UNIVERSITY OF LIVERPOOL

Upgrade of the T2K near detector

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HEP seminar, University of Liverpool

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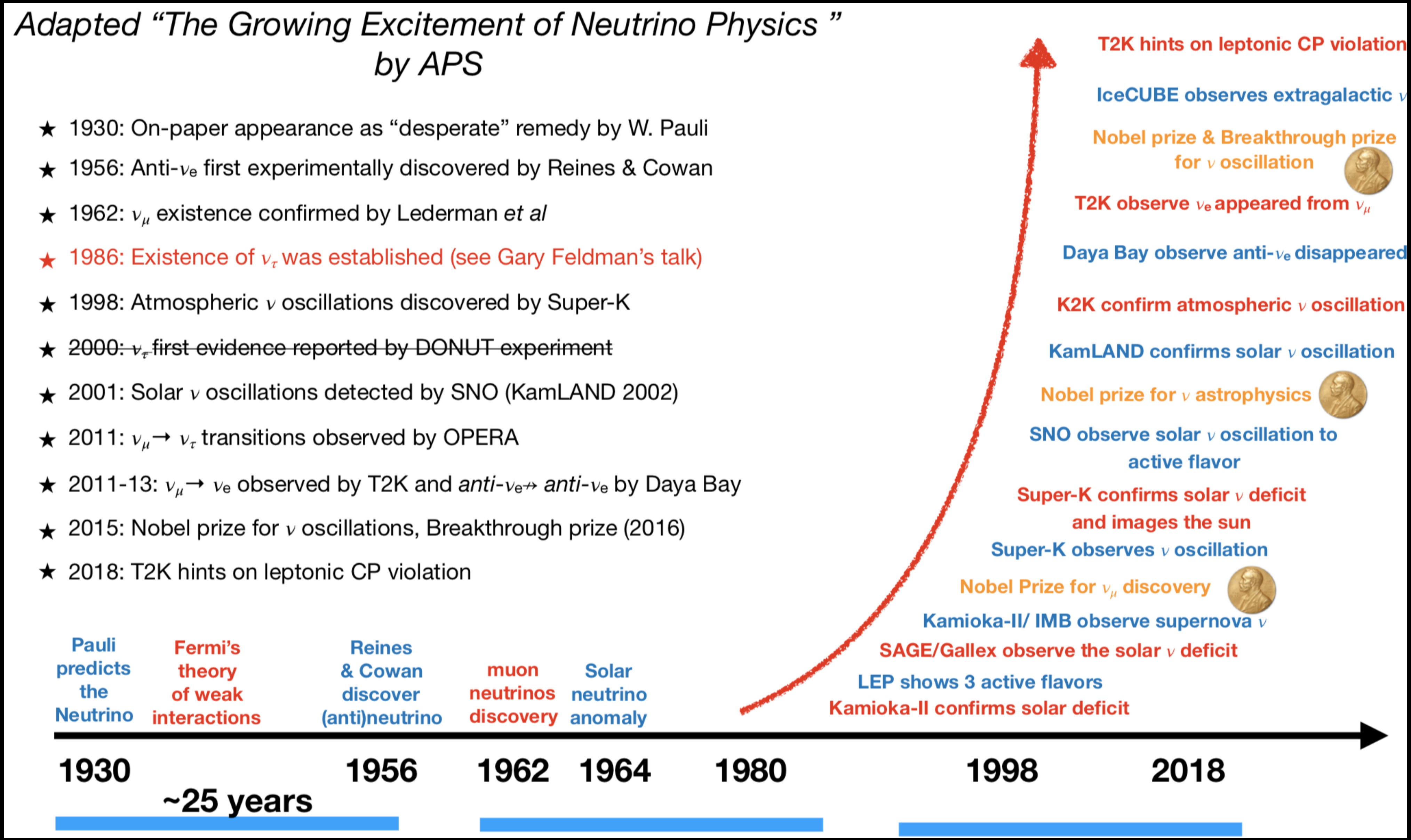
T2K

Introduction

In this seminar I will cover the following..

1. General overview of oscillation experiments, T2K and the importance of near detectors
2. The design, construction and installation of the upgraded near detector
3. A first look at data taken with the upgraded near detector and physics potential
4. A brief look ahead to HK era and potential further upgrades

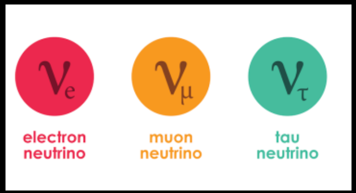
Part One:
Overview of T2K experiment and ND280



Taken from S. Cao's slide at "3 neutrinos and beyond" 2019

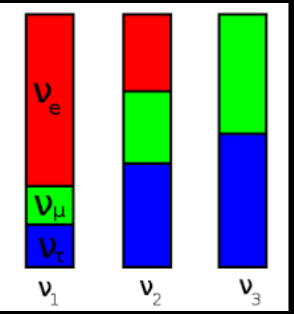
Neutrino oscillation

Flavour states



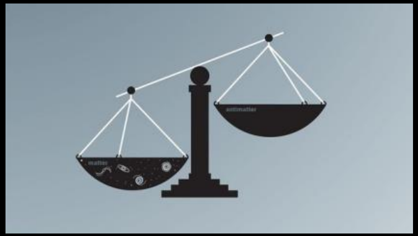
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass states



- Discovery of neutrino oscillation → neutrinos have mass
- Each neutrino flavour state (electron, muon or tau) is a superposition of different mass states
- The PNMS matrix describing neutrino mixing contains four parameters
  - Three mixing angles, θ_{12}, θ_{23}, and θ_{13}
  - The CP-violating phase, δ_{CP}
- The probability of neutrino oscillation also depends on
  - Mass squared differences between the mass eigenstates (Δm_{12}^2 and Δm_{23}^2)
- Experiments detecting atmospheric, accelerator, reactor and solar neutrinos have different complimentary sensitivity to these neutrino oscillation parameters

Neutrino oscillation



$\delta_{CP} \neq 0$ or π implies CP violation in neutrino sector

Flavour states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass states

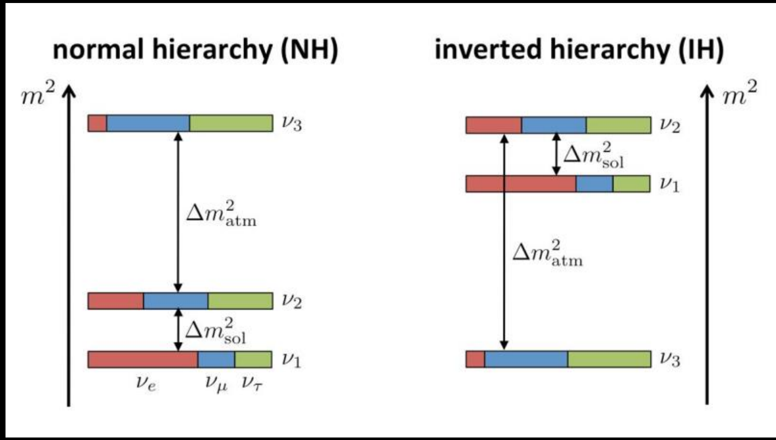
IC24 with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Best known values of neutrino oscillation parameters

Taken from JHEP 12 (2024) 216

Normal or inverted mass hierarchy?

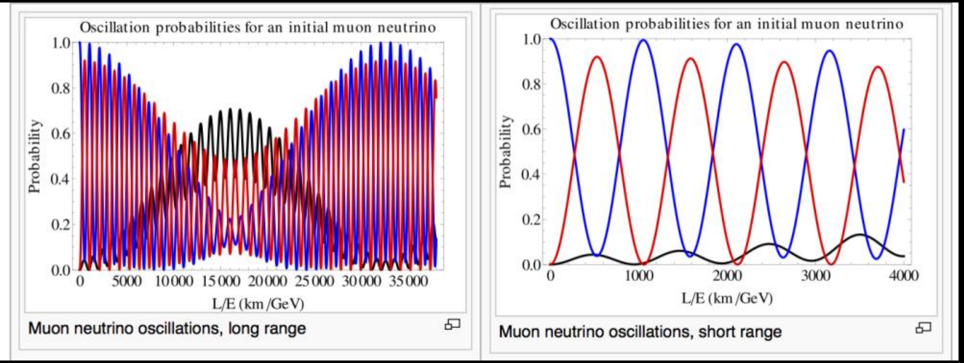


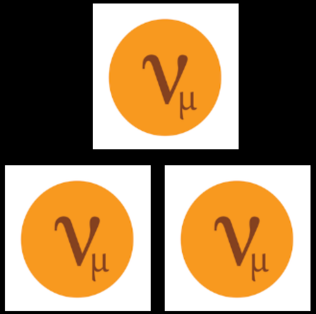
Long baseline experiments

Produce neutrinos of specific flavour at energy E

Detect neutrinos

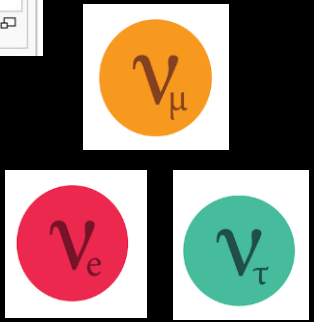
Long baseline experiments





Produce neutrinos of specific flavour at energy E

Travel distance L



Detect neutrinos

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

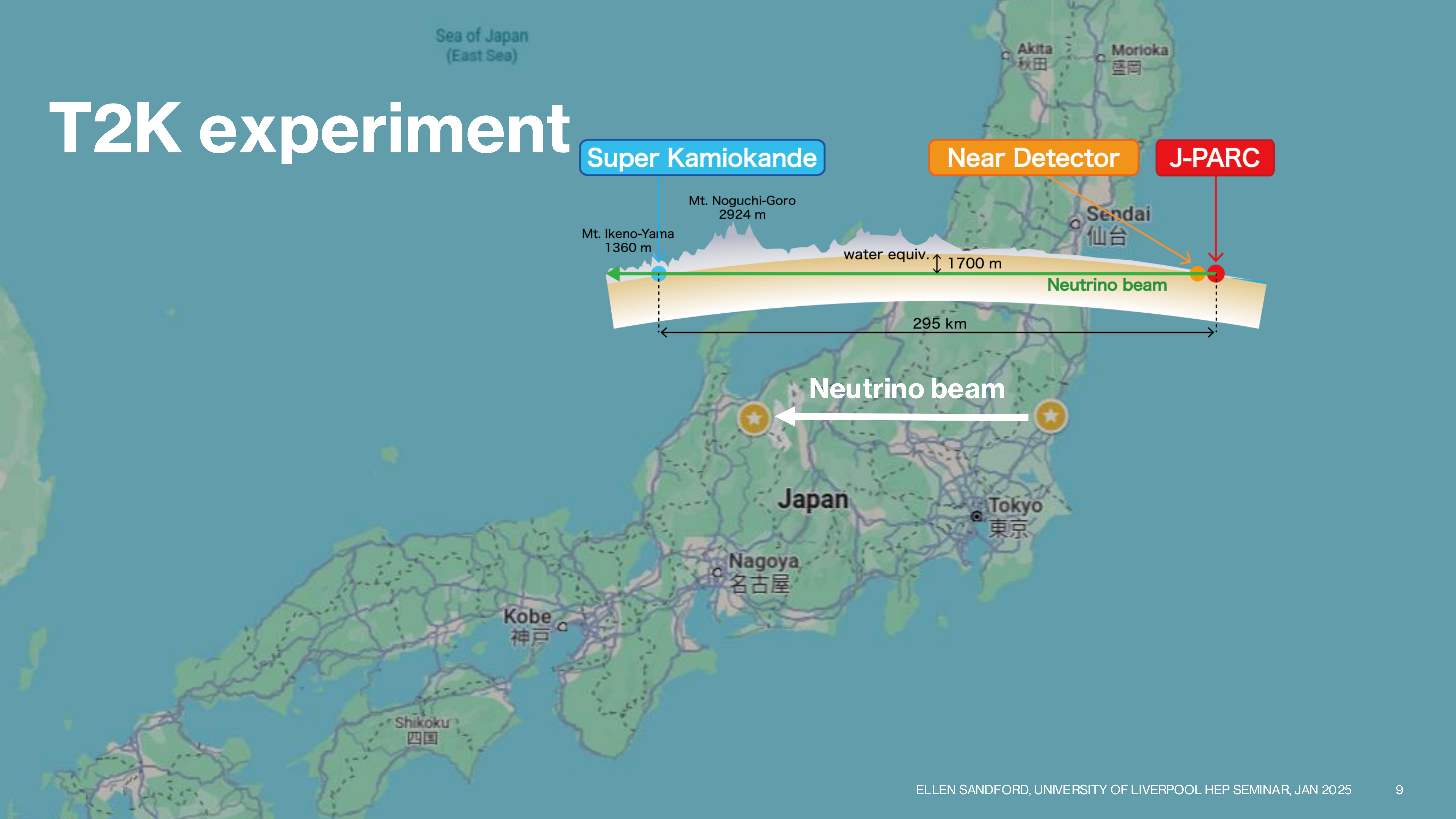
$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$+ 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

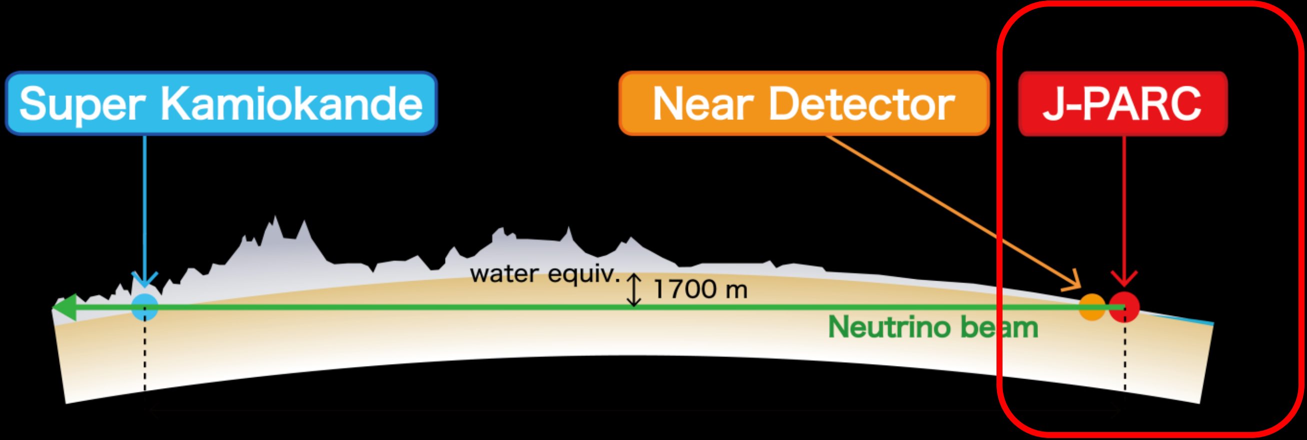
where $\Delta m^2_{ij} = m^2_i - m^2_j$ and we can rewrite:

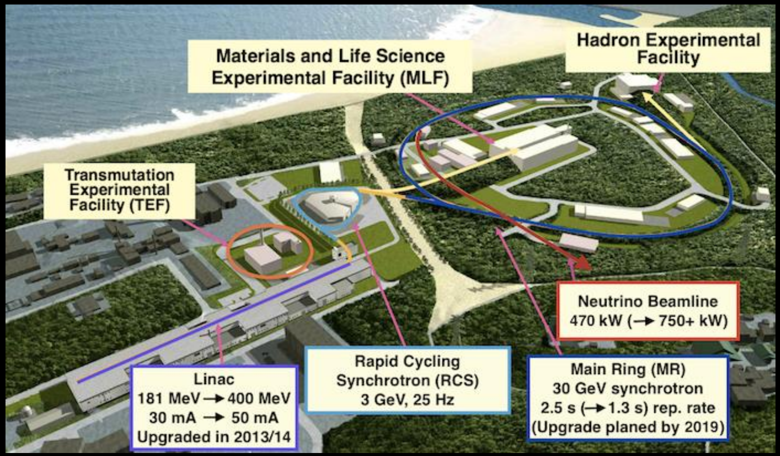
$$\frac{\Delta m^2_{ij} L}{4E} \approx 1.267 \frac{\Delta m^2_{ij}[eV^2] \times L[km]}{E[GeV]}.$$

T2K experiment

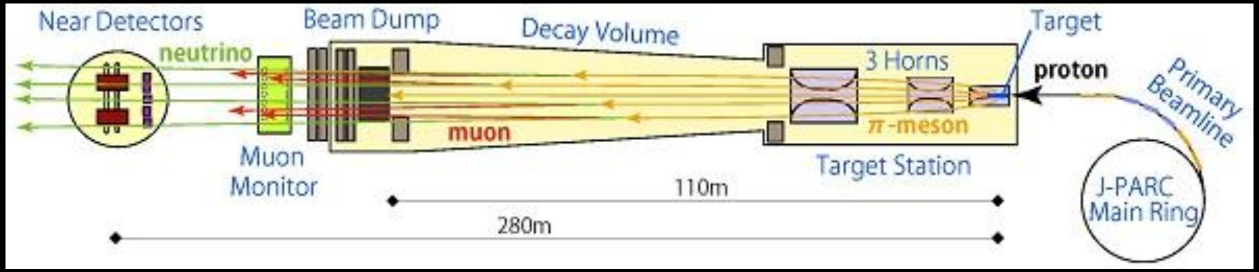


1. Beam production



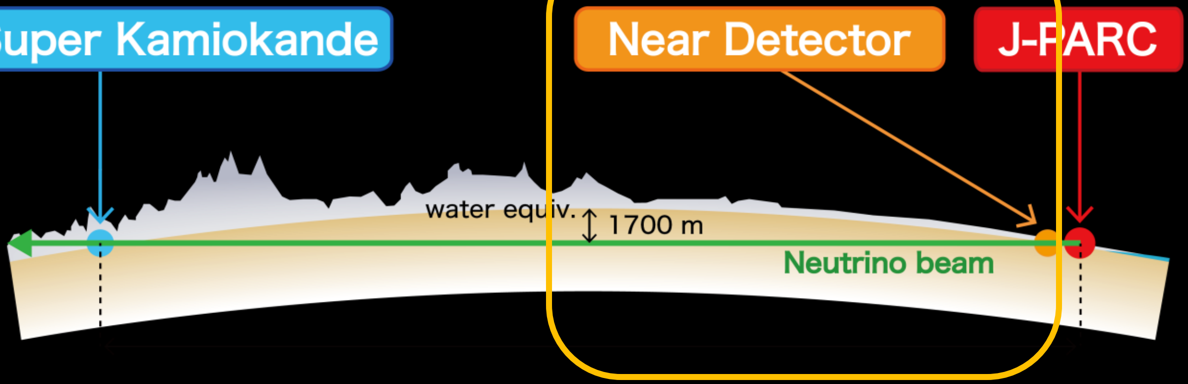


- High energy protons collided on graphite target
- Charged pions and kaons produced which then decay inside a decay volume
- This produces **neutrinos or anti-neutrinos** depending on whether +/- charged pions are focused with magnetic horn

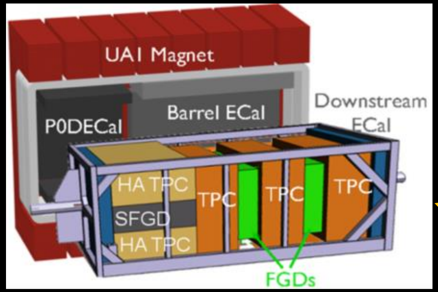


direction of Super-K

2. Near detectors



ND280



2.5 deg off axis

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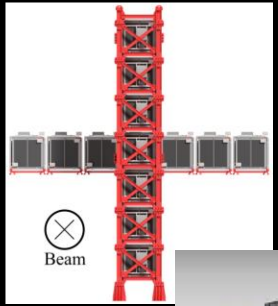


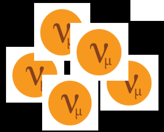
Beam direction

0 deg off axis

Beam from JPARC

Wagasci-BabyMIND

1.5 deg off axis

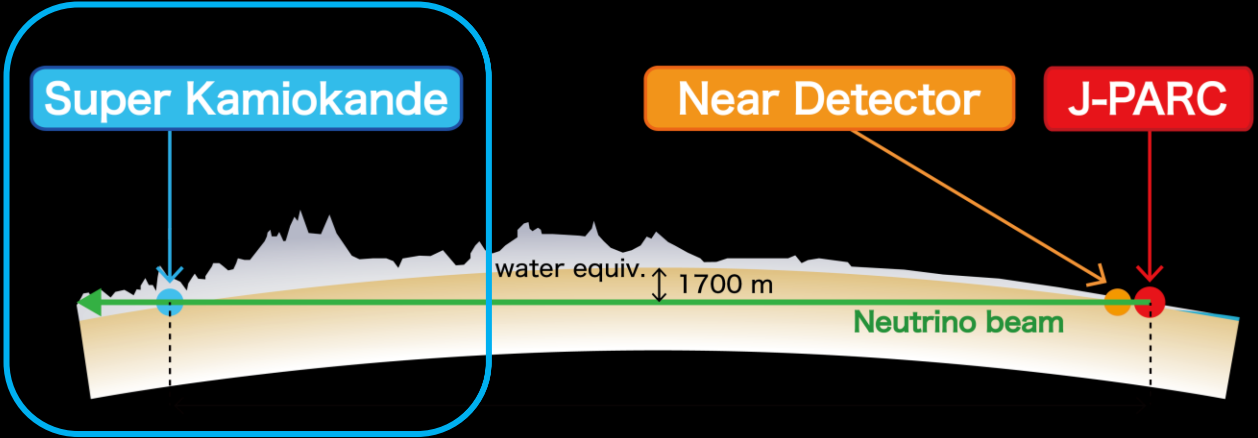


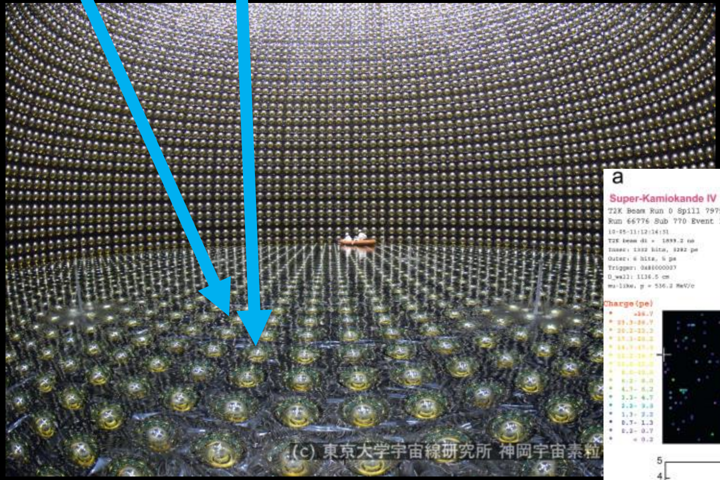
280 m

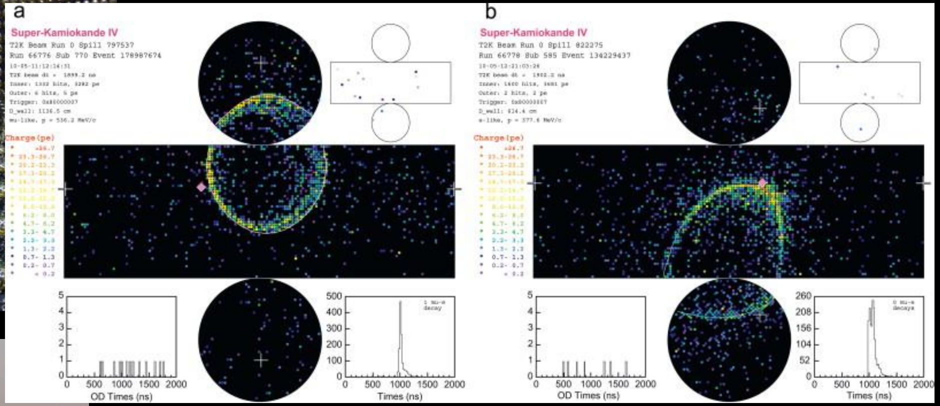
- **Different targets**
- **Different off-axis angles give different neutrino energy spectra (peak energy and broadness)**

as well as neutrinos from the JPARC beam, SK also detects atmospheric and solar neutrinos

