UNIVERSITÉ DE GENÈVE

T2K

Super Fine-Grained Detector for the T2K long-baseline neutrino experiment

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(University of Geneva)
on behalf of the SuperFGD group

European Physical Society
Conference on High Energy Physics
Marseille, July 9th, 2025

Outline

1. The T2K experiment and ND280 upgrade
2. SuperFGD design and installation
3. SuperFGD performance
4. Neutrino physics with SuperFGD
5. Conclusions

1. The T2K experiment and upgrade of ND280

The T2K Experiment

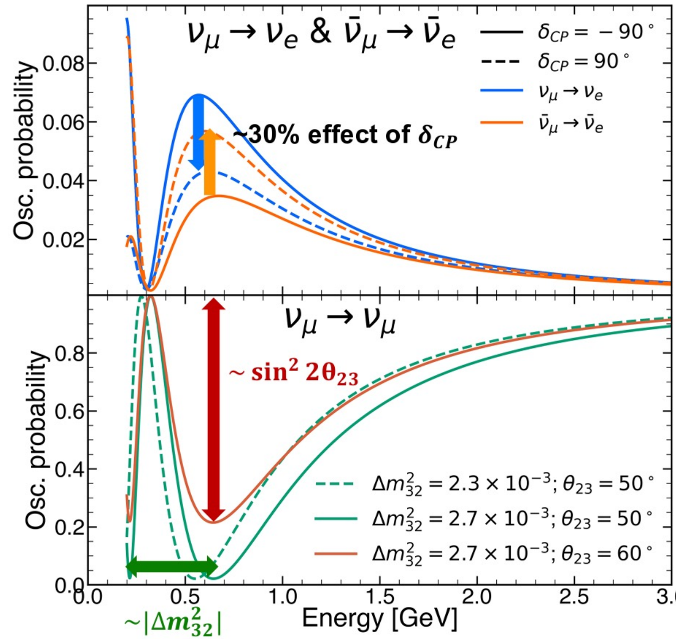
Measuring neutrino oscillations 295 km away from the source

T2K physics program:

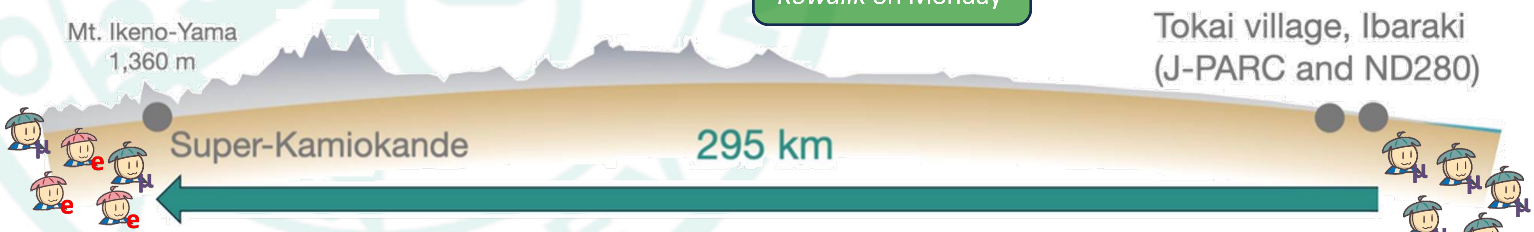
- ν_μ disappearance and $\nu_e/\overline{\nu_e}$ appearance:
  Sensitive to $\boldsymbol{\theta_{23}}, \boldsymbol{\Delta m^2_{23}}$ and $\boldsymbol{\delta_{CP}}$: **CP-violation**
- Measure ν-nucleus cross sections

T2K concept:

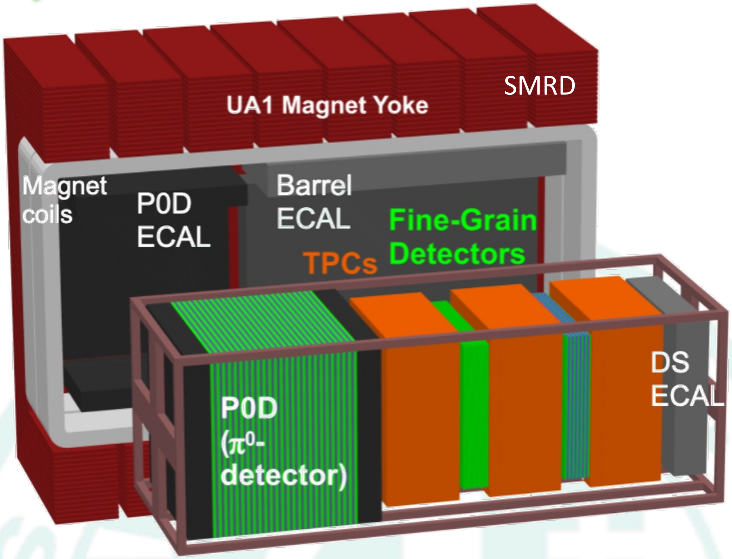
- **Beam:** ~0.6 GeV muon (anti-) neutrino from J-PARC
- **Near Detector (ND280)**: characterize unoscillated flux
- **Far Detector (Super-Kamiokande)**: observe oscillated neutrino flux



Talk by *Katarzyna Kowalik* on Monday



ND280



Original ND280:
Neutrino scintillating targets with gas-based trackers (in 0.2 T magnetic field)

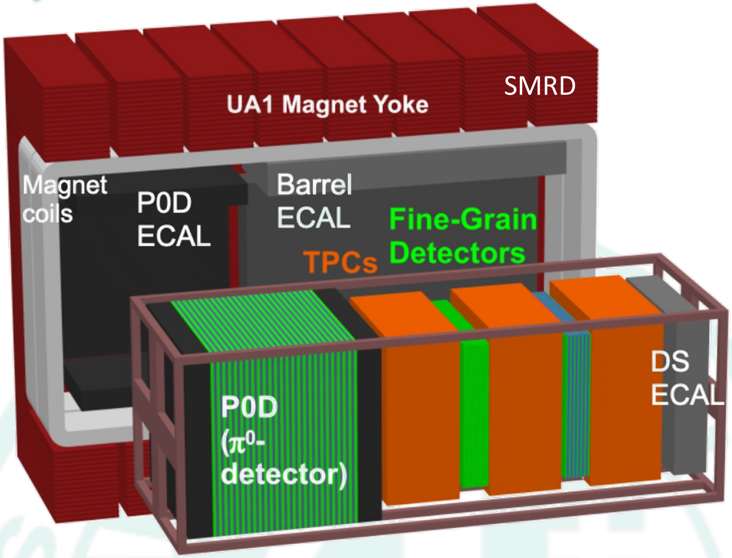
Goal of the Near Detector (*ND280*):
reduce systematic uncertainties on **cross-section** and flux – great impact on oscillation analysis!

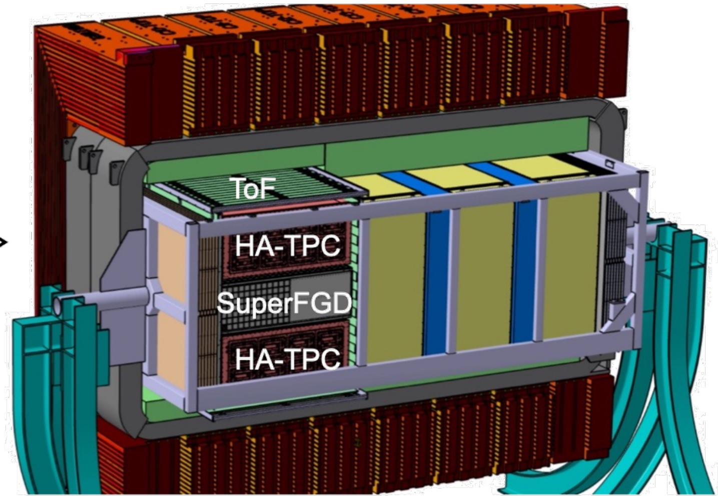
Talk by *Xingyu Zhao* this afternoon

Limitations of original ND280:

- Limited angular acceptance
- High proton tracking threshold

ND280 upgrade





4 new subdetectors:

- 2 High-Angle TPCs: precise momentum measurement
  - Merlin Varghese's talk
- TOF detector: veto and forward/backward discrimination
  - Poster session!
- **SuperFGD:** neutrino active target

Improvements:

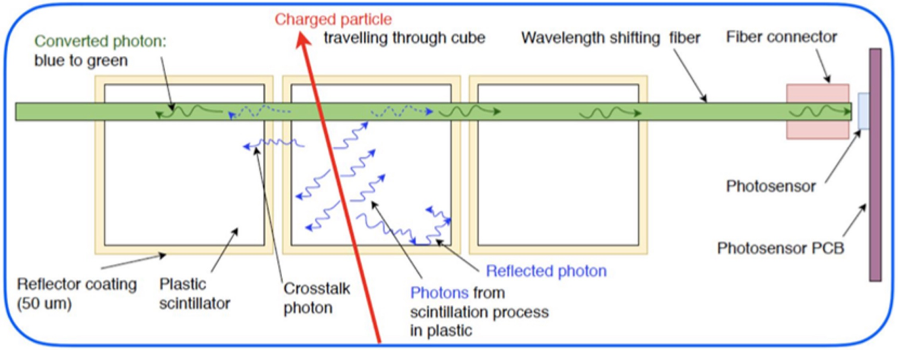
- Achieve 4π acceptance
- Double fiducial mass
- Lower proton tracking threshold
- Neutron detection

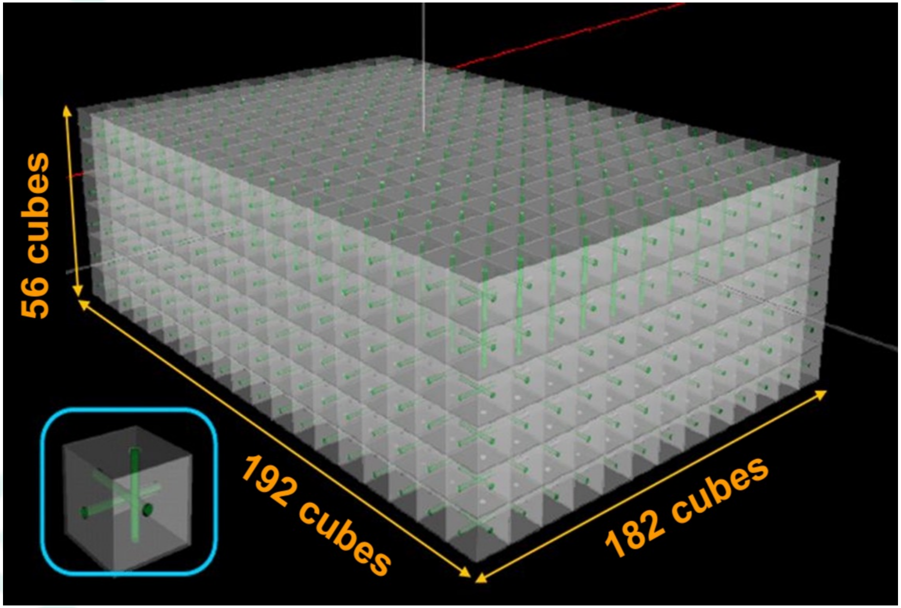
See talk by *William Saenz*

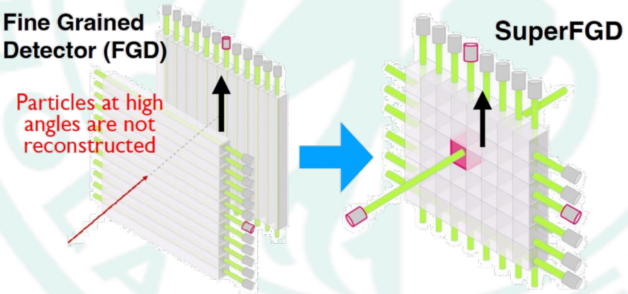
2. SuperFGD: Design and installation

SuperFGD concept

- 2 tons fiducial mass
  $(2\,m \times 0.6\,m \times 2\,m)$
- 2 million scintillating cubes $1\,cm^3$ each
  → **high granularity**
- Each cube crossed by 3 orthogonal fibres,
  → **3D tracking**
- $\sim$ 56k WLS fibres coupled with MPPCs (Hamamatsu 13360-1325PE)

