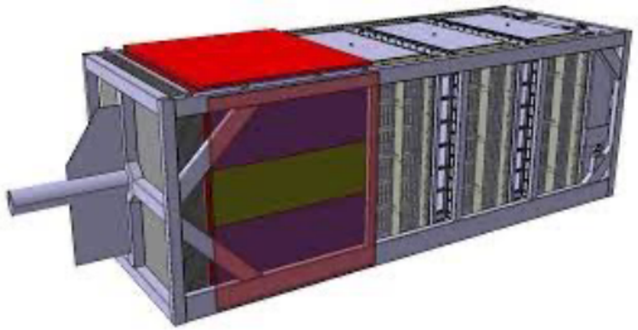
São Paulo, Brasil

# T2K Near Detector Upgrade

**NuInt 2024**

**14th Workshop on Neutrino-Nucleus Interactions**

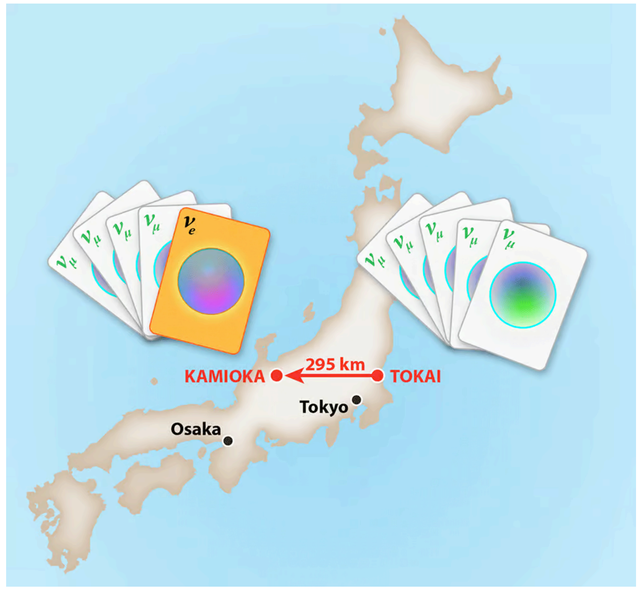
**Uncertainties and Prospects for Future Improvements**

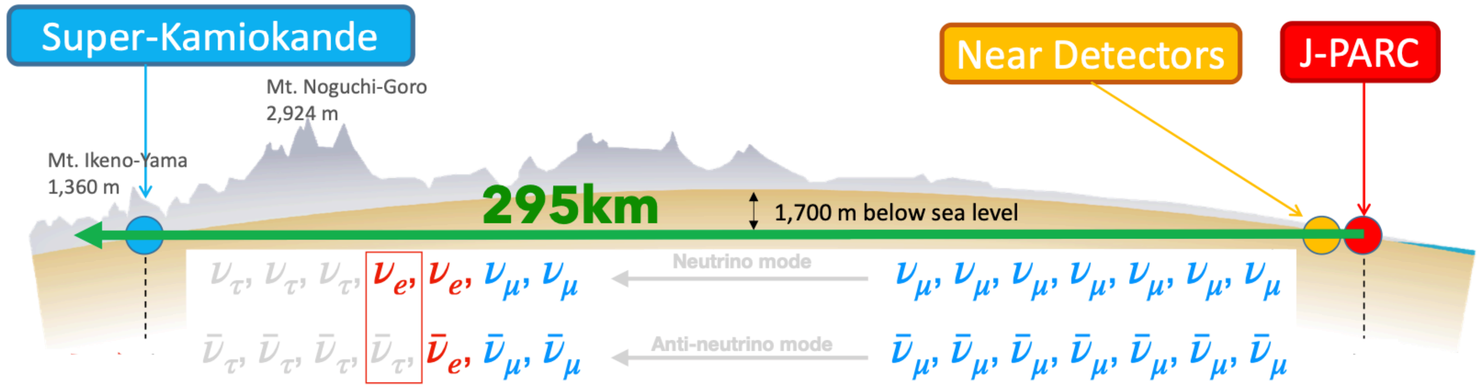


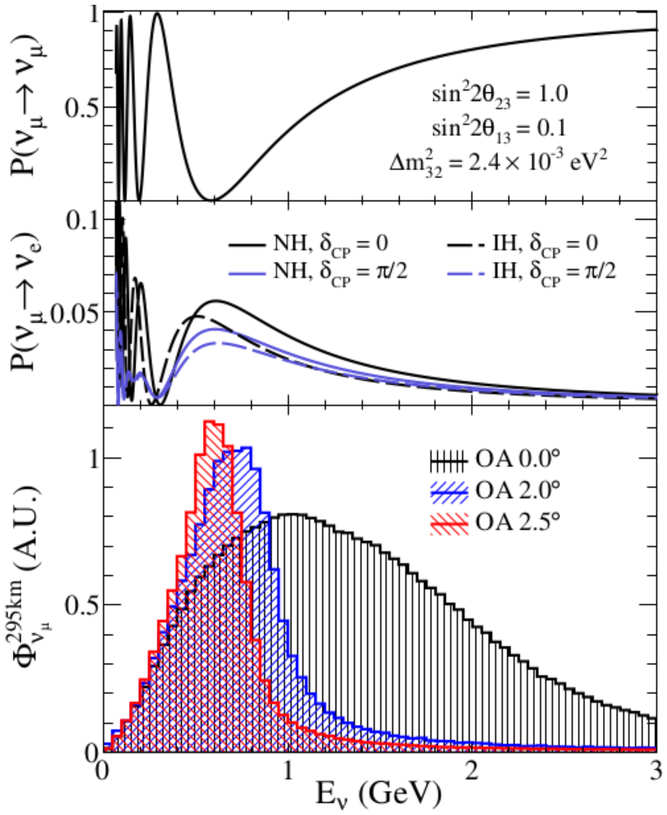
Ulysse VIRGINET, on behalf of the T2K Collaboration

Friday, April 19th 2024

# The T2K experiment



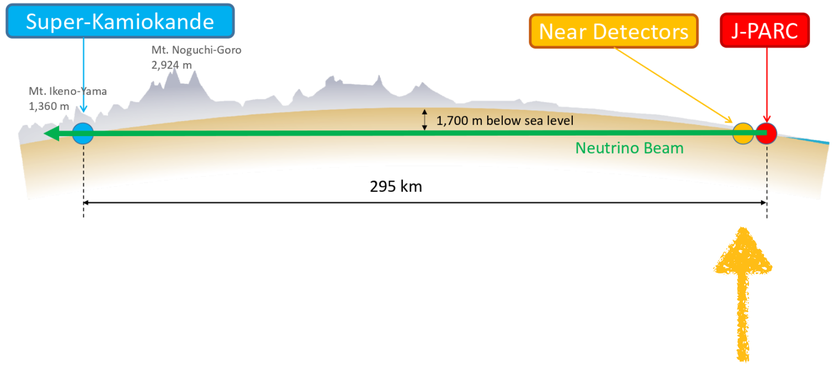



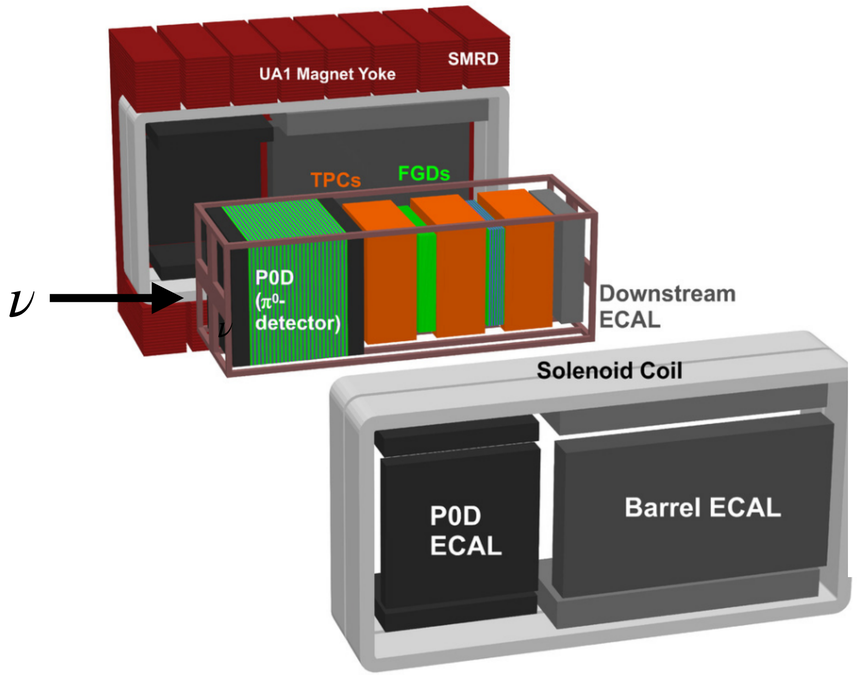




- Long-baseline neutrino oscillation experiment
- Has taken data in Japan since 2010
- 2.5° off-axis angle peaks $\nu_\mu$ energy spectrum at ~600 MeV
- Measures $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance in a $\nu_\mu(\bar{\nu}_\mu)$ beam, 295km away at Super-Kamiokande

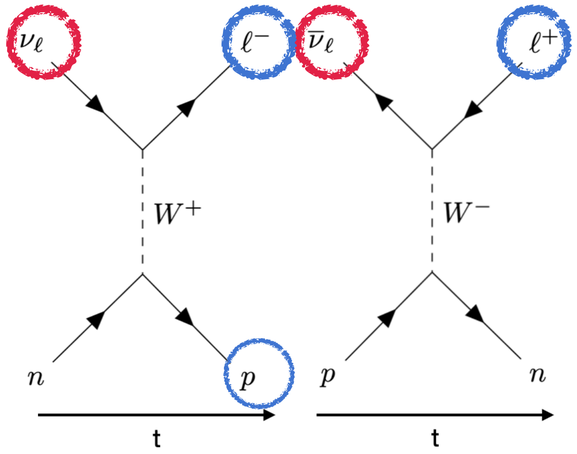
# T2K: ND280

- Magnetized (thanks to **magnet yoke** coming from CERN UA1 experiment) series of detectors, located 280m downstream of the J-PARC graphite target
- **PoD** ($\pi^0$ detector): measurement of $\pi^0$ production ($\pi^0 \rightarrow \gamma + \gamma$ mimics $\nu_e$ interaction)
- **FGDs** (Fine Grain Detectors): plastic scintillator bars planes 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)