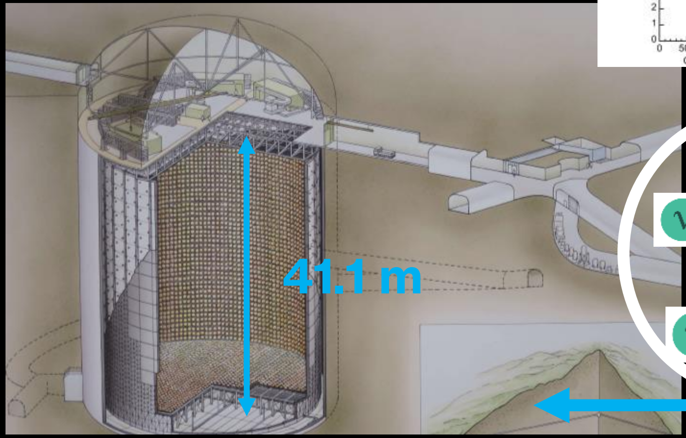
3. Far detector

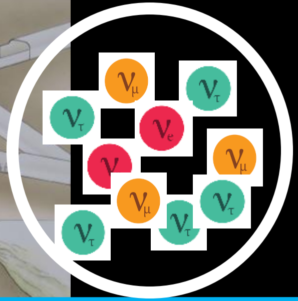






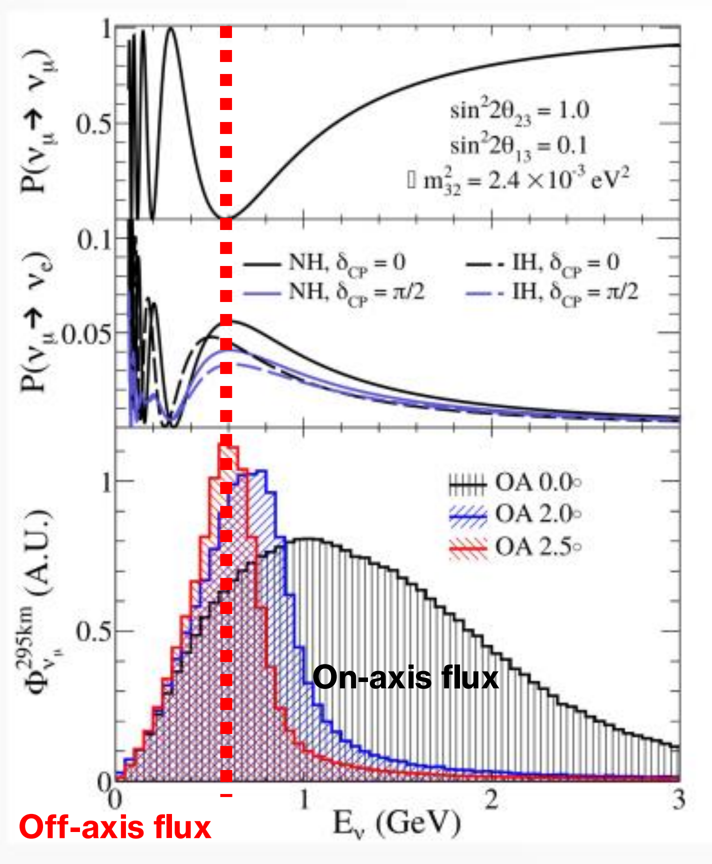
- Water Cherenkov detector (50,000 tons of water)
- Cherenkov light detected by 13,000 PMTs





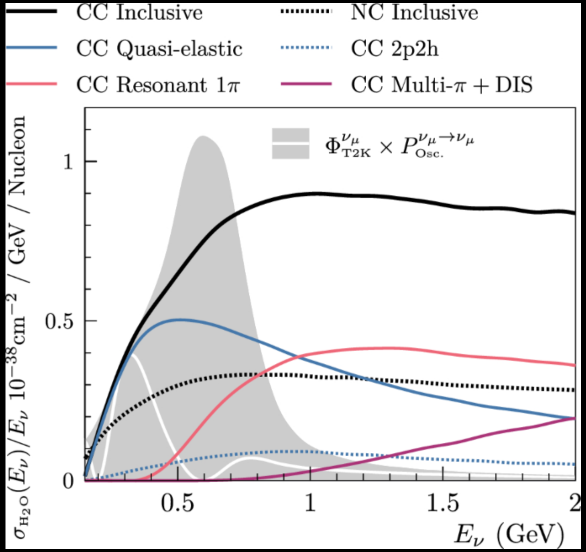
295 km

Why are our detectors "off-axis"?



Neutrino energy

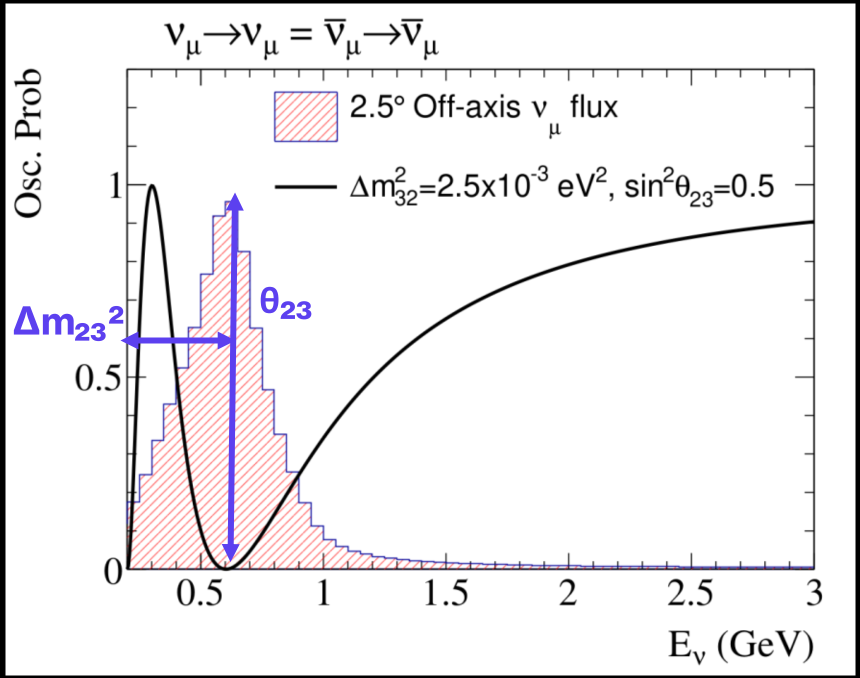
- ND280 and SK detectors sit 2.5° off-axis
- This results in a neutrino beam energy distribution which is **narrower**, with less spread in energies
- Peak of the energy distribution also shifts with the off-axis angle, to **600 MeV peak** at 2.5°
- This energy corresponds to **maximum neutrino oscillation** at 295 km
- This distribution also results in more CCQE like events and fewer high energy backgrounds



T2K measurements

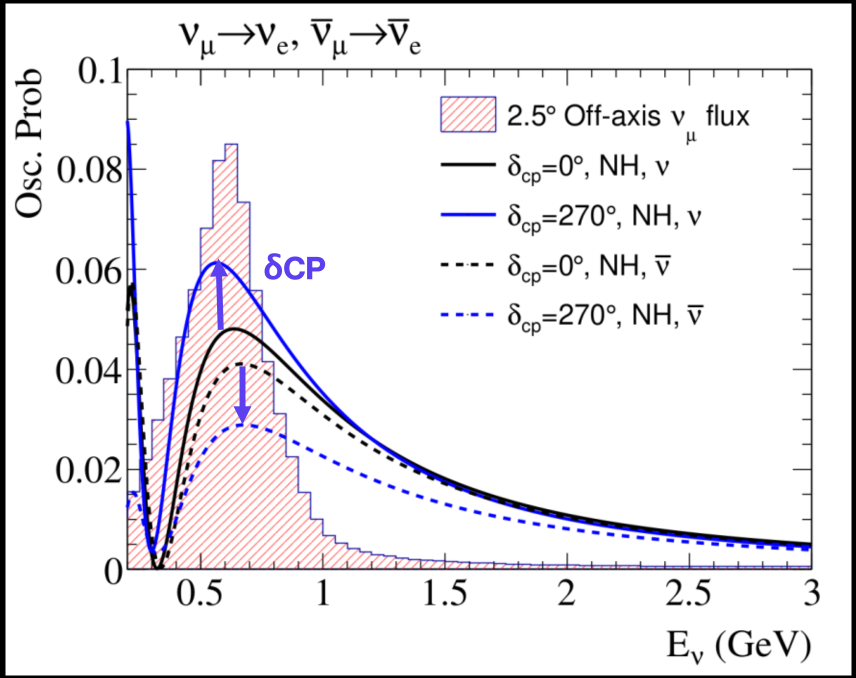
Muon neutrino disappearance

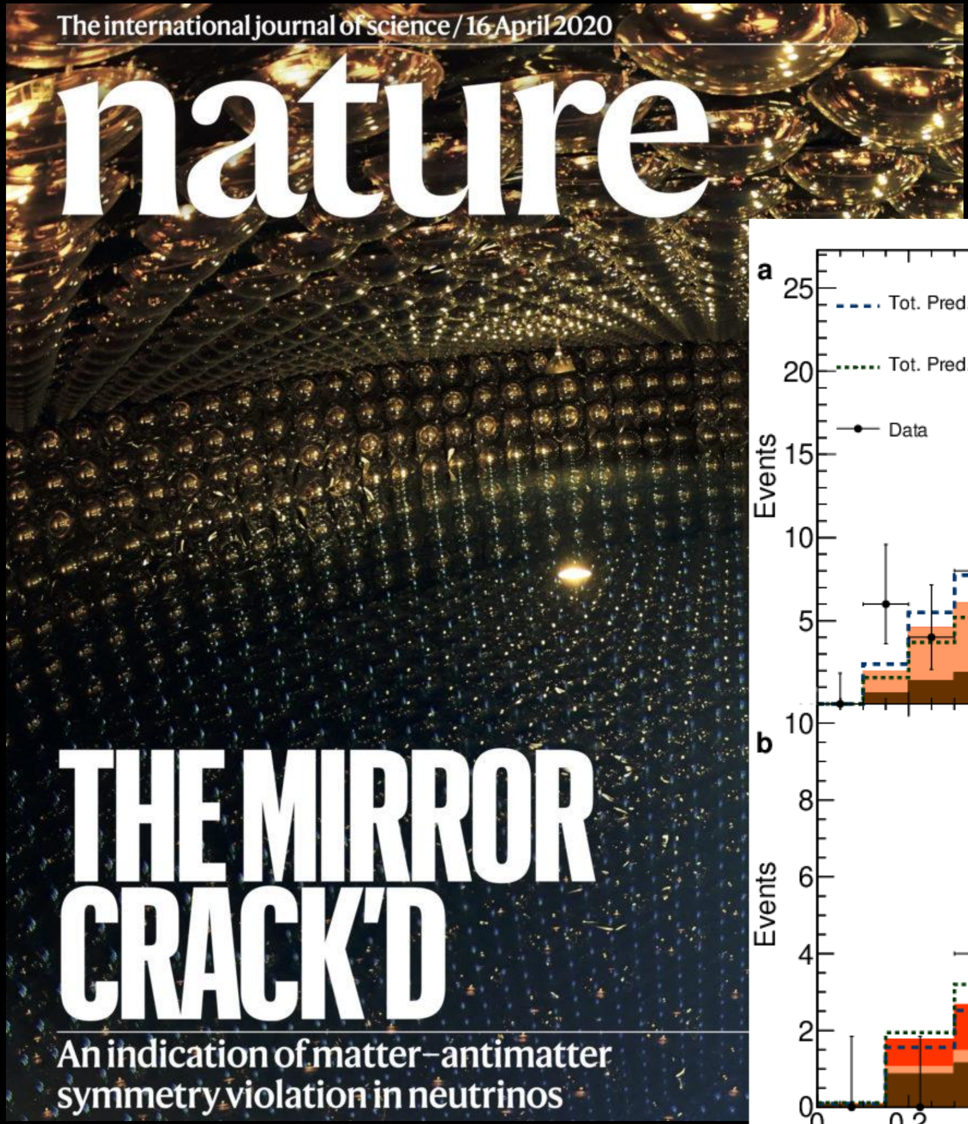
$$P_{\mu\to x} \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$

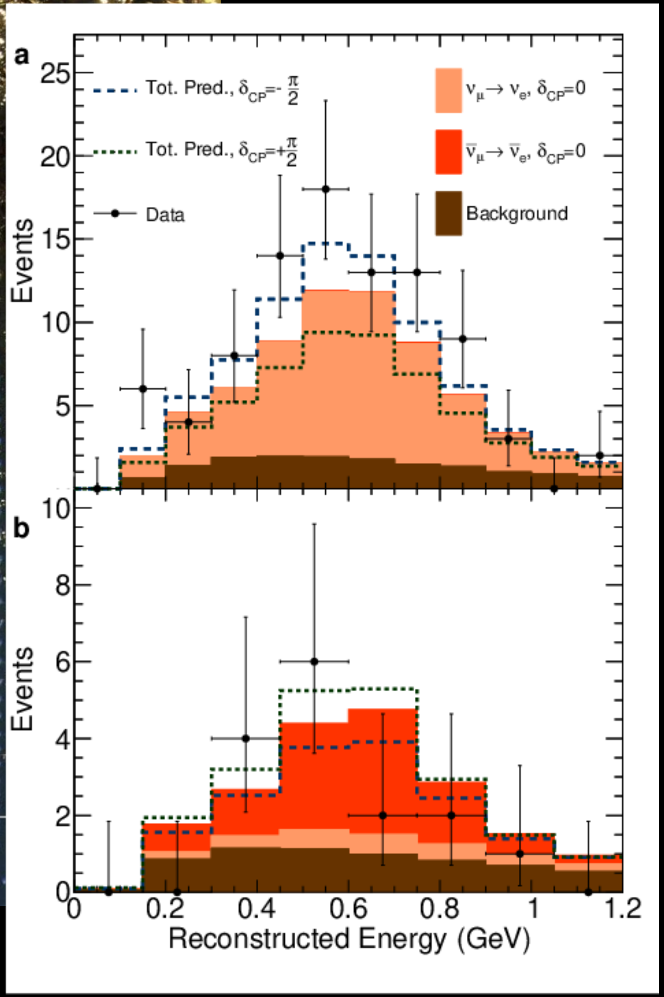


Electron neutrino appearance

$$P_{\mu\to e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{23} L}{4E_\nu}\right)$$

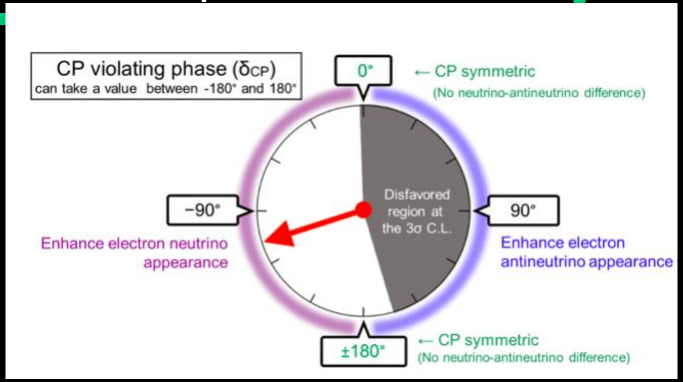






- In 2012 T2K produced the first evidence of $\theta_{13} \neq 0$ with a measurement of electron neutrino appearance in a muon neutrino beam

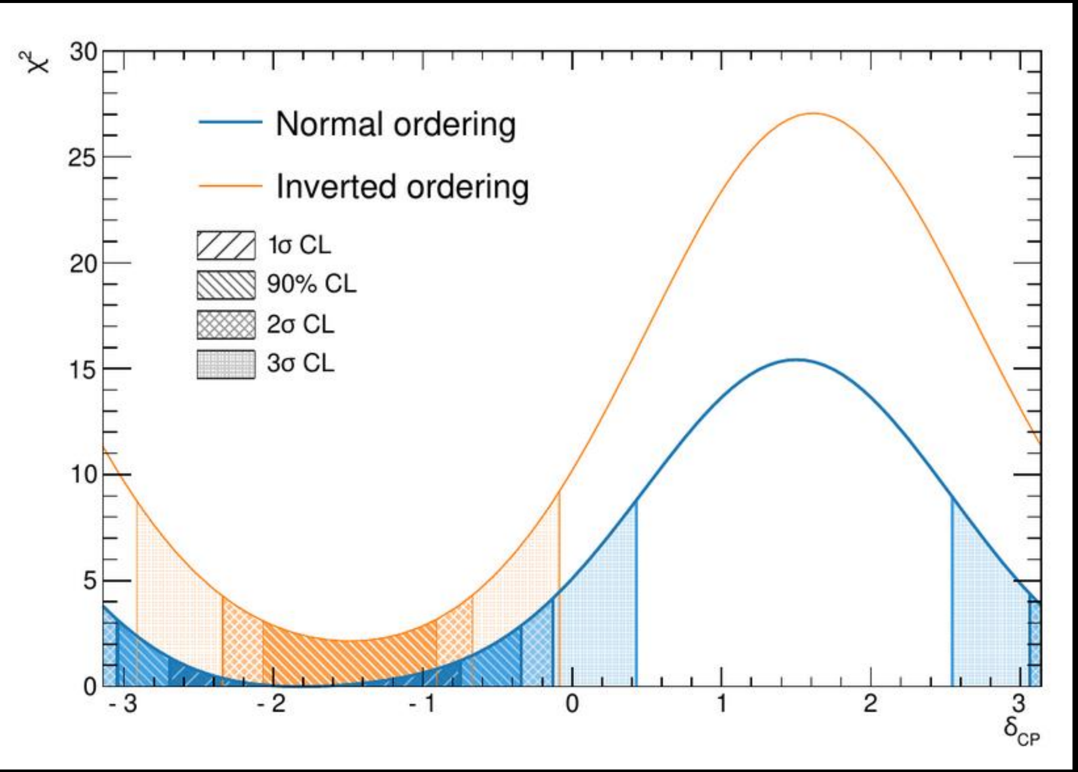
- By 2020 T2K were able to compare the electron neutrino / antineutrino appearance to provide a strong indication for CP violation in leptons



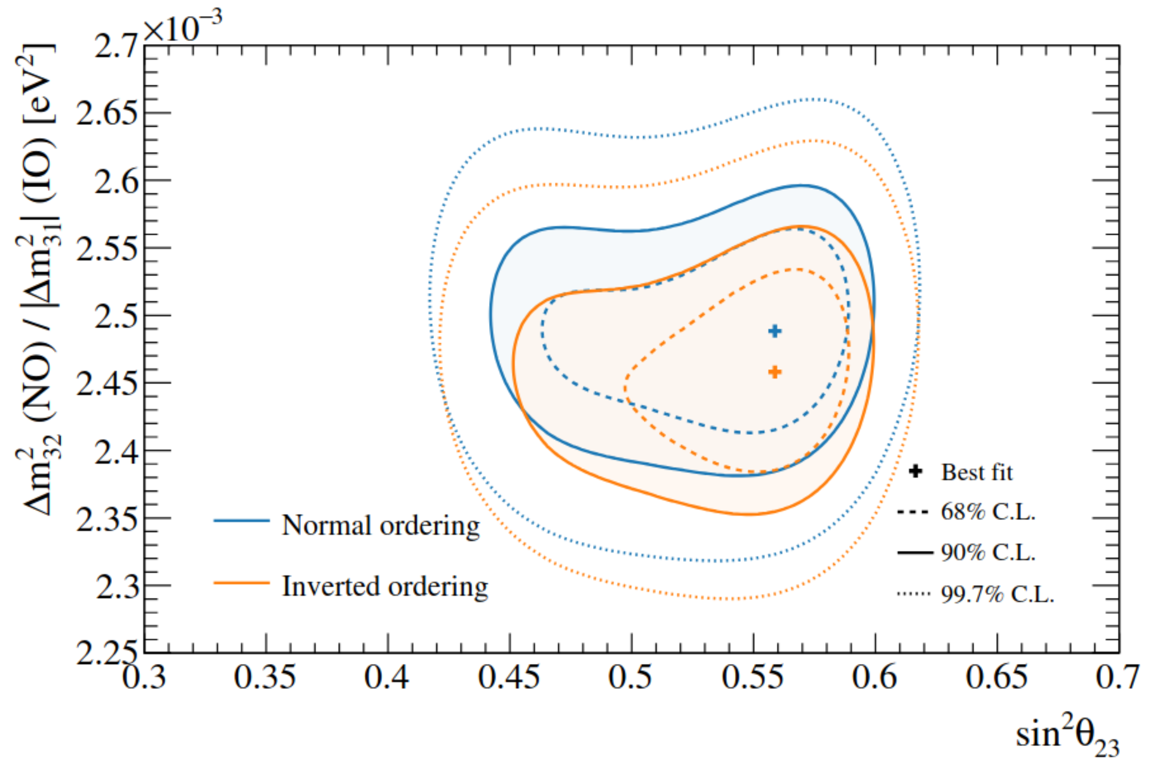
Recent results

Updated oscillation analysis

- 3.6x10^21 protons on target (POT)
- Normal ordering and upper octant favoured
- δ_{CP} =0 and π excluded at more than **90% confidence level**
- Nearly maximal CP violation favoured
- Measured sin^2(θ_{23}) consistent with reactor experiments



