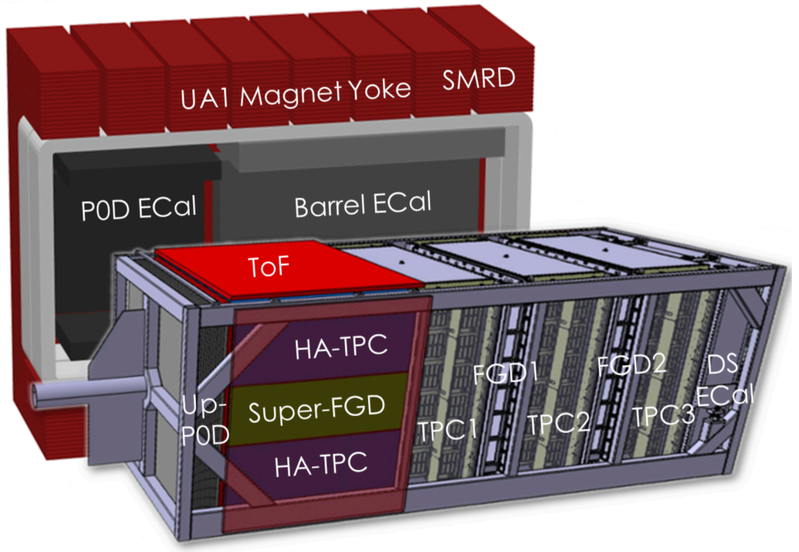
São Paulo, Brasil



T2K Near Detector Upgrade

NuInt 2024

14th Workshop on Neutrino-Nucleus Interactions

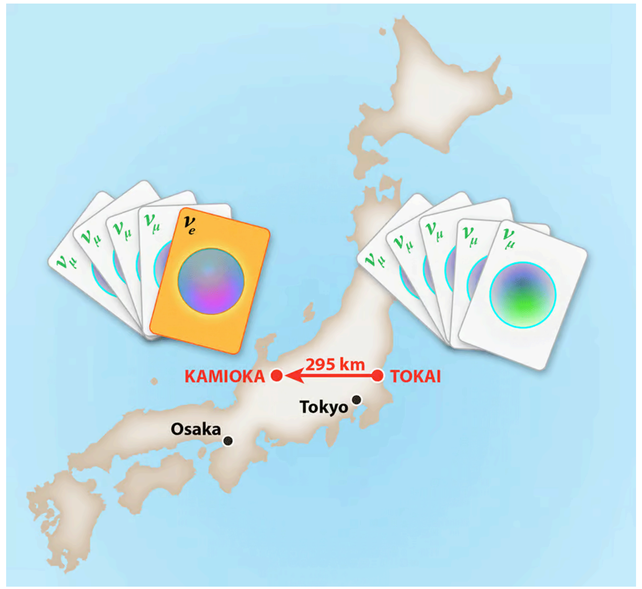
Uncertainties and Prospects for Future Improvements

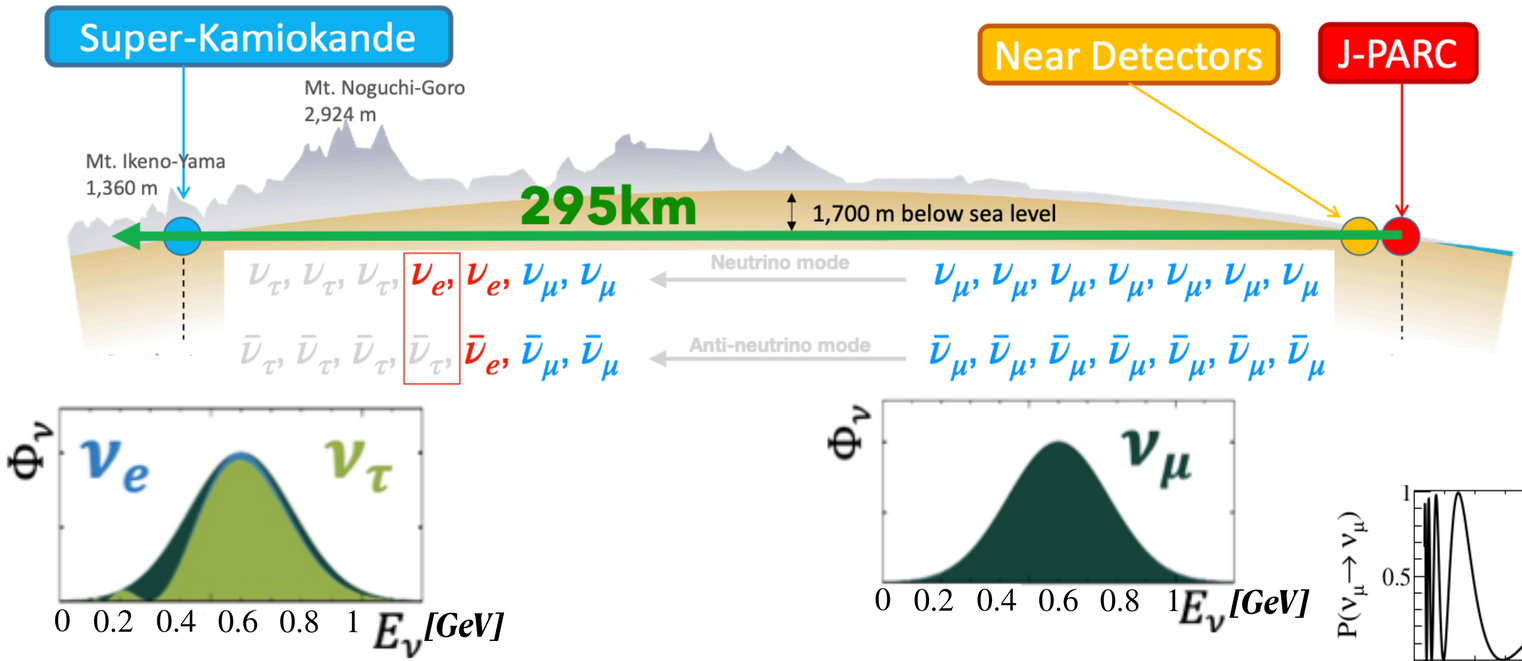
SCIENCES SORBONNE UNIVERSITÉ
LPNHE PARIS

Ulysse VIRGINET, on behalf of the T2K Collaboration

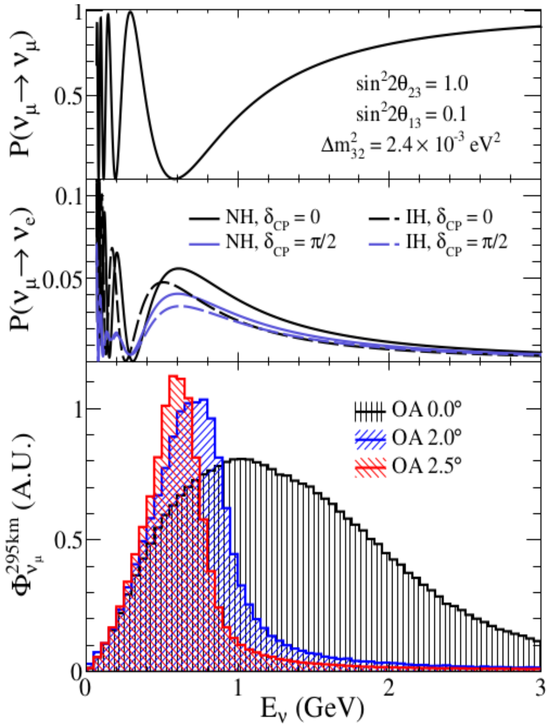
Friday, April 19th 2024

The T2K experiment



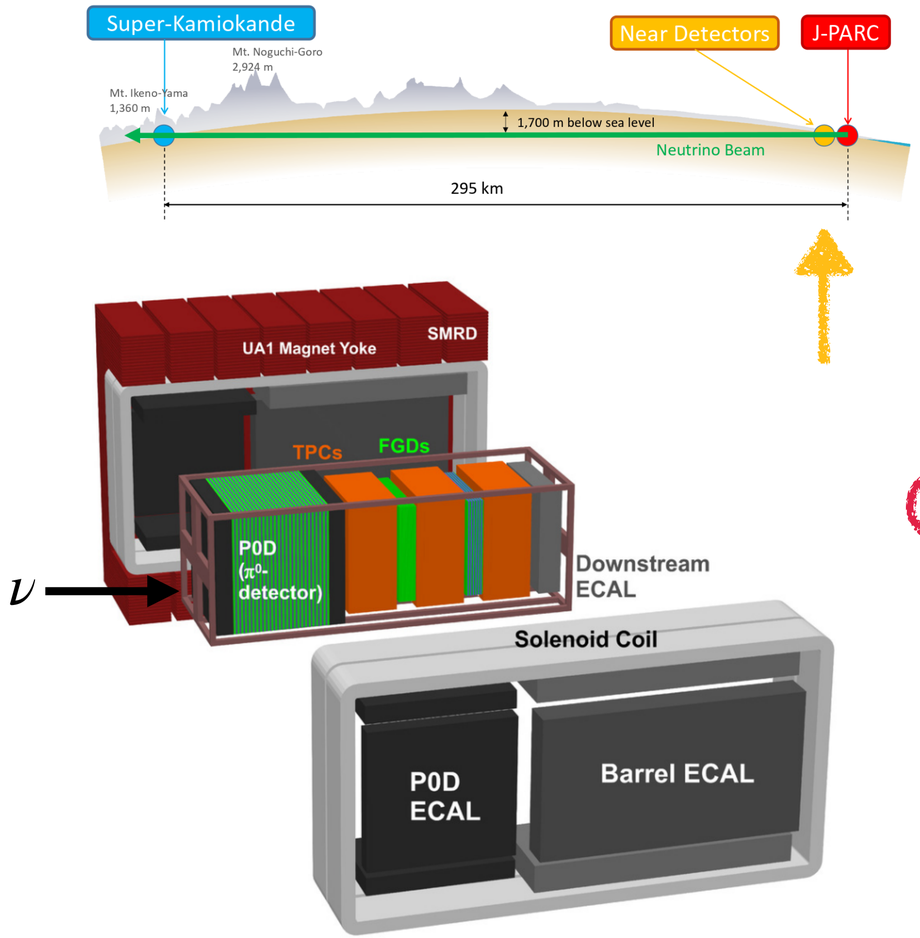


- Long-baseline neutrino oscillation experiment
- Has taken data in Japan since 2010
- 2.5° off-axis angle peaks ν_μ energy spectrum at ~600 MeV
- Measures $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance in a $\nu_\mu(\bar{\nu}_\mu)$ beam, 295km away at Super-Kamiokande

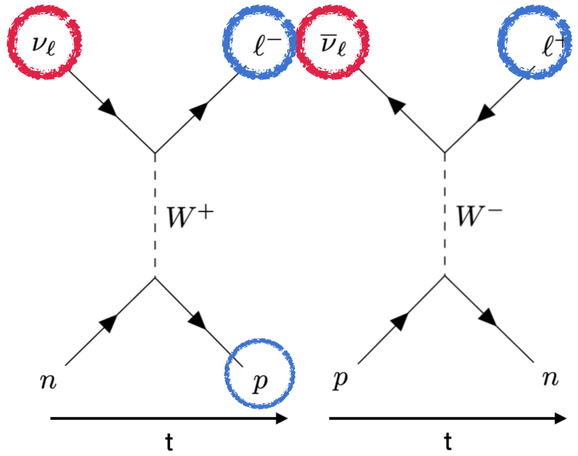


T2K: ND280

- Magnetized (thanks to **magnet** coming from the CERN UA1 experiment) series of detectors, located 280 m downstream of the J-PARC graphite target
- **PoD** (π^0 detector): measurement of π^0 production ($\pi^0 \rightarrow \gamma + \gamma$ mimics ν_e interaction)
- **FGDs** (Fine Grain Detectors): plastic scintillator bars planes (+ water planes for FGD2) where (anti)neutrino interaction (most probably) takes place: target (+ tracker)
- **TPCs** (Time Projection Chambers): highly accurate reconstruction of particle's momentum: very precise tracker
- **ECAL** (Electromagnetic calorimeter): measures energy deposit



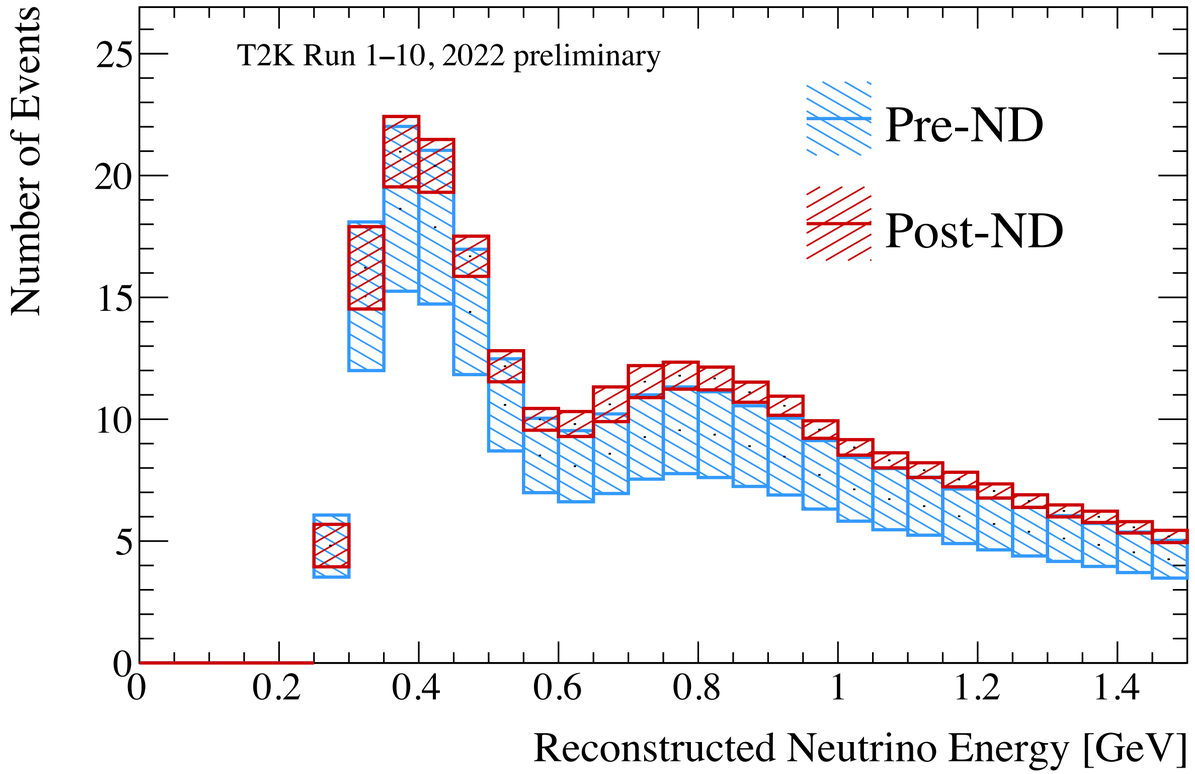
Schematic view of ND280 original configuration (2010-2022)