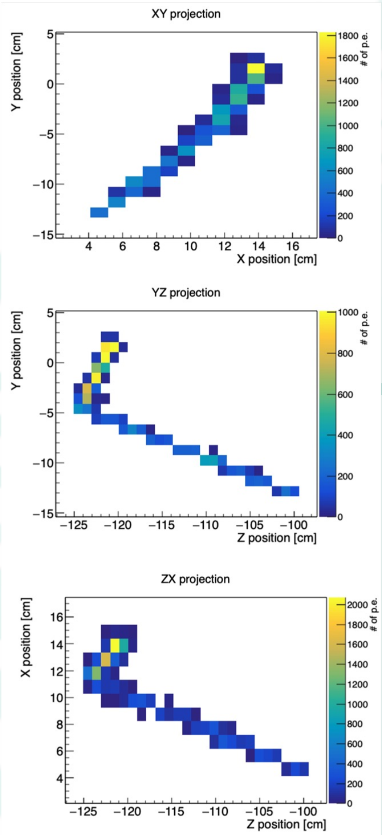






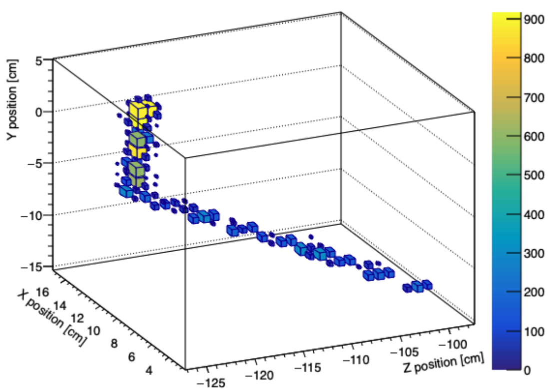
Track reconstruction

Three projections with **time, charge** and **2D position** information



Build 3D hits:

- light attenuation
- charge sharing
- cube time reconstruction



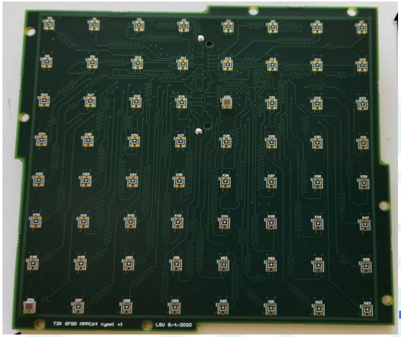
DBSCAN + particle filter (sequential Bayesian resampling)

Tracks, clusters and vertices

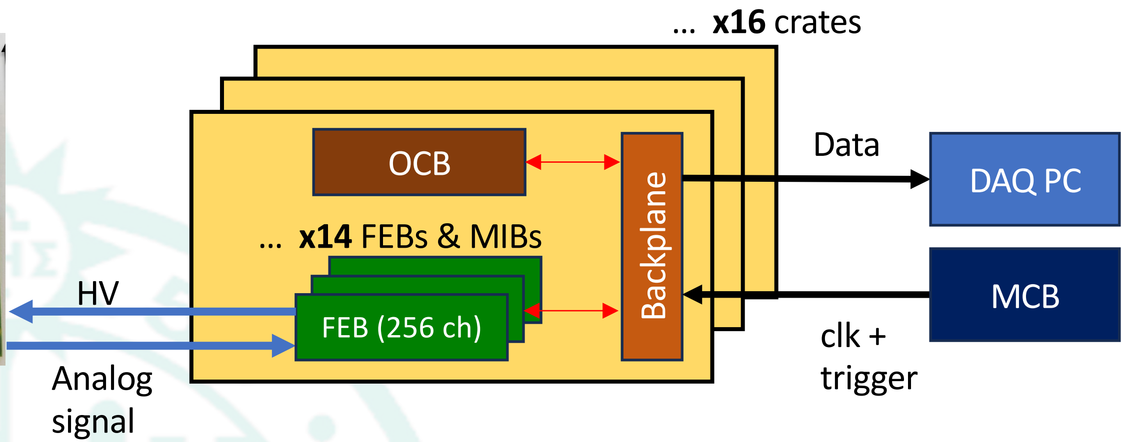
! Also exploring reconstruction using machine learning techniques

Talk by *Anaelle Chalumeau* on Monday

Electronics and calibration system

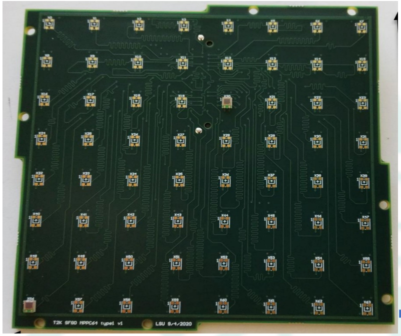


Sensors: MPPC64 (**x881**)



55’888 channels -> 222 Front-End Boards

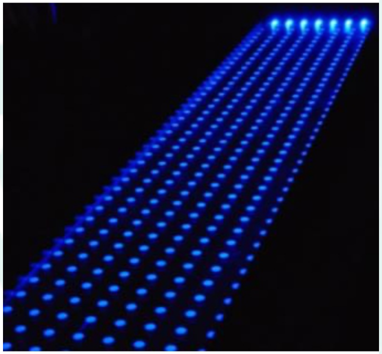
Electronics and calibration system

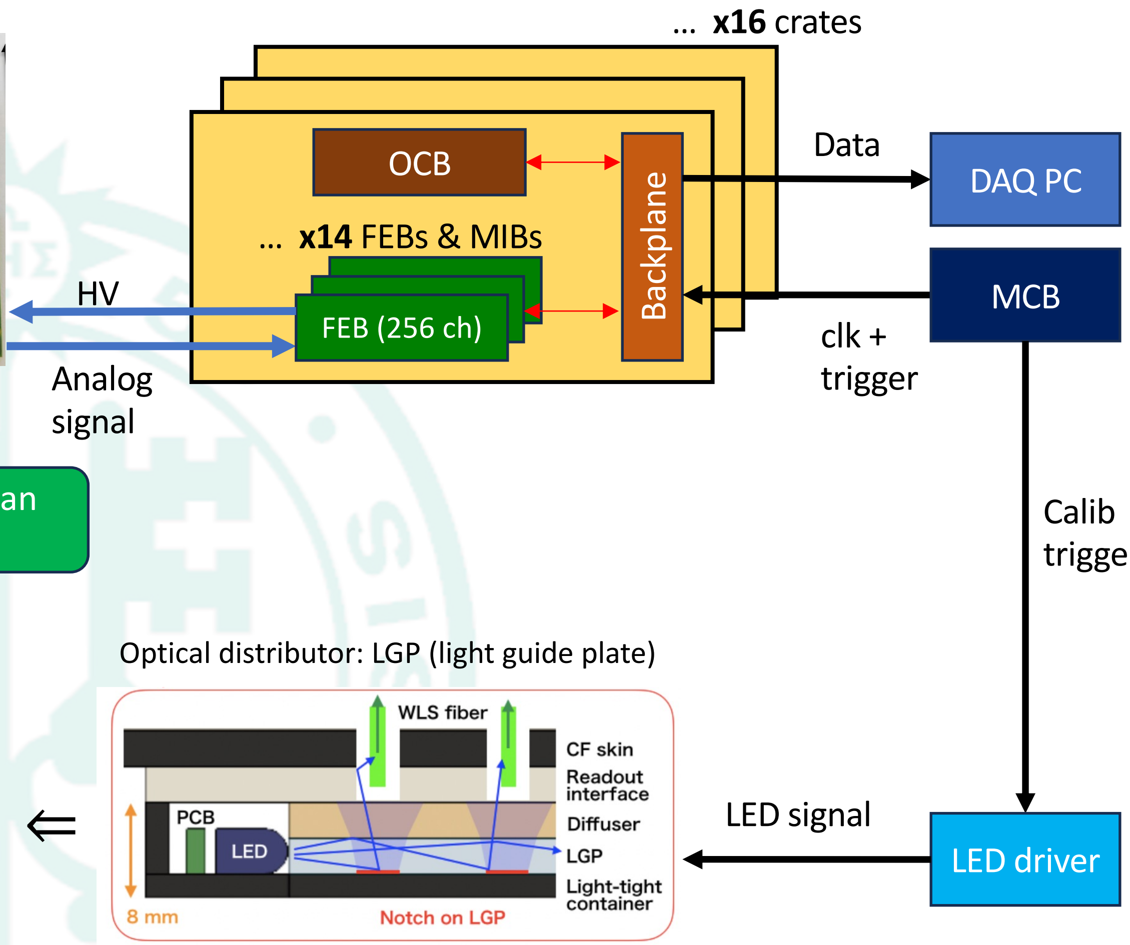


Sensors: MPPC64 (**x881**)

Two opposite ends of an optical fibre

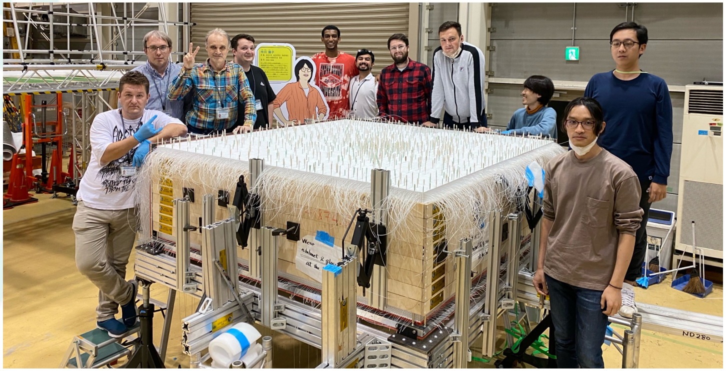
Diffused light from LGP





Assembly and installation

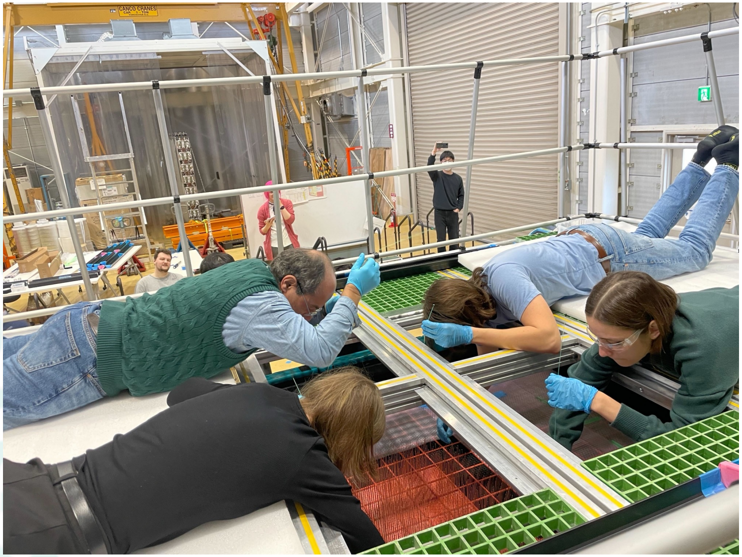
Assembly and installation



1. Assemble cube layers (~20 months!), then stack them in the mechanical box. Use fishing lines and metal rods.

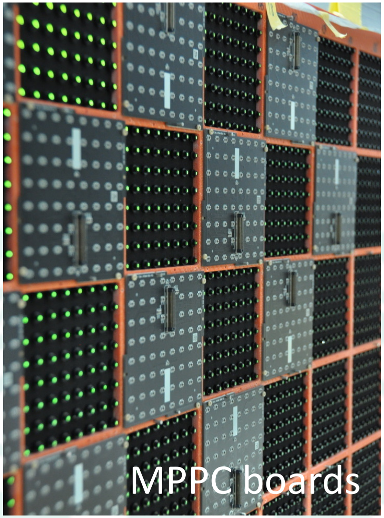
Assembly and installation

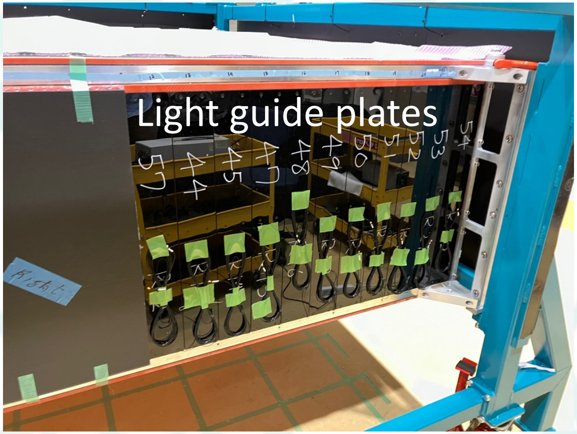
2. Remove fishing lines, insert WLS fibres.