Eur. Phys. J. C 83, 782 (2023)

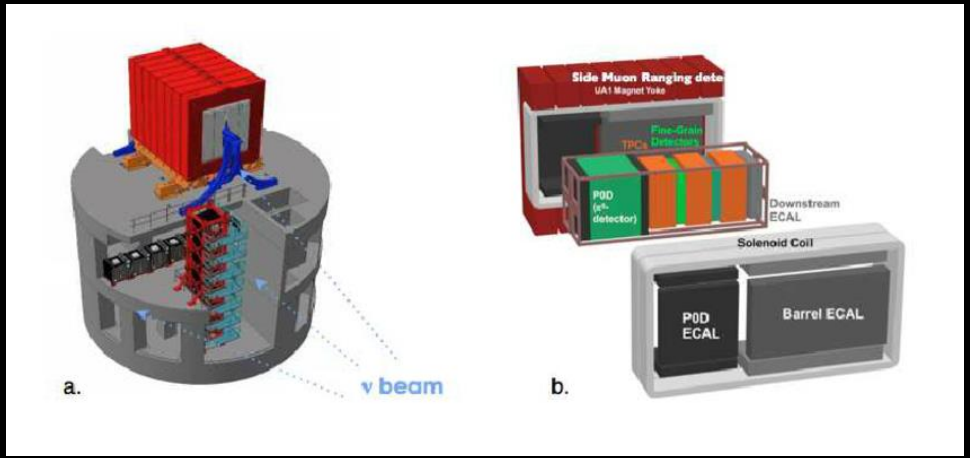


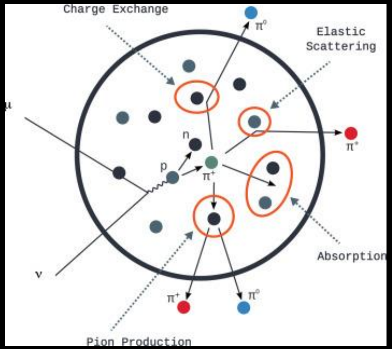
Plus recent **joint analyses**: **T2K-SK and T2K-NOvA**

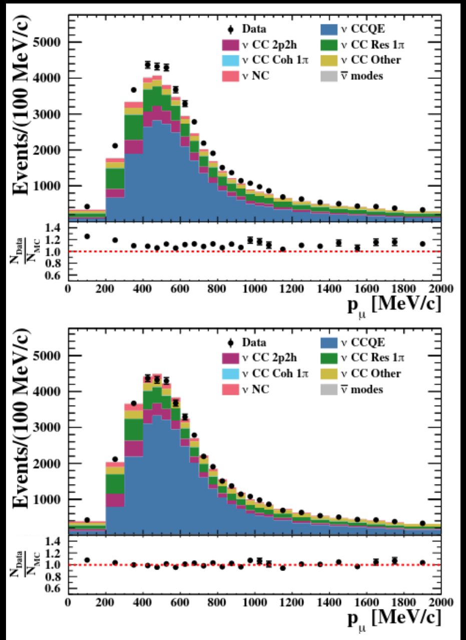
Near detector

$$N_{\mathrm{ND}}^{\alpha}(\vec{x}) = \Phi^{\alpha}(E_{\nu}) \times \sigma^{\alpha}(\vec{x}) \times \epsilon_{\mathrm{ND}}^{\alpha}(\vec{x})$$
$$N_{\mathrm{FD}}^{\alpha}(\vec{x}) = P(\nu_{\alpha} \rightarrow \nu_{\alpha}) \times \Phi^{\alpha}(E_{\nu}) \times \sigma^{\alpha}(\vec{x}) \times \epsilon_{\mathrm{FD}}^{\alpha}(\vec{x})$$

- The **beam flux** and **interaction model** are consistent between the near and far detector
- Carry out a near detector fit to constrain a model describing these + ND detector effects
- As such the near detector provides important measurements of
  - Electron neutrino contamination of the beam (important to ensure any electron neutrino appearance is actually due to oscillation)
  - Flux and energy distribution of beam
  - Neutrino interaction rates and cross sections

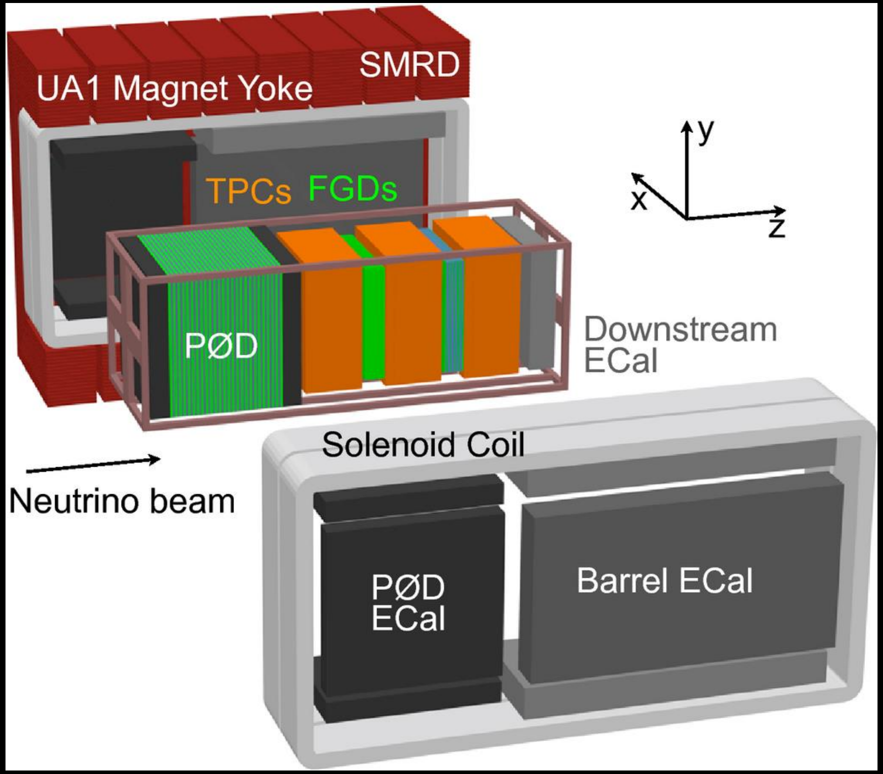






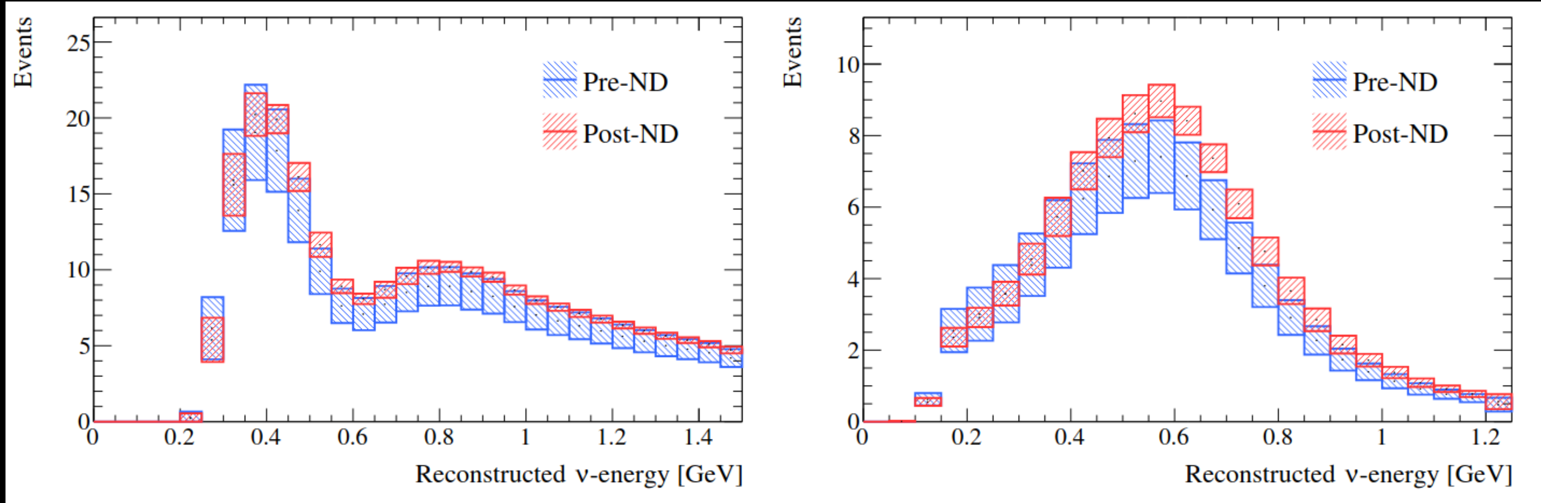
(a) FGD1 ν-mode ν_{μ} CC0π

Pre-upgrade ND280



- The UK and Liverpool have a long history of working with ND280
- The electromagnetic calorimeter (ECal) was designed and constructed in the UK during 2007-2010
  - The barrel ECal was built between Daresbury lab and Liverpool

Systematic uncertainties



(a) ν-mode 1Rμ (b) ν-mode 1Re

Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

Interaction model uncertainties are the largest source of uncertainty for the oscillation analysis → the near detector is crucial for reducing these

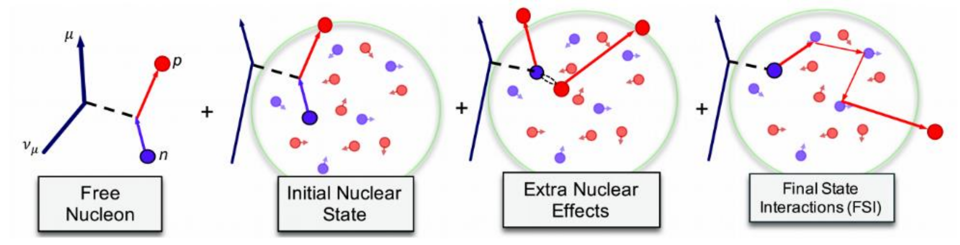
Total event rate uncertainty reduction from ND fit: ~17% → ~5%

Interaction model

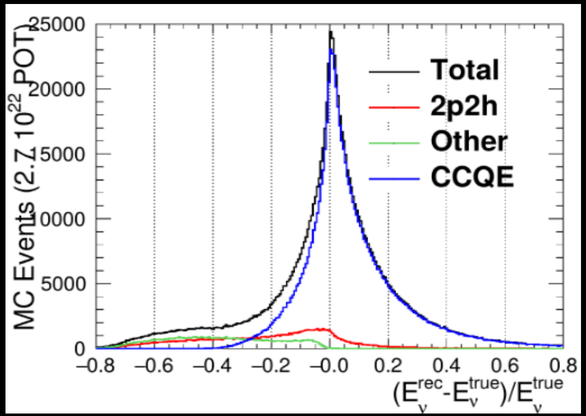
- Reconstruction of the neutrino energy for QE scattering on a nucleon at rest:

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

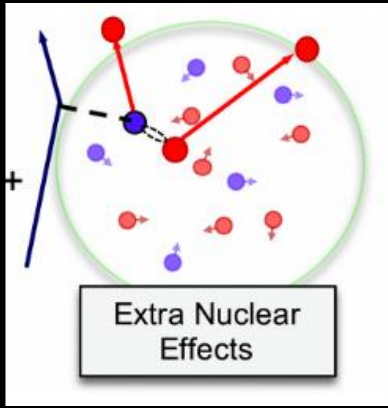
- In reality there are effects from
  - Nucleons may have non-zero momenta
  - Final state interactions
  - Interaction on two nucleons (2p-2h)



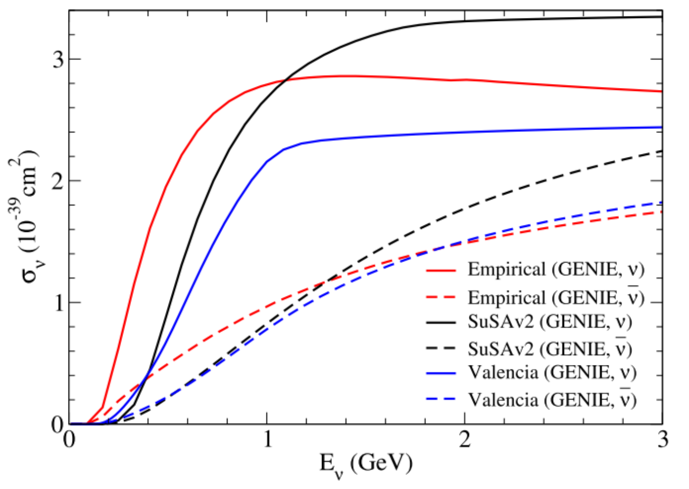
- Require sufficient models and uncertainties to cover any physics that could affect the oscillation analysis
- Measure interaction topologies (CC0pi, CC1pi etc) rather than interaction modes (CCQE, 2p2h, CCRES)

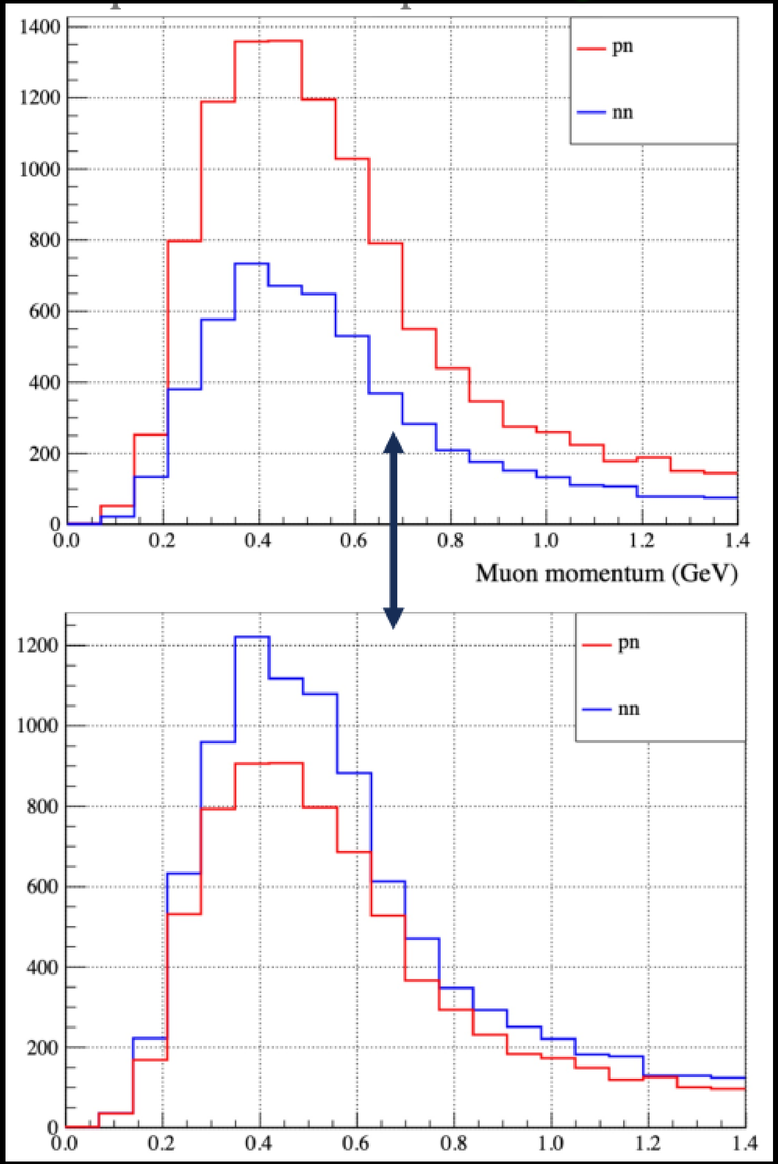


Example: 2p2h



- 2p2h or **two-particle two-hole** interactions can occur when a neutrino interactions with a pair of nucleons, due to short range correlations or meson exchange currents
- Can be simulated using Nieves et al. 2p2h model
- Require uncertainties for:
  - Fraction of pn / nn pairs
  - Normalisation
  - Shape
  - Neutrino energy dependence

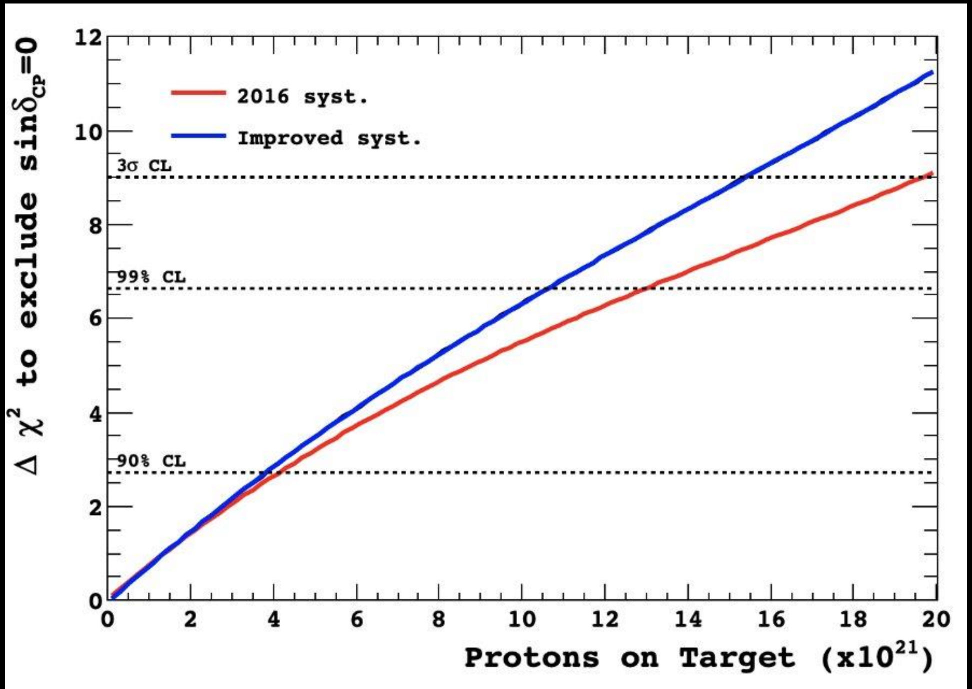




Part Two:
Upgrade of J-PARC beam and ND280

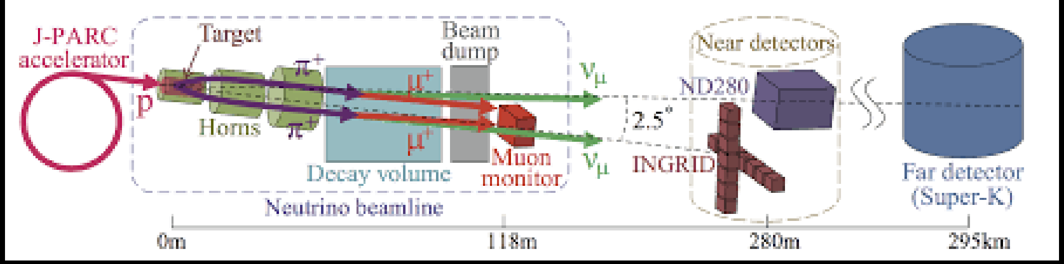
What do we need now?

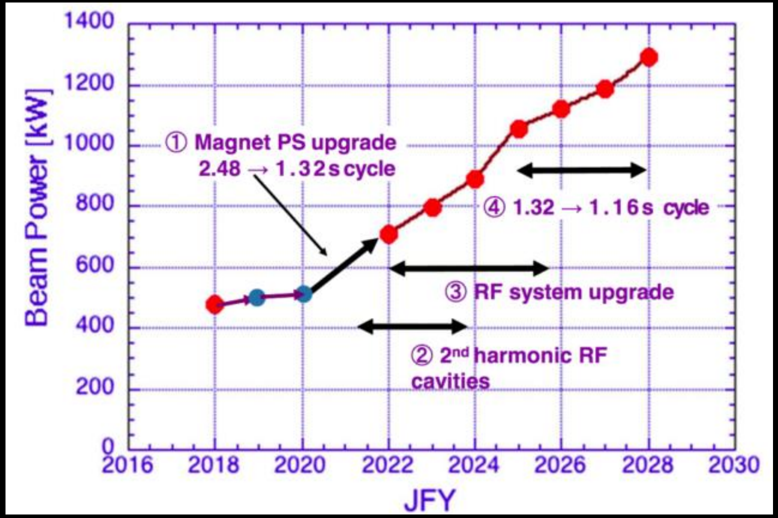
- ND280 has been extremely successful in reducing the uncertainties due to neutrino fluxes and cross-section to ~5% level
- T2K has entered **precision phase** – can the data collected at ND280 be improved even further?



