^2_{23}) through measurement of ν_μ survival and ν_e appearance
- Off-axis analysis to increase statistics
- Results would reveal first evidence of CP-violation in lepton sector

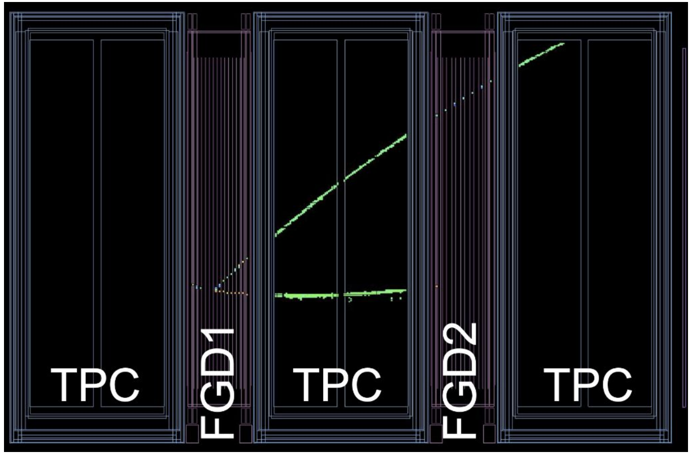
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavour eigenstates | U_{PMNS} matrix | mass eigenstates

See talk on T2K results by Katarzyna Kowalik

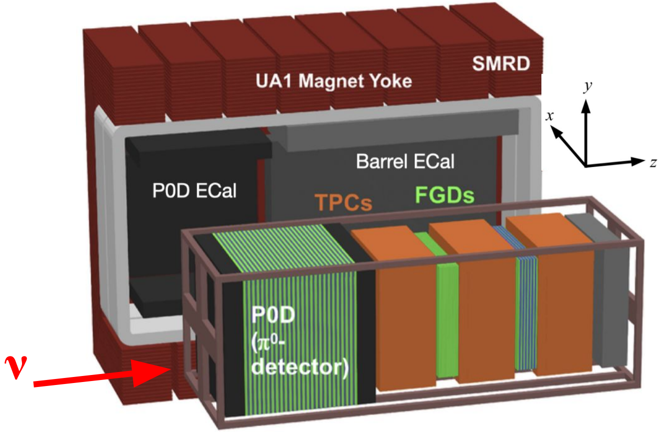
T2K's near detector ND280

- Estimates ν cross-section and ν flux before oscillation (280 m from proton target)
- Multi-detector enclosed by 0.2 T magnet
  - P0D (π^0): main background for ν_e appearance at FD
  - FGD (Fine grained detector): target mass + tracker
  - TPC (Time Projection Chamber): 3D tracking, PID, momentum
  - ECAL (EM calorimeter): complement inner detectors



$$N_\mu(E_\mu) \propto P(\nu_\mu \to \nu_\mu)\, \sigma(E_\nu)\, \Phi_{\nu_\mu}(E_\nu)$$

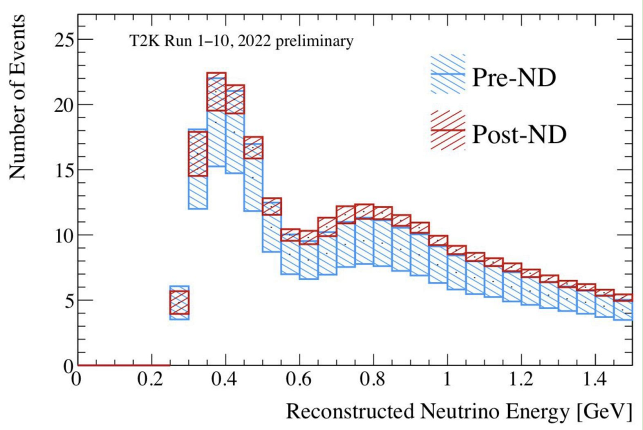
- Detected muon neutrinos at FD
- ν_μ survival probability
- Cross section, from ND and other measurements
- ν flux, from ND and beam measurements



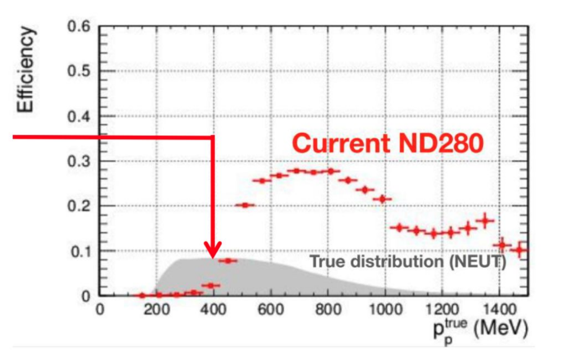
Original configuration (2010-2022)

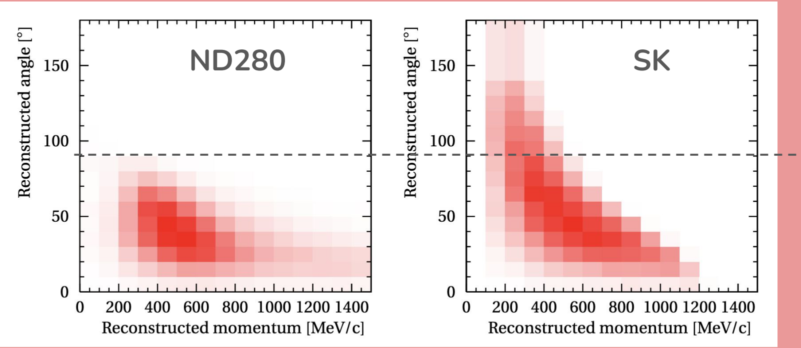
ND280 achievements and limitations

- FD energy spectra uncertainties reduced from ~17% to ~3% after including ND constraints



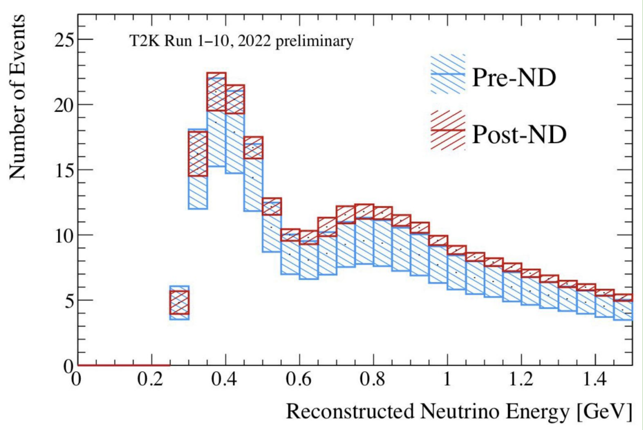
- There is room for improvement:
  - Limited angular acceptance
  - High proton reconstruction threshold





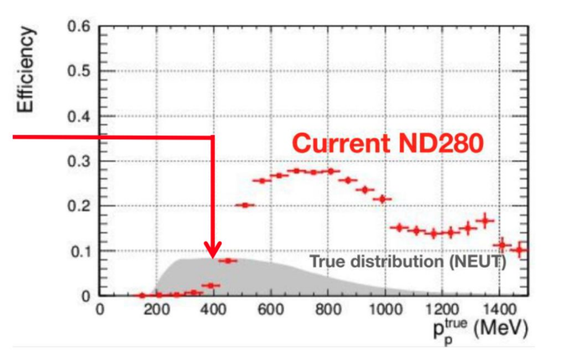
ND280 achievements and limitations

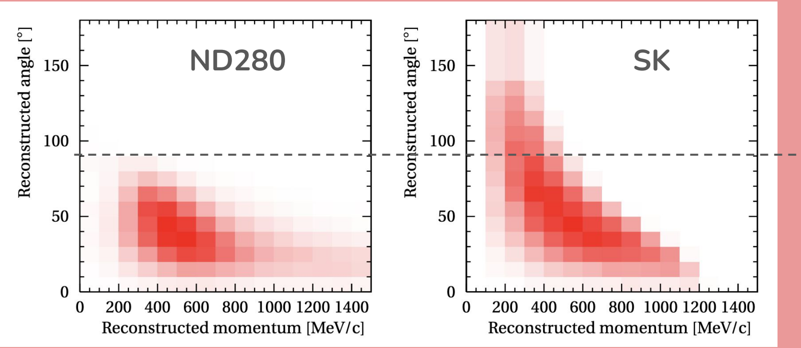
- FD energy spectra uncertainties reduced from ~17% to ~3% after including ND constraints