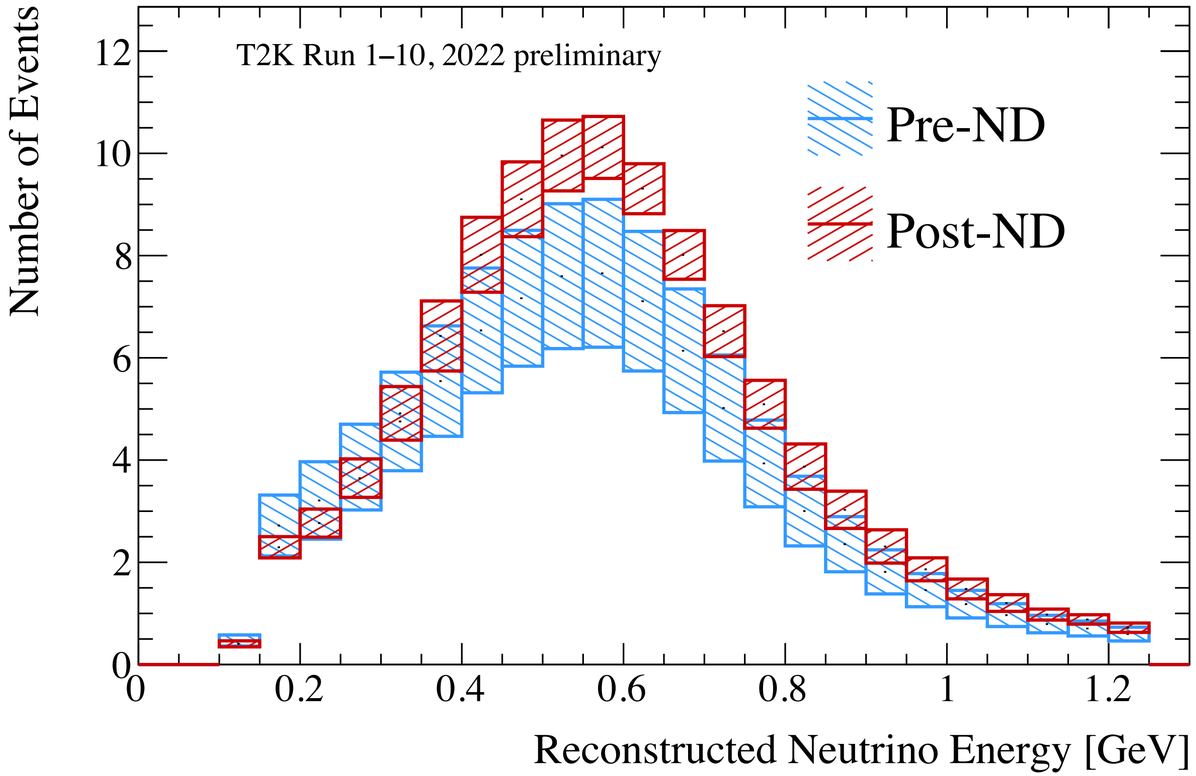


$\ell \in \{e, \mu, \tau\}$

Reduction of systematics thanks to ND280

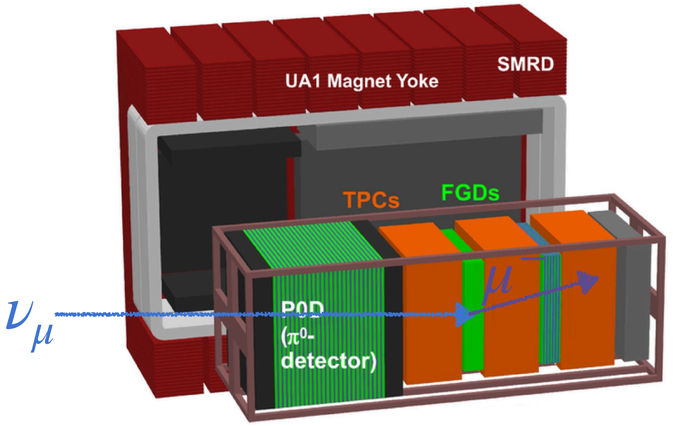
- Thanks to ND280 fit systematics uncertainties on ν_μ and ν_e energy spectra at SK are reduced from 15% to 5% !

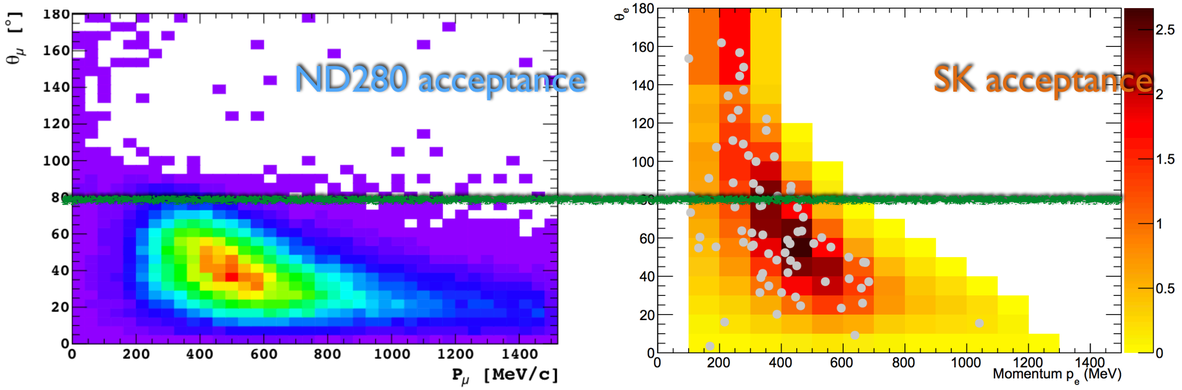




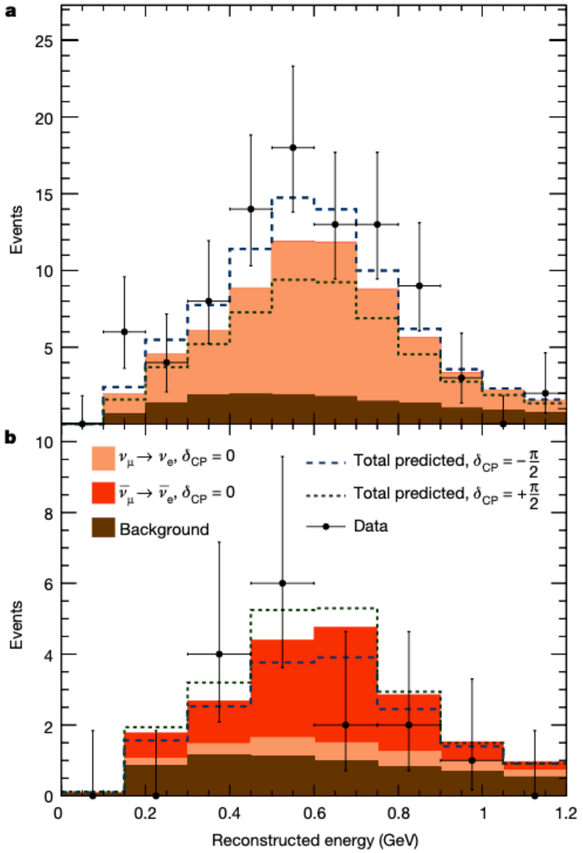
T2K (2010-2022)...

- T2K was the first to observe ν_e appearance in ν_μ beam: $\theta_{13} \neq 0$ at 7.3σ ***[PRL 112, 061802 (2014)]***
- Later, $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ CP-conserving points were ruled out at the 2σ confidence level !





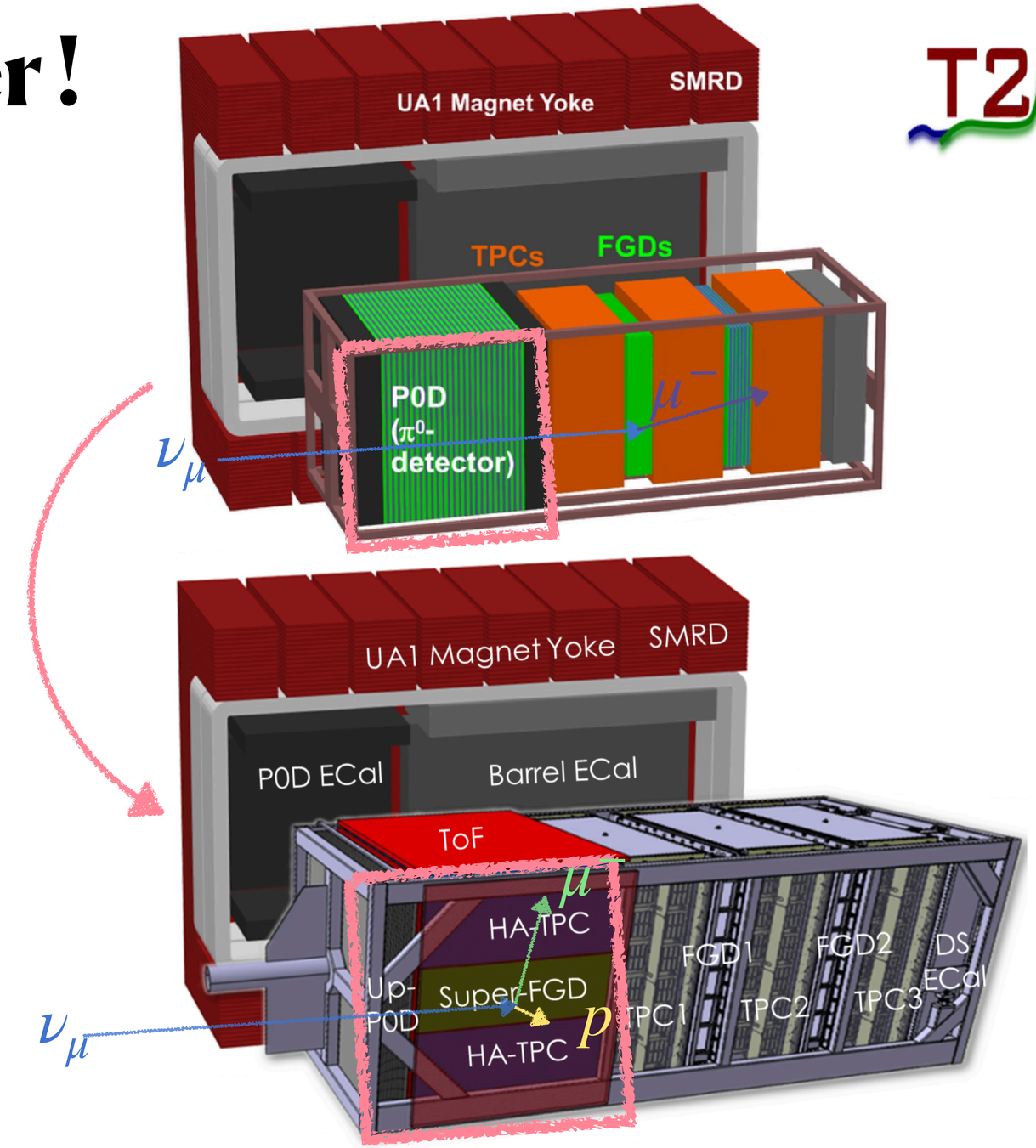
Nature volume 580, pages 339–344 (2020)



- **But** at ND280, mainly ν_μ ($\bar{\nu}_\mu$) interactions with forward-going μ^- (μ^+) are selected
- Small number of events and relatively low purity in ν_e and $\bar{\nu}_e$ selections
- High threshold to reconstruct protons in ν_μ interactions, no selection of neutrons → only muon kinematics used in T2K Oscillation Analyses

… so we can do even better !

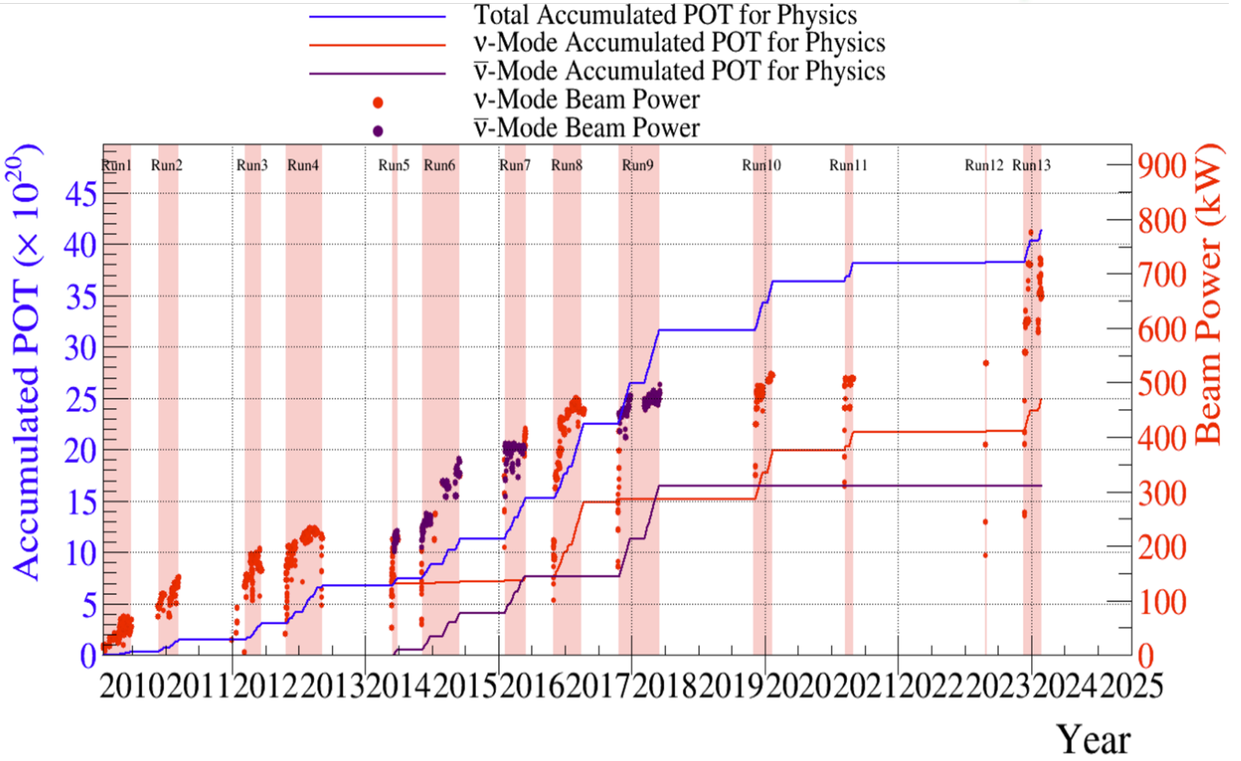
- Upgrade of the ND280: replacement of PoD by:
  - **SFGD** (Super Fine Grain Detector): 2 million 1cm^3 plastic scintillator cubes:
    - **Higher granularity** to better reconstruct *p* and *n*
    - Total target mass (SFGD+FGD1+FGD2) **multiplied by 2** (compared to FGD1+FGD2)
  - **2 HA-TPC** (High-Angle TPC): new TPCs equipped with the new Resistive Micromegas technology:
    - **Increase** of the **angular acceptance**
  - 6 **TOF** planes surrounding this structure:
    - **Precise time-of-flight** to reject background from outside the SFGD and improve the reconstruction



T2K Upgrade (2023-2027?)

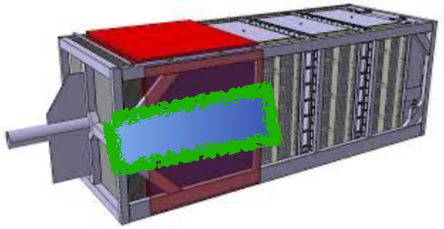
More details in L.Machado's talk!

