Ближний нейтринный детектор SuperFGD эксперимента T2K

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ИЯИ РАН

(On behalf of the SuperFGD group)

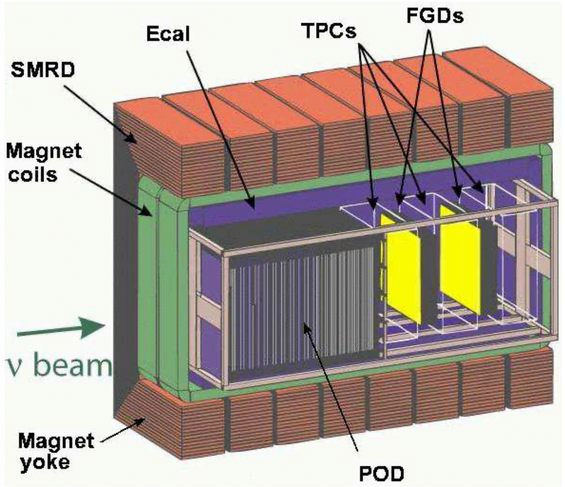
03.04.2024

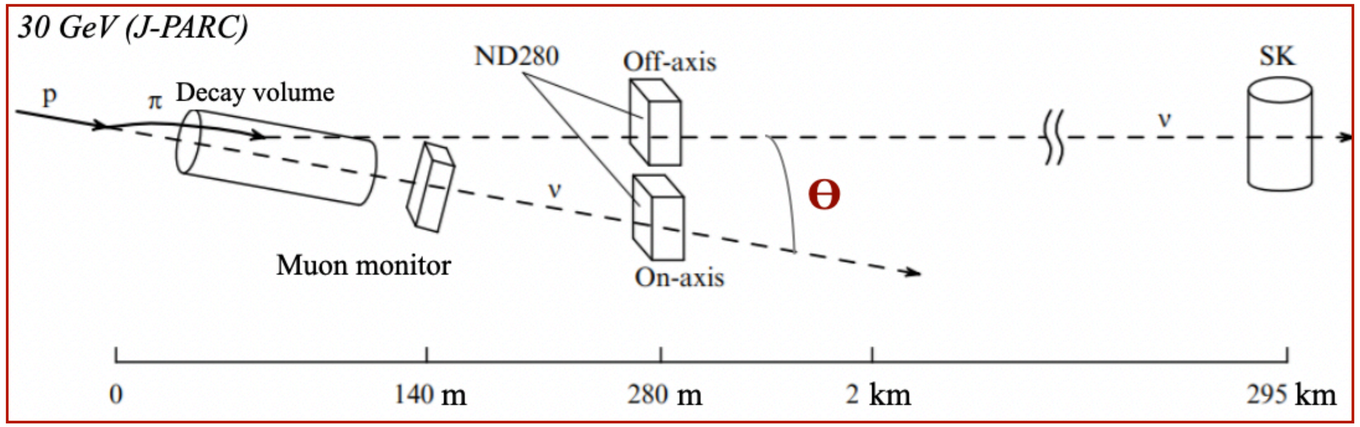
T2K experiment ("Tokai to Kamioka")

The main experiment goals:

- *precision measurements of the oscillation parameters with ν_μ ($\overline{\nu}_\mu$) beam;*
- *search for CP violation in neutrino sector*

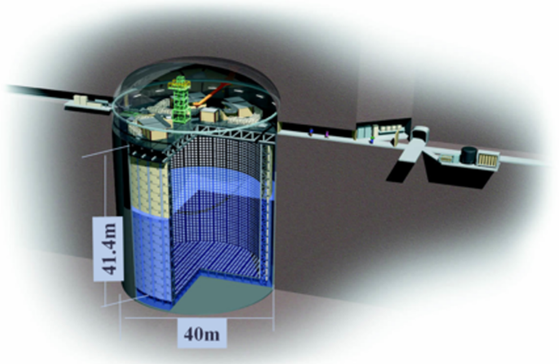
Near off-axis ν-detector (ND280)



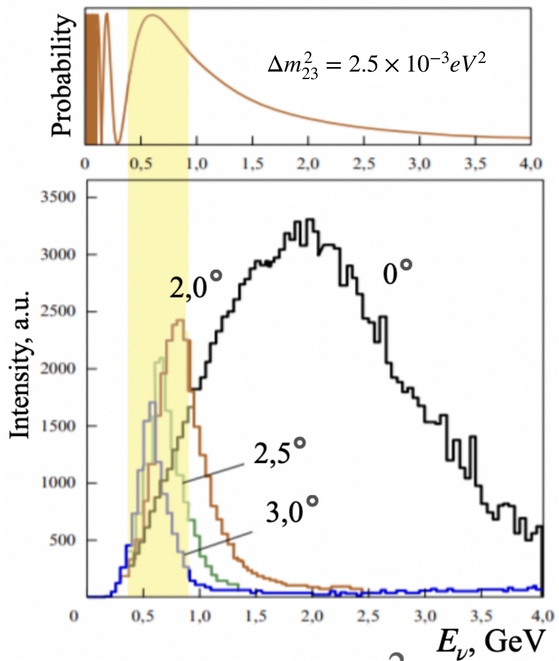


T2K experiment scheme

Super-Kamiokande

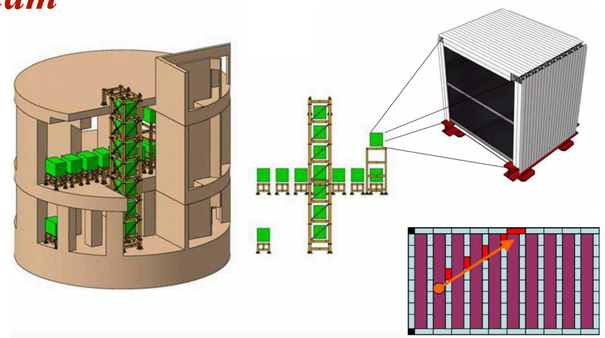


Off–axis ν-beam



$$\Theta = 2.5^\circ \longrightarrow E(\nu)_{max} = 0.6 \text{ GeV}$$

Neutrino beam monitor (INGRID)



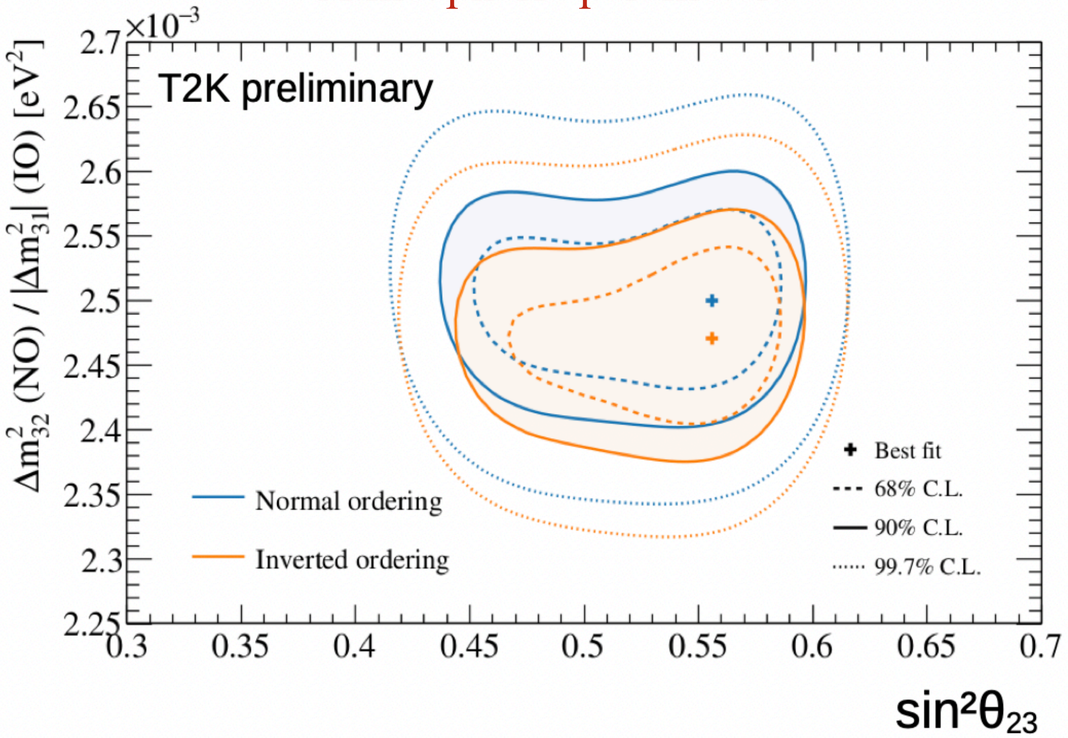
To improve T2K sensitivity to the δ_{CP}

we need to reduce any systematic uncertainties in predicted events at the far SK from 6-7% up to 3-4%

The latest T2K results

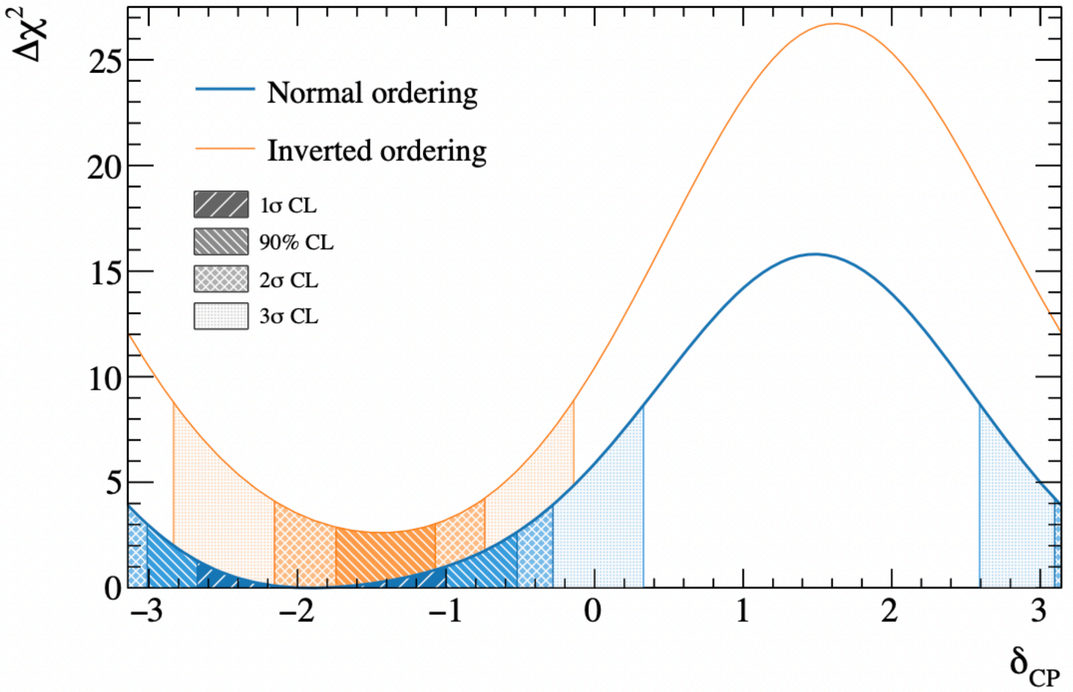
19.7 (16.3) $\times 10^{20}$ protons on target (POT) in ν_μ ($\overline{\nu}_\mu$) - mode at SK

Atmospheric parameters



- Best fit in the upper octant
- Lower octant still allowed at the 68% CL level

CP violation phase



- $\Delta\chi^2$ distribution for δ_{CP} in each mass ordering
- a large region of the δ_{CP} is excluded at 3σ
- CP-conservation ($\delta_{CP} = 0, \pm\pi$) is excluded at 90% CL
- preference for maximal CP violation ($\delta_{CP}^{max} = -\pi/2$)

Using θ_{13} constraint from reactor experiments:
$sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

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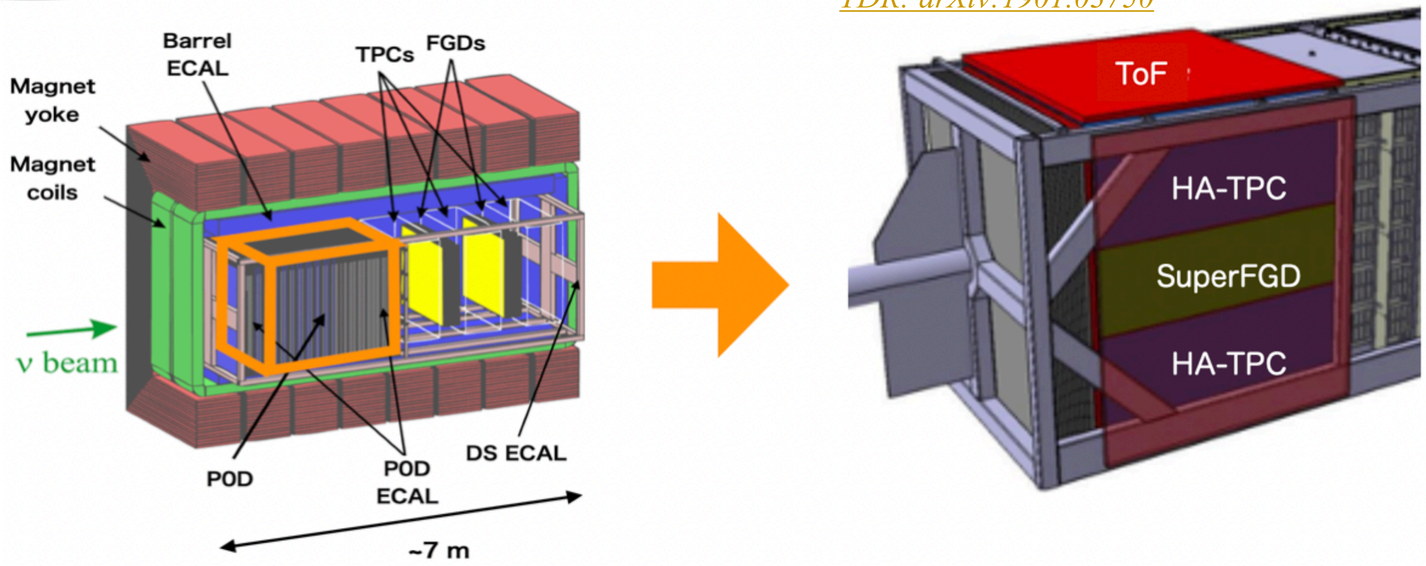
Physics motivations for ND280 Upgrade

