Institute for High Energy Physics

The T2K ND280 Upgrade

Thorsten Lux

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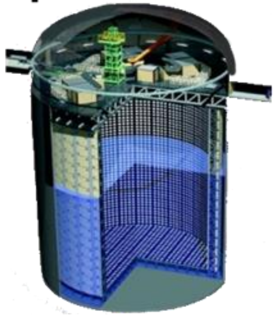
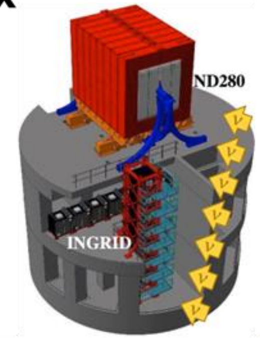
Far detector

Super Kamiokande



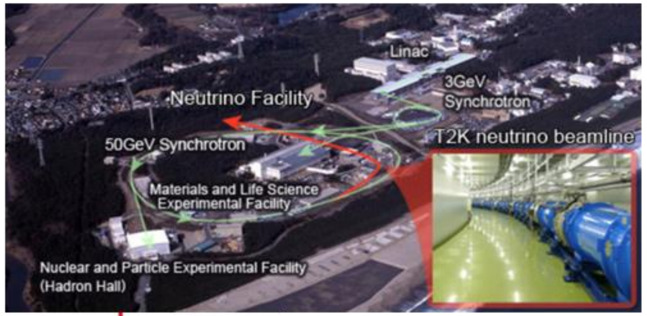
Near detector

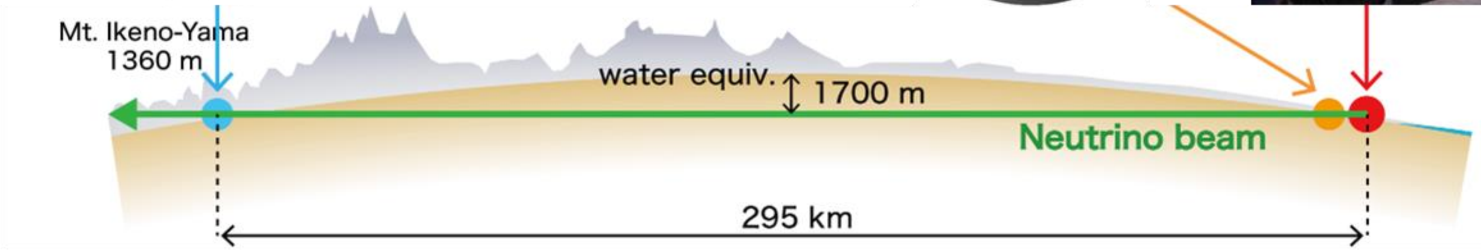
complex



J-Parc

Neutrino Beam





@SK

Measure oscillated beam

←

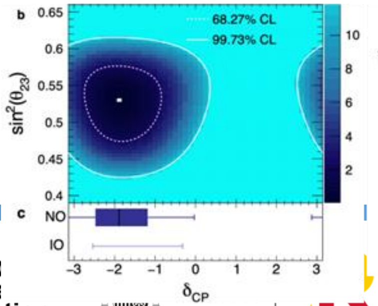
@ND280

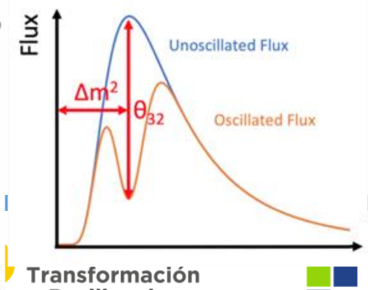
Characterize beam and ν interactions

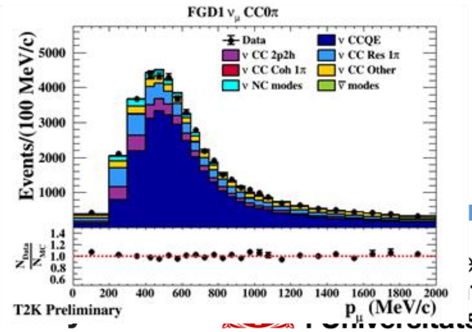
←

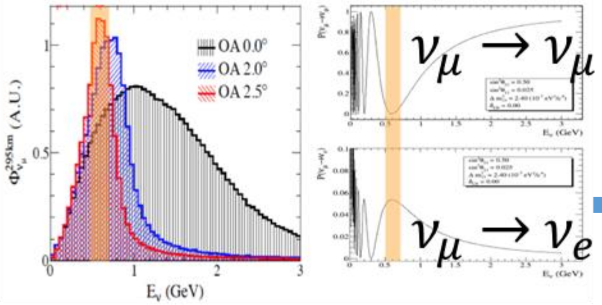
@J-PARC

Create Neutrino's off-axis beam ν_μ or $\bar{\nu}_\mu$









Neutrino Oscillation Parameters

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In principle, we need oscillation probabilities to extract oscillation parameters:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2([1-x]\Delta)}{[1-x]^2}$$

Leading term

$$-\alpha \sin \delta_{CP} \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \Delta \frac{\sin[x\Delta] \sin([1-x]\Delta)}{x[1-x]}$$

CP violating term

$$+\alpha \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \Delta \frac{\sin[x\Delta] \sin([1-x]\Delta)}{x[1-x]}$$

CP conserving term

For $P(\overline{\vartheta_\mu^R} \to \overline{\vartheta_e^R})$:

- "-" => "+"
- replace δ and x with $-\delta$ and $-x$

$$x = \frac{2\sqrt{2} G_F n_e E_\vartheta}{\Delta m_{31}^2}, \alpha = \left|\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right| \cong \frac{1}{30}, \Delta = \frac{\Delta m_{31}^2 L}{4E_\vartheta}$$

δ_{CP} = 0 implies violating tem vanishes!

But detectors provide event rates:

$$dN/dE_\nu = \Phi \sigma N_{target}$$

Number of target isotopes given by detector

Neutrino flux, depends on E_ν

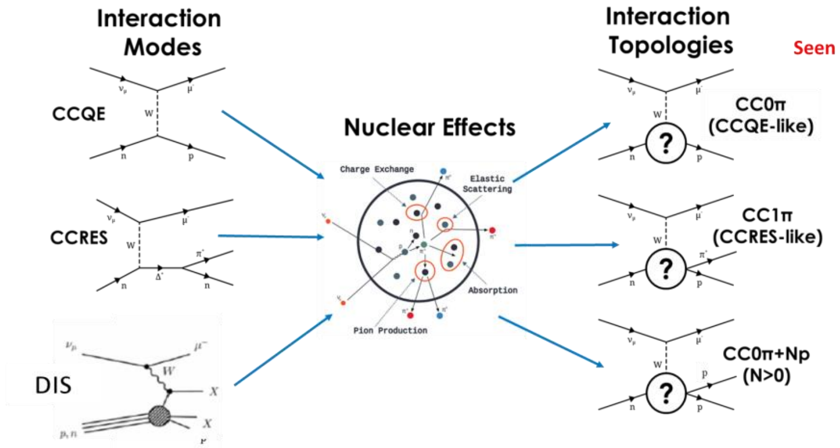
Cross-section (interaction probability), depends on E_ν, target isotope

