# The SuperFGD for the T2K experiment

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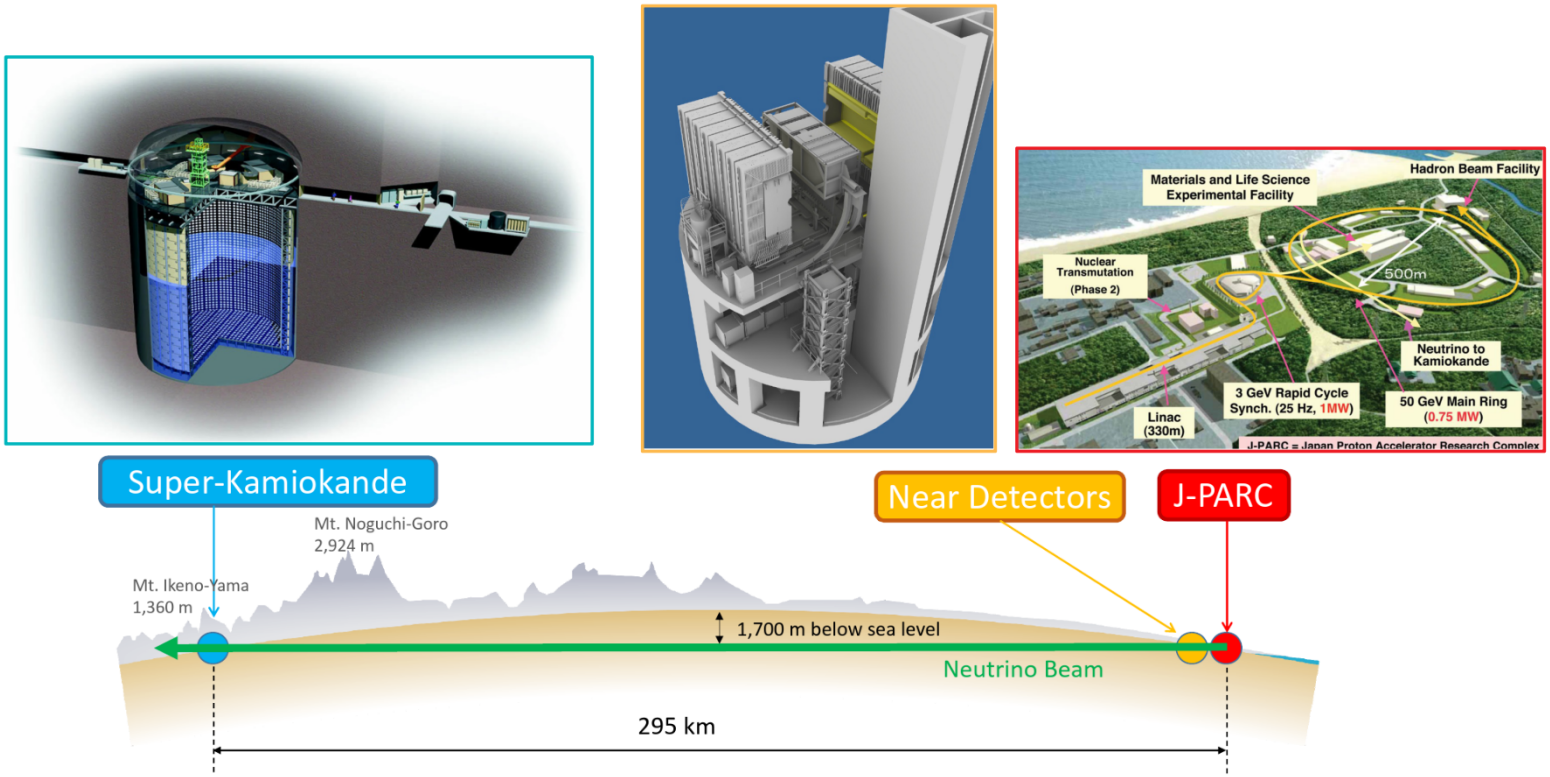
on behalf of the SuperFGD group

