Super-FGD: an innovative scintillating target for near detectors

Jaafar Chakrani
On behalf of the T2K collaboration
Laboratoire Leprince-Ringuet (LLR)
<jaafar.chakrani@polytechnique.edu>

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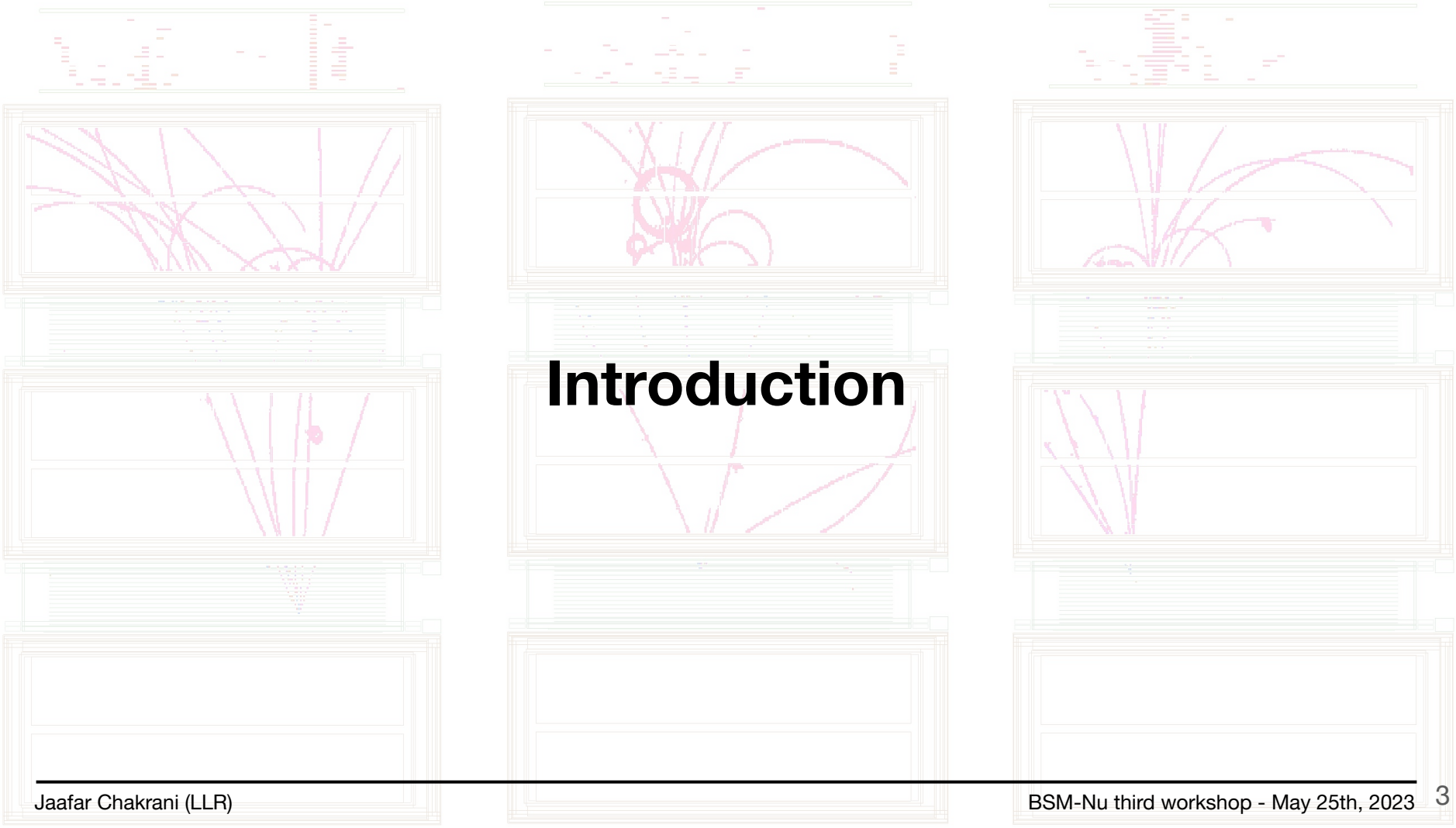
May 25th, 2022

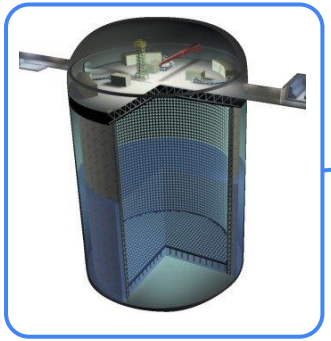
Outline

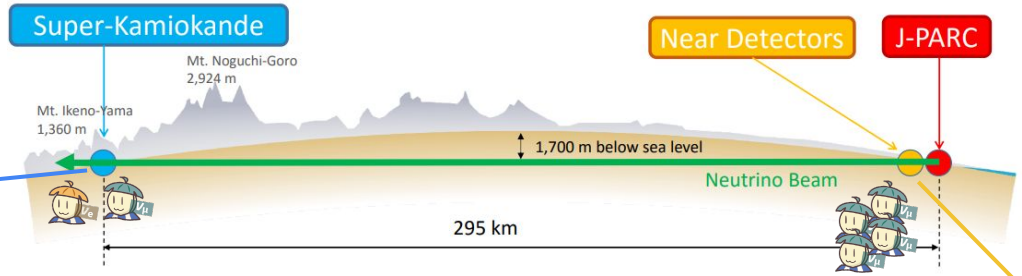
- Introduction
- T2K Near Detector Upgrade
- Super-FGD construction
- Super-FGD prototypes
- Expected physics performances
- Summary and prospects

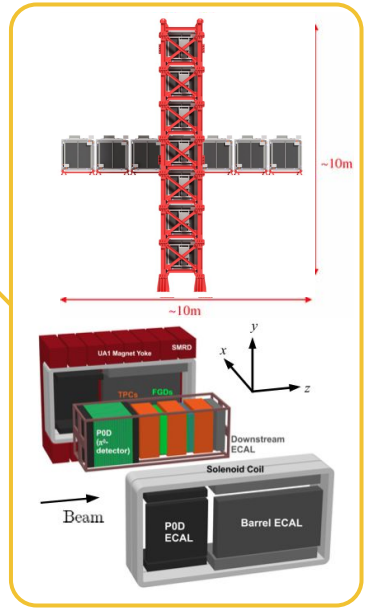


Introduction

T2K Experiment

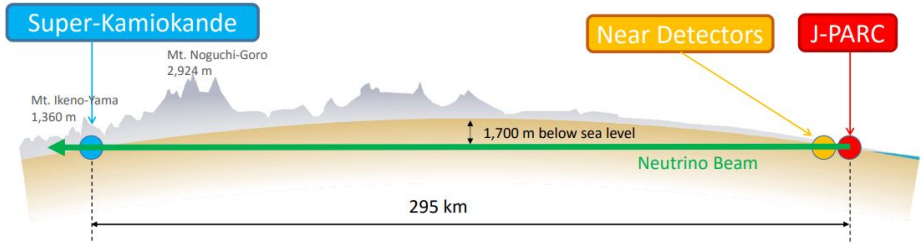






- Main goals:
  - Measure $\nu_e/\bar{\nu}_e$ appearance: sensitive to $(\delta_{CP}, \theta_{13})$
  - Measure $\nu_\mu/\bar{\nu}_\mu$ disappearance: sensitive to $(\theta_{23}, \Delta m^2)$
- How?
  - Produce an intense ν_μ (or $\bar{\nu}_\mu$) beam
  - Measure the unoscillated flux at the near detector complex to monitor the beam and constrain systematic uncertainties
  - Measure the oscillated flux at Super-Kamiokande

T2K Oscillation Analysis strategy



Flux model | Detector model | Neutrino interaction model

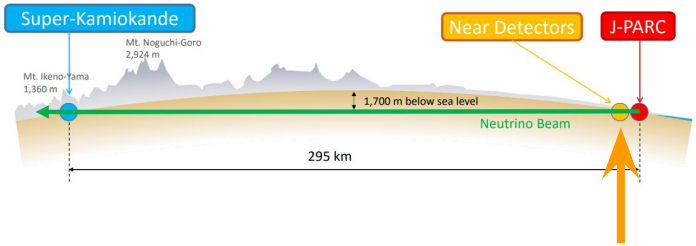
$$N^{ND}_{\nu_\alpha}(E_\nu) = \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu)$$

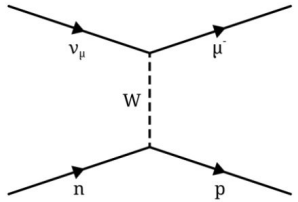
$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

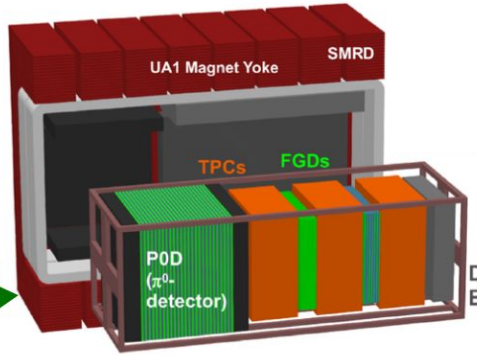
- Far/Near ratio does not fully cancel systematic uncertainties, *e.g.*:
  - Flux model different at ND vs. FD due to geometry and oscillation
  - Different detectors, *i.e.* different acceptance and efficiencies
  - Mainly $\nu_\mu(\bar{\nu}_\mu)$ at ND interacting with CH → use model to infer interactions of $\nu_\mu/\nu_e(\bar{\nu}_\mu/\bar{\nu}_e)$ on H_2O

↪ **T2K's approach is to propagate the constraints on the flux and the neutrino interaction models from the ND to the FD**

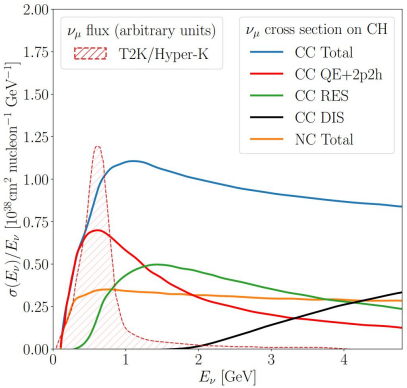
Off-axis Near Detector at 280m (ND280)

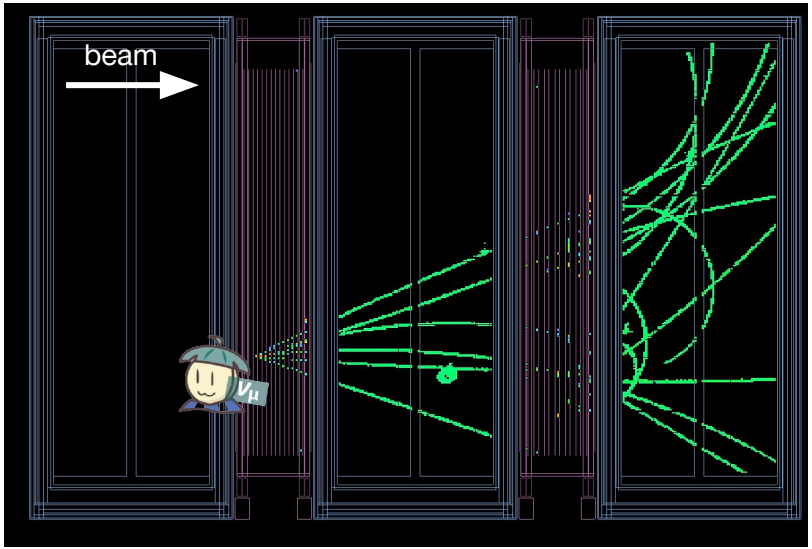






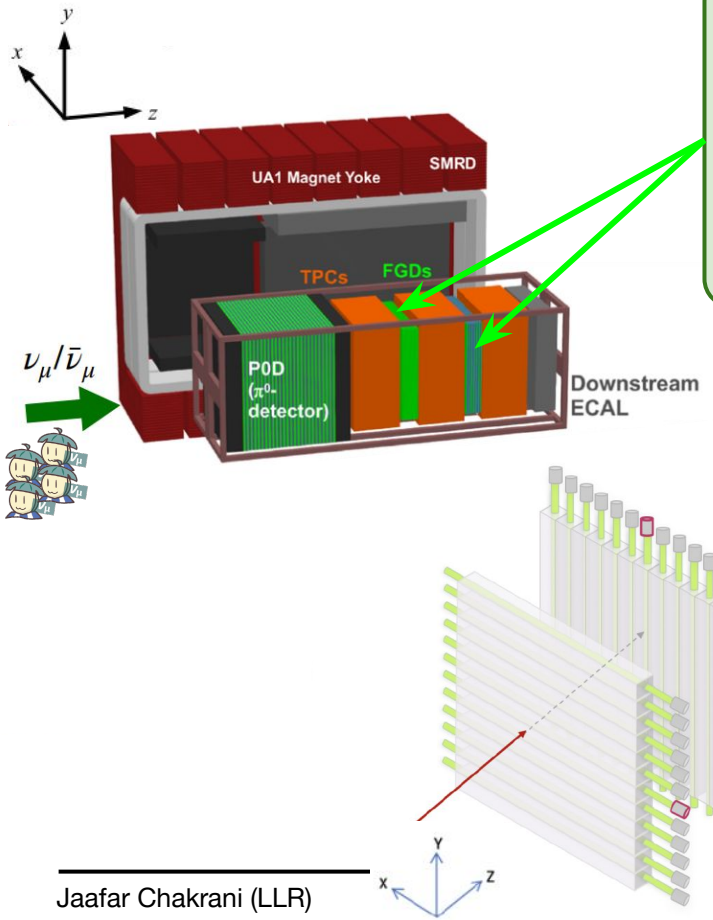
$\nu_\mu / \bar{\nu}_\mu$





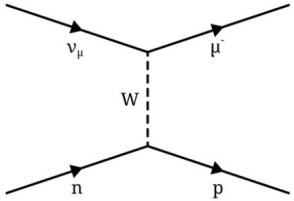
Deep Inelastic Scattering event display

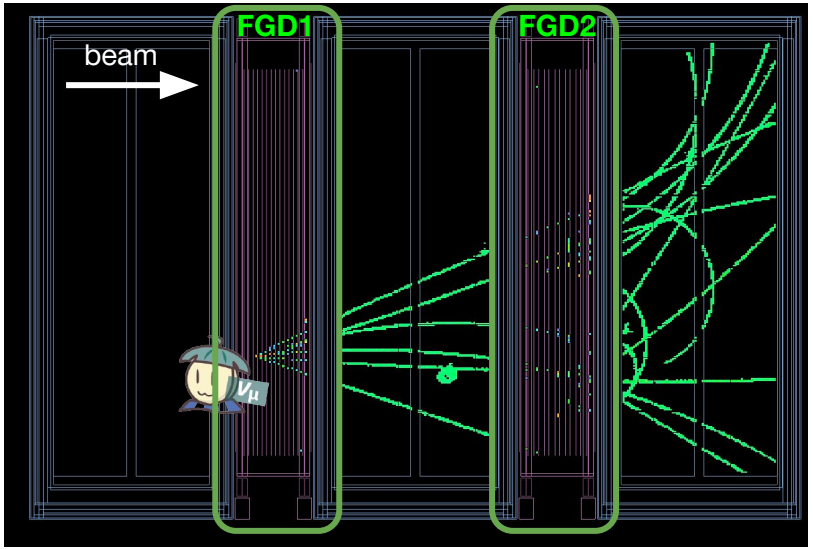
Off-axis Near Detector at 280m (ND280)



