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Commissioning of 3D-segmented neutrino detector SuperFGD in the T2K neutrino beam

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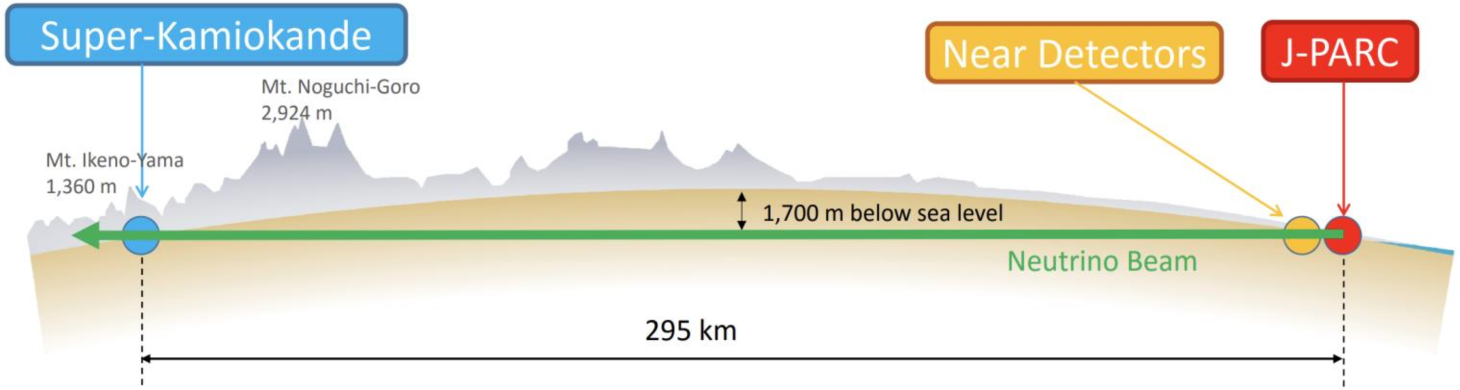
T2K experiment

T2K (Tokai–to–Kamioka) experiment is a long-baseline neutrino experiment in Japan studying neutrino oscillations. The main goals of T2K are:

- The probe of CP violation, providing further constraints on the δ_{CP} phase,
- Precise measurements of oscillation parameters (Δm^2_{23} and θ_{23}) via disappearance studies,
- Measurements of various neutrino interaction cross-sections for different types of targets.

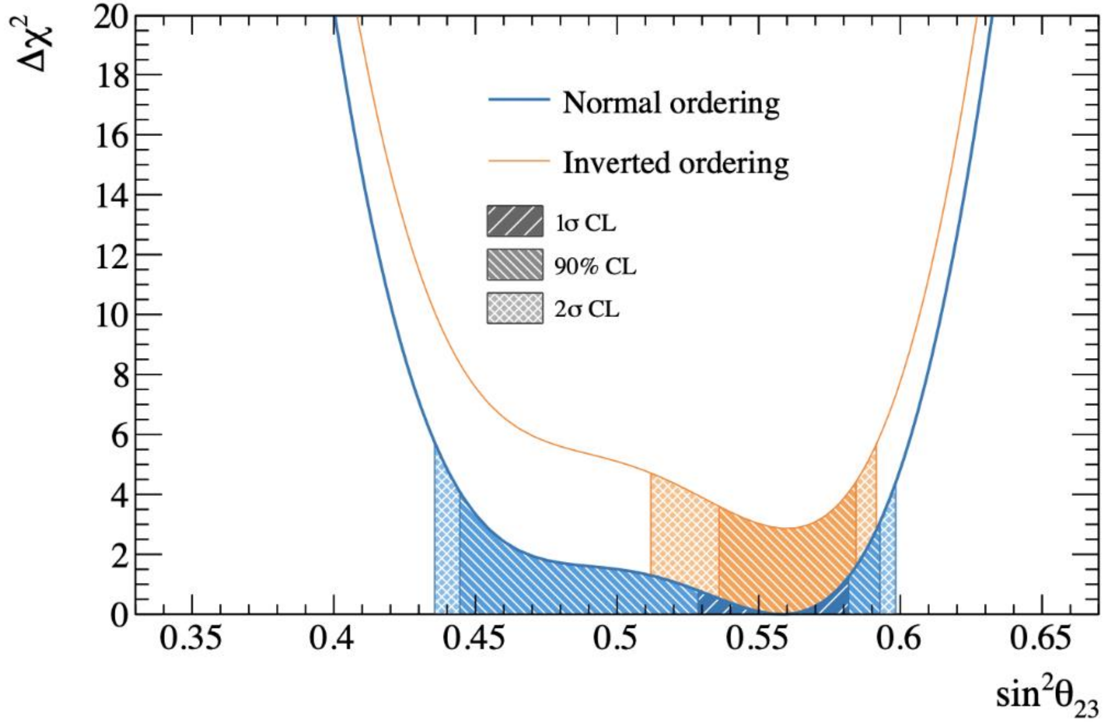
The experiment uses a muon-neutrino beam generated at the J-PARC accelerator in Tokai and sent 295 km to the far detector, Super-Kamiokande, in Kamioka.

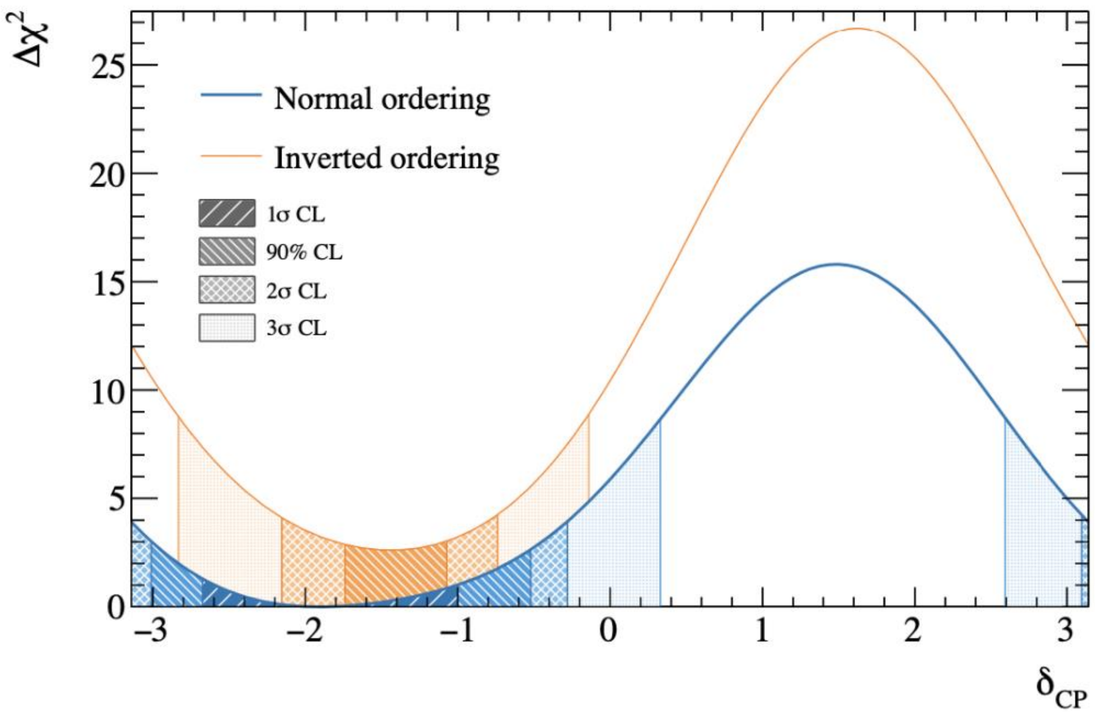
The focus of this talk will be on the near detector ND280, and more specifically on its important part, the SuperFGD detector and its commissioning.



The latest T2K results

$\Delta\chi^2$ surface for θ_{23} and δ_{CP} with Feldman-Cousins CL intervals for both mass orderings





	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

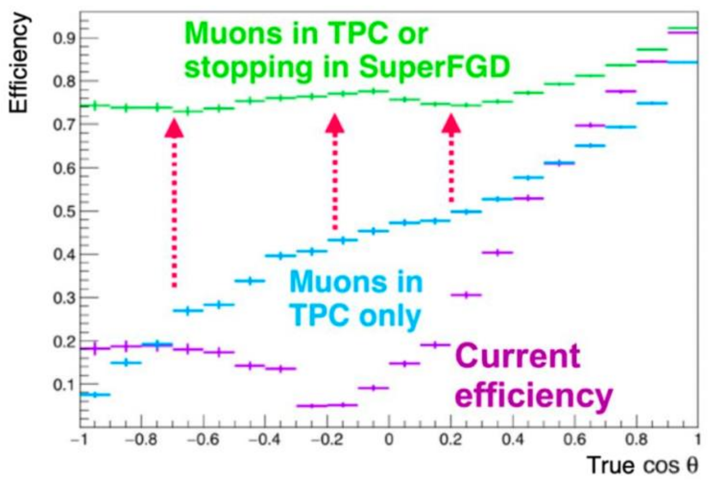
- Large region of $\delta_{CP} > 0$ is excluded at $> 3\sigma$
- The CP conserving value of ***$\delta_{CP} = 0$*** is excluded at ***2σ*** C.L., ***$\delta_{CP} = \pi$*** is exclude at about ***90%*** C.L.
- Preference for maximal CP violation ***($\delta_{CP} \sim -\frac{\pi}{2}$)***
- $\delta_{CP} = -2.08^{+1.33}_{-0.61}$

T2K Collaboration (A. Ajmi), "Latest Results from the T2K and NOvA Experiments," PoS, vol. HQL2023, p. 024, 2024

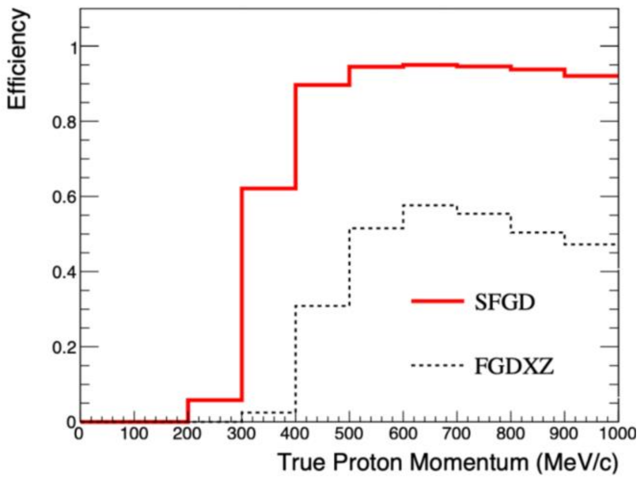
Motivation of the ND280 Upgrade

The uncertainties of current T2K oscillation measurements are dominated by statistics. However, systematics will limit T2K (and Hyper-Kamiokande) sensitivity in the future.

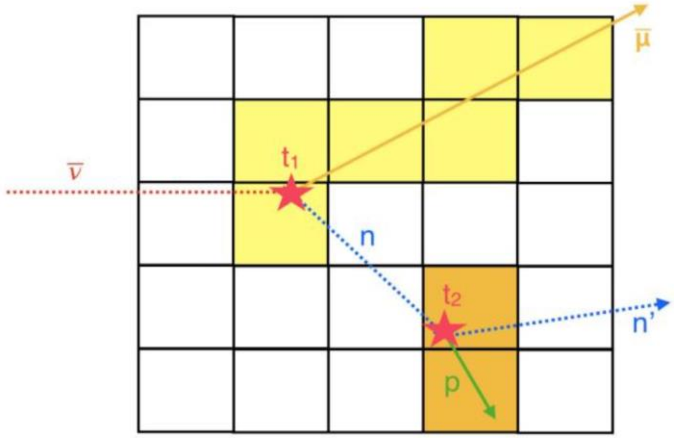
- It is important to measure neutrino interactions in all phase space.
- Precisely detect particles produced at any angle.
- Reduce detection threshold to measure protons with low energy.
- Measure neutrons in anti-ν_μ interactions.
- Reduce background and obtain better track identification using ToF (Time-of-Flight).
- Reduce total systematics to ≤ *4%* level (from the current *~6%*) for appearance modes.