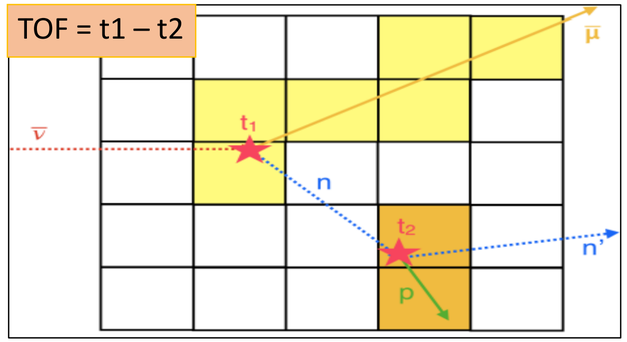
TDR: arXiv:1901.03750



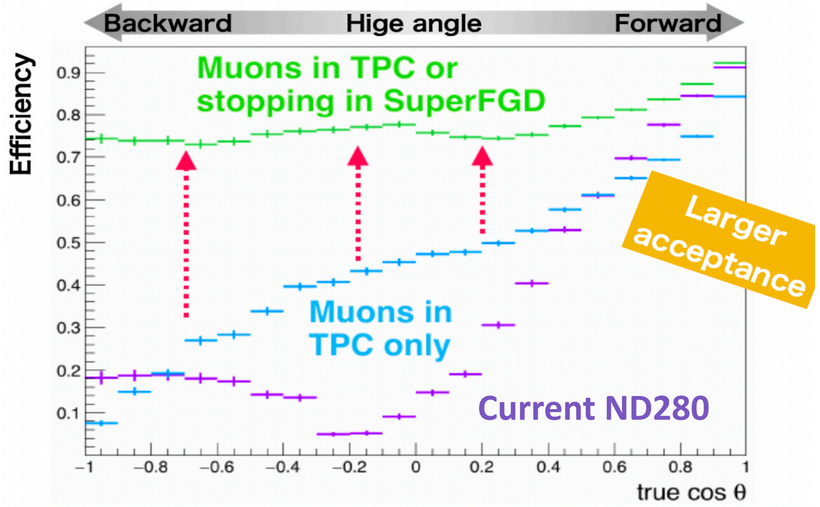
New upstream tracker:

- 2 × High-Angle TPC (Covering large acceptance)
- 1 × SuperFGD (Target & tracking detector)
- 6 × Time-of-Flight (Veto, Particle ID, Cosmic calibration trigger)

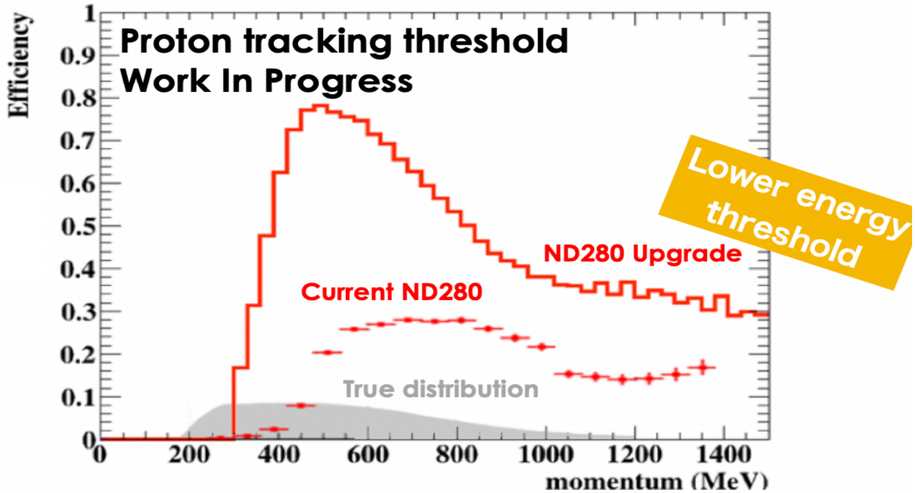
- detection of neutrons:



- 4π-acceptance for charged particles



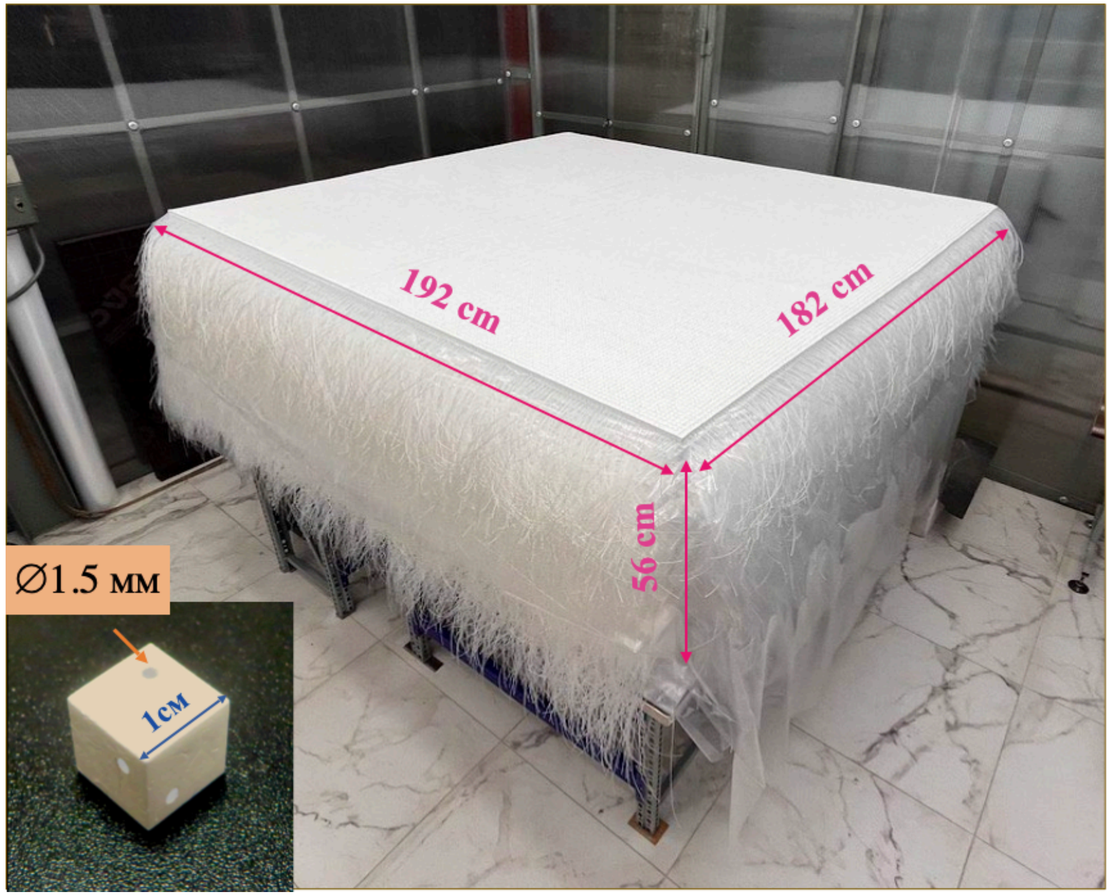
- a low threshold for proton and pion detection (~300 MeV/c)



- an electron/gamma separation

Expected result: Reducing of systematic error in T2K to the level of 3-4%

SuperFGD (Super Fine-Grained Detector)



- Detector size: **192**(x) × **182**(z) × **56**(y) **cm**^{3}
- **1,956,864** optically-isolated plastic scintillator cubes with size of **1** × **1** × **1 cm**^{3}
- Three orthogonal through holes ∅1.5 mm in each cube
- **56,384** readout channels for:
  - Wavelength Shifting (WLS) fibers ∅1 mm Kuraray Y-11 (200) multiclad S-type
  - Hamamatsu Photonics MPPCs S13360-1325PE
- Detector active mass ~2 tons

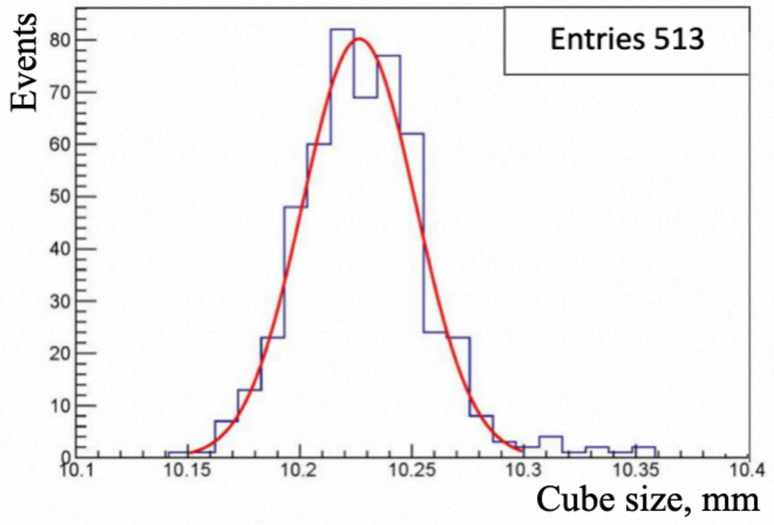
~100 participants in total

From Russia:
- INR RAS
- JINR
- LPI RAS

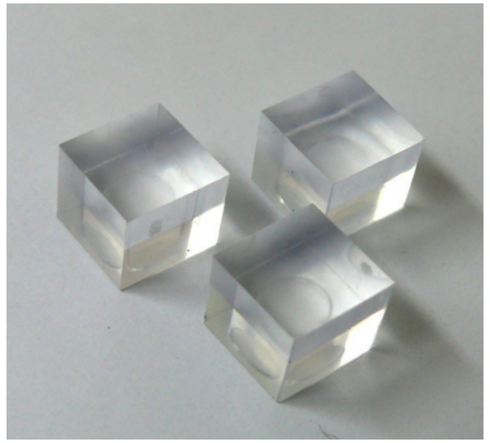
SuperFGD cubes

- Manufactured in Vladimir, Russia (UNIPLAST Co.)
- Cubes size: $10 \times 10 \times 10$ mm^3
- Material: polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of 1,4-bis benzene (POPOP)
- Method: injection molding
- White reflective layer: 50–80 μm thick
- Holes for WLS fibers: three in each cube, ∅1.5 mm

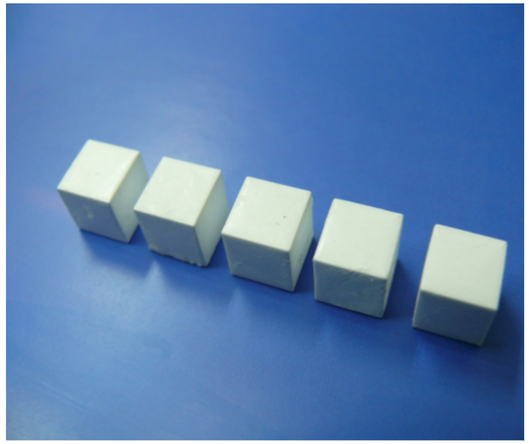
Cube side size:
10.23 ± 0.025 mm



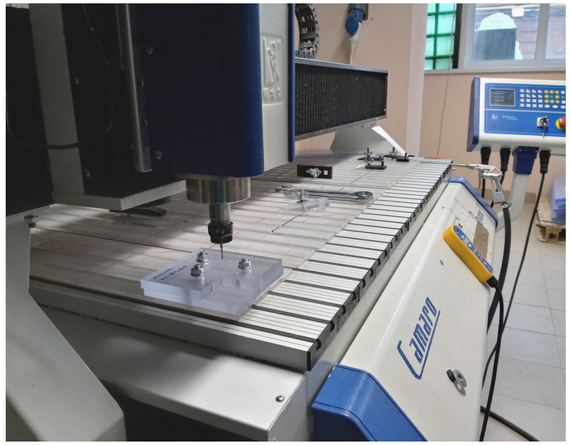
injection molding method



etching in a chemical substance (a reflective layer formation)



drilling three orthogonal through holes in each cube

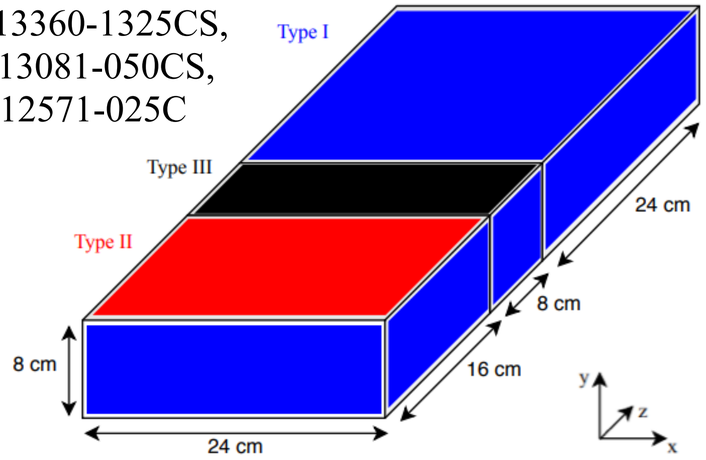


SuperFGD prototype beam test

p = 0.8 GeV/c
B = 0.2 T

SuperFGD prototype $24 \times 8 \times 48$ cm^3 (9,216 cubes and 1,728 readout channels) has been tested on a charged particle beam of 0.4 - 8 GeV/c at CERN

1,152 – **Type I** S13360-1325CS,
384 – **Type II** S13081-050CS,
192 – **Type III** S12571-025C

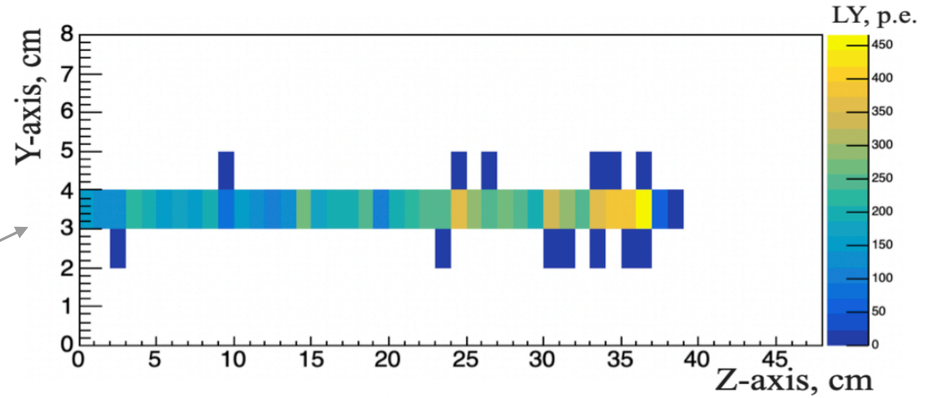


JINST 15 (2020) P12003
arXiv: 2008.08861

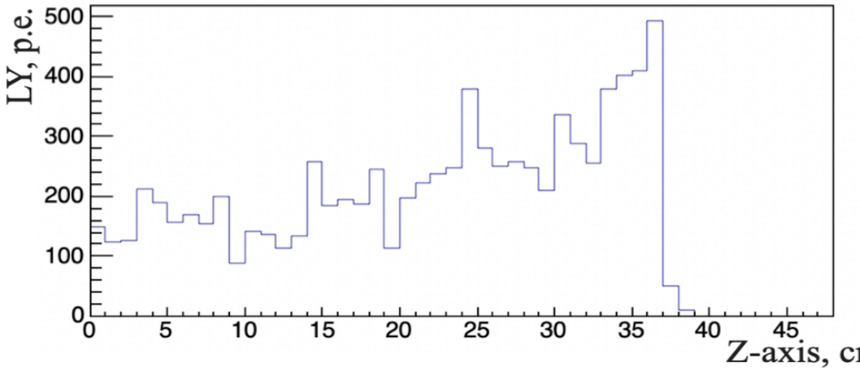
Partially instrumented SuperFGD prototype from the bottom face

