Highly Segmented Neutrino Detector SuperFGD for the T2K Experiment

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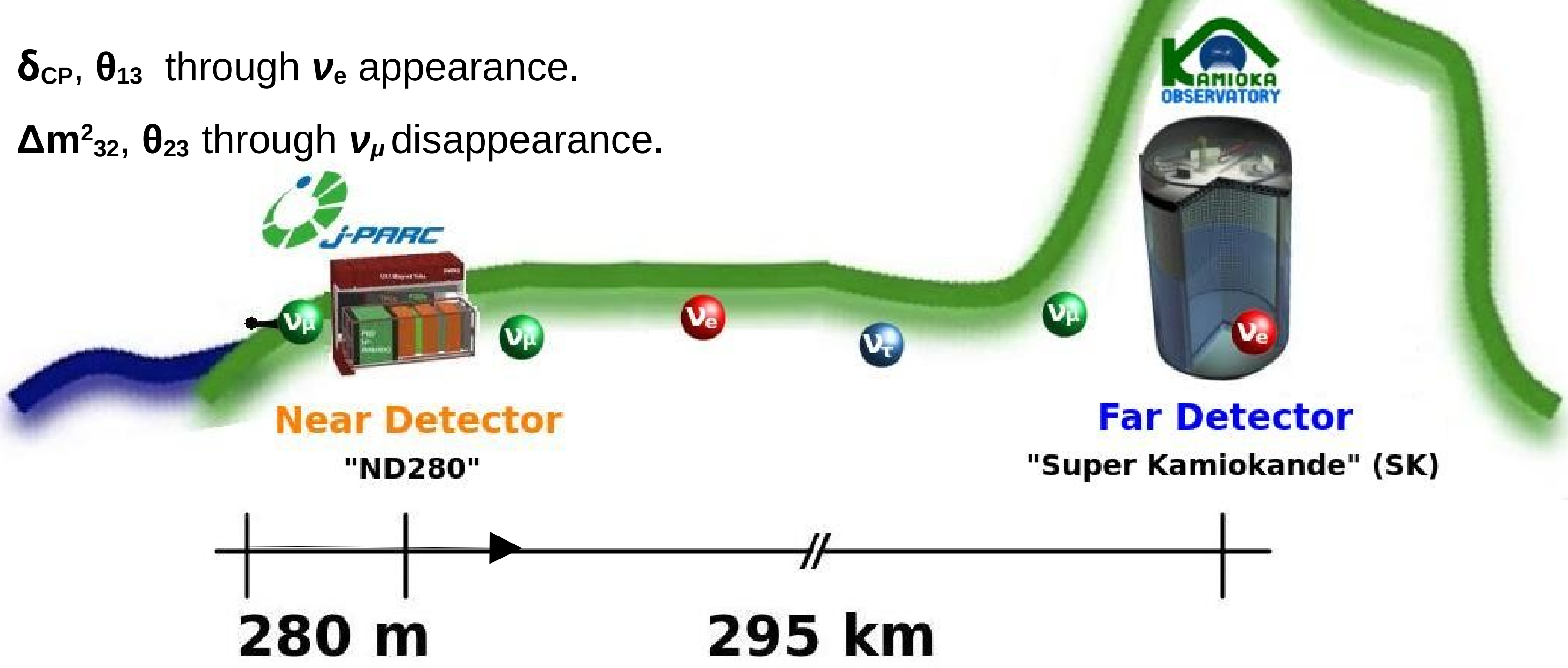
Content

What Is T2K?

Tokai to Kamioka

- Long baseline neutrino **oscillations** and neutrino **interactions** experiment.
- It measures neutrino cross sections and un-oscillated flux in the **Near** detector.
- It uses its **Near** and **Far** detectors to measure the oscillated flux and extract oscillation parameters:
  - $\boldsymbol{\delta_{CP}}$, $\boldsymbol{\theta_{13}}$ through $\boldsymbol{\nu_e}$ appearance.
  - $\boldsymbol{\Delta m^2_{32}}$, $\boldsymbol{\theta_{23}}$ through $\boldsymbol{\nu_\mu}$ disappearance.



Excerpt of T2K Achievements (So Far)

$\nu_\mu \rightarrow \nu_\mu$ Disappearance

- θ_{23}-Δm^2_{32} constraint.
- Consistent with both octants.

K. Abe et al. (T2K), Eur. Phys. J. C 83, 782 (2023)

$\nu_\mu \rightarrow \nu_e$ Appearance

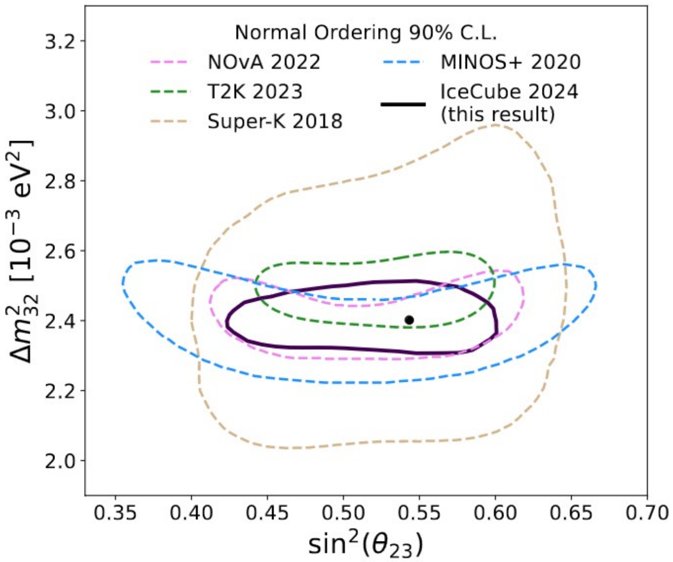
- θ_{13}-constraint.
- Consistent with stronger reactor constraint!

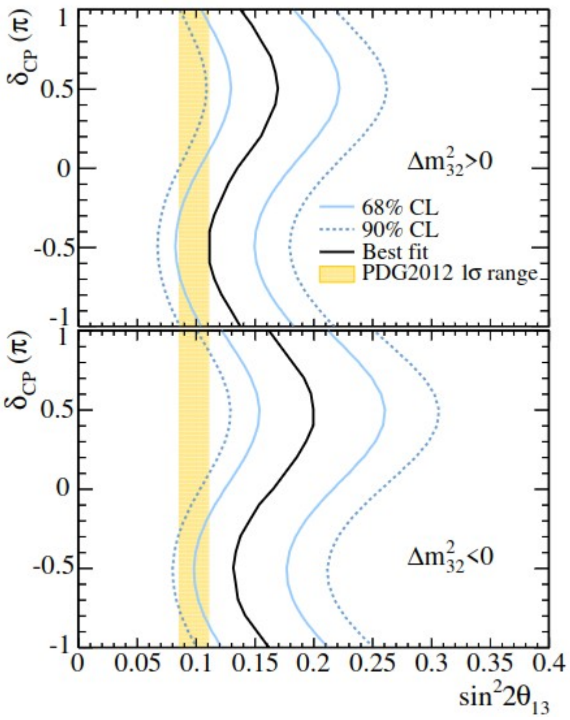
Phys. Rev. Lett. 112, 061802 (2014)

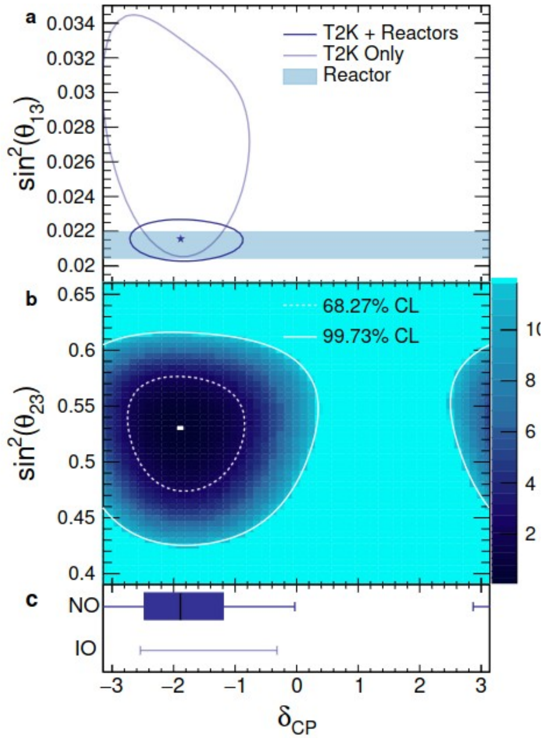
δ CP constraint

- {0, π} excluded at 90%.
- Best fit close to maximal CP violation!

Nature 580, 339–344 (2020)



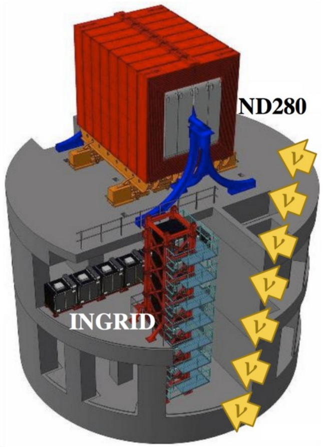




Original Near Detector Complex

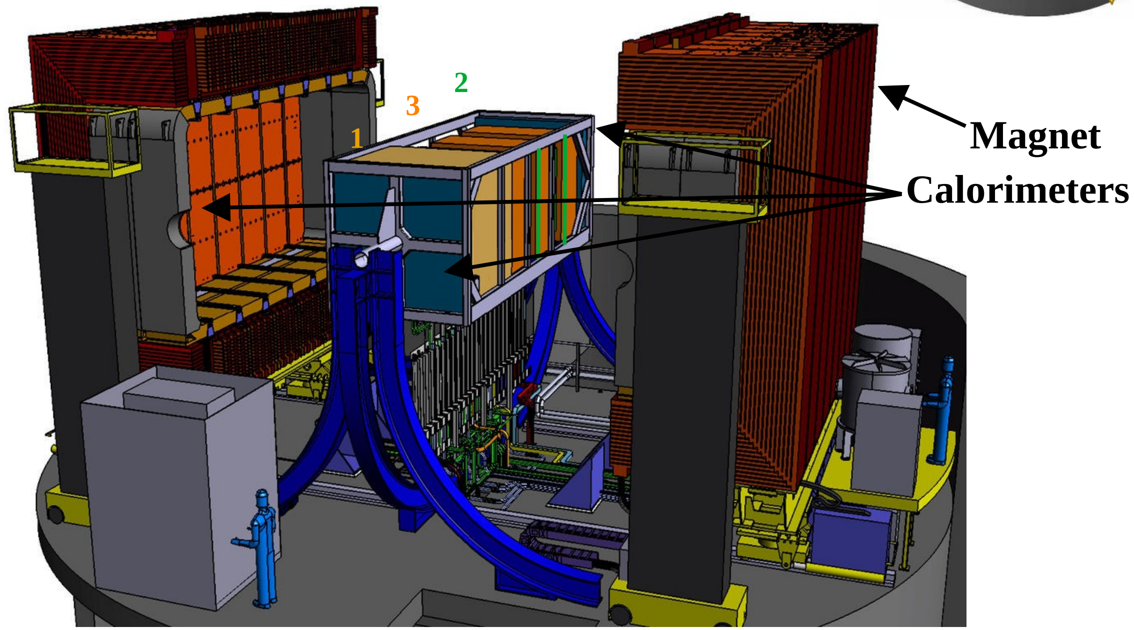
Components

- Neutrino monitor on-axis (INGRID).
- UA1 magnet (0.2 T)
- Outer calorimeters.
- "Basket" with off-axis sub-detectors.
  - π^0 detector (P0D[1])
  - Fine-Grained Detectors (FGDs[2])
  - Time Projection Chambers (TPCs[3])
  - Inner calorimeters.

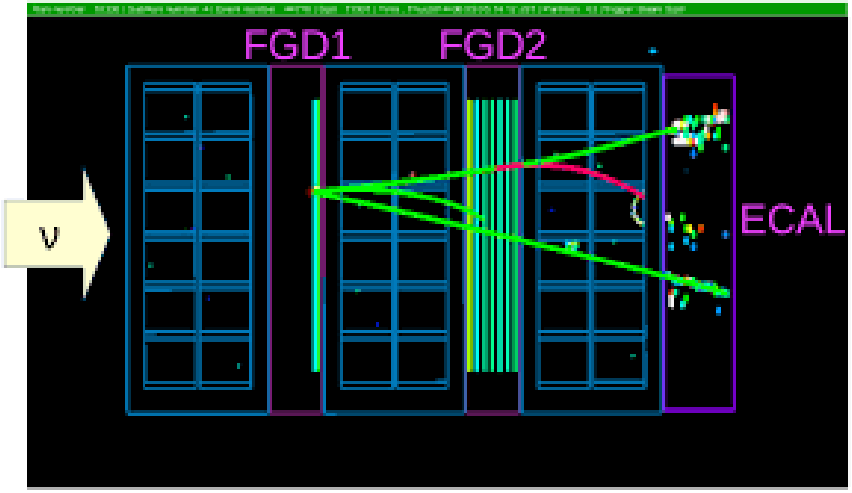


Limitations

- High momentum threshold (specially for protons, > 400 MeV/c).
- Limited angle acceptance (< 50º).
- Limited neutron detection capabilities (important for anti-neutrinos).
- Poor efficiency for $E\nu_e < 1$ GeV
  (limited statistics for a good flux constraint).



Neutrino candidate in FGD1

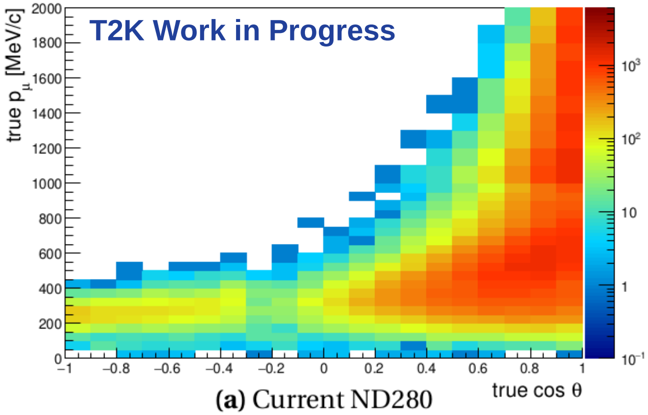


ND280 Upgrade

Expected Capabilities

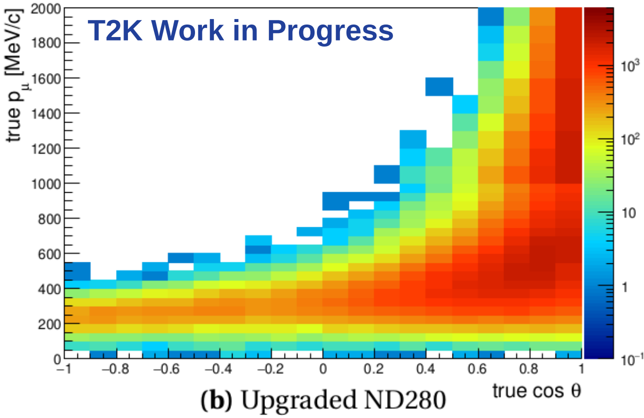
- Lower momentum threshold (> 300 MeV/c for protons).
- 4π angular acceptance.
- Event-by-event neutron reconstruction.
- e/γ separation (including $E\nu_e$ < 1 GeV).
- Increased tracker mass (x2).
- Improved μ/e PID.

