Overview of the T2K Near Detector Upgrade

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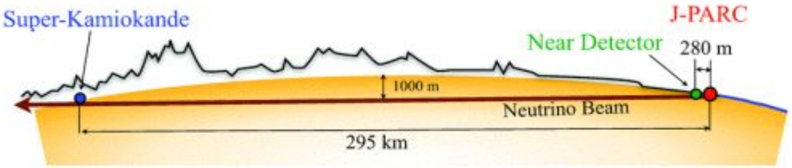
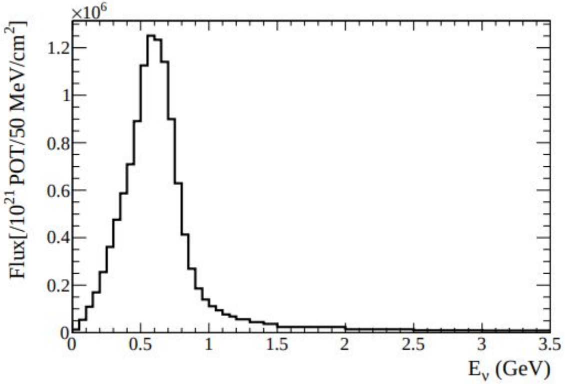
on behalf on
T2K Collaboration
DPF-PHENO 2024
May 16th 2024

T2K Experiment

- Long-baseline neutrino oscillation experiment
- $\nu_\mu(\bar{\nu}_\mu)$ beam generated from accelerator facility in J-PARC

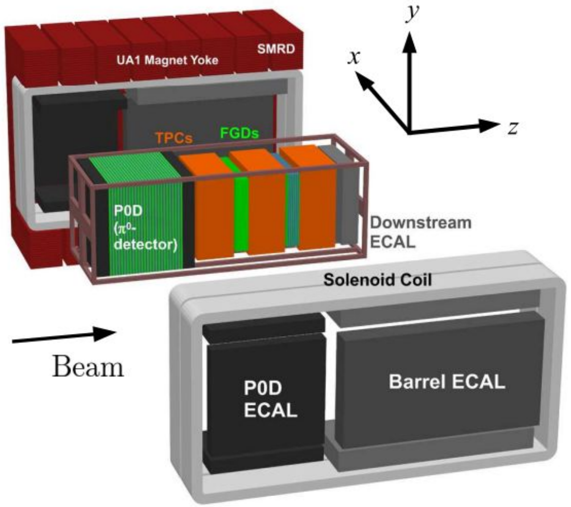




- Near detector (ND280) located 280 m from J-PARC
- 2.5° off-axis angle with energy spectrum peaking at ~ 600 MeV
- Far detector (SK) with a baseline of 295 km
- Measures $\nu_\mu(\bar{\nu}_\mu)$ disappearance and ν_e $(\bar{\nu}_e)$ appearance at SK

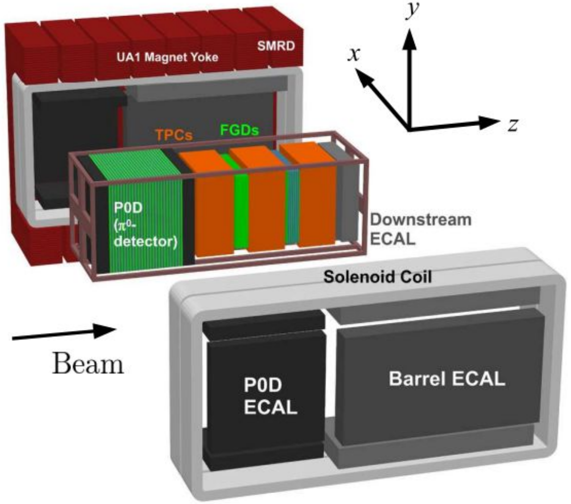
ND280

- Magnetized off-axis tracking detector
- Measures neutrino energy spectrum, flavor content and interaction rates of the unoscillated beam
- **P0D** (π^0 detector): Measures π^0 production ($\pi^0 \rightarrow \gamma + \gamma$ mimics $CC\nu_e$ interaction)
- **FGDs** (Fine Grained Detector): Neutrino target (+ tracker) consisting of plastic scintillator bar planes (water planes for FGD2)



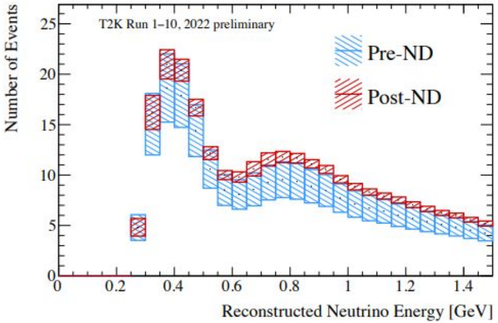
ND280

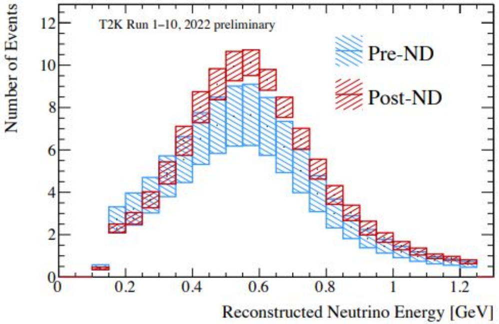
- Magnetized off-axis tracking detector
- Measures neutrino energy spectrum, flavor content and interaction rates of the unoscillated beam
- **TPCs** (Time Projection Chamber): Gas argon time projection chambers for momenta reconstruction
- **ECAL** (Electromagnetic Calorimeter): Measures energy deposit
- **SMRD** (Side Muon Range Detector): Measures momenta of muon that escapes inner detector

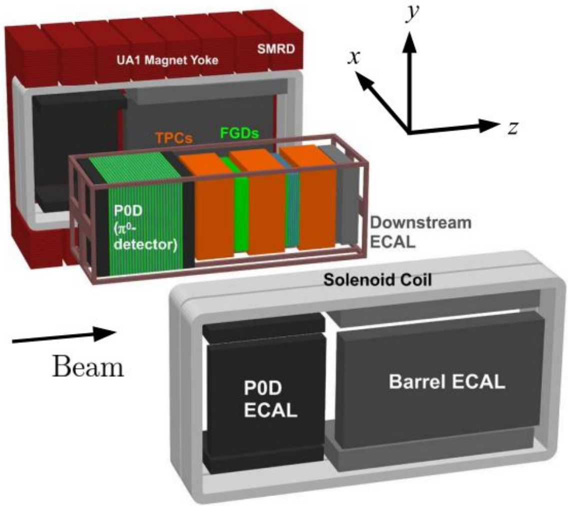


ND280

- Magnetized off-axis tracking detector
- Measures neutrino energy spectrum, flavor content and interaction rates of the unoscillated beam
- Systematic uncertainties on ν_μ and ν_e energy spectra at SK reduced from 15% to 5% thanks to ND280 fit

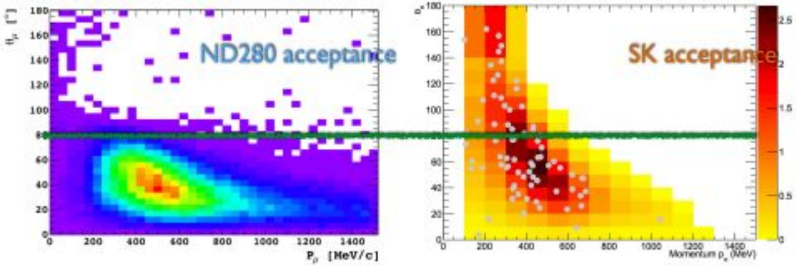




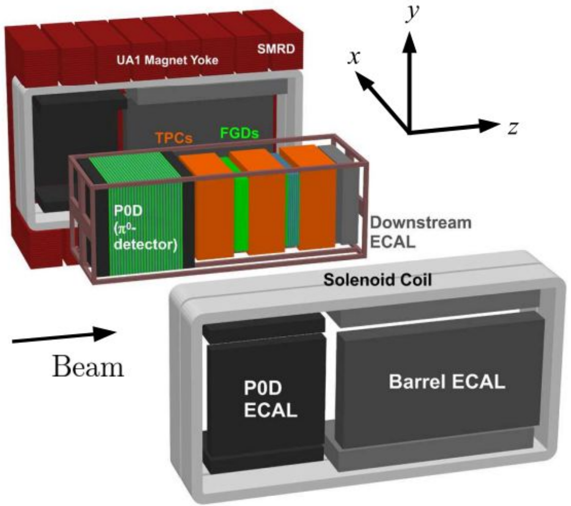


ND280

- Magnetized off-axis tracking detector
- Selection bias towards ν_μ ($\bar{\nu}_\mu$) interactions with forward going μ^-(μ^+)

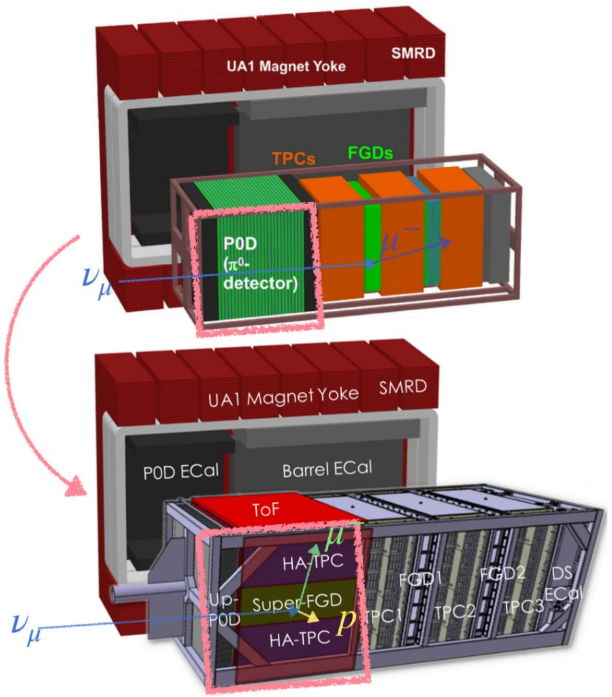


- Small number of events and relatively low purity in ν_e($\bar{\nu}_e$) selections
- High threshold on protons reconstruction
- Poor neutrons selection



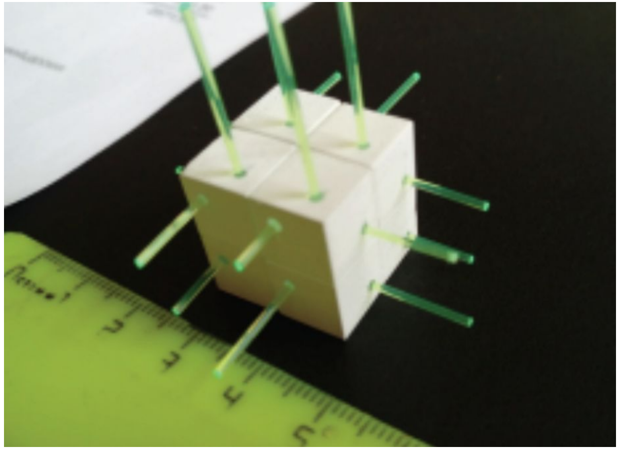
ND280 Upgrade

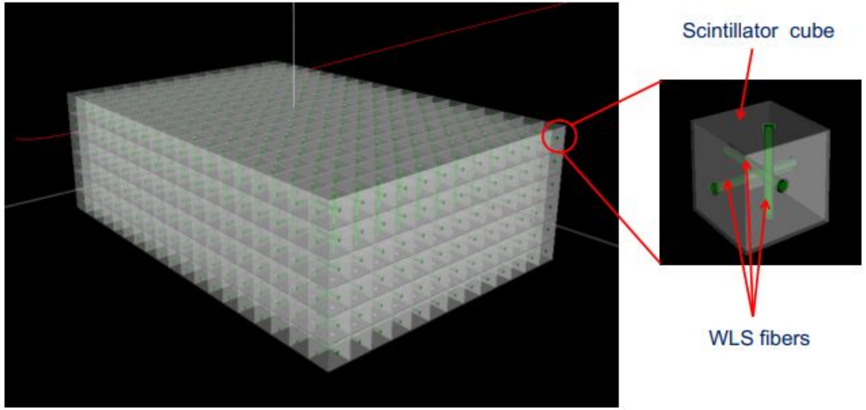
- Replacement of P0D with 3 new sub-detectors
- **SFGD** (Super-Fine Grained Detector): Neutrino target (+ tracker) consisting of plastic scintillator cubes
- **HA-TPCs** (High-Angle Time Projection Chamber): 2 TPCs sandwiching SFGD for momentum reconstruction of high angle tracks
- **TOFs** (Time-of-Flight): 6 plastic scintillator bar planes covering SFGD and HA-TPCs



SFGD

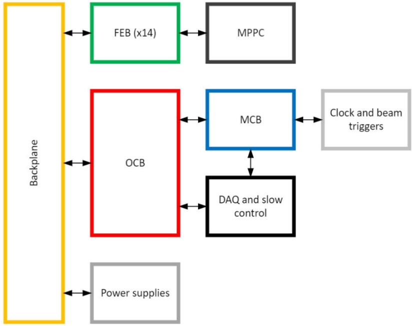
- Plastic scintillator detector capable of 3D readout
- Consist of ~ 2 million cubes (1 cm^3) weighing ~ 2 tons
- 3 orthogonal wavelength-shifting (WLS) fibers passes through each cube
- Multi-Pixel Photon Counter (MPPC) instrumented at 1 end of each fiber

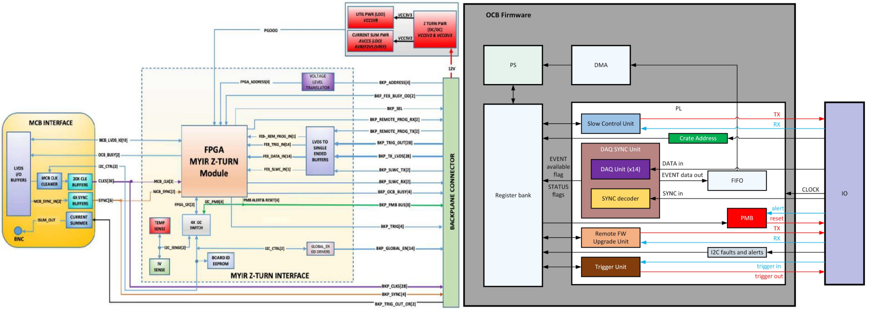




SFGD

- ~ 60k electronic channels
- Instrumented with 256 frontend boards and 16 data concentrator boards (joint effort between Europe and US groups)

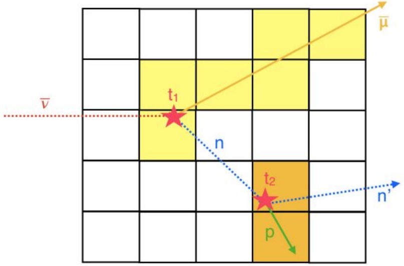


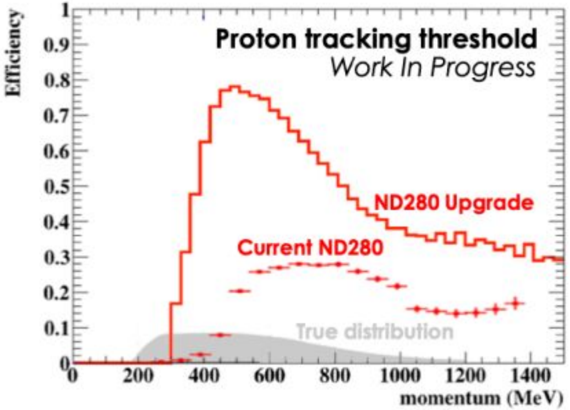


- UPenn responsible for the backplane and data concentrator boards
- Actively involved in board design and primary designer of the firmware

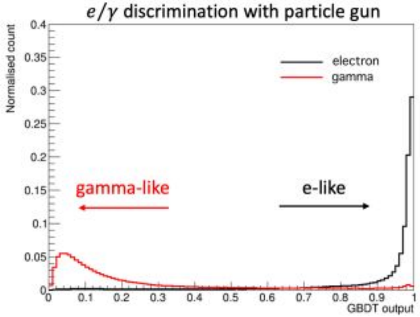
SFGD

- 4π reconstruction of outgoing particles
- Lower energy threshold for proton reconstruction
- Capable of event-by-event neutron kinematic reconstruction using the time-of-flight method





- Better separation of e^- coming from ν_e interactions than the ones coming from $\gamma \rightarrow e^+e^-$ conversions



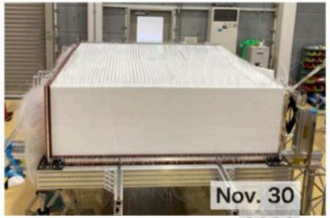
SFGD

- Assembly highlights!

First cube layer assembly

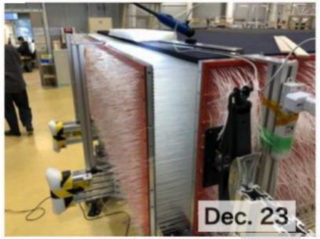
Oct. 28
2022

Stop panels removed



Nov. 30
2022

Box closure

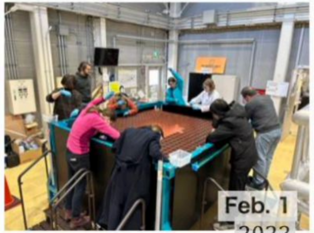


Dec. 23
2022

Horizontal fibers assembly

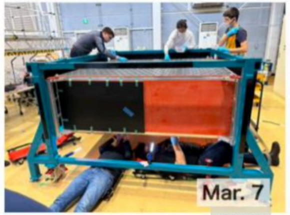
Jan. 23
2023

Vertical fibers assembly



Feb. 1
2023

Top MPPCs assembly



Mar. 7
2023

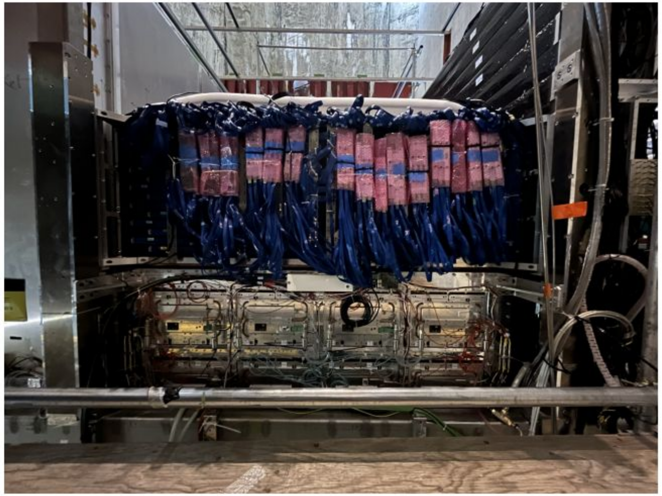
Light barrier/cables assembly

Apr. 12
2023

SFGD

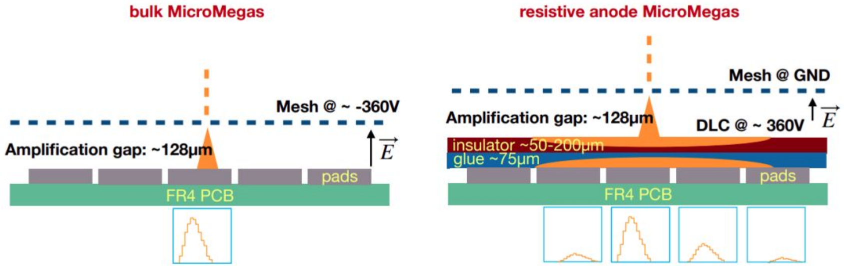
- Installation highlights!

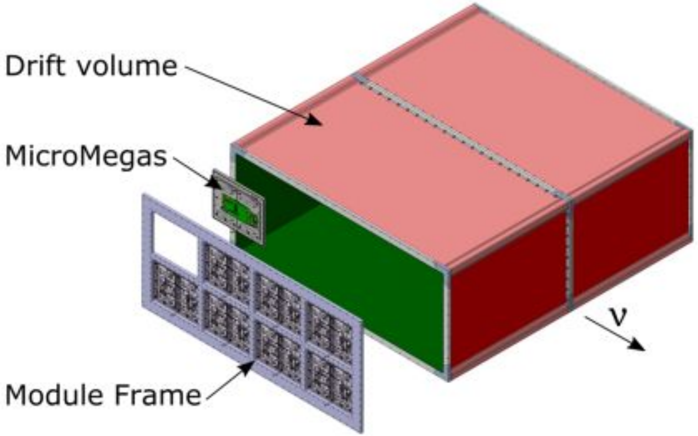




HA-TPC

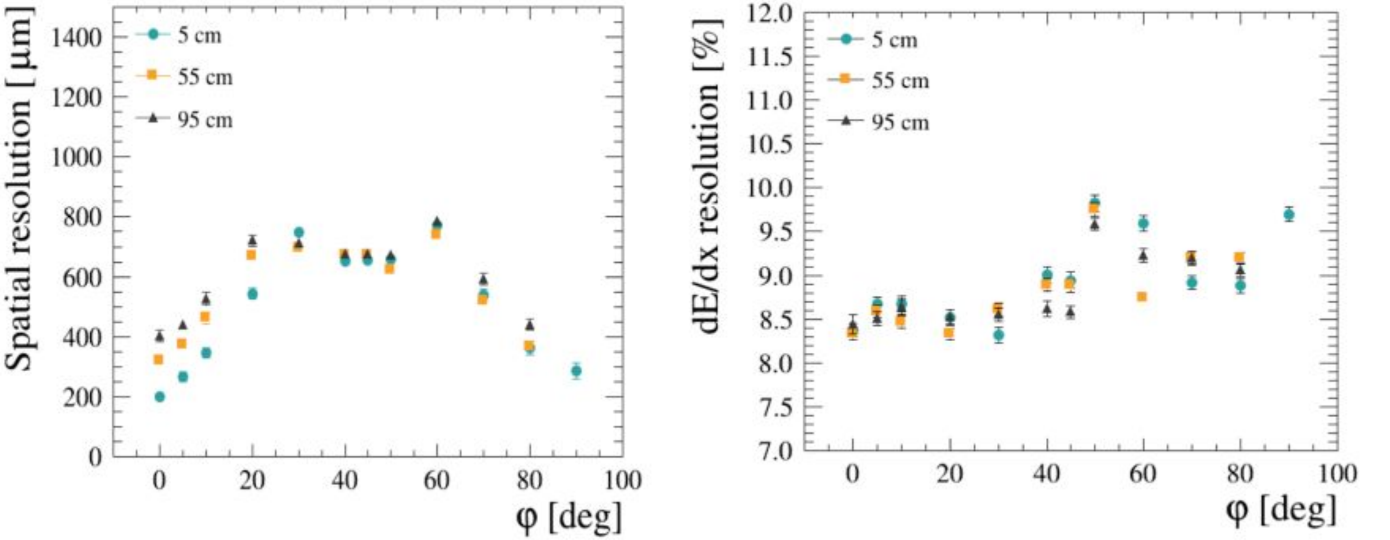
- New TPCs equipped with resistive anode MicroMegas (ERAM)
- Allows for charge spreading on several pads
- Installed top and bottom of SFGD for momentum reconstruction of high angle muon tracks





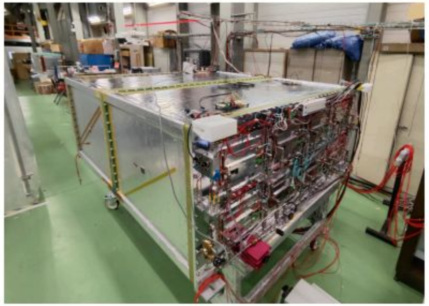
HA-TPC

- 200 to 800 μm spatial resolution
- dE/dx resolution of less than 10%



HA-TPC

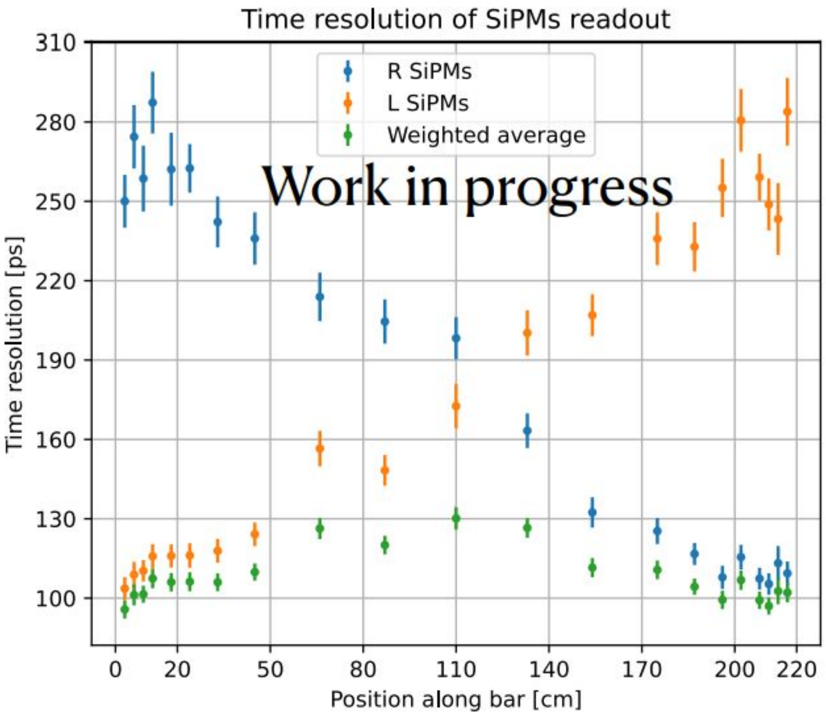
- Assembly and installation highlights!



Aug.25
2023

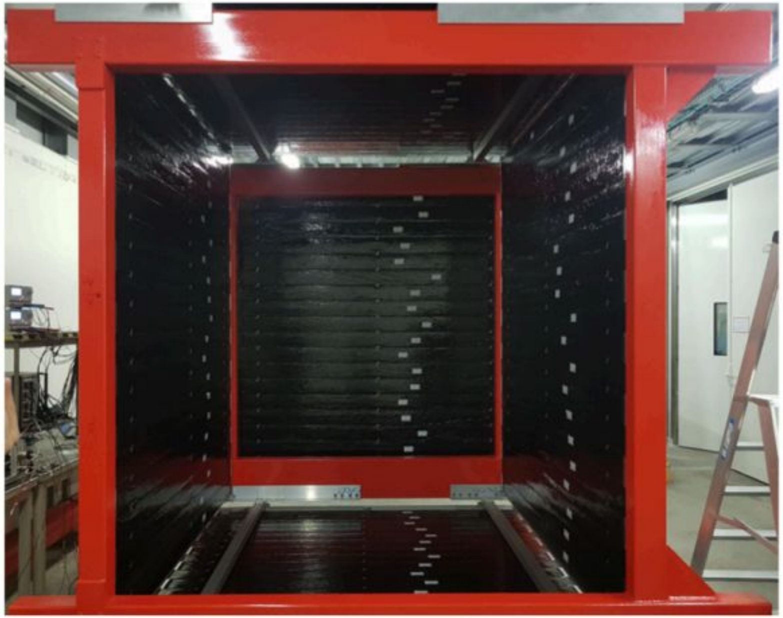
TOF

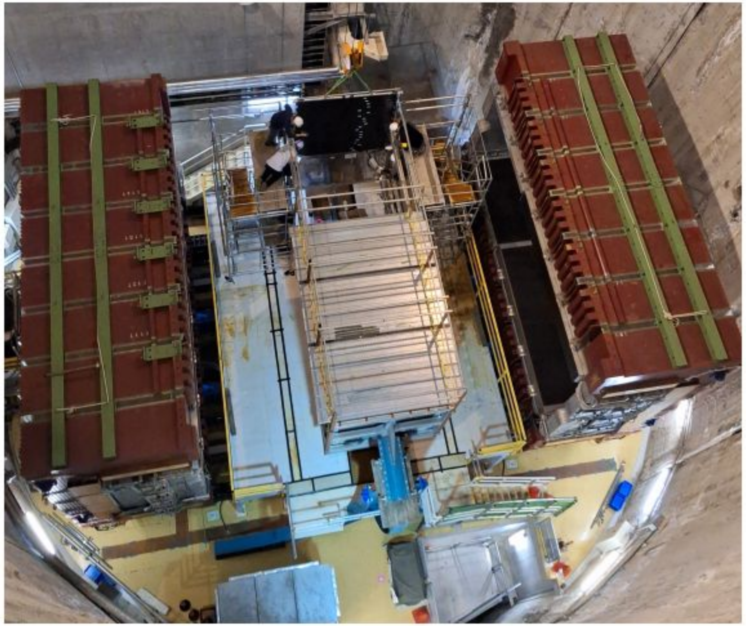
- 6 plastic scintillator planes fully surrounding the SFGD and HA-TPCs
- Timing resolution between 100 and 130 ps



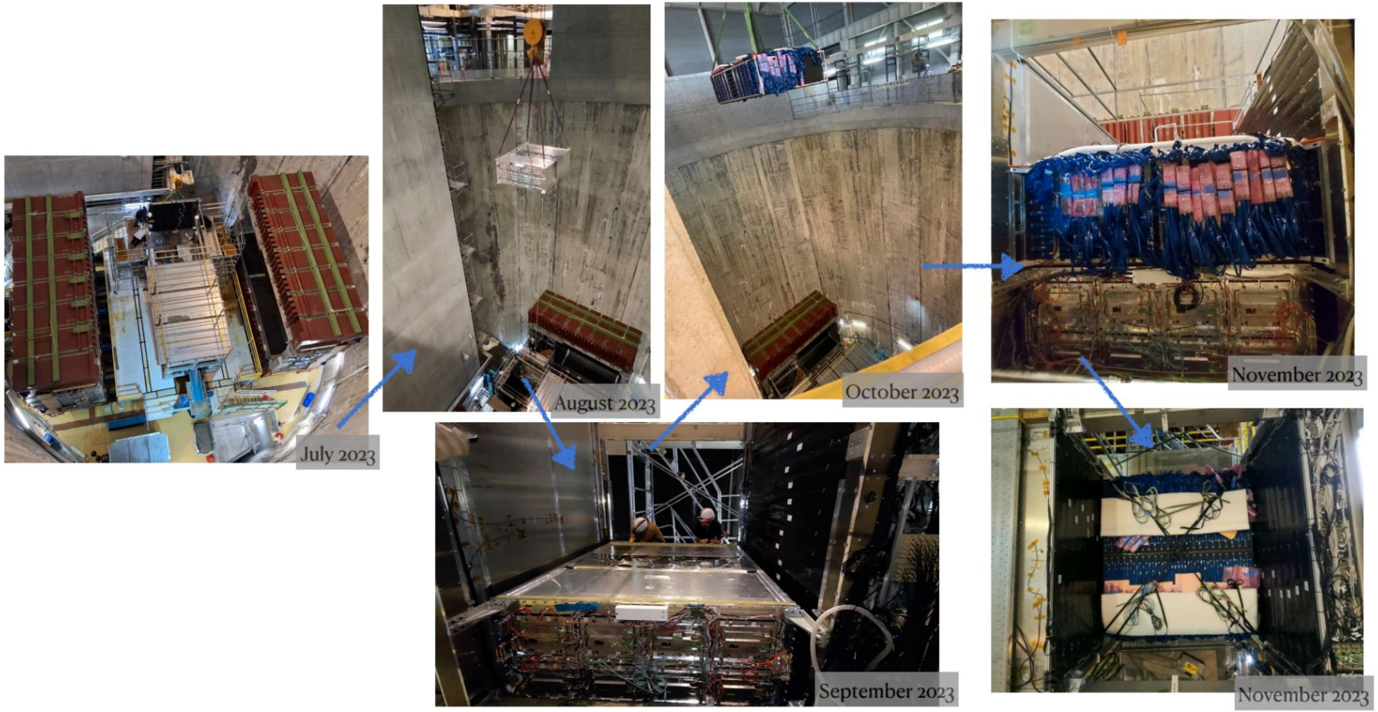
TOF

- Assembly and installation highlights!



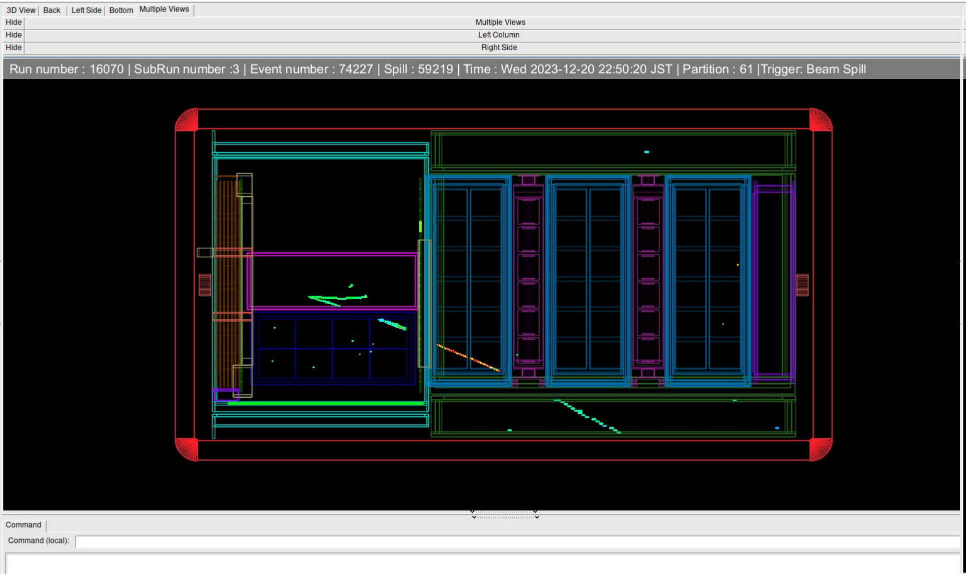


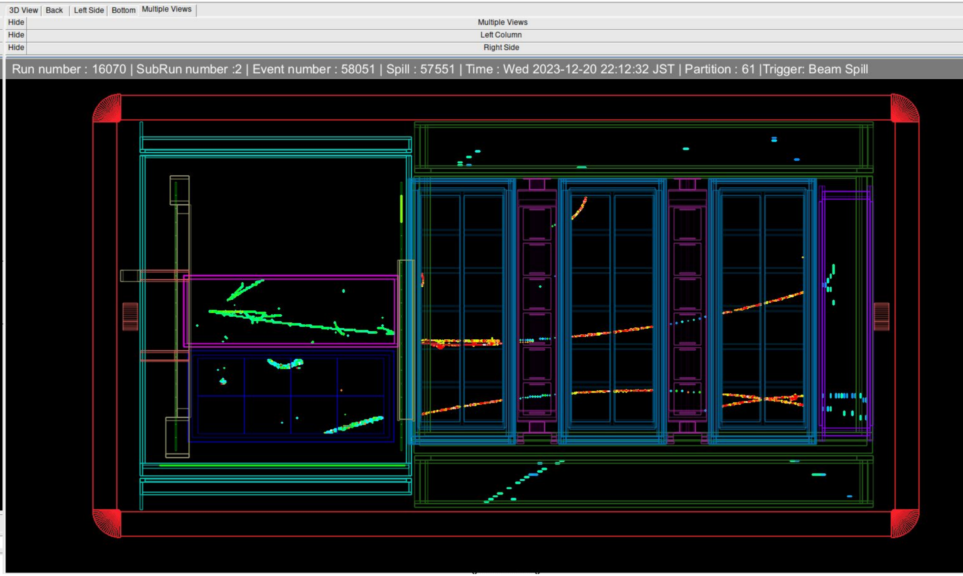
ND280 Upgrade Installation



ND280 Upgrade Status

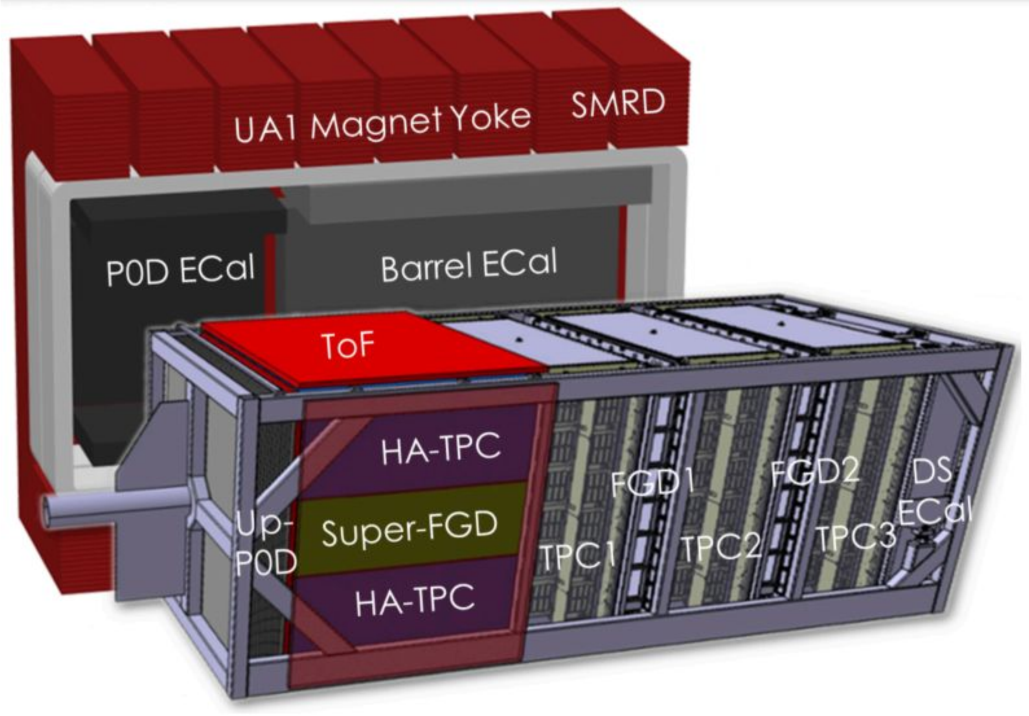
- Data taking started at the end of 2023 with bottom HA-TPC, SFGD (~ 85% instrumented) and 4/6 TOF in ND280





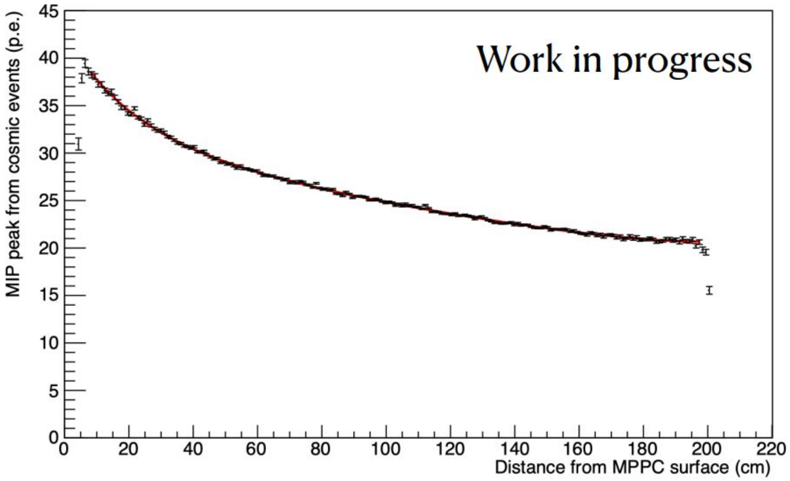
ND280 Upgrade Status

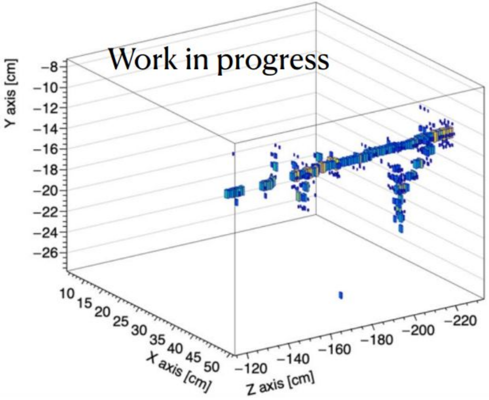
- SFGD fully instrumented at the end of March 2024
- Top HA-TPC installed at the end of April 2024
- Last 2 TOF panels installed 2 days ago
- Full ND280 upgrade ready for beam in June!

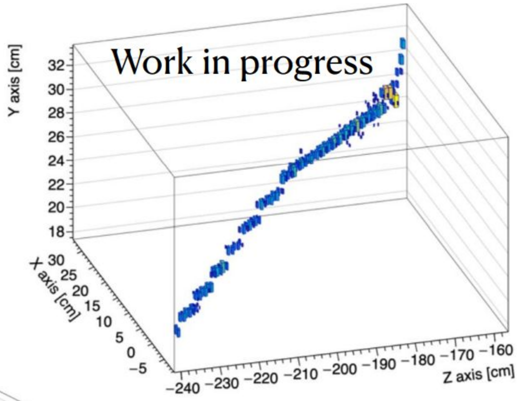


ND280 Upgrade Data

- **SFGD preliminary results:**
- Reconstruction of 3D tracks
- A light yield of ~ 20 to 40 PE/MIP/fiber

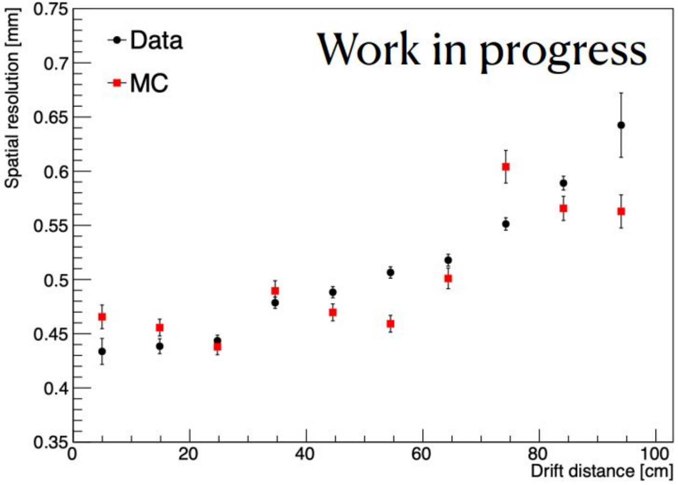


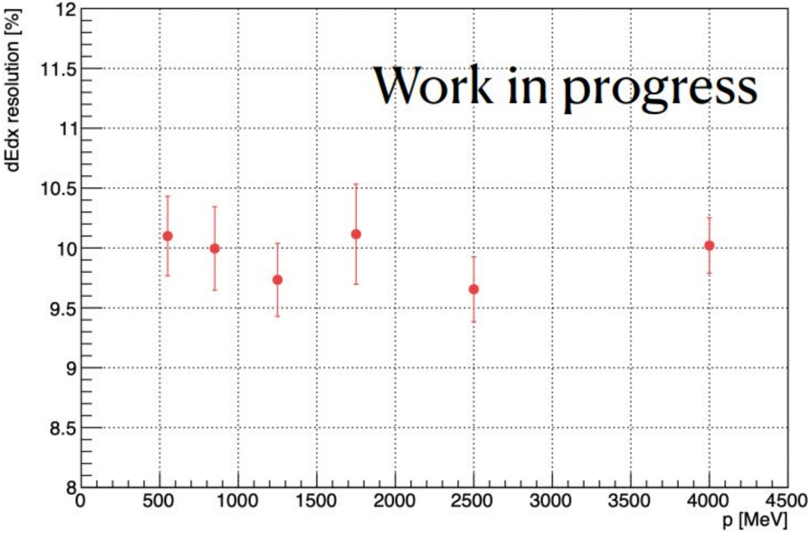




ND280 Upgrade Data

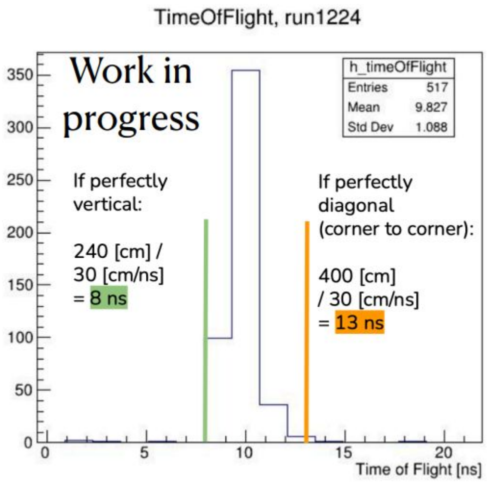
- **HA-TPC preliminary results:**
- ~ 500 μm spatial resolution (~ 10% momentum resolution)
- dE/dx on the order of 10%

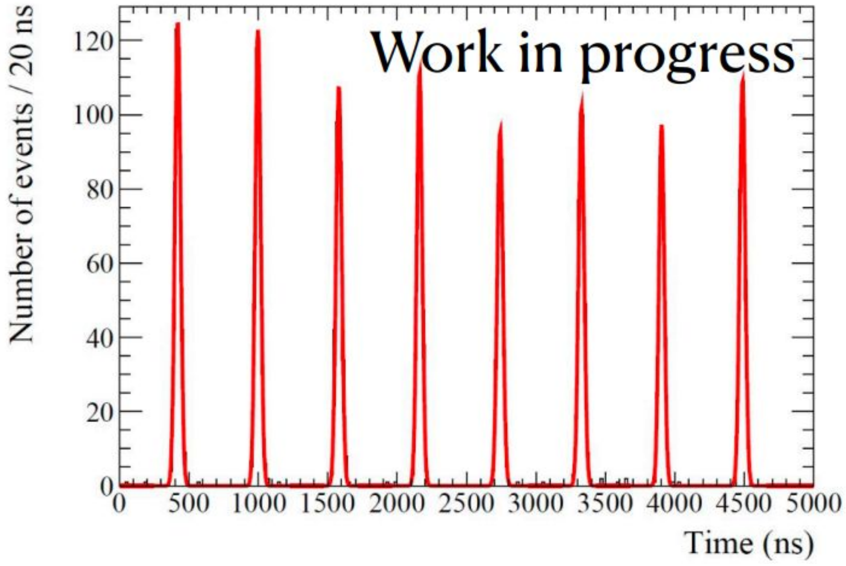




ND280 Upgrade Data

- **TOF preliminary results:**
- Provided cosmic triggers for SFGD and HA-TPC
- Clear beam bunches structure





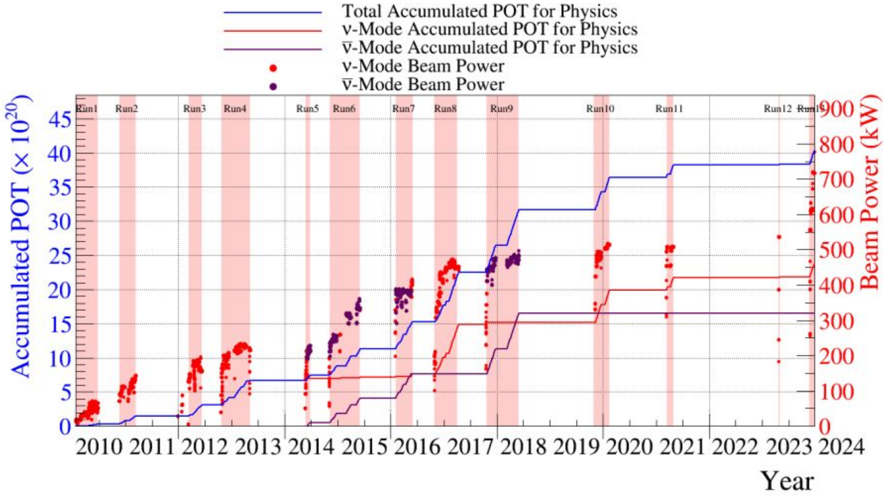
Summary and Prospects

- ND280 is in the final stages of the upgrade thanks to the hard work from many people
- 2 data taking periods with an almost complete ND280 upgrade (bottom HA-TPC, ~85% instrumented SFGD and 4/6 TOF)
- Upgrade detectors shown to be operational together with the existing ND280 sub-detectors
- Fully upgraded ND280 ready for data taking in June 2024!

Backup

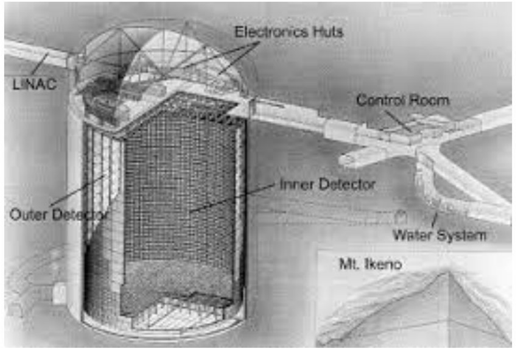
T2K Beam Upgrade

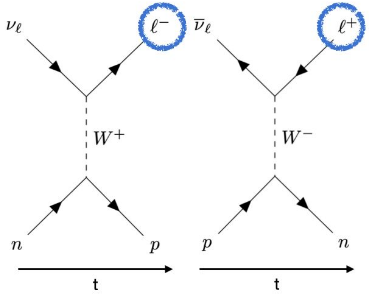
- Proton beam power increases from ~ 500 kW to 750 kW (1.3 MW expected in 2027) thanks to fast cycle from 2.48s ➜ 1.36s
- Electromagnetic horn current increased to 320 kA (10% increase in neutrino flux)
- Stable operation with 710 kW beam power and 320 kA horn current successfully achieved (continuous operation at 760 kW also demonstrated)

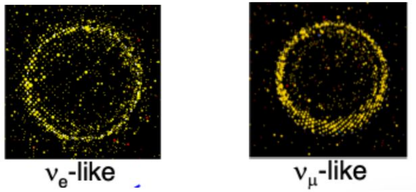


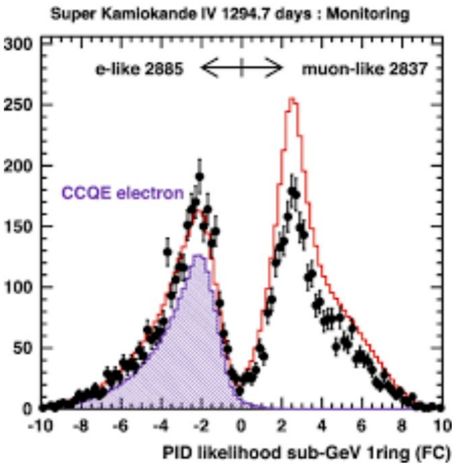
Super-Kamiokande (SK)

- ~ 40 m diameter by ~ 40 m tall cylinder
- ~ 50 ktons of ultra pure water
- > 10000 PMT for detecting Cherenkov light emitted by outgoing lepton from (anti)neutrino interaction



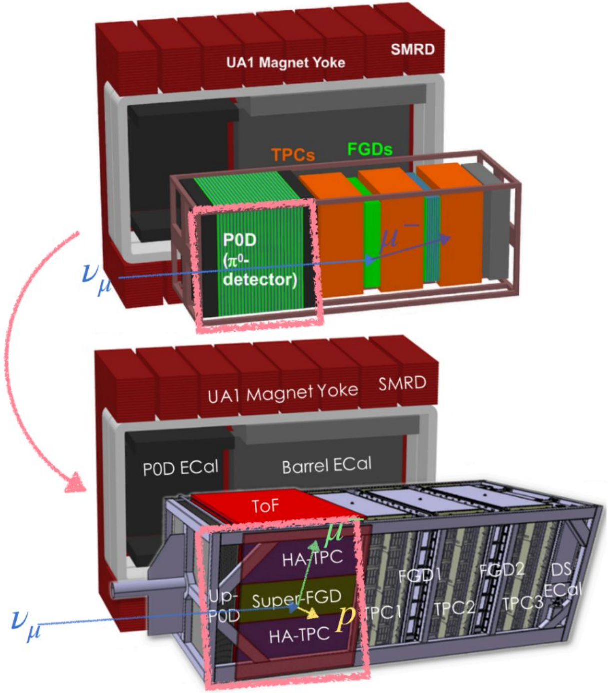






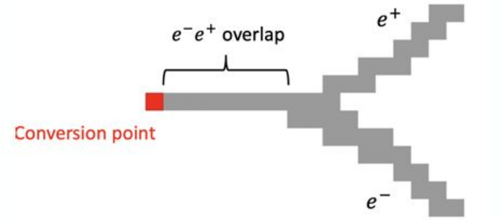
ND280 & ND280 Upgrade

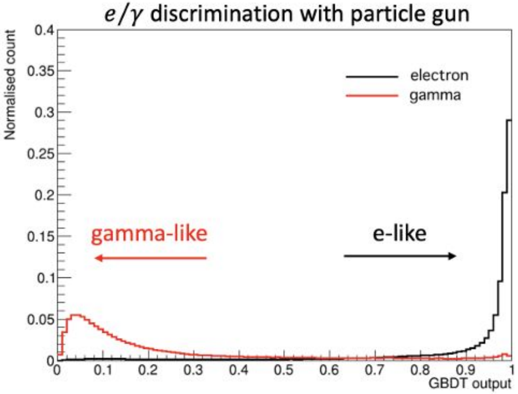
- **Magnet**: 0.2T in + x-direction
- **P0D**: 2103 mm × 2239 mm × 2400mm (~ 16.3 tons)
- **FGD**: 2300 mm × 2400 mm × 365 mm (~ 1.1 tons)
- **TPC**: 2.3 m × 2.4 m × 1.0 m
- **SFGD**: 182 cm × 192 cm × 56 cm (~ 2 tons)
- **HA-TPC**: 2.0 m × 0.8 m × 1.8 m



SFGD

- Better separation of e^{-} coming from ν_e interactions than the ones coming from $\gamma \rightarrow e^{+}e^{-}$ conversions
- Cleaner sample of low energy ν_e





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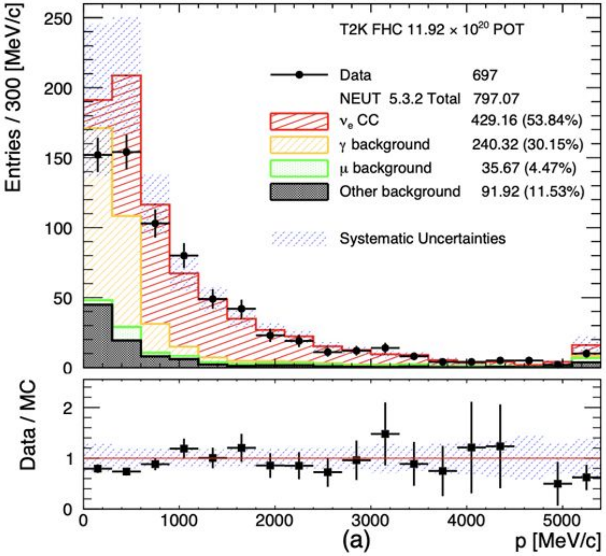
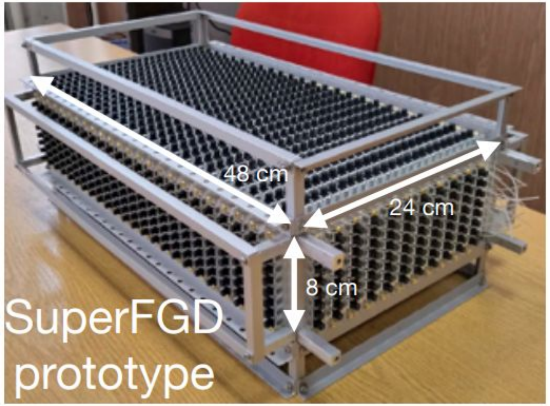
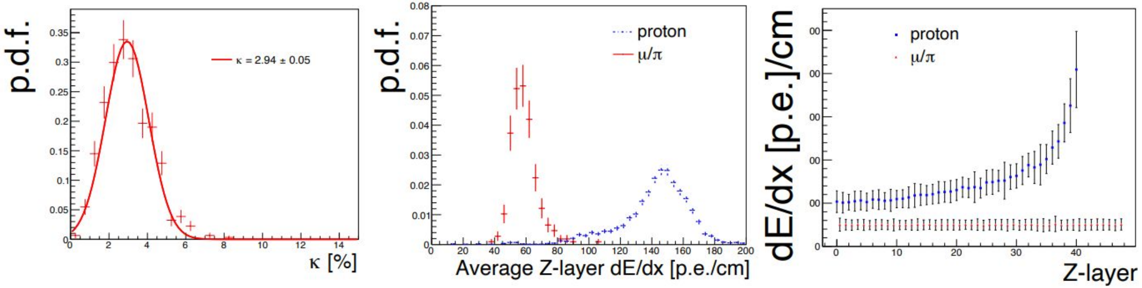


SFGD Prototype

- Prototype detector developed and exposed to charged particle beams (p and π) at CERN in 2018
- Good performances observed from beam tests:
  - Average light yield of 58 PE per MIP per cube
  - 3% cube-to-cube optical crosstalk
  - 0.97 ns single channel time resolution (see here)
  - Good particle identification





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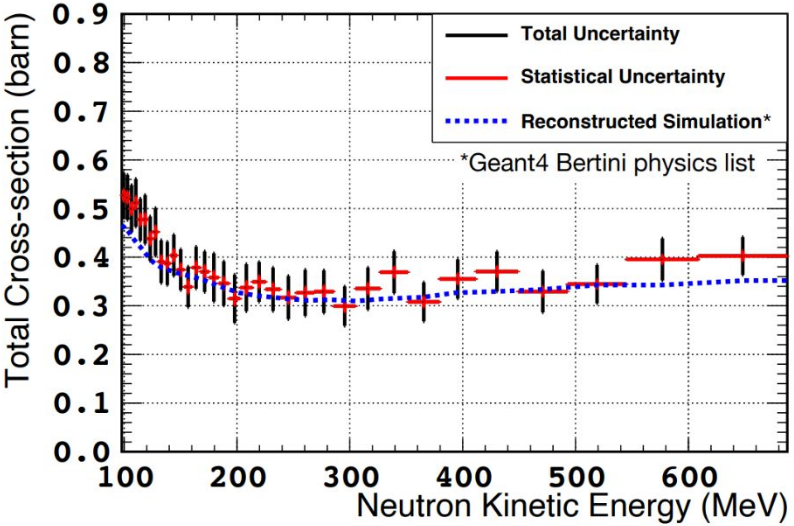
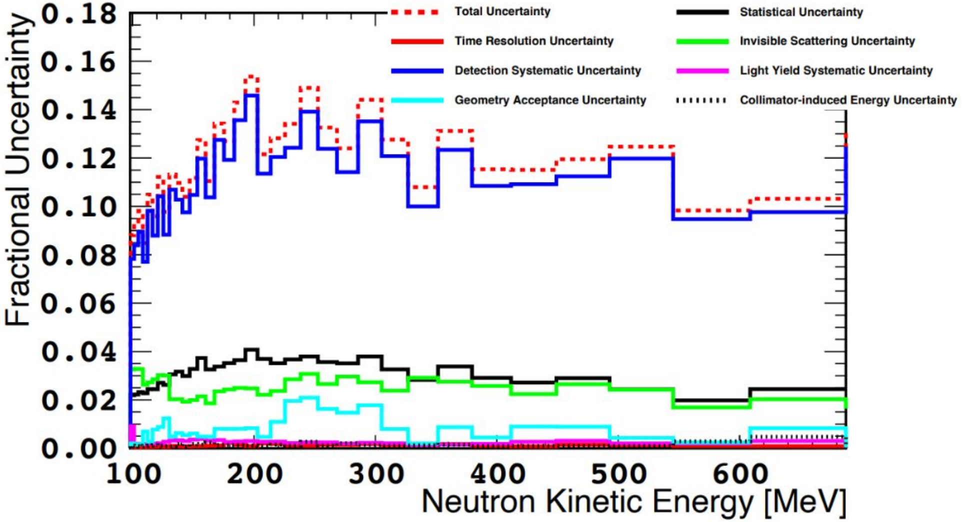
SFGD Prototype

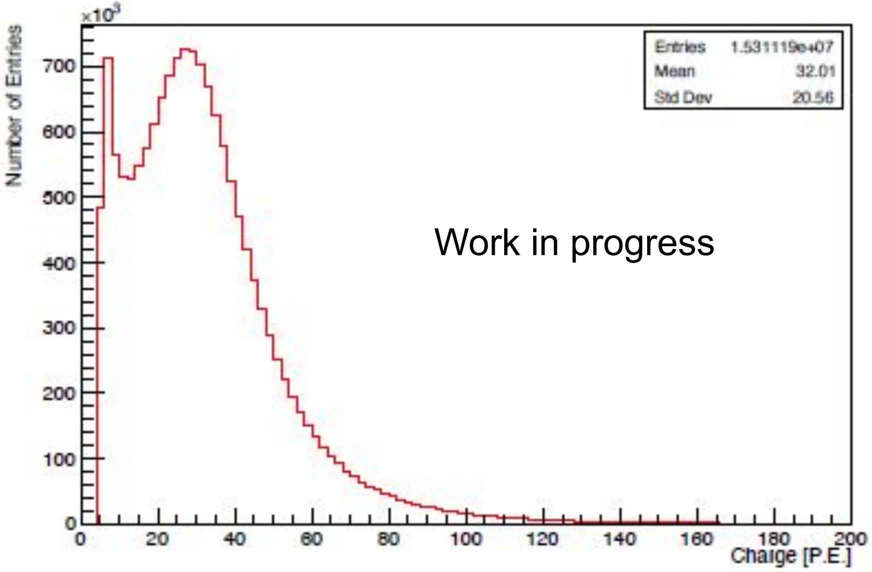
- Prototype detector deployed at LANL for neutron beam test in 2019
- Total n-CH cross section published (see here)

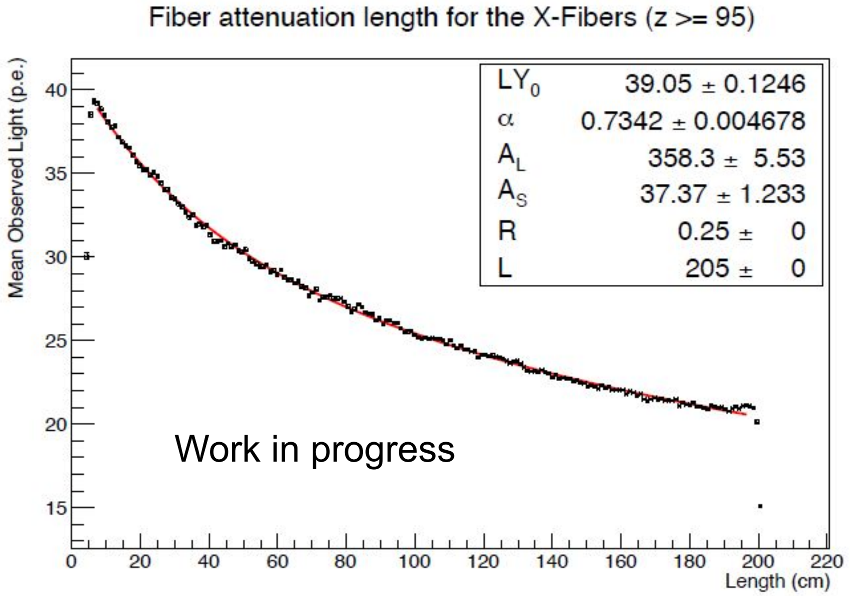




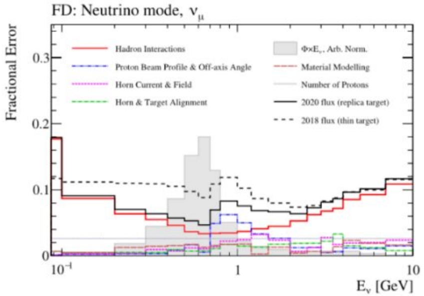
SFGD Data

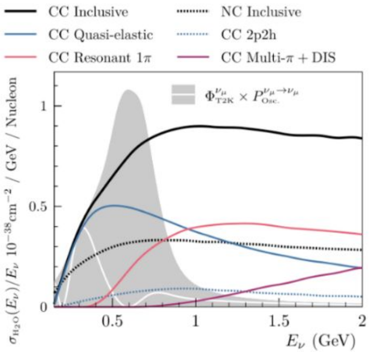
- SFGD preliminary results:





T2K Oscillation Analysis





$$R_{\nu_\ell} = \mathscr{P}_{\nu_\mu \to \nu_\ell}(E_\nu) \times \sigma(E_\nu) \times \Phi(E_\nu) \times \epsilon(E_\nu)$$

Event rate | Oscillation probability | ν x-sec | ν flux | Detector efficiency

Flux prediction:
Proton beam measurement
Hadron production (NA61 2009 replica target data)

Neutrino interactions:
Cross-section models
External data

ND280 measurements:
ν_μ and $\bar{\nu}_\mu$ selections to constrain flux and cross-sections

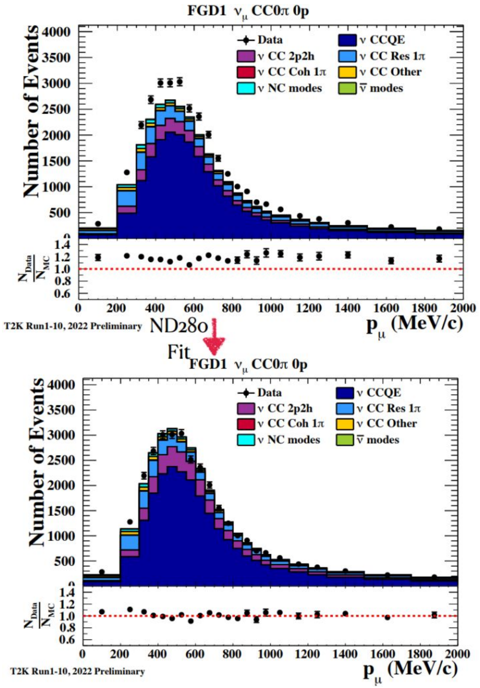
Prediction at the Far Detector:
Combine flux, cross section and ND280 to predict the expected events at SK

Extract oscillation parameters!

SK measurements:
Select CC ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ candidates after the oscillations

T2K Oscillation Analysis

- Fit unoscillated $\nu_\mu(\bar{\nu}_\mu)$ spectrum



- Reduction of flux and cross section systematic uncertainties