The T2K near detector upgrade and SuperFGD electronic

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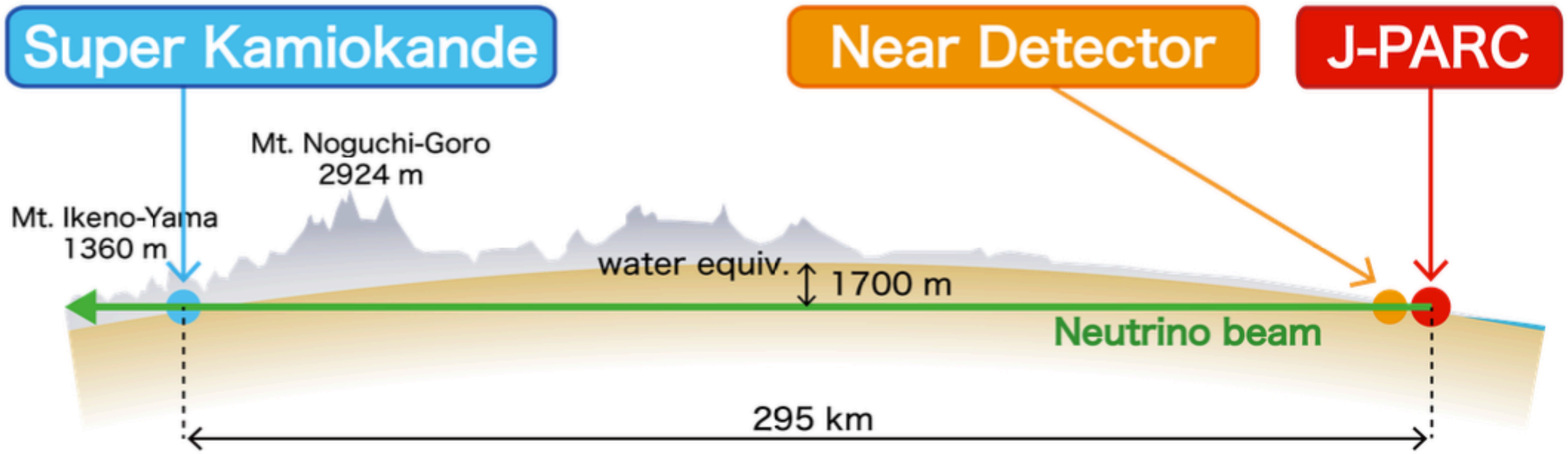
Biennale LLR 2024

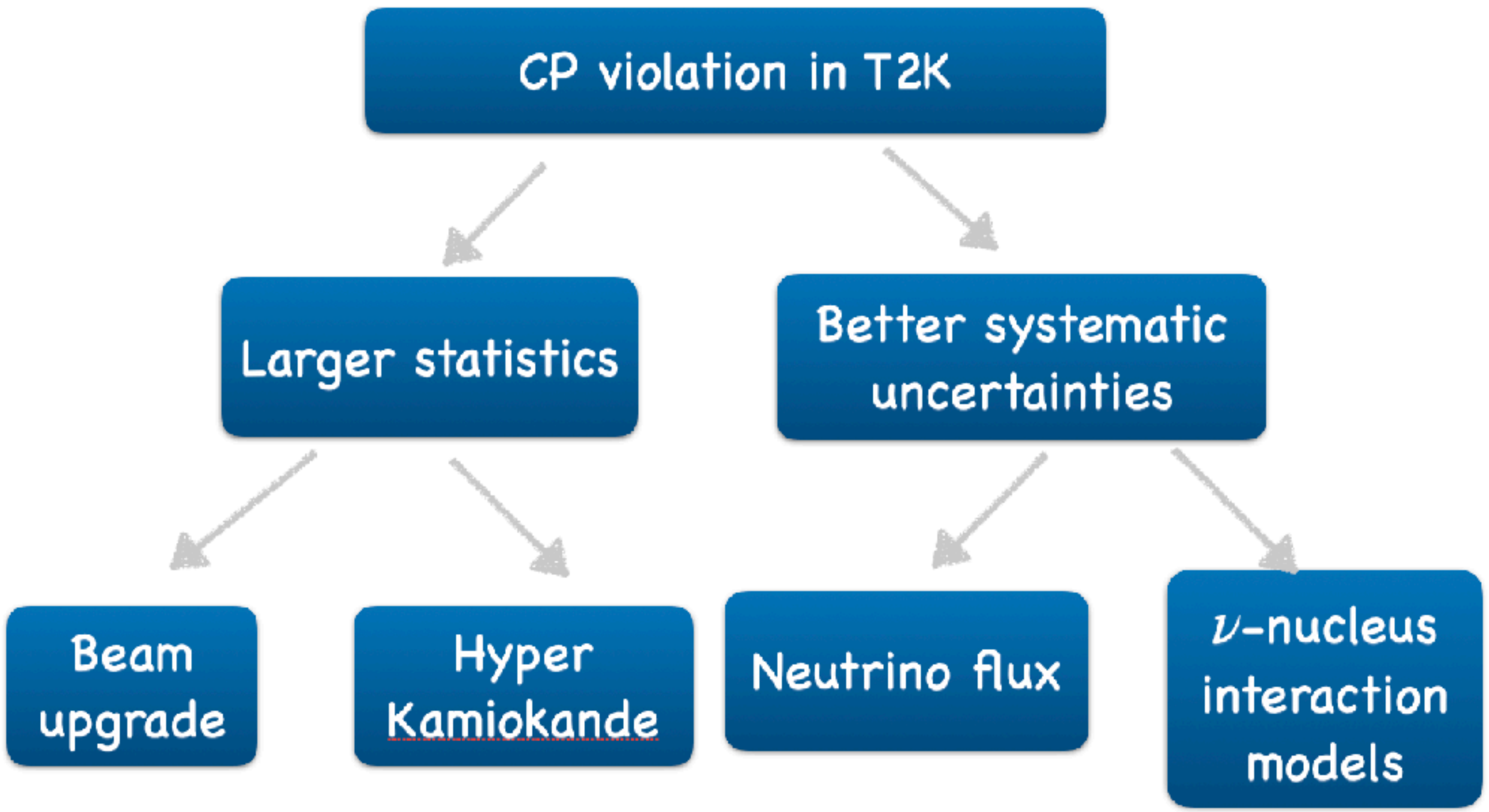
T2K EXPERIMENT



- T2K (Tokai to Kamioka) is a long-baseline neutrino experiment in Japan, and is studying neutrino oscillations.
- T2K is the first experiment to report evidence for the neutrino appearance oscillation ($\nu_\mu \rightarrow \nu_e$) in 2013 (Phys. Rev. Lett:12:061802, 2014.)
- The current goal of T2K is searching for the CP violation in the lepton sector by comparing the appearance probabilities of neutrino and antineutrinos. (T2K can produce either neutrino or anti-neutrino beam).
  => First hint of CP violation at 3sigma CL in 2020 (Nature 580, 339-344 (2020))

T2K EXPERIMENT

ROAD TO CP VIOLATION DISCOVERY



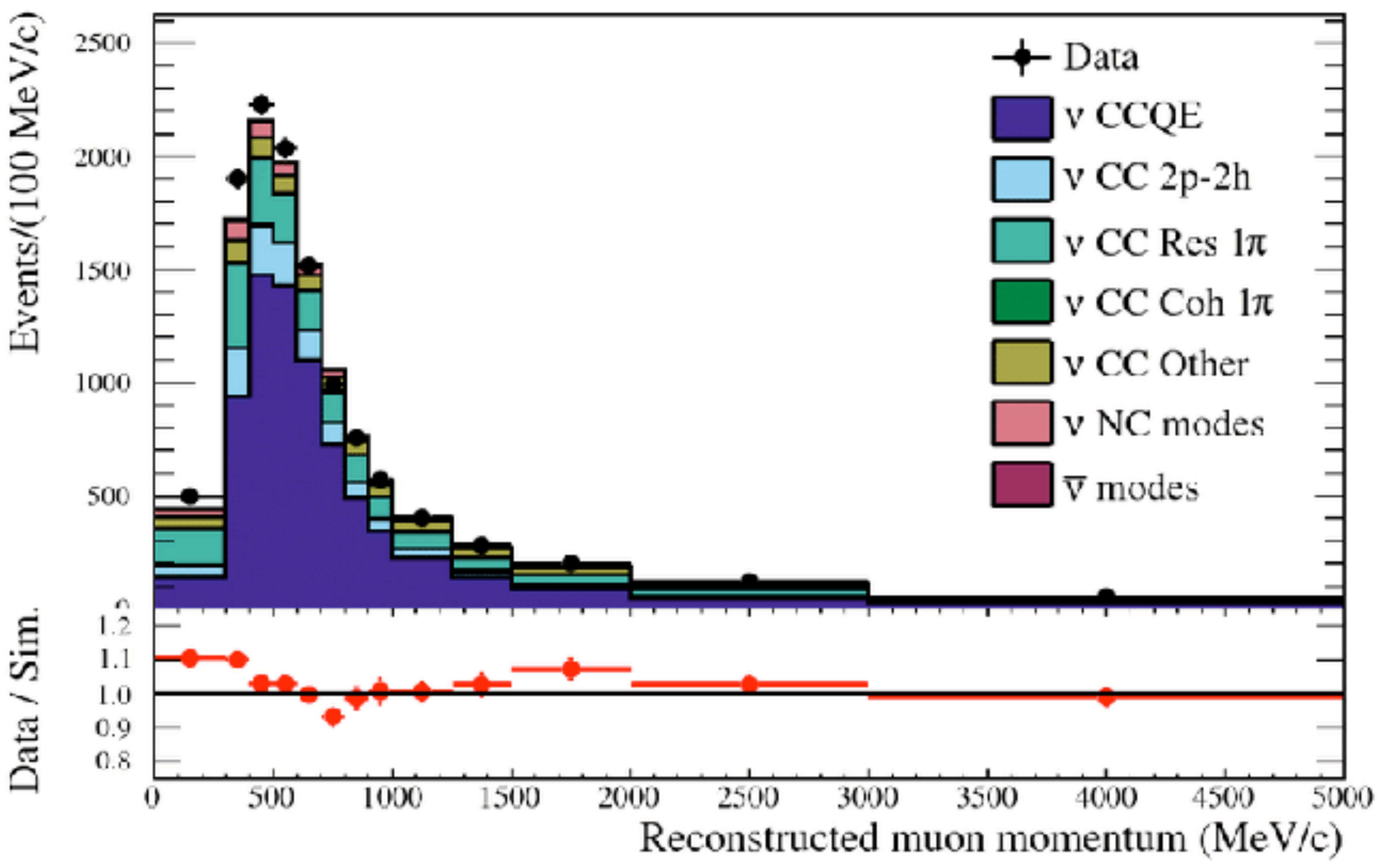
- Need more statistics to be more sensitive to CP violation
- For T2K oscillation analysis 2022: over a total systematic uncertainty of 5.2% (ν_e appearance in neutrino mode), ~4% of the error budget comes from the uncertainty on neutrino interaction processes.
- Today not the major problem, we have ~100ν_e appearance events… but this will become a problem soon
- We need to reduce the systematic uncertainties before the Hyper Kamiokande era

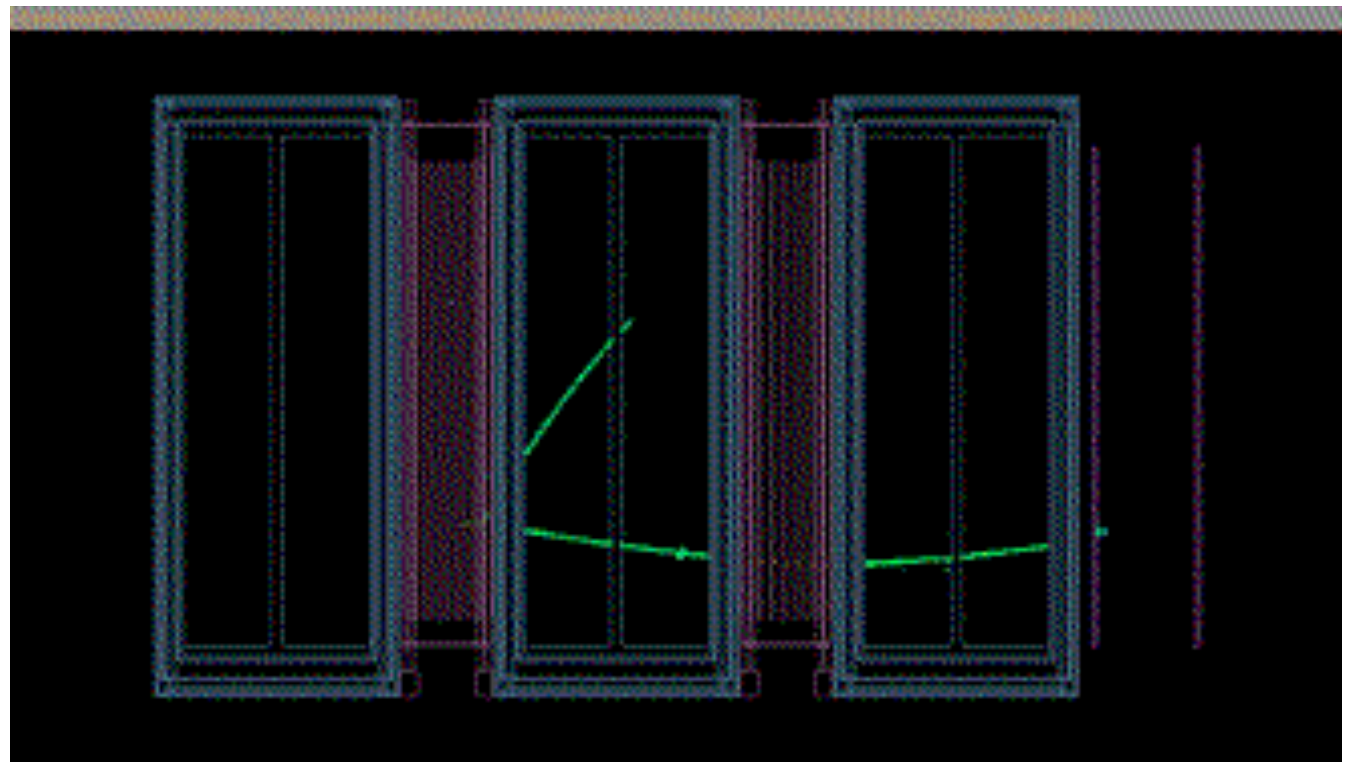
=>Near detector upgrade: better constrain ν-nucleus interactions and hence improve systematic uncertainties

T2K EXPERIMENT: NEAR DETECTOR (ND280)

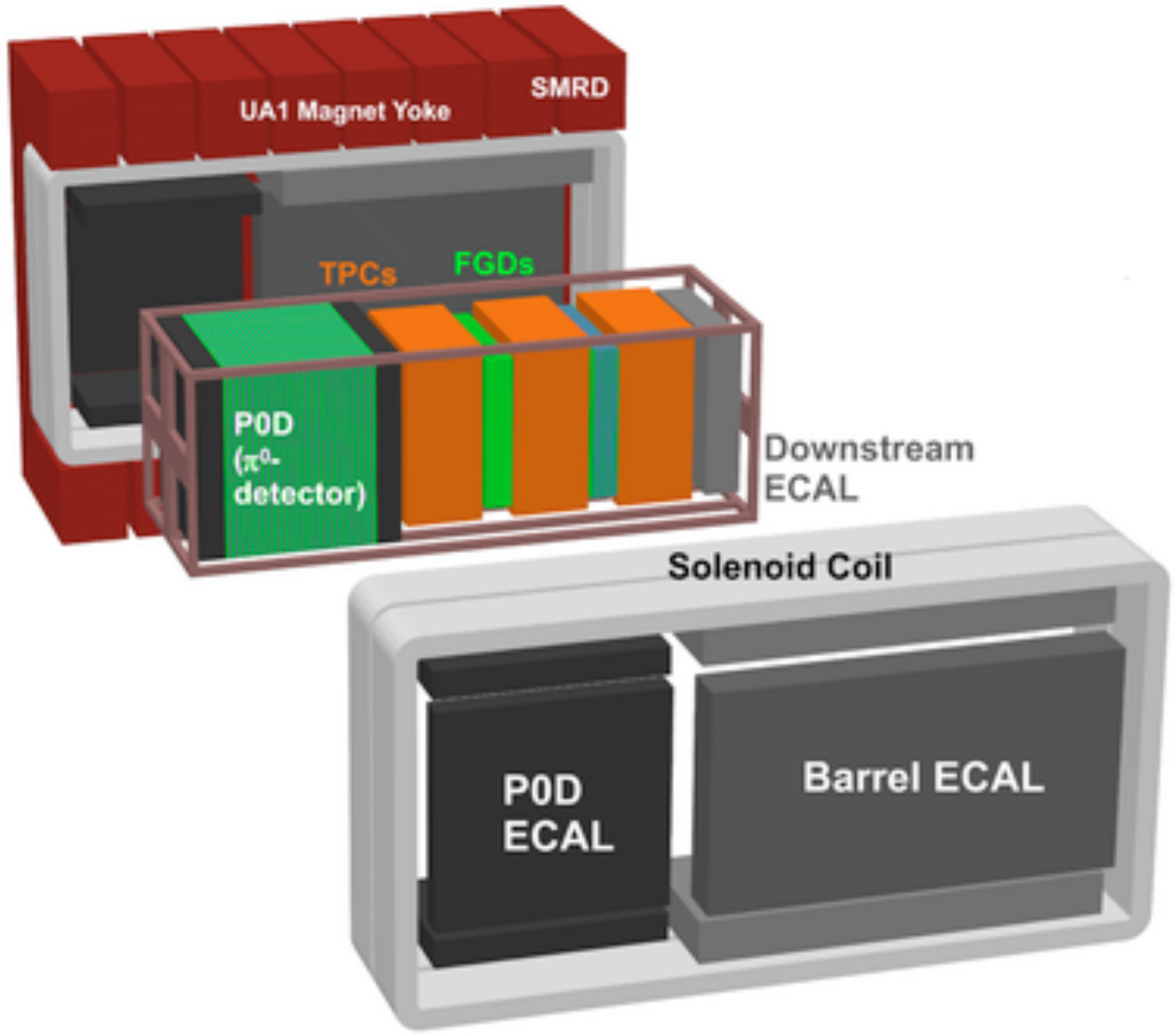
- Near detector ND280 is designed to constrain the neutrino flux⊗cross-section

- The tracker includes 2 Fine Grained Detectors (FGD) and 3 Time Projection Chambers (TPC)
  => measure the momentum of charged particles and particle identification.



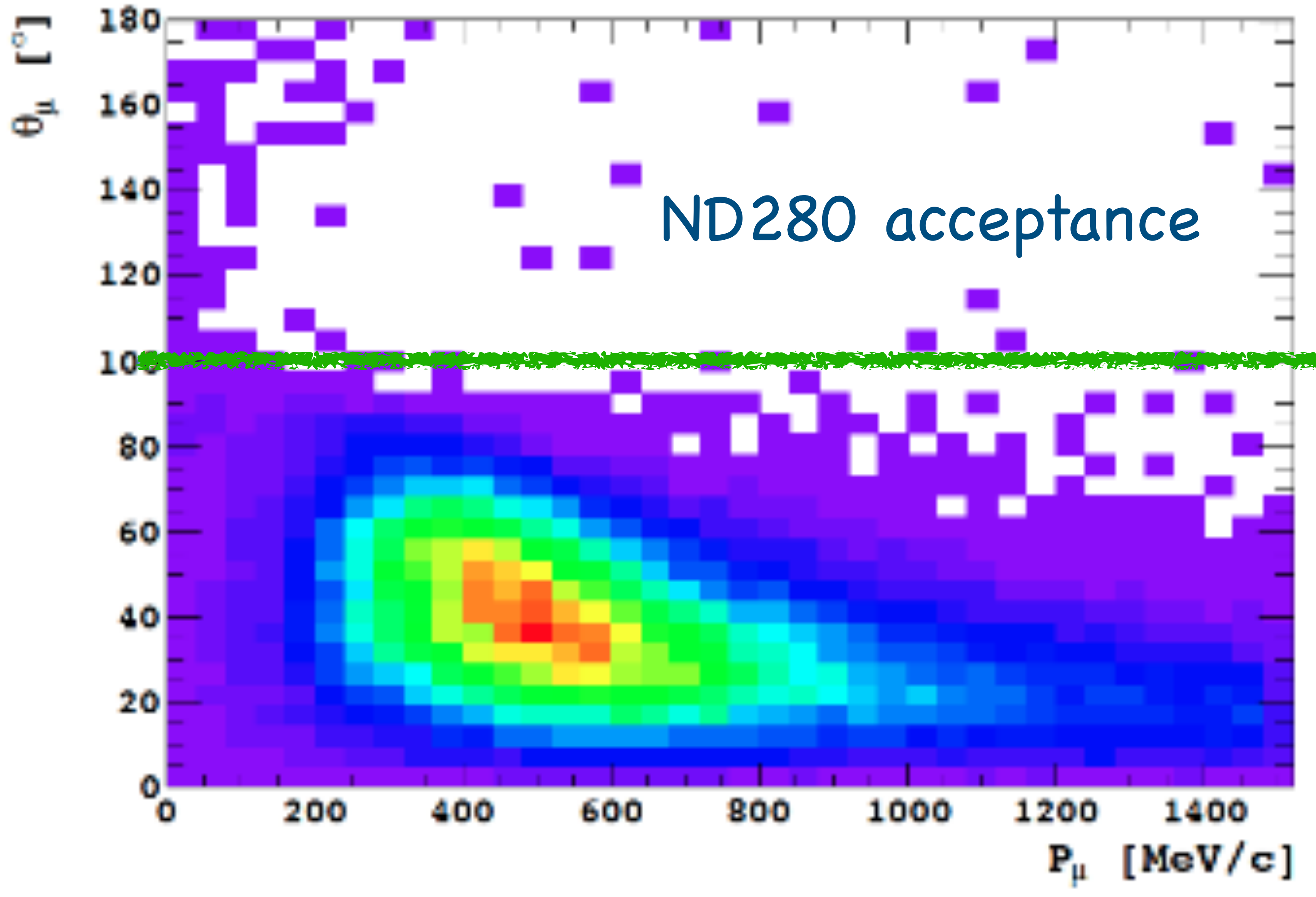


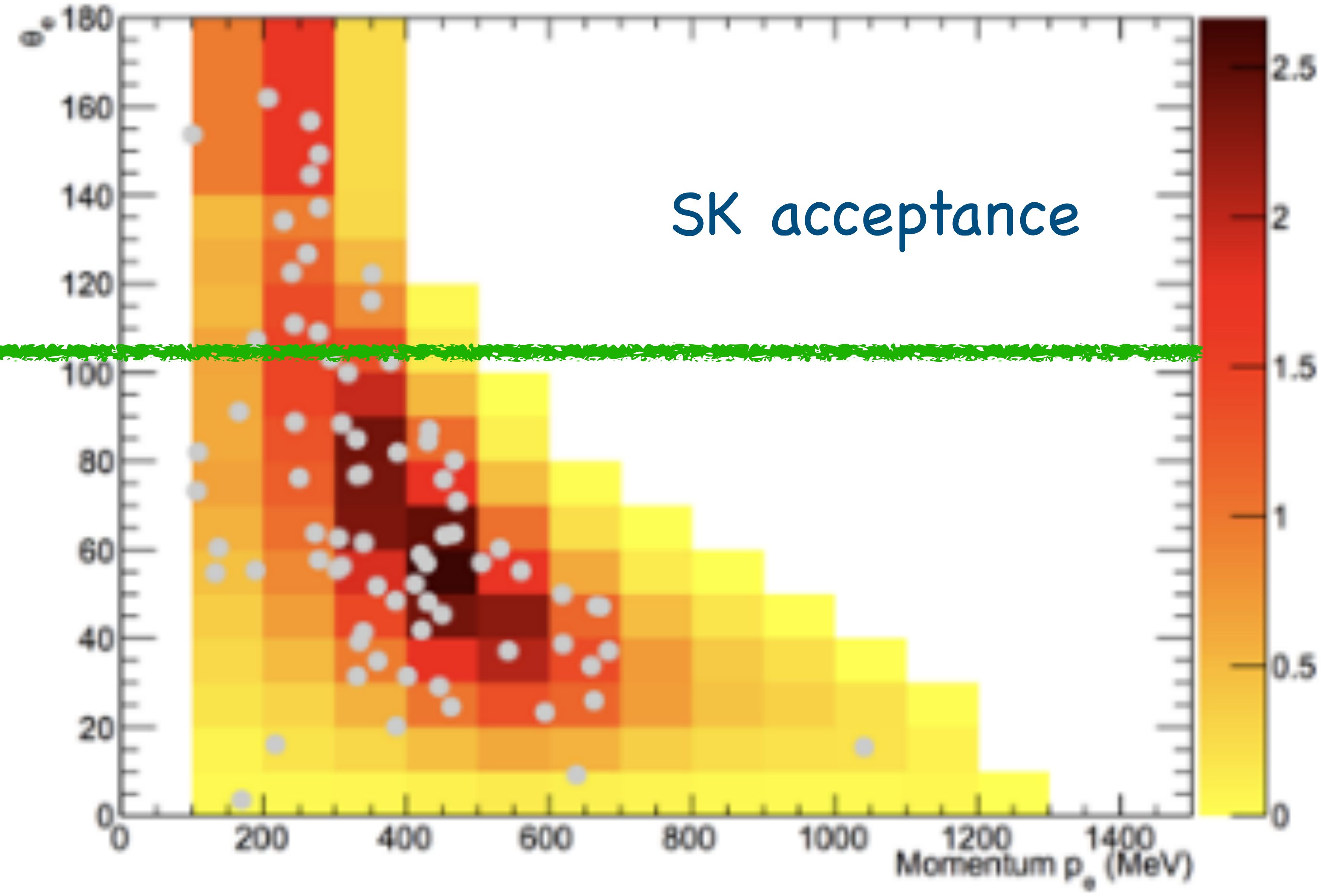
QE event at ND280



ND280 configuration

ND280 upgrade motivation

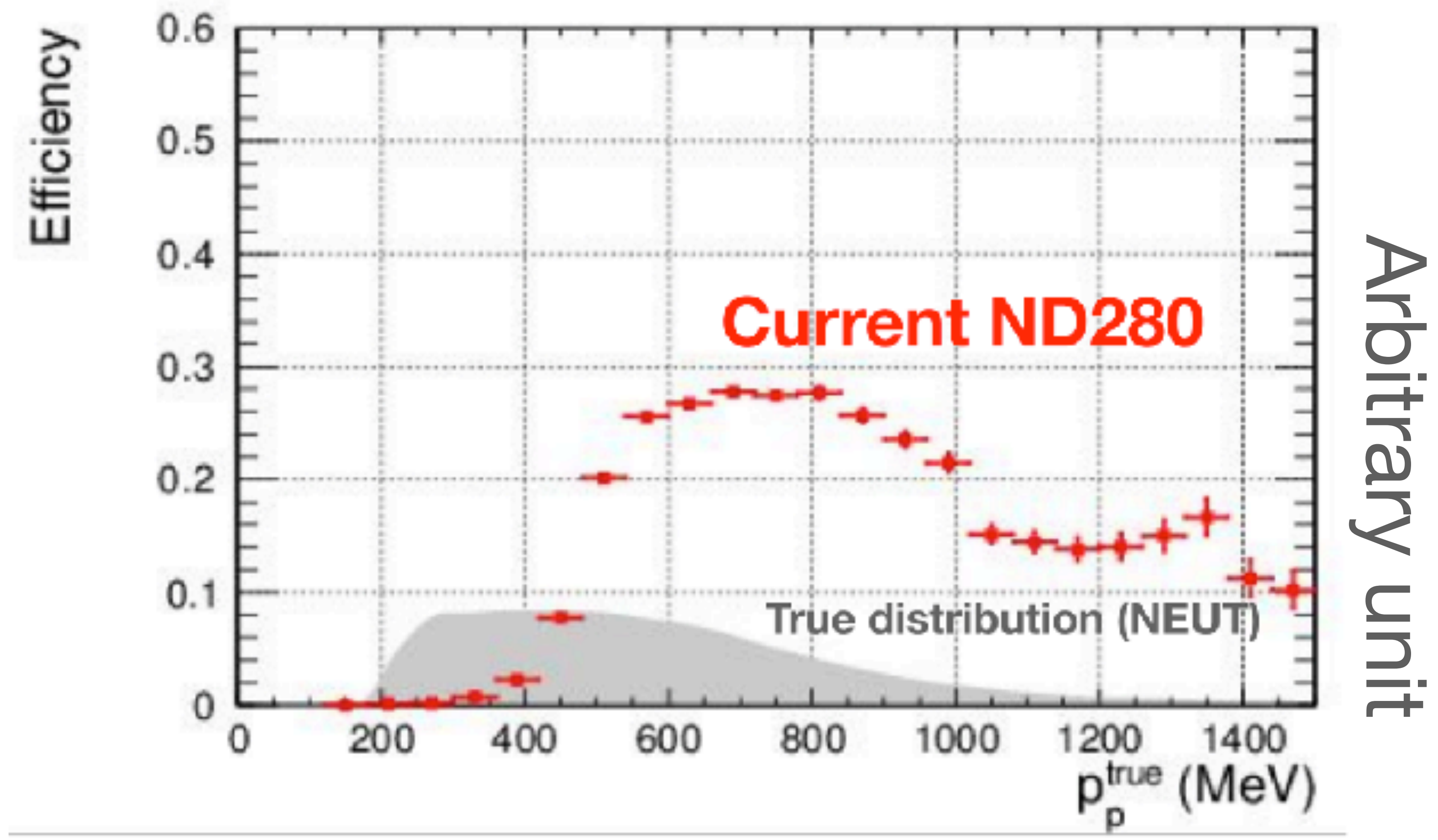




- The polar angle acceptances are not comparable between near and far detector

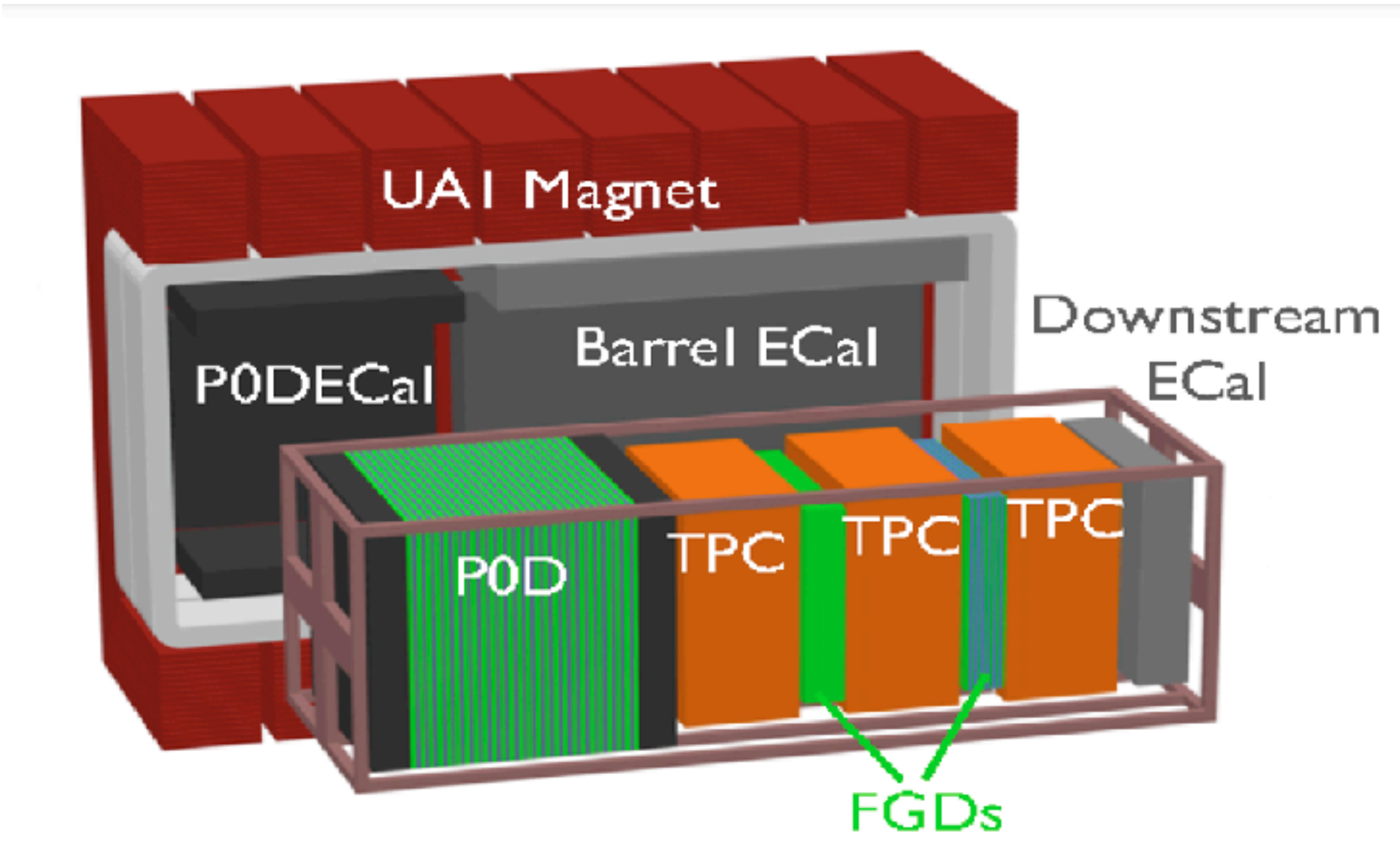
- The proton detection threshold is high