- Upgrade of J-PARC neutrino beam line: proton **beam power** gradually **increase** from $\simeq$ 500 kW to 750 kW (1.3 MW expected in 2027) thanks to faster cycle from 2.48s $\rightarrow$ 1.36s
- Electromagnetic horns current increase $\rightarrow$ 320 kA instead of 250 kA $\rightarrow$ **10% increase** in neutrino flux
- Goal: collect >10×10^{21} POT by 2027 $\rightarrow$ 3σ **measurement** of CP violation if $\delta_{CP} \simeq -\frac{\pi}{2}$
- Successfully achieved 710 kW stable operation with 320 kA horn current $\rightarrow$ **continuous operations at 760 kW** were also demonstrated



- 750 kW beam runs and upgraded ND280 will collect **in ~4 months a statistics equivalent** to the one provided by ND280 for **the most recent T2K OA (2010-2022)**

SFGD



- 2 million optically independent plastic scintillator cubes of 1 cm^3 made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.
- **~40 p.e./MIP/fiber**

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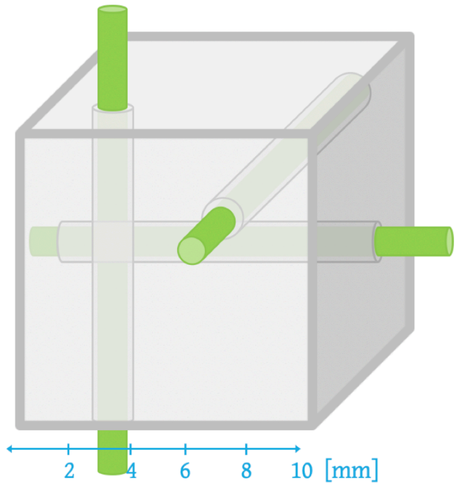
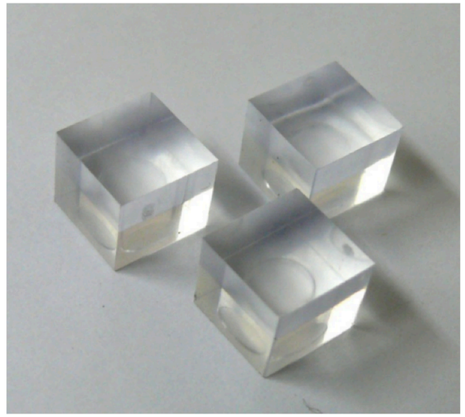
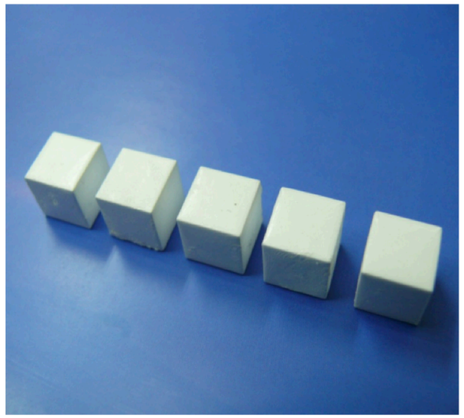


- SFGD cubes production at UNIPLAST (Russia)

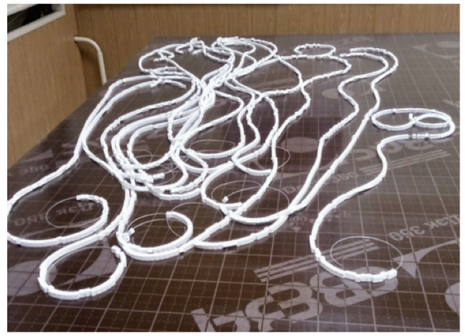
Produce cubes by injection molding

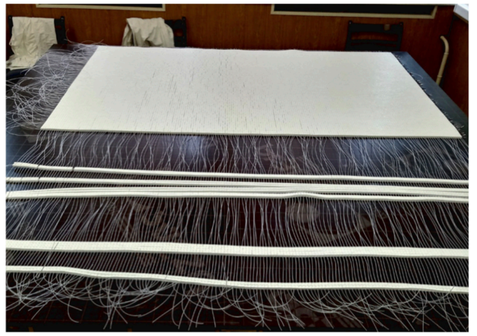


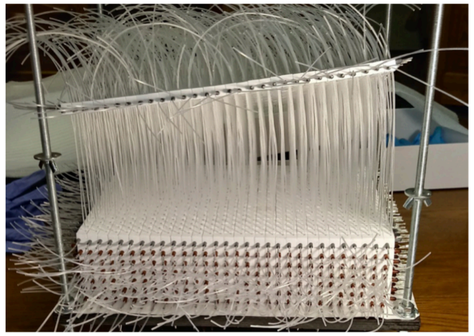
Etched in a chemical to deposit a reflective layer



3 orthogonal holes are drilled



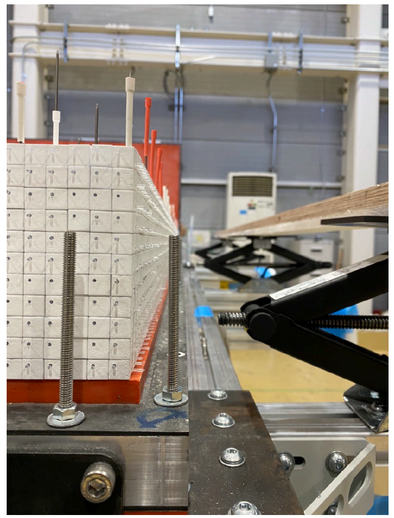




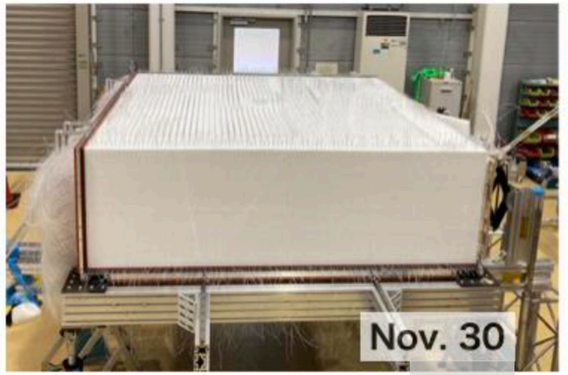
Assembled in 56 X-Y layers with fishing lines before shipment to Japan

SFGD assembly at J-PARC

First cube layer assembly



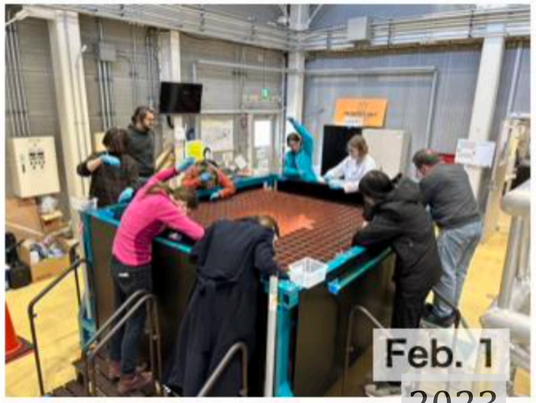
Stop panels removed



Box closure

Horizontal fibers assembly

Vertical fibers assembly



Top MPPCs assembly

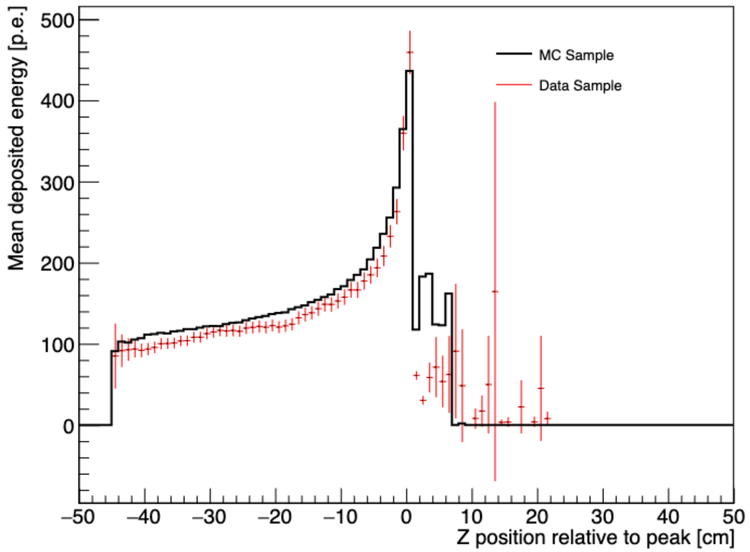
Light barrier/cables assembly

SFGD test beams

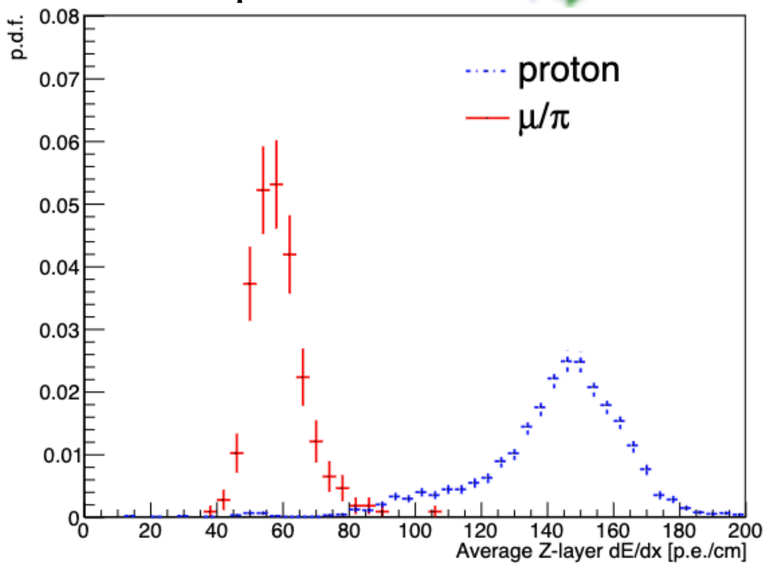
- A 24 × 8 × 48 SFGD prototype array as tested extensively at the T9 beamline of the Proton Synchrotron (PS) accelerator at CERN in 2018

2020 JINST 15 P12003

Proton Bragg peak

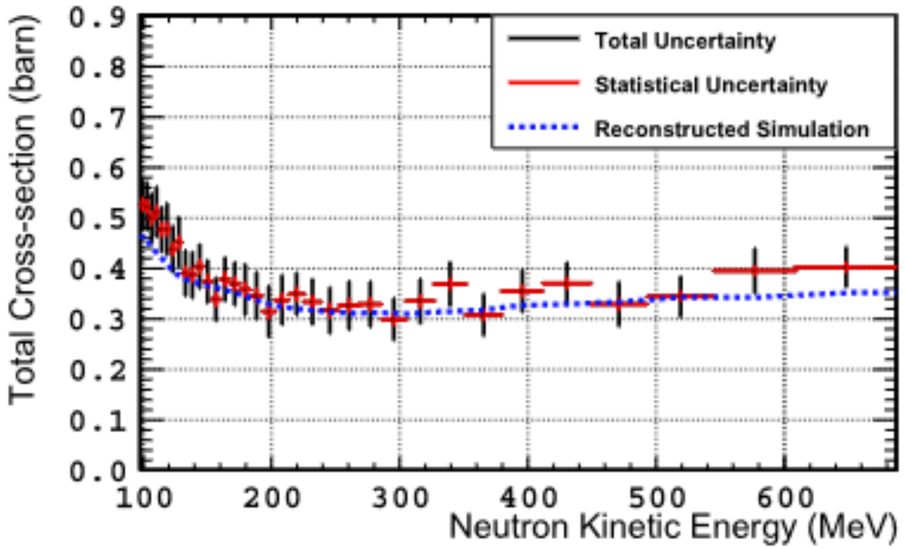


dEdx for protons and MIP



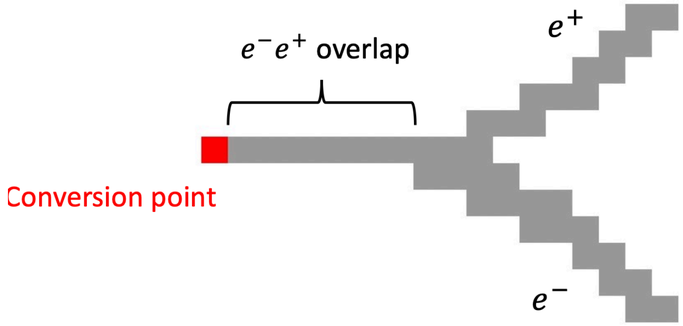
- Same prototype was also exposed at LANL neutron beam in 2019-2020

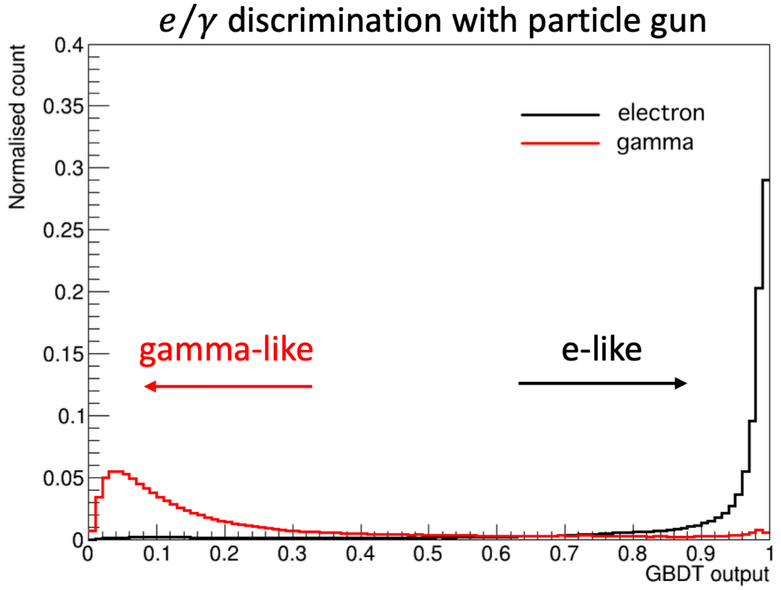
Physics Letters B 840 (2023) 137843



SFGD: ν_e reconstruction

- SFGD high-granularity means better separation of e^- coming from ν_e interactions and the ones coming from $\gamma \rightarrow e^+e^-$ conversions
- **Expect a cleaner sample of low energy ν_e**





