The T2K ND280 Upgrade

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Institute for High Energy Physics

Objectives of this Talk

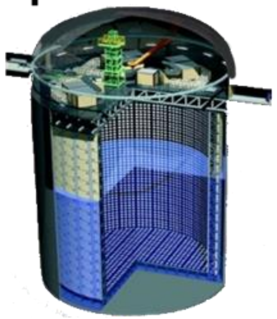
I hope at the end of this talk, you know/understand/get feeling for:

- What a long-baseline neutrino oscillation (LBNO) experiment is
- That near detectors are crucial for the success of LBNO experiments
- Why the T2K collaboration decided to upgrade their near detector (ND280)
- That detectors are not a gift brought by Santa Claus
- That many people spent many years to build and install them
- Many challenges have to be overcome before you get your reward
- That the ND280 upgrade is important beyond T2K

Do not worry, a lot of it will be a photo show!

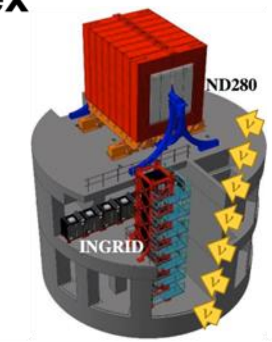
Far detector

Super Kamiokande



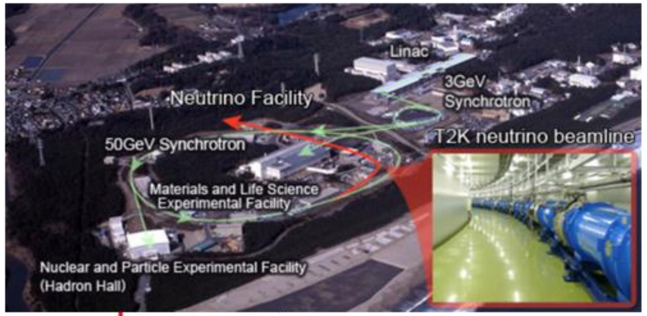
Near detector

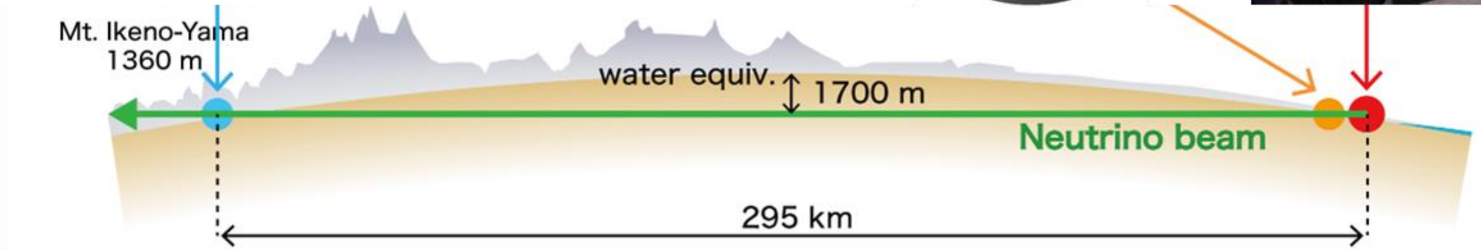
complex



J-Parc

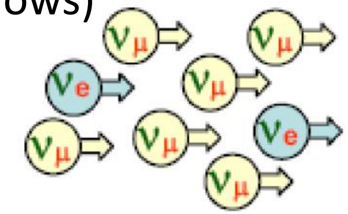
Neutrino Beam





@SK

Detect electron and muon neutrinos (ignore arrows)

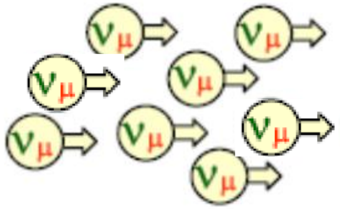


@ND280

Check what you have produced + cross sections

@J-PARC

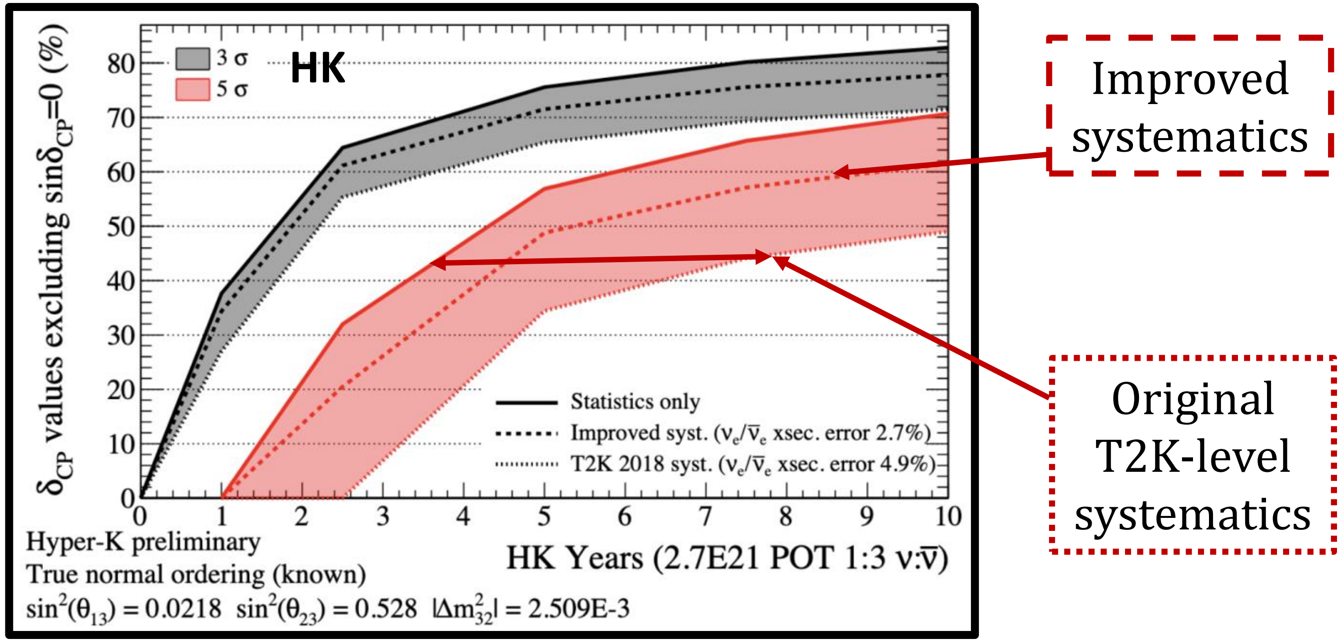
Produce muon neutrinos (ignore arrows)



Why do we need Near Detectors?

Objective of current and future LBNO experiments is to measure with precision δ_{CP} phase (related to matter-antimatter asymmetry in the universe)

$\Rightarrow$ Systematic uncertainties are the big enemy!



Sensitivity to exclude CP conserving values for δ_{CP}

Can delay physics results **by several years.**
Or prevent them altogether!

But we luckily have Near Detectors!

LBNO Concept

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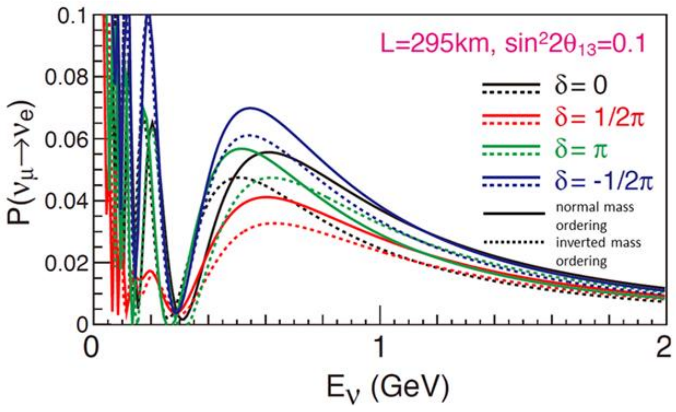
Detectors provide event rates in bins of reconstructed neutrino energy:



ND: $$\frac{dN_{\beta}^{ND}}{\Delta E_{\upsilon}^{reco}} = N_{target}^{ND} \sum_{i} \phi^{ND}(E_{\upsilon}) \sigma_{i}^{ND}(E_{\upsilon}) T_{i}^{ND}(E_{\upsilon}, E_{\upsilon}^{reco}) \epsilon_{i}^{ND}(E_{\upsilon}, E_{\upsilon}^{reco}) dE_{\upsilon}$$

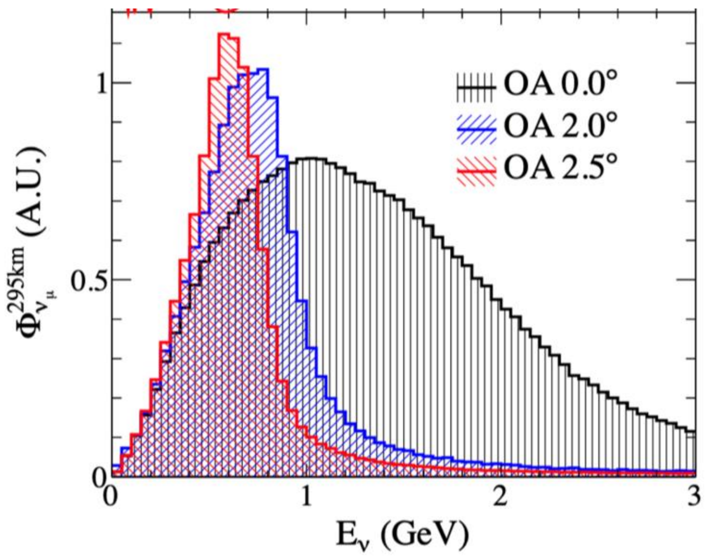
FD: $$\frac{dN_{\beta}^{FD}}{\Delta E_{\upsilon}^{reco}} = N_{target}^{FD} \sum_{i} \phi^{FD}(E_{\upsilon}) \sigma_{i}^{FD}(E_{\upsilon}) T_{i}^{FD}(E_{\upsilon}, E_{\upsilon}^{reco}) \epsilon_{i}^{FD}(E_{\upsilon}, E_{\upsilon}^{reco}) P_{\upsilon_{\alpha} \to \upsilon_{\beta}}(E_{\upsilon}) dE_{\upsilon}$$

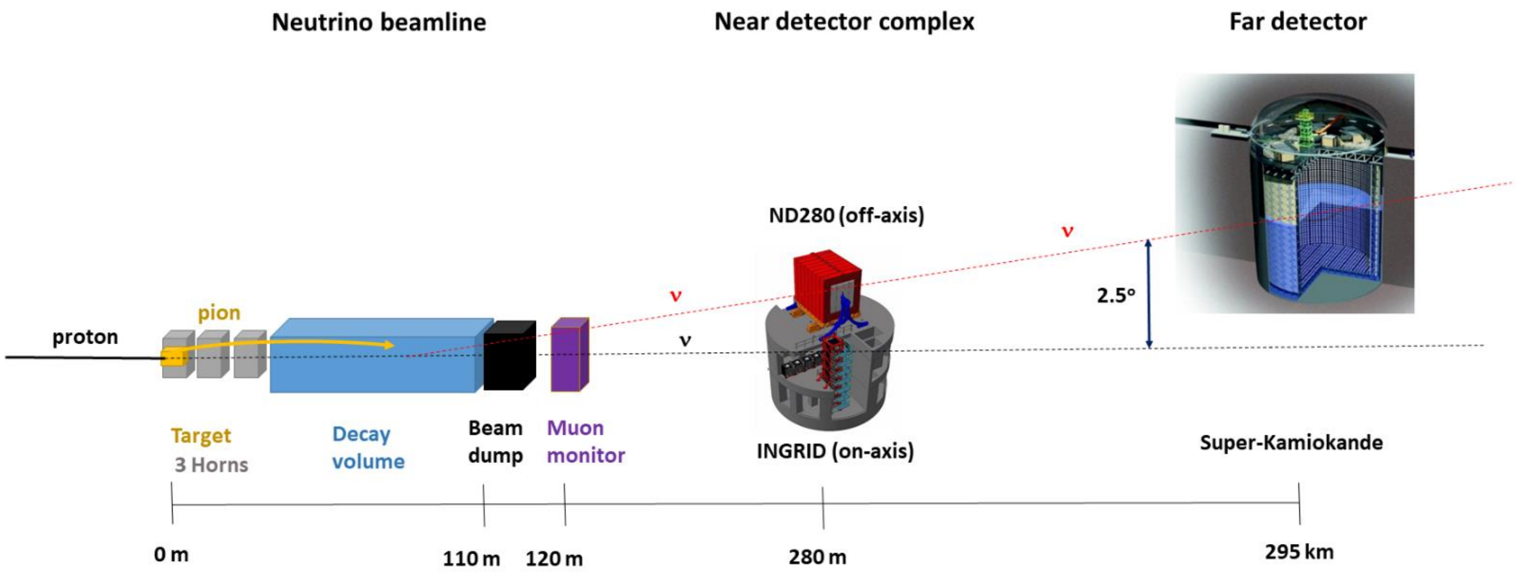
Neutrino flux | **Cross-sections for *i*th interaction mode** | **Energy migration tensor** | **Efficiency/ acceptance** | **Oscillation probability**

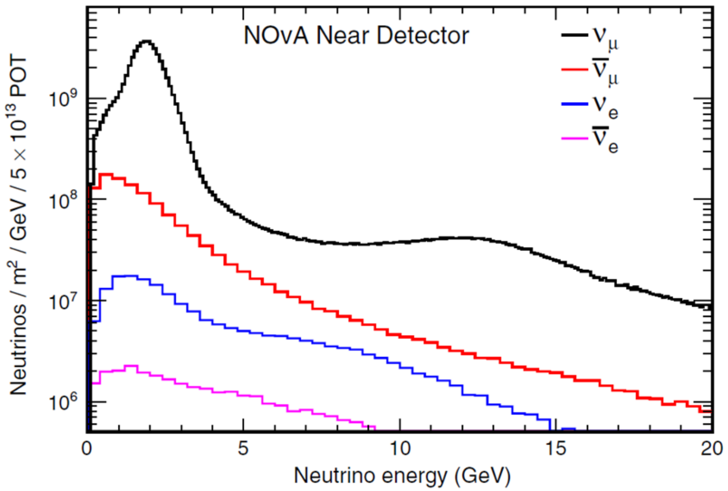
- Aim: Get oscillation probability => allows to extract oscillation parameters
- Near Detector contributes to reduce uncertainty from neutrino flux and cross-sections
- Crucial to understand relation between reconstructed and true neutrino energy

Neutrino Flux

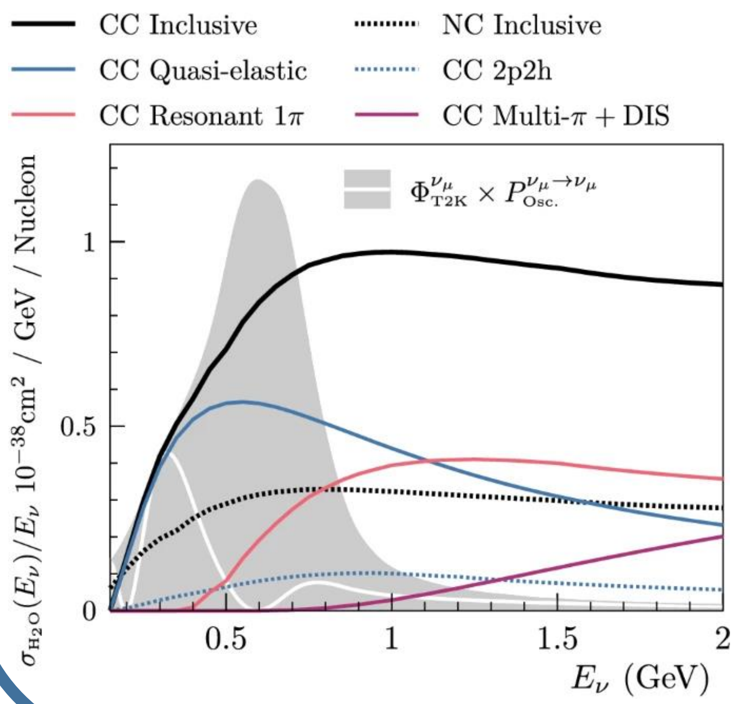
- A neutrino beam is not well focused as LHC beam
- Neutrino energy depends on angle and not well defined
- Not a clean muon neutrino beam but contaminations
- Good to have them to measure cross-sections of electron neutrinos

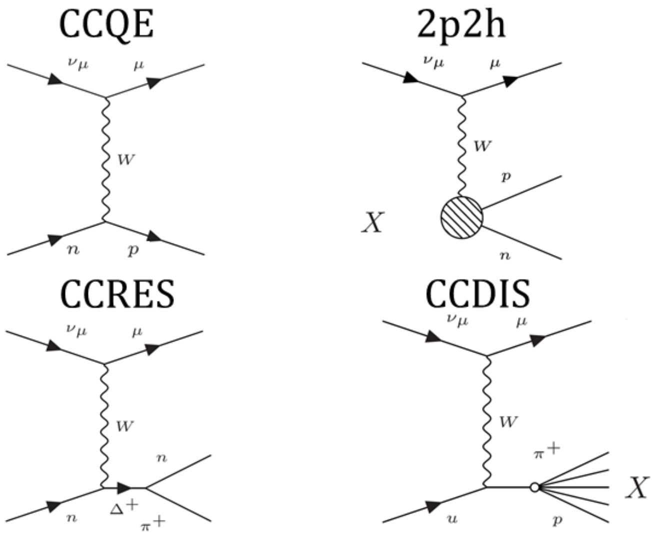




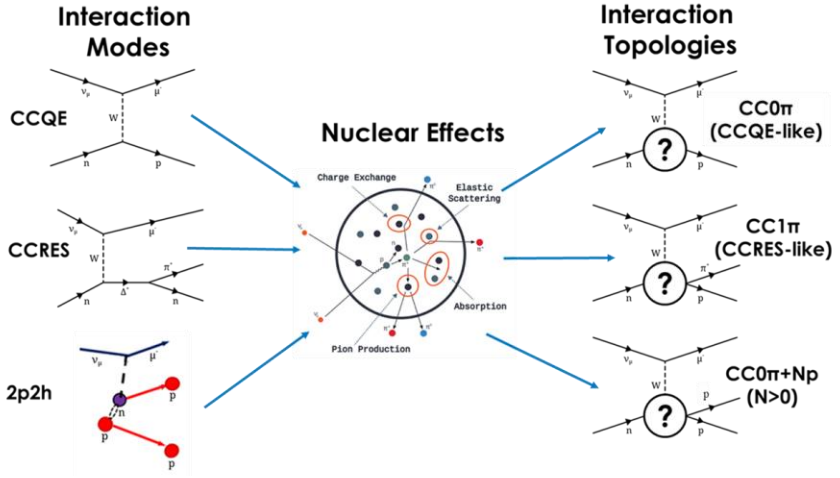


At neutrino energies relevant for LBNO, there are 4 interaction modes:





But we have nuclear effects (Final State Interactions):



Affects energy reconstruction => ND provides crucial knowledge about these effects!