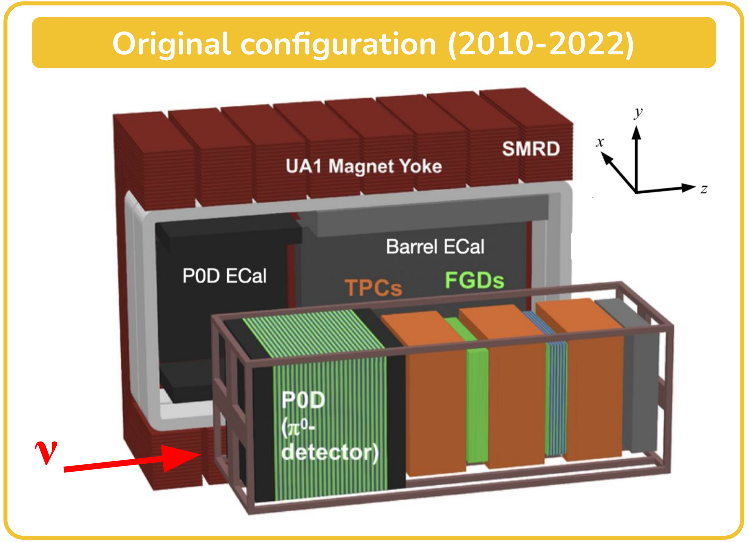
ND280 upgrade

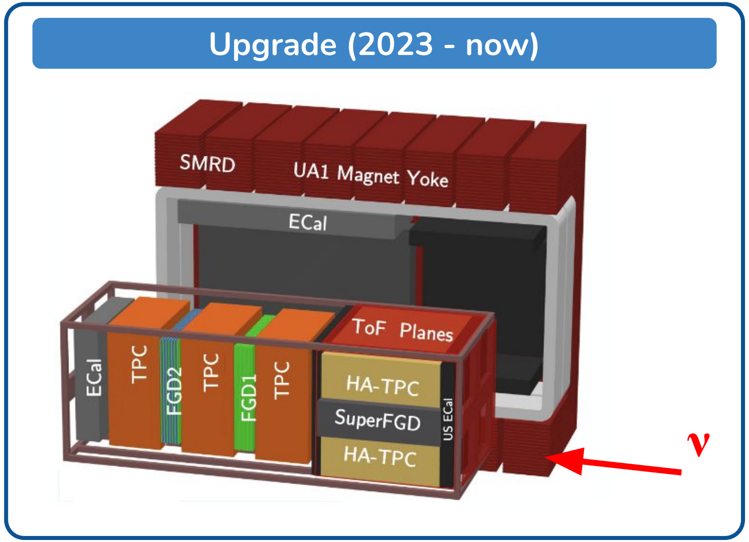
- There is room for improvement:
  - Limited angular acceptance
  - High proton reconstruction threshold





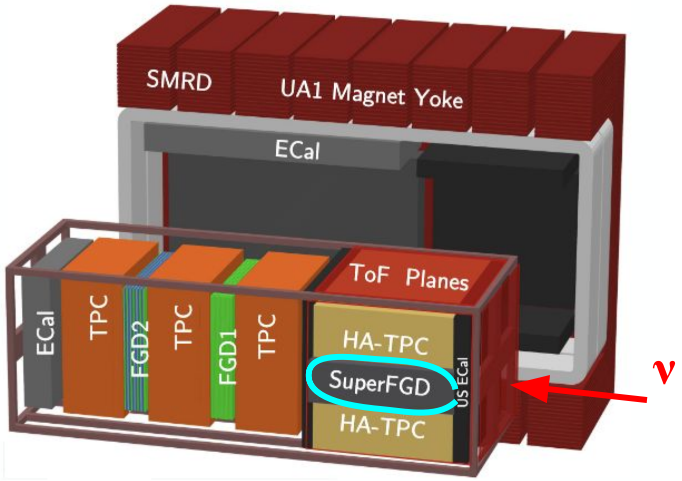
ND280 Upgrade





- P0D replaced three new detectors
  - **SuperFGD**: 3-dimensional highly segmented scintillator detector. Improved tracking capabilities
  - **High Angle TPCs (HA-TPC)**: analysis of backward-going particles
  - **Time-of-Flight (ToF)**: precise timing information for background suppression and better reconstruction

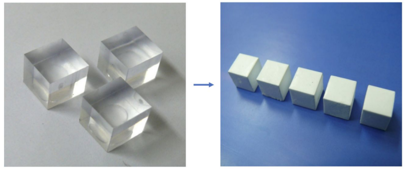
SuperFGD

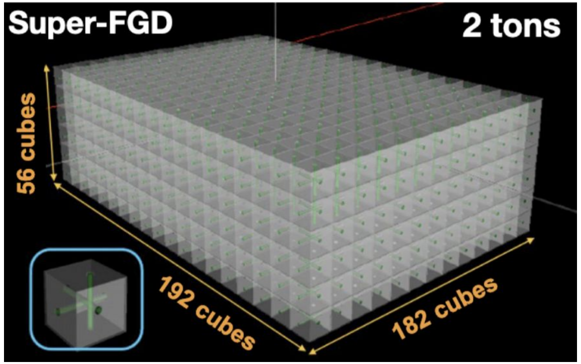


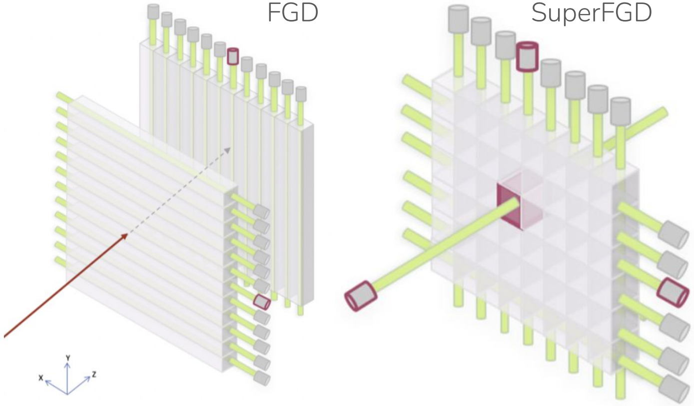
Details in talk by L. Giannessi

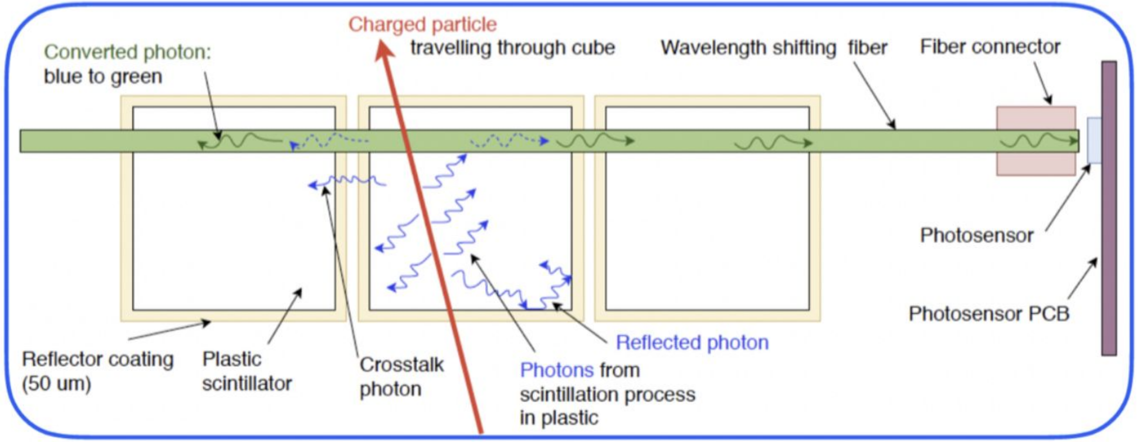
SuperFGD - Concept

- 2 million 1 cm^3 plastic scintillating cubes
- Reflecting coating by chemical etching of cubes
- Highly segmented readout in X-Y-Z
- Three orthogonal Y11 Kurarey WLS fibers per cube
- Each WLS fiber coupled to a MPPC