Current True θμ vs True Pμ



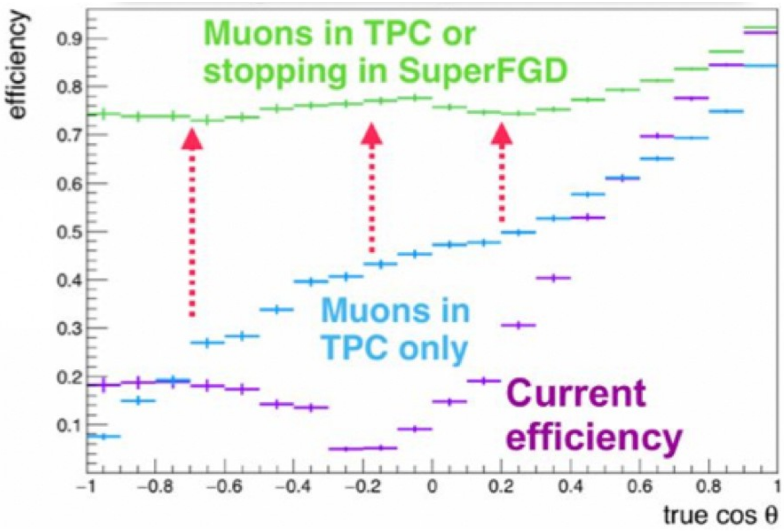
(a) Current ND280

Upgrade True θμ vs True Pμ

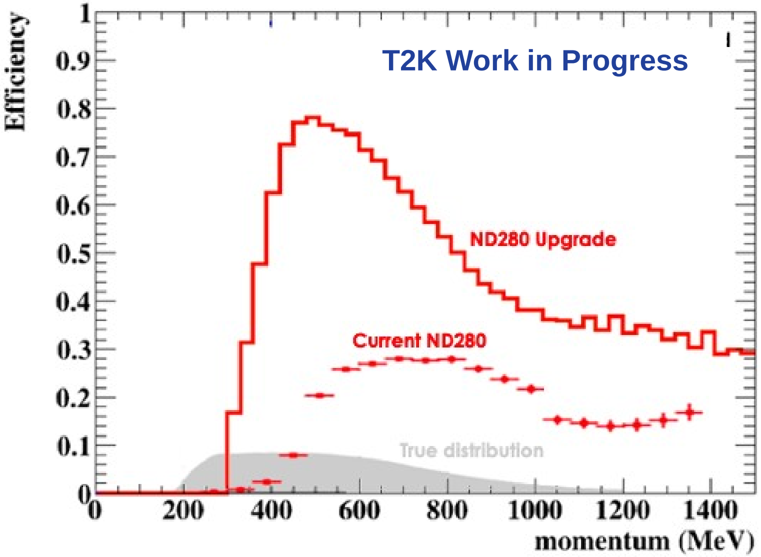


(b) Upgraded ND280

θμ efficiency (current vs upgrade)

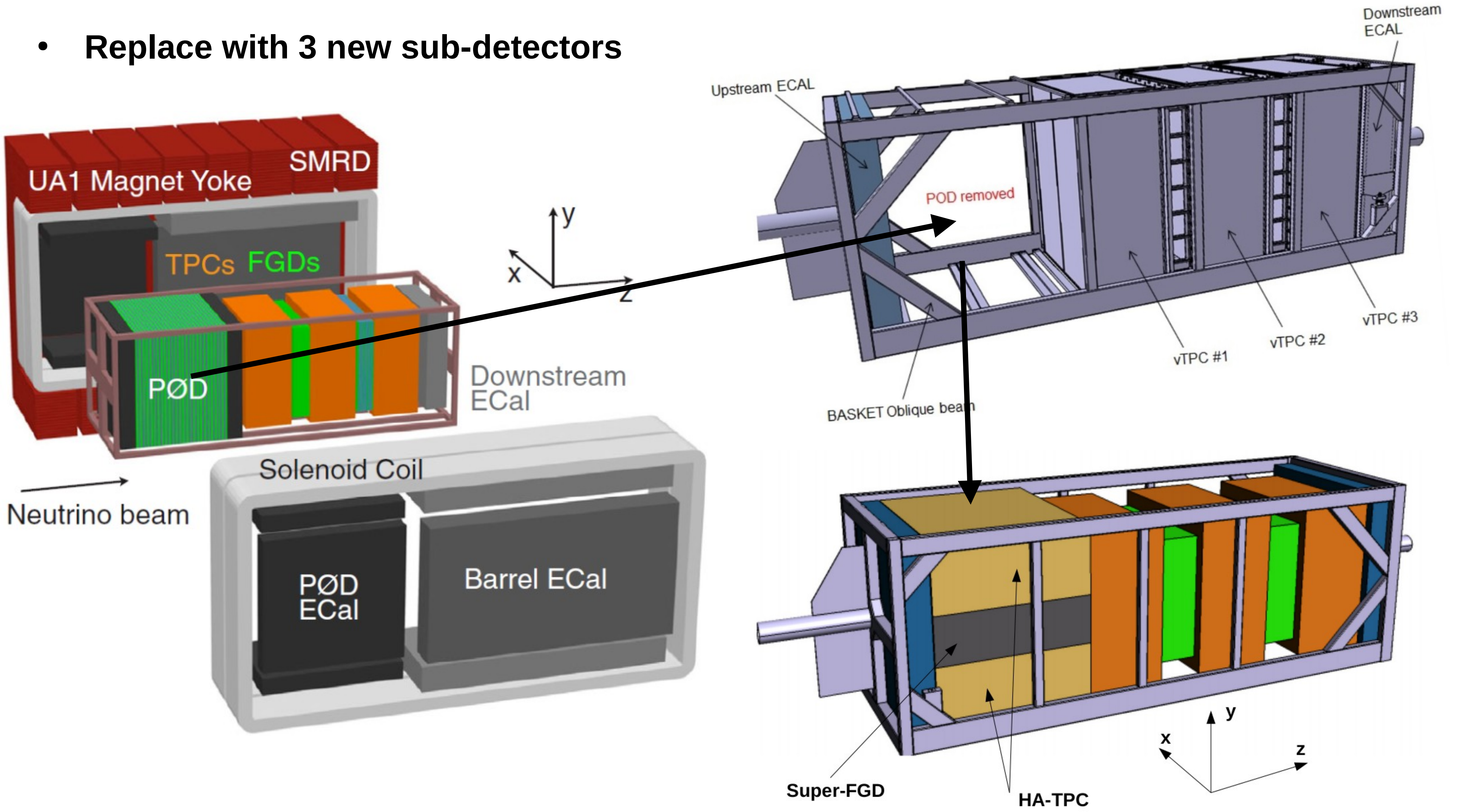


Pp efficiency (current vs upgrade)



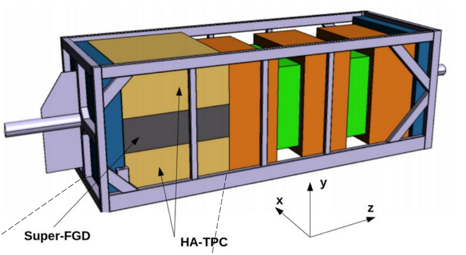
Proposed Modifications

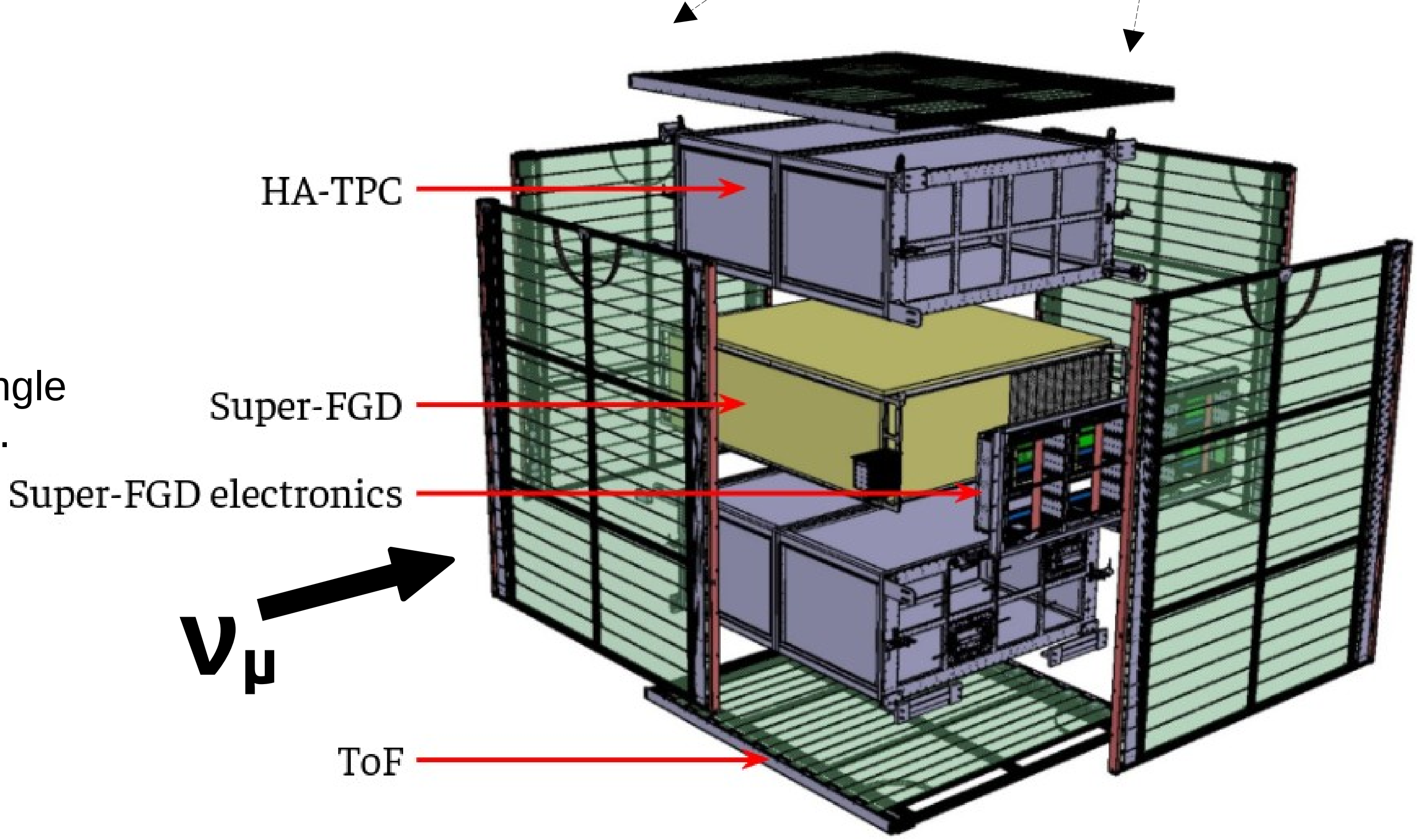
- **P0D removal**
- **Replace with 3 new sub-detectors**



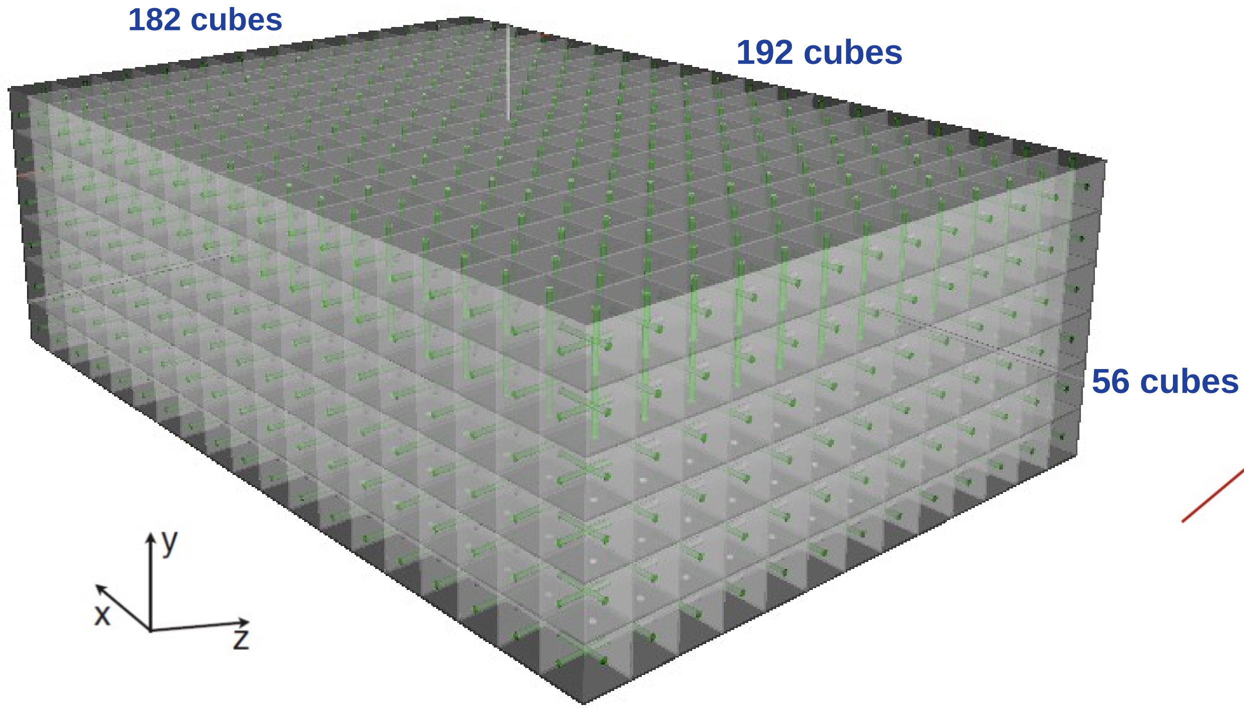
New Sub-detectors

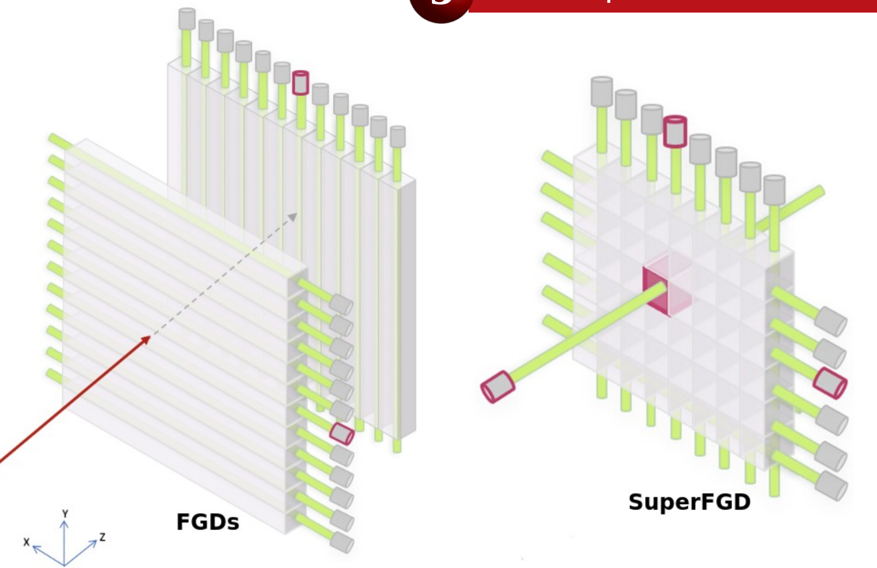
- **Super fine-grained detector (SuperFGD)**
  - Same mass and material (plastic scintillator) as previous FGDs (doubling total target mass!).
  - 3D tracking and full solid angle coverage.
- **2 High-angle TPCs (HATPC)**
  - Low (high) momentum threshold (resolution).
  - Ideal for e/μ PID.
- **Time of Flight panels**
  - Reconstruct direction of particles produced in SuperFGD and FGD.
  - Complementary polar angle not covered by HATPCs.