Fine Grained Detectors (FGDs):

- Plastic scintillator tracker
- Target for neutrino interactions
- FGD2 has water target layers





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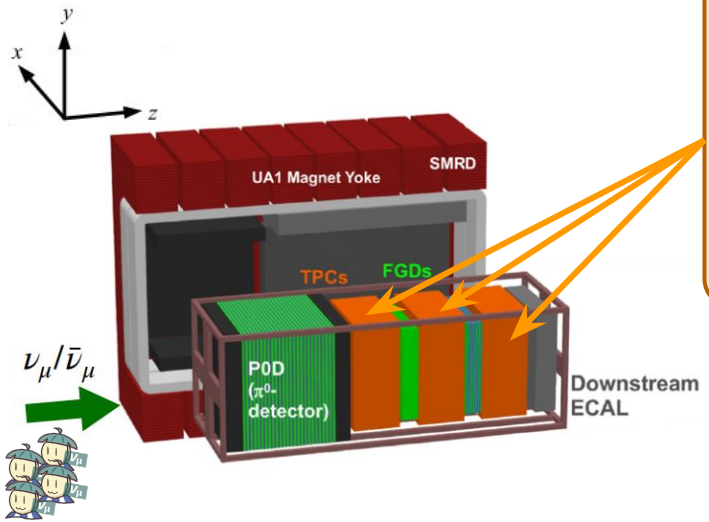
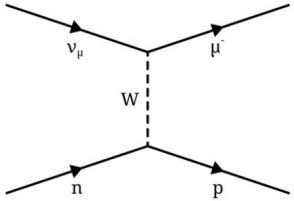
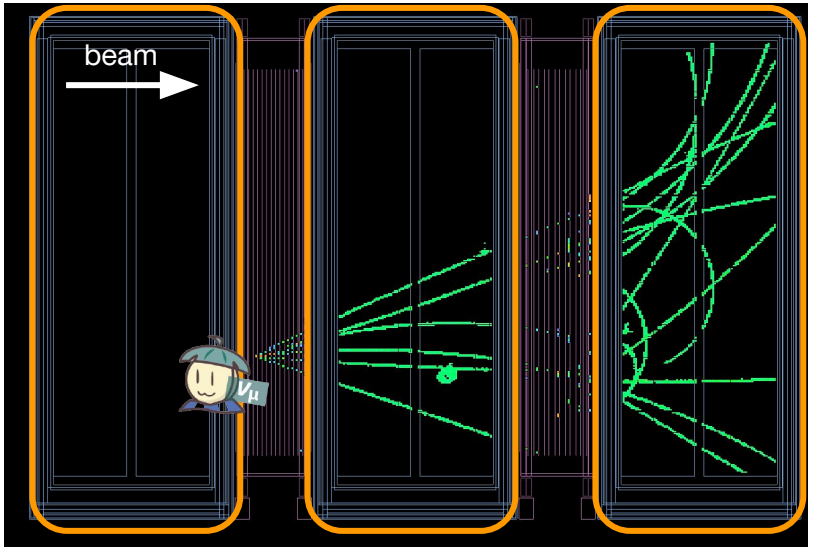


Time Projection Chambers (TPCs)

- Tracking detectors
- Charged particle momentum
- Particle ID



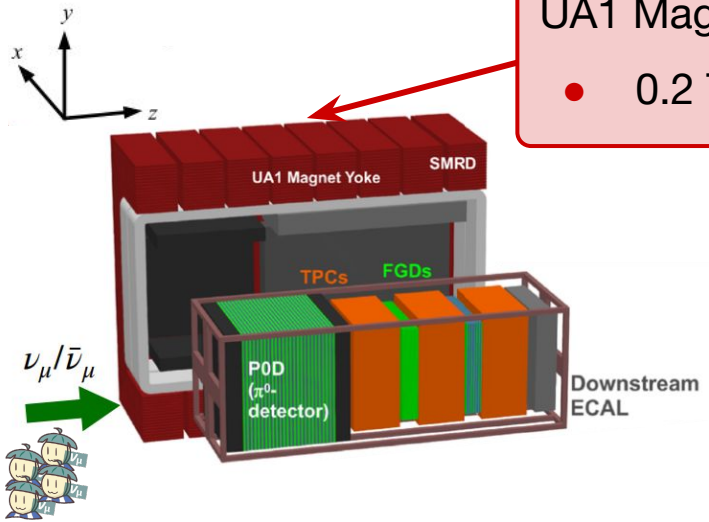


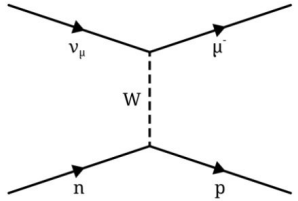
Deep Inelastic Scattering event display

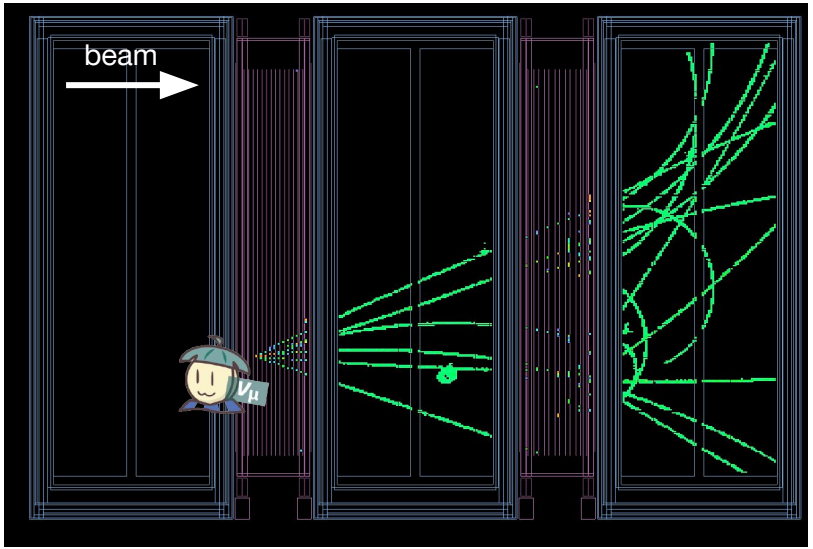
Off-axis Near Detector at 280m (ND280)

UA1 Magnet:

- 0.2 T magnetic field for charge identification







Deep Inelastic Scattering event display

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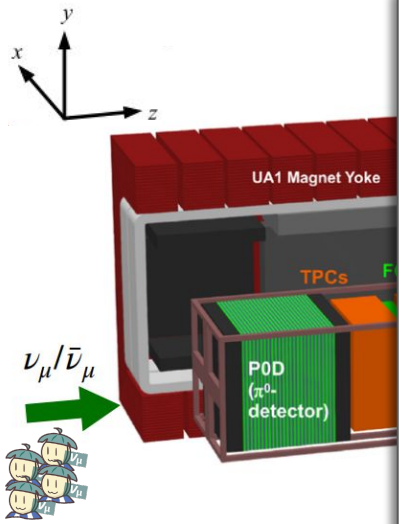

T2K Oscillation Analysis strategy

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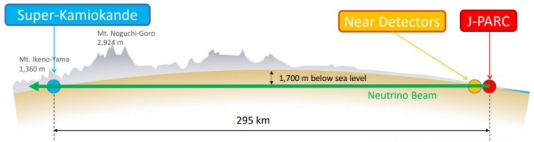

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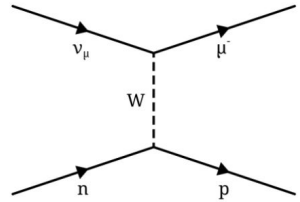
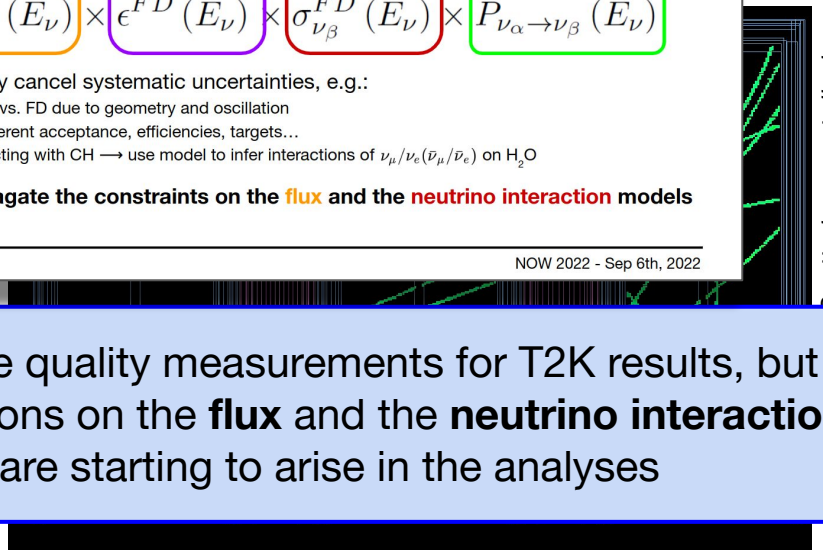
Jaafar Chakrani (LLR) NOW 2022 - Sep 6th, 2022



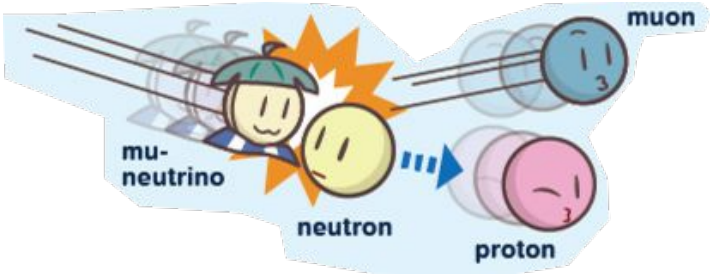


Scattering event display

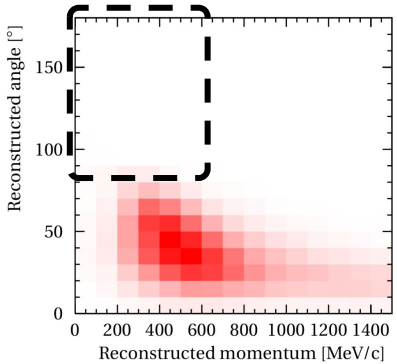
ND280 has been able to provide quality measurements for T2K results, but with the **increasing statistics** its limitations on the **flux** and the **neutrino interaction model uncertainties** are starting to arise in the analyses

Limitations of current ND280

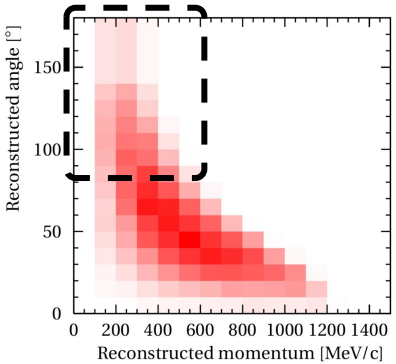
- Non-isotropic efficiency (unlike Super-Kamiokande)
- High momentum proton threshold (~450 MeV/c)
- For the oscillation analysis, neutrino interactions are characterized in **muon kinematics only**