Some Key Definitions

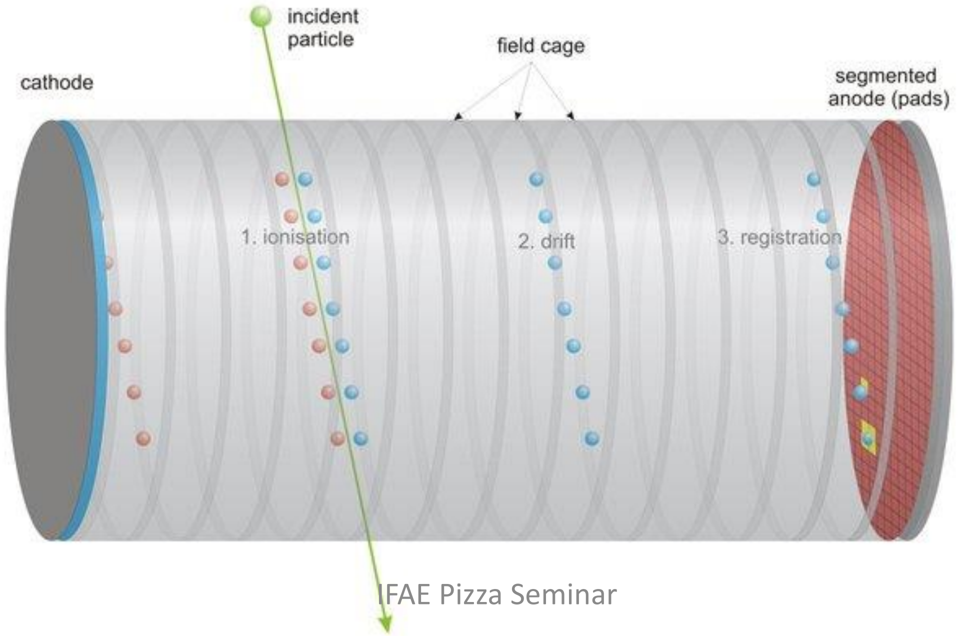
TPC: Time Projection Chamber => gaseous tracking detector

ERAM: Encapsulated Resistive Anode Micromegas => Gas amplification

SuperFGD: Super Fine Grain Detector => scintillator tracker

TOF: Time of Flight Detector => fast scintillator detector to provide timing information

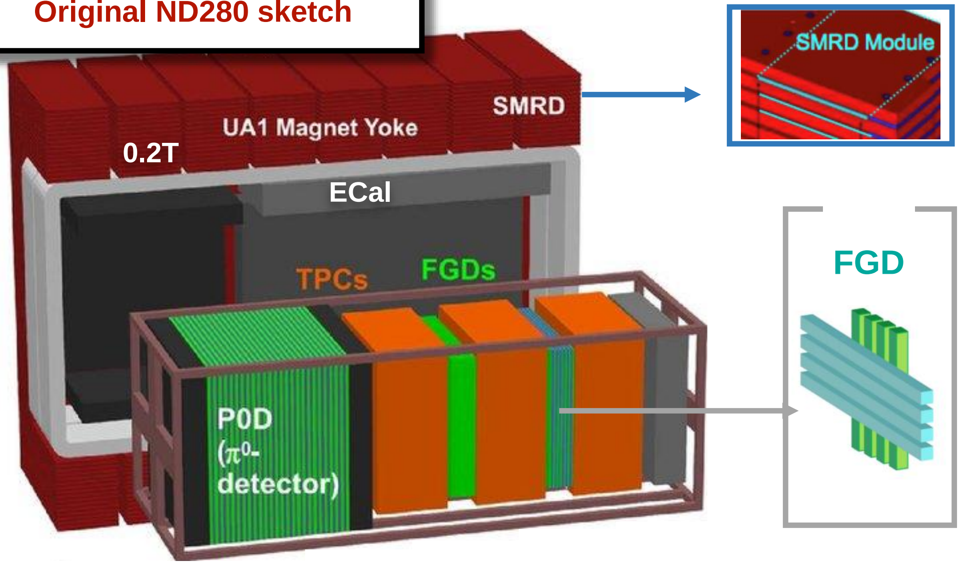
TPC Principle



Amplification close to pads: ERAM

The original ND280 detector (2009-2022)

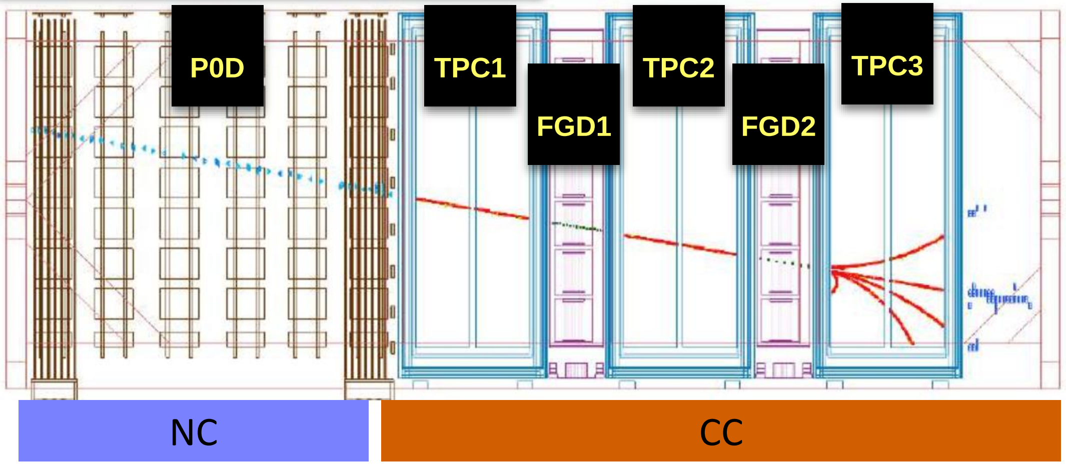
Original ND280 sketch

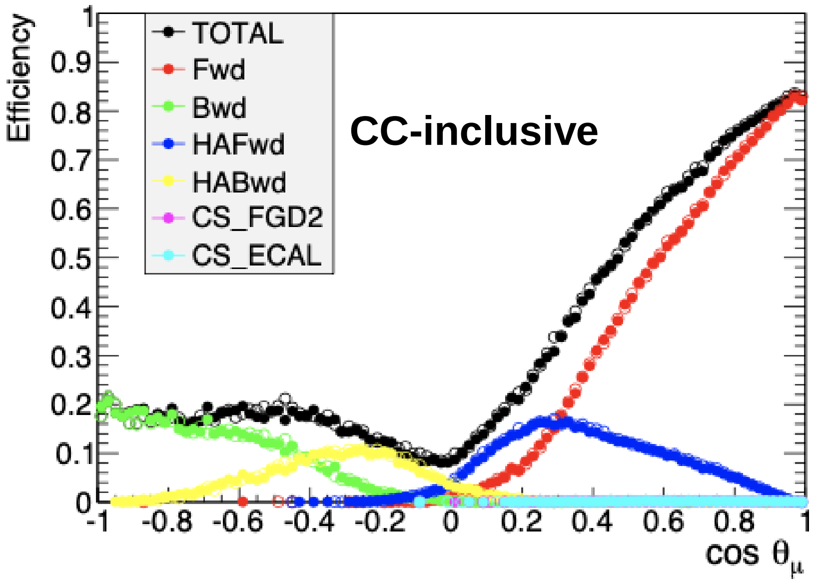


Limitations

- Tracks w/o TPCs (high angle).
- Tracks w/o TPCs (low momentum).
- Limited timing information => no direction information
- No neutron info
- Poor electron/photon separation
- High detection threshold

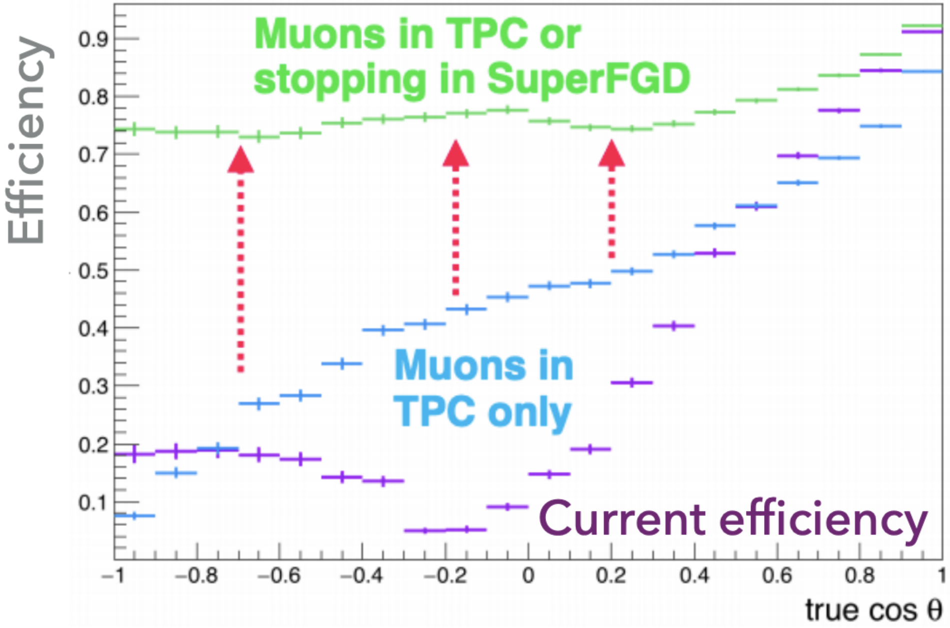
Event display of basket elements



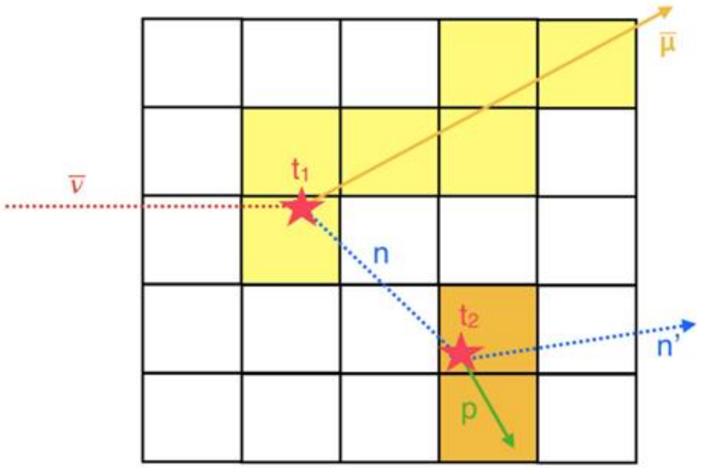


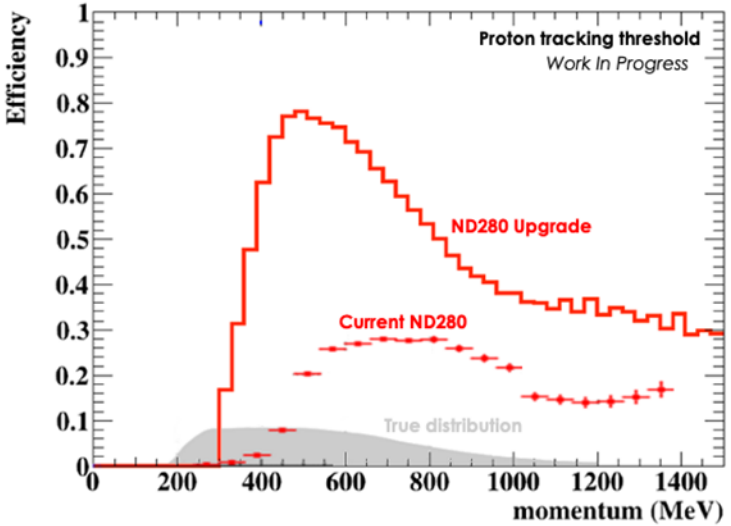
What one would like to have

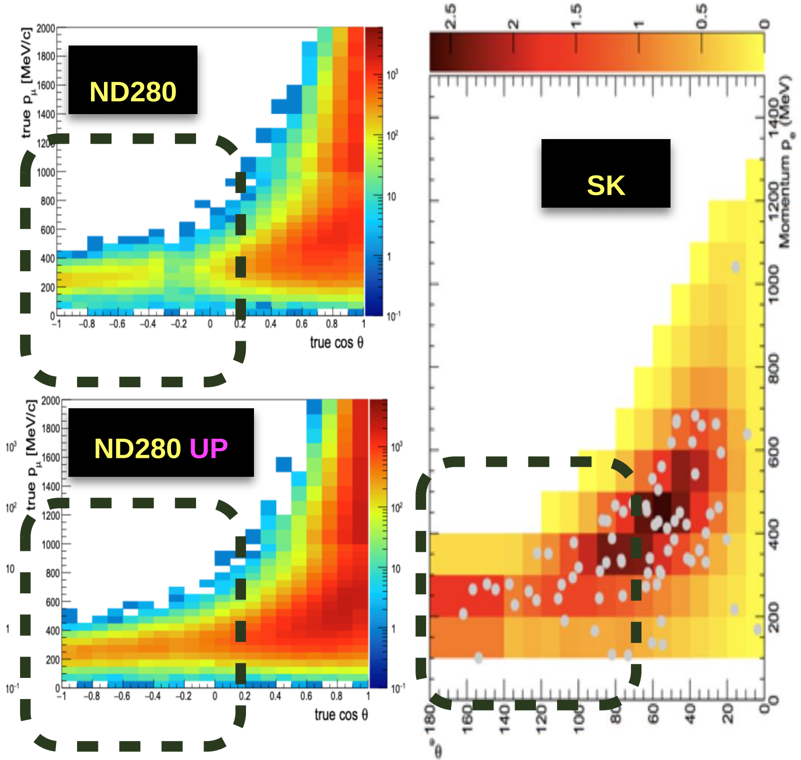
- Similar phase space coverage as SuperKamiokande
- Significant lower energy threshold
- Neutron detection and energy reconstruction capability



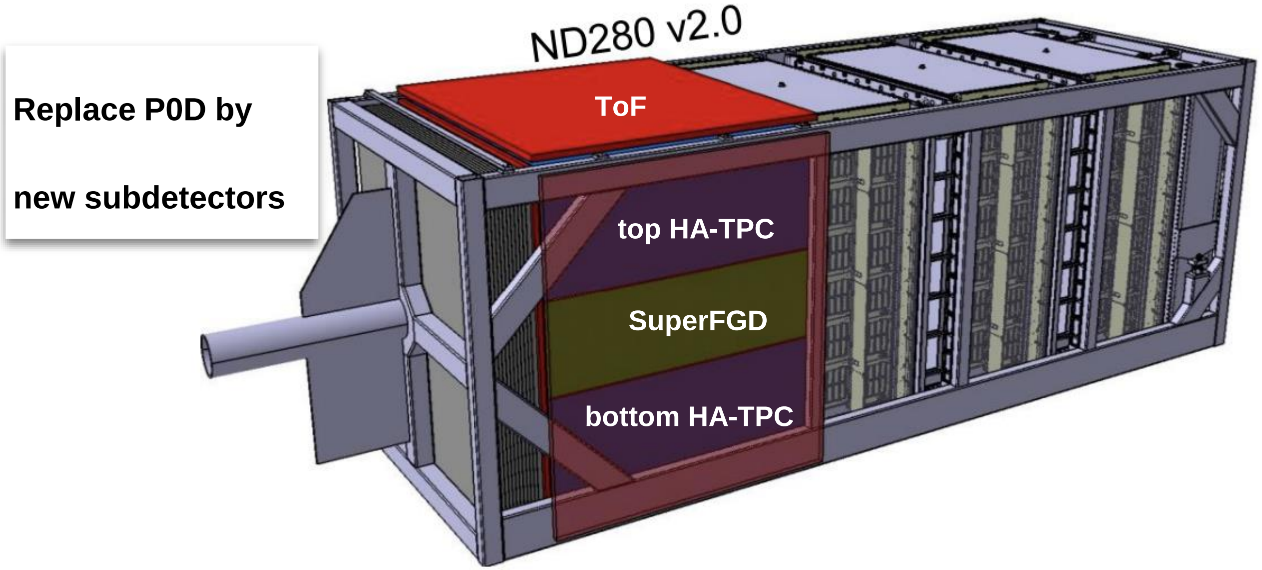
Major improvement on systematic uncertainties!





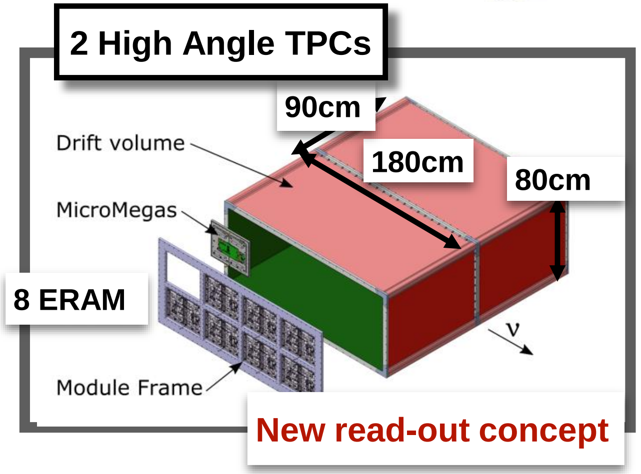


The upgraded ND280 detector

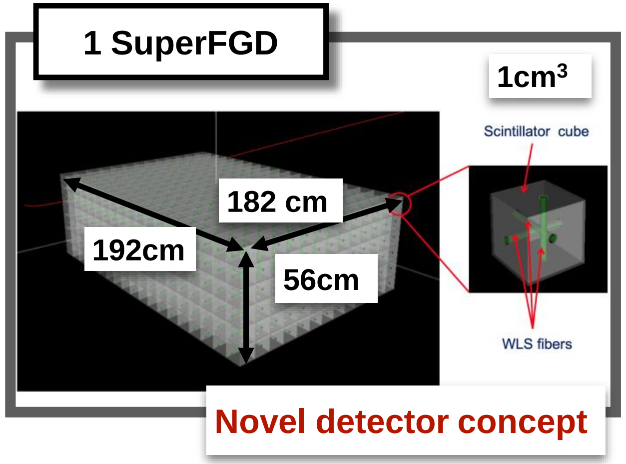


Milestones

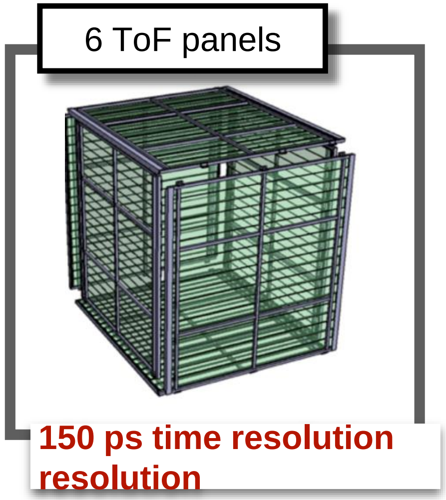
- Projected started 2016
- 2018 → TDR arXiv:1901.03750
- 2023/2024 final modules
- 2023/24 installation



NIM A 957 163286 (2020)



JINST 13, P02006 (2018)
JINST 15 P12003 (2020)



JPS Conf. Proc. 27, 011005 (2019)

Sounds simple …

… but it is not:

1) First, one has to design new subdetectors
2) Then one needs to produce and assemble them
3) Ship the assembled detectors or the parts to Japan
4) Remove the old detectors and prepare ND280 to install new detectors
5) Install the new subdetectors one after the other
6) Ensure that the new and the old subdetectors work together
7) Understand the upgraded ND280
8) Use it for physics

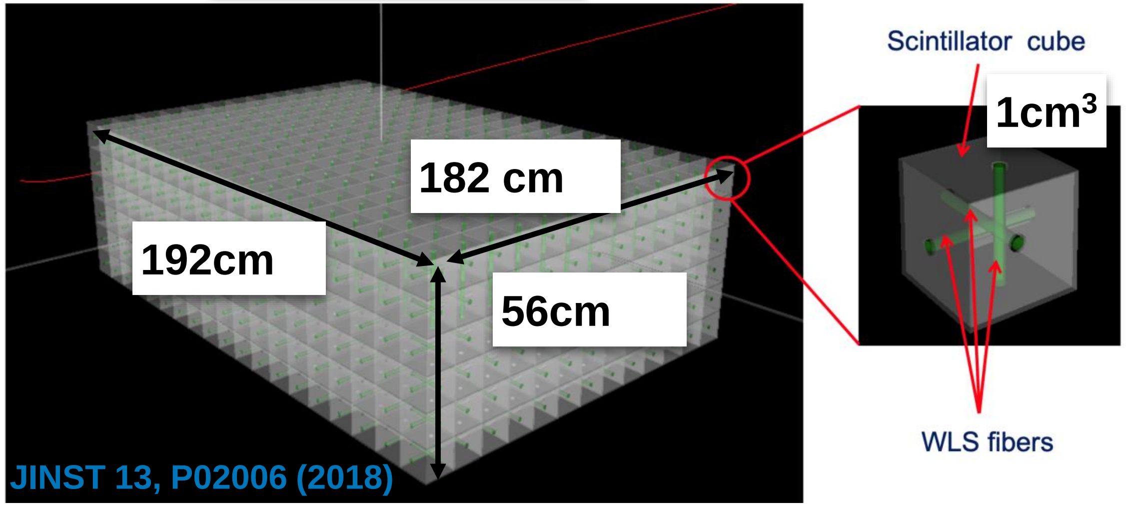
=> Global pandemic and Russian invasion did not help making easier!

