T2K near detectors and upgrade

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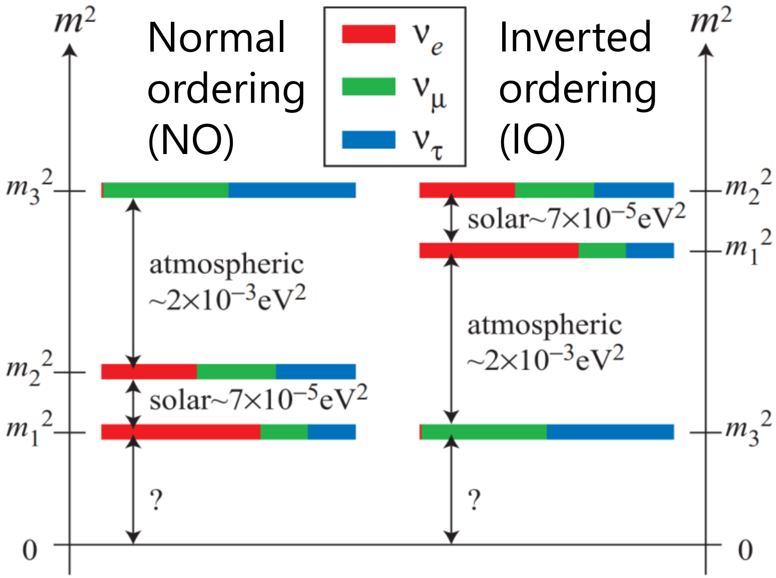
Outline

- Introduction of T2K
- T2K near detectors
  - INGRID
  - ND280
  - WAGASCI-BabyMIND
- ND280 upgrade
  - Super-FGD
  - High-angle TPC
- ND280 upgrade++

Questions in neutrino oscillations

- There are still many questions about neutrino.
- Precise measurement of neutrino oscillations will give us answers.
  - CP violation in lepton.
    Is sin$\delta_{CP} \neq 0$?
  - Atmospheric mixing.
    Is $\theta_{23} = 45°$?
  - Mass ordering.
    Is ν_3 the heaviest or lightest?

Neutrino mass ordering



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

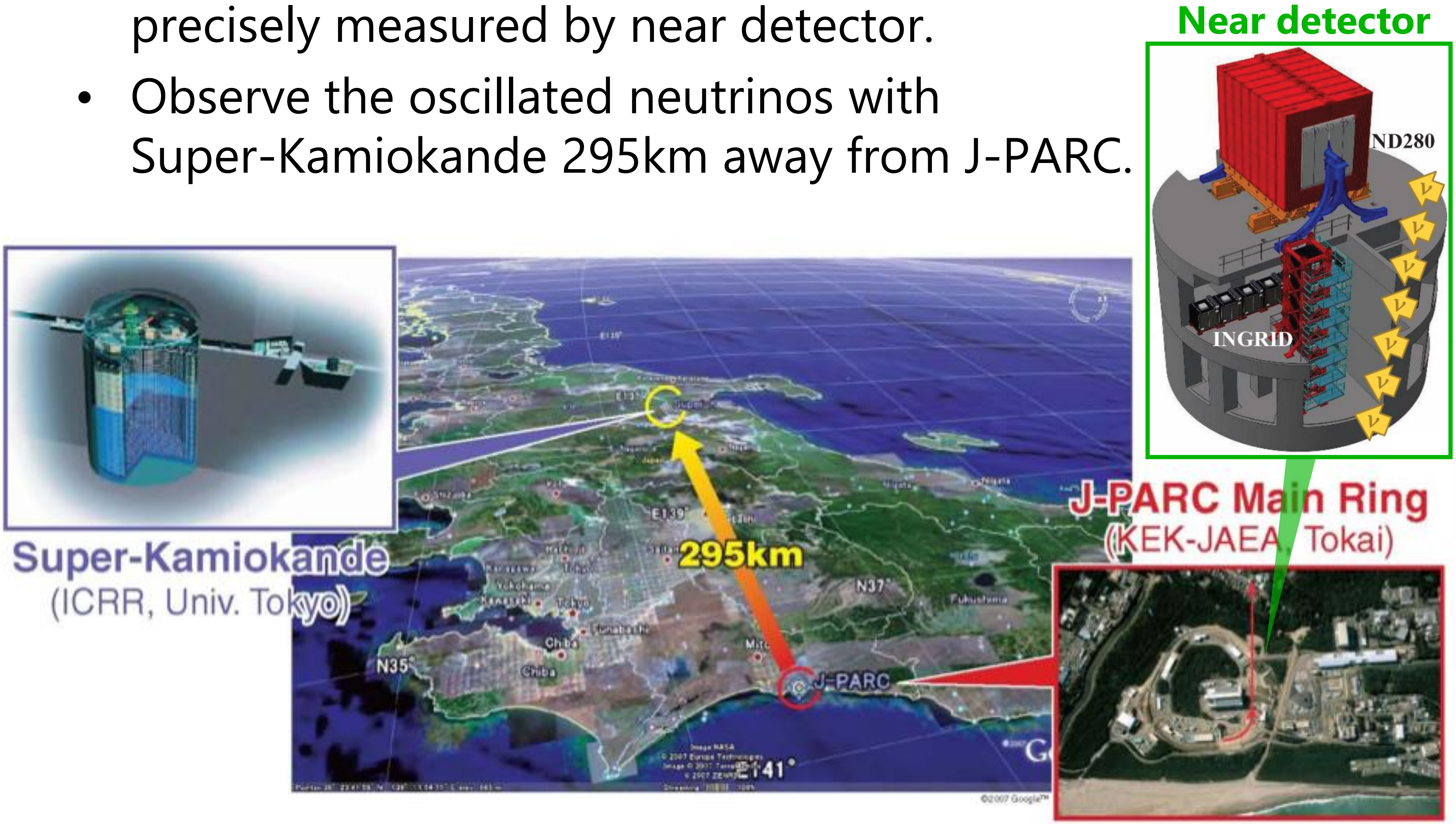
Flavor eigenstate

PMNS matrix

Mass eigenstate

T2K experiment

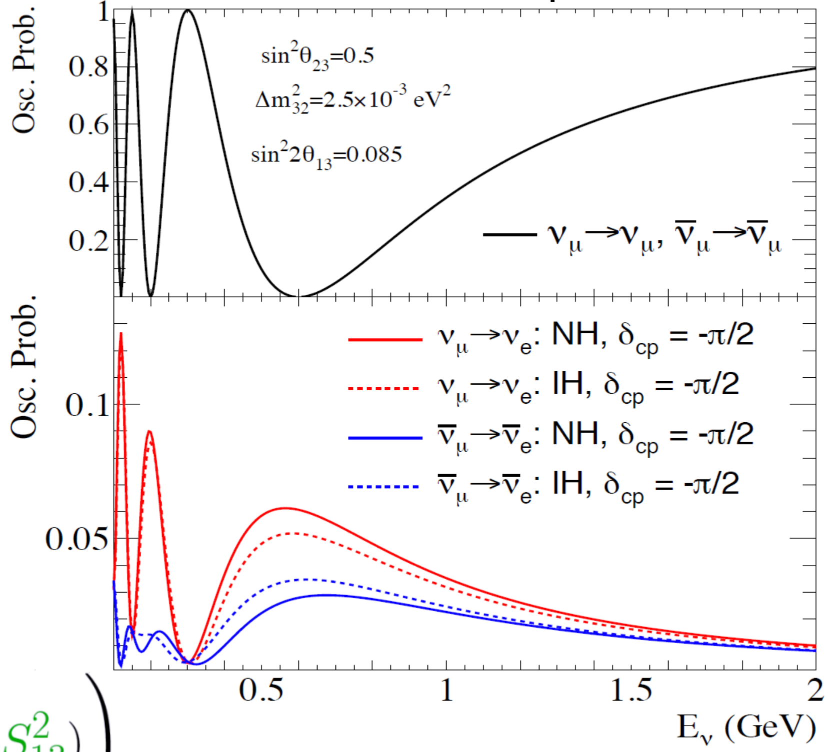
- Long-baseline neutrino oscillation experiment.
- ν_μ or $\bar{\nu}_\mu$ beam generated by J-PARC accelerator and precisely measured by near detector.
- Observe the oscillated neutrinos with Super-Kamiokande 295km away from J-PARC.



Neutrino oscillations in T2K

- Muon (anti)neutrino disappearance is sensitive to $\sin^2 2\theta_{23}$ and Δm^2_{32}.
- Electron (anti)neutrino appearance is sensitive to δ_{CP} and mass ordering through matter effect as well as $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$ and Δm^2_{32}.

Neutrino oscillation probabilities



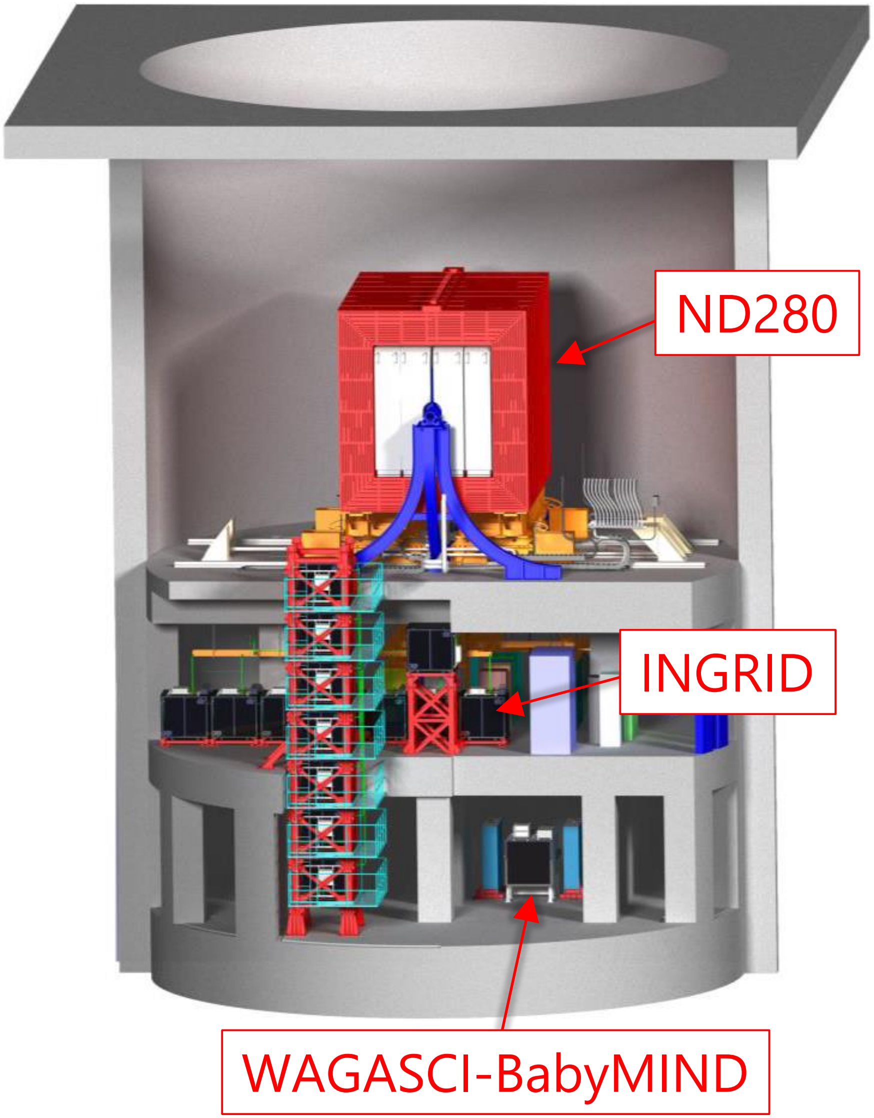
$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m^2_{31}}(1 - 2S_{13}^2)\right)$$
$$+ 8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$- 8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$
$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

$$C_{ij} = \cos\theta_{ij},$$
$$S_{ij} = \sin\theta_{ij},$$
$$\Phi_{ij} = \Delta m^2_{ij} L/4E$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\frac{\Delta m^2_{31} L}{4E}$$

T2K near detectors

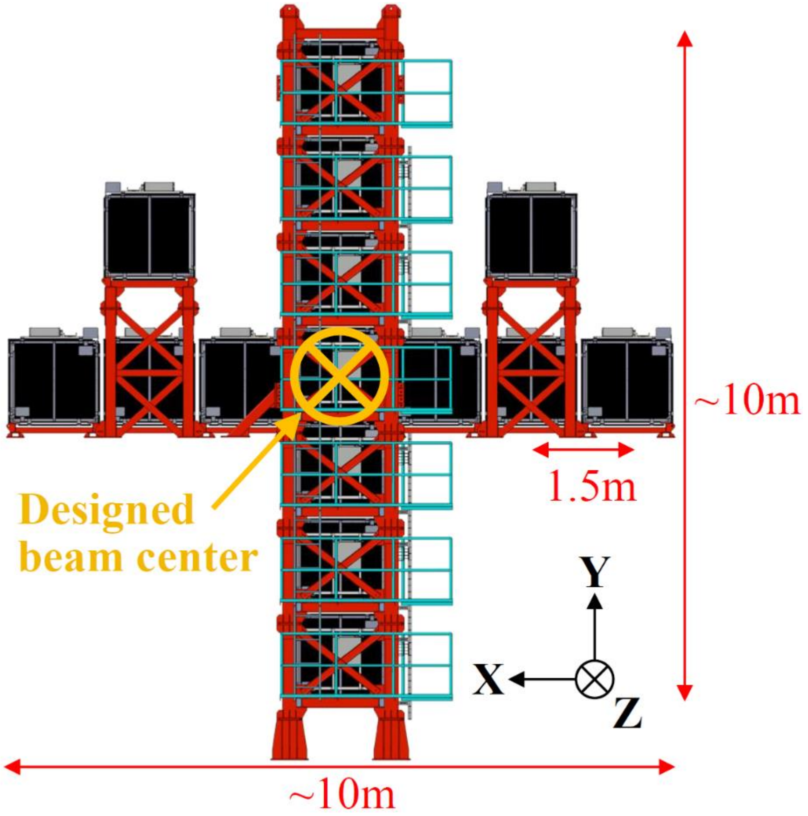
- INGRID (on-axis)
  - Measure neutrino event rate and beam direction.
- ND280 (2.5 deg. off-axis)
  - Measure neutrino beam to Super-K direction before oscillation.
  - Measure neutrino interactions.
- WAGASCI (1.5 deg. off-axis)
  - Measure neutrino interaction at different off-axis angle. (different flux)



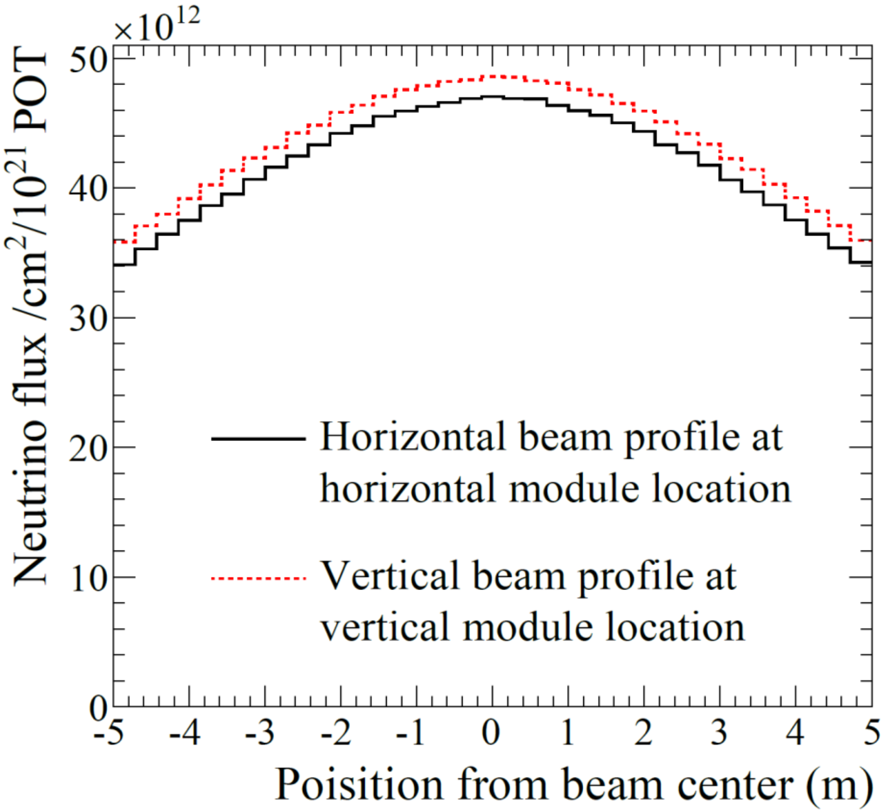
INGRID detector

- 14 identical modules arranged in a cross shape covering ±5m area from beam center.
- Measure beam direction with < 1 mrad precision and event rate stability with < 1% precision.