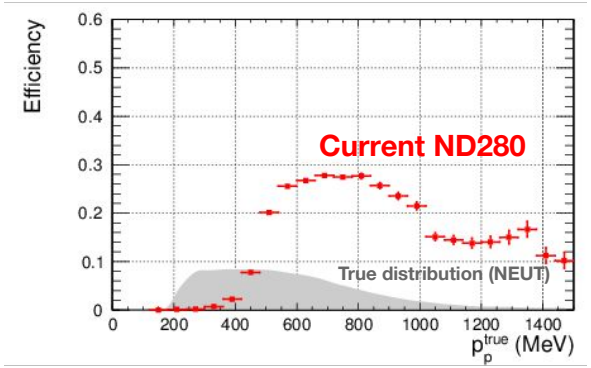
Muon neutrino events at ND280



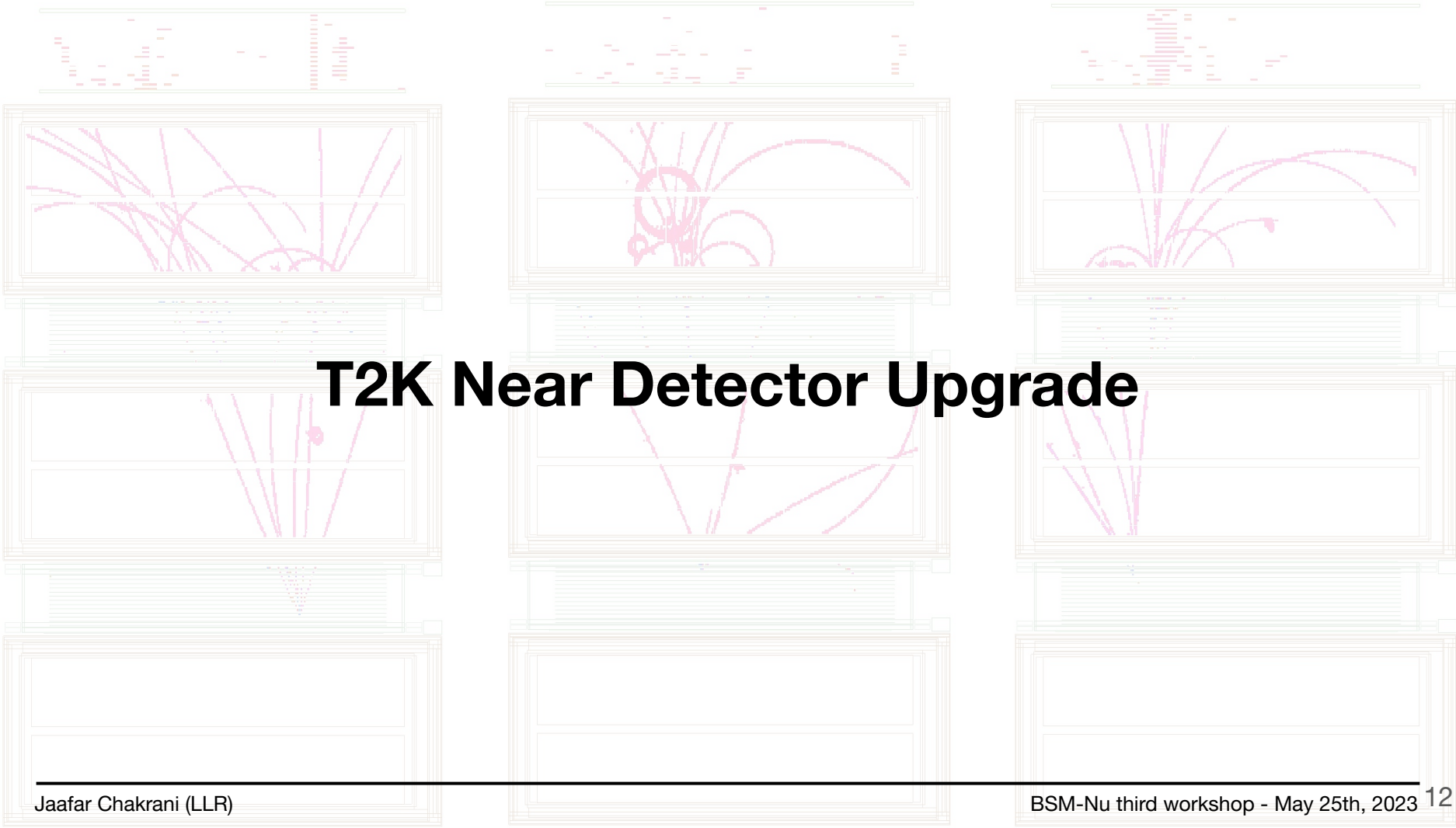
Electron neutrino events at Super-K



Proton detection efficiency



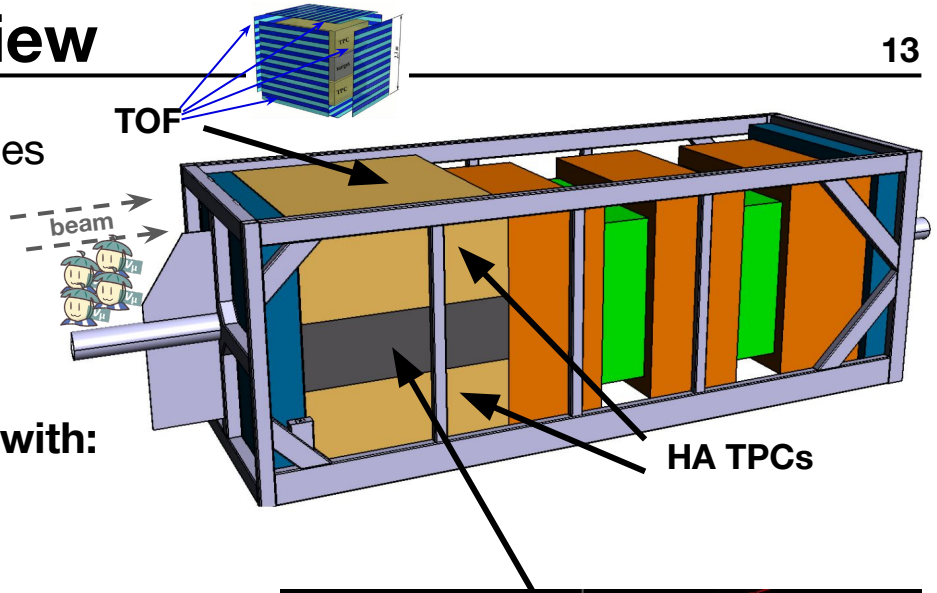
⇒ T2K is currently upgrading ND280 to overcome these limitations



T2K Near Detector Upgrade

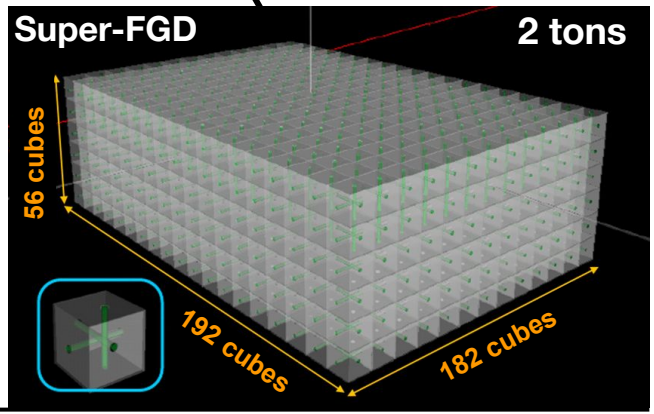
T2K ND280 Upgrade Overview

- Super-FGD: 2.10^6 1 cm^3 scintillator cubes
- New high-angle TPCs
- New Time Of Flight detector

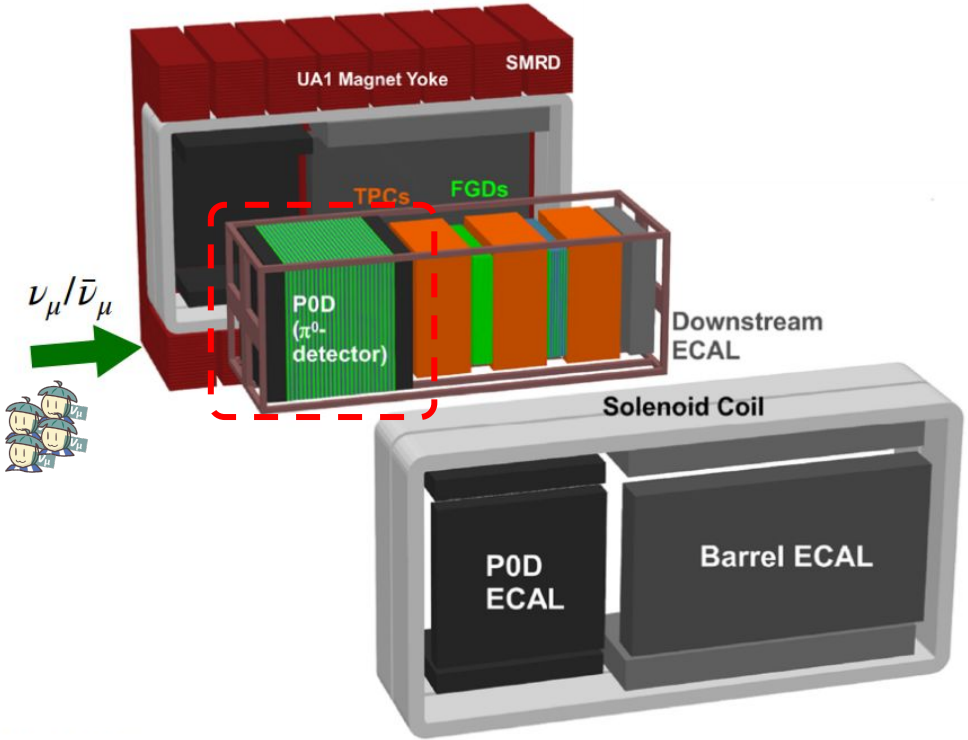


The goal is to reduce the ND systematics with:

- Fully active target
- 4π acceptance for charged particles
- Lower proton momentum threshold (~300 MeV/c)
- Neutron kinematics reconstruction
- Larger statistics



T2K ND280 Upgrade Overview



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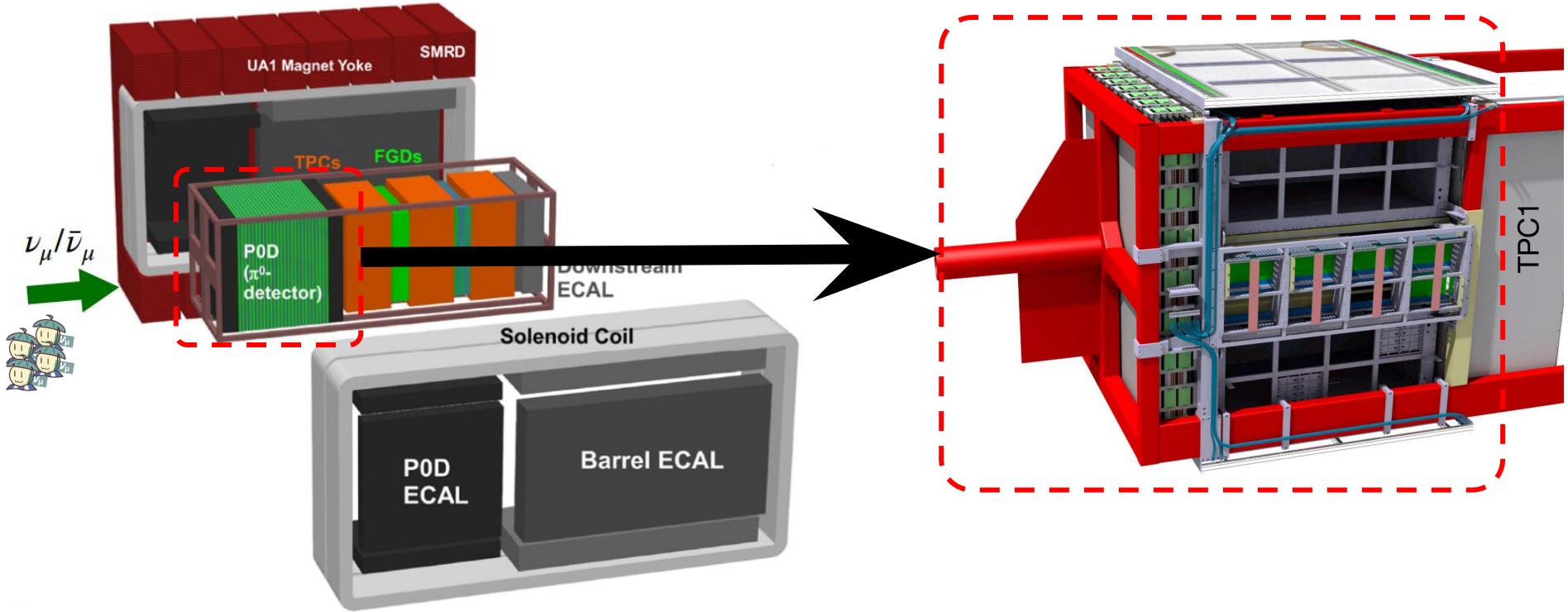

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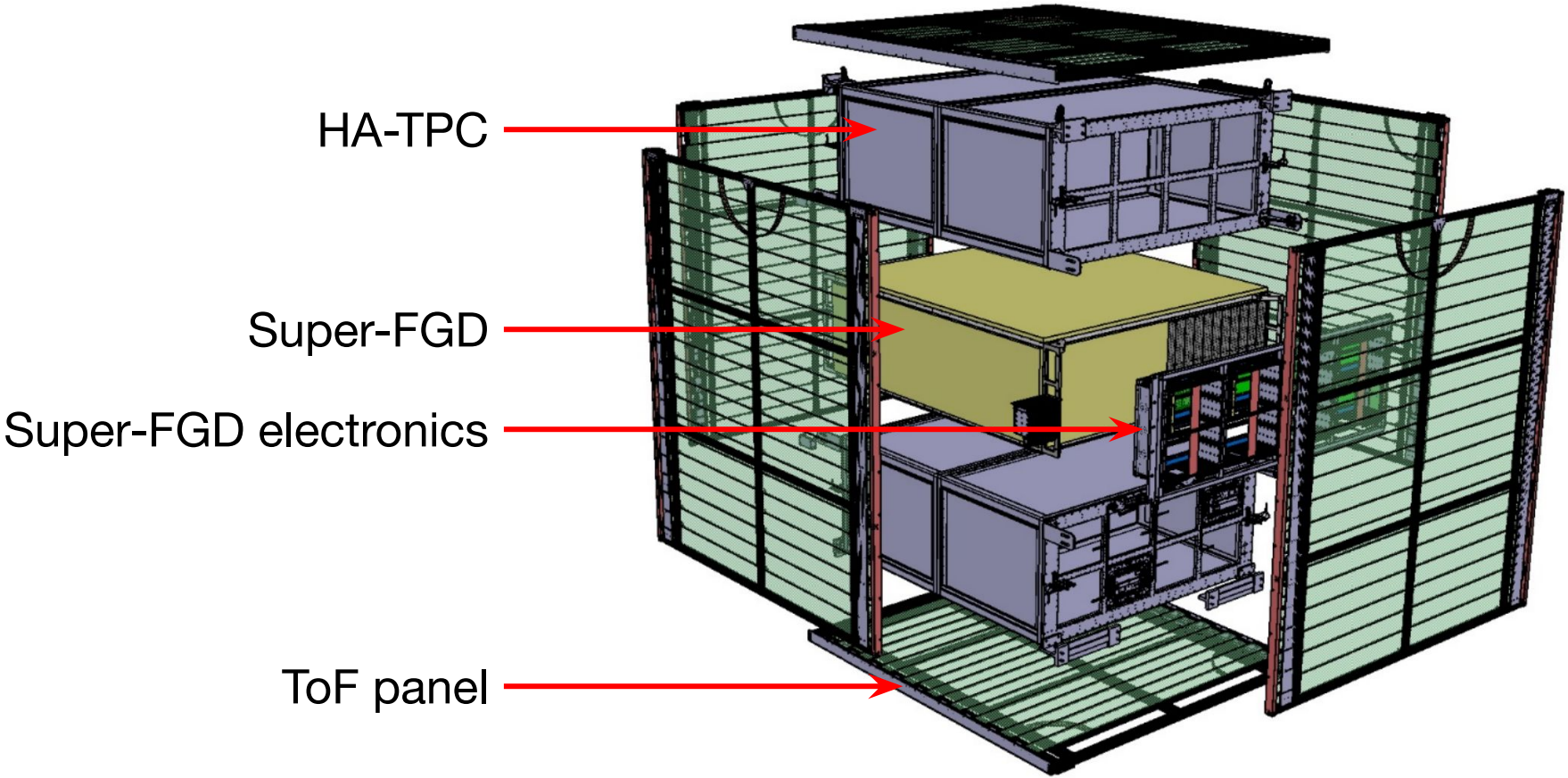
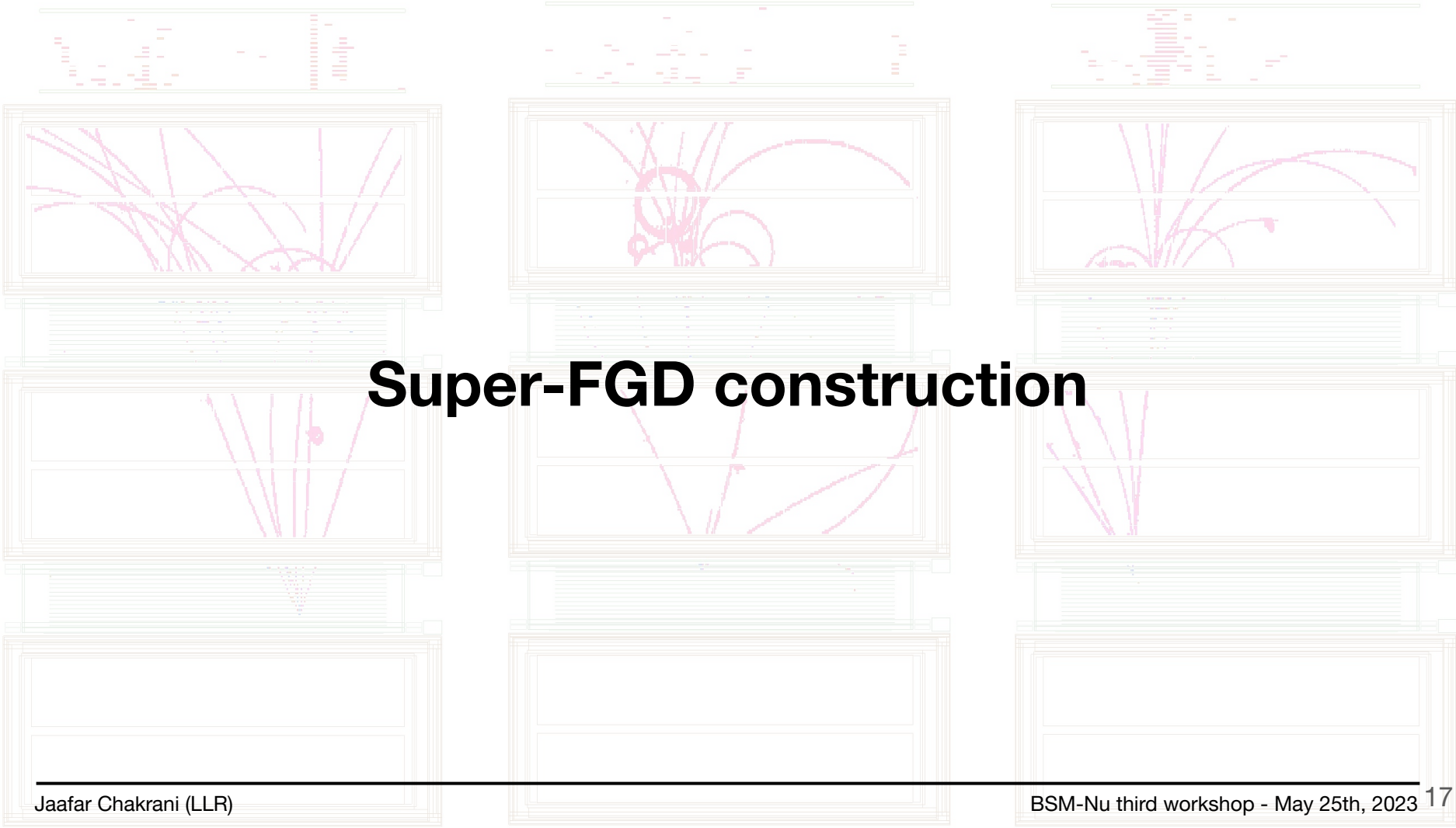