High angle acceptance

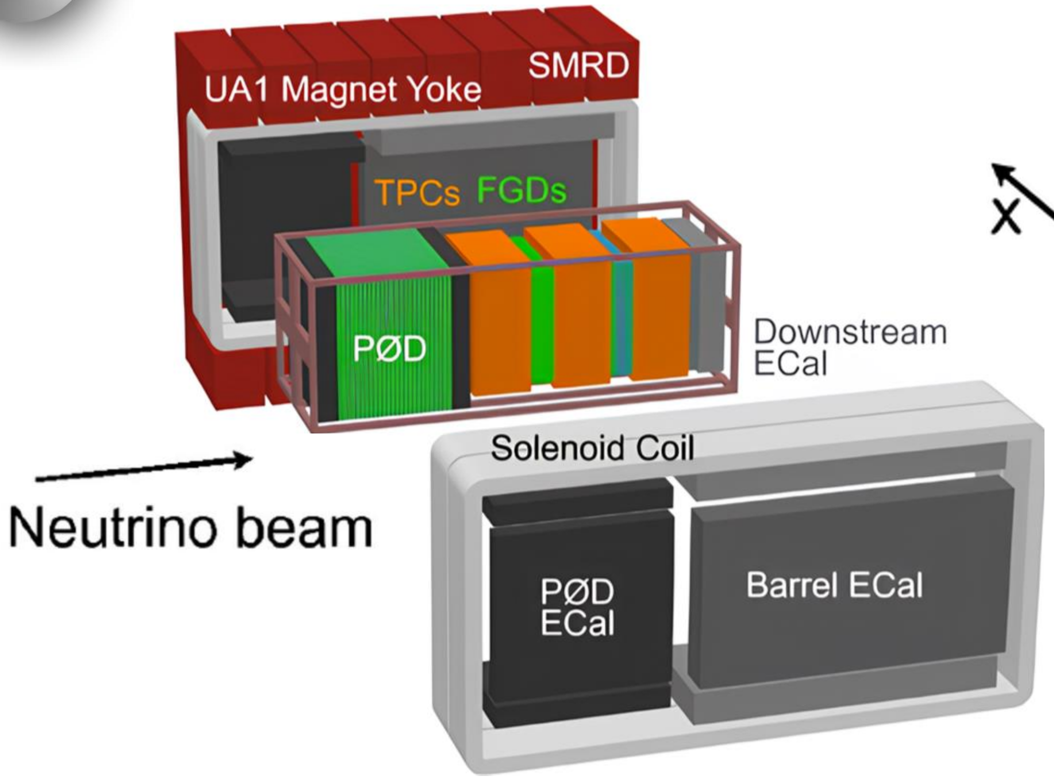


Efficiency for stopping

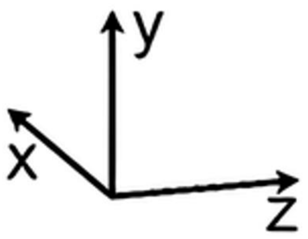


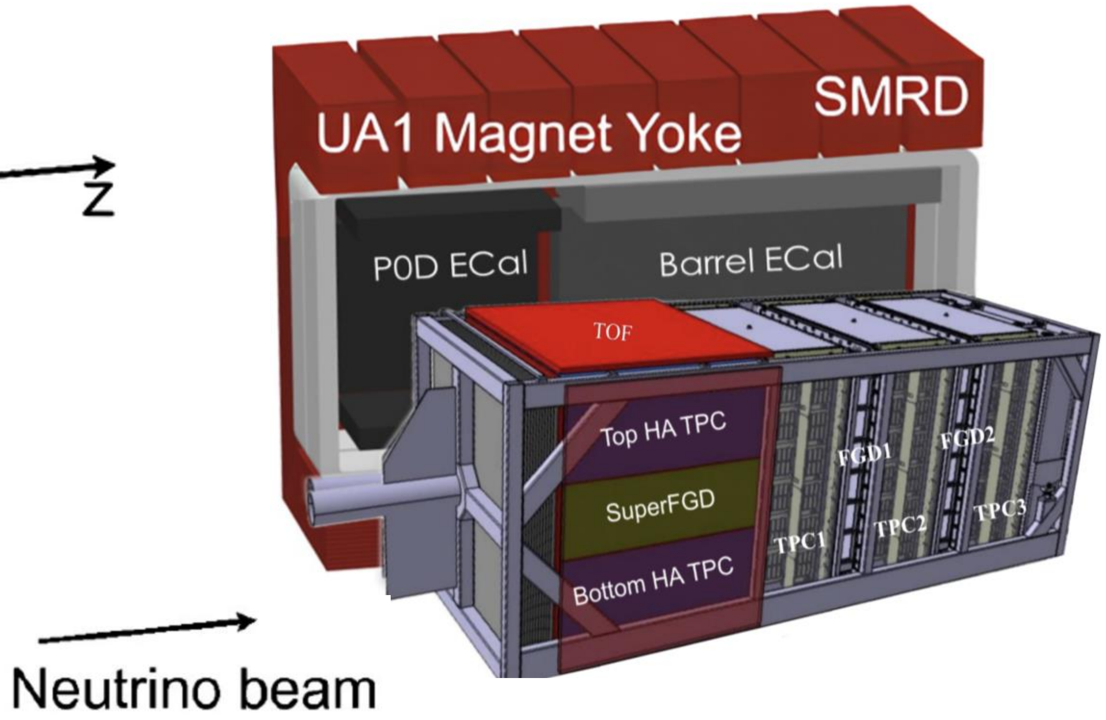
Neutron detection by SuperFGD using Time-of-Flight

ND280 Upgrade



ND280 **before** modernization





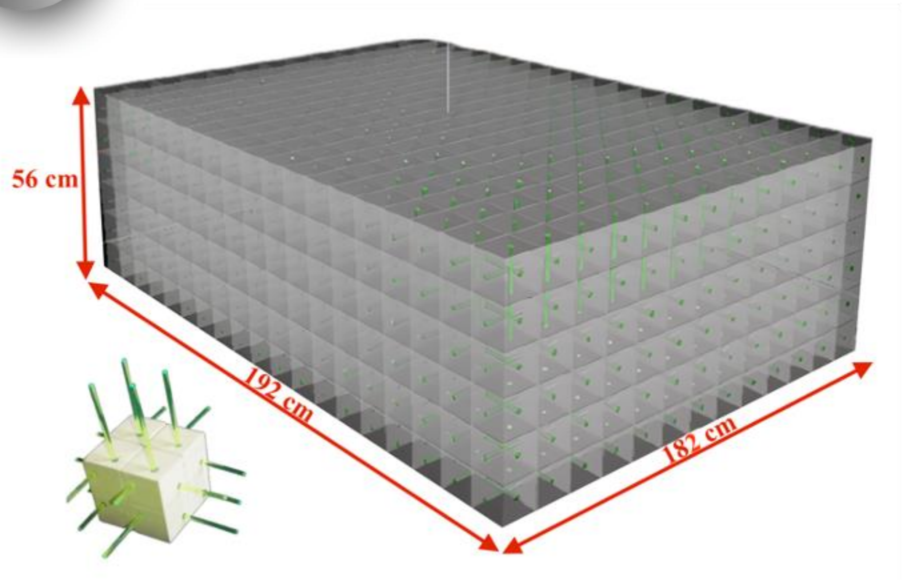
ND280 **after** modernization

P0D replaced by new detectors:

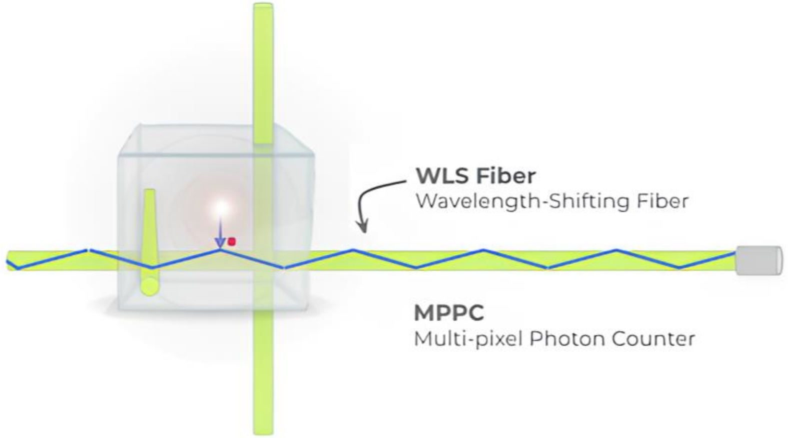
- 3D fine-grained scintillator detector **SuperFGD**
- Two High-Angle Time-projection chambers (HA-TPCs)
- ToF system around new tracker

arXiv:1901.03750

SuperFGD



Detector design



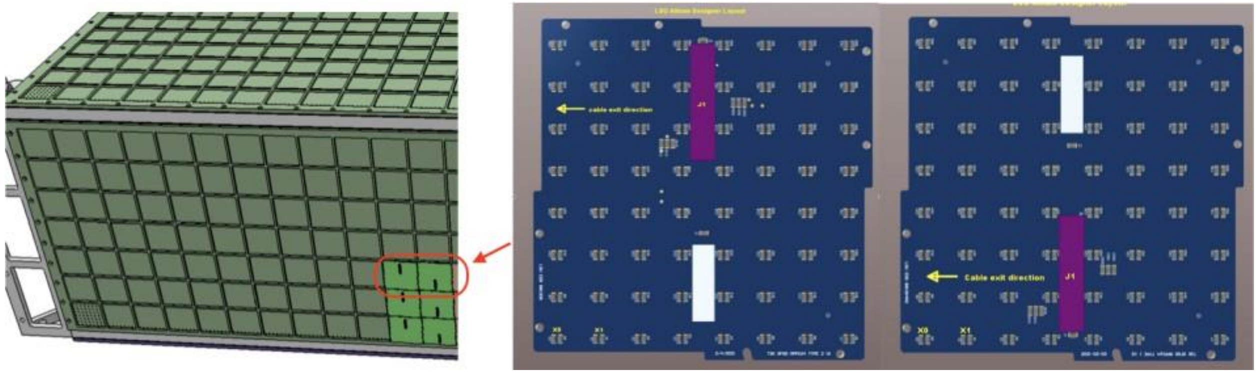
Signal readout

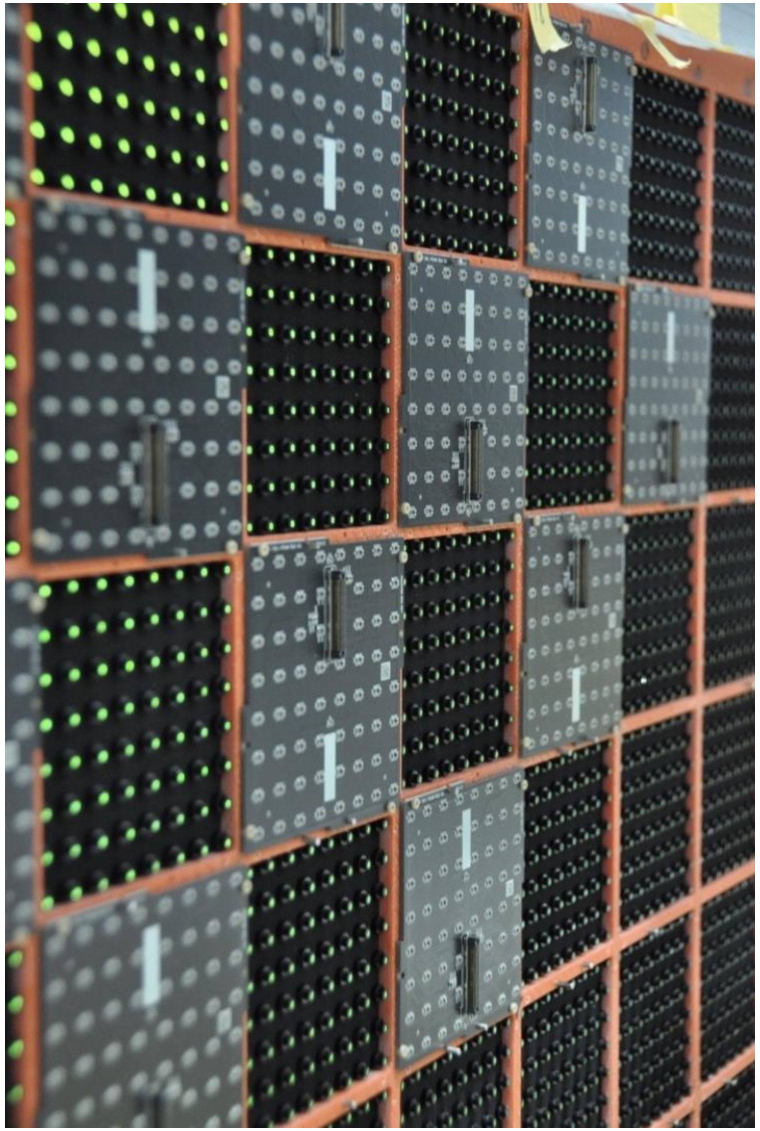
- SuperFGD (Super Fine-Grained Detector) is the active target for neutrino interactions in the upgraded ND280 detector.
- It consists of **~2** million cubes (192 x 56 x 182 cm^3) with 1 cm side.
- Cubes are injection molded by Uniplast (Vladimir, Russia).
- Cubes are made of polystyrene, and doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP, and coated with a chemical reflector for optical independence.
- SuperFGD provides 3D readout for each cube via three orthogonal wavelength-shifting fibers.

MPPCs and PCBs

- *56,382* MPPCs (Multi-Pixel Photon Counters)
- MPPC model S13360-1325PE (Hamamatsu Photonics K.K)
- *8 x 8* arrayed MPPCs on a PCB (Printed Circuit Board)
- *881* MPPC-PCBs in the SuperFGD

MPPC64-PCB designs for the two connector positions



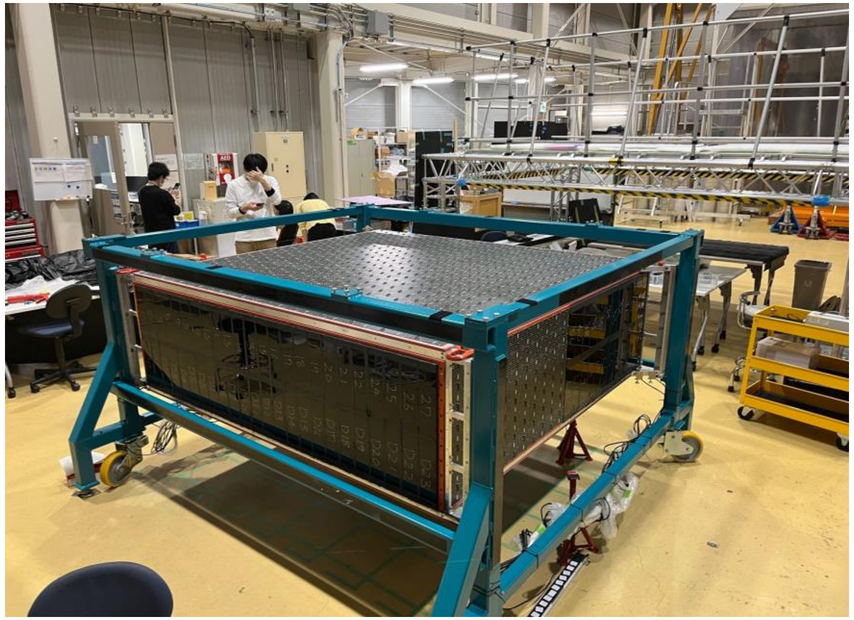


MPPC’s parameters

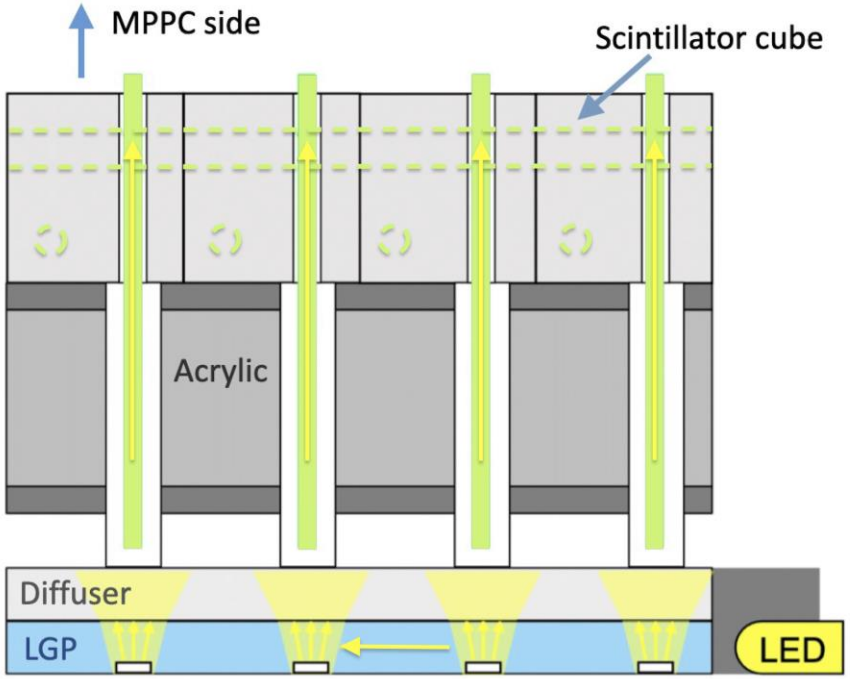
- Effective photosensitive area: $1.3 \times 1.3\ mm^2$
- Number of pixels: *2668*
- Pixel pitch: *25 μm*
- Breakdown voltage: $(53 \pm 5)\ V$
- Gain: 7.0×10^5
- Dark noise rate: *70 kHz*
- Crosstalk: *1%*
- Photon detection efficiency (PDE): *25%*

LED calibration system

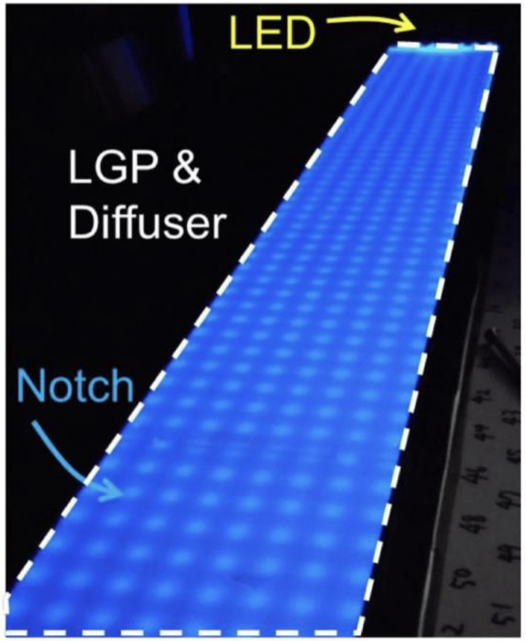
- For MPPCs calibration, special LED system was designed.
- This system contains an LED driver, Light-Emitting Diode, LGP (Light Guide Panel) and diffuser.
- Main advantages: this system is easily integrated into the mechanical box of the SuperFGD and provides simultaneous calibration of all channels.