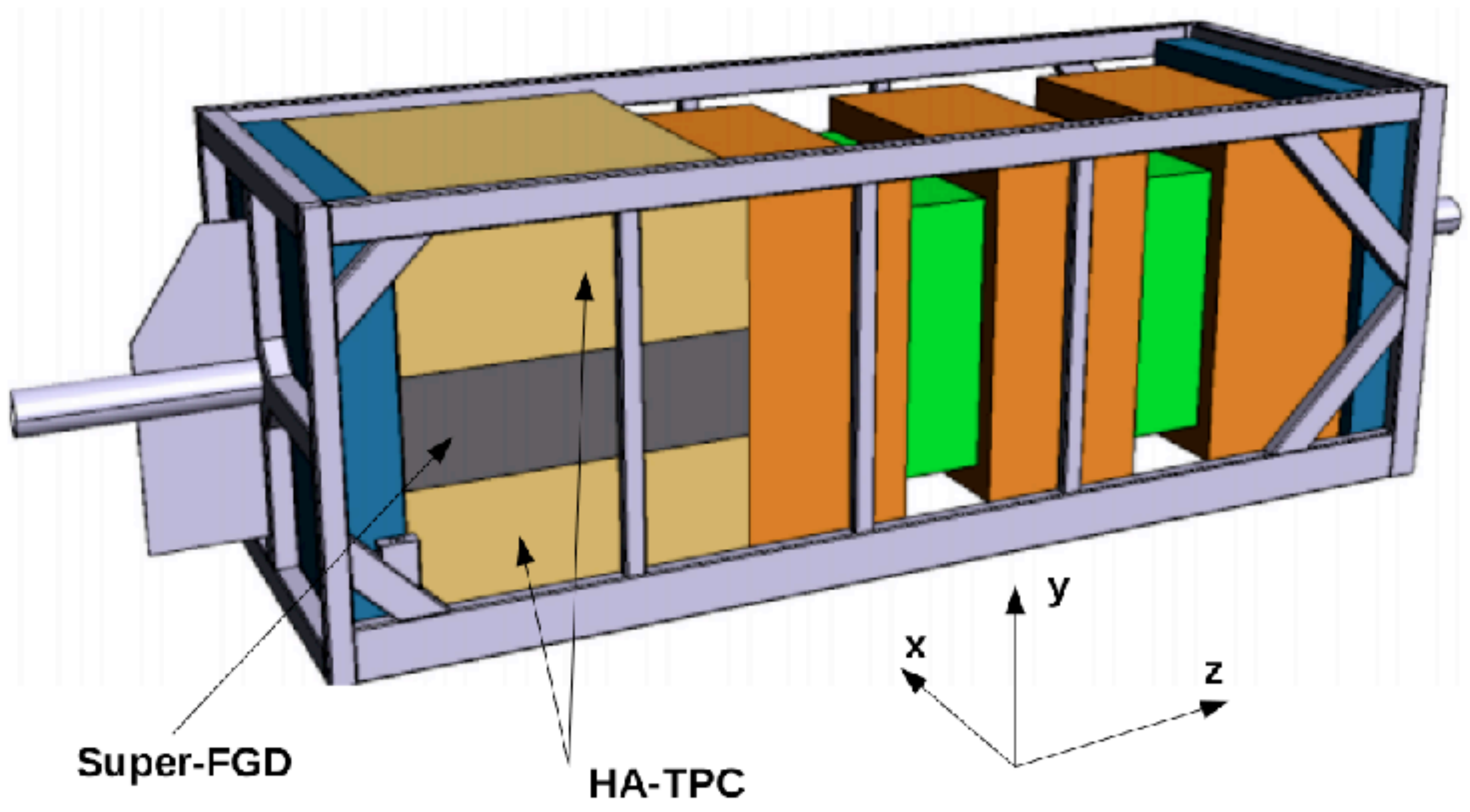
- Only muon kinematics are used to reconstruct neutrino energy



Proton detection efficiency

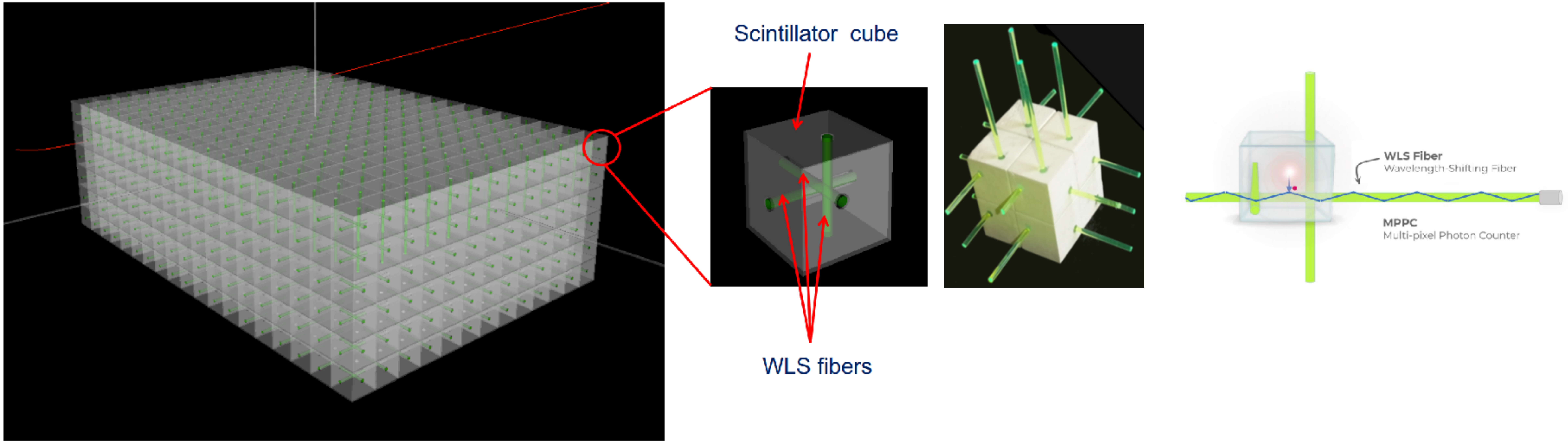
UPGRADED NEAR DETECTOR ND280: CONFIGURATION





- 2 new High Angle TPC (HA-TPC)
- New Time Of Flight detector (TOF)
- 1 Super-fine-grained-detector (super-FGD) => the core of the detector where the LLR is involved

SUPER FGD DETECTOR



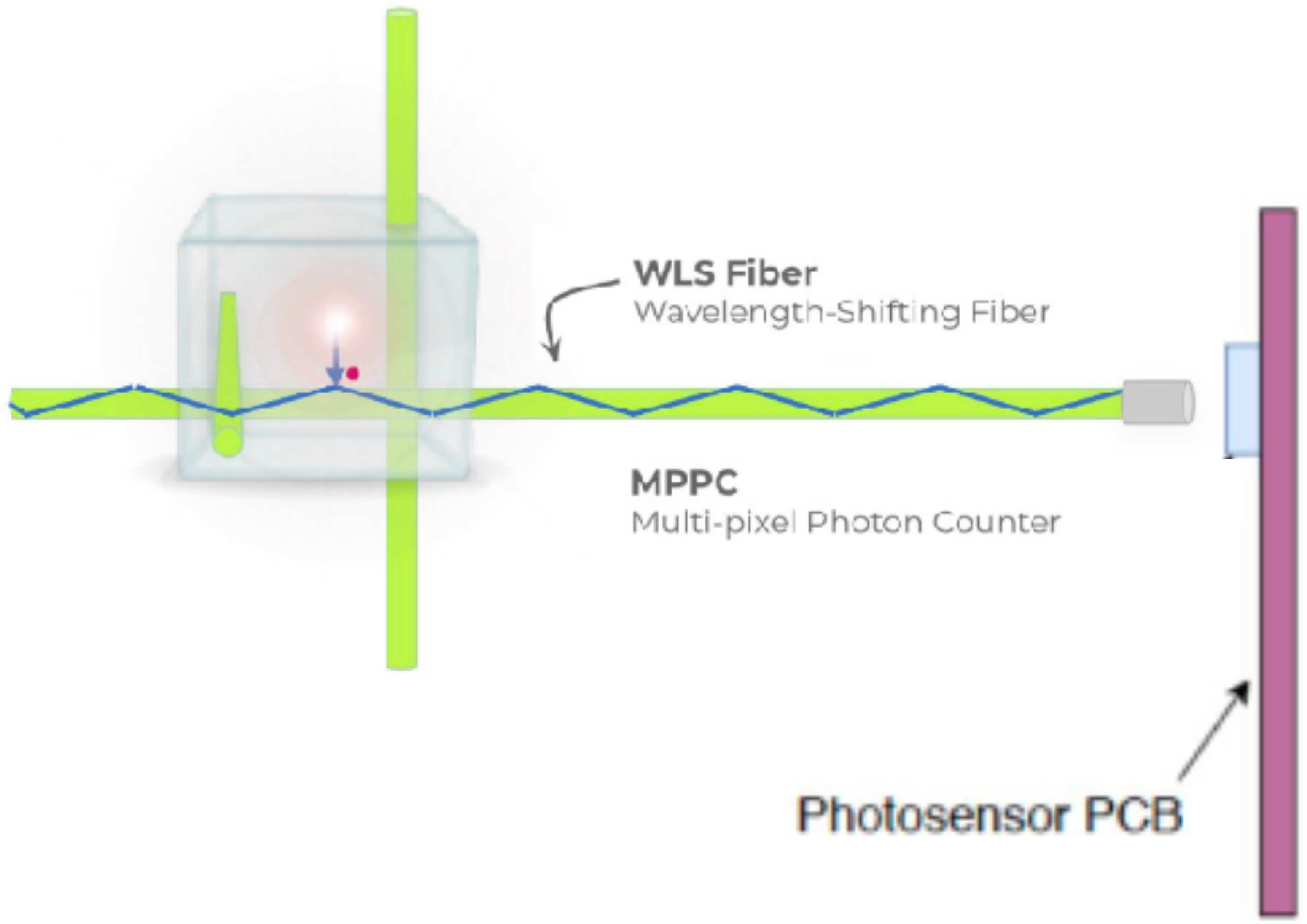
- Super-FGD: 192 × 192 × 56 scintillator cubes (2 million) with 3D readout => 2 tons of fully active target

- Wavelength shifting (WLS) fibers are used to collect light from scintillator cubes. (70 km of WLS fiber in total)

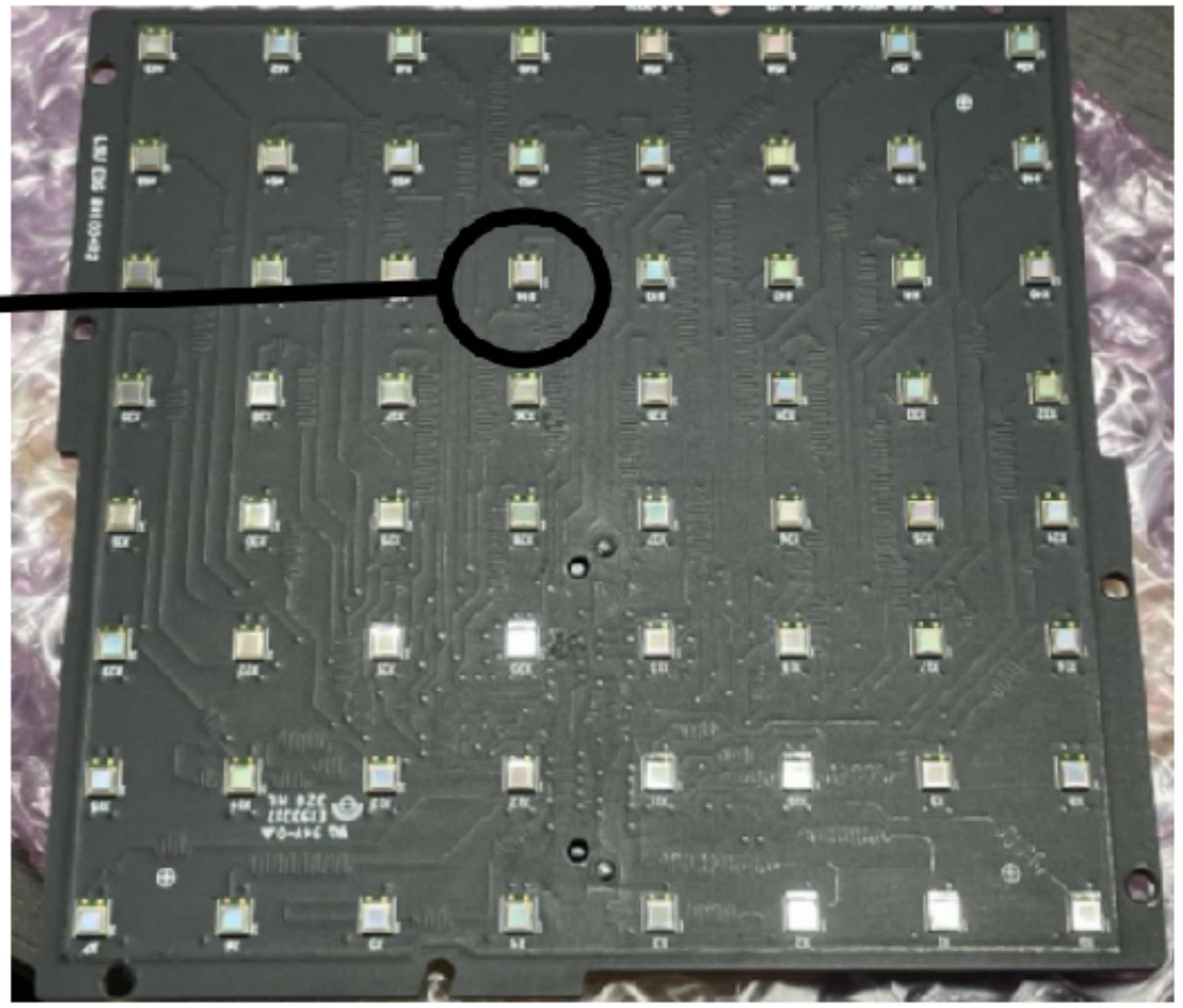
- One end of the fibers is connected to a Multi-Pixel Photon Counter (MPPC) the other end is mirrored.
  => around 60.000 channels.

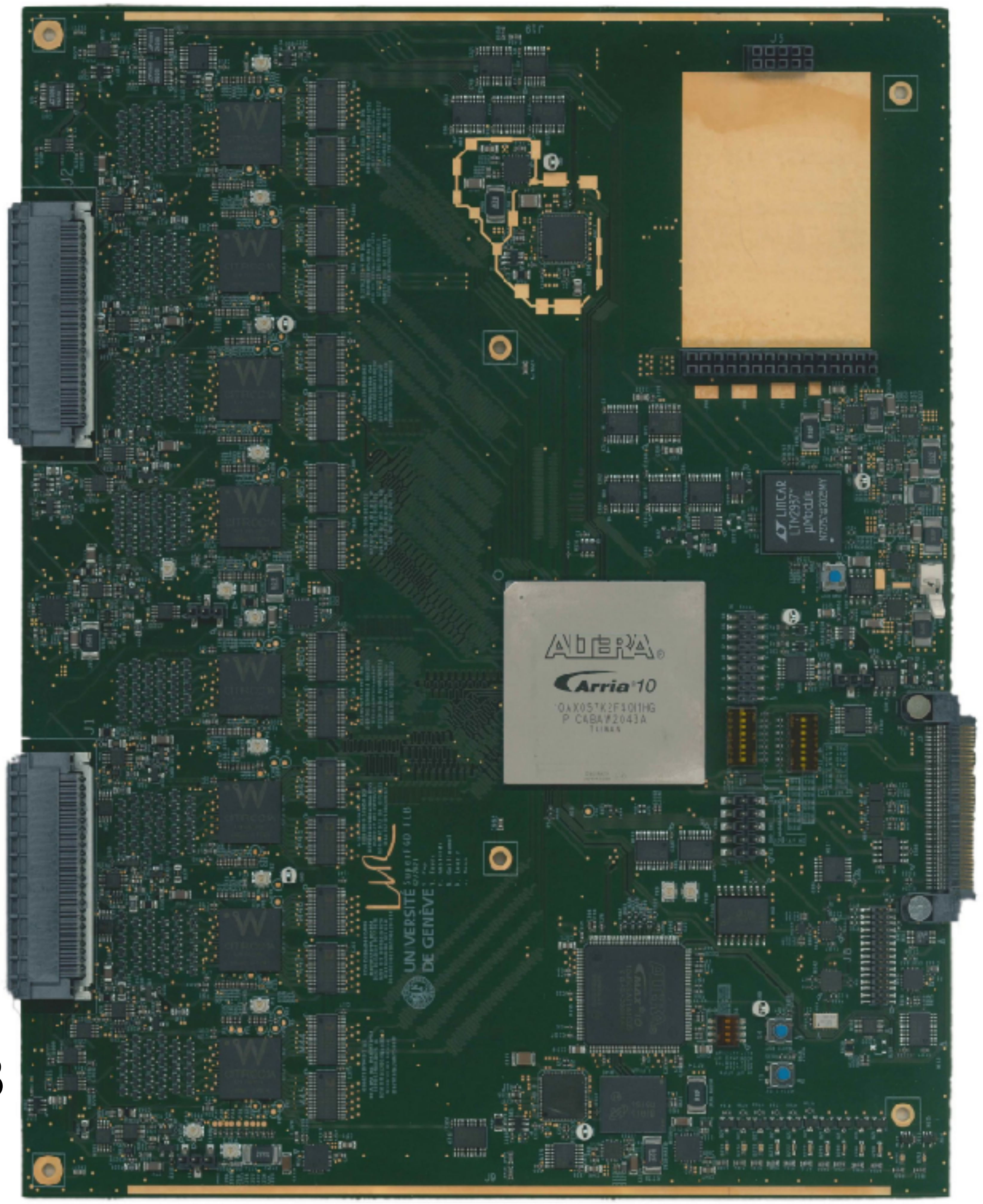
SUPER FGD DETECTOR READOUT

Front-End Board (FEB)



64 MPPCs





X4 MPPC => 1 FEB

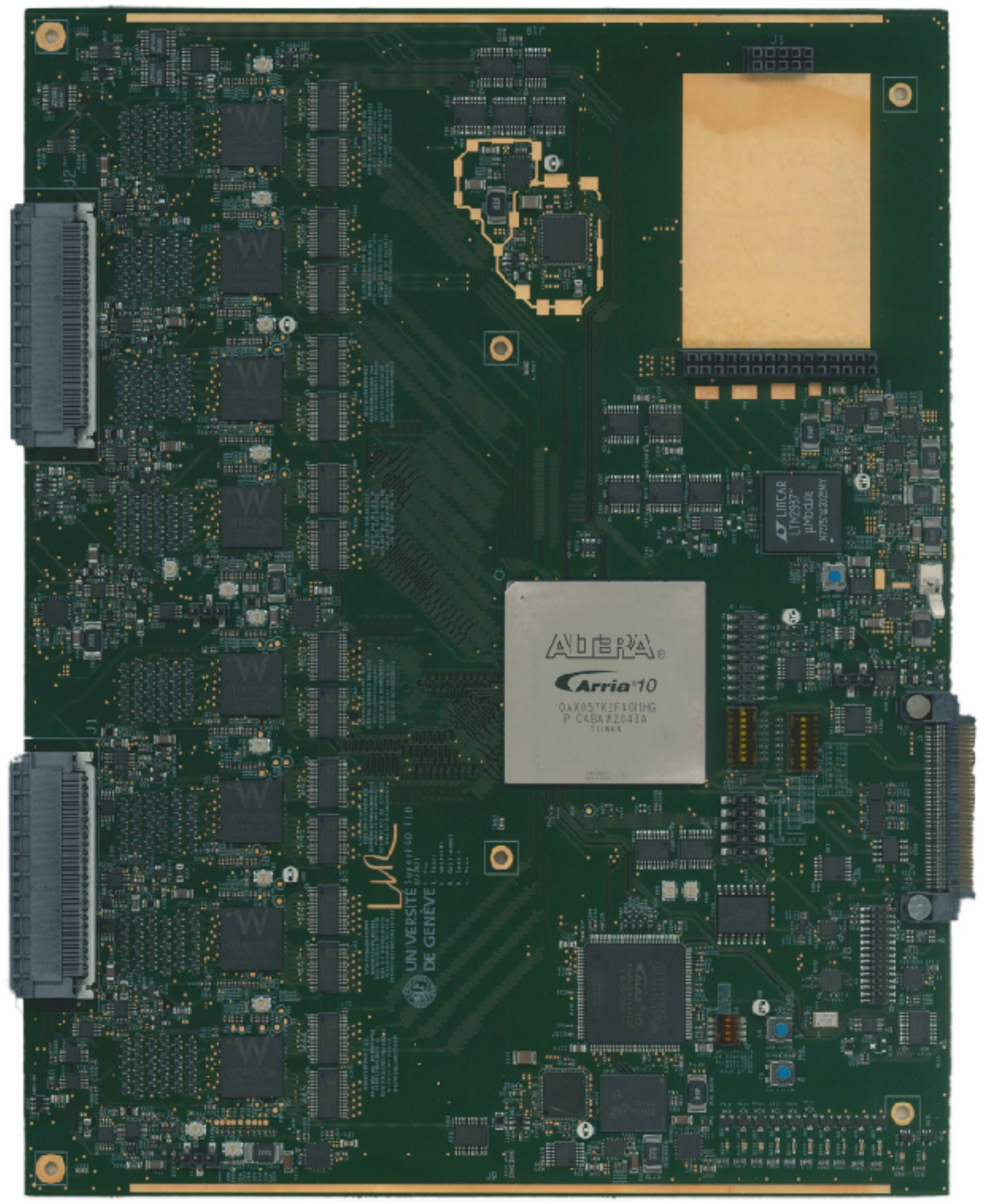
64 channels

256 channels

FRONT-END BOARD (FEB)

- The FEB is the heart of the electronic system. The electronic team at LLR also participated in designing this FEB.
- The baseline design is structured around the CITIROC (Cherenkov Imaging Telescope Integrated Read Out Chip) readout chip. CITIROC
- Each CITIROC can read 32 channels => 256 channels for 1 FEB.
- For each channel, the input is handled by two independent signal paths:
    - Low gain (LG) path
    - High gain (HG) path