More complex

Nuclear effects

Relevant for neutrino oscillations

Seen by detector



Detector effects

- ***P*** depends on true E_ν but a detector provides E_ν^{reco}
- Energy migration described by matrix: $T(E_\nu, E_\nu^{reco})$
- Additional detector effects/efficiencies which depend on E_ν/E_ν^{reco}: $\epsilon(E_\nu, E_\nu^{reco})$
- Both require an excellent understanding of the detector response
- Different for every interaction process

ND event rate:

$$\frac{dN_\beta^{FD}}{\Delta E_\nu^{reco}} = N_{target}^{ND} \sum_i \int_{E_{min}}^{E_{max}} \Phi^{ND}(E_\nu)\sigma_i^{ND}(E_\nu)T_i^{ND}(E_\nu, E_\nu^{reco})\epsilon_i(E_\nu, E_\nu^{reco})dE_\nu$$

FD event rate:

$$\frac{dN_\beta^{FD}}{\Delta E_\nu^{reco}} = N_{target}^{FD} \sum_i \int_{E_{min}}^{E_{max}} \Phi^{ND}(E_\nu)F_{\frac{FD}{ND}}(E_\nu)\sigma_i^{FD}(E_\nu)T_i^{FD}(E_\nu, E_\nu^{reco})\epsilon_i(E_\nu, E_\nu^{reco})P_{\nu_\alpha\to\nu_\beta}(E_\nu)dE_\nu$$

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More complex

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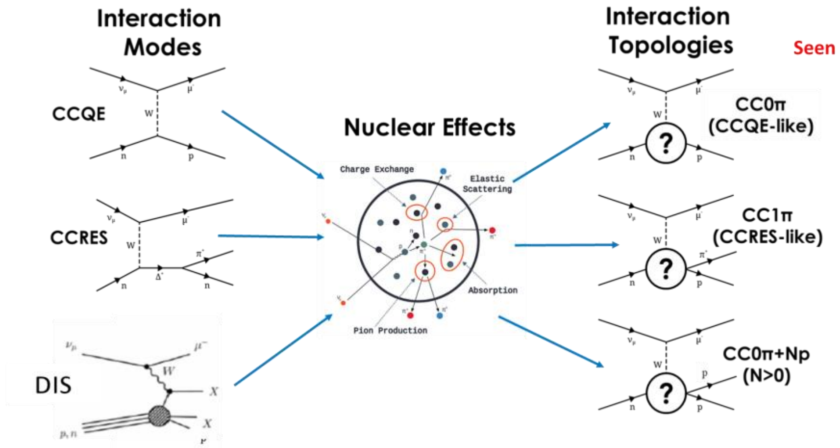
Relevant for neutrino oscillations



Seen by detector

Detector effects

- ***P*** depends on true E_ν but a detector provides E_ν^{reco}
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- Both require an excellent understanding of the detector response
- Different for every interaction process

Provided by near detector!

ND event rate:

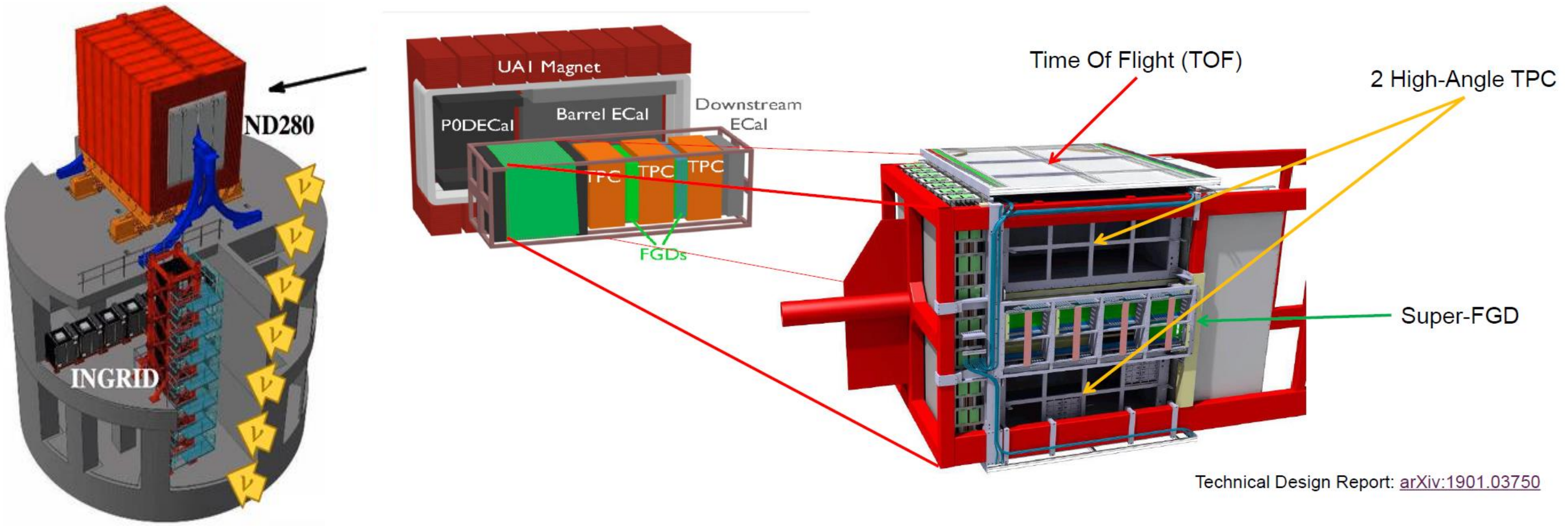
$$\frac{dN^{FD}_{\beta}}{\Delta E^{reco}_{\nu}} = N^{ND}_{target} \sum_i \int_{E_{min}}^{E_{max}} \Phi^{ND}(E_\nu)\sigma_i^{ND}(E_\nu) T_i^{ND}(E_\nu, E_\nu^{reco})\epsilon_i(E_\nu, E_\nu^{reco}) dE_\nu$$

FD event rate:

$$\frac{dN^{FD}_{\beta}}{\Delta E^{reco}_{\nu}} = N^{FD}_{target} \sum_i \int_{E_{min}}^{E_{max}} \Phi^{ND}(E_\nu) F_{\frac{FD}{ND}}(E_\nu)\sigma_i^{FD}(E_\nu) T_i^{FD}(E_\nu, E_\nu^{reco})\epsilon_i(E_\nu, E_\nu^{reco}) P_{\nu_\alpha \to \nu_\beta}(E_\nu) dE_\nu$$

ND280 and the T2K Near Detector Complex

- T2K has on-axis (INGRID) and off-axis (ND280 and more) detectors
- ND280 upgrade project started 2016 with aim to install 3 new subdetectors
- Official CERN experiment (NP07) with 130 persons from 30 institutes from 10 countries involved