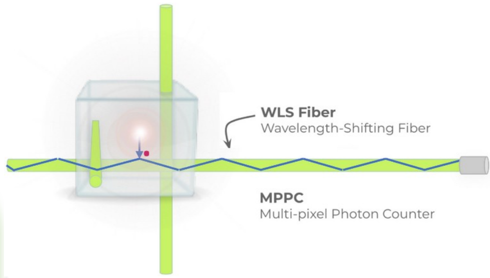


SuperFGD Design





Previous FGDs → **SuperFGD's Higher Granularity**



Physical Characteristics

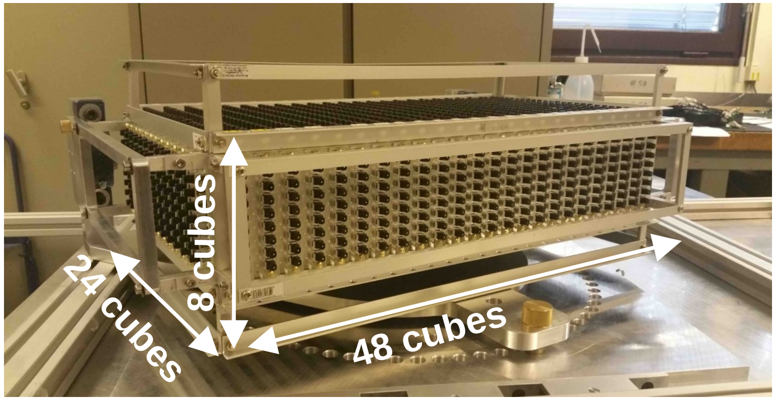
- ~2x10^6 1-cm^3, plastic scintillator, optically isolated cubes (~2 tons).
- 3 orthogonal WLS fibers per cube, ~56x10^3 in total, 1 readout channel per fiber.
- 3 1.5-mm Φ holes to insert the fibers.

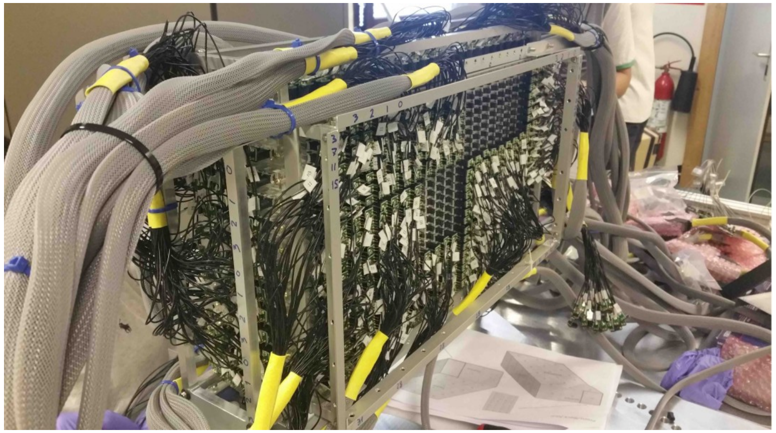
Improvements

- 3D tracking.
- Full polar angle acceptance.
- Lower momentum threshold.
- Event-by-event neutron measurement.
- Improved timing resolution.

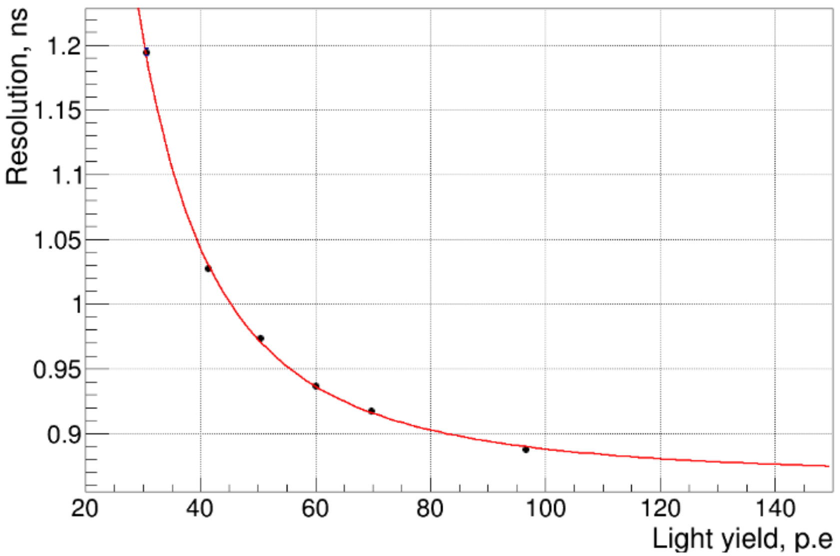
SuperFGD Prototype Detectors

- One prototype was tested with charged particles at CERN, and neutrons at LANL.
- Performance test using the same photosensors and similar electronics as the final SuperFGD.
- Light yield of ~50 pe/MIP, cross talk at ~3% and ~1 ns channel resolution.
  NIMA 936 (2018), JINST 15, 12 (2020)
- Total neutron cross section extracted!
  Physics Letters B, 840 0370-2693 (2023)

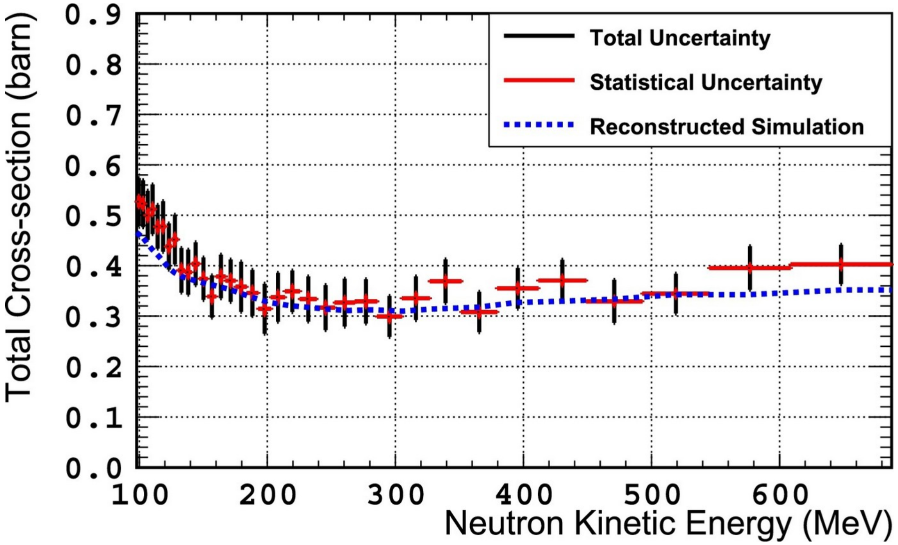




Time resolution vs Light yield



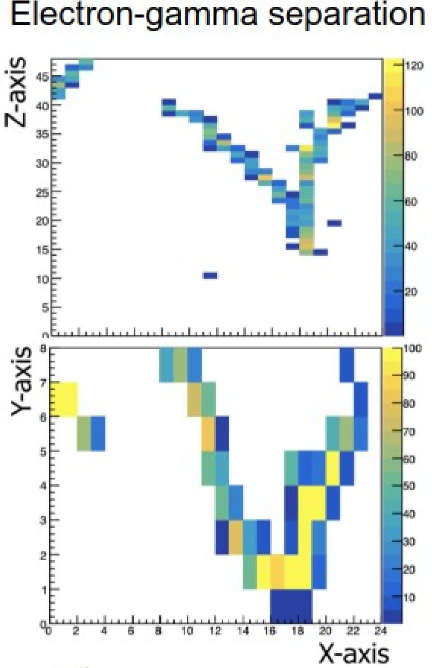
Measured neutron's total cross section



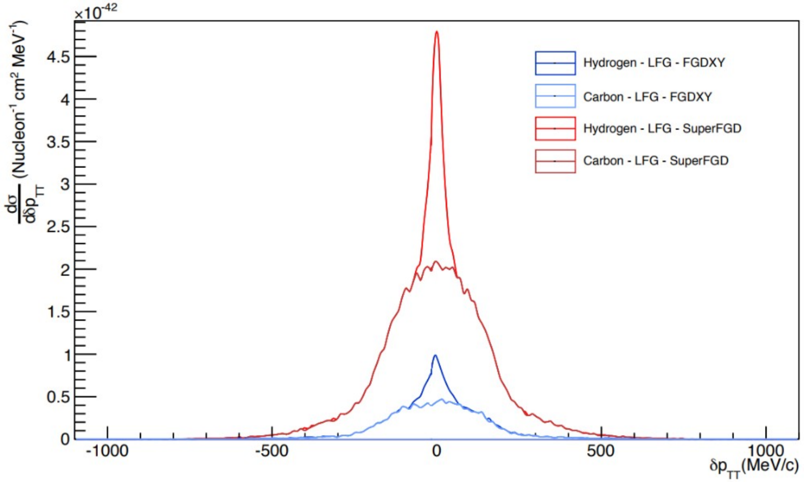
SuperFGD Potential Physics Results

- **Electron/Gamma Separation**
  - Due to its low energy acceptance and high granularity, SuperFGD can identify the “ionization pattern” near the interaction vertex, from the low momentum positron.
  - This can separate e^+/e^- events from **γ** decay, from pure e^- events from $\nu+e^- \rightarrow \nu+e^-$
  - This technique will be very important to constrain neutrino flux uncertainties.

- **Probe of Nuclear Effects**
  - High angle and low momentum acceptance, allow the measurement of “transverse kinematic variables”, crucial to measure nuclear effects like “Final State Interactions” or “Nucleon Correlations”.
  - Very important to reduce systematic uncertainties in the E***ν*** measurement, and therefore in oscillation parameters



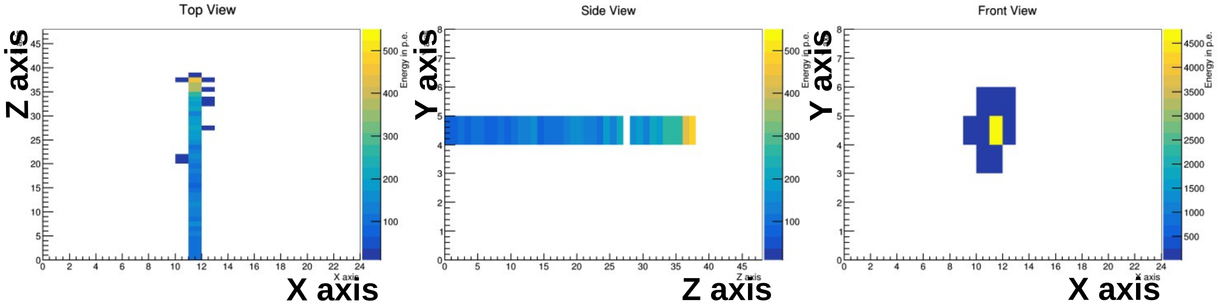
Gamma conversion candidate observed in the “SuperFGD prototype”.



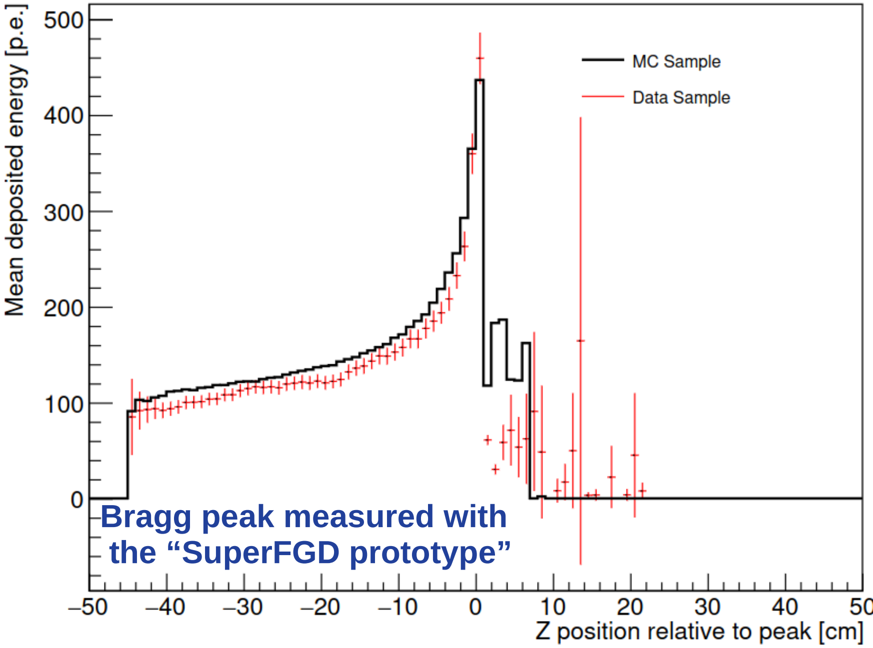
“Double momentum imbalance” SIMULATION on FGDs and SuperFGD, showing their ability to separate neutrino interactions on Hydrogen and Carbon

SuperFGD Potential Physics Results

- **Stopping Protons**
  - Due to its particle containment, particle ID is possible through dE/dx, using SuperFGD only!