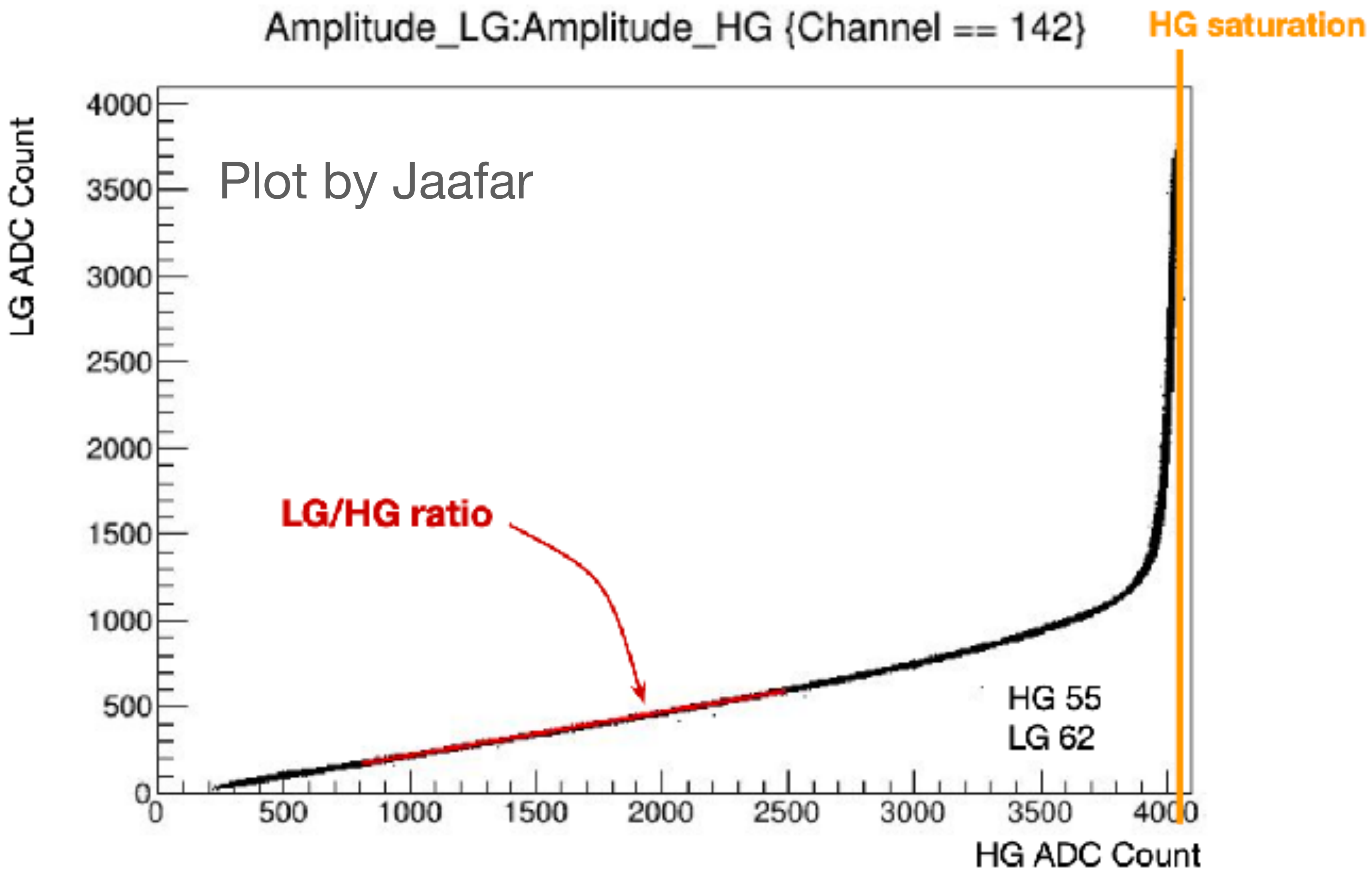
Front-End Board (FEB) 256 channels



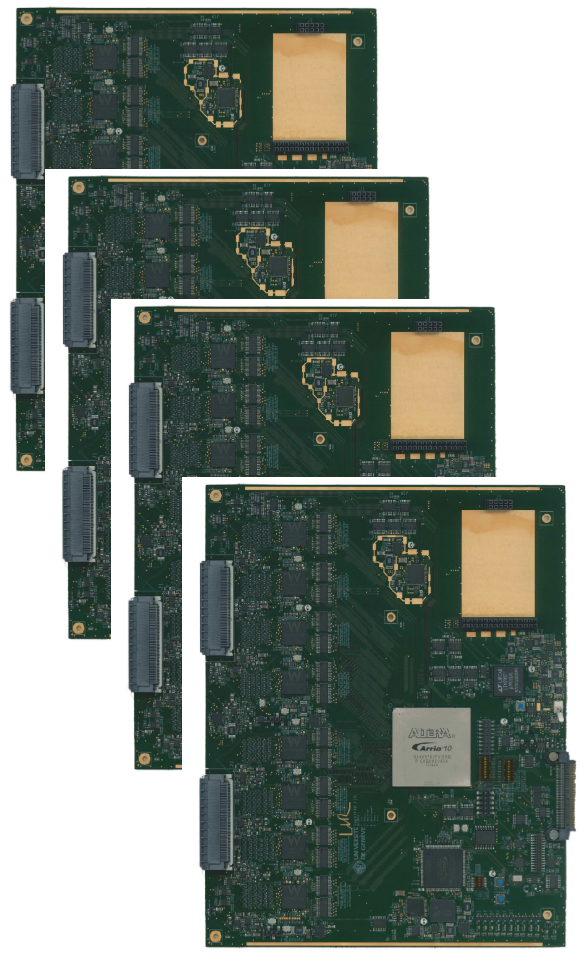
Signal to each channel

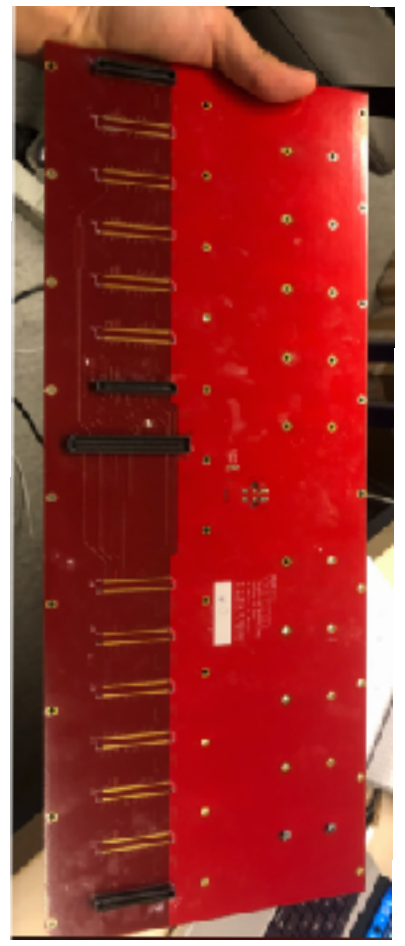
AMPLITUDE
- LOW GAIN (LG)
- HIGH GAIN (HG)

TIME
- Rising edge
- Falling edge

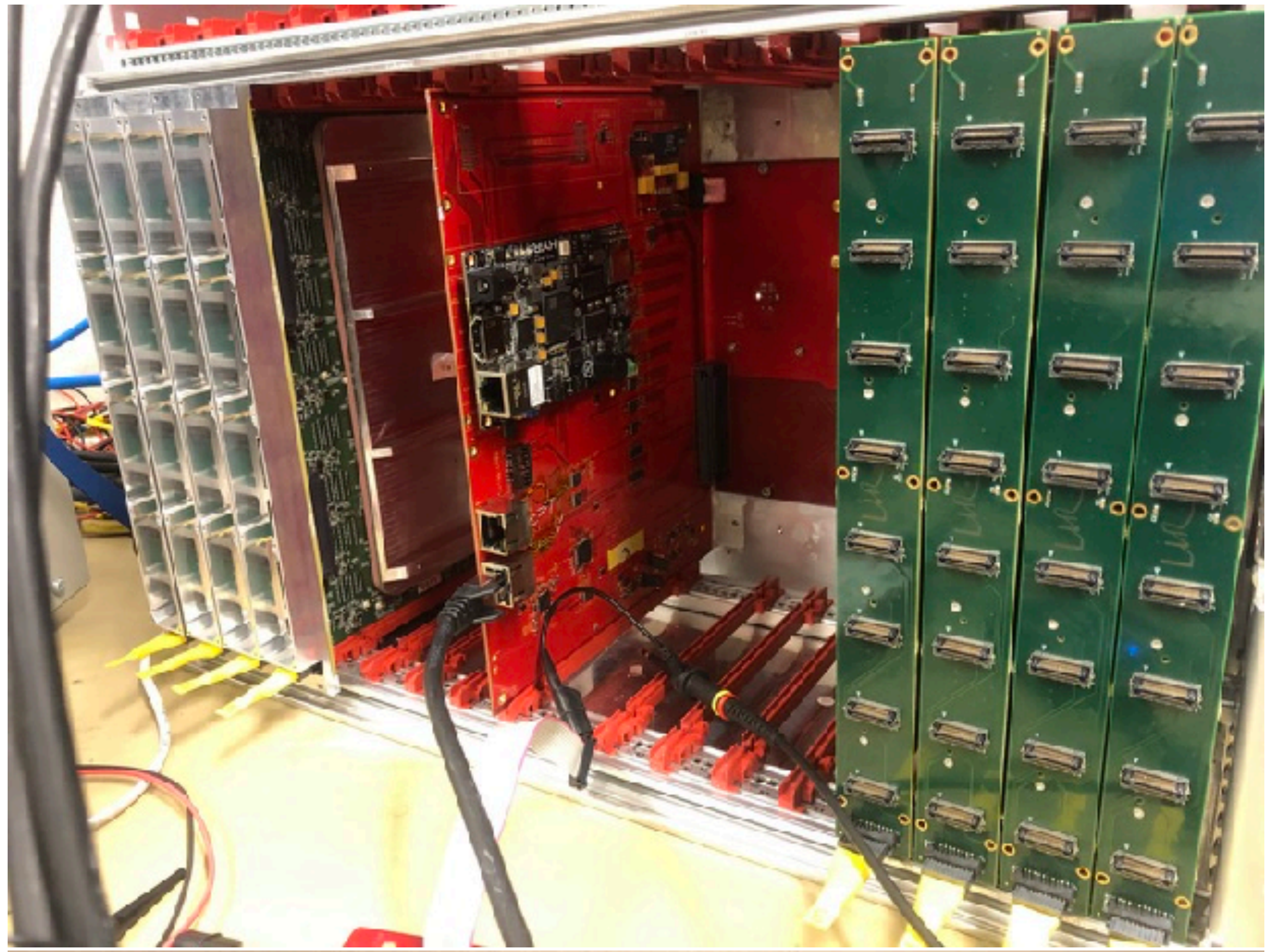


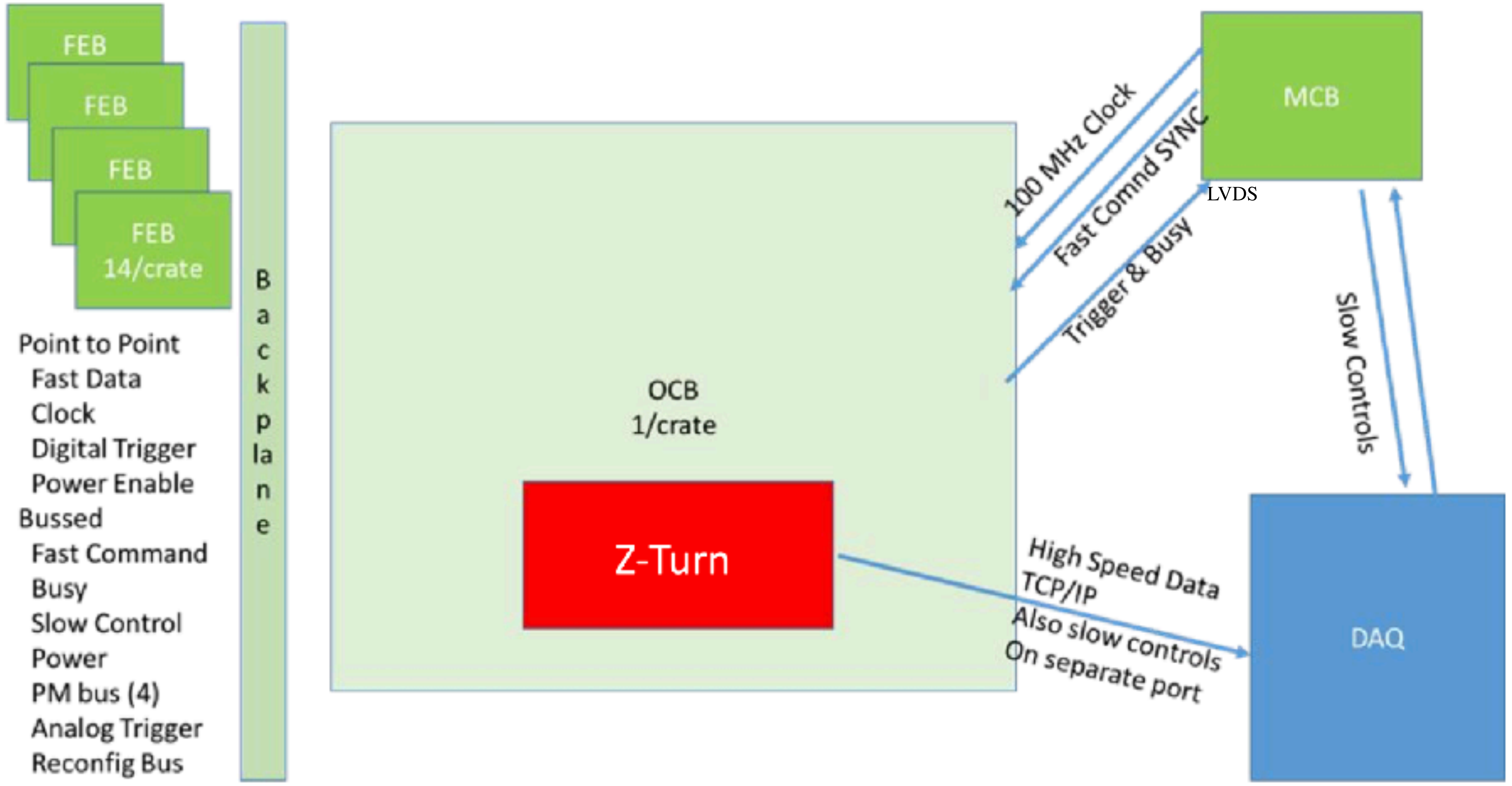
OVERVIEW OF SUPER-FGD ELECTRONIC SYSTEM



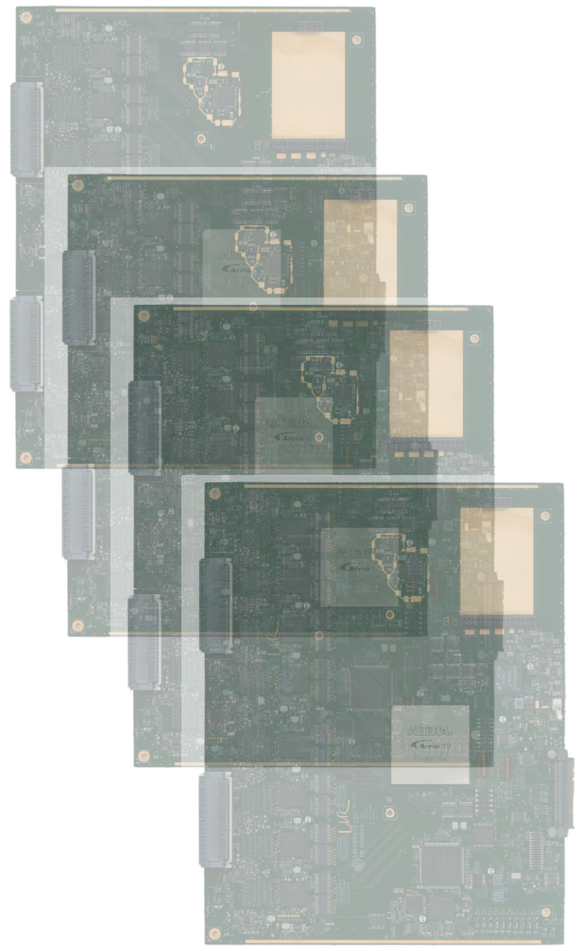


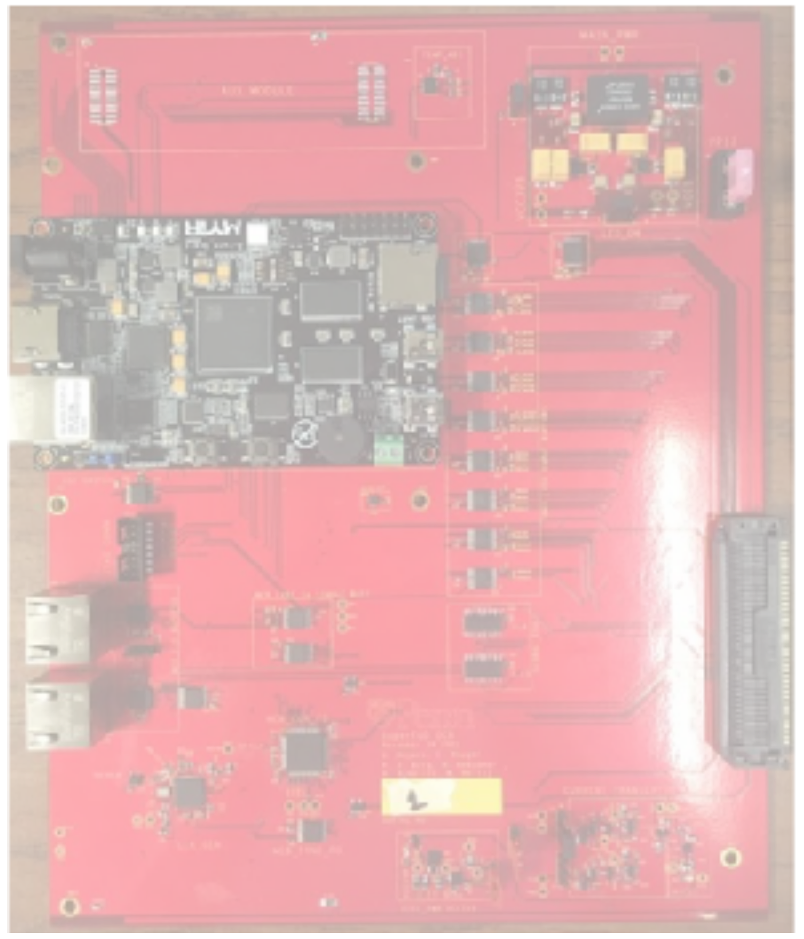
The whip

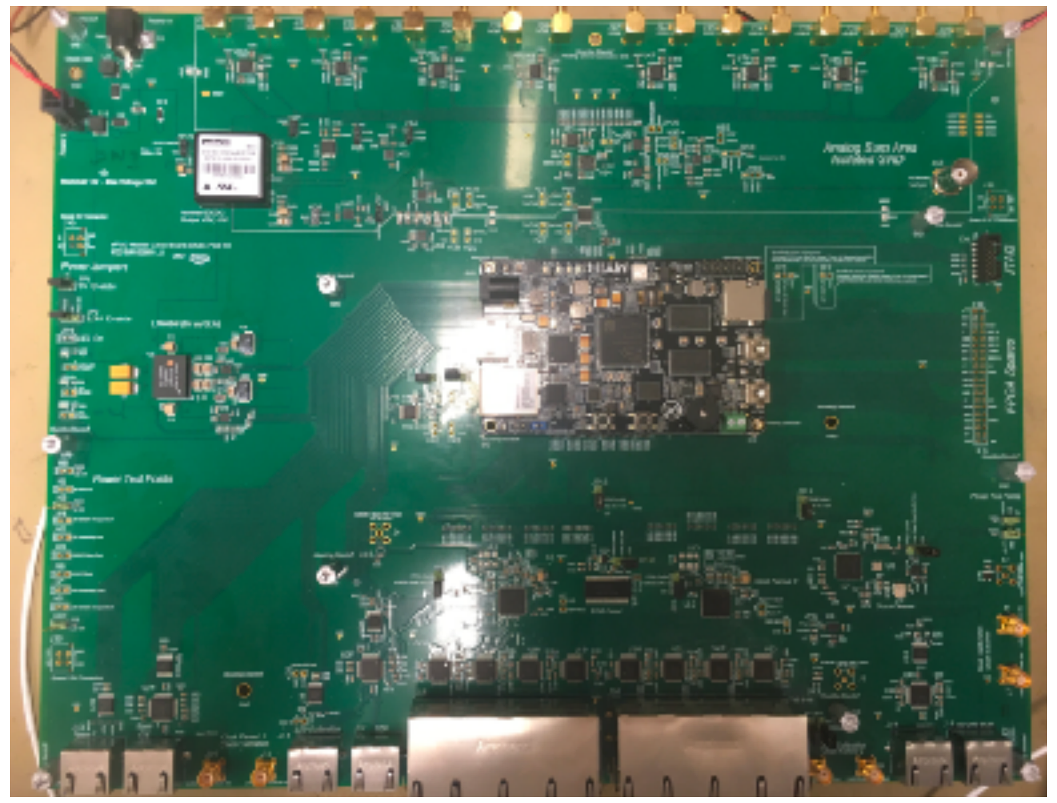


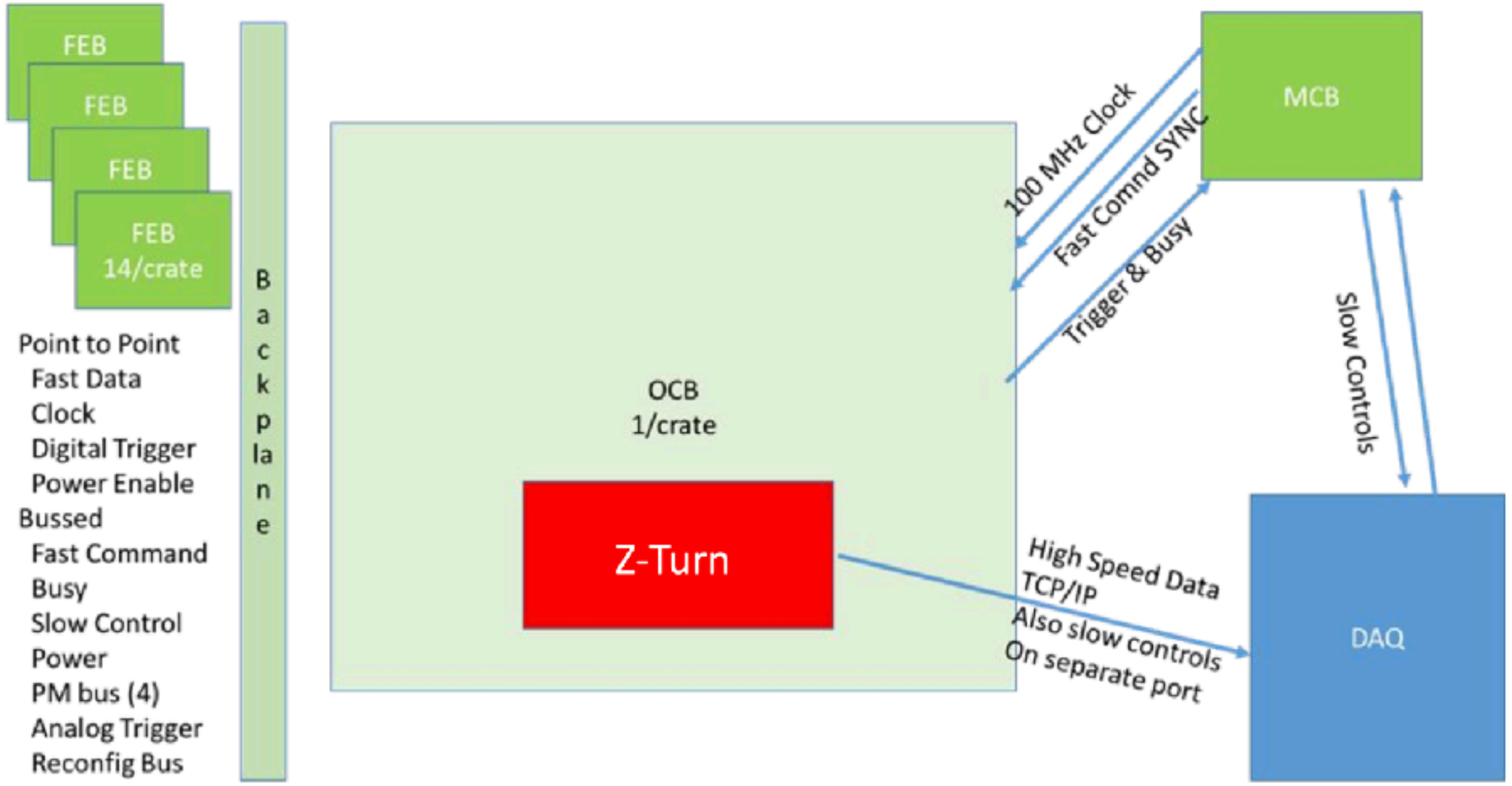


MASTER CLOCK BOARD (MCB)



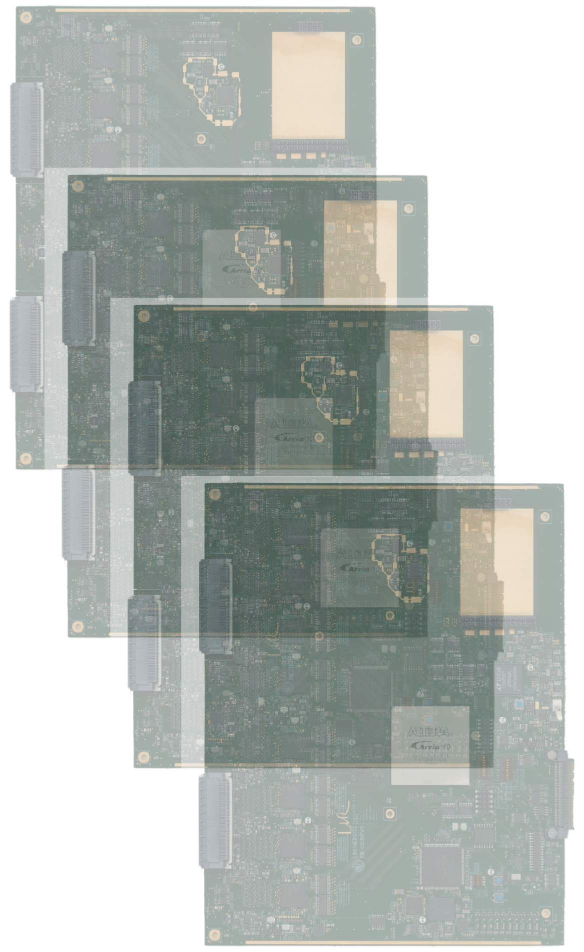




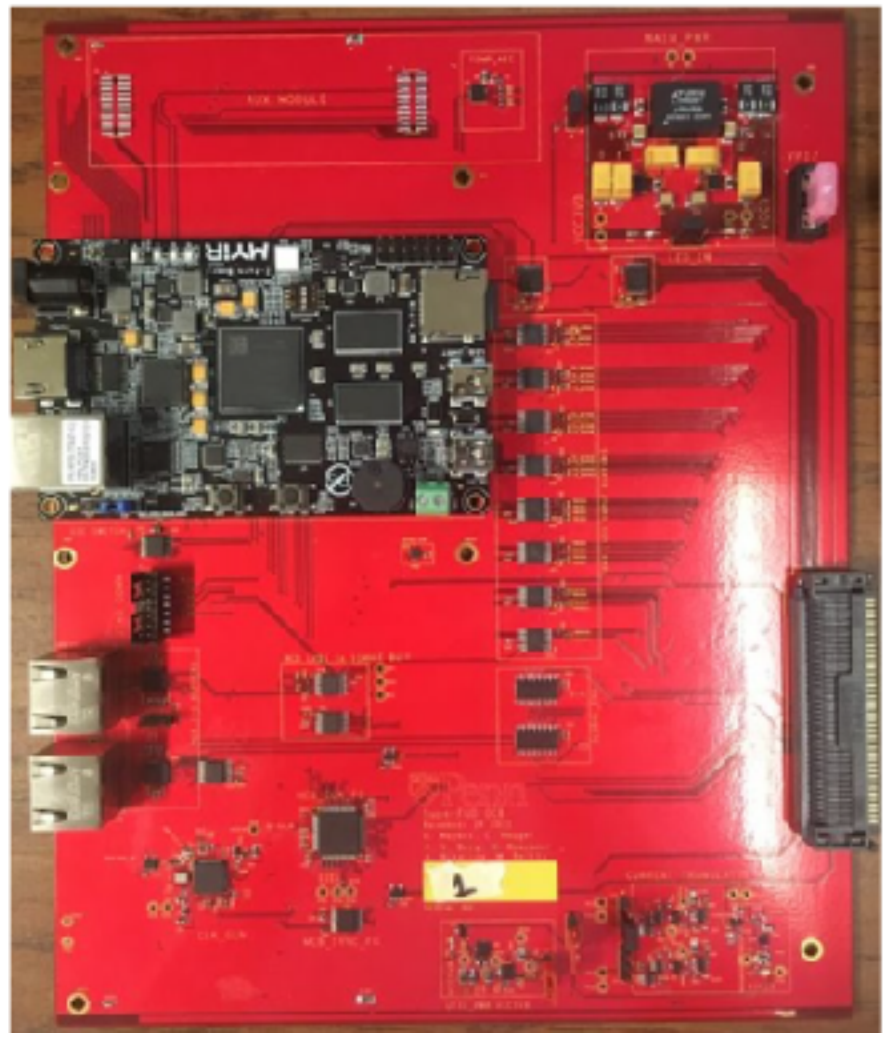


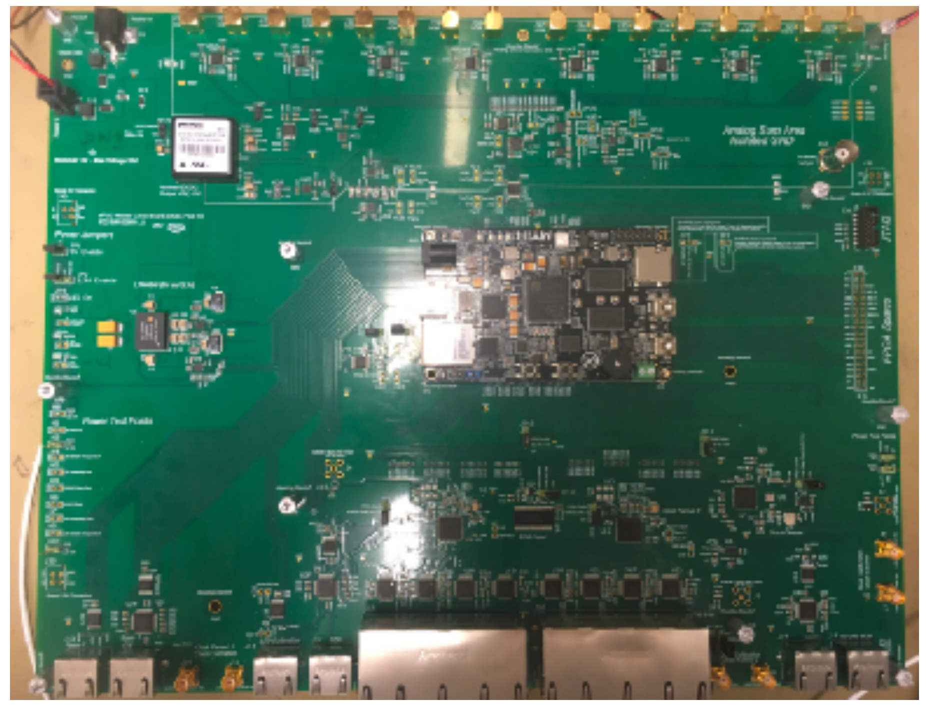
- MCB is used to send digital signals such as the clock, SYNC (GTS, gate, event number), trigger.