Technical Design Report: arXiv:1901.03750

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SuperFGD

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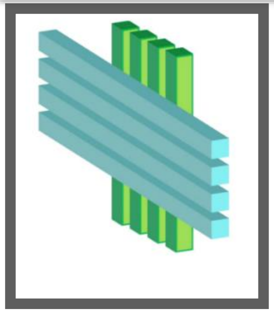
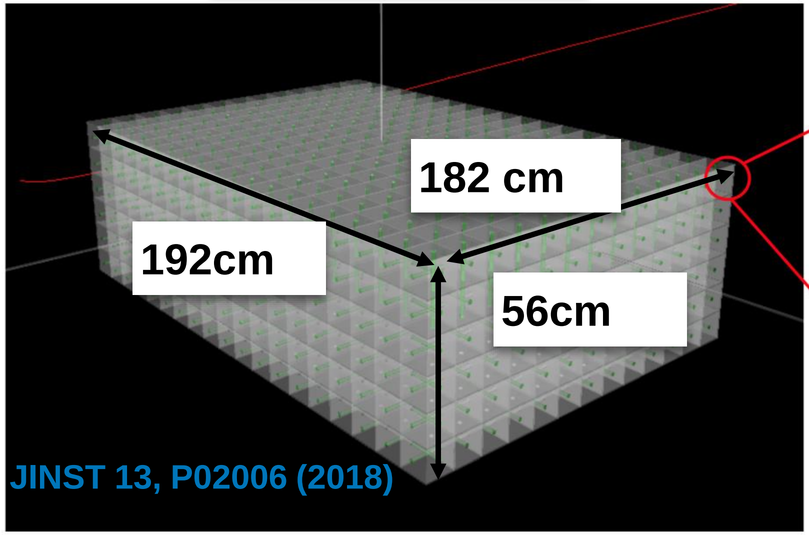
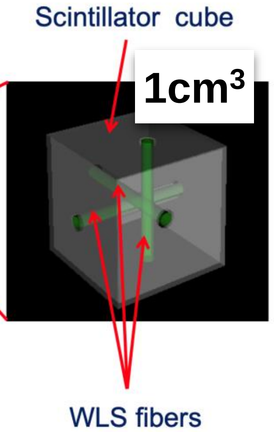
To improve the granularity the new active target will be a novel 3D tracking technology