The SuperFGD with installed panels



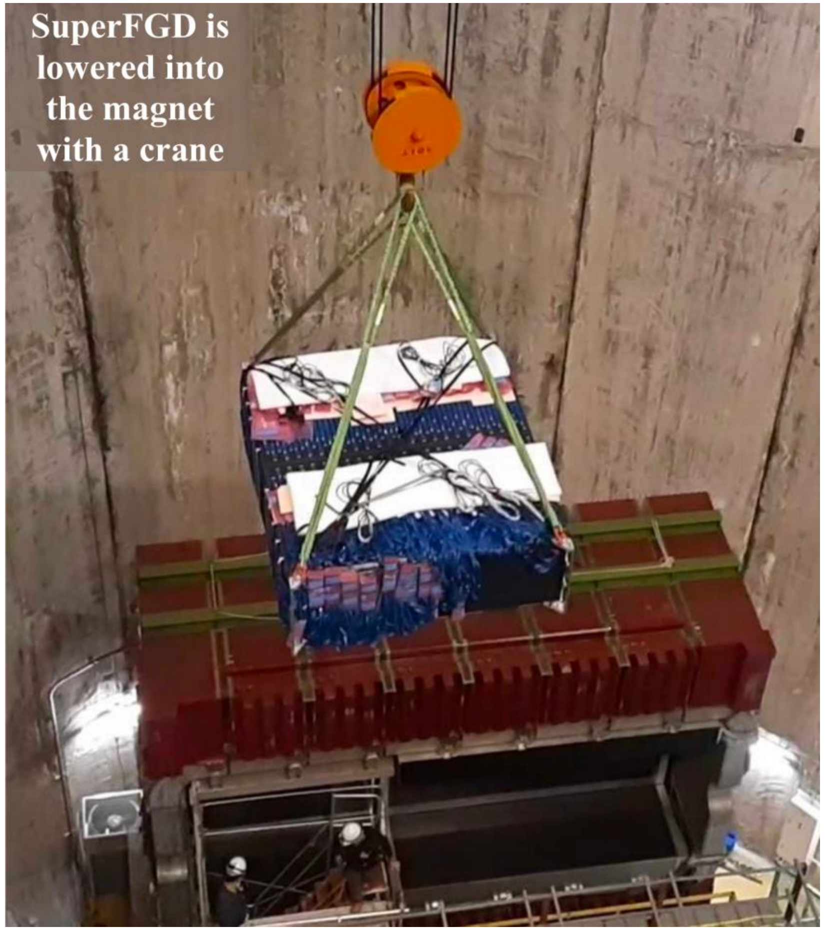
General view of the LED calibration module with LGP

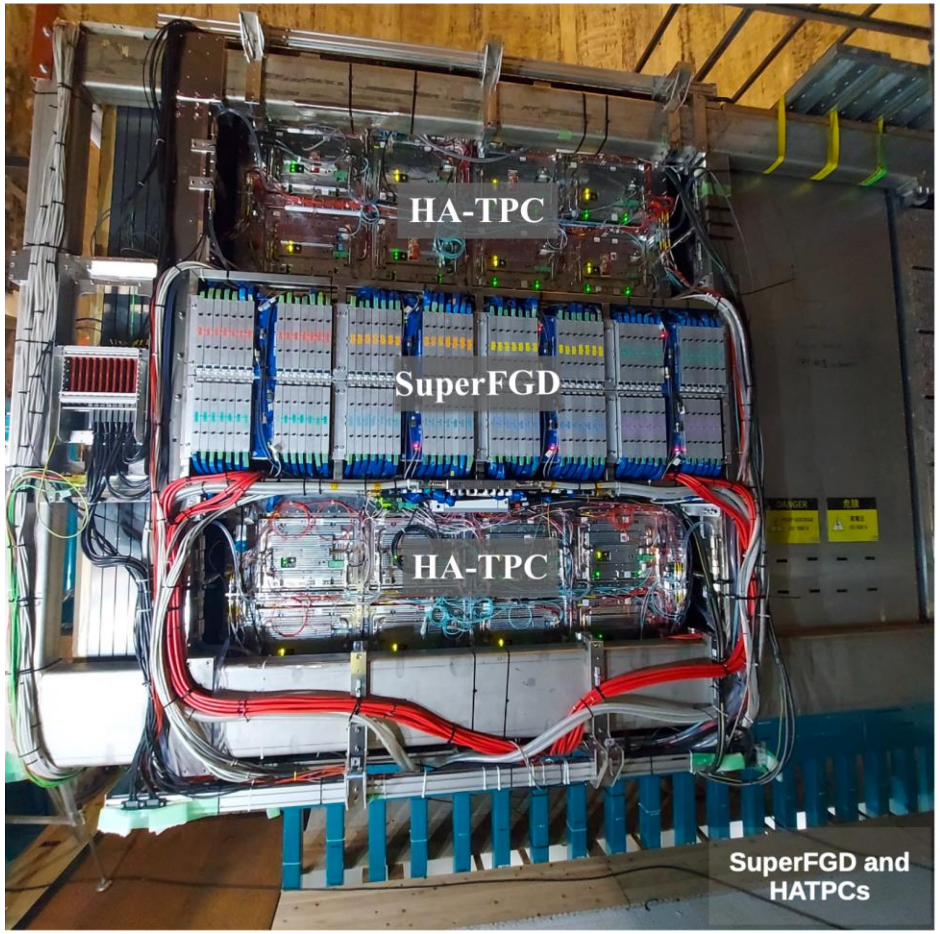


The LGP module distributes LED light to all MPPCs

New ND280 detectors

Installation of all detectors (SuperFGD, HA-TPCs, ToF) into ND280 magnet completed in **May 2024**.

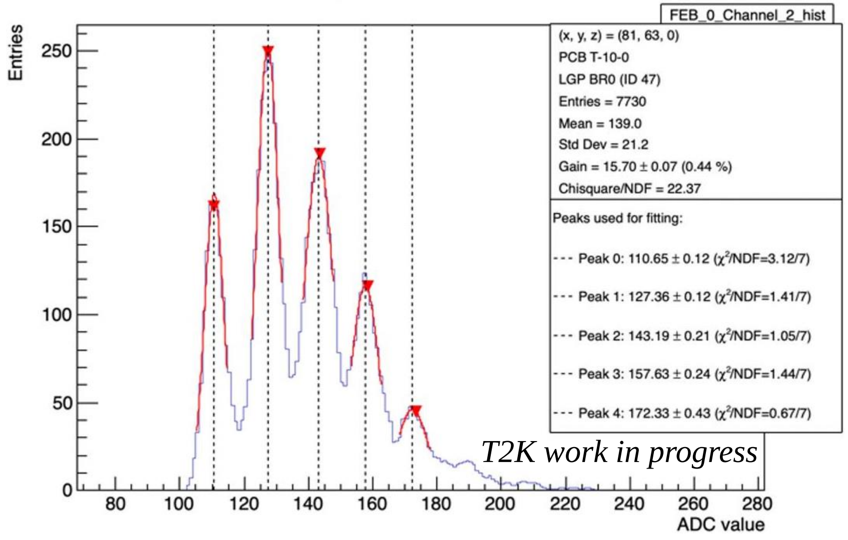




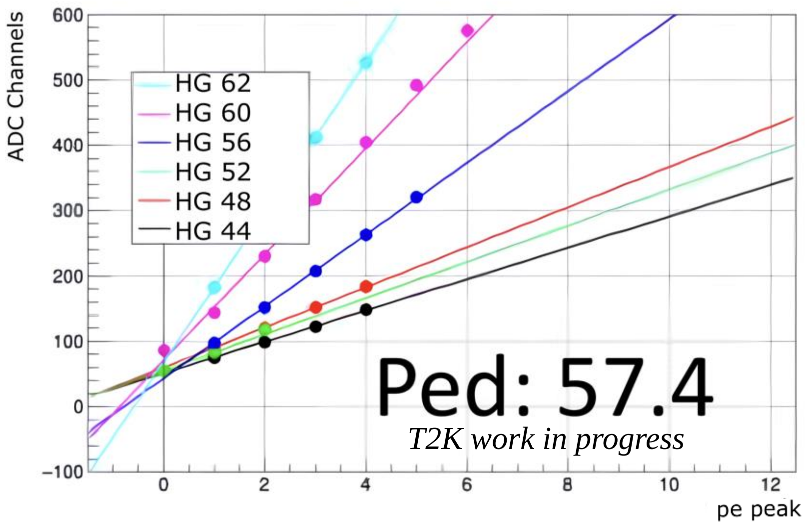
MPPC calibration and gain calculation

- LED system is used.
- Extract the HG calibration ratio (ADC/p.e.) from MPPC fingerplots. The mean distance between peaks is the **gain** value.
- Several HG values are used to find the pedestal. The intersection point of these graphs is the **pedestal** position.

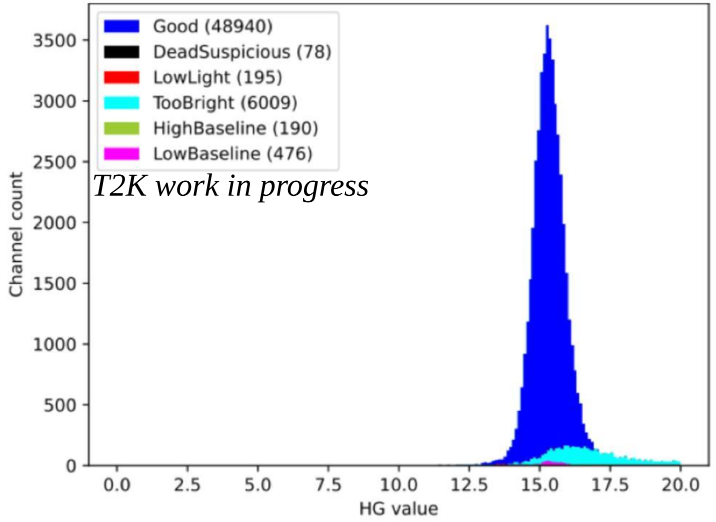
Number of events on single channel



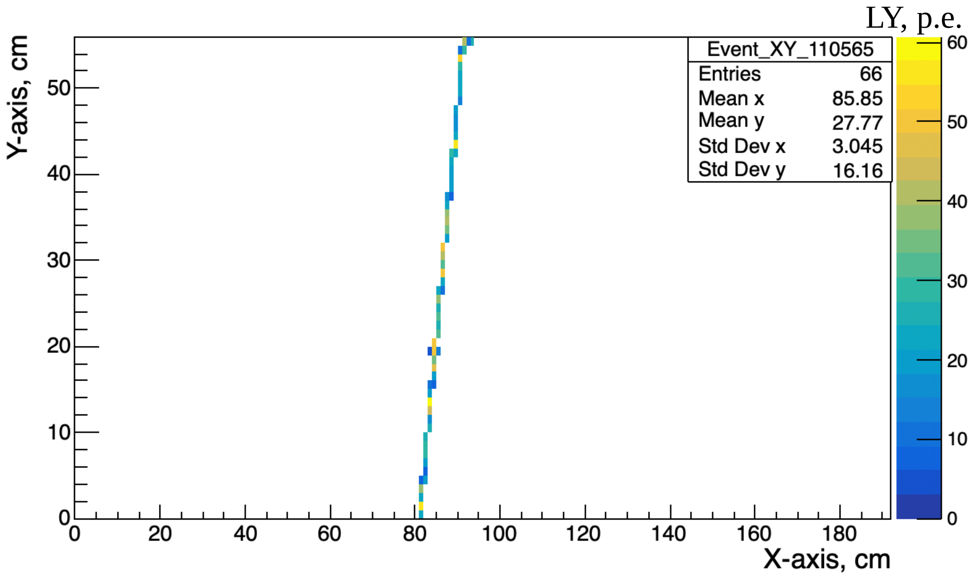
The pedestal calculation for single channel