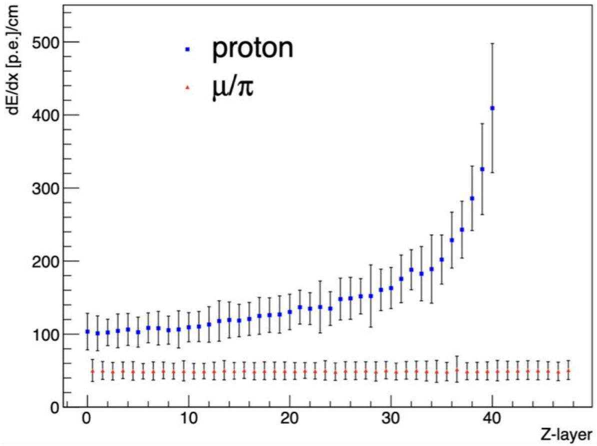


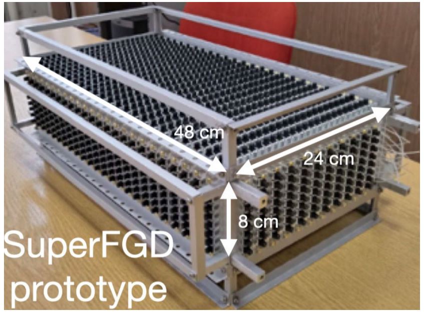




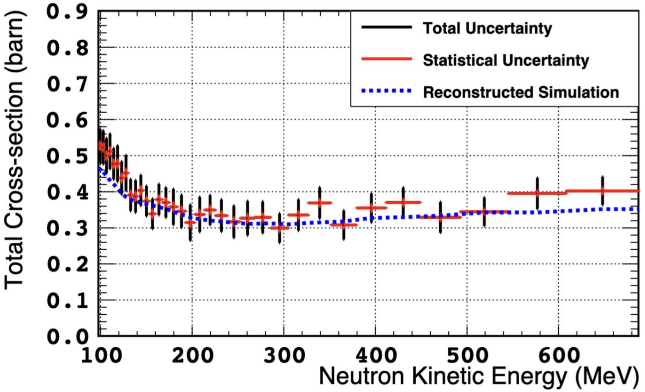
SuperFGD - Prototype and test

- 2018 Prototype (~200 smaller) tested at CERN - PS
  2020 JINST 15 P12003
  Average light yield = 58 PE / MIP / cube / fiber
  3% cross-talk
  1.1 ns time resolution per channel
  Good PID



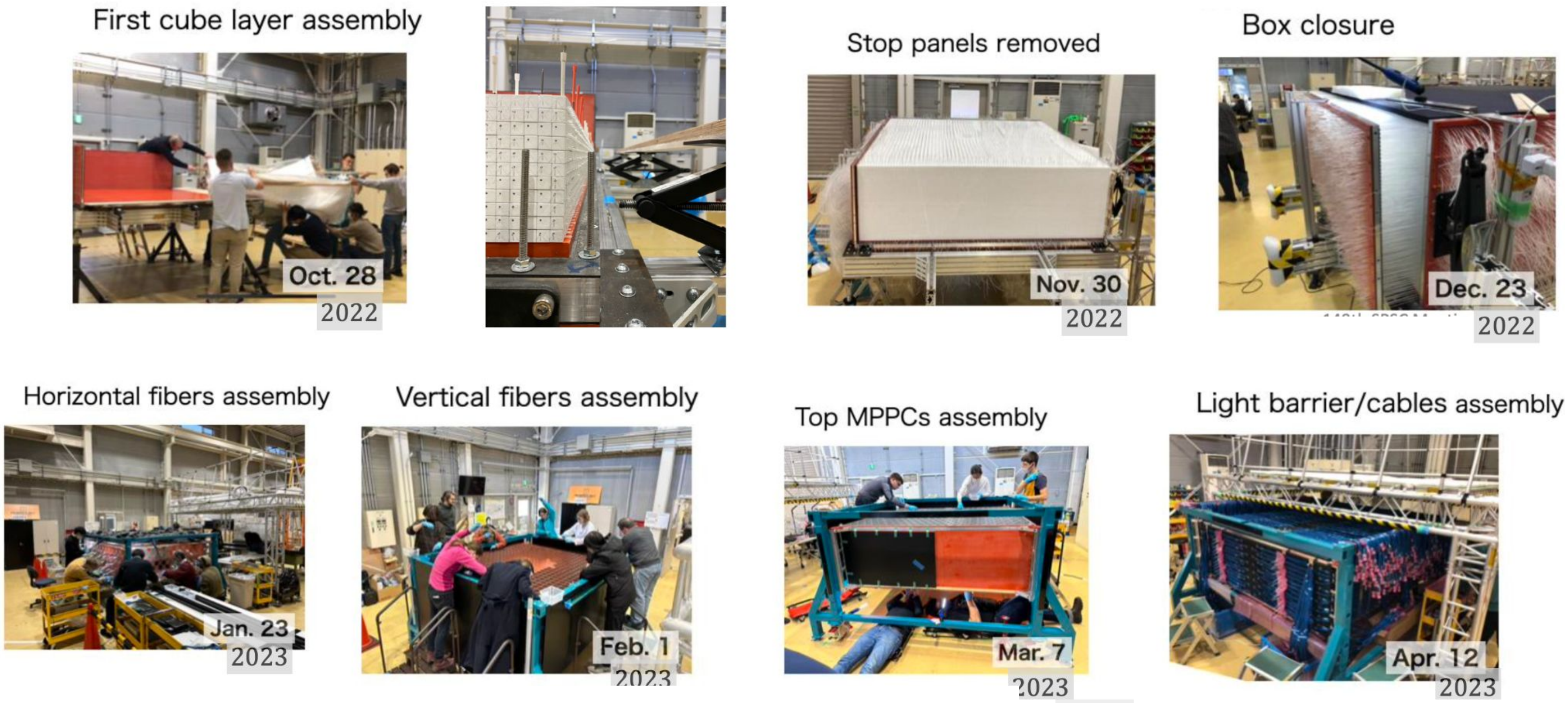


- 2020 Neutron beam test at LANL (2 prototypes)
  Physics Letters B 840 (2023) 137843
  Neutron energy from time-of-flight (pulsed beam)
  Neutron cross section from beam attenuation



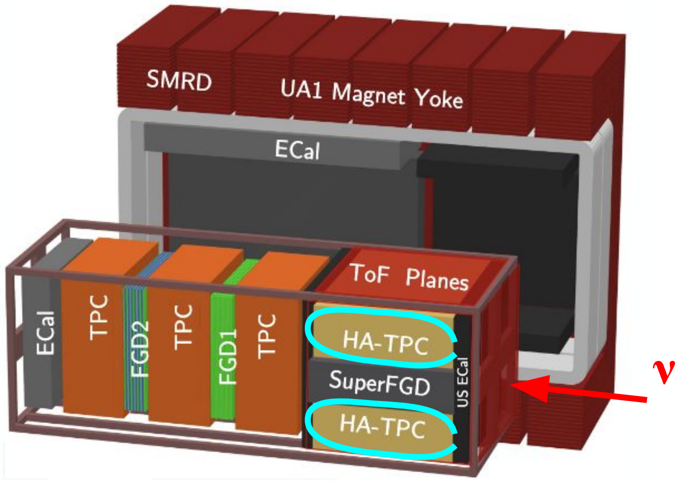
US-Japan prototype:

SuperFGD - Assembly at J-Parc



- ~20 months of cubes knitting with fishing lines
- First layer by layer, then moved to mechanical box
- Fiber insertion + MPPC installation + LED calibration + light tightness + cabling ~ 6 months