FGD concept

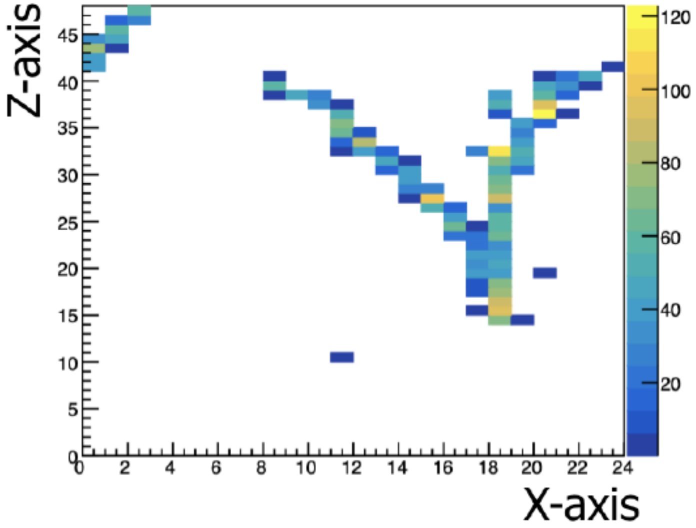


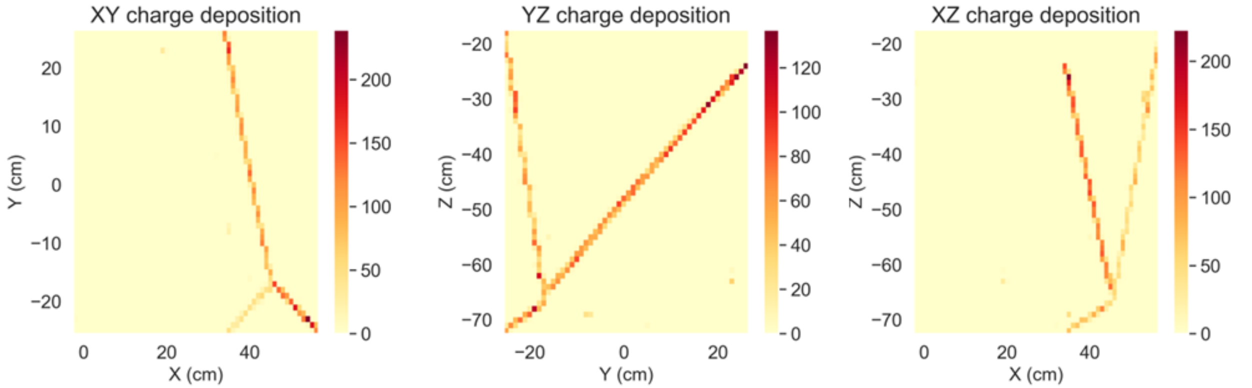
SuperFGD concept

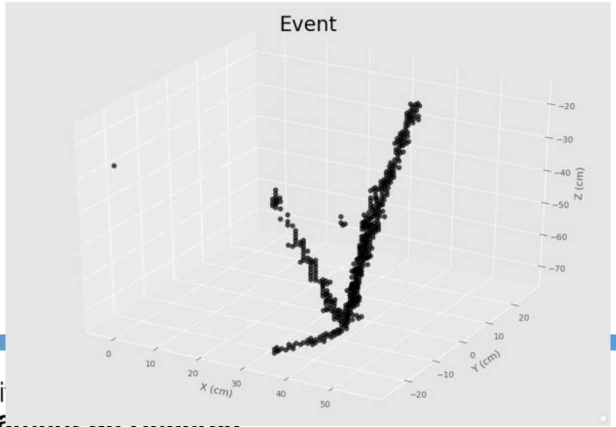




Testbeam event

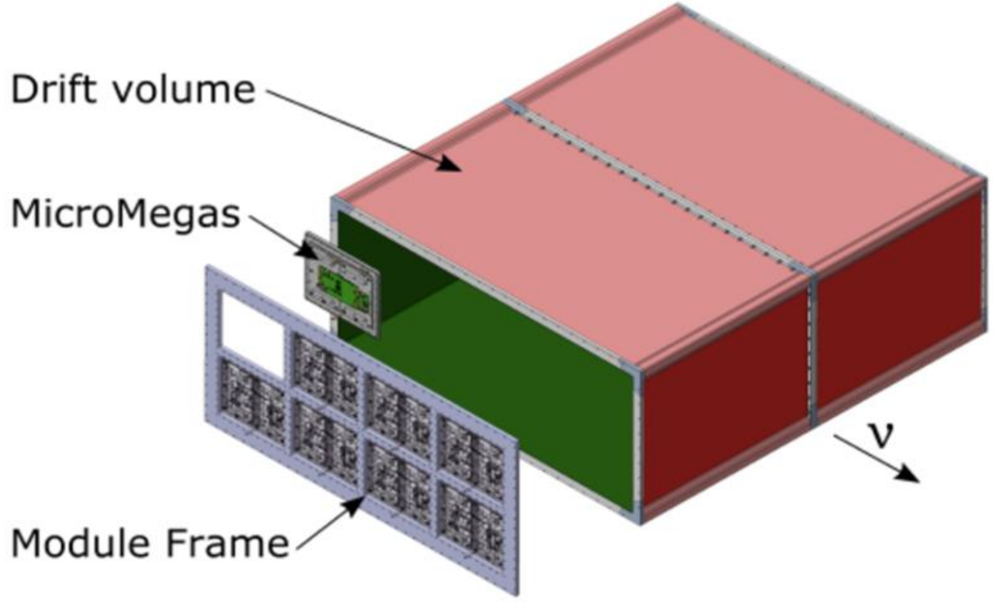


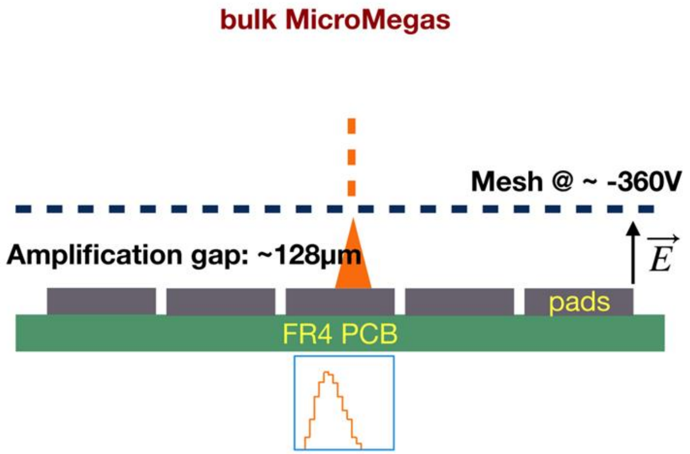


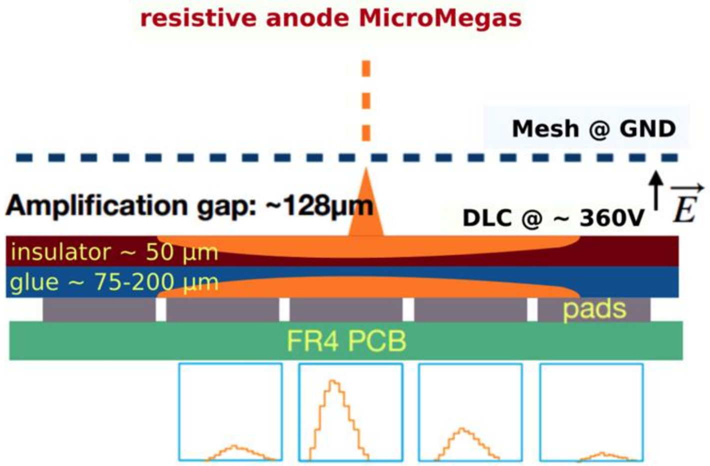


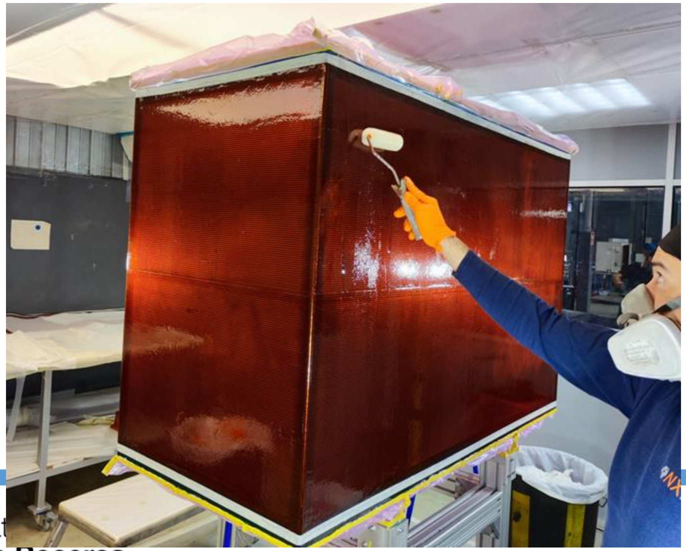
High-Angle TPC

- Dimensions: 1865x2000x820 mm3 (two halves of 1 m)
- Composite materials for field cage produced by NEXUS Projects SL (Martorell)
- Readout by 8 resistive Micromegas (ERAM) per side (novel technology)
- T2K gas (95 Ar, 3 CF4, 2 iC4H10)
- Providing tracking and particle identification









Physics Benefits

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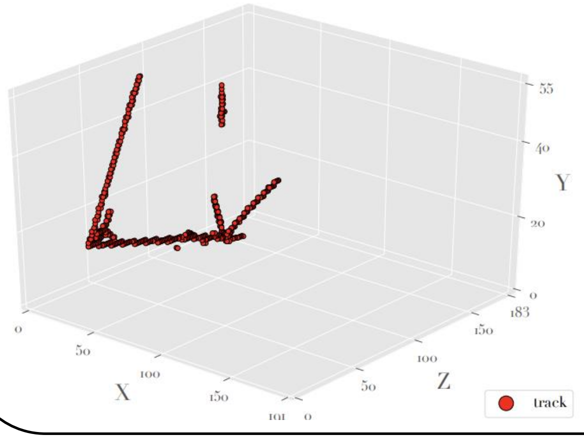
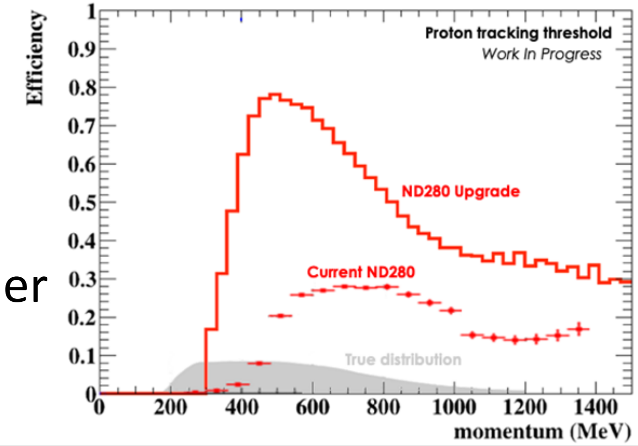


SuperFGD segmented homogeneously in 3D with fine pitch of 1 cm

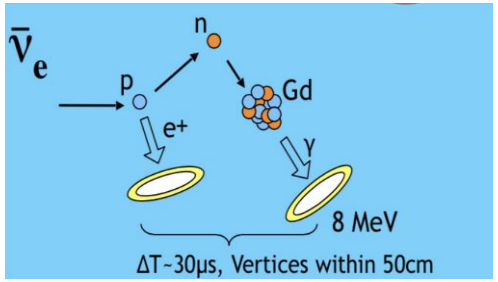
Lower detection threshold and higher efficiencies



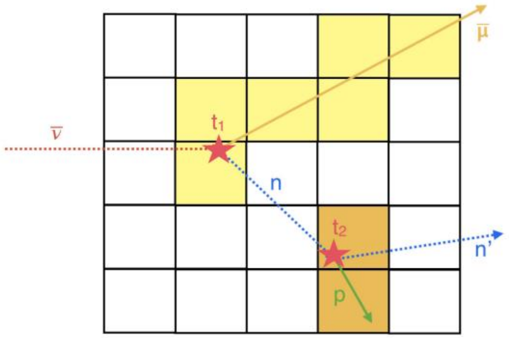
antineutrino CCQE:

$$\overline{\nu_\mu} + p \rightarrow \mu + n$$

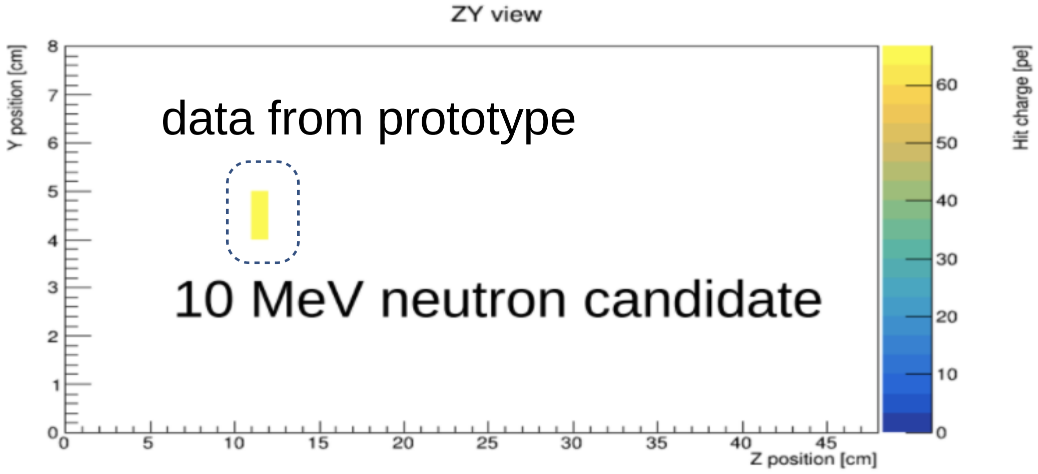
Visible in SK …



… and visible in SuperFGD including energy information via TOF (~50% efficiency)



Proven in neutron testbeam an LANL



Physics Benefits

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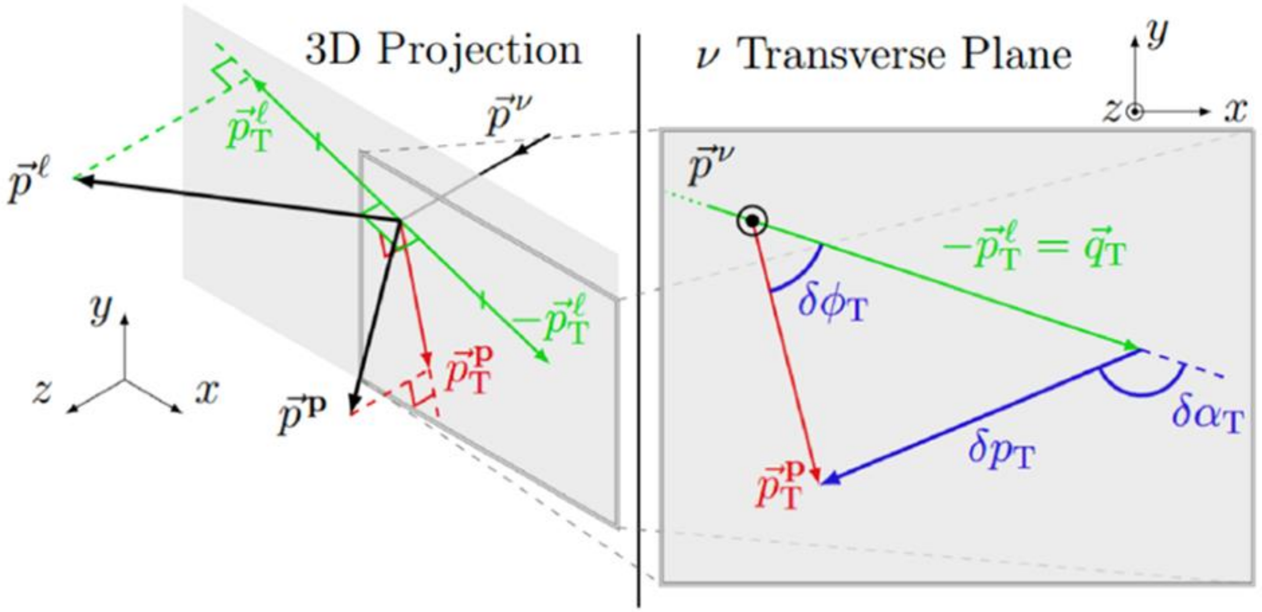
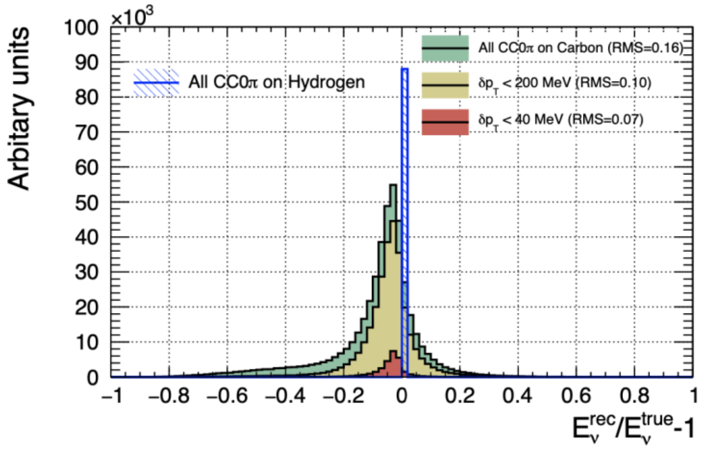
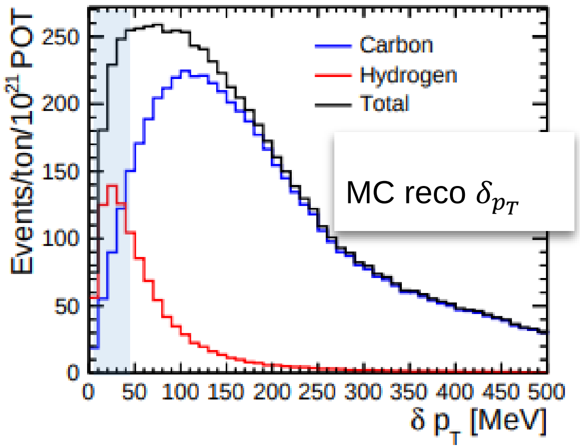
Nuclear effects result in transverse kinematic imbalance in the final state => upgraded ND280 will allow studying these effects







Target material is CH => selecting events with small δpt will allow to select interactions with small nuclear effects or H