A new scintillator tracker concept (SuperFGD)

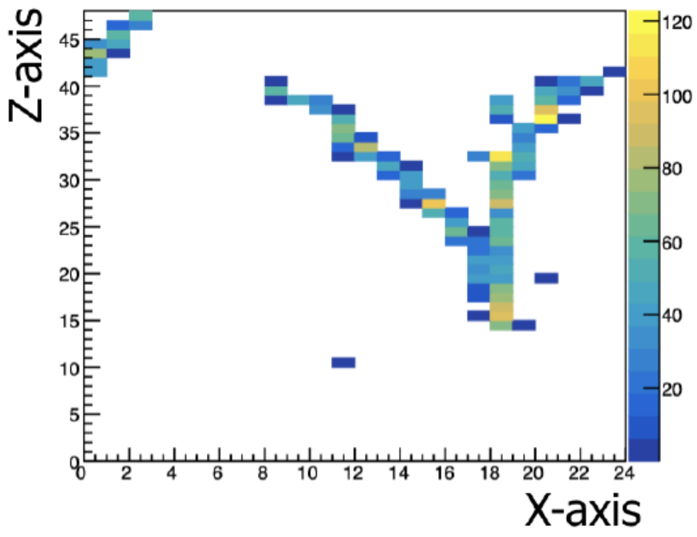
To improve the granularity the new active target will be a novel 3D tracking technology

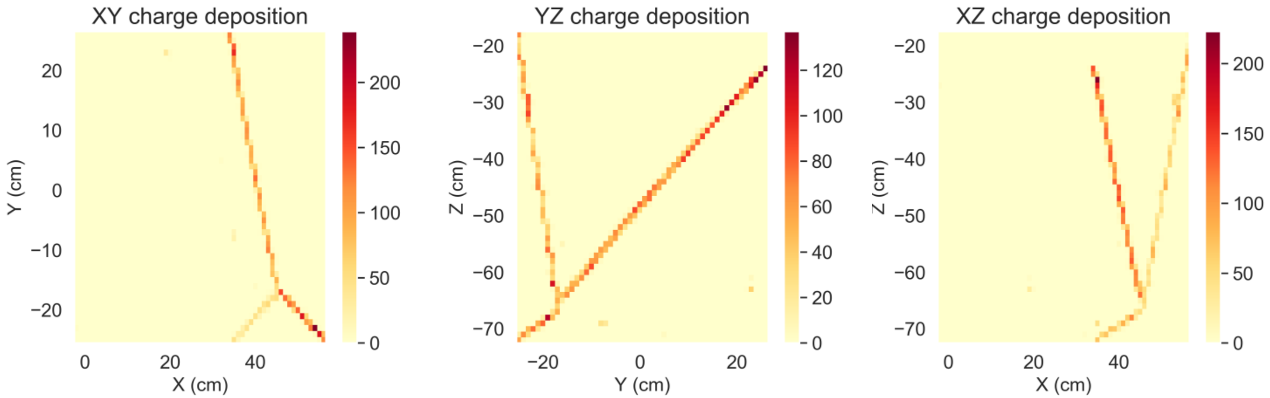
SuperFGD concept

- **2 million cubes**
- **6 million holes to be drilled**
- **56,000 WLS fibers to be inserted**

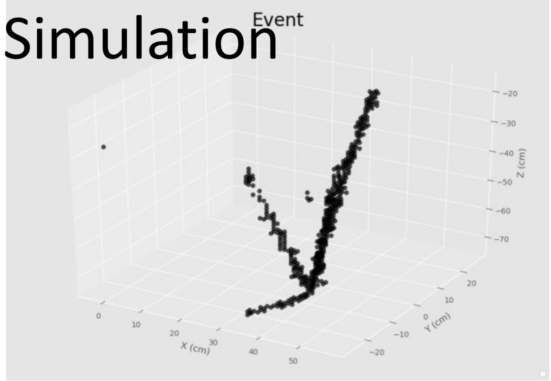


Testbeam event



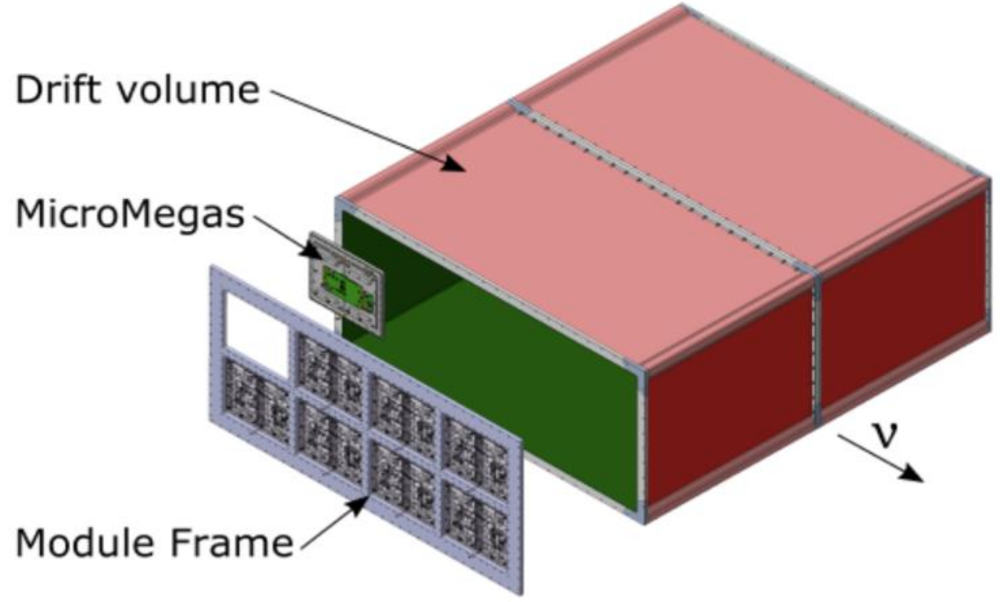


Simulation

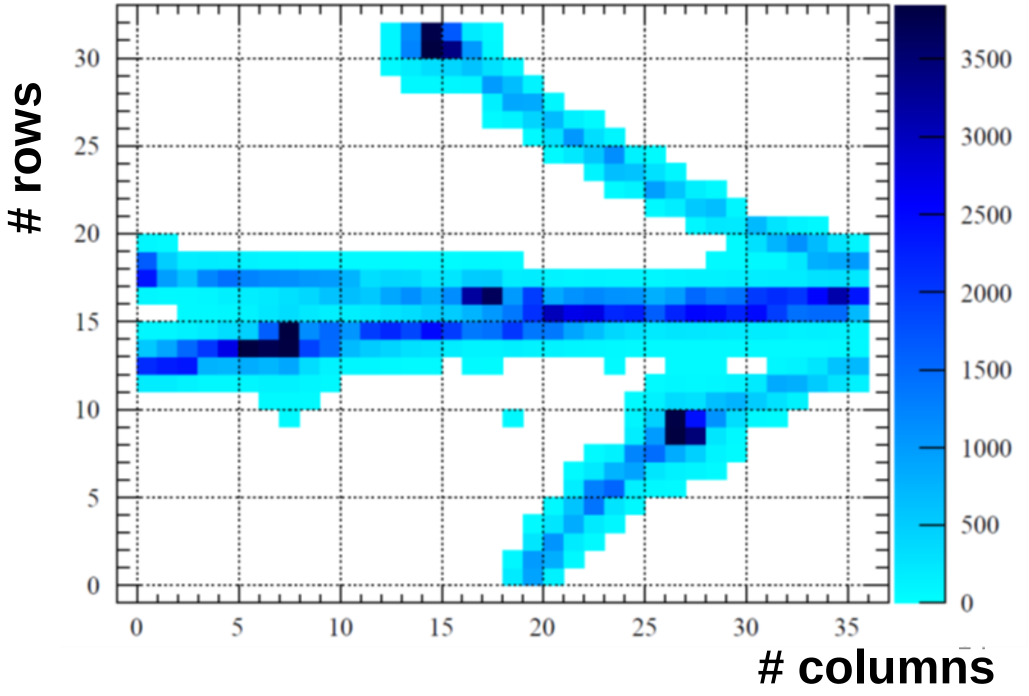


High Angle-TPCs

- 2 new TPCs being produced
- Dimensions: 1865x2000x820 mm3
- Composite materials for field cage
- Readout by 8 resistive Micromegas (ERAM) per side (novel technology)
- 1152 readout channels with 10.09x11.18 mm2 pads per ERAM
- T2K gas (95 Ar, 3 CF4, 2 iC4H10)
- Providing tracking and particle identification

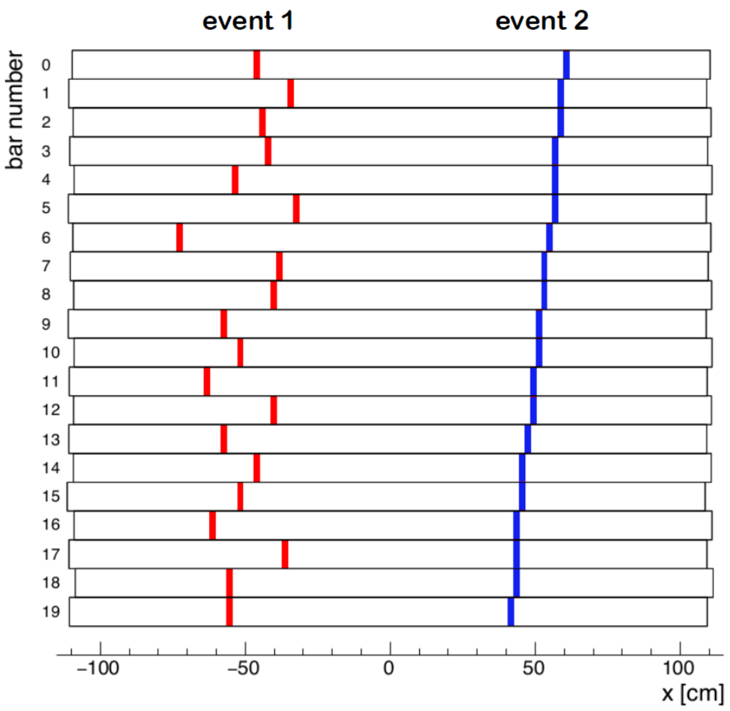


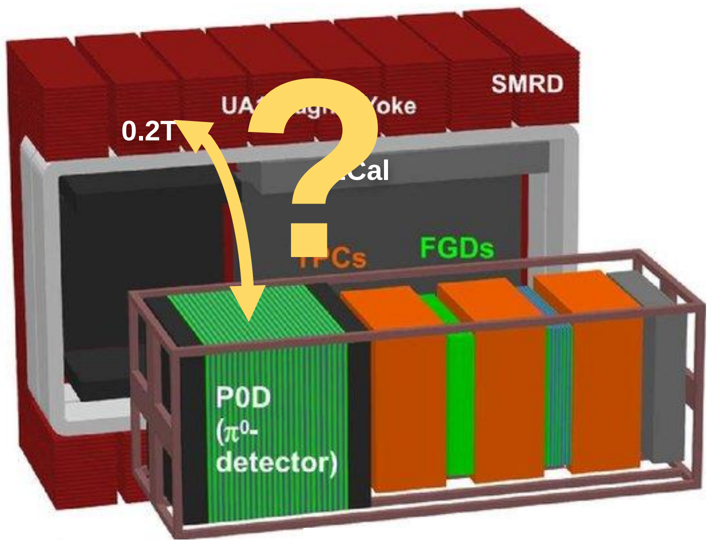
Testbeam event

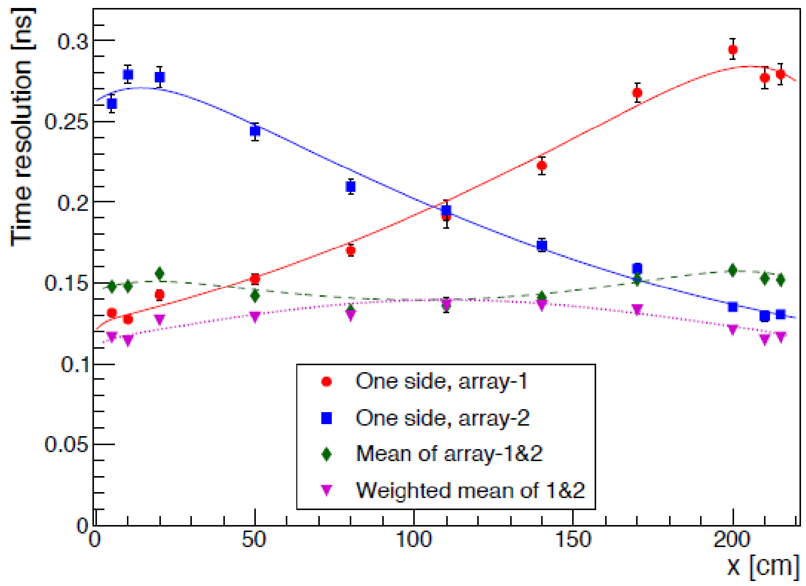


TOF

- 6 modules (2.3x2.5 m2) mounted each with 20 bars
- Double sided readout with 12 SiPMs per side
- Tested in several testbeams
- Excellent time resolution of 150 ps achieved
- Currently quality control of all modules using cosmics
- Important to determine direction of particles

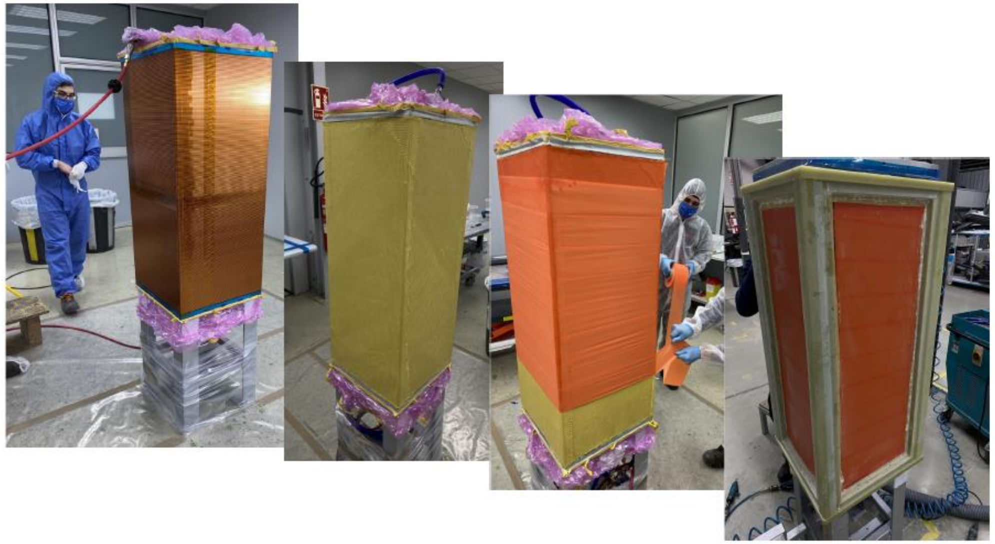


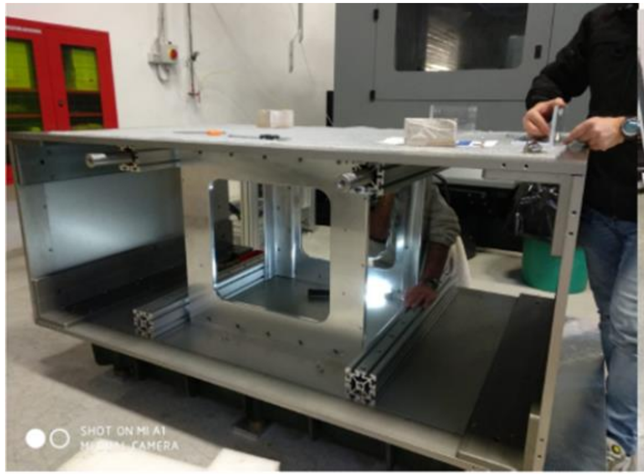


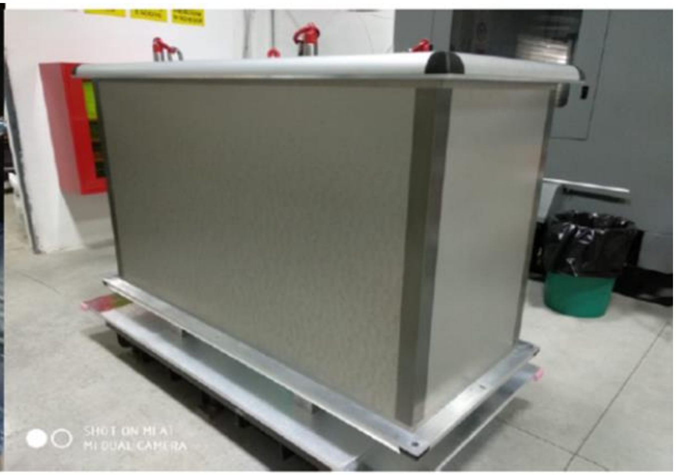


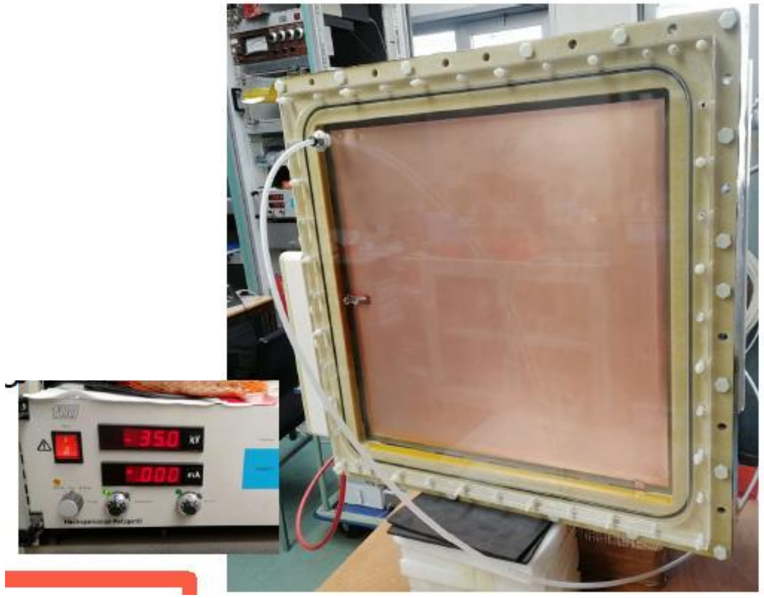
HA-TPC Field Cage

- TPC consists of 2 halves and separate cathode
- Production based on layers wrapped around mould
- 2 full length prototypes for 1 MM + several mock-ups were produced and tested
- Successfully tested:
  - Metrology
  - HV stability in air and argon up to 35 kV
  - Gas tightness
  - testbeams