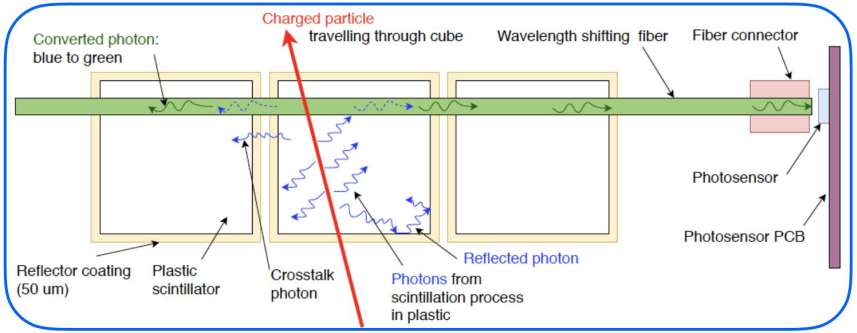


Super-FGD construction

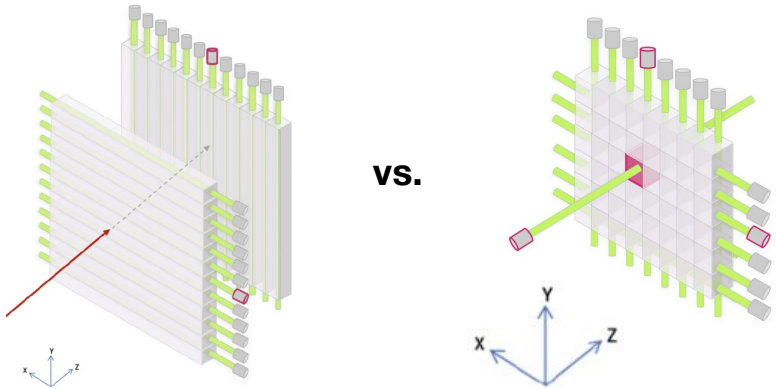
Super-FGD

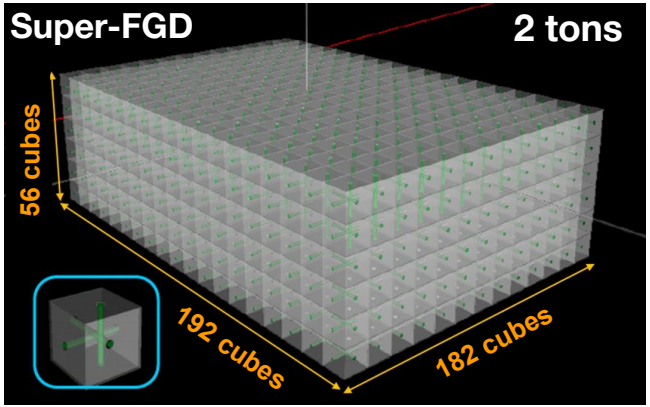
JINST 13 P02006 (2018)

- ~2 million 1x1x1 cm3 cubes made of plastic scintillator ⟶ ~2 tons
- Cubes covered by reflector will be read out with 3 orthogonal WLS fibres each with MPPC on one end
  ⟶ total of 56,382 fibers



FGD1&2 vs. **Super-FGD**

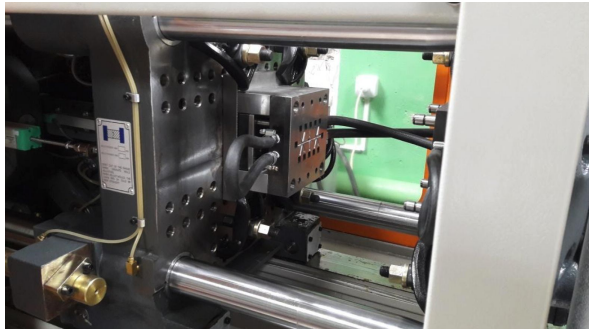




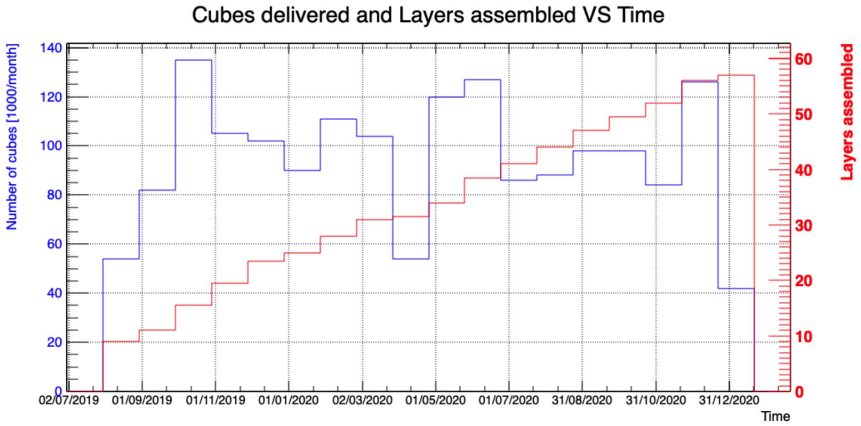
Cube production and pre-assembly

- The production of the 2 million cubes was done by Uniplast (Vladimir, Russia), with a rate of **~100,000 cubes/month**, and took over 1.5 years

Compound of polystyrene + paraterphenyl loaded in this tank



~500 cubes/hour



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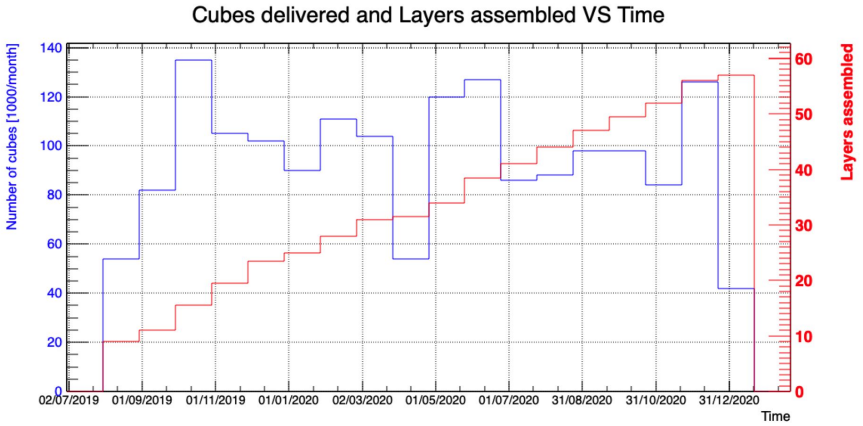

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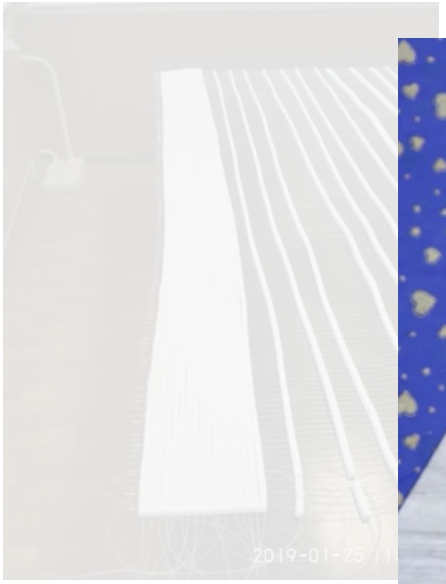
https://www.wikihow.com/Make-a-Beaded-Bracelet



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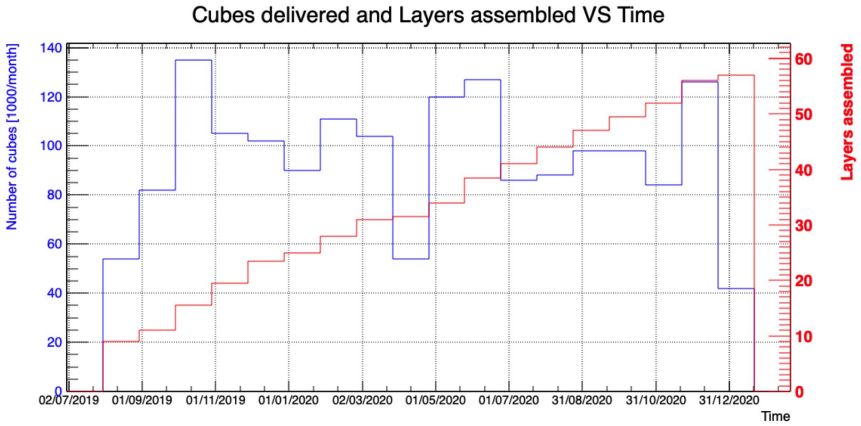

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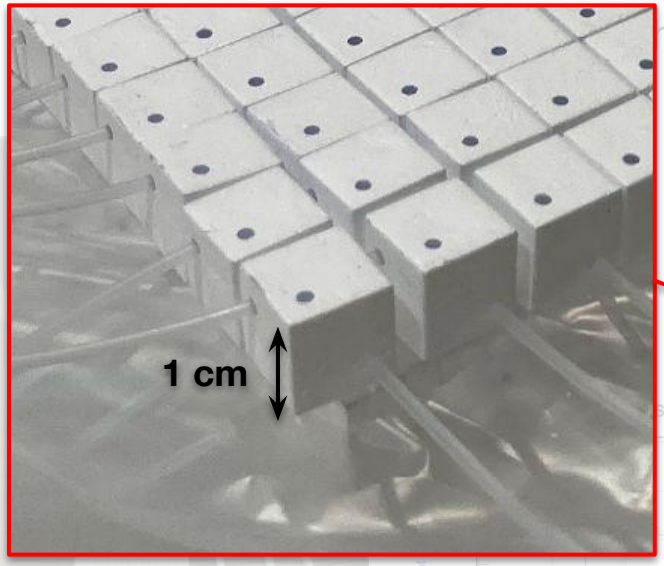

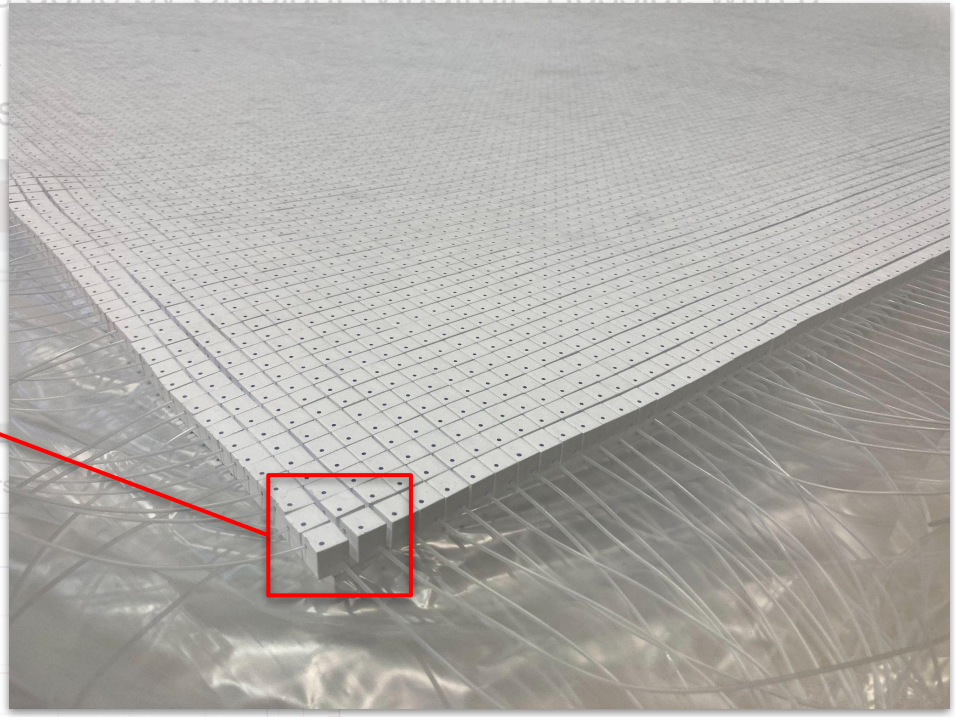

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- As the cubes were delivered, they were assembled **layer by layer** using fishing lines after quality checks
- The pre-assembled layers were shipped in two boxes to J-PARC by plane

The (empty) wooden shipment box weighs 500 kg

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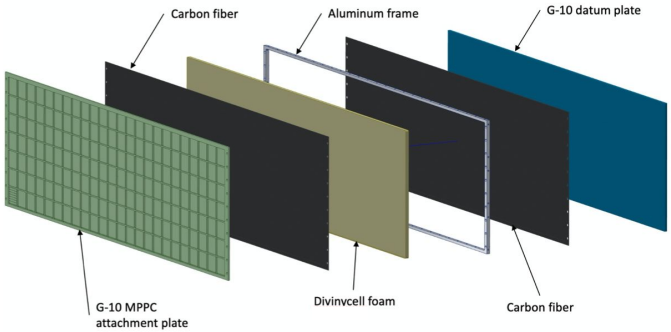
- In the meantime, the Super-FGD box was being designed