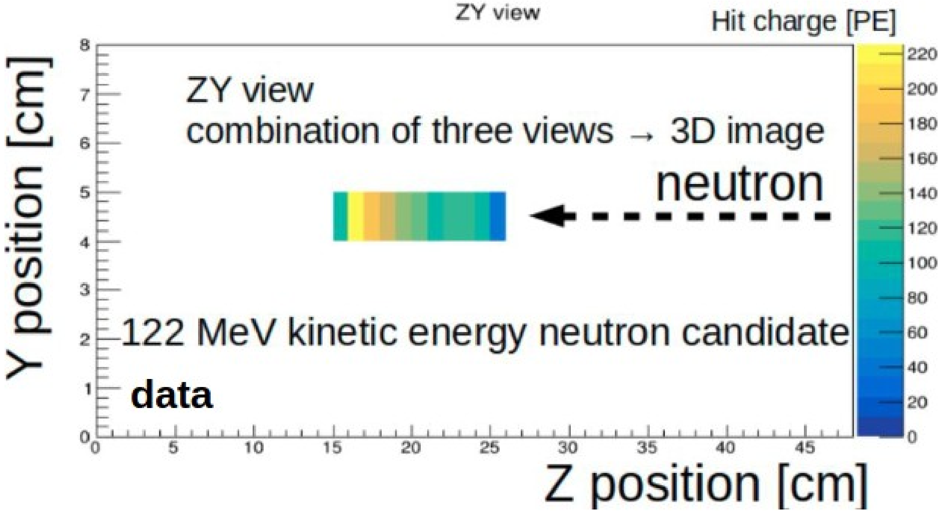


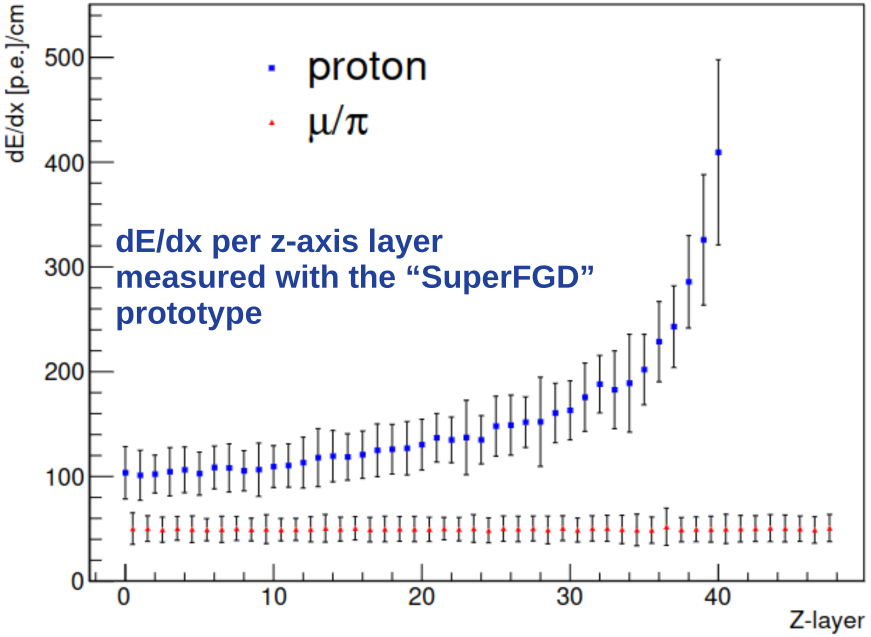
Example of an stopping proton in the "SuperFGD" prototype.



Bragg peak measured with the "SuperFGD prototype"

- **Event-by-event Neutrons**
  - Enabled due to higher granularity and size.

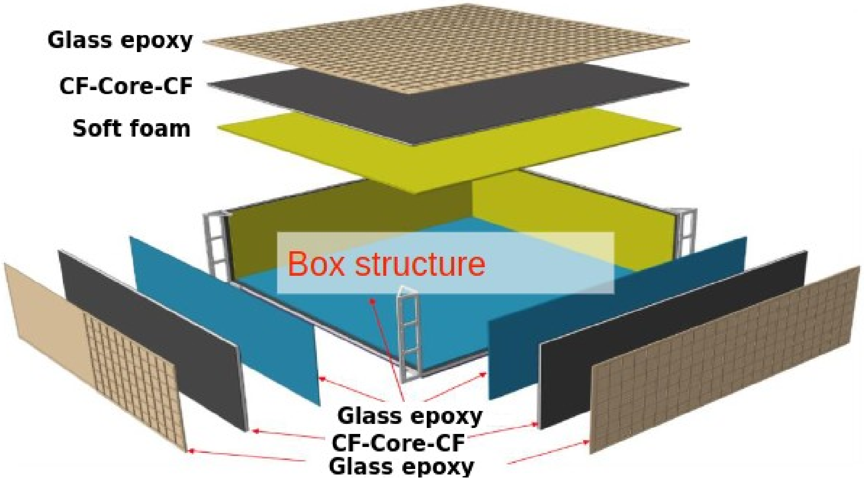


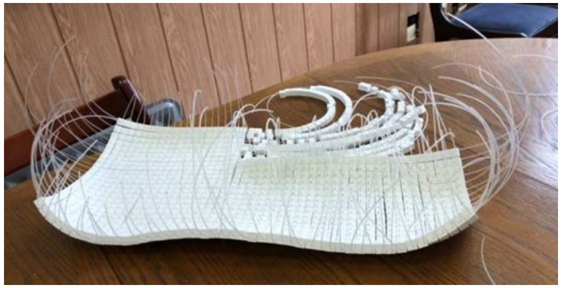


dE/dx per z-axis layer measured with the "SuperFGD" prototype

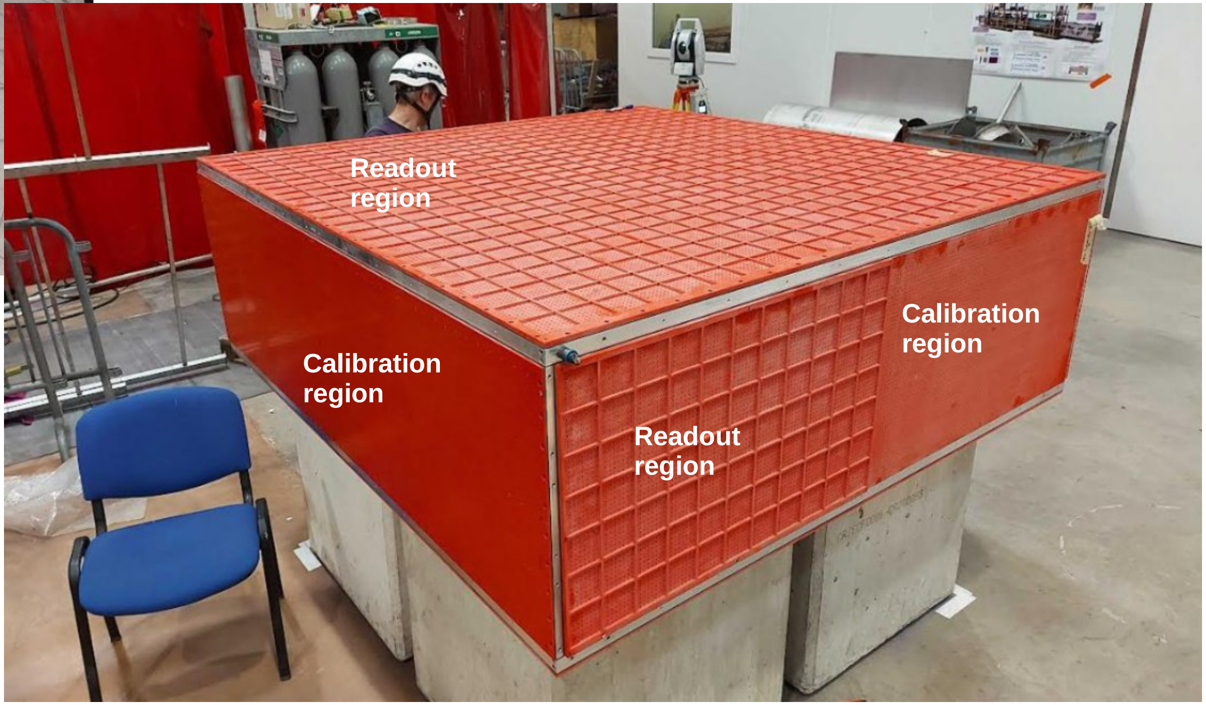
Planes/Box Assembly

Planes & Box Preassembled





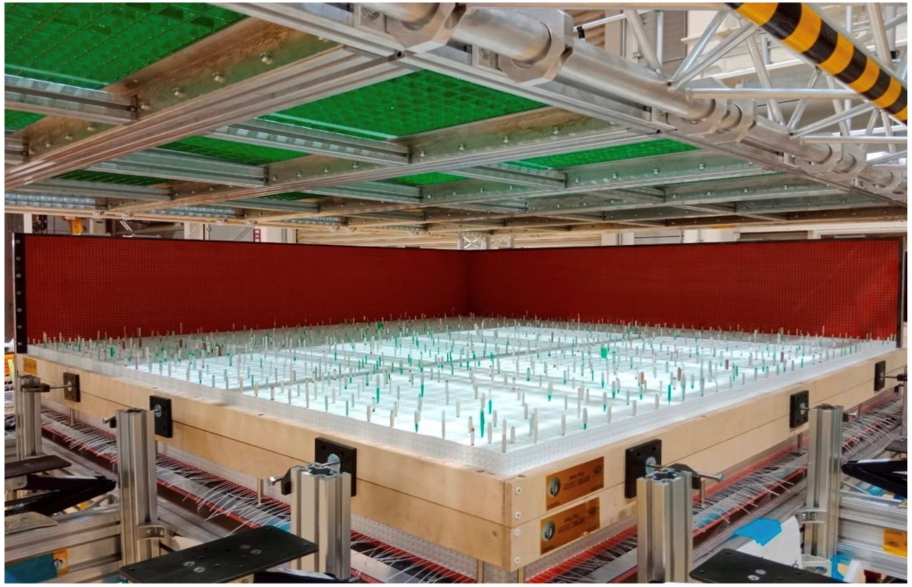
Cube planes joined with Fishing lines



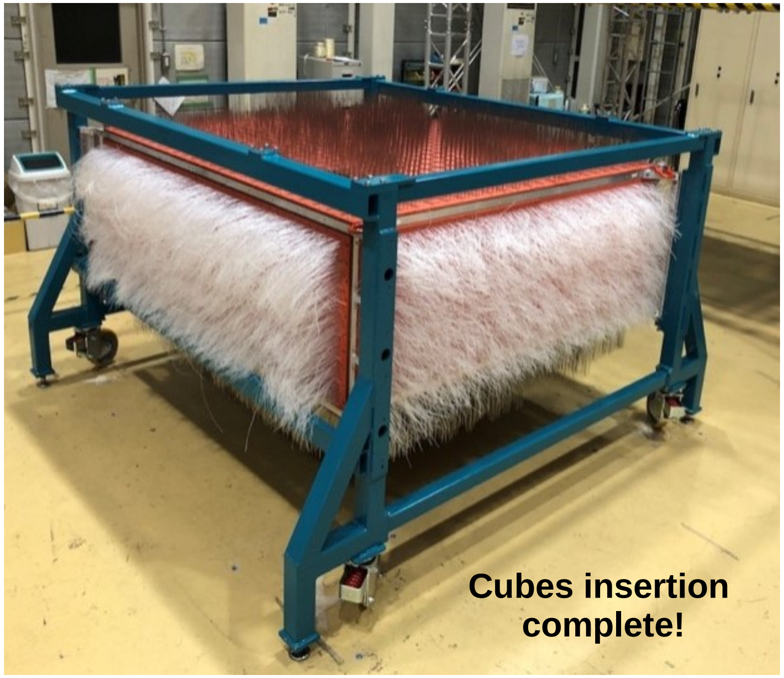
Cubes Installation (On-Site)

Box preparation and installation of first plane

Stacking and alignment of planes



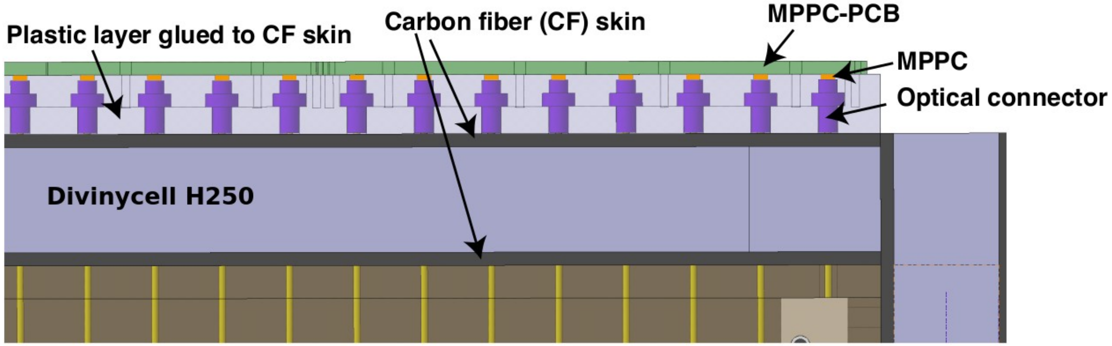
40 out of 56 planes stacked and aligned



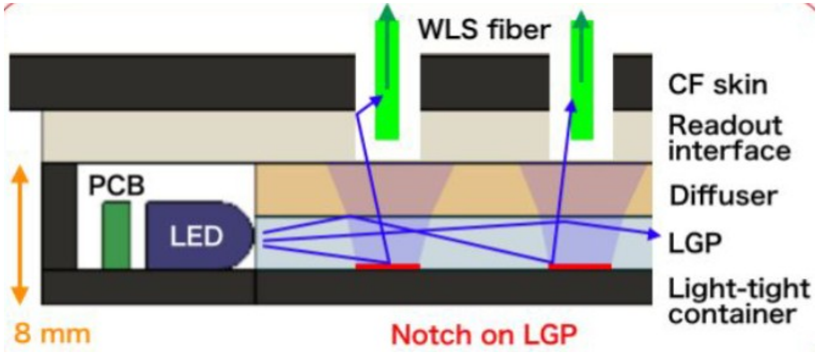
Cubes insertion complete!