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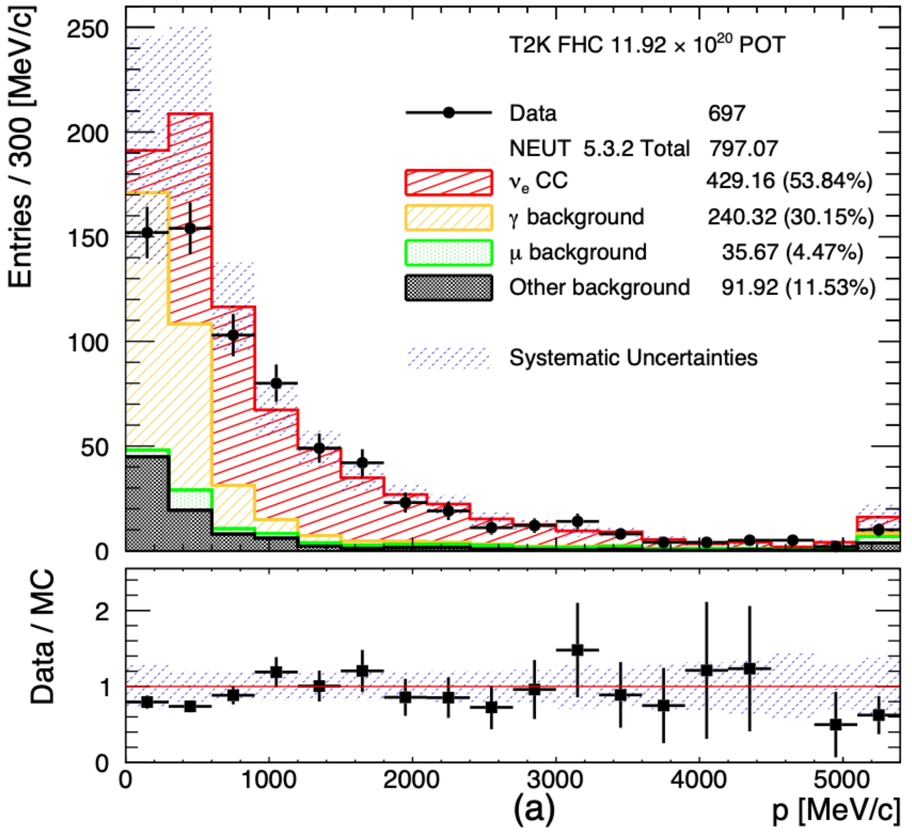
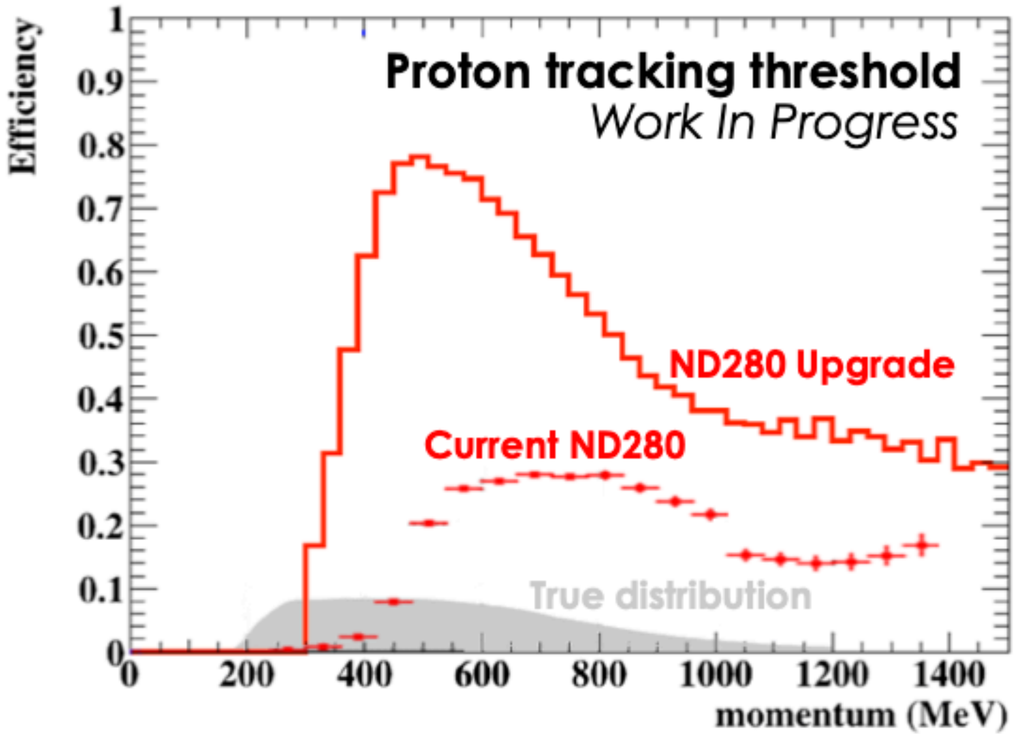
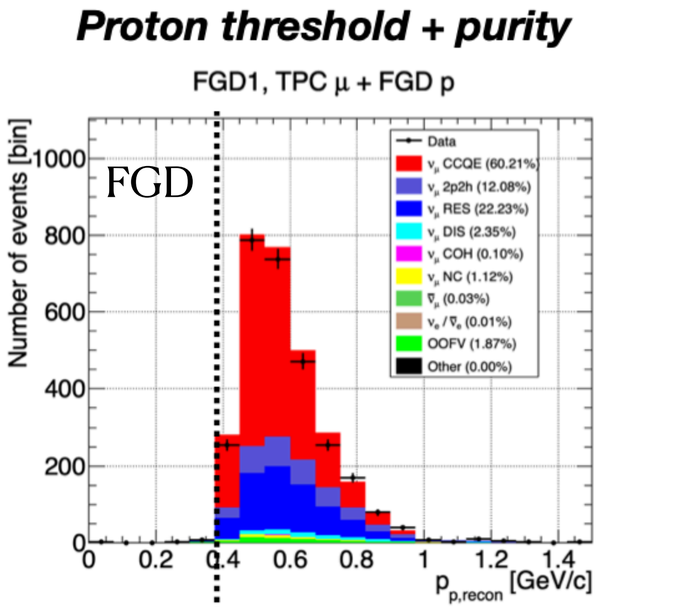


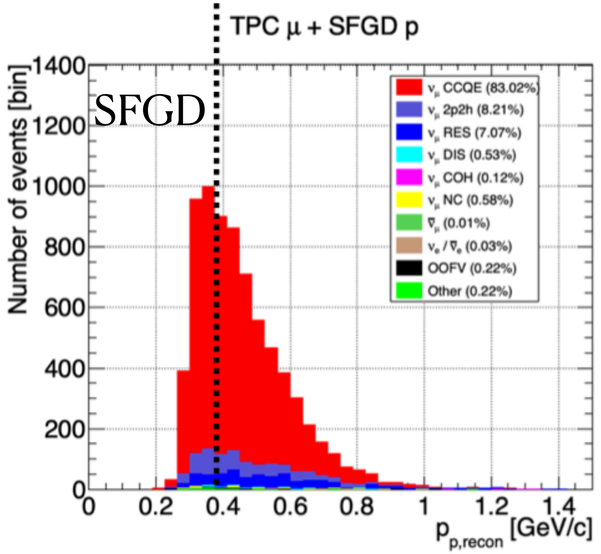
SFGD: proton reconstruction

- Better efficiency to **reconstruct proton** at low energy, **threshold is at 300 MeV/c** !



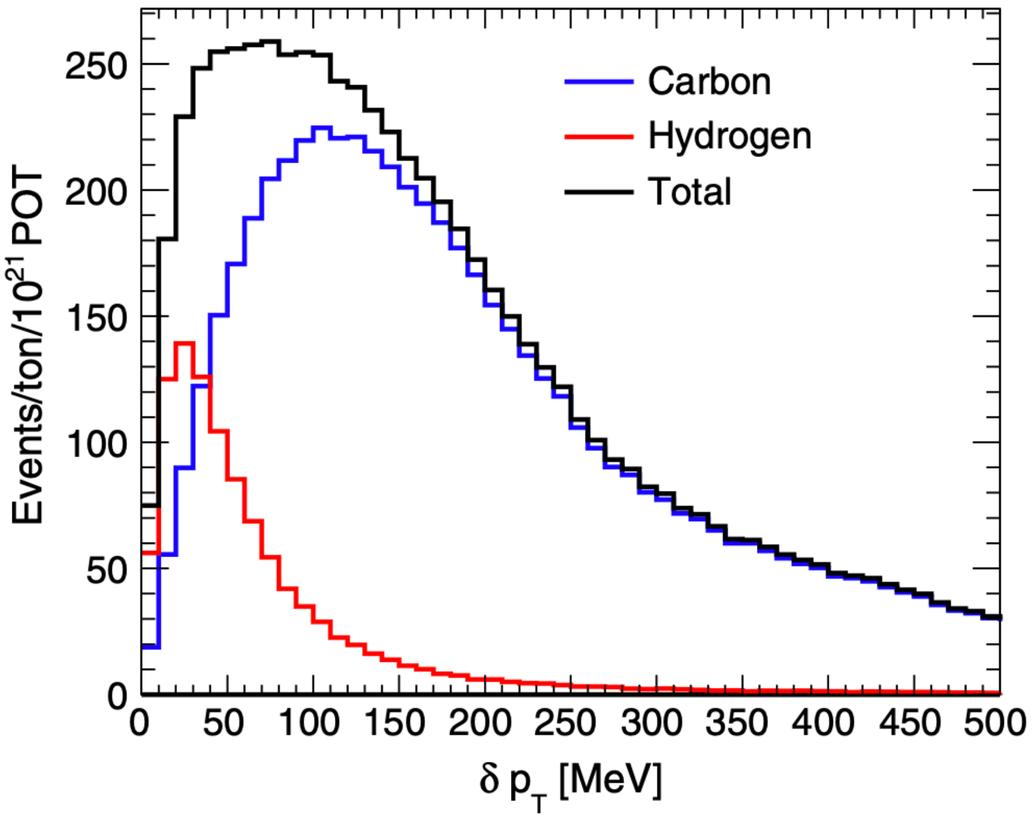


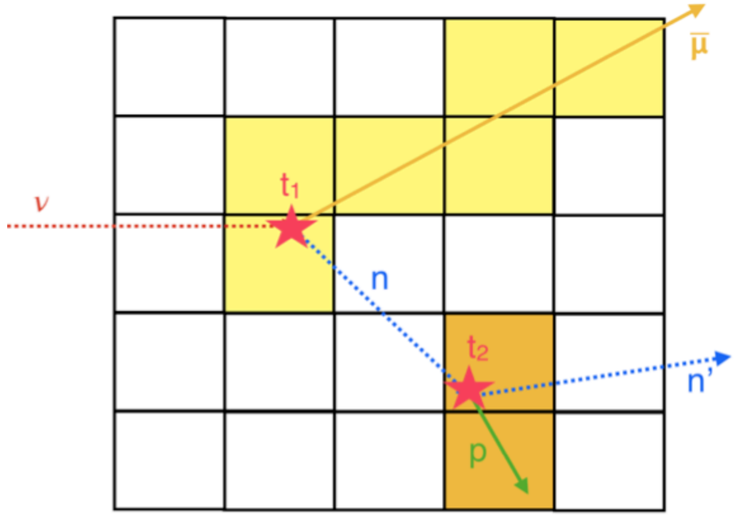
Lower proton threshold
Better CCQE purity



SFGD: neutron reconstruction

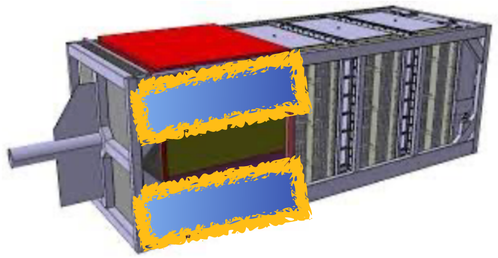
Phys. Rev. D 101, 092003

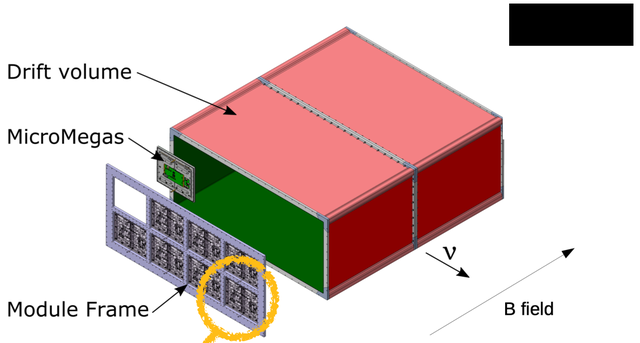




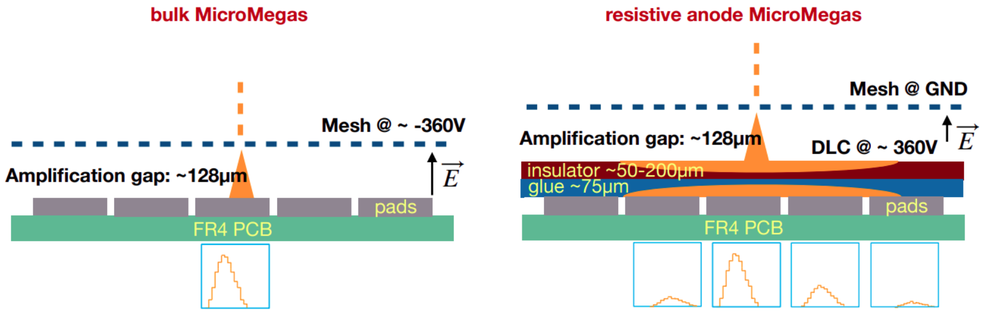
- Reconstruction of **neutron kinematics event-by-event** for the first time, thanks to their pre-thermalization scattering on protons
- Exclusive selection of $\mu^+ + n$ **samples** of $\bar{\nu}_\mu$ interaction similar to what is done with $\mu^- + p$ in ν_μ case
- Sample used to measure $\bar{\nu}_\mu$ interactions on H, **no nuclear effect so accurate measurement of neutrino flux !**

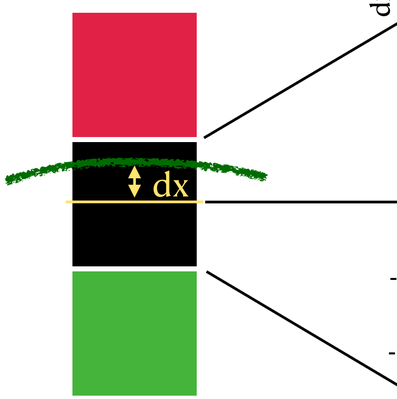
HA-TPC

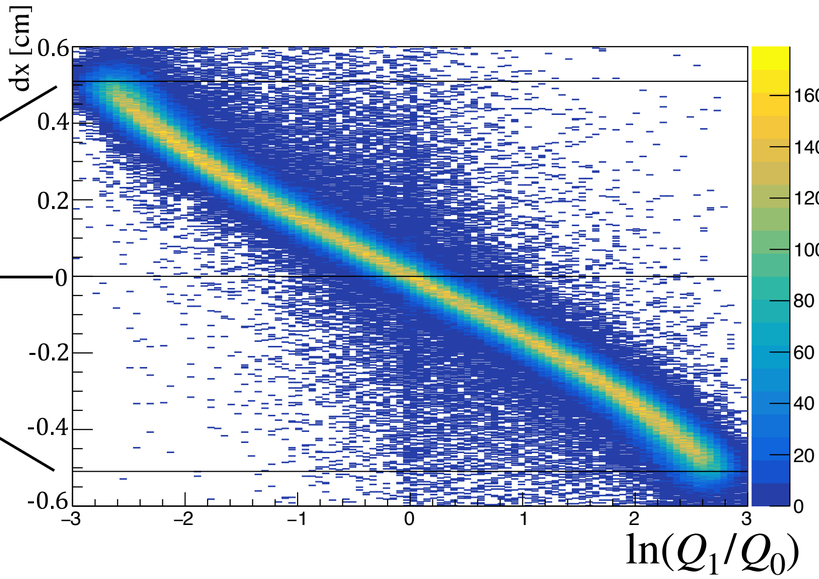


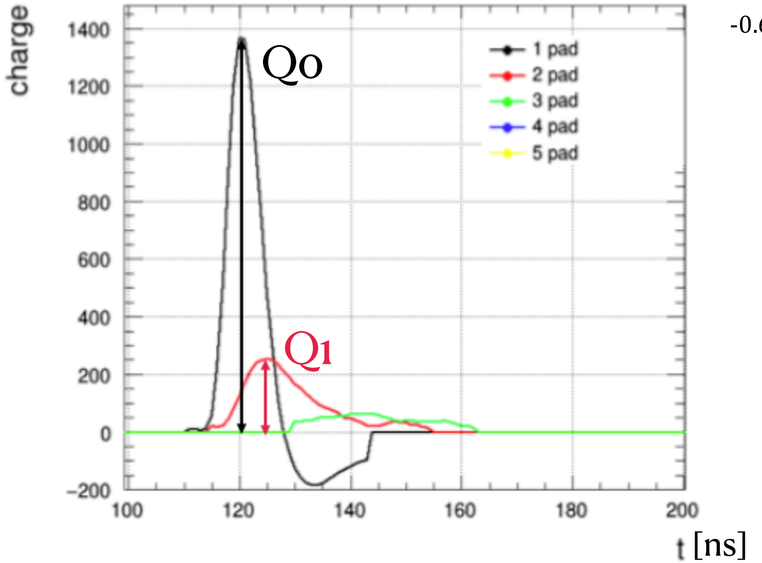


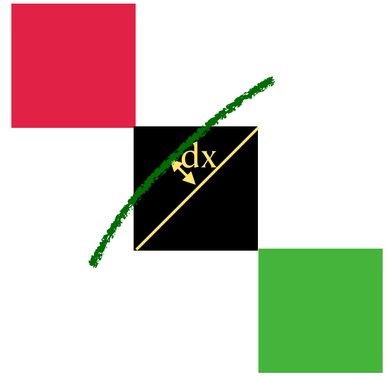
- New TPCs equipped with the **resistive anode MicroMegas (ERAM) technology**
- Contrary to the bulk MicroMegas which equip the vertical TPC, ERAM allow a charge spreading on several pads