Assembly and installation

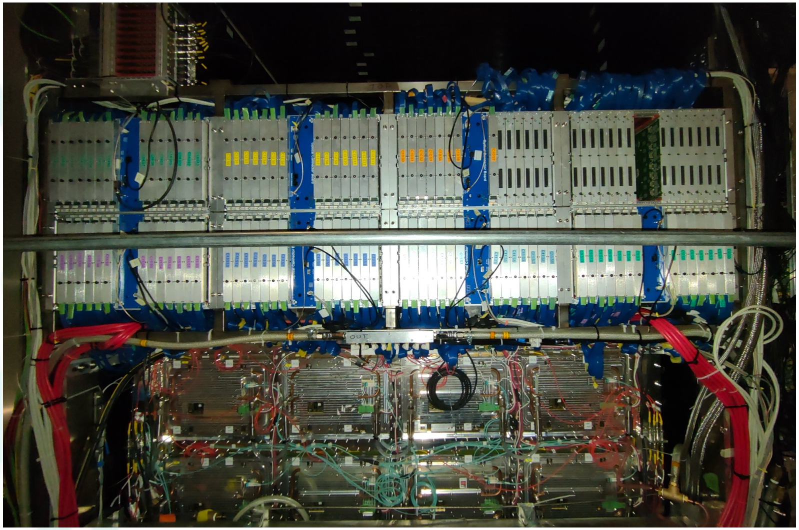
3. Install MPPCs, LGPs, light barrier. Close the mechanical box and install cables.





Assembly and installation

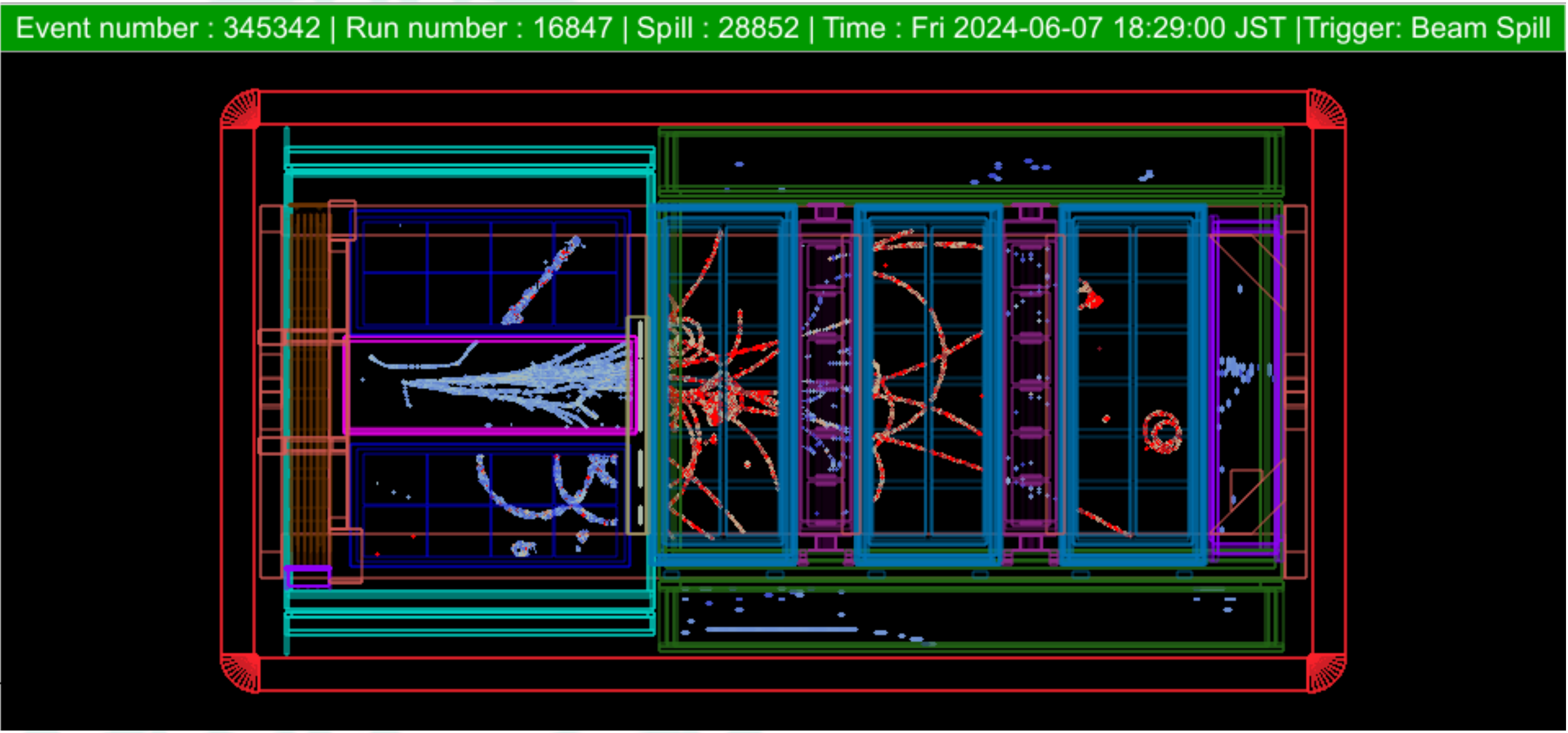
4. Lower SuperFGD in the ND280 pit and connect electronics system.



Installation ended in **March 2024**.

June 2024:

First neutrino beam events in SuperFGD, with tracks propagating in other ND280 subdetectors

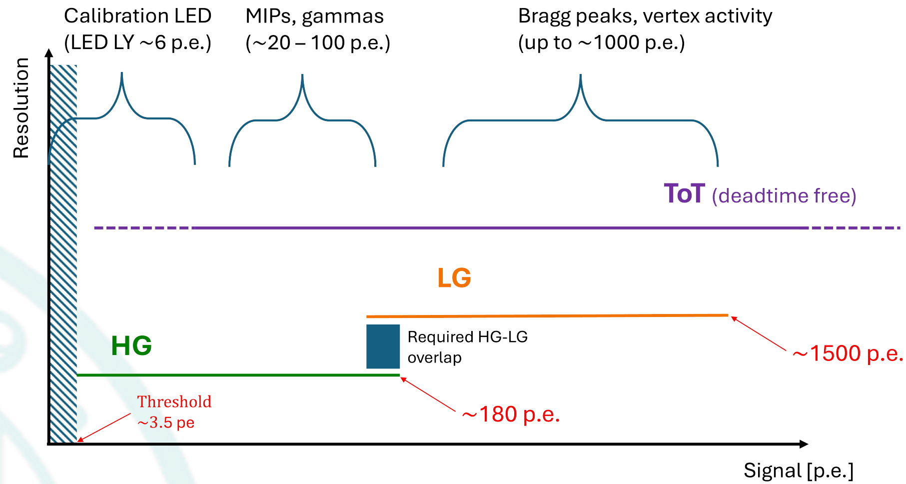


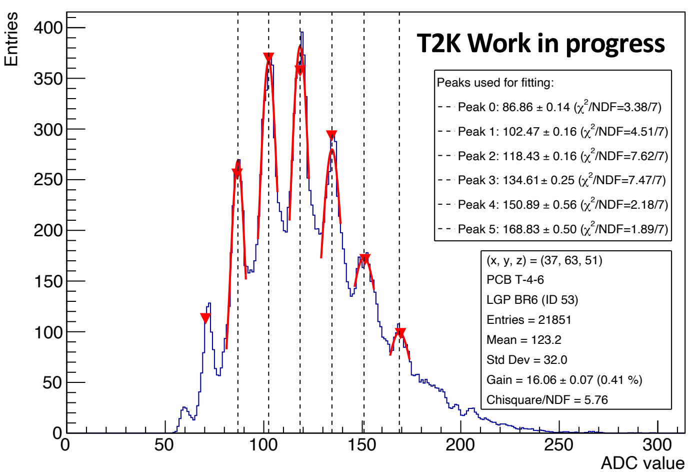
3. SuperFGD: Detector performance

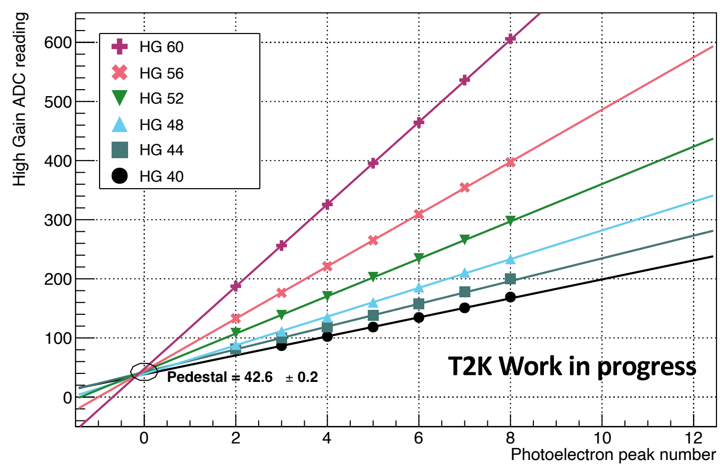
- Selected topics -

Calibration and dynamic range

- **3** types of charge read-out: HG, LG, ToT
- LED system: calibrate HG response (gain + pedestal)
  - ~15 ADC/p.e.
- Cross-calibrate LG and ToT in signal overlap regions with cosmic and neutrino beam runs
- **Dyn. range up to 1500 p.e.**