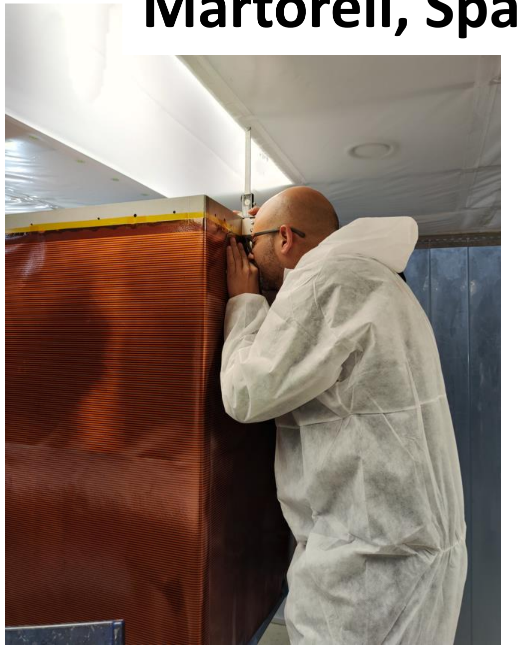


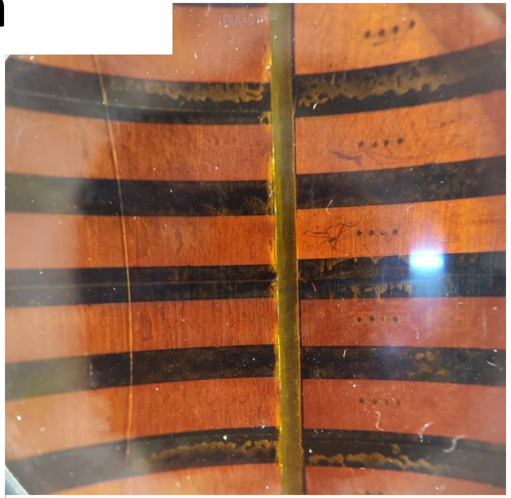




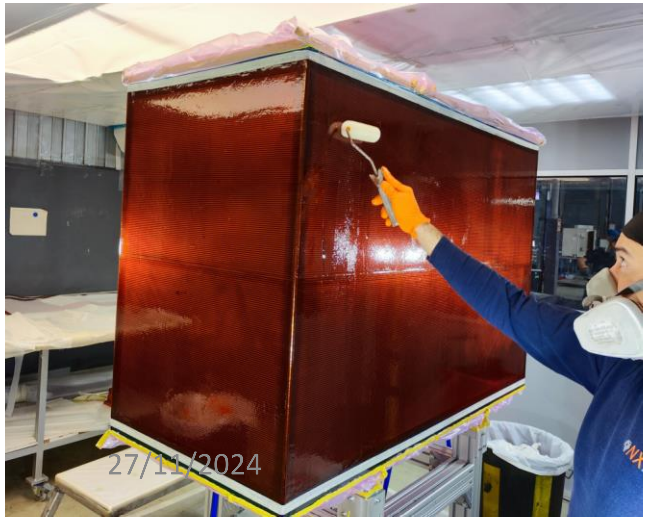
HA-TPC: Field Cage Production

NEXUS Projects SL, Martorell, Spain



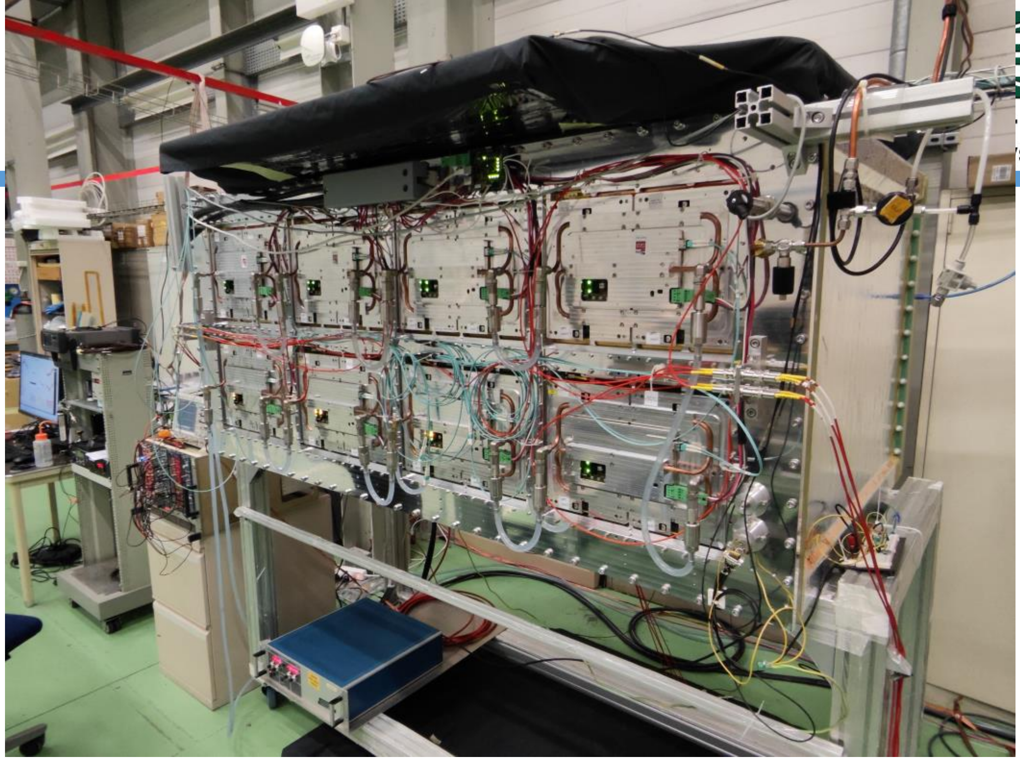


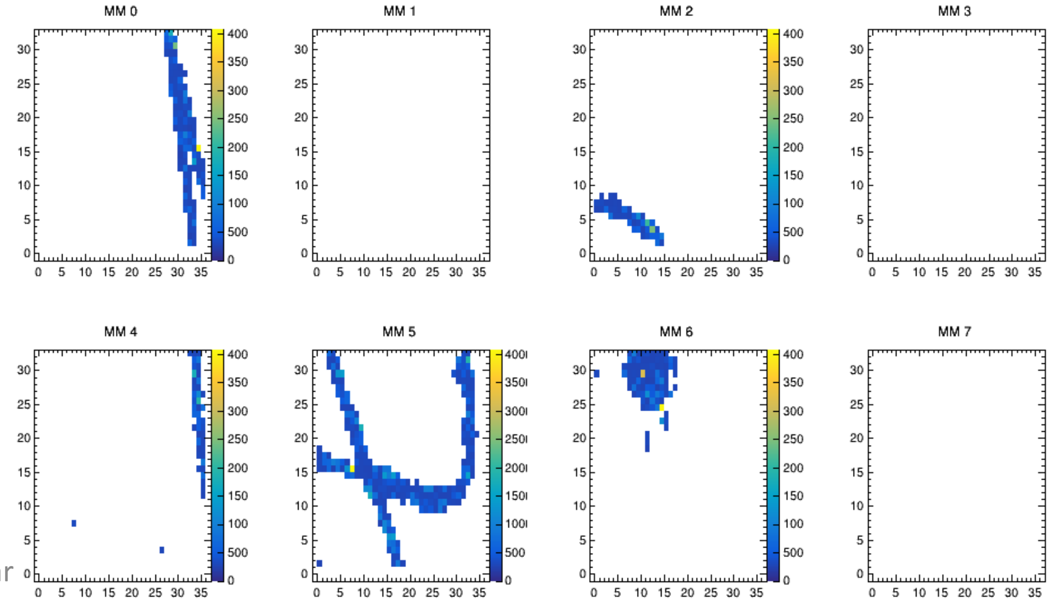
Tolerances of better than 100 um

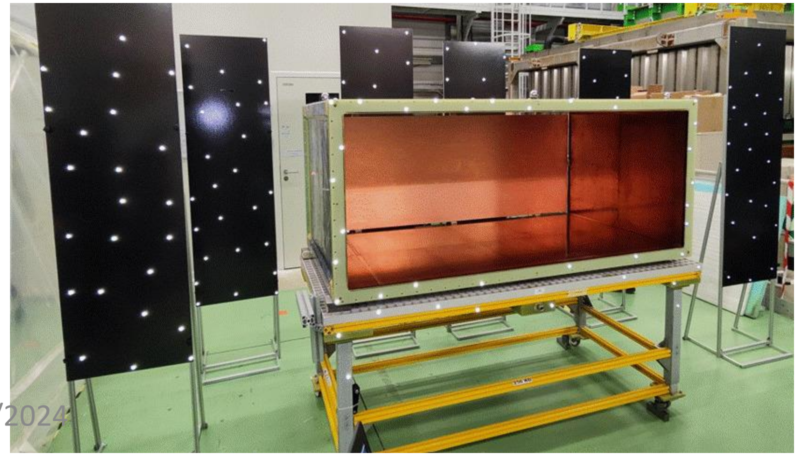


HA-TPC: Field Cage Tests at CERN

- Intensive tests after arrival at CERN: metrology, gas tightness, HV
- FC0 did not pass => months of delay to identify problem and improve production
- Next 4 FC passed all tests successfully
- 2 FC were mounted together to form one TPC (bottom and top) + installation of ERAMs
- Production, assembly + testing took more than 1 year
- Stable operation with 10+ millions of cosmics before shipping



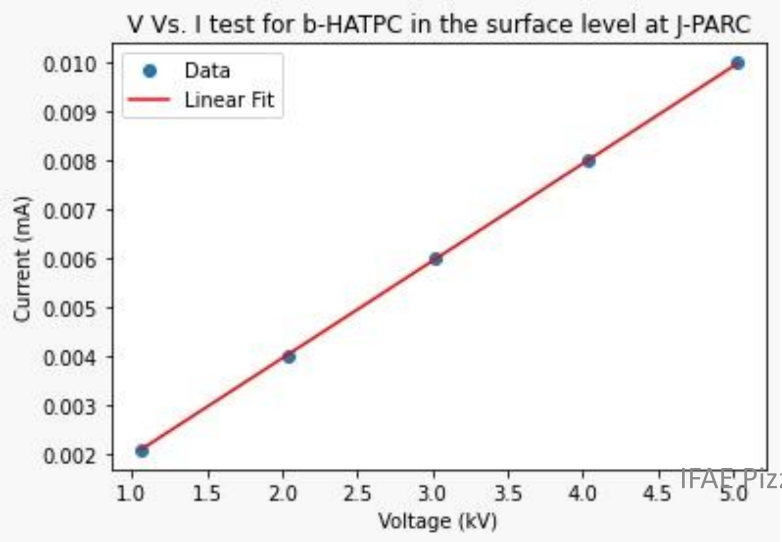




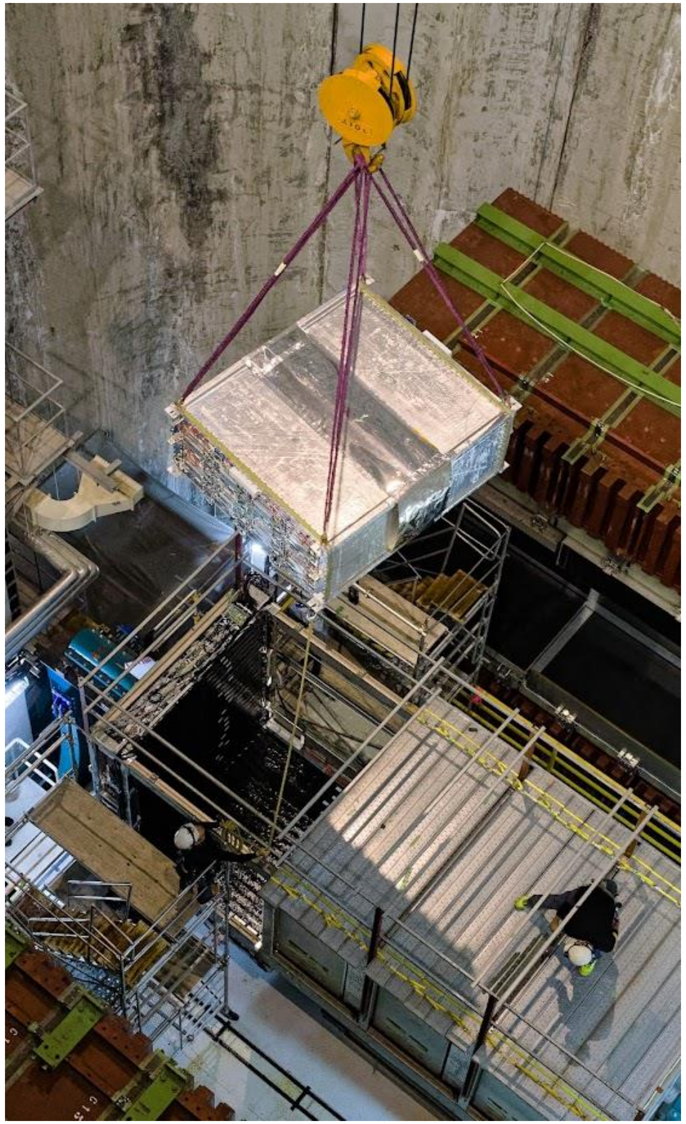
HA-TPC at J-PARC

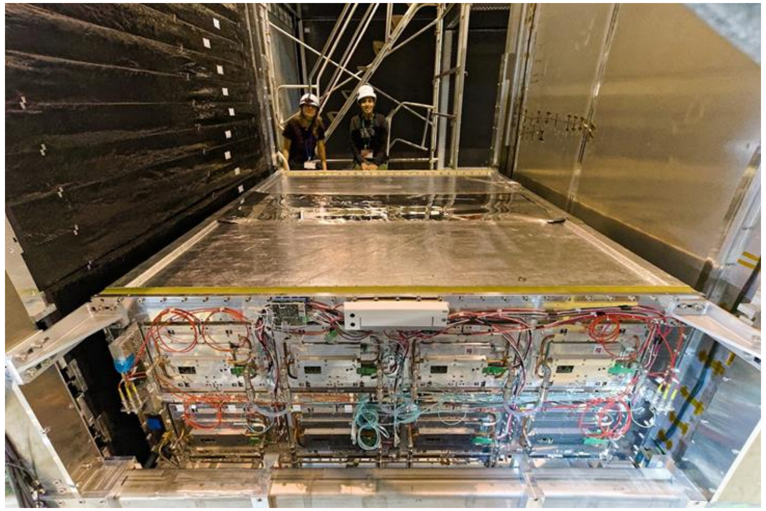
- 25th of August 2023: bTPC arrived at NA building
- Box and chamber were in perfect shape
- Quality control on surface:
  - Cathode HV => passed
  - ERAM HV => passed
  - Gas tightness => passed

=> Ready to install in basket!



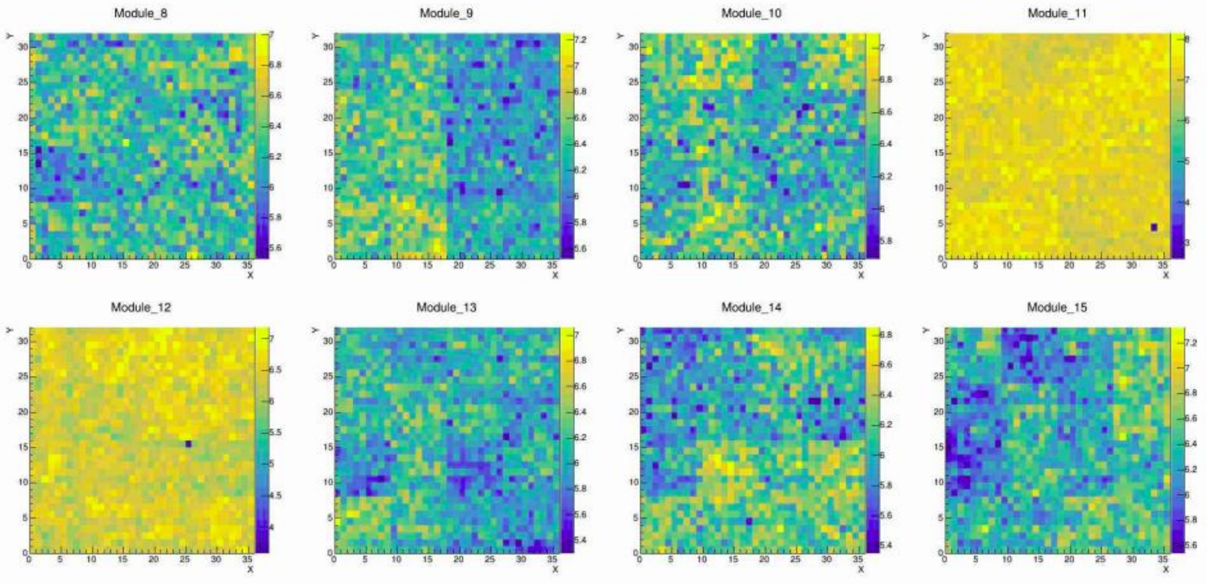
HA-TPC Installation



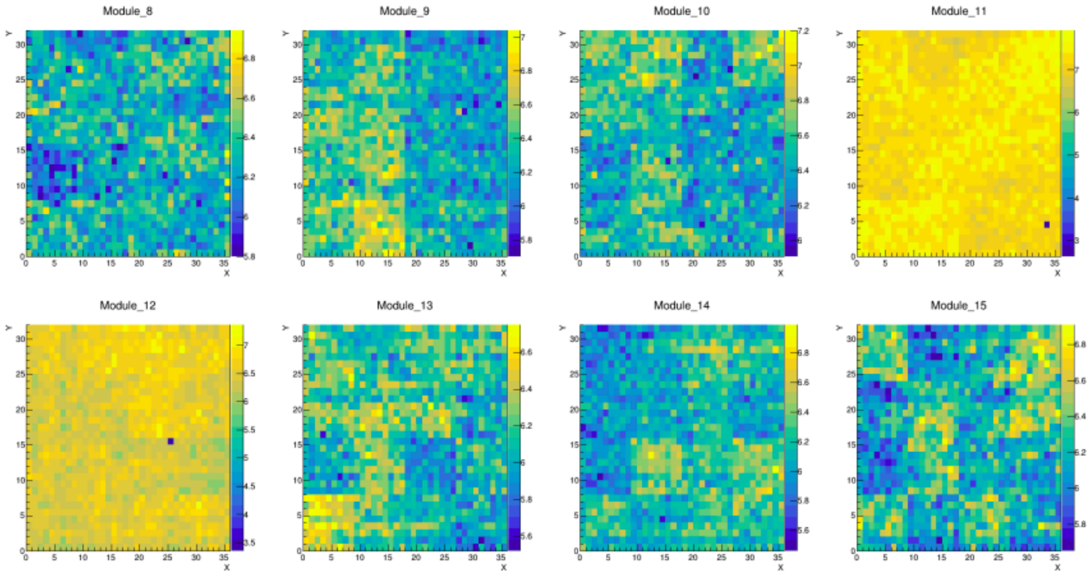


HA-TPC: First Checks

EP1 CERN



EP1 Tokai - pit

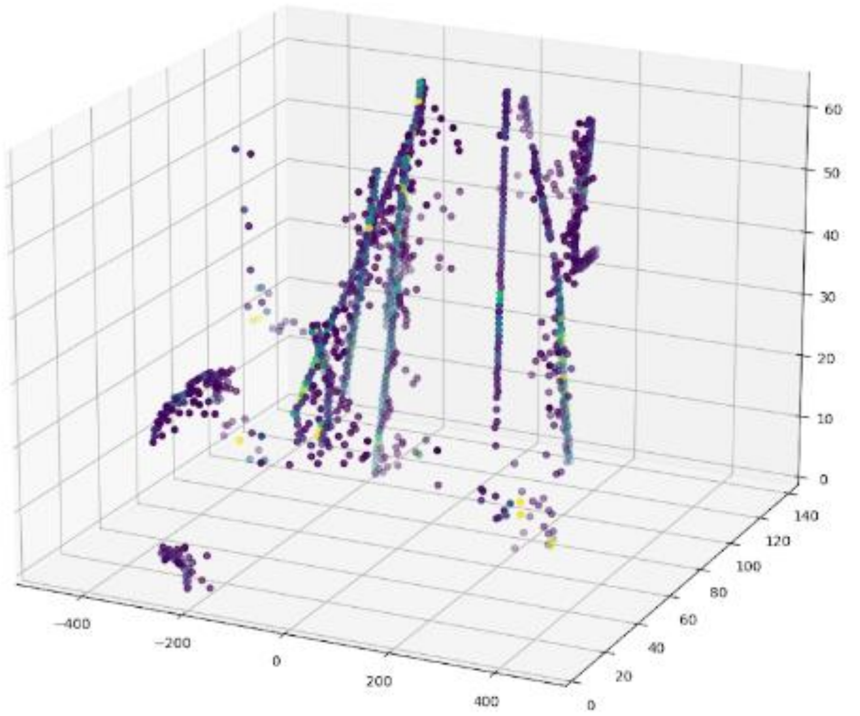


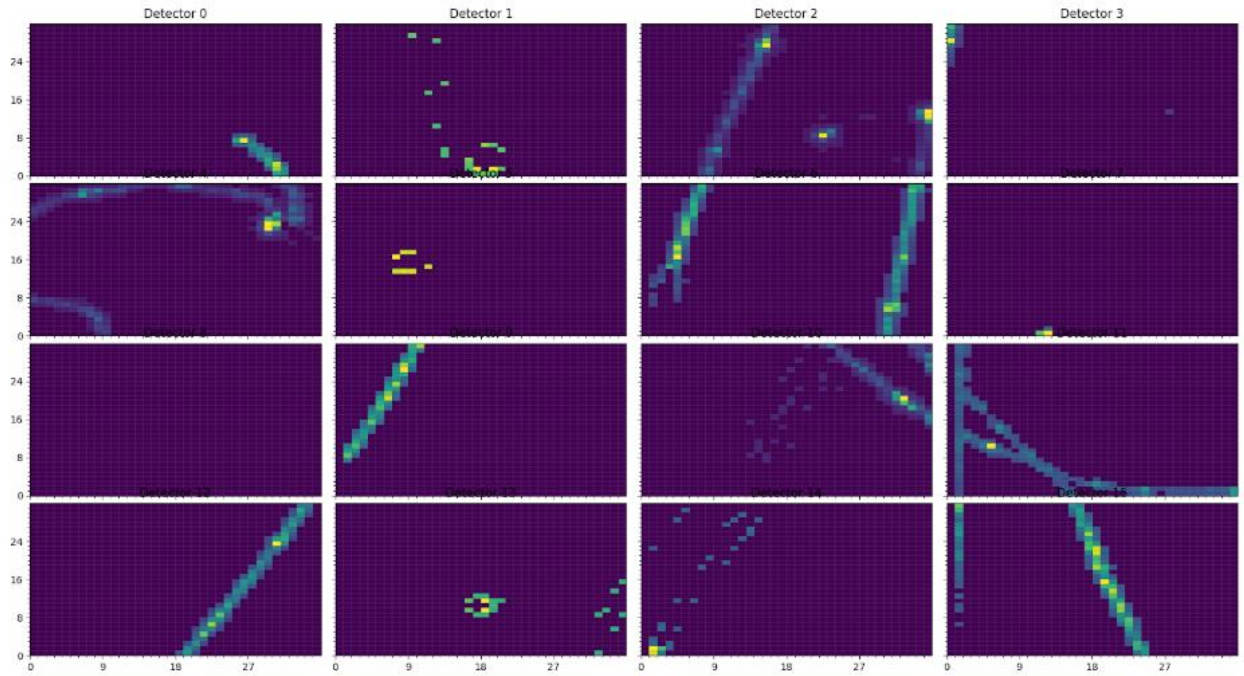
The first pedestal from the basket at J-PARC looks same as the one from CERN !!

Only 16 dead channels and all were already there at CERN.