Optical Interface / Calibration System

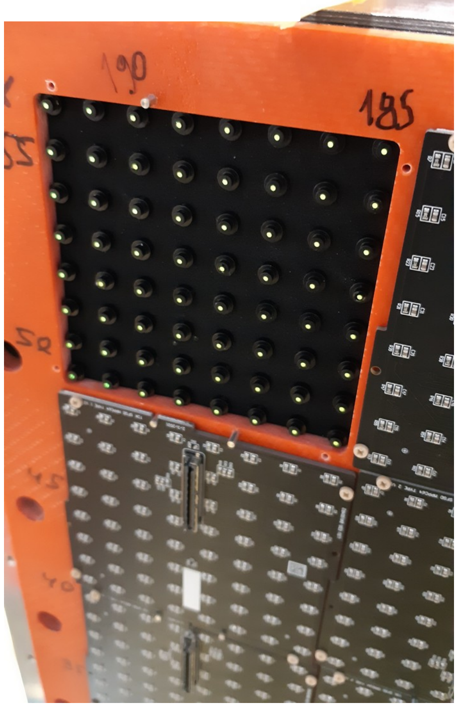
Light Collection Side

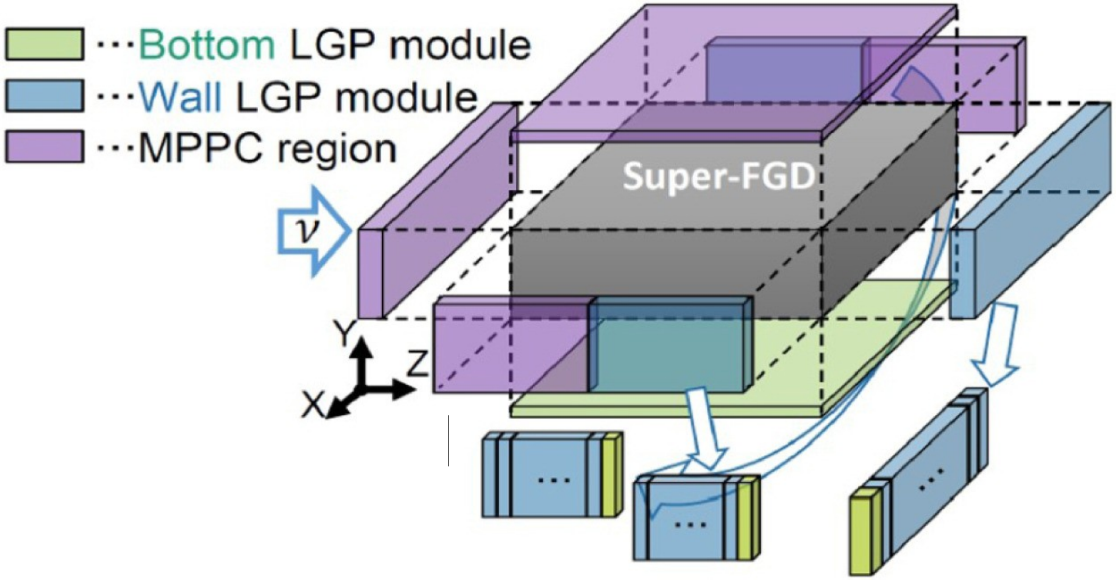

Plastic layer glued to CF skin
Carbon fiber (CF) skin
MPPC-PCB
MPPC
Optical connector
Divinycell H250

Light Injection Side

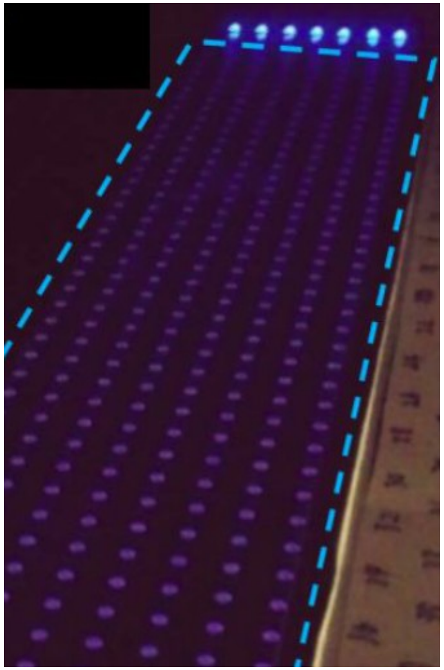


MPPC Region

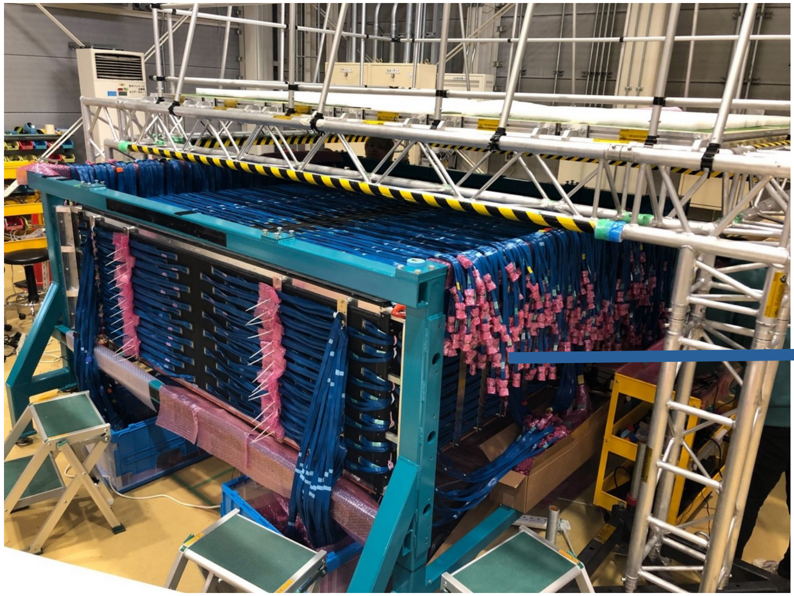


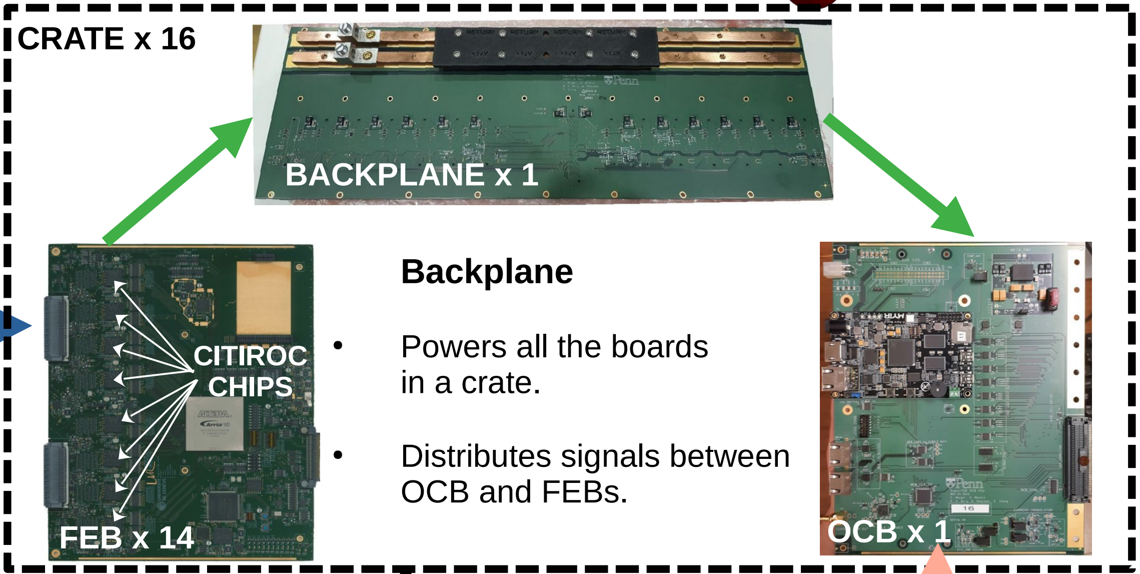


LGP Module



Electronics





Backplane

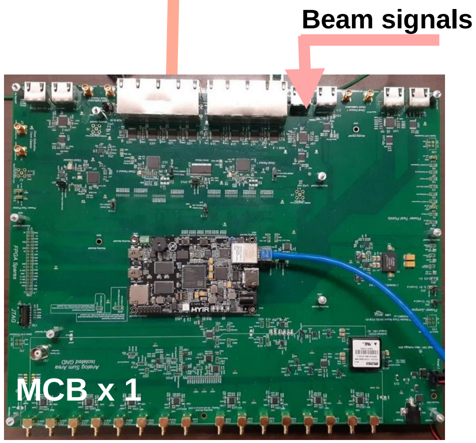
- Powers all the boards in a crate.
- Distributes signals between OCB and FEBs.

Analog Signal Processing

- Coaxial cables send the (photoelectron) signals from MPPCs to the frontend boards (**FEBs**) for discrimination, and for amplitude and timing digitization.

Digital Signal Processing

- Each crate has an "OCB" board that concentrates the synchronized digital data from all 14 FEBs in a crate.
- It forms SuperFGD events which are sent to the DAQ PC.



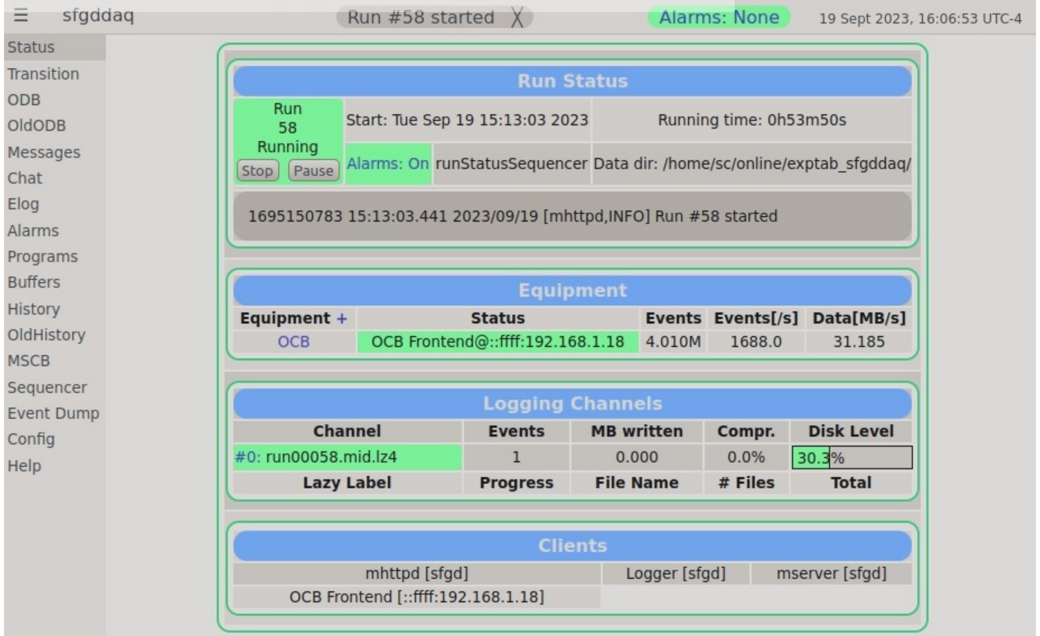
"Clock" Signals

- Master Clock Board (MCB) propagates clock, gate and trigger beam signals to OCB and FEBs.

On-surface Commissioning

- **Hardware in general tested on the surface**
  - Electronics tested extensively all the way to data taking.
  - Monitoring of ~700 sensors through Slow Control software.
  - Direct Memory Access (DMA) implemented in the OCB FW for fast data transmission, reaching bandwidths of ~30 MB/s.
  - SuperFGD DAQ and Slow Control fully integrated in the “ND280” global systems.

Bandwidth reached several MB/s during data taking.



Run #58 started

Alarms: None

19 Sept 2023, 16:06:53 UTC-4

Run Status

Run 58 Running	Start: Tue Sep 19 15:13:03 2023		Running time: 0h53m50s
	Alarms: On	runStatusSequencer	Data dir: /home/sc/online/exptab_sfgddaq/

1695150783 15:13:03.441 2023/09/19 [mhttpd,INFO] Run #58 started

Equipment

Equipment +	Status	Events	Events[/s]	Data[MB/s]
OCB	OCB Frontend@::ffff:192.168.1.18	4.010M	1688.0	31.185

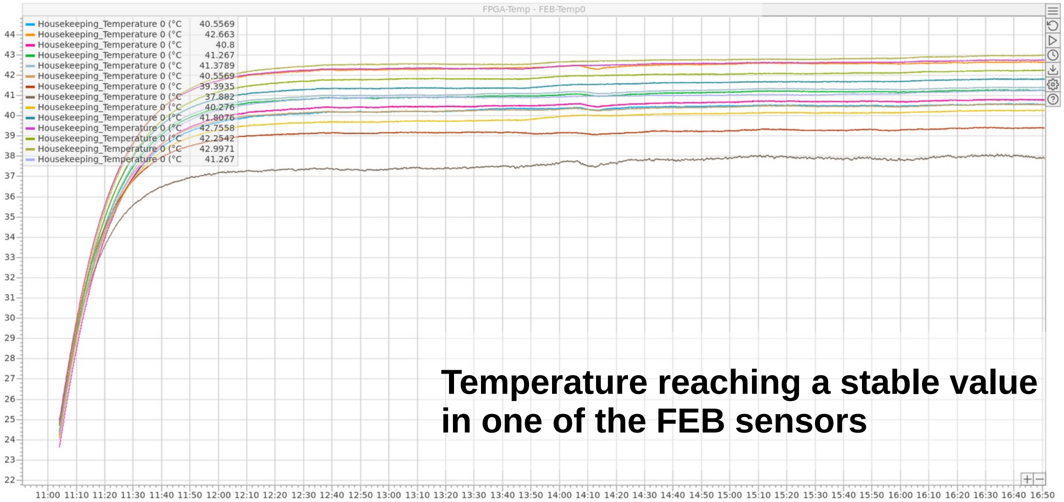
Logging Channels

Channel	Events	MB written	Compr.	Disk Level
#0: run00058.mid.lz4	1	0.000	0.0%	30.3%
Lazy Label	**Progress**	**File Name**	**# Files**	**Total**

Clients

mhttpd [sfgd]	Logger [sfgd]	mserver [sfgd]
OCB Frontend [::ffff:192.168.1.18]		

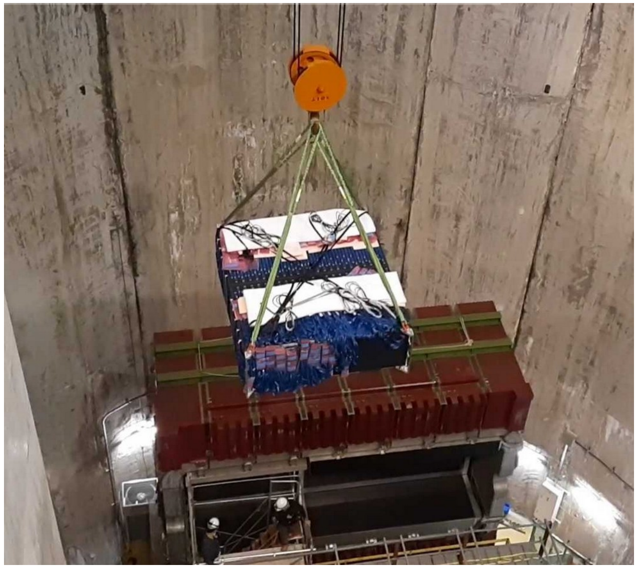
Cooling system for the electronics, tested through Slow Control software.