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Physics Benefits

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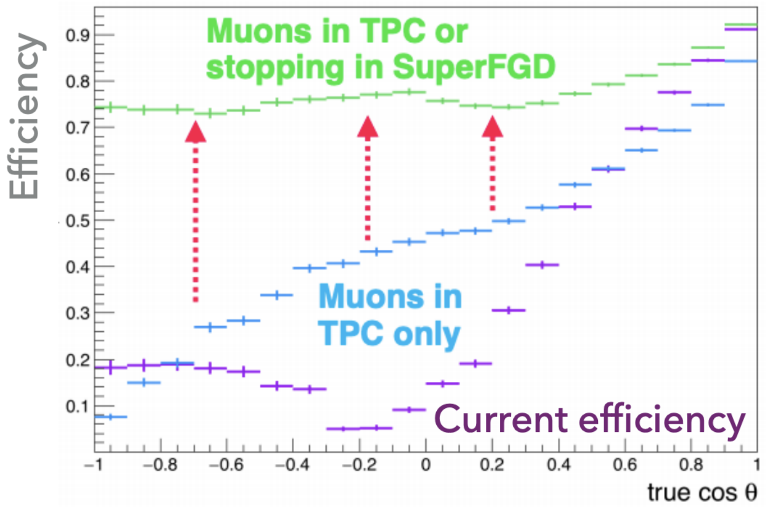
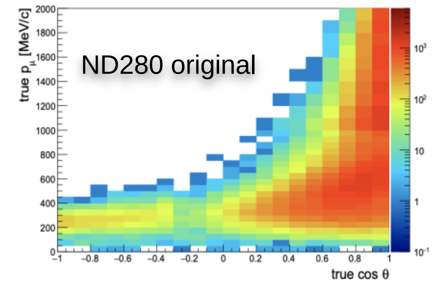
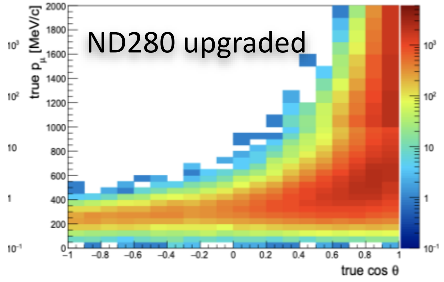
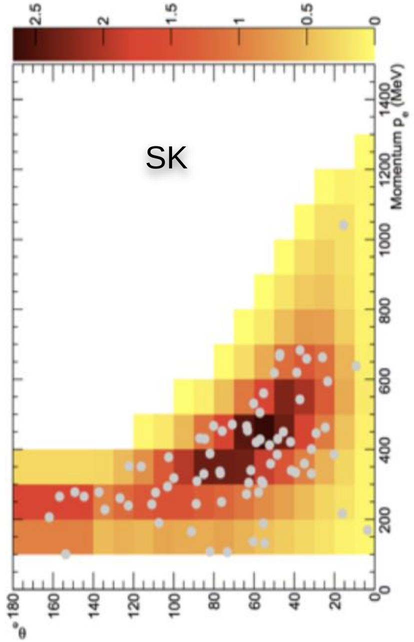
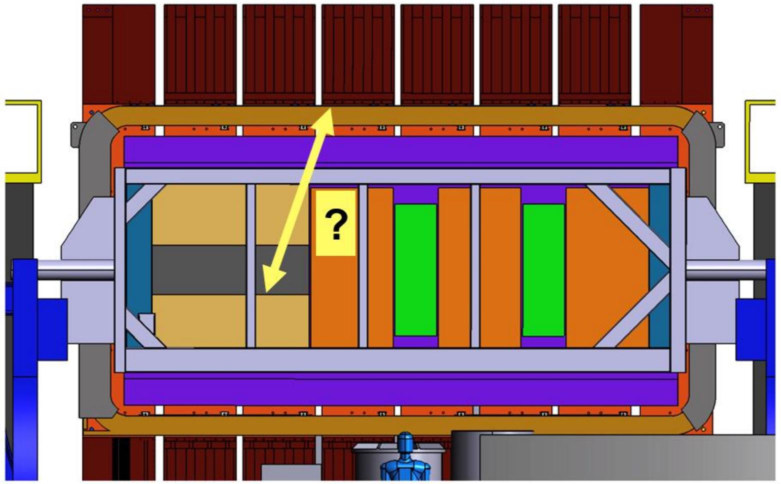
- Upgraded ND280 4π detector as SK => helps to reduce systematic uncertainties
- Neutrino beam is very wide and significant fraction of events happen in magnet => TOF will allow to reduce external background

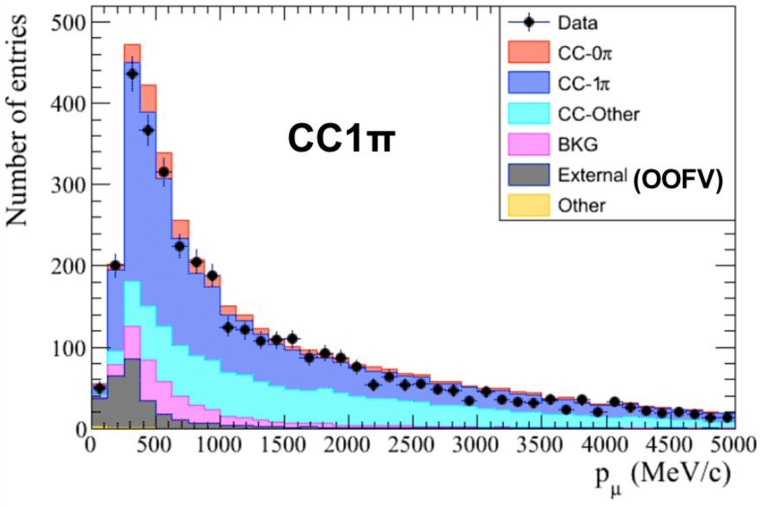












Expected Improvements

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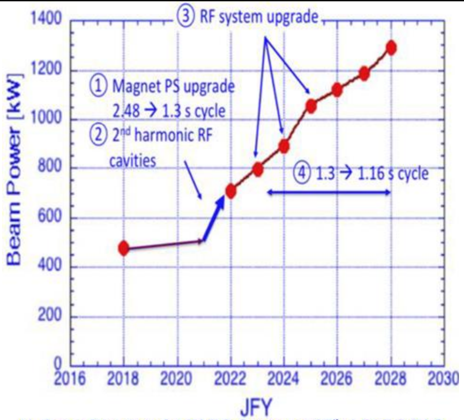


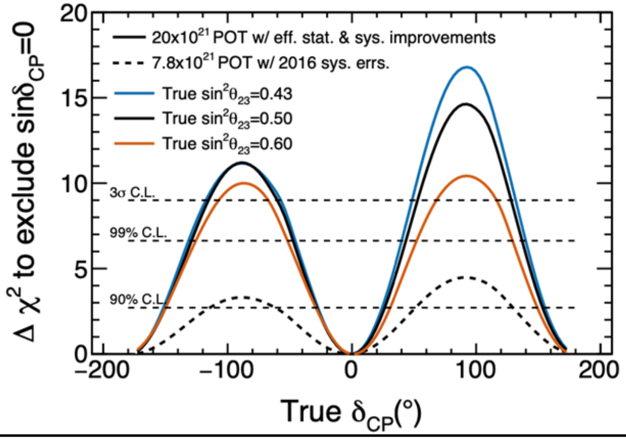
N. Saito, Director of J-PARC Center, at 27th J-PARC PAC

- Significant increase in statistics
- Beam power upgrade: 0.5 MW → 1.1 MW → 1.3 MW
- Doubling the target mass from 2 to 4 tonne

=> Statistics: 3E21 POT (2018) → 10E21 POT (2026)

- Significant reduction of systematic uncertainties expected

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4



- Key to improve CP violation result significantly => crucial for HyperK physics performance