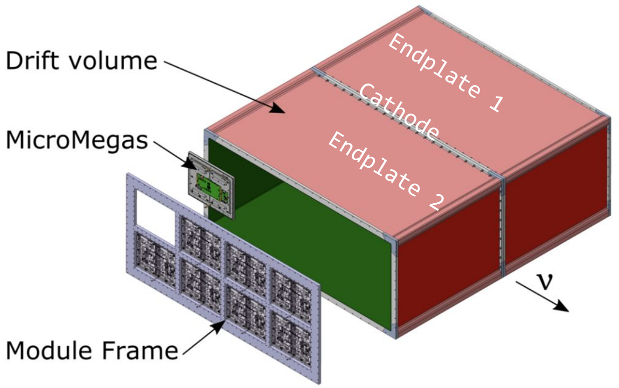
HA-TPC

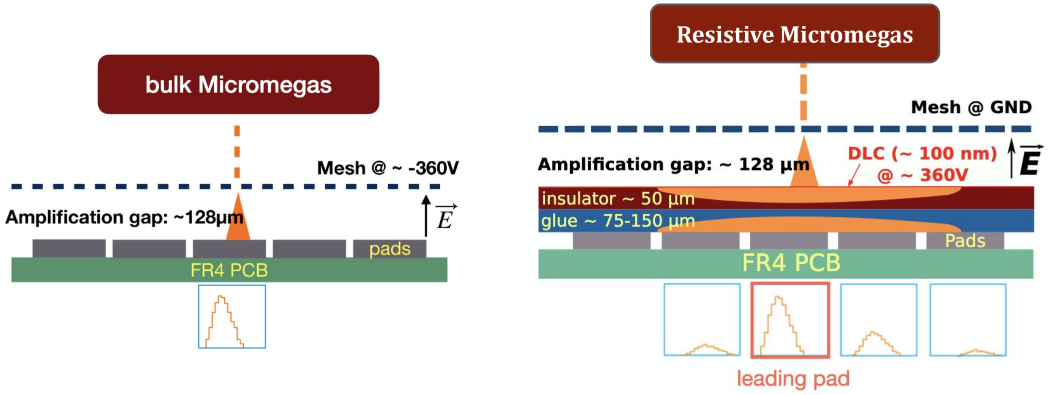


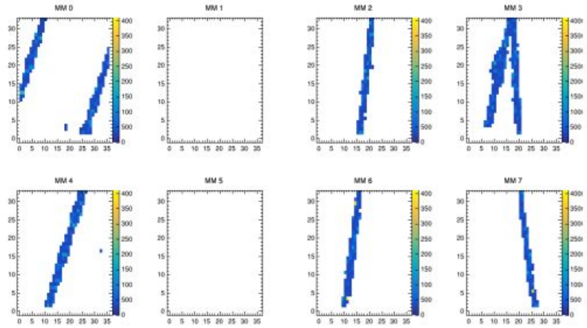
Details in talk by M. Varghese
& Poster by U. Virginet

HATPC - Concept

- Box-like shape $Ar:CF_4:iC_4H_{10}$ based TPC
- 1 m drift length with cathode at 27.5 kV
- New anode technology ERAM: Encapsulated Resistive Anode MicroMegas
- Charge spreading over multiple pads allows to better spatial resolution
- 2 endplates (1 full TPC) share the same cathode
- Each endplate hosts 8 ERAM modules
- 1152 pads per ERAM (32 x 36 grid)



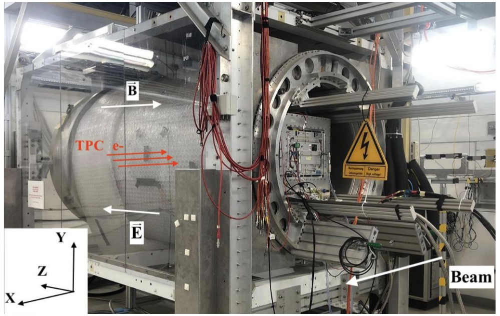




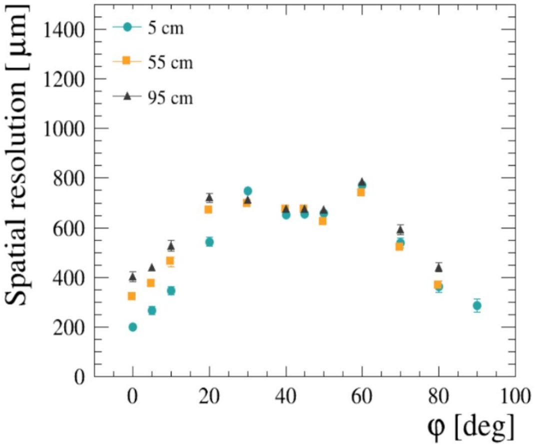
HATPC - Prototype and tests

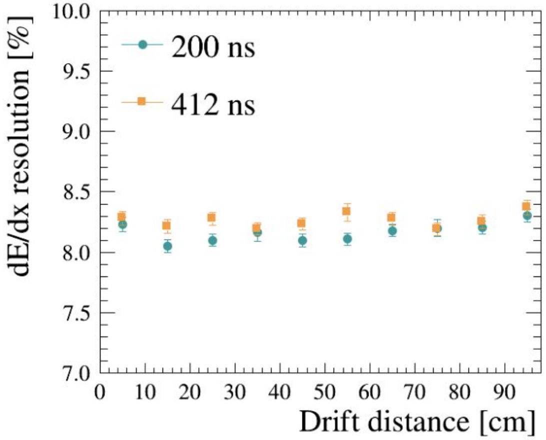
- 2019 → Single ERAM TPC prototype tests at DESY [arXiv:2212.06541].
  ERAMs characterisation with X-ray at CERN [arXiv:2303.04481]

  Spatial resolution ~ 0.4 mm
  dE/dx resolution better than 10%



- 2022 → Beam test of a single endplate (half TPC) at CERN
  Performance study with different beams (e, p, π, μ)



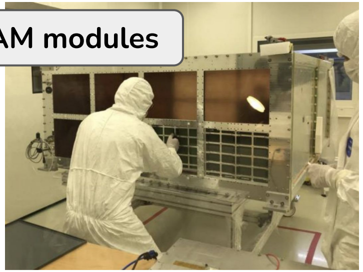


HATPC - Construction and commissioning

- 2022 → Construction/assembling at Nexus (Barcelona) and CERN

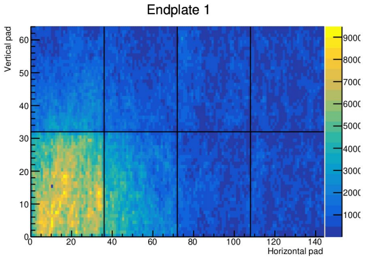
Field cage

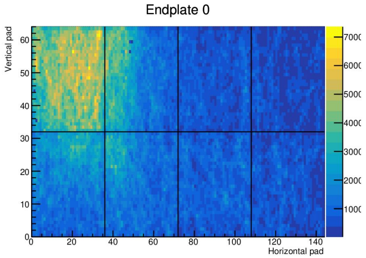
ERAM modules



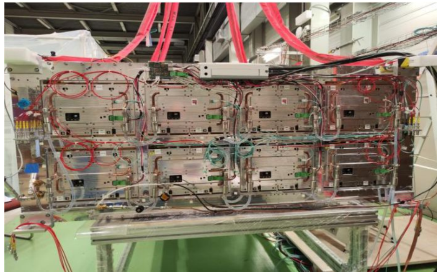
Metrology

- 2023 → Cosmic test of a full TPC at CERN
  Drift velocity computation
  Performance as a function of the drift distance

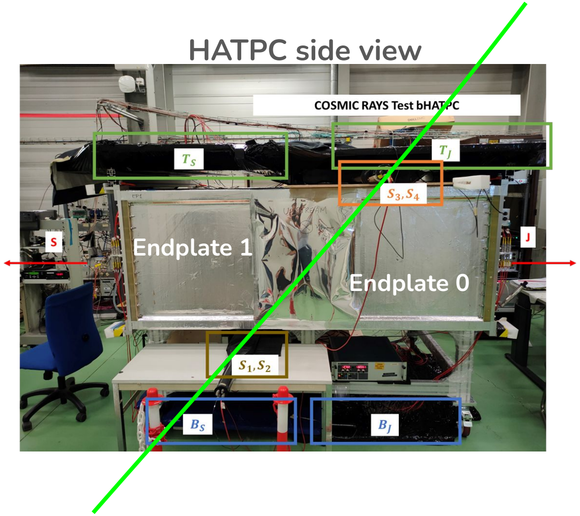




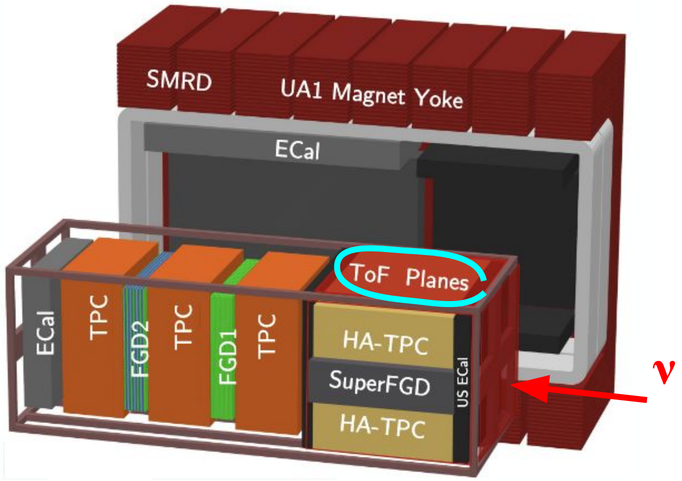
HATPC front view



HATPC side view



TOF



Details in poster by L. Giannessi

TOF - Concept

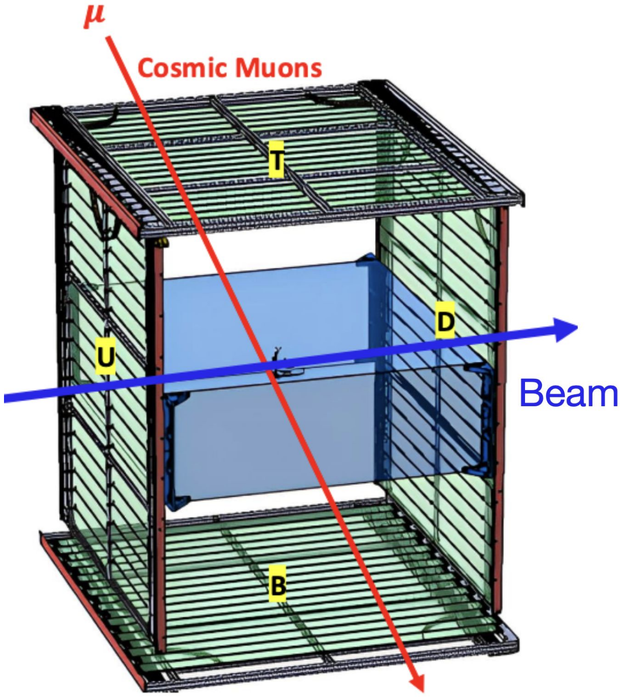
Configuration:

- 6 planes made of 20 plastic scintillator bars each
- Total coverage of SuperFGD and HATPC volume (5.4 m^2 per plane)
- Double end readout by SiPMs for each plane bar

TOF goals

- PID using time-of-light
- Background tagging from out-of-fiducial volume
- Provide T0 (drift coordinate) to HATPCs
- Improve SFGD neutron time-of-flight measurement
- Beam and horizontal muons monitoring

In addition has provided cosmic triggers to upgrade detectors



Plus 2 hidden side panels for a 4pi coverage of detectors

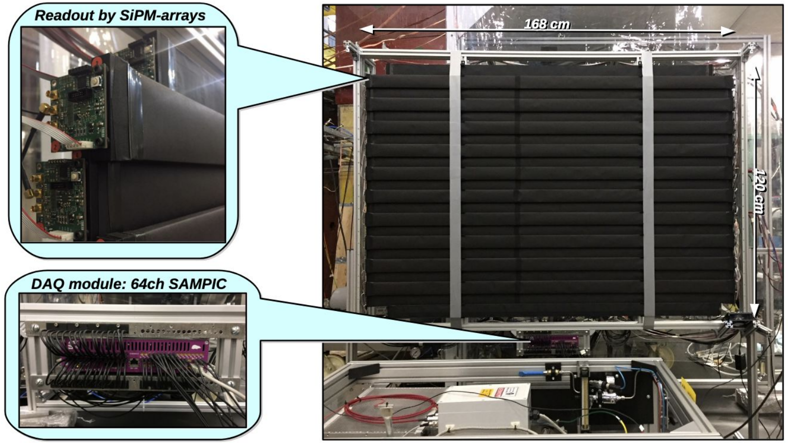
TOF - Prototype and tests

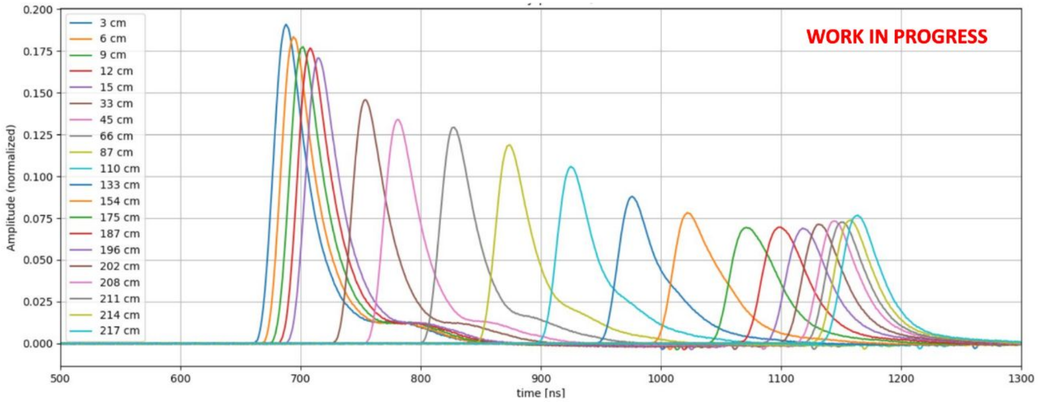
- 2018 → Smaller TOF prototype tested at CERN - PS [arXiv:1901.07785]

- 2021 → Single bar study with cosmic rays at CERN [arXiv:2109.03078]