HA-TPC: First Events

Trigger provided by first 2 TOF panels





SFGD: Cubes Production and Shipping

Cubes produced in Russia

CERN contribution

Excellent sagging behaviour following load test at CERN

24.06.2022

24.10.2022

SFGD: Assembly

(i) Support system assembly

(ii) First cube layer assembly

(iii) All 56 layers assembled

(iv) Stop panels removed

(v) Box closure

(vi) Transfer to new support

SFGD: Assembly

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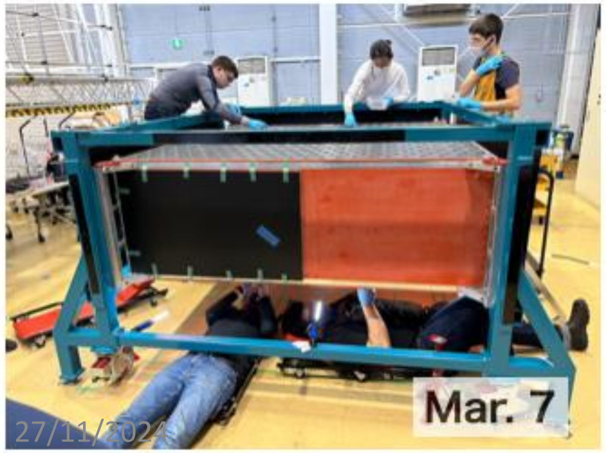
(vii) Horizontal fibers assembly

(viii) Wall MPPCs assembly

(ix) Vertical fibers assembly

(x) Top MPPCs assembly



(xi) LED calib. modules assembly

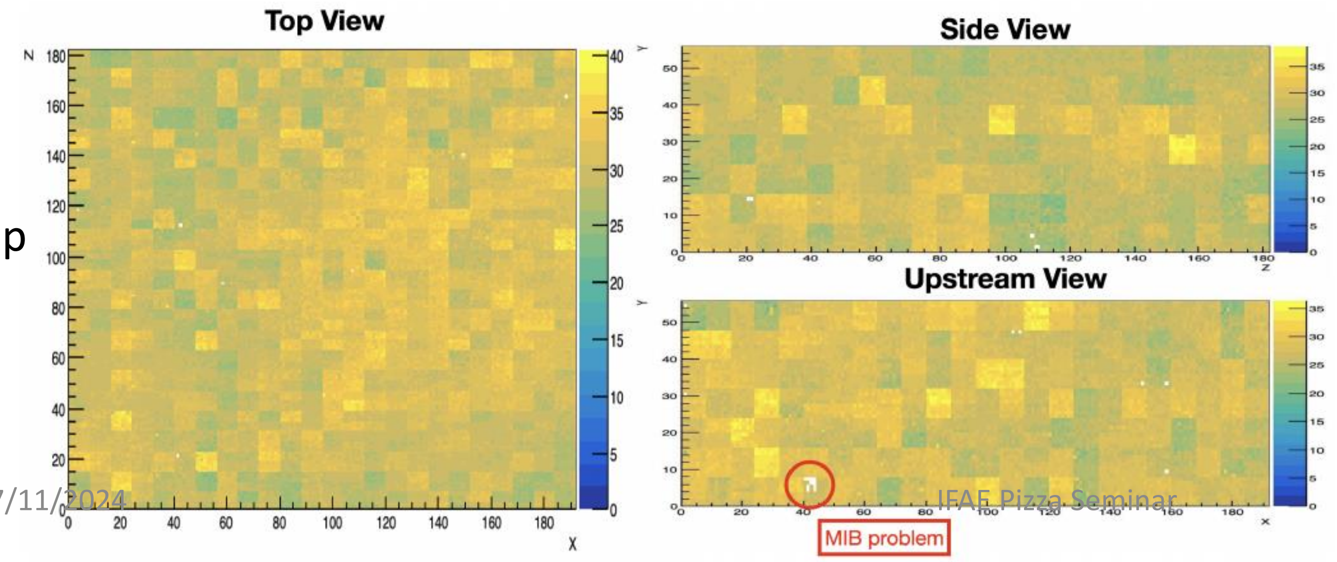
(xii) Light barrier/cables assembly

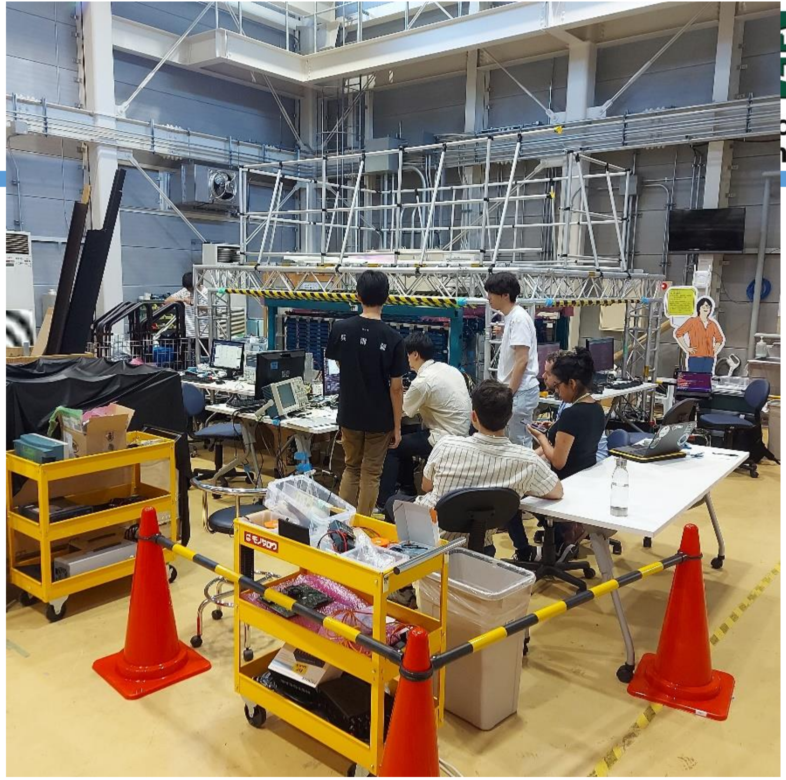
SuperFGD

- Allowed to test all channels with LED calibration system on surface
- Only 27 out of ~56k channels found to be problematic!!!!
- Cosmics in 3D taken in addition to LED
- Significant work on DAQ/SC/firmware/calibration

=> Goals for surface tests were accomplished!

Gain map





SFGD Installation

- With test results on surface comfortable to install SFGD on 12th / 13th of October






HA-TPC: Top TPC + TOF Installation (May 2024)

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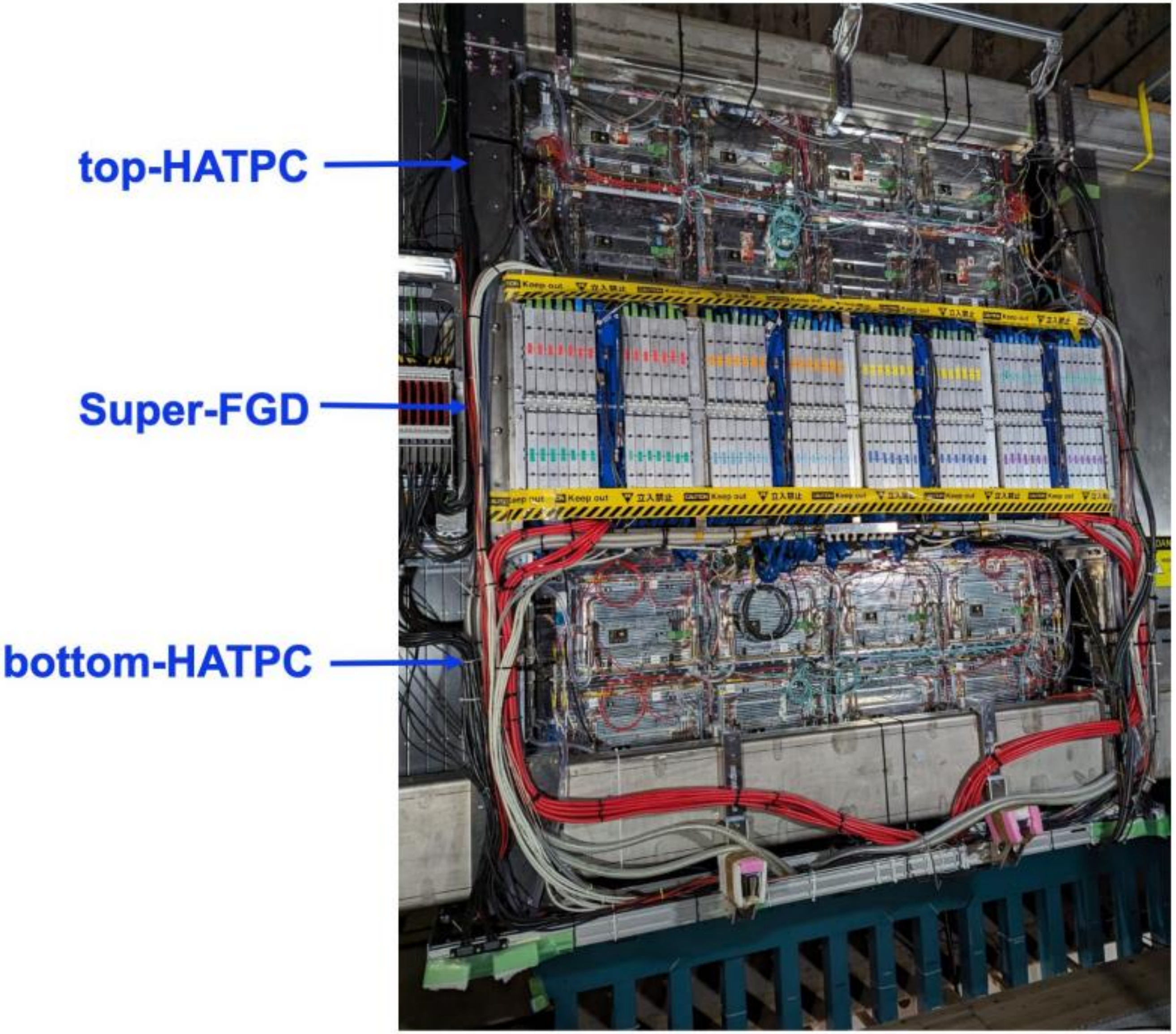
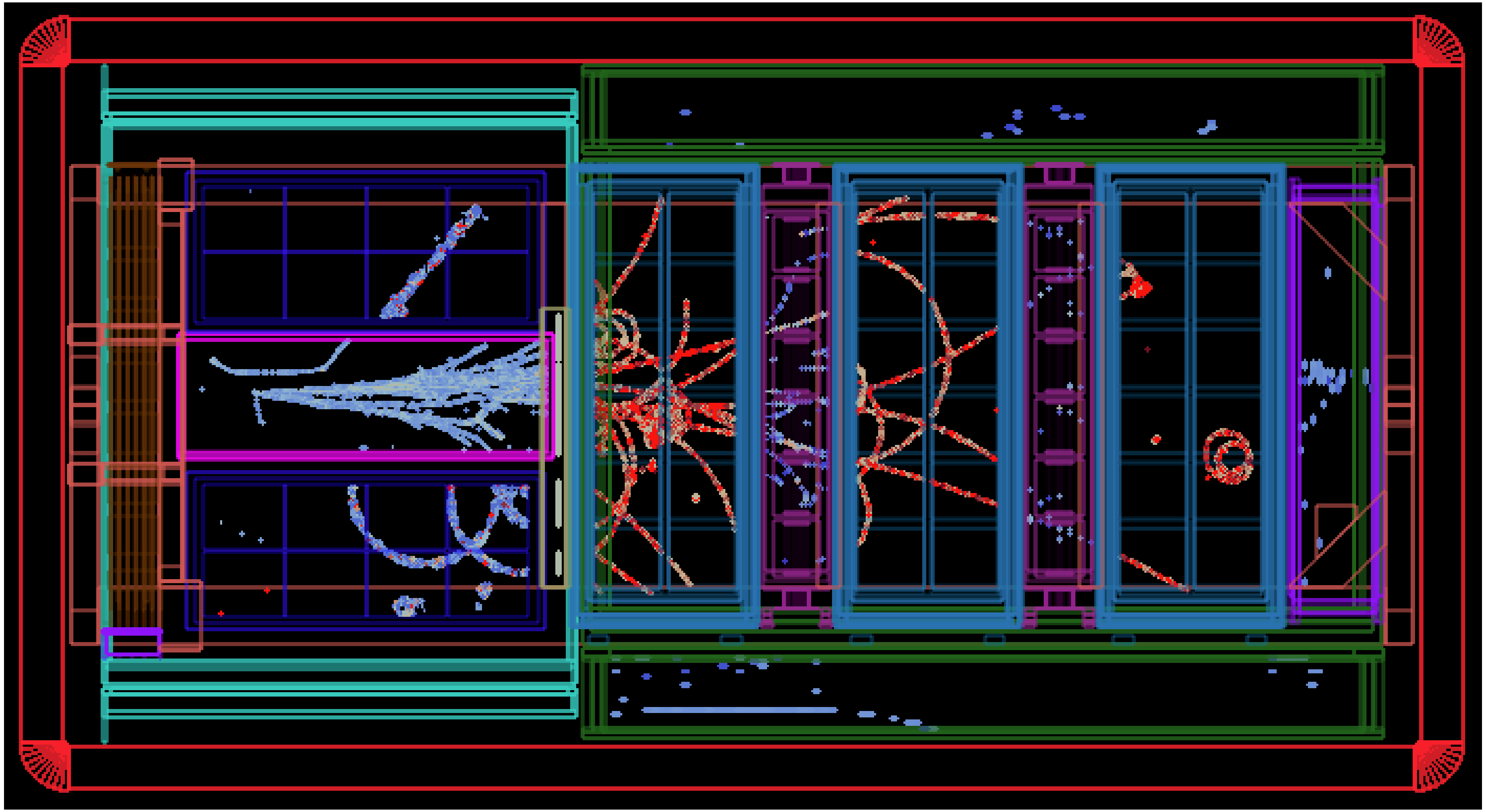
Finally …



15th of May 2024 after 10.5 months of installation work and 6 years after the TDR!

Does it work?

Real neutrino DIS event (not typical at all)



Typical Event

IFAE
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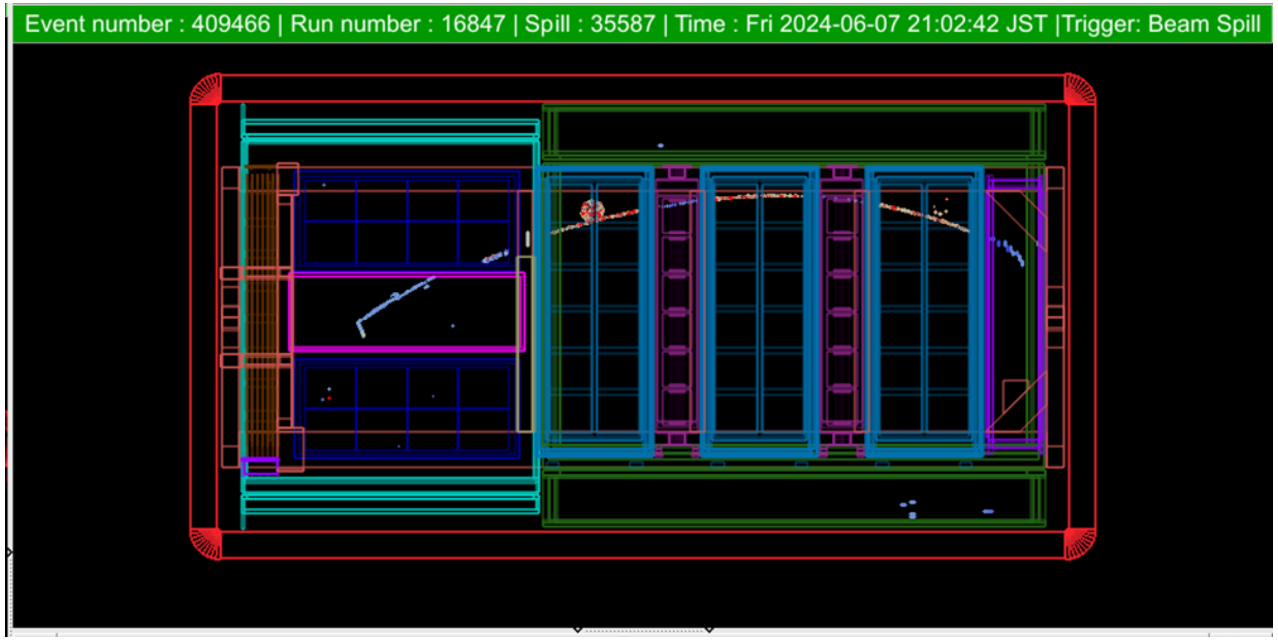

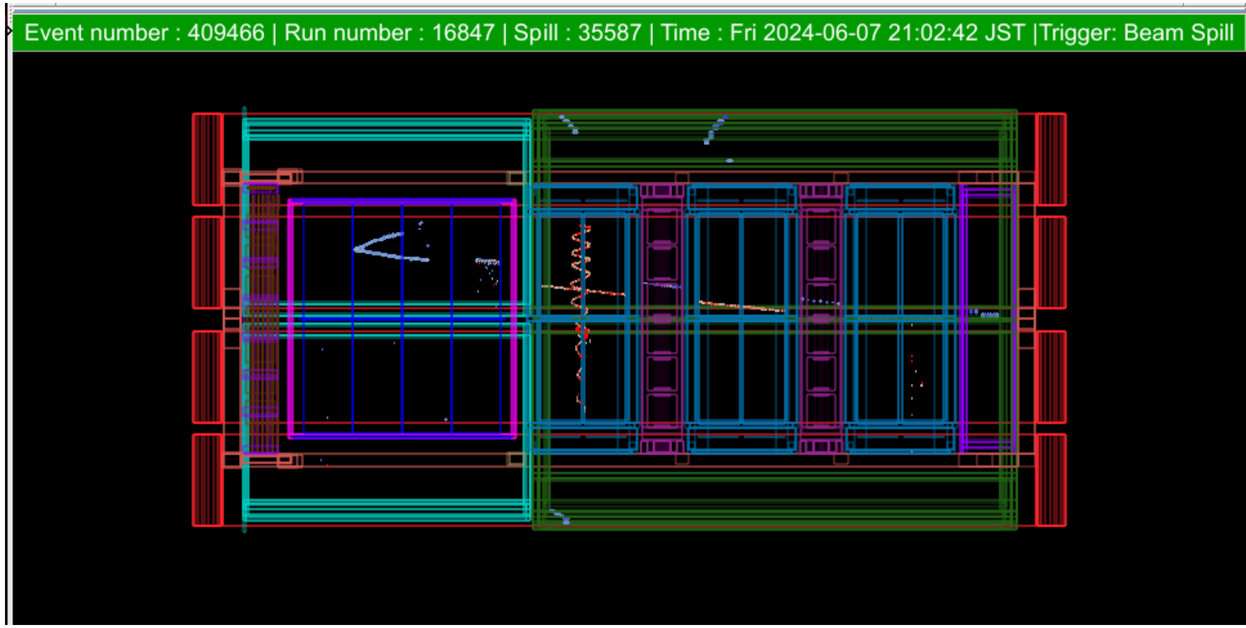

QE event:

- Long muon track including delta electron in vertical TPCs
- Short proton track in SuperFGD
- Now detector performance is studied

Towards Hyper-K (2027-)

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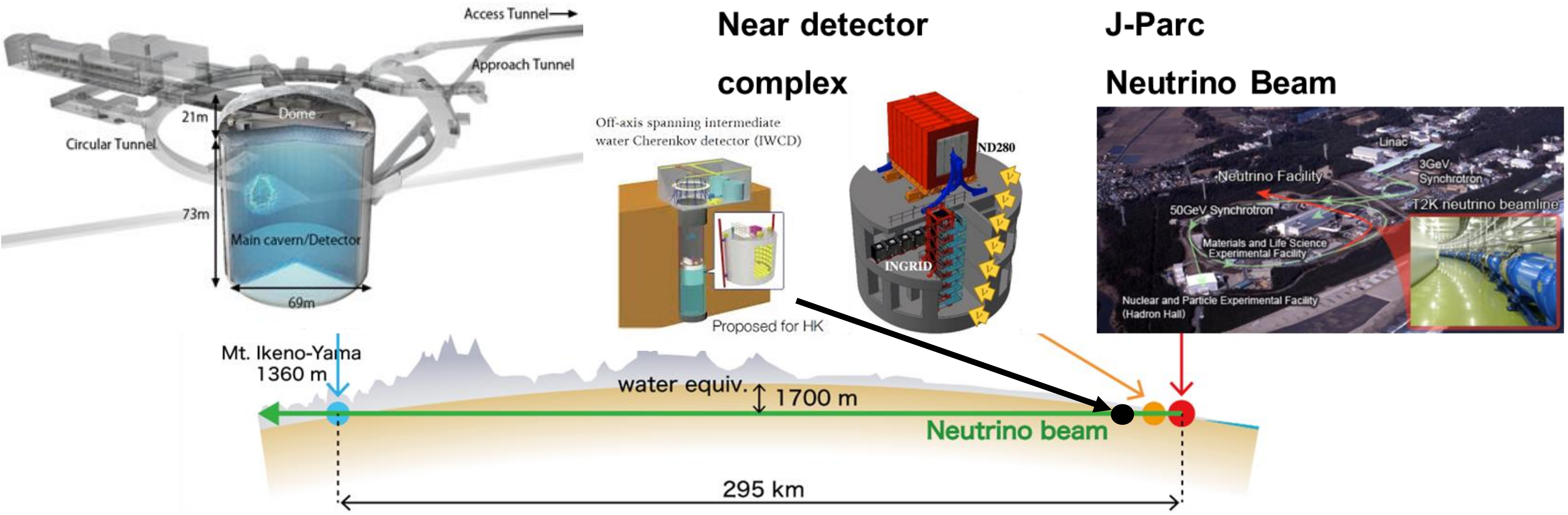

- Replace SK by new FD: ~ 9 times the fiducial mass of SK
- Build new intermediate detector (IWCD) complementary to ND280
- Upgrade beam power to 1.3 MW from now 800 kW
- ND280 will be crucial for the success of HK

After the T2K ND280 Upgrade is before the HK ND280 Upgrade++

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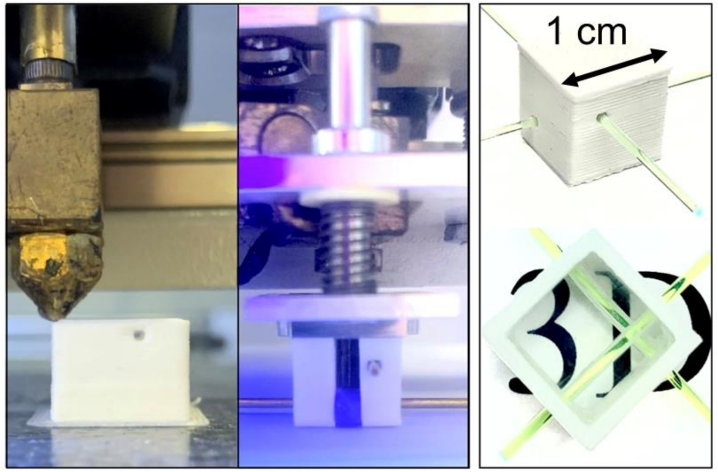
How to build HyperFGDs (SuperFGD++)?