Empty Super-FGD box



Super-FGD assembly

1. Insert the 2 million cubes in the Super-FGD box layer by layer

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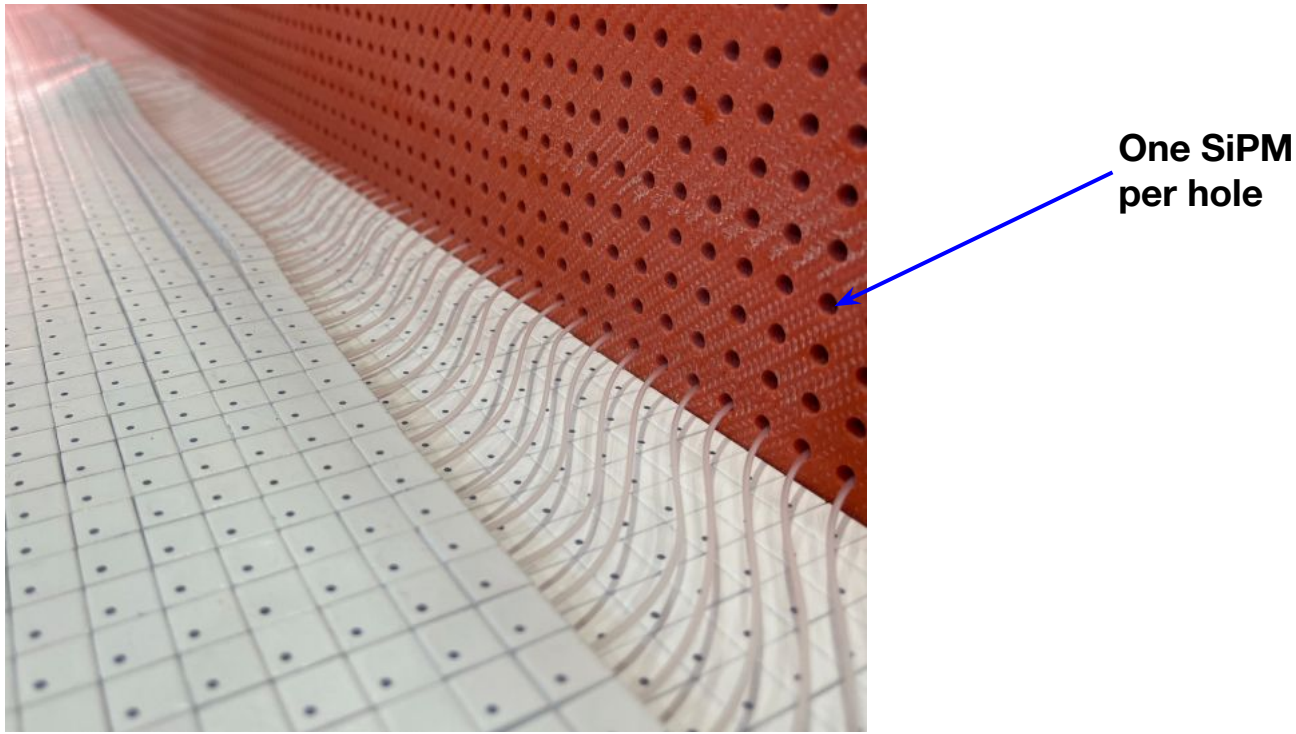
2. Insert the fishing lines in the corresponding holes of the Super-FGD box for each layer



Super-FGD assembly

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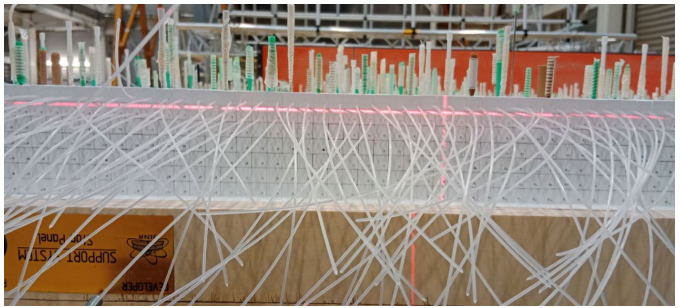
3. Ensure vertical alignment with vertical metal “rods” for each added layer



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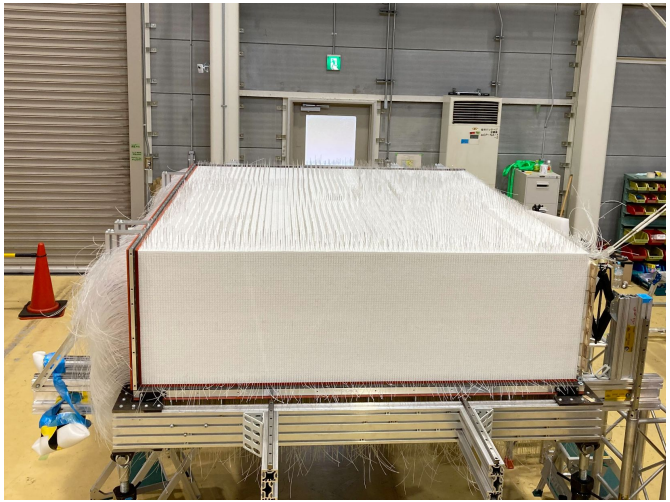

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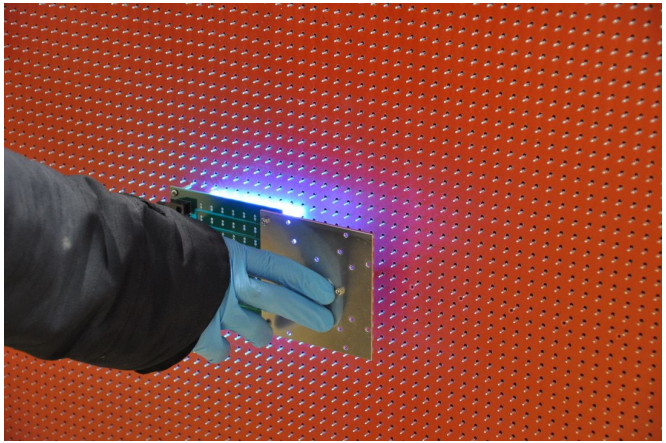

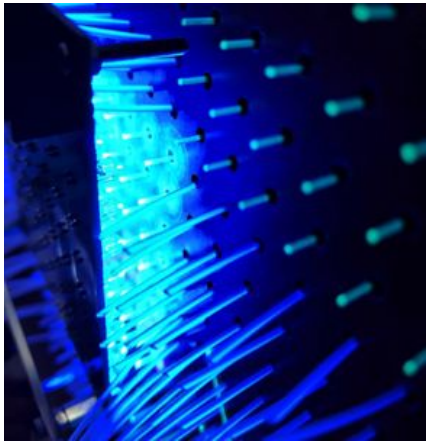

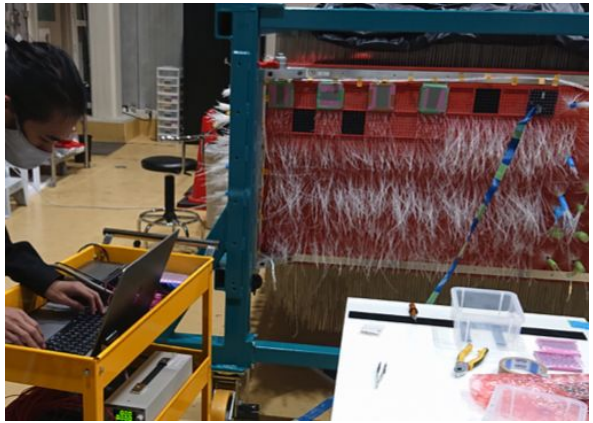

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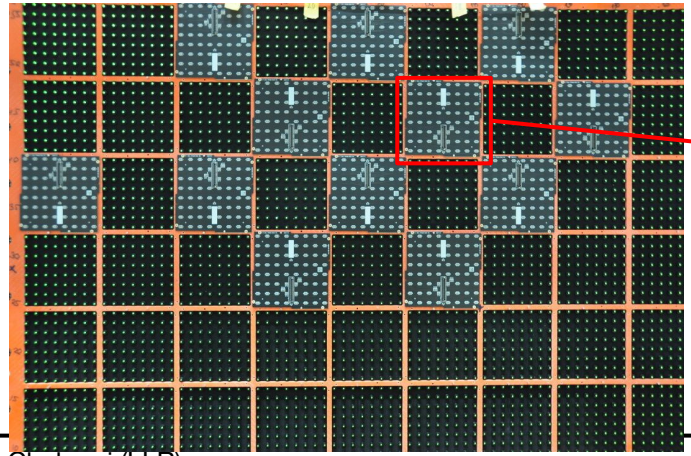

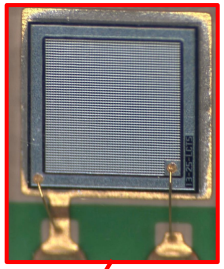

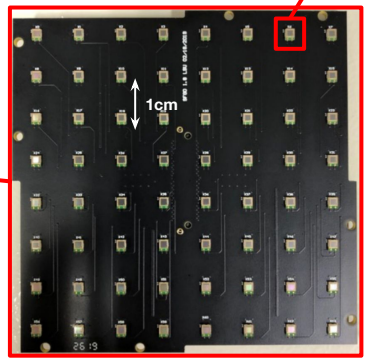

MPPC64 board

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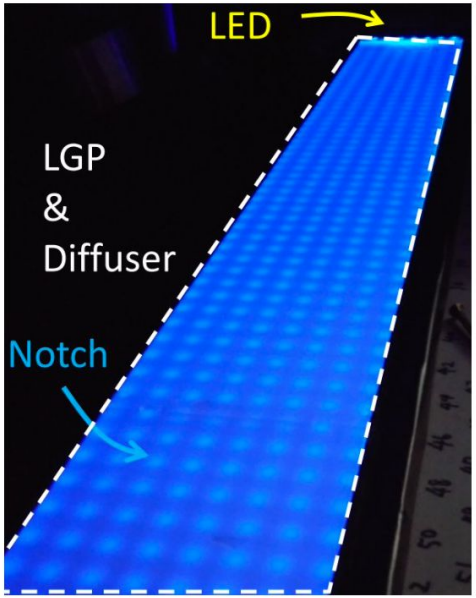

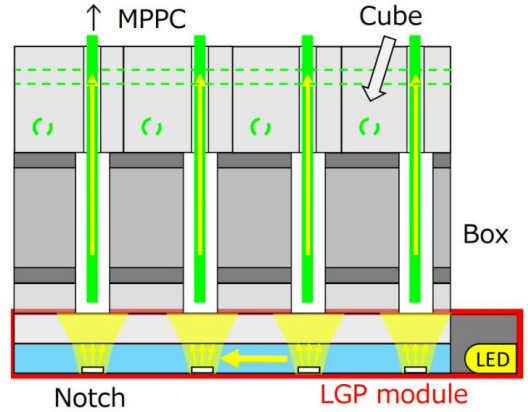

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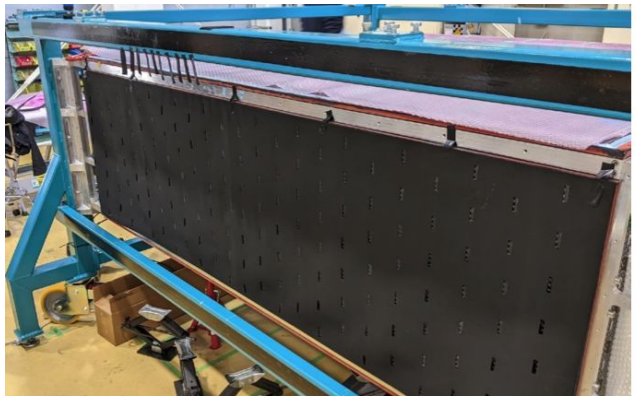

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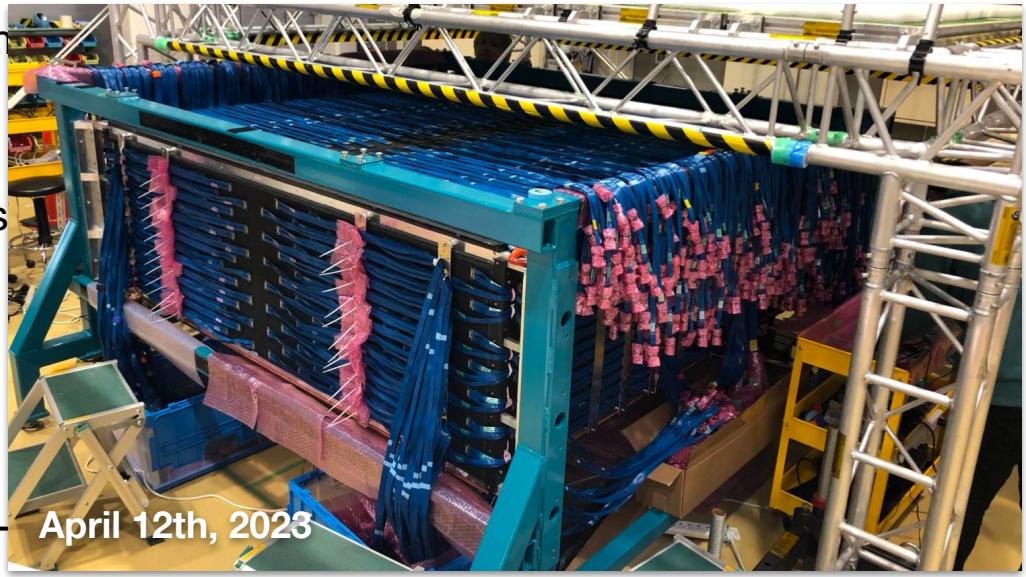