Installation 2023/2024

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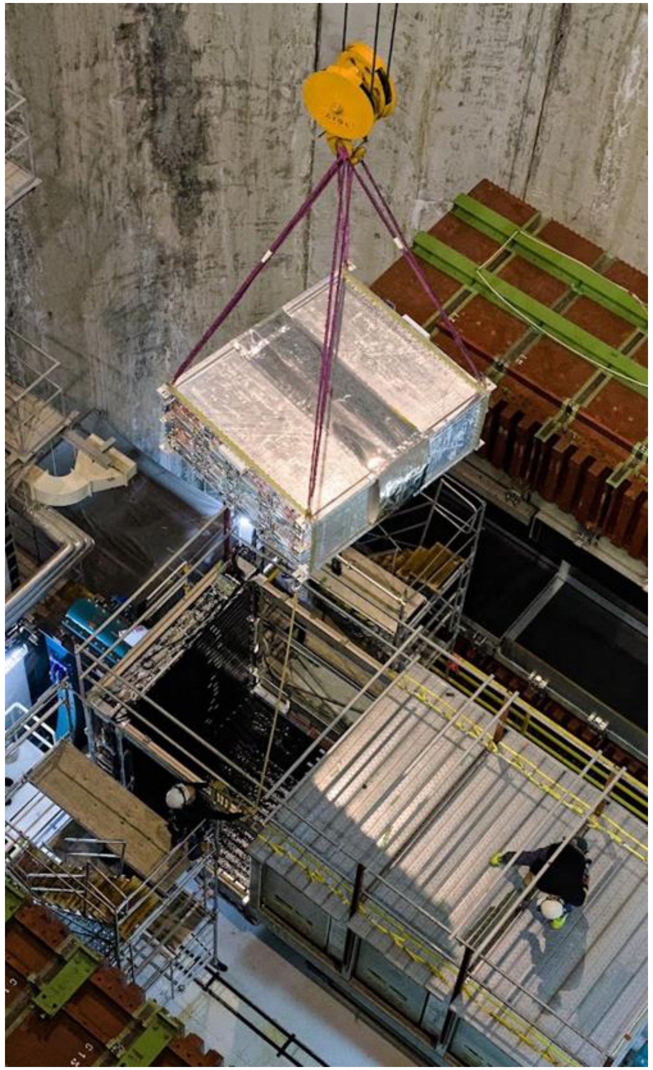