Overview of INGRID



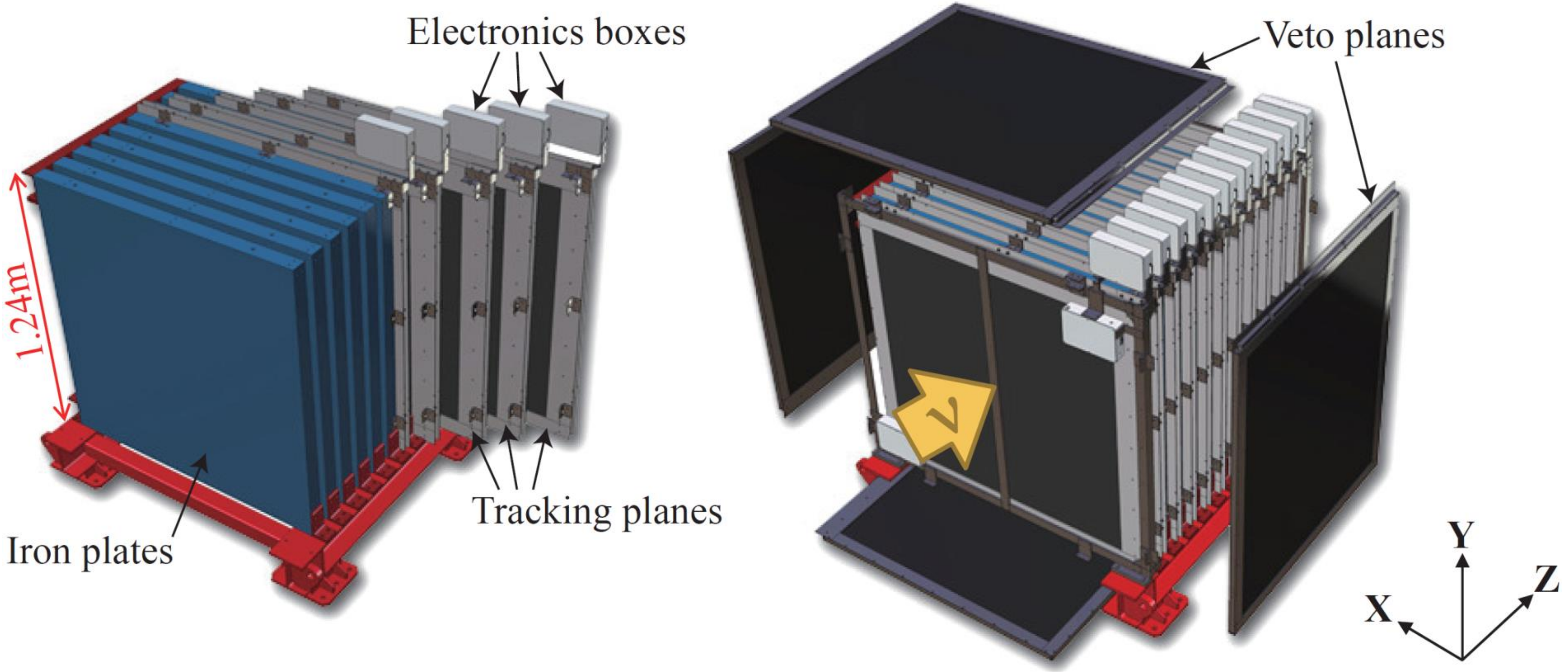
Expected neutrino beam profile at INGRID



Module structure

- Each module has a sandwich structure of 9 iron target plates and 11 scintillator tracking planes.
- Surrounded by veto planes to reject charged particles from outside.

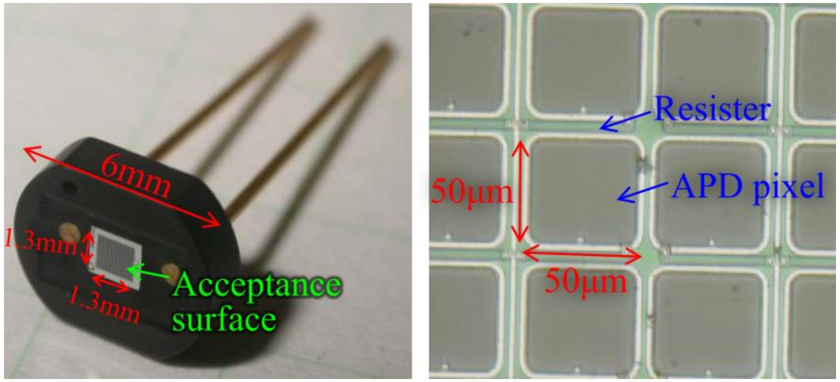
Exploded view of an INGRID module

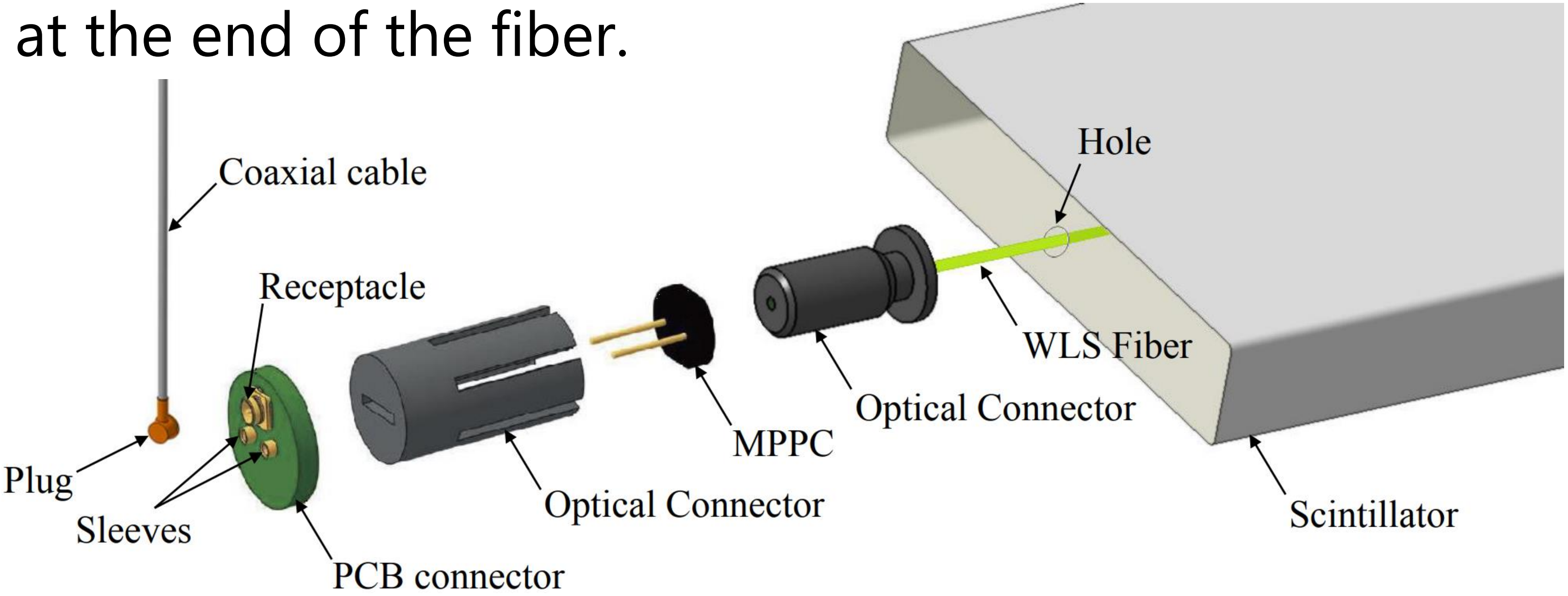


Signal readout

- Scintillation light is collected by wavelength shifting fiber and converted from blue to green.
- Light travels through the fiber by total reflection and is detected by MPPC (semiconductor photosensor) at the end of the fiber.

MPPC and its acceptance surface

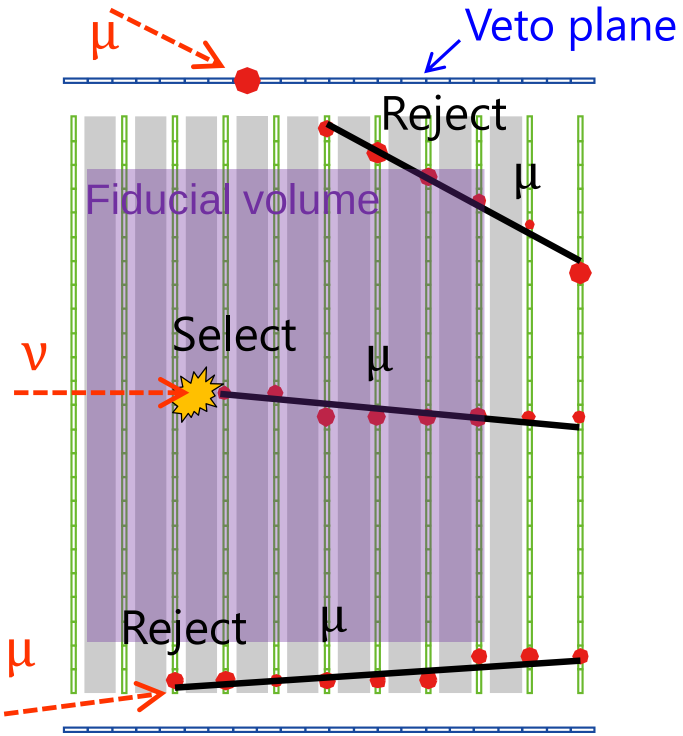




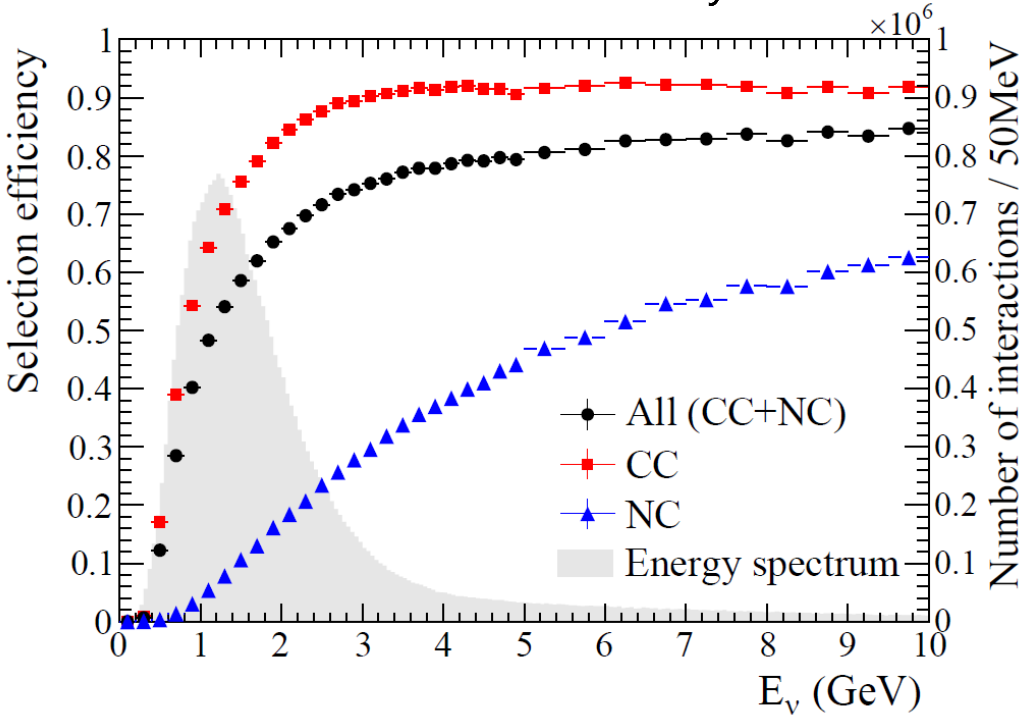
Event reconstruction and selection

- Track and vertex reconstruction. → Select muon tracks.
- Vertex in fiducial volume. } Reject muons from outside.
- Veto plane cut. } Reject muons from outside.
- 99.5% purity and 58.6% efficiency for neutrino events in INGRID.

Event selection



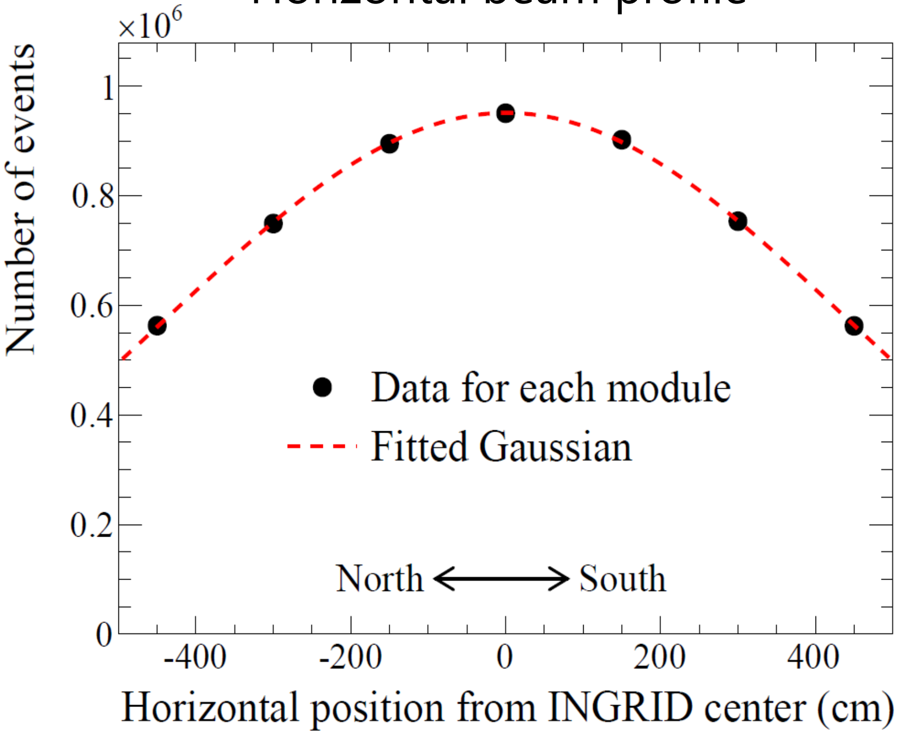
Selection efficiency



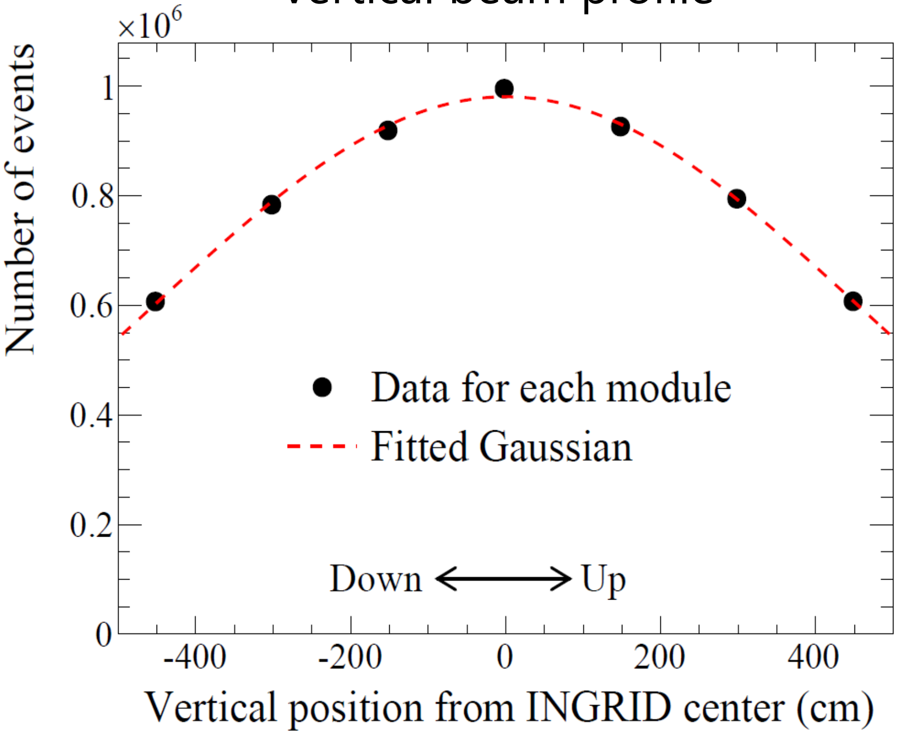
Reconstruction of neutrino beam profile

- Neutrino beam profile is reconstructed from the number of detected neutrino events in each module.
- Beam center is determined from Gaussian fitting.