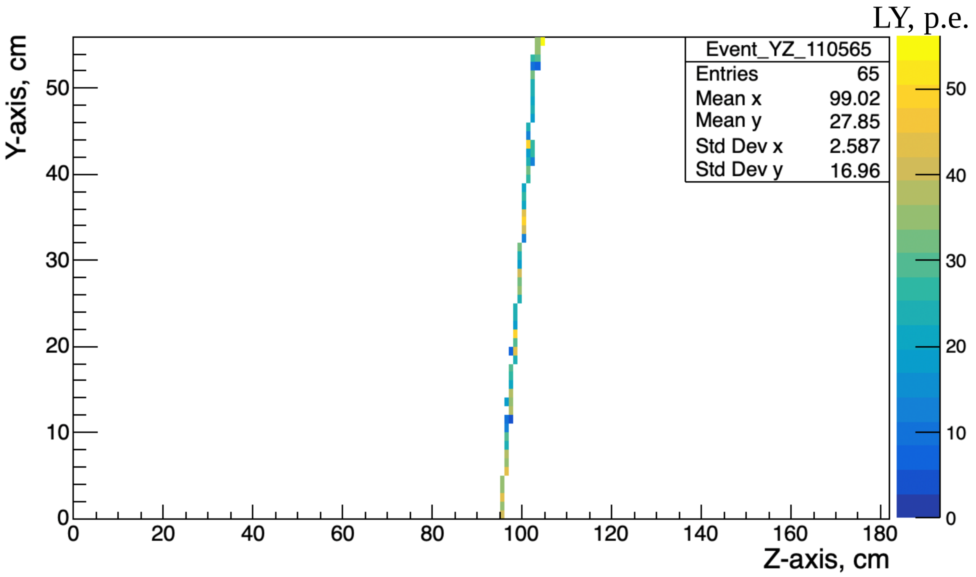


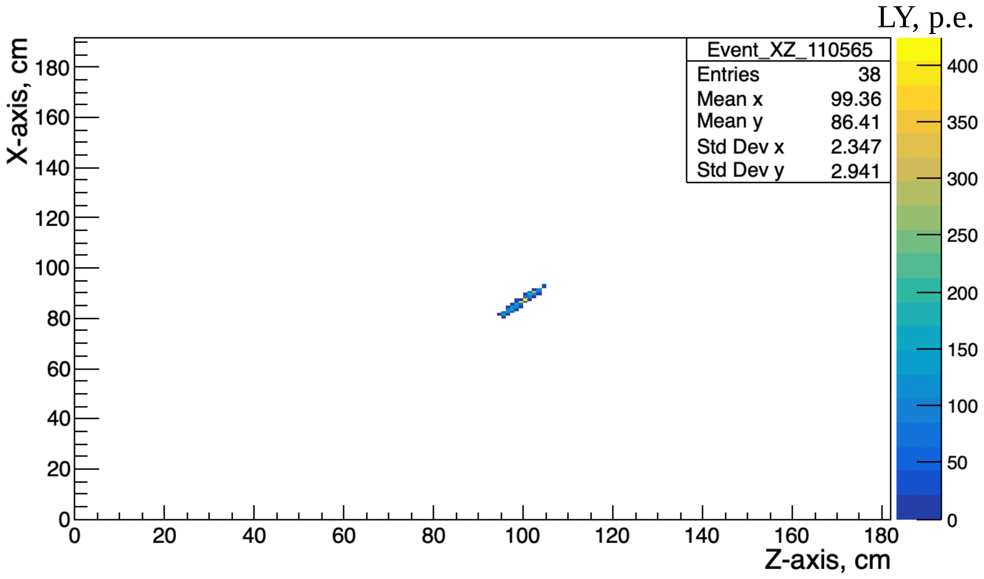
Gain distribution for all channel



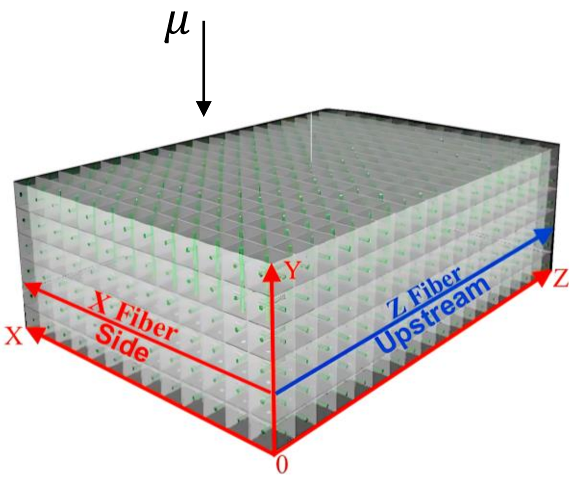
Cosmic muons



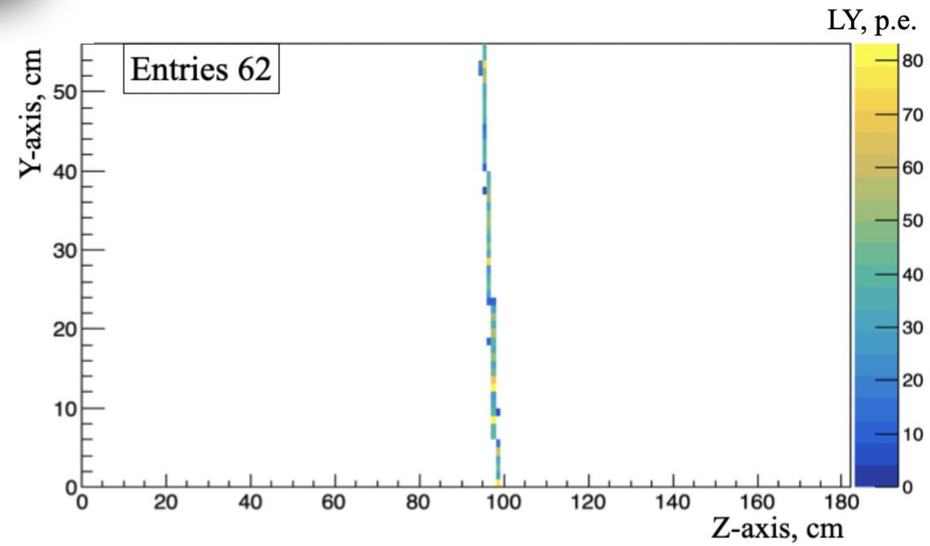


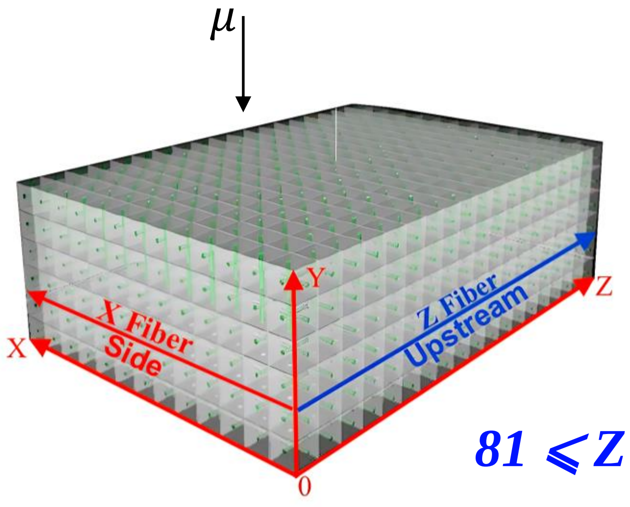


- Event from June 2024, cosmic trigger.
- Cosmic muons are used to calibrate attenuation and reflection in WLS fibers.

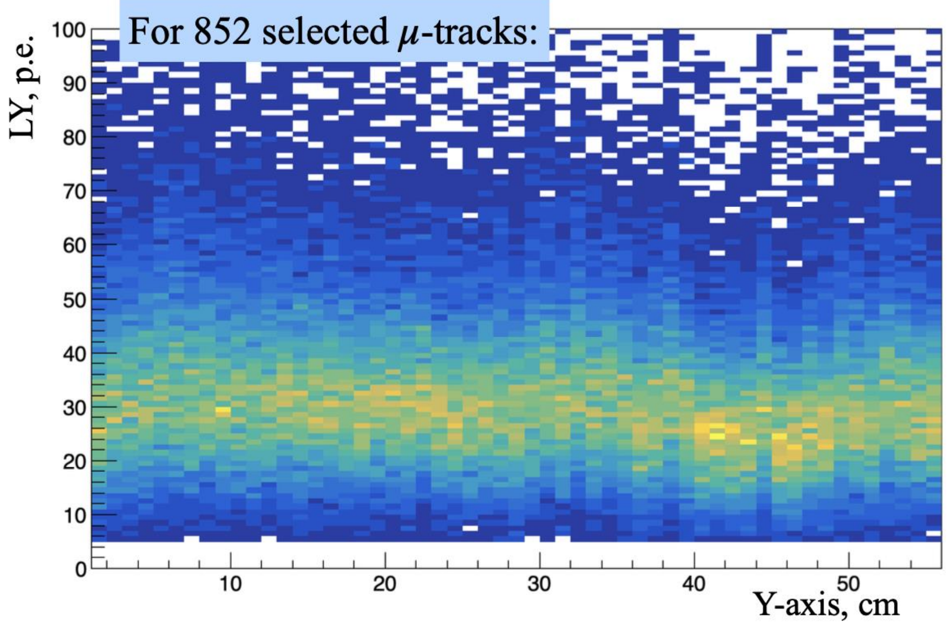


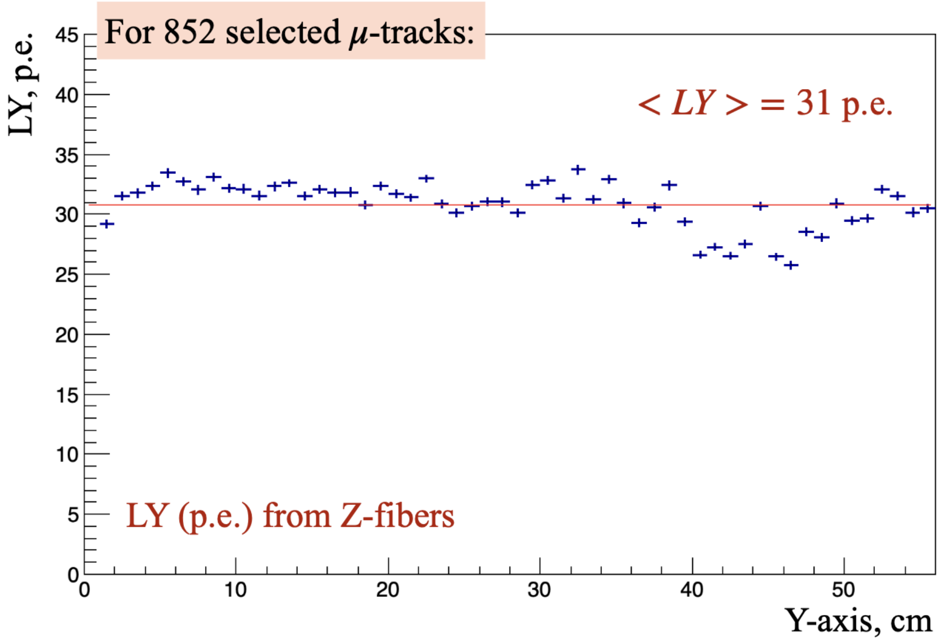
Light Yield from cosmic muons





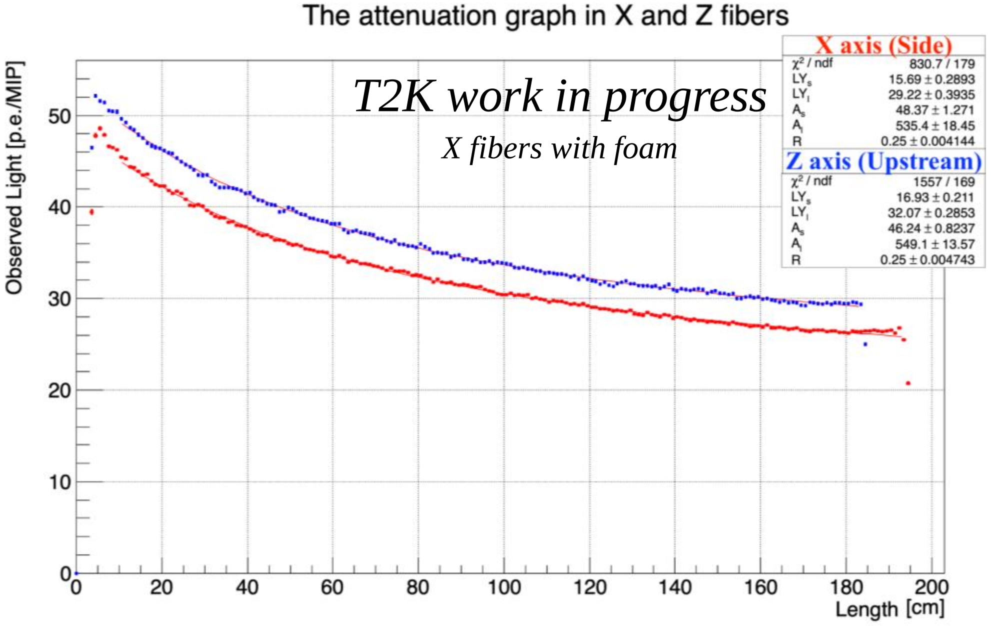
$81 \leqslant Z \leqslant 101$

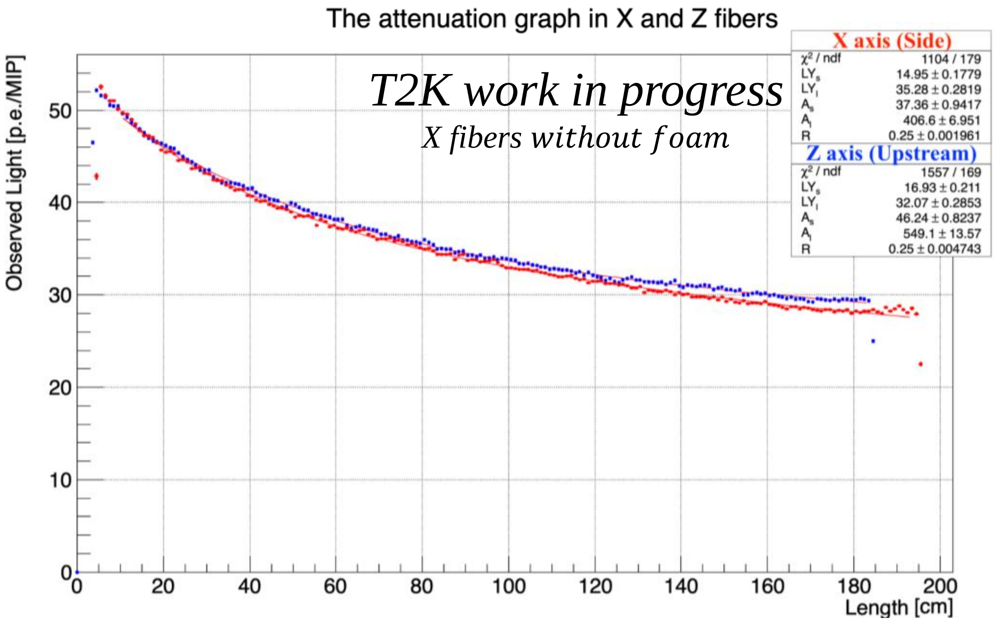




Attenuation length for horizontal WLS fibers

Cosmic trigger, cosmic muon tracks with angles from -5° to 5°





$$\mathbf{LY} = \mathbf{LY_S} \cdot \mathbf{e}^{-\frac{\mathbf{x}}{\mathbf{A_s}}} + \mathbf{LY_L} \cdot \mathbf{e}^{-\frac{\mathbf{x}}{\mathbf{A_L}}} + \mathbf{R} \cdot \left(\mathbf{LY_S} \cdot \mathbf{e}^{-\frac{\mathbf{2L-x}}{\mathbf{A_s}}} + \mathbf{LY_L} \cdot \mathbf{e}^{-\frac{\mathbf{2L-x}}{\mathbf{A_L}}}\right)$$