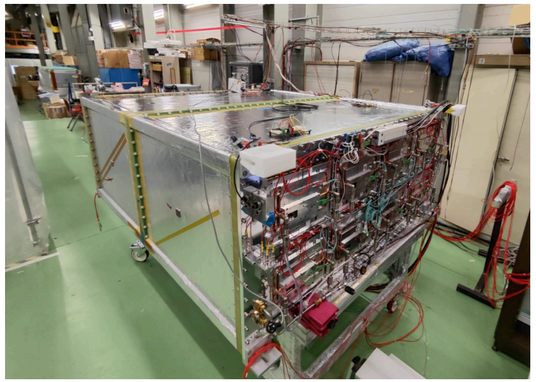




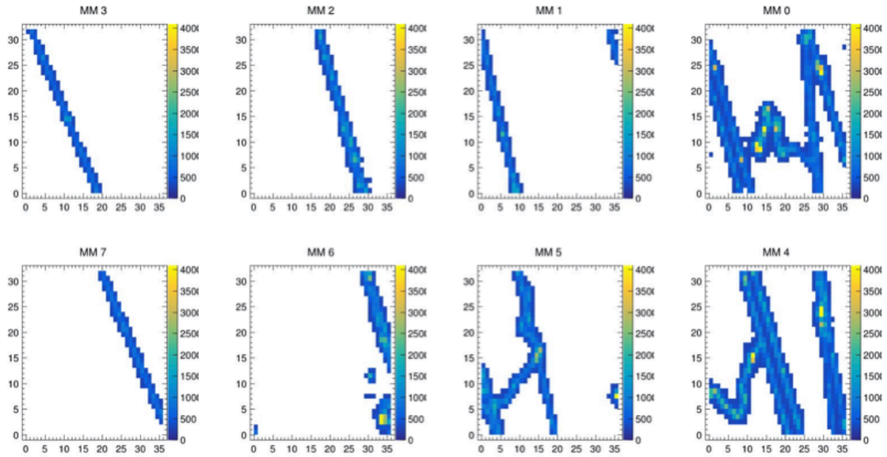


HA-TPC commisioning and assembly

- Bottom HA-TPC assembly and commisioning at CERN



Cosmics data taken at CERN previous to J-PARC shipment

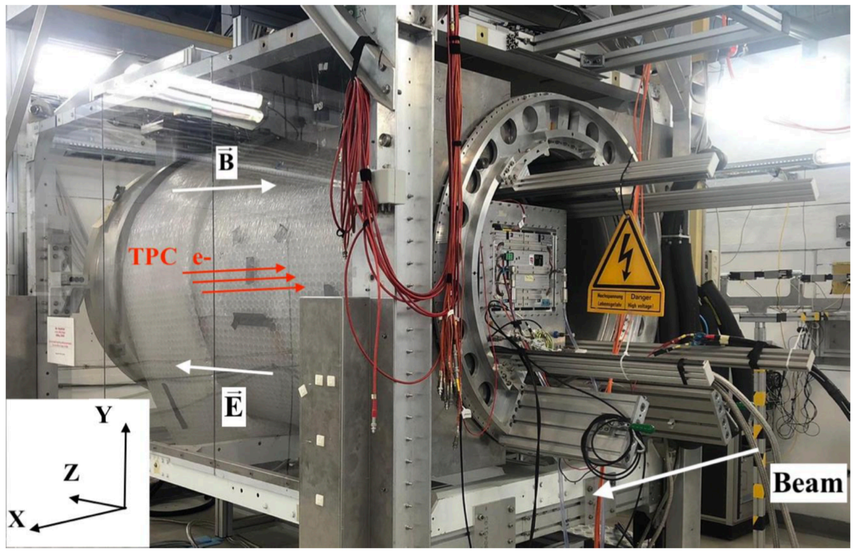


- Arrived fully instrumented at J-PARC !

Aug.25 2023

HA-TPC performances

- At DESY 2021 test beam, a spatial resolution between 200-800 μm has been measured, as opposed to 600-1600 μm for vertical TPCs



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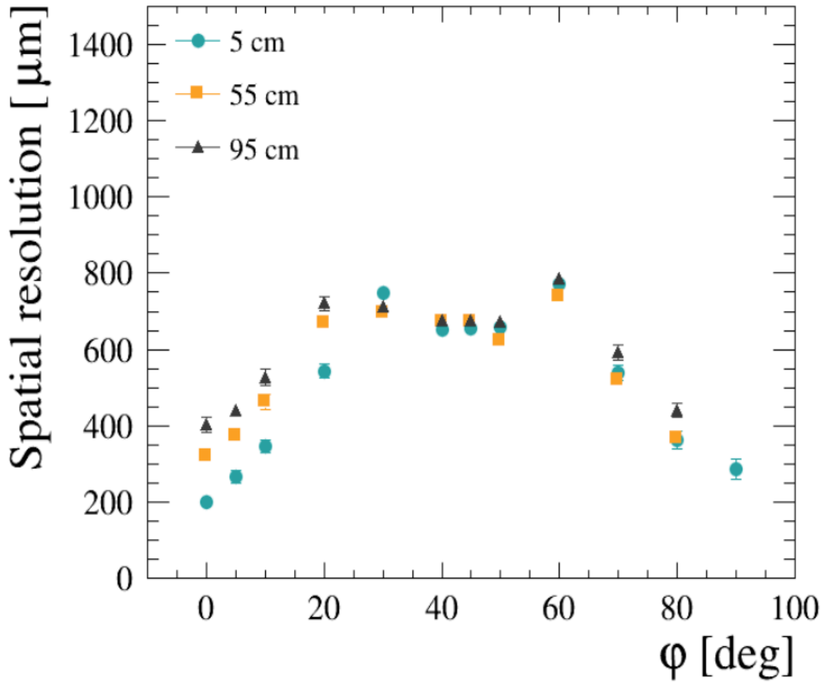
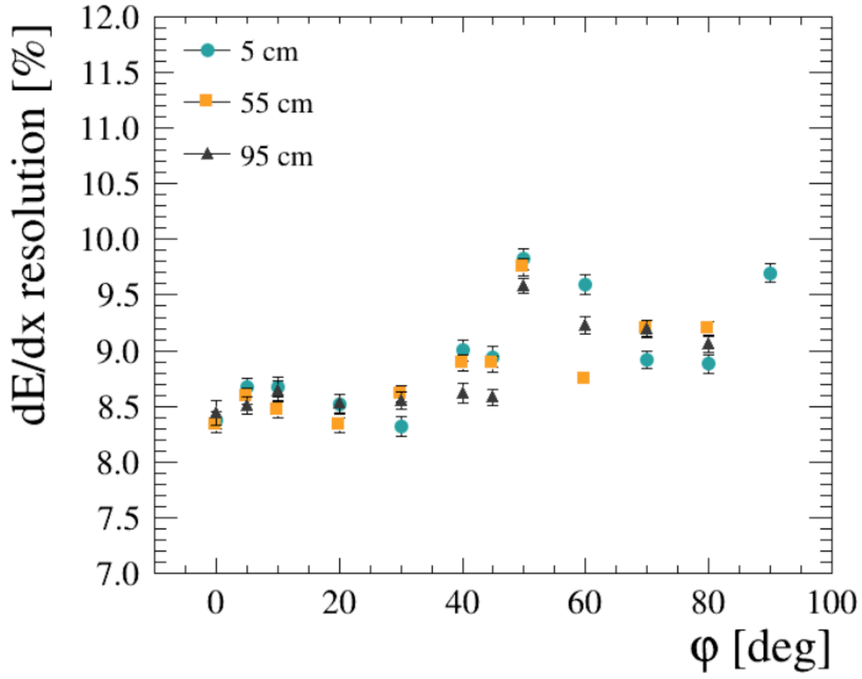
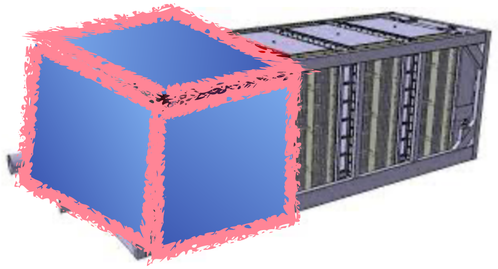


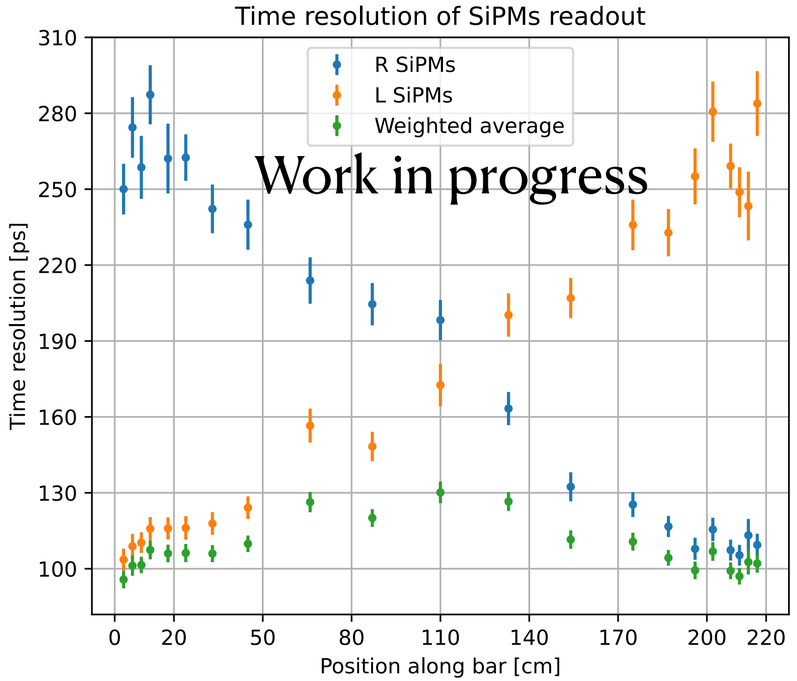


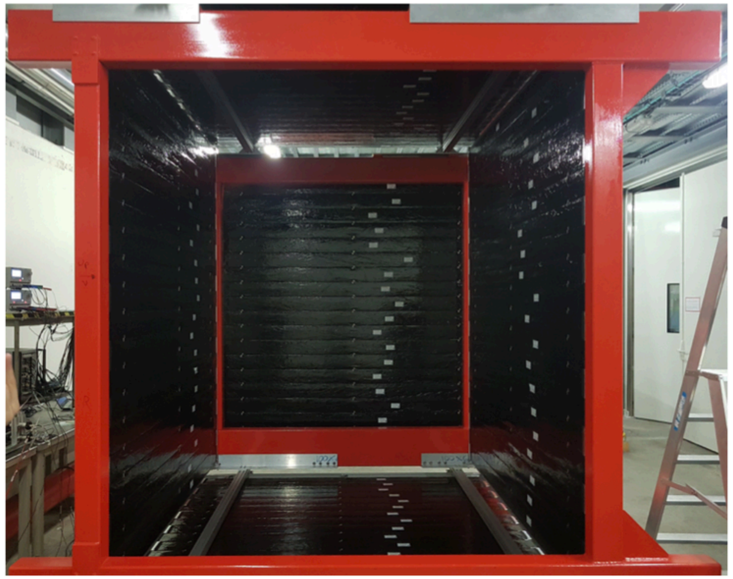
- dE/dx resolution of less than 10% has also been measured in this test beam campaign

TOF

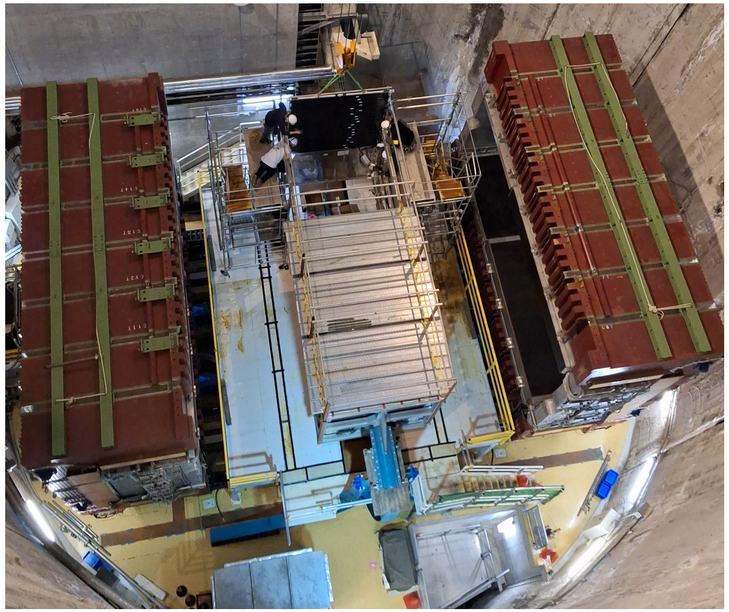


- 6 Plastic scintillator planes forming a cube that surround SFGD and HAT
- Reconstruction of track timing with a resolution between 100 and 130 ps



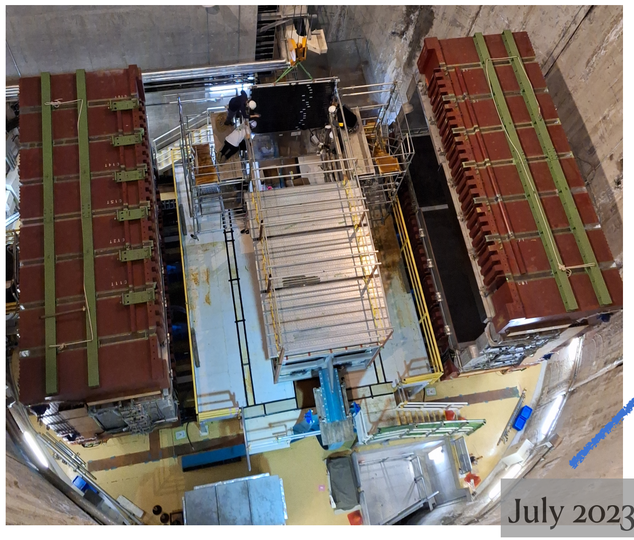


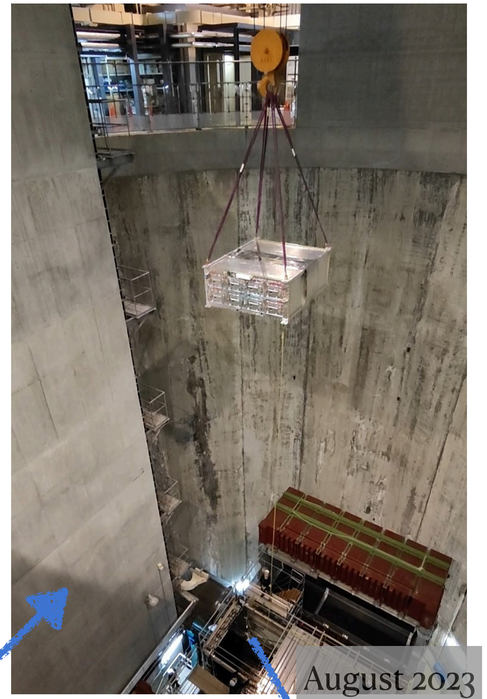
TOF panels assembled in ND280 basket prototype at CERN, June 2022