Proton stopped inside the SuperFGD volume

for a single event

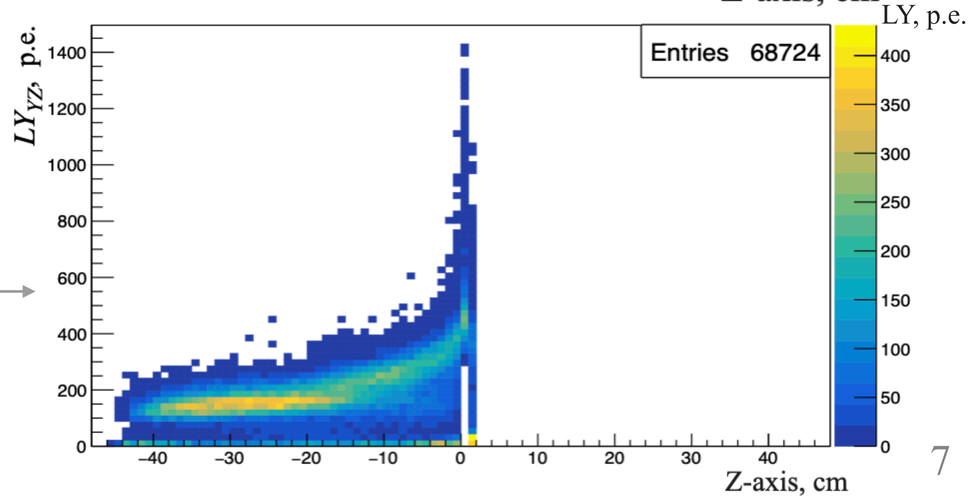


Light Yield distribution along Z-axis



Light Yield distribution **relative to the proton stop point**

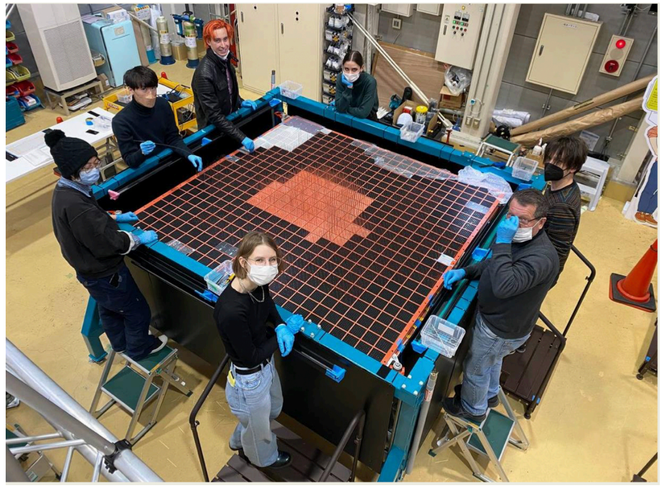
for selected 1854 proton events



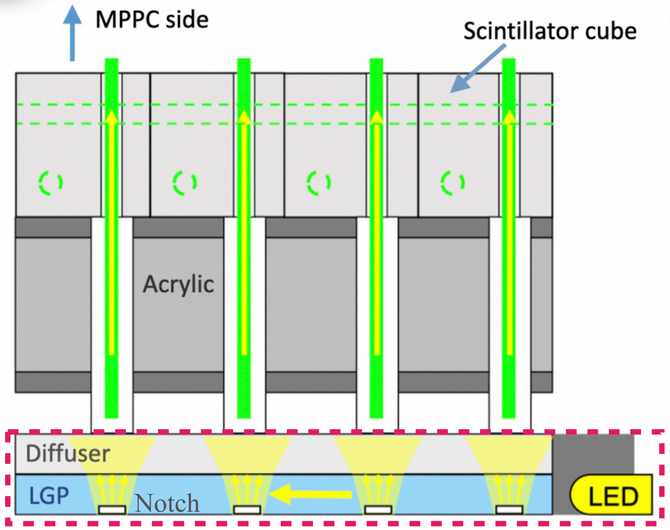
SuperFGD assembling

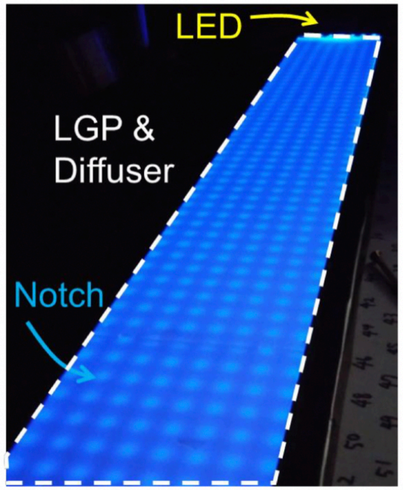
SuperFGD mechanical box containing scintillator cubes on horizontal fishing lines and vertical welding rods inside the mini Baby-Basket frame

Installation of horizontal and vertical ⌀1 mm Y-11 WLS fibers instead of fishing lines (~21k, ⌀1.3 mm) and welding rods (~12k, ⌀1.2 mm), respectively



SuperFGD calibration system

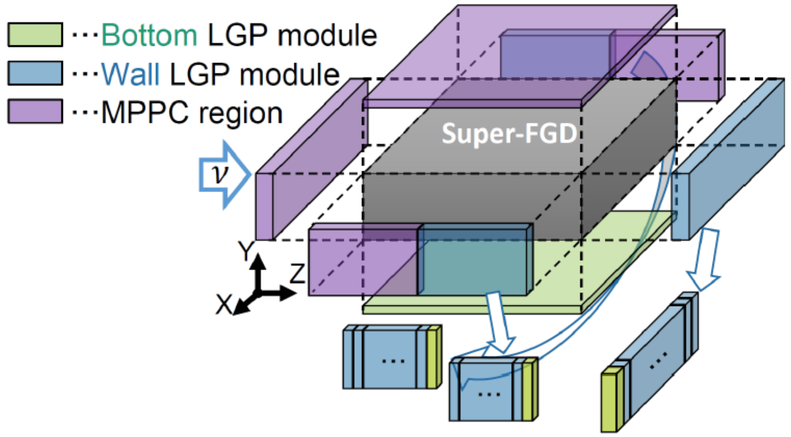


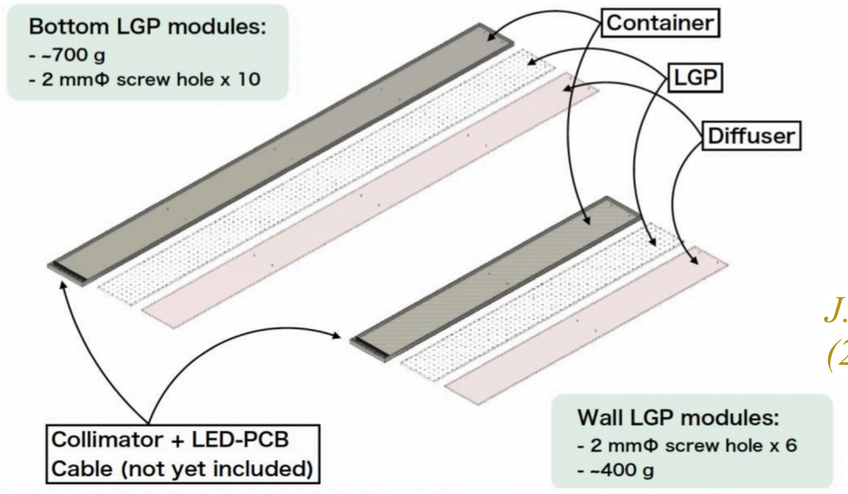


LGP module

Integration design of the LGP modules and MPPCs on the box surface:

- Bottom LGP module
  - 8 x 96 = 768 Notches
  - 46 modules in total
- Wall LGP module
  - 8 x 56 = 448 Notches
  - 47 modules in total





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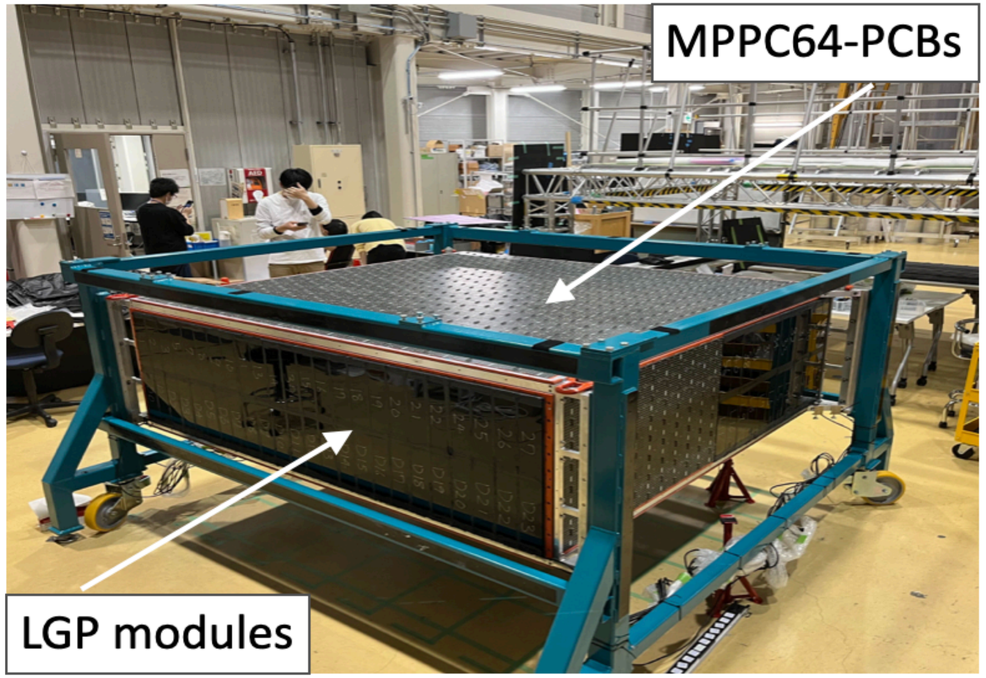
LGP modules and MPPC64-PCBs mounted on the mechanical box panels



Bottom and wall LGP modules with a length of about 1 m and 0.6 m, respectively

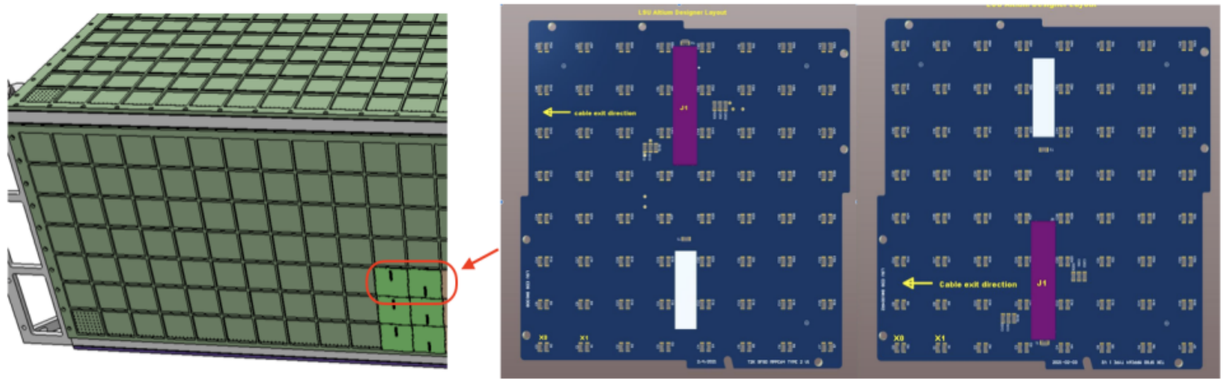
* **LGP** – **L**ight **G**uide **P**late
LED – **L**ight-**E**mitting **D**iode

MPPC64 – PCB. MPPC's characteristics

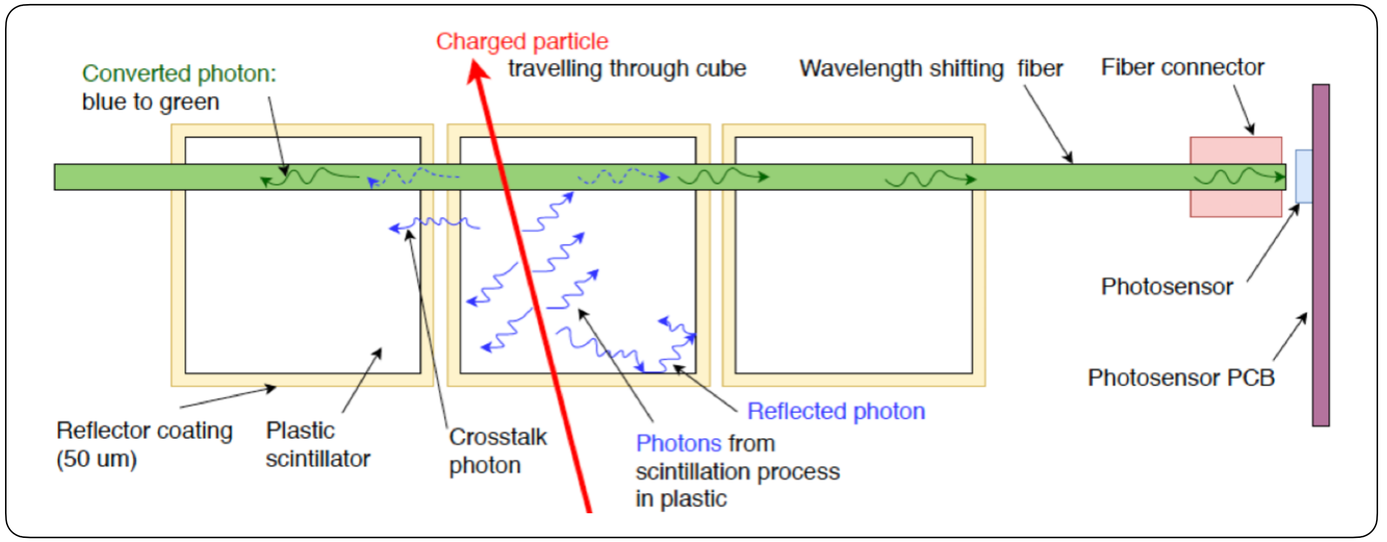
- 56,384 Multi-Pixel Photon Counters (MPPCs)
- MPPC S13360-1325PE (Hamamatsu Photonics K.K)
- 8 × 8 arrayed MPPCs on a printed circuit board (PCB)
- 881 MPPC-PCBs in SuperFGD in total

Item	Specification
Pixel pitch (μm)	25
Effective photosensitive area (mm)	1.3 x 1.3
Number of pixels	2668 pixels
Package type	Surface mount
Fill factor (%)	47
Breakdown voltage (V)	53 ± 5
Photon detection efficiency (%)	25
Gain	7.0×10^5
Dark noise rate (kHz) at 0.5 p.e.	70
Crosstalk (%)	1