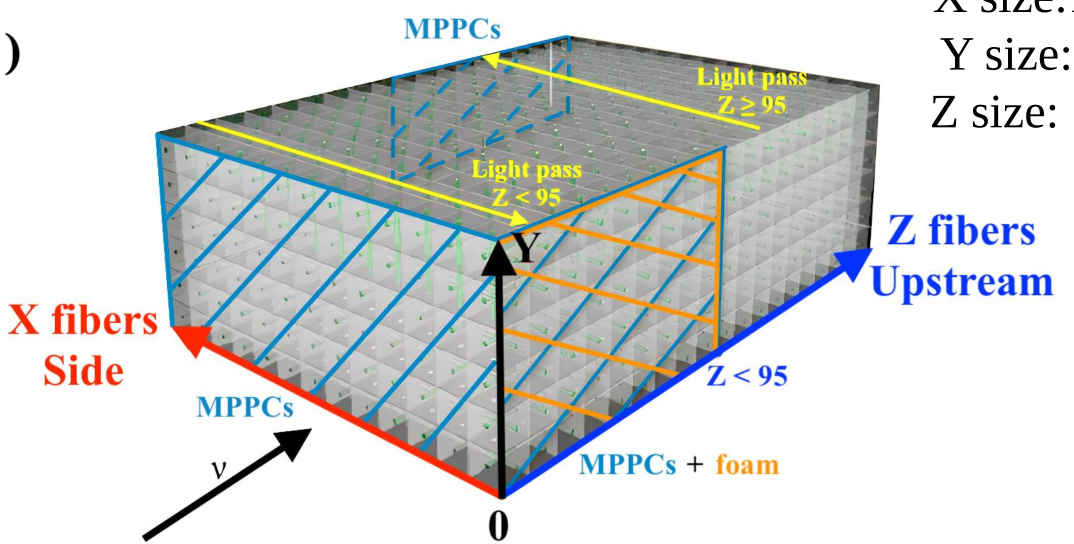
$\mathbf{LY_S}$ and $\mathbf{LY_L}$ – short and long Light Yield coefficients, p.e./MIP

$\mathbf{A_S}$ and $\mathbf{A_L}$ – short and long attenuation components, cm

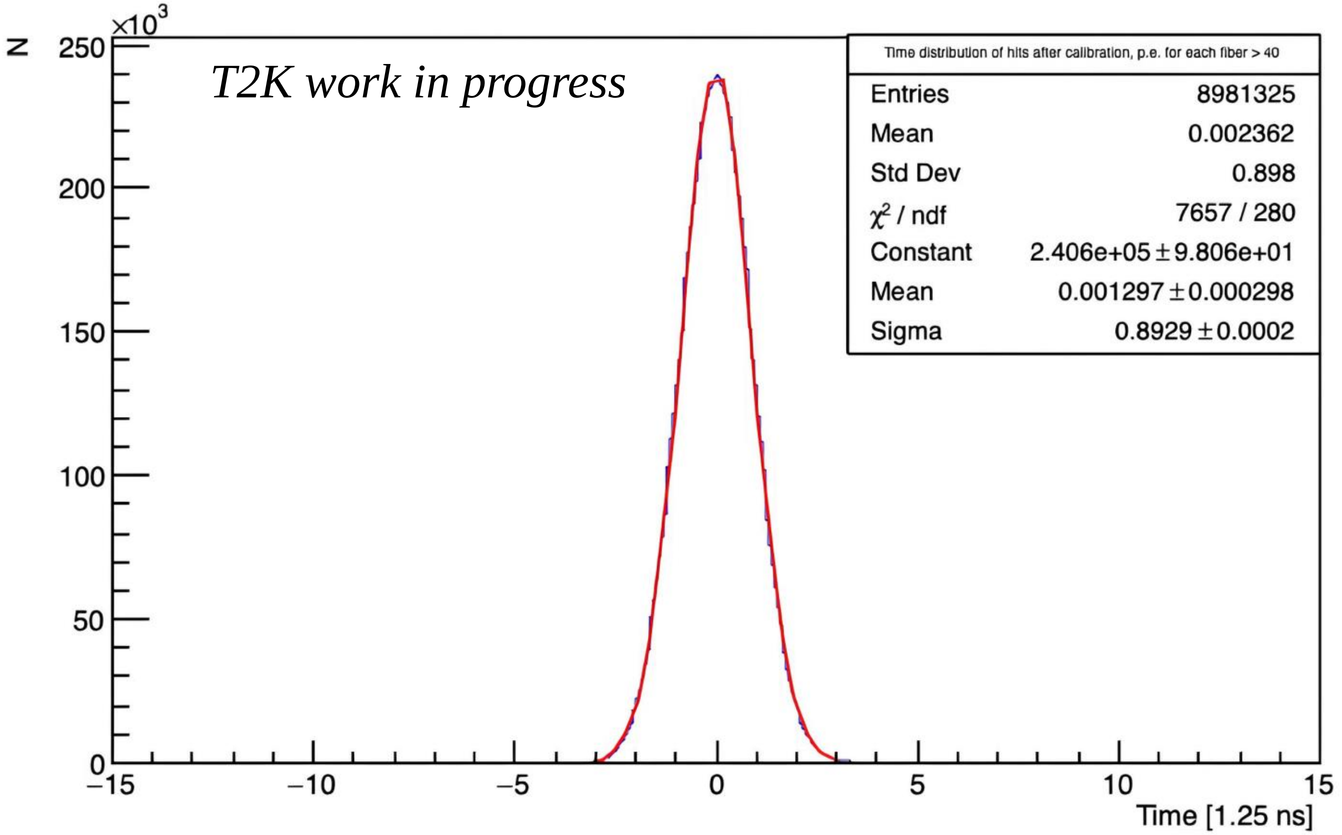
x – distance from photosensor, cm

R – reflection coefficient, %

X size:192
Y size: 56
Z size: 182



Time resolution

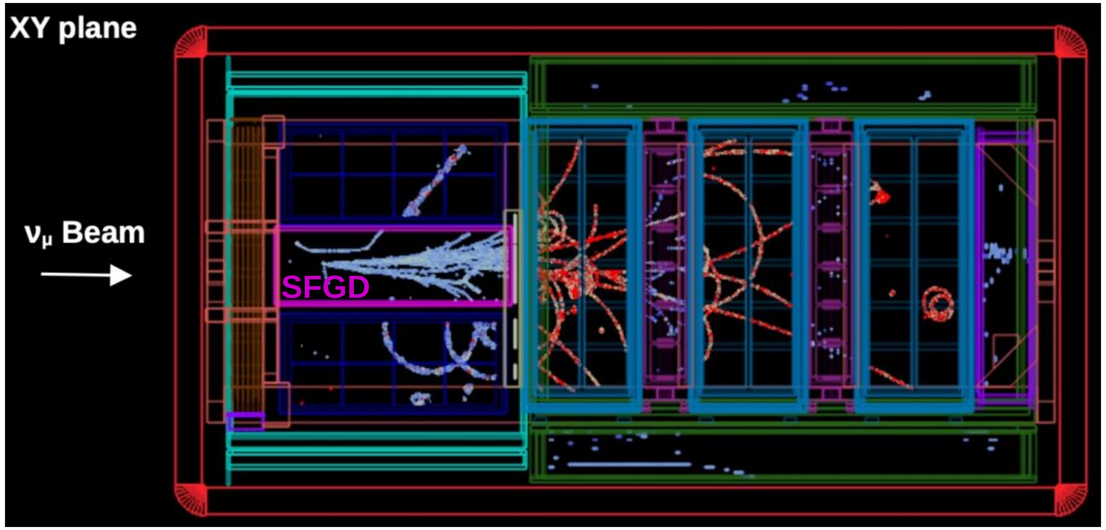


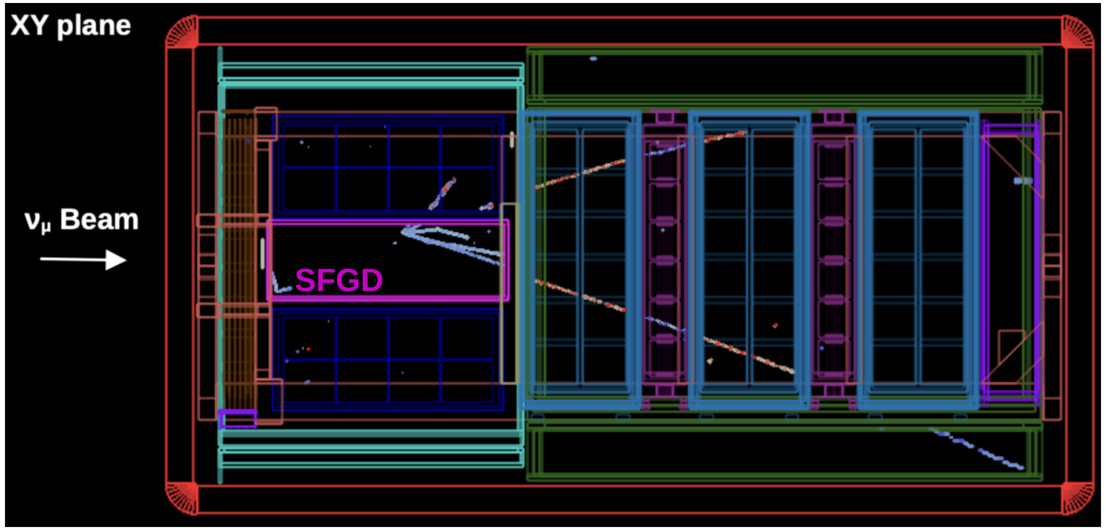
- Real cosmic data were used (only events from horizontal fibers).
- Cosmic trigger.
- Select hits ***> 40 p.e.*** matched in all three dimensions.
- Compare mean time of hit to mean time for event.
- Gives ***~1.2 ns*** time resolution.

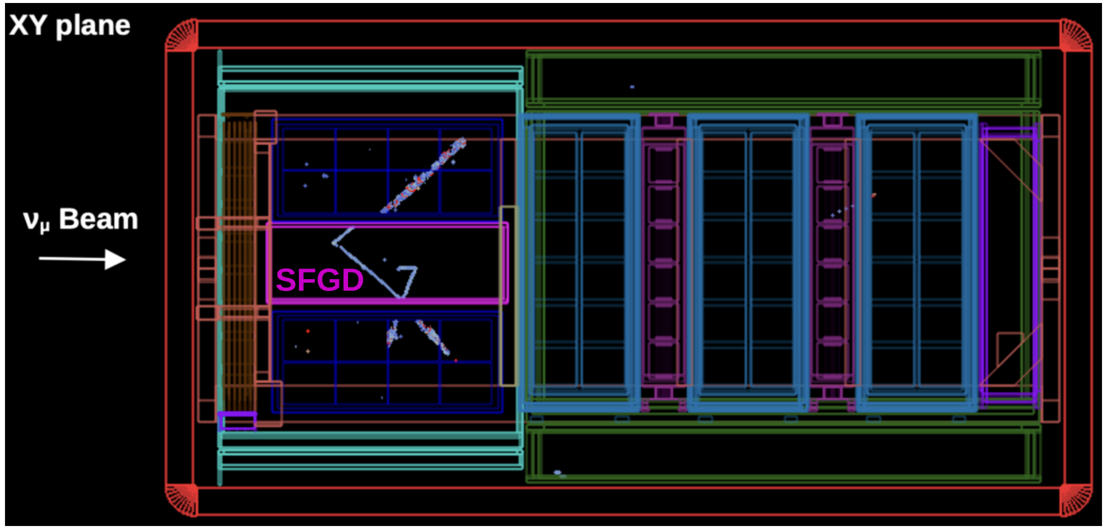
Will be presented by M. Kolupanova,
poster «The study of the time resolution of the 3D neutrino detector SuperFGD»

First event displays with upgraded ND280

Events found in the beam data taken in June 2024.