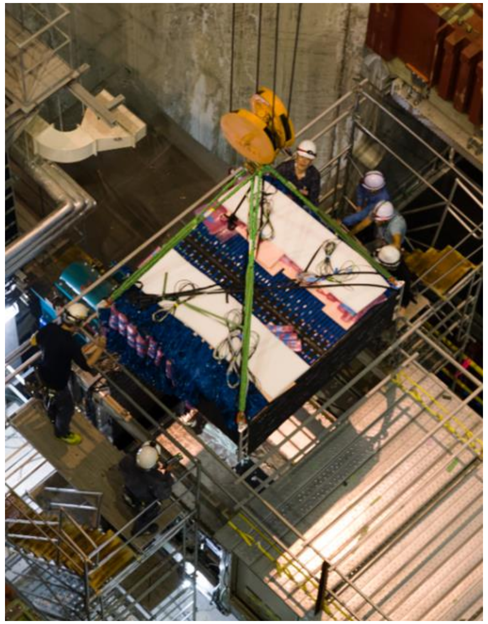

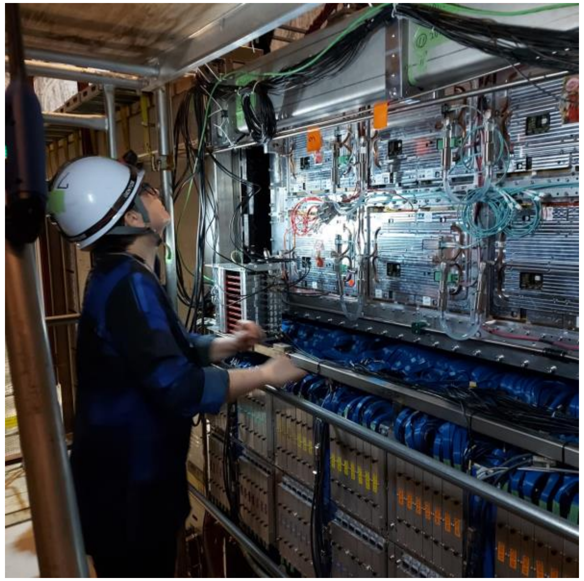

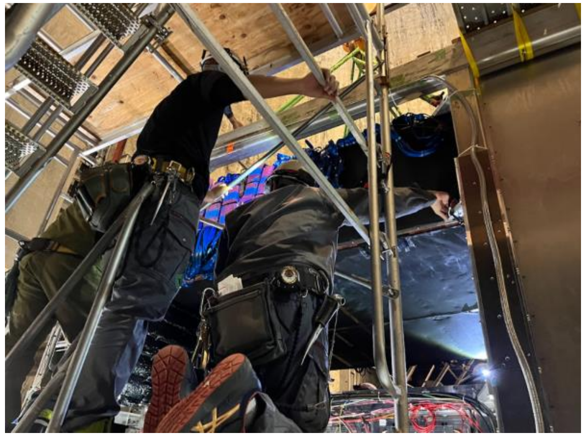

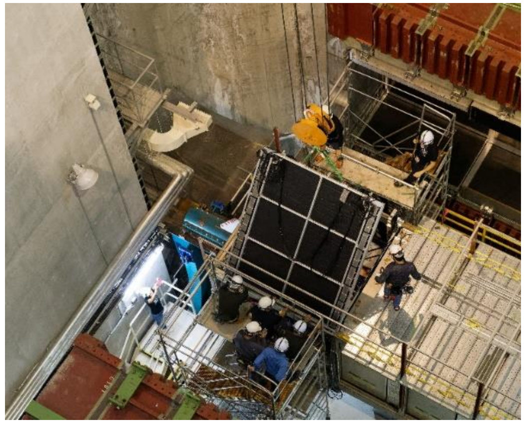

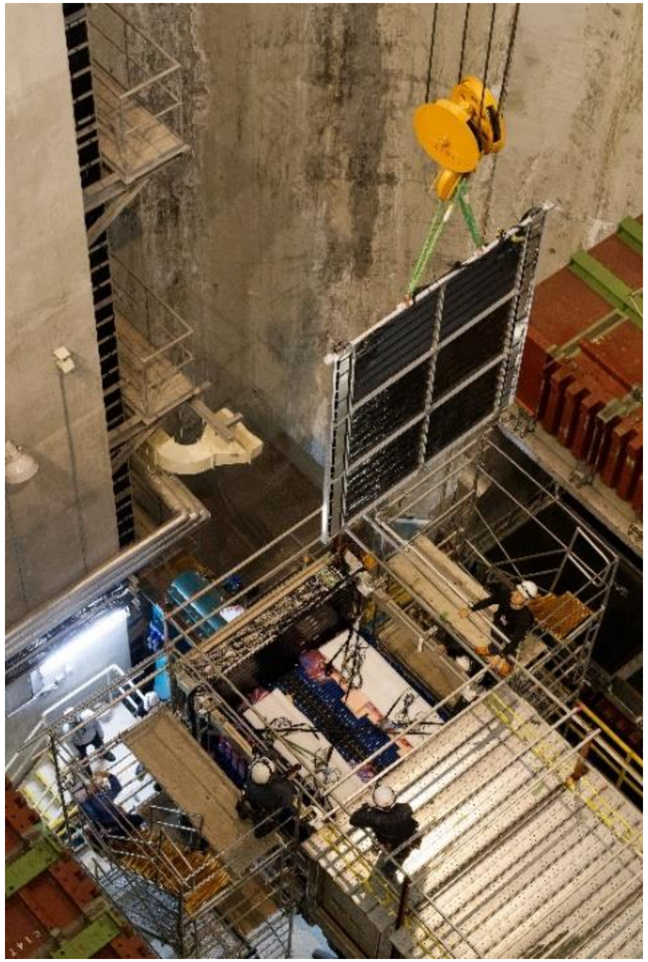

Current Status

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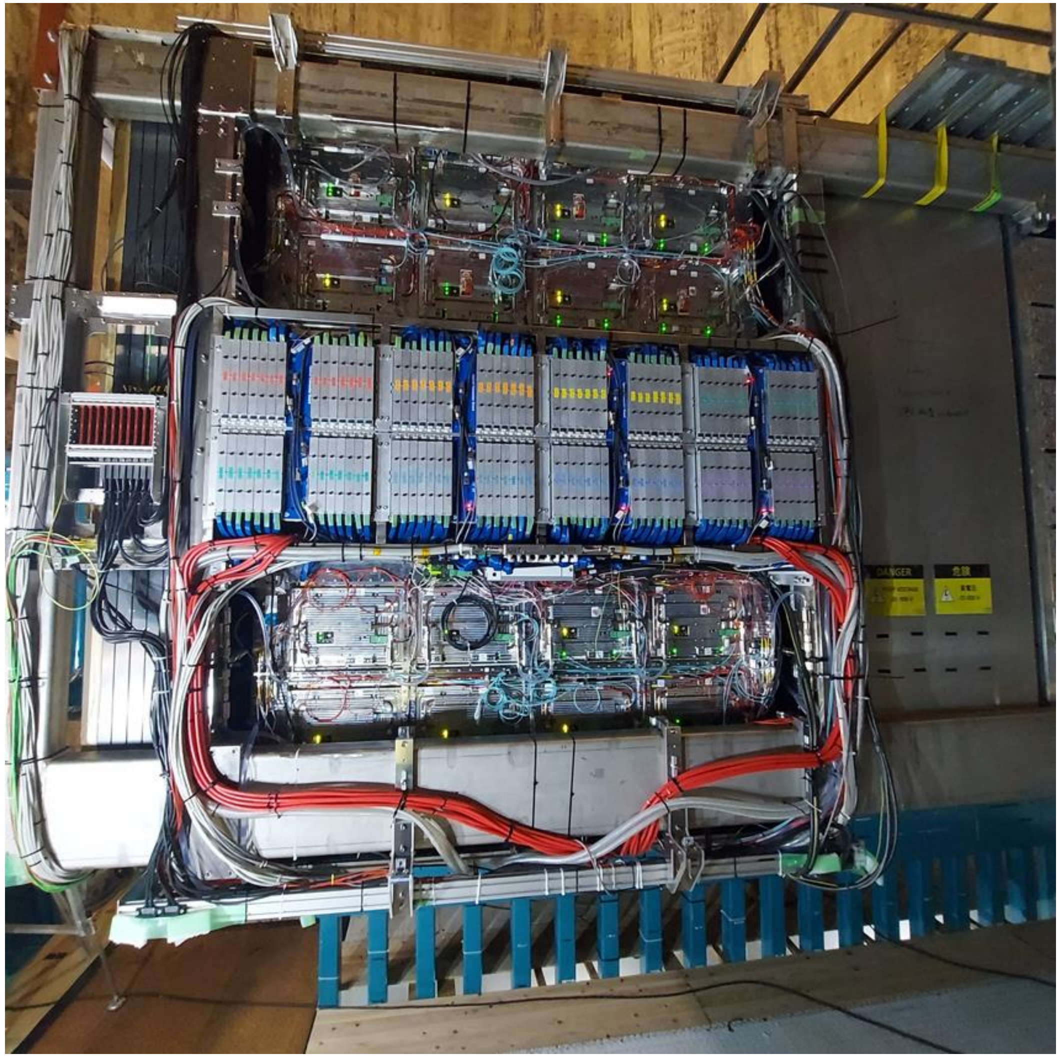
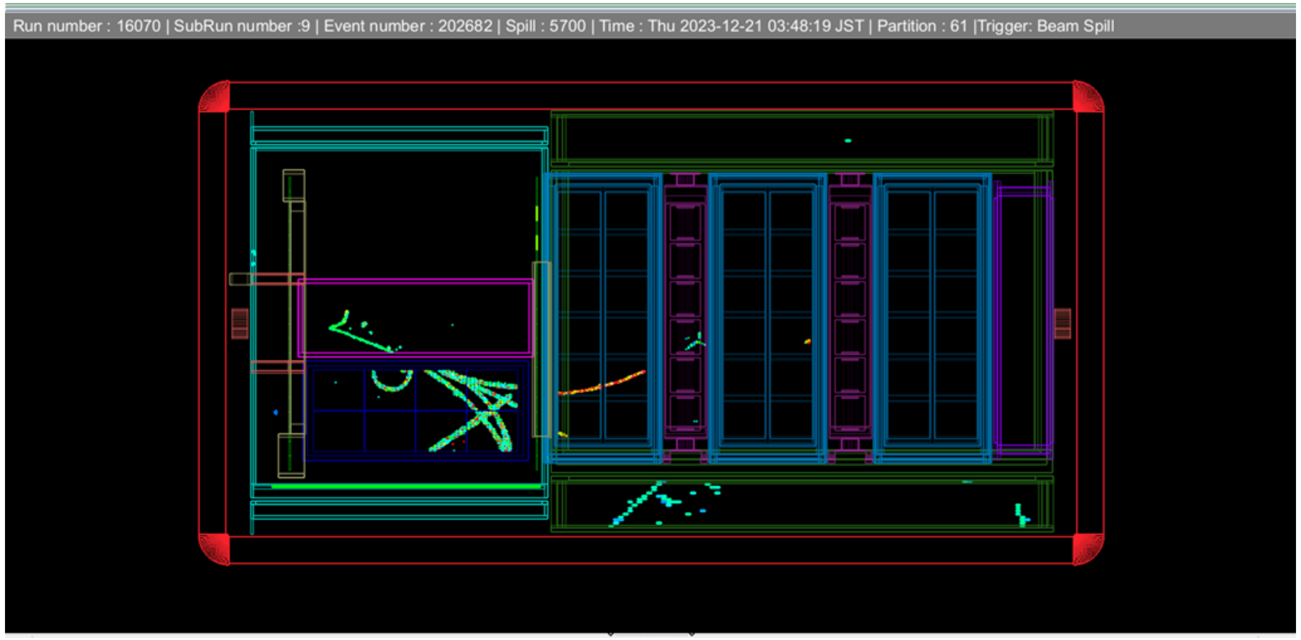


- Installation completed in May 2024
- First neutrino data taken (without top TPC)
- Currently first neutrino beam with fully upgraded ND280 detector



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Summary and Outlook

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- ND280 Upgrade installation have been completed in May 2024
- First neutrino beam being recorded currently with full upgraded ND280
- Data taking as T2K until start of Hyper-Kamiokande (2027)
- Upgraded ND280 will be crucial for Hyper-Kamiokande performance
- ND280 for Hyper-Kamiokande part of MINECO HK MOU
- IFAE with significant contributions to ND280 Upgrade and T2K:
  - Hardware:
    - Mainly to HA-TPCs (cathode HV system, slow control, design)
    - Smaller contributions to SuperFGD and TOF (electronics crates, testbeam data analysis)
  - Management:
    - Co-project leader and technical coordinator
    - T2K Executive Committee
    - HK WG leader: “ND280 Day-1” (preparation of ND280 for HK era)

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