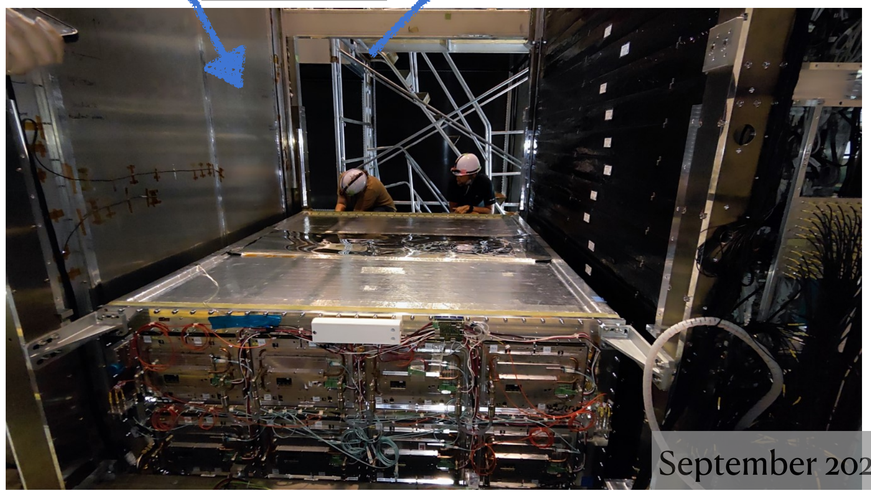


TOF panel installation in the ND280 pit at J-PARC, July 2023

ND280 Upgrade's installation

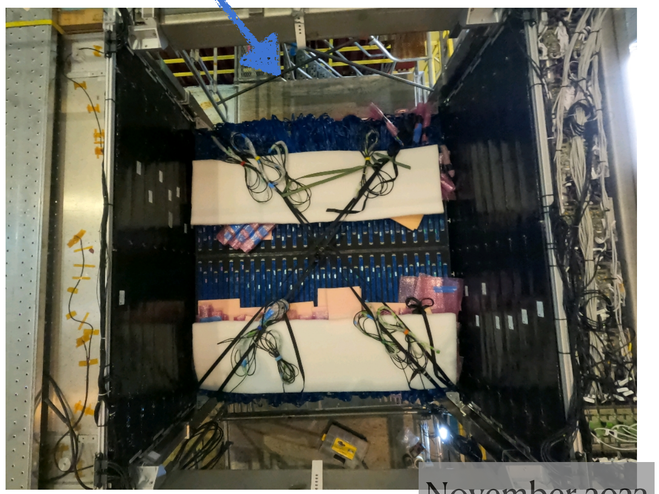

July 2023


August 2023


September 2023

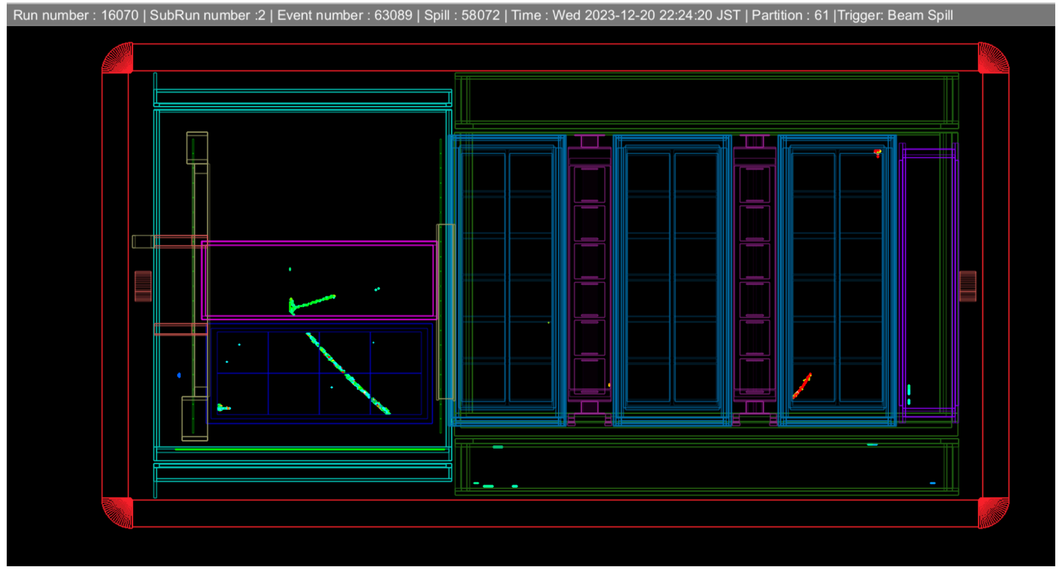

October 2023

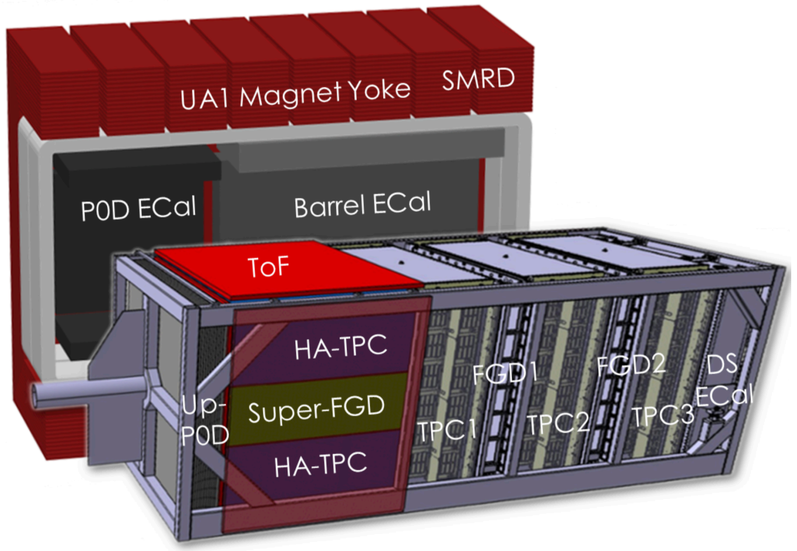

November 2023


November 2023

T2K Upgrade is truly happening !

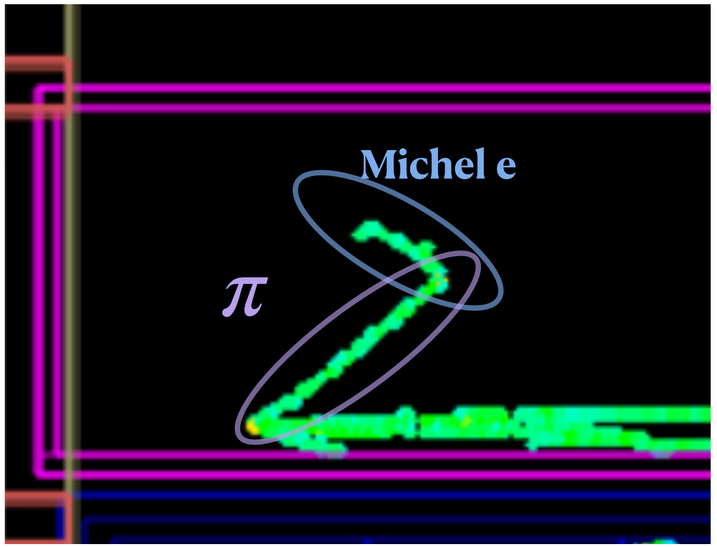
- The Bottom HAT, SFGD and 4/6 TOF planes were installed in the ND280 pit in end of 2023 and have started to take data
- The Top HAT will be installed by end of April
- The 2 last TOF panels will follow by end of May
- The full upgrade should be ready for June run!

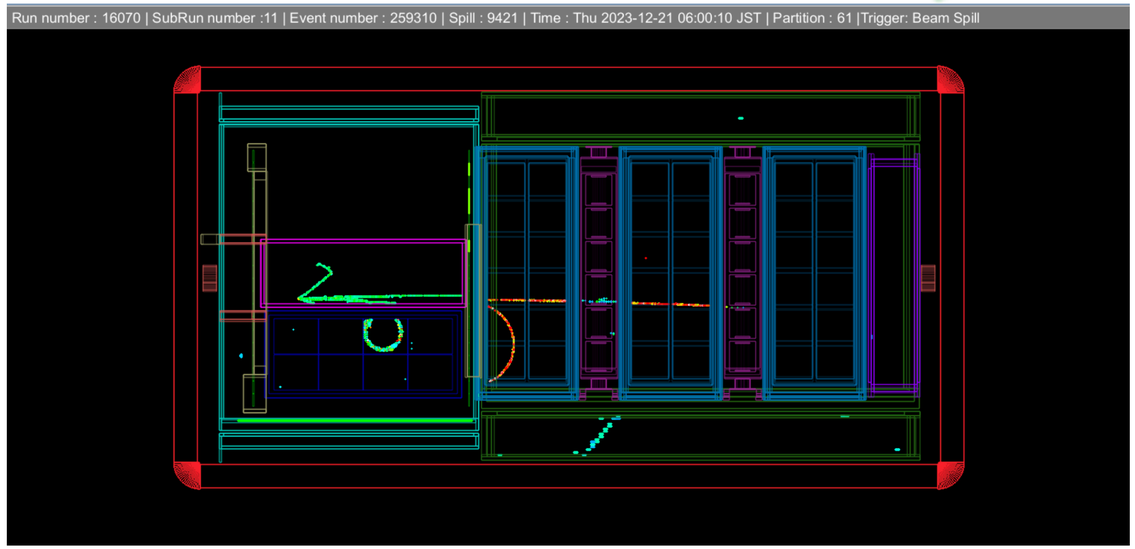




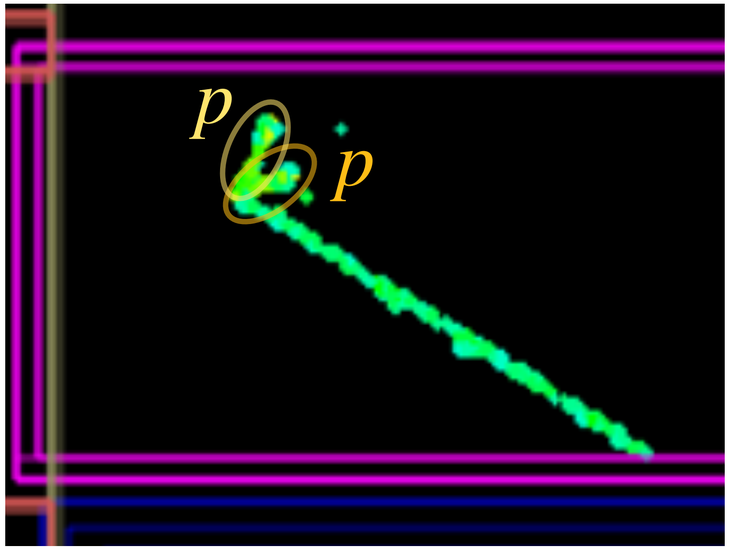
Some nice event displays

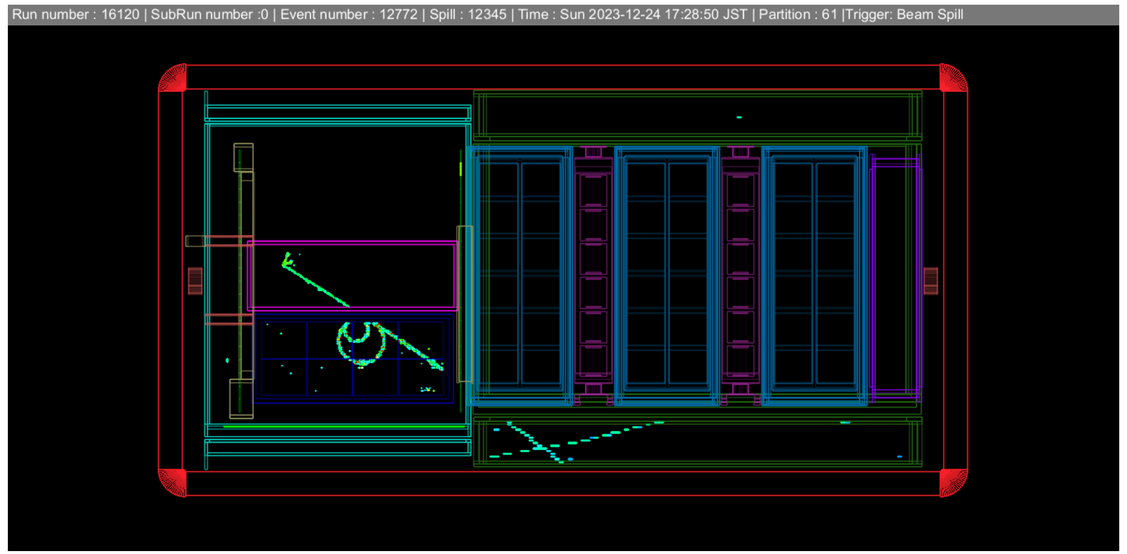
- Pion and Michel electron ?





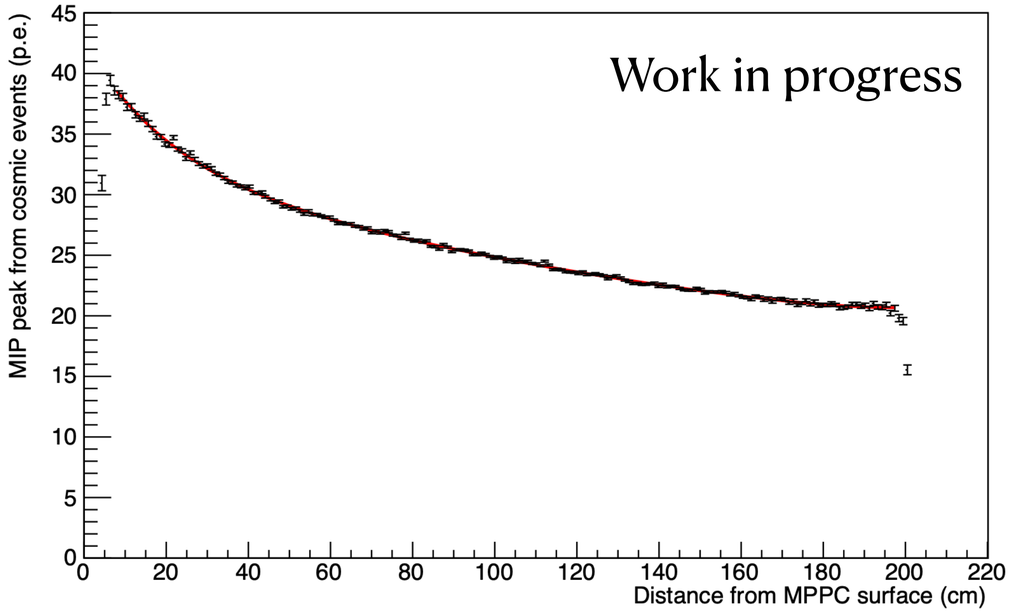
- 2 stopping protons from 2p2h excitation ?