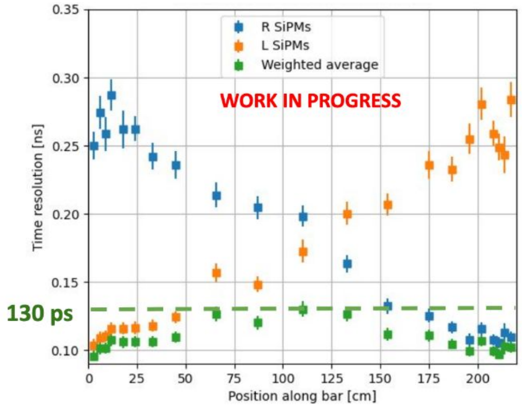
  Nominal time resolution: 130 ps

  Effective light velocity in scintillator = 16 cm/ns



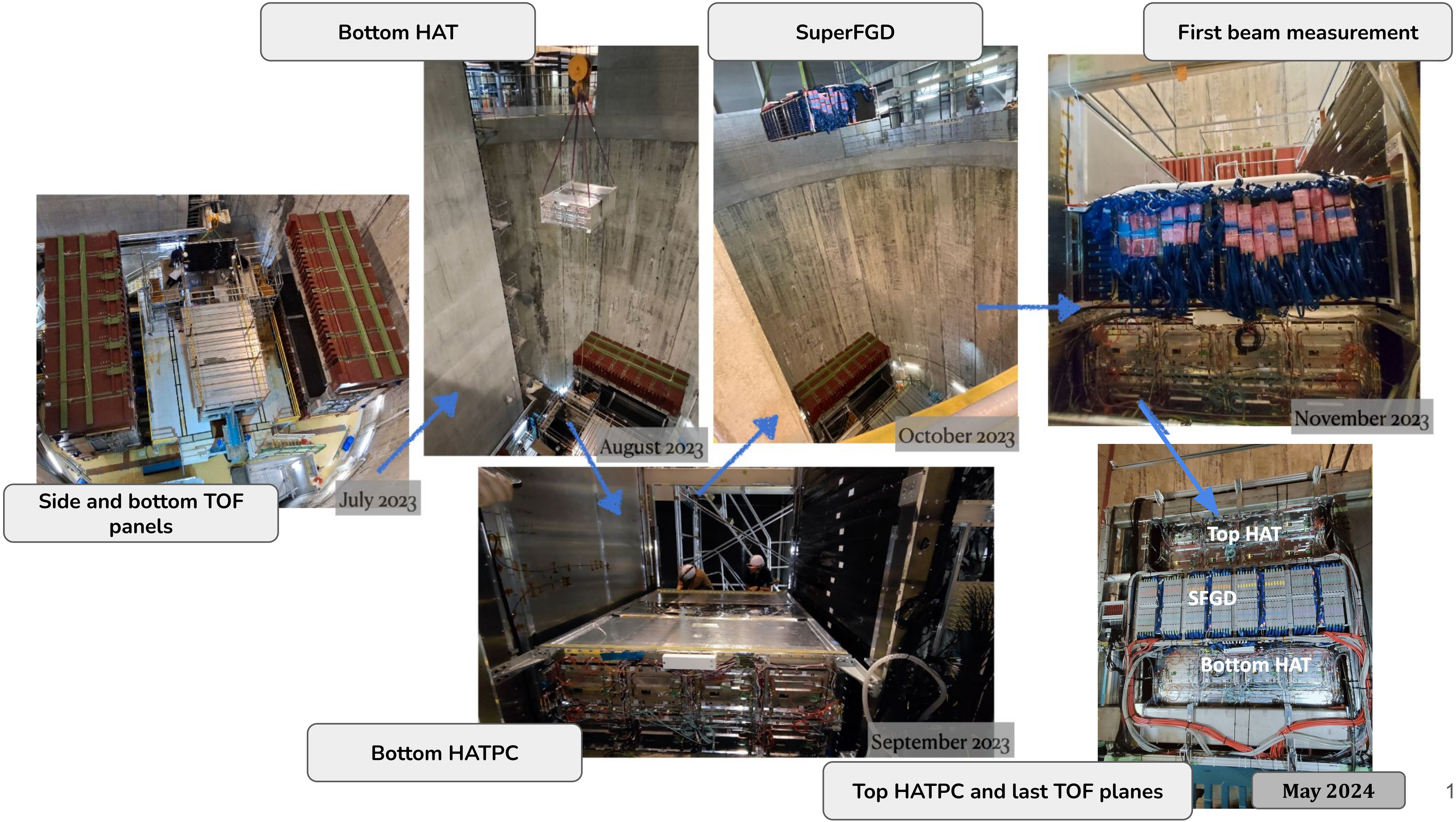


Average waveforms along TOF bar



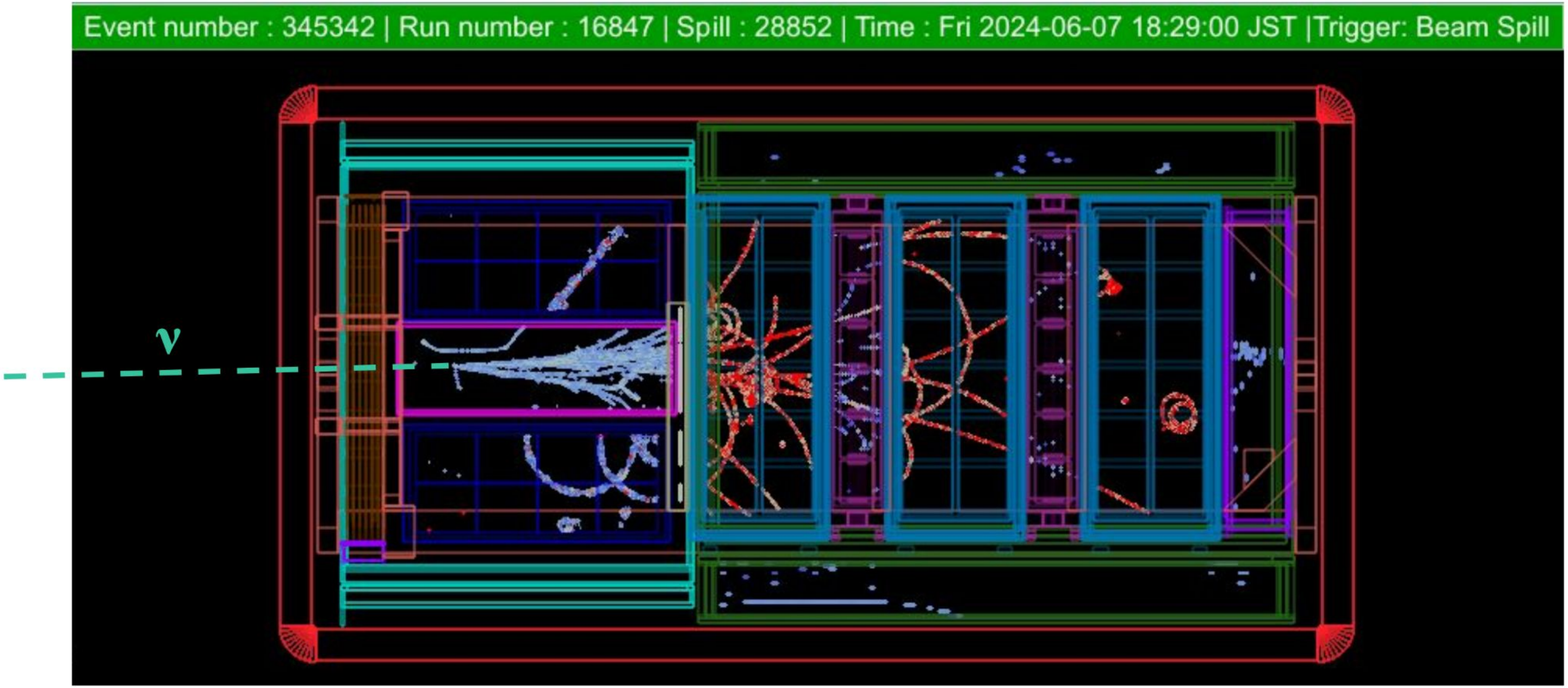
TOF time resolution

Full upgrade at J-Parc



Side and bottom TOF panels
July 2023
Bottom HAT
August 2023
Bottom HATPC
September 2023
SuperFGD
October 2023
First beam measurement
November 2023
Top HAT
SFGD
Bottom HAT
Top HATPC and last TOF planes
May 2024

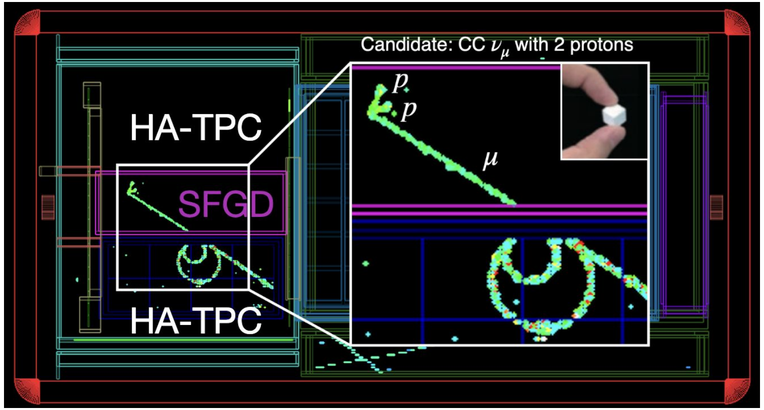
Neutrinos and cosmics with full ND280 upgrade



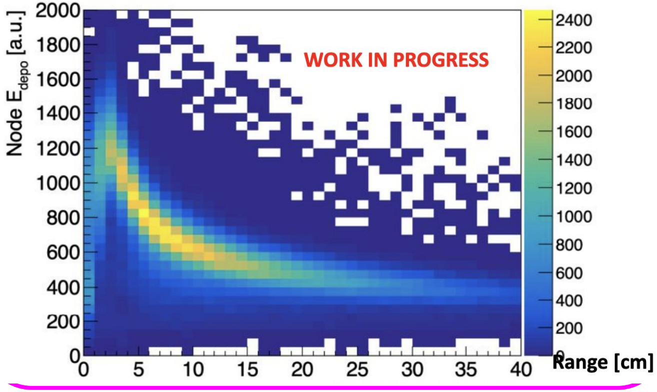
- Data taking since June 2024

ND280 performance - Preliminary

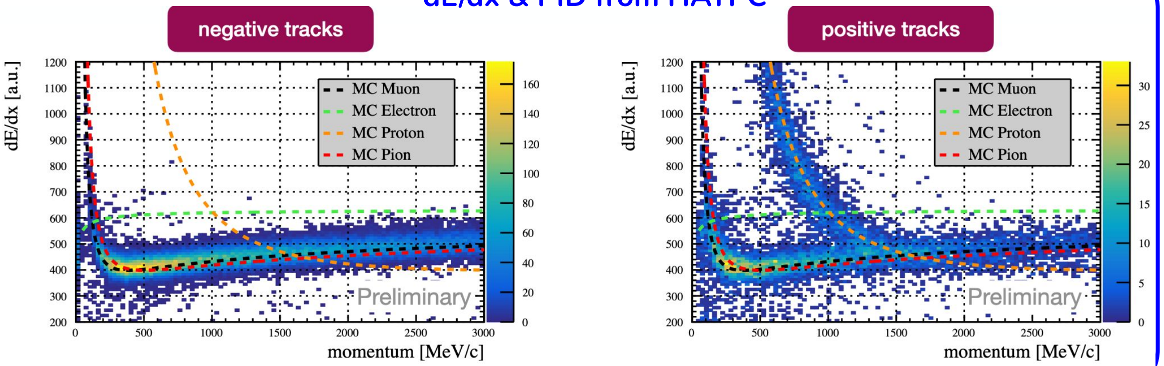
- Good PID due to high superFGD granularity and well behaved Bragg peak
- Complementary PID information from HATPC reconstruction