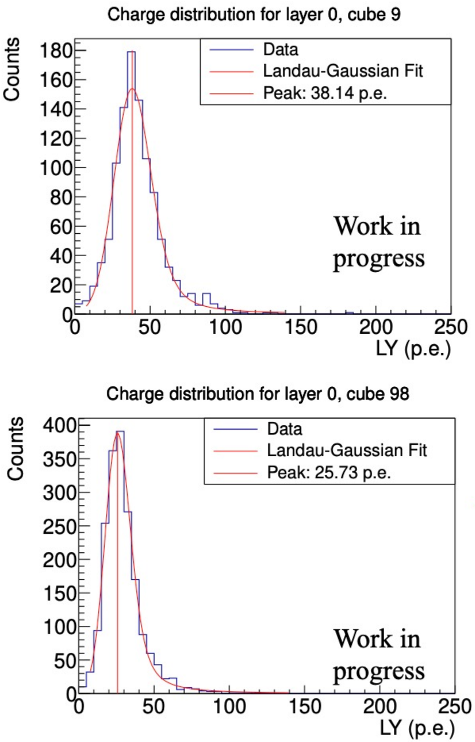


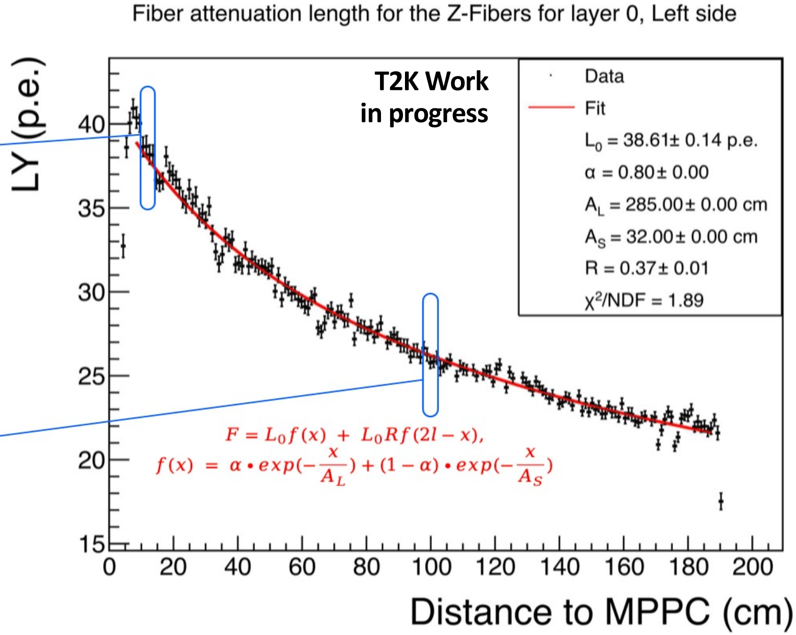
Light attenuation

Important for cube charge reconstruction

- **Cosmic muon data:** fit the light yield as a function of the cube position along the fibre
- Model attenuation + reflection
- Repeat for each WLS fibre

$$F = L_0\ [f(x) + R\ f(2l - x)]$$
$$\text{where } f(x) = \alpha\ e^{-x/A_L} + (1-\alpha)\ e^{-x/A_S}$$





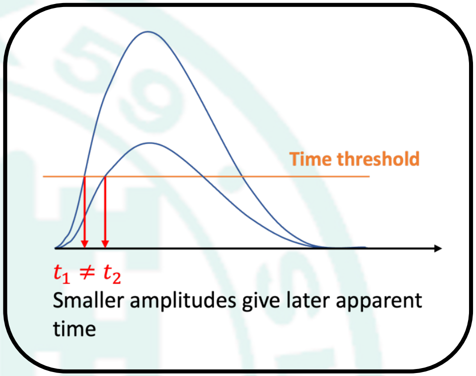
Time calibration & resolution

Two sources of time measurement deterioration:

1. Time walk
2. Mutual mis-synchronization of channels

Time walk:
Fit function on apparent time delay vs. hit charge

$$\Delta t(q) = \frac{p_0}{\log(p_1 * q + p_2)} - \frac{p_3}{q + p_4}$$



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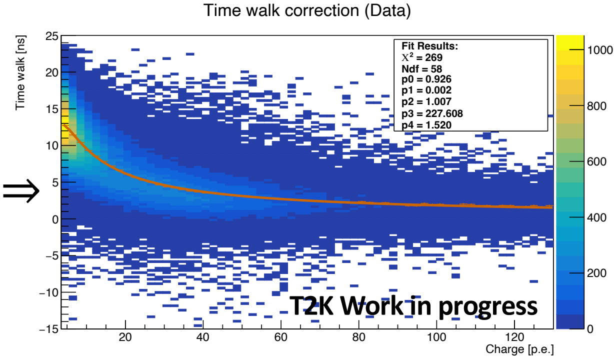
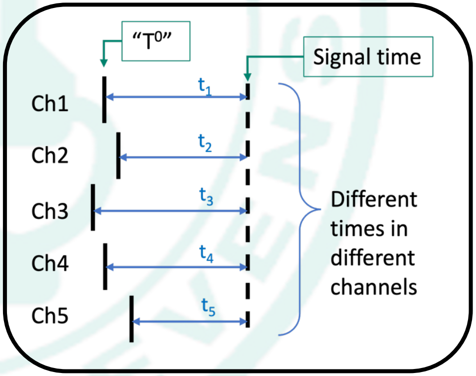


Channel mis-sync:
Innovative method based on Markov Chain.
[paper in preparation]



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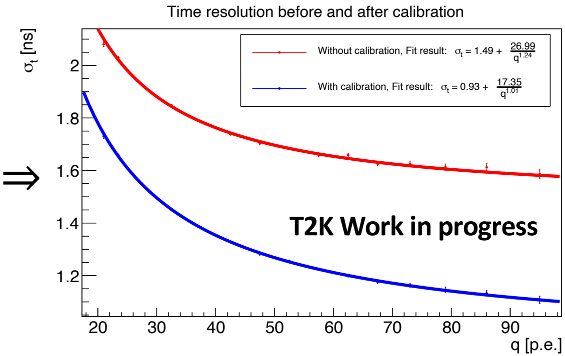
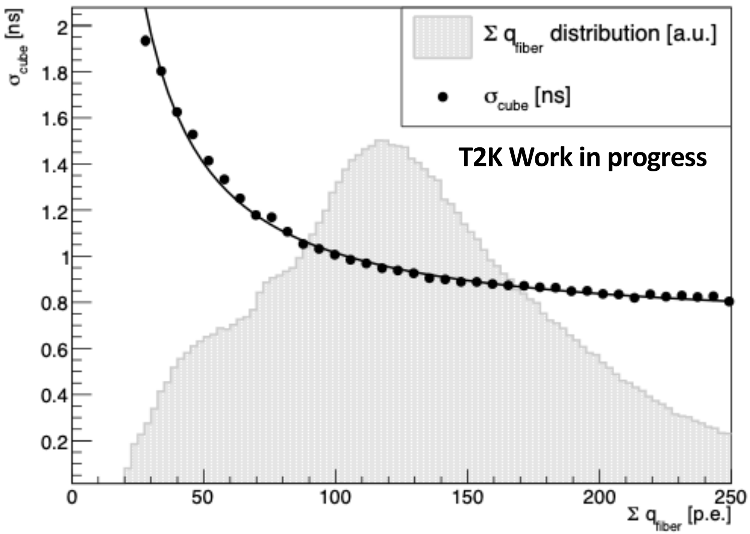


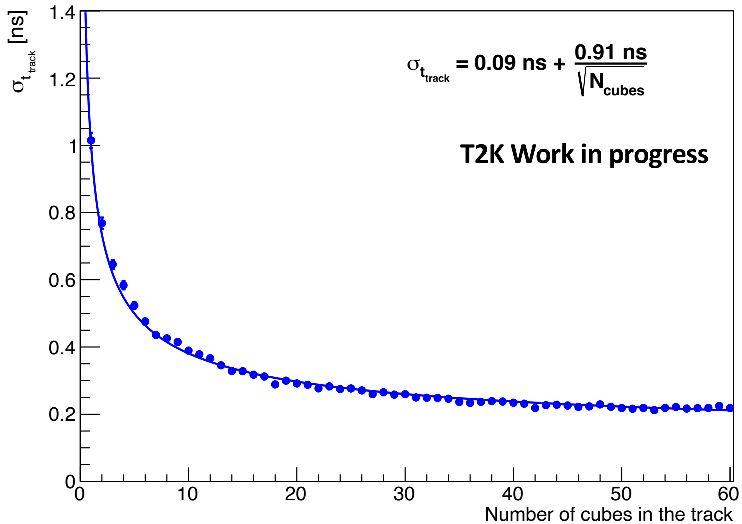
Work by L.G., H. Zheng, G.Reina

Time resolution

Cube time resolution



Track time resolution



- Crucial for **neutron** time-of-flight analysis
- Achieved **sub-ns** resolution for the single cube
- Down to $\sim 200\ ps$ time resolution for long tracks
  - Measured on cosmic data samples

4. Neutrino physics with SuperFGD

- Highlights -

ν_μ CC with no π and N p

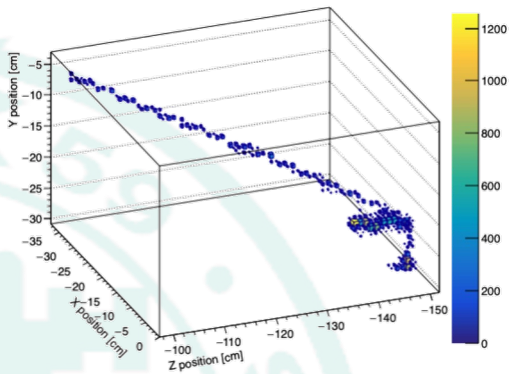
Processes with no pions and N protons in final state are important to inform ν-Nucleus cross section models.

Among most common x-sec analyses in ND280:

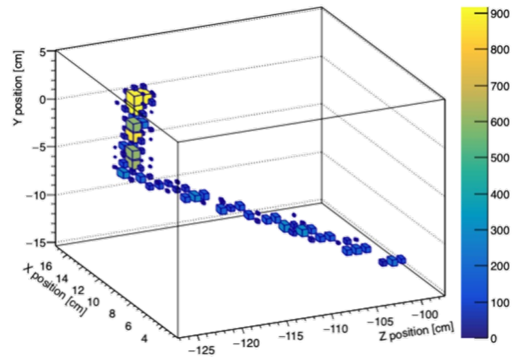
$\nu_\mu + N \rightarrow \mu^- + N' + p\ (+p)$

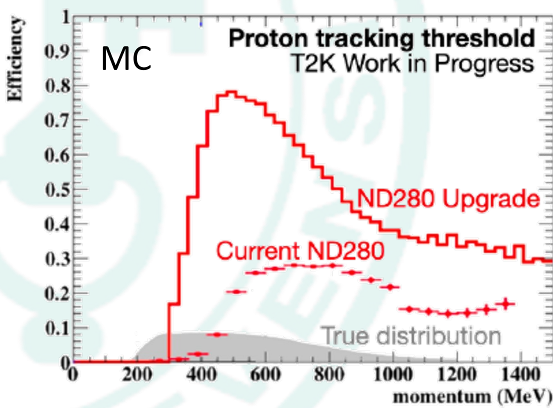
- Low momentum protons: range + Bragg peak
- Expected proton tracking threshold: ~**300 MeV/c**
- Enables using full final state kinematics in oscillation analysis

2 protons, 1 muon final state (data)

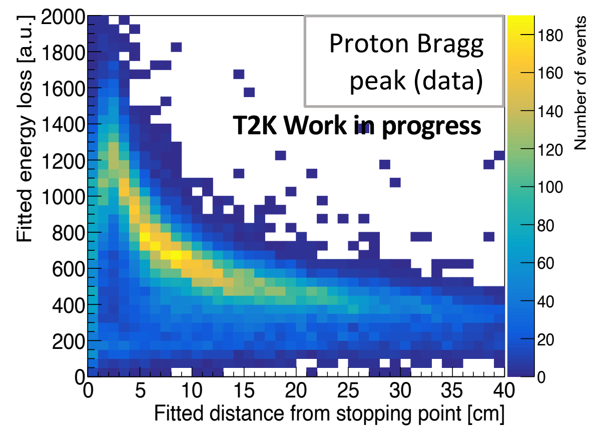


1 proton, 1 muon final state (data)





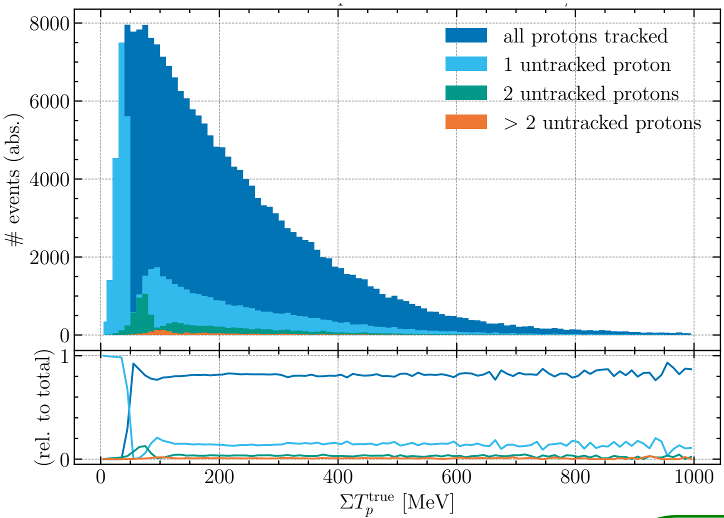
Protons originating outside SFGD, stopping inside



Work by X.Zhao

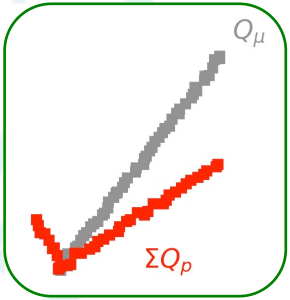
Low q_0 - calorimetry analysis

What about protons below the tracking threshold?