MPPC64-PCB designs
with two connector positions

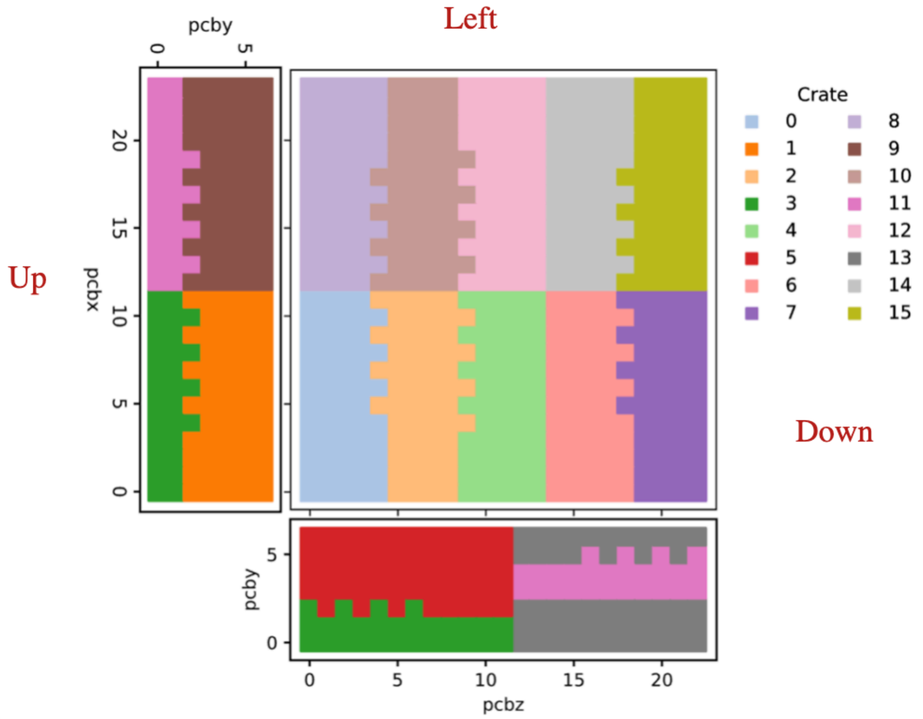


Charged particle interactions
with the SuperFGD scintillator cubes:

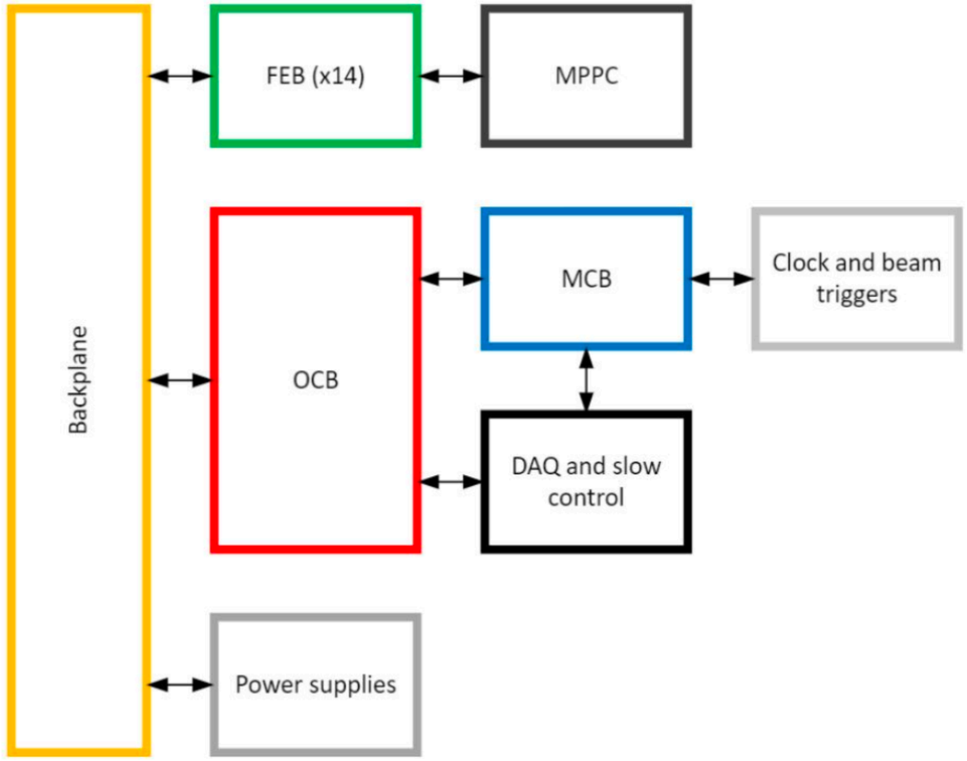


SuperFGD electronics

- **In a crate** of SuperFGD electronics:
  - 14 Front-End Boards (FEBs)
    ⇒ Processing and digitization of analog signals from MPPC
  - 1 Optical Concentrator Board (OCB)
    ⇒ Data concentrator with crate level event building
  - 1 Backplane



16 such crates in total

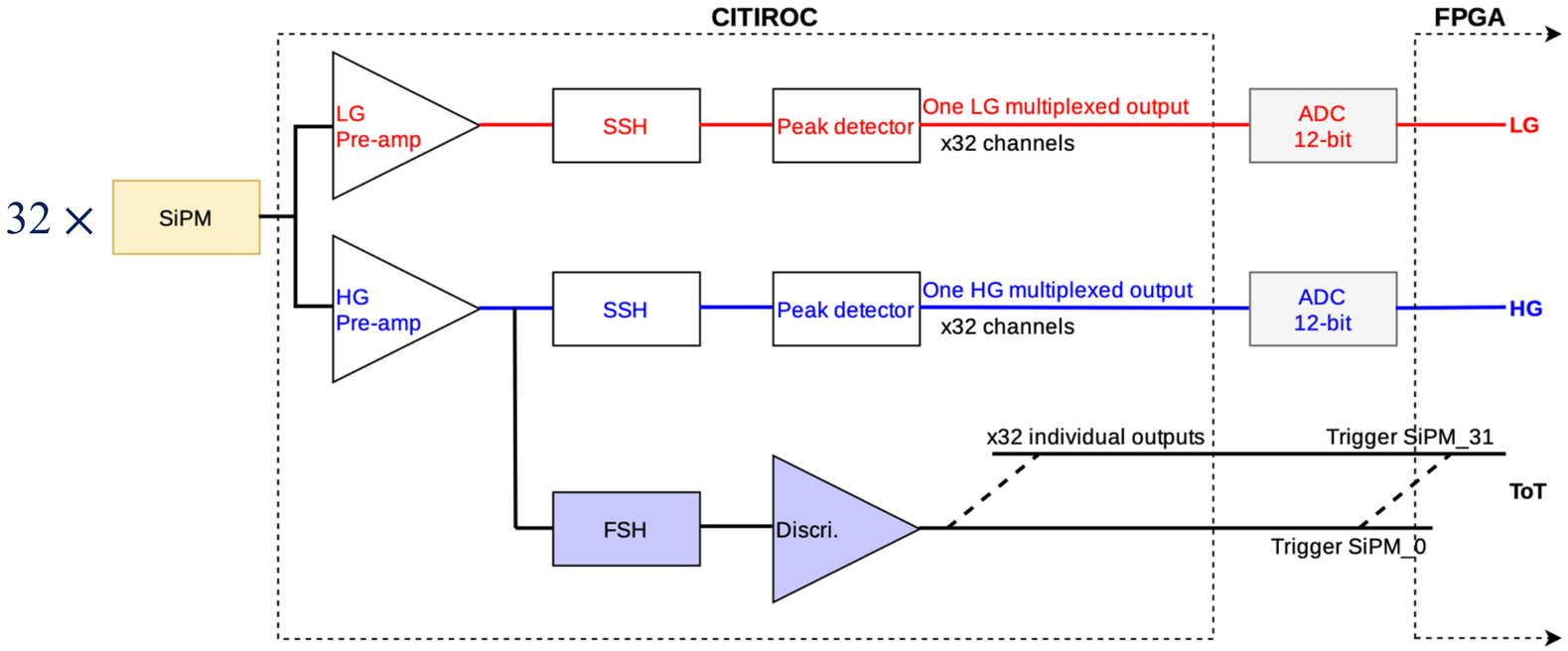


- Outside the crate:
  - 1 Master Clock Board (MCB)
    ⇒ Sends timing, gate and trigger information to sub-detectors

SuperFGD electronics

- 1 FEB
  ⇐ 8 Cherenkov Imaging Telescope Integrated Read Out Chip (CITIROCs)
  with Application-Specific Integrated Circuit (ASICs)

- 1 CITIROC chip
  ⇐ 32 input readout channels for the MPPCs

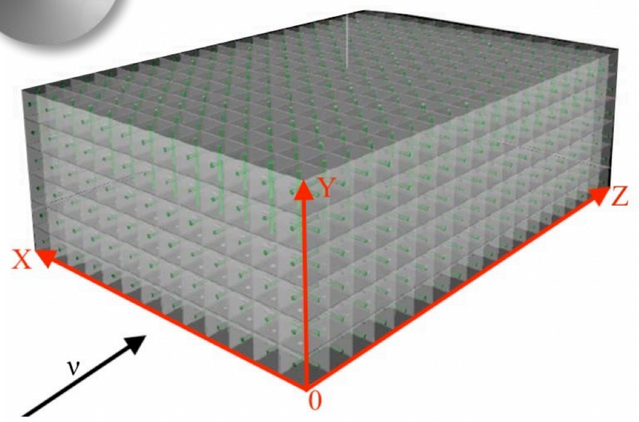


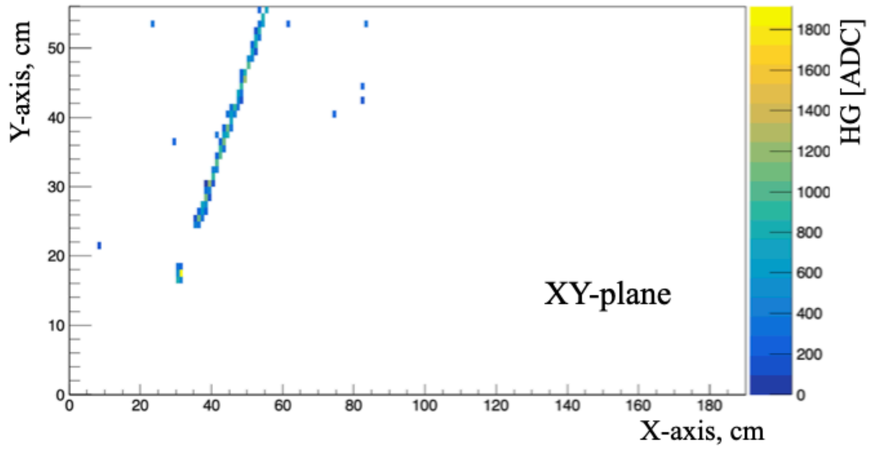
Low gain

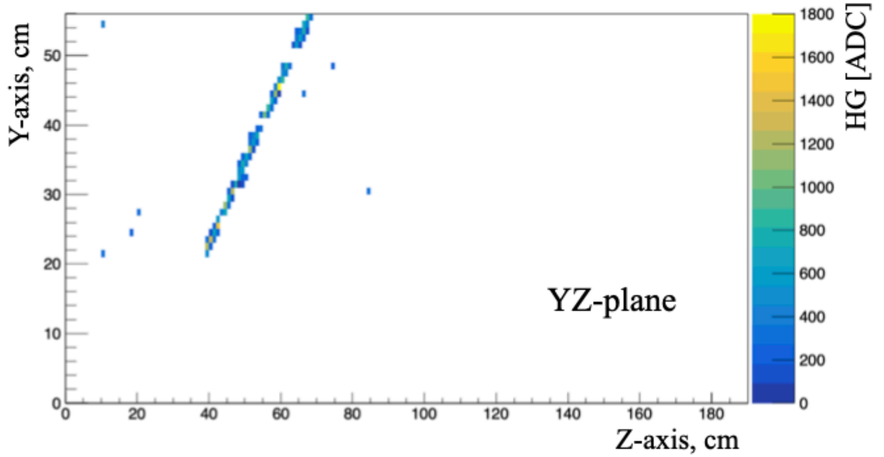
High gain

Time - of - Threshold

Cosmic event inside SuperFGD

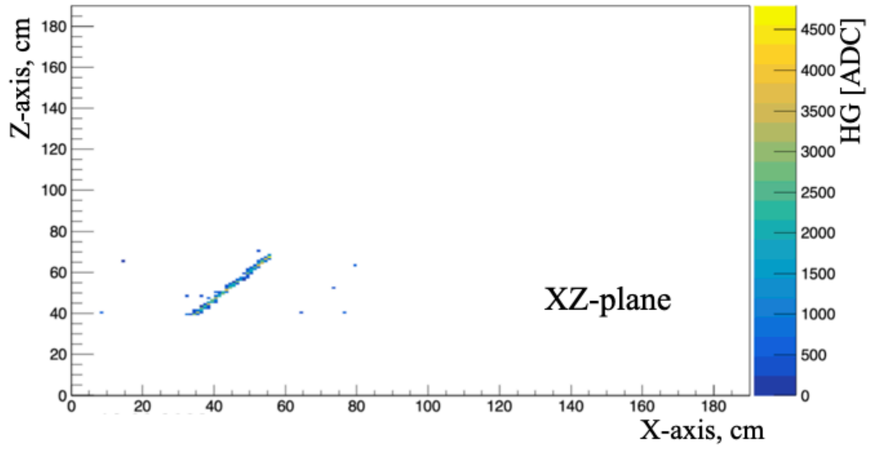




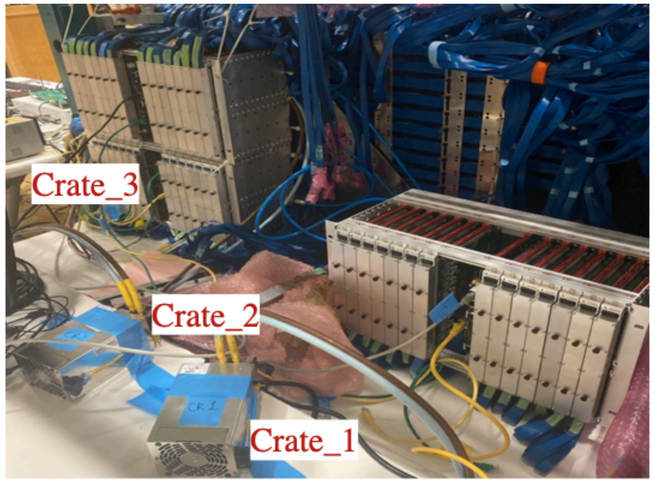


On surface:

– 3 Crates
– 42 FEBs
– 10752 channels

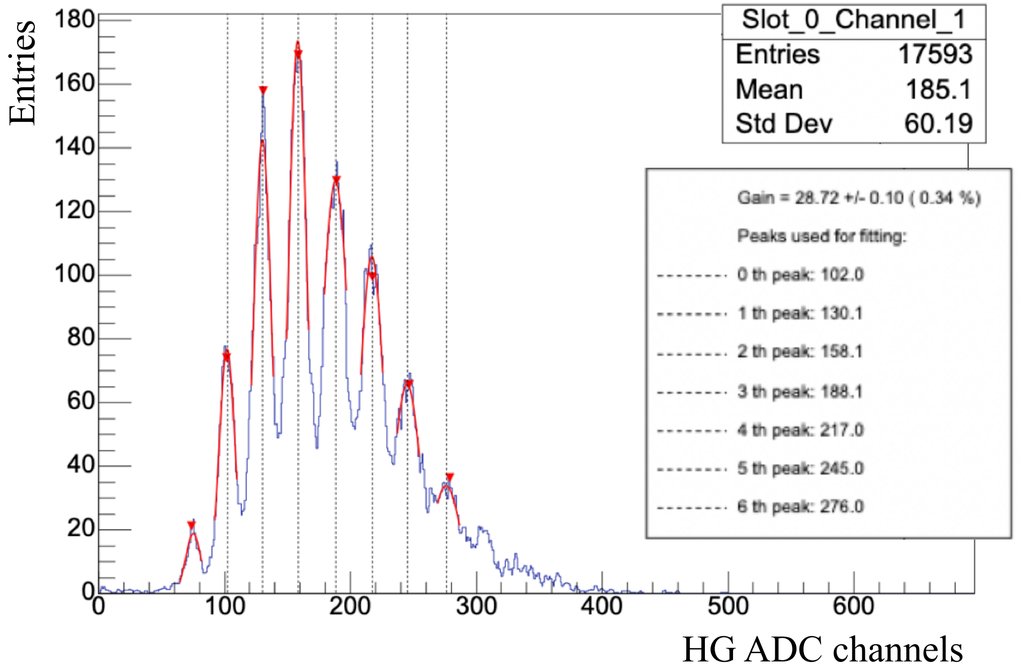


Crate	Direction	
5	horizontal	x
2	vertical	y
1	horizontal	z

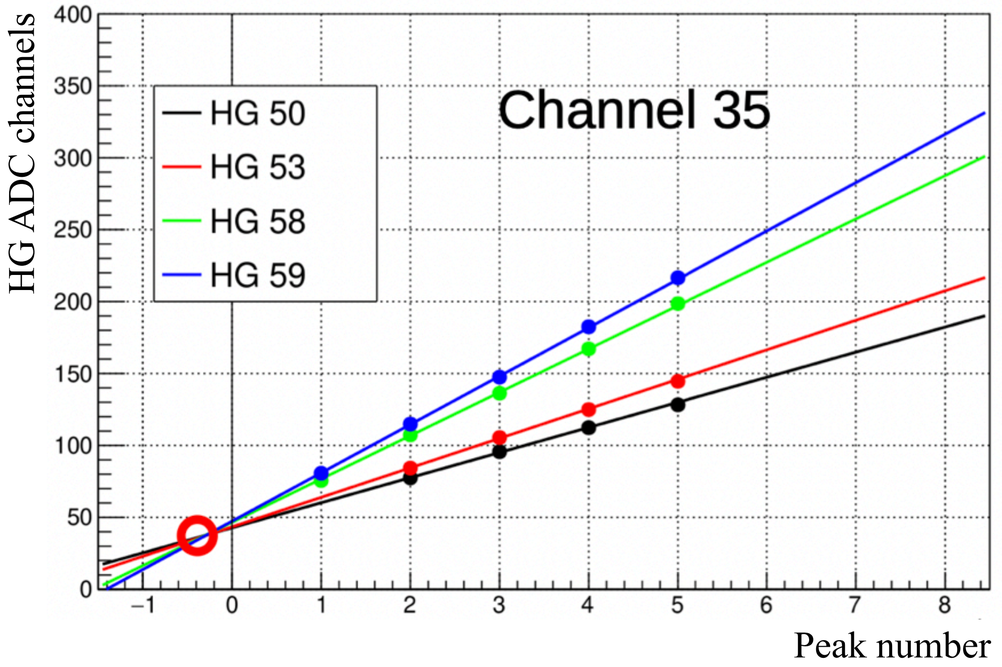


MPPCs calibration with LED

Typical calibration plot for a single channel



Pedestal finding method for a single channel using different HG values

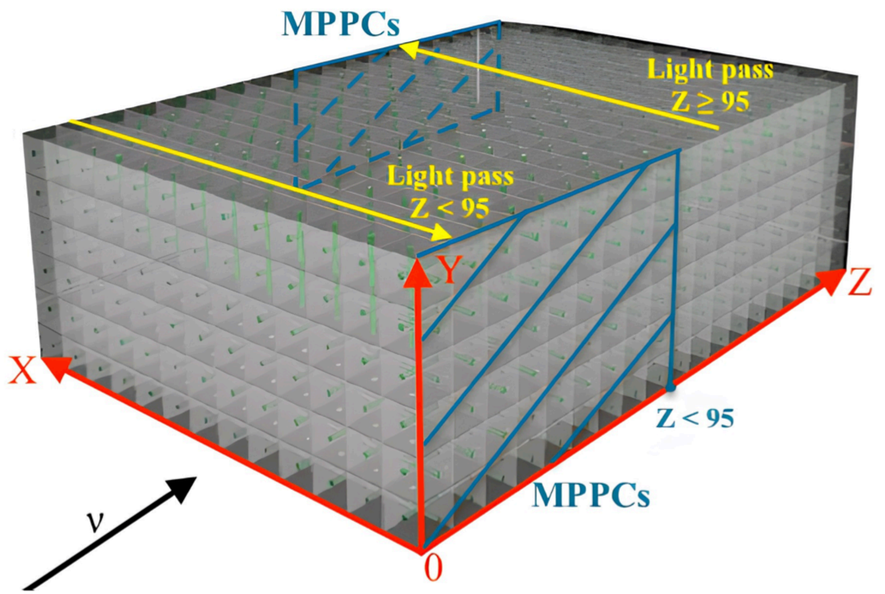


T2K work in progress

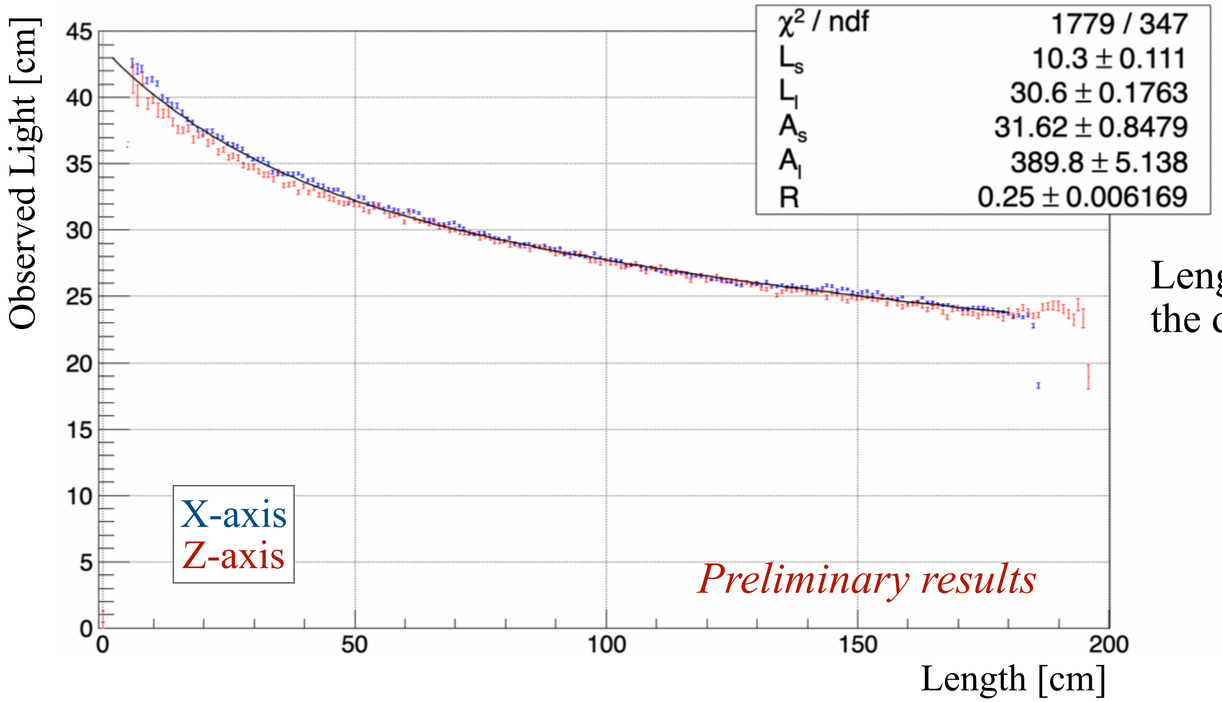
Attenuation length for horizontal fibers

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

LY - Light Yield, p.e.
R - reflection coefficient (15-25%)
LY_S - short Light Yield coefficient, p.e.
LY_L - long Light Yield coefficient, p.e.
A_S - short attenuation component, cm
A_L - long attenuation component, cm
x - distance from photosensor, cm



– area is connected to the MPPCs

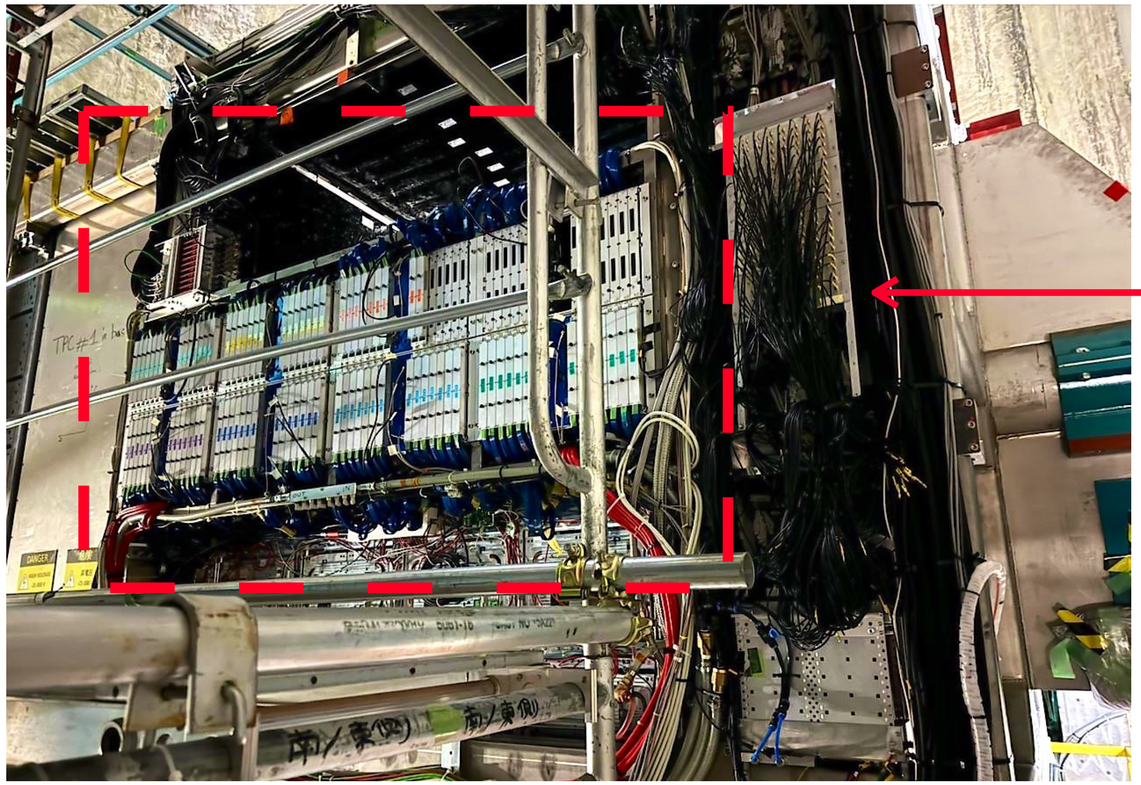


Length [cm] -
the distance from MPPCs

Average cube's Light Yield:
LY_0 = (40.9 ± 0.29) p.e.

SuperFGD in T2K neutrino beam

SuperFGD fully installed into the ND280 pit
with all of the 222 FEBs and 16 OCBs



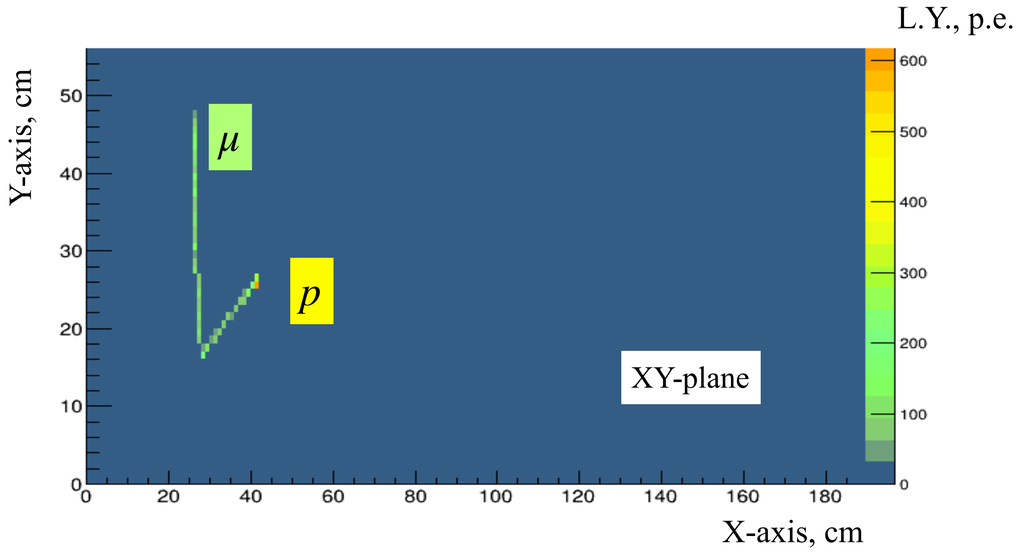
Beam power: 760 kW

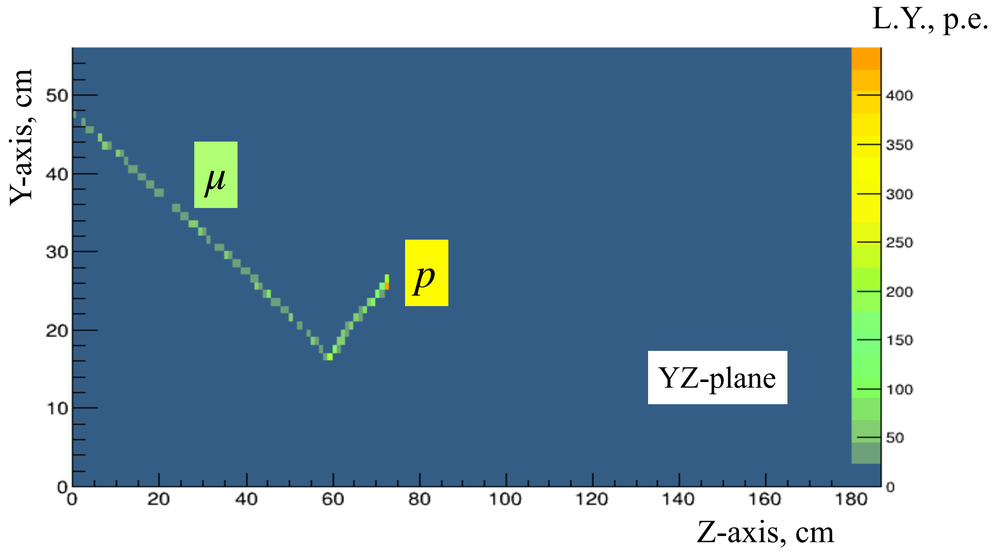
off-axis ν_μ-beam
at 2.5° to the *p*-beam axis