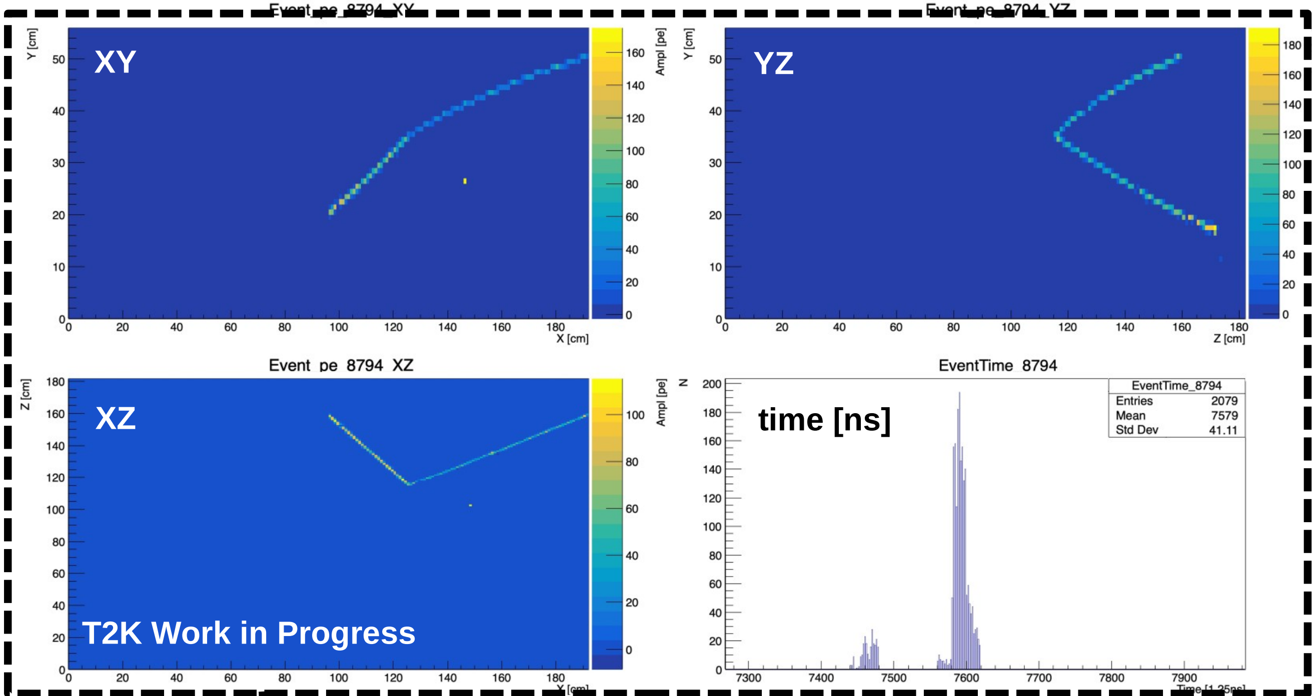


Temperature reaching a stable value in one of the FEB sensors

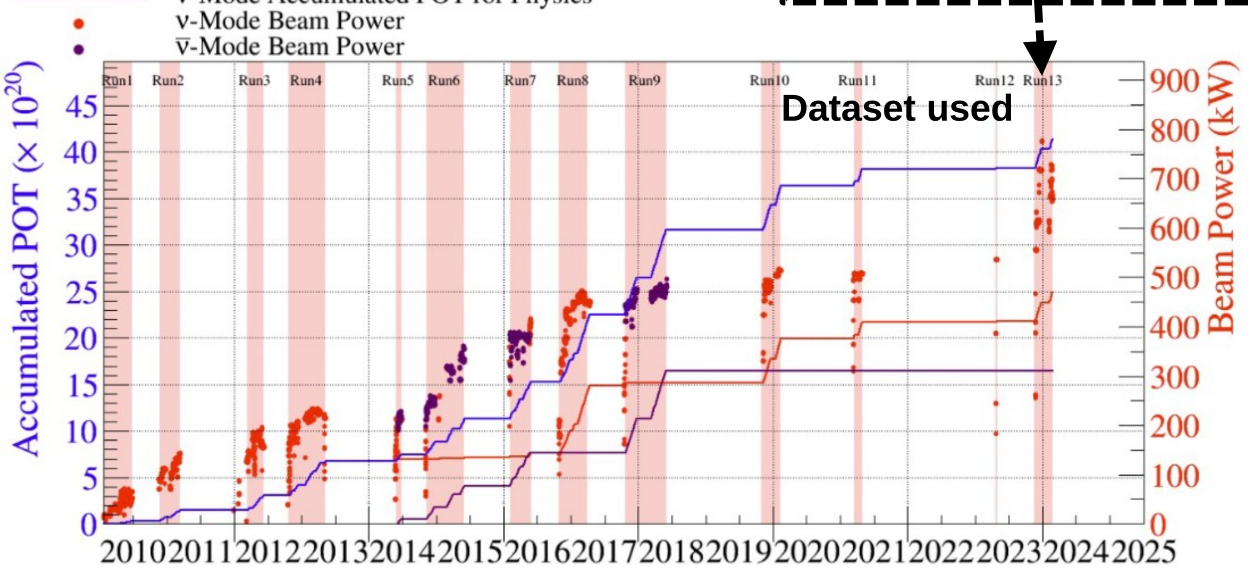
First SuperFGD Beam Data

Installed on October 2023





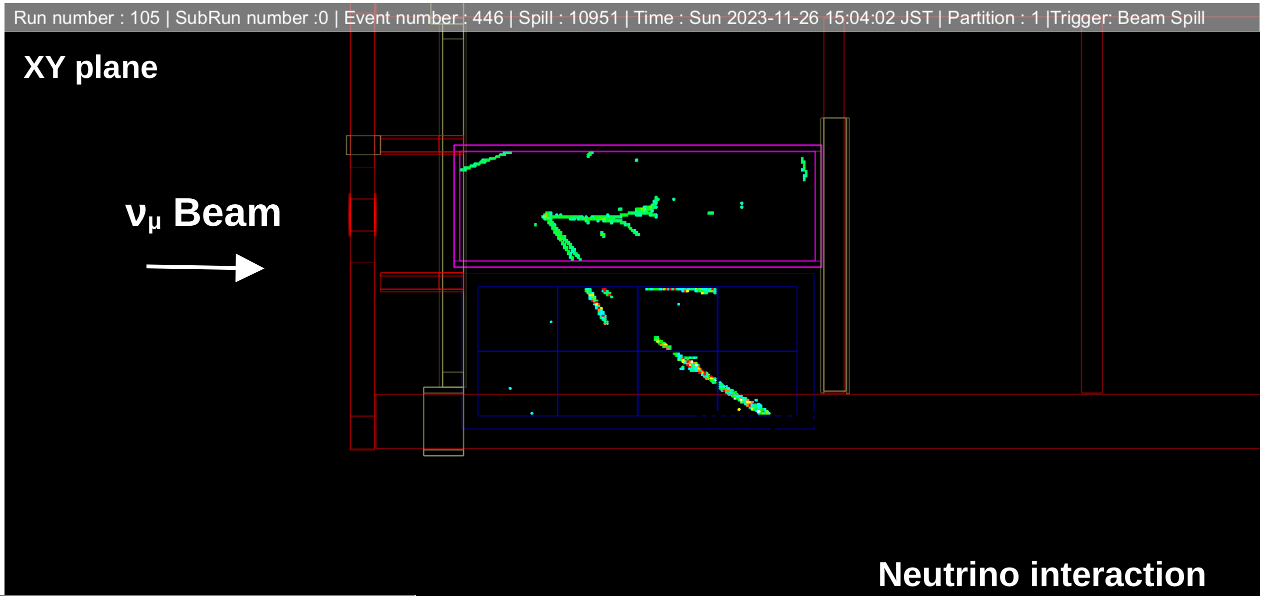
First neutrino candidate recorded on December 2023



Operation With Other Sub-Detectors

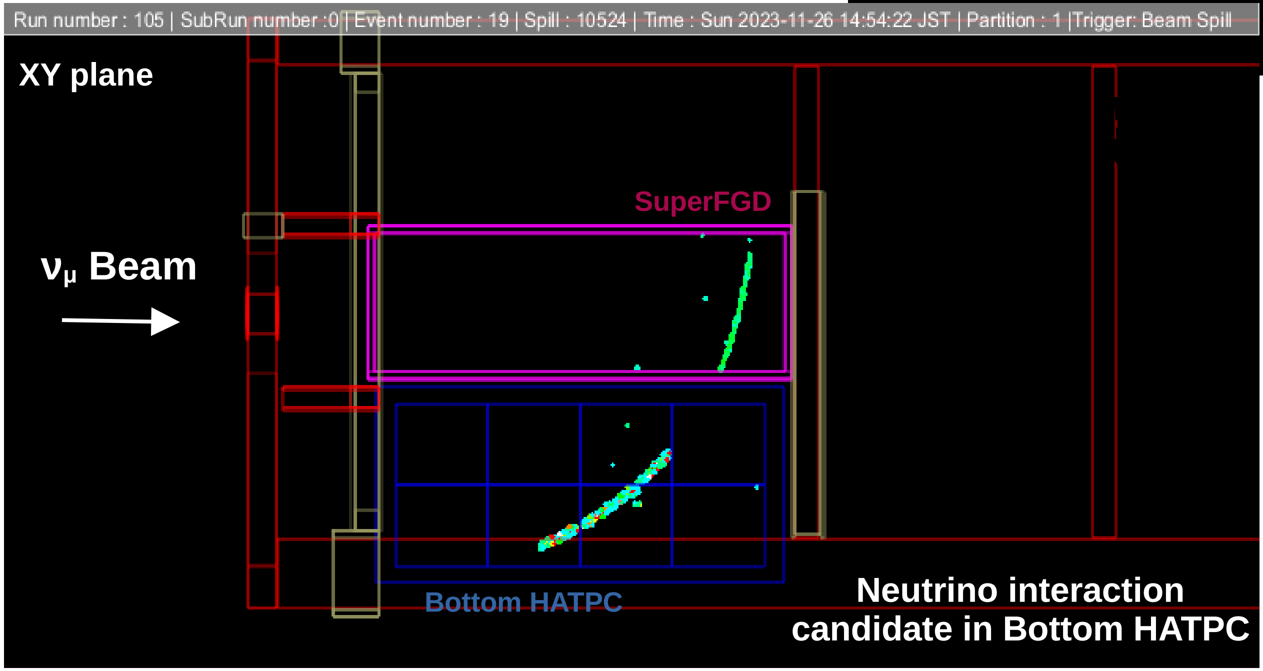
December 2023

- First simultaneous operation with the other new sub-detectors.
- Neutrino interactions seen in SuperFGD and High Angle TPC
- Full integration ongoing.



Run number : 105 | SubRun number :0 | Event number : 446 | Spill : 10951 | Time : Sun 2023-11-26 15:04:02 JST | Partition : 1 |Trigger: Beam Spill

Neutrino interaction candidate in SuperFGD



Run number : 105 | SubRun number :0 | Event number : 19 | Spill : 10524 | Time : Sun 2023-11-26 14:54:22 JST | Partition : 1 |Trigger: Beam Spill

Neutrino interaction candidate in Bottom HATPC

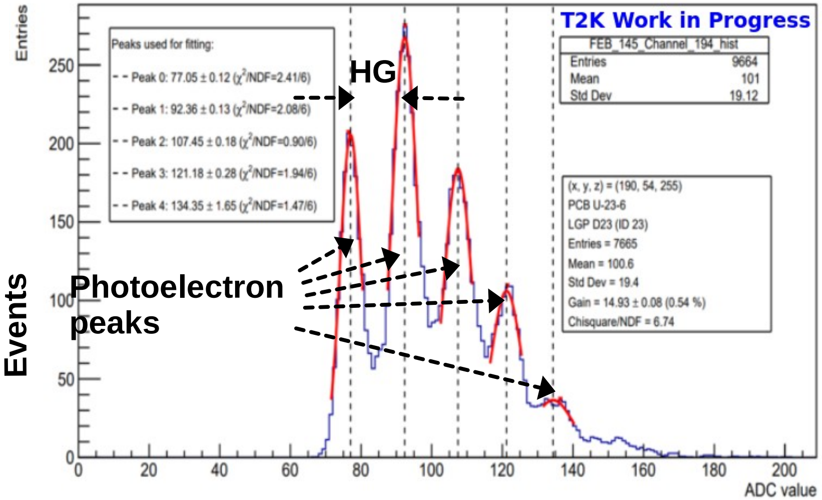
SuperFGD Performance

Preliminary Results

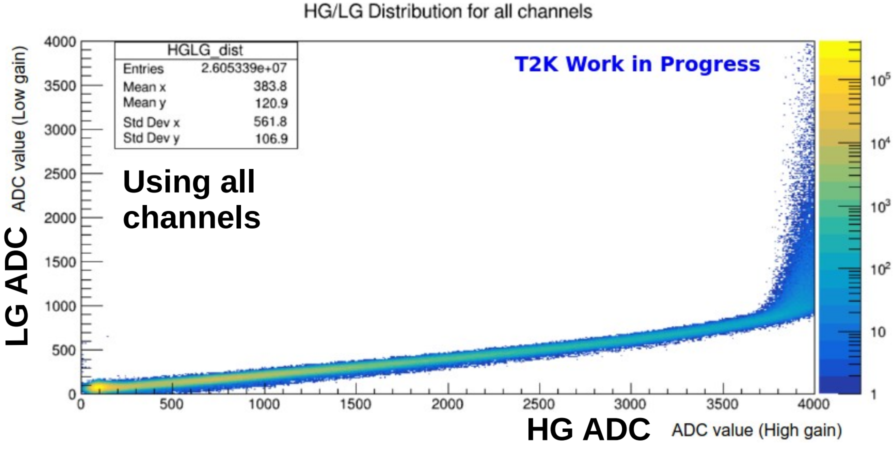
*HG: Readout path for the low energy dynamic range (up to ~200 p.e.)

*LG: Readout path for higher energy activity, like stopping protons.

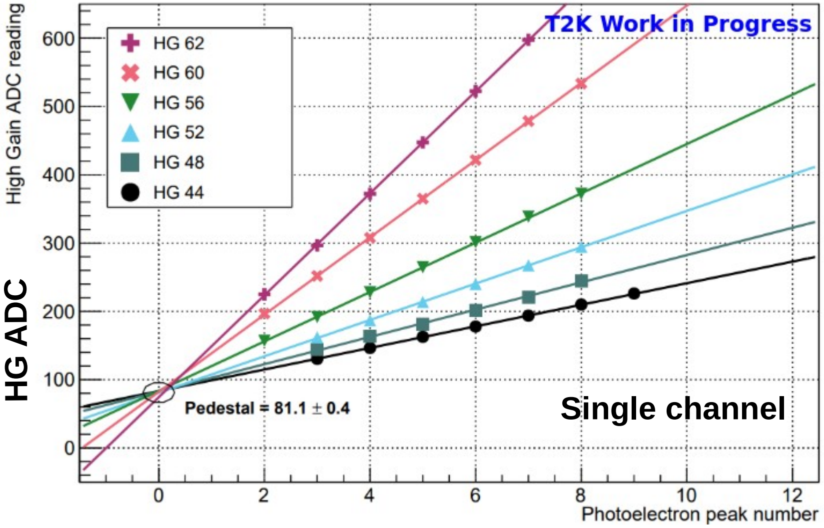
ADC counts in FEBs as a response to photons from light injection system



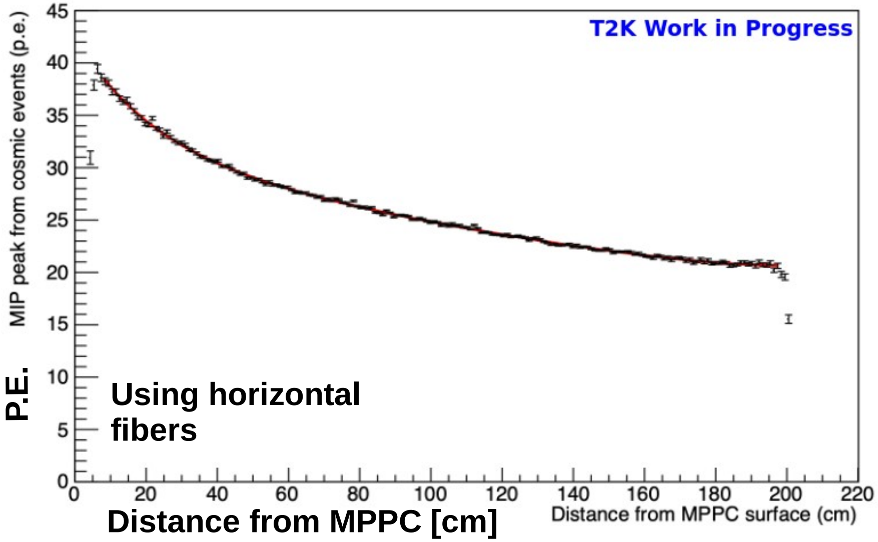
High Gain (HG) and Low Gain (LG) Calibration