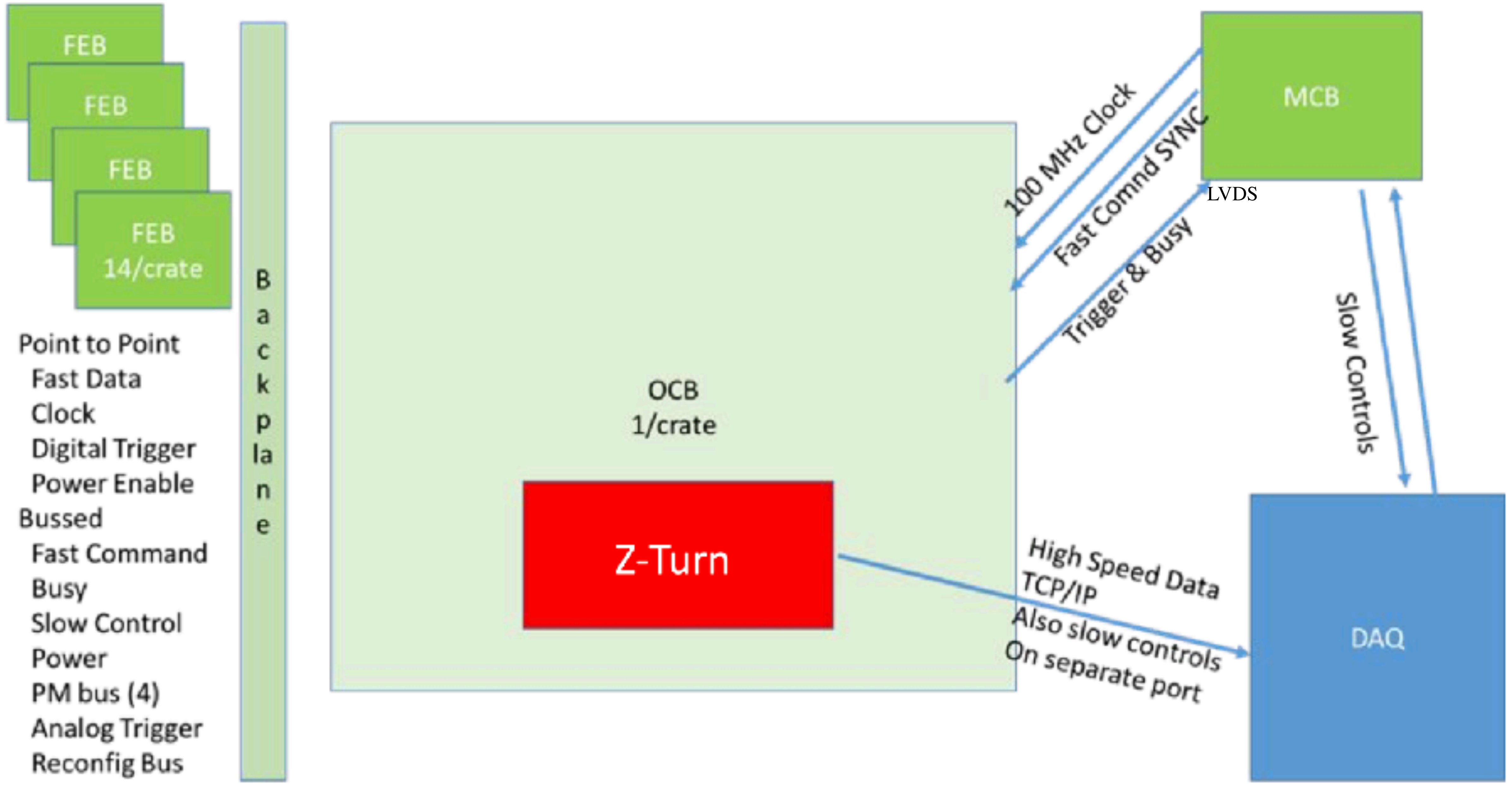
OPTICAL CONCENTRATOR BOARD (OCB)



The whip

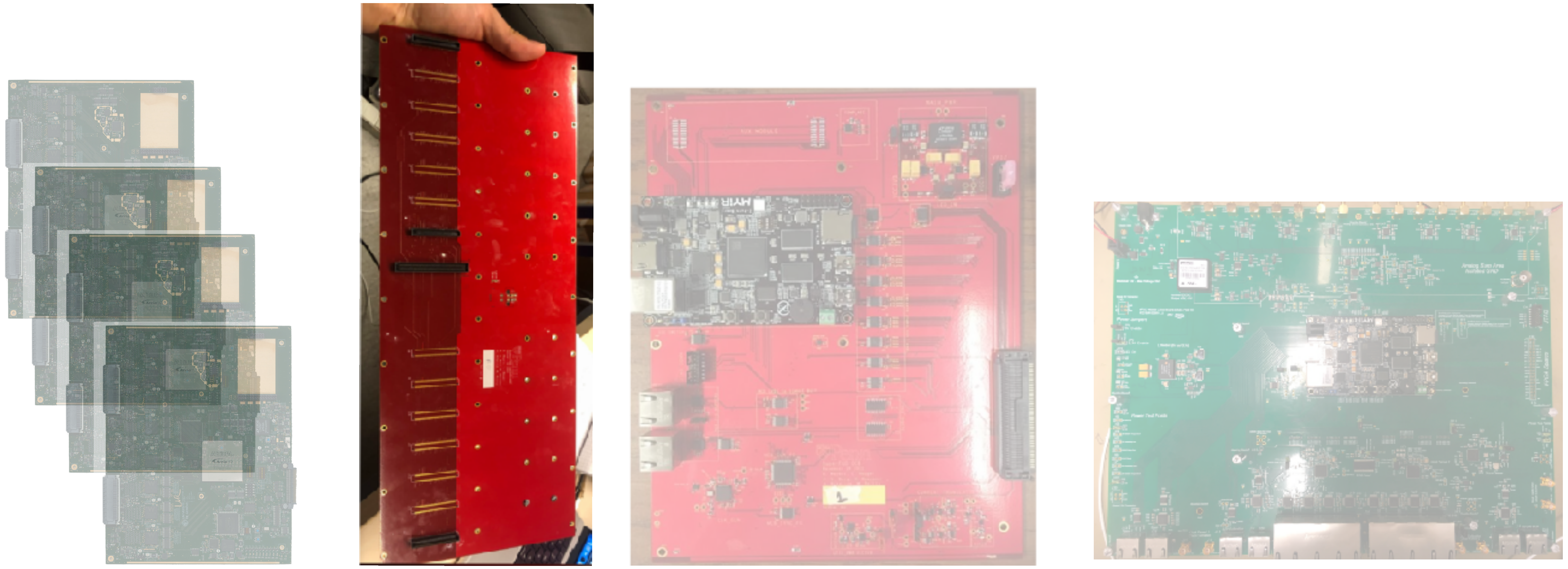


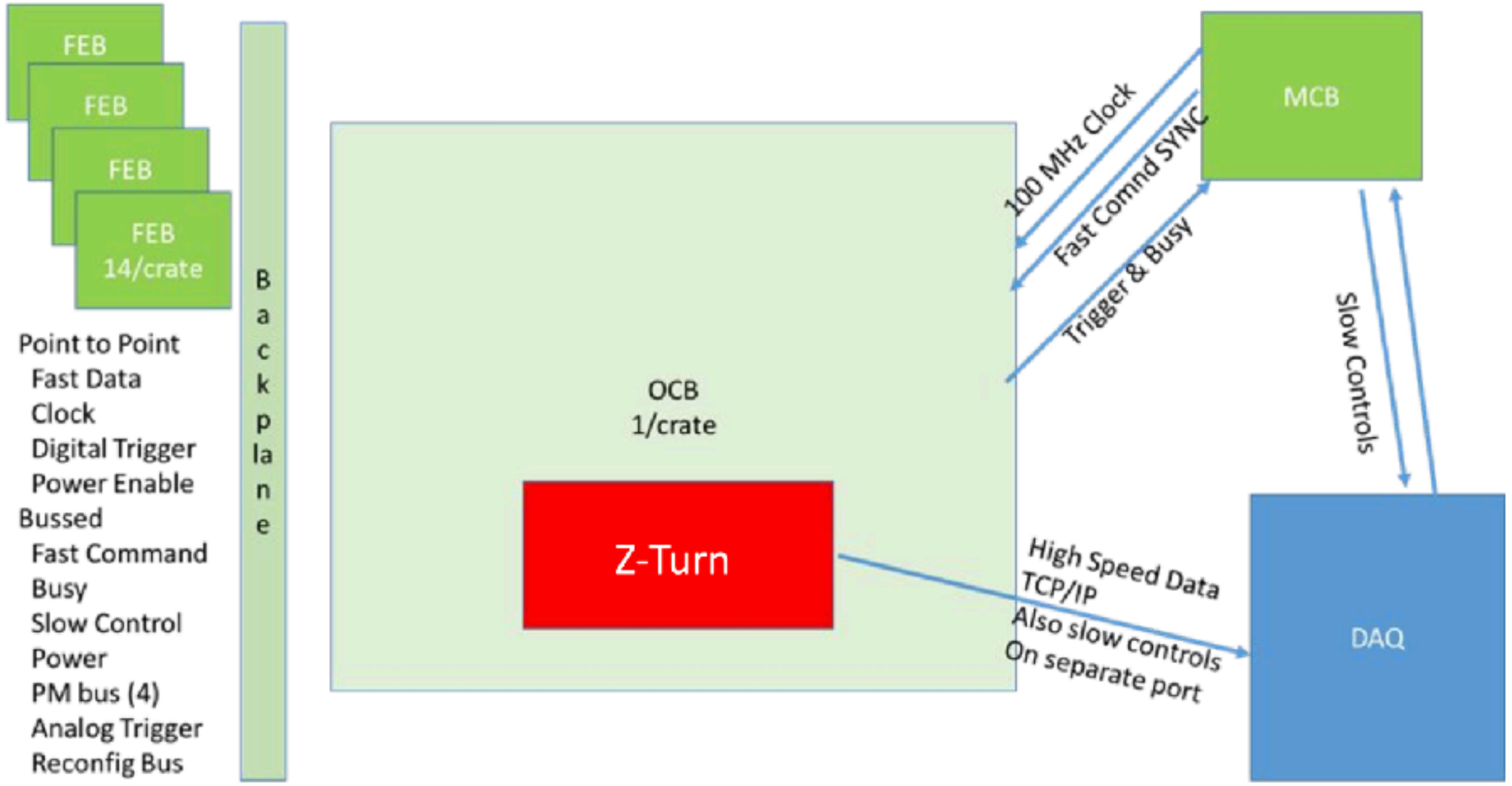




- The primary function of the Optical Concentrator Board (OCB) in the sFGD electronics system is to move and organise digital data and commands.
- The DAQ and slow control systems are connected to 14 FEBs in a sFGD crate via the OCB.
- Moreover, OCB functions as a link between the MCB and the 14 FEBs.

BACKPLANE

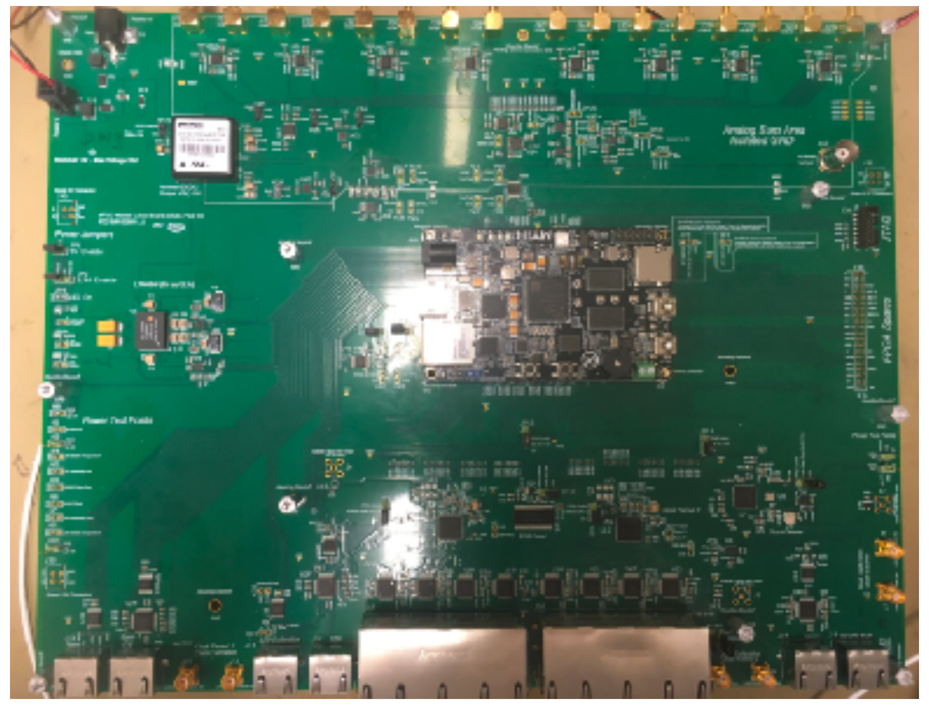




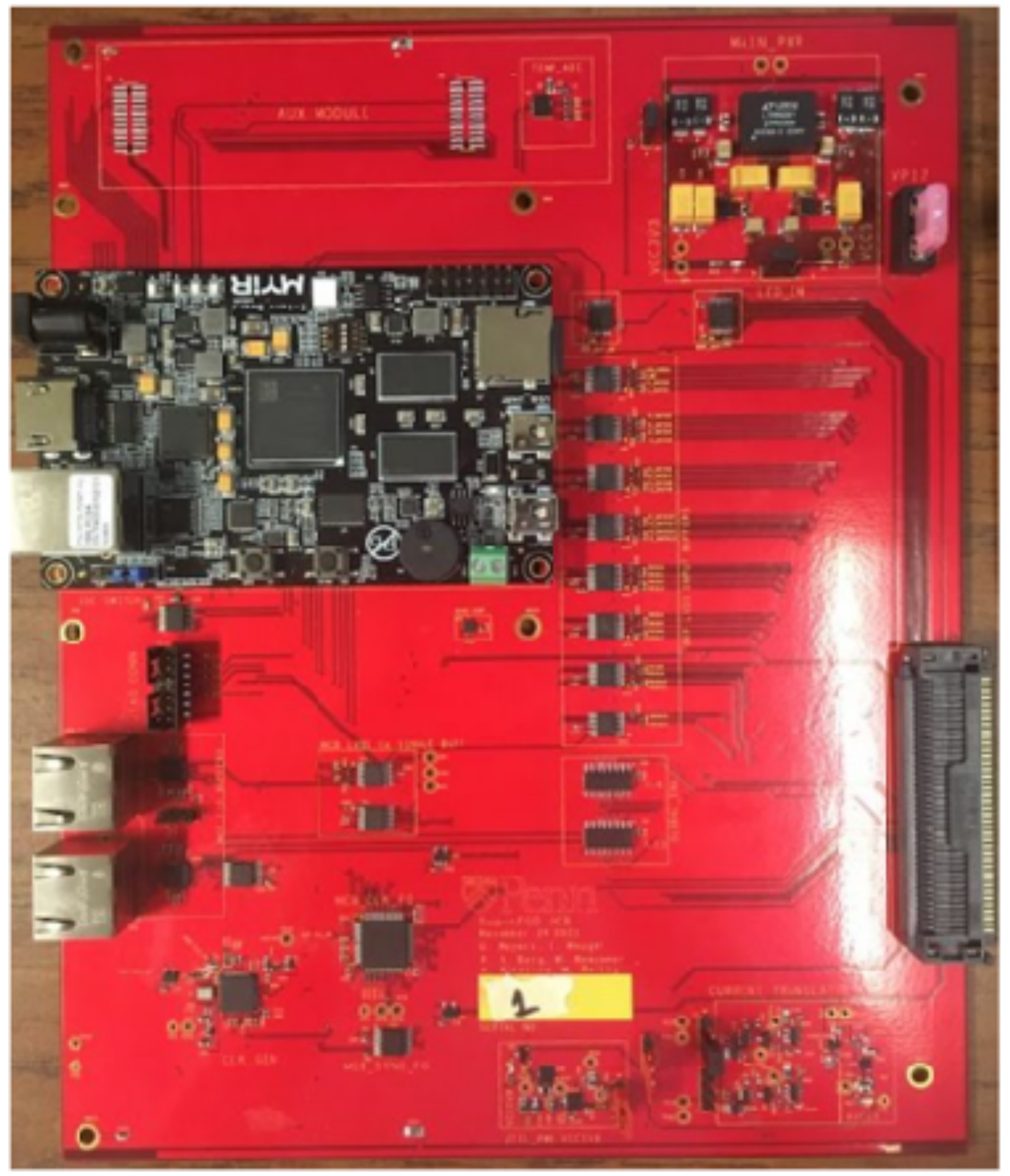
- Point-to-point and multi-drop signals that transit via the backplane make up the FEB - OCB communication.

SUMMARY OF RELATIONSHIP BETWEEN BOARDS

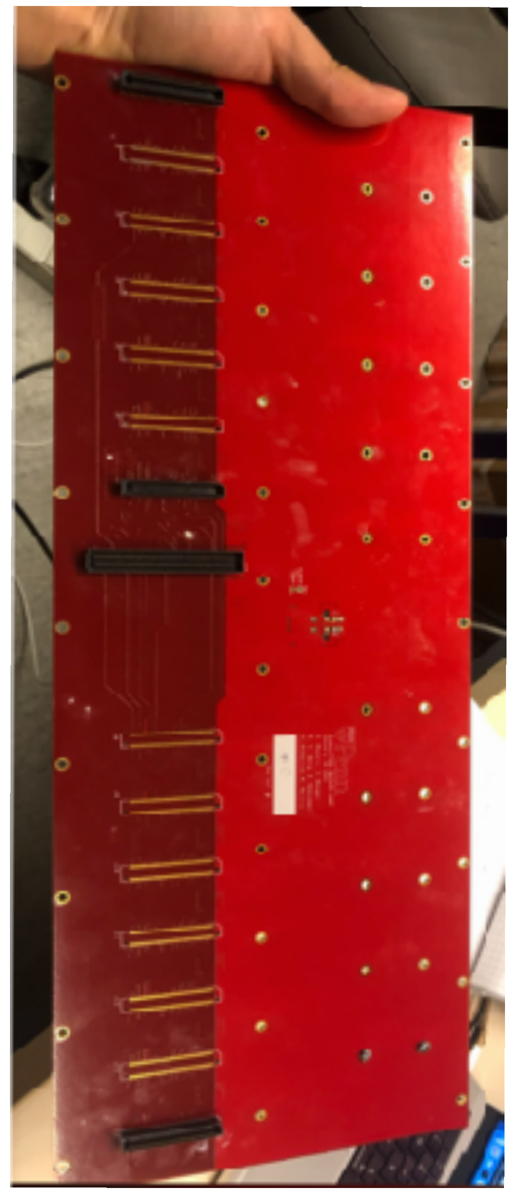
- In document: the FEB is the heart of the electronic system.
- In reality:



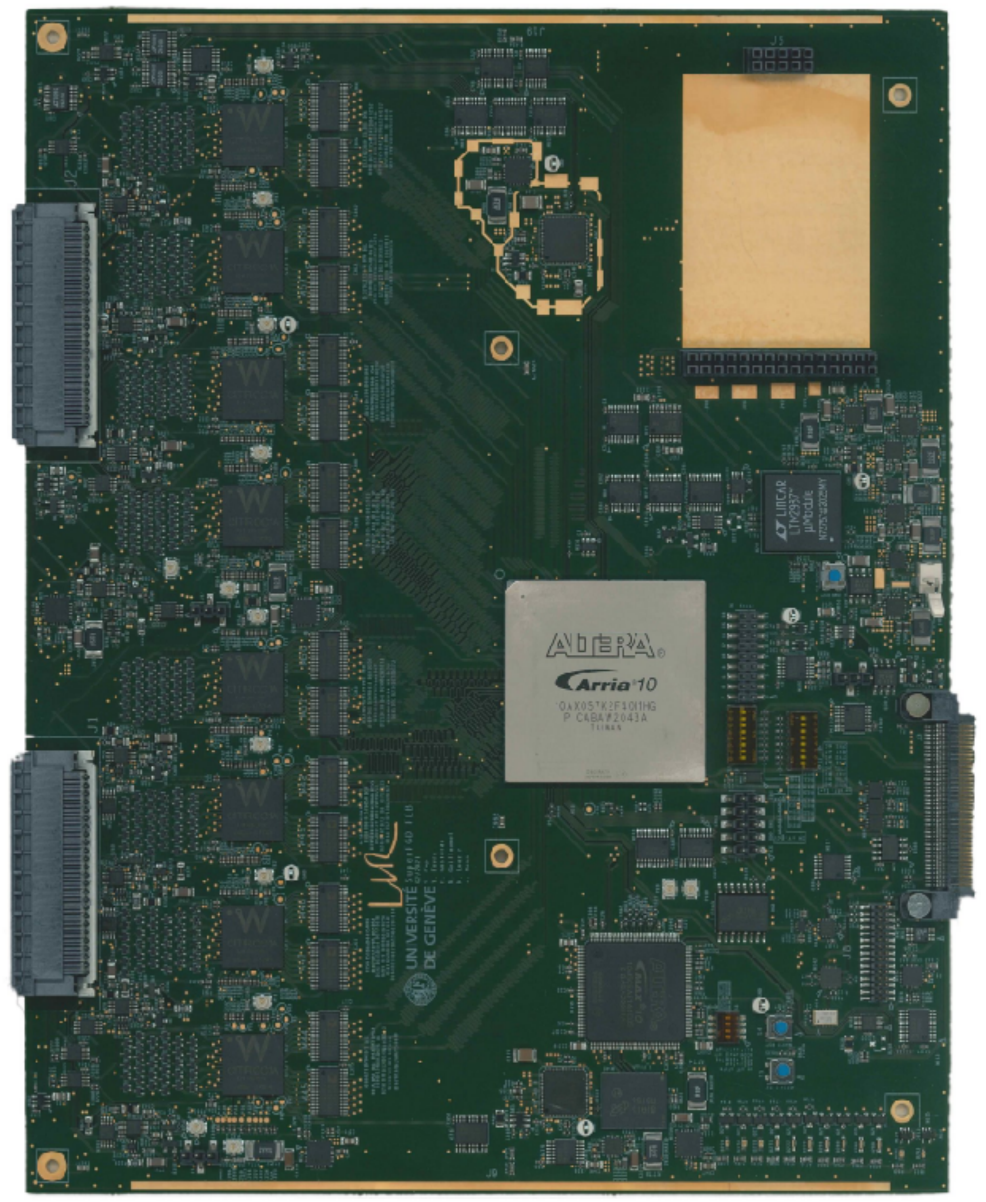
MCB: the OCB advisor



OCB: the master



Backplane: the whip



FEBs: the slaves

FRONT-END BOARD (FEB) COOLING PLATE PRODUCTION AT LLR

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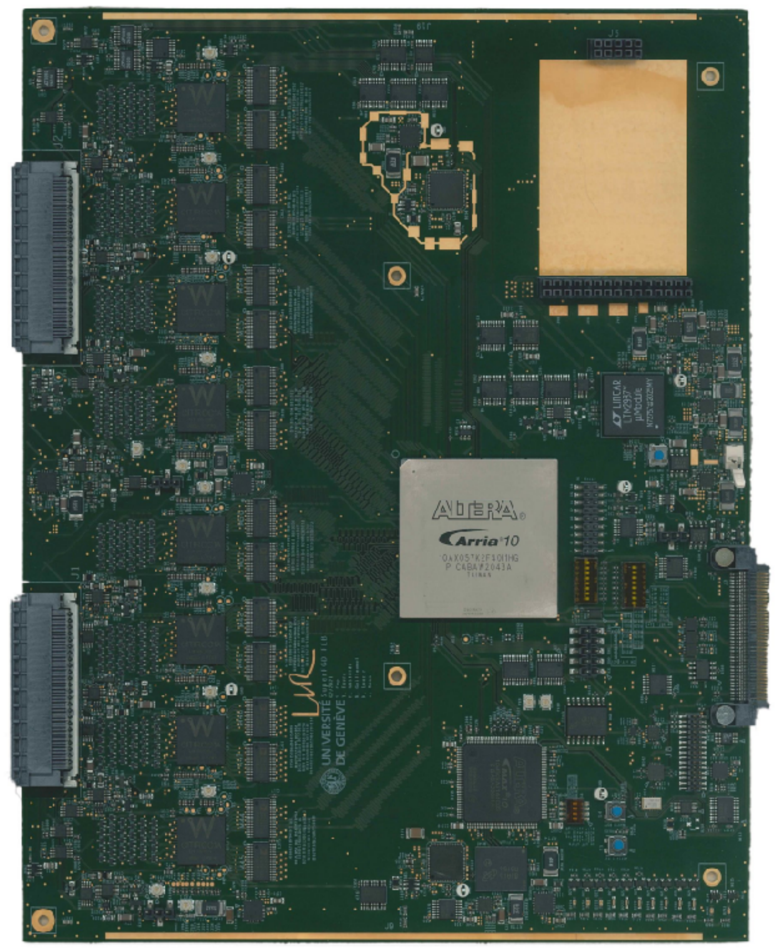

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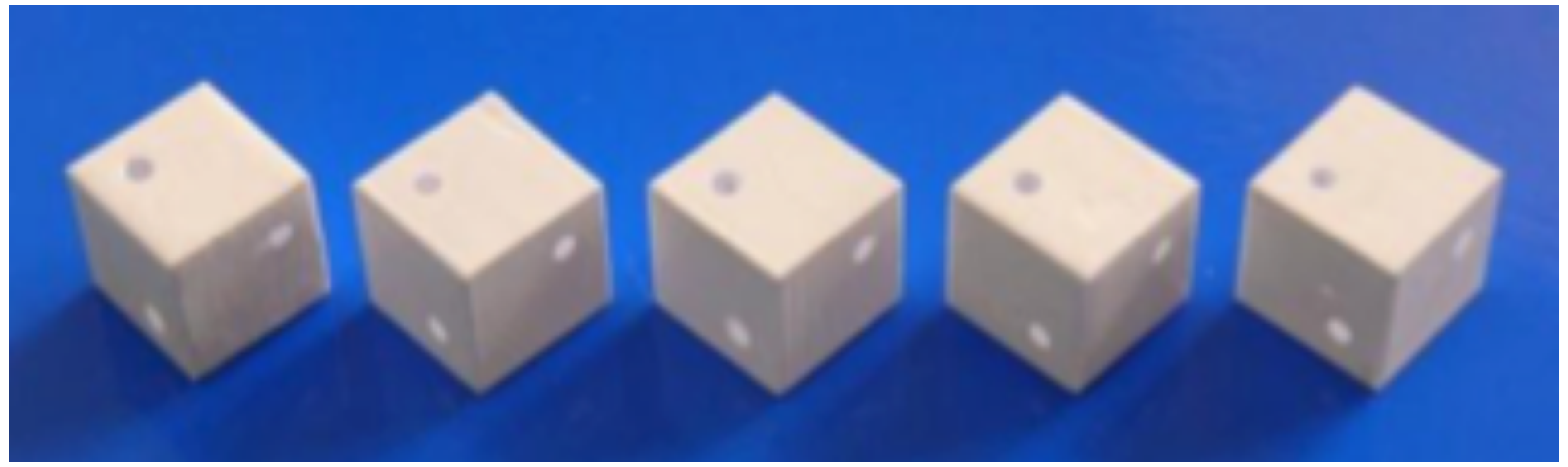
In June 2023:

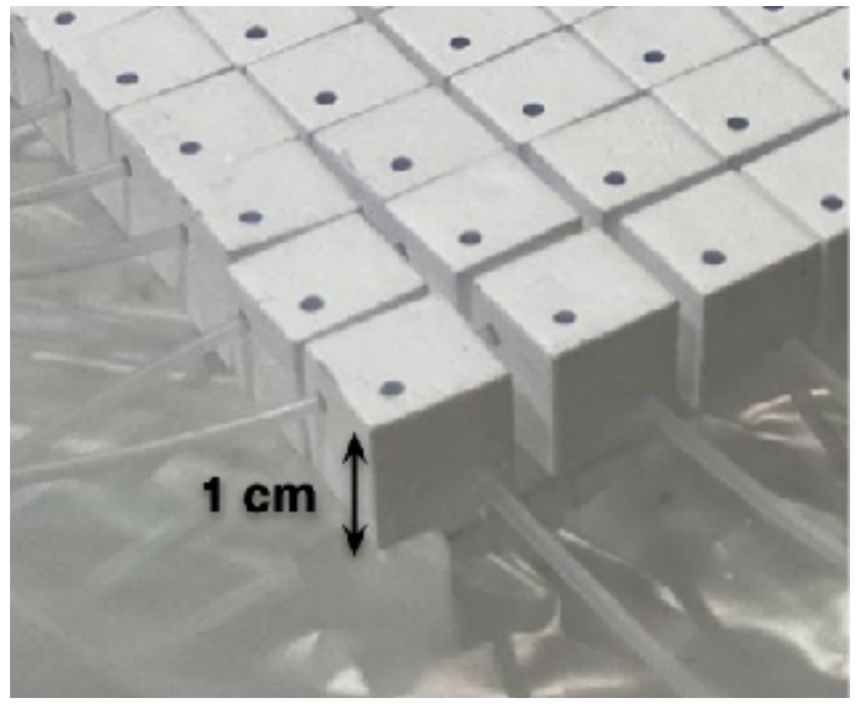
~230 cooling plates were produced at LLR with a lot of help from SK group and Mechanic group!!

Thanks a lot !!! (^.^)

SUPER FGD 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
- After quality checks, all the cubes were assembled layer by layer using fishing lines before delivering.