Model predicted untracked proton multiplicities (NEUT LFG)

- Important to understand ν-Nucleus interactions at very **low** q_0
- Reconstruct with calorimetry!
  - Remove muon track and treat the rest as hadronic energy deposition: $\sum T_P$



$\sum Q_p \rightarrow \sum T_p$ using Birks law

$$\frac{dQ}{dx} = \epsilon \frac{dE}{dx} \cdot \frac{1}{1 + c_B \frac{dE}{dx}}$$

Need assumption on FS multiplicity (model dependent), or compare data/MC in $\sum Q_p$

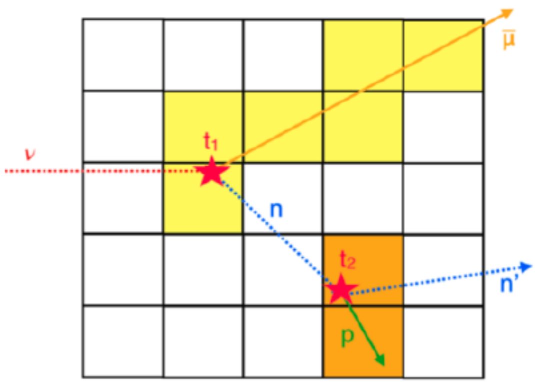
Work by K.Lachner

$\nu_\mu/\overline{\nu_\mu}$ CC with neutrons in FS

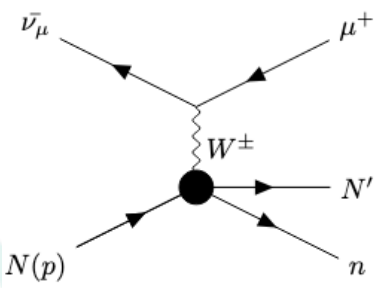
Some processes with neutrons in FS:

$$\overline{\nu_\mu} + N(p) \rightarrow \mu^+ + n + N'$$
$$\nu_\mu + N(n) \rightarrow \mu^- + p + n + N'$$

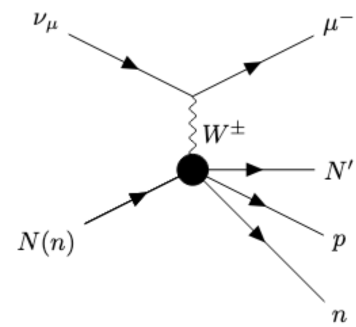
- Neutrons re-scatter emitting proton "blips"
- In SuperFGD, this shows up as isolated energy deposit.
- Measure neutron time of flight and lever arm → estimate T_n from neutron speed



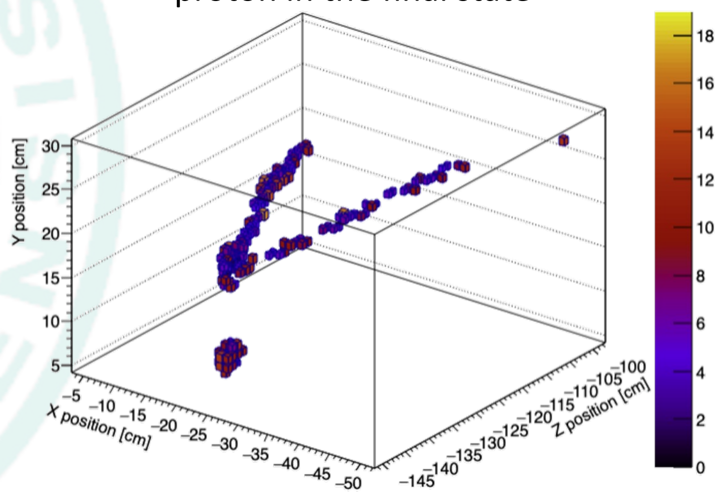
Quasi-elastic $\overline{\nu_\mu}$ CC



2p2h-np ν_μ CC



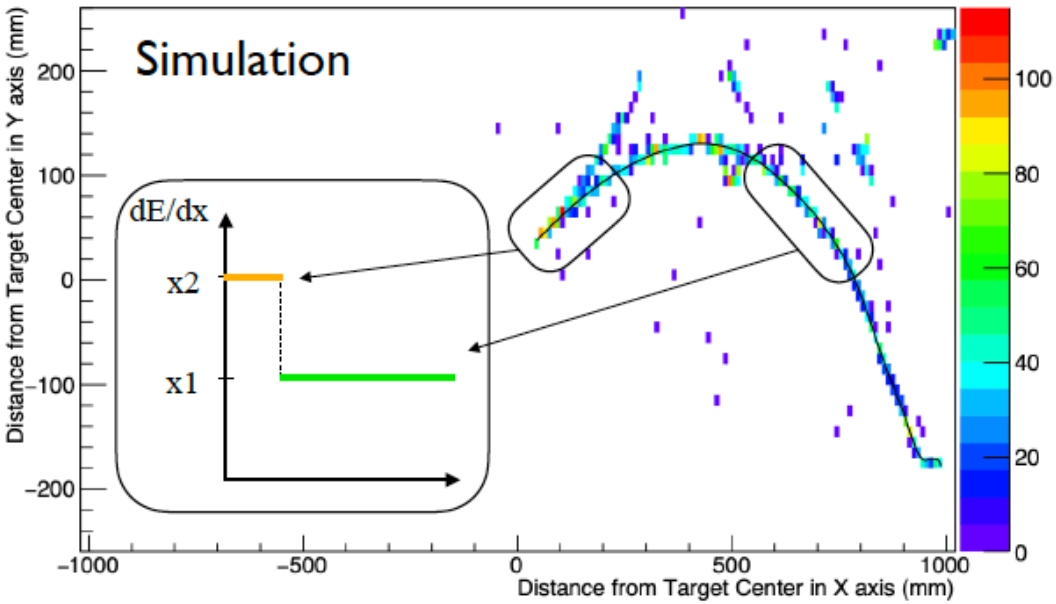
Event candidate with one neutron and one proton in the final state



- ND280 sees small ν_e contamination in the ν_μ beam (low stats):

$$\nu_e + N \rightarrow e^- + X$$

- ***ν*-Beam upgrade**: more ν_e statistics
- Main background to ν_e CC is $\gamma \rightarrow e^- e^+$ from π^0 in ν_μ NC interactions
- dE/dx analysis at the beginning of the shower to discriminate $e^\pm/\gamma$
  - Possible thanks to SuperFGD's fine granularity and radiation length



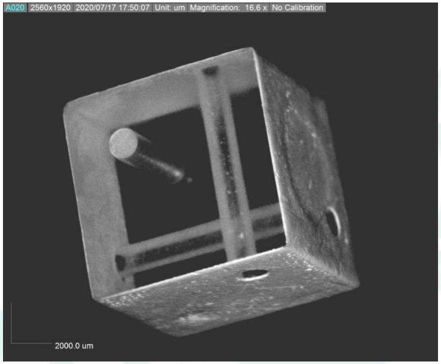
5. Conclusions

Conclusions

- SuperFGD is the new neutrino active target of T2K Near Detector.
- It is the result of a joint effort of **37 research institutes** from different countries (CERN, France, Germany, Japan, Russia, Switzerland, UK, USA)
- With a novel design, it overcomes many limitations of ND280:
  - **4π acceptance**
  - **3D tracking**
  - **calorimetric** capability
  - **sub-ns time resolution**.
- A comprehensive SuperFGD paper is in preparation
- It will open new paths for neutrino-nucleus cross-section measurements, detecting **neutron final states** and **very low energy protons**
- It will contribute to reduce systematics uncertainties on neutrino oscillation measurements, preparing the **Hyper-K** era.

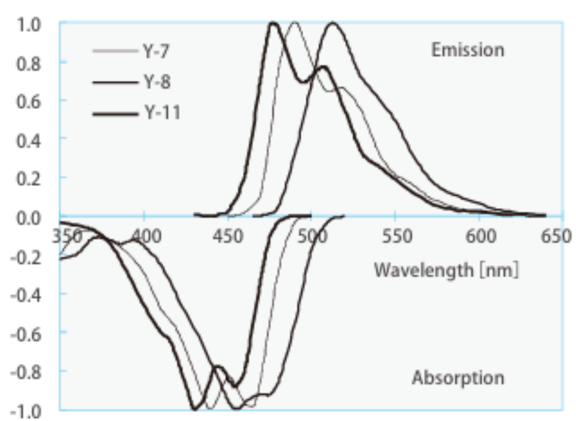
Back up

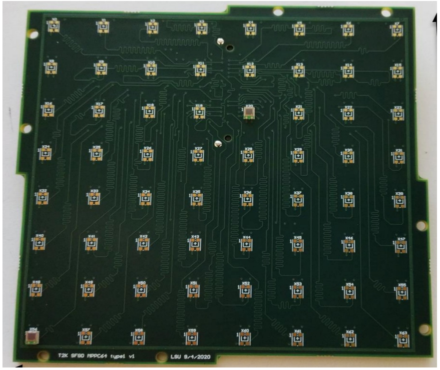
Cubes, fibres, sensors



Cubes:
Polystirene doped with 1.5% paraterphenyl (PTP) and 0.01% POPOP. Etched reflective layer (80 μm thickness).
Holes 1.5 mm in diameter