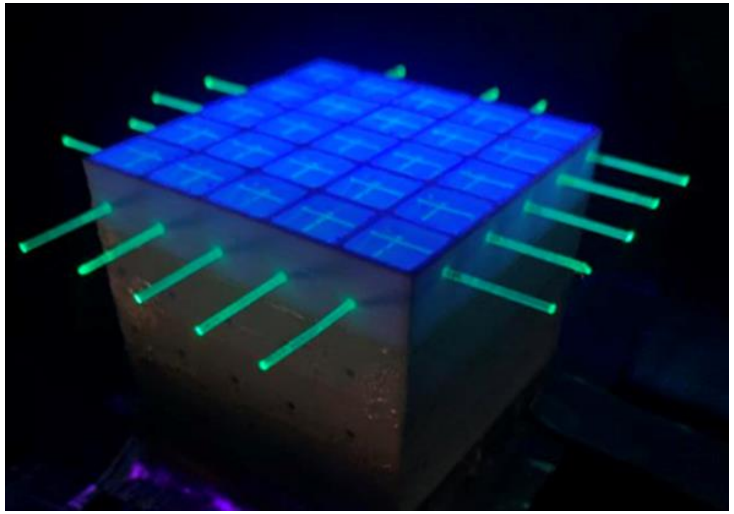
$\Rightarrow$ You do not want to handle 10M cubes and drill 30M holes by hand …

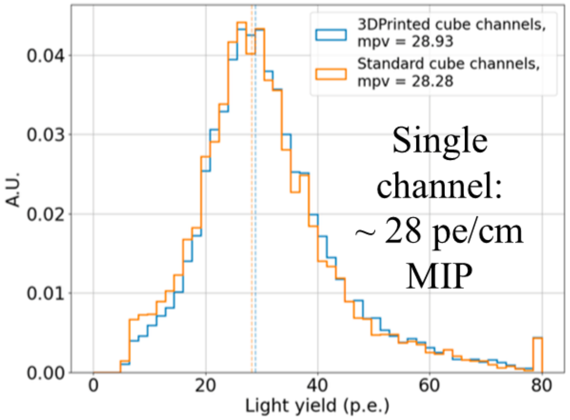
$\Rightarrow$ 3DET collaboration is developing 3D printing of plastic scintillator

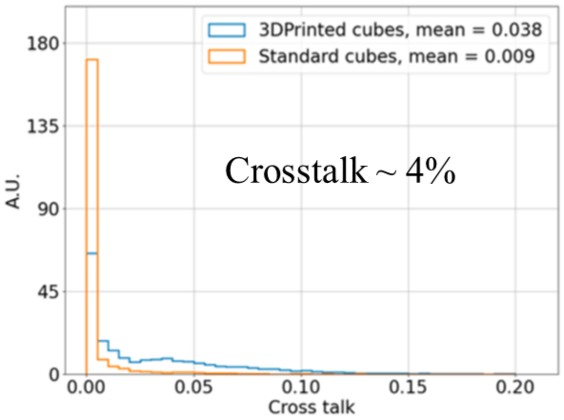
$\Rightarrow$ Prototype has been printed

$\Rightarrow$ Performance similar to standard cube production









Summary

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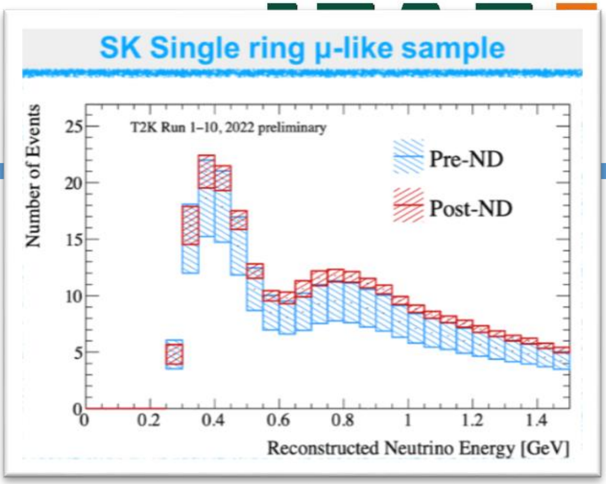
- Near detectors are crucial for the success of LBNO experiments
- The ND280 Upgrade is a mayor improvement for T2K
- It was a tough job done by many people (~120) from 11 countries over several years
- Detectors are not falling from the sky, remember this when you do your analysis!
- Upgraded ND280 works amazingly well
- Studies to understand the upgraded detectors ongoing (performance, alignment, reconstruction algorithms, …)
- ND280 will be used by HK and transfer will be mayor task
- Studies for additional HK ND280 Upgrade have started
- **If there is still a Master student without topic … Very interesting topic about feasibility study related to a near detector still available …**

Backup

Importance of Systematic Uncertainties



Changing from statistics limited to systematic uncertainties limited!

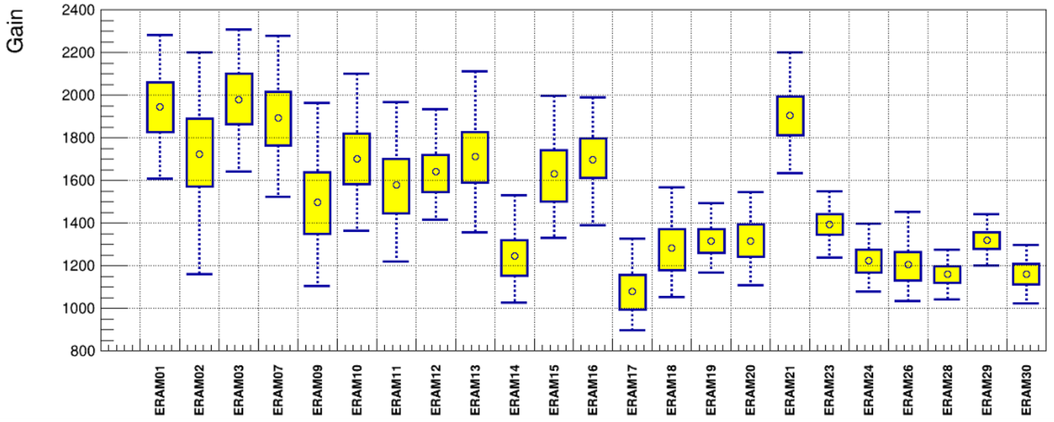
Experiment	ν_μ events	$\bar{\nu}_\mu$ events	ν_e events	$\bar{\nu}_e$ events	Systematic error
T2K arXiv:2303.03222	318	137	94	16	~5%
NOvA PRD106,032004 (2022)	211	105	82	33	~5%
Hyper-K TDR	**~10000**	**~14000**	**~2000**	**~2000**	**?**
DUNE FD TDR	**~7000**	**~3500**	**~1500**	**~500**	**?**

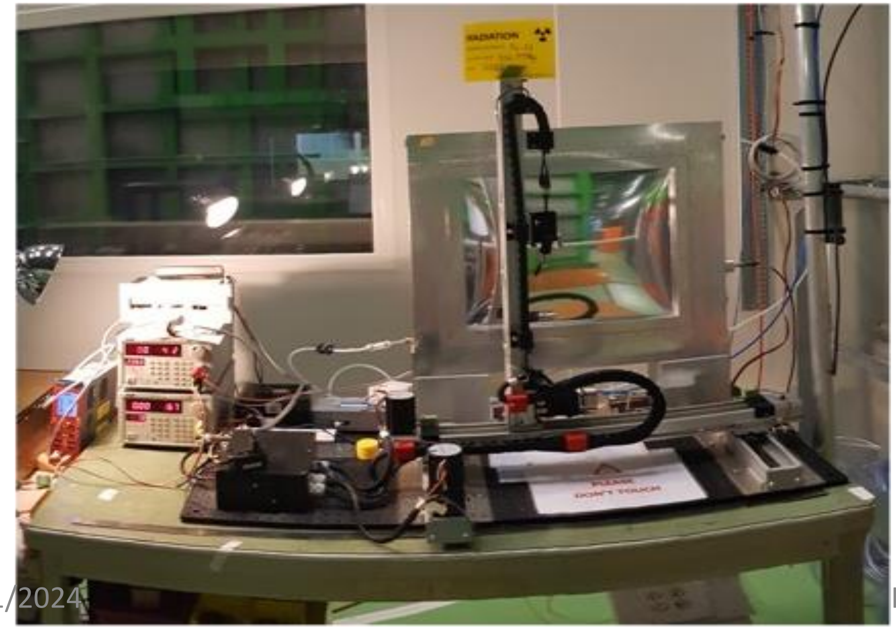
Now (already reduction from ~20 % with ND)

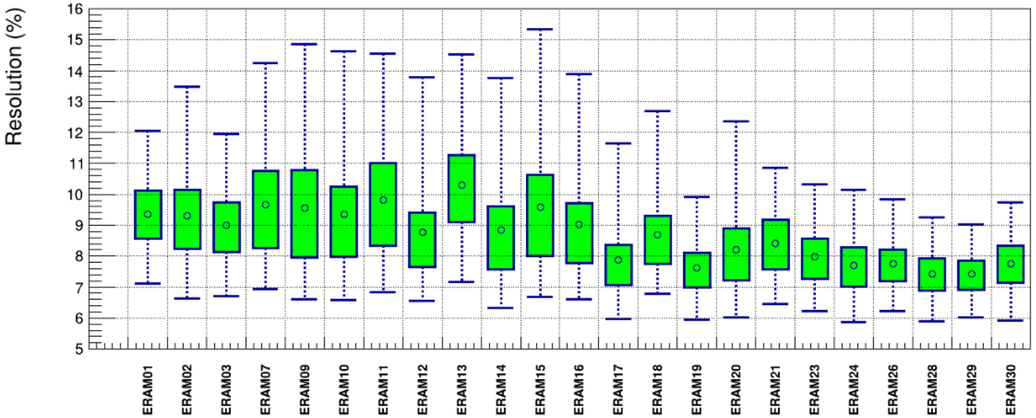
Near future

HA-TPC: ERAM Production (CERN)

- ERAM production at MPGD workshop over 18 months
- QC performed with test bench
- Some performance effects observed over production time for gain
- 36 ERAMs within requirements (32 + 4 spares)

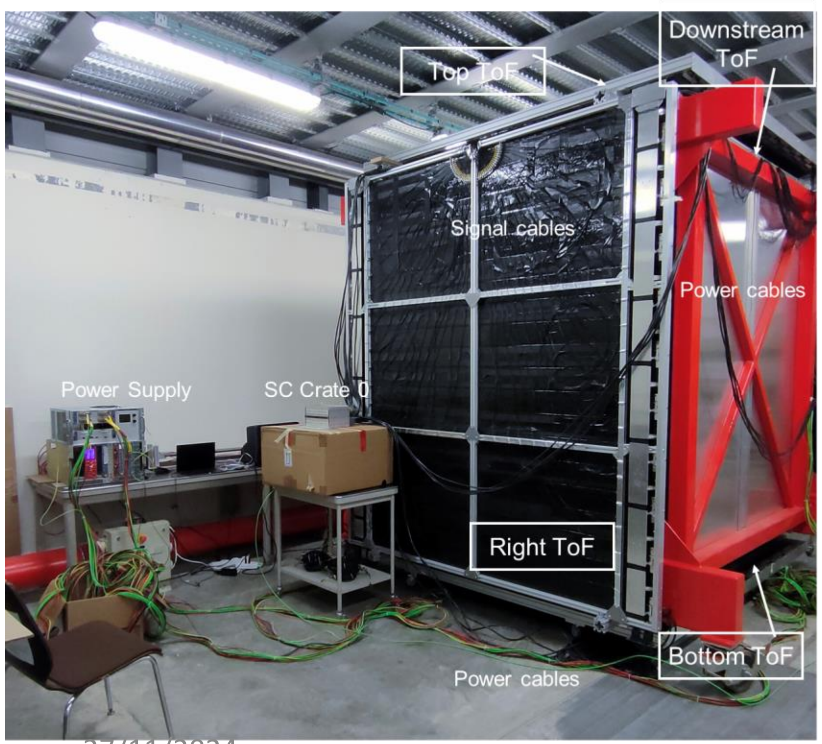


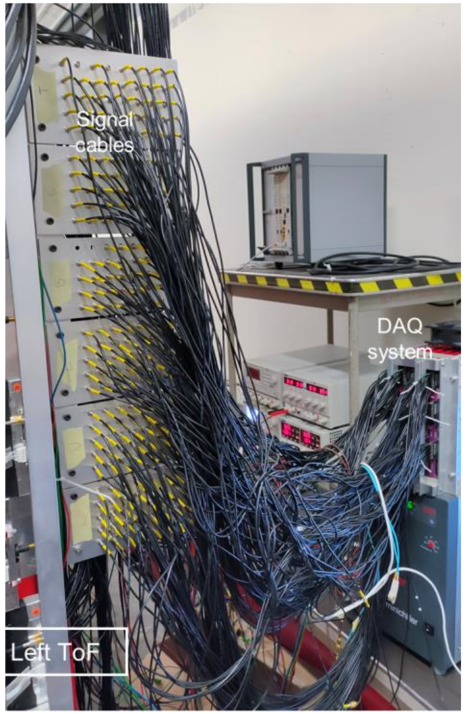




TOF

- Detector fully installed at CERN on the baby basket and being operated since September
- Since last week all detector working with all final HW components (cables, PS, DAQ, SC)
- Preliminary tests successful of all custom made software

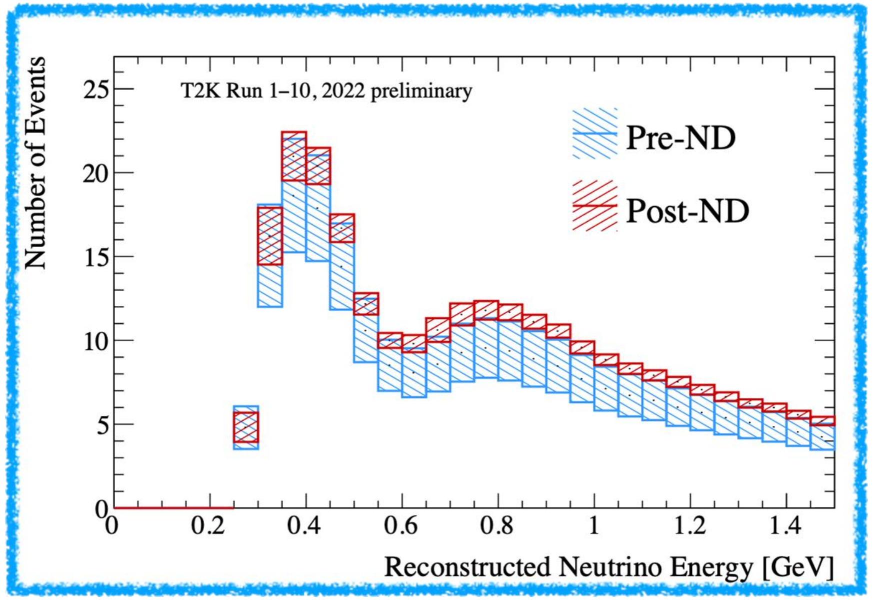




Conclusions

- Near detectors are crucial for success of LBNO experiments
- Especially true for DUNE and HK which will be systematic uncertainties limited
- Reduction of systematic uncertainties from about 15-20% to about 3-6%
- Achieved by development of large variety of excellent ND technologies
- There is not “the-one-and-only” ND technology but the combination of different ones is the key
- Possibly opens possibilities for new BSM studies
- Still room for a lot of R&D and new ideas!
- Join the WG6 sessions for much more detailed talks

SK Single ring μ-like sample



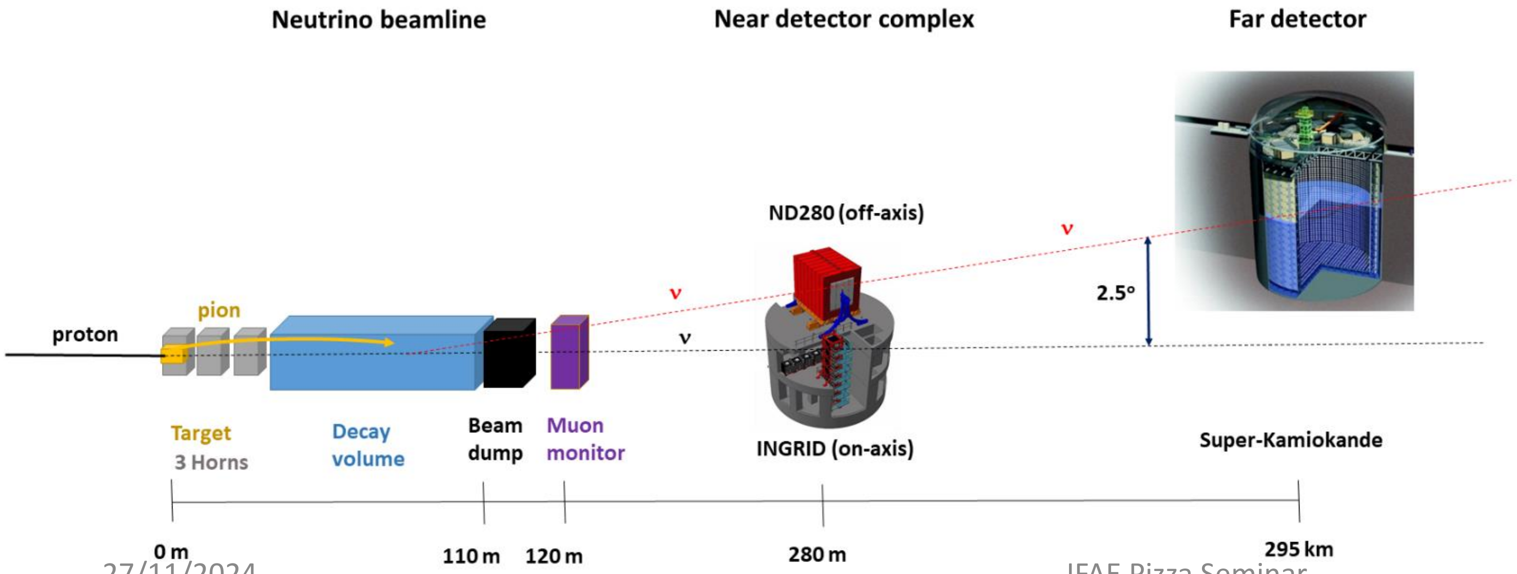
C. Giganti talk at Neutrino 2024

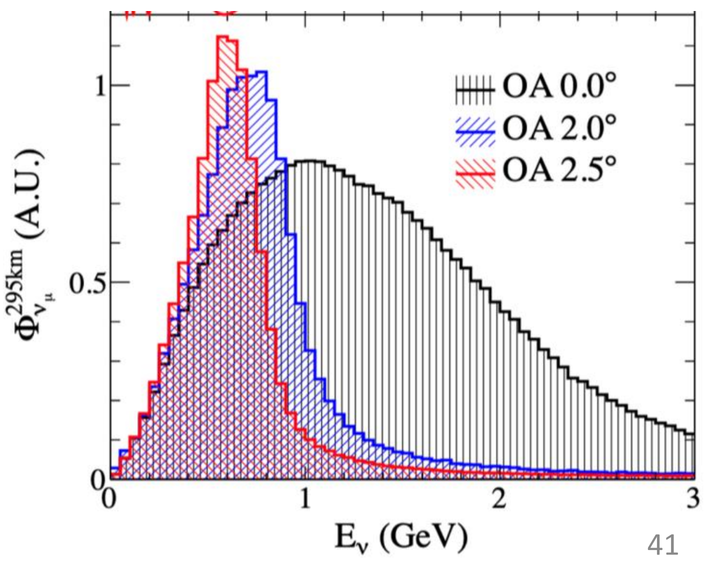
Neutrino Fluxes: Energy Spectrum

- Important to understand what neutrino fluxes one can expect
- Are the detectors on-axis or off-axis?
- On-axis: Wide neutrino energy spectrum
- Off-axis: Narrower neutrino energy spectrum peaking at lower energies