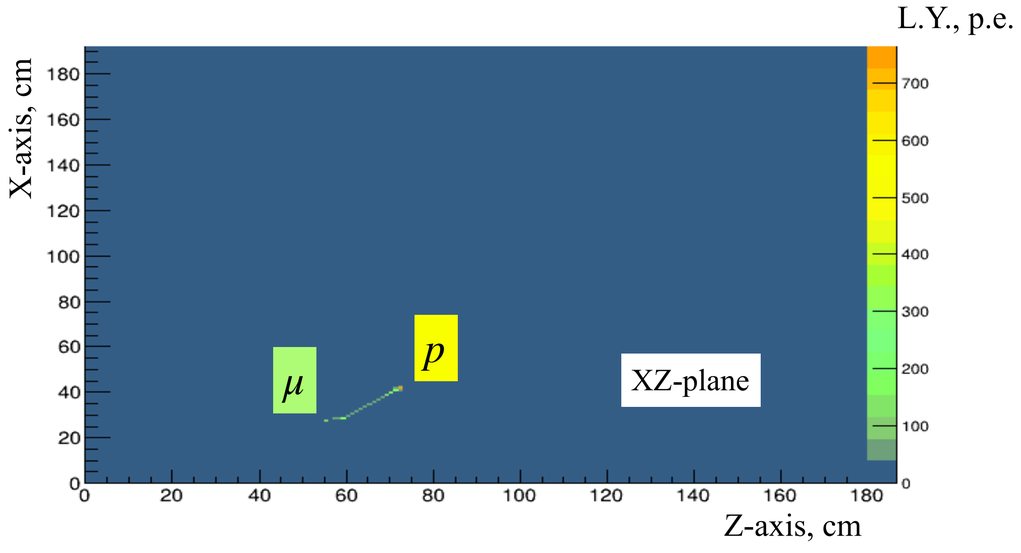
At the first oscillation maximum: $E_\nu^{peak} = 0.6$ GeV

Neutrino event inside SuperFGD

Example #1





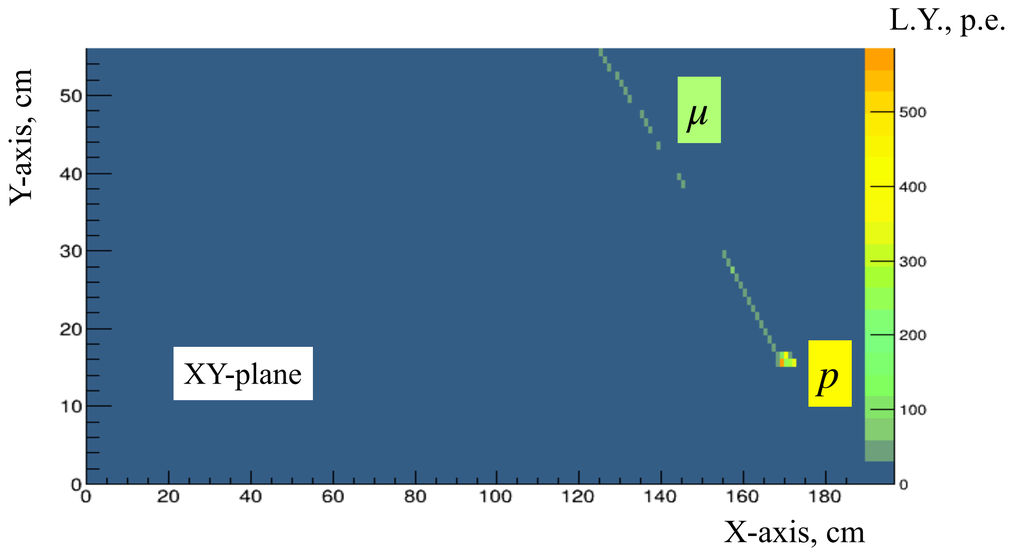


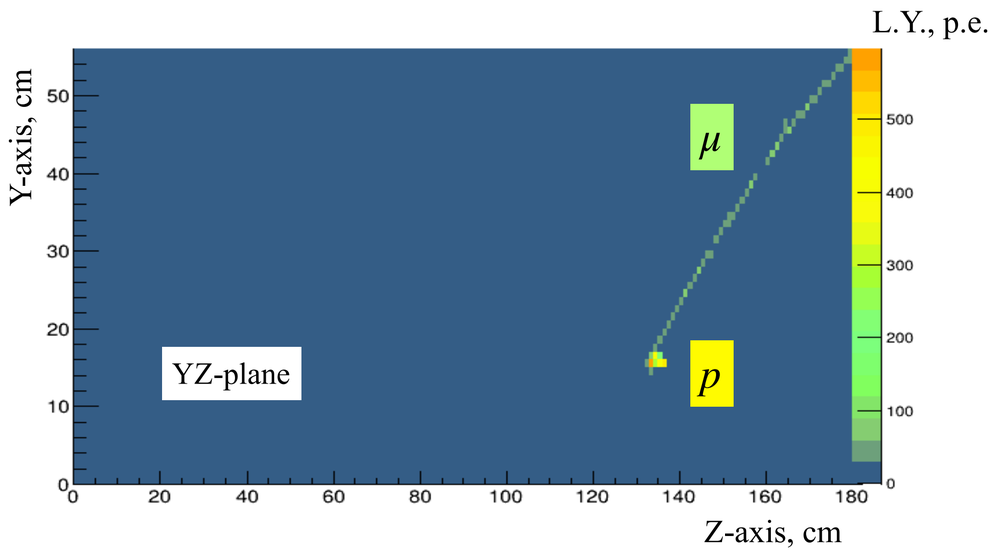
Charged-current quasi elastic (CCQE) scattering of ν_μ with nuclei gives muon and proton at the final state:

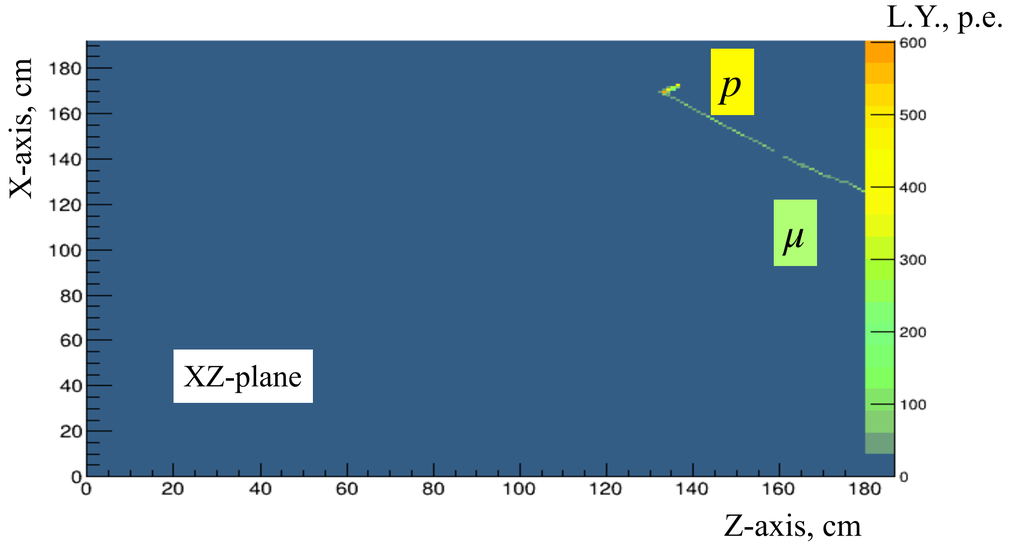
$$\nu_\mu + n \rightarrow \mu^- + p$$

Neutrino event inside SuperFGD

Example #2







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

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

Заключение

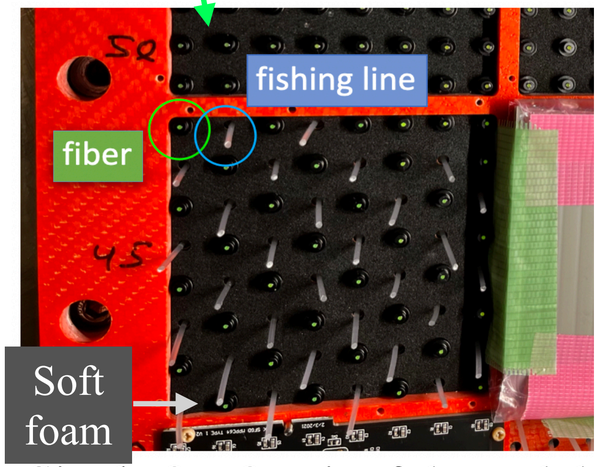
- Детектор SuperFGD, состоящий из ~2 млн оптически изолированных пластиковых сцинтилляционных кубиков $1 \times 1 \times 1$ см^3, является центральным элементом модернизованного ближнего off-axis нейтринного детектора ND280 эксперимента T2K
- Модернизация ND280 направлена на снижение систематических ошибок осцилляционного анализа в T2K и на улучшение чувствительности эксперимента к CP-нечетной фазе δ_{CP}
- В настоящий момент детектор SuperFGD установлен на нейтринном канале в составе комплекса ближних детекторов ND280 для набора статистики на пучке J-PARC
- Выполнена калибровка каналов электроники SuperFGD с помощью LED калибровочной системы на космических мюонах
- Измерена средняя величина световыхода на кубик с учетом ослабления вдоль горизонтальных X- и Z- волокон
- Зарегистрированы первые нейтринные события в объеме детектора SuperFGD — ноябрь 2023
- Детектор SuperFGD будет ключевым элементом ближнего детектора в проекте Hyper-Kamiokande

Backup slides

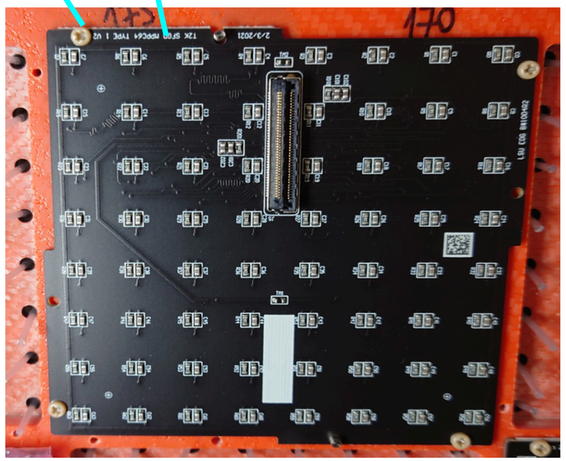
WLS fibers installation

56k WLS fibers ∅1 mm in place of:
- fishing lines (~21k, ∅1.3 mm)
- welding rods (~12k, ∅1.2 mm)

Upstream panel

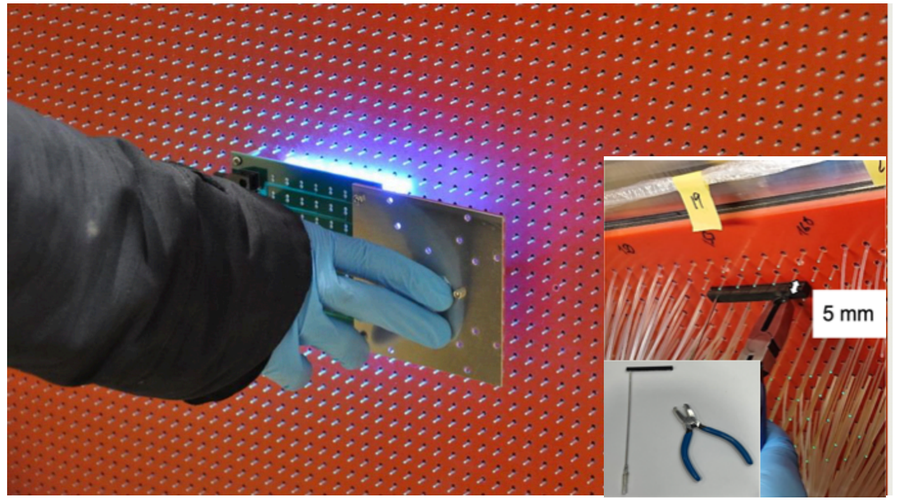


Single 8 × 8 unit of through holes on the upstream panel



MPPC64-PCB

Quality control:
Light yield > 70%



Downstream panel

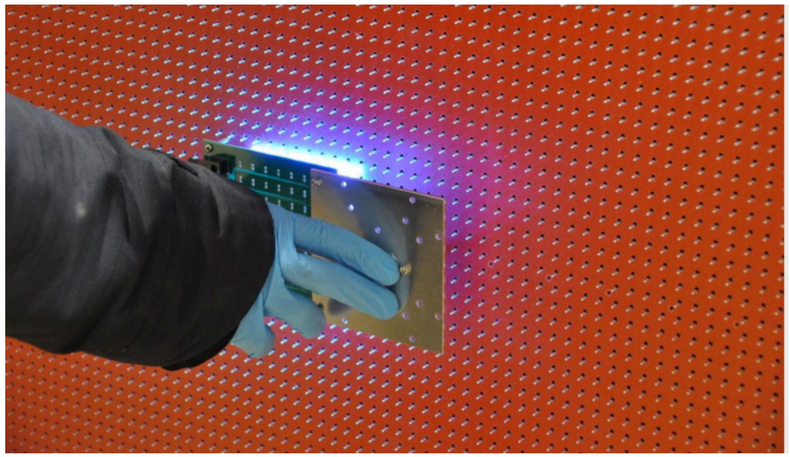
Vertical fibers:
- **In total**: ~35k fibers (552 PCBs)
- **Broken**: 42 fibers

Horizontal fibers:
- **In total**: ~21k fibers (329 PSBs)
- **Broken**: 21 fibers