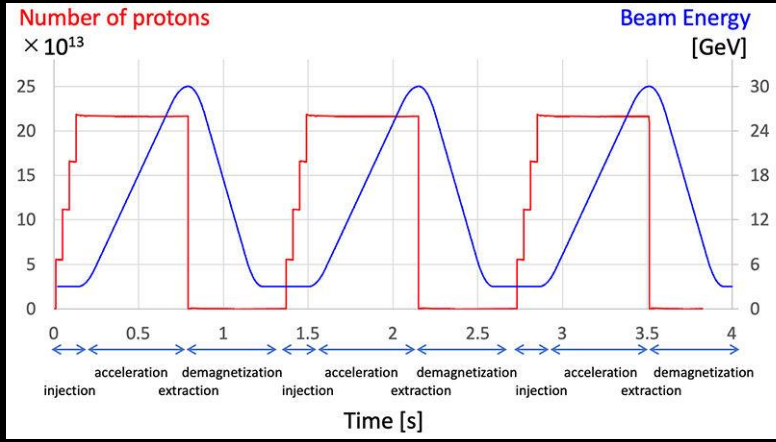
We need to
1. **Maximise statistics** AND
2. **Reduce systematic uncertainties**
in order to have the best chance of measuring delta_CP with precision

JPARC beam upgrade

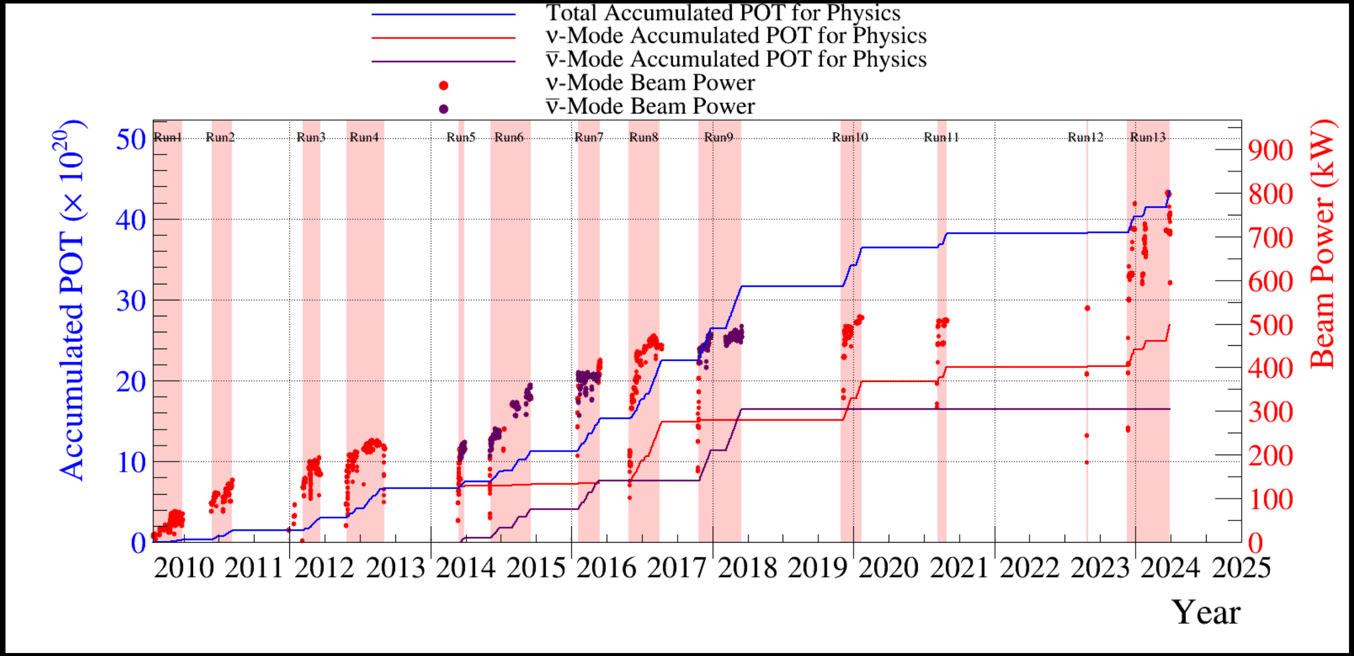




- The J-PARC neutrino beam was recently upgraded
- Electromagnetic horns current increased from 250 kA → 320 kA, increasing neutrino flux
- Beam cycle decreased from 2.48s → 1.36s, increasing beam power
- Steady increase of beam power:
  - December 2023 the beam ran stably at 760kW, increased from ~500kW and **surpassing for the first time the original design power of 750kW**
  - June 2024: increased further to 800kW
  - Further upgrades planned to reach 1.3MW



JPARC beam upgrade

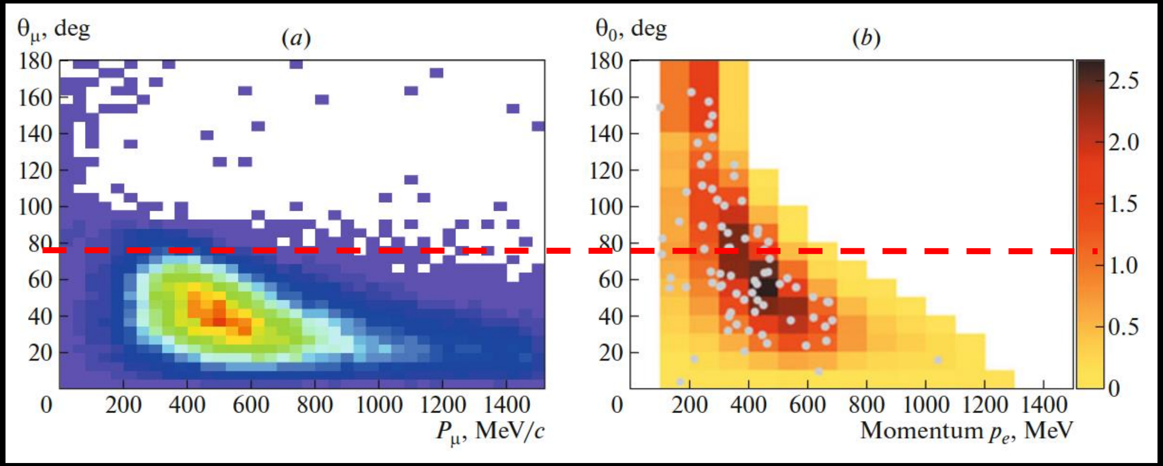


We can now collect the same POT in 4 months as we did in the whole period 2010-2022 !

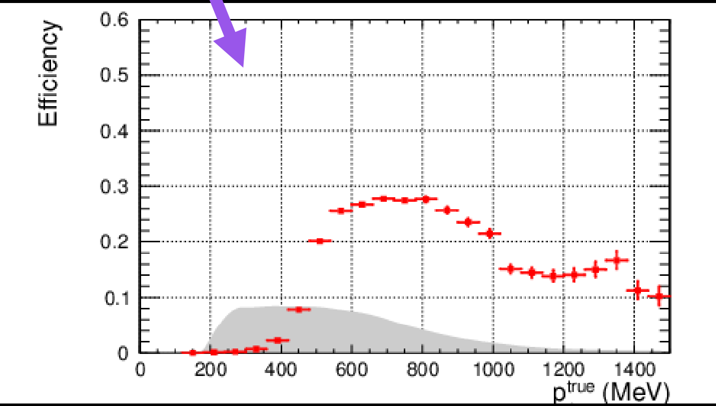
What could be improved for ND280?

Limitations:

- Tracks at high angles (would like an angular acceptance more similar to SK)
- Limited timing information
- No neutron information
- Poor electron/photon separation
- High detection threshold



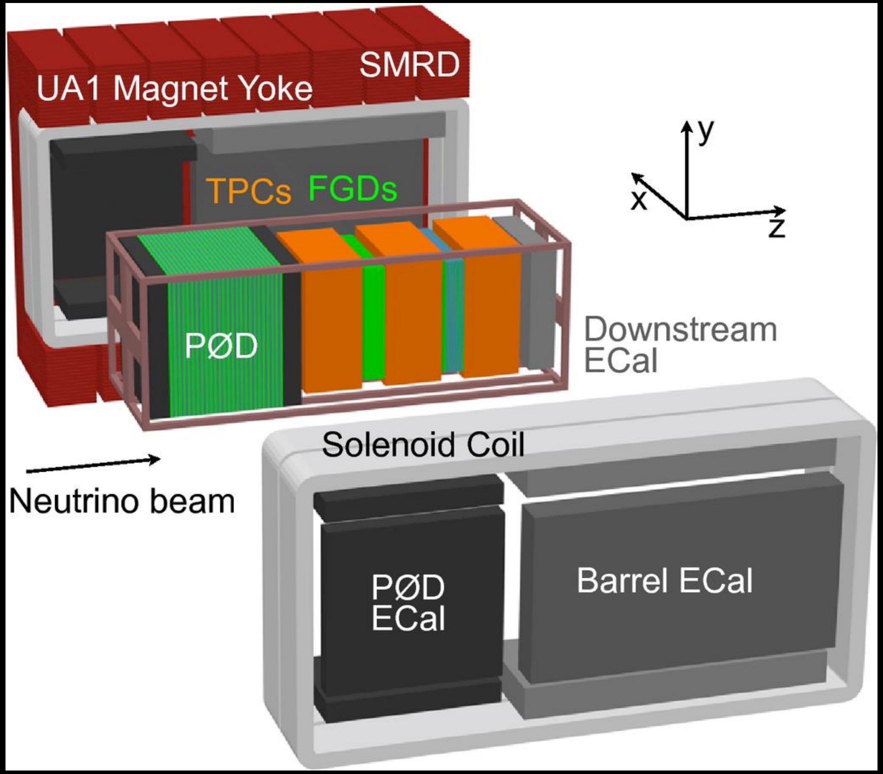
Reconstructed momentum and angle for muons selected at ND280 (left) and electrons selected at SK (right)

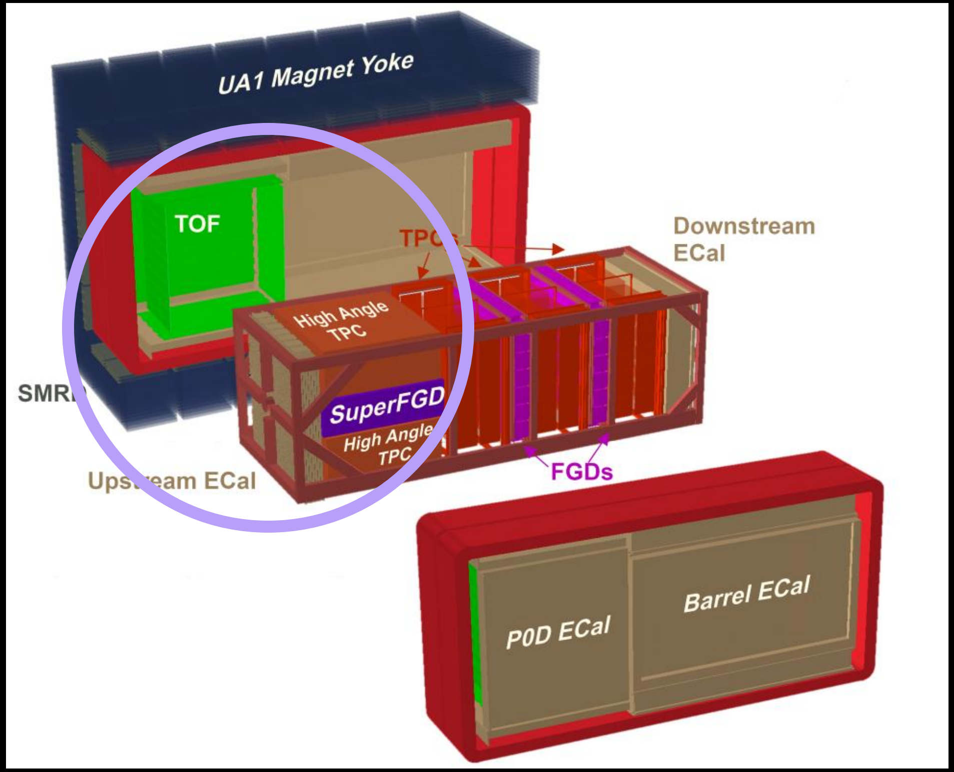


Proton reconstruction efficiency in ND280.

ND280 upgrade

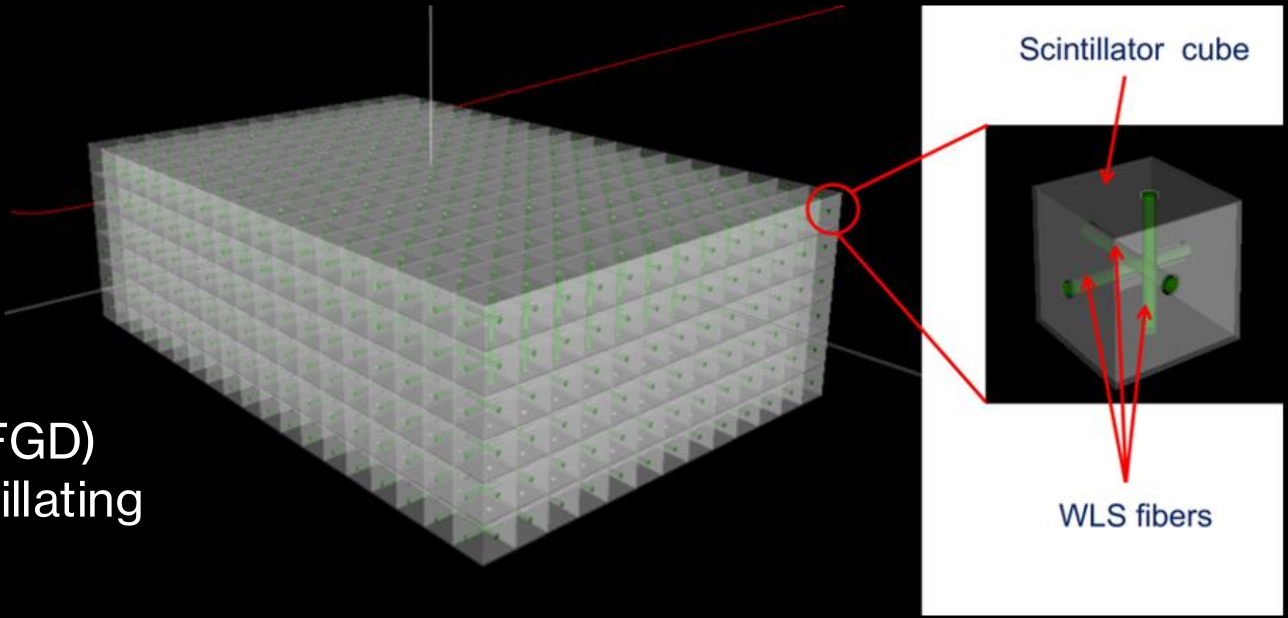
In 2023/24 the P0D detector was removed from ND280 and replaced with three new sub-detectors

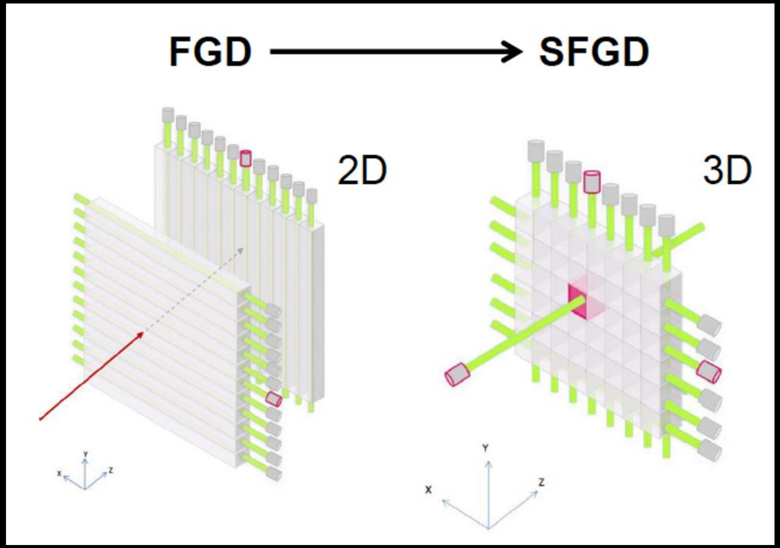




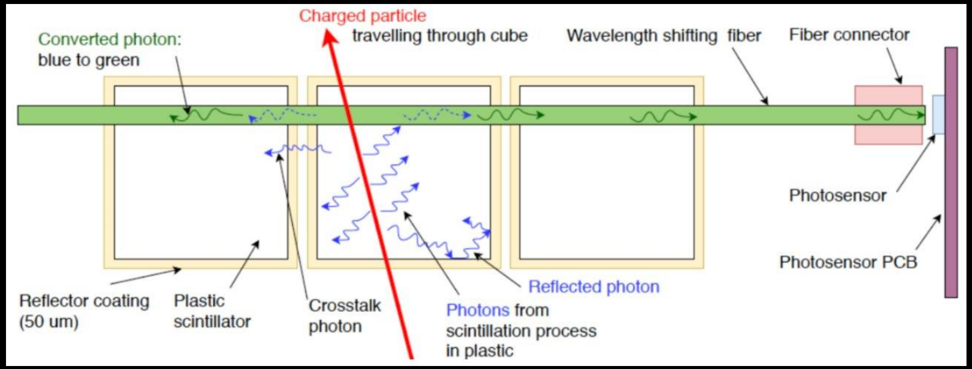
SFGD design

- Super Fine Grained Detector (SFGD) made up of 2 million plastic scintillating cubes
- Total fiducial mass of 2 tonnes
- Each cube is 1x1x1 cm and optically isolated, with three WLS fibers going through each one
- 3D granularity
    - High angle tracks can be reconstructed
    - Short low momentum tracks
- Sub-ns timing resolution
- Two prototypes built and tested in test beams at CERN

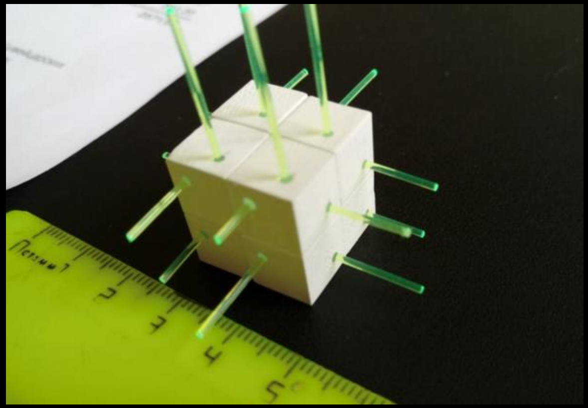


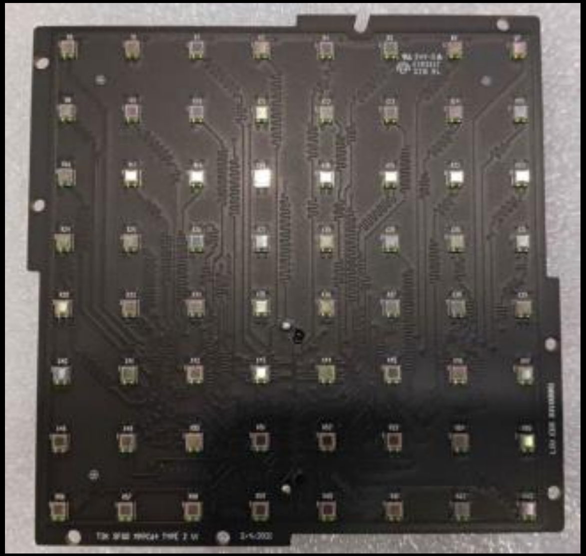


SFGD readout



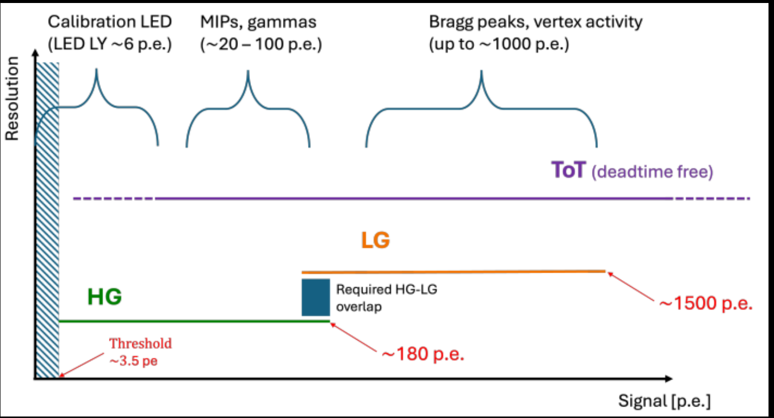
- Three WLS fibres through each SFGD cube requires **56k readout channels**
- Single ended readout of Hamamatsu Multi-Pixel Photon Counters (MPPC)
  - High dynamic range from 3.5 to 2000 PE