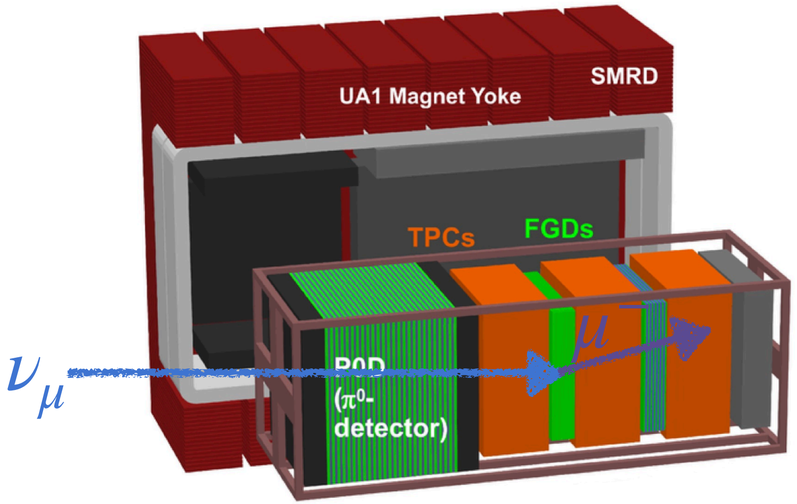


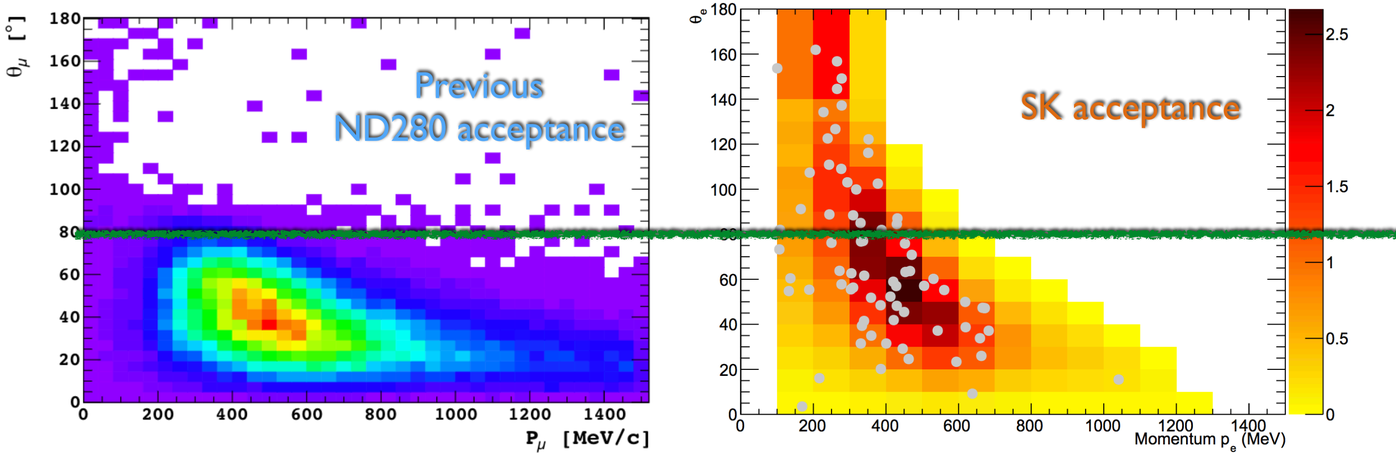

$\ell \in \{e, \mu, \tau\}$

Successfully used in all T2K OA

# T2K: some limiting factors...

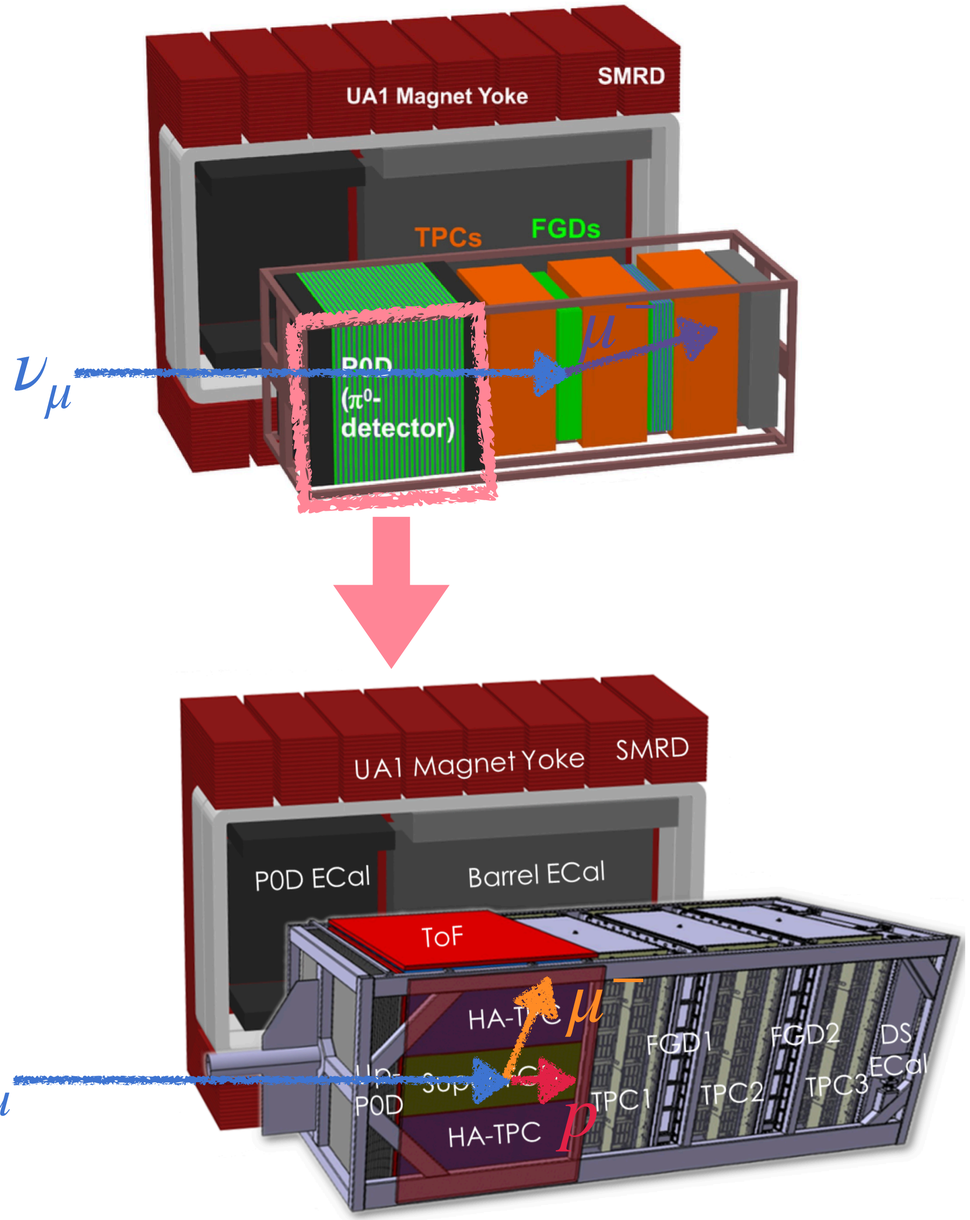
- Only $\nu_\mu$ ($\bar{\nu}_\mu$) interactions with forward-going $\mu^-$ ($\mu^+$) are selected
- Small number of events and relatively low purity in $\nu_e$ and $\bar{\nu}_e$ selections
- High threshold to reconstruct protons in $\nu_\mu$ interactions, no selections of neutrons → only muon kinematics used in T2K Oscillation Analyses



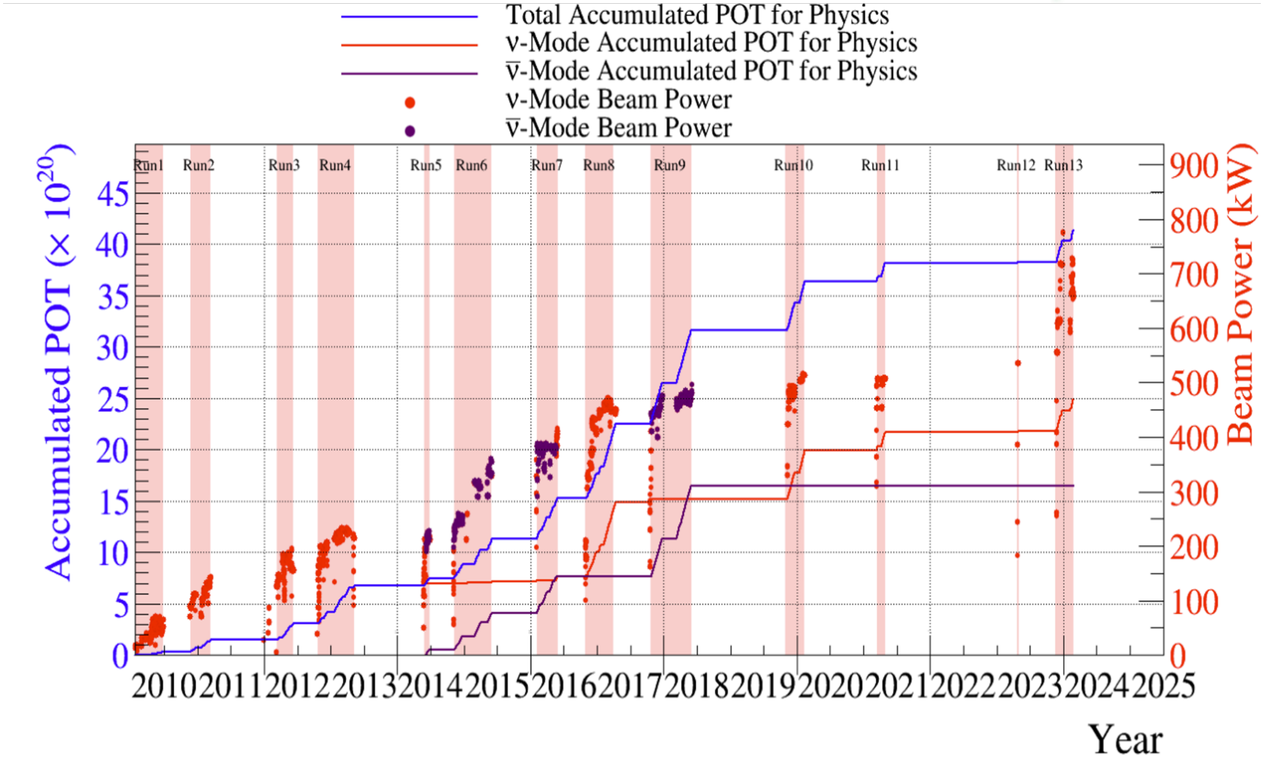
# ... but can do even better: T2K-II !

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



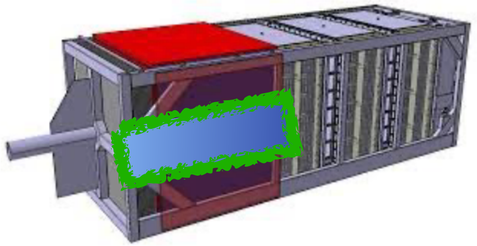
# ... but can do even better: T2K-II !

- Upgrade of J-PARC neutrino beam line: proton **beam power** gradually **increase** from $\simeq$ 500 kW to 1.3MW (in 2027) thanks to faster cycle from 2.48s $\rightarrow$ 1.36s
- New electromagnetic horns $\rightarrow$ 320 kA instead of 250 kA $\rightarrow$ **10% increase** in neutrino flux
- Goal: collect >$10 \times 10^{21}$ POT by 2027 $\rightarrow$ $3\sigma$ **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



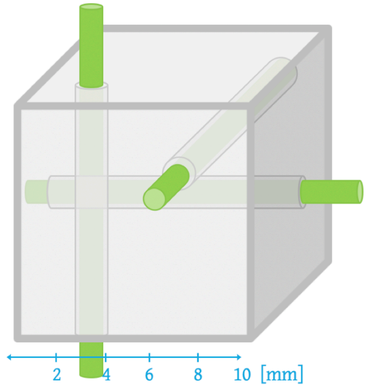

- **750 kW beam runs and upgraded ND280 will collect in ~4 months a statistics equivalent to the one provided by ND280 for the most recent T2K OA (2010-2022)**

# SFGD



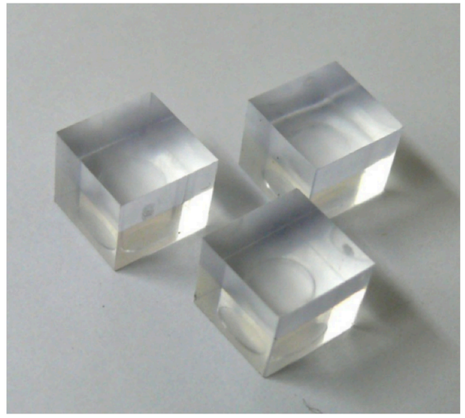
- 2 millions optically independent plastic scintillator cubes of 1 cm3 made of polystyrene and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP.
- **~40 p.e./MIP/fiber**

*Nucl.Instrum.Meth.A 1041 (2022) 167219*

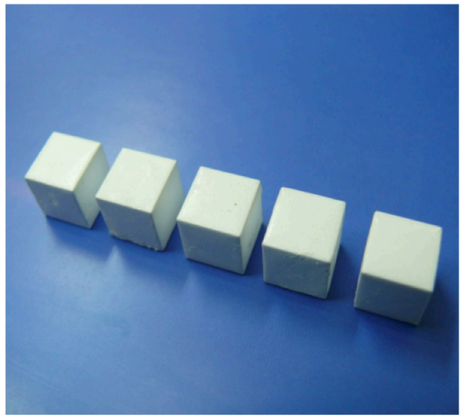



- SFGD cubes production at UNIPLAST (Russia)

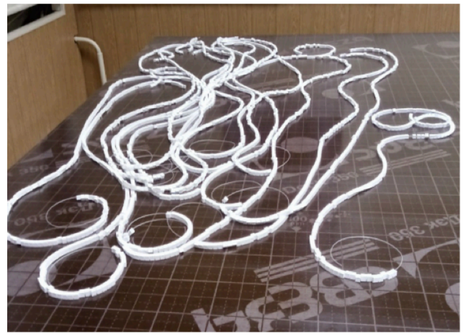
**Produce cubes by injection molding**

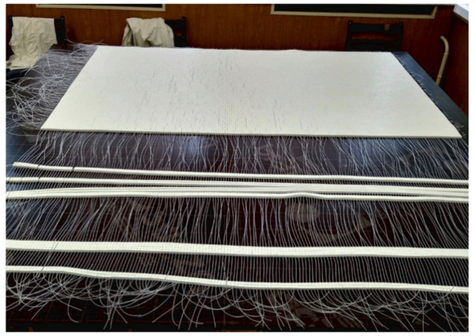


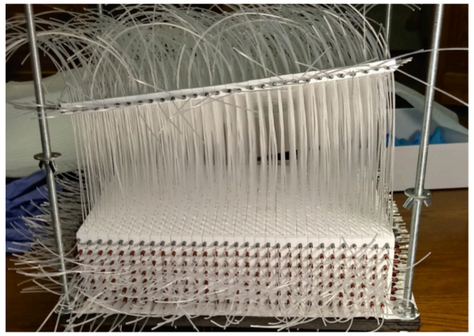
**Etched in a chemical to deposit a reflective layer**