Horizontal beam profile

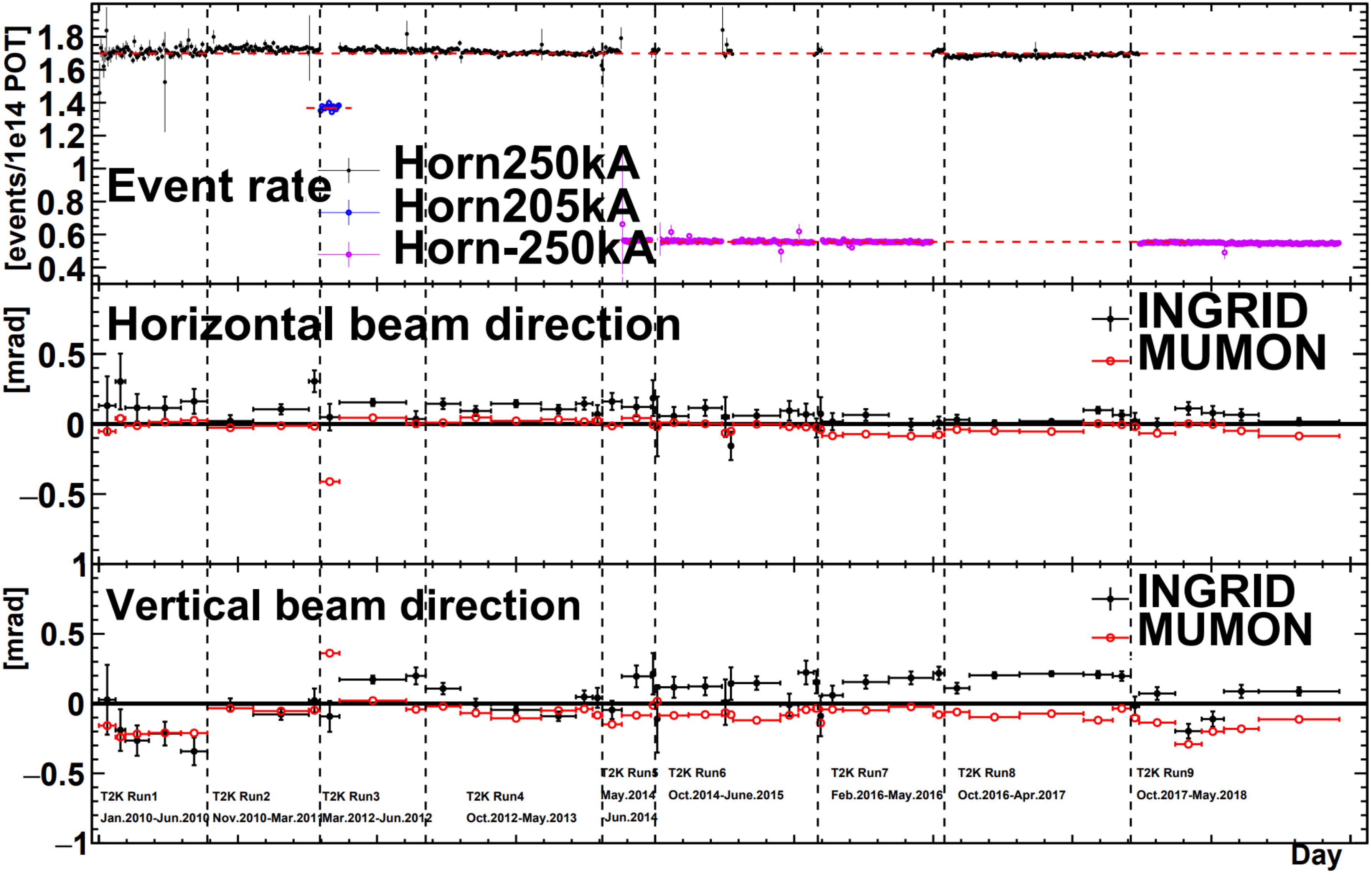


Vertical beam profile



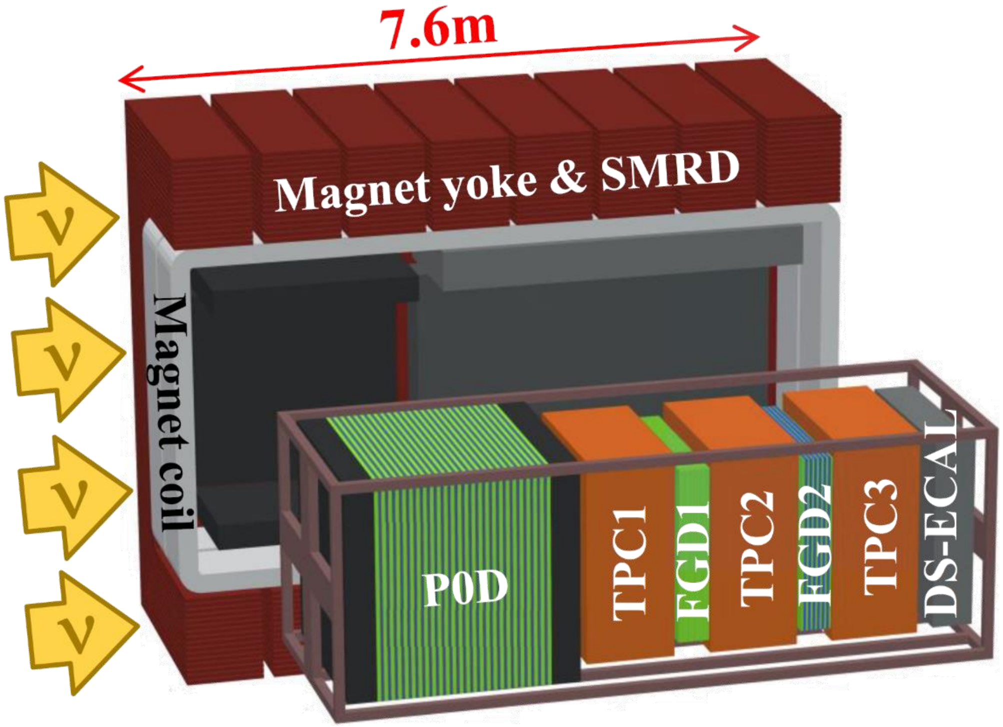
Beam stability measurement

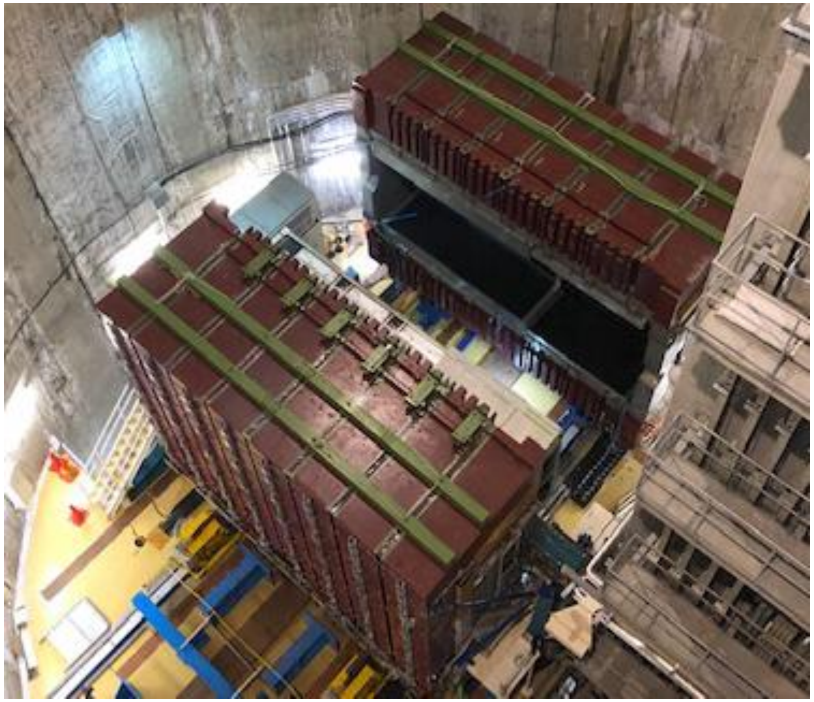
Result of T2K Run1-9 measurement



ND280

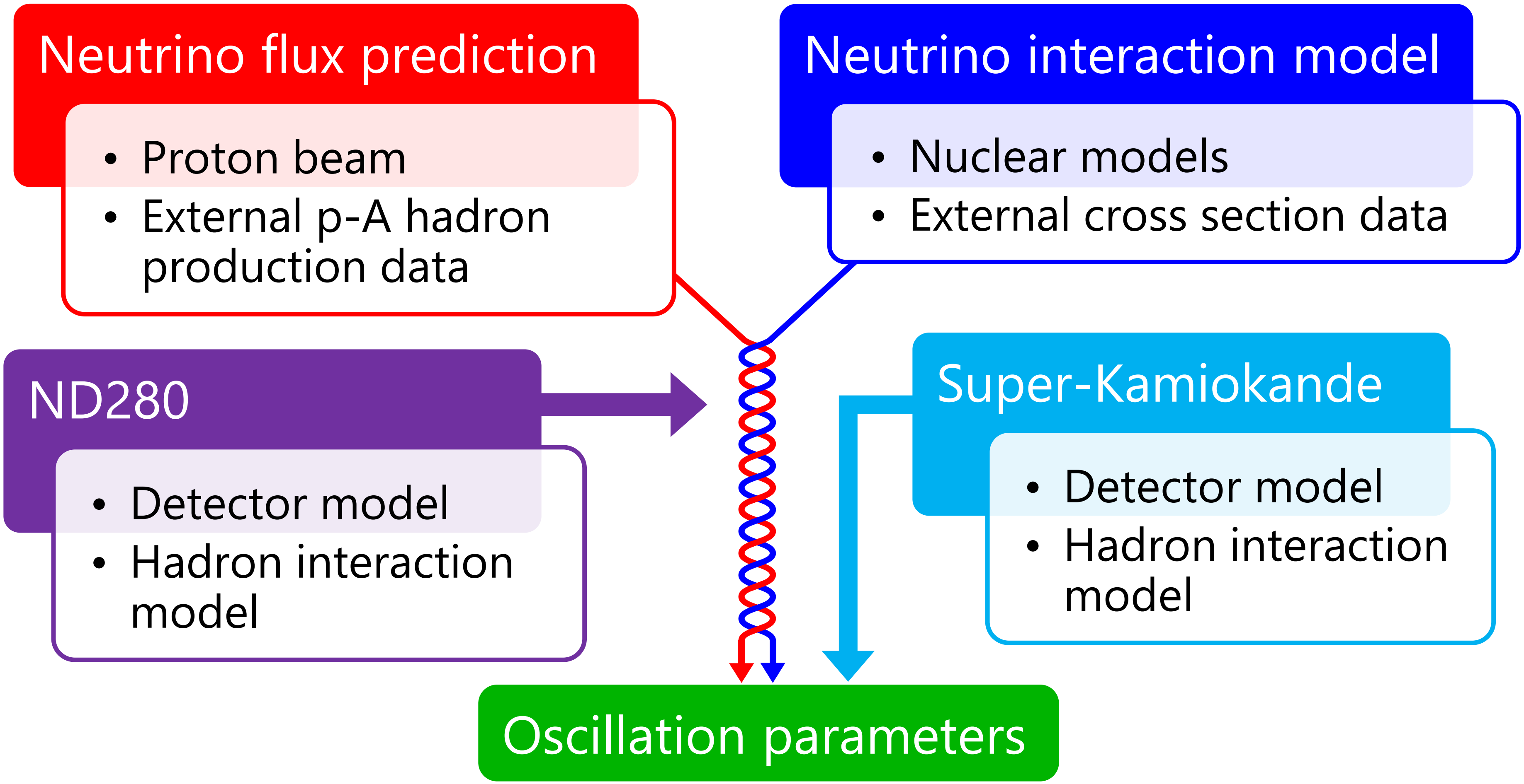
- Dipole magnet provide 0.2T magnetic field to bend charged particles to measure charge and momentum.
- Several sub-detectors are placed in the magnet to measure the neutrino flux and cross section precisely.





Role of ND280 in T2K oscillation analysis

- ND280 fit plays a very important role in T2K oscillation analysis to reduce the systematic error.