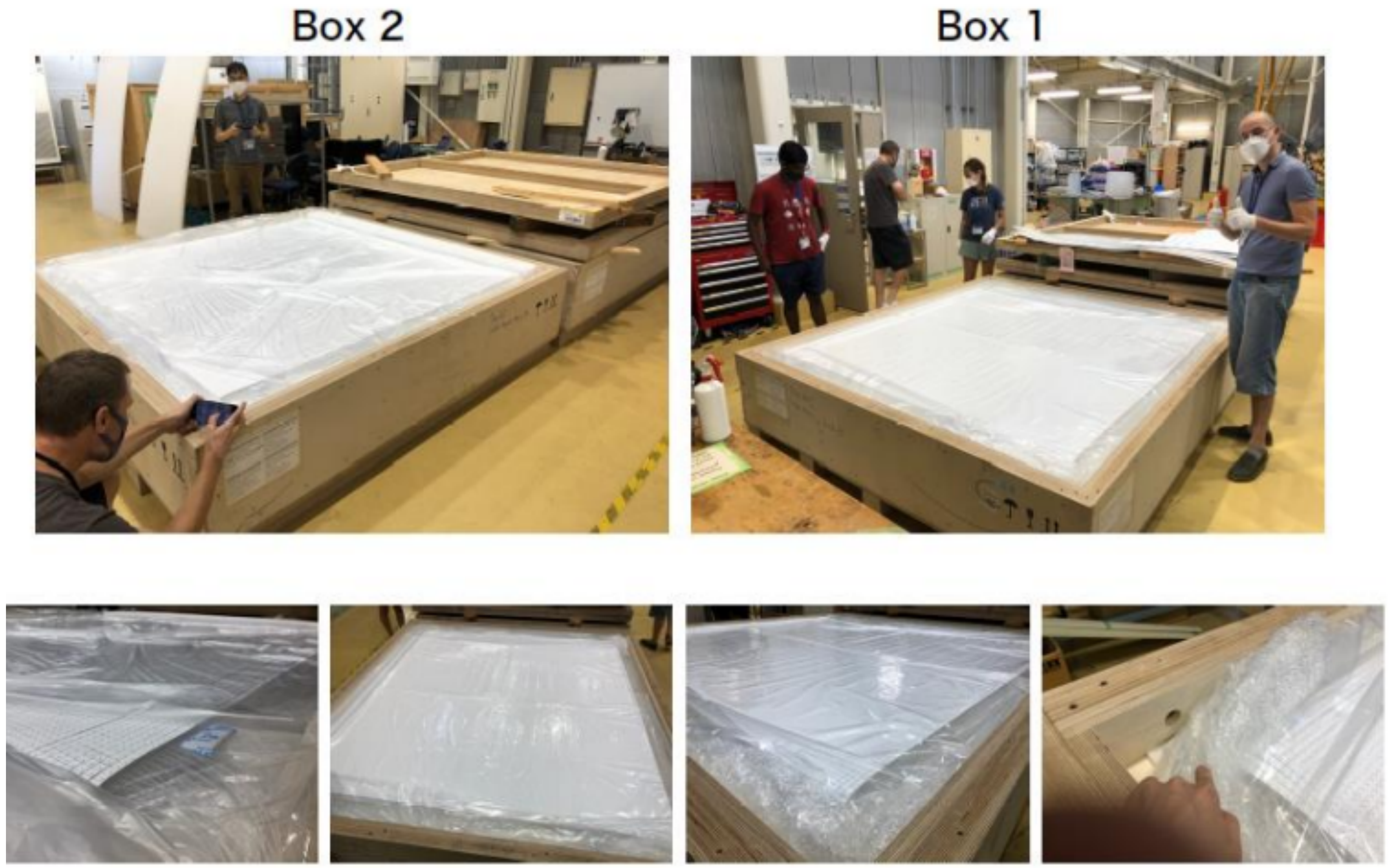




First layers

All (56) layers

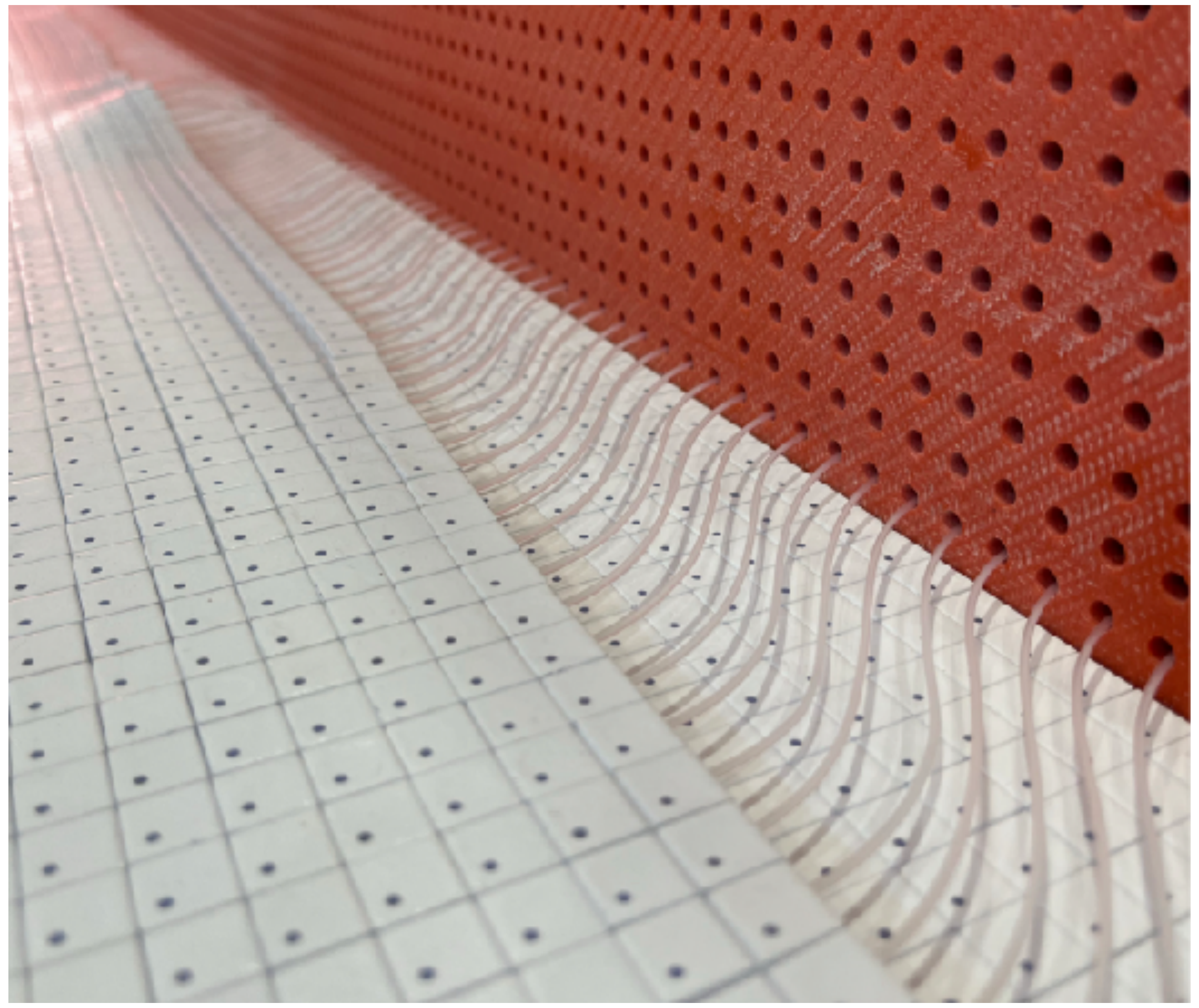
SUPER FGD ASSEMBLY AT J-PARC



The cubes were shipped to Japan by plane

The Super-FGD box which carry all the cubes

SUPER FGD ASSEMBLY AT J-PARC



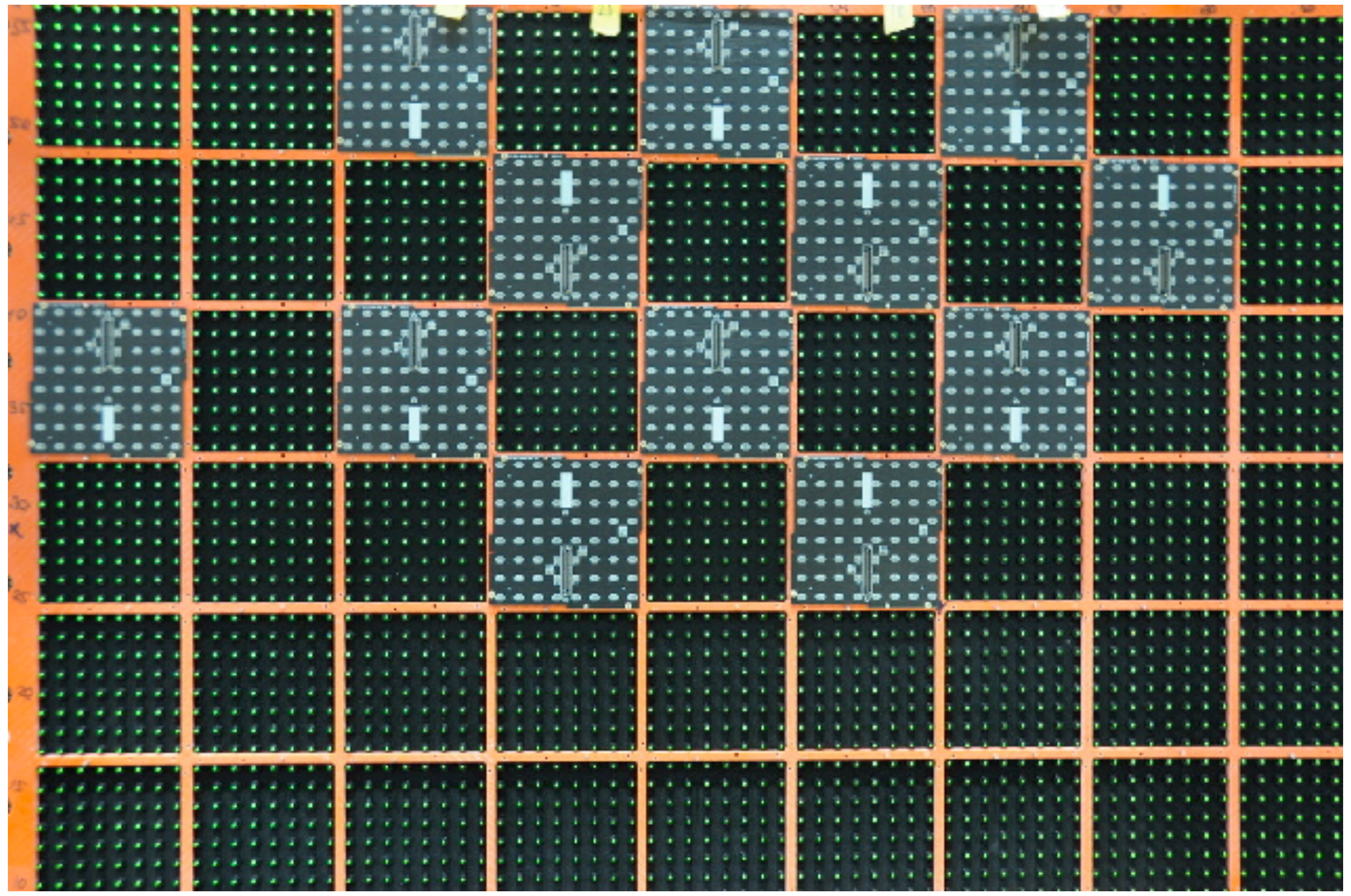
Insert the 2 million cubes in the Super-FGD box layer by layer

Insert the fishing lines

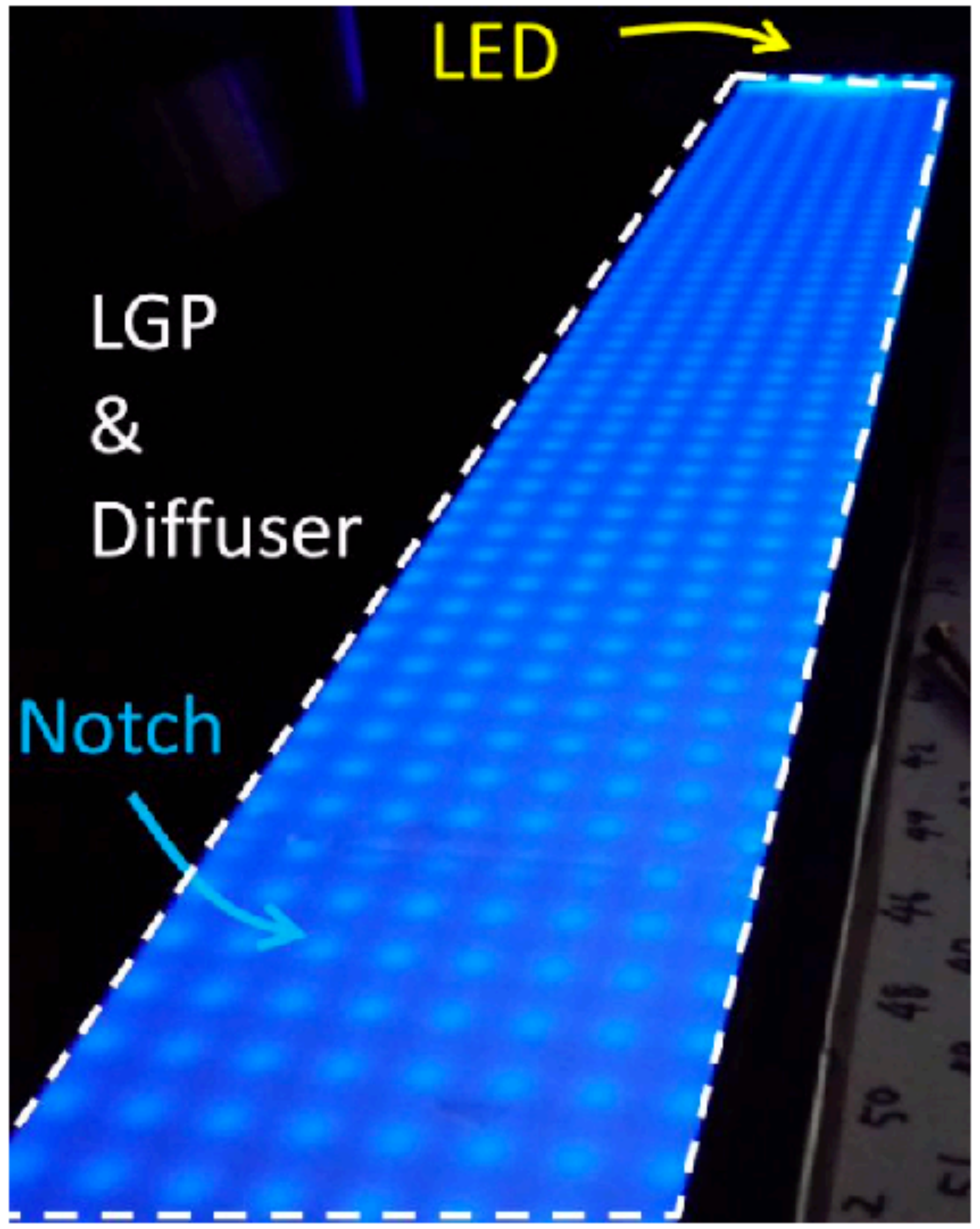
After closing the Super-FGD box, the fishing lines will be replaced by the wavelength shifting fibers

SUPER FGD ASSEMBLY AT J-PARC

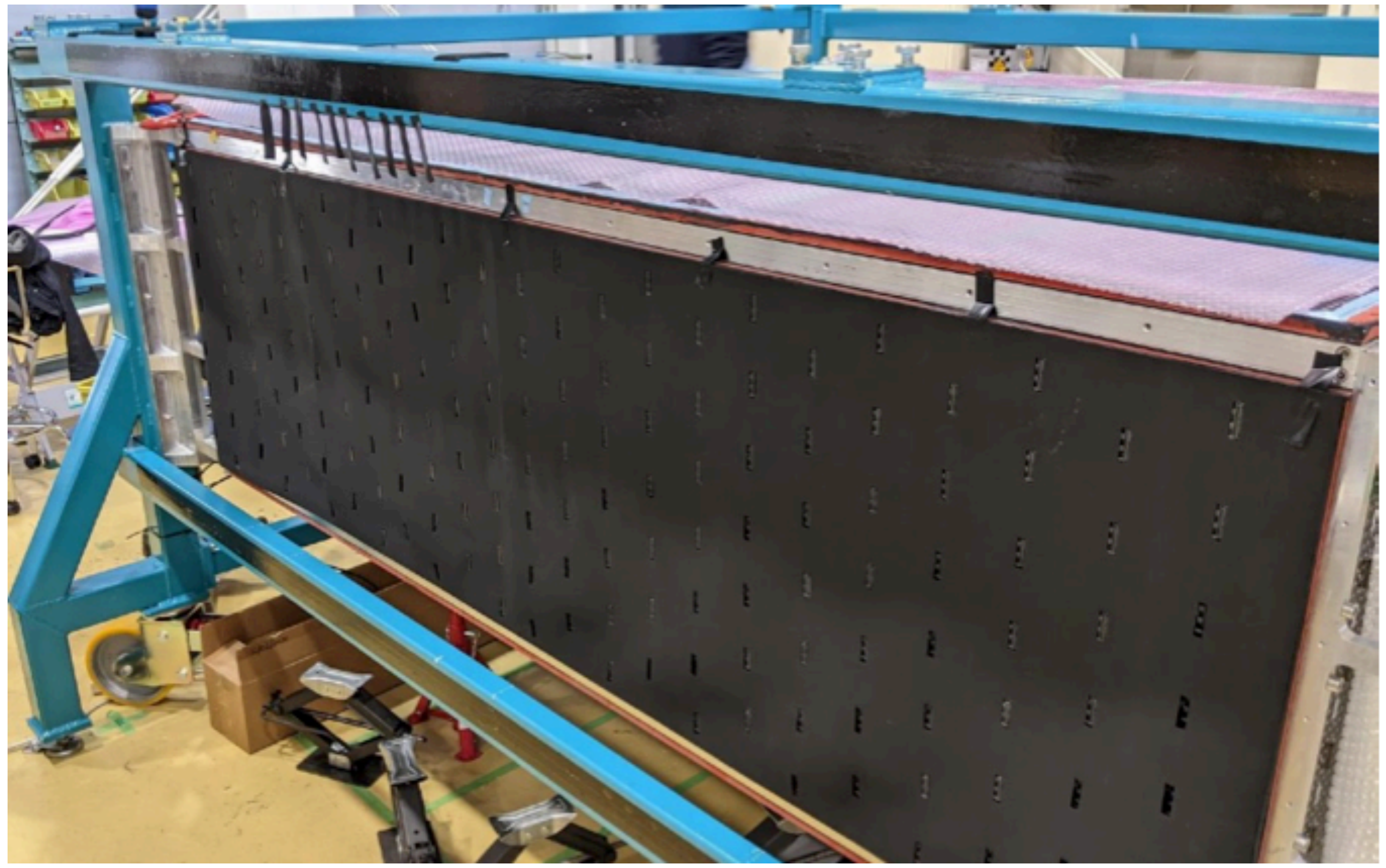
Attach MPPC boards on the sides of the box



Install LED calibration system

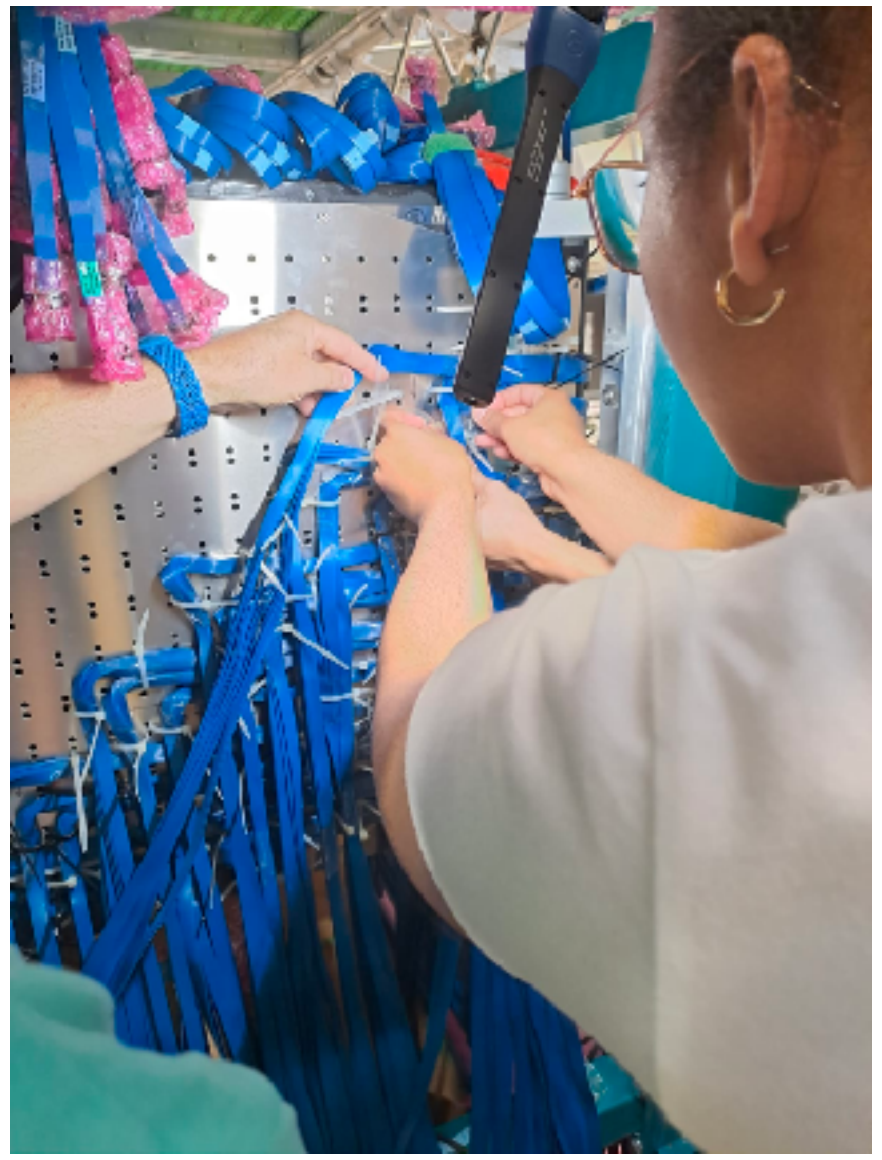


Install light barriers

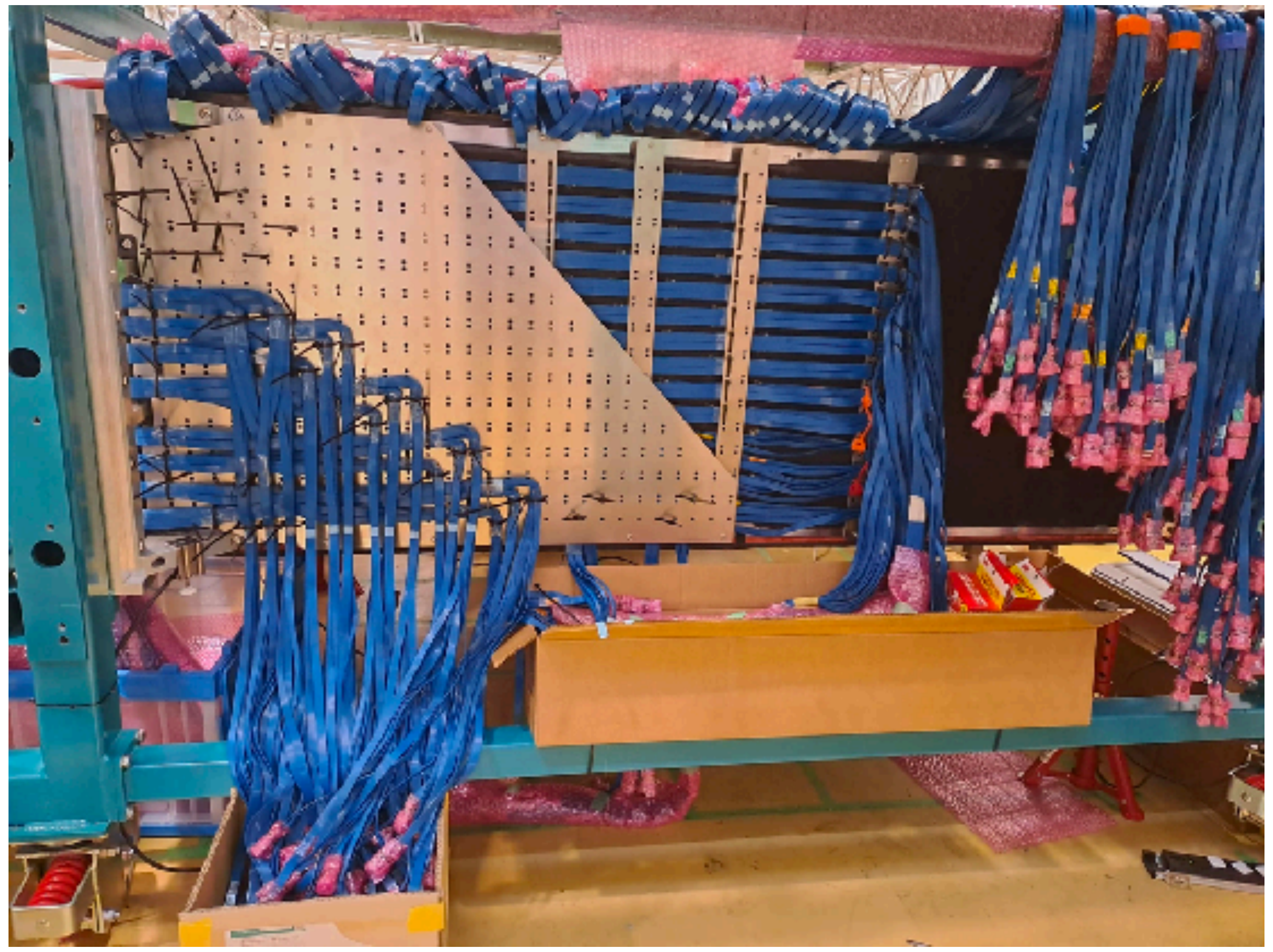


SUPER FGD ASSEMBLY AT J-PARC

Then the cables were attached on the MPPC64 boards and arranged.



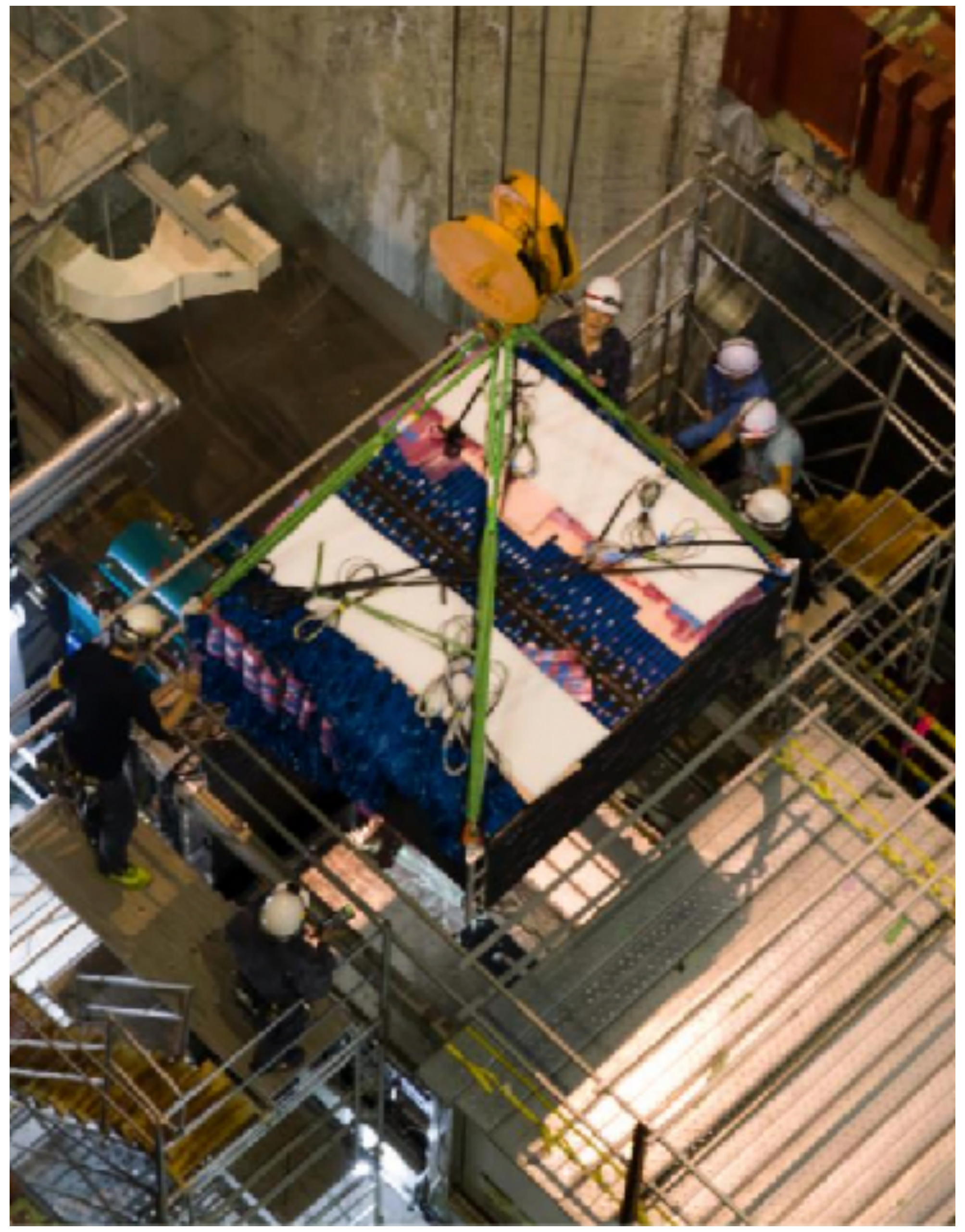
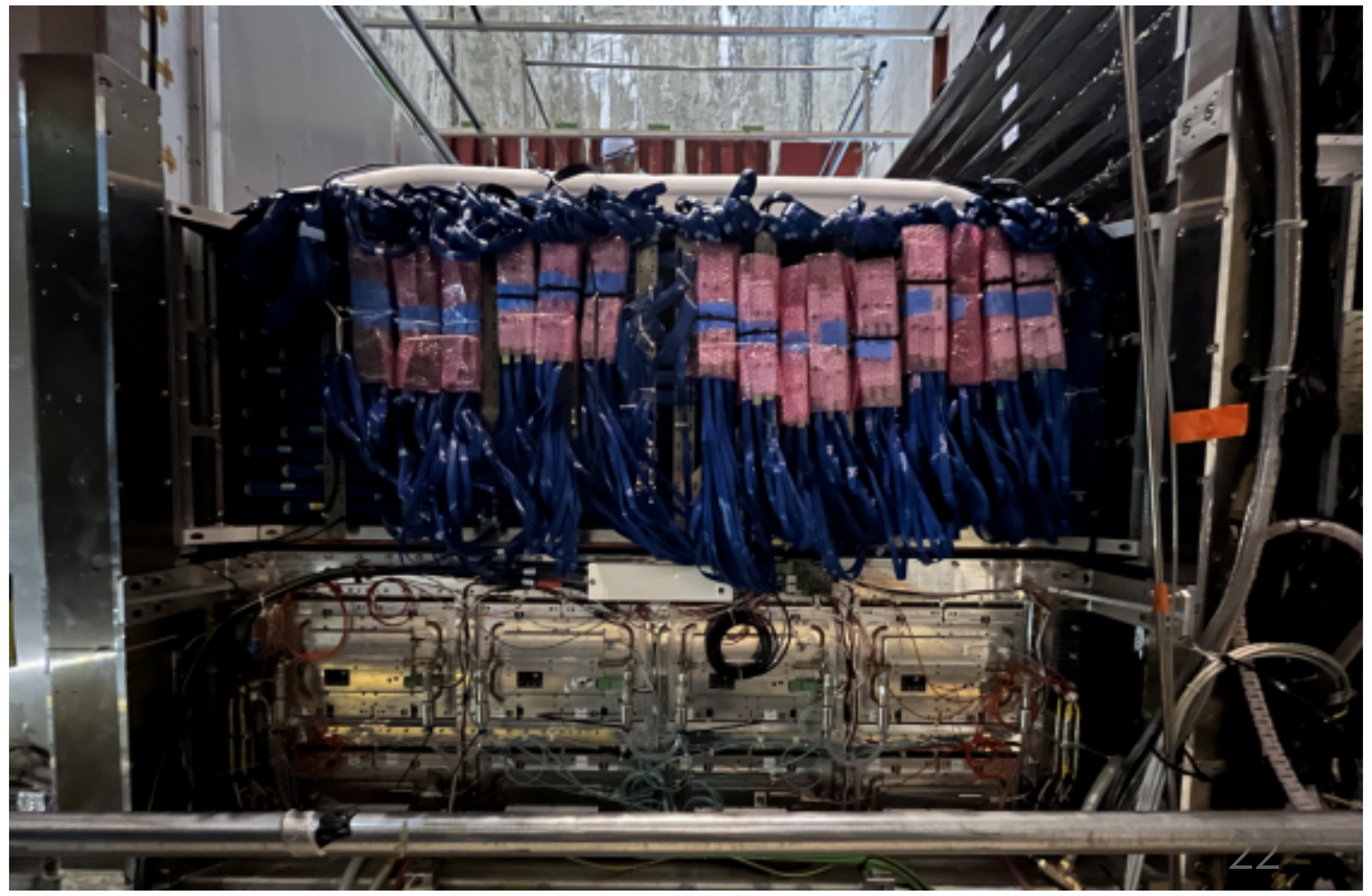
Lena working on arranging the cables.