**3 orthogonal holes are drilled**

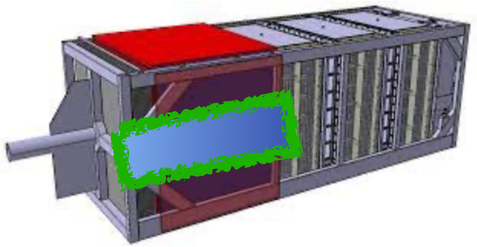




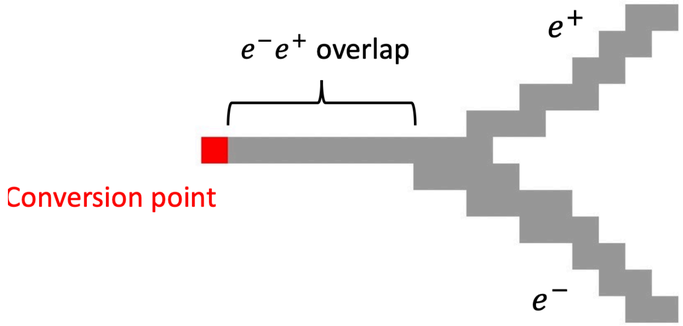


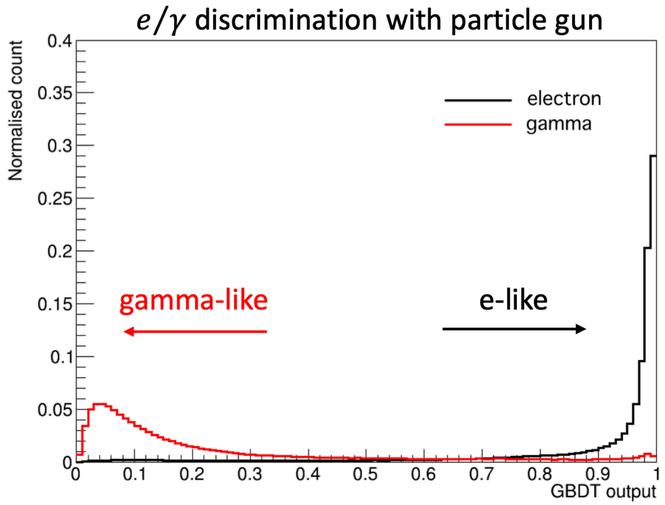
**Assembled in 56 X-Y layers with fishing lines before shipment to Japan**

# SFGD: $\nu_e$ reconstruction

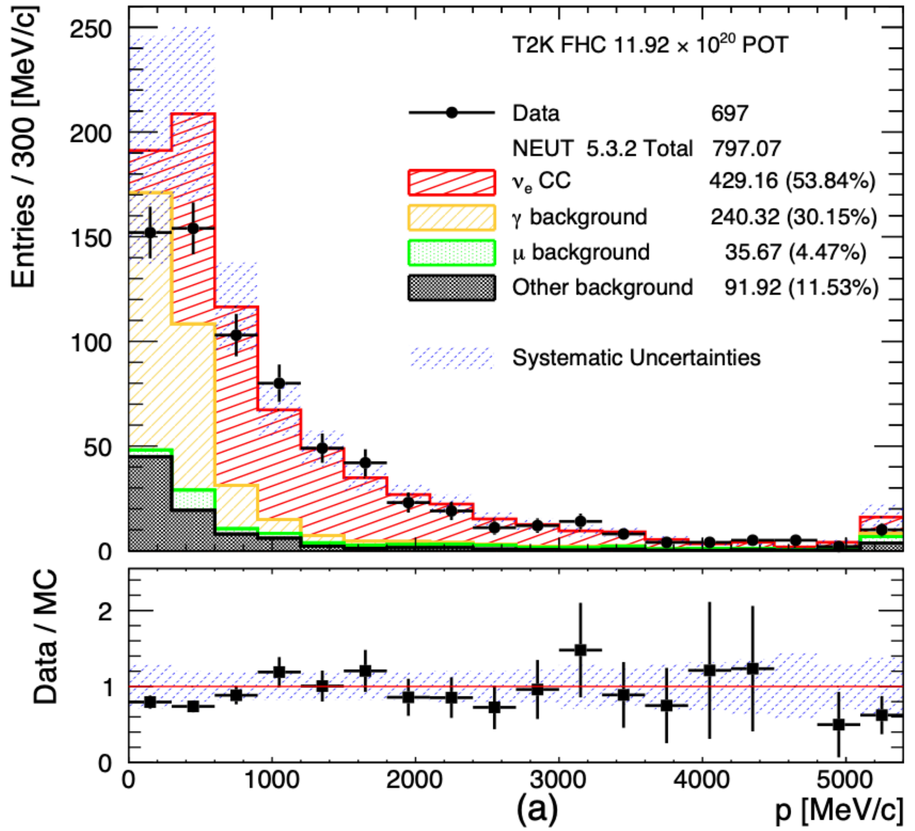


- SFGD high-granularity means better separation of $e^-$ coming from $\nu_e$ interactions and the ones coming from $\gamma \rightarrow e^+e^-$ conversions
- **Expect a cleaner sample of low energy $\nu_e$**

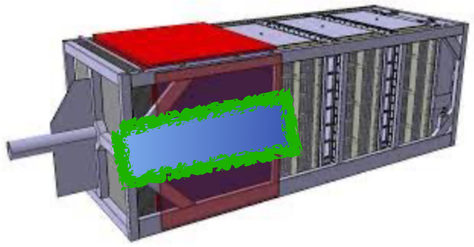


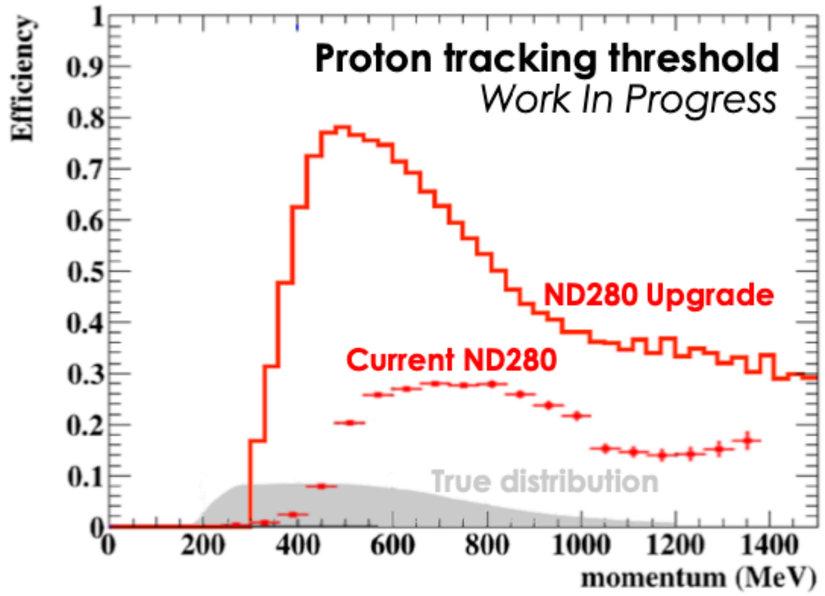

*JHEP 10 (2020) 114*

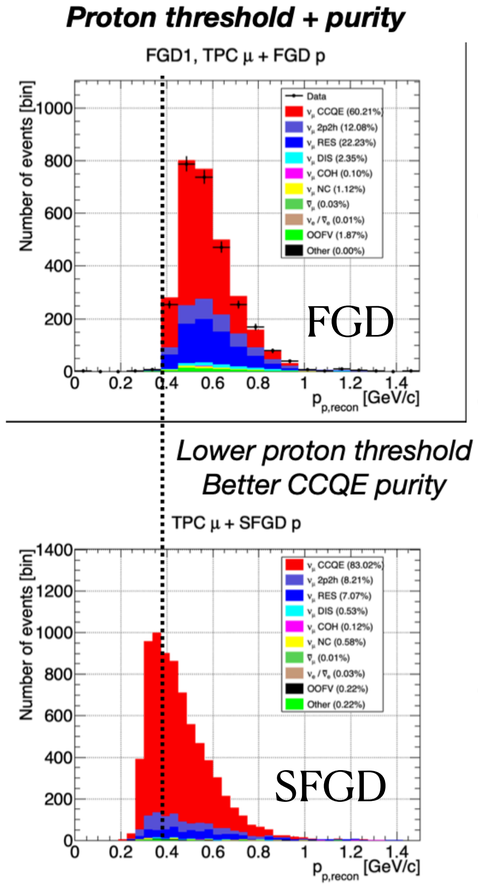


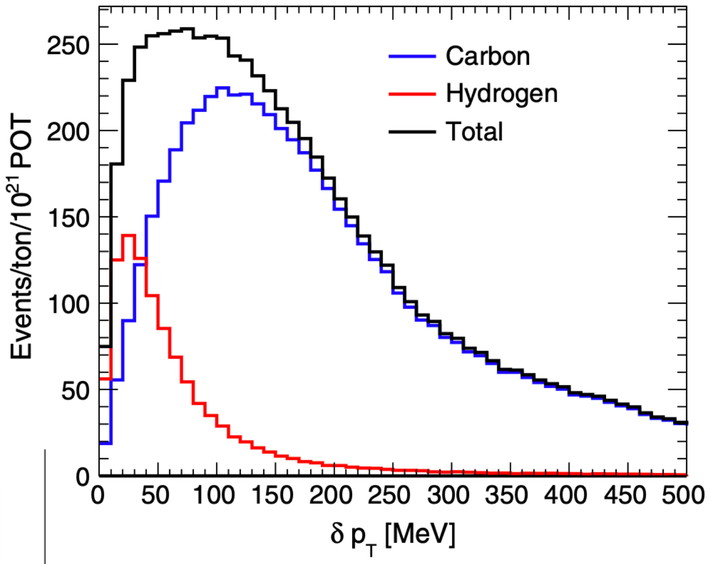
# SFGD, hadronic part

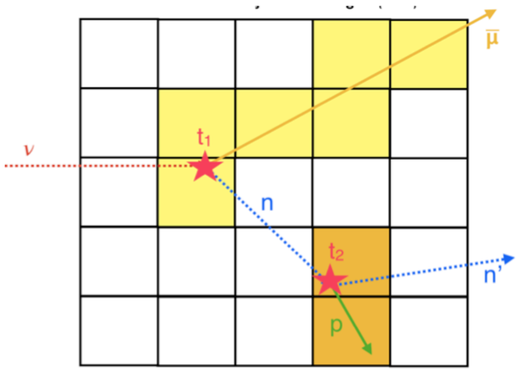


- Better efficiency to **reconstruct proton** at low energy, **threshold is at 300 MeV/c** !



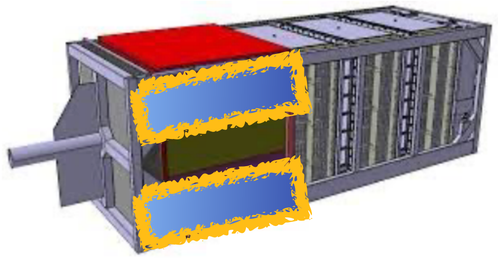



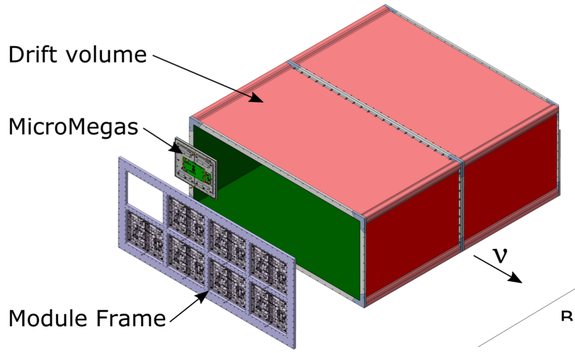



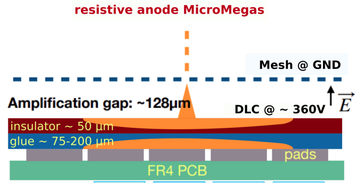




- Reconstruction of **neutron kinematics** thanks to their pre-thermalization scattering on protons
- Exclusive selection of $\mu^+ + n$ **samples** of $\overline{\nu}_\mu$ interaction similar to what is done with $\mu^- + p$ in $\nu_\mu$ case
- Sample used to measure $\overline{\nu}_\mu$ interactions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