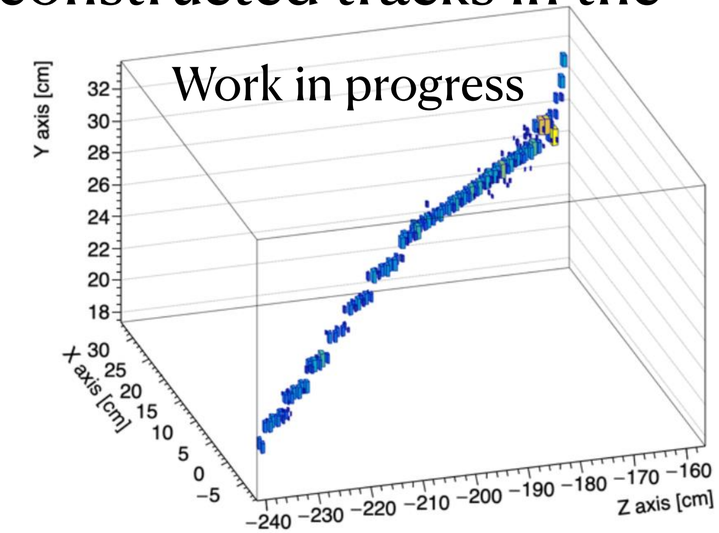


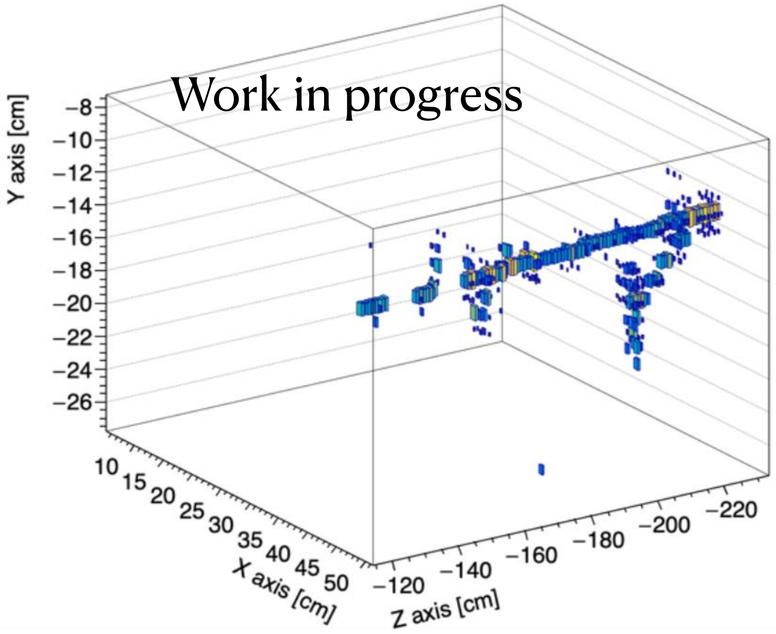
ND280 Upgrade: SFGD Preliminary results

- Thanks to the cosmics data collected at J-PARC, a lightyield of 20-40 p.e./MIP/fiber has been measured for SFGD cubes



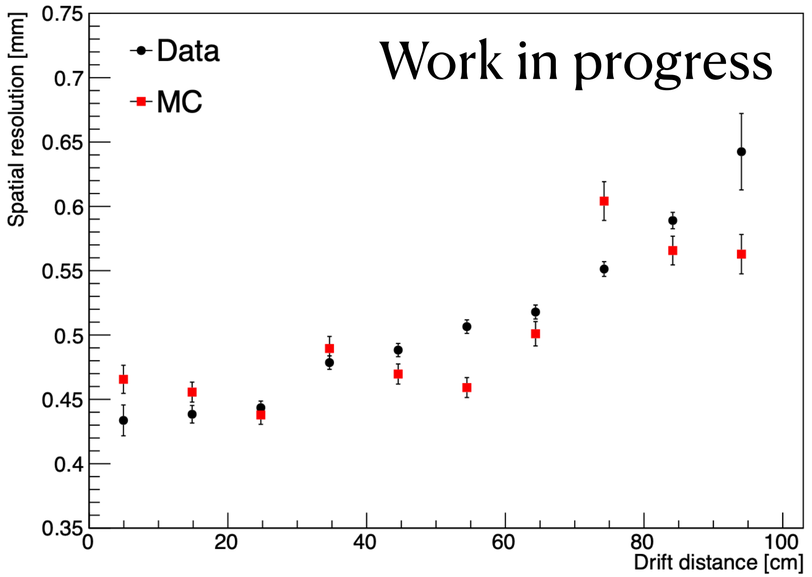
- Examples of 3D reconstructed tracks in the SFGD at J-PARC



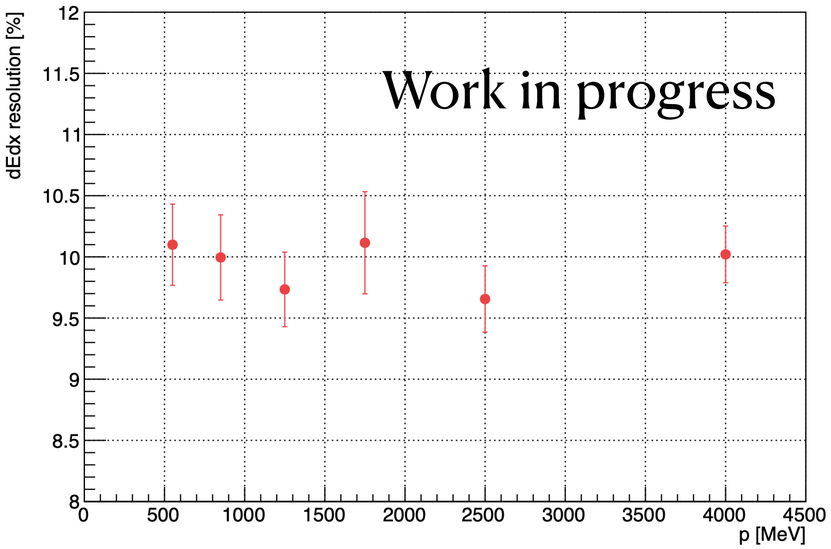


ND280 Upgrade: HA-TPC Preliminary results

- Cosmics data taken at J-PARC in end of 2023 → spatial resolution of ~500 μm (about 10% momentum resolution), in both data and simulation

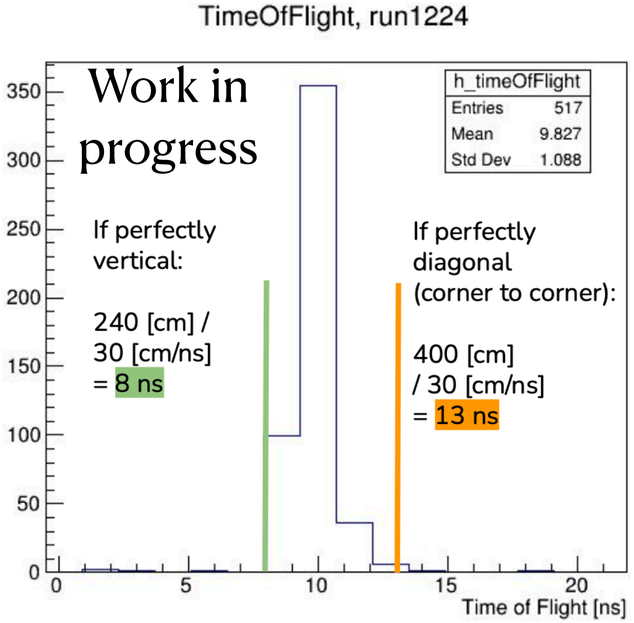


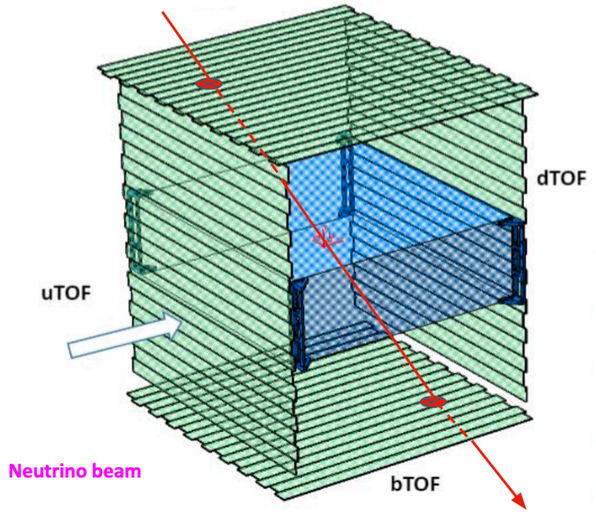
- dEdx resolution of the order of 10% has been measured in a wide range of momenta



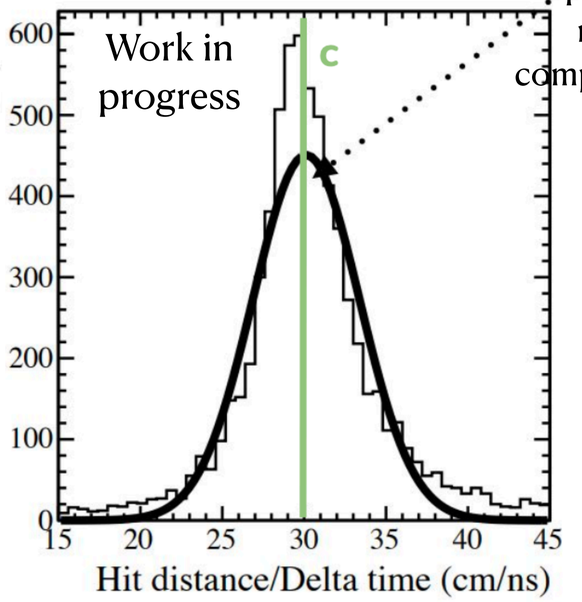
ND280 Upgrade: TOF Preliminary results

- Cosmics data taking

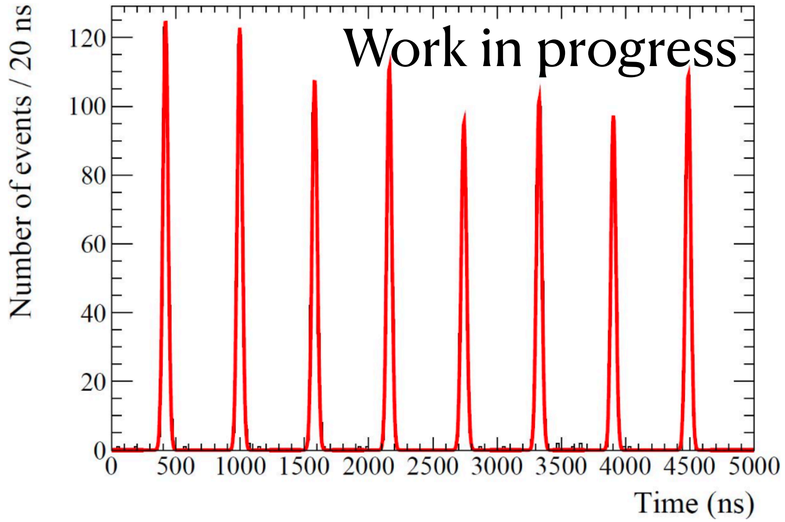




Cosmic crossing Top and Bottom



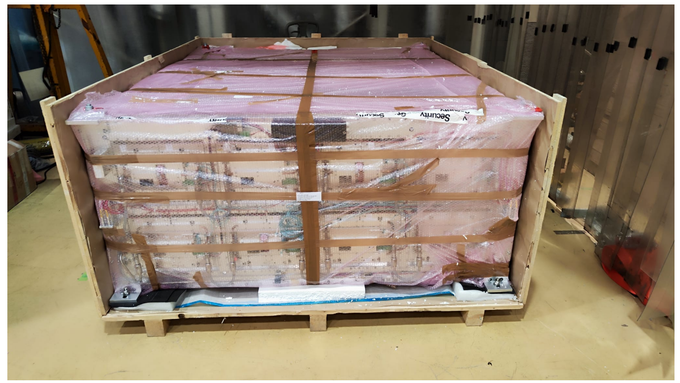
Speed of light measured compatible with c!



- Beam data taking
- TOF clearly distinguish the eight beam bunches structure!

Summary and perspectives

- Thanks to a lot of work from many people, T2K has entered its second phase!
- 2 runs of data-taking were done with SFGD, 1 of the 2 HA-TPC and 4 of the 6 TOF installed
- Detectors are working very well
- Already observed very nice neutrino interactions
- Top HA-TPC has arrived in J-PARC and should be installed in the pit by end of April
- The 2 other TOF will follow by end of May
- The whole upgraded ND280 should be ready for June run, ~20000 $\nu_\mu CC0\pi$ interactions are expected in SFGD in only one month of data taking!

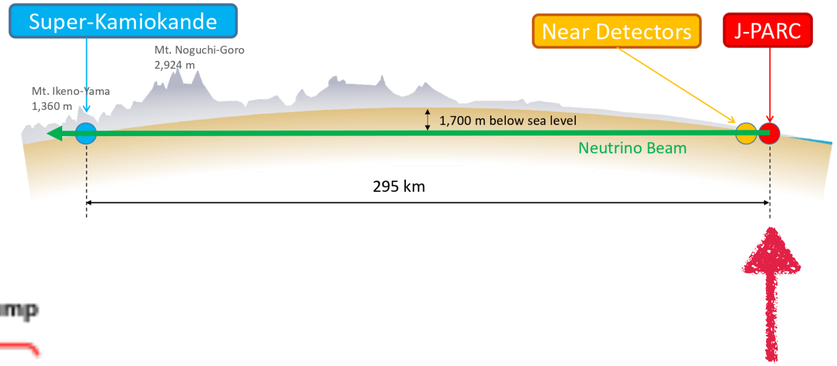


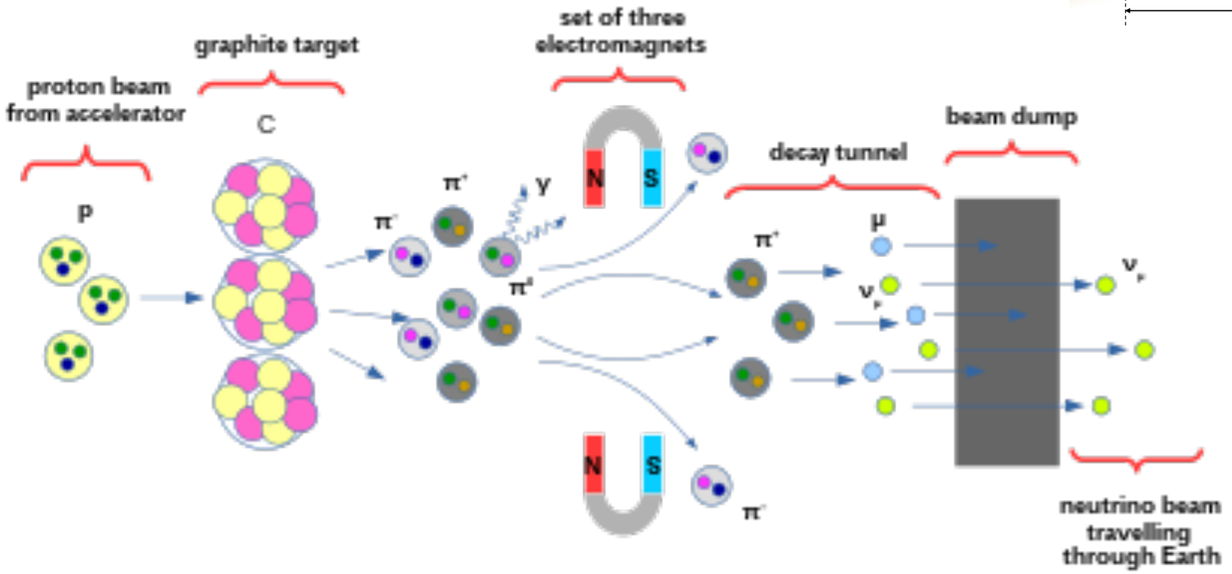
Top HA-TPC is well arrived at J-PARC!
April 8th 2024

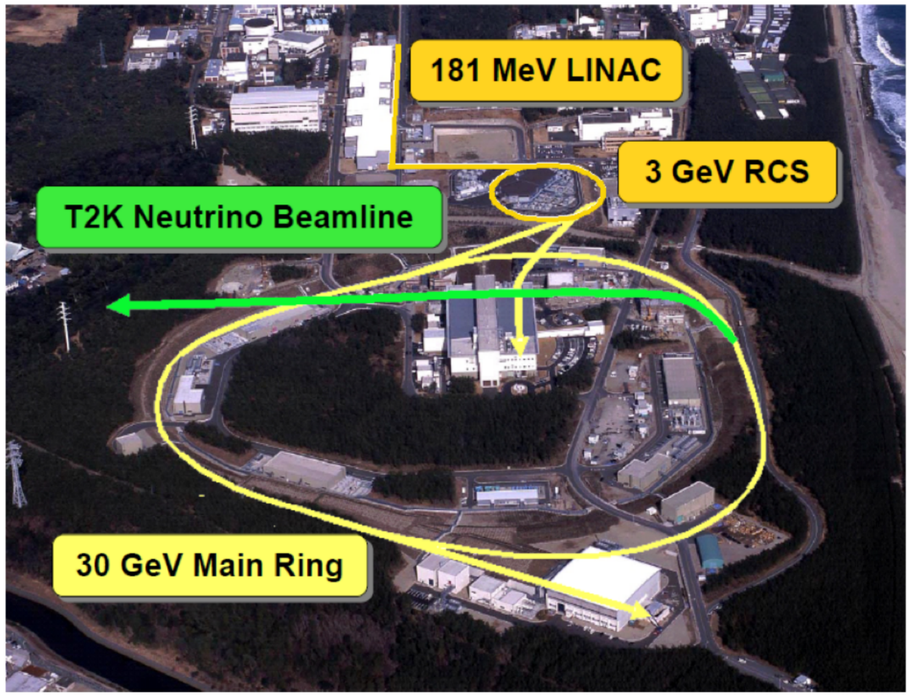
Thank you for your attention!