Bragg peak from SFGD

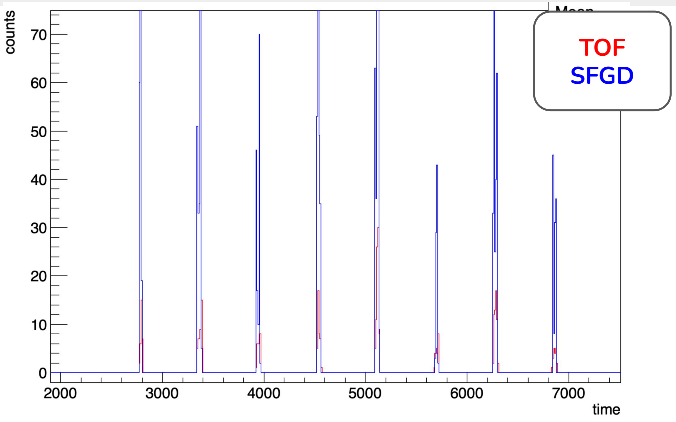


dE/dx & PID from HATPC

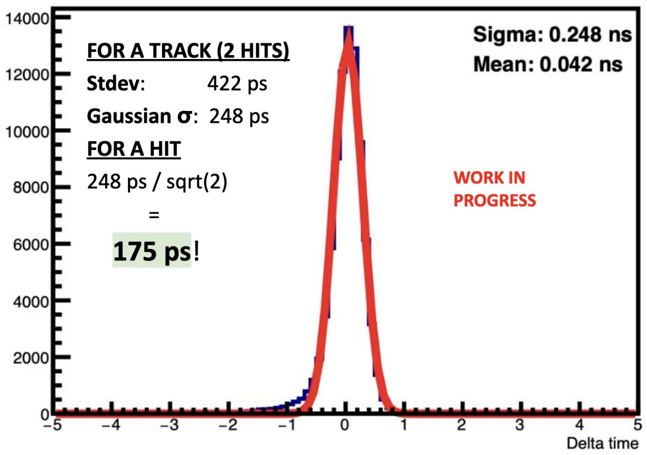


ND280 performance - Preliminary

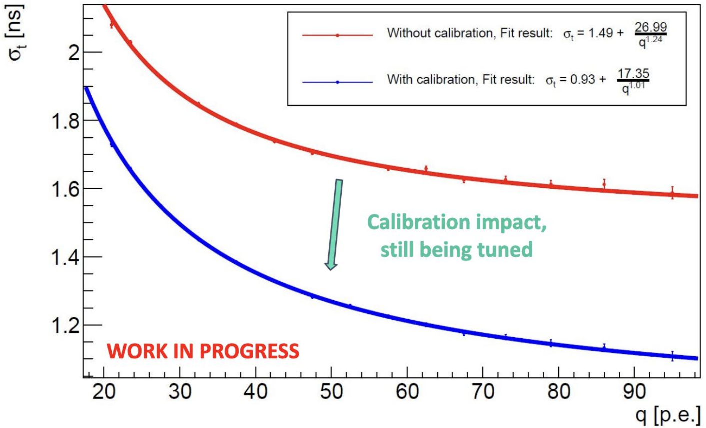
- TOF time resolution (~175 ps) good enough for exclusion of out-of-volume events
- Refining SFGD calibration gives expected time resolution ~1.1 ns
- TOF-SFGD alignment and 8 bunches structure of beam spills easily reconstructed



TOF time resolution

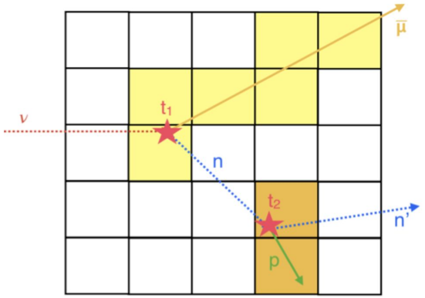


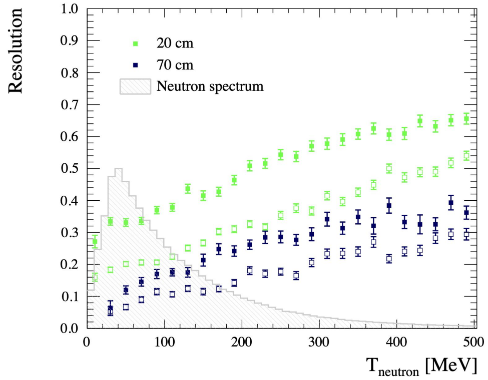
SFGD time resolution

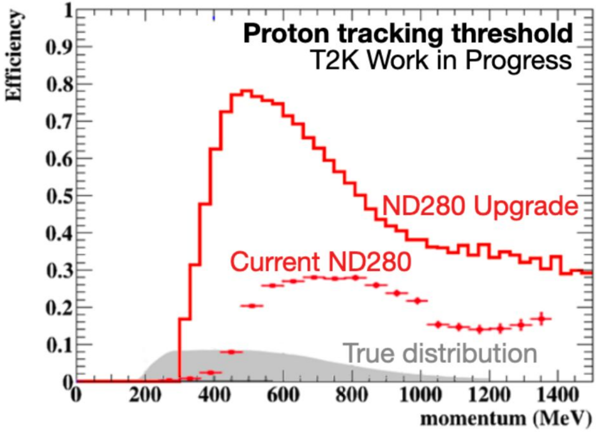


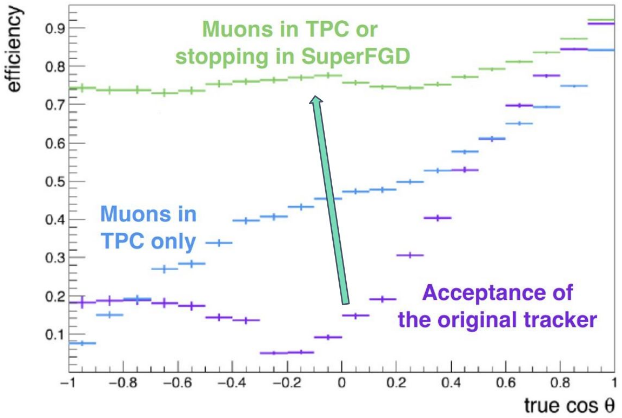
ND280 - physics benefits

- New anti-neutrino energy reconstruction channel: **CCneutron** [arXiv:1912.01511]
    - Possible thanks to high superFGD time resolution (neutron energy from time-of-flight)
    - Interaction with hydrogen → free of nuclear effects
- Lower proton detection threshold and higher overall efficiency
- Higher efficiency for high angle muon reconstruction [arXiv:1901.03750]









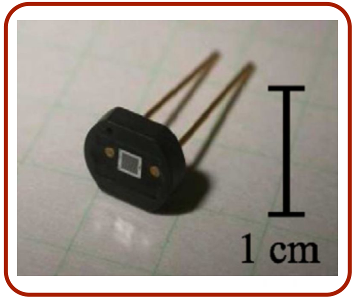
Summary

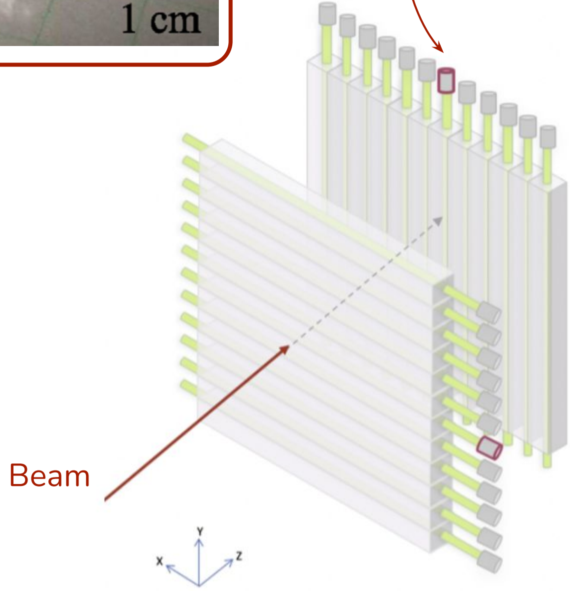
- Huge efforts from all collaborators to prototyping, testing, construction and commissioning
- T2K’s near detector upgrade fully installed and taking data since summer 2024
- Ongoing calibration and performance studies for all upgraded detectors

- Exciting upcoming studies: new selection samples, systematics analysis, refining tracking algorithms
- Discussions around second ND280 upgrade for HK project