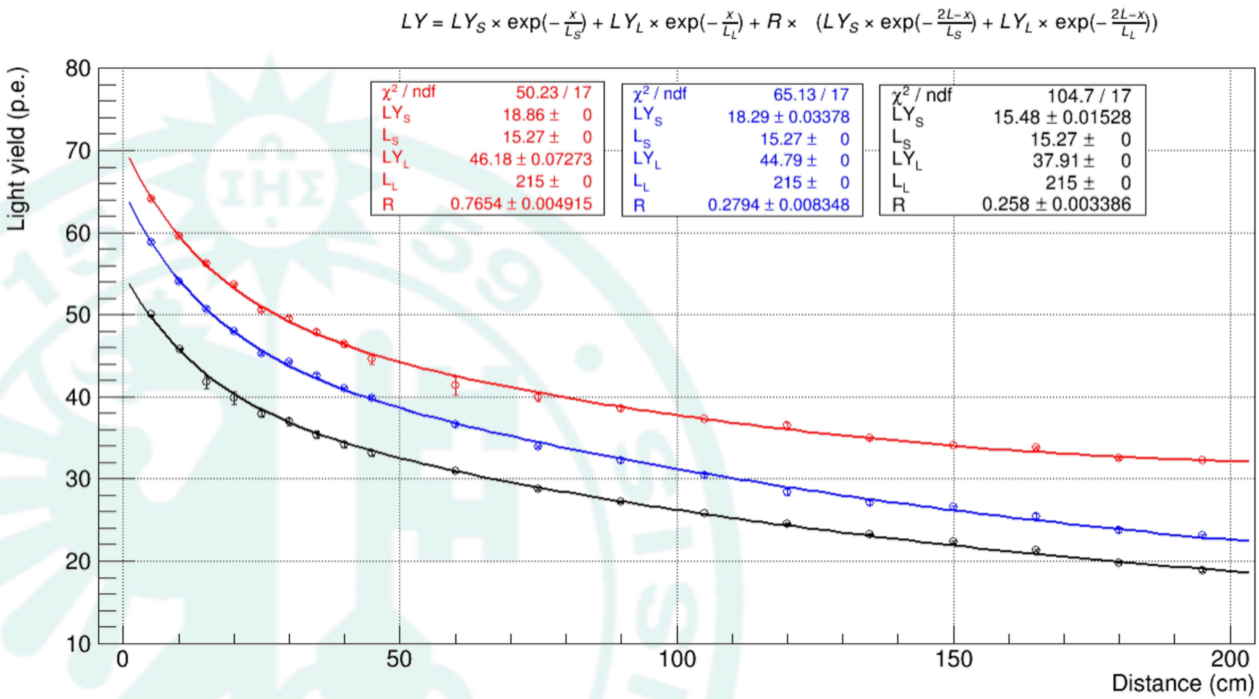
Fibres:
WLS multi-cladding fibres Kuraray Y-11 (200)
1 mm in diameter
Horizontal fibres: 2 meters long
Vertical fibres: 0.6 meters long





Sensors:
MPPCs Hamamatsu 13360-1325PE mounted on custom PCB
$1.3 \times 1.3\ mm^2$ sensitive area
2668 pixels

Study on fibre attenuation length



Fibre end polished and painted

Fibre end polished

Fibre end cut at 45° and painted

SuperFGD Front-end Board

256 channel charge + timing readout

- 8 CITIROC by Omega:

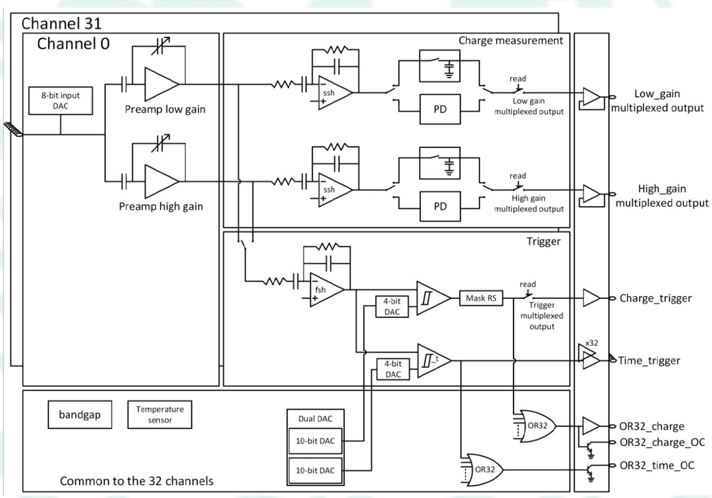
32-ch read out chips

Types of read-out:

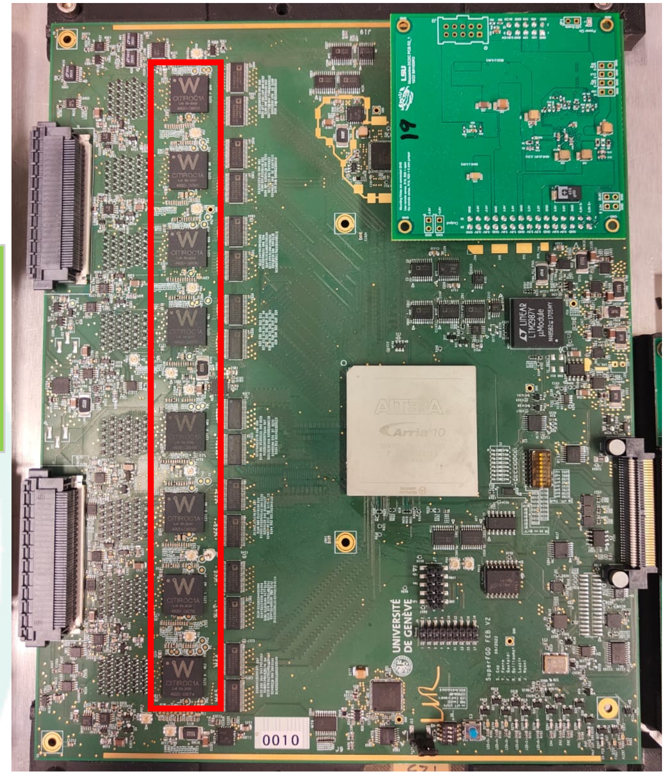
- Timing: constant threshold trigger output
- Charge: dual gain peak detector (HG, LG)

Programmable devices:

- Timing and analog thresholds: 10(+4)-bit
- Gain for charge readout: 6-bit
- Shaping time: 3-bit



To detector



To back-end

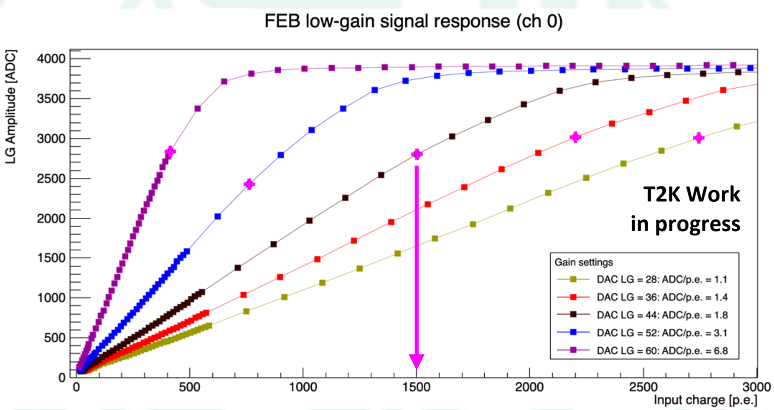
Dynamic range & energy resolution

Dynamic range

Limited by **non-linearity** of the CITIROC response.

Upper limit: LG linear limit

LG linear limit > 1000 p.e

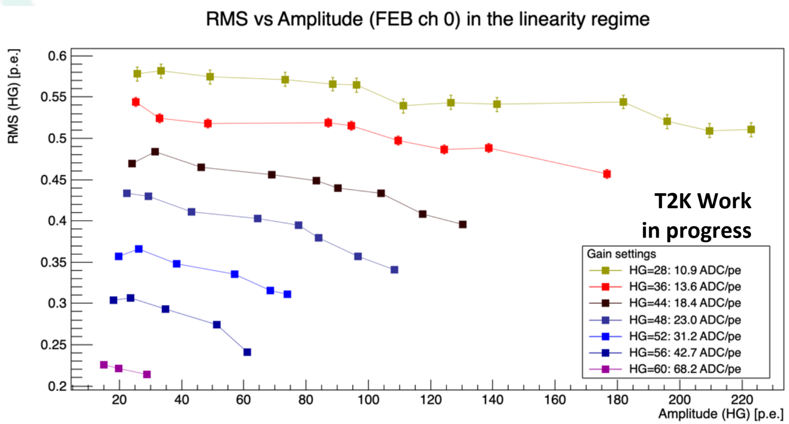


Energy resolution (HG output)

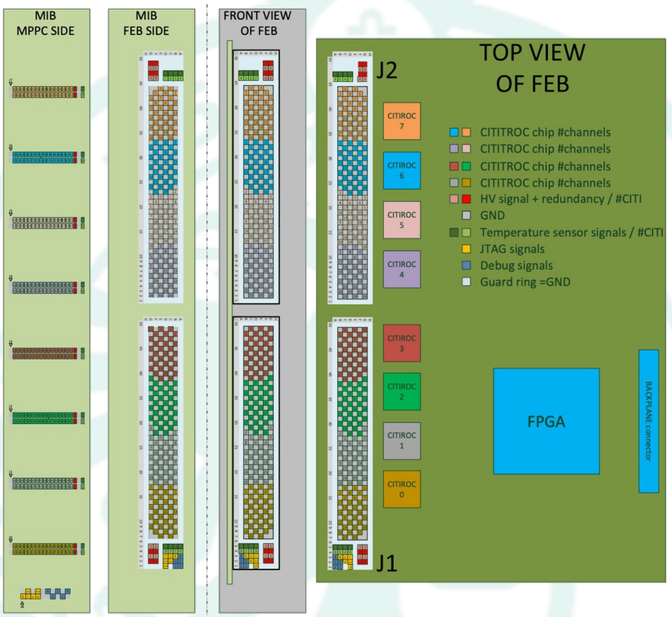
Electronic noise degrades energy resolution.

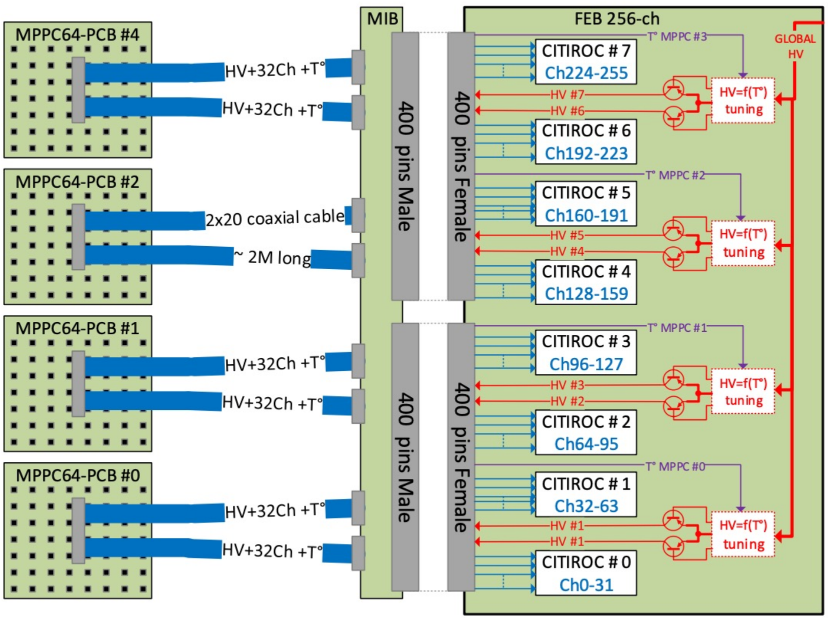
Study RMS of the signal in HG mode.

RMS < 1 p.e.