Back-up

The T2K experiment: J-PARC

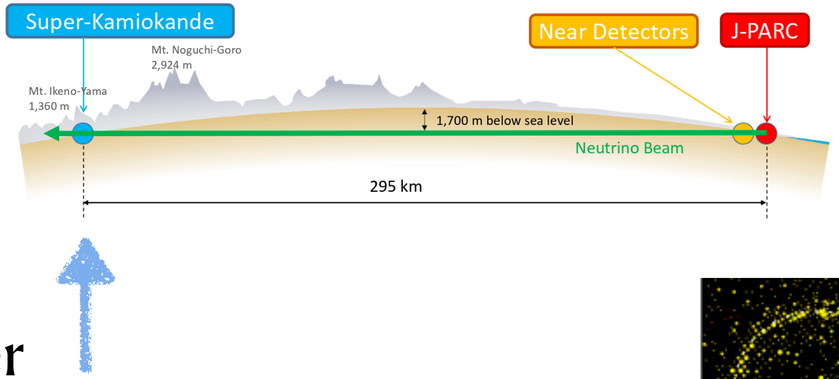




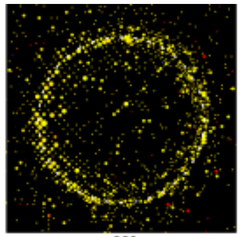


- Japan Proton Accelerator Research Complex: Acceleration of protons
- Collisions on a graphite target produce mainly mesons: $\pi^{\pm}$, $K^{\pm}$
- Thanks to magnetic horns, select:
  - Either π^{+}, K^{+} which decay mainly in $\mu^{+} + \nu_{\mu} \rightarrow \nu_{\mu}$ **beam**
  - Or π^{-}, K^{-} which decay mainly in $\mu^{-} + \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}$ **beam**

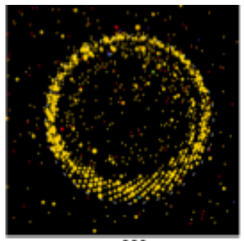
The T2K experiment: SK



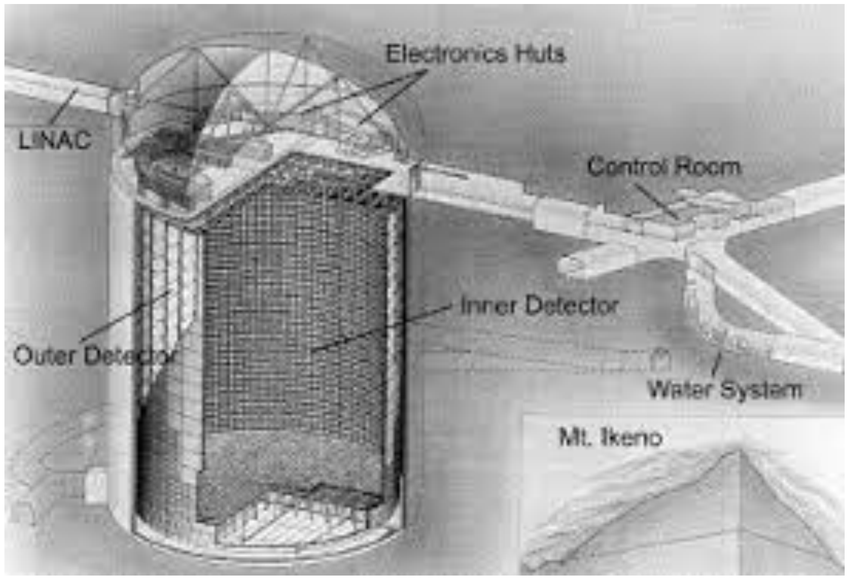
- 40m diameter × 40m height cylinder
- Filled with 50000 tons of ultra pure water
- More than 10000 PMT aim to detect Cherenkov light emitted by charged lepton coming from ν interaction

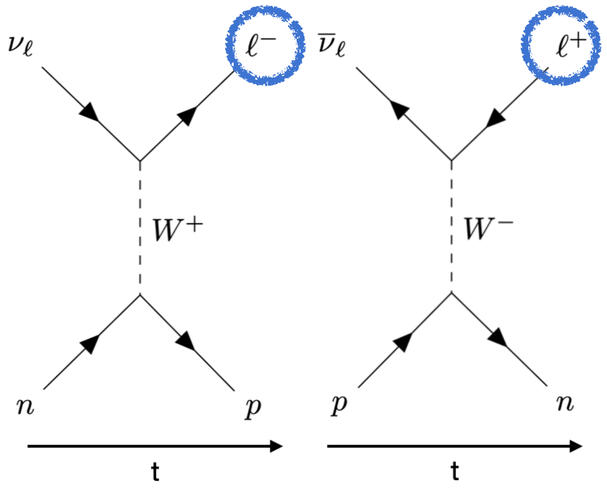


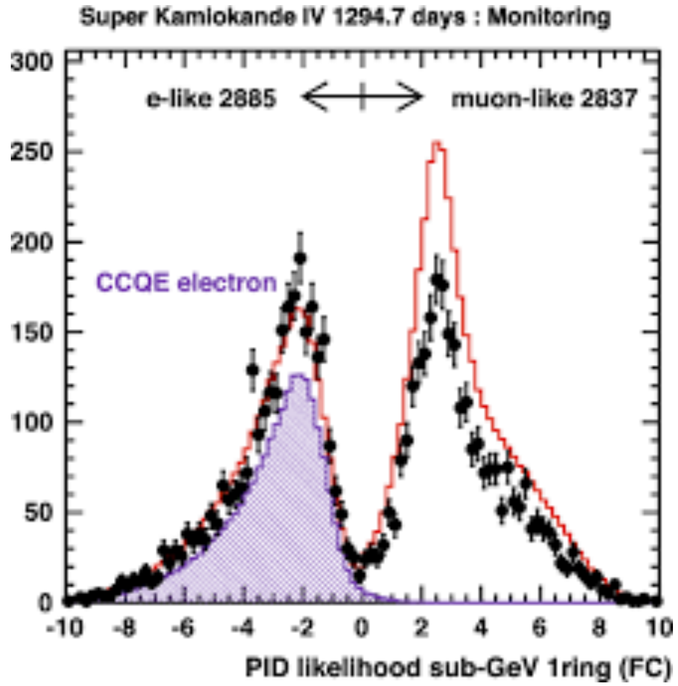
ν_e-like



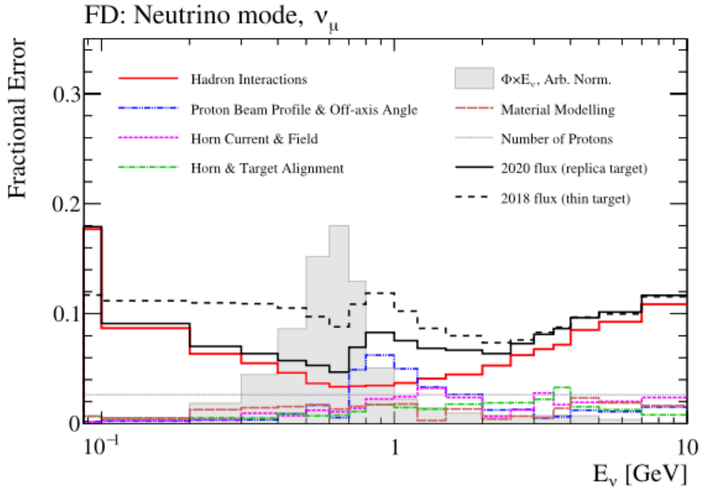
ν_μ-like

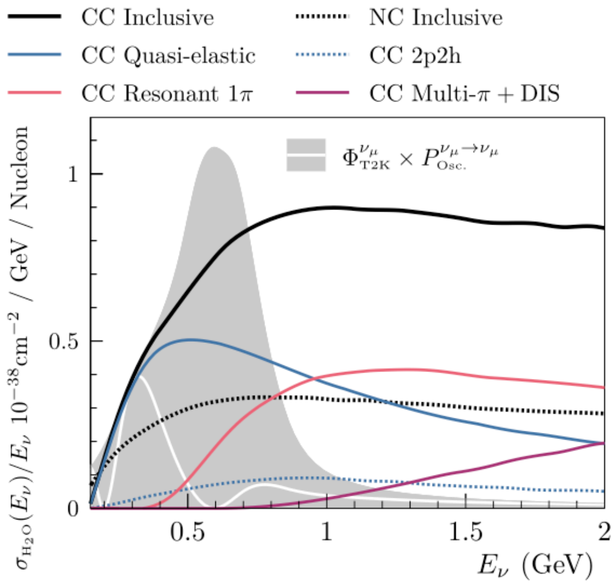






The T2K oscillation analysis





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

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

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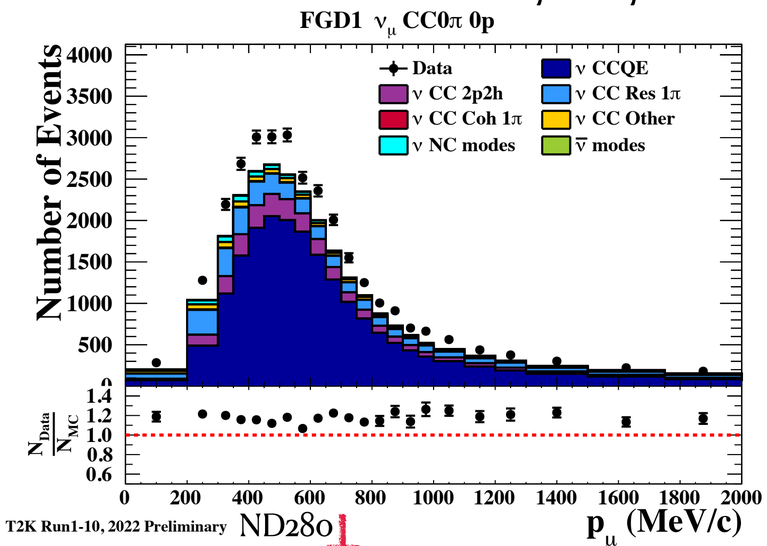
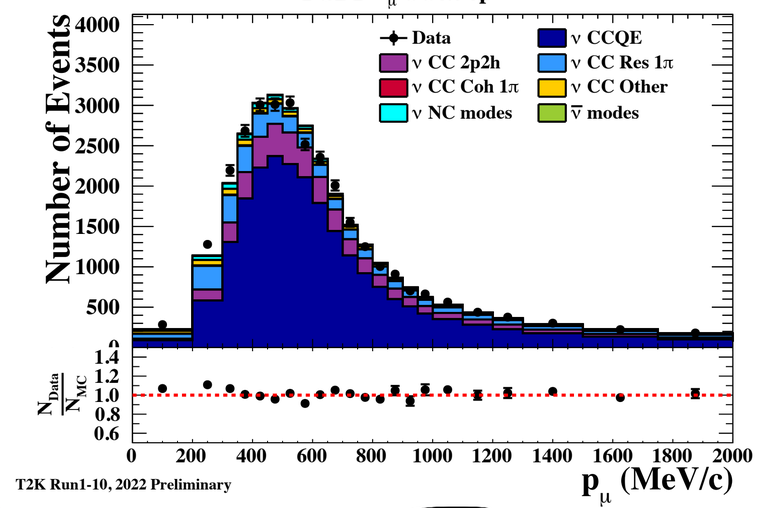
Reduction of flux and x-sec uncertainties at ND280

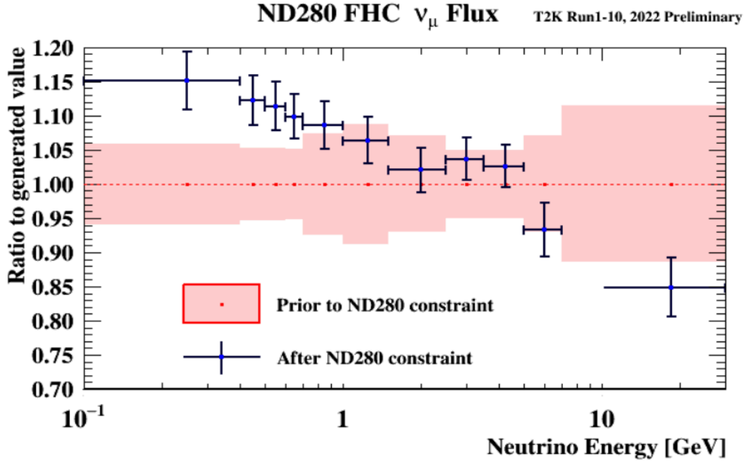
- Fit non-oscillated ν_μ ($\bar{\nu}_\mu$) spectrum

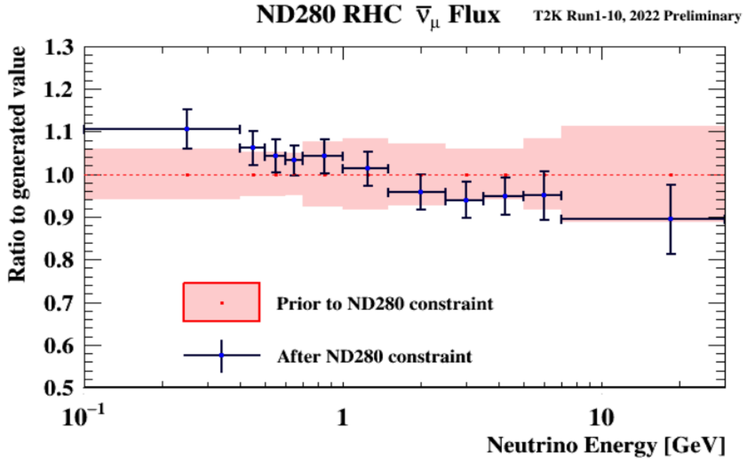


ND280 Fit



- Reduction of flux and cross-section systematic uncertainties





2p2h and CCQE x-sec parameters