Pedestals

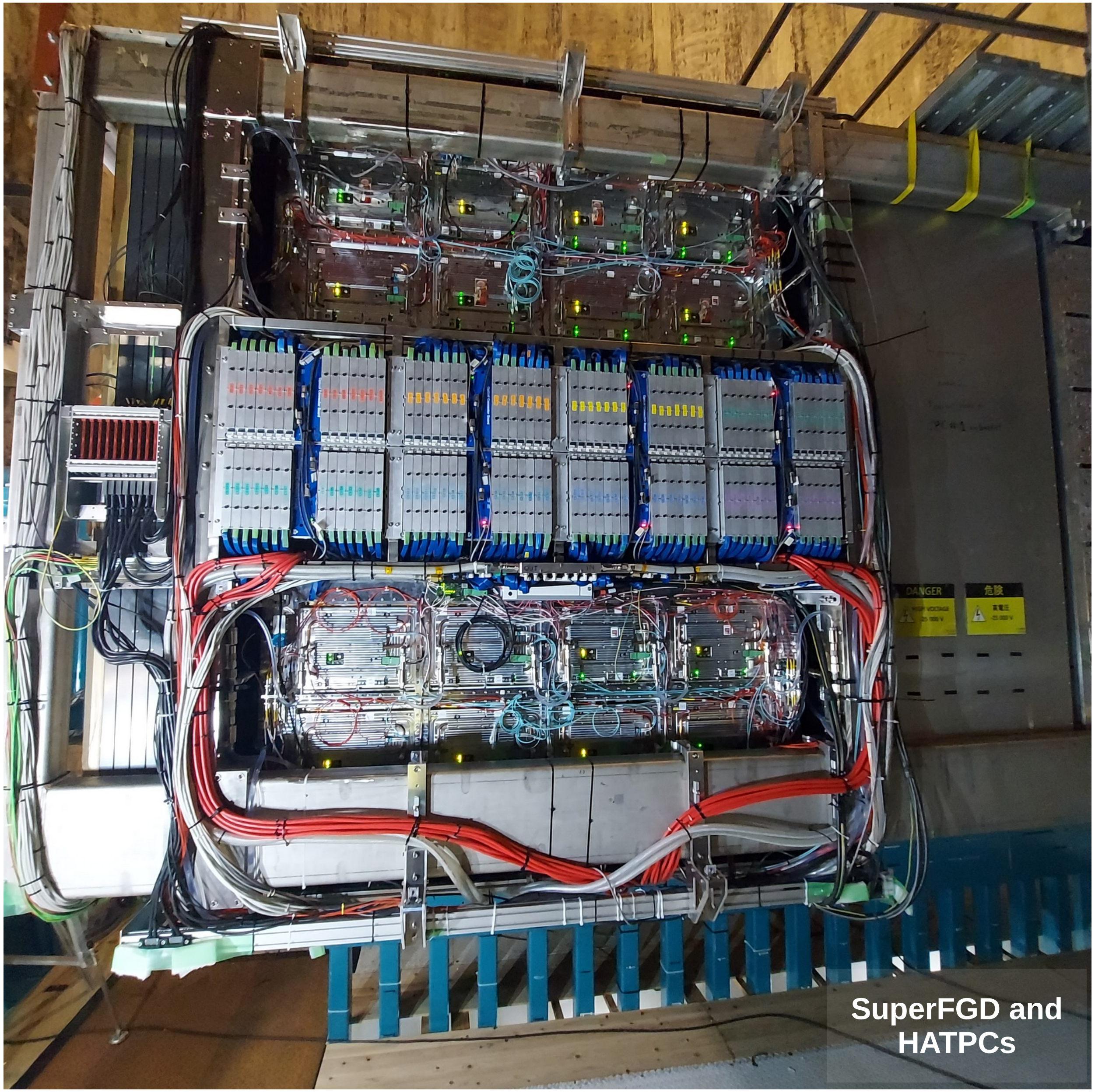


Light yield and attenuation

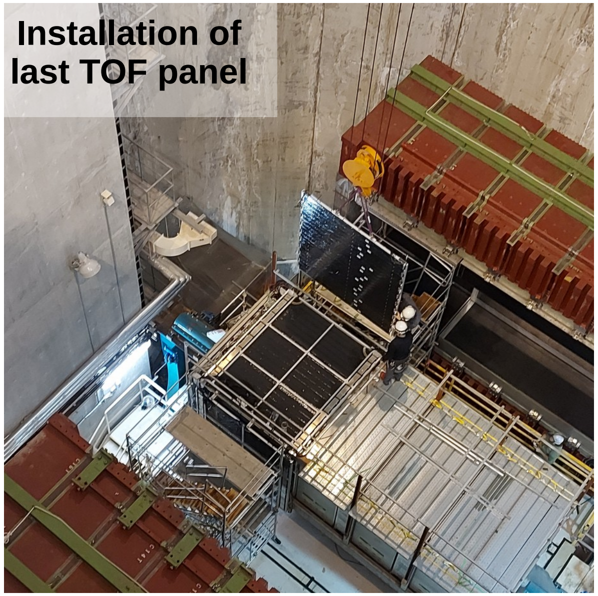


SuperFGD In the Pit!

All new sub-detectors installed



SuperFGD and HATPCs



Installation of last TOF panel

Installation Complete!

In Summary

1. The T2K collaboration envisioned an ambitious plan to upgrade its Near detector to reduce the key uncertainties in the measurement of oscillation parameters.

2. It designed, built and successfully commissioned 3 new sub-detectors, which are now installed in the “Off-axis” Near detector of its neutrino baseline.

3. The new tracker sub-detector “SuperFGD” involves a novel technique, its ~2 million cubes allow a full solid angle coverage, enabling the study of high-angle and low momentum particles, of great importance for understanding nuclear effects!

4. Besides doubling the mass of the target, it allows for the exploration of physics until now inaccessible to T2K’s near detector, like electron/gamma identification at low energies.

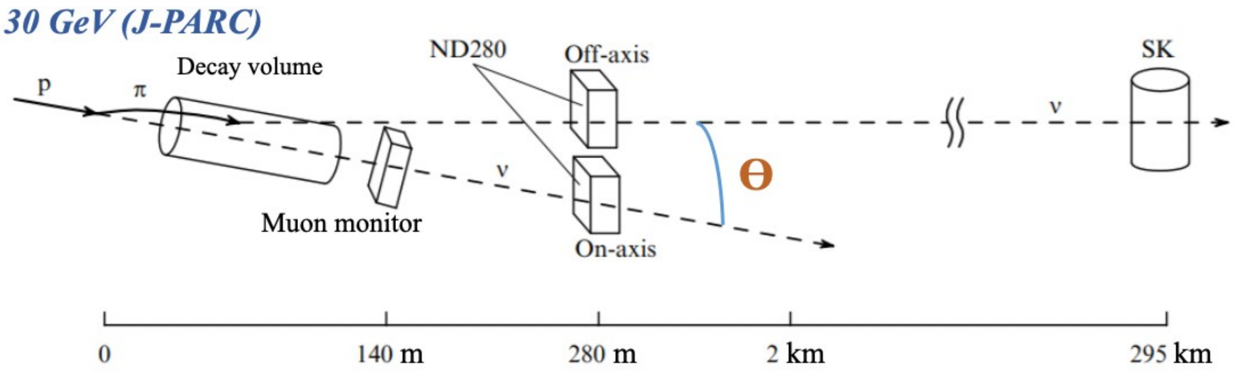
5. With the installation just complete, and calibration and performance studies ongoing, SuperFGD has already started collecting the data of certainly very interesting results to come.

THANKS!

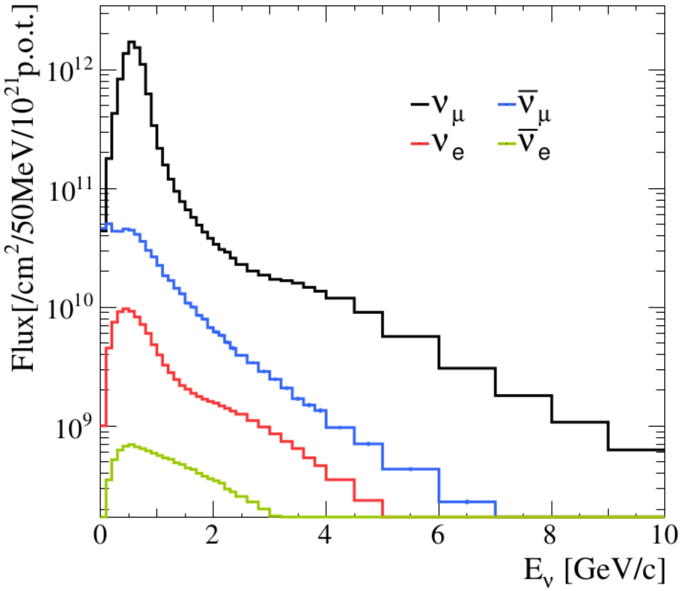
BACKUP

Neutrino Beam & Flux

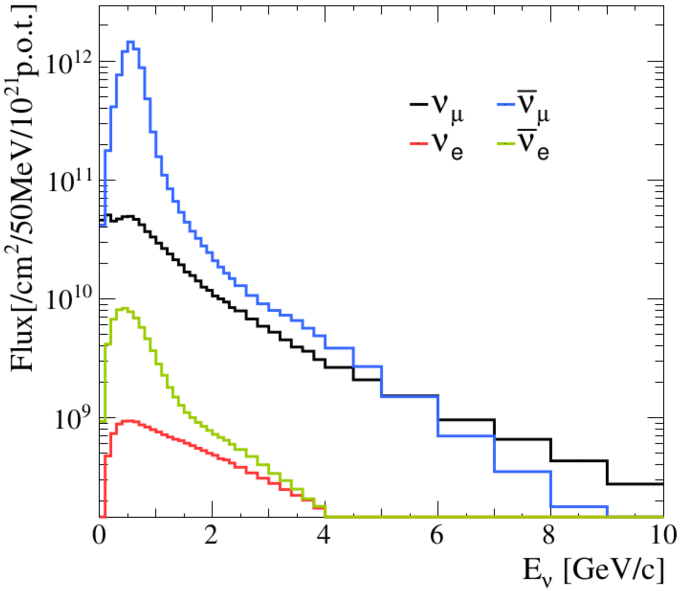
- 30 GeV protons hit graphite target, producing charged hadrons.
- Hadrons ultimately decay into neutrinos.
- Neutrino flux is $\boldsymbol{\nu_\mu}$-dominated.
- ND280-SK baseline is Off-axis.
- Narrow E$\boldsymbol{\nu}$ spectrum.



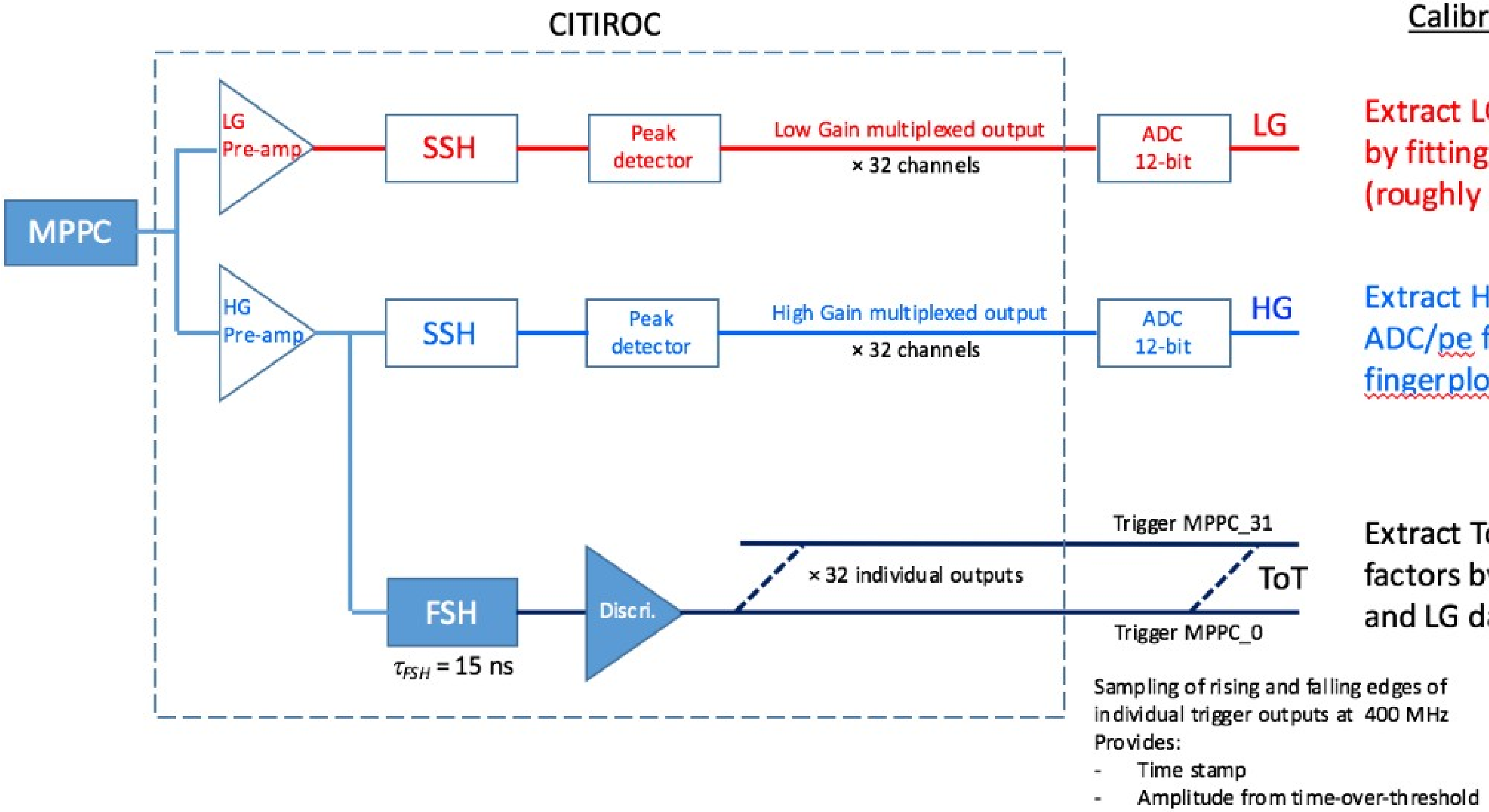
Tuned run1-10b flux at ND280



Tuned run5c-9d flux at ND280



CITIROC Circuit – Gain Calibration



Sampling of rising and falling edges of individual trigger outputs at 400 MHz
Provides:
- Time stamp
- Amplitude from time-over-threshold

Calibration method

Extract LG calibration factors by fitting against HG data (roughly linear)