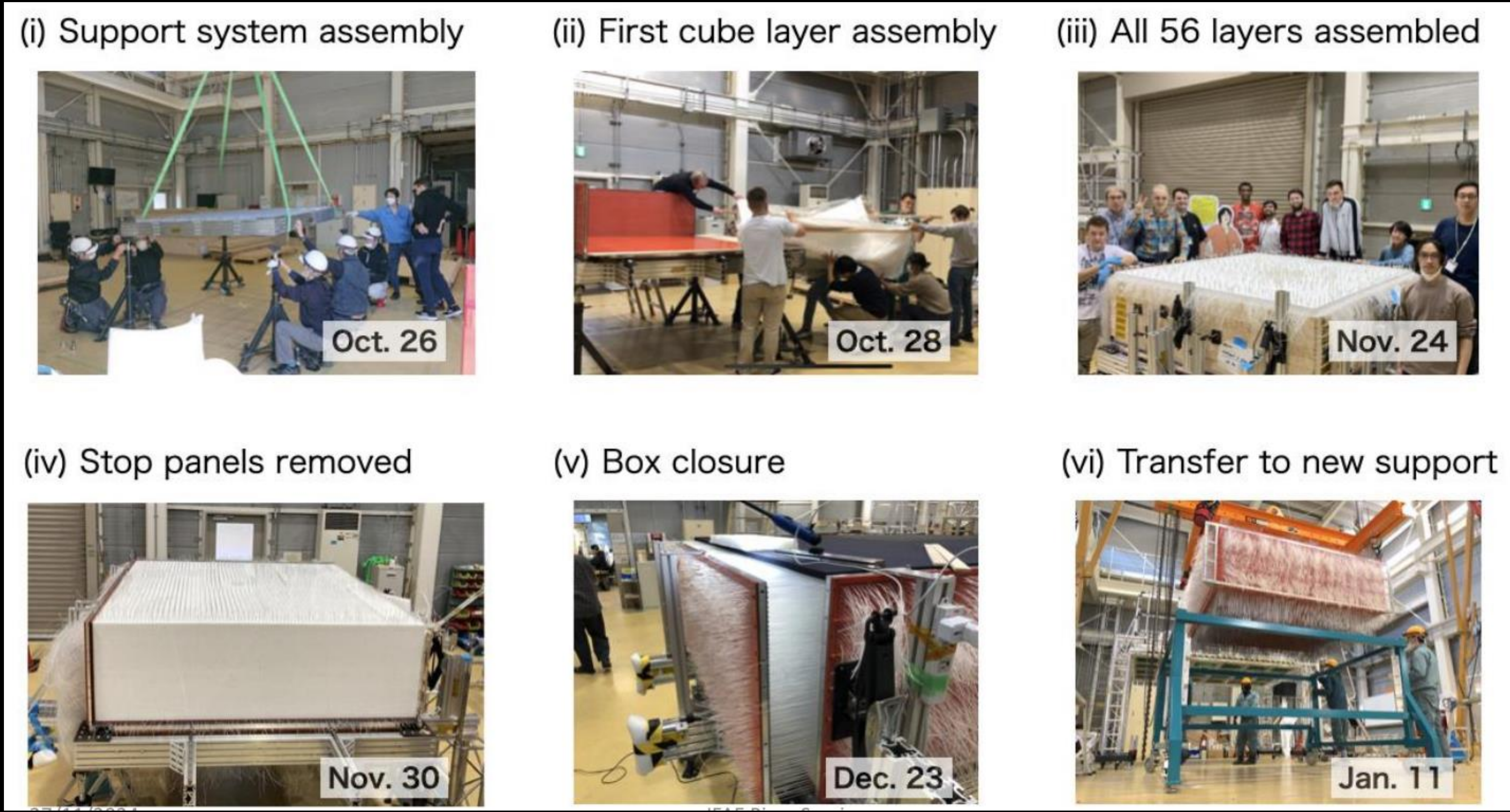


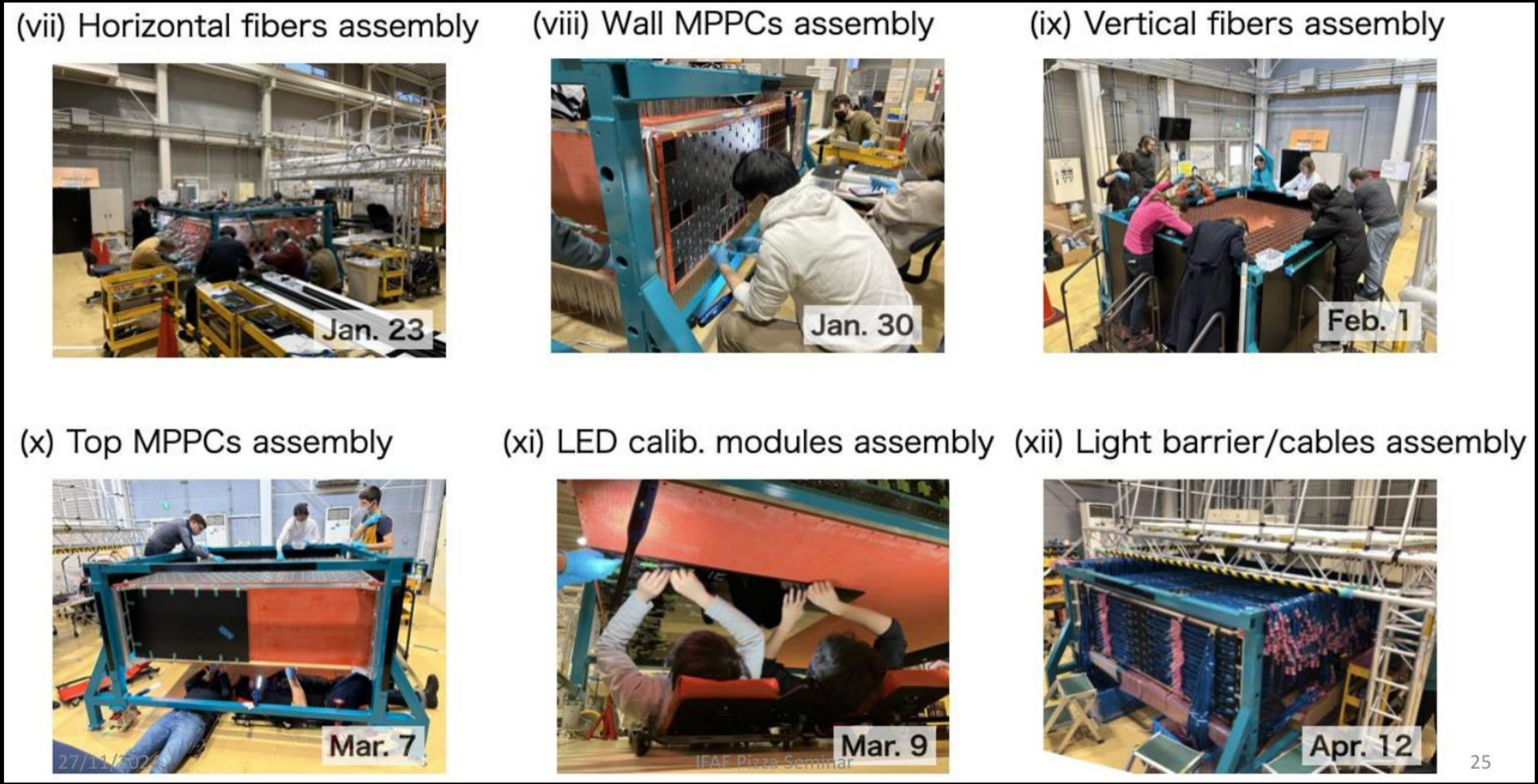


PCB with 8x8 array of surface mounted MPPCs

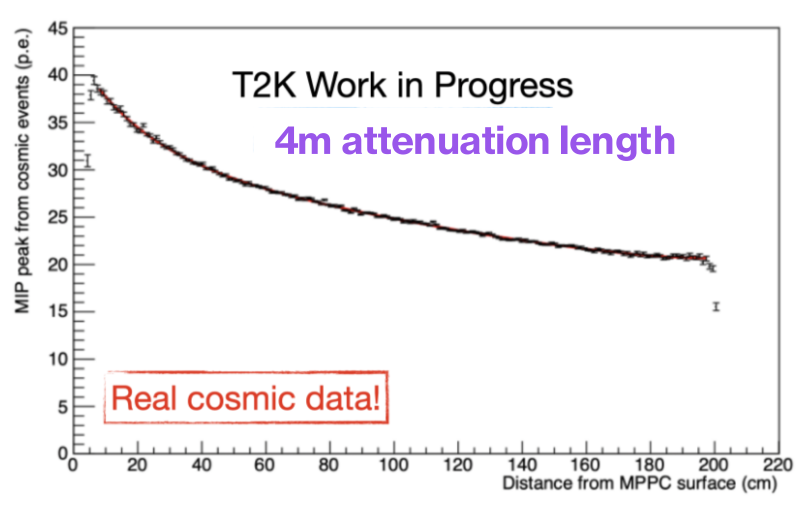
Item	Specification
Effective photosensitive area	1.3 mm x 1.3 mm
Pixel pitch	25 μm
Number of pixels	2668 pixels
Fill factor	47%
Package type	Surface mount
Breakdown voltage (V_{BR})	53 $\pm$ 5 V
Peak sensitivity wavelength	450 nm
Photo detection efficiency	25%
Gain	7.0 x 10^5
Dark count	70 kcps (typ.)
Crosstalk probability	1%

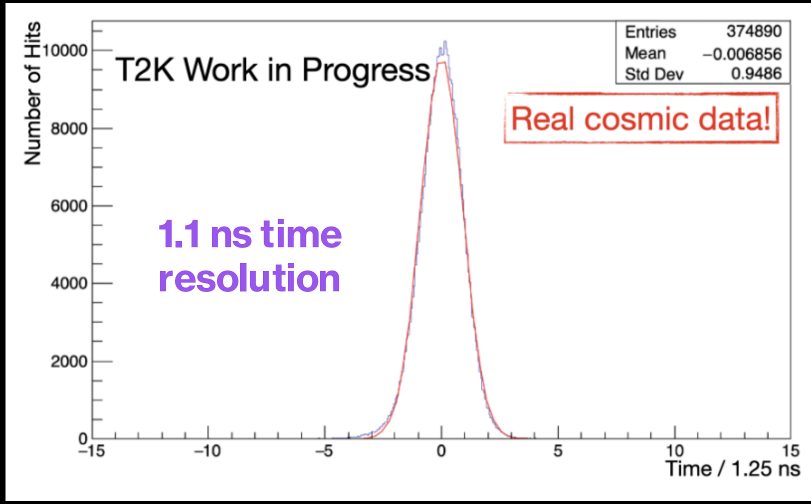


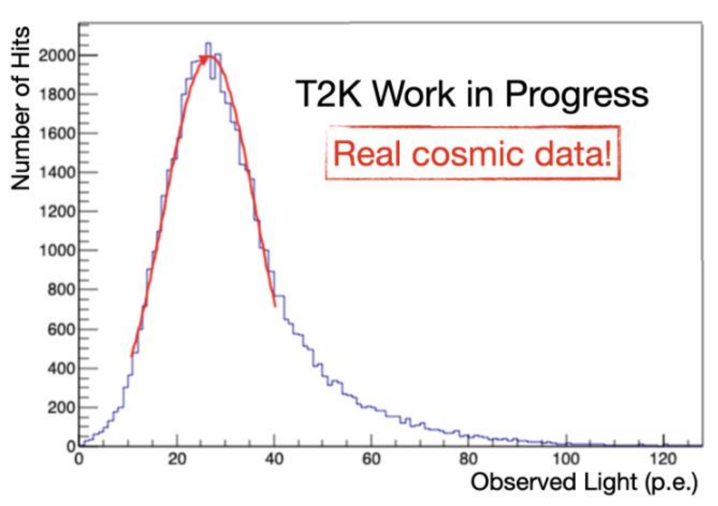

(i) Support system assembly
Oct. 26
(ii) First cube layer assembly
Oct. 28
(iii) All 56 layers assembled
Nov. 24
(iv) Stop panels removed
Nov. 30
(v) Box closure
Dec. 23
(vi) Transfer to new support
Jan. 11

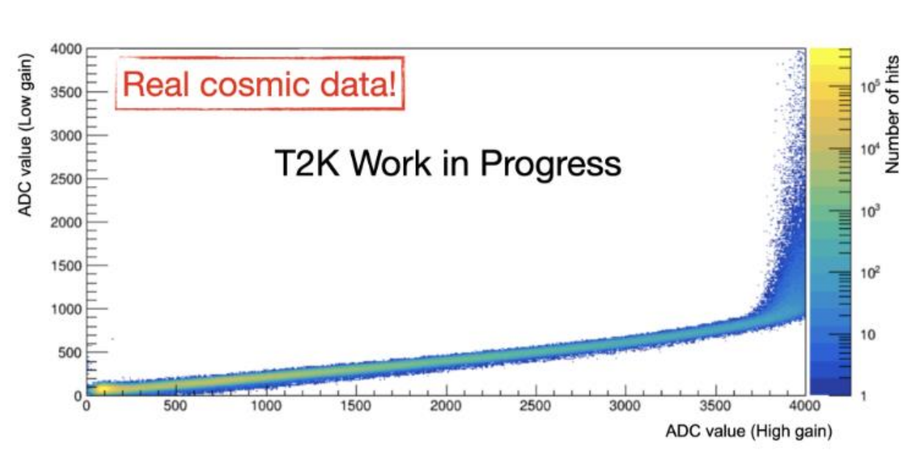

(vii) Horizontal fibers assembly
Jan. 23
(viii) Wall MPPCs assembly
Jan. 30
(ix) Vertical fibers assembly
Feb. 1
(x) Top MPPCs assembly
Mar. 7
(xi) LED calib. modules assembly
Mar. 9
(xii) Light barrier/cables assembly
Apr. 12
IFAE Pizza Seminar
25

Detector performance with cosmics



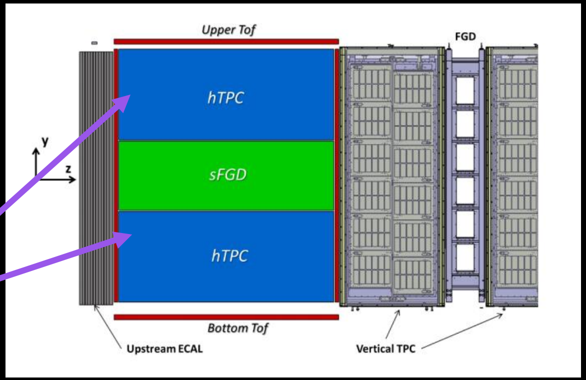


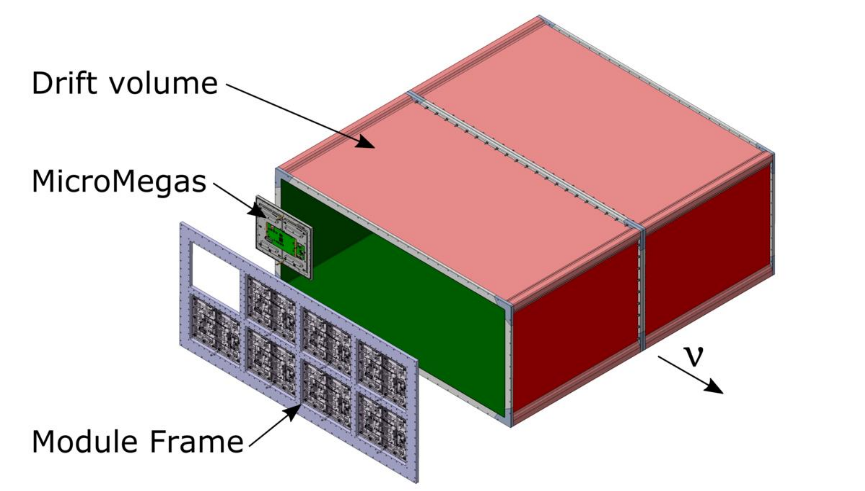




High angle TPCs

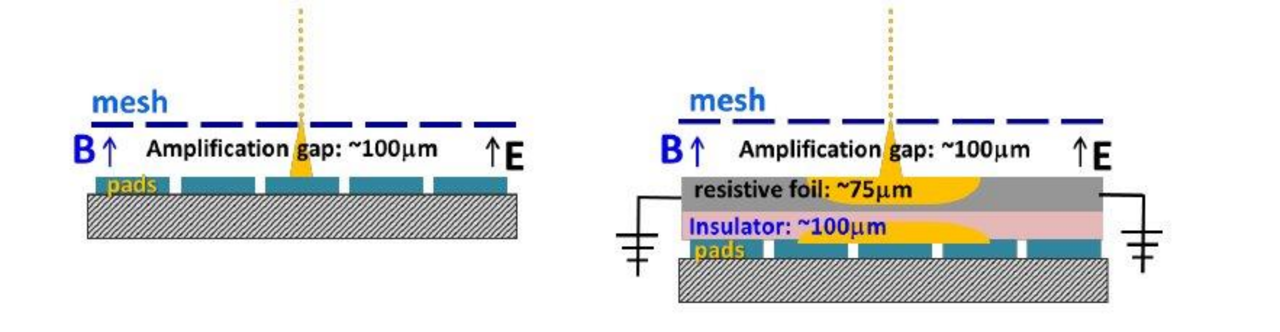
- Two new time projection chamber detectors
  - Dimensions 2.0 × 0.8 × 1.8 m
  - Gaseous mix, 95% Ar
  - 275 V/cm electric field
  - Two Cu field cages joined by a central cathode producing a 90 cm drift distance
- Similar to the present ND280 TPCs, they provide high granularity 3D track reconstruction, charge and momentum measurement and PID
- Instead of downstream, these are above and below SFGD, providing information about charged particles emitted at high angles





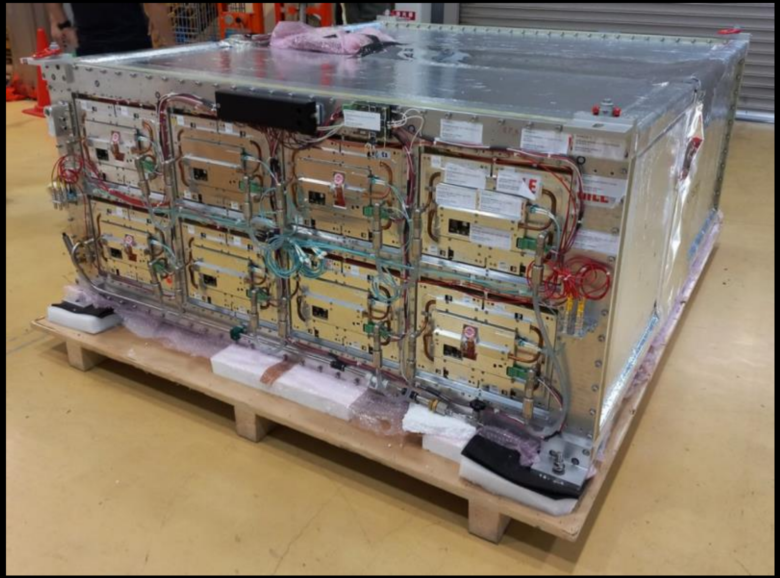
Major changes to design: novel readout technology and new field cage design to minimise dead space + position of TPCs designed for high angle tracks

Resistive Micromegas readout



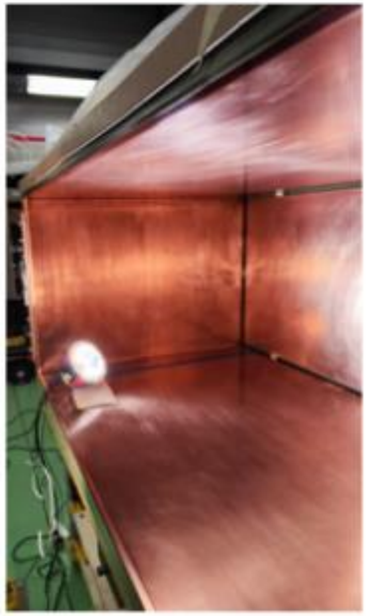
- Novel technology - Encapsulated Resistive Anode Micromegas (ERAM)
- Additional resistive layer spreads charge over several readout pads on anode plane
- Results in a much better point resolution
- Resistive layer additionally prevents sparks, allowing higher gain to be used and simplified front end electronics

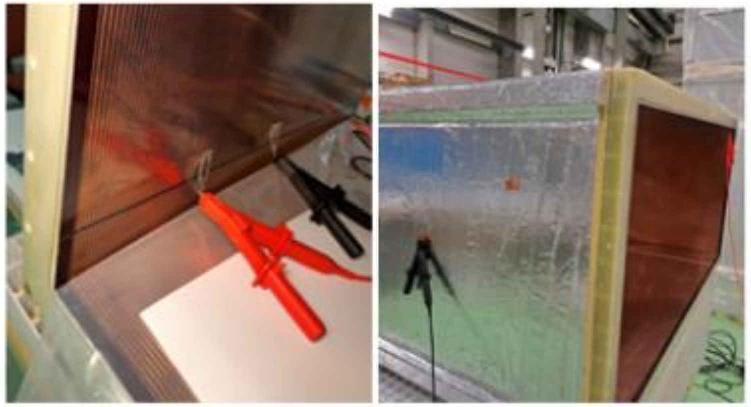
Signals read out by 8 Micromegas organised in a 4x2 readout plane



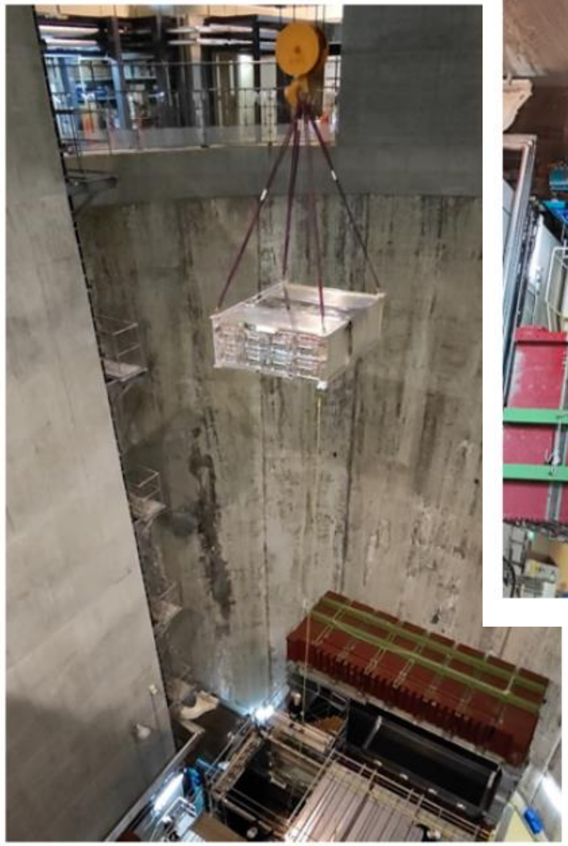
Inner cage surfaces polishing

Checking grooves for o-ring and for charge labyrinth on cathode flanges





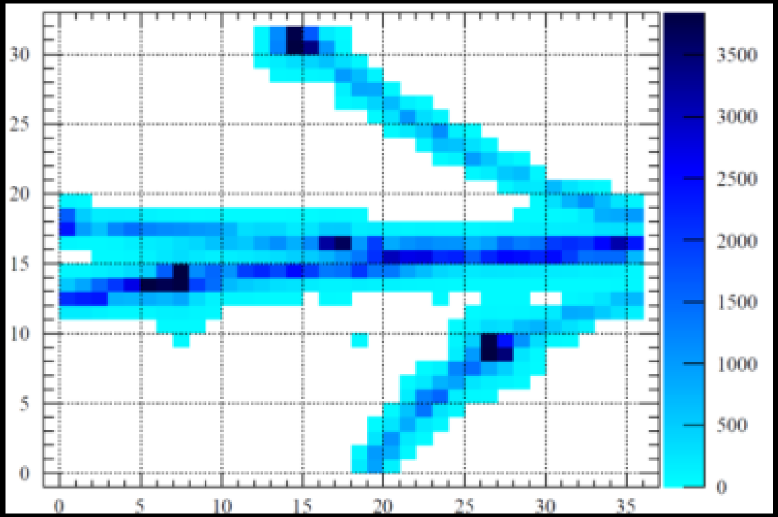
Measuring strip-strip and strip-shield insulation at high voltage



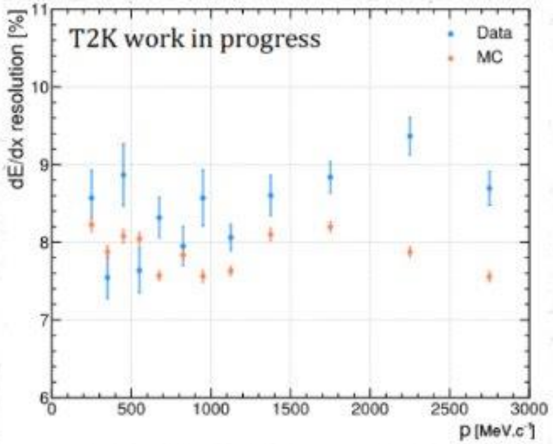
Lowering bottom HATPC
2023.9.8

ND280 after lowering of top HATPC
2024.4.25

HATPC performance

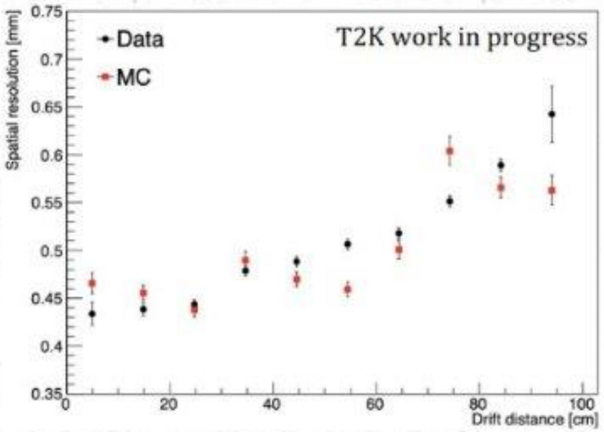


dE/dx resolution



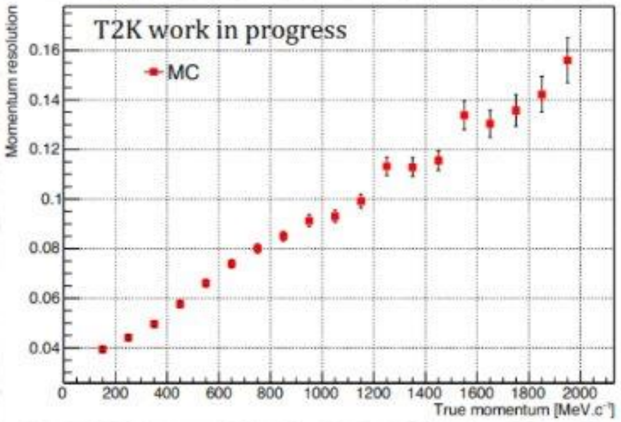
- dE/dx resolution **better than 10 %**.
- Behaves as expected.