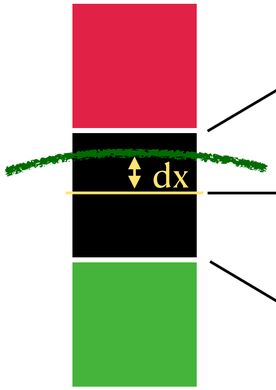
# HA-TPC

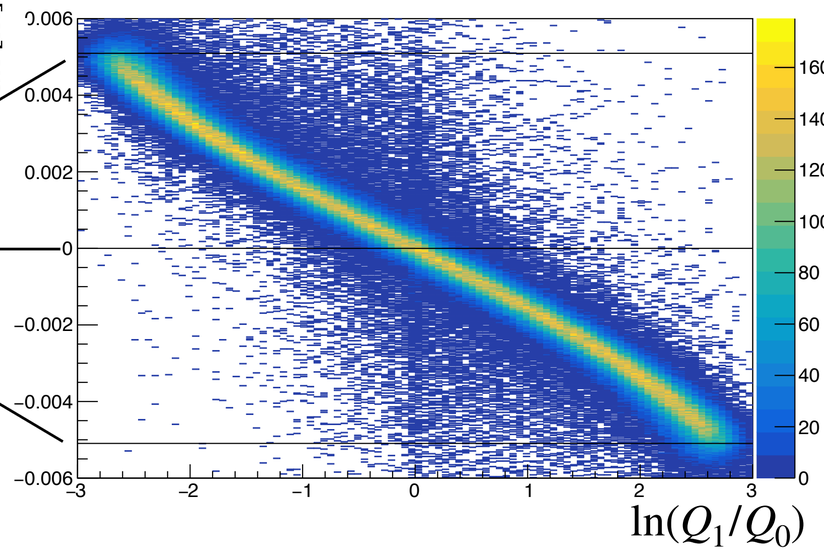


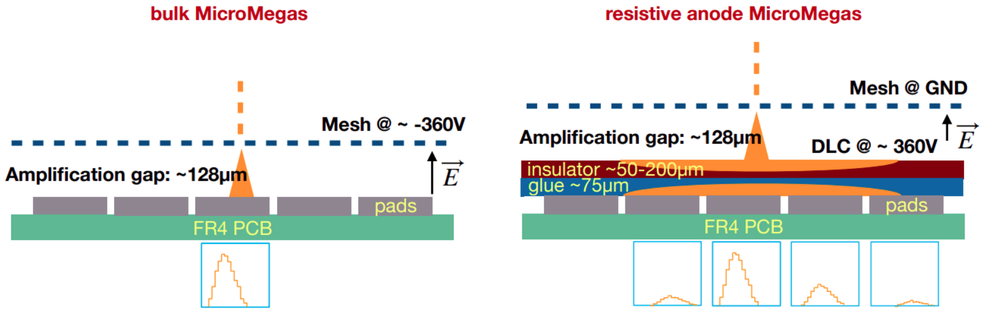


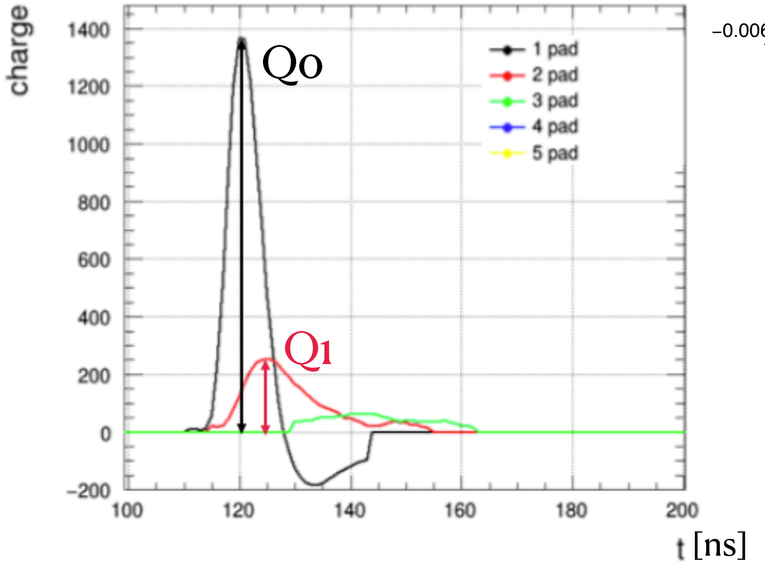




- New TPCs equipped with the **resistive anode MicroMegas (ERAM) technology**
- Contrary to the bulk MicroMegas which equip the vertical TPC, ERAM allow a charge spreading on several pads

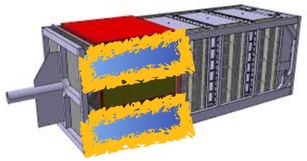


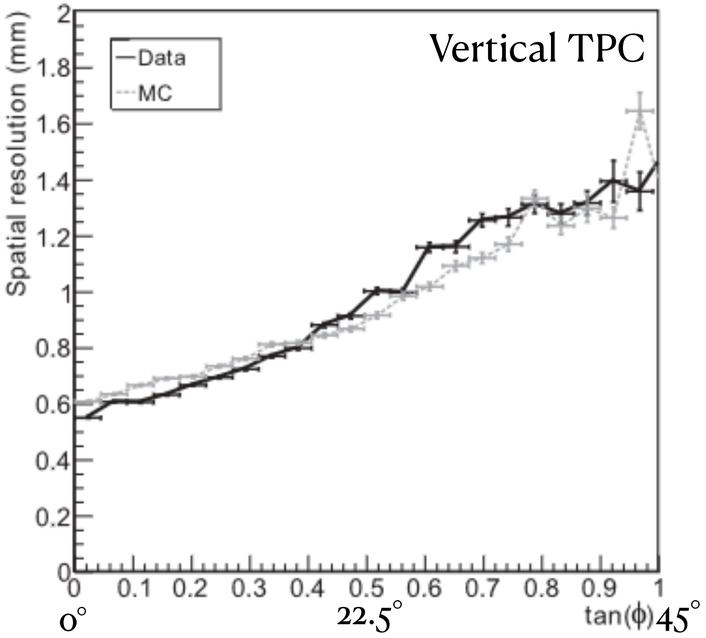



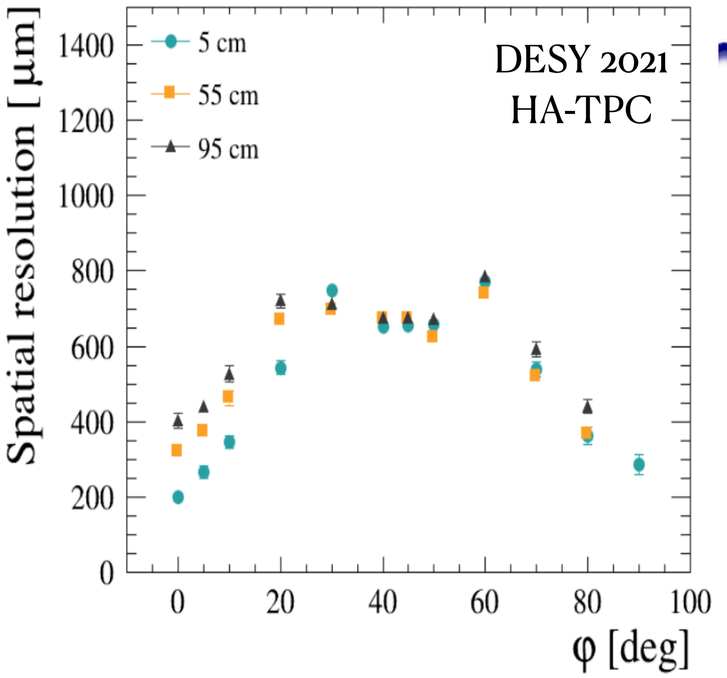



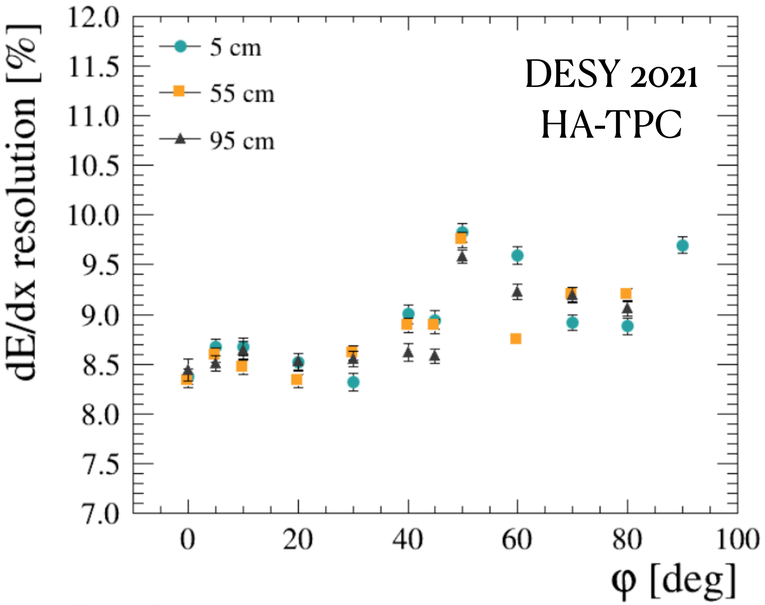
# HA-TPC



- At DESY 2021 test beam, a spatial resolution between 200 and 800 $\mu$m has been measured, as opposed to 600-1600 $\mu$m for vertical TPCs
- dE/dx resolution of less than 10% has also been measured in this test beam campaign

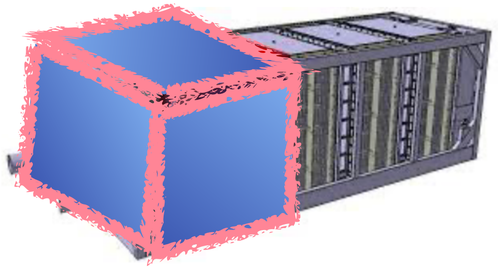


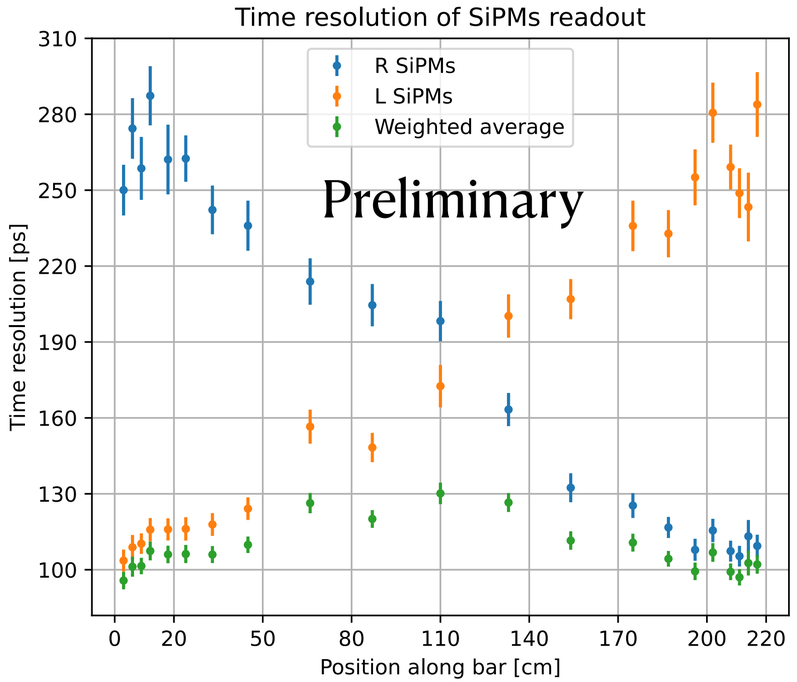



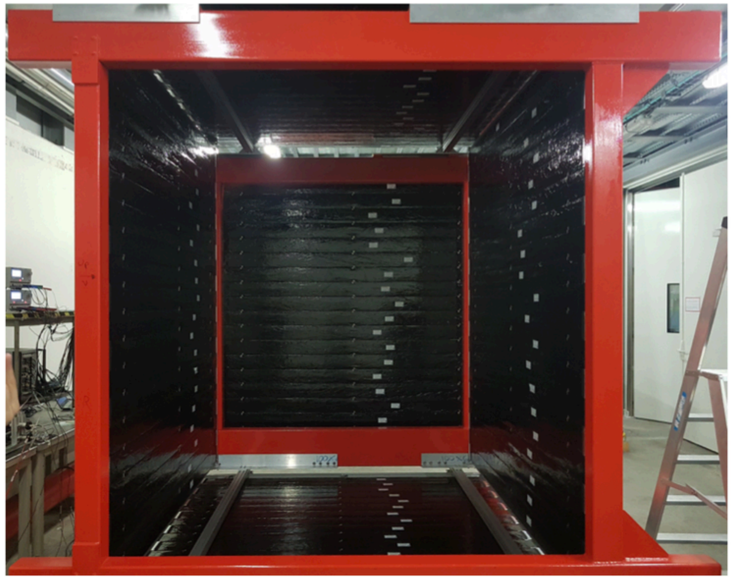

*Nucl.Instrum.Meth.A 1052 (2023) 168248*

# TOF

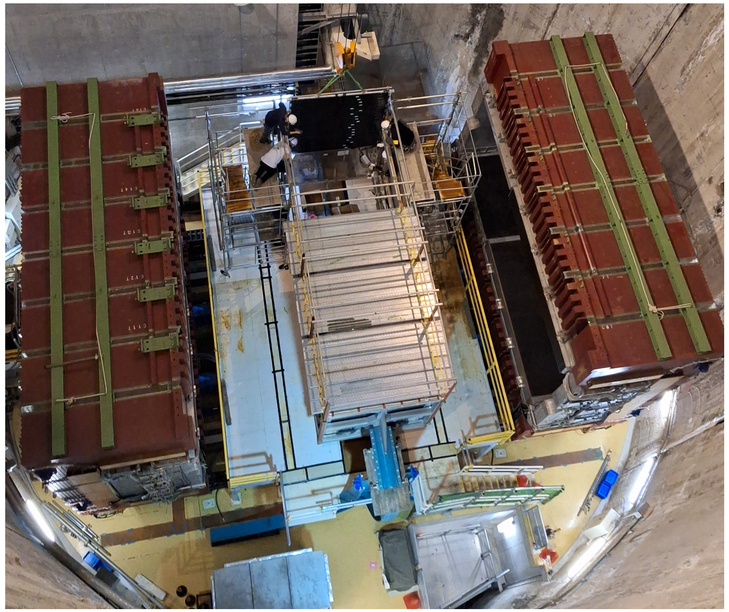


- 6 Plastic scintillator planes forming a cube that surround SFGD and HAT
- Reconstruction of track direction with a time resolution between 100 and 300 ps