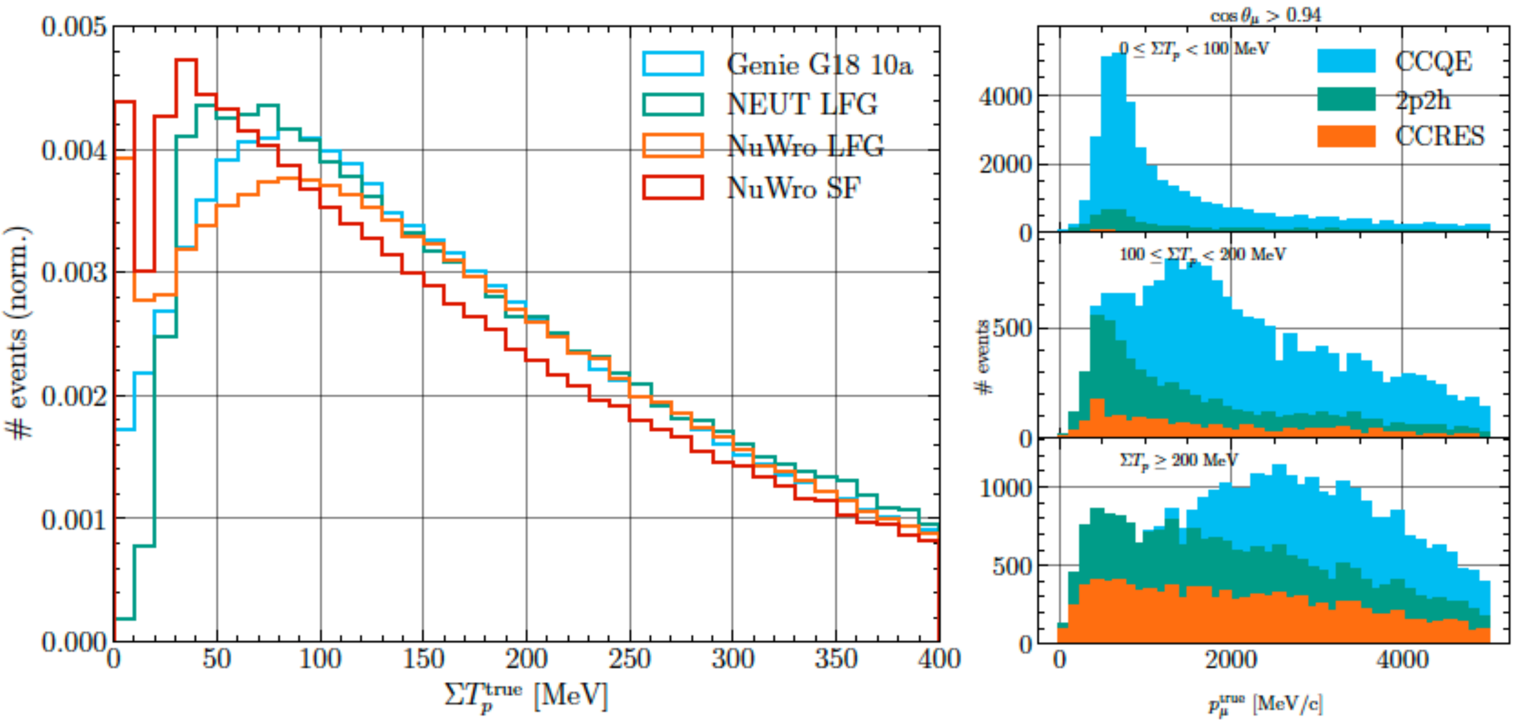


Front-end connectivity





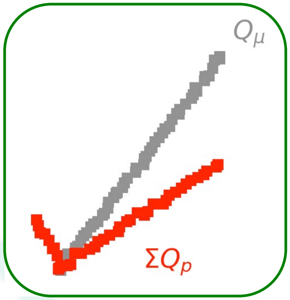
Calorimetric energy reconstruction



Low q_0 - calorimetry analysis

What about protons below the tracking threshold?

- Important to understand ν-Nucleus interactions at very **low q_0**
- Reconstruct with calorimetry!
  - Remove muon track and treat the rest as hadronic energy deposition: $\sum T_P$

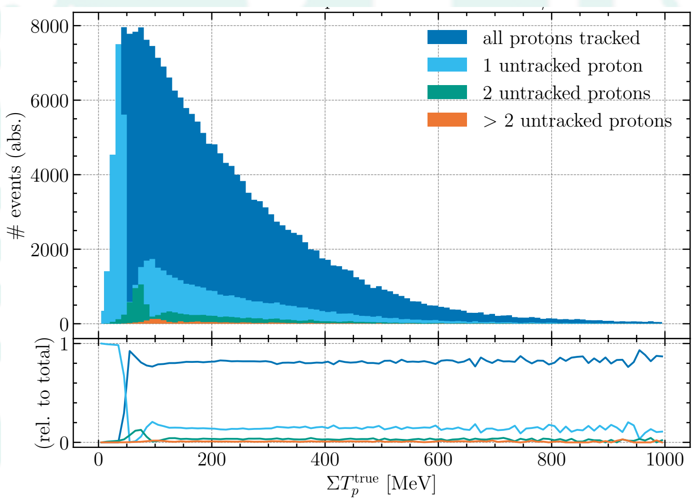


$\sum Q_p \rightarrow \sum T_p$ using Birks law

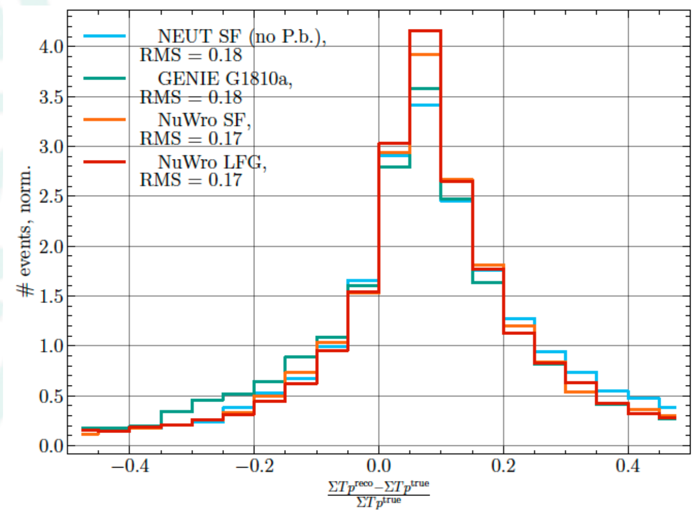
$$\frac{dQ}{dx} = \epsilon \frac{dE}{dx} \cdot \frac{1}{1 + c_B \frac{dE}{dx}}$$

Need assumption on FS multiplicity (model dependent), or compare data/MC in $\sum Q_p$

Model predicted untracked proton multiplicities (NEUT LFG)

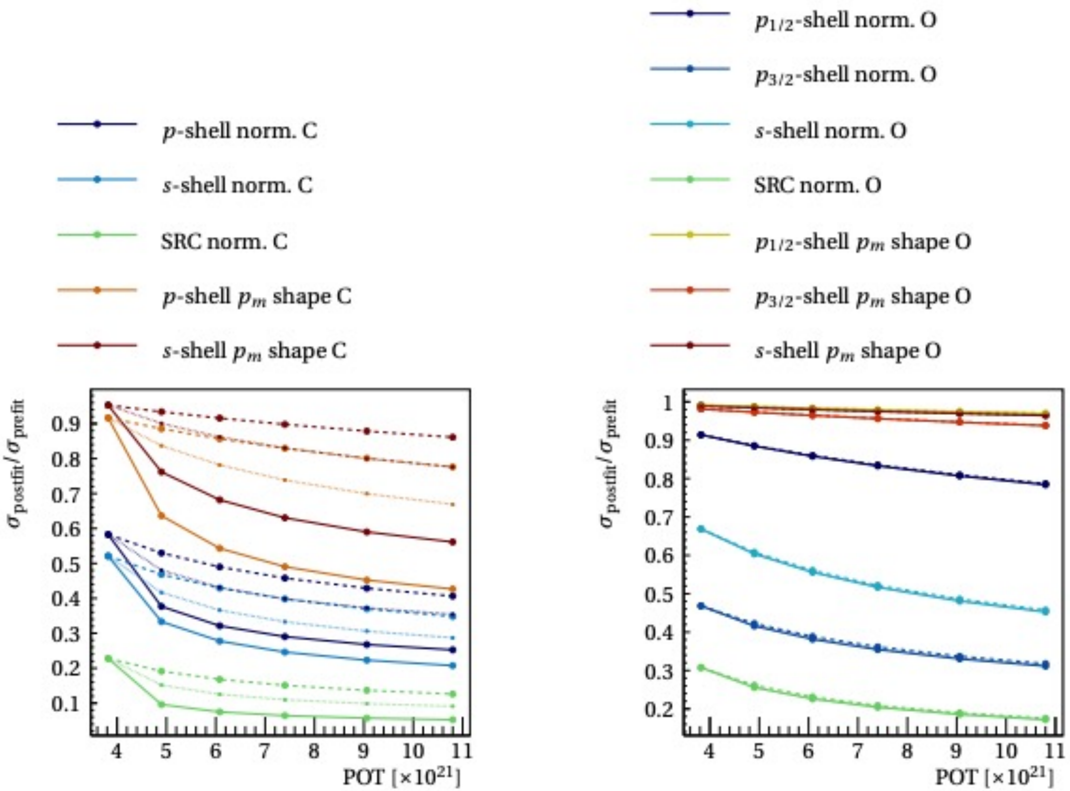


$\sum T_P$ resolution, different models



Work by K.Lachner

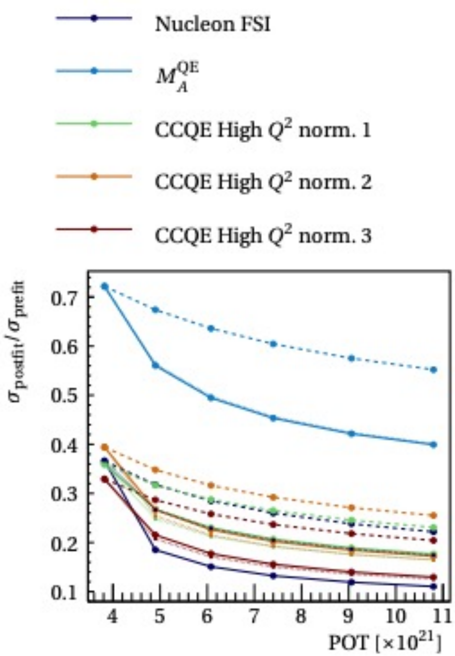
ND280Up sensitivity studies



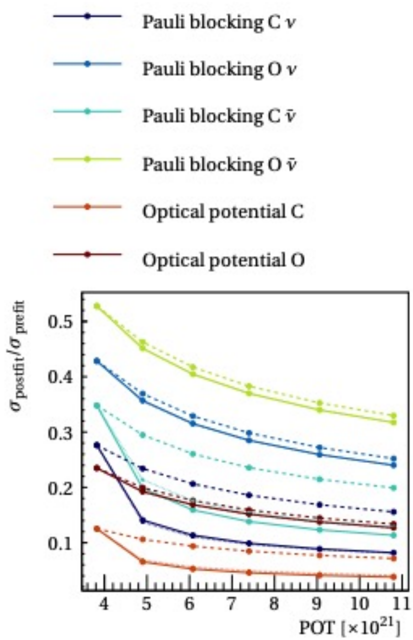
(a) Carbon SF model

(b) Oxygen SF model

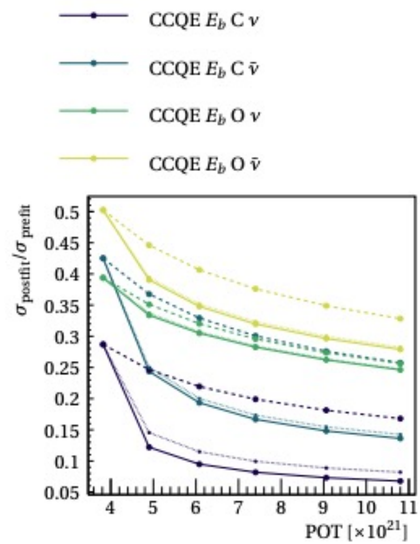
ND280Up sensitivity studies



(a) Other CCQE parameters



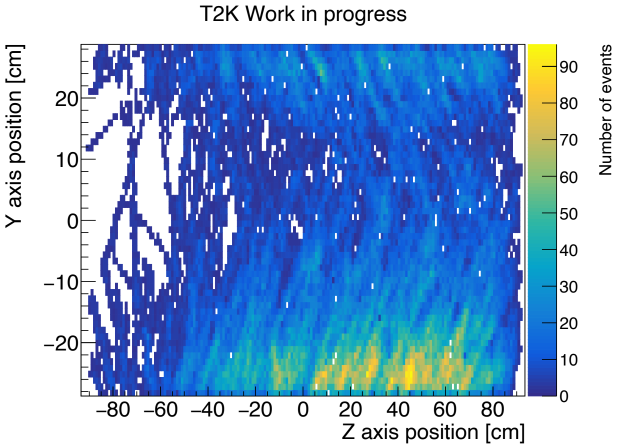
(c) Pauli blocking and optical potential