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8. Install LED calibration system
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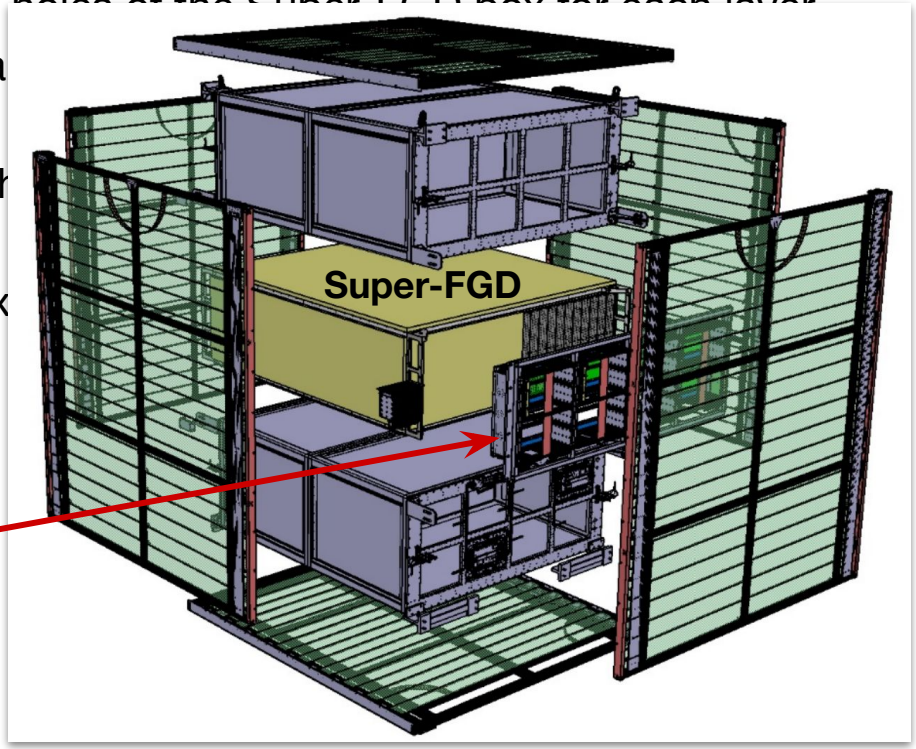
10. Attach cables on the MPPC64 boards
11. Install readout electronics (ongoing…)



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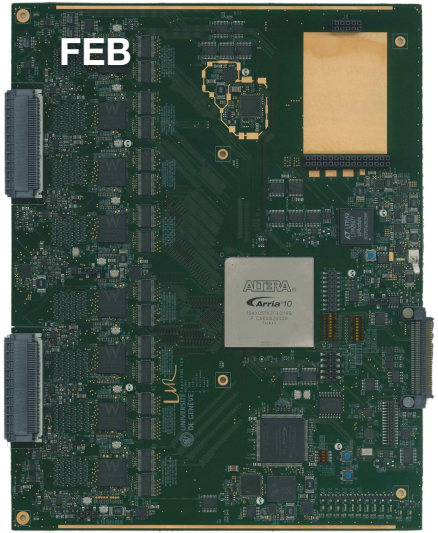

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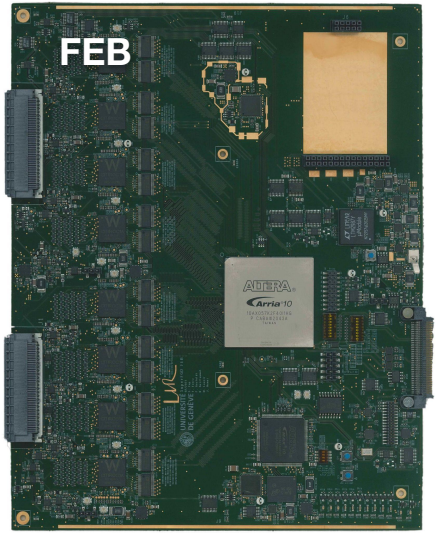

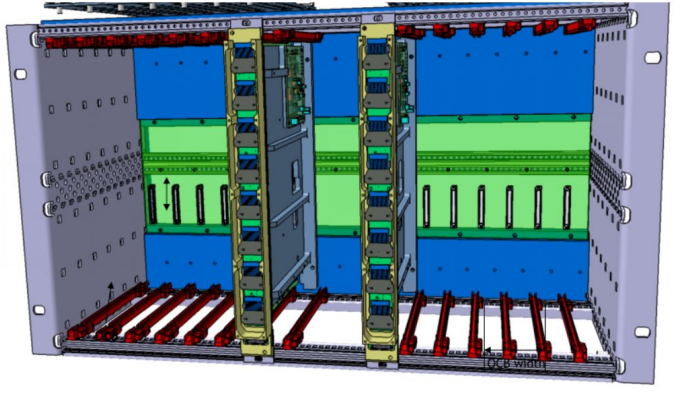

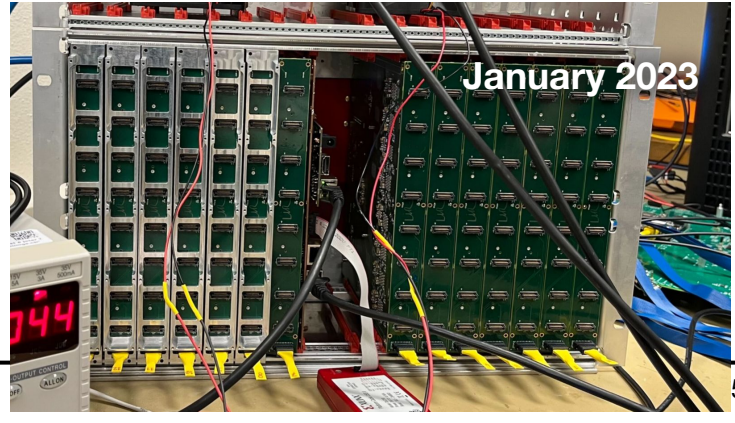

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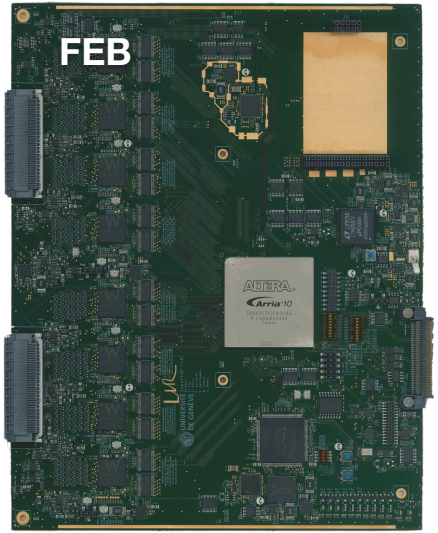

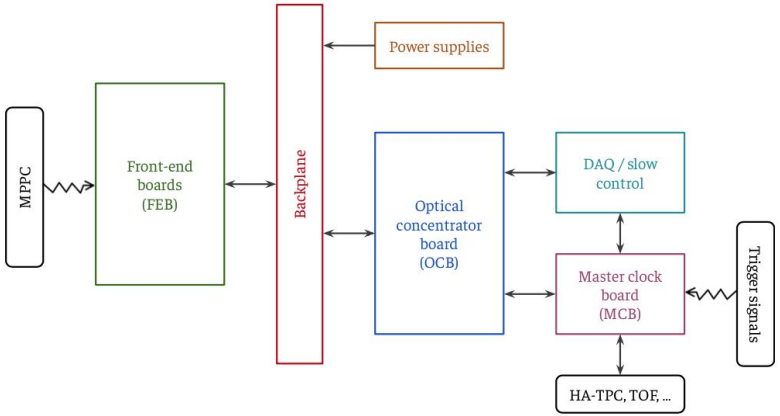

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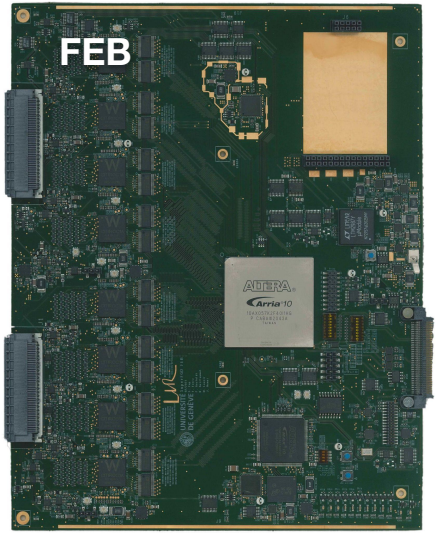

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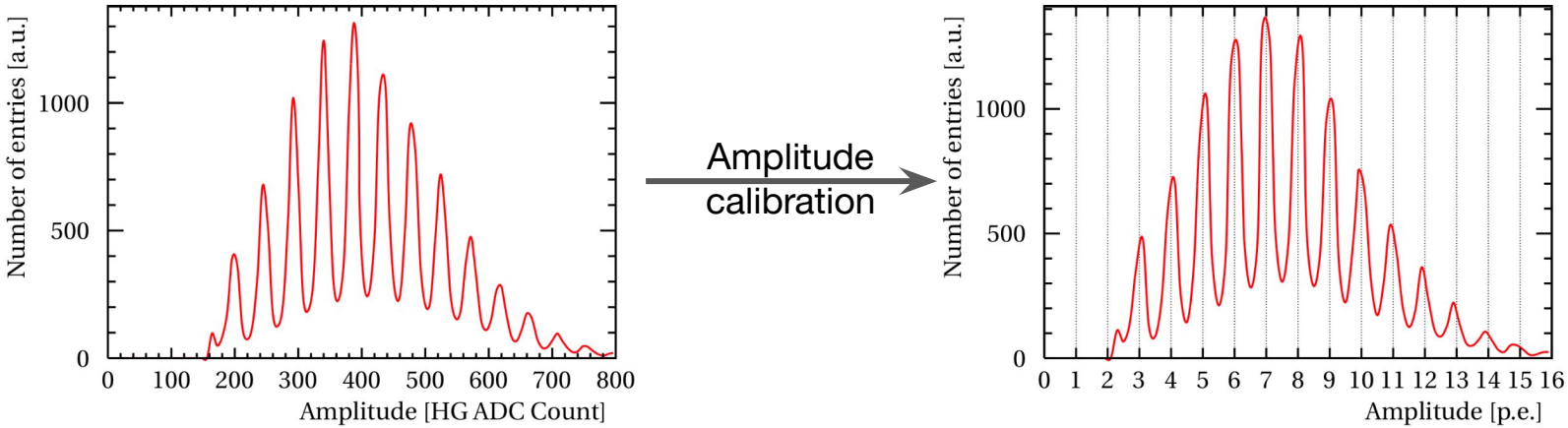
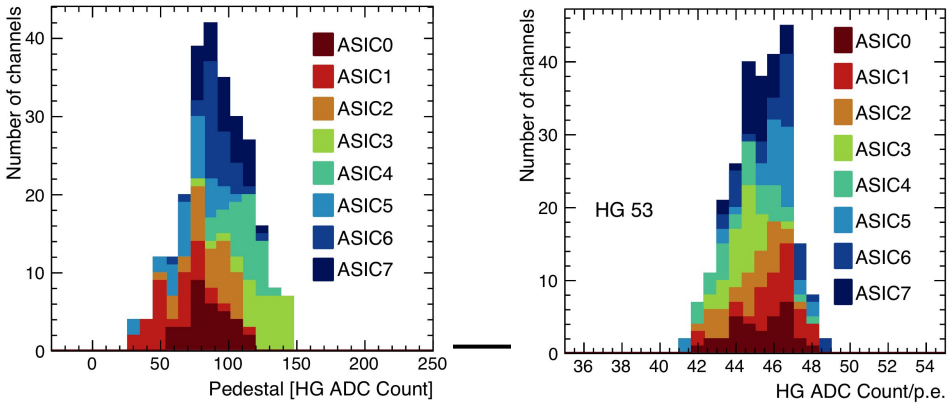
  - A series of intermediate boards allow to distribute the power, send the beam trigger, configure the FEBs, preprocess data, …
- Before launching the production of the FEBs, various performance tests were performed on prototypes to validate the final design

FEB tests

- Charge readout in all the 256 channels and basic calibration (pedestal, gains, etc.)





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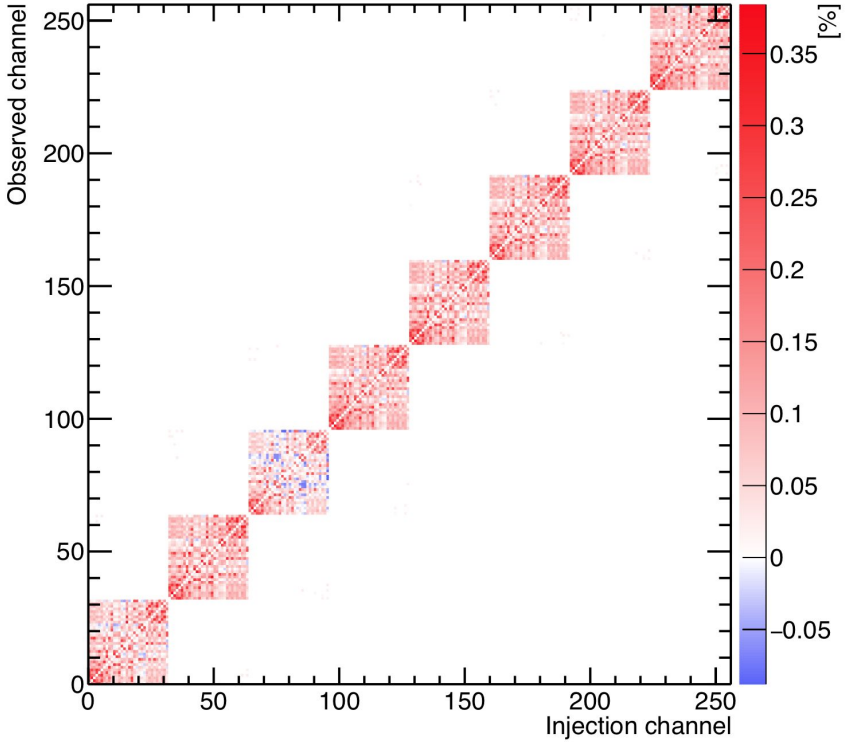

FEB tests

- Charge readout in all the 256 channels and basic calibration (pedestal, gains, etc.)
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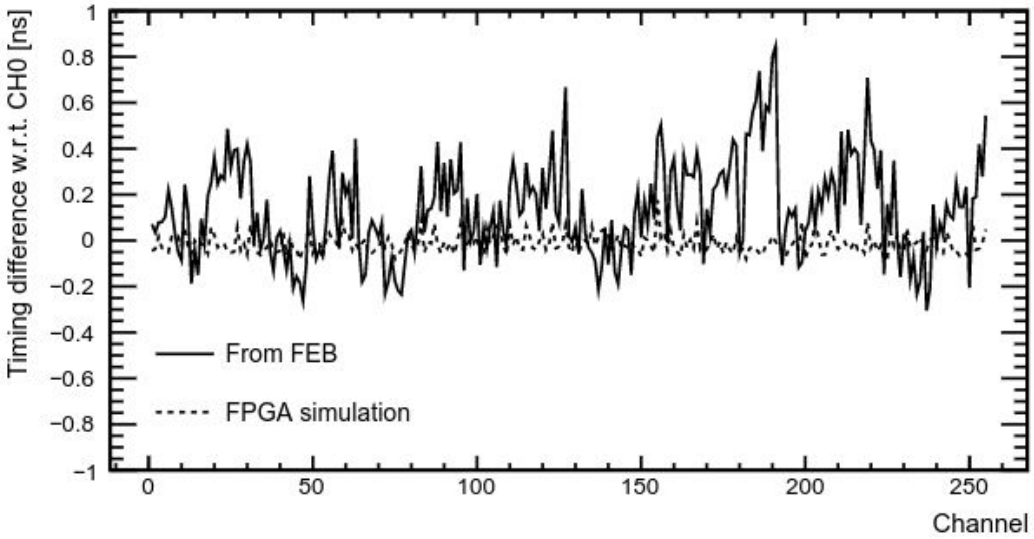