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



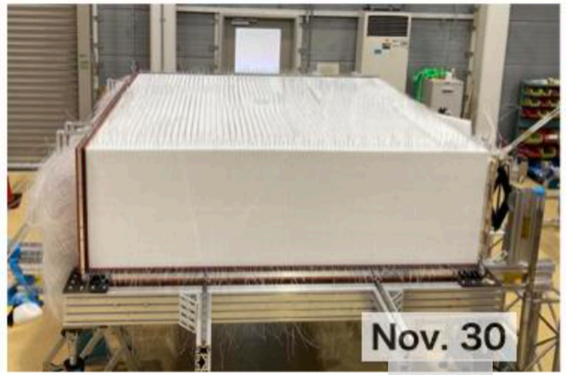
TOF panel installation in the ND280 pit at J-PARC, July 2023

# Super-FGD and HA-TPC assemblies

- SFGD assembly at J-PARC

First cube layer assembly

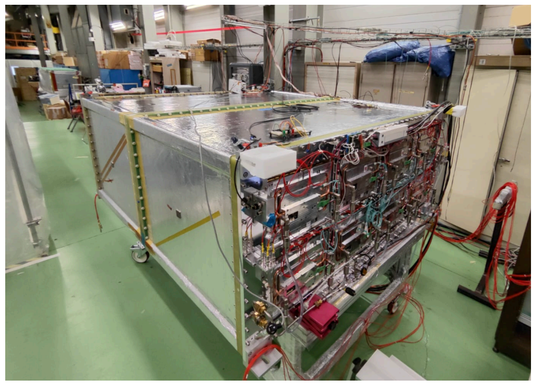

Stop panels removed




Box closure

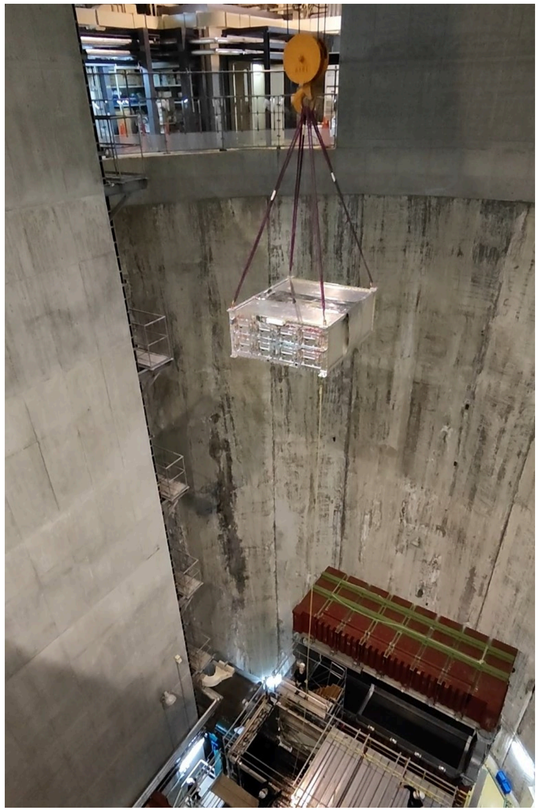

Light barrier/cables asse

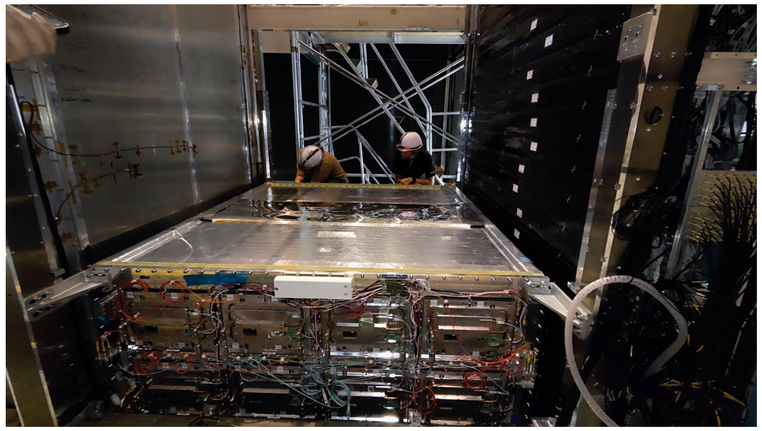

- HA-TPC assembly and commisionning at CERN, arrived fully instrumented at J-PARC!

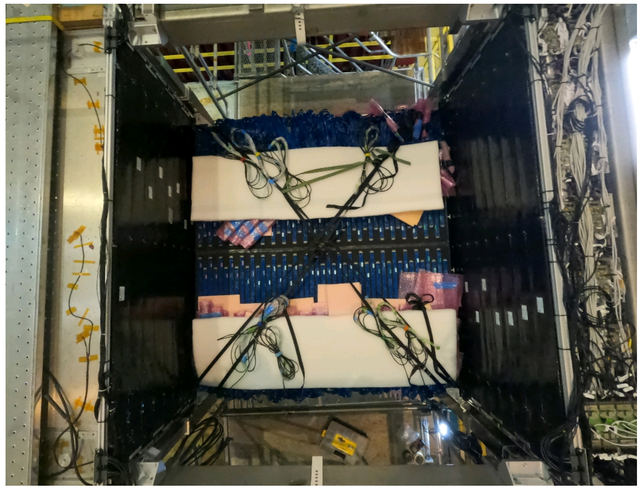



HA-TPC delivered at J-PARC

# ND280 Upgrade's installation

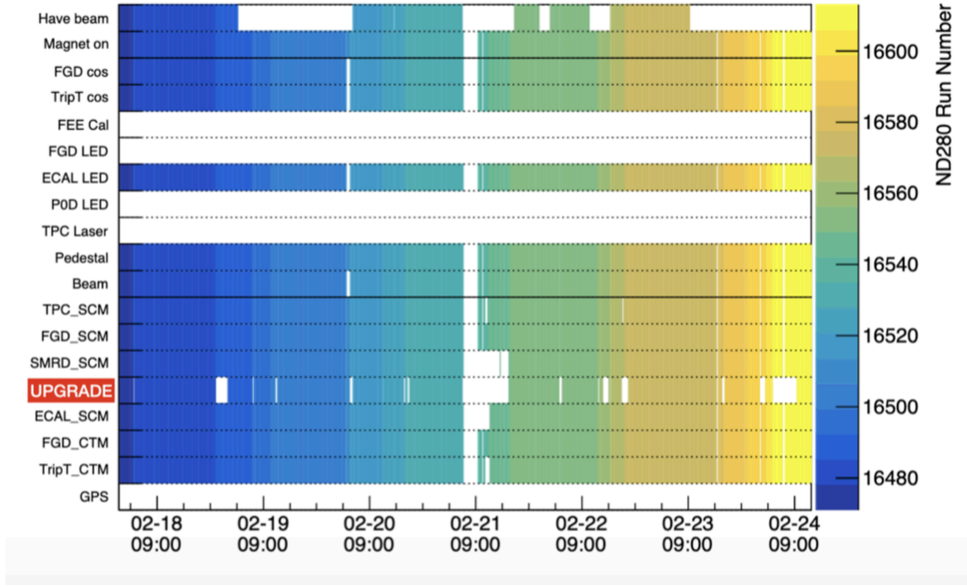


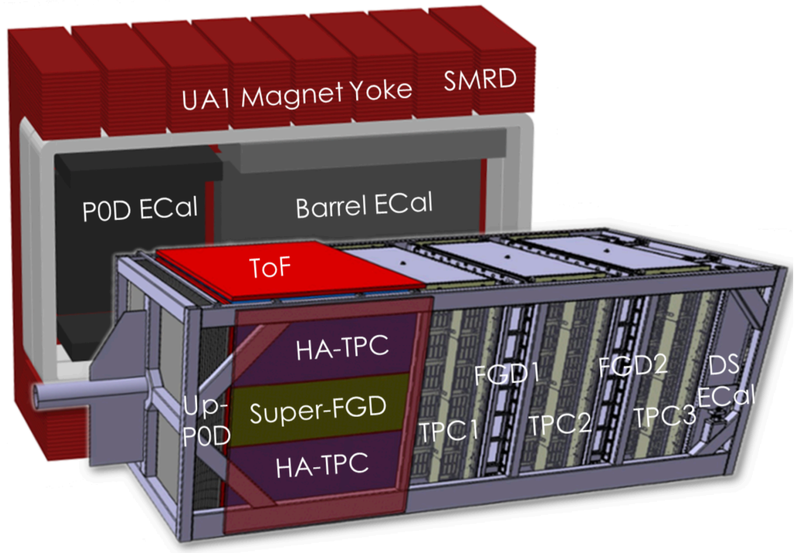


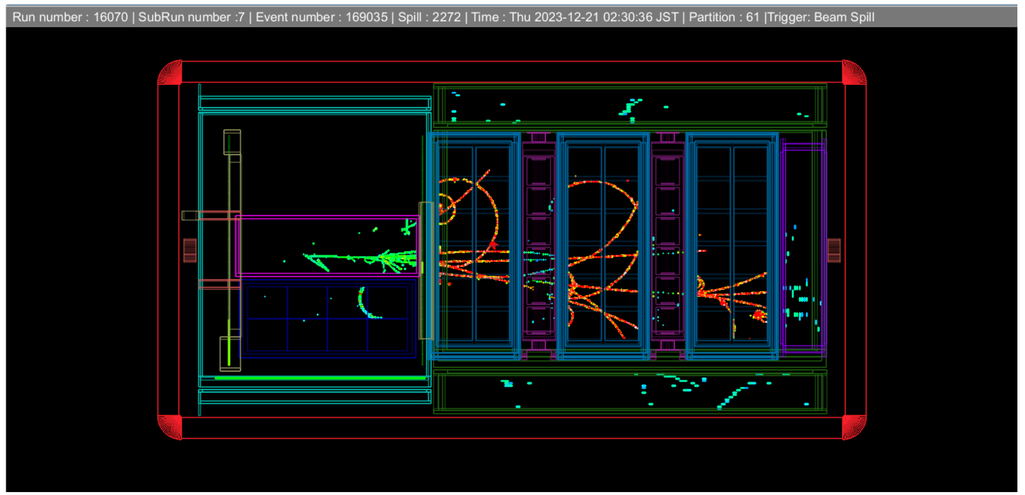


# T2K-II is truly happening !

- 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 together with the 2 last TOF panels by end of April 2024 and should be ready for May-June runs!