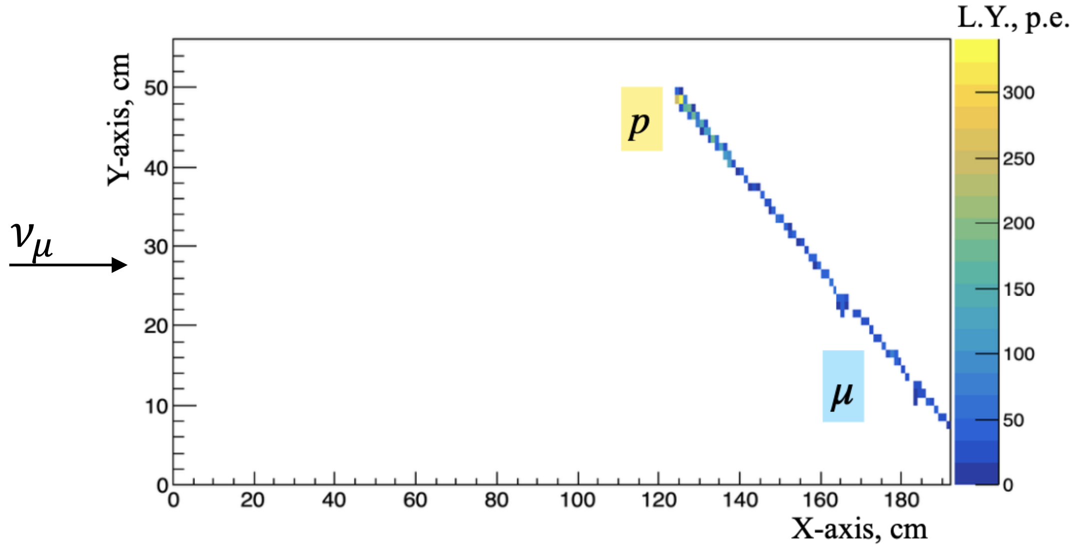


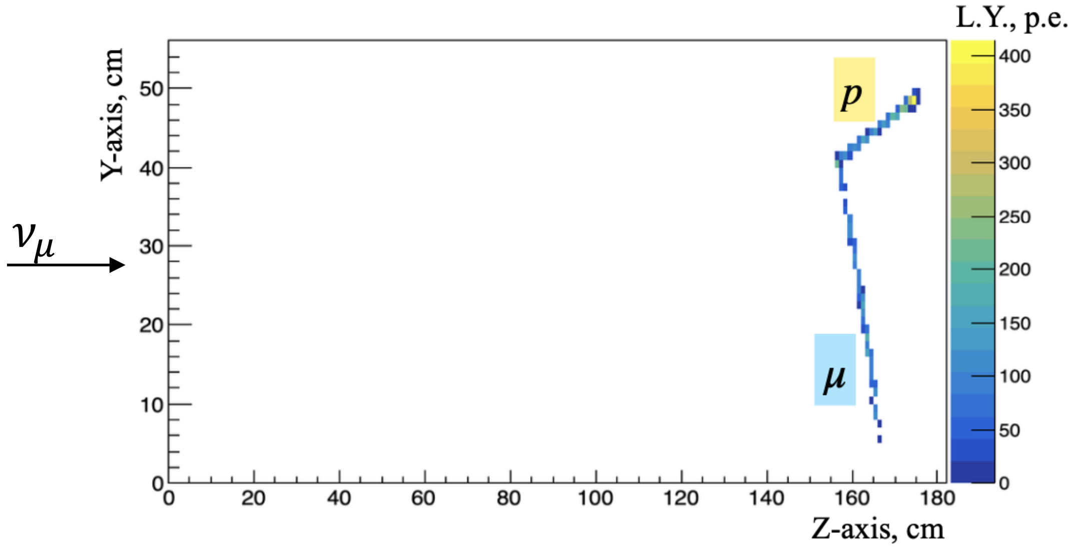


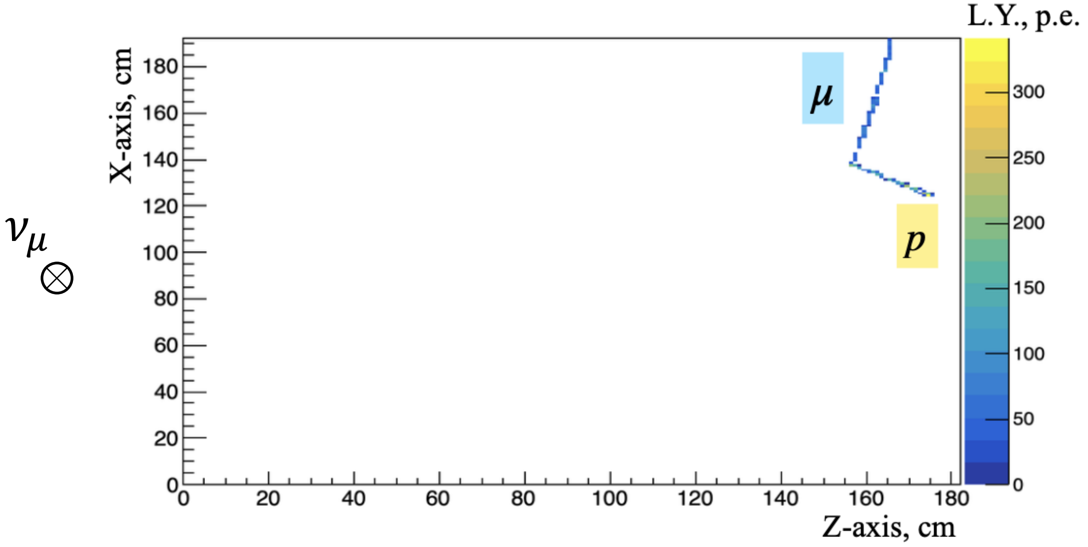


Neutrino event in SuperFGD

Example №1







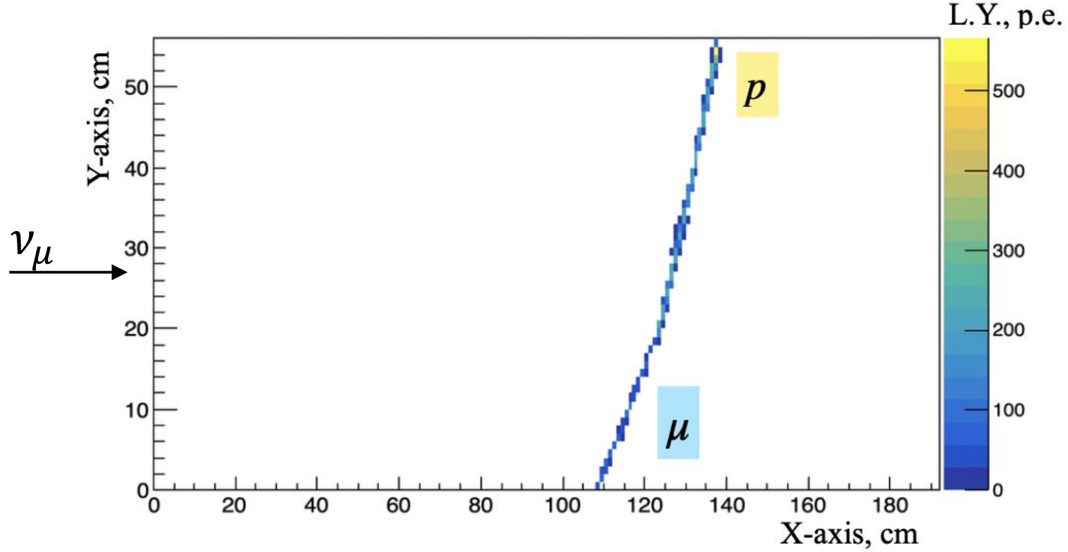
Charged-current quasi elastic (CCQE) scattering of ν_μ with nuclei gives **muon** and **proton** at the final state:

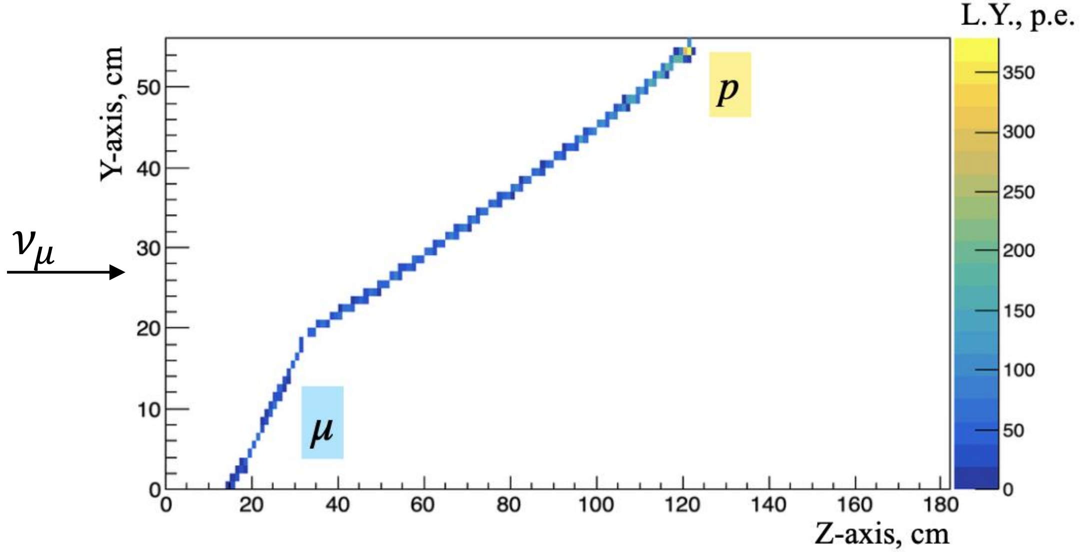
$$\nu_\mu + n \rightarrow \mu^- + p$$

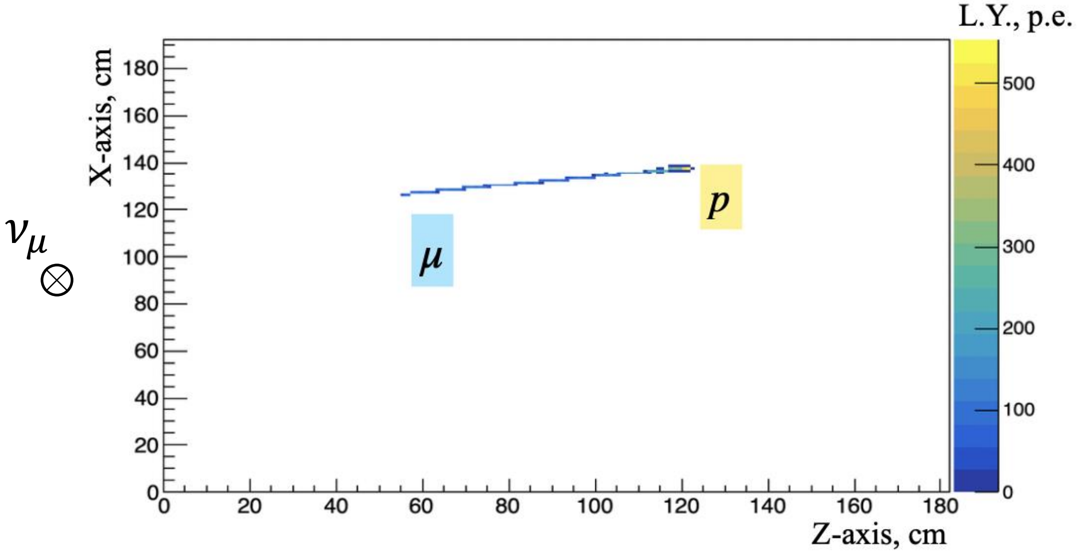
The beam of ν_μ with power P = 750 kW
(that peaks around E = 0.6 GeV)

Neutrino event in SuperFGD

Example №2







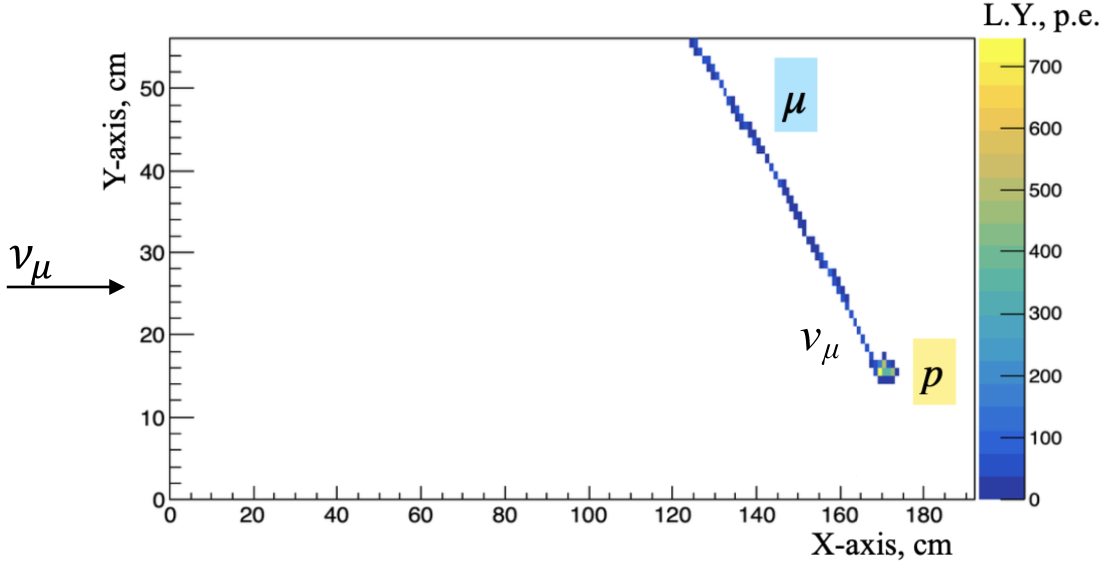
Charged-current quasi elastic (CCQE) scattering of ν_μ with nuclei gives **muon** and **proton** at the final state:

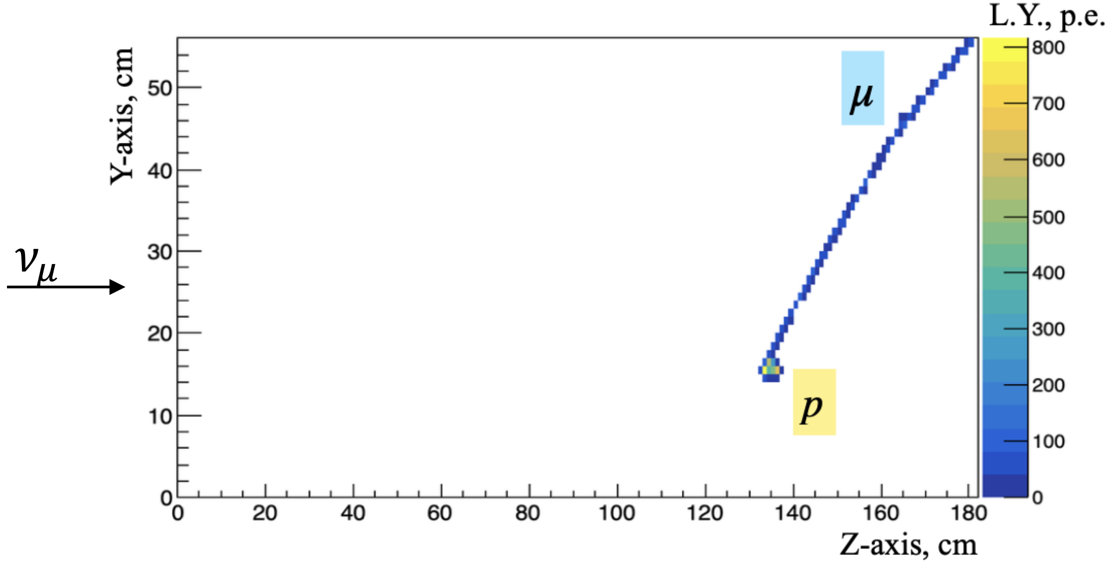
$$\boldsymbol{\nu_\mu + n \rightarrow \mu^- + p}$$

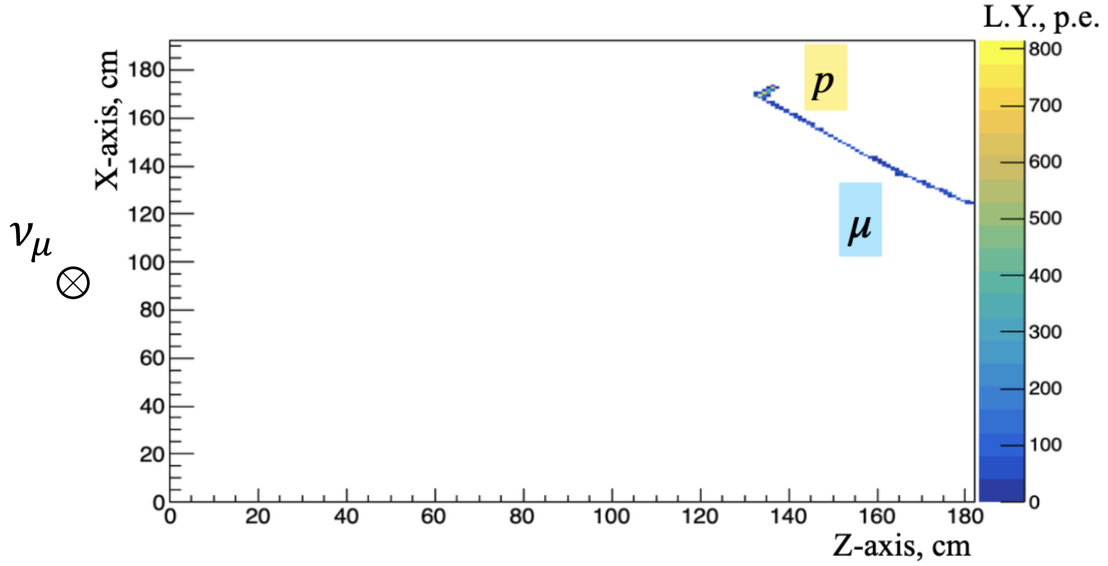
The beam of ν_μ with power P = 750 kW (that peaks around E = 0.6 GeV)