SFGD installation (October 2023)

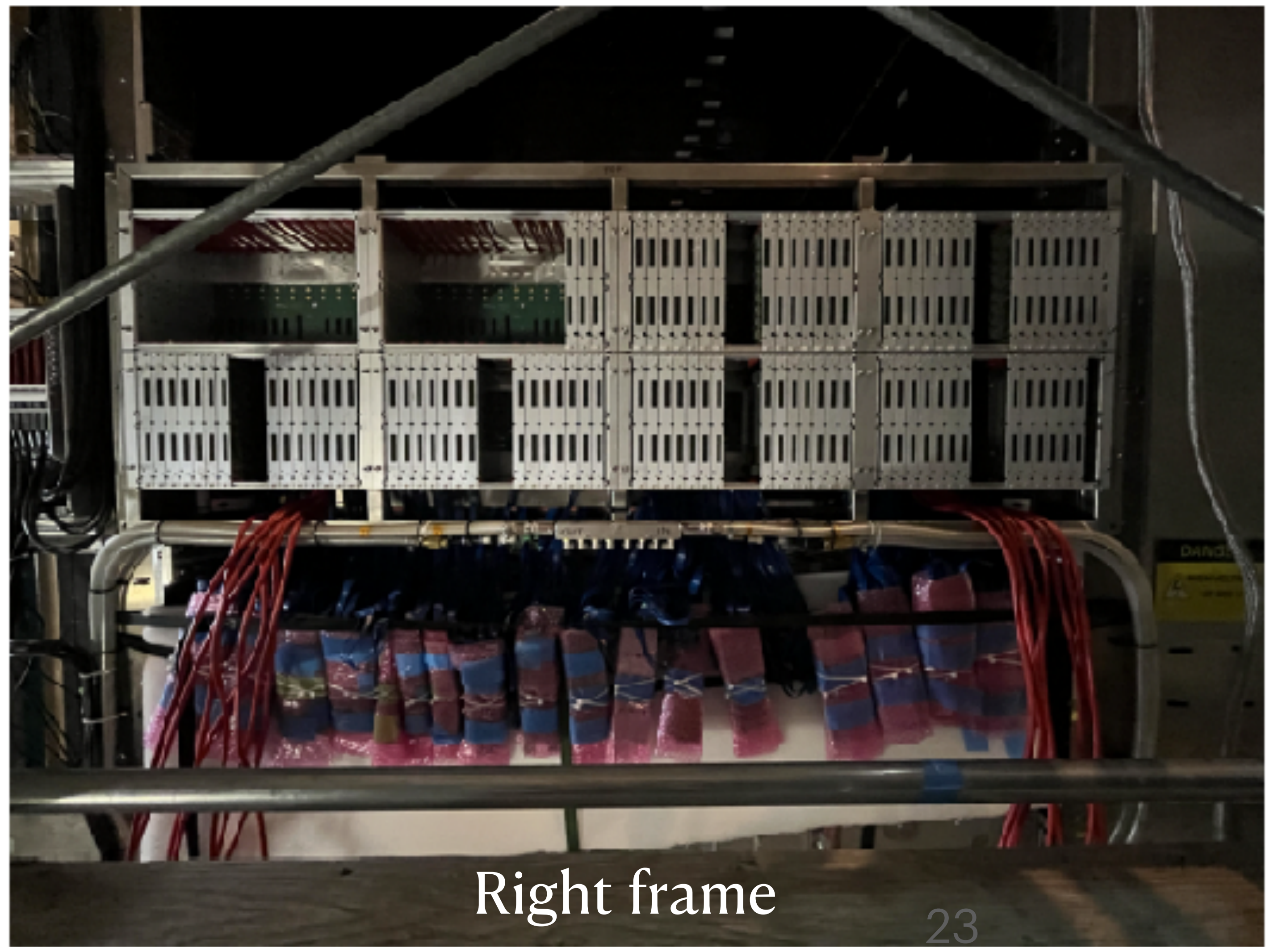




SFGD electronic installation (16th-17th October)

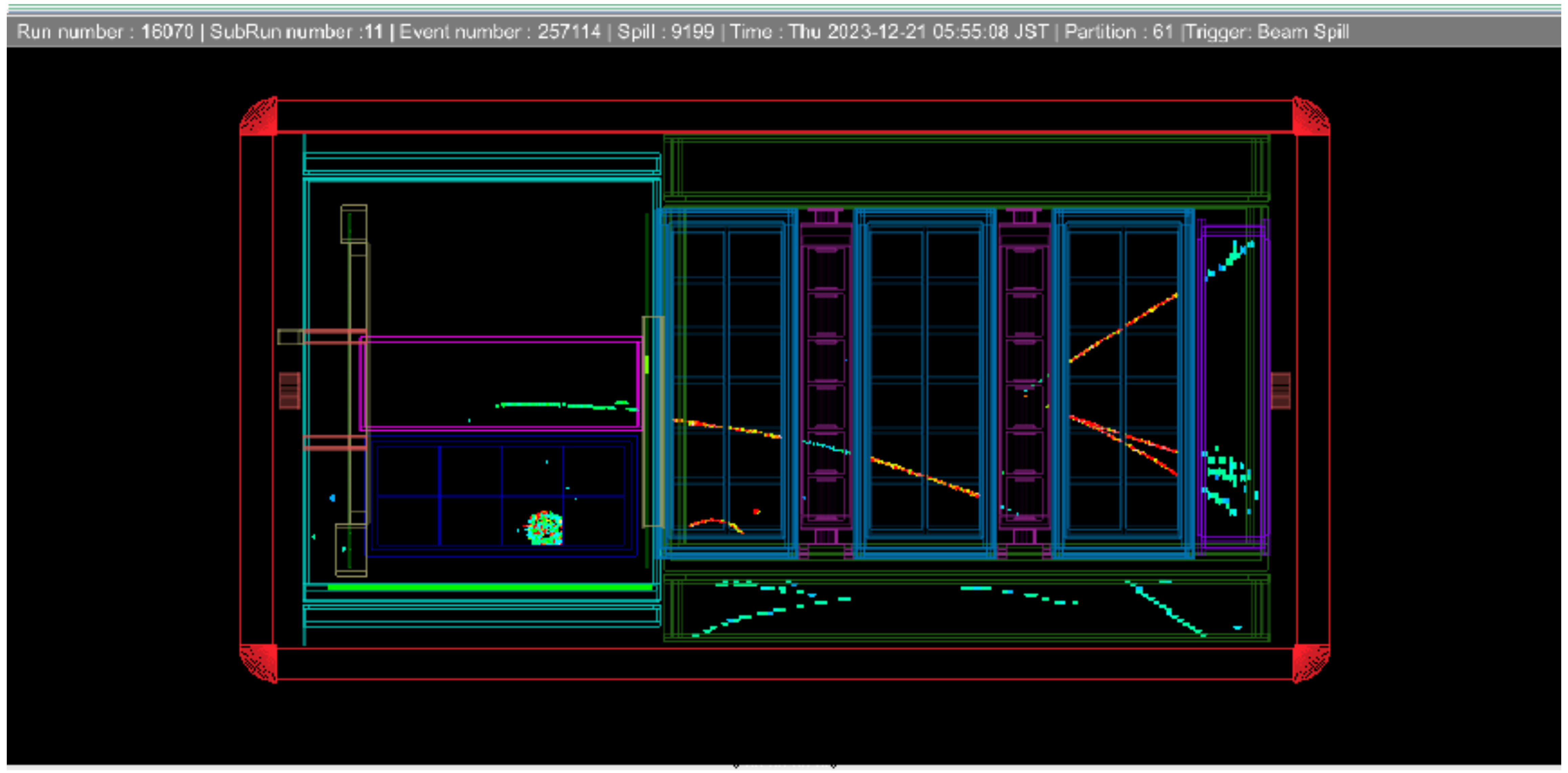
Left frame

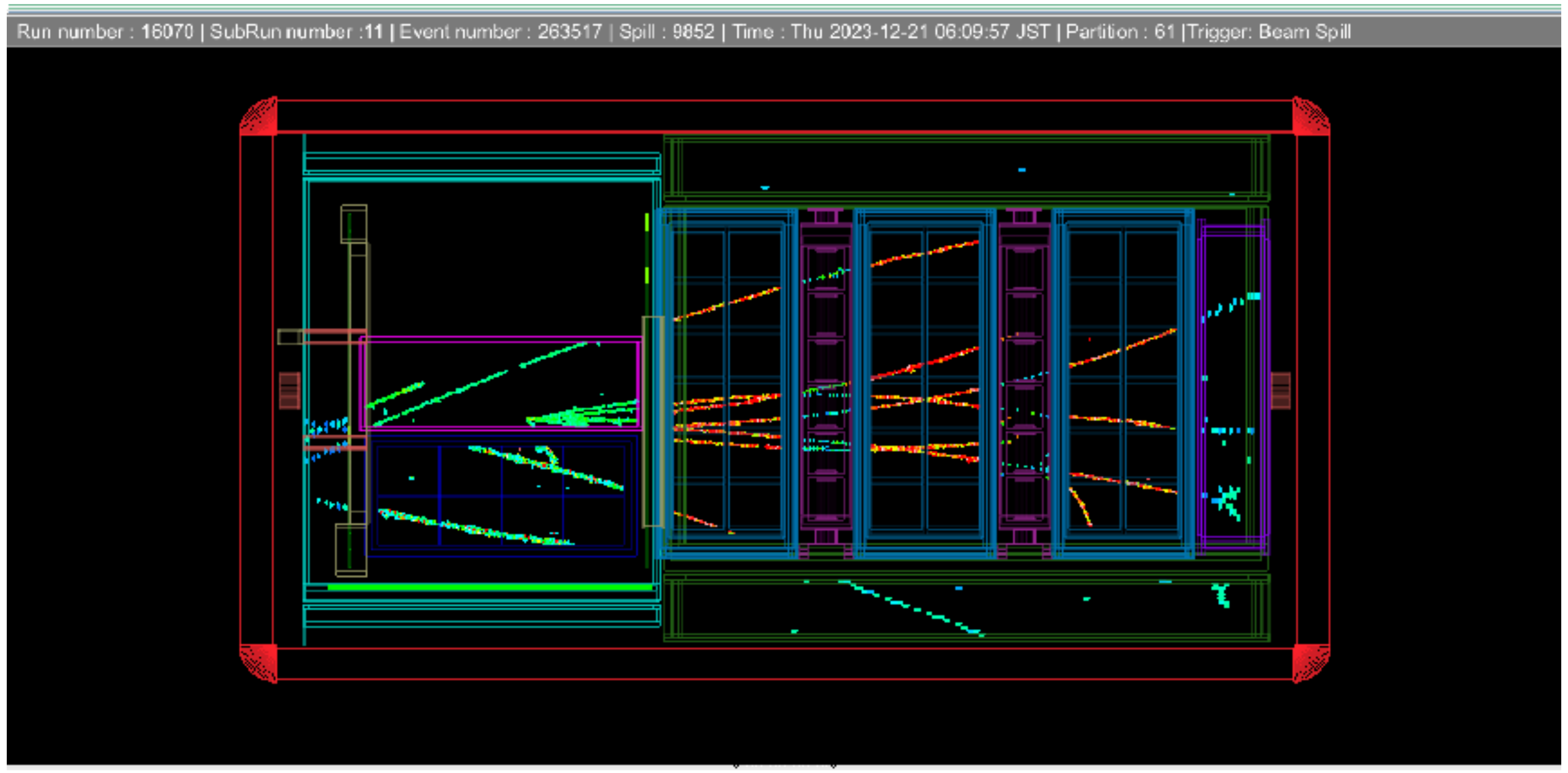


Right frame

Around 190 FEBs (out of ~230) were inserted into 2 frames, the rest are under debugging in Geneva and will be inserted at the next magnet open time.

SOME FIRST EVENTS WITH NEW ND280 CONFIGURATION

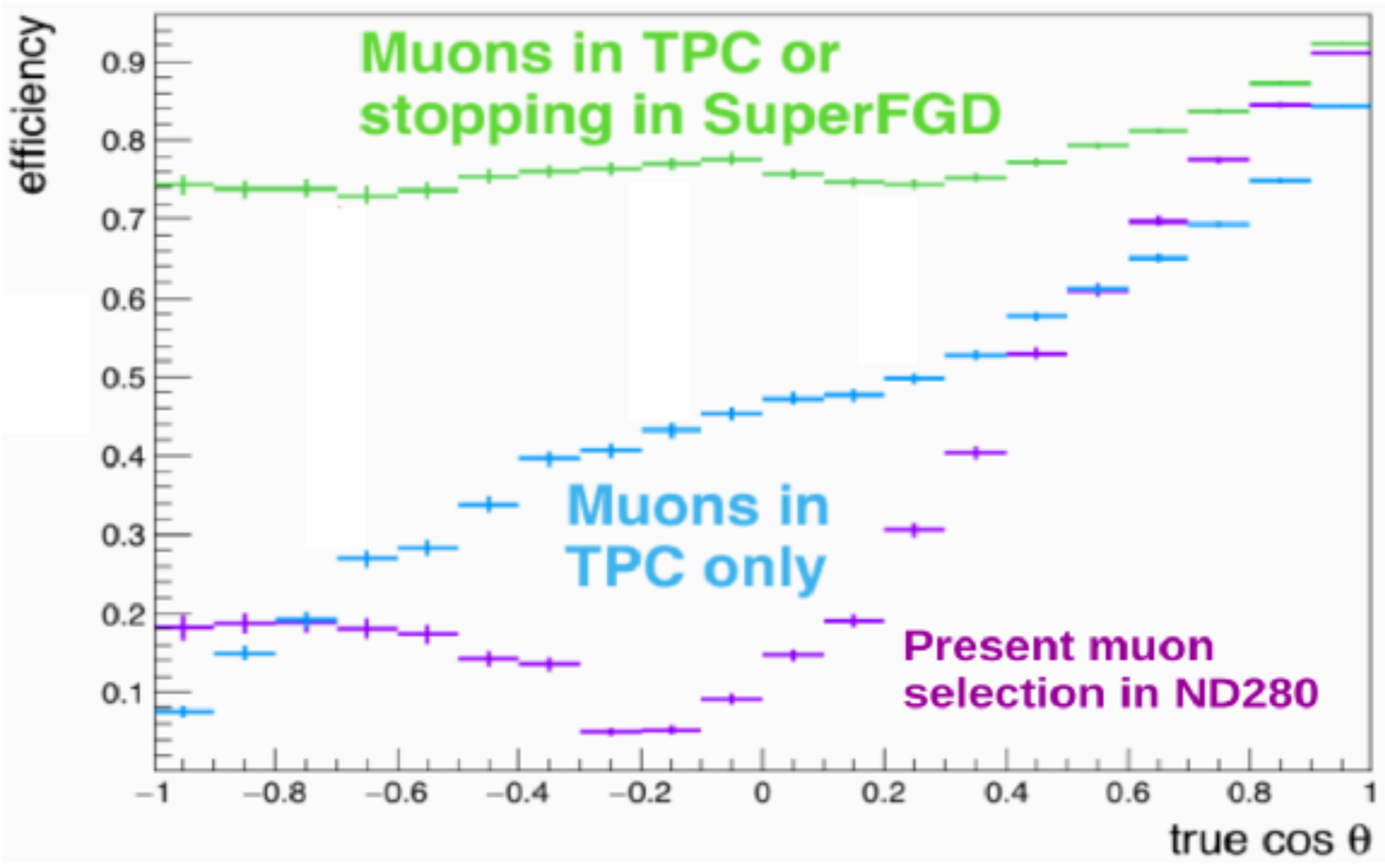


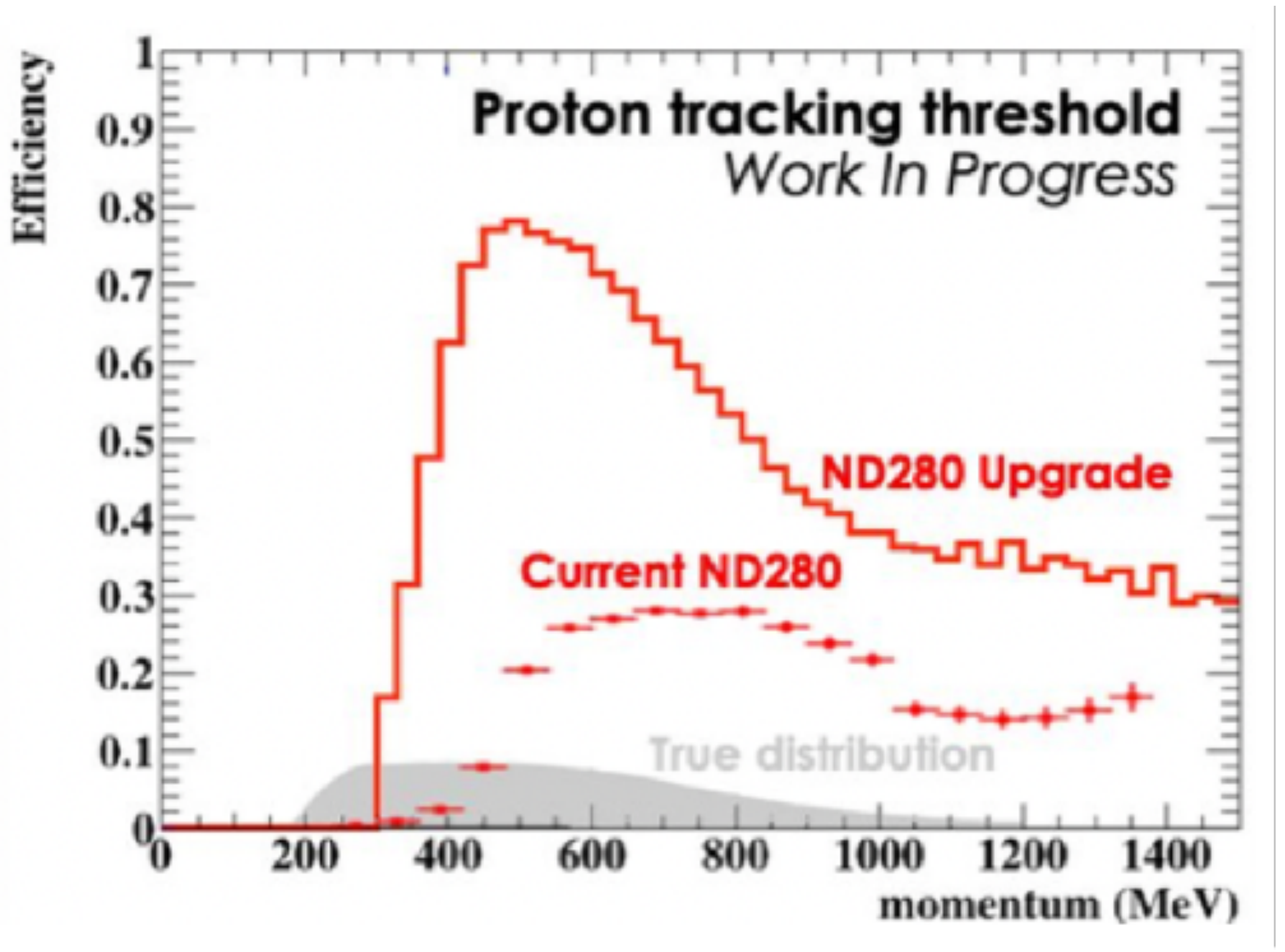


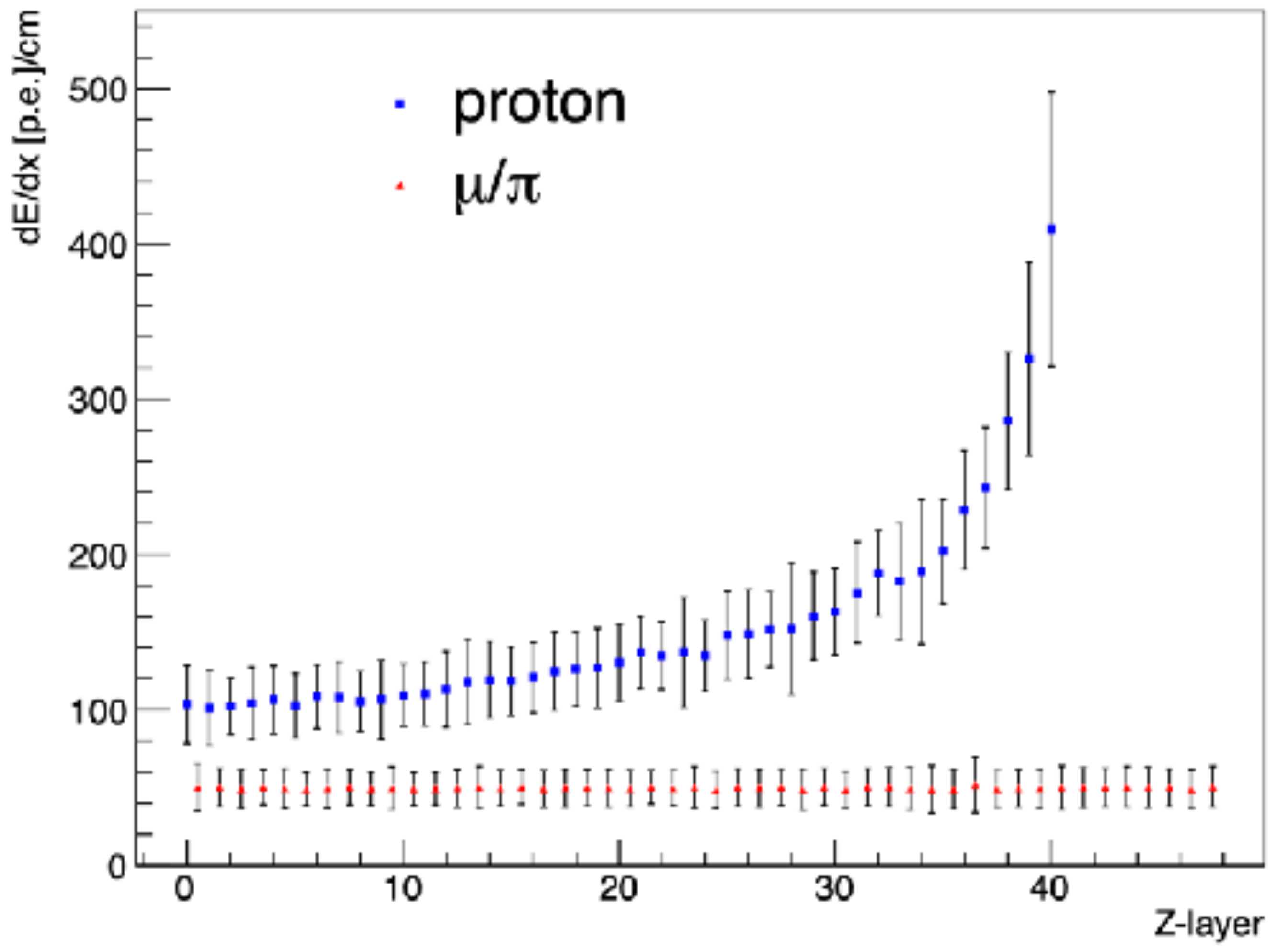
Technical run at the end of last year

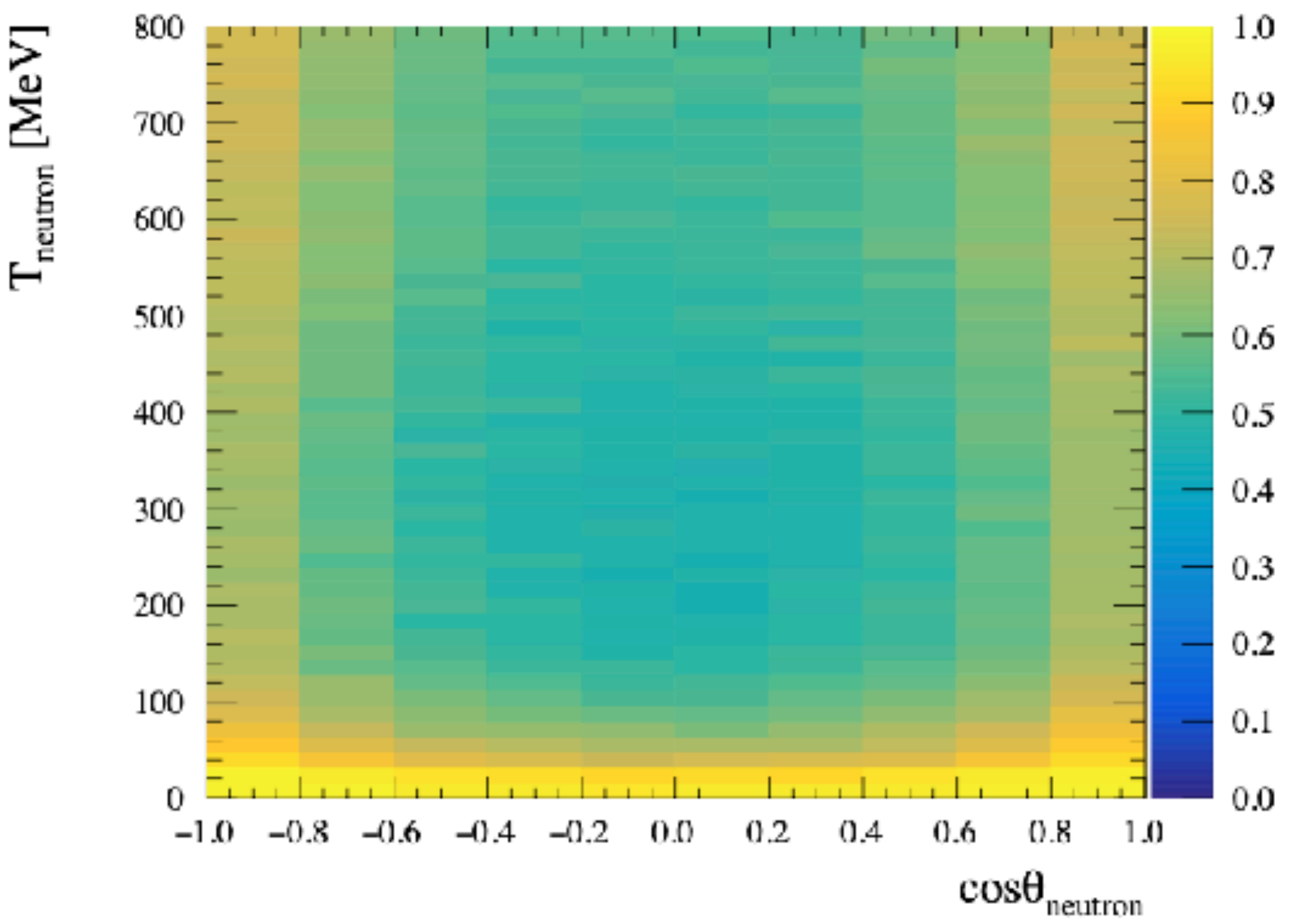
A lot of work related to mapping, calibration, global DAQ have done for these nice events