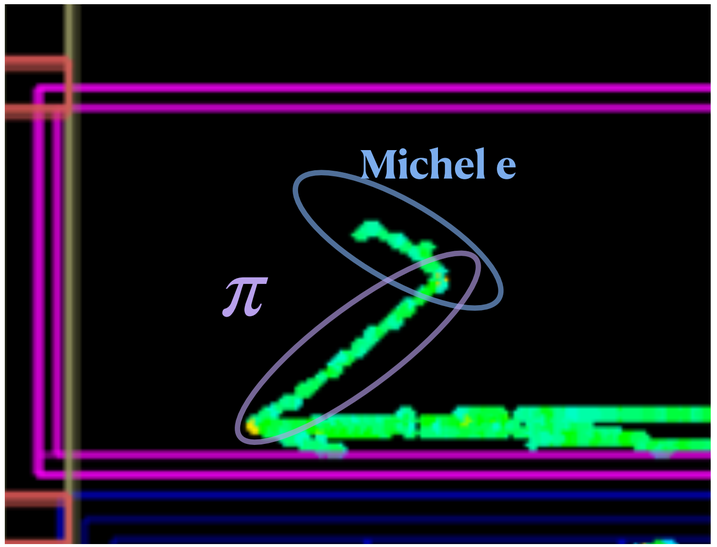


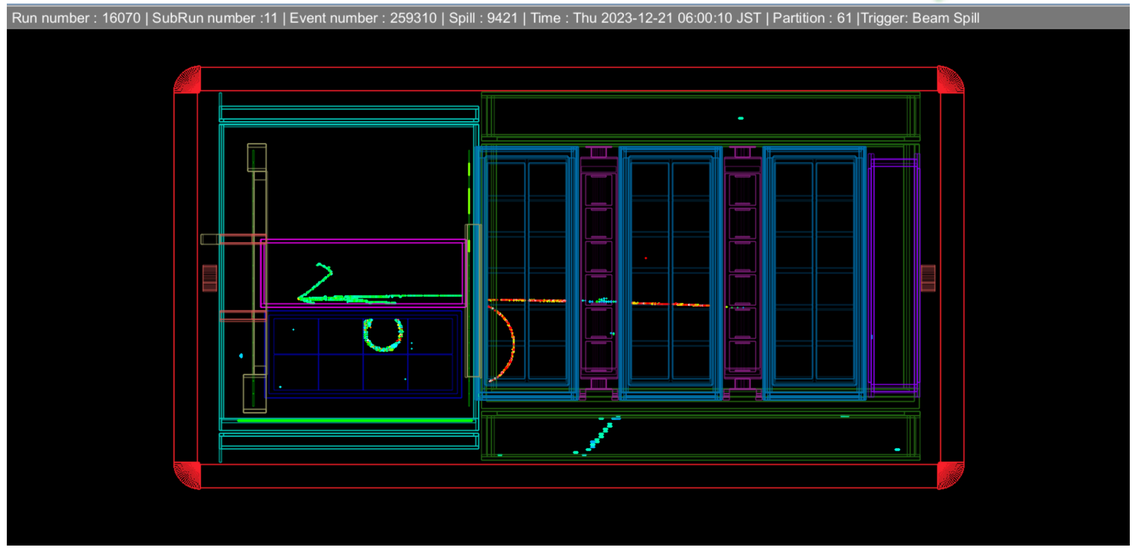



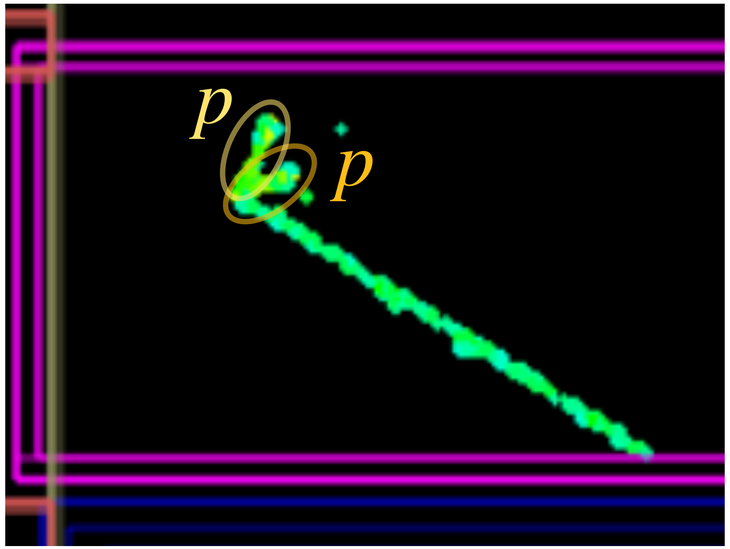
# Some nice event displays

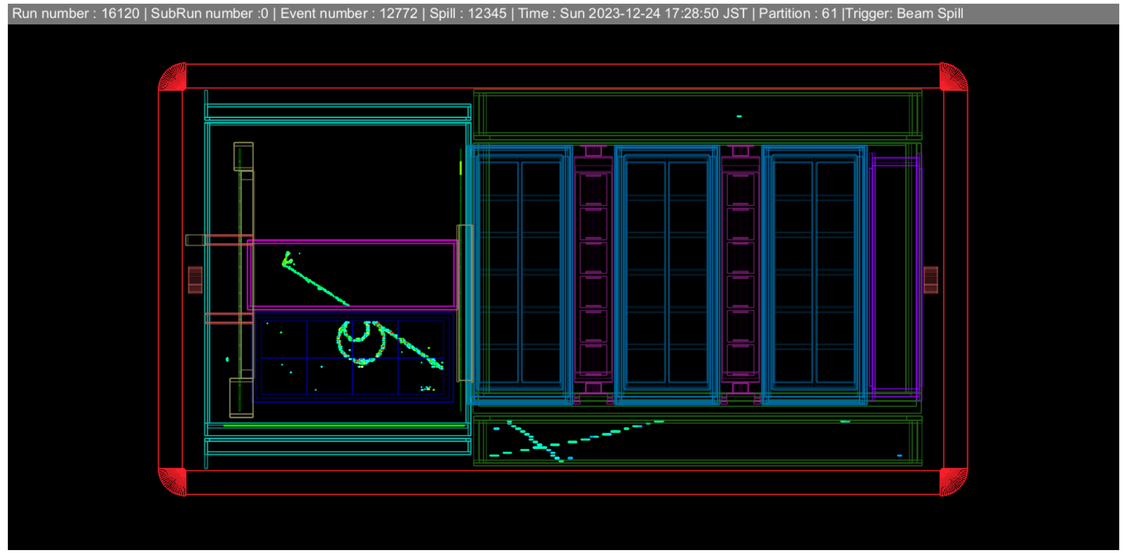
- Pion and Michel electron ?



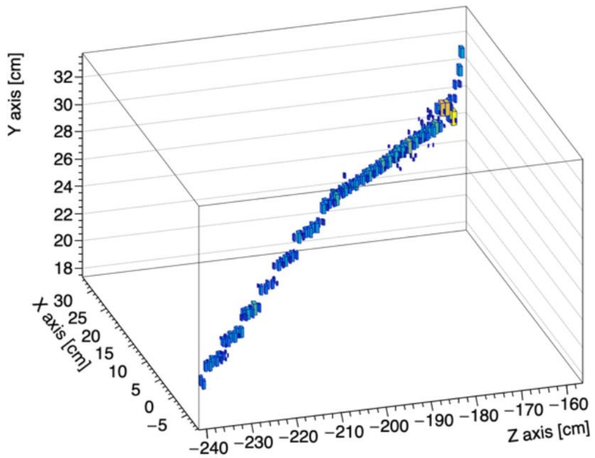

- 2 stopping protons from 2p2h interaction ?

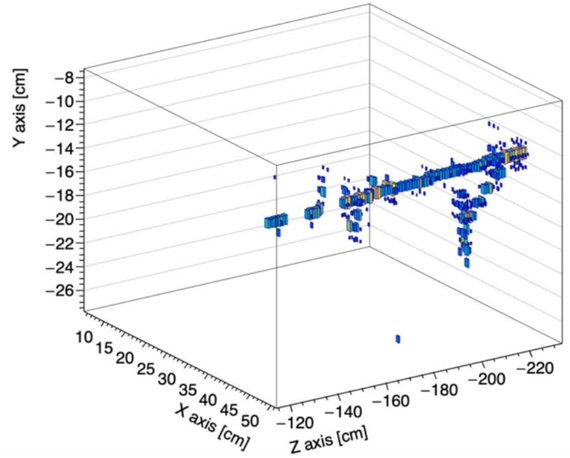


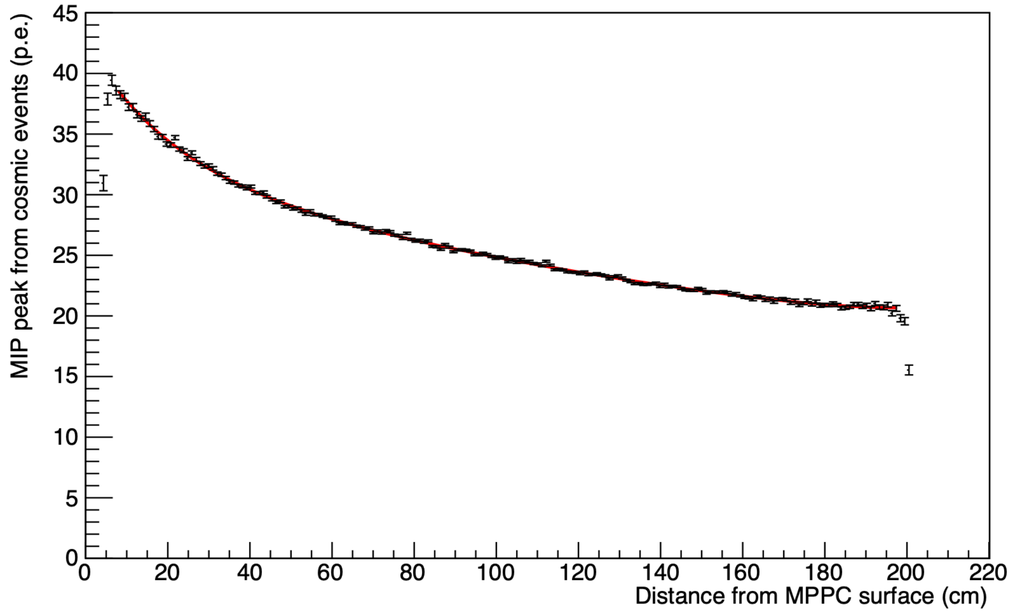



# ND280 Upgrade: SFGD Preliminary results

- Plots of ND280 physics meeting ?

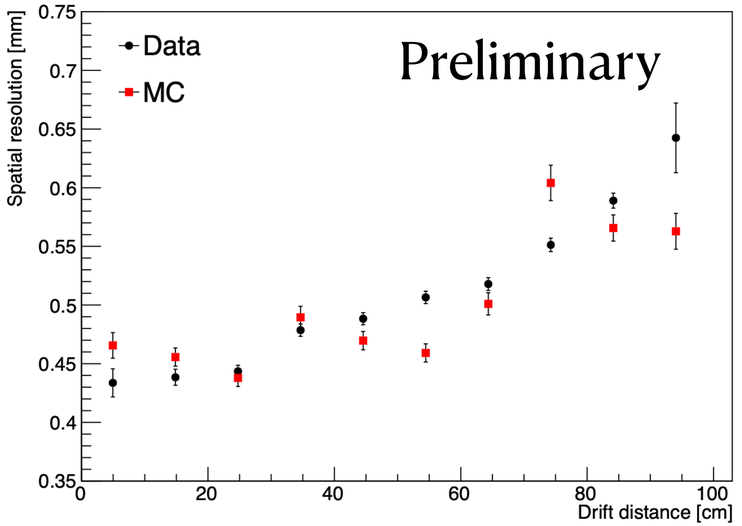


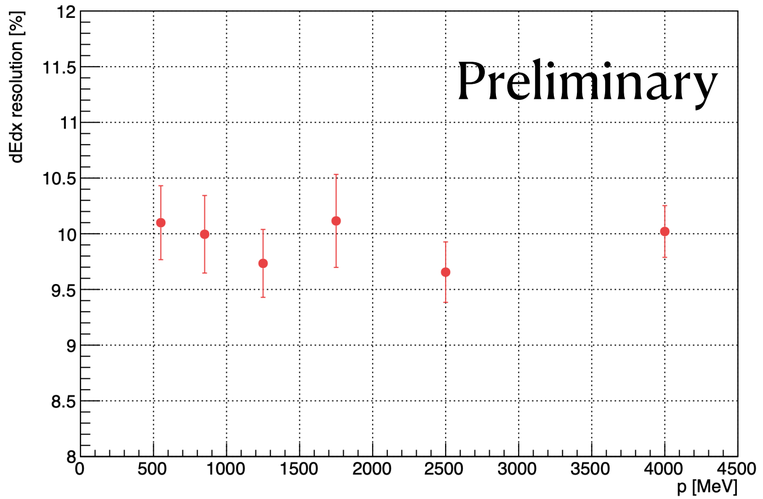



# ND280 Upgrade: HA-TPC Preliminary results

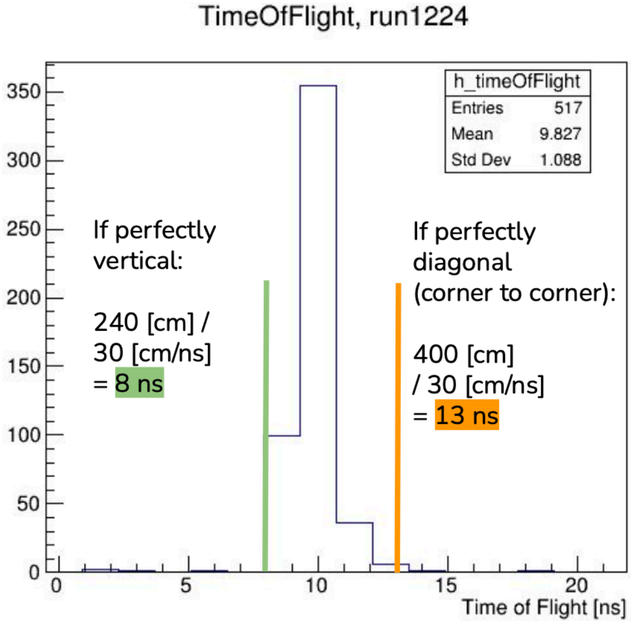
- Cosmics data taken at J-PARC in end of 2023 -> spatial resolution of ~500 $\mu$m, in both dqtq qnd si,ulqtions
- dEdx resolution of the order of 10% has been measured in a wide range of momenta