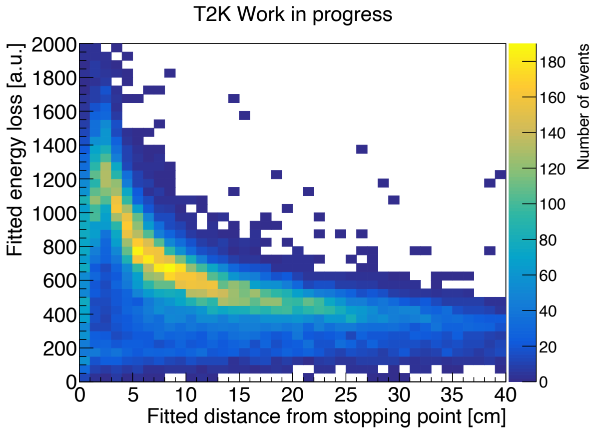


(d) Global removal-energy shifts

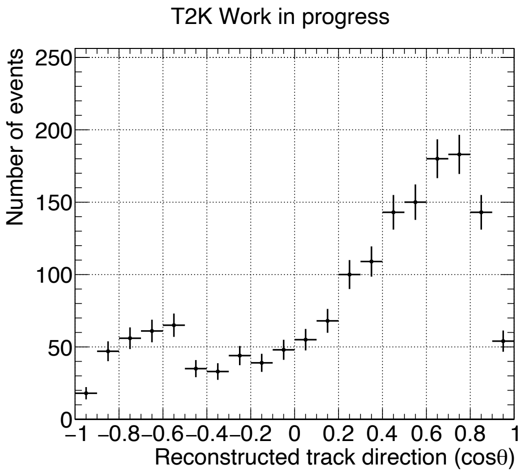
Work by J.Chakrani

Bragg peak





From a selected sample of proton tracks coming from outside the SuperFGD and stopping inside it.



Time calibration

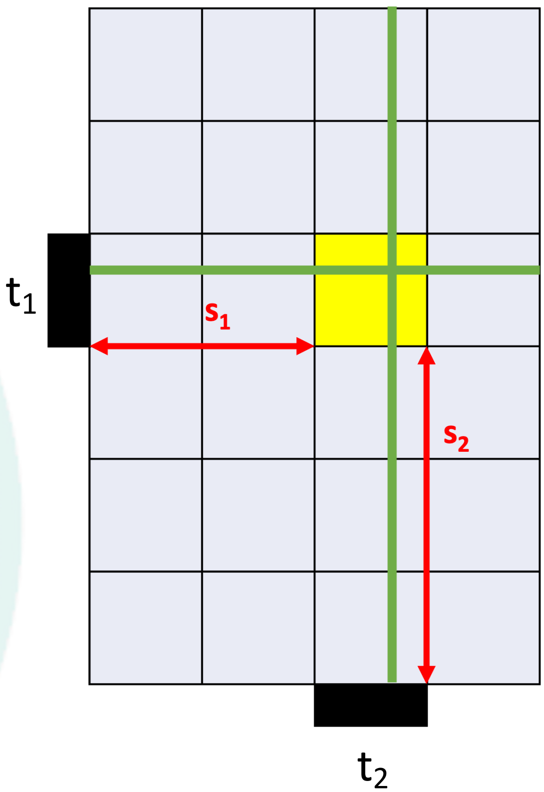
- Work with hit pairs time differences:

minimize

$$\Delta = t_1 - t_2 - (s_1 - s_2)$$

iteratively over all hits.

- At each iteration, correct the time of channel i by $\alpha \cdot \langle \Delta \rangle$
- The evolution of the time correction follows a **discrete Markov Chain**.



Time calibration

Vector of time offsets:

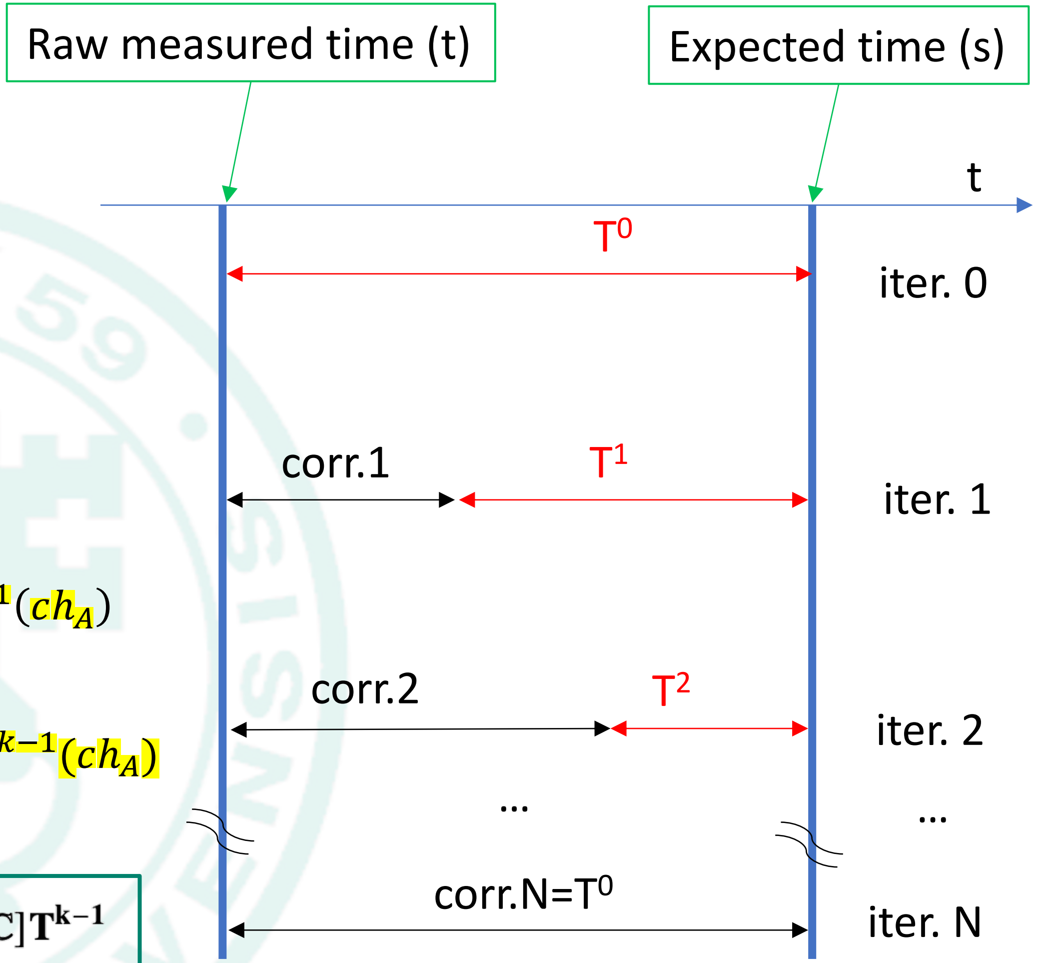
$$\mathbf{T^0} = \begin{pmatrix} T^0(ch_1) \\ T^0(ch_2) \\ \vdots \\ T^0(ch_{N_{ch}}) \end{pmatrix}$$

$$t^k(ch_A) = t^{k-1} - \alpha\Delta^{k-1}(ch_A)$$

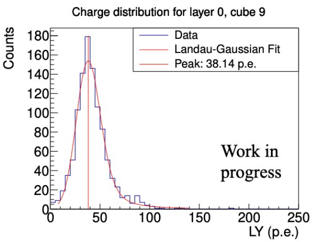
$$\Downarrow$$

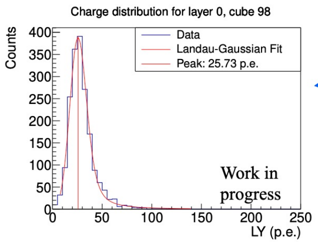
$$T^k(ch_A) = T^{k-1}(ch_A) - \alpha\Delta^{k-1}(ch_A)$$

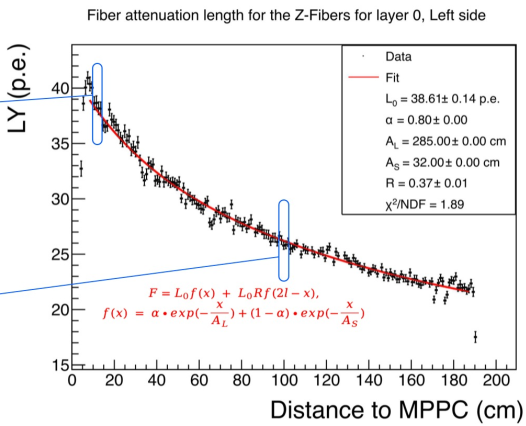
$$\mathbf{T^k} = M\mathbf{T^{k-1}} = [(1-\alpha)\mathbb{I} + \alpha\mathbb{C}]\mathbf{T^{k-1}}$$



Light attenuation and optical cross-talk







Light attenuation

- Fit the light yield as a function of the distance from MPPC
- Model attenuation + reflection

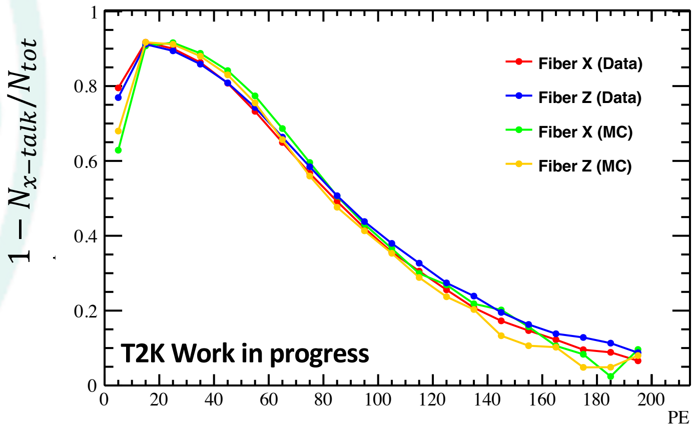
$$F = L_0\ [f(x) + R\ f(2l - x)]$$

$$\text{where } f(x) = \alpha\ e^{-x/A_L} + (1-\alpha)\ e^{-x/A_S}$$

Optical cross-talk

- Select hits surrounding a muon track: cross-talk generated
- Count number of cross-talk hits as a function of the track total charge
- Compatible with MC simulation with **3%** cross-talk.
- Electronics cross-talk is negligible

Number of cross-talk hits in a cosmic muon track



Work by B.Li, J.Hu

Electronics cross talk

- Electronics cross-talk happens only intra-ROC
- Affecting neighboring channels
- But effect below 0.5%: negligible