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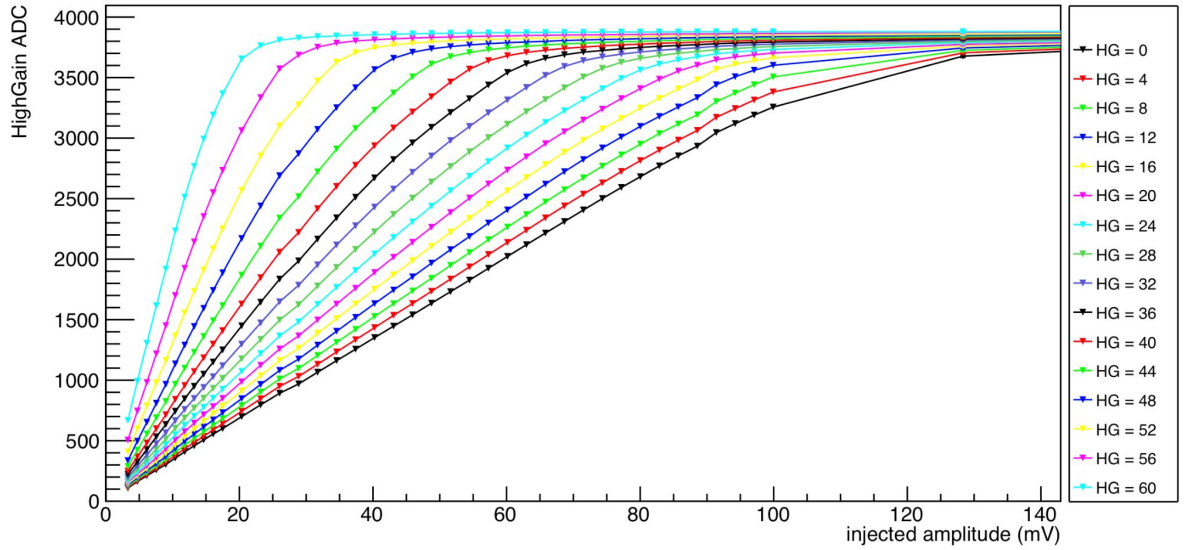

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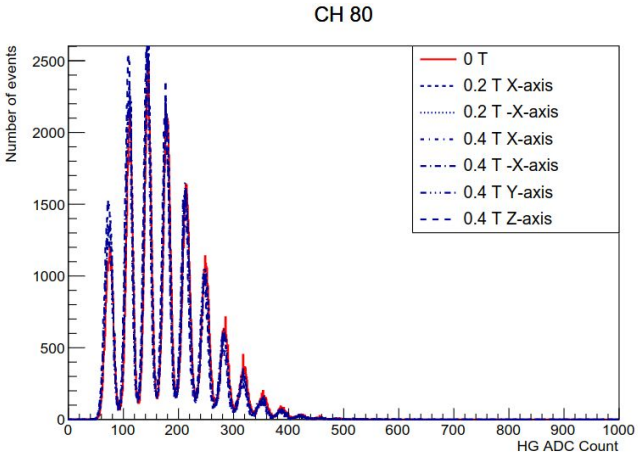

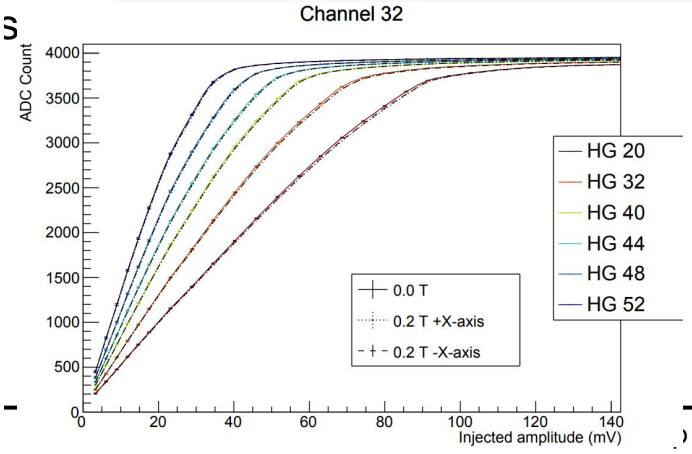

FEB tests

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- Channel-to-channel timing differences (will be calibrated in the actual Super-FGD setup)
- Linearity of the FEB response
- Impact of the 0.2-T magnetic field in the orientations expected in the Super-FGD setup

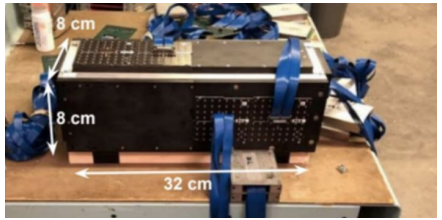
- Satisfactory performances with minimal changes to the design
  ⟹ **Green light for mass production**
- Installation expected during this summer

Prototypes of the Super-FGD

Super-FGD prototypes

- Multiple beam tests with prototypes have been performed to confirm the Super-FGD concept:

Super-FGD prototype (8x24x48 cm)



US-Japan prototype (8x8x32 cm)

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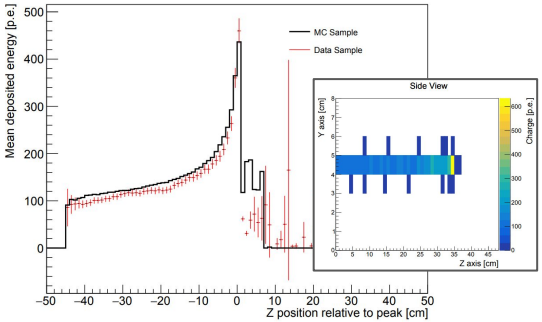
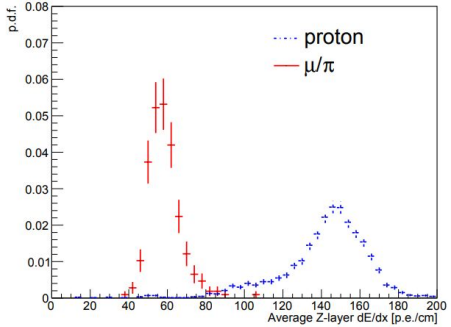
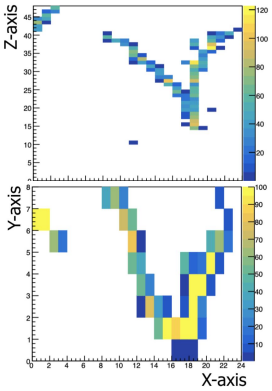


dE/dx measured for different particles



Electron-gamma separation



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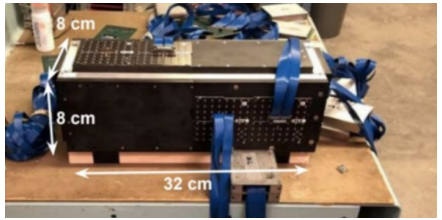

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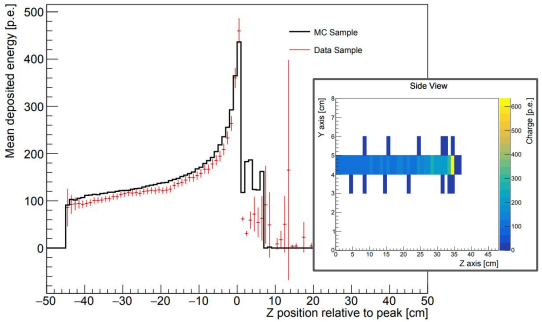

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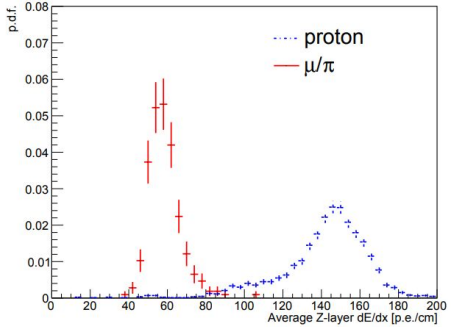

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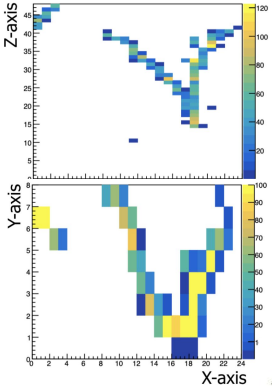

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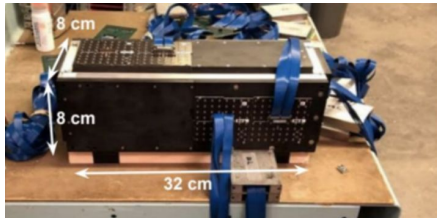
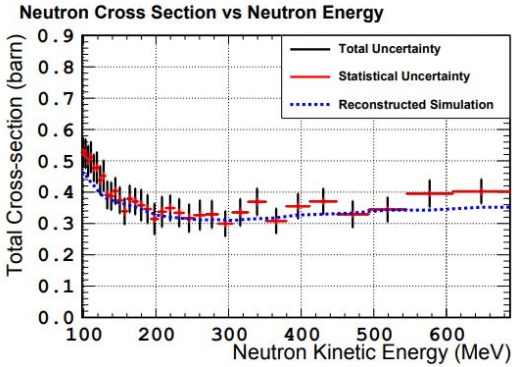


US-Japan prototype (8x8x32 cm)

  - At LANL with neutrons: arxiv:2207.02685
    - Measurement of the total cross section as a function of the neutron kinetic energy using event rate depletion along the beam axis: $N(z) = N_0 e^{-T\sigma_{\mathrm{tot}} z}$



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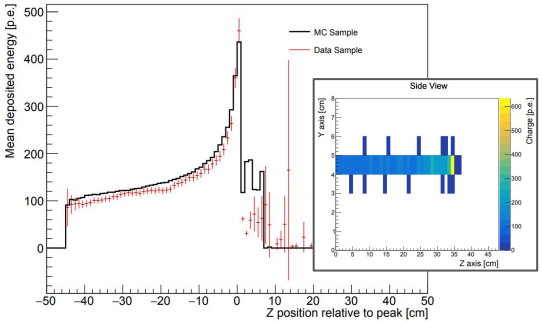

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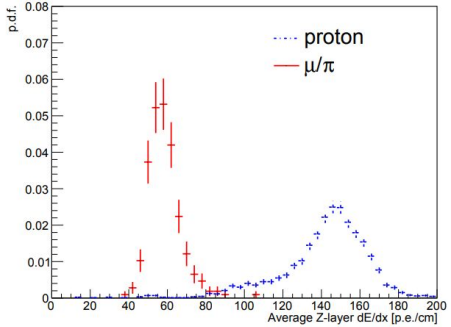

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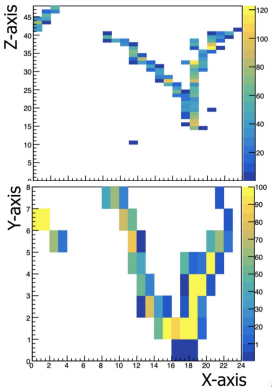

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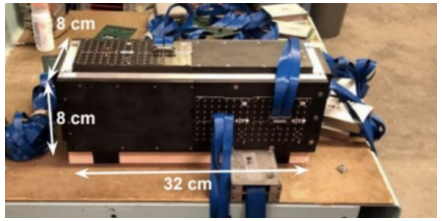

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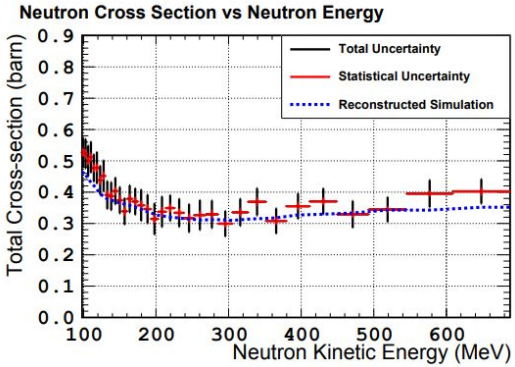
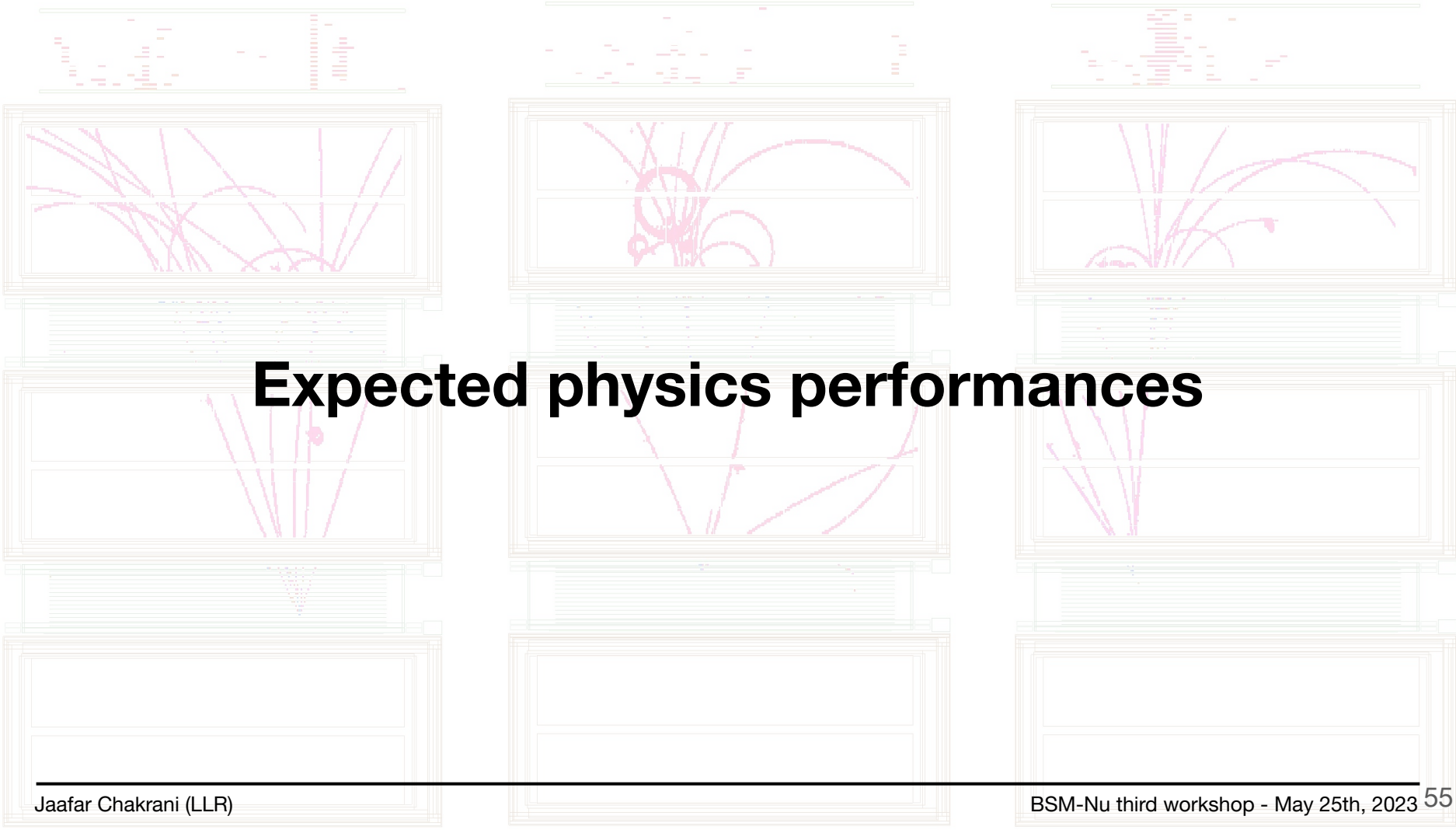