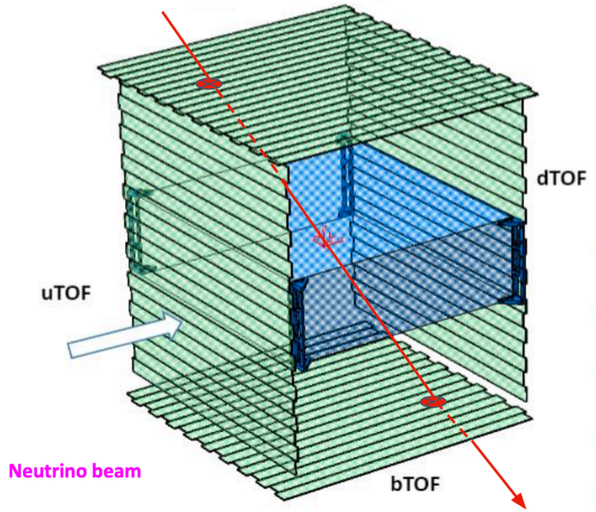


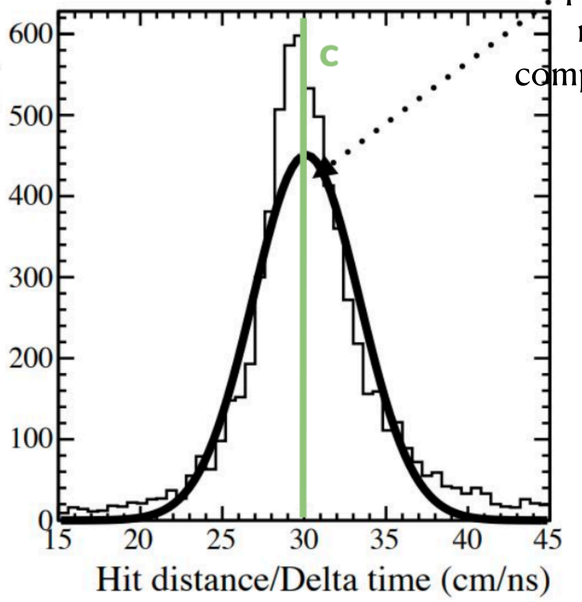
# ND280 Upgrade: TOF Preliminary results

- Cosmics data taking

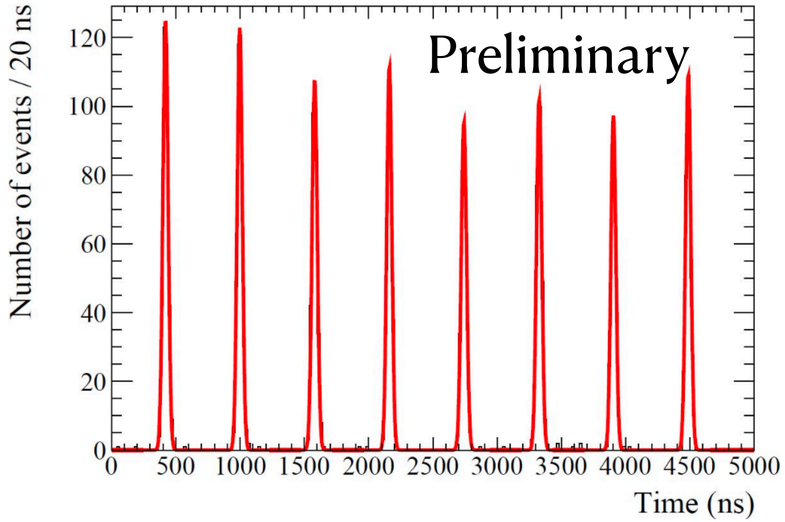



Cosmic crossing Top and Bottom




Speed of light measured compatible with c!




- Beam data taking
- TOF clearly distinguish the eight beam pulses 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
- Top HA-TPC has arrived in J-PARC and should be installed in the pit with the 2 other TOF before June run
- ~20000 $\nu_\mu CC0\pi$ interactions are expected in SFGD in only one month of data taking!

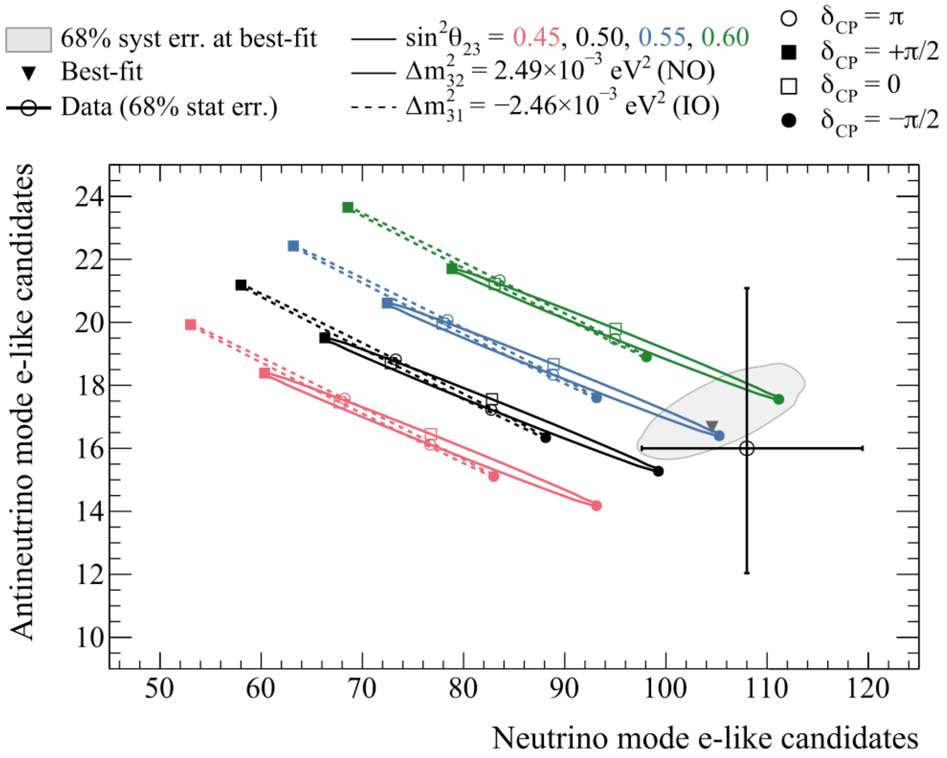

Top HA-TPC is well arrived at J-PARC!
April 8th 2024

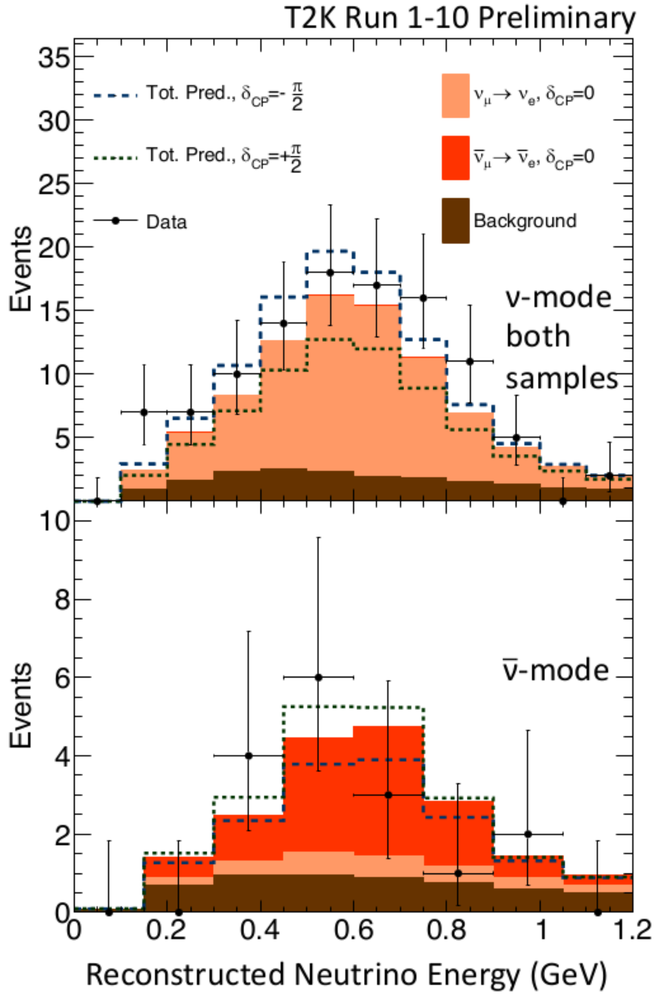
# Thank you for your attention!

# Back-up

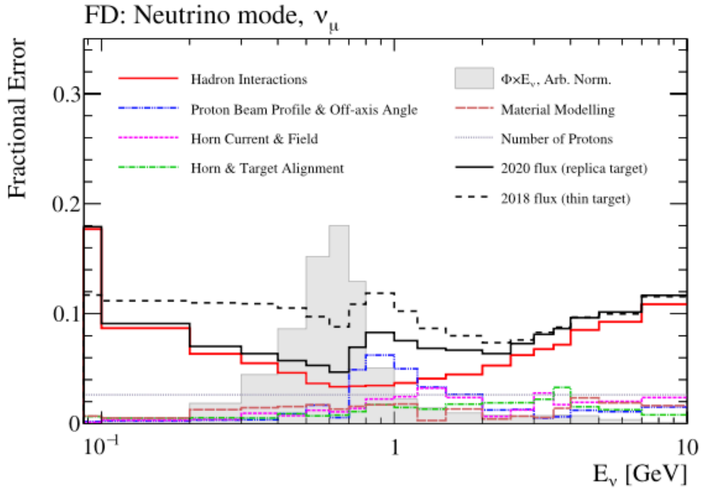
# Promising results...

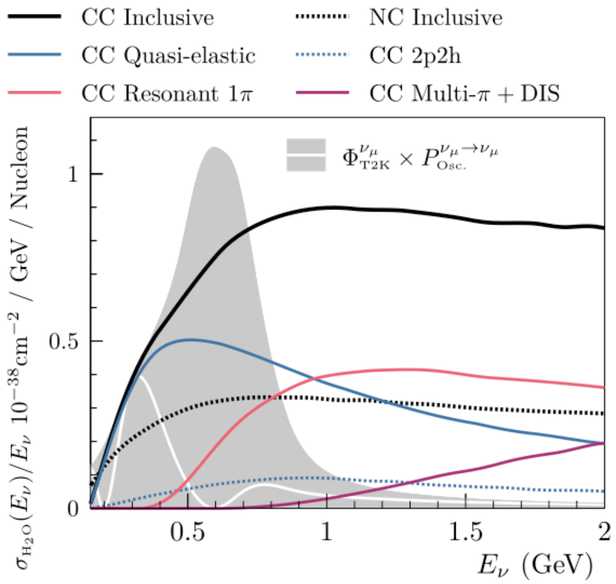
- 2 CP symmetry conserving points ruled out at the $2\sigma$ confidence level [ https://www.nature.com/articles/s41586-020-2177-0 ]




# 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 — $\nu$ x-sec — $\nu$ flux — Detector efficiency

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

**Neutrino interactions:**
Cross-section models
External data

**ND280 measurements:**
$\nu_\mu$ 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 $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$ candidates after the oscillations