Spatial resolution



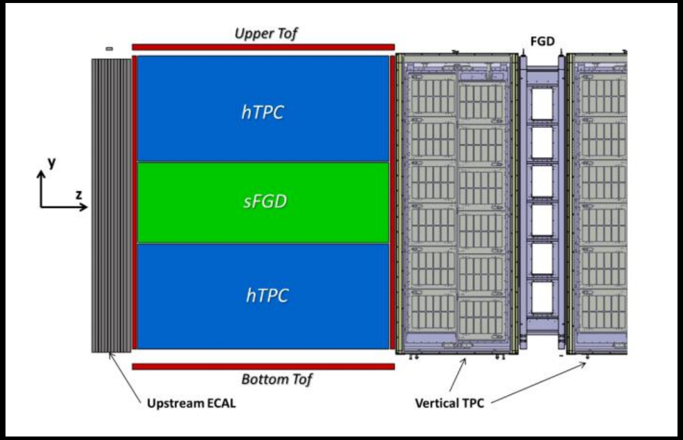
- Spatial resolution **≈ 500 μm**.
- In reasonable agreement with MC.

Momentum resolution



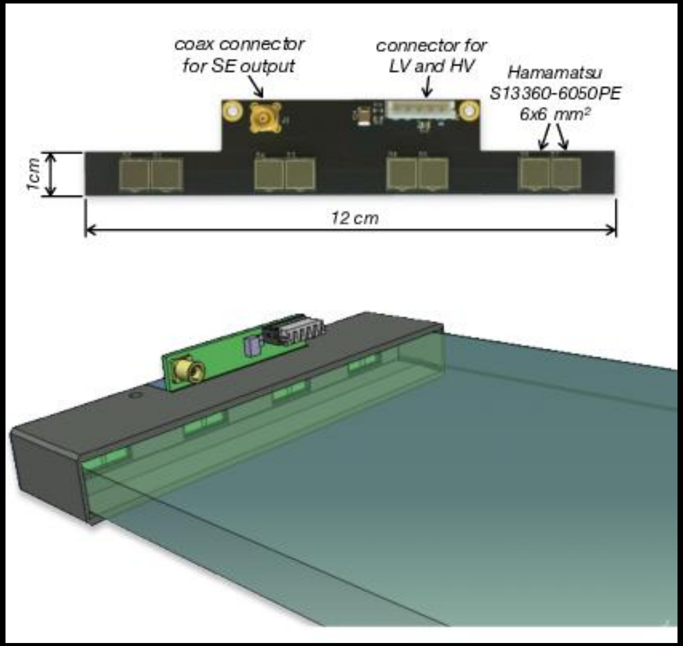
- Momentum resolution **better than 10%** for vertical muons with momenta < 1.2 GeV/c and L > 600 mm.

Time of flight (ToF) detectors

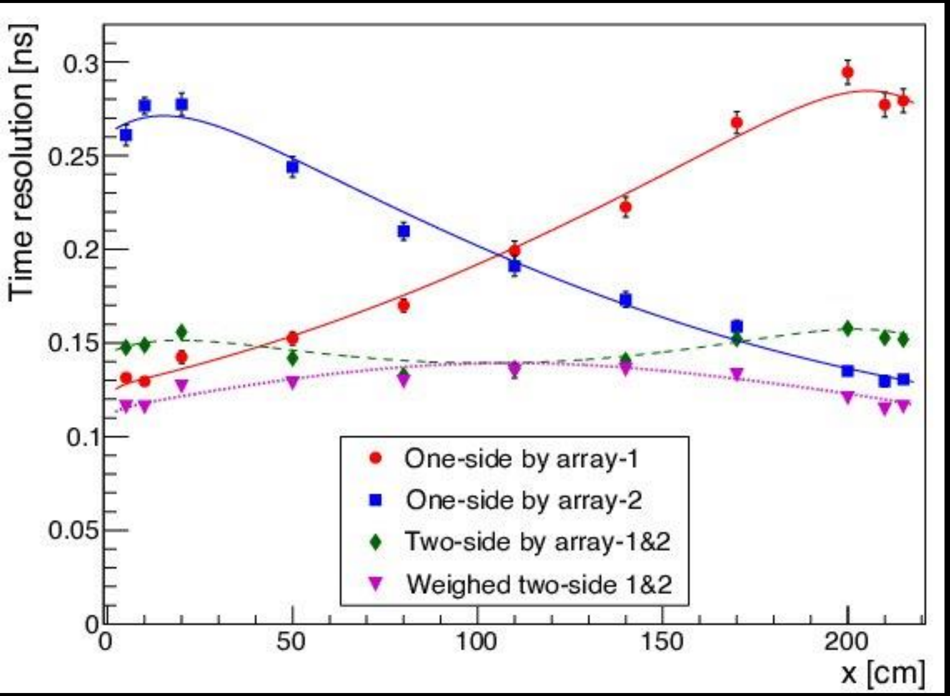


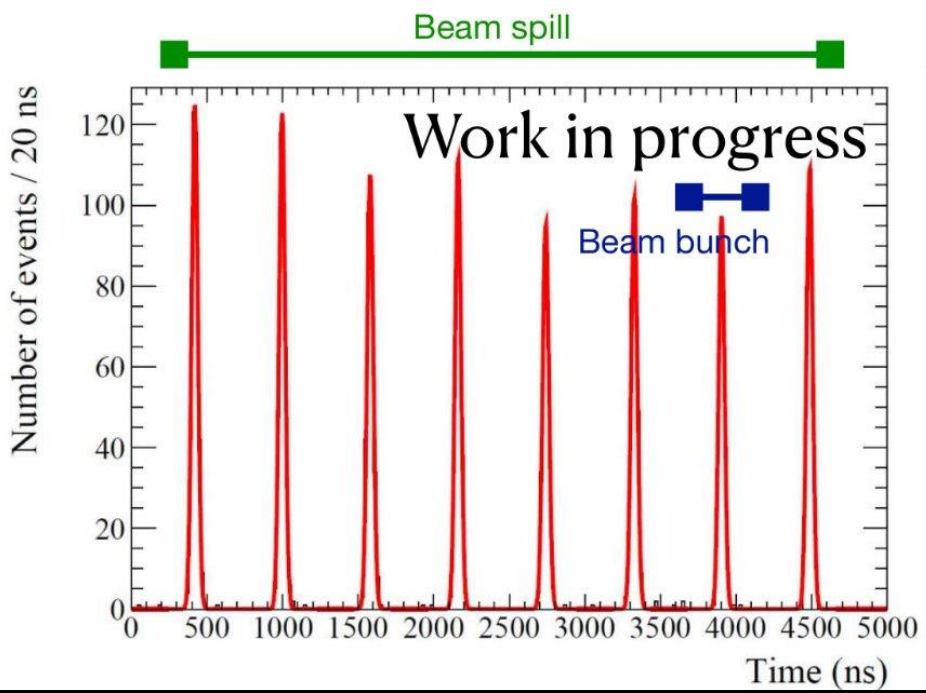
- Six time of flight modules surround the SFGD and HATPC volume
- Each plane is 2.3 by 2.5 m2 and is made up of 20 1cm thick scintillator bars with high light output, stable attenuation length and fast timing
- Scintillation light propagates through the bars and is read out by double ended SiPM readout

ToF modules during commissioning at CERN



ToF timing performance



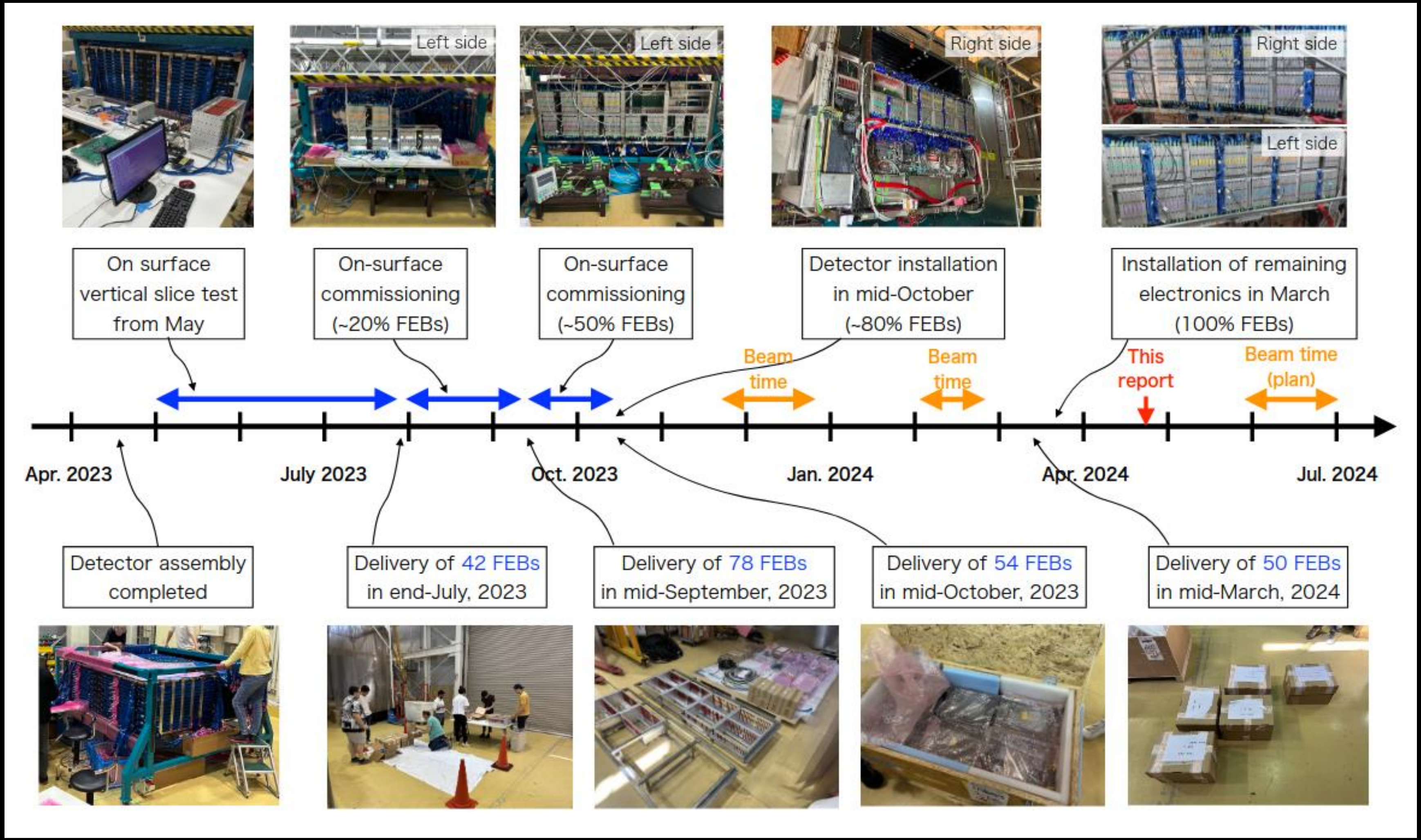


Timing resolution of 150 ps is achieved

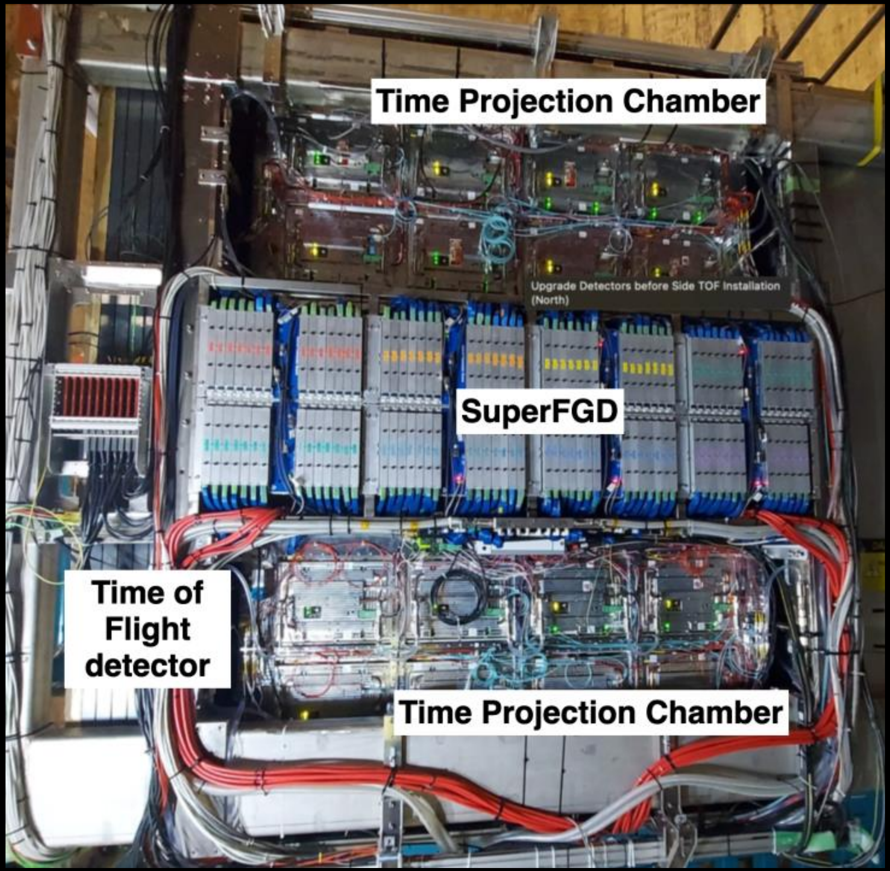
Beam structure clearly captured by ToF

Part Three:
First data with ND280 upgrade!

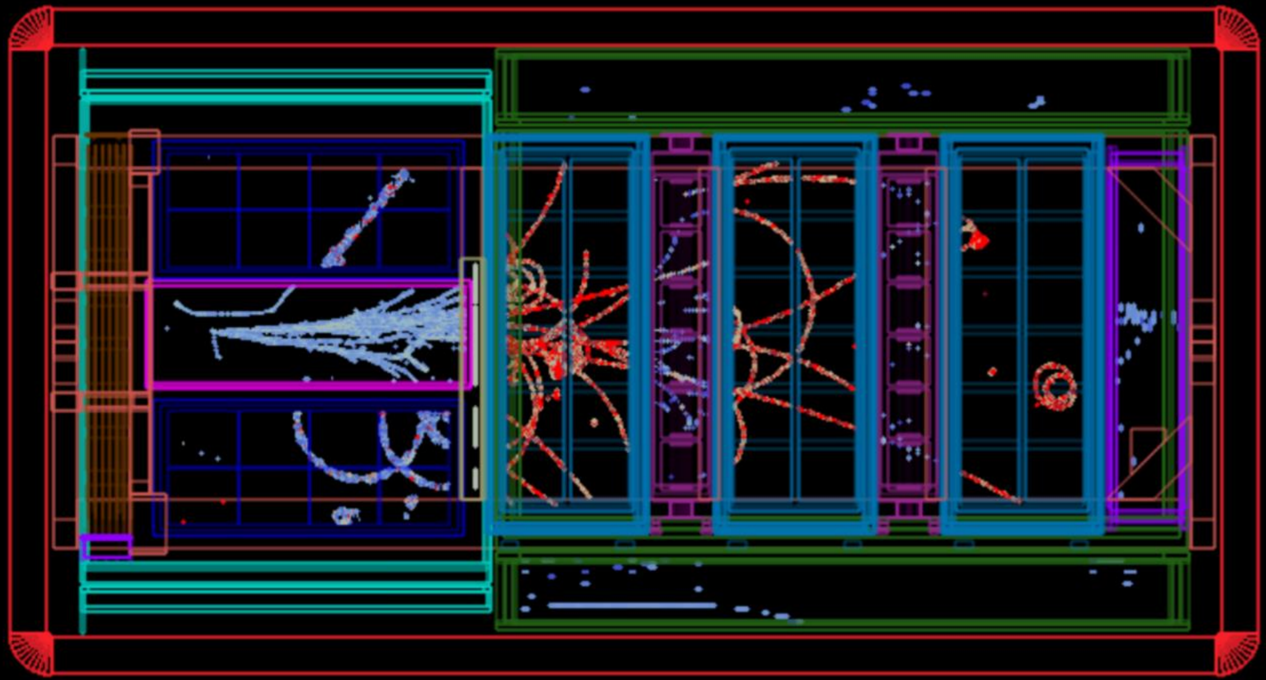
Building ND280 upgrade



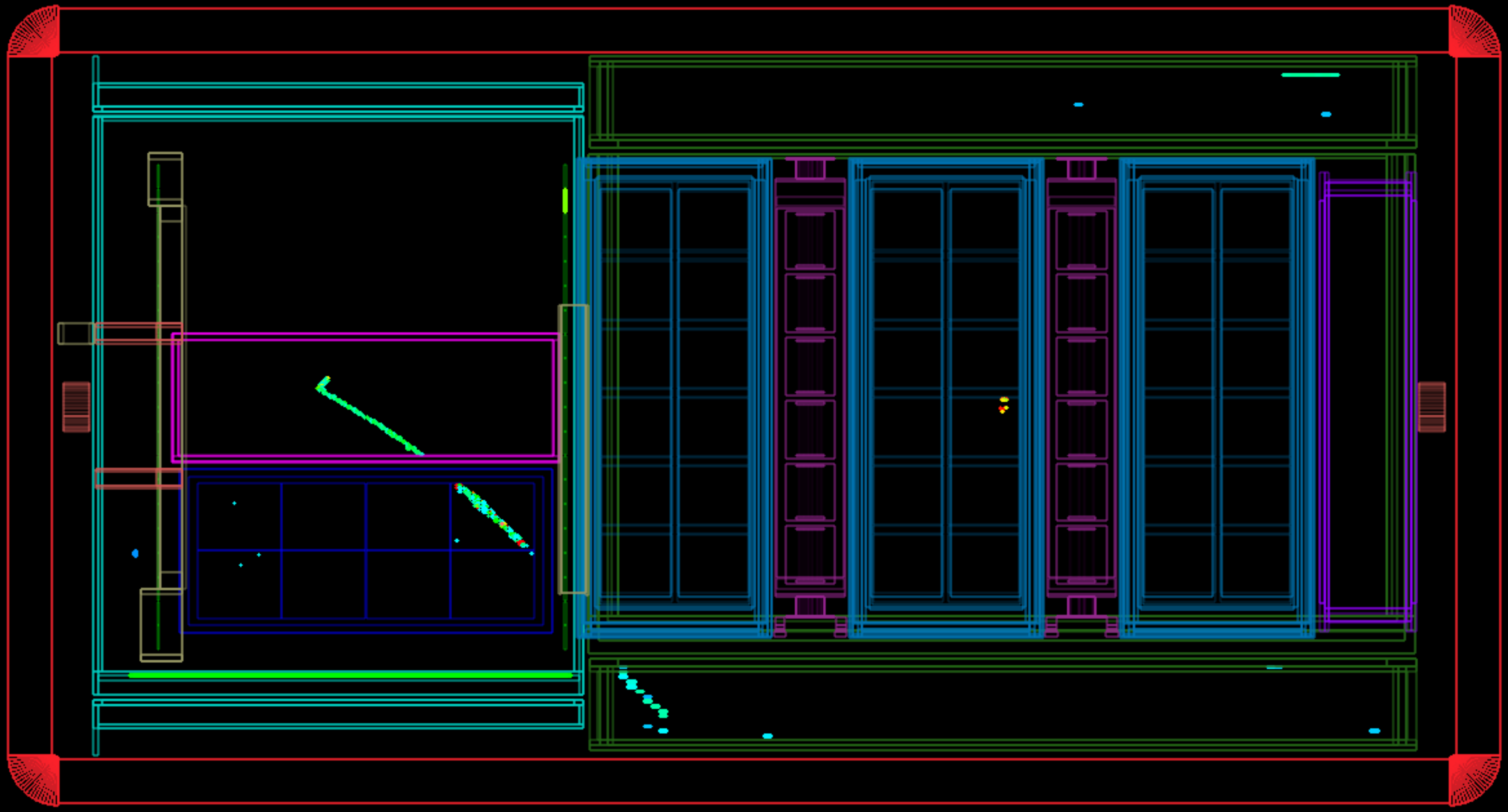
First data taking



- Technical runs taken in Nov/Dec 23 and Feb 24 with SFGD, bottom HAT and first TOF panels
- Installation of all sub-detectors completed with final two ToF panels in May 2024
- **First physics run with completed upgrade in June 2024**