Neutrino event in SuperFGD

Example №3





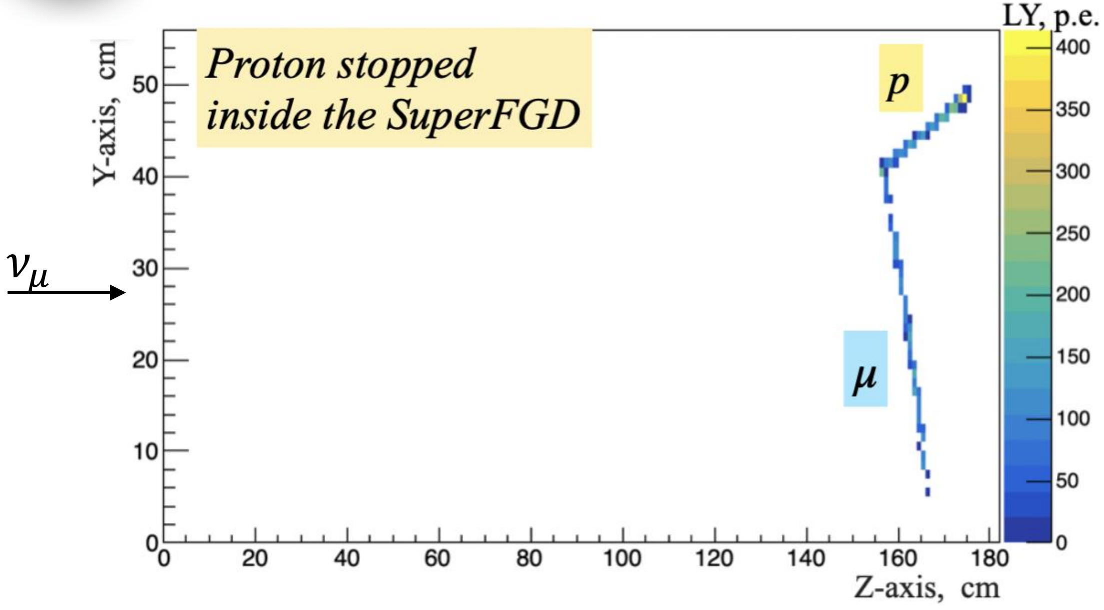


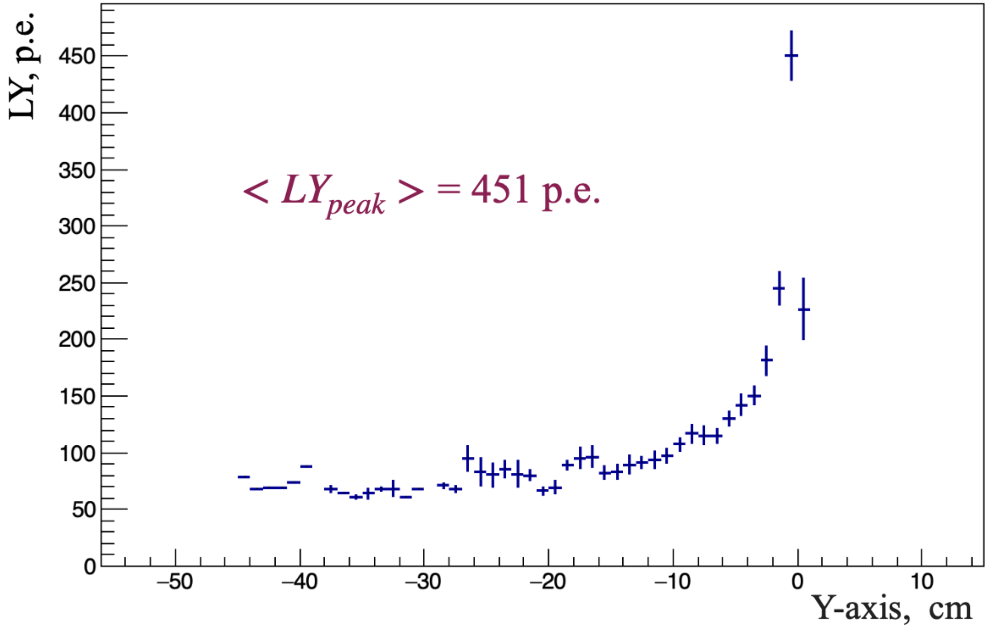
Charged-current quasi elastic (CCQE) scattering of ν_μ with nuclei gives **muon** and **proton** at the final state:

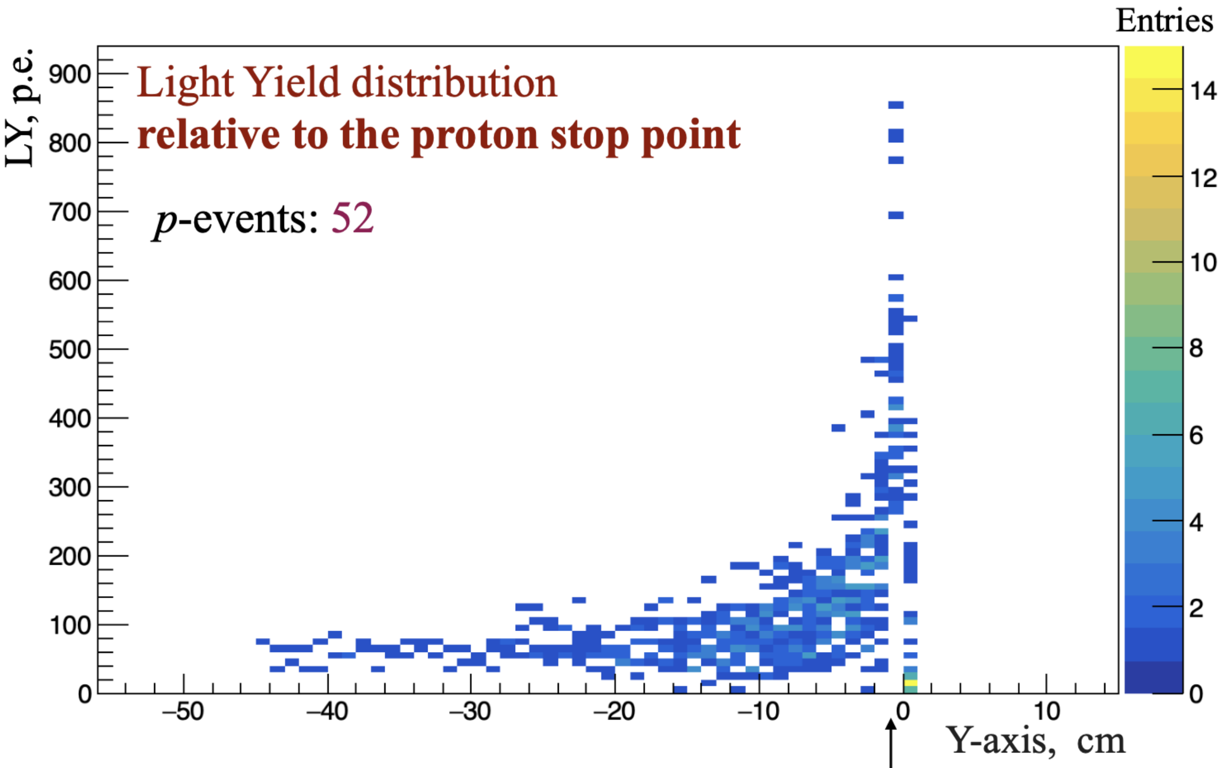
$$\nu_\mu + n \rightarrow \mu^- + p$$

The beam of ν_μ *with power P = 750 kW (that peaks around E = 0.6 GeV)*

Stopped protons from ν_μ-interactions







Protons stopping point

Conclusion

The highly segmented neutrino detector, SuperFGD, is the central part of the near detector complex ND280 of the T2K experiment.

It is the key element for a sensitive search for CP violation in T2K and Hyper-Kamiokande.

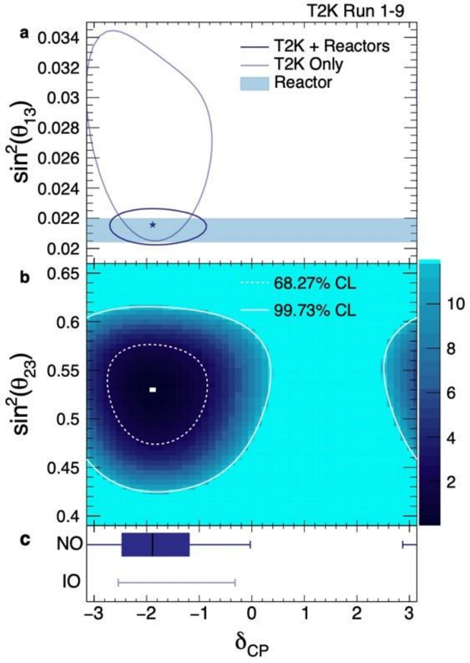
- The SFGD construction and commissioning have been completed.
- The calibration system and electronics are tested. Data on cosmic events are being collected.
- The main SuperFGD parameters, such as **attenuation length** in horizontal WLS fibers and **time resolution**, were preliminary measured.
- The detector has been collecting data since May 2024.
- The first ν_μ**-events** were detected **via (CCQE) interaction** and reconstructed in SuperFGD with muon and proton in the final state.

Supported by the RSF grant # 24-12-00271

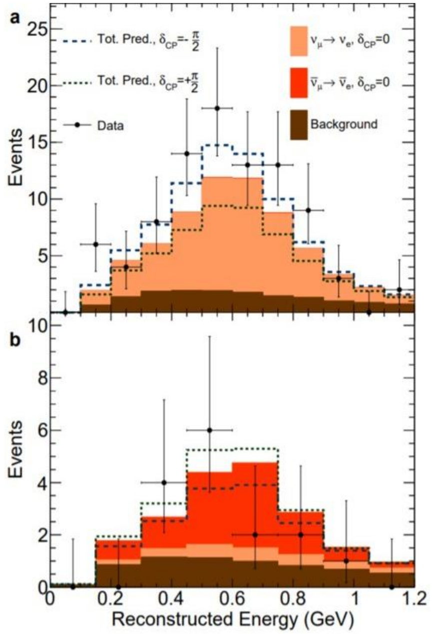
Back up

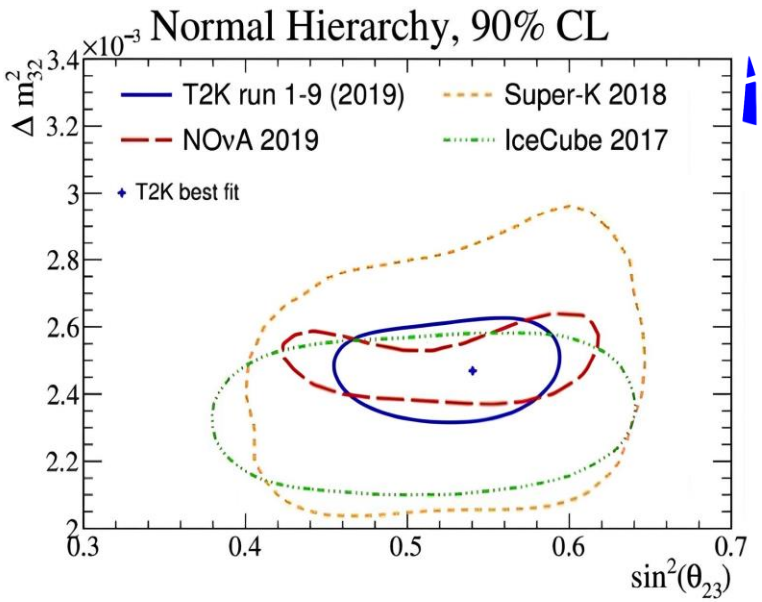
The T2K Results

Constraints on CP violating parameter δ_{CP}

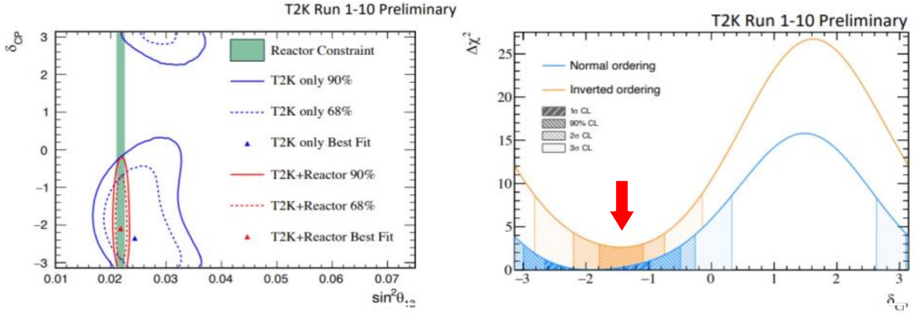


Number of observed electron neutrinos in the beam of the muon neutrinos

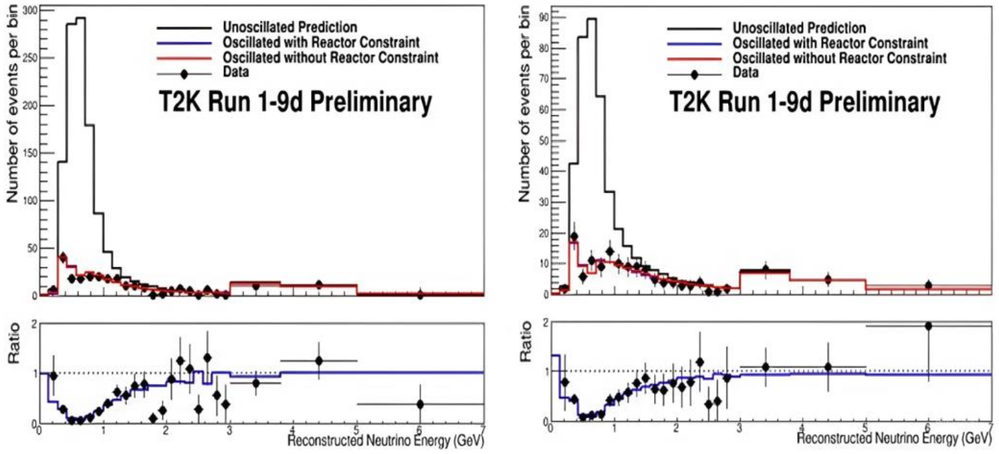




The $sin^2\theta_{23}$ and Δm^2_{32} restrictions under the normal hierarchy of neutrino masses