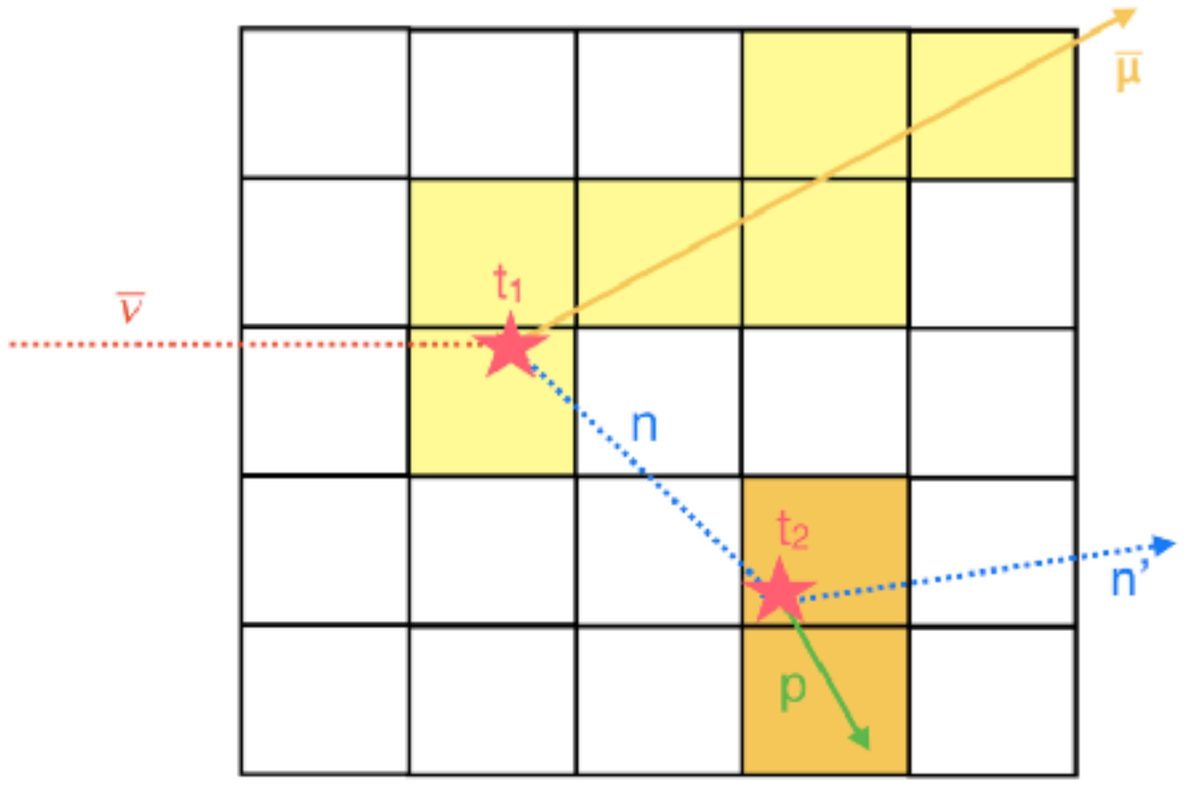
SUPER FGD PERFORMANCE











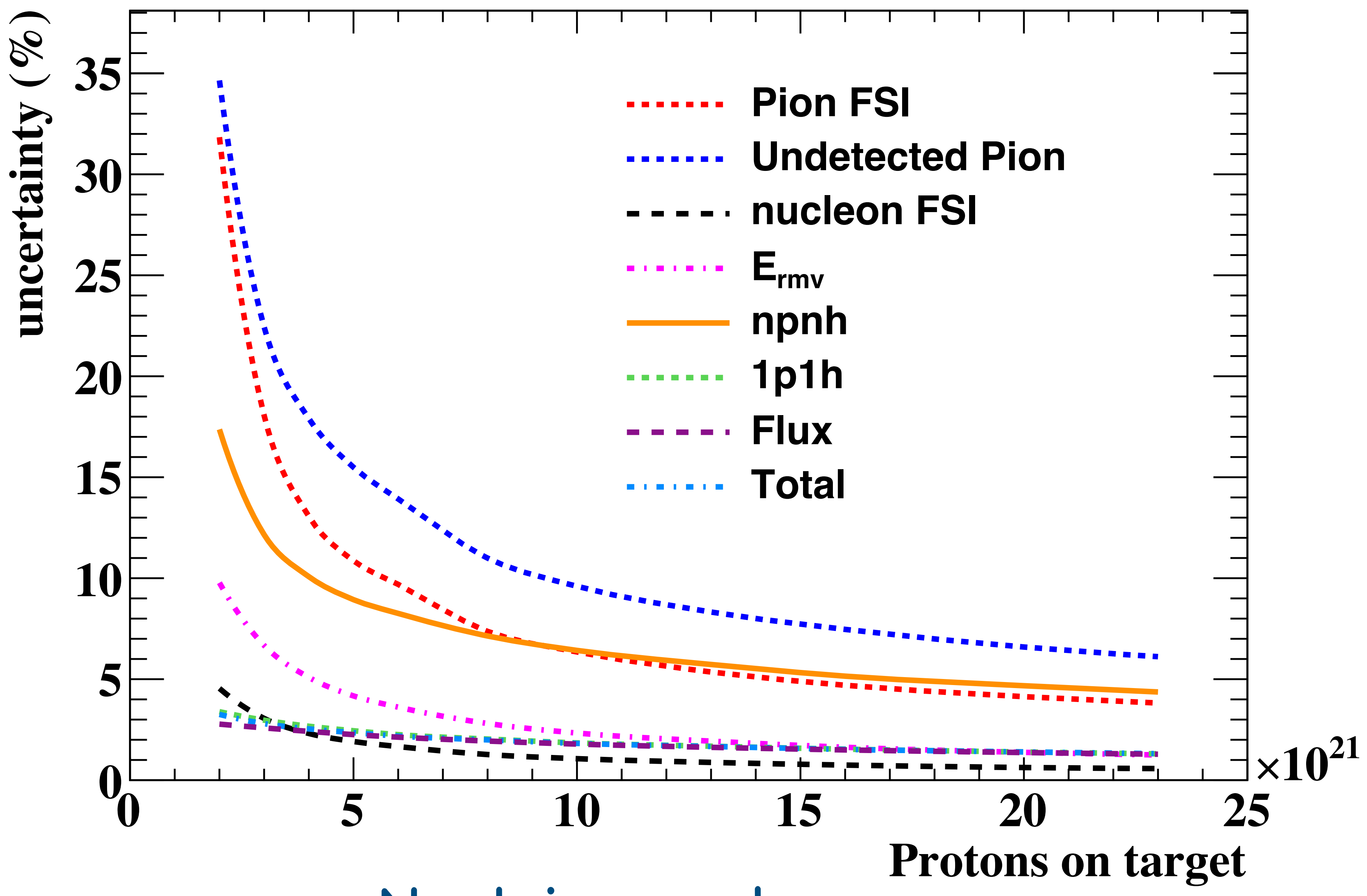
- 4π coverage (isotropic)
- Lower proton momentum threshold (300MeV/c)
- Neutron kinematics reconstruction by time of flight technique (0.6 ns time resolution)
- Very enhanced PID

Neutron detection through time of flight technique

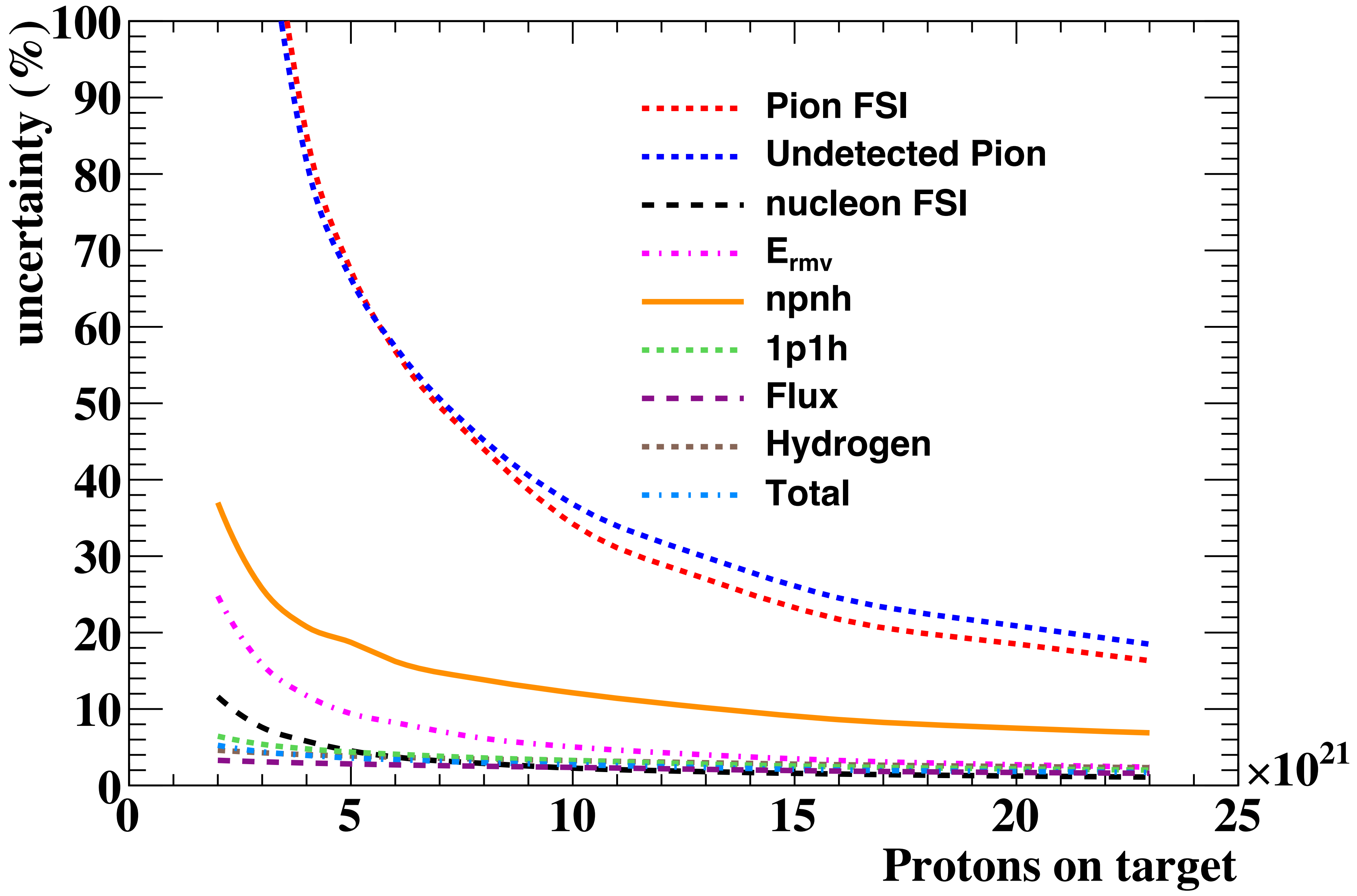
UPGRADED NEAR DETECTOR ND280: PERFORMANCE

To be repaired for the upgrade ND280, a new near detector fit have been devoloped (GUNDAM). LLR has strongly participated in its development validation and coordination. Also, GUNDAM has become the reference fitter for the ND fit.

At ultimate statistic, the systematic uncertainties are below 10% in neutrino mode and below 20% in anti-neutrino mode



Neutrino mode



Anti-Neutrino mode

Phys. Rev. D 105, 032010

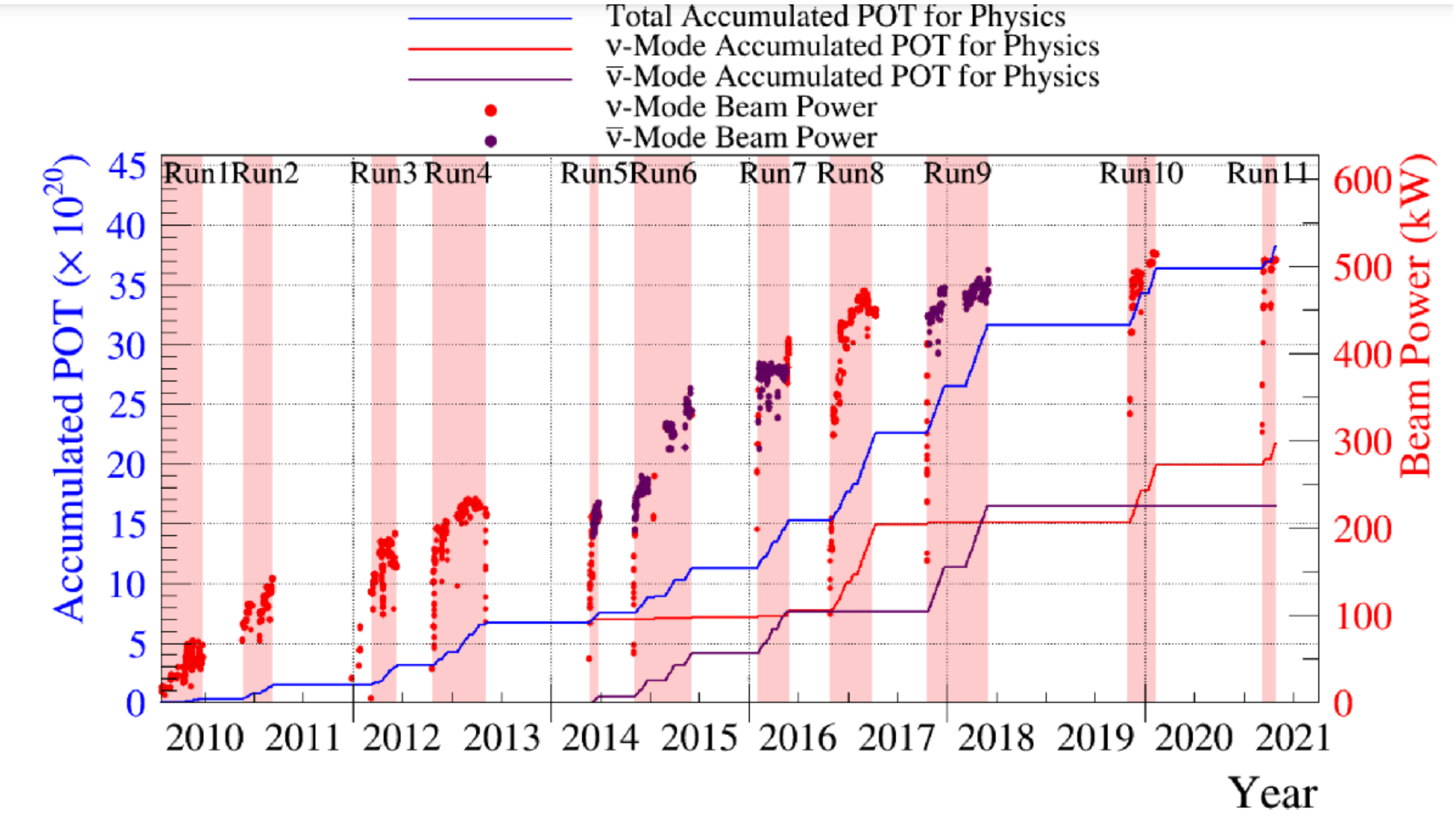
SUMMARY

- To be ready for the Hyper-K period, where the statistical uncertainty is reduced and the systematic uncertainty becomes dominant, ND280 Upgrade helps significantly with improving systematic uncertainties.
- Upgraded ND280 is actively under installation and near to completion.
- Many new tools related to simulation and reconstruction are actively under development for the new detector.
- The T2K Collaboration has started data taking using the enhanced neutrino beam and new neutrino near-detectors from December 2023.
  - The neutrino beam power has been successfully achieved at 760kW,
  - The current applied to the electromagnetic horn has been increased from 250 kA to 320 kA
  - Neutrino intensity increases by about 10%

Stay tuned for new results with upgraded ND280!

BACK UP

T2K STATISTIC

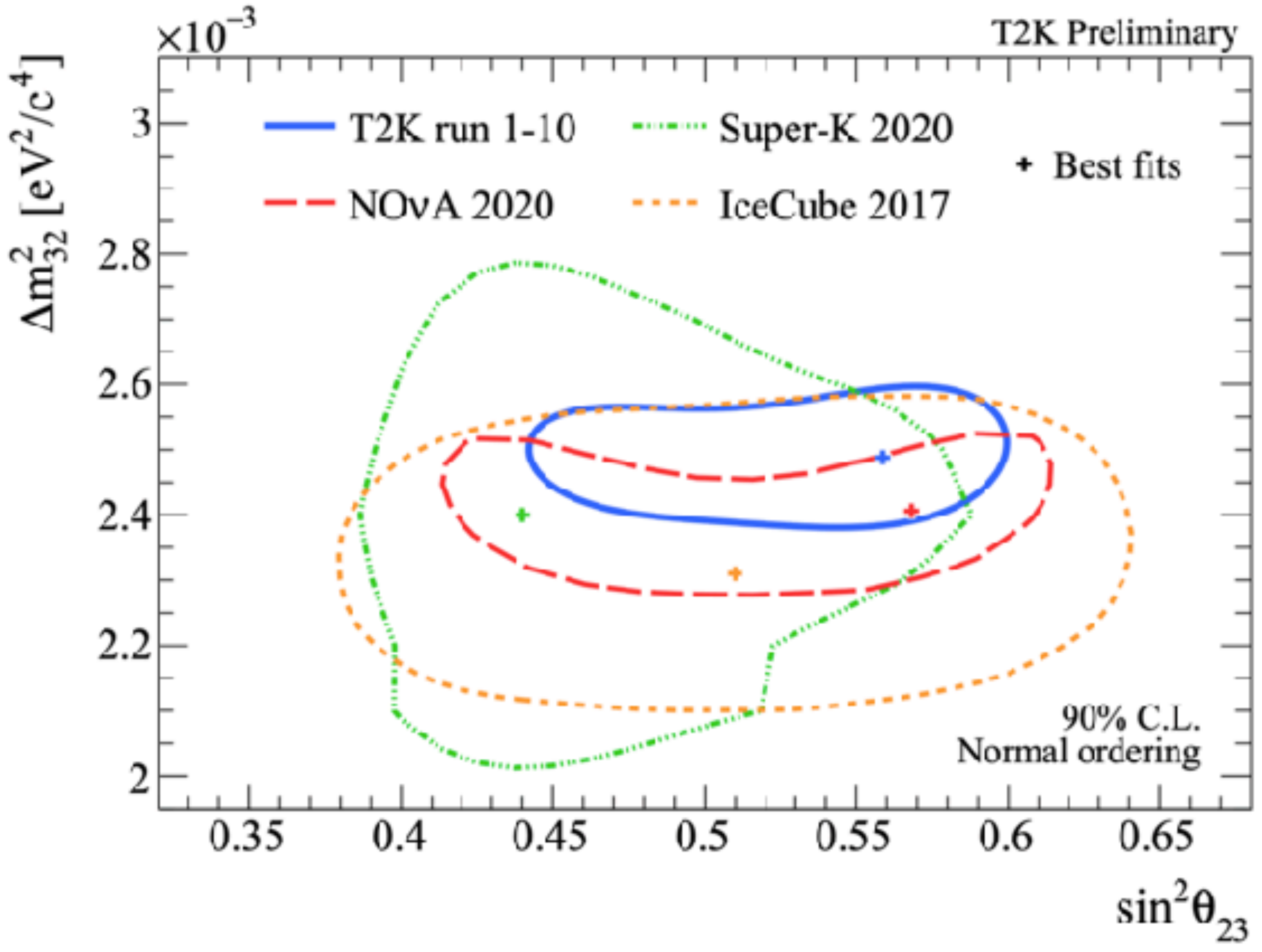


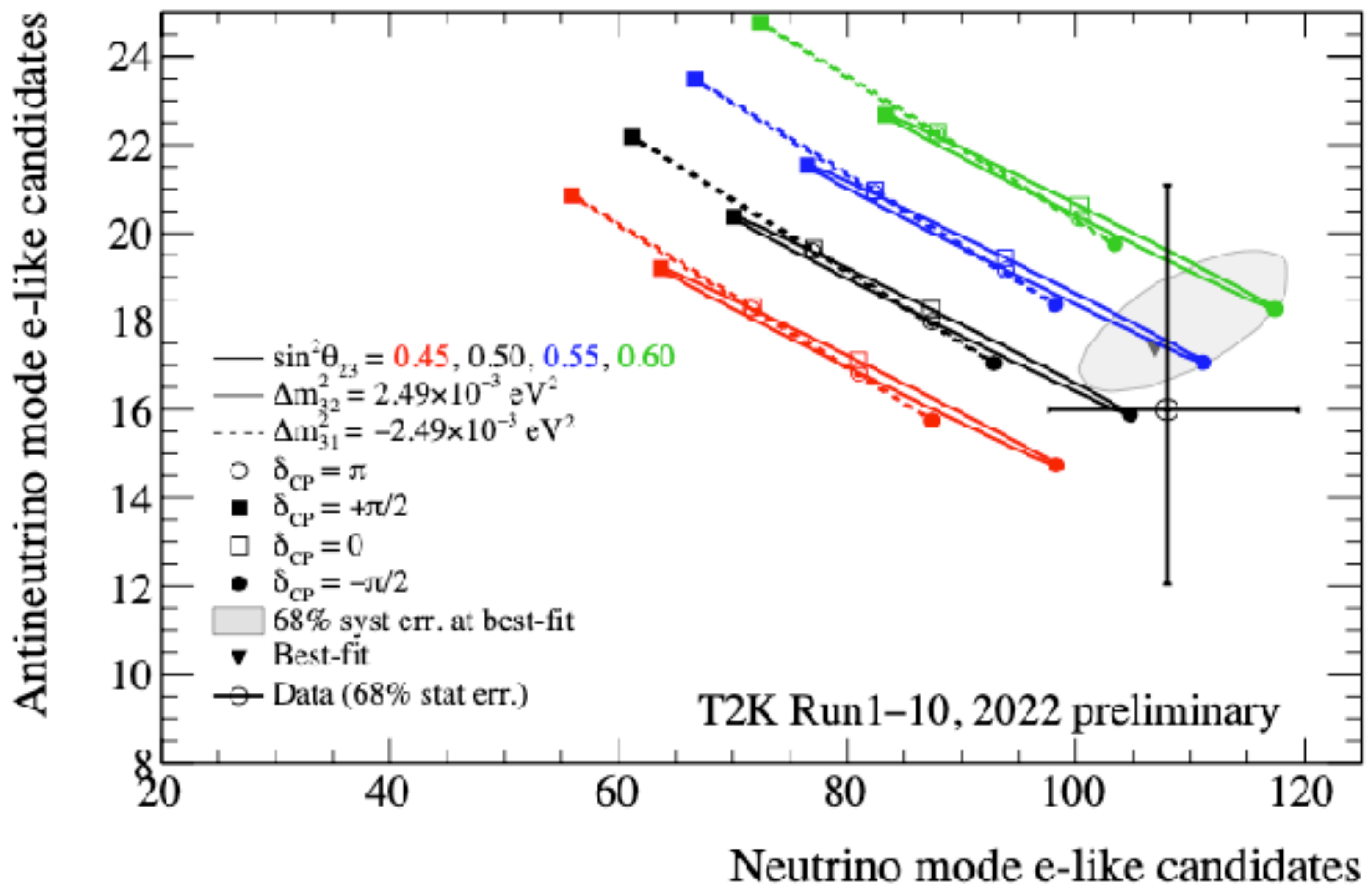
23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}
(maximum power 522.6 kW)

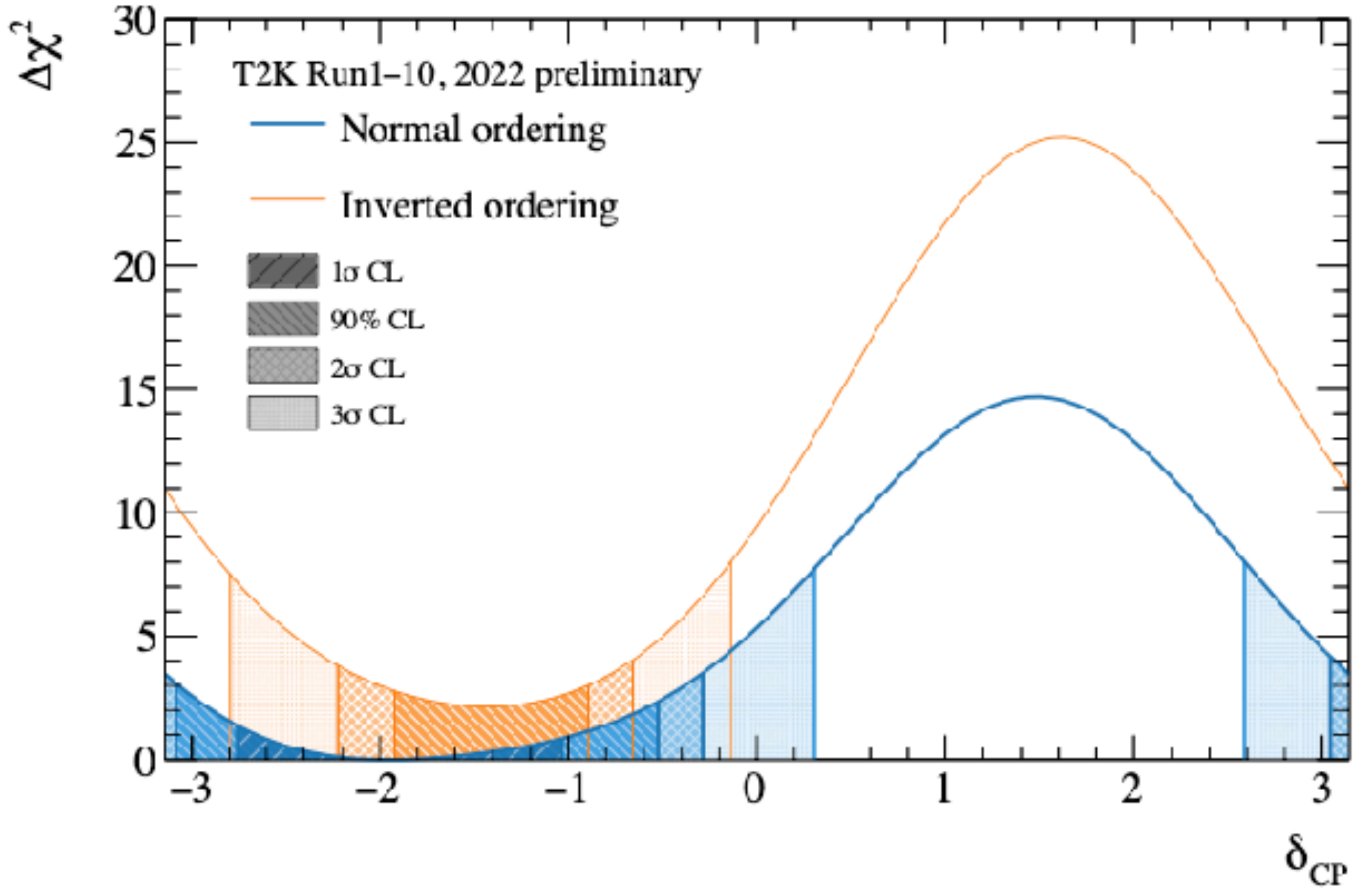
ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

T2K EXPERIMENT: CURRENT RESULTS

- 4 main oscillation channels in T2K: $\nu_\mu \to \nu_\mu$ disappearance (dominated by θ_{23} and Δm^2_{23}) and $\nu_\mu \to \nu_e$ appearance (dominated by θ_{13}, θ_{23} and δ_{CP} and mass hierarchy) and similar two for anti-neutrino.