$\Rightarrow$ Neutrino beams are very wide and covering the whole experimental area

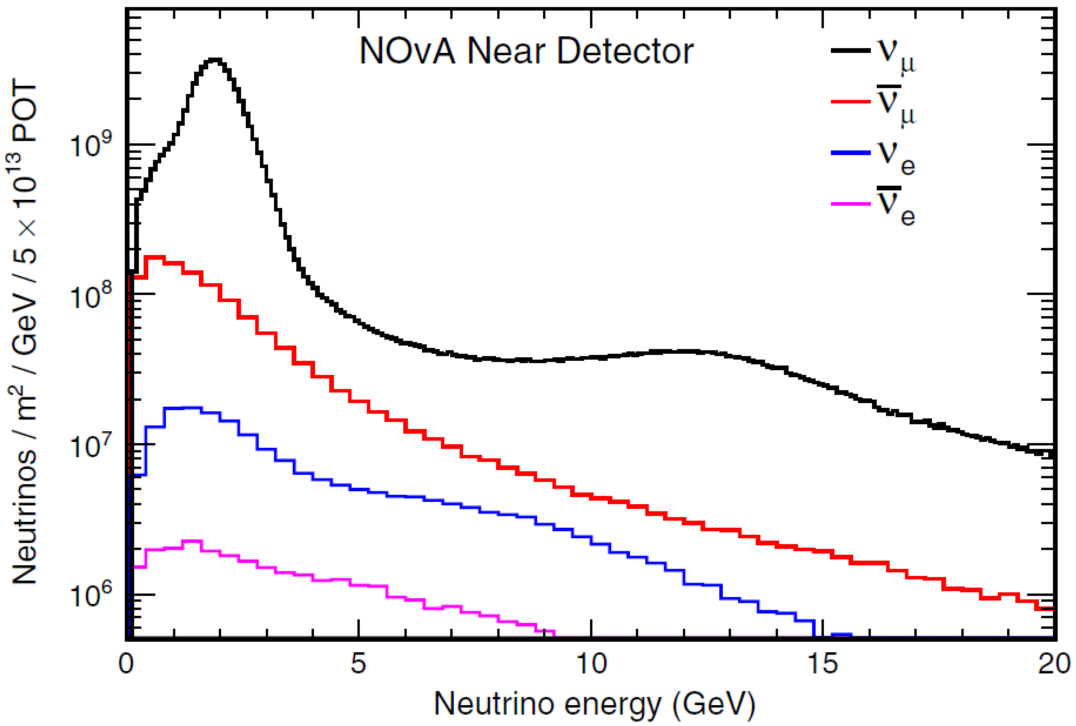
$\Rightarrow$ Measuring at different angles helps to deconvolute flux and cross-section





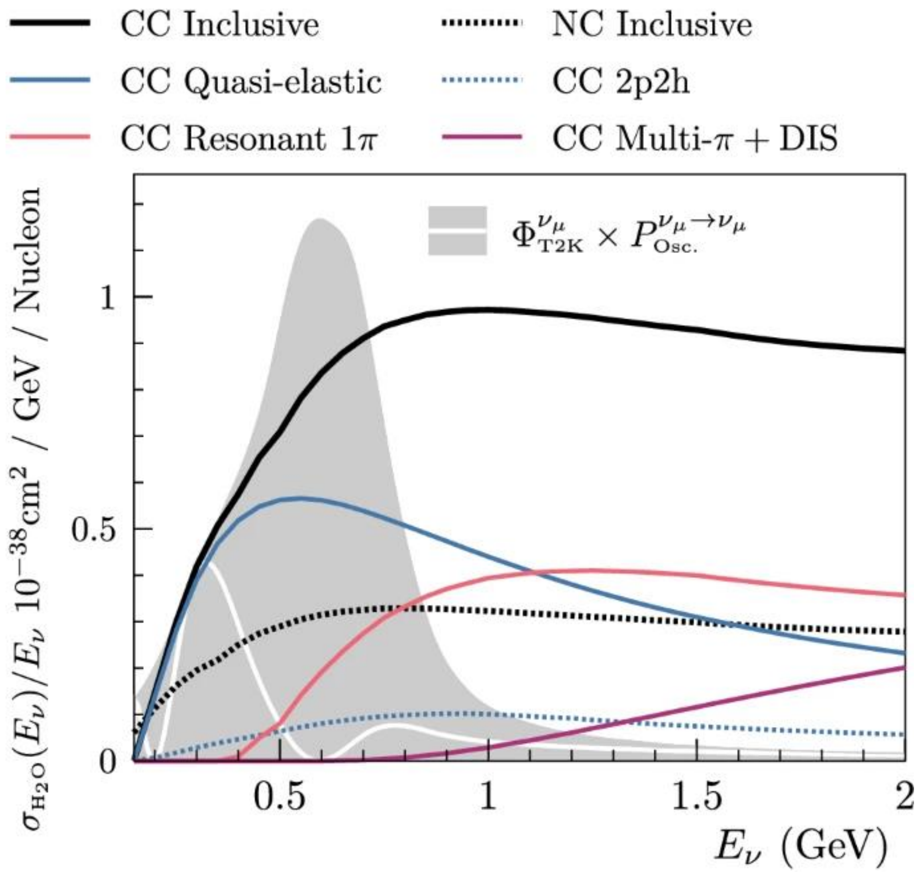
Neutrino Fluxes: Composition

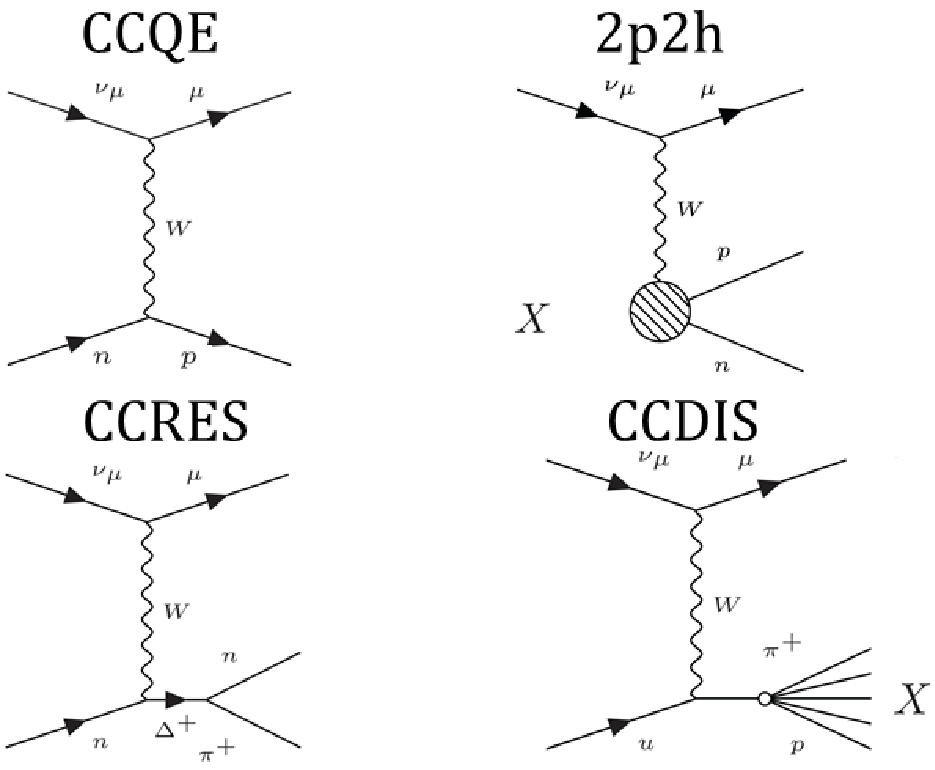
- Naïve picture: Start with pure ν_μ beam characterized at ND and measure oscillated beam containing ν_μ and ν_e at FD
- Reality: Production process of neutrino beam results in contamination
- Fractions depends on several experimental aspects: proton energy, target geometry, horn system, beam angle, …
- Knowledge important for experiment sensitivity
- Enables to measure cross-sections also for ν_e



Cross-Sections and FSI

At neutrino energies relevant for LBNO, there are 4 interaction modes:

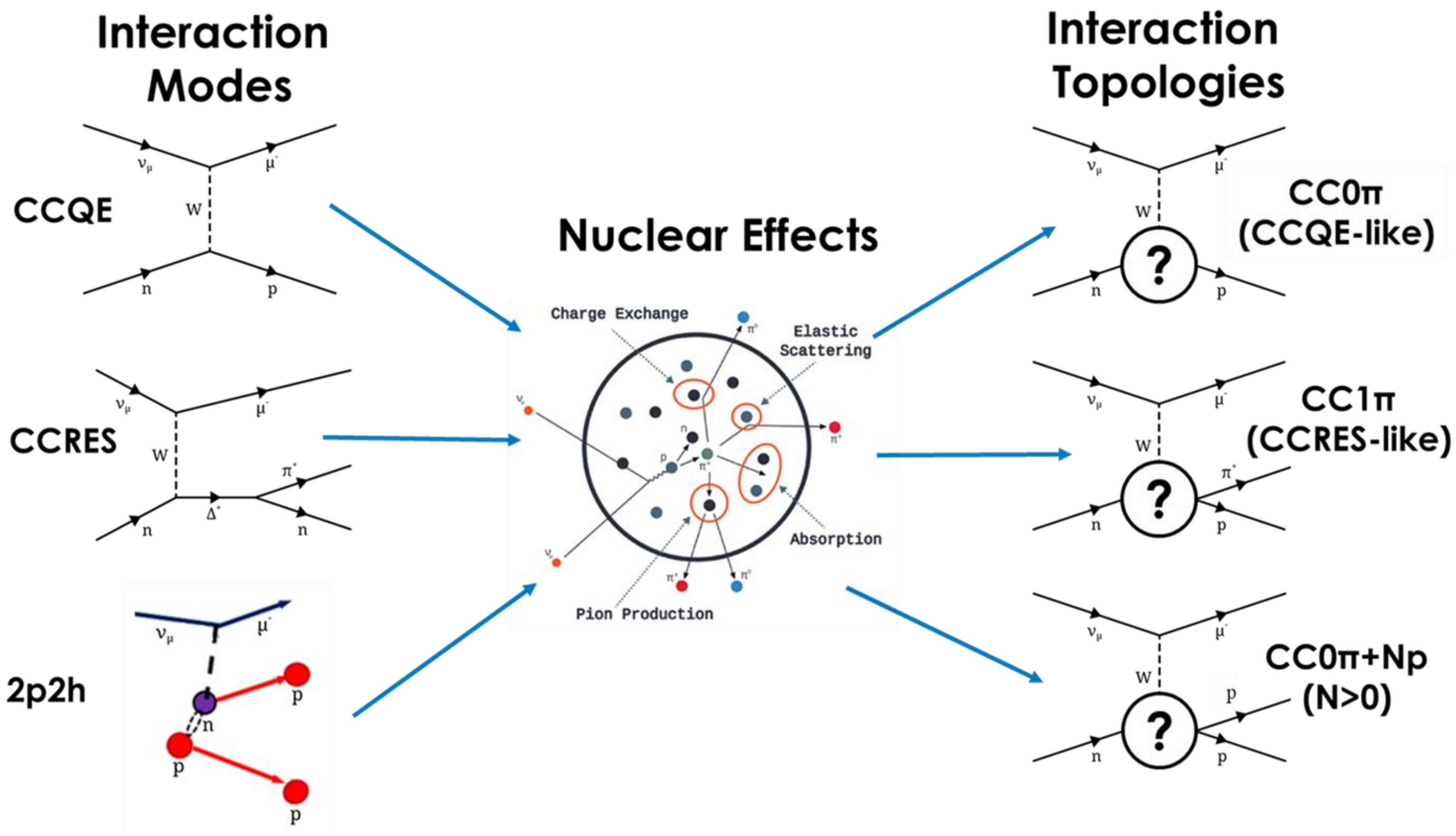




Depend on target material => ND should provide cross-sections for FD target!

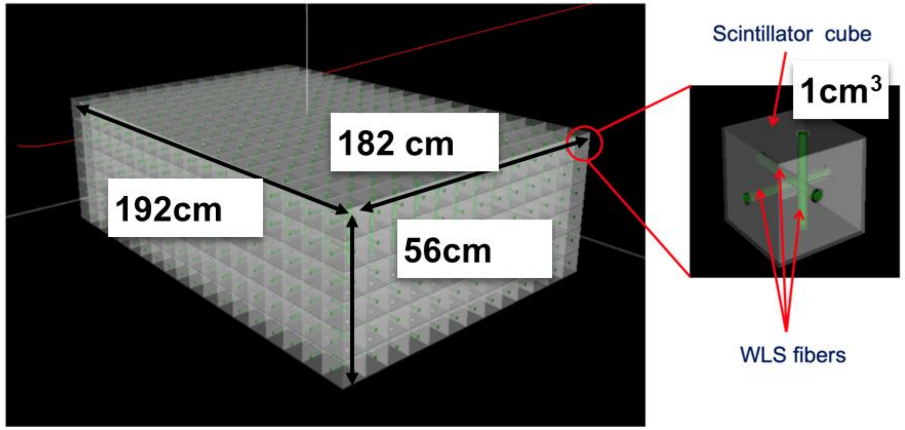
Event Topologies

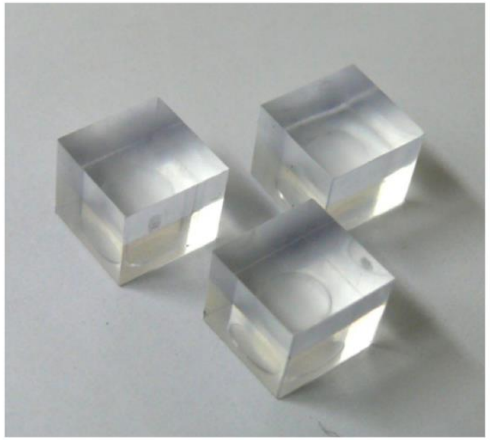
- Interaction not on free nucleons
- Nuclear effects/ Final State Interactions (FSI) can alter the event observables
- Effects depend on target material
- More relevant for low neutrino energies
- **ND provides insight in FSI**

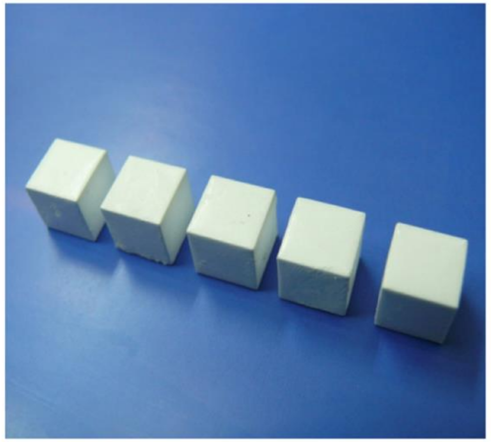


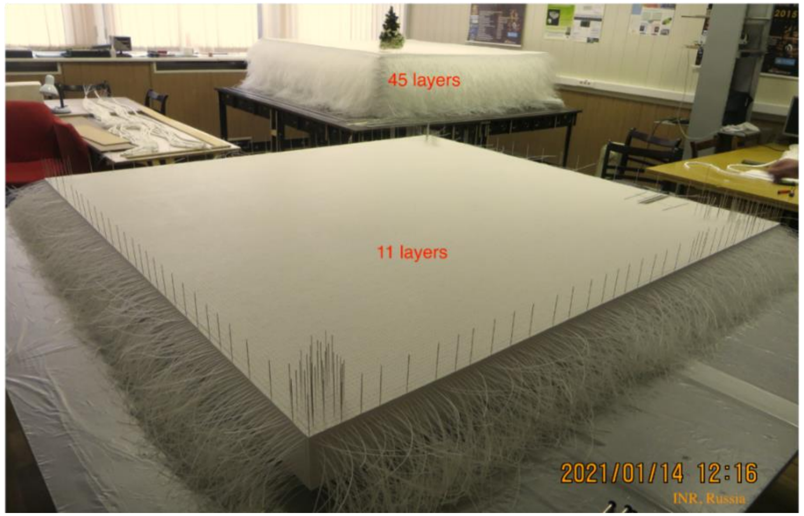
3D Scintillator Tracker: SuperFGD

- Built for T2K ND280 Upgrade and installed in October 2023
- 2M optically isolated cubes produced and 6M holes precisely drilled
- Assembled in 56 layers with fishing lines
- Final assembly in box with WLS fibers









Neutrino fluxes: Intensity/Beam Power

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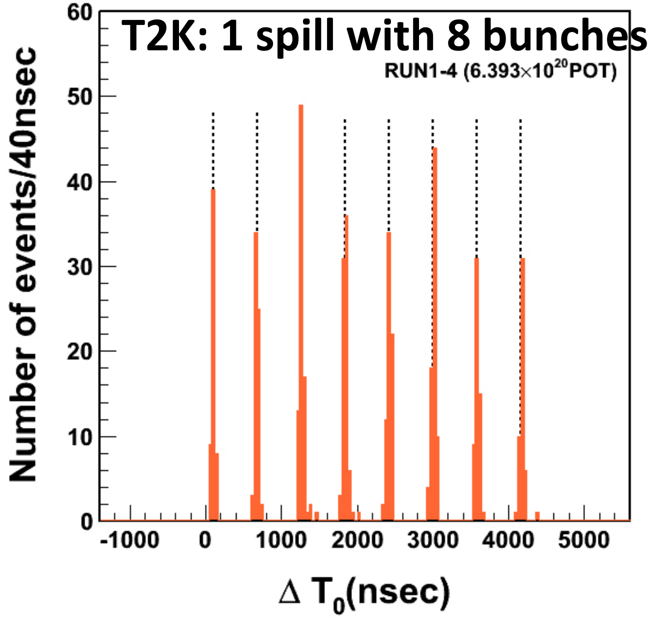
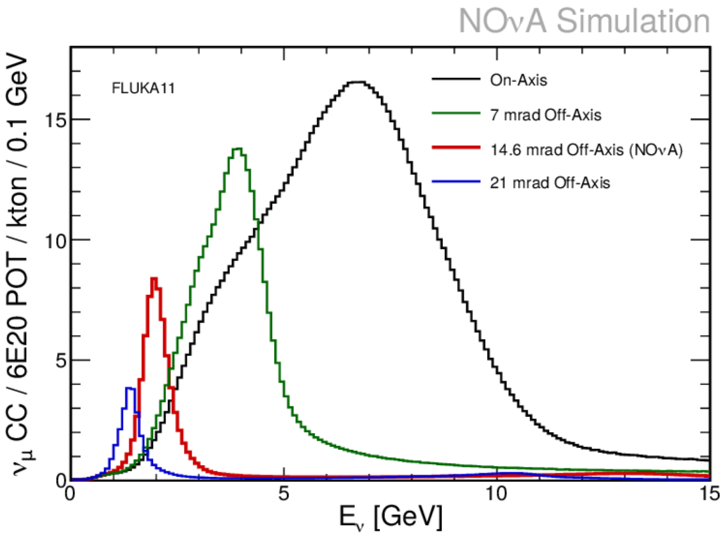
- Intensity of neutrino flux impact on ND design
- Higher flux means more statistics opening new opportunities
- Beam power can be increased by more spills or more neutrinos per spill
- More neutrinos per spill implies more pile up background (also from out of fiducial volume interactions)
- Impressive increase in intensity and neutrinos per spill over last decades:
  - Past: K2K => 1.4 x 10^{12} p.o.t.
  - Current: T2K => 2.65 x 10^{14} p.o.t.
  - Next generation: DUNE => 7.5 x 10^{13} p.o.t.
    HK => 3.2 x 10^{14} p.o.t.

⇒ ND technologies with smaller N_{target} become interesting!

See talk by T. Sekiguchi and A. Burleigh





Neutrino Energy Reconstruction

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The oscillation parameters depend on the true neutrino energy => precise knowledge of energy response function **T(E_{rec}, E_{true})** crucial.