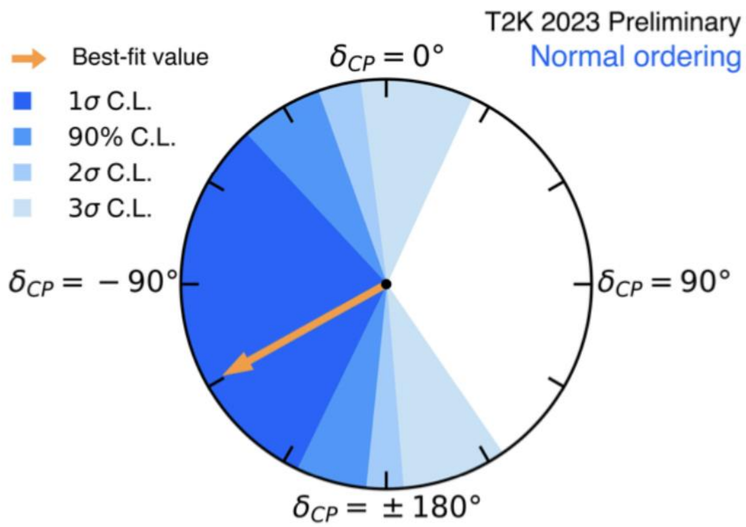


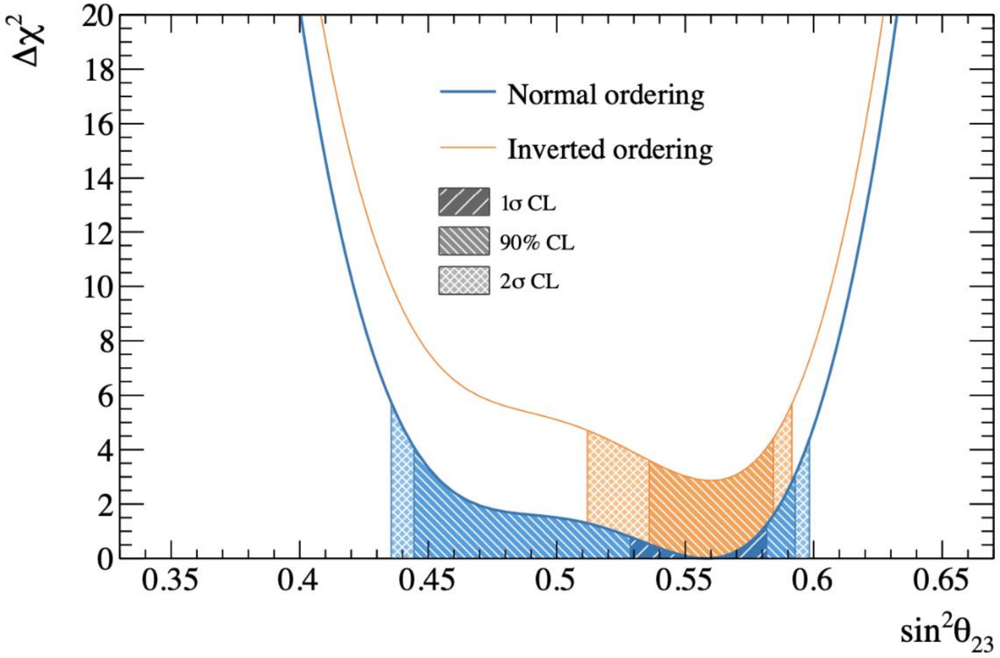
Indication of maximal CP violation in neutrino oscillations $\delta_{CP} \sim -\frac{\pi}{2}$



Number of observed muon neutrinos and antineutrinos in the far detector with/without oscillations

The latest T2K results





	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

Neutrino oscillations

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

Atmospherics and LBL
$\theta_{23} \sim 45°$
$|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ eV^2$

Reactors
$\theta_{13} \sim 10°$
LBL
θ_{13} and δ_{CP}

Solar and reactors
$\theta_{12} \sim 35°$
$\Delta m^2_{21} \sim 7.5 \times 10^{-3}\ eV^2$

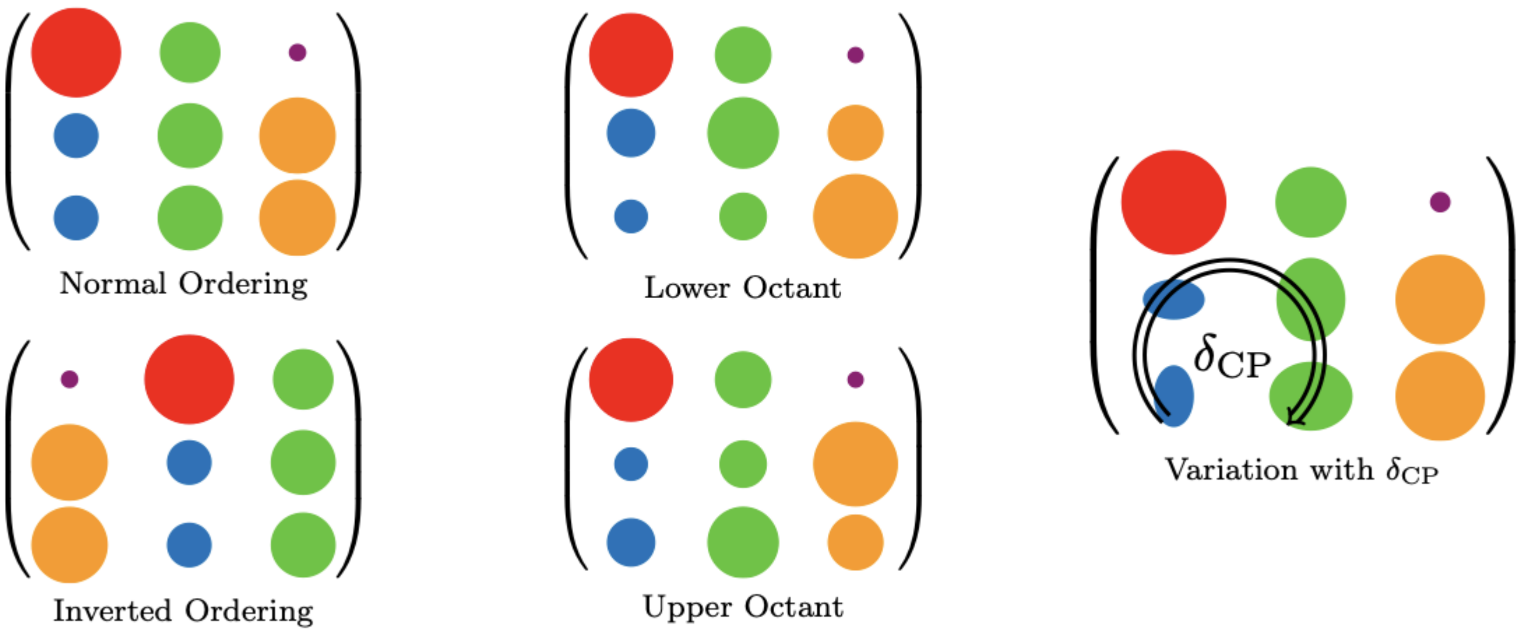
- Long baseline (LBL) experiments sensitive to 5 of the PMNS parameters
- θ_{23}, $|\Delta m^2_{32}| \rightarrow$ LBL provides the most precise measurements of these parameters
- $\theta_{13} \rightarrow$ dominated by reactor experiments
- δ_{CP} and sign of Δm^2_{32} (normal or inverted ordering) $\rightarrow$ still unknown and accessible to LBL

Claudio Giganti, Report at Neutrino 2024

Unresolved questions about neutrinos and leptonic mixing

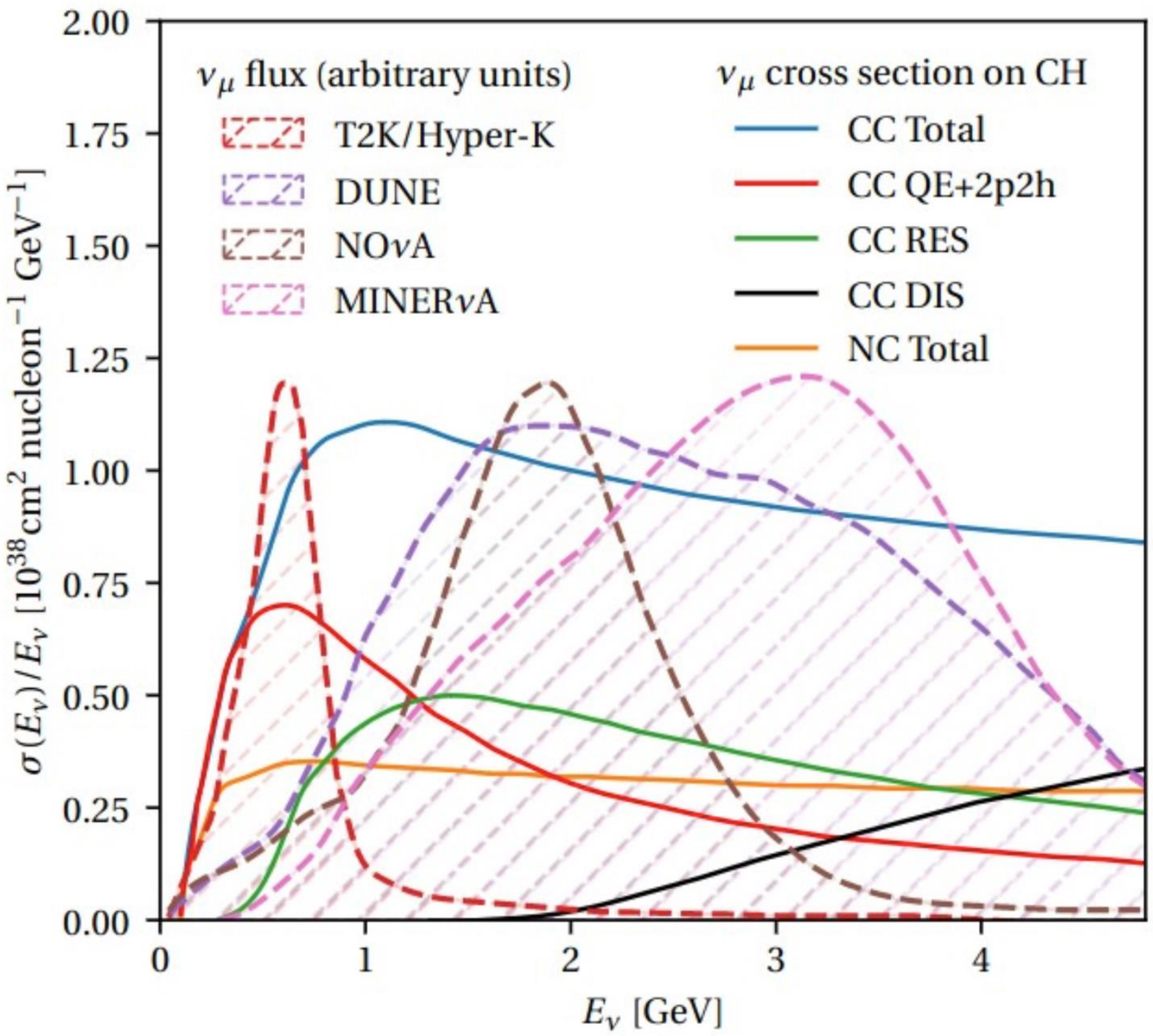
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}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

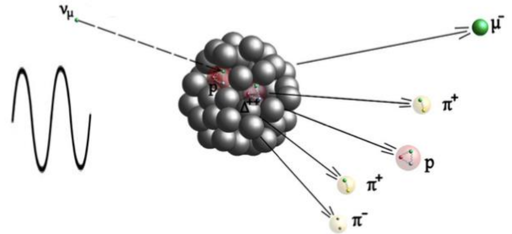
- There are discrete options for the mass ordering and octant.
- In only one of them (NO, $\theta_{23} < \frac{\pi}{4}$) would the leptons retain a generational (i.e. leading diagonal) structure.
- The matrix may also have a unitary form, leading to CP violation.



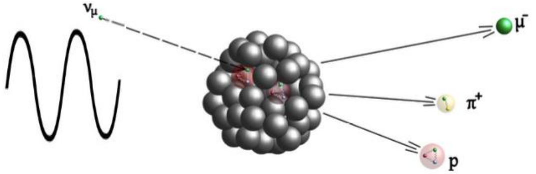
Fluxes and interaction channels

QE + 2p2h dominance for T2K

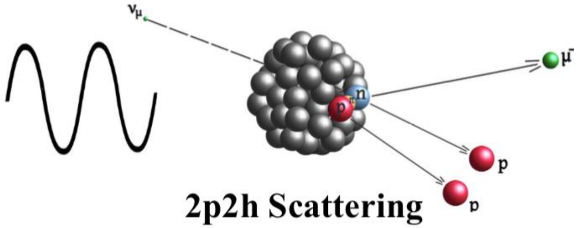




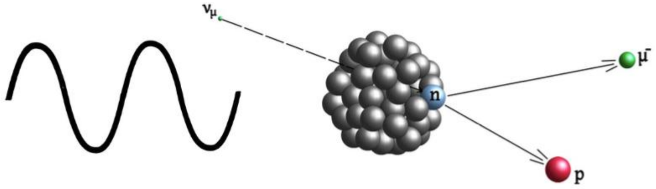
Deep Inelastic Scattering



Resonant Pion Production



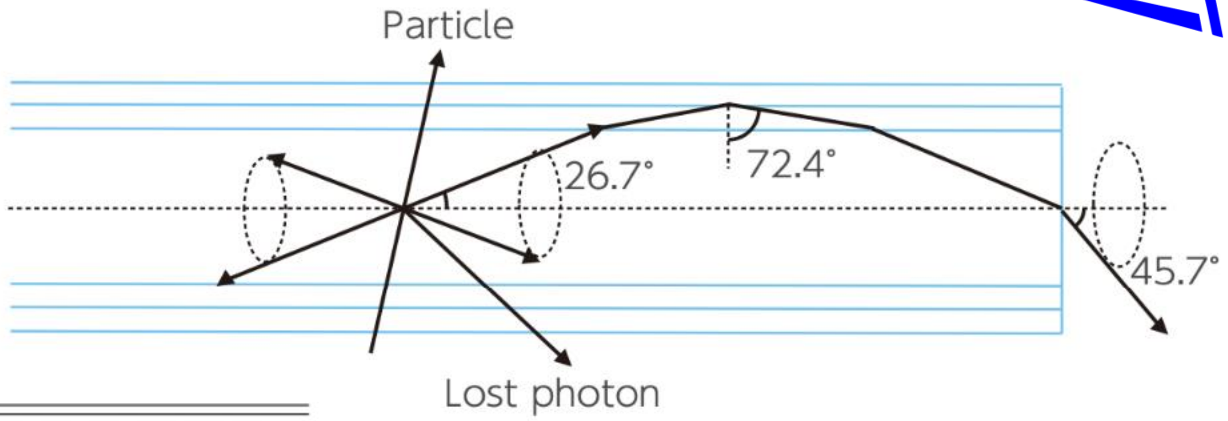
2p2h Scattering



Quasielastic Scattering

WLS fibers

Y-11 (200) produced by KURARAY CO.



Item	Specification
Fiber type	Round shape, Multi-cladding
Diameter	1.0 mm
Materials	Core: Polystyrene (PS), Middle clad: Polymethylmethacrylate (PMMA), Outer clad: Fluorinated polymer (FP)
Refractive index	Core: 1.59, Middle clad: 1.49, Outer clad: 1.42
Density	Core: 1.05 g/cm^2, Middle clad: 1.19 g/cm^2, Outer clad: 1.43 g/cm^2
Absorption wavelength	430 nm (peak)
Emission wavelength	476 nm (peak)
Trapping efficiency	~5.4%
Attenuation length	>3.5 m

Crates connection