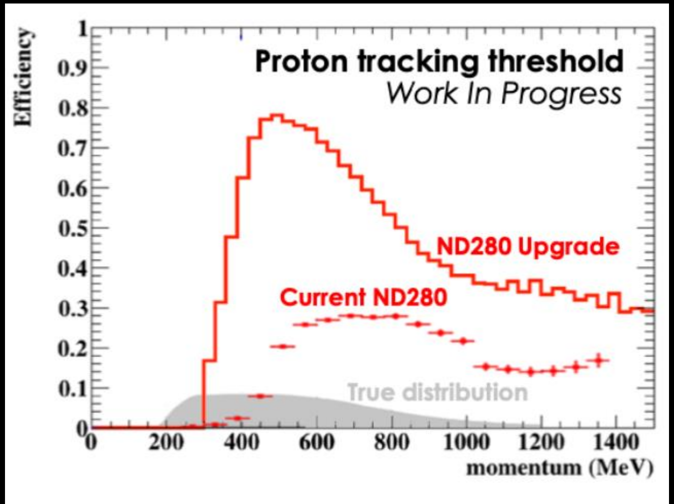


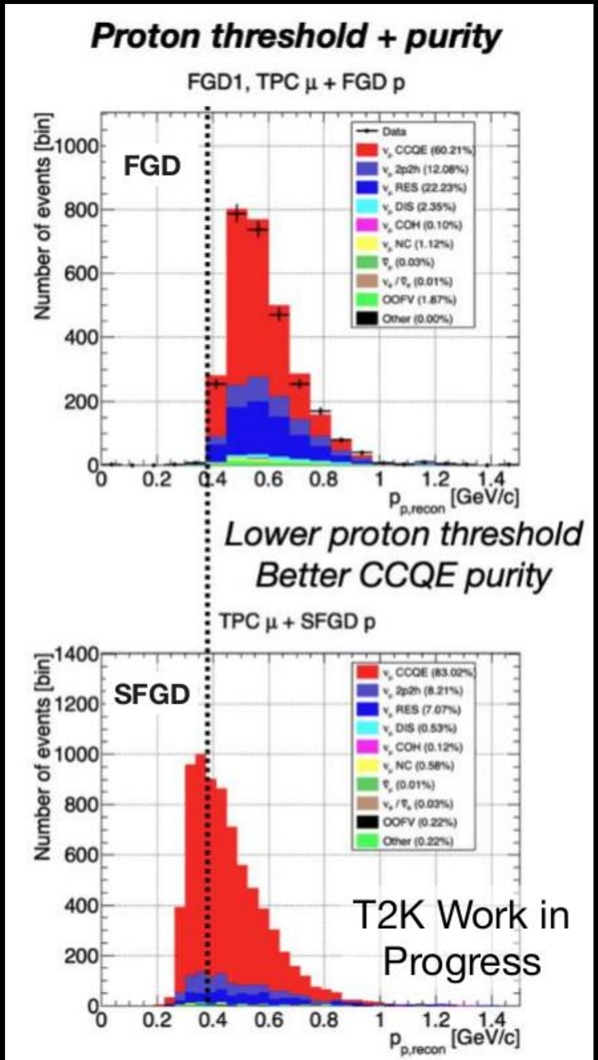
Event display



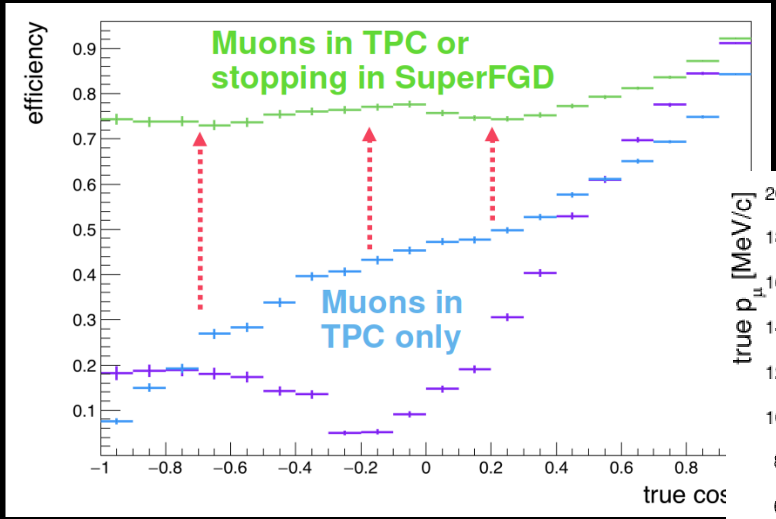
Lower momentum threshold

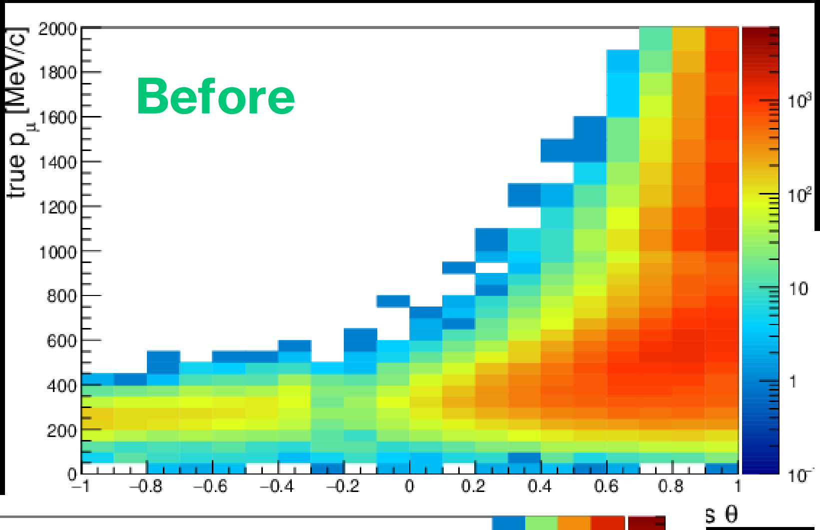
- SFGD has reduced momentum threshold for pions and protons
- Proton threshold reduced to approx 300 MeV
- Additionally, a higher efficiency over the whole momentum range

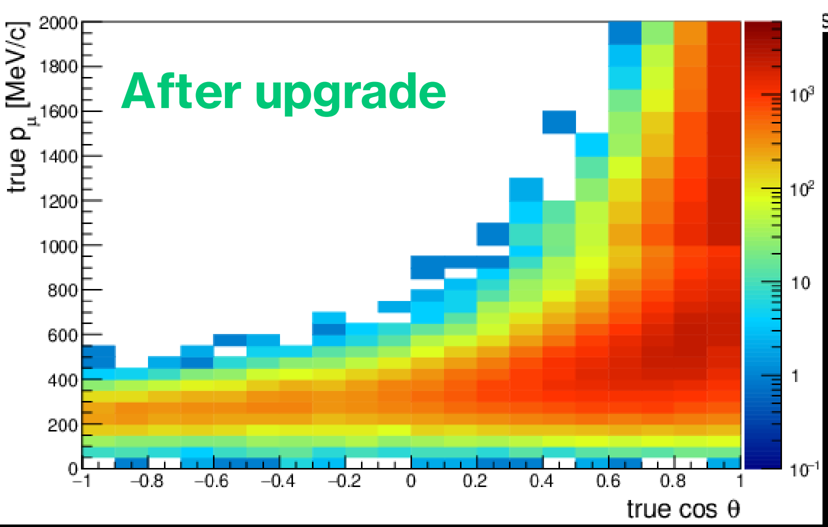




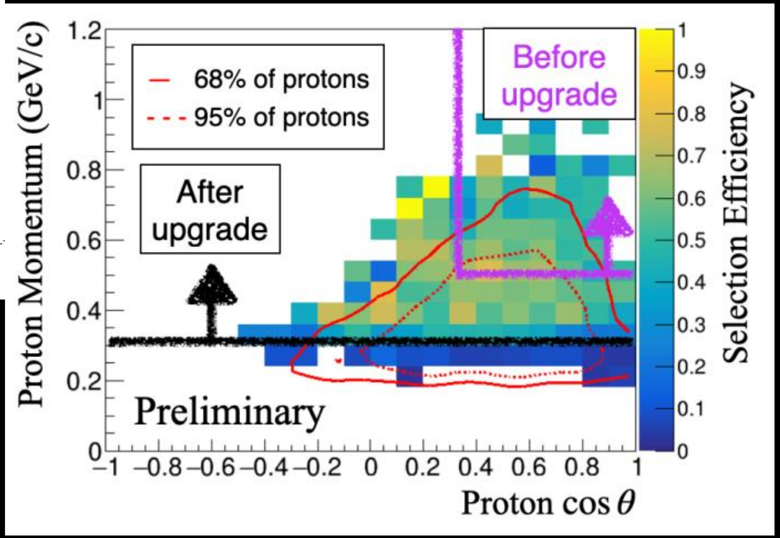
Better angular acceptance







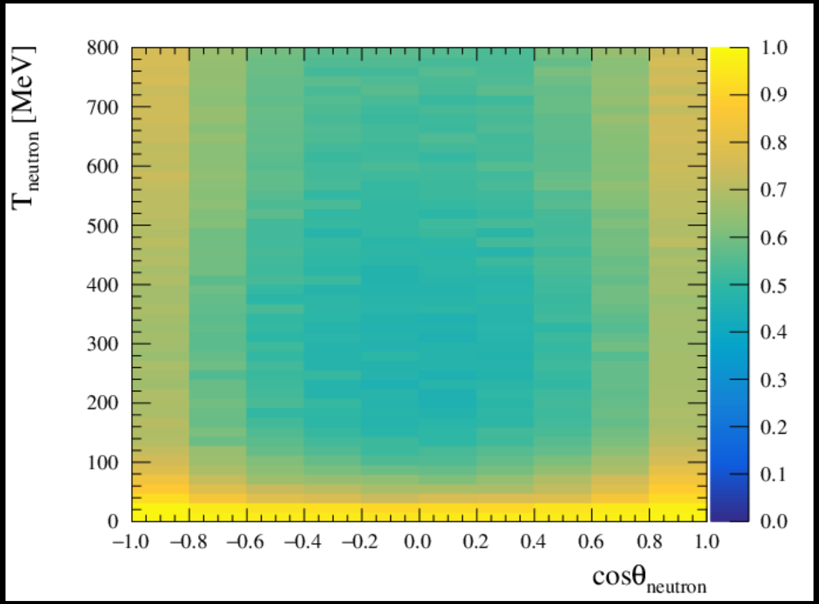
Proton distribution

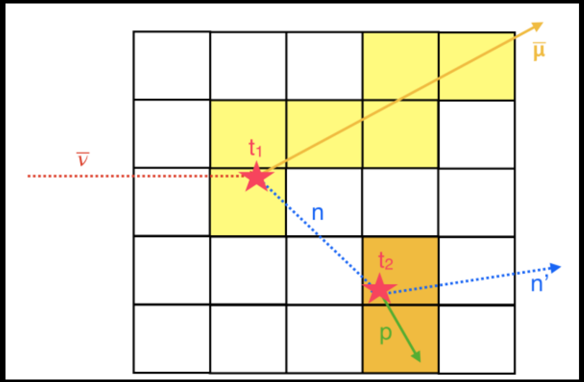


4π acceptance for tracks due to HATPC detectors

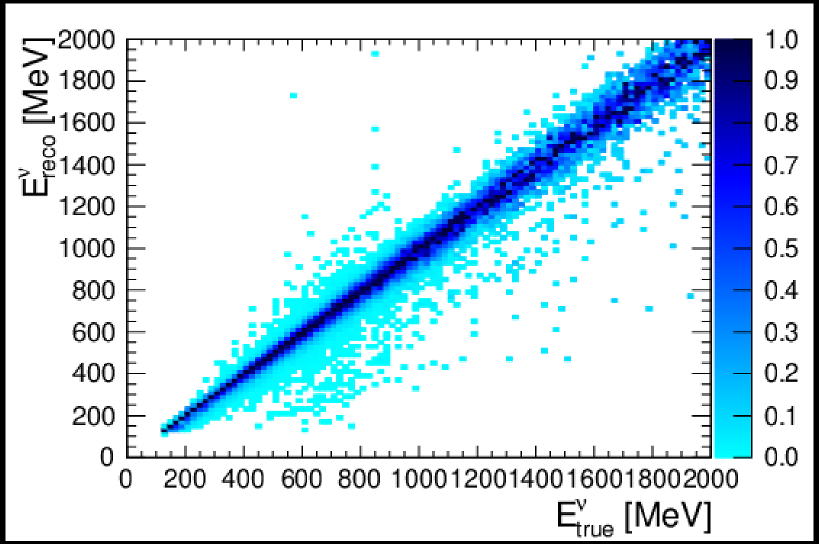
Neutron detection

Efficiency of neutron detection





Time of flight between neutrino vertex and secondary vertex can be used to reconstruct neutrons in the SFGD



- This is especially important for anti-neutrino channels, where the reconstruction of the neutron will massively increase resolution of reconstructing the neutrino energy
- Approx 50% tagging efficiency expected

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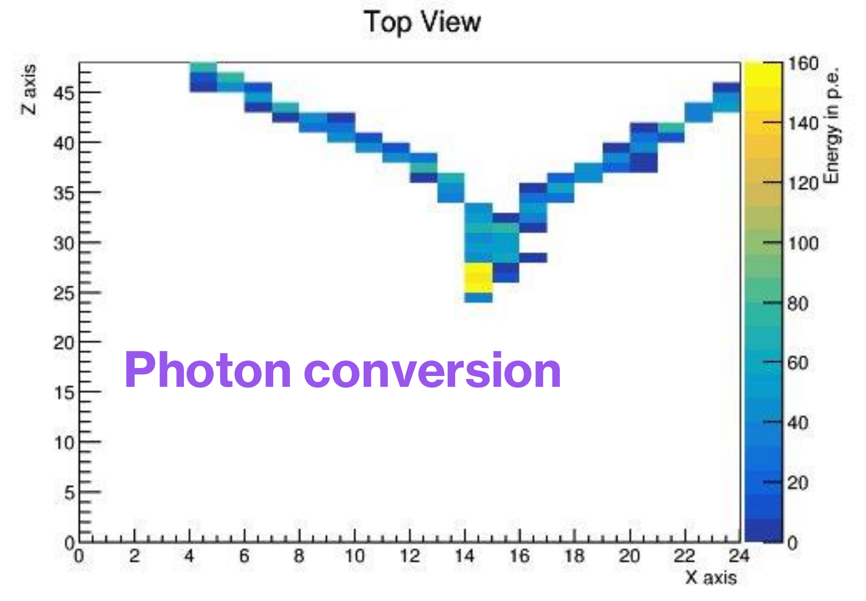
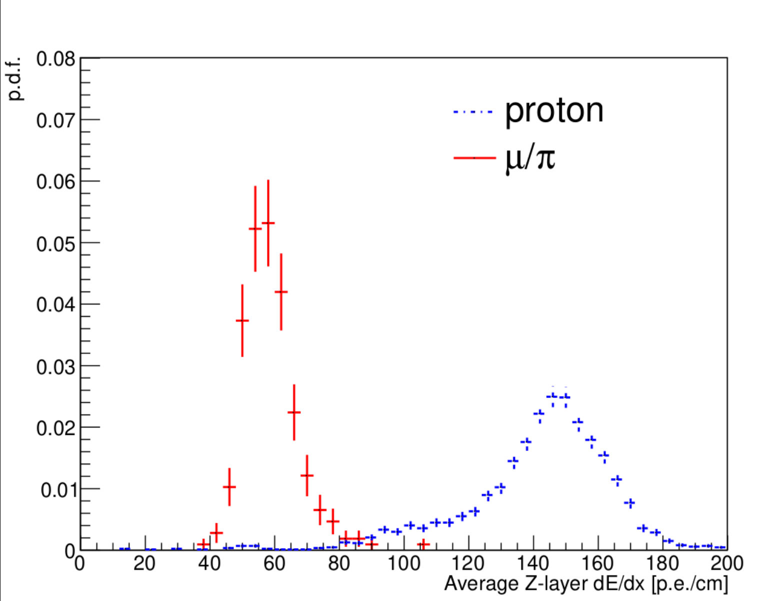
Better PID

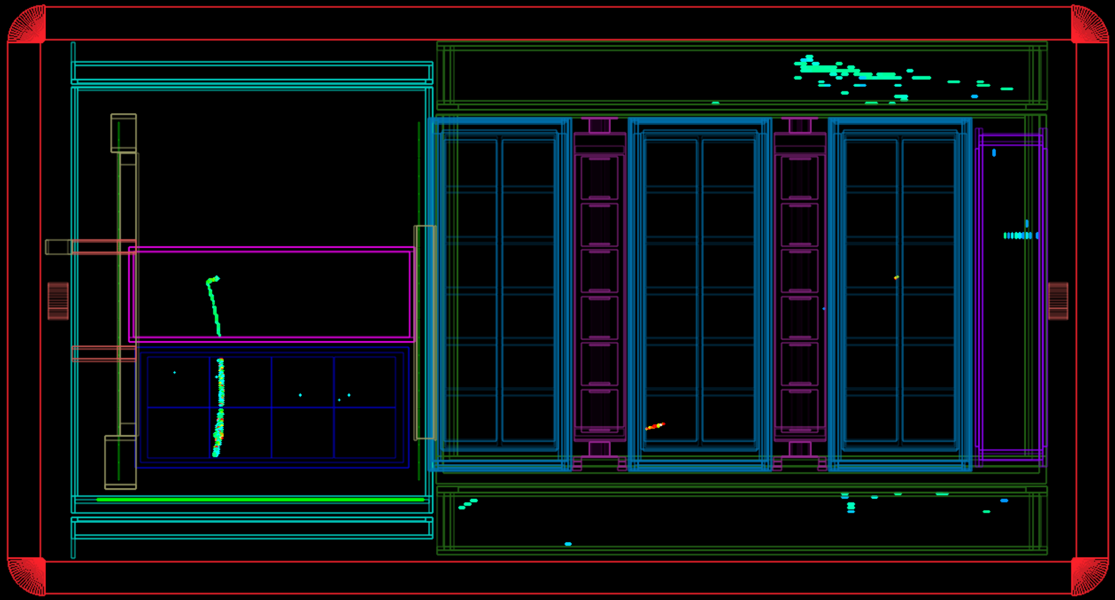
- Photons from π0 production are a dominant background to electron neutrino selections in ND280
- SFGD high granularity has much improved electron/gamma identification



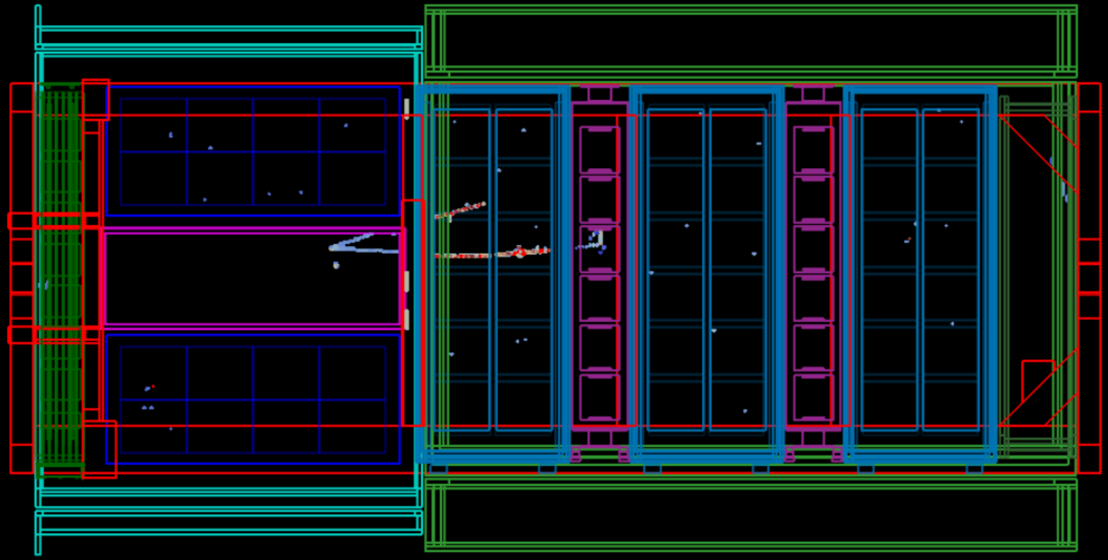
- Excellent proton /MIP separation



Interesting events

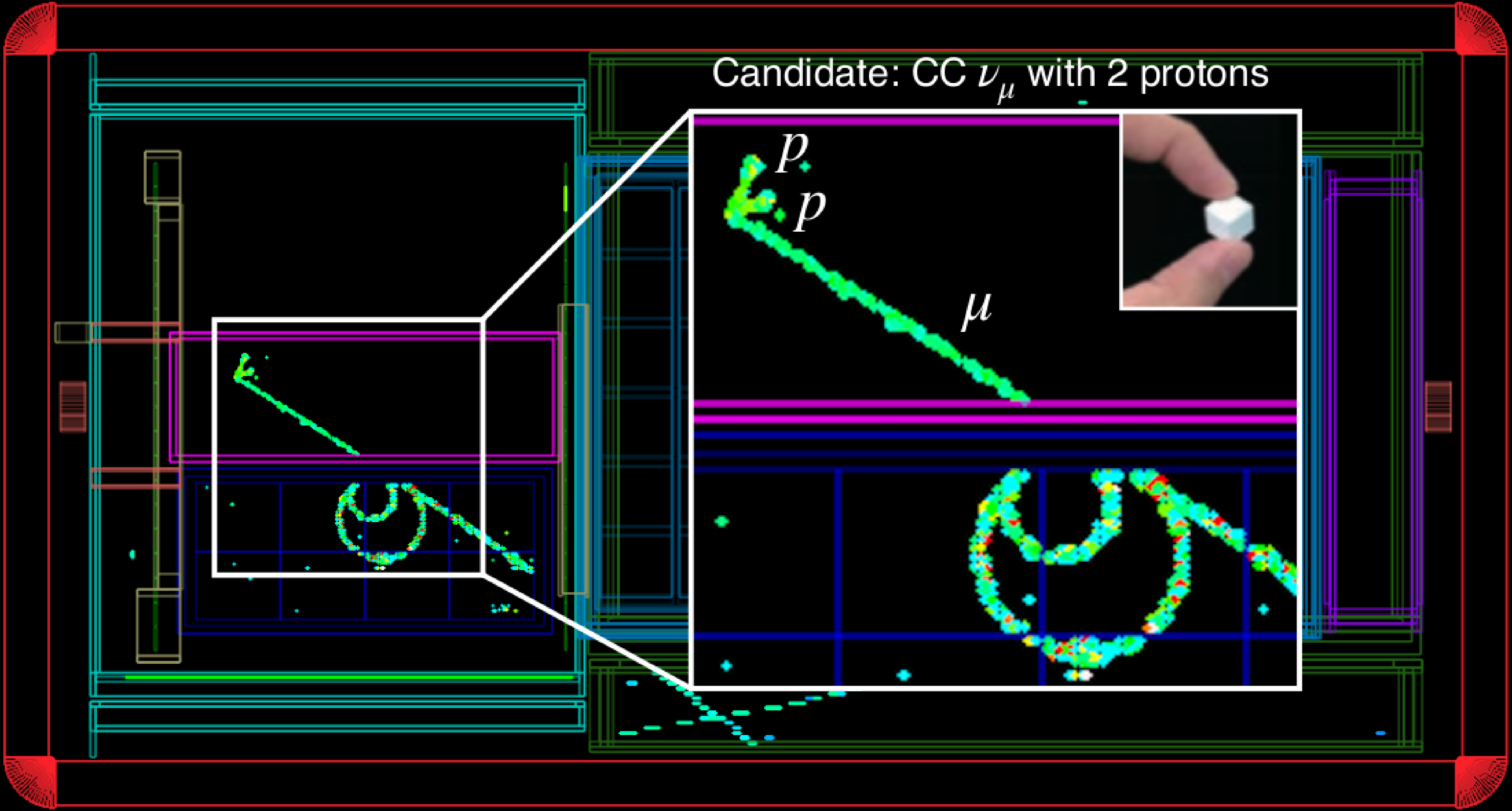


Candidate event with very **high angle muon** and forward going proton (would be hard to measure pre-upgrade)



Candidate event with **neutron** emitted from neutrino vertex

Run number : 16120 | SubRun number :0 | Event number : 12772 | Spill : 12345 | Time : Sun 2023-12-24 17:28:50 JST | Partition : 61 |Trigger: Beam Spill



Part Four:
Future plans for ND280?