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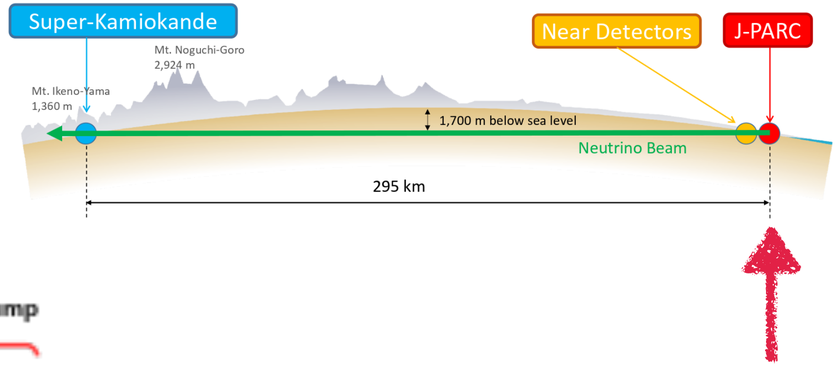
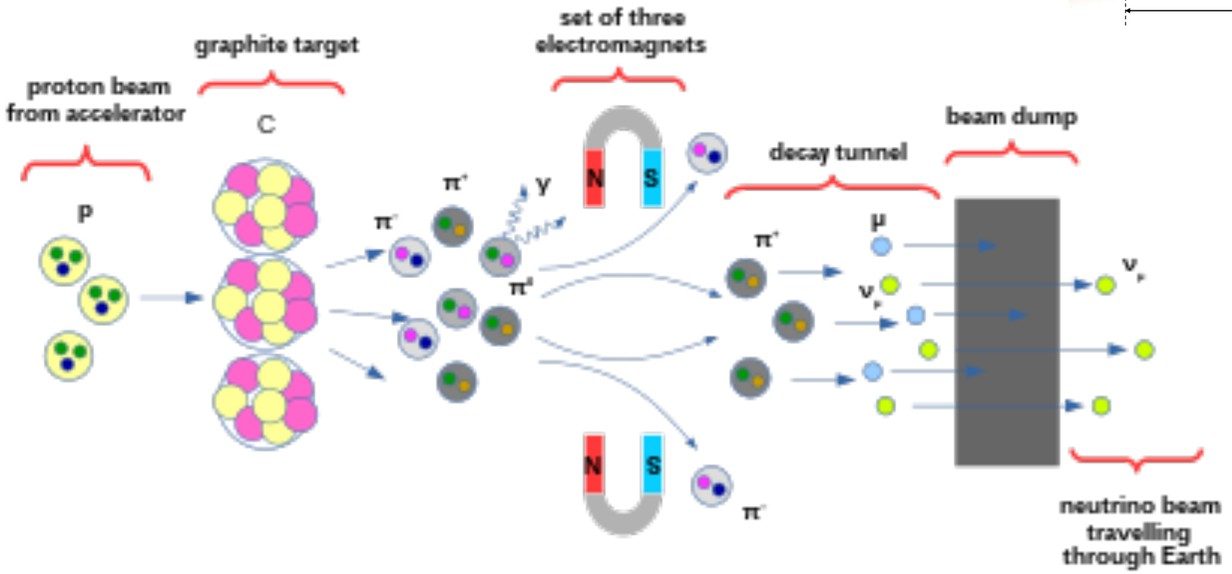
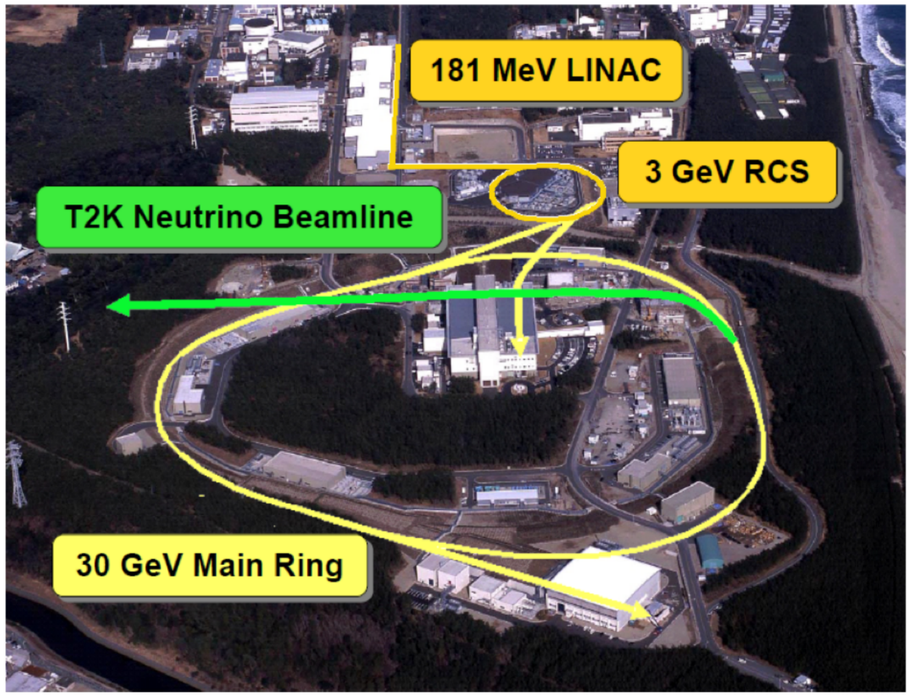
# The T2K experiment: J-PARC

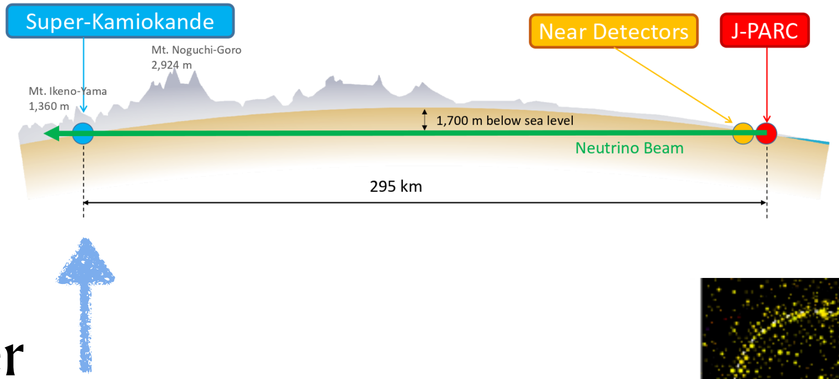


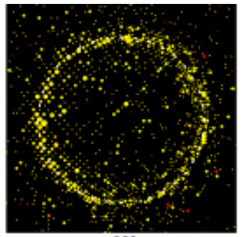

- Japan Proton Accelerator Research Complex: Acceleration of protons
- Collisions on a graphite target produce mainly mesons: $\pi^{\pm}, K^{\pm}$
- Thanks to magnetic horns, select:
  - Either $\pi^{+}, K^{+}$ which decay mainly in $\mu^{+} + \nu_{\mu} \rightarrow \nu_{\mu}$ **beam**
  - Or $\pi^{-},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



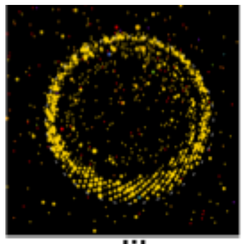
# The T2K experiment: SK



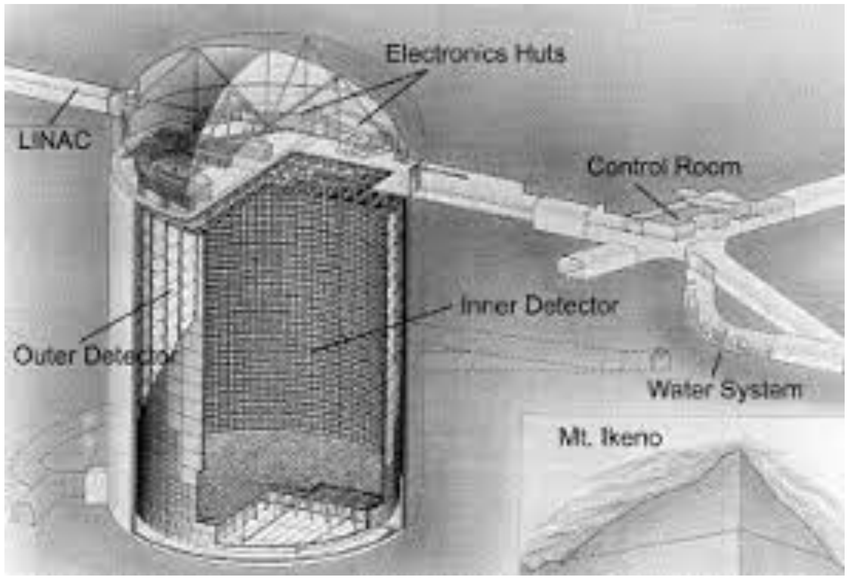

- 40m diameter × 40m height cylinder
- Filled with 50000 tons of ultra pure water
- More than 10000 PMT aim to detect Cherenkov light emitted by charged lepton coming from $\nu$ interaction

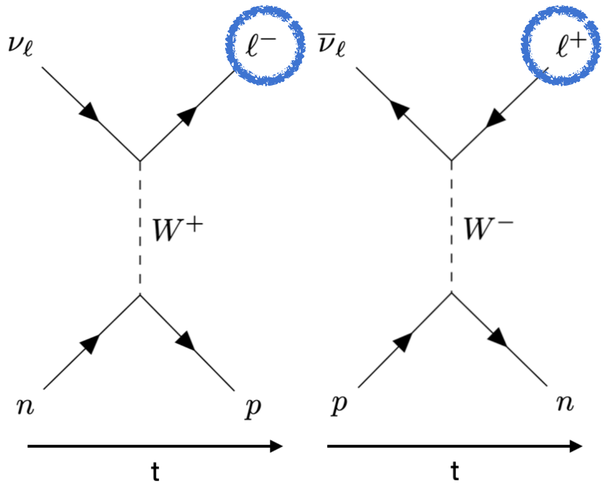


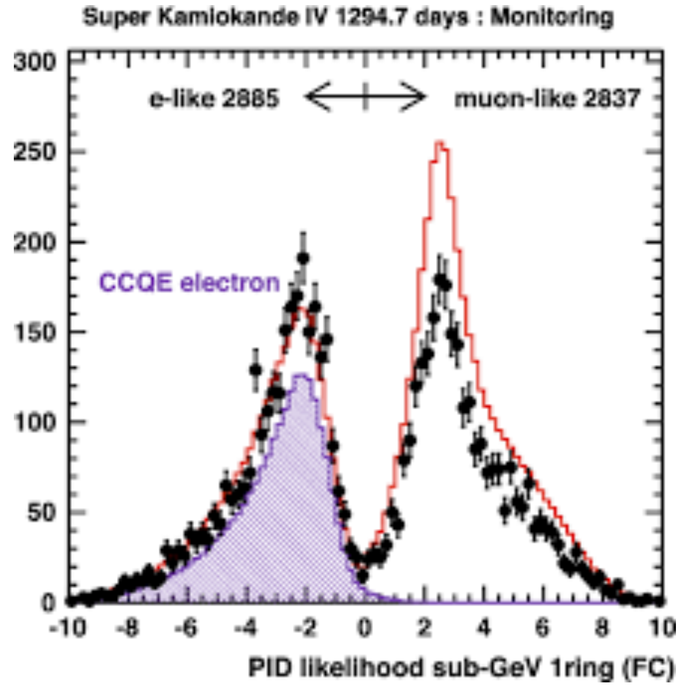
$\nu_e$-like



$\nu_\mu$-like

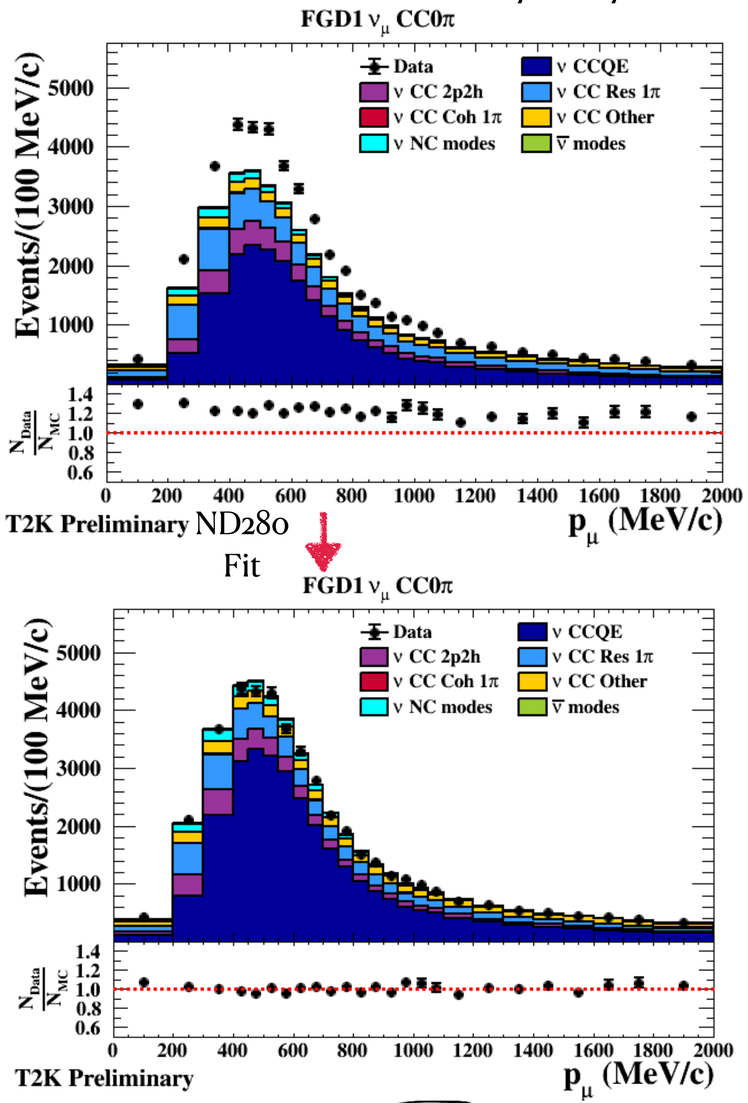


# Reduction of flux and x-sec uncertainties at ND280

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




- Reduction of flux and cross-section systematic uncertainties