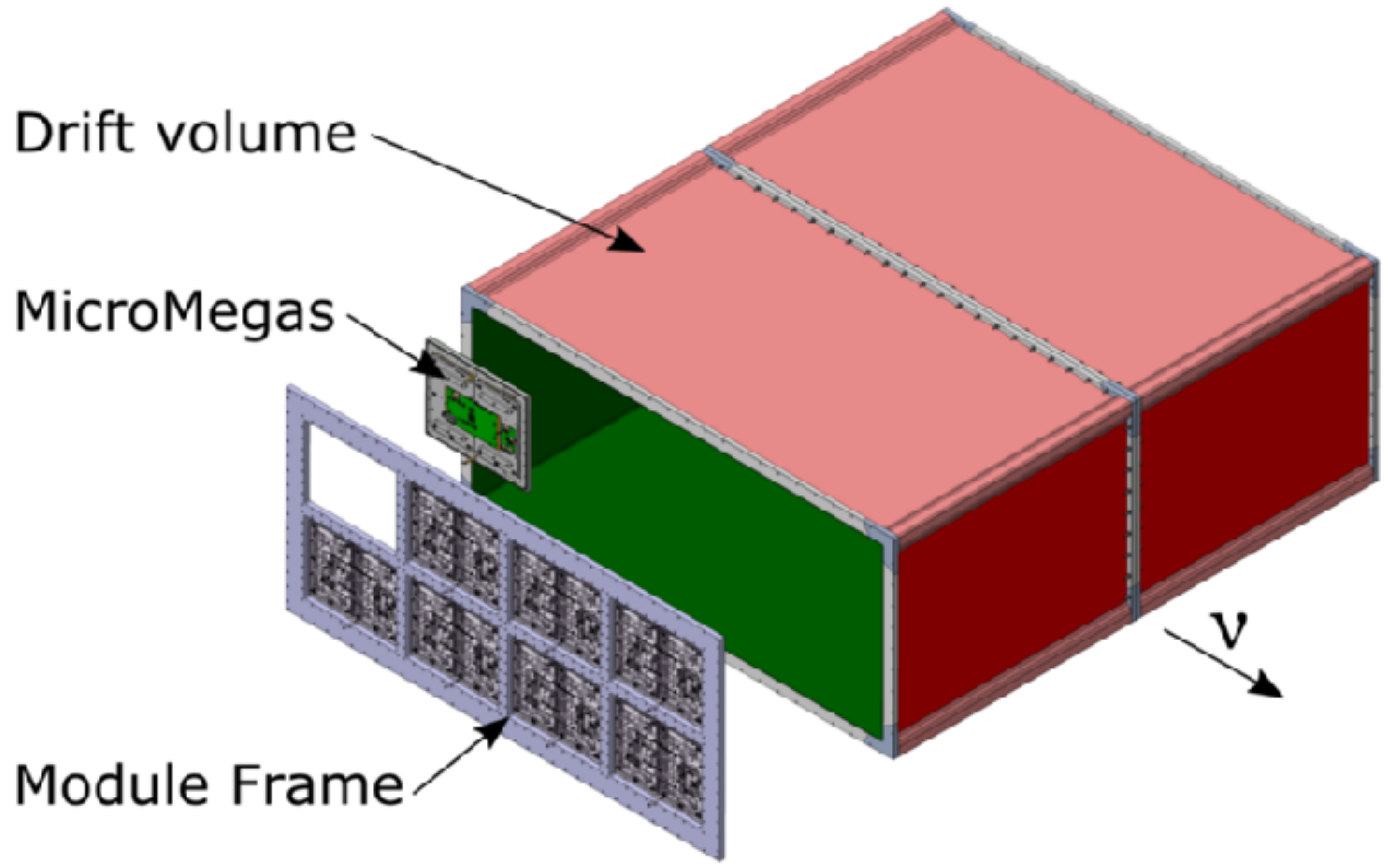


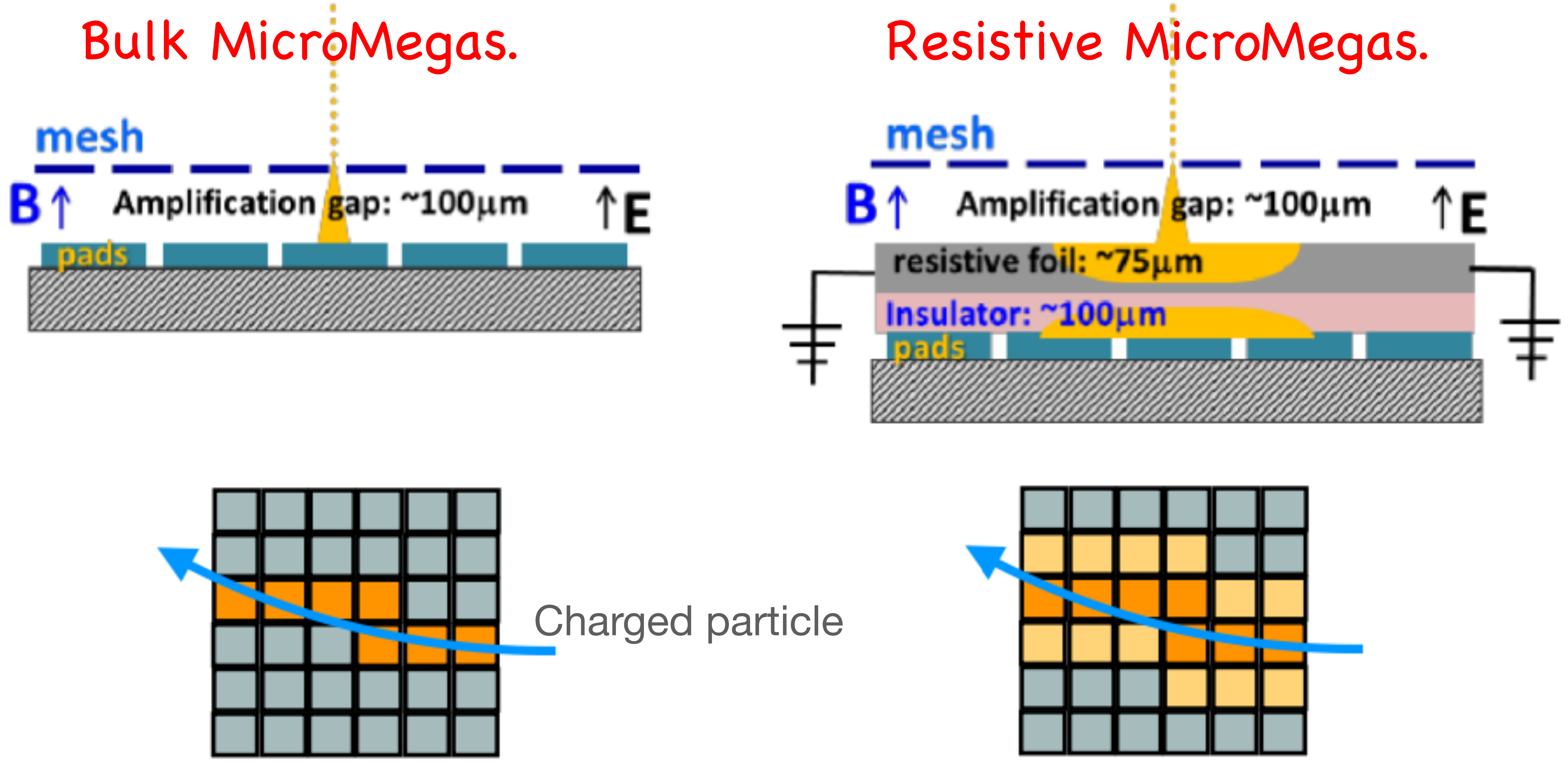
- Data point around the maximum CP-violating value of $-\pi/2$
- A wide region of δ_{CP} space is excluded at 3σ C.L.
- The constraints for $\nu_e/\bar{\nu}_e$ appearance are still dominated by the statistical uncertainty

More results on T2K plenary talk on Aug. 10th by Son Cao

High Angle Time Projection Chamber (HA-TPC)

- Two new HA-TPCs
  - Dimensions: 1.865 x 2.0 x 0.82 m^3
  - Track reconstruction in 3D, PID by measuring momentum and deposited charge
- Main differences with current ND280 TPC
  - High-Angle TPC contains a new type of detector which is the Resistive MicroMegas (ERAM modules) with better spatial resolution.

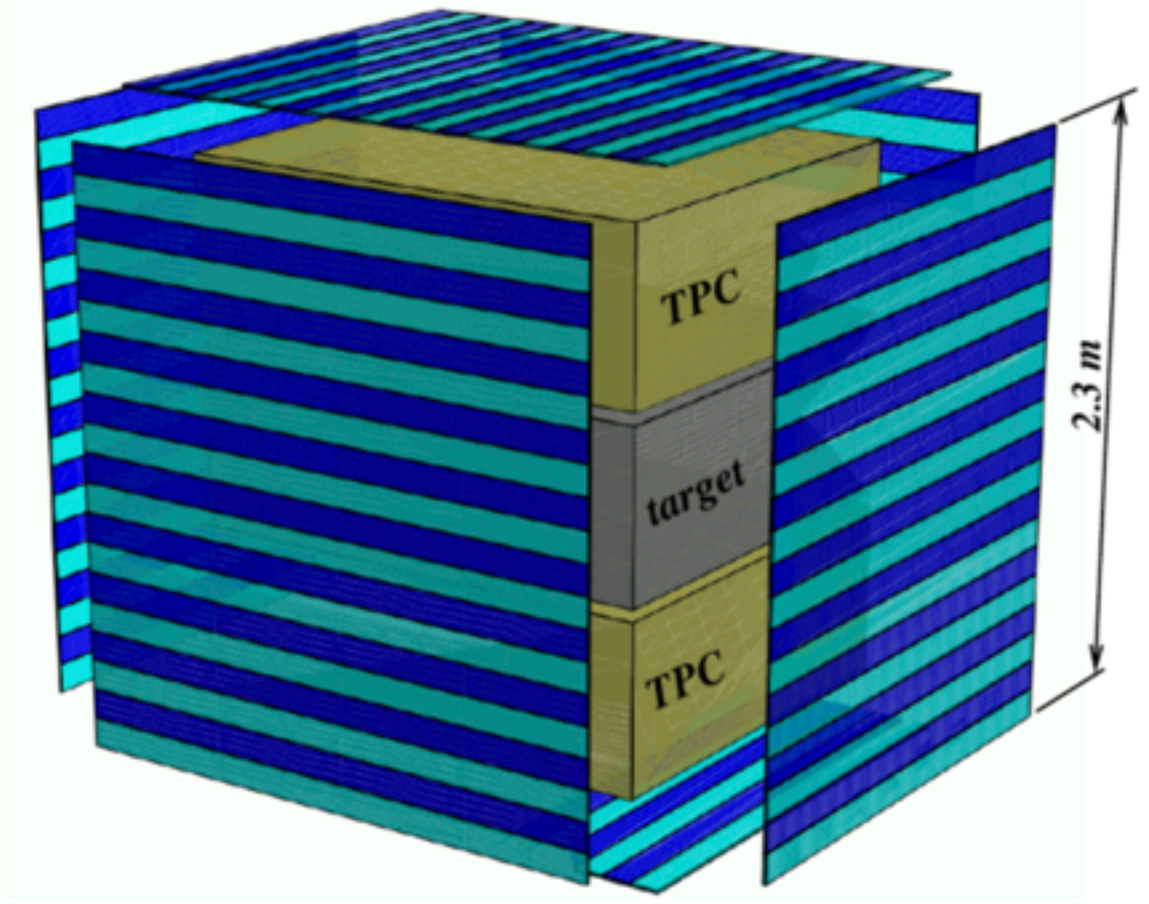




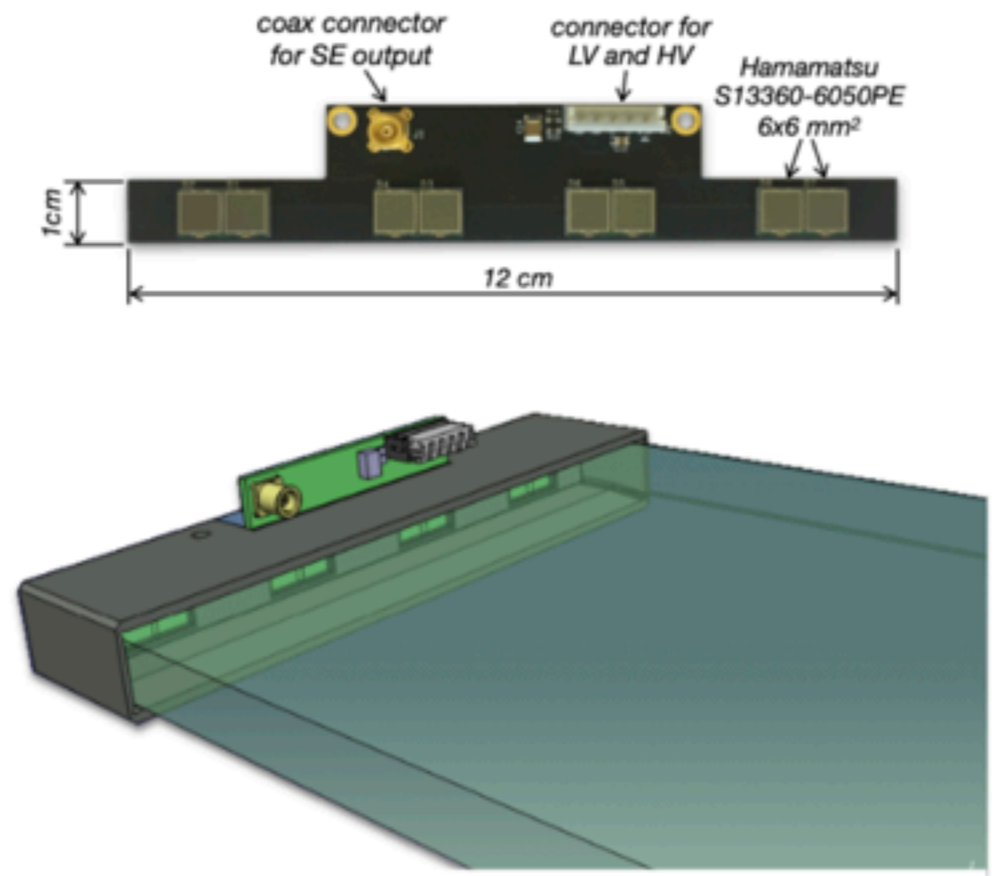
TIME OF FLIGHT DETECTOR (TOF)

- Six TOF planes will cover 2 HA-TPCs and SuperFGD.
- Each plane of 2.2×2.4 m^2 consists of 20 scintillator bars.
- Both ends readout by 8 MPPCs on each end of each bar.

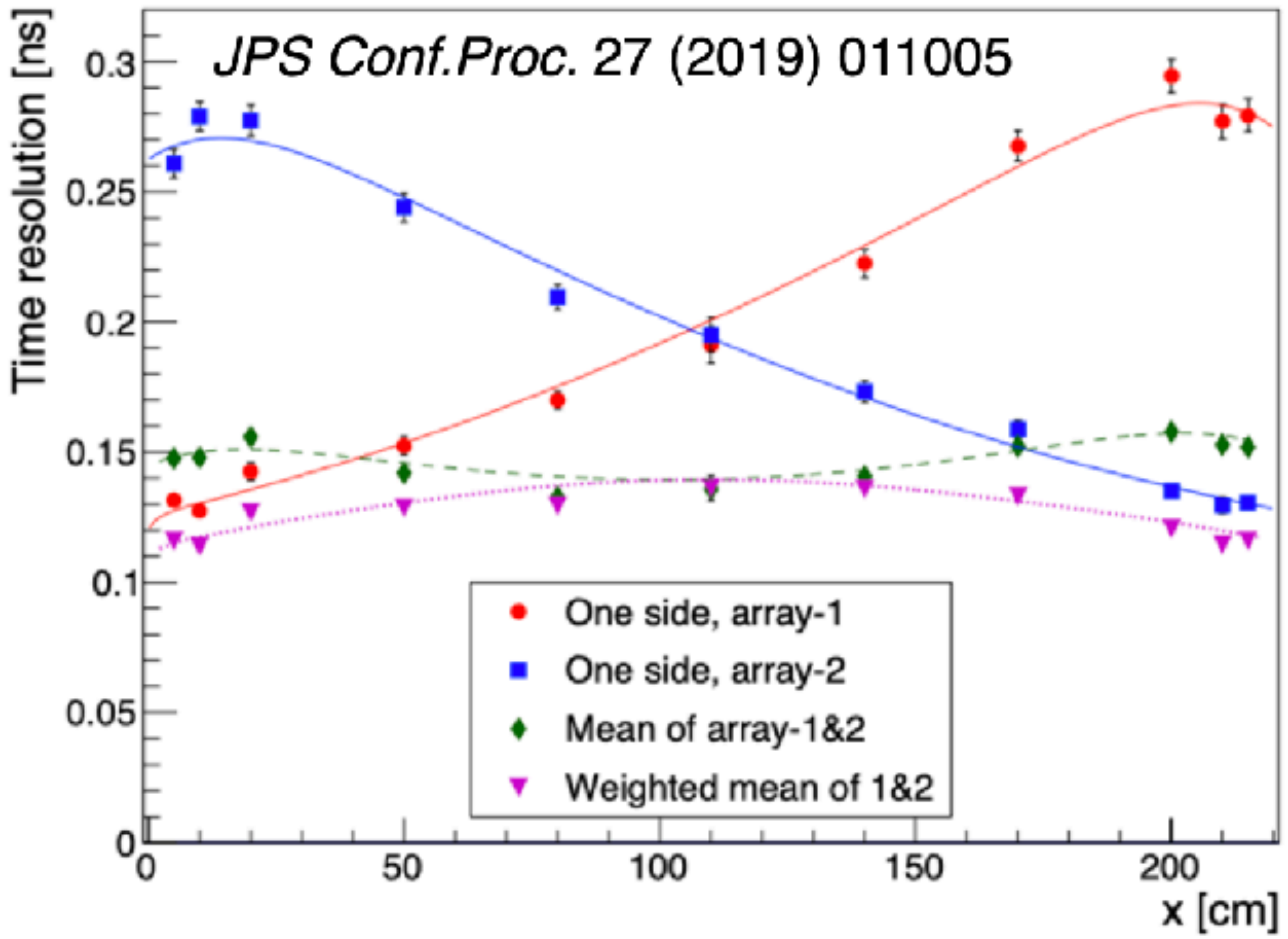
- Precise timing measurement for particles as they traverse the TOF modules (resolution of 150 ps during commissioning at CERN).
- Determine the track direction and minimise background
- It is used as the cosmic trigger to calibrate SuperFGD and HA-TPCs



TOF schematic view



Scintillator bar and end-cap

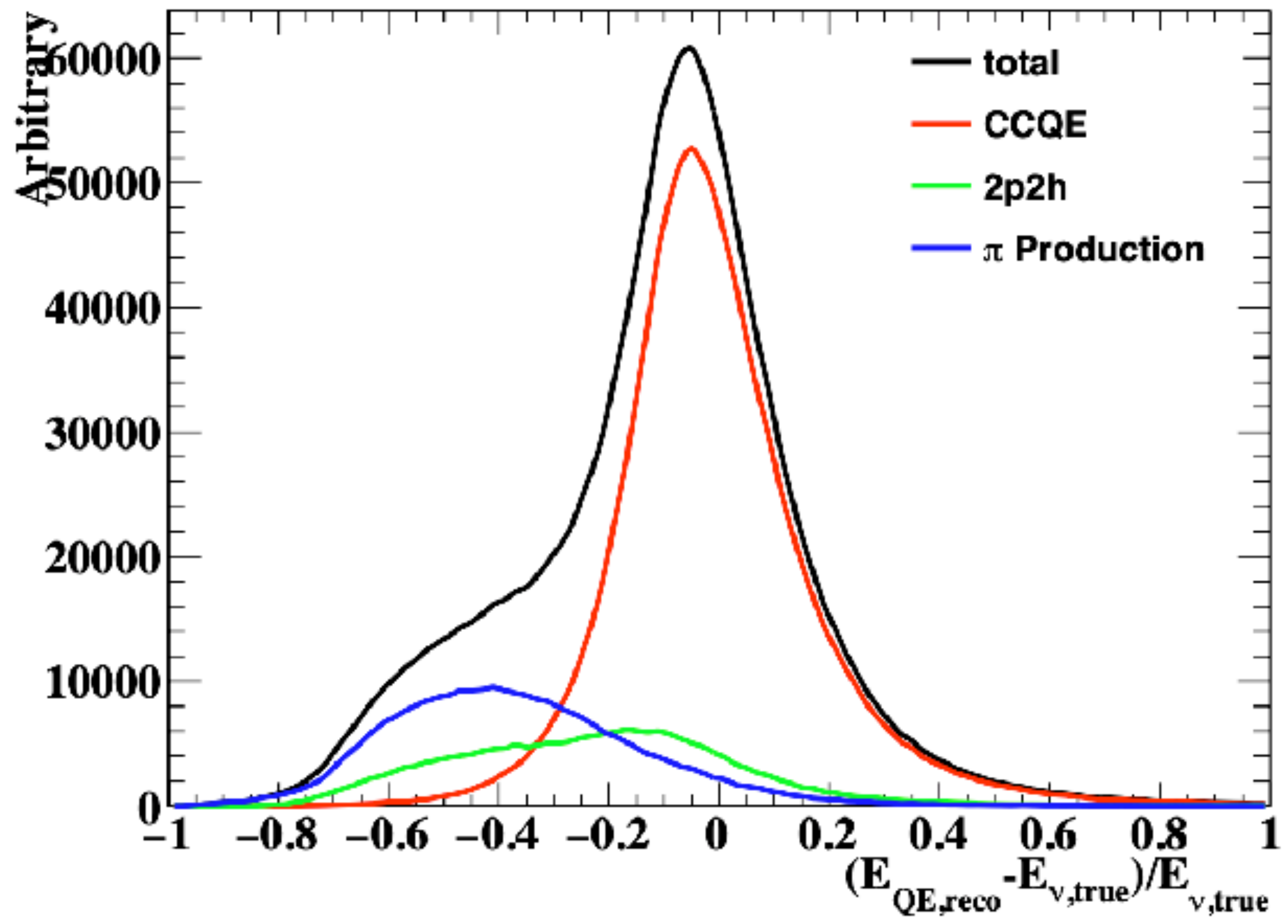


Neutrino-nucleus interaction

Neutrino energy reconstruction is based on the Charge Current Quasi-Elastic (CCQE) kinematics

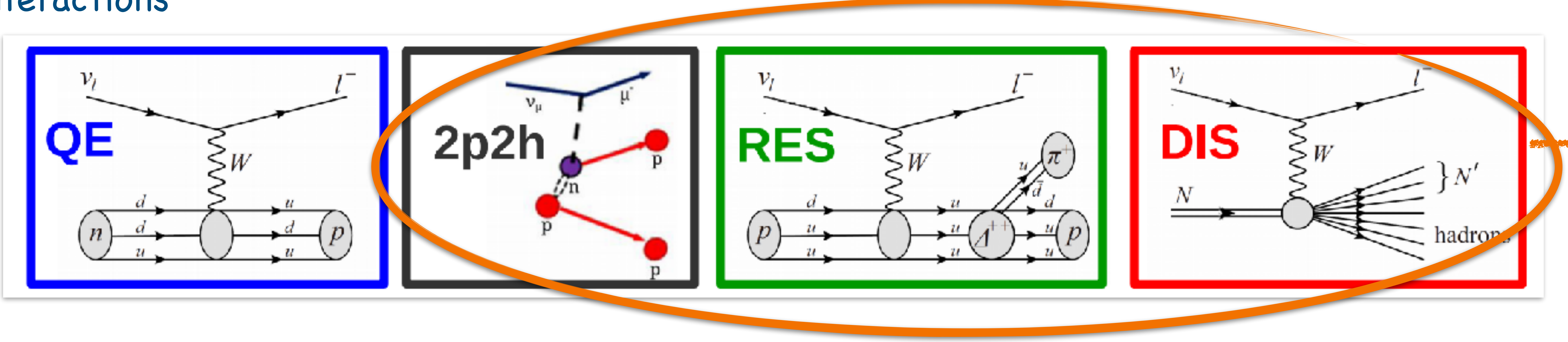
$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_{rmv})^2 + 2E_\mu(m_n - E_{rmv})}{2(m_n - E_{rmv} - E_\mu + p_\mu^z)}$$

=> only lepton kinematics



Only single ring is selected at SK. Unfortunately, sometime the hadronic part is below Cherenkov threshold and hence not reconstructed. These modes could mimic CCQE events.

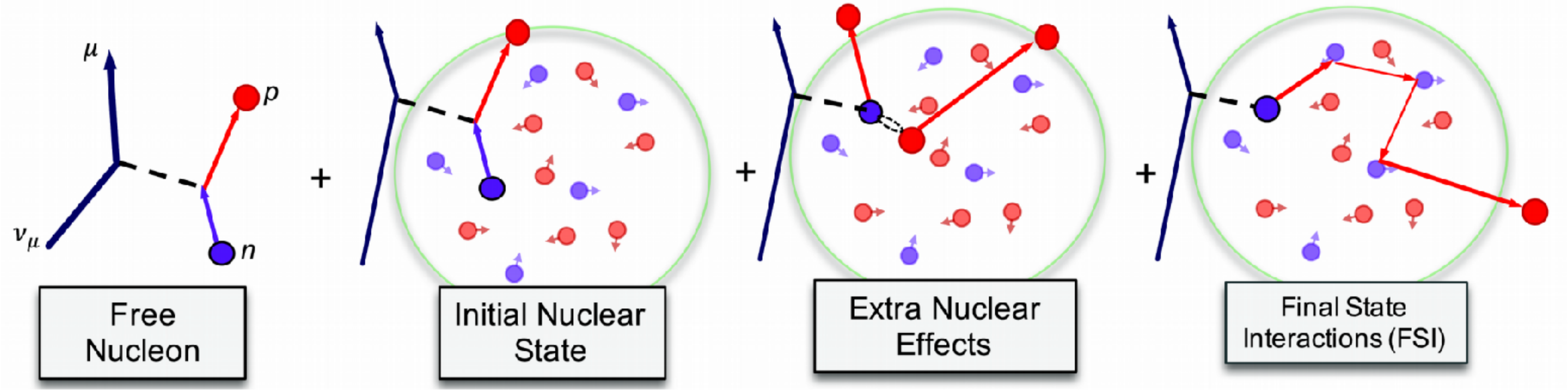
=> ND280 need to carefully model the QE and the non-QE interactions



These modes also contribute to reconstructed quasi-elastic events

The nuclear effects can change the final state topology and kinematic => Bias in neutrino energy reconstruction.

Neutrino-nucleus interaction: Nuclear effects



No nuclear effects

Fermi motion: Contribute to the energy transfer in the interaction

A nucleon strongly correlates with another nucleon. => one additional nucleon in the final state and changes the interaction topology.

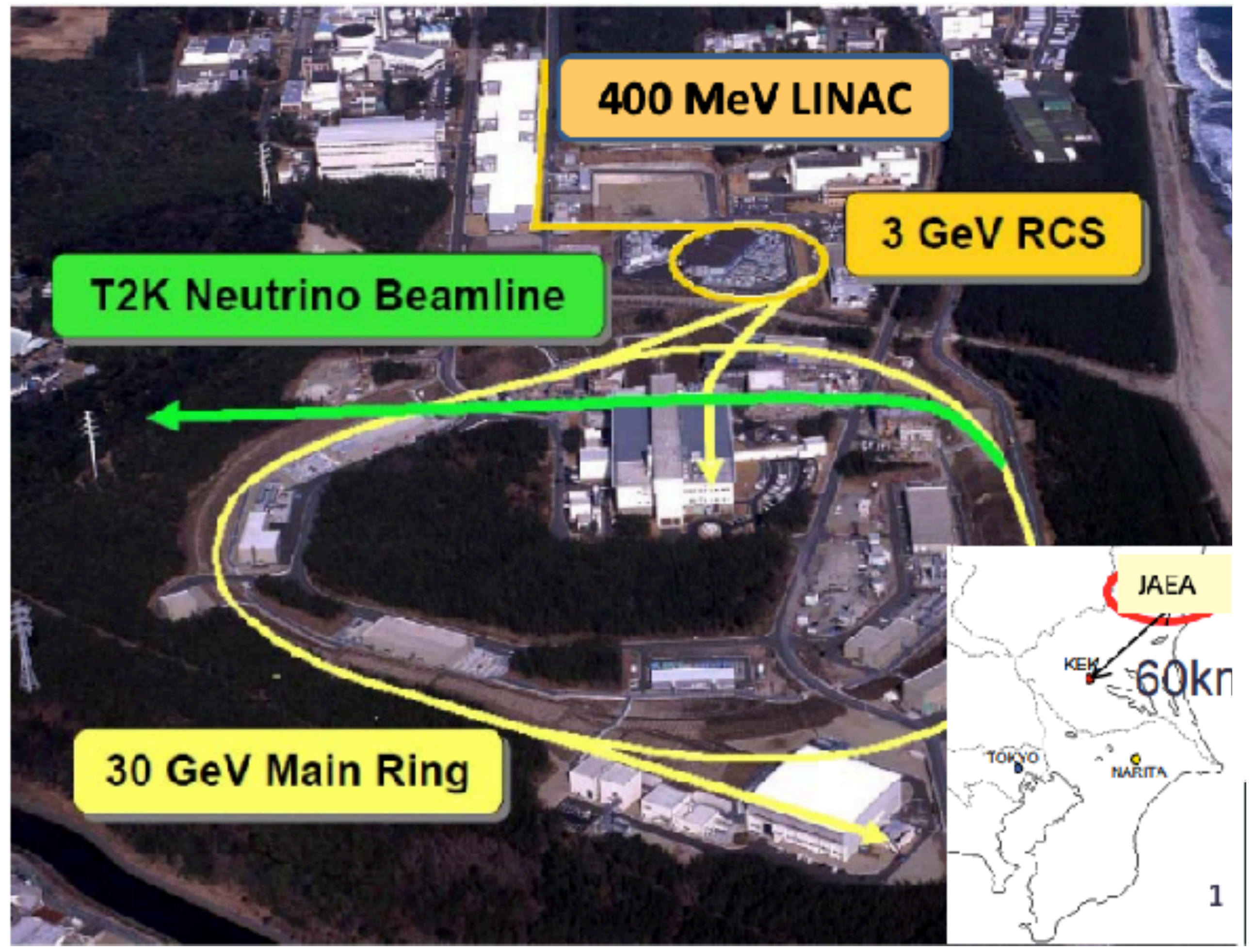
Final State Interactions (FSI): Particles in the final state re-interact before going out of the nucleus.

T2K EXPERIMENT: BEAM

- An intense muon neutrino beam is sent through 295~km from Tokai to Kamioka, produced by high-intensity accelerated proton beam produced by the J-PARC beamline

- T2K uses the off-axis beam technique => the flux is narrower at 0.6 GeV which is sensitive to the first oscillation maximum with the 295Km baseline.

- Since the flux peaks at 0.6 GeV, the Quasi-Elastic (QE) is the dominant interaction.



J-PARC