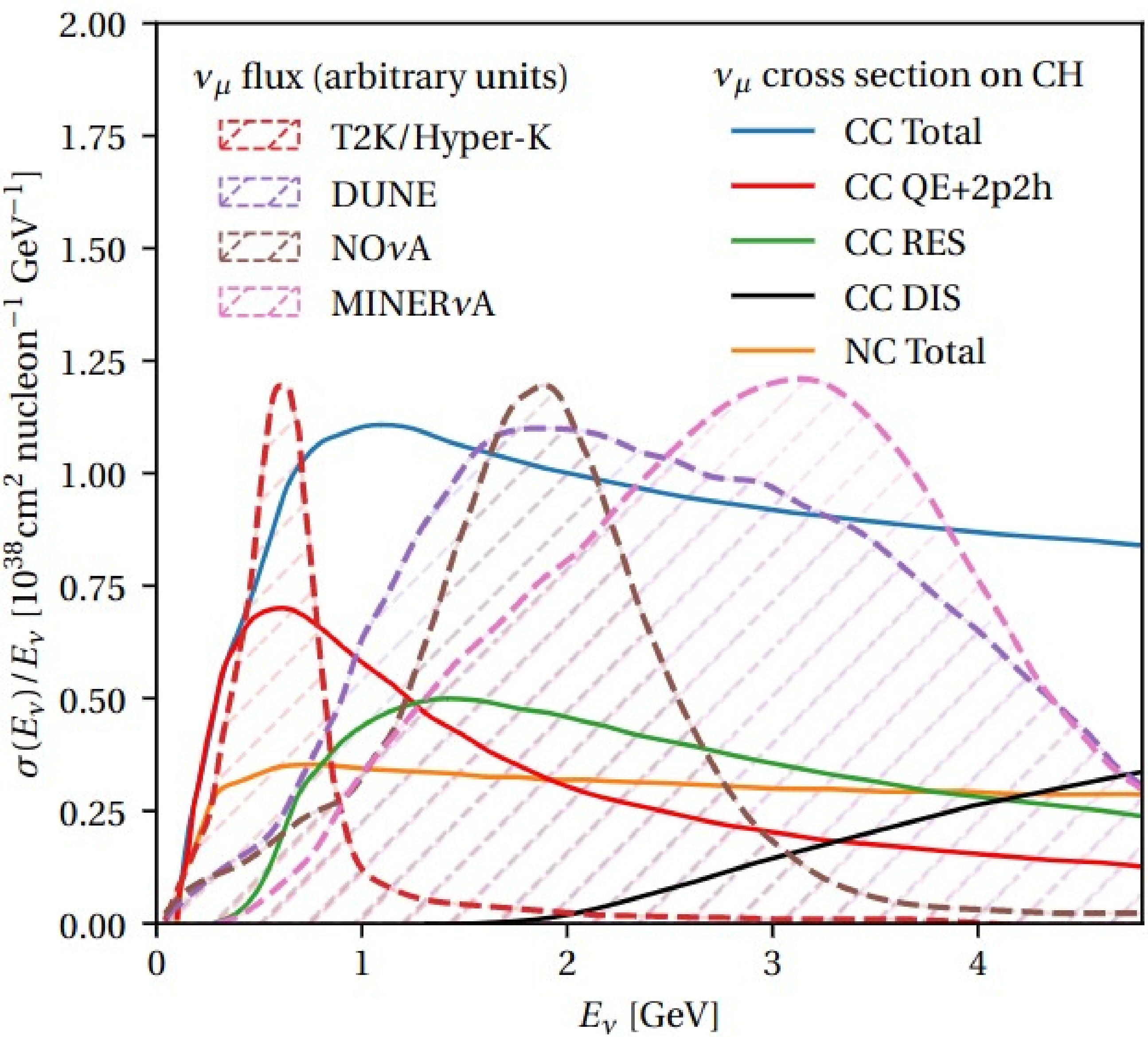
Extract HG calibration ratio ADC/pe from MPPC fingerplots

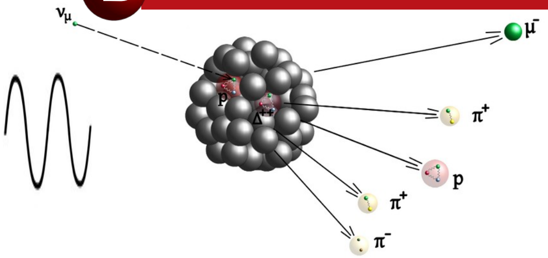
Extract ToT calibration factors by fitting against HG and LG data (non-linear)

Fluxes and Interaction Channels

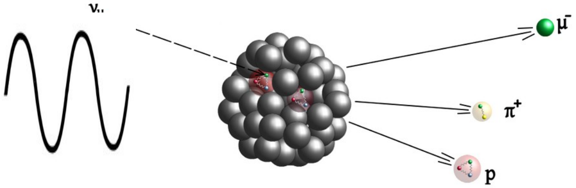
BACKUP

QE+2p2h Dominance For T2K

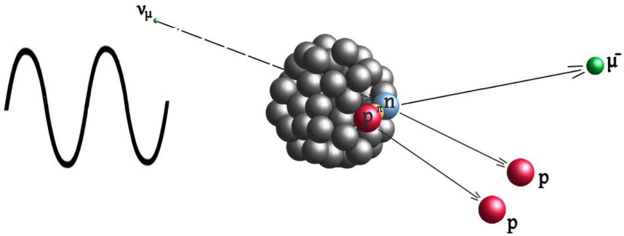




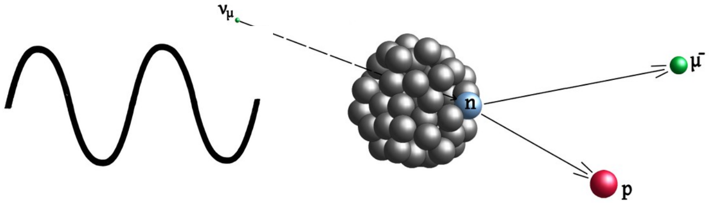
Deep Inelastic Scattering



Resonant Pion Production



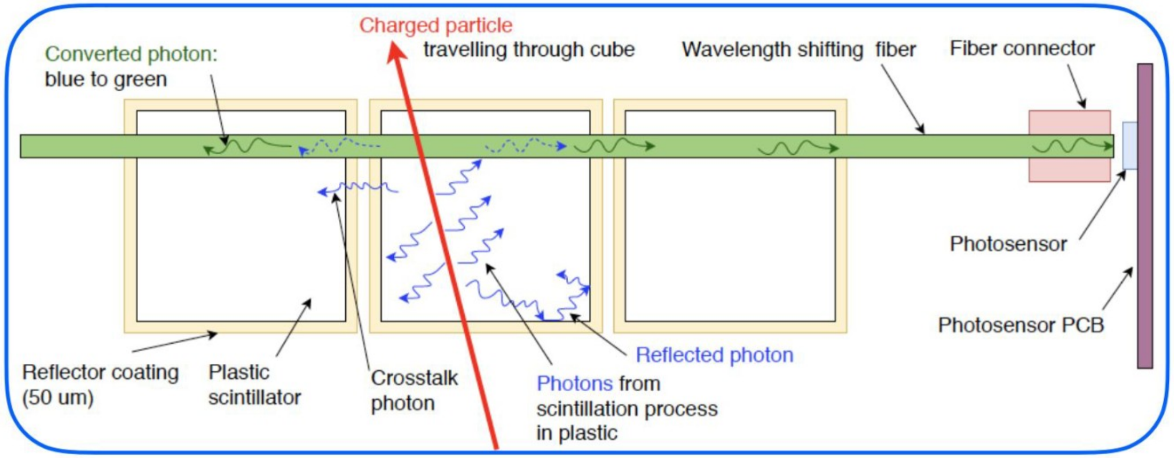
2p2h Scattering

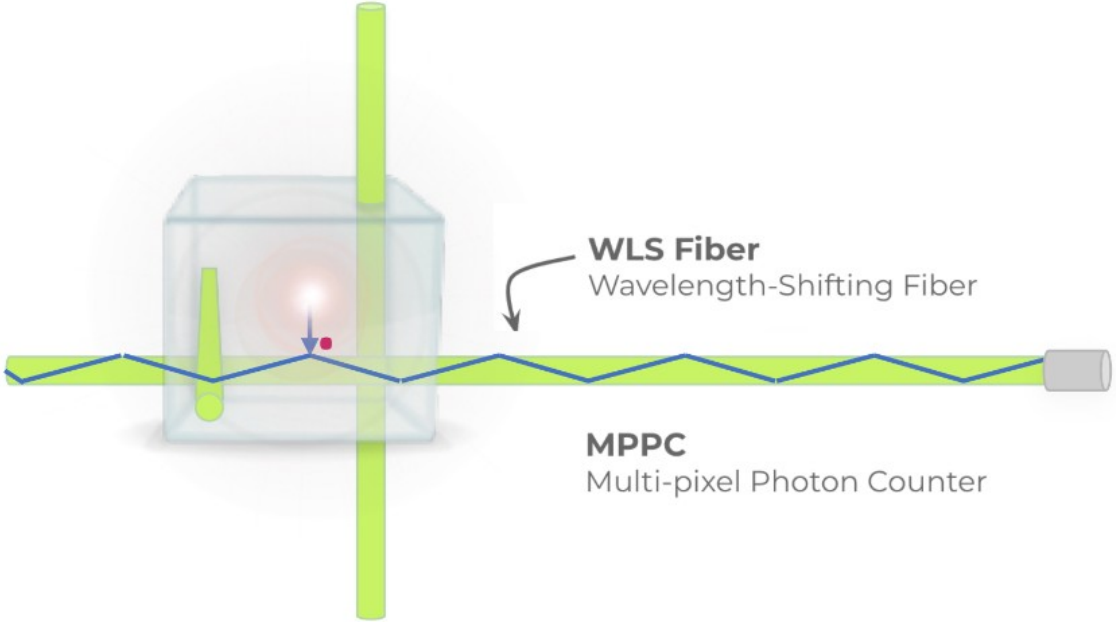


Quasielastic Scattering

Readout Channel

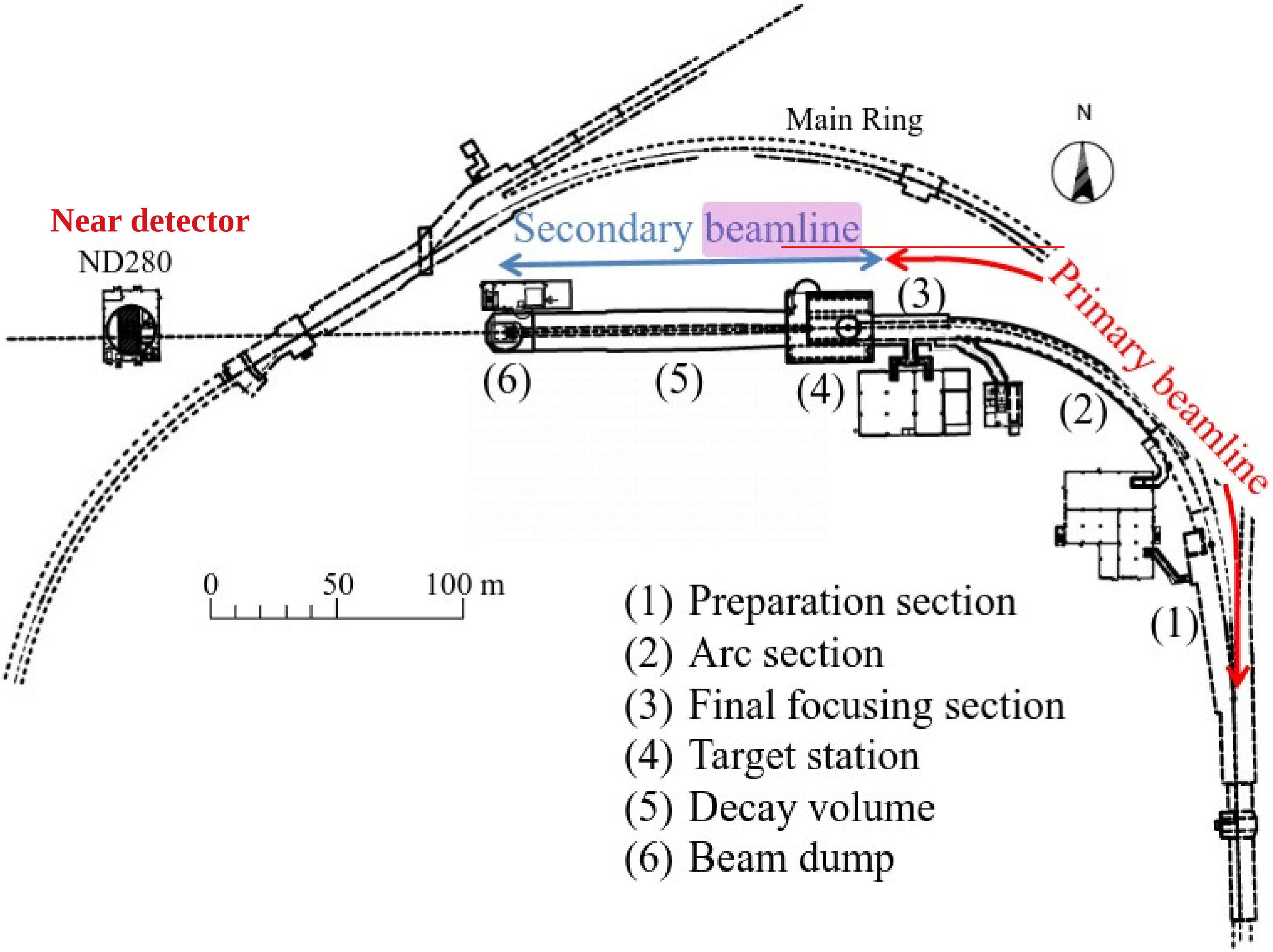
Example of Readout Channel





J-PARC Beamline

Primary and Secondary Beamlines



(1) Preparation section
(2) Arc section
(3) Final focusing section
(4) Target station
(5) Decay volume
(6) Beam dump

Why To Upgrade ND280?

- Original Near detector limitations have non-negligible effects in the “oscillations” models uncertainties:
  - **Limited low momentum acceptance**.
    - Particles need enough momentum to reach the TPC where they are reconstructed.
    - Low energy particles can’t make short tracks or be detected at all.
  - **Limited high-angle acceptance** (> 50º).
    - Due to 2-D tracking (lack of granularity in the transverse direction).
  - **Limited neutron detection capabilities**.
    - Reduced tracker granularity and lack of time of flight.

Flux model

Detector model

Neutrino interaction model

$$
\begin{aligned}
N^{ND}_{\nu_\alpha}(E_\nu) &= \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu) \\
N^{FD}_{\nu_\beta}(E_\nu) &= \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times \boxed{P_{\nu_\alpha \to \nu_\beta}(E_\nu)}
\end{aligned}
$$

- To improve constraints in oscillation parameters, a significant reduction of some of the uncertainties involved, is needed!

SuperFGD Expected Tracking Efficiency

BACKUP

- **FGD**
  - 2D tracking
  - Pp threshold ~400 MeV/c.
  - Maximum efficiency ~30%.
- **SuperFGD**
  - Both 2D and 3D tracking expected to perform better than FGDs.
  - Pp threshold ~300 MeV/c.
  - Efficiency ~60 to ~80%