1) Kinematic energy reconstruction (suitable for true QE events):

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

Requires only kinematics of outgoing muon

2) Calorimetric energy resolution:

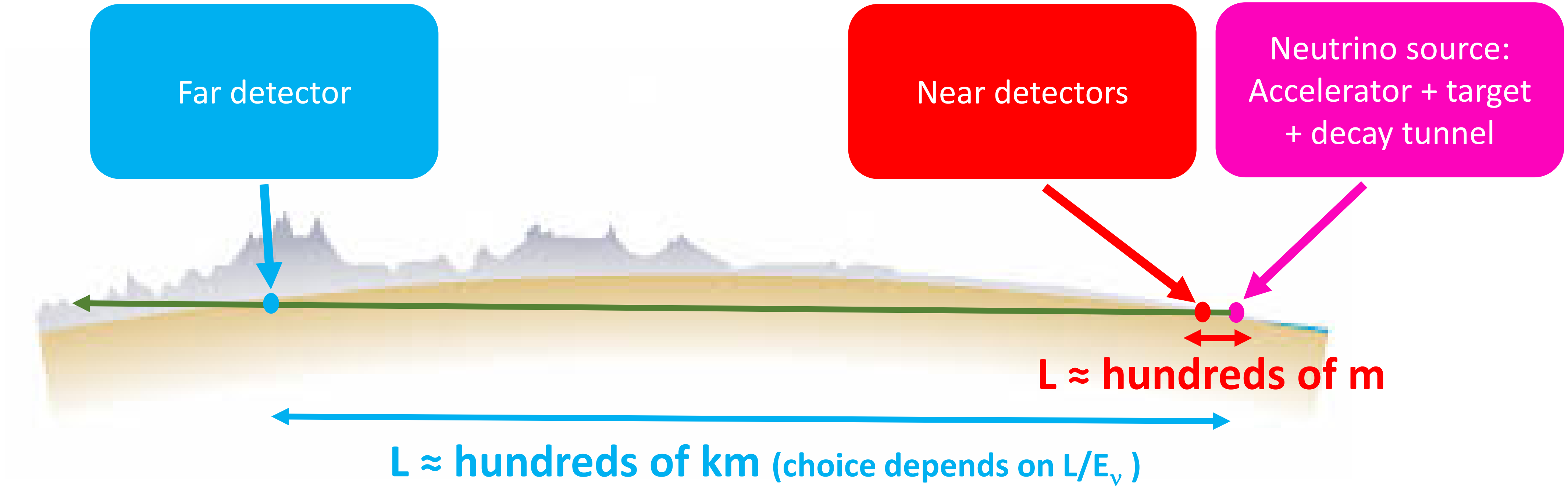
$$E_\nu^{\mathrm{cal}} = \epsilon_n + E_\ell + \underbrace{\sum_i (E_{\mathbf{p}'_i} - M)}_{\text{Kinetic energy of outgoing nucleons}} + \underbrace{\sum_j E_{\mathbf{h}'_j}}_{\text{Total energy of outgoing mesons}}$$

Kinetic energy of outgoing nucleons

Total energy of outgoing mesons

Problem: Sums include neutral particles (neutrons, π0) which might escape undetected

LBNO Concept



- Huge masses of 10s of ktons
- Often underground
- Oscillated neutrino spectrum

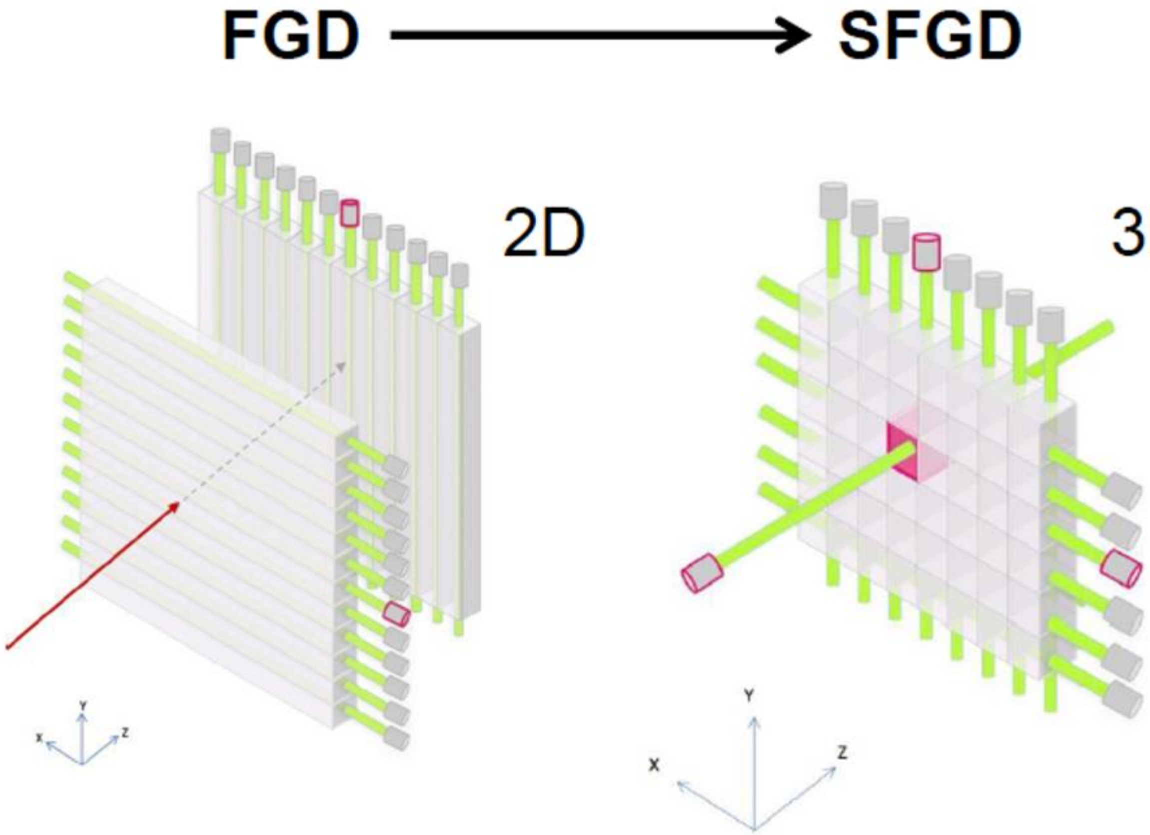
- Constraints on neutrino flux before oscillation
- Neutrino cross sections
- Direction of neutrino beam

- Proton synchrotron (30-120 GeV)
- Target to produce mesons
- Magnetic system to select polarity
- Decay tunnel to let mesons decay and produce neutrinos

3D Scintillator Tracker

Institute for High Energy Physics

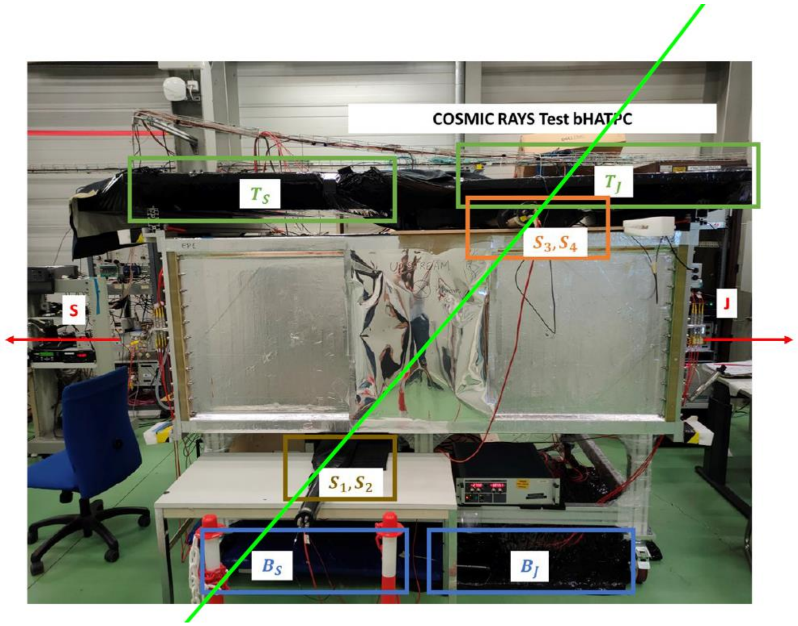
- How to overcome the drawbacks of the 2D tracker?
- Go 3D using cubes instead of bars and 3 WLS fibers per cube!
- “Minor” issues (for 2 ton detector):
  - Instead of 10,000 bars (1x1x200 cm^3), one needs 2,000,000 cubes (1x1x1cm^3)!
  - Readout channels go up from 10,000 to about 60,000!
  - Very stringent requirements on tolerances and alignment of the different components
- But impressive advantages as ND target

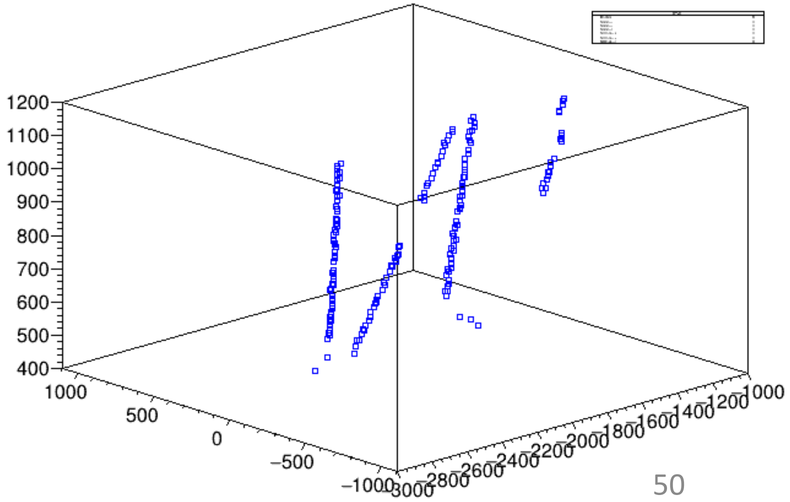


HA-TPC

- Full bottom HA-TPC tested at CERN in July 2024
- First tracks crossing the cathode recorded
- No problems found during 2 weeks
- Preparation for shipping started
- bTPC left CERN 7th of August 2023

=> Perfect timing with European vacation time





SuperFGD: Performance

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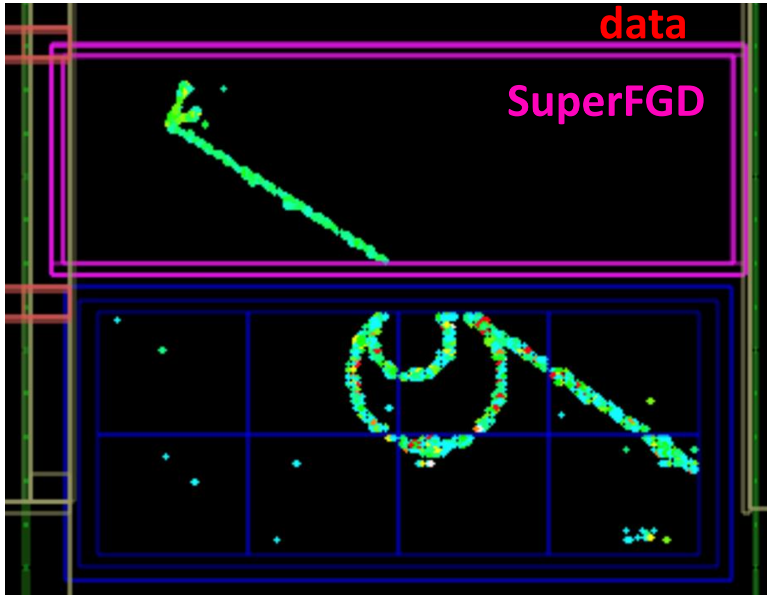
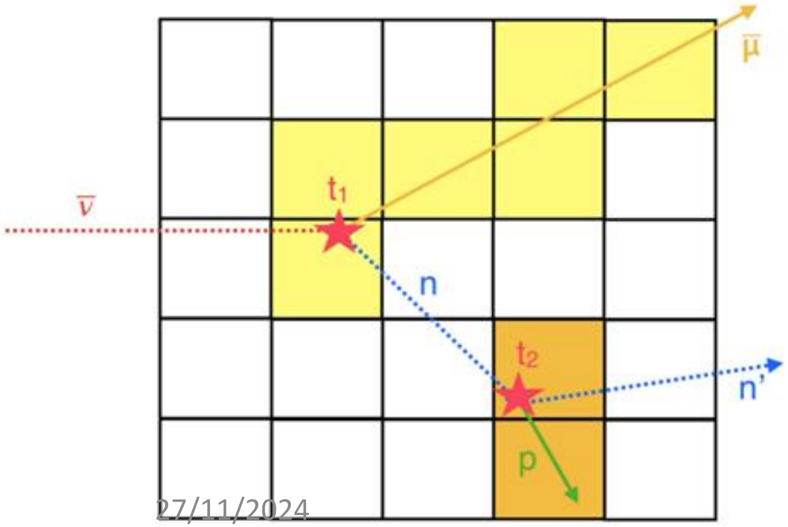
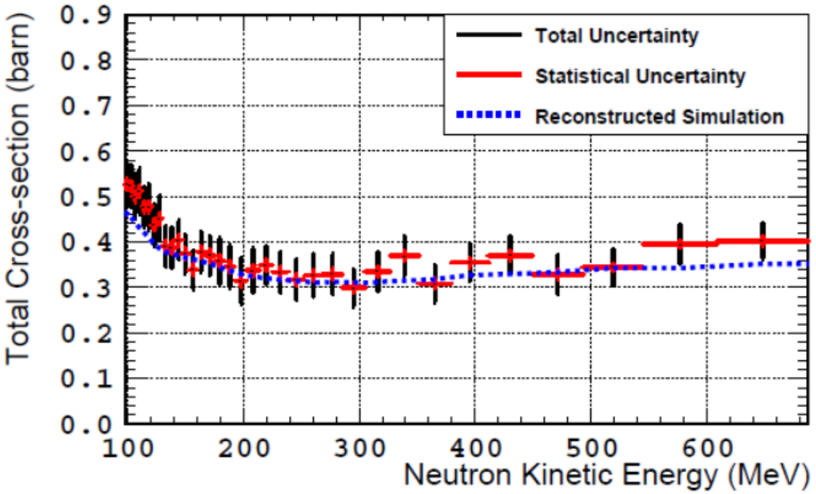
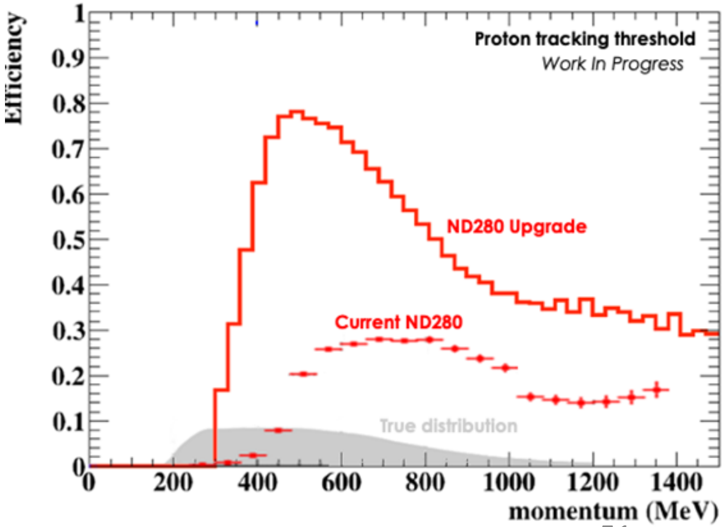
- First data with neutrino beam taken
- Much lower threshold for protons and much higher efficiency
- Allows detecting neutrons (tested with neutron testbeam) with about 50% efficiency
- Neutron energy reconstruction via TOF measurement possible



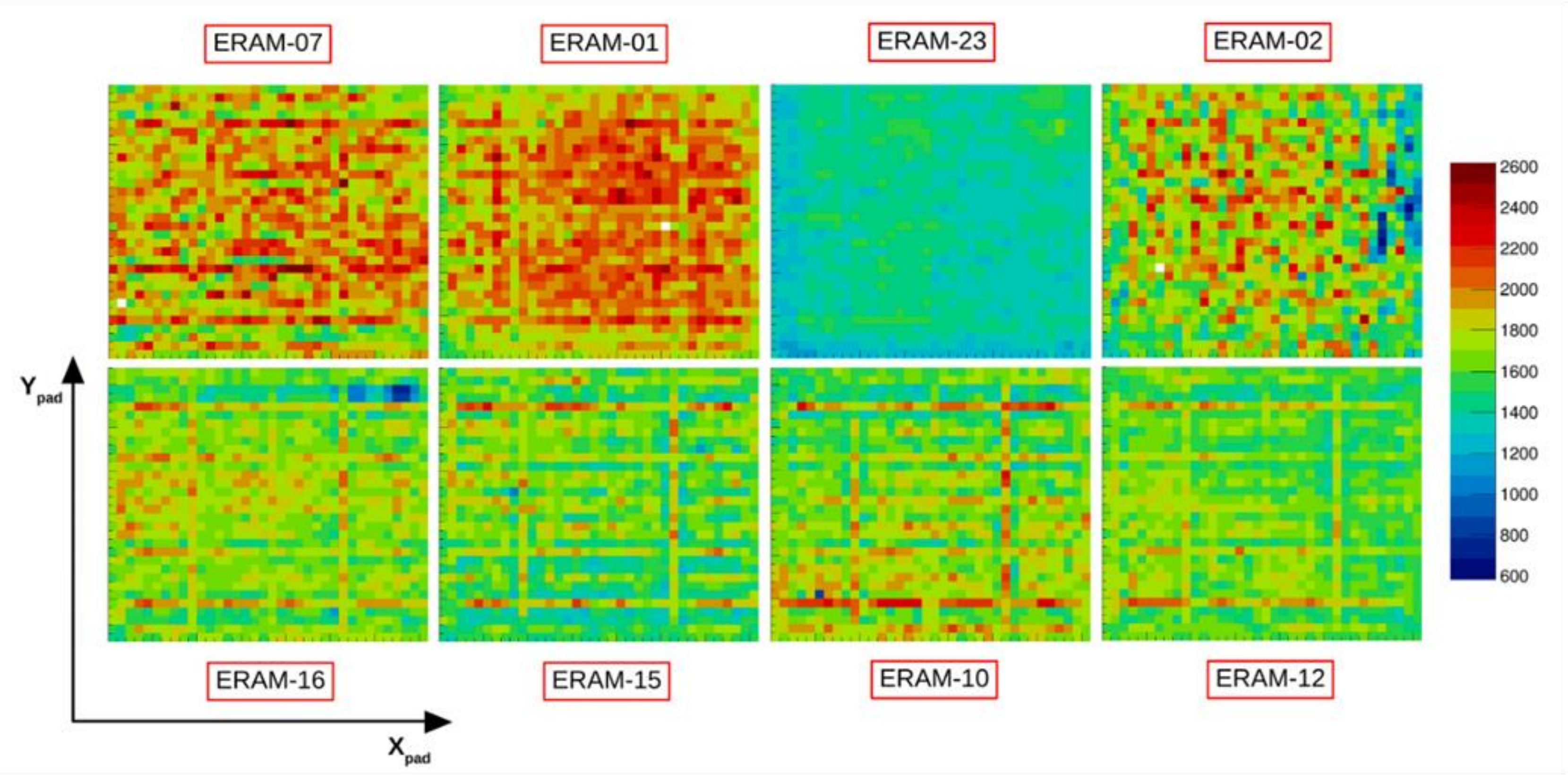


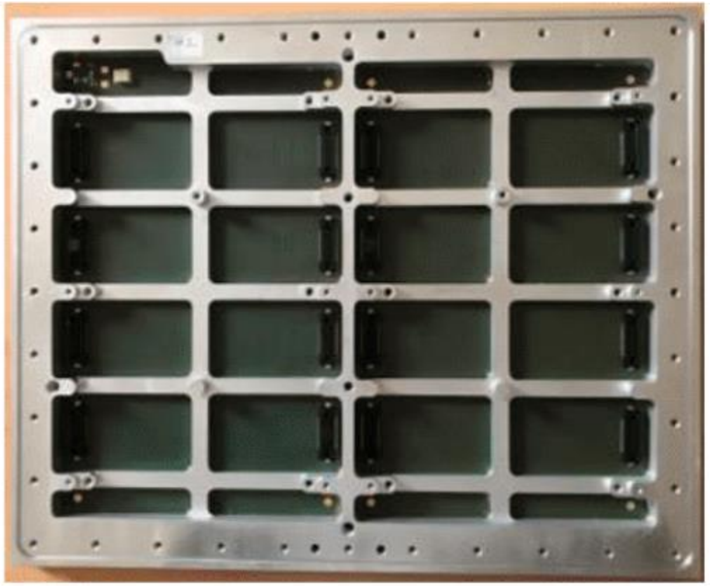




TOF Installation

- TOF was first and last subdetector to be installed
- First modules very useful to get vertical cosmics
- Originally not foreseen to use TOF for triggering but common efforts of many collaborators, made it possible


ERAM-07
ERAM-01
ERAM-23
ERAM-02
ERAM-16
ERAM-15
ERAM-10
ERAM-12
Y_pad
X_pad
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600



HA-TPC ERAM Modules

- Novel resistive MM readout
- Charge over several pads => better point resolution
- 32 ERAM modules needed + 8 spares
- Various prototypes with different RC parameters produced and tested
- Pre-production of 8 modules ongoing at CERN MPGD workshop