The broken fibers were replaced

Quality control of inserted WLS fibers

Quality criterion:
Light yield > 70%



Vertical fibers:
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Horizontal fibers:
- **In total**: ~21k fibers (329 PSBs)
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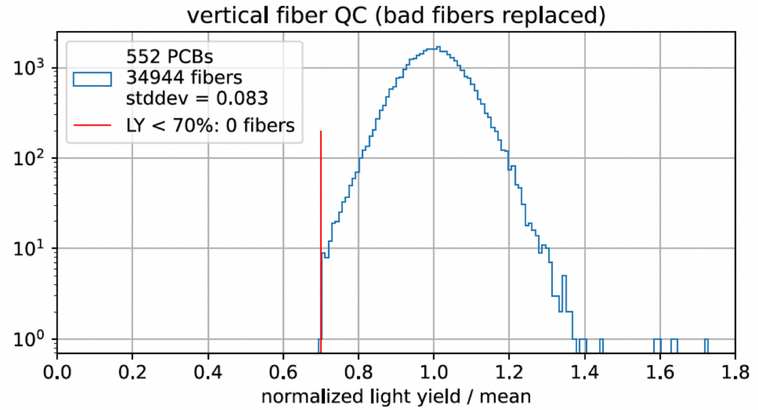
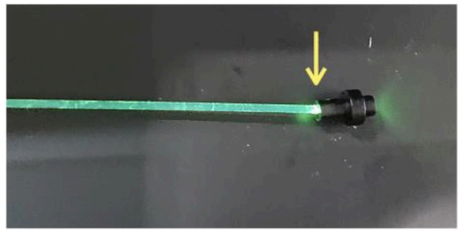
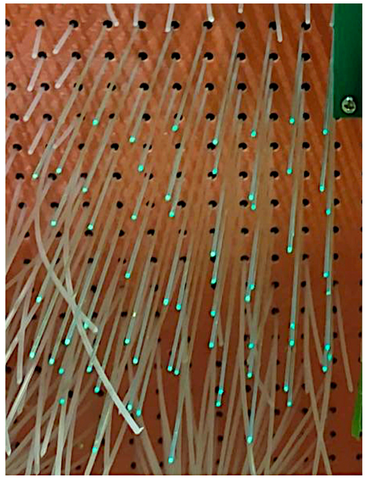
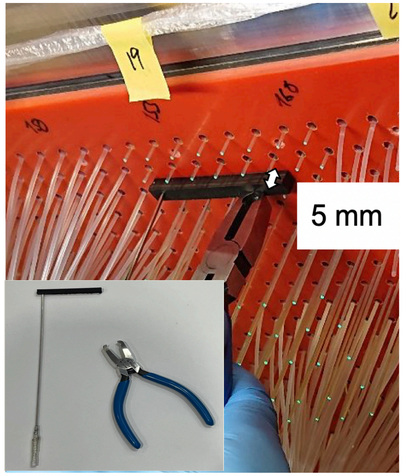


the main cause of fiber damage:



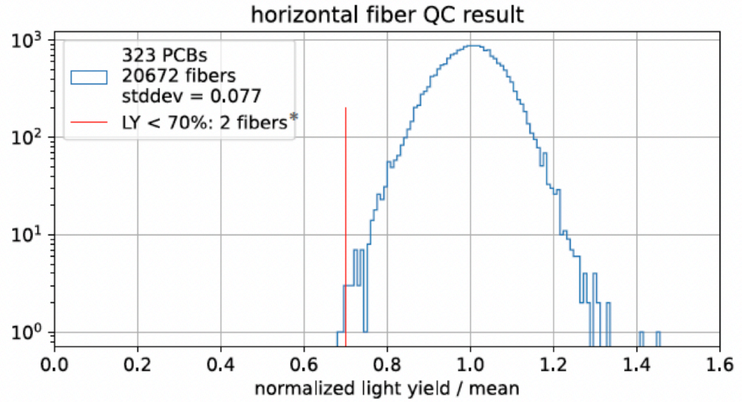
The broken fibers were replaced



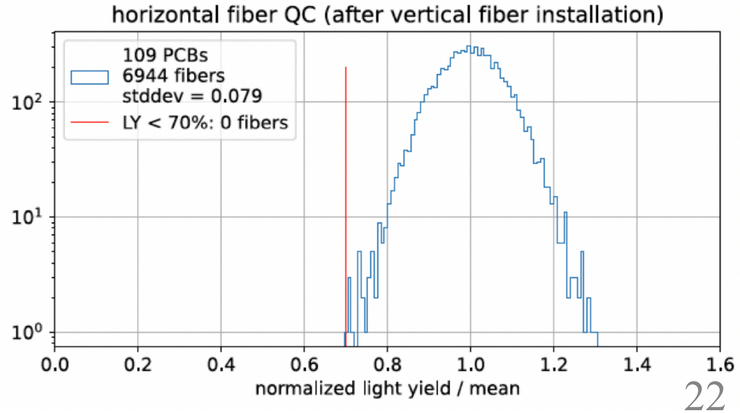


Re-test of horizontal fibres after vertical fibres installation

before vertical fiber installation



after vertical fiber installation



Attenuation length for horizontal fibers Algorithm

1. Read track projections on the YX and YZ planes

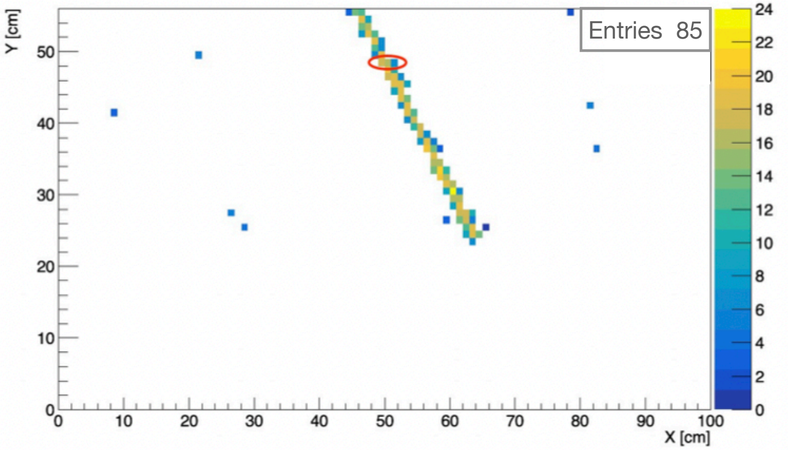
2. For each Y_value:

- Max_LY along the X (Z) axis
- Find the X (Z) coordinate that corresponds to the maximum LY - position X (Z)

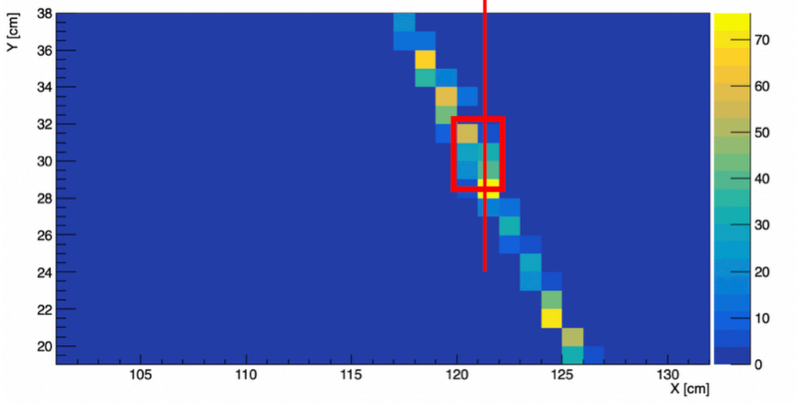
3. Assign Max_LY from one plane and position from another plane to each fixed Y_value

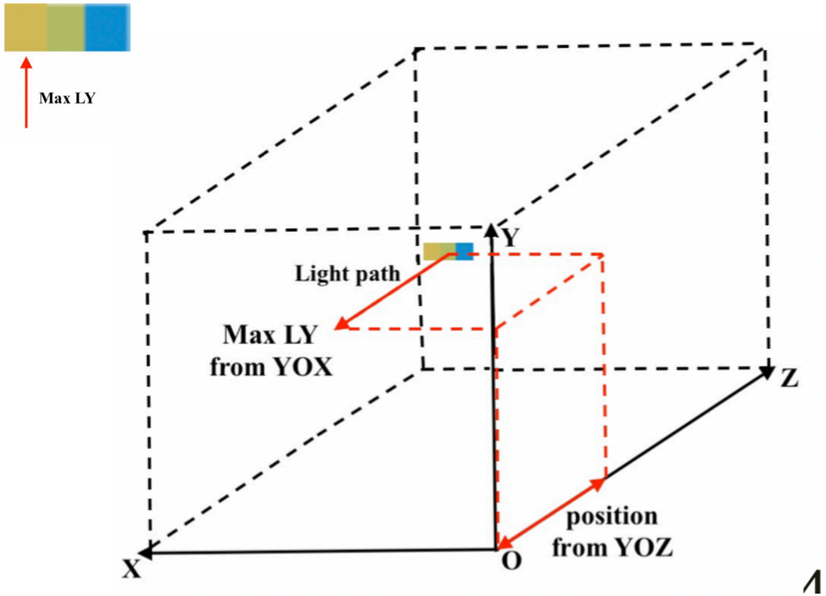
4. Obtain the dependence of Max_LY on position X (Z) – signal attenuation length

Event_example



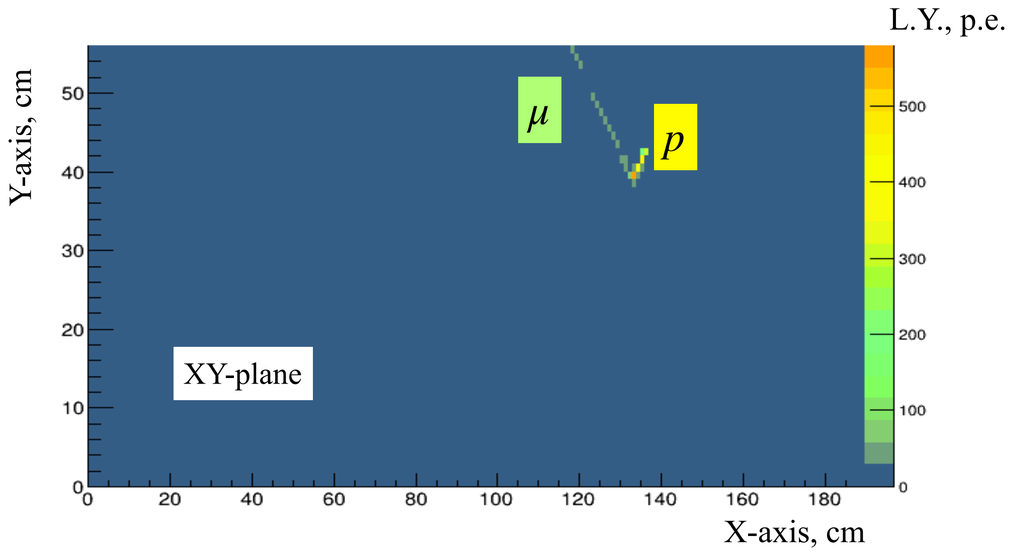
Max LY in the same line
for [y-1] and [y+1]