Spare

Fine grained detectors (FGD) of J-Parc near detector



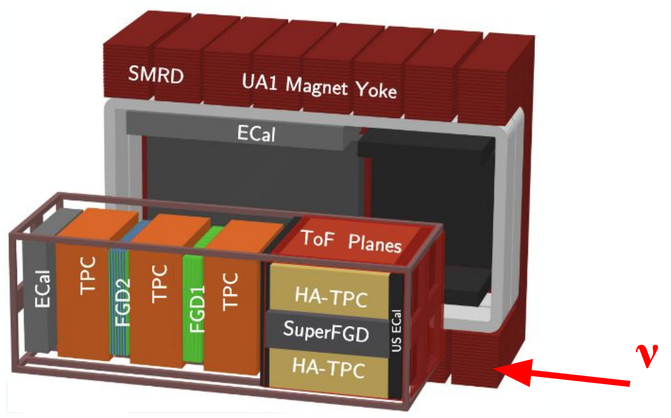


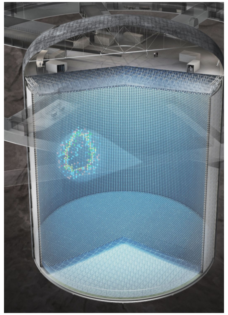
1st generation: FGD1 & FGD2

- Polystyrene scintillator bars: 9 x 9 x 1864 mm^3
- 1.1 ton per FGD
- Composition:
  - FGD1: 5760 bars (30 layers)
  - FGD2: 2688 bars (7 layers) + 6 layers of H_2O
- Alternating direction layers for X-Y readout
- Wavelength shifting (WLS) fibers: 1 mm ∅ Y11 Kurarey
- Multi-pixel photon counters (MPPC)
  - 667 pixels
  - 1.3 x 1.3 mm^2
  - Gain ~ 10^6
  - PDE (525 nm) ~ 30%

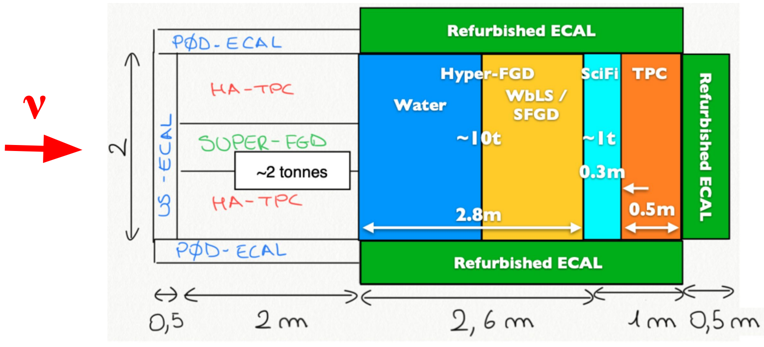
FGD prototypes for HK's near detector

2nd generation: SuperFGD





Next generation: HyperFGD



Upgraded near detector limitations:

- Large uncertainty of $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ reduces δ_{CP} exclusion power by HK
- Opposite to near detector, far detector is water base:
  - Cherenkov light yield < scintillation light
  - Water is inactive and cannot track protons

Near detector ultimate upgrade (2031)

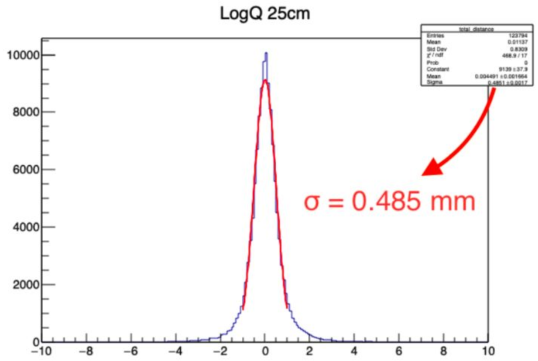
- Former **FGD + TPC** replaced by active water-base tracker detectors
- Proposal: 5 ton of water-base liquid scintillator (WbLS) → HyperFGD

How to get the spatial resolution ?

- each track is fitted with a circle/parabola
- for each cluster in the track compute the residuals:

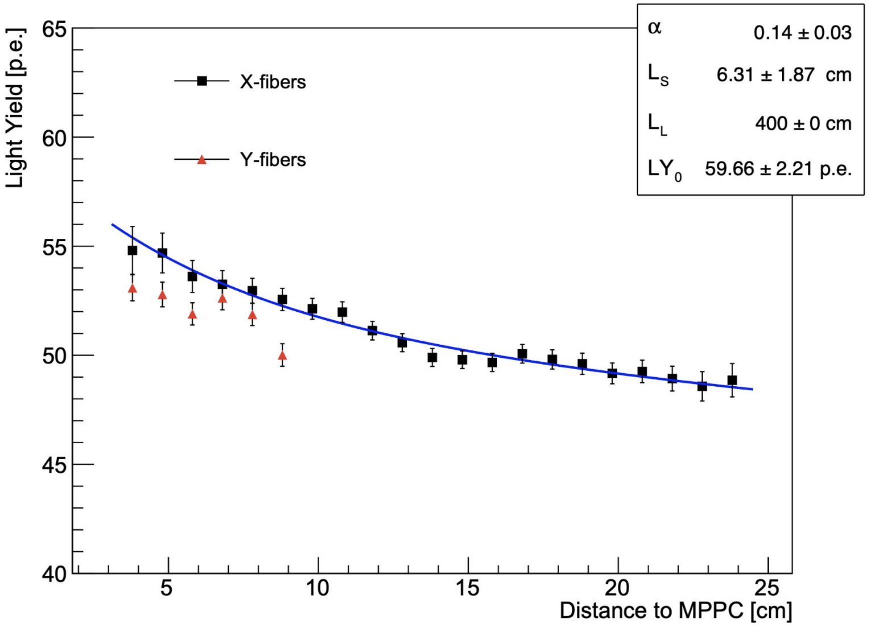
$$res = \sqrt{(\ z_{rec}^{cluster} - z^{track\ fit}\ )^2\ + (\ y_{rec}^{cluster} - y^{track\ fit}\ )^2} - R$$

- fill a histogram with res from all the tracks
- fit the histogram with a gaussian
- SR = σ from the fit



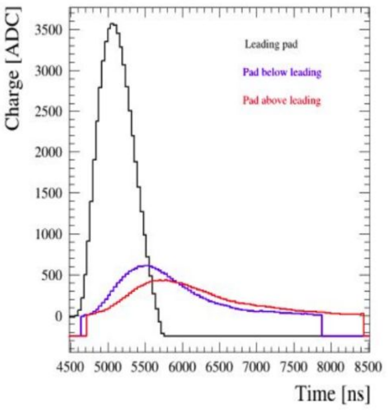
SFGD WLS fiber - light attenuation

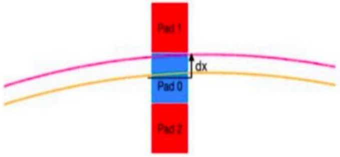
$$y(d) = LY_0 \left(\alpha e^{\frac{-d}{L_S}} + (1-\alpha) e^{\frac{-d}{L_L}} \right)$$



Reconstruction Algorithm

The position of the track is reconstructed based on the logarithm (ln) of the charge in the leading pad and in the neighboring pads



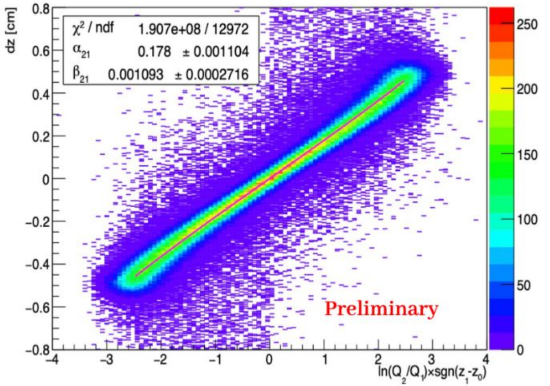


$$dx = f(\log(Q_1/Q_0) \text{ or } \log(Q_2/Q_1))$$

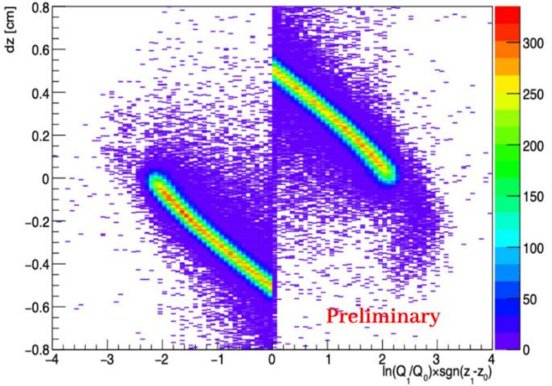
Q0: Charge on the leading pad
Q1: Charge on the 1st sub-leading pad
Q2: Charge on the 2nd sub-leading pad

Poster by *Ulysse Virginet*

MC Simulation



Track near the **center of the pad**, Q0 ≫ Q1 ~ Q2 & **ln(Q2/Q1) is informative**



Track near the **edge between two pads**: Q0 ~ Q1 ≫ Q2 & **ln(Q1/Q0) is significant**