Timeline

- T2K will continue to run until 2027
- Beam power to continue to increase up to 1.3 MW
- Plan to collect 10x10^21 POT, for a 3 sigma measurement of δ_{CP}

ND280 upgraded

End of T2K running

2010

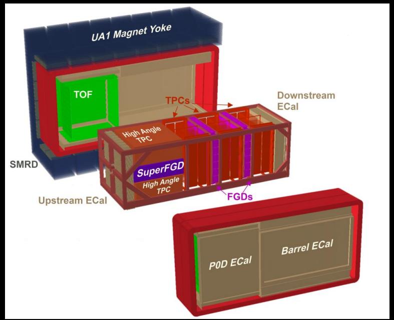
2022

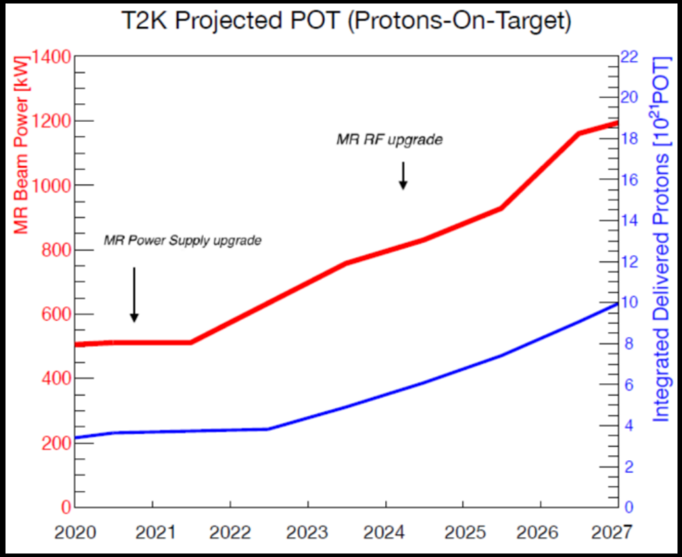
2024

2027

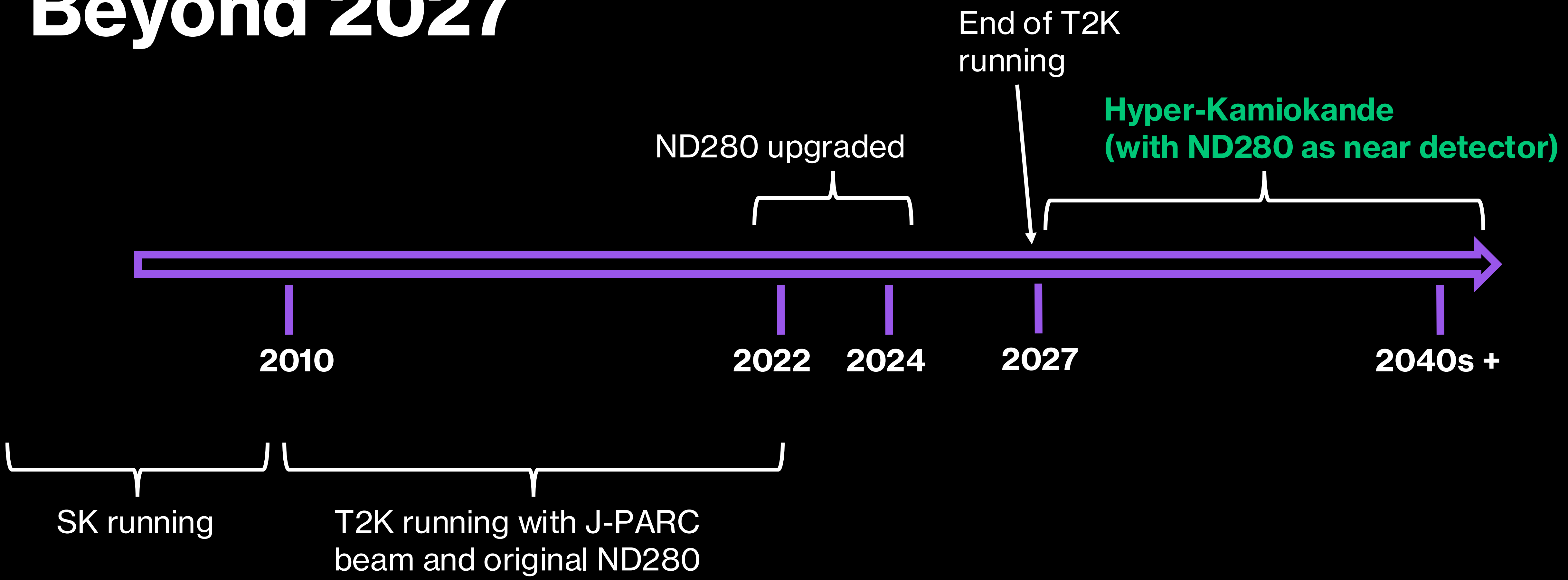
SK running

T2K running with J-PARC beam and original ND280



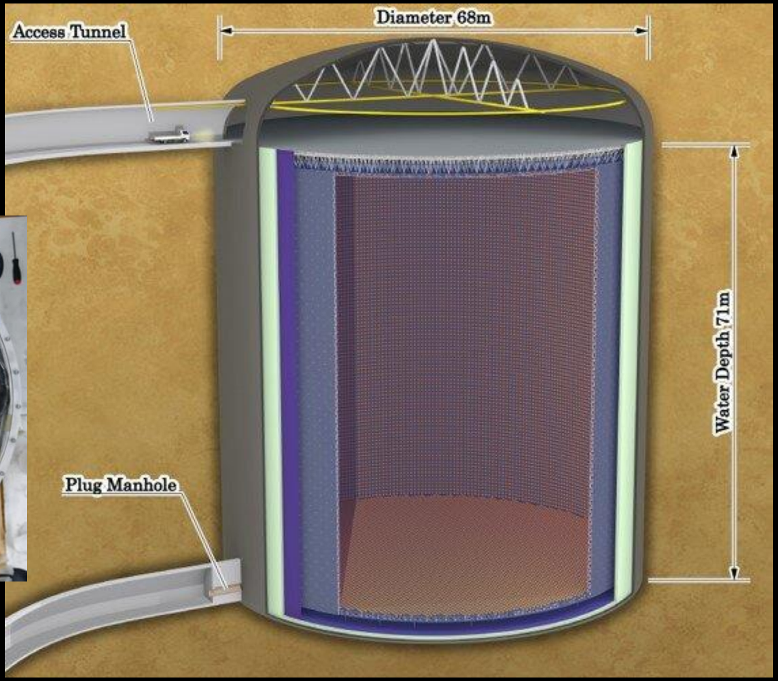


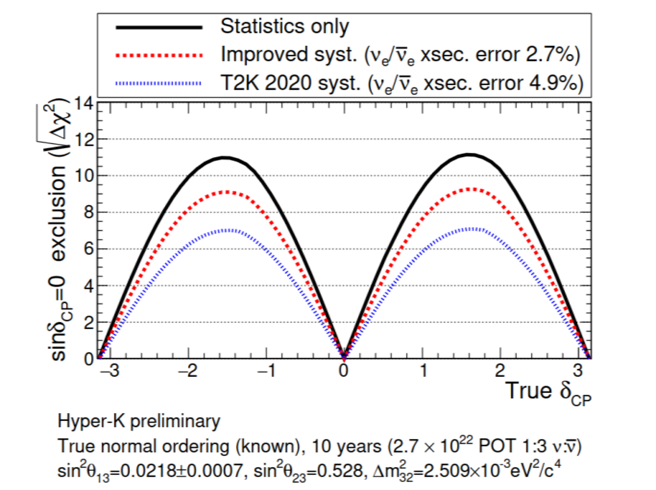
Beyond 2027

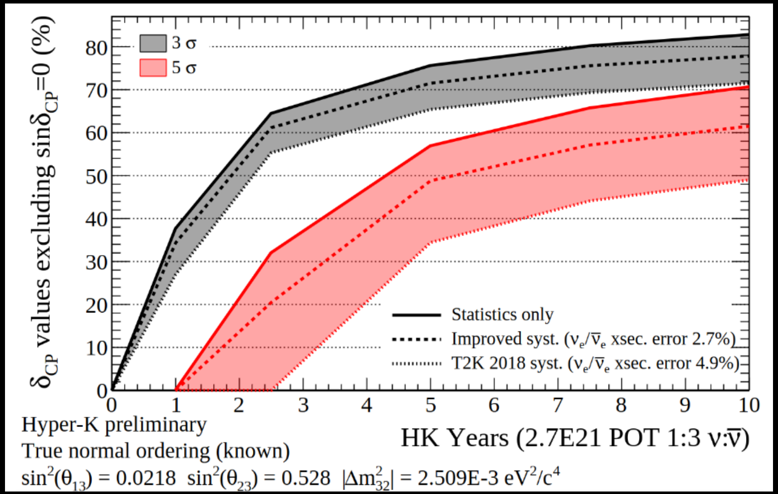

End of T2K running
Hyper-Kamiokande (with ND280 as near detector)
ND280 upgraded
2010
2022
2024
2027
2040s +
SK running
T2K running with J-PARC beam and original ND280

Hyper-Kamiokande

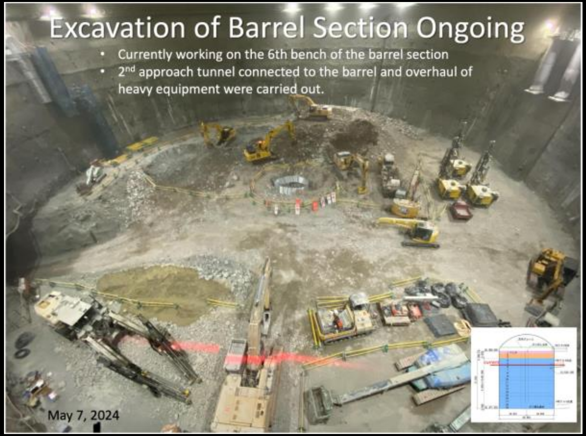
- Next generation water Cherenkov detector currently under construction, with fiducial volume approximately 8 time larger than Super-K
- Liverpool strongly involved in the calibration system for HK and in particular the light injection system
- Expected to take data from 2027 onwards
- Will use ND280 as the near detector

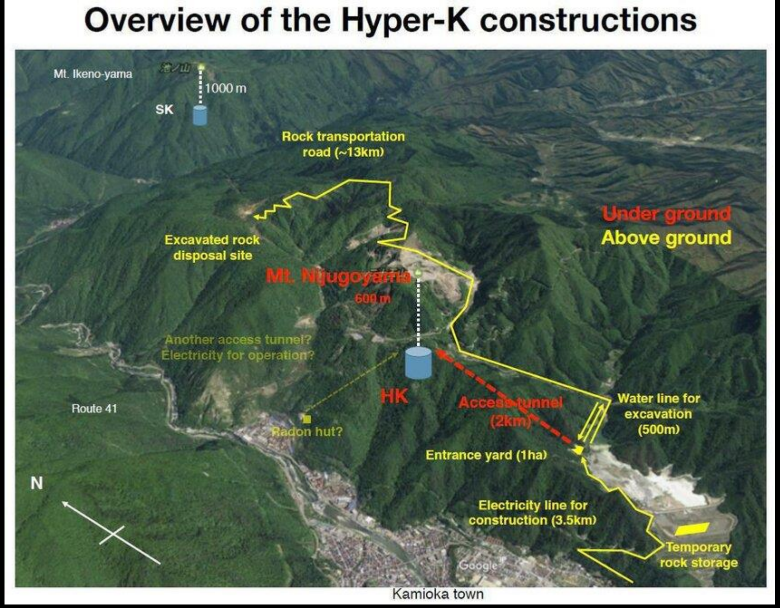






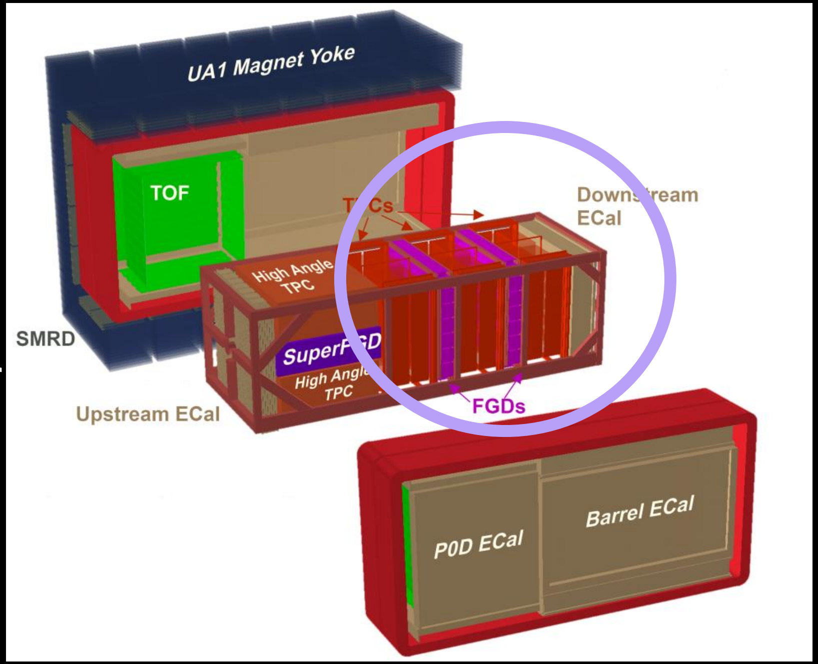
Hyper-Kamiokande is currently under construction

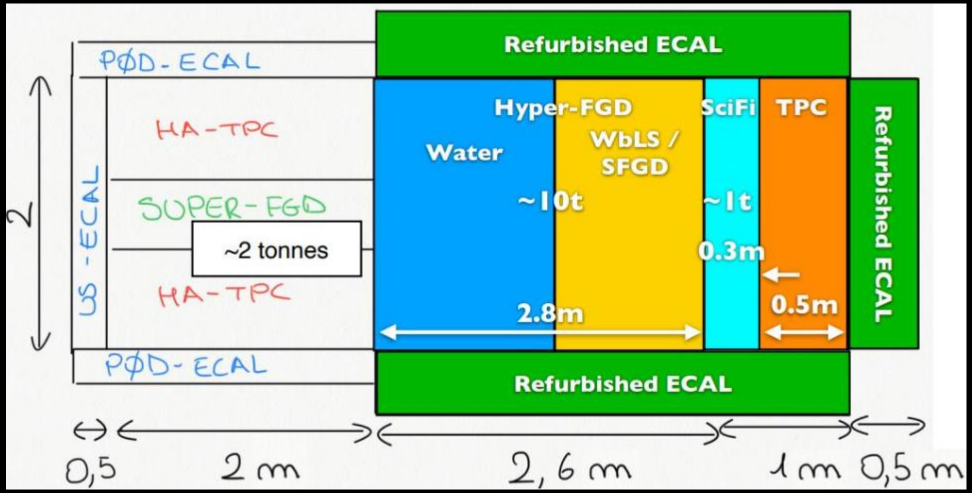




ND280++?

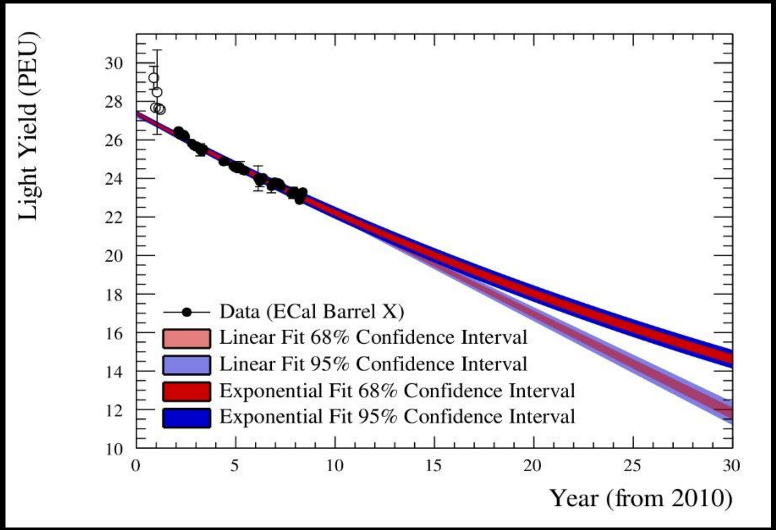
- Proposal to carry out additional upgrades to ND280 for the HK era
- This would primarily involve the "tracker" part of the detector which was not upgraded in the last few years
- Goal of high granularity and large mass of hydrogen/water
- R&D ongoing to develop new technology
  - "hyper"-FGD (larger volume of SFGD)
  - Water based liquid scintillator in segmented cubes
  - Scintillating fibres

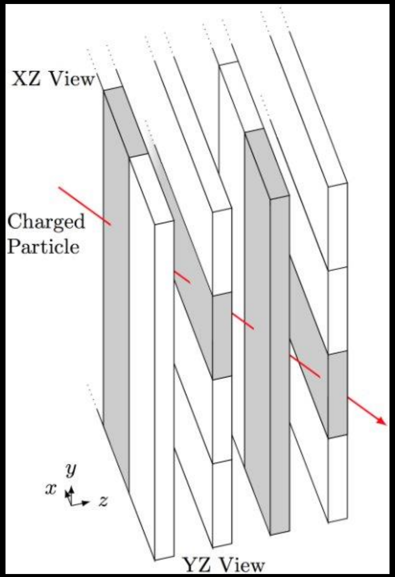


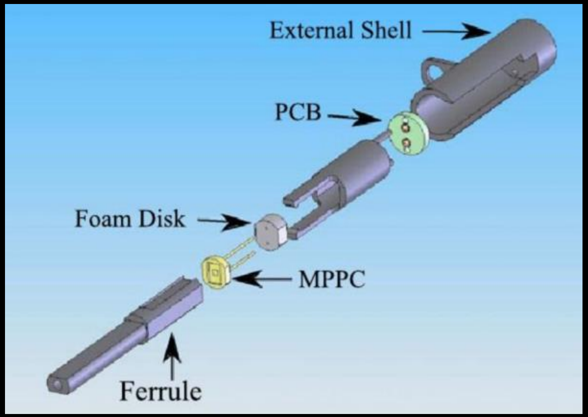


ND280 ECal refurb

- The Electromagnetic Calorimeter part of ND280 is made up of scintillator bars with wavelength shifting fiber running through them – the light collected travels along the fiber to MPPC sensors
- Over time, the scintillator bars have aged, reducing the light yield
- Not currently a problem for physics, however ageing will continue during HK era
- Large increase in light yield could be achieved by replacing the MPPCs to newer sensors, due to improvements in tech since 2009
- This refurb could massively lower the threshold for detecting eg. low energy gammas exiting the detector
- Studies ongoing at Liverpool to understand the requirements and possible benefits of this refurb

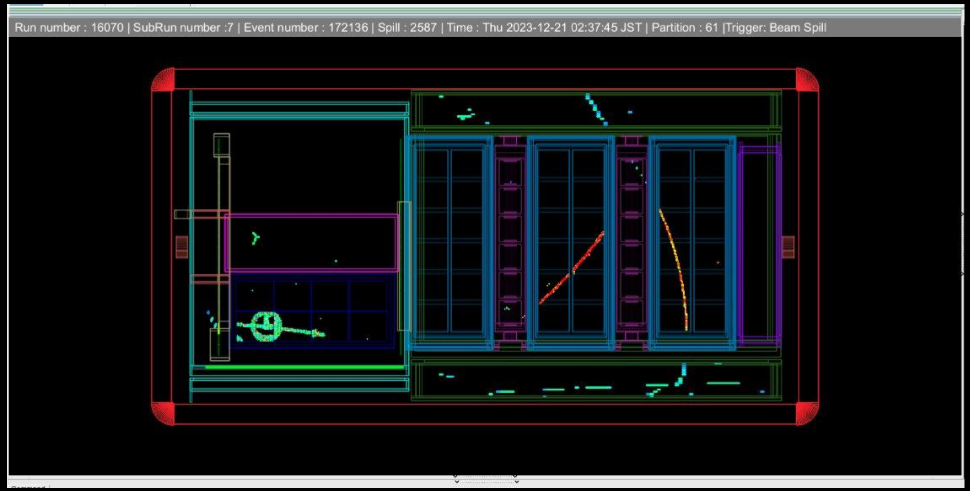






Conclusions

- The near detector suite, including ND280, are a crucial part of the T2K long baseline neutrino oscillation experiment
- An upgrade of ND280 was completed in 2024
  - Three new subdetectors
  - Improvements including neutron detection, better angular acceptance and low energy thresholds
  - Huge amount of work into designing, building, installing and commissioning these detectors
- First data has been taken with the upgrade and analyses are underway
- Targeting summer conferences to show first event selections with data
- Starting to look ahead to further upgrades for the HK era



Thank you for listening

T2K