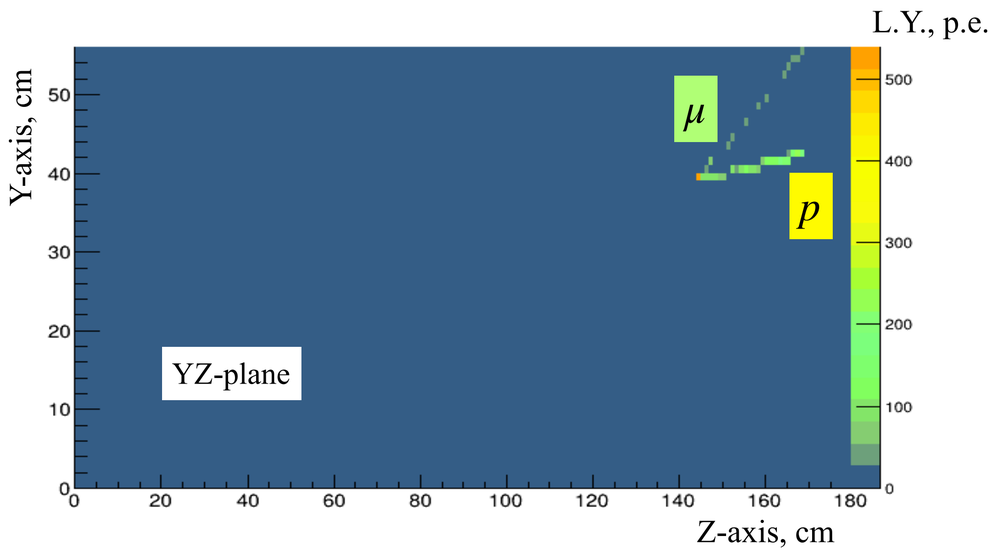


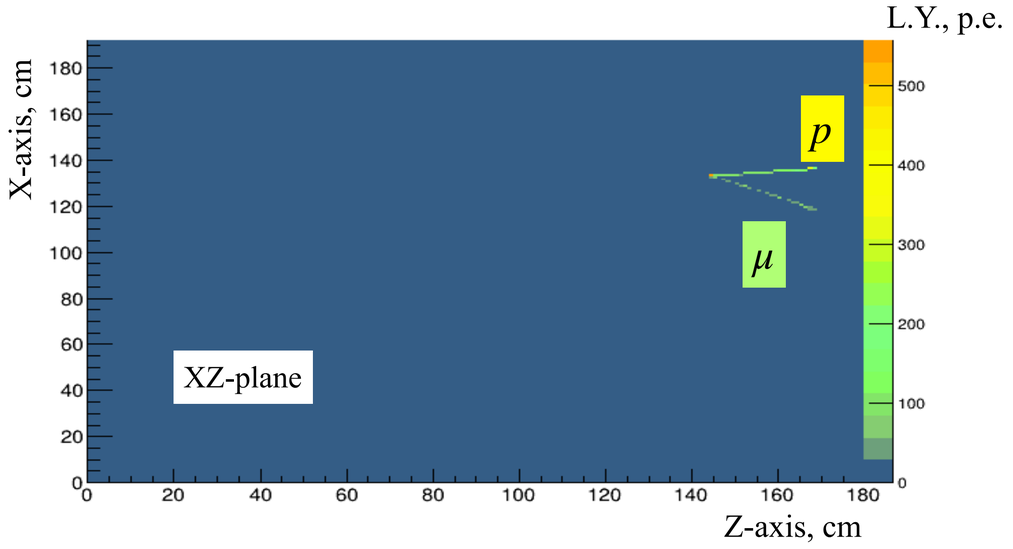


Neutrino event inside SuperFGD

Example #3





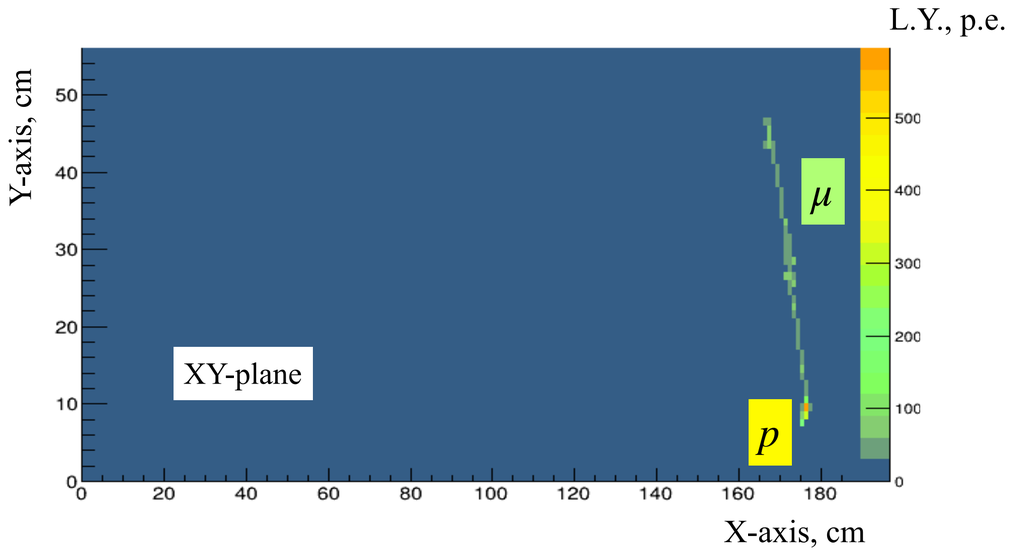


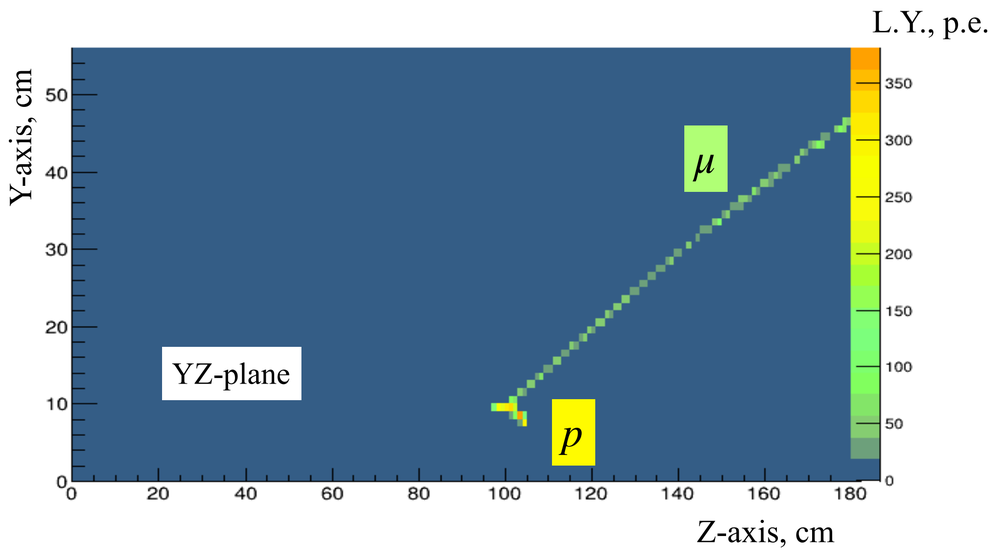
Charged-current quasi elastic (CCQE) scattering of ν_μ on CH gives muon and proton at the final state:

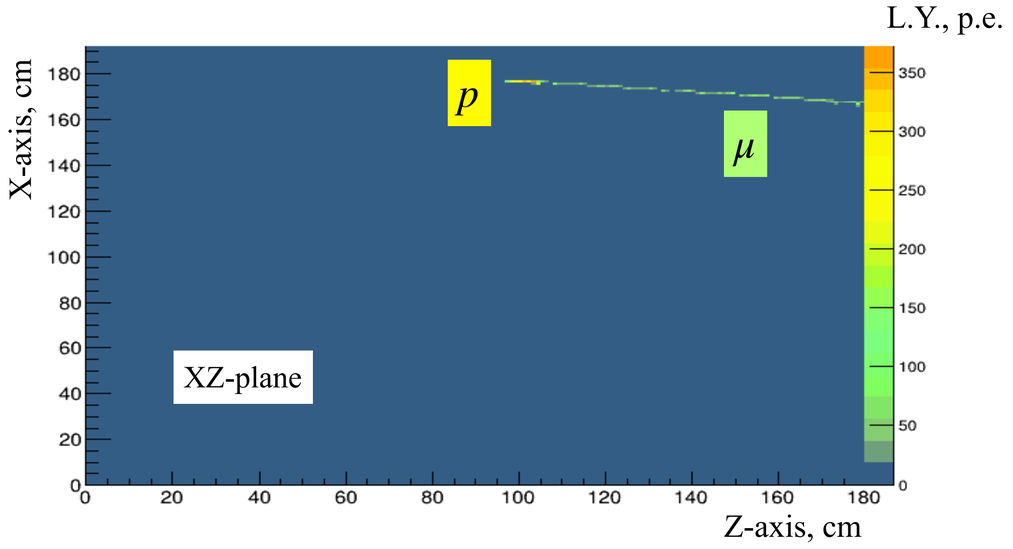
$$\nu_\mu + n \rightarrow \mu^- + p$$

Neutrino event inside SuperFGD

Example #4







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

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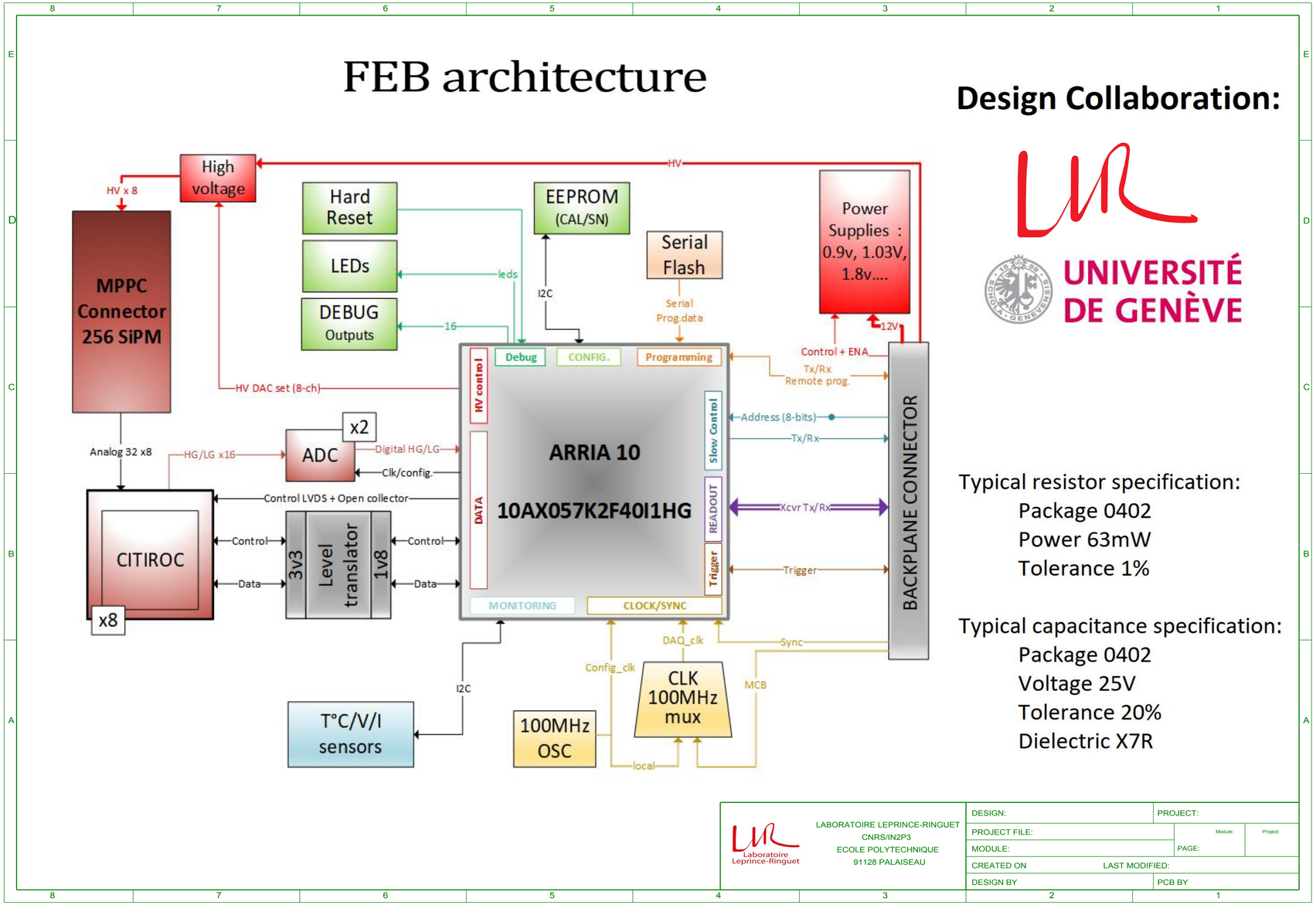
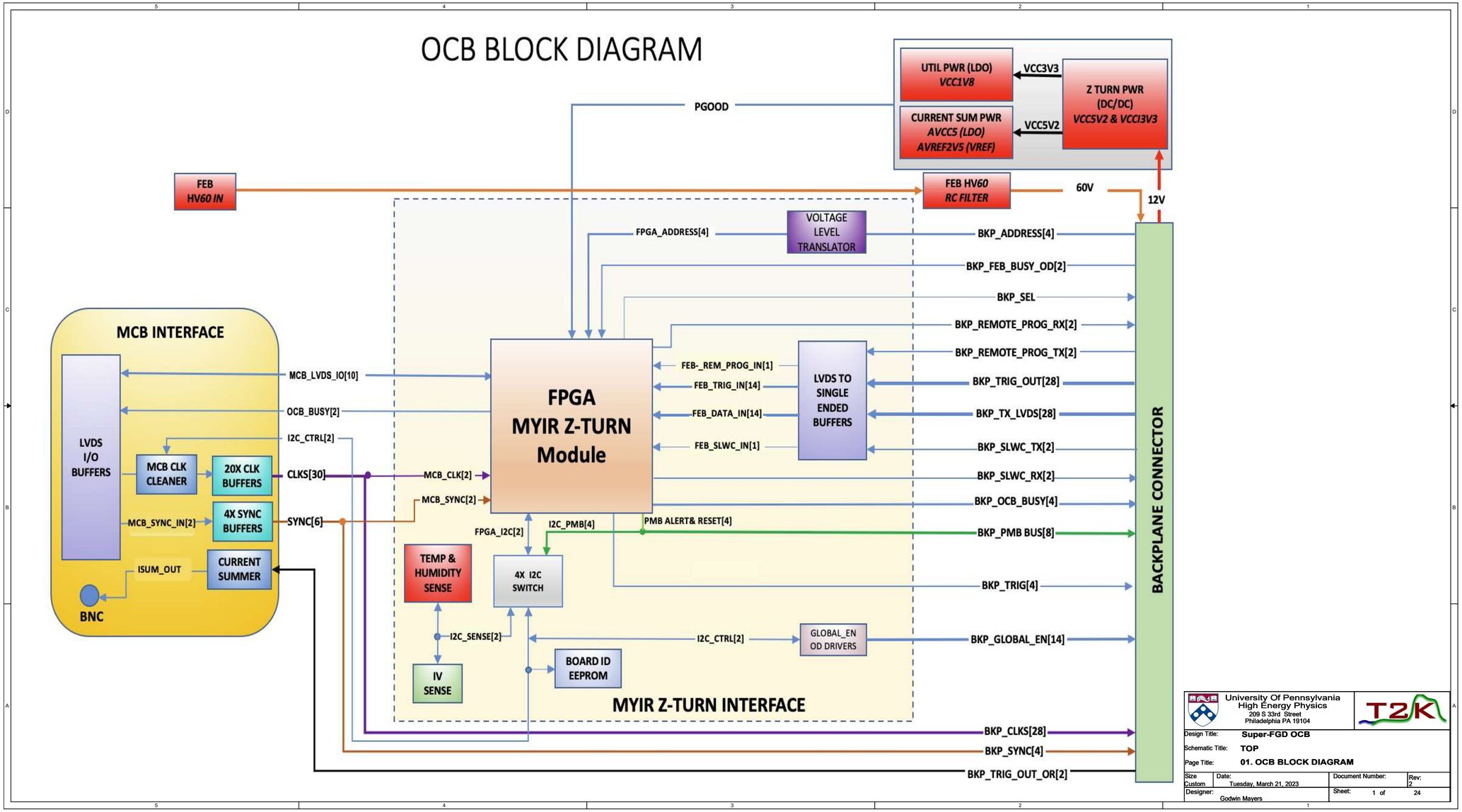
SuperFGD readout electronics scheme



SuperFGD readout electronics scheme

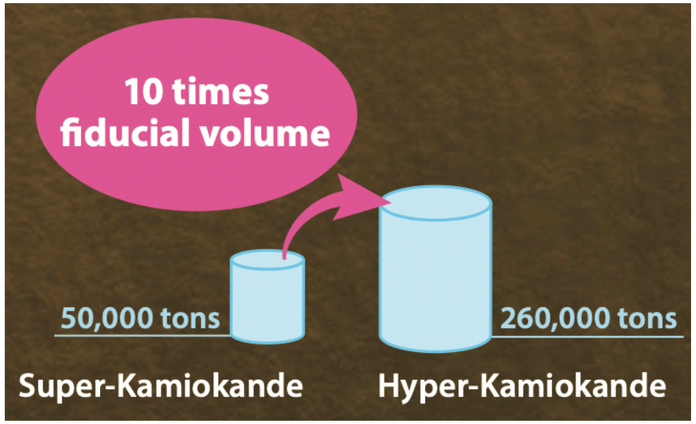


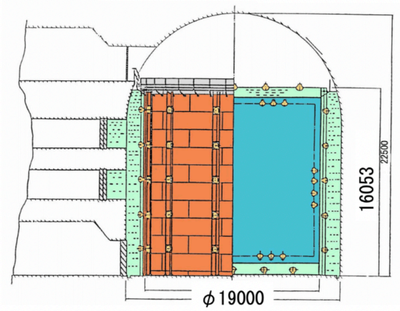
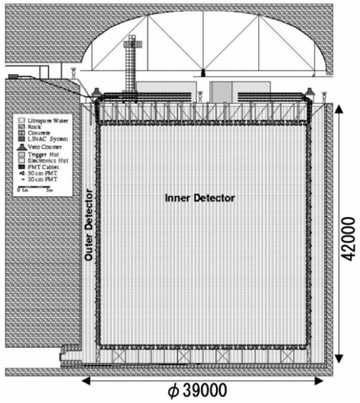
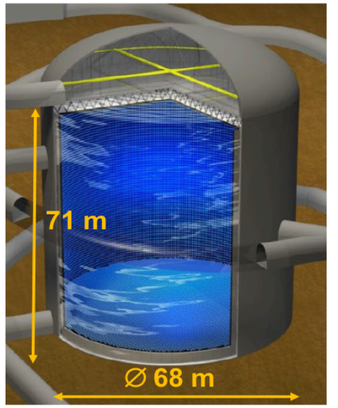
Hyper-Kamiokande Detector

Ultra-pure water Cherenkov detector, 600 m underground at the Kamioka Mine, aiming to start observation in 2027

The main experiment goals:

- *Discovery of the **CP violation** and precise measurements to elucidate **the origin of matter in the universe***
- *Proof of "unification of elementary particles" and "unification of electromagnetic, weak and strong force" by the discovery of **proton decay***



Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983～1996	1996~Present	Aiming to start observation in 2027
		
Size		
19m diameter x 16m hight	39m diameter x 42m hight	68m diameter x 71m hight
Water mass (Fiducial mass)		
4500 ton※ (680~1040 ton) ※The waer mass in the tank(inner tank and, upper and bottom outer tank) is 3000	50000 ton (22500 ton)	260000 ton (190000 ton)
Photomultiplier Tubes		
50cm diameter / 948	50cm diameter / 11146	50cm diameter / about 40000

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