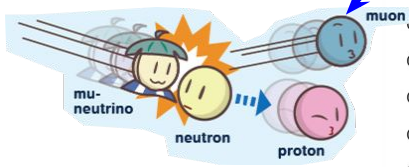
↪ **The tests show that the Super-FGD concept is promising!**

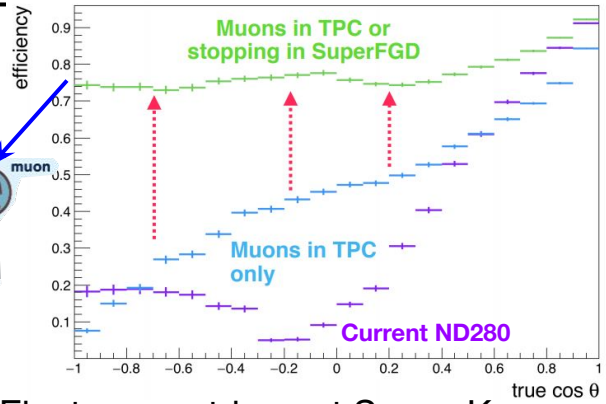


Expected physics performances

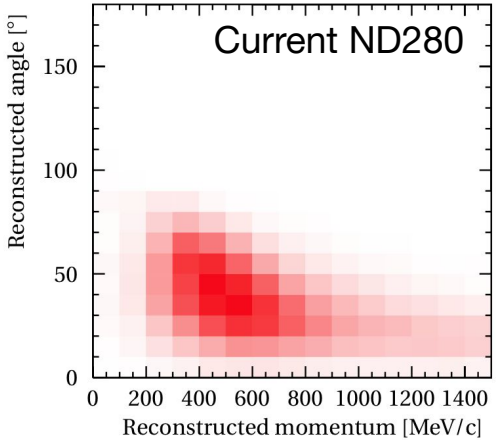
Expected performances

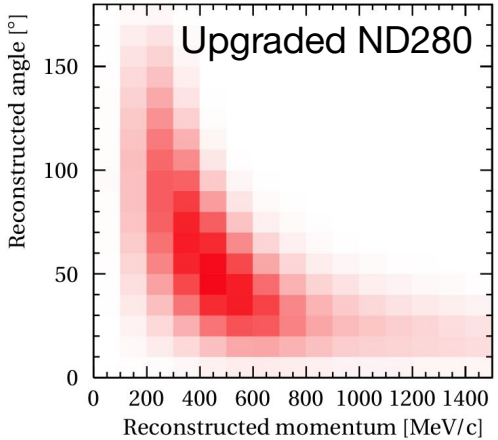
- Improved reconstruction at high and backward angles
  ⟶ better constraints on the neutrino interaction model



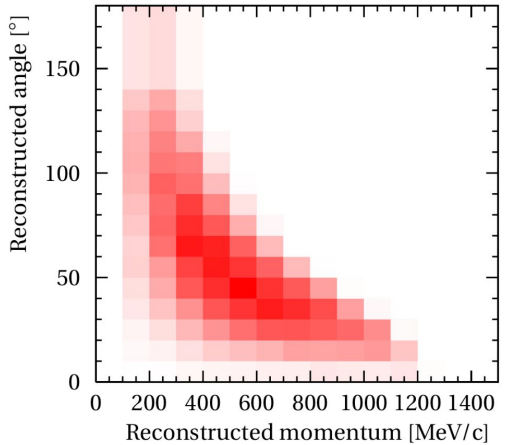


Muon neutrinos at ND280



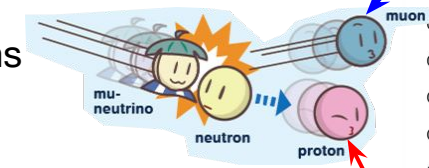


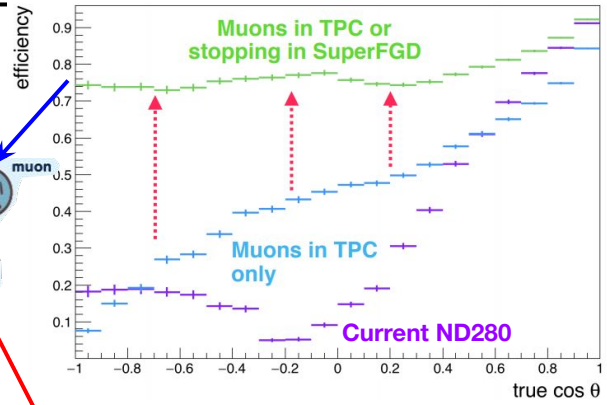
Electron neutrinos at Super-K

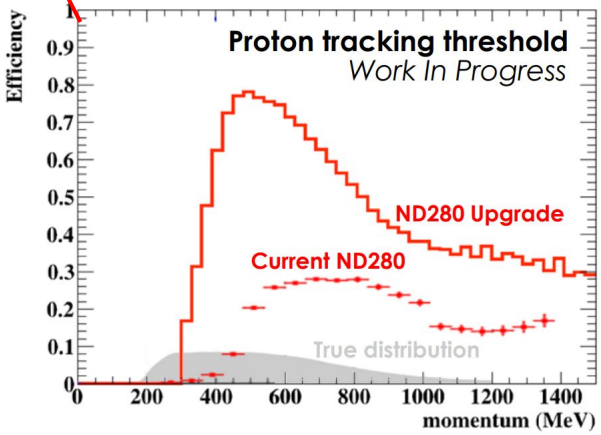


Expected performances

- Improved reconstruction at high and backward angles
  ⟶ better constraints on the neutrino interaction model
- Better reconstruction of outgoing nucleons
  ⟶ access to new observables







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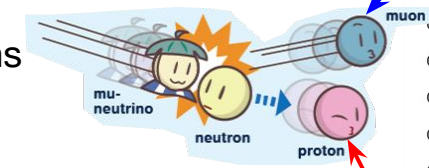
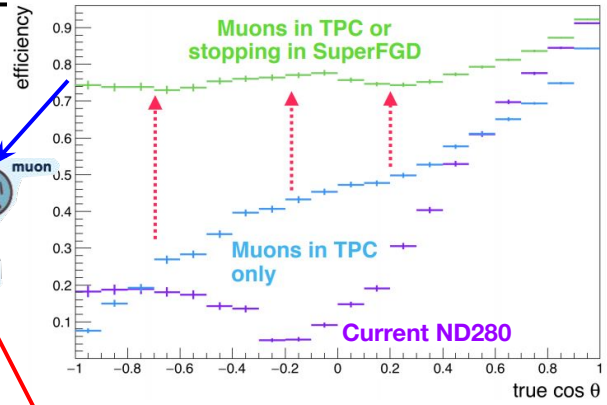
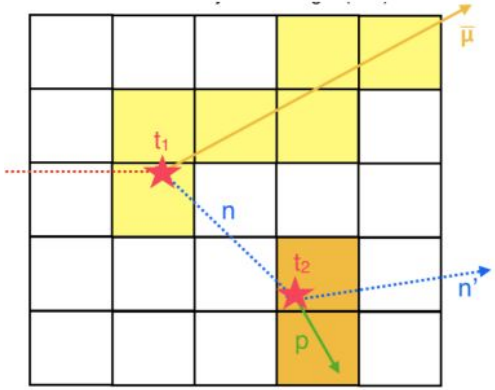




Neutron kinematics reconstruction by measuring their time-of-flight when they interact within the Super-FGD



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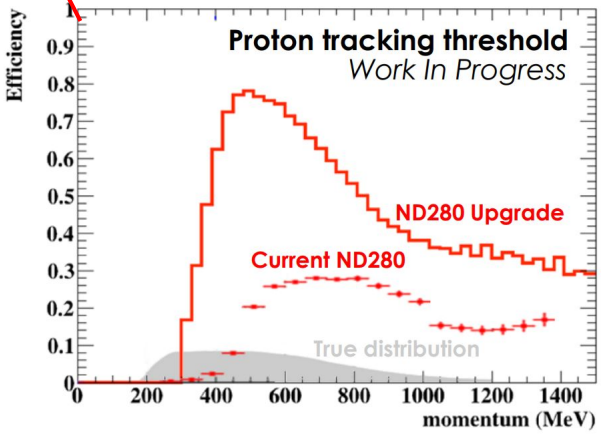

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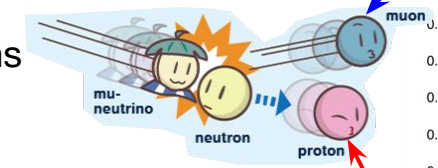
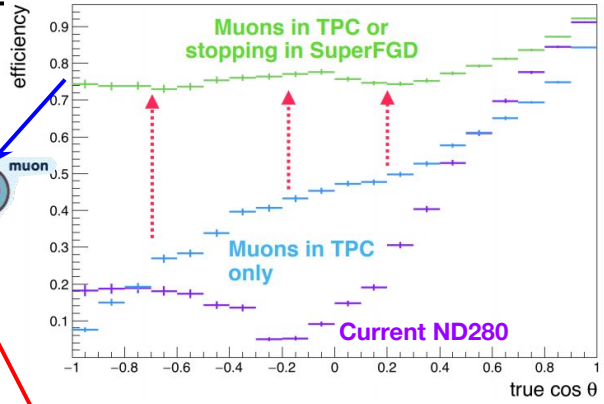
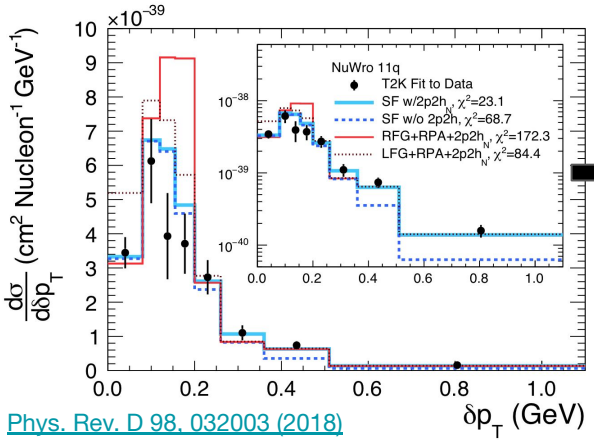
- Increased target mass (x2 current ND280)
  ⟶ more statistics







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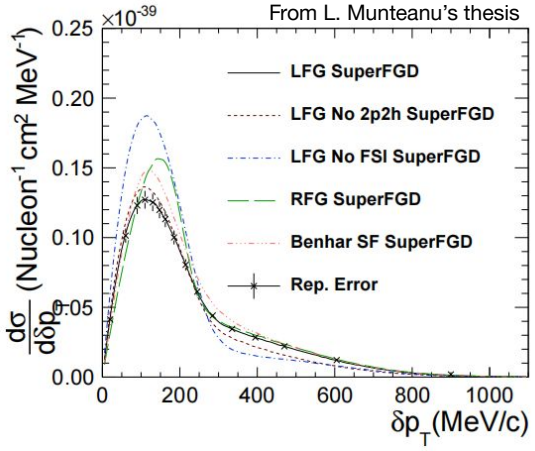
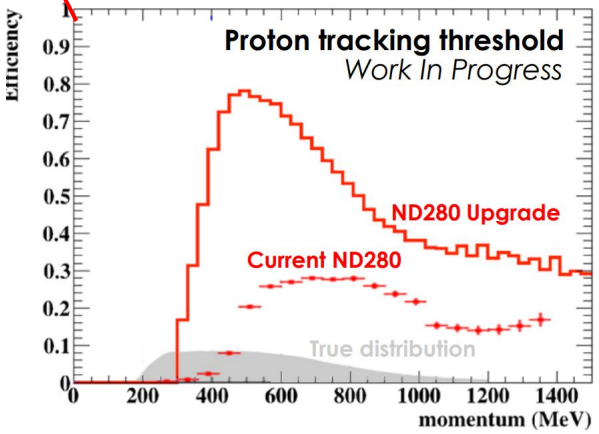
From L. Munteanu's thesis





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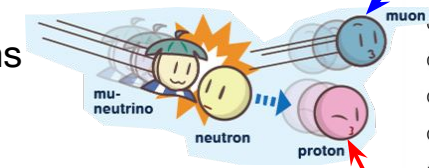
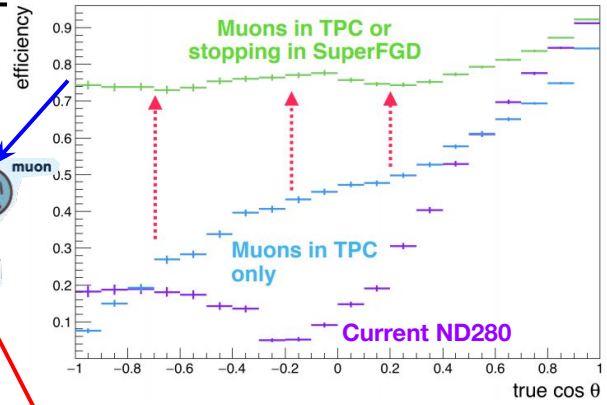
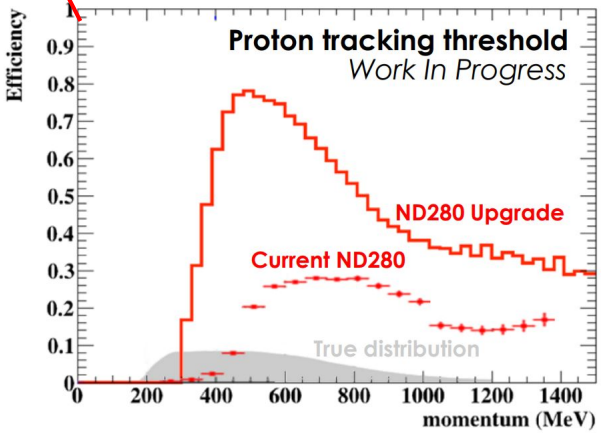
↪ **Probe neutrino interaction physics at an unprecedented level!**







Summary and prospects

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- The Super-FGD is a new addition to the T2K near-detector complex as part of the ND280 upgrade
- It is a novel **highly granular** plastic scintillator tracker with a (quasi-)**3D** readout
- The Super-FGD is **fully assembled** and the installation of the electronics is expected early this Summer, with a full **commissioning before the Fall**
- The granularity of the Super-FGD is a key characteristic that allows it to precisely measure the kinematics of the outgoing particles from neutrino interactions, and particularly **hadrons with an unprecedented precision**