Neutrino flux prediction

- Proton beam
- External p-A hadron production data

Neutrino interaction model

- Nuclear models
- External cross section data

ND280

- Detector model
- Hadron interaction model

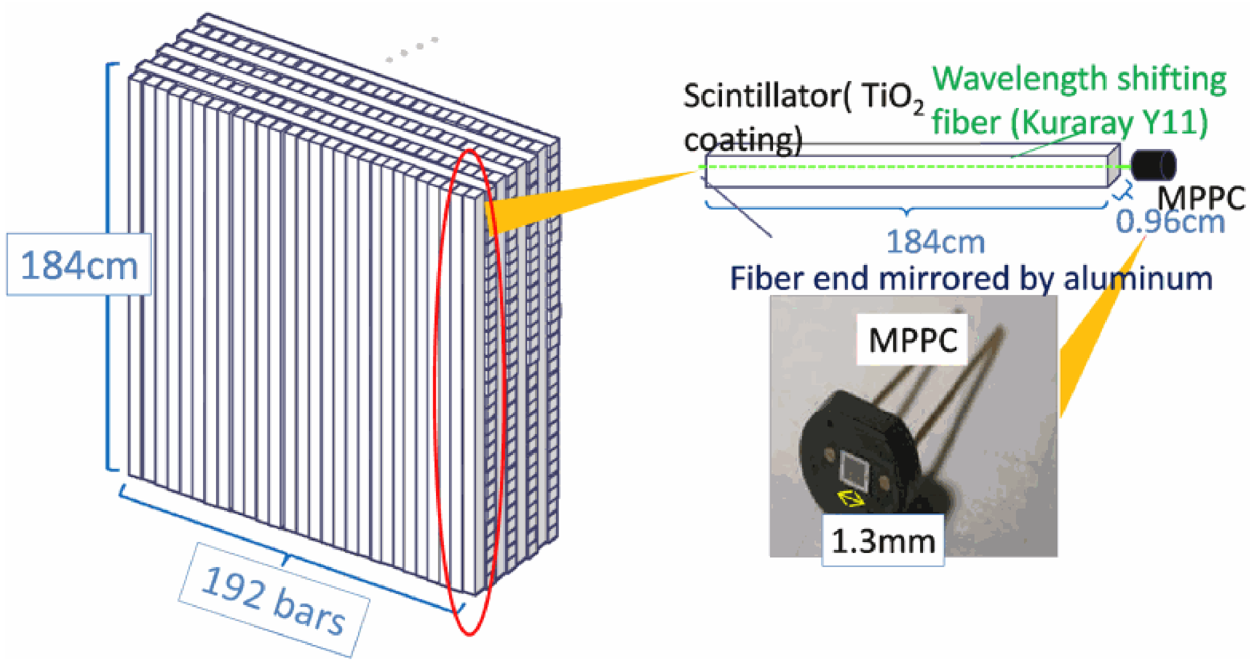
Super-Kamiokande

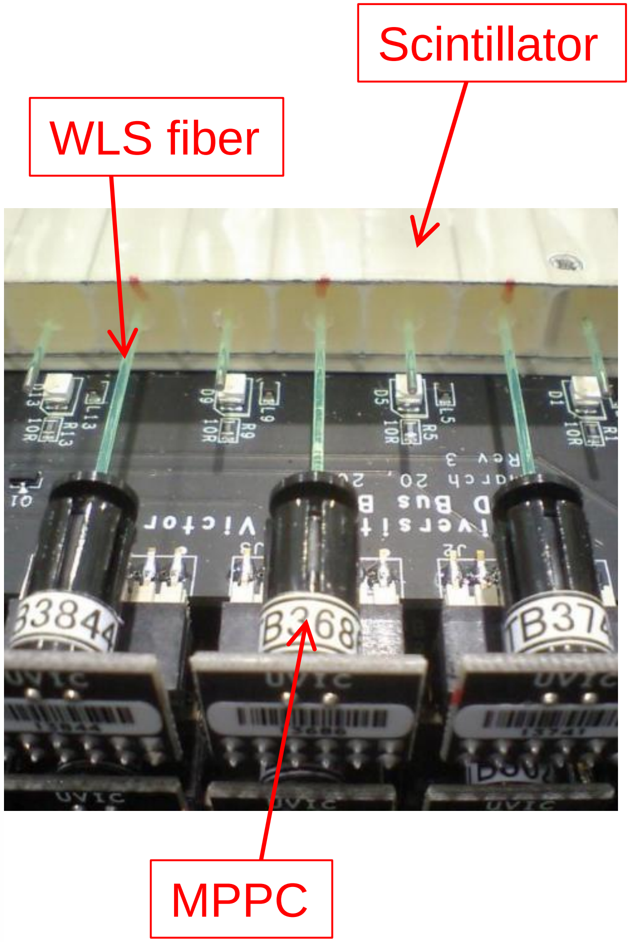
- Detector model
- Hadron interaction model

Oscillation parameters

Fine Grained Detector (FGD)

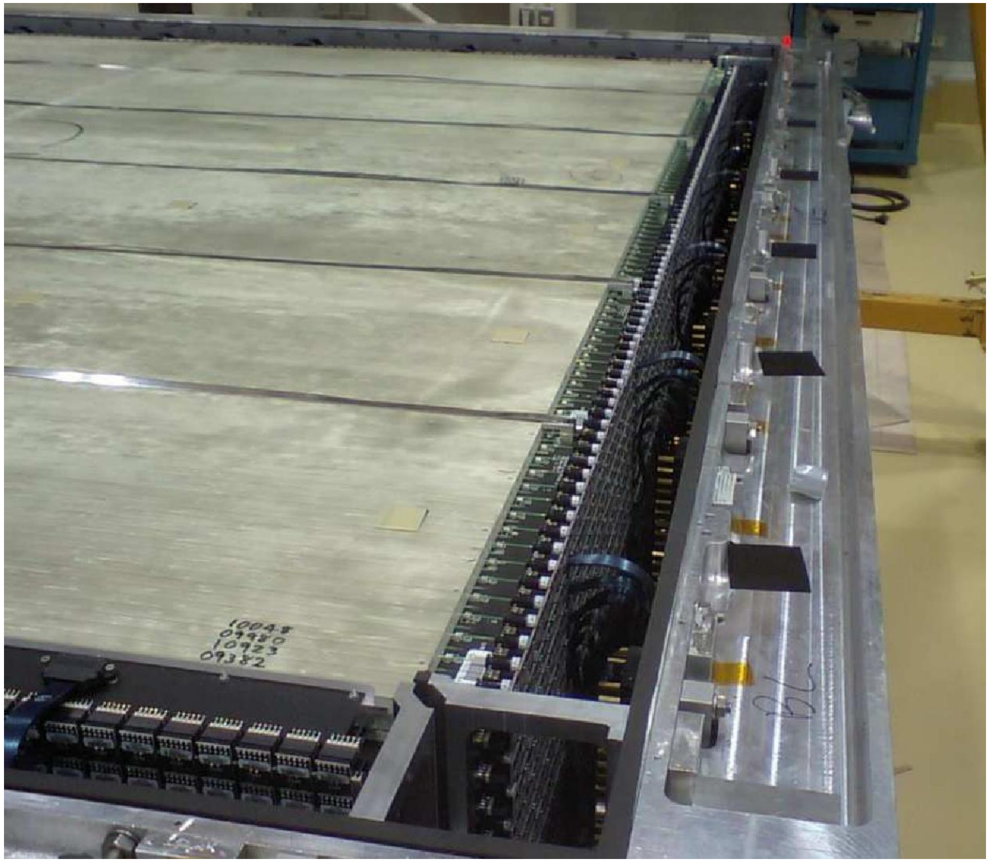
- Tracking detector which consists of 8448 scintillator bars (1cm×1cm×2m).
- Fiber-MPPC readout as with INGRID.
- Used as neutrino interaction target and reconstruct tracks from neutrino interactions.





Fully active FGD (FGD1)

- Two FGD modules.
- FGD1 is a fully-active tracking detector which consists of only scintillators.



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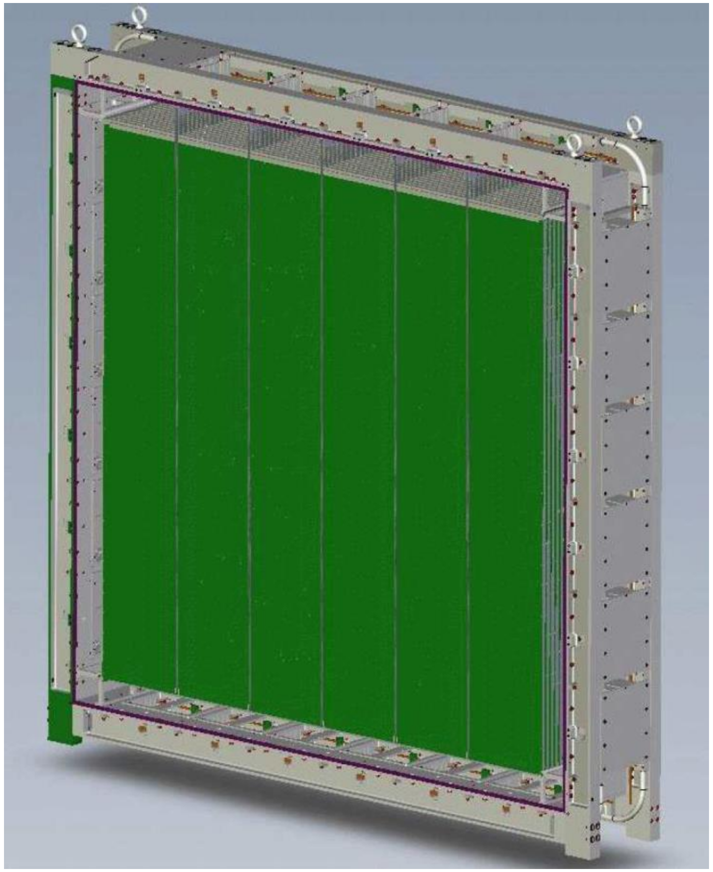
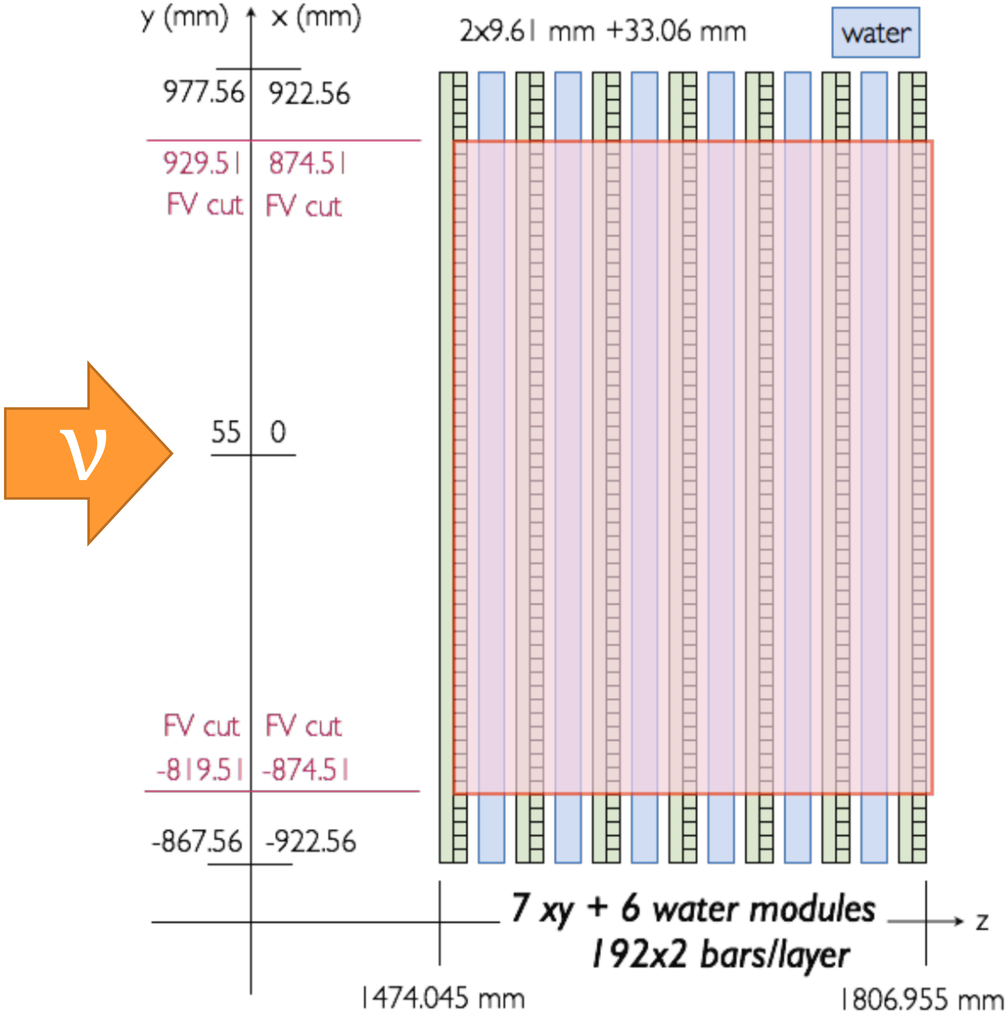


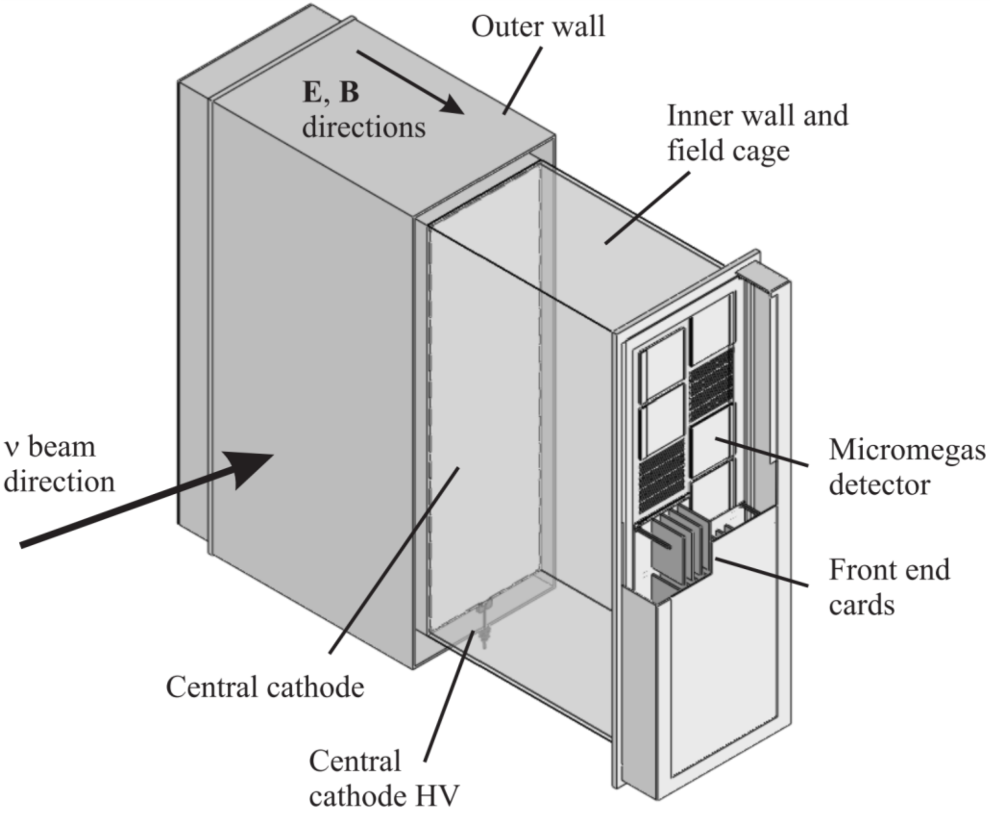
FGD with water (FGD2)

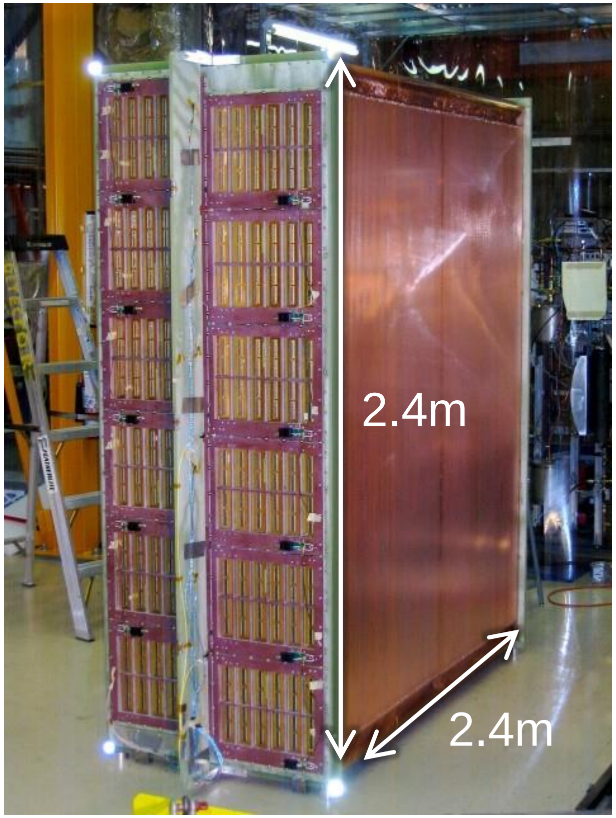
- FGD2 is sandwich structure of scintillator layers and water tank.
- Measure neutrino interaction on water which is neutrino interaction target in Super-K.



Time Projection Chamber (TPC)

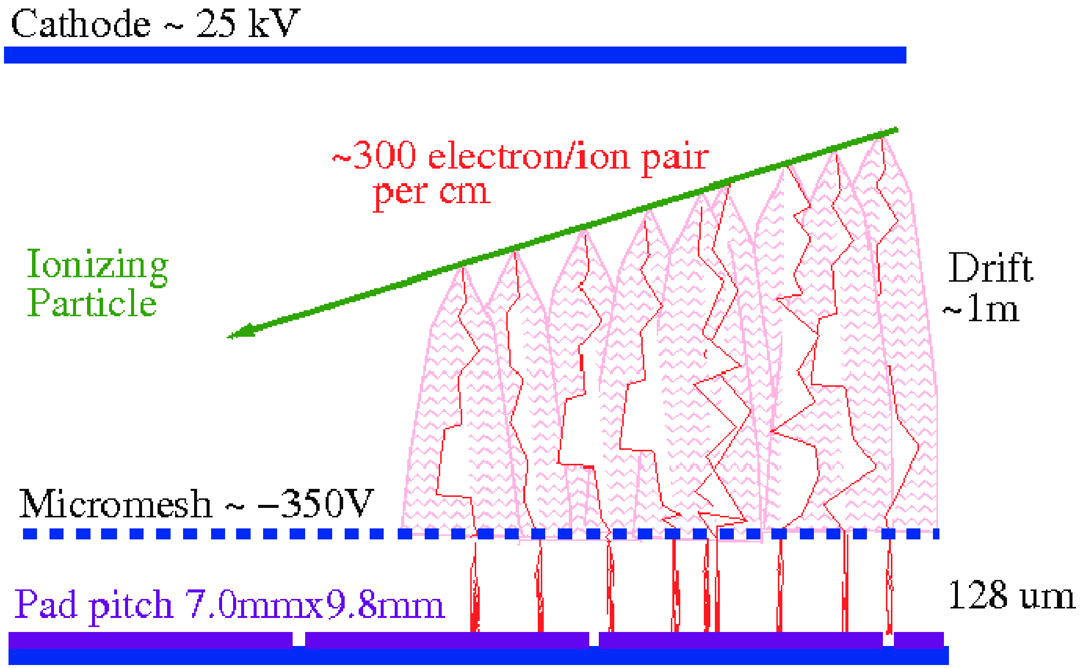
- Gaseous time projection chamber.
- Precisely reconstruct 3D tracks of particles from neutrino interactions in FGD.
- From the curvature of tracks in magnetic field, charge and momentum of the particles are reconstructed.





Signal readout in TPC

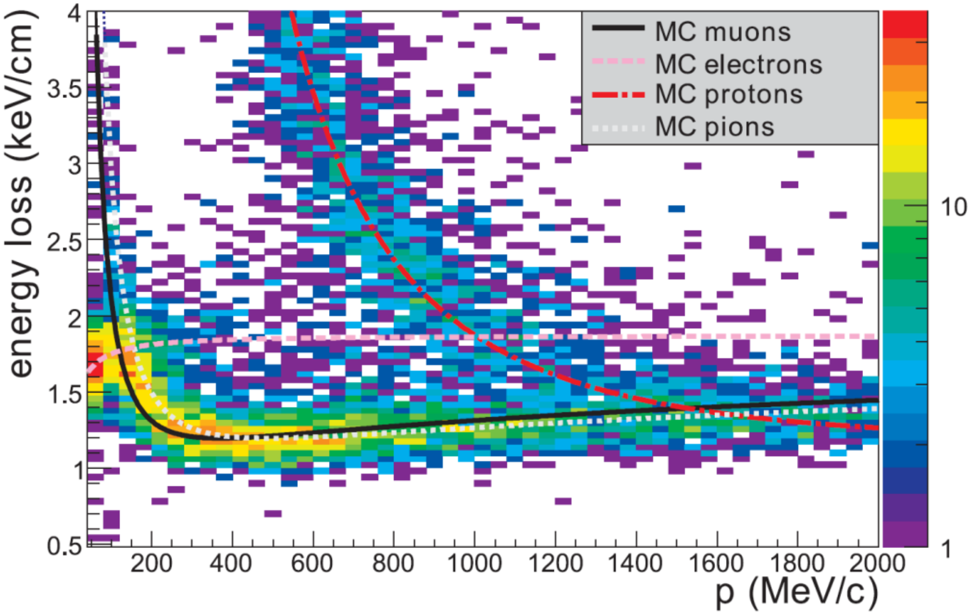
- Electron-ion pairs are generated by charged particles.
- Electrons drift to anode and are amplified in a high electric field (~27 kV/cm) formed by micromesh.
- Amplified signal is read out by pads.



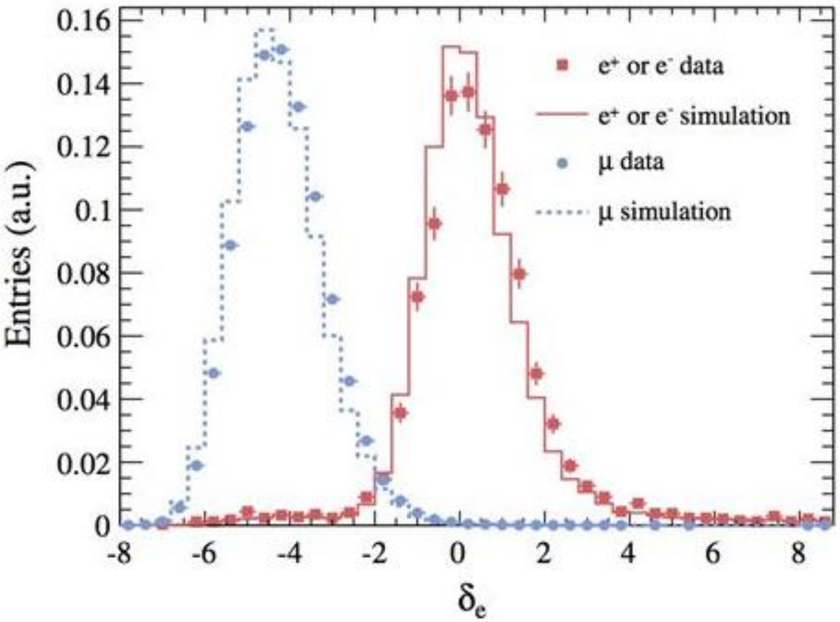
Particle identification with TPC

- dE/dx is measured from the signal size.
- Proton can be separated from muon/pion by dE/dx and momentum.
- Electron can be separated from muon by the likelihood. (shower like or track like)

p separation from μ/π using dE/dx and momentum



e and μ separation using likelihood

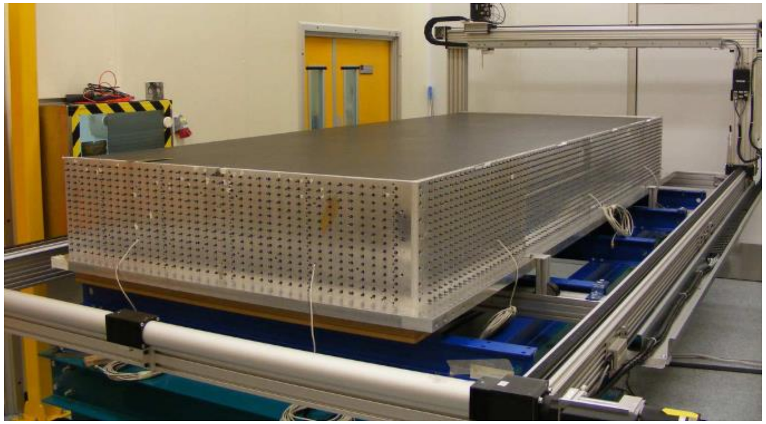


Other sub-detector in ND280

- P0D
  - Measure neutrino interactions producing π^0.
- ECal
  - Measure energy of electromagnetic shower (γ-rays or electrons)
- SMRD
  - Measure the high-angle muons which do not enter TPC.
- They are all scintillator detector with fiber-MPPC readout.

P0D

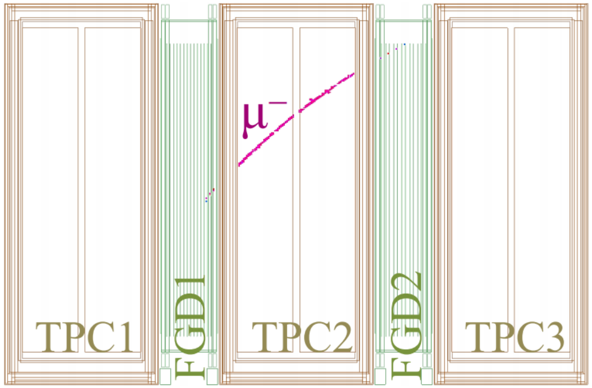
ECal



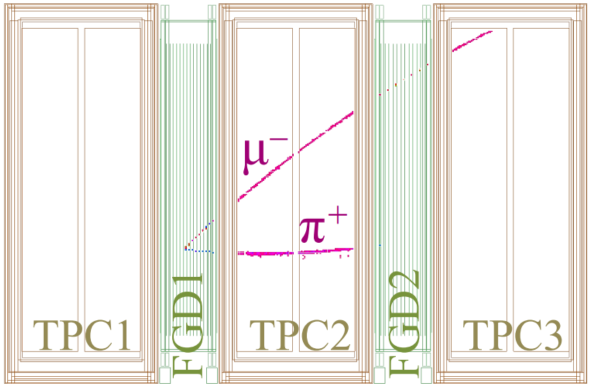
ND280 measurement

- Select CC events (muon from FGD to TPC) and classify the events into three groups:
    - CC0π (mainly CCQE events)
    - CC1π (mainly CC resonant events)
    - CC-other (mainly CC DIS events)

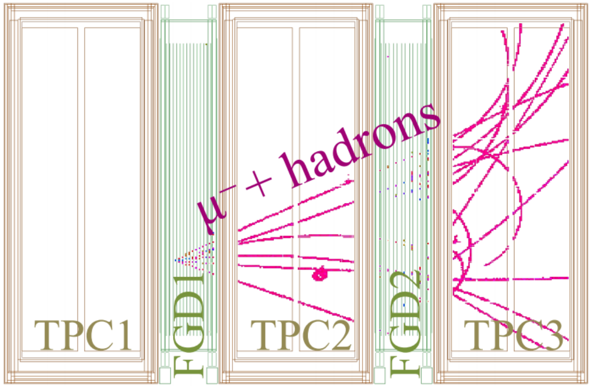
CC0π event



CC1π event



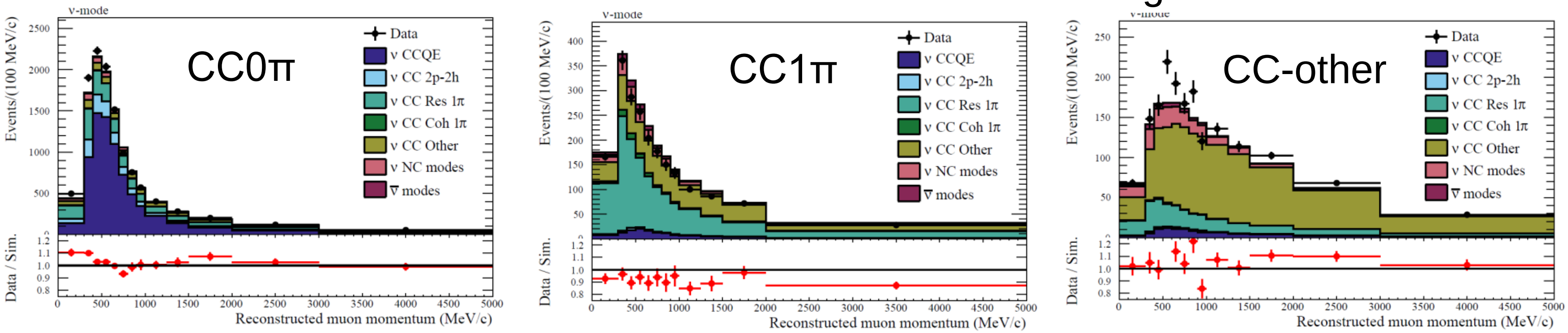
CC-other event



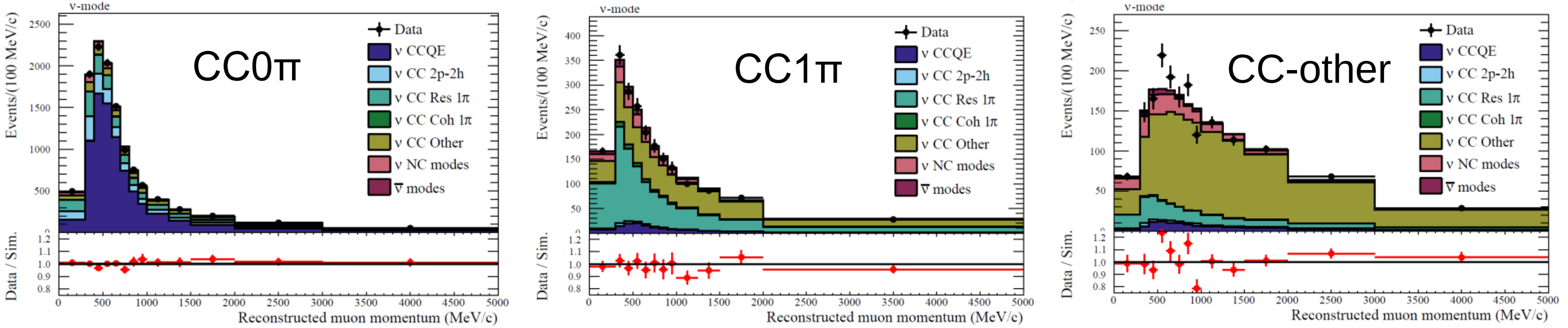
ND280 fit

- Muon momentum-angle distribution of MC with flux and cross section parameters are fitted to data.

Muon momentum distribution before fitting



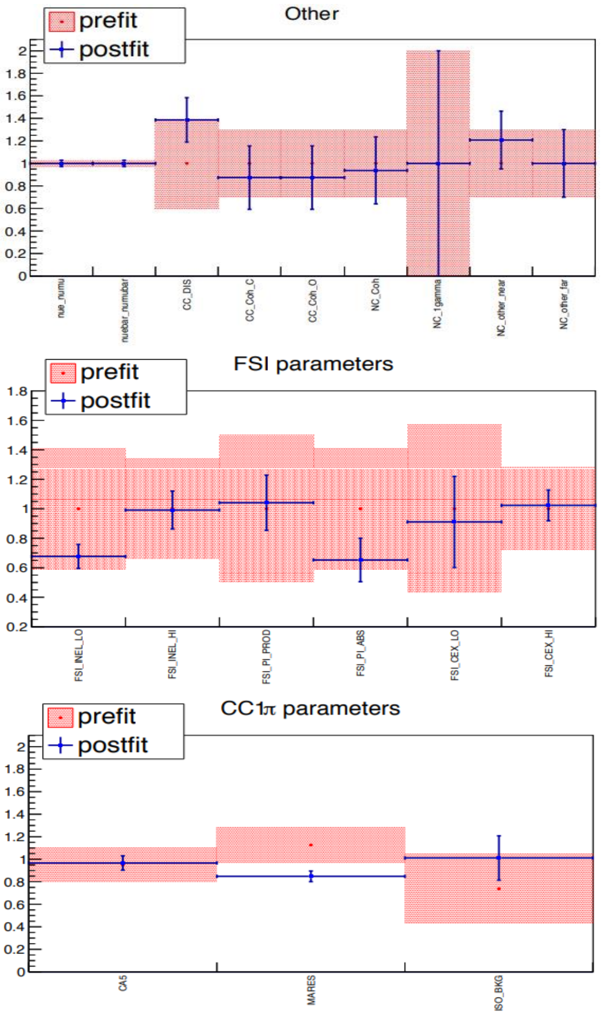
Muon momentum distribution after fitting



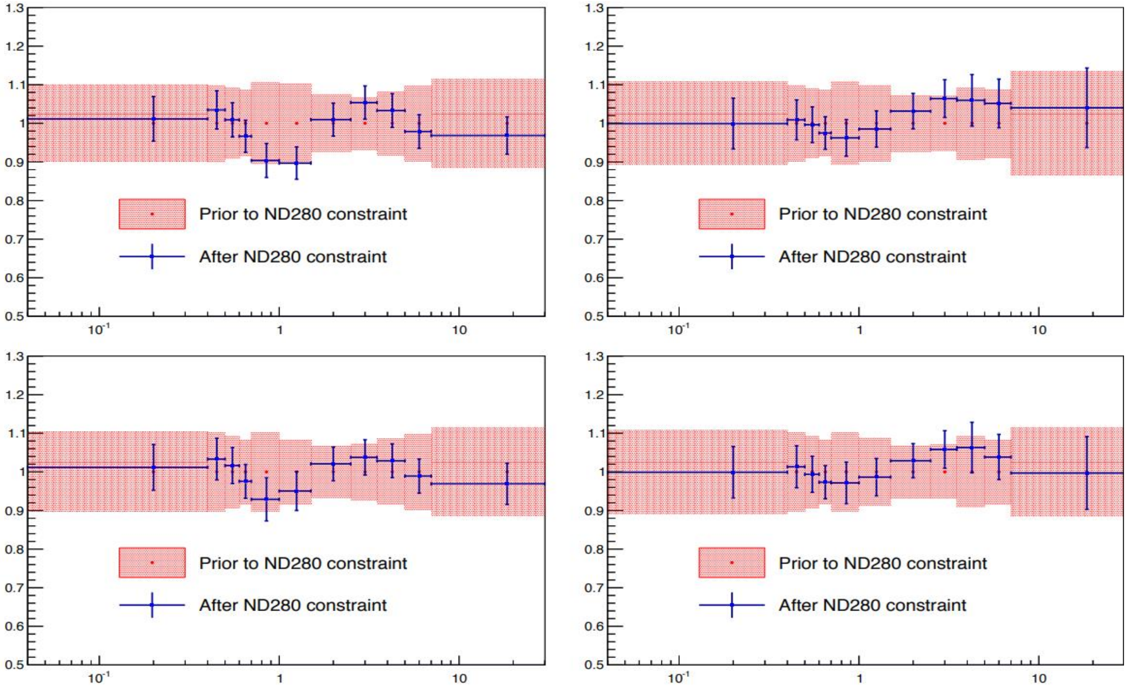
Constraints on flux and cross section

- By fitting flux and cross section parameters are varied to optimal values and their uncertainties are constrained.

Cross section parameters



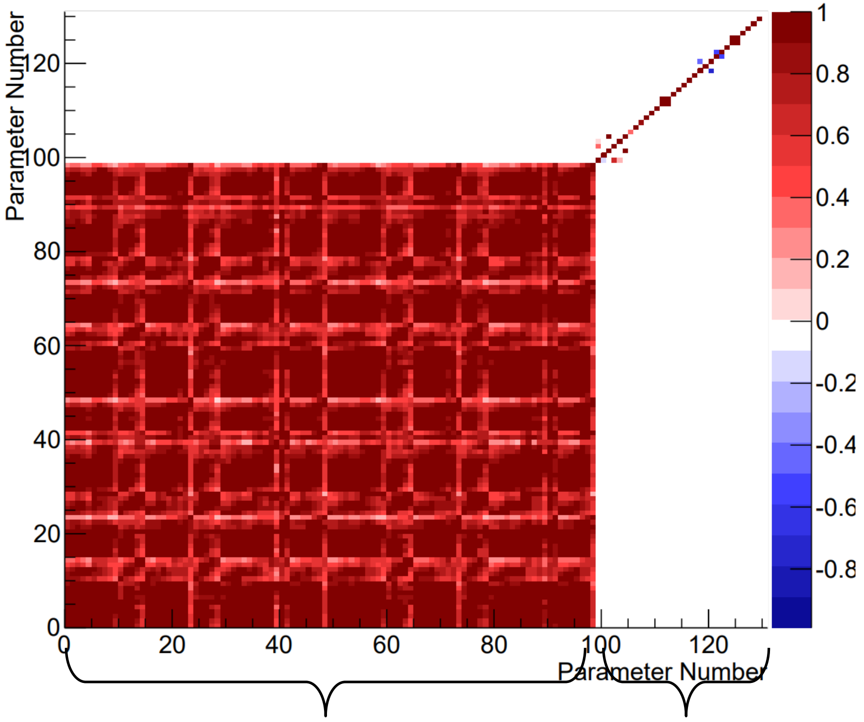
Neutrino flux parameters



Correlation of parameters

- ND280 fit also gives the correlations among the flux and cross section parameters.

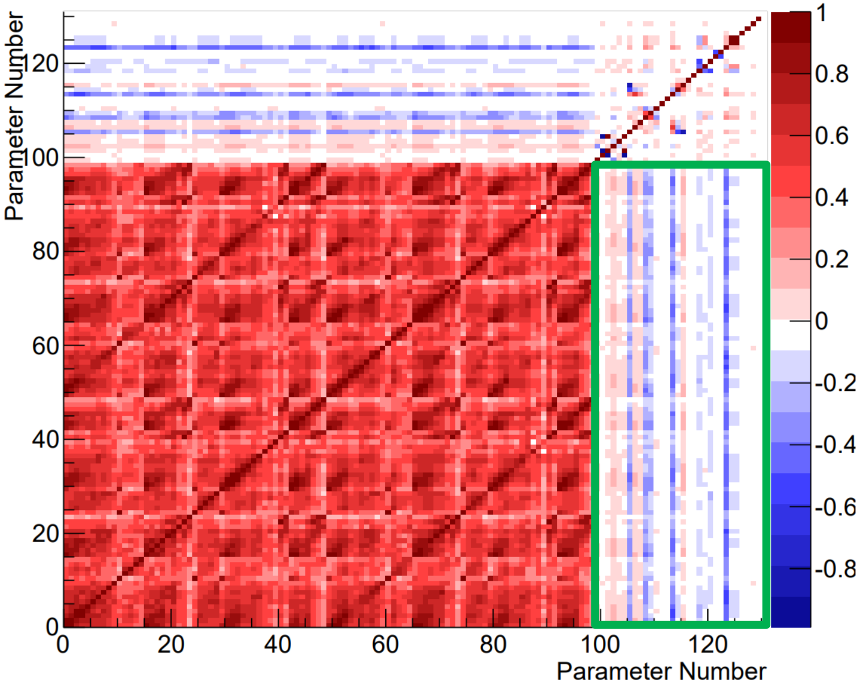
Correlation matrix before ND280 fit



Flux parameters

Cross section parameters

Correlation matrix after ND280 fit

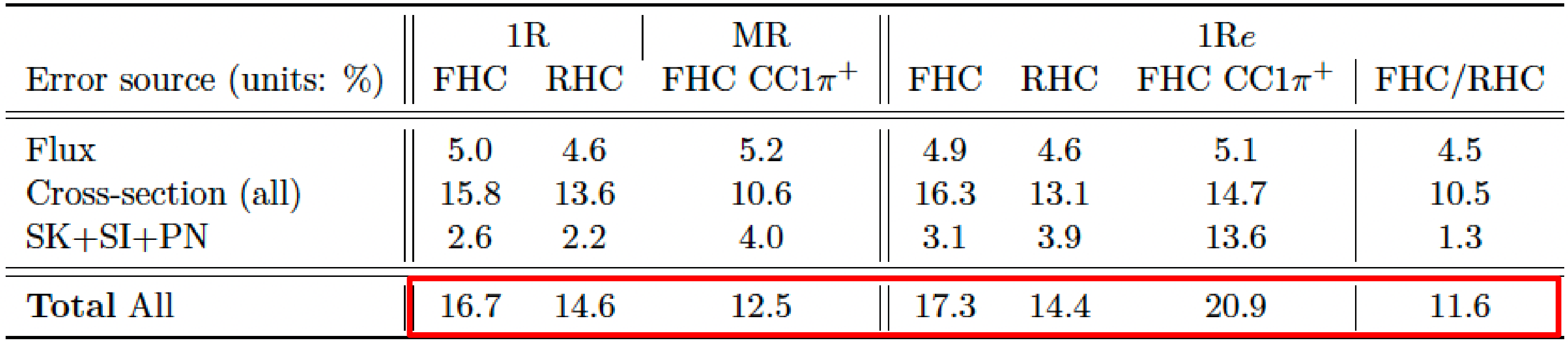


Anti-correlation between flux and cross section parameters

Systematic error reduction by ND280

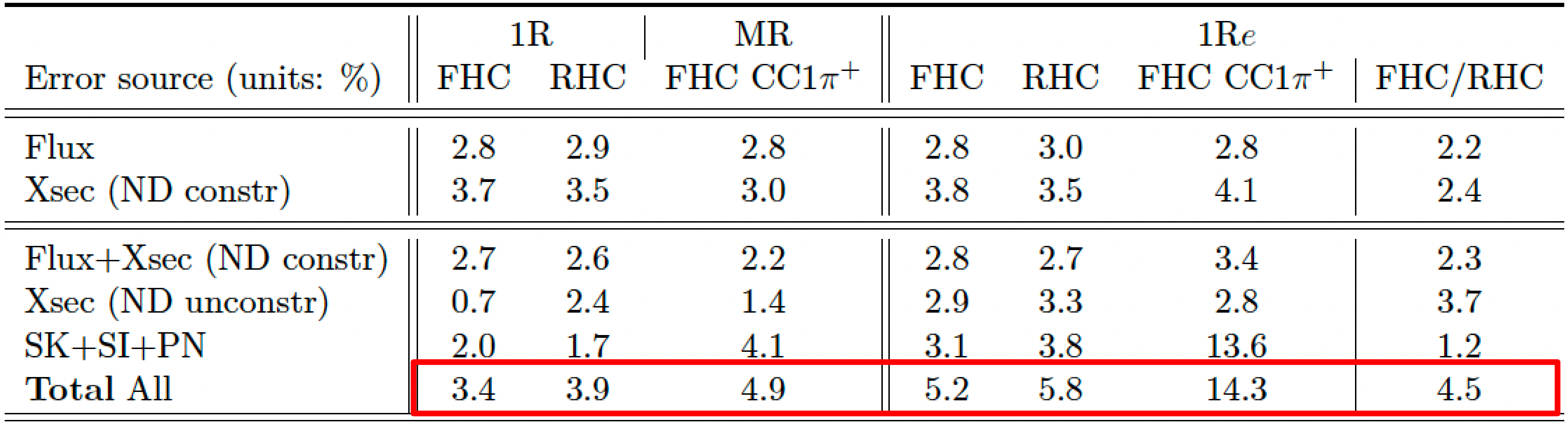
- Systematic errors are significantly reduced in all the samples in Super-Kamiokande thanks to the ND280 fit.

Systematic errors on the number of events in Super-Kamiokande before ND280 fit



	1R		MR	1Re			
Error source (units: %)	FHC	RHC	FHC CC1π^+	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

Systematic errors on the number of events in Super-Kamiokande after ND280 fit

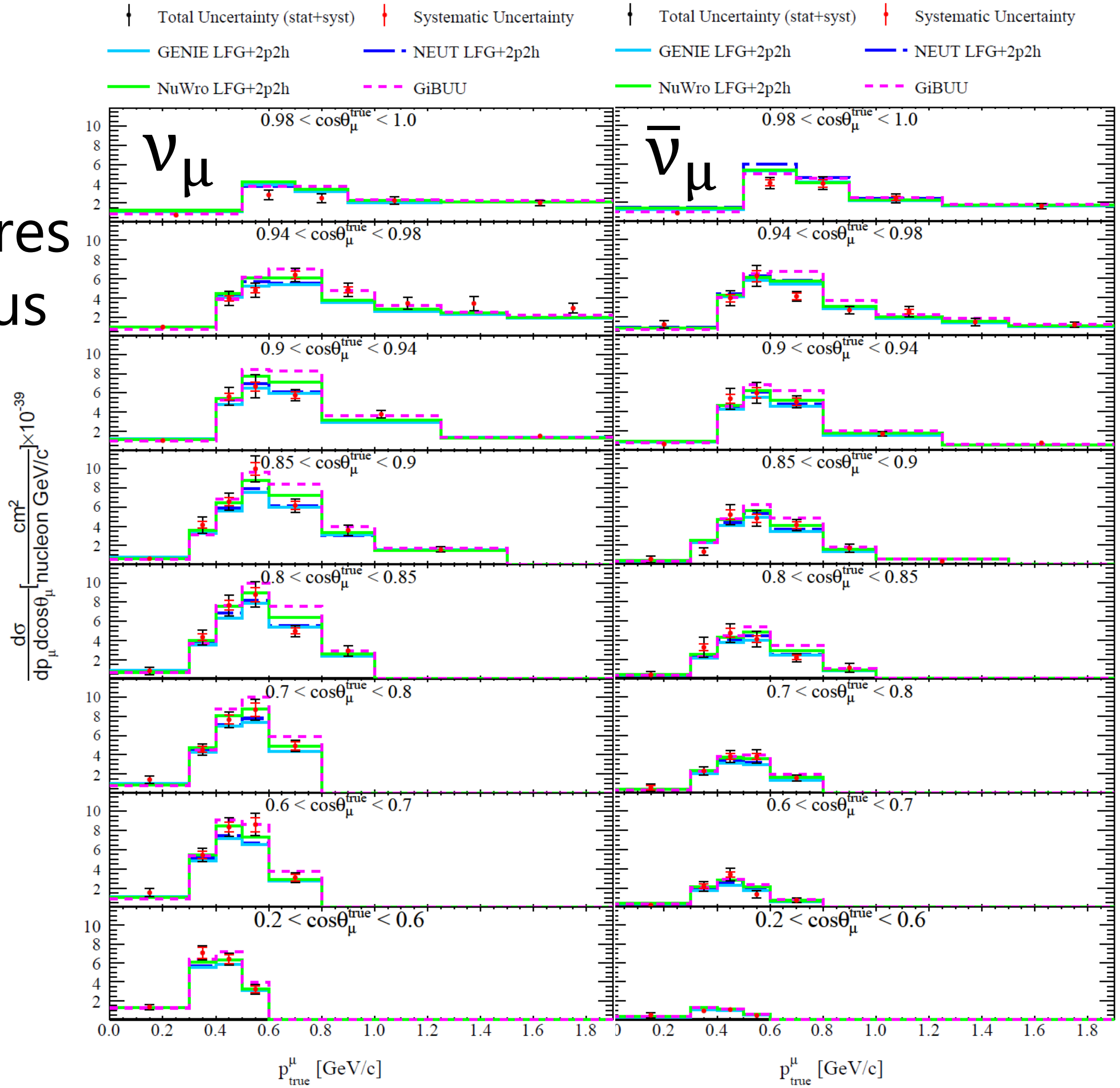


	1R		MR	1Re			
Error source (units: %)	FHC	RHC	FHC CC1π^+	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

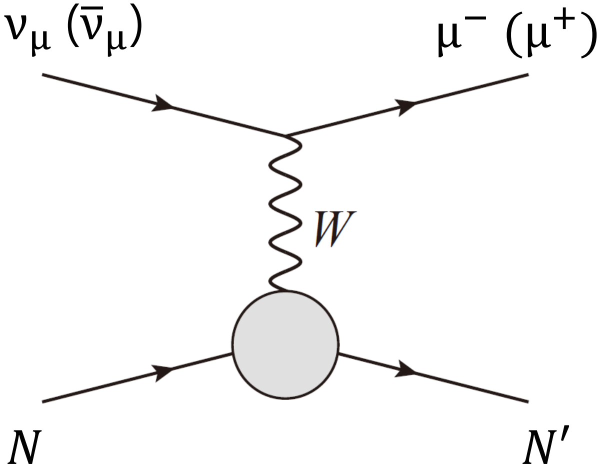
Cross section measurement with ND280

- In addition to the systematic error reduction in the oscillation analysis, ND280 also measures the neutrino-nucleus cross section.

ν_μ and $\bar{\nu}_\mu$ CC0π double differential cross section with ND280

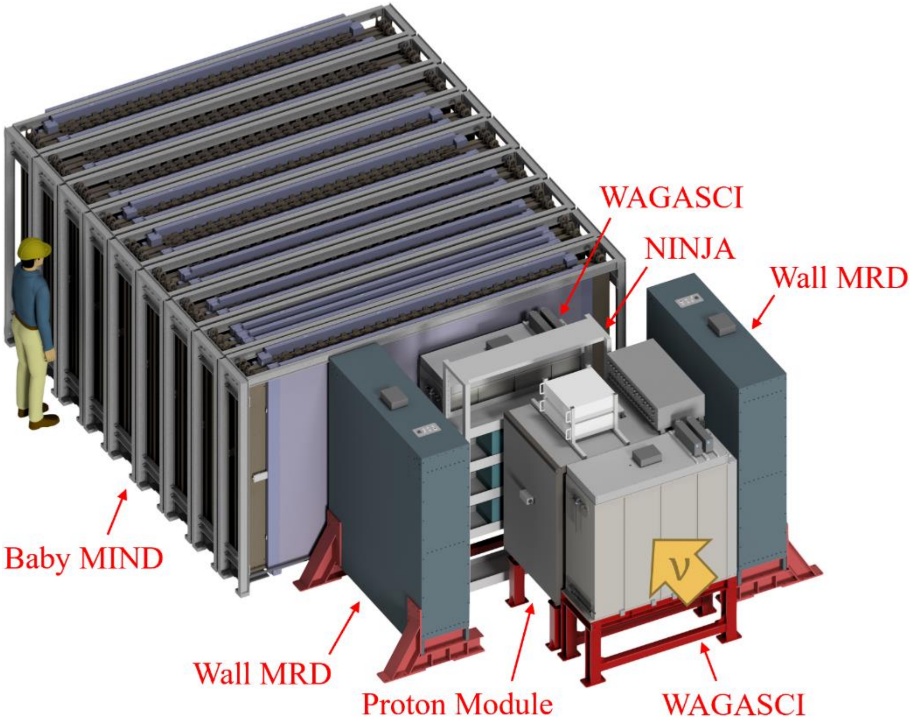


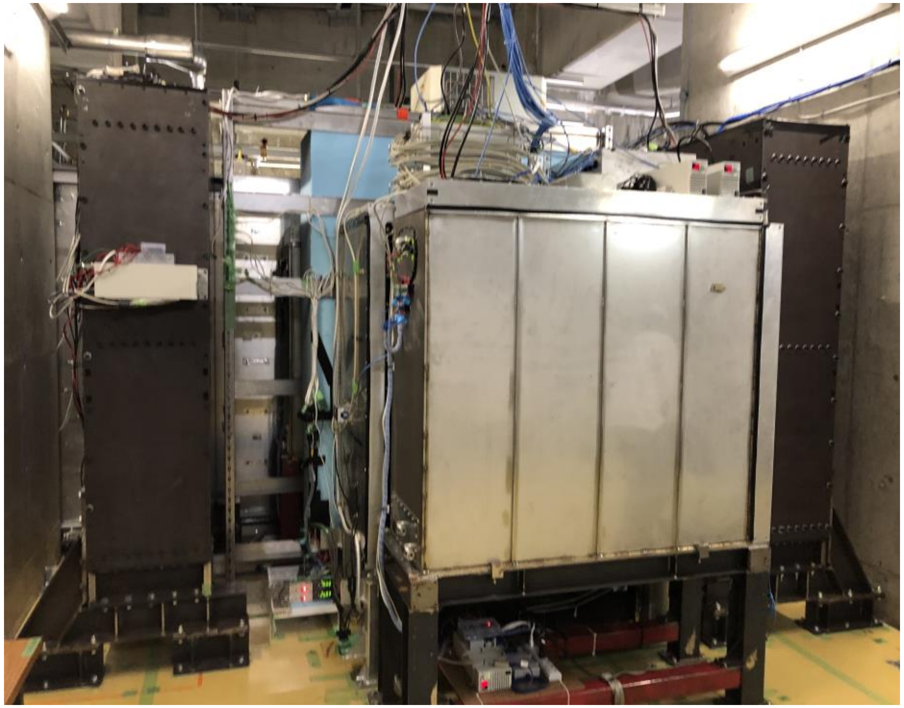
ν_μ ($\bar{\nu}_\mu$) CC0π interaction



WAGASCI-BabyMIND detector

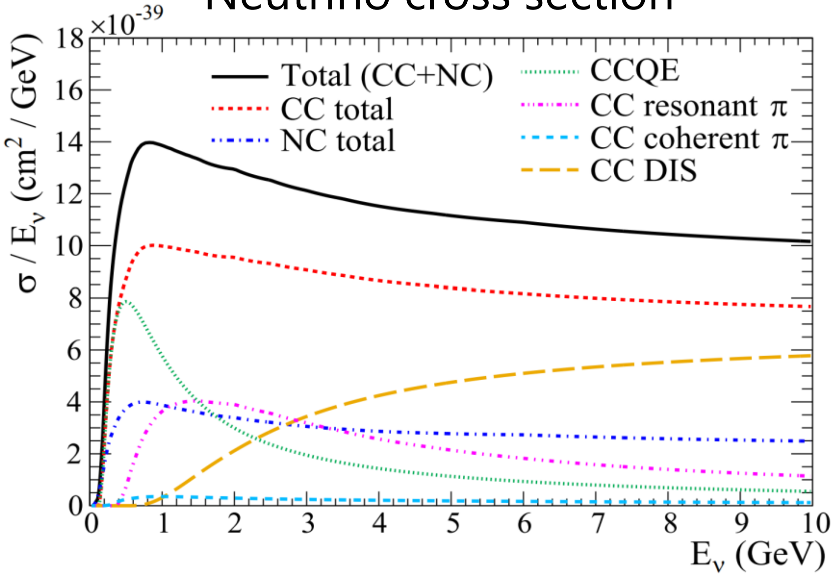
- Newly installed in 2019.
- Scintillator-based detectors in the bottom floor of near detector hall corresponding to 1.5° off-axis.
- Water and plastic target neutrino detectors.
- Surrounding muon range detectors, one magnetized.



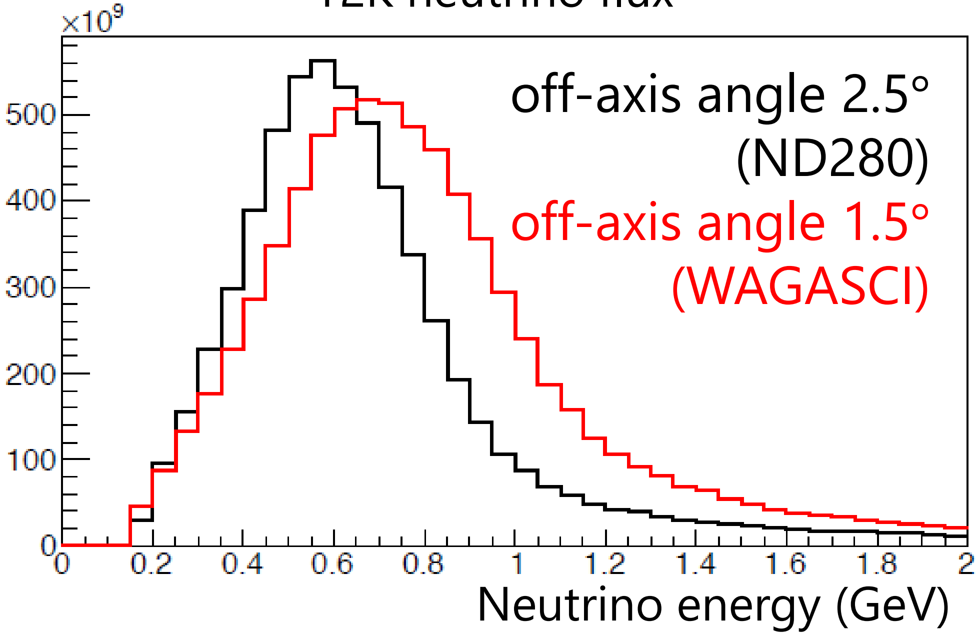


WAGASCI-BabyMIND detector

- Neutrino interaction is strongly dependent on its energy.
- Energy distribution of the neutrino flux changes when the detector position changes.
- WAGASCI-BabyMIND will measure the neutrino interaction for higher energy neutrinos than ND280.



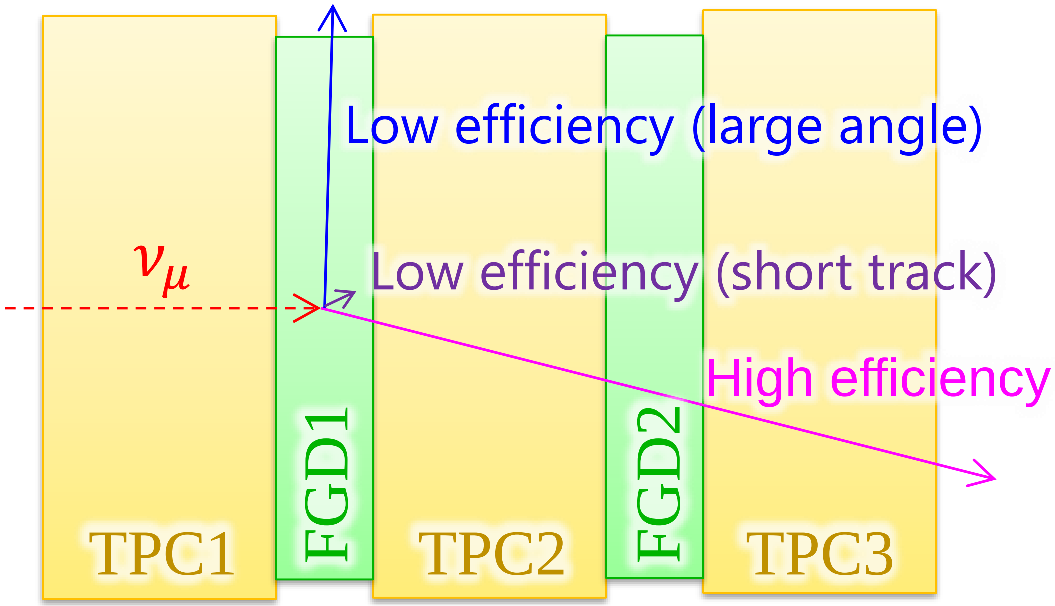
Neutrino cross section



T2K neutrino flux

Weak points of ND280

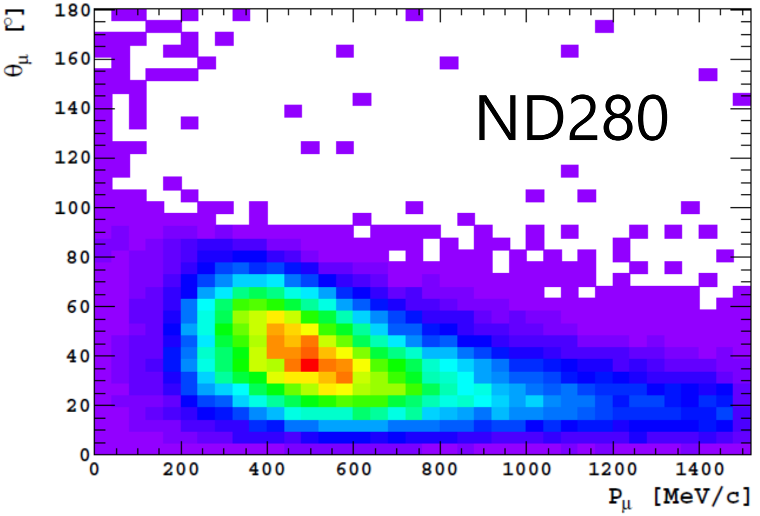
- Efficiency is low for
  - Large-angle scatted particles.
  - Short track particles (mainly low momentum protons)
- ν_e cross section cannot be measured precisely because of γ-ray backgrounds from outside.

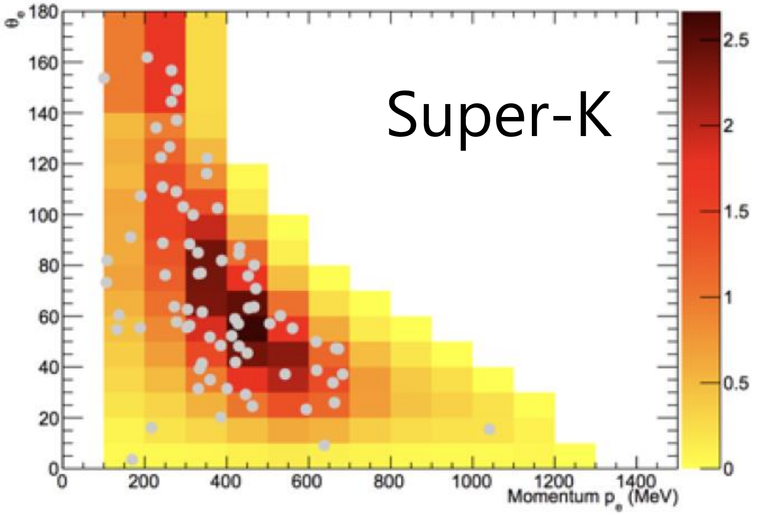

Low efficiency (large angle)

Low efficiency (short track)

High efficiency

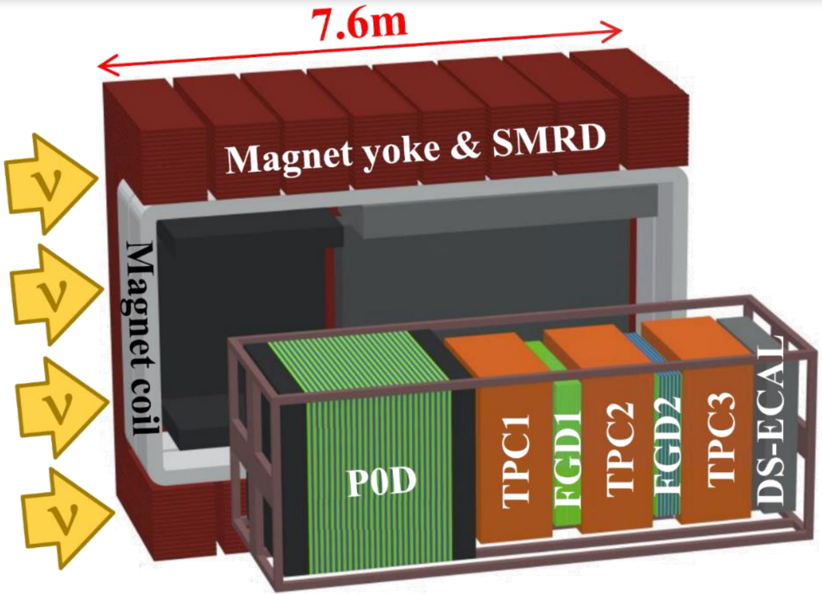
Muon momentum-angle distribution in ND280 and Super-Kamiokande

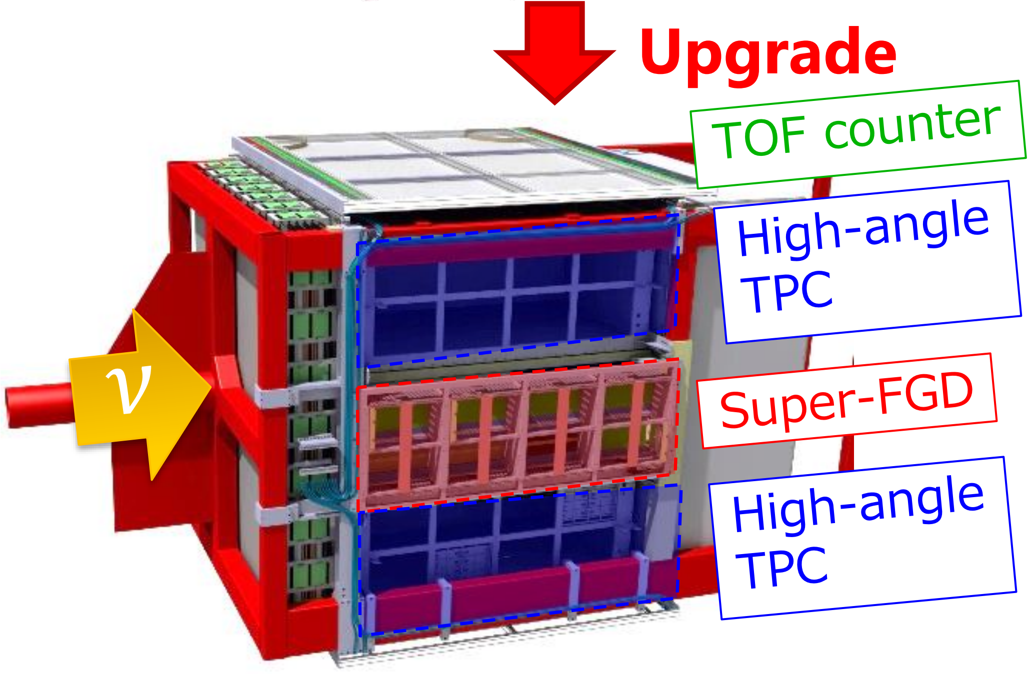




ND280 upgrade

- P0D will be removed and new detectors will be installed.
  - Super-FGD
  - High-angle TPC
  - TOF counters
- Construction is ongoing to start beam data taking from 2023.

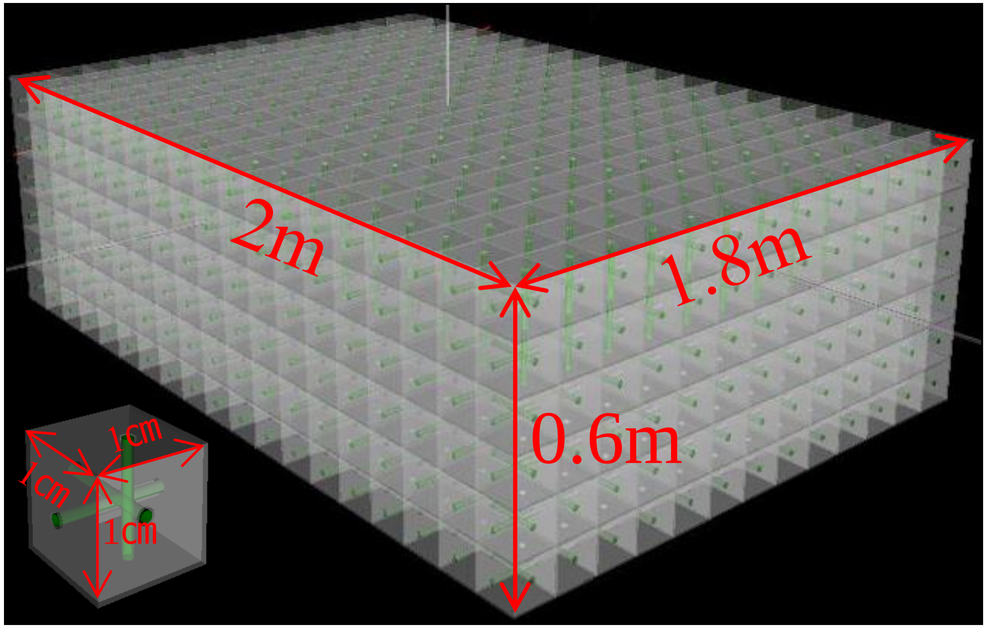




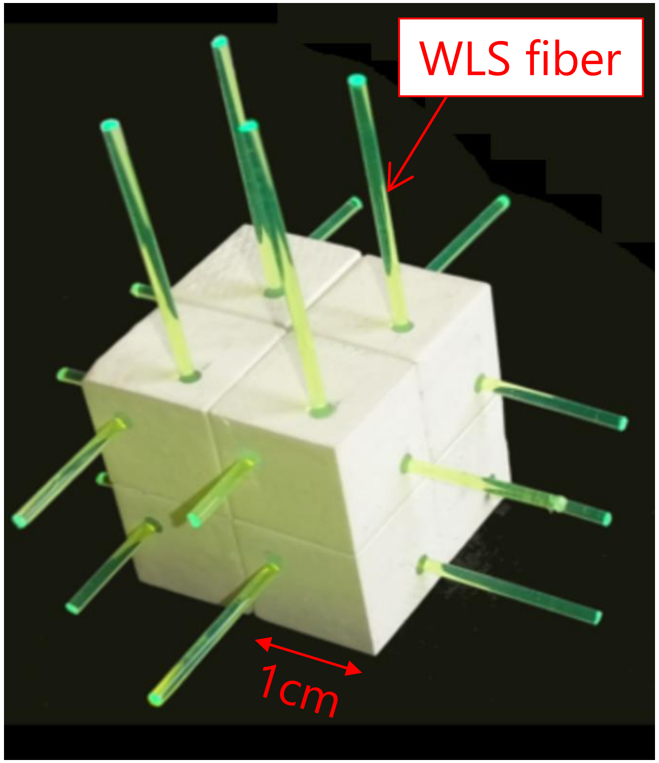
Super-FGD

- Two million scintillator cubes (1cm×1cm× 1cm).
- Readout along wave-length shifting fiber in three directions.
- Photon detection by MPPC.

Super FGD



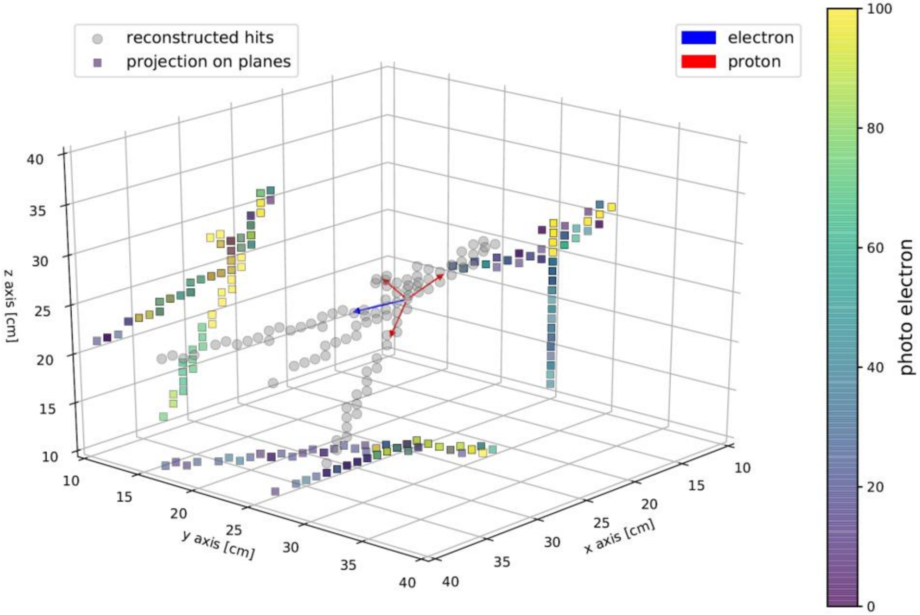
Super FGD scintillator



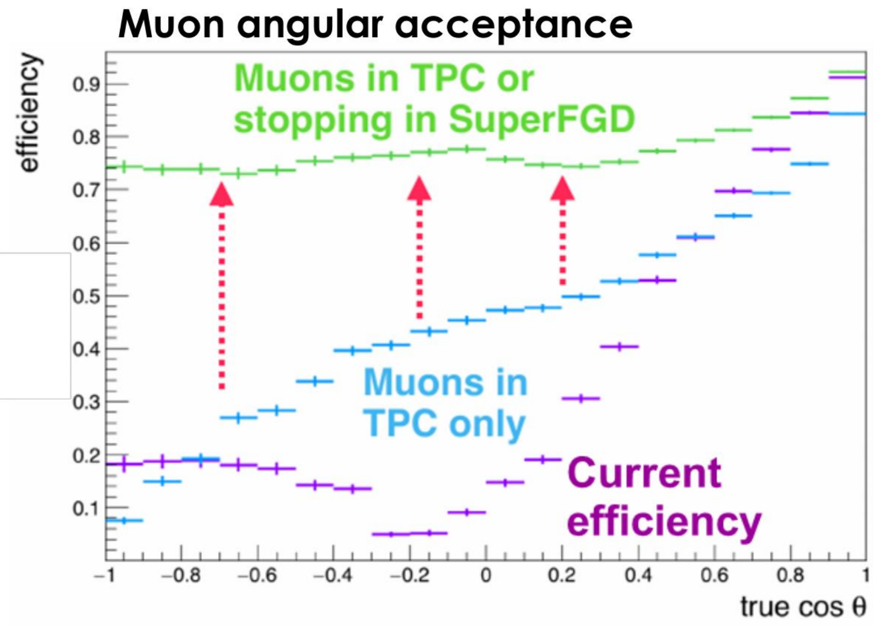
Angular acceptance of Super-FGD

- Tracks are observed as projections in three directions.
- Sensitive to particles going to every direction.

Event display in Super-FGD
by simulation

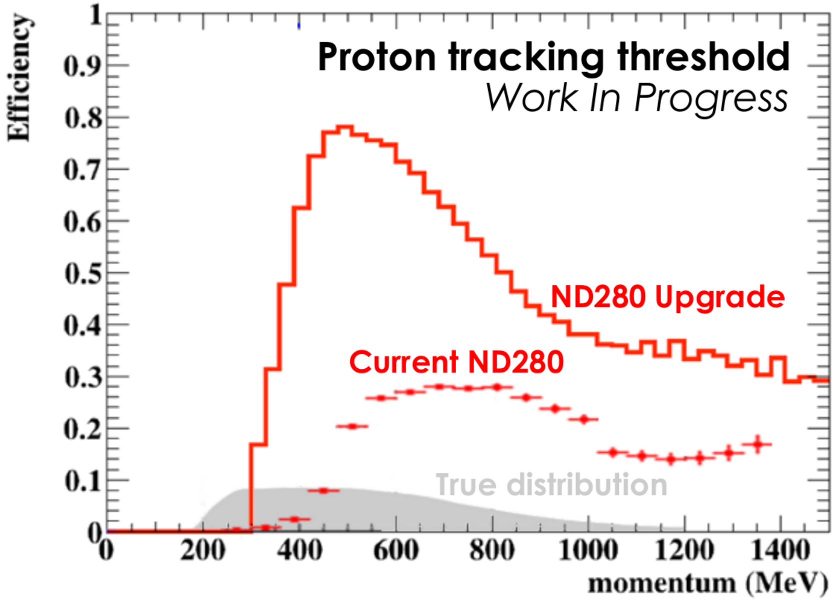


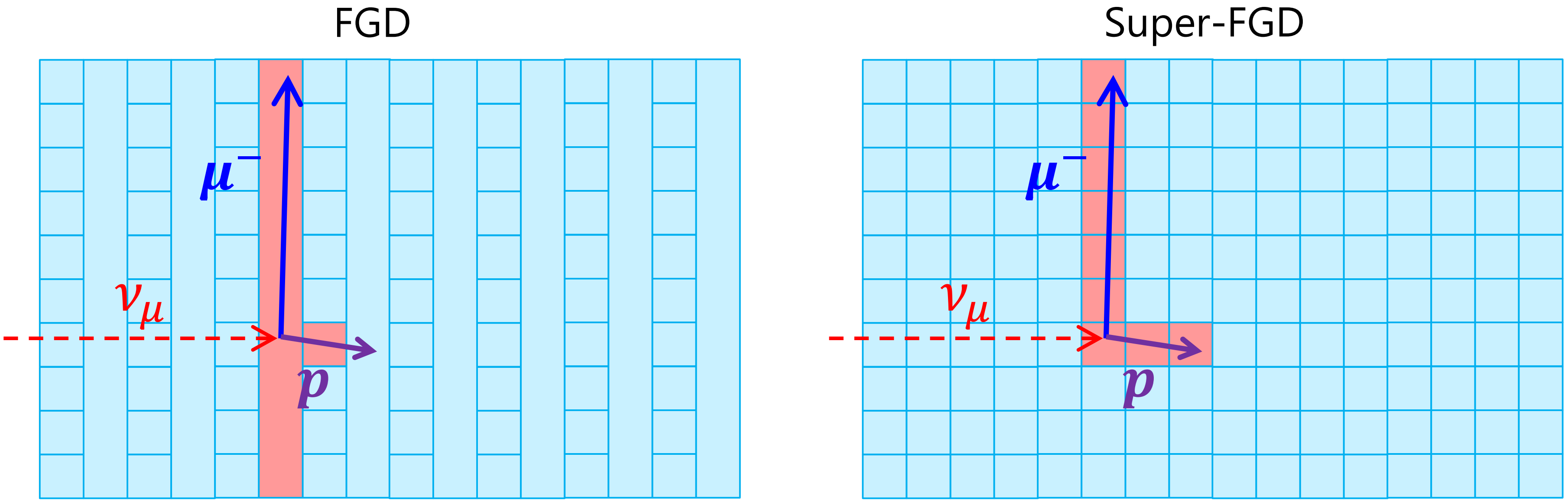
Efficiency as a function of muon angle



Short track detection with Super-FGD

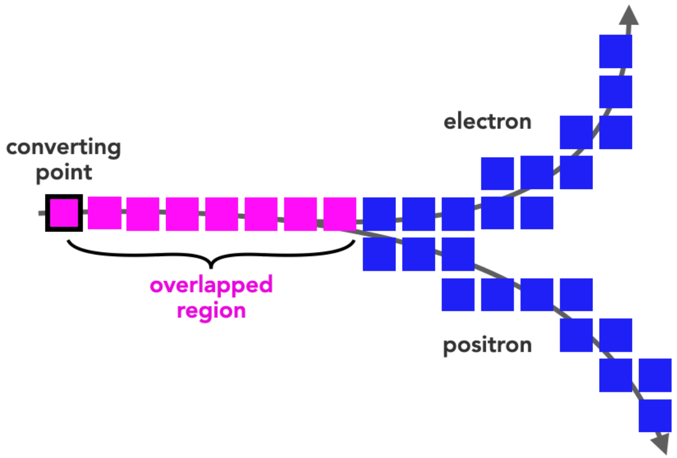
- Tracks must penetrate six layers for reconstruction in case of FGD.
- In case of Super-FGD, tracks can be reconstructed from only three scintillator cubes.
- Efficiency for low momentum particle is high.