NuFACT 2024

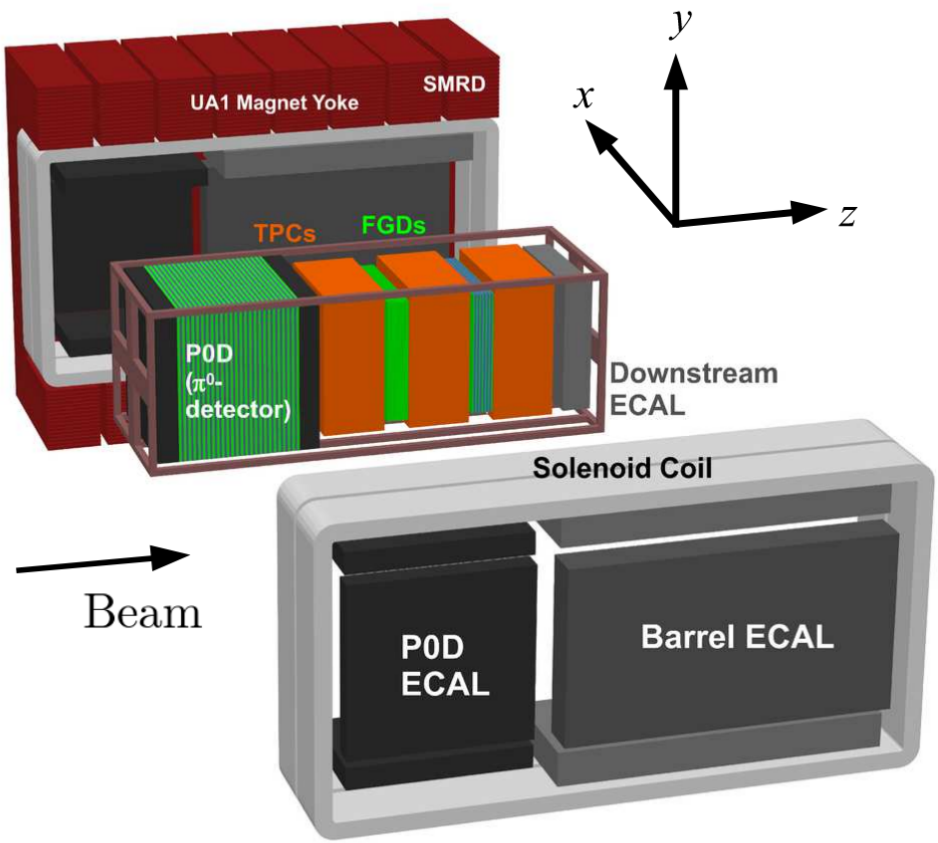
Thursday 19th September 2024

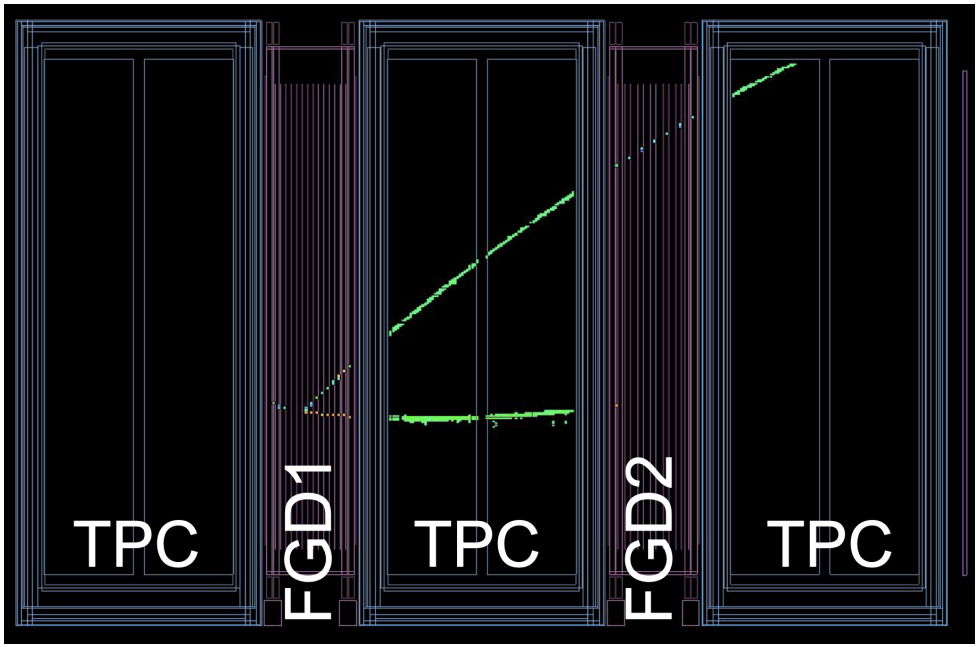
# The T2K Experiment



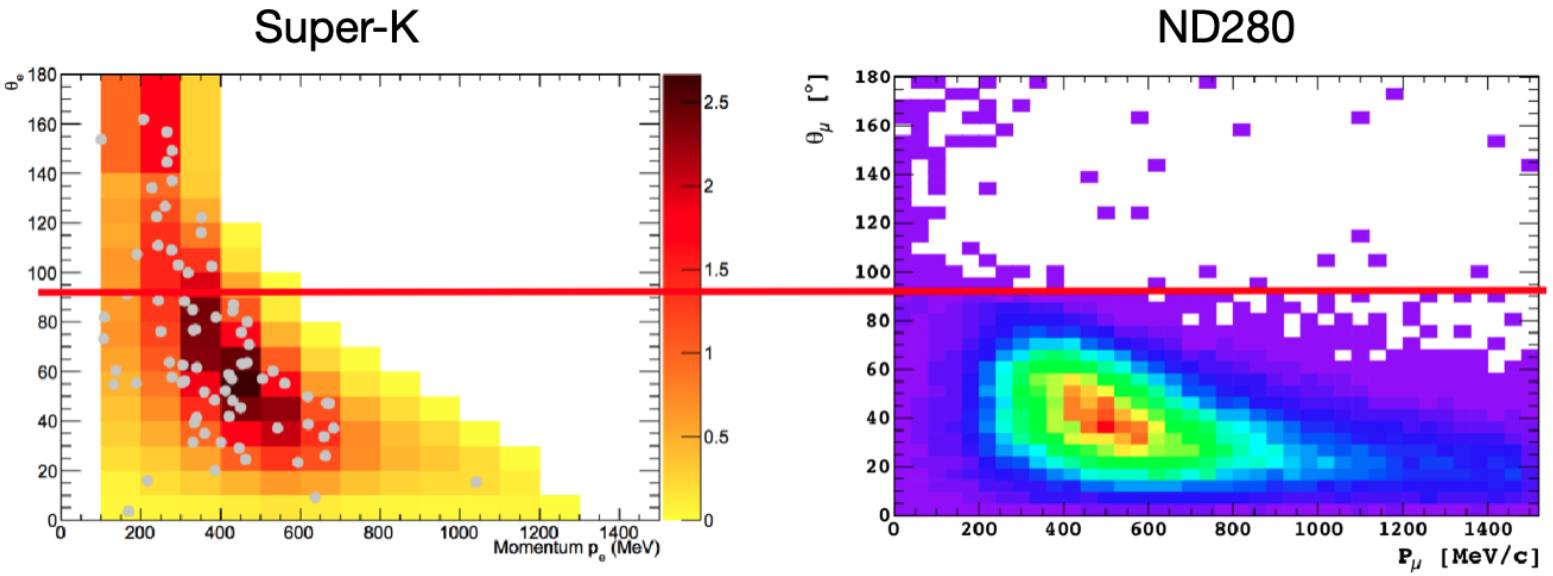

- Neutrino oscillation measurements
  - → See talks by Ed Atkin and myself
- Neutrino cross-section measurements
  - → See talk by Laura Munteanu

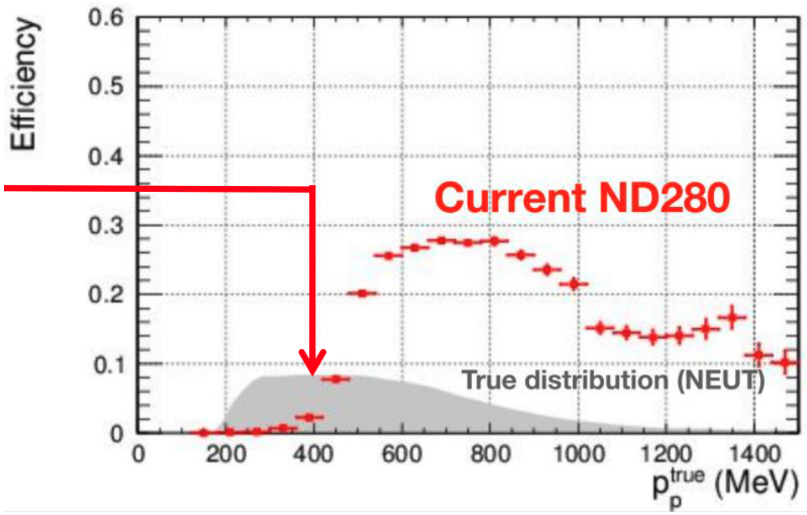
# Original Off-Axis Near Detector: ND280



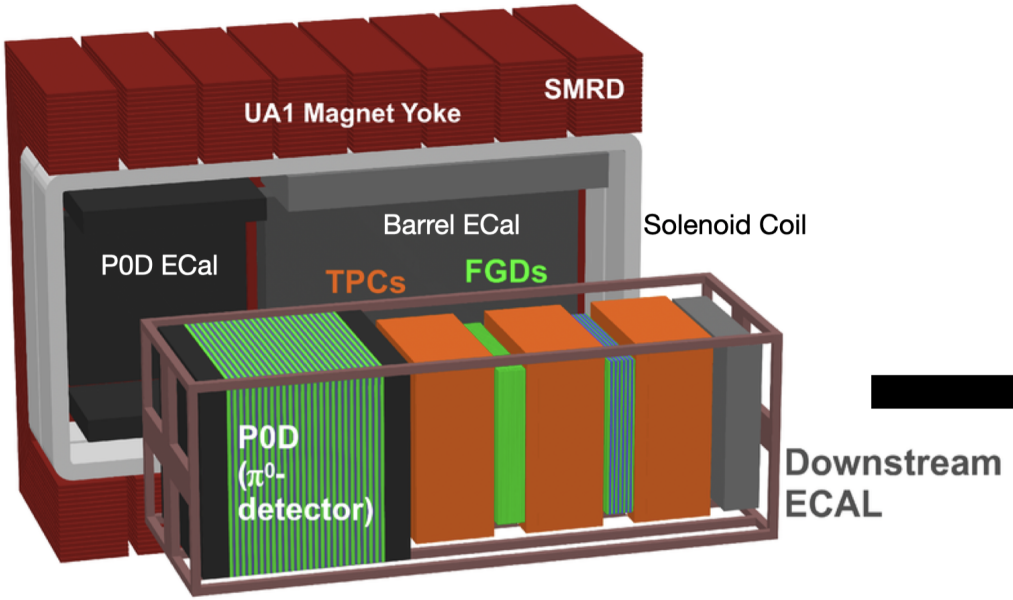
# ND280 Limitations

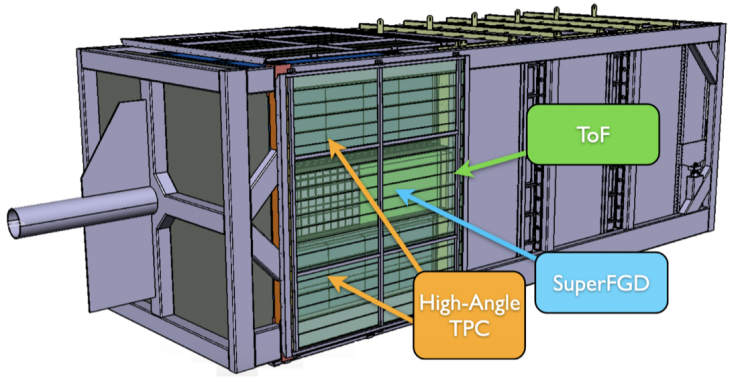



- Limited angular acceptance
- High proton reconstruction threshold

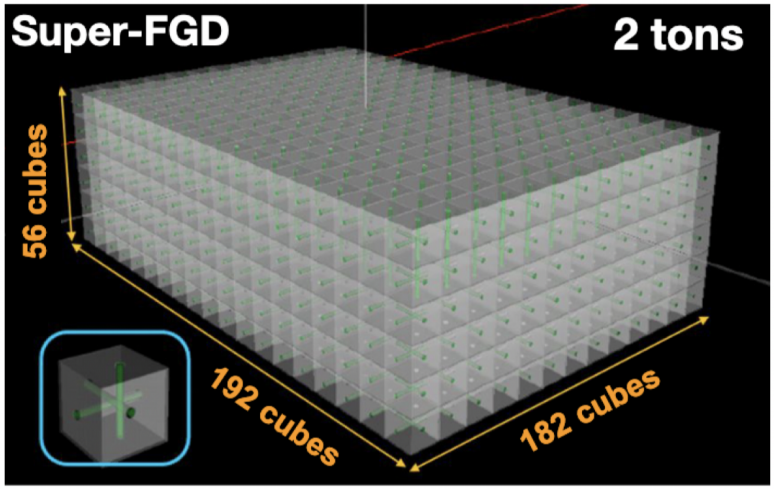
# ND280 Upgrade

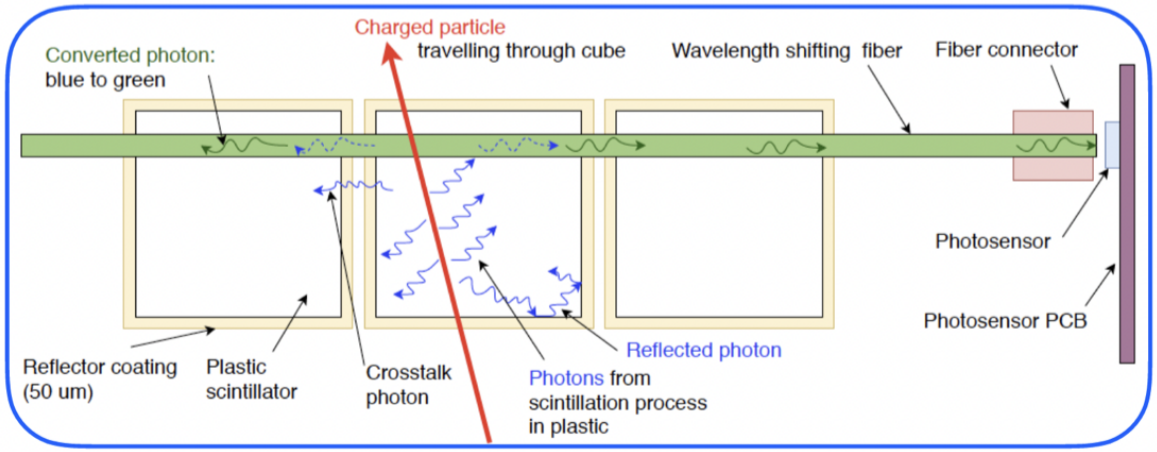


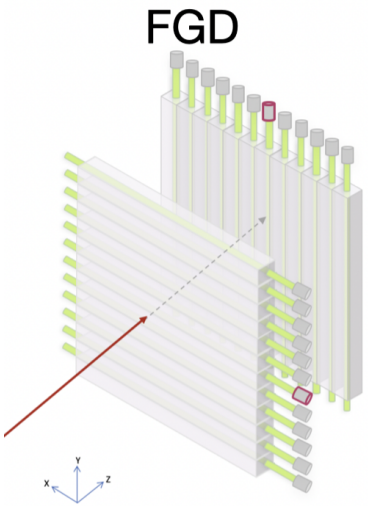



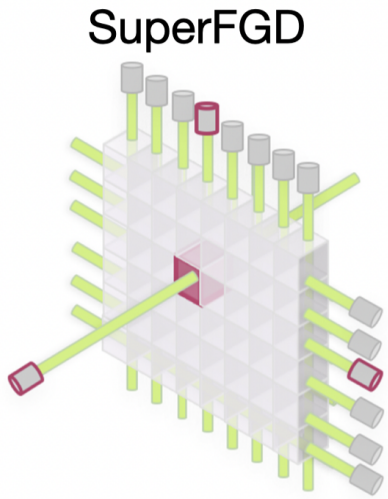

- To address limitations of ND280, replace PØD with three new subdetectors:
  - → SuperFGD: highly segmented target material with excellent tracking capability → this talk
  - → High Angle TPCs: measure momentum, charge and particle ID with better angular acceptance → see talk by Samira Hassani
  - → Time-of-Flight: precise timing information to reject backgrounds and improve reconstruction

# SuperFGD



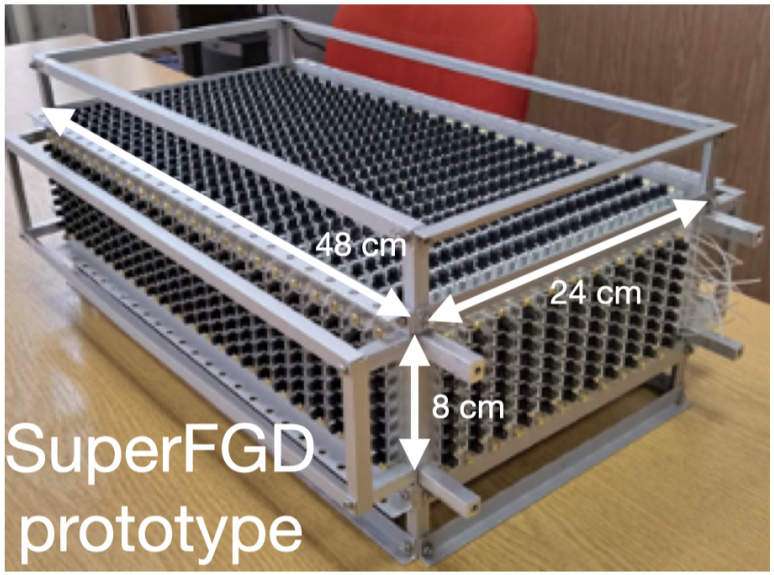



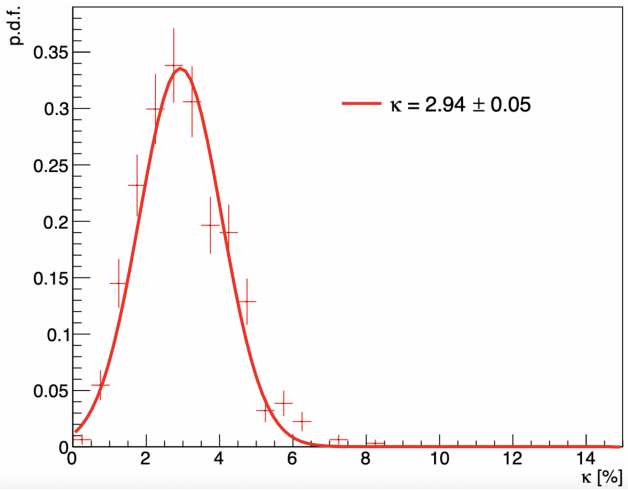



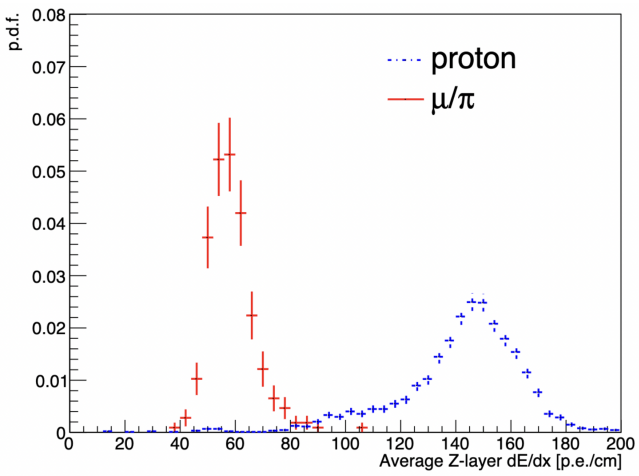

- 2 million optically isolated 1 $cm^3$ plastic scintillator cubes
- 56,000 wavelength shifting fibers
  - → Three orthogonal fibers per cube
  - → Each coupled to an MPPC

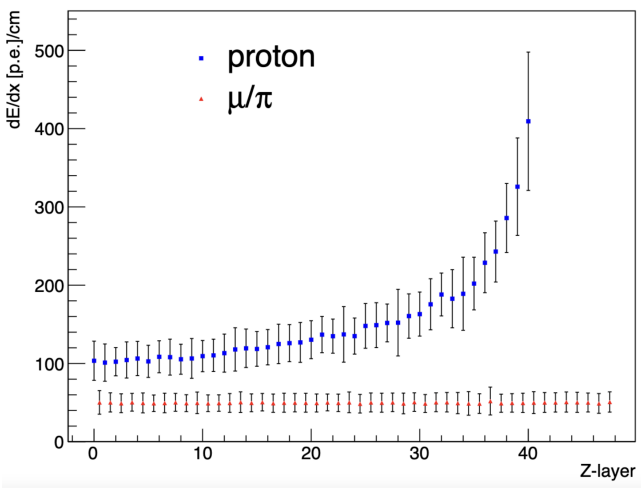
# SuperFGD Prototype and CERN Beam Test

- Technology demonstrated using small-scale prototypes
- $48 \times 24 \times 8$ cm$^3$ prototype exposed to charged particle beams at CERN
  - → 2020 JINST 15 P12003
  - → Average light yield = 58 PE per MIP
  - → 3% cross-talk
  - → 1.1 ns time resolution per channel
  - → Very good particle ID



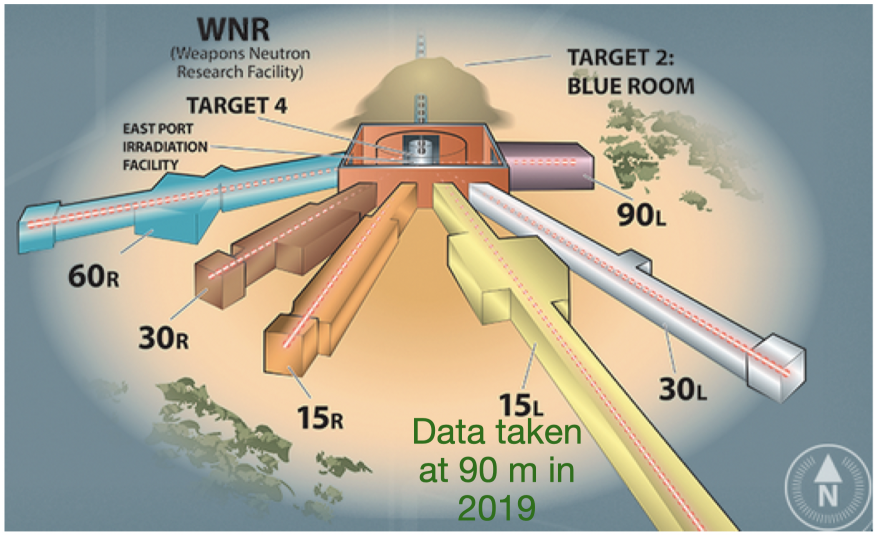



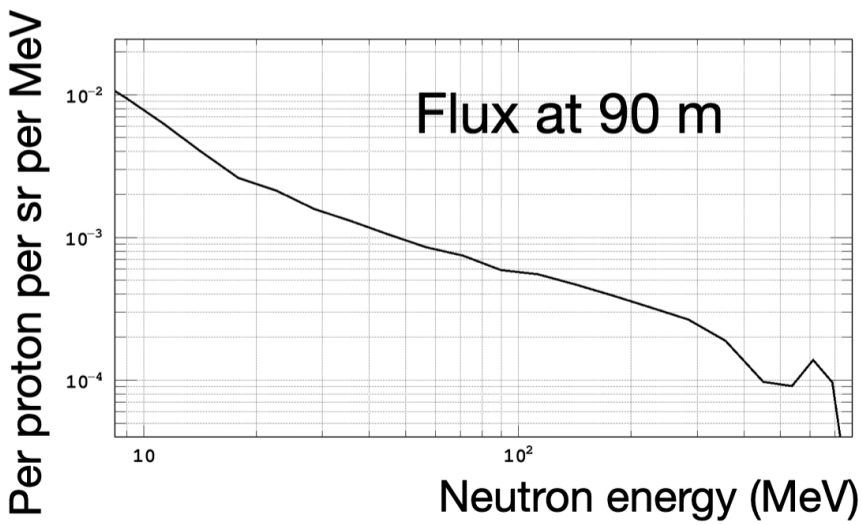



# Neutron Beam Test at LANL

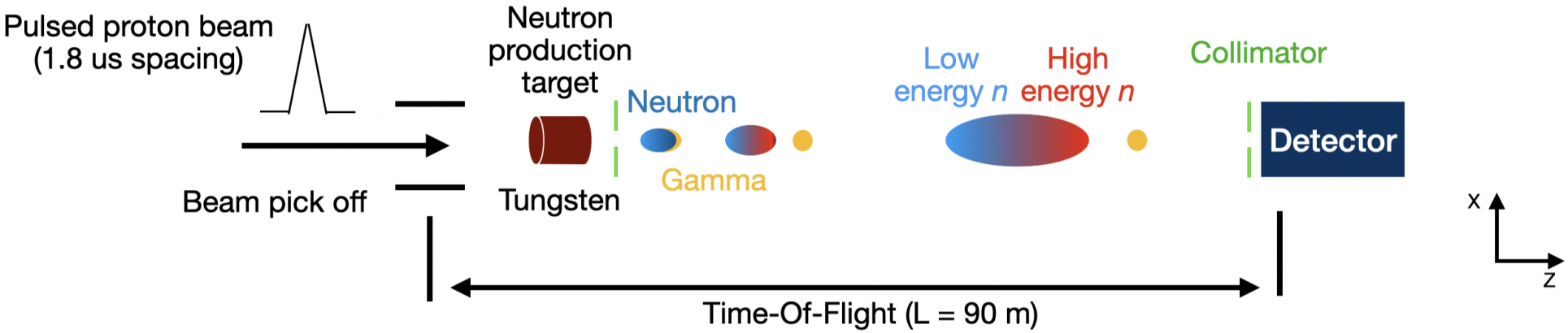
- Ability to measure neutron kinematics demonstrated by exposing same prototype to LANL neutron beam
- Also exposed a second prototype (US-Japan prototype) to the beam
- Data taken in 2019 and 2020

US-Japan prototype:

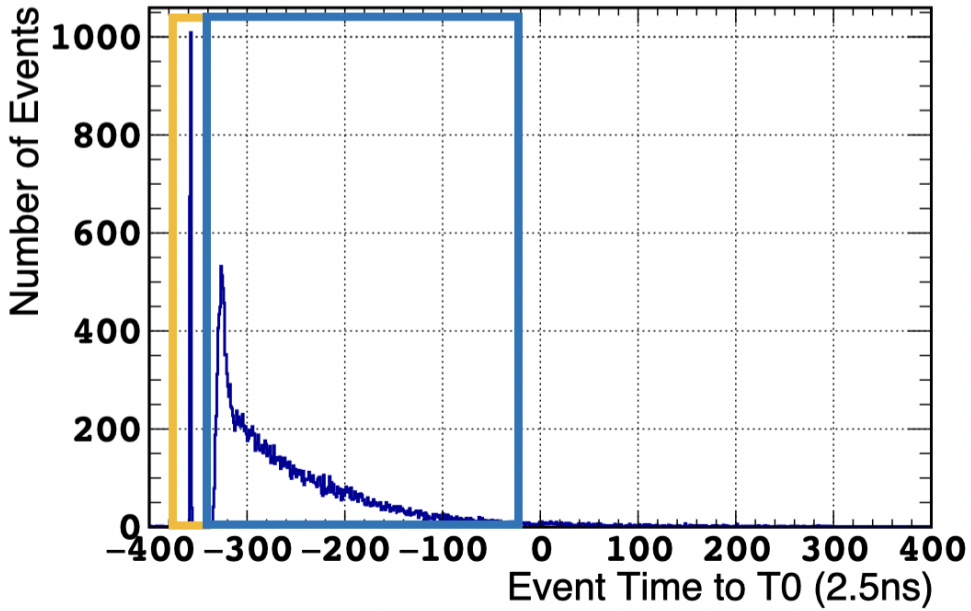


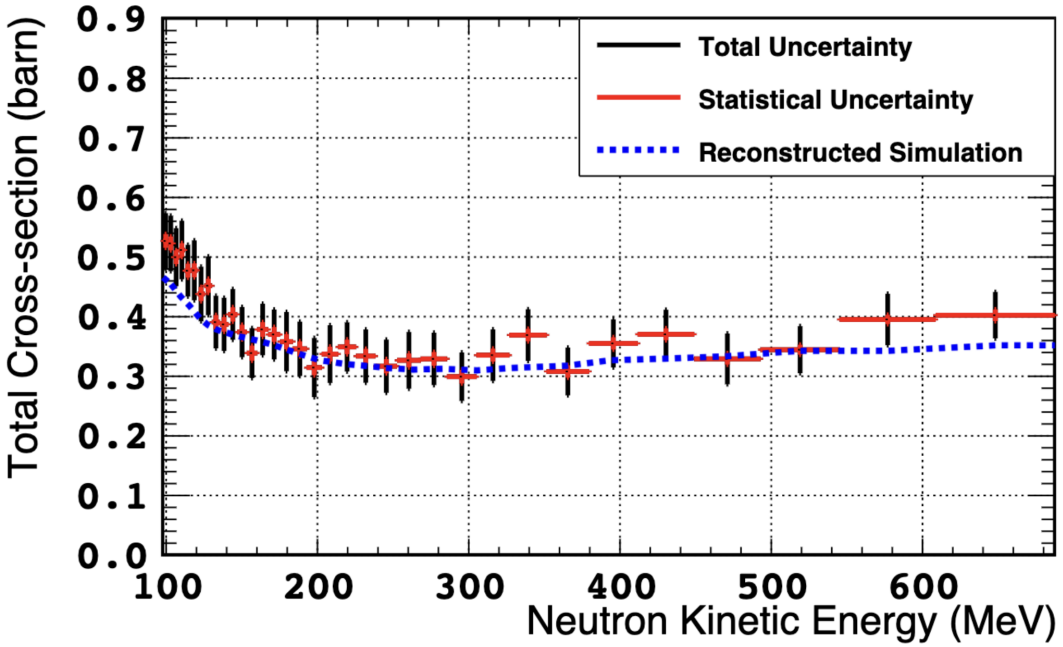
# Measuring Neutron Energy with SuperFGD Prototype

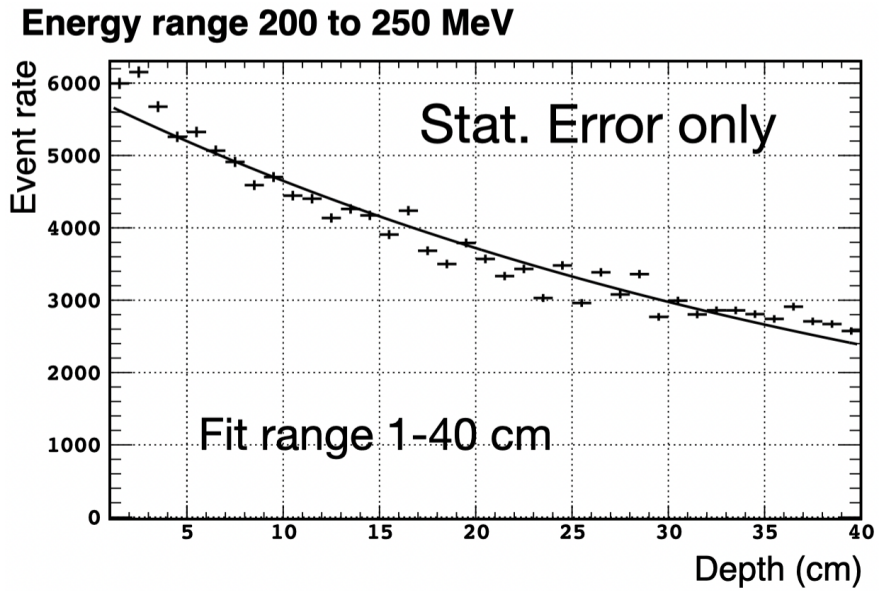



- A gamma flash arrives before the neutron
  - → Can be used as a trigger
- Measure neutron energy event-by-event using time-of-flight



# Neutron Cross-Section Measurement with SFGD Prototype

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- Measure cross section in each energy bin using attenuation of the neutron beam
  - → Select simple topology: single track
  - → Extract total cross section using extinction method $N_0 e^{-T\sigma z}$
- Data above prediction from Geant4 Bertini model below 200 MeV
- Measurement made with 2019 data, investigation of 2020 data ongoing

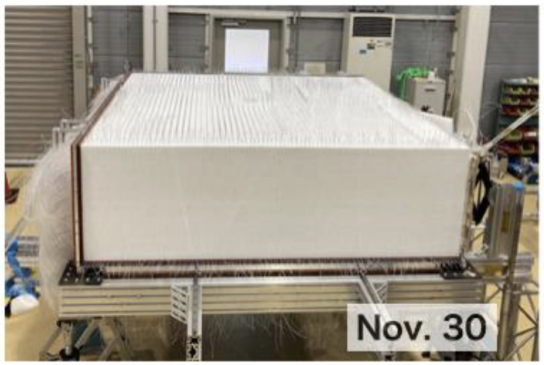
# SuperFGD Assembly

(i) Support system assembly


(ii) First cube layer assembly


(iii) All 56 layers assembled


(iv) Stop panels removed




(v) Box closure


(vi) Transfer to new support


- Cubes first assembled in 56 layers using fishing lines
  - → Very labour intensive, took ∼20 months!
- Layers then assembled in mechanical box at J-PARC

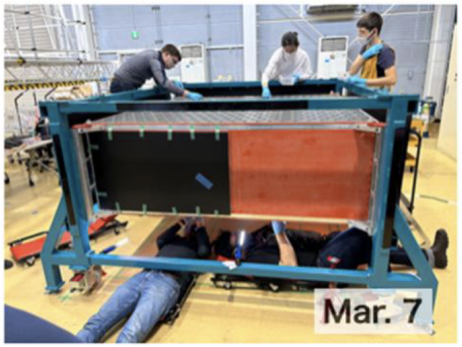
# SuperFGD Assembly

(vii) Horizontal fibers assembly


(viii) Wall MPPCs assembly

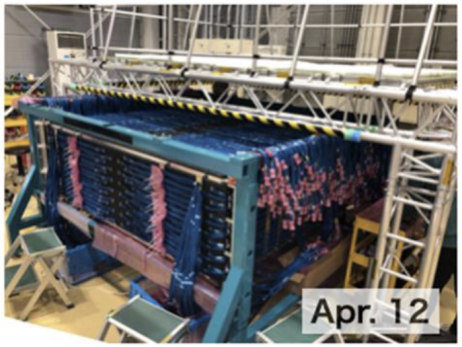

(ix) Vertical fibers assembly


(x) Top MPPCs assembly



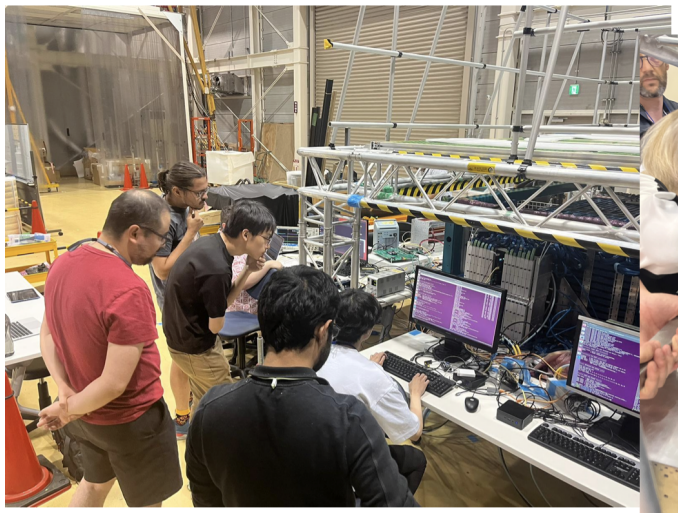

(xi) LED calib. modules assembly

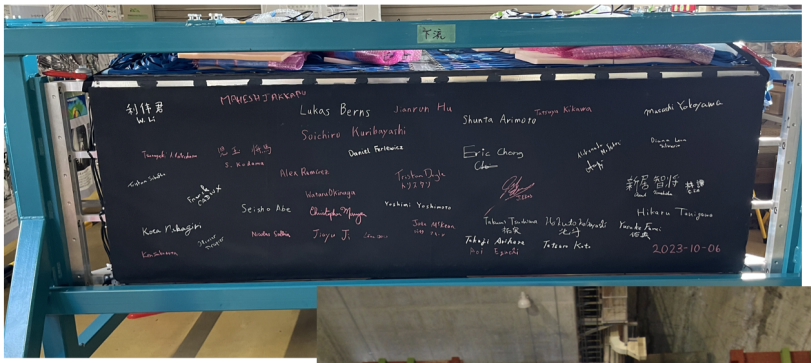

(xii) Light barrier/cables assembly

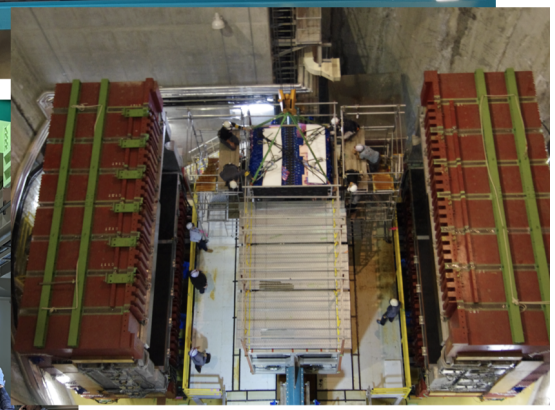


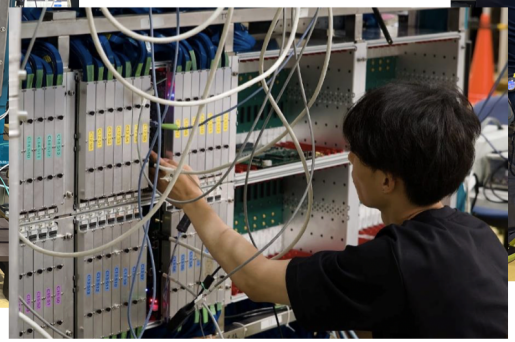

- After cube installation: inserted fibers and installed MPPCs, LED calibration system, light barrier, and cables
  - $\rightarrow$ Total time for this + layer installation = $\sim$6 months

# Commissioning and Installation

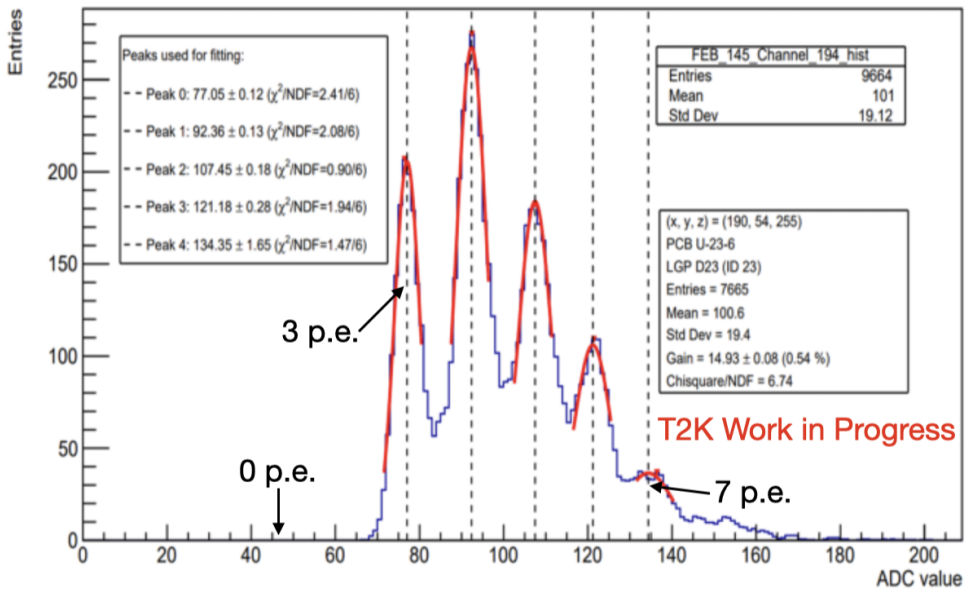


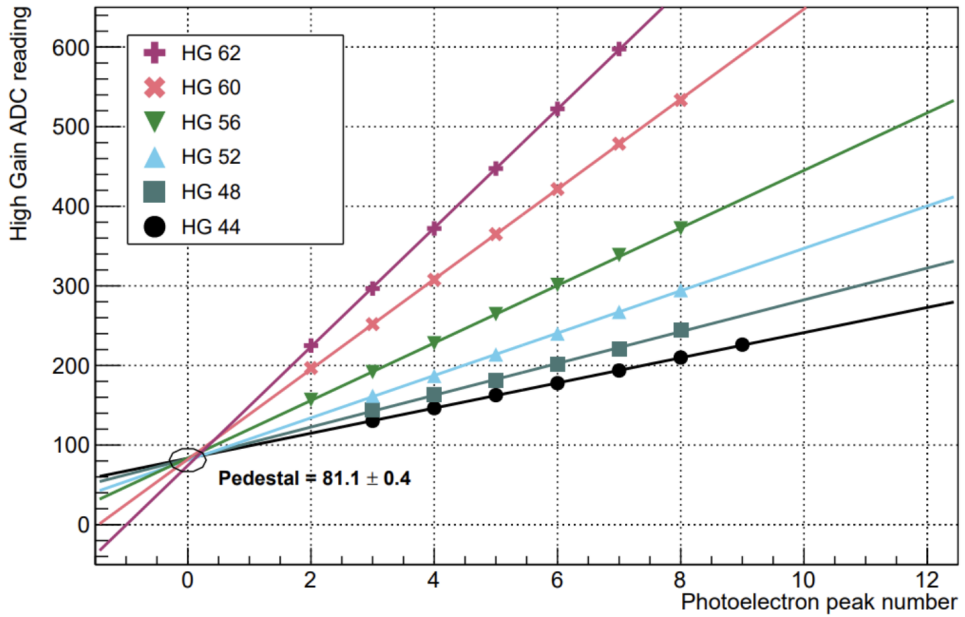




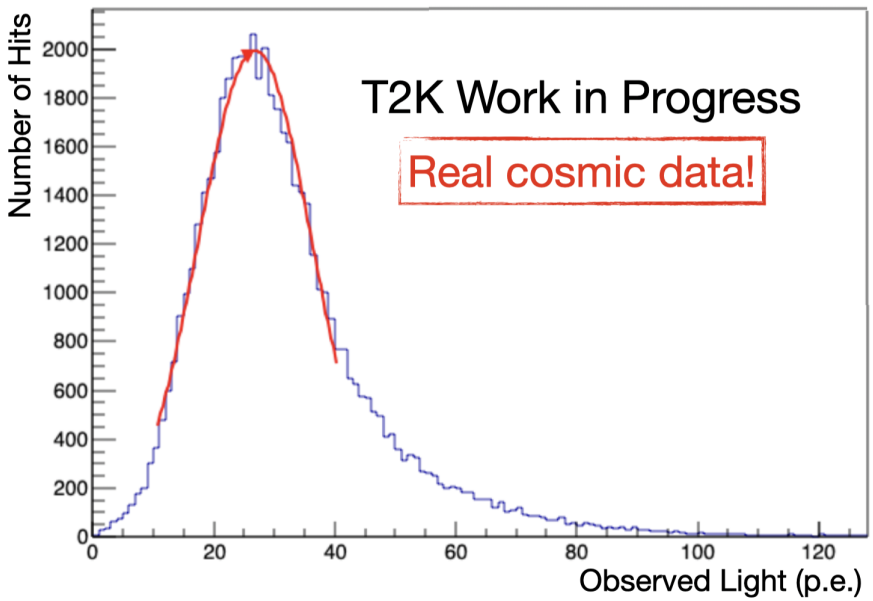
# High Gain and Pedestal Calibration

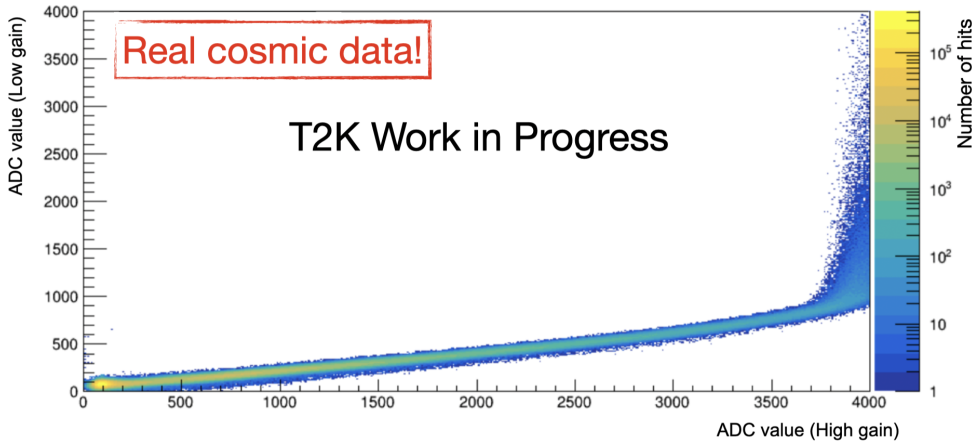



- LED panels at one end of WLS fibers used for calibration
- Peaks in "finger plot" correspond to p.e. values
- Fit Gaussian to each peak and calculate gain as distance between peaks
- 0 p.e. point (pedestal) comes from extrapolation of peak positions found with different gain voltage settings

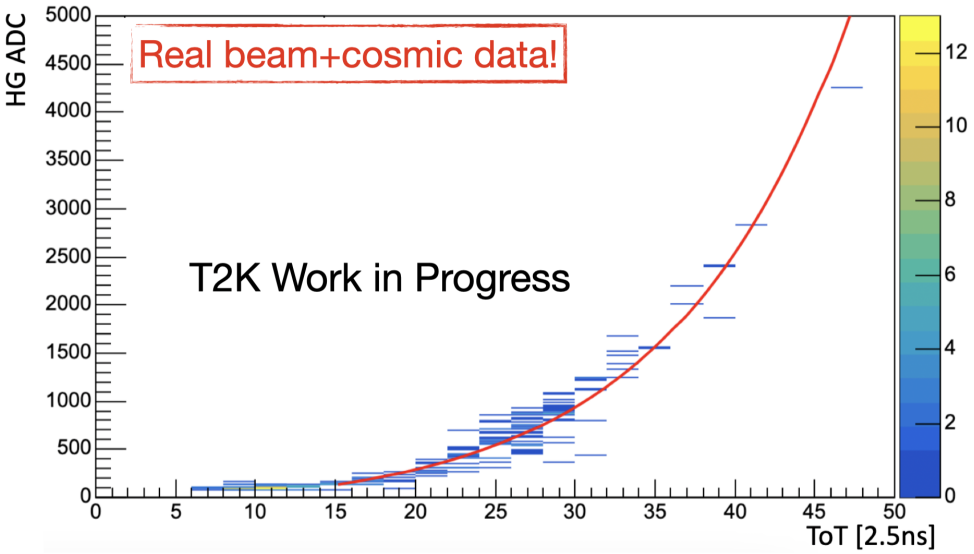
# Detector Performance - Light Yield

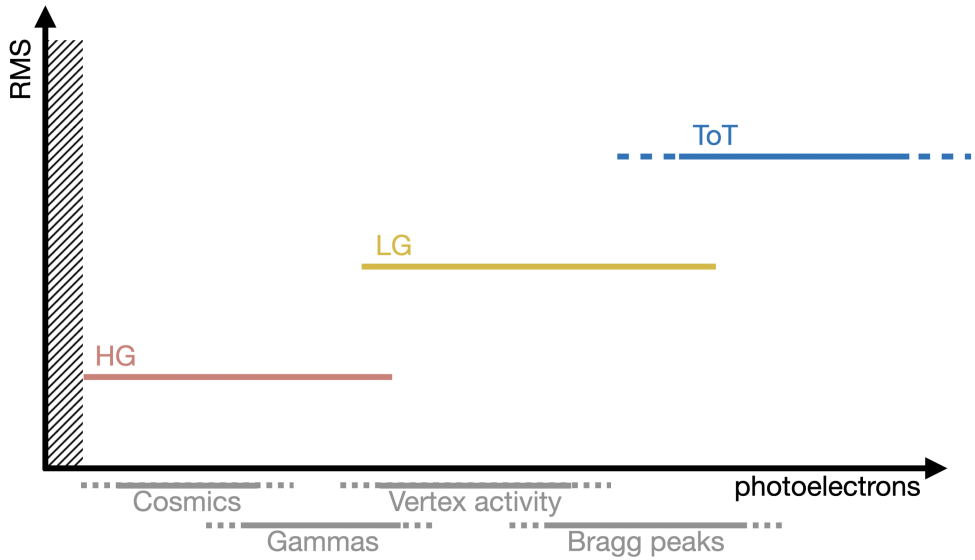



- For each hit there is a high gain (HG) ADC and a low gain (LG) ADC
  - → LG calibrated using cosmic data
- Linear relationship between HG and LG provides larger dynamic range

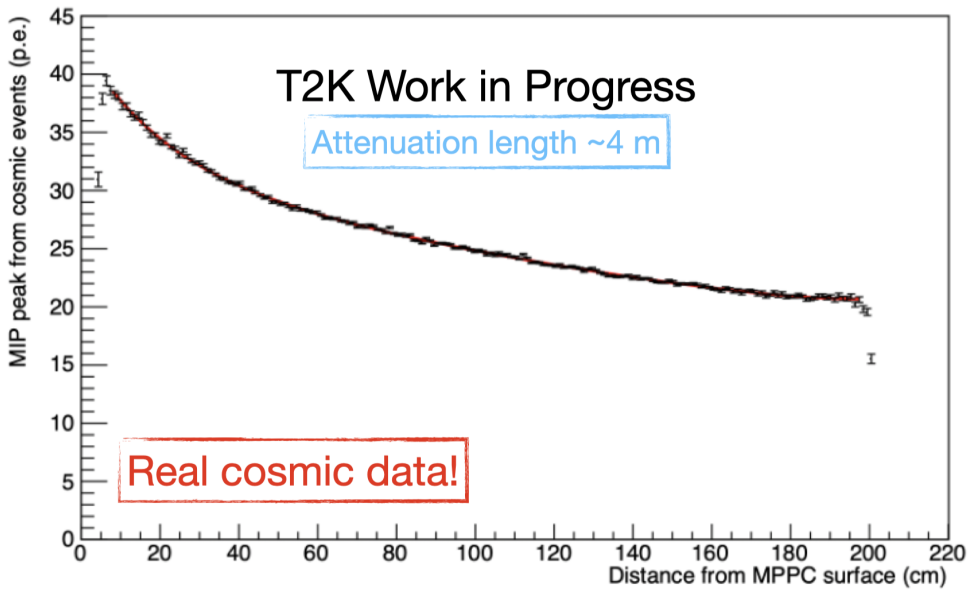
# Detector Performance - Light Yield



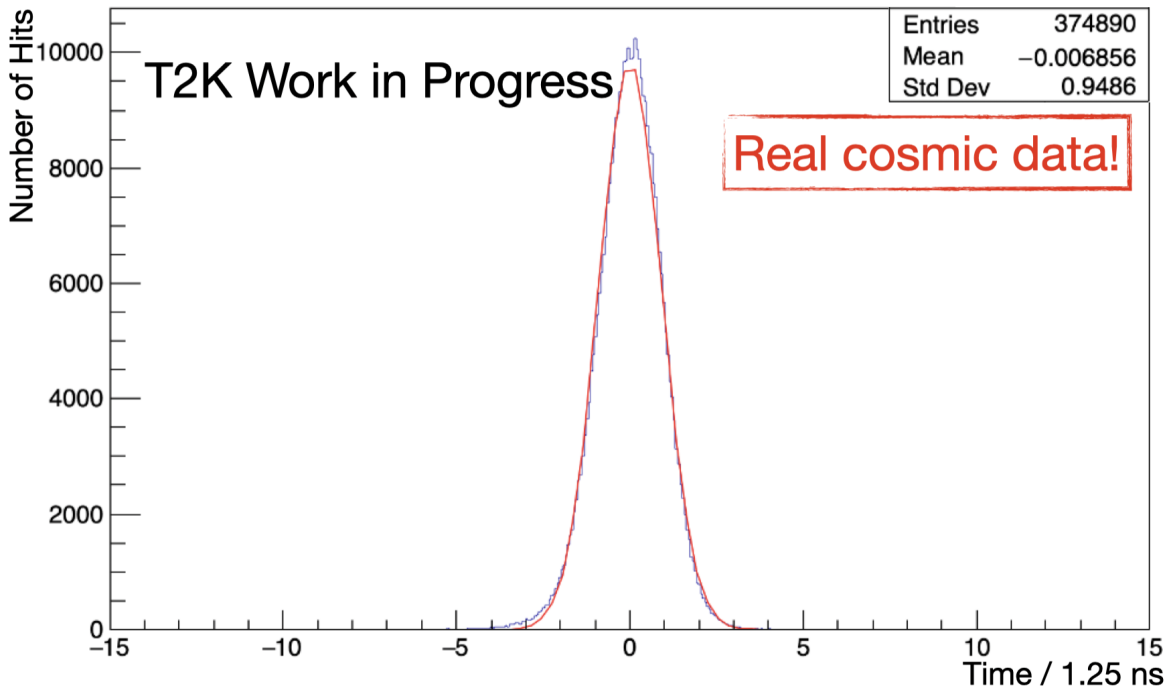

- Also measure time over threshold (ToT) for each hit
- Can convert ToT to HG using exponential relationship
- Provides even larger dynamic range than LG
  - → Together HG, LG and ToT provide coverage over many signals

# Detector Performance - Attenuation Length



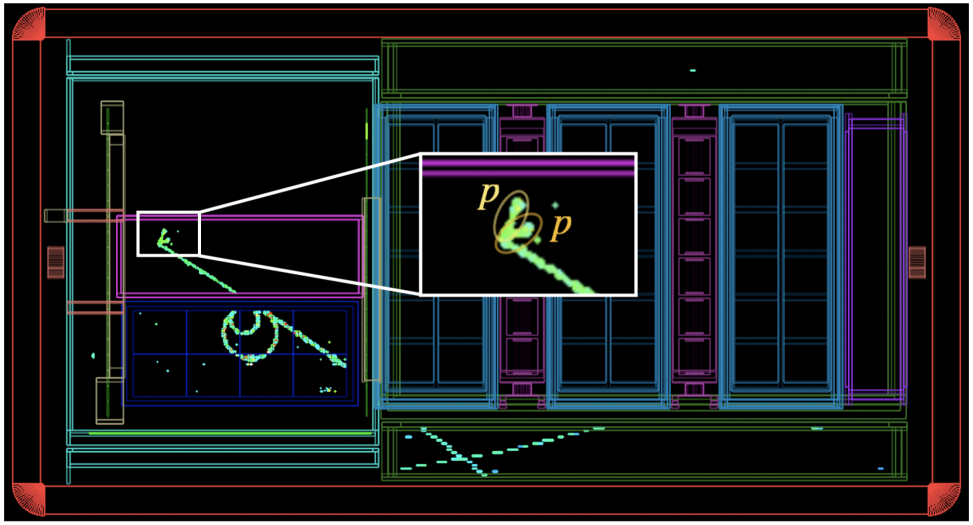

- Three fibers per cube allows construction of attenuation length plot
  - → More reliable characterisation of response and calibration
- For a given distance from the MPPCs, plot observed light from hits in cosmic events
- Fit distribution as a function of distance with an exponential function to extract attenuation length
  - → Measured attenuation length consistent with specification of WLS fibers

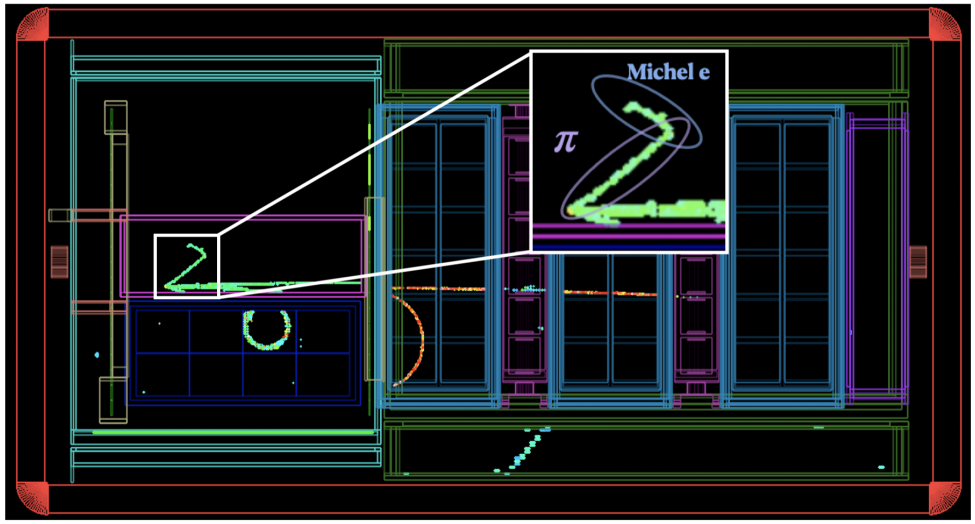
# Detector Performance - Timing Resolution




- Select hits $>$ 40 p.e. matched in all three dimensions
- Compare mean time of hit to mean time for event
- Gives $\sim$1.2 ns time resolution per channel
  - $\rightarrow$ Can be improved by electronics firmware update!

# First Neutrino Interactions in the SuperFGD

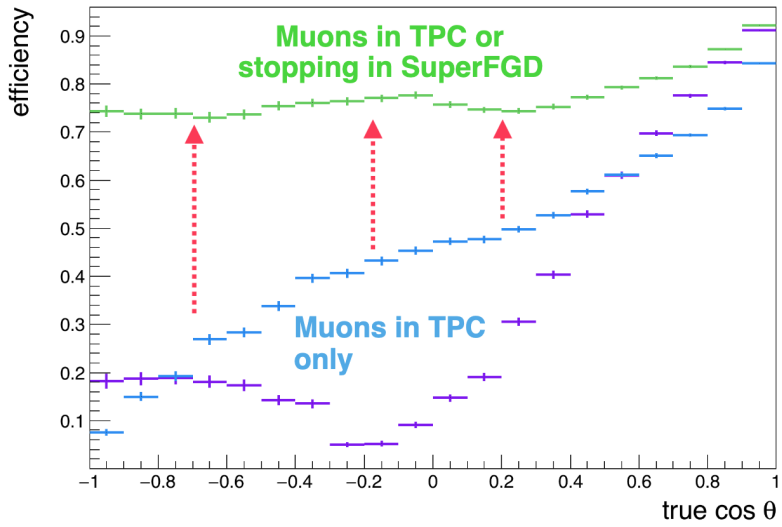


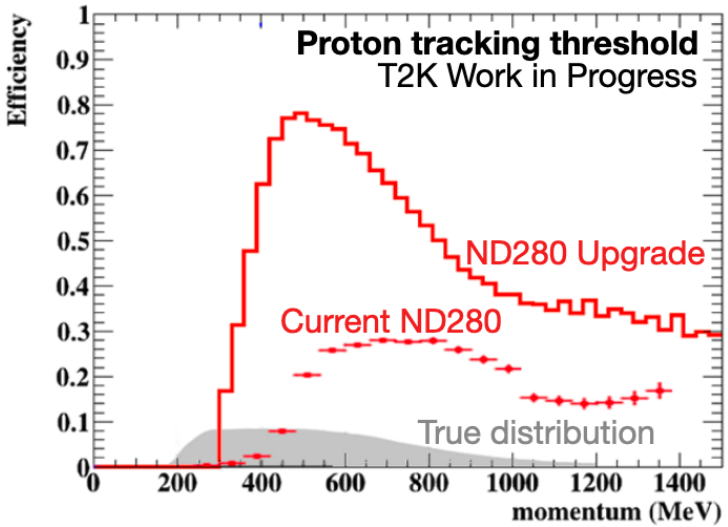



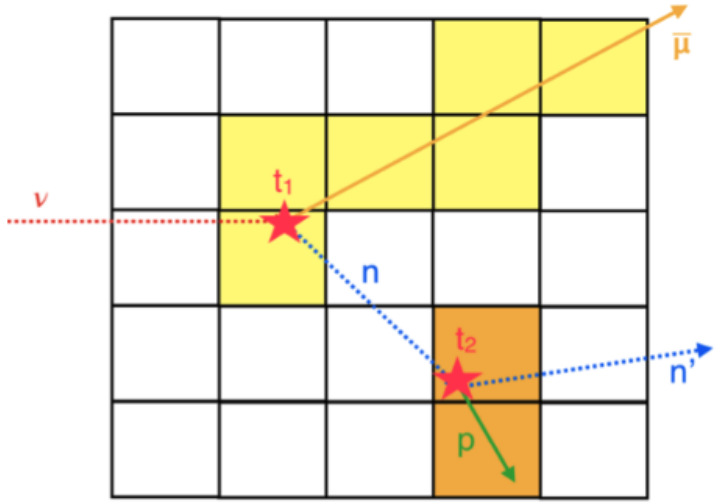

- First beam data taken in November/December 2023 and February 2024 with SFGD, bottom HAT and four TOF panels

# Physics Benefits

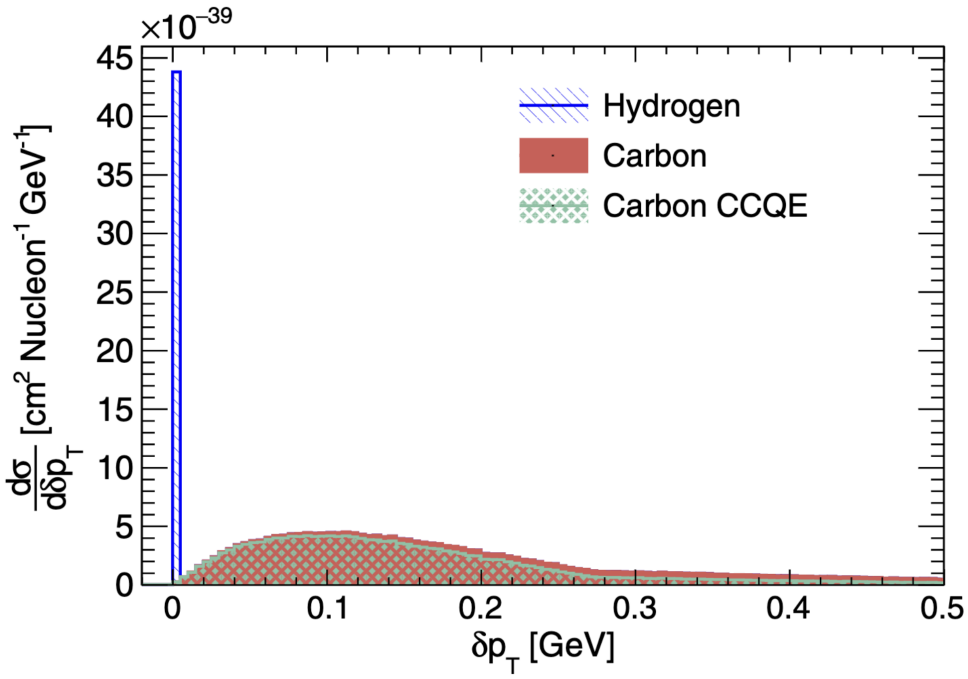
- Higher efficiency for backwards and high-angle muons
- Lower proton reconstruction threshold
- Reconstruct neutron kinematics event by event for the first time

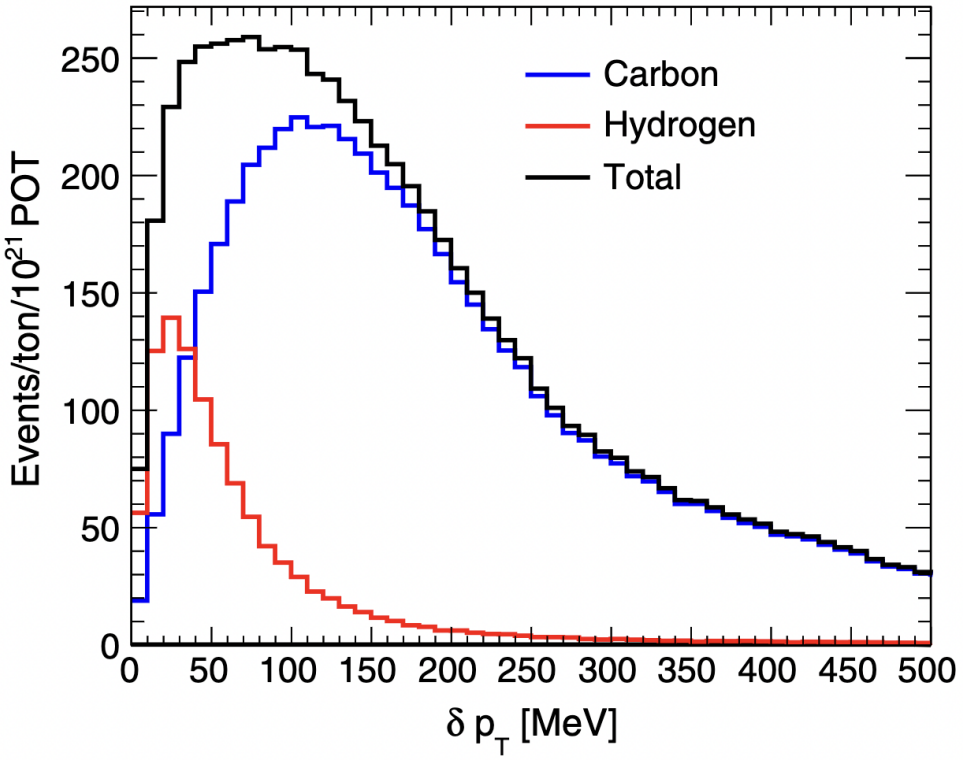


# New Analyses are Possible




PhysRevD.101.092003 (2020)

- Interactions on hydrogen with measured neutron kinetic energy
  - → A sample free of nuclear effects!

# Summary

- The SuperFGD has been assembled, commissioned and installed as part of the T2K near detector upgrade
- It provides a highly segmented target material with excellent tracking capability
  - → Demonstrated with prototypes before full scale production
- Studies of the detector response are advancing well, with general agreement with test beam results
- The detector is now taking neutrino data!
  - → Lots of exciting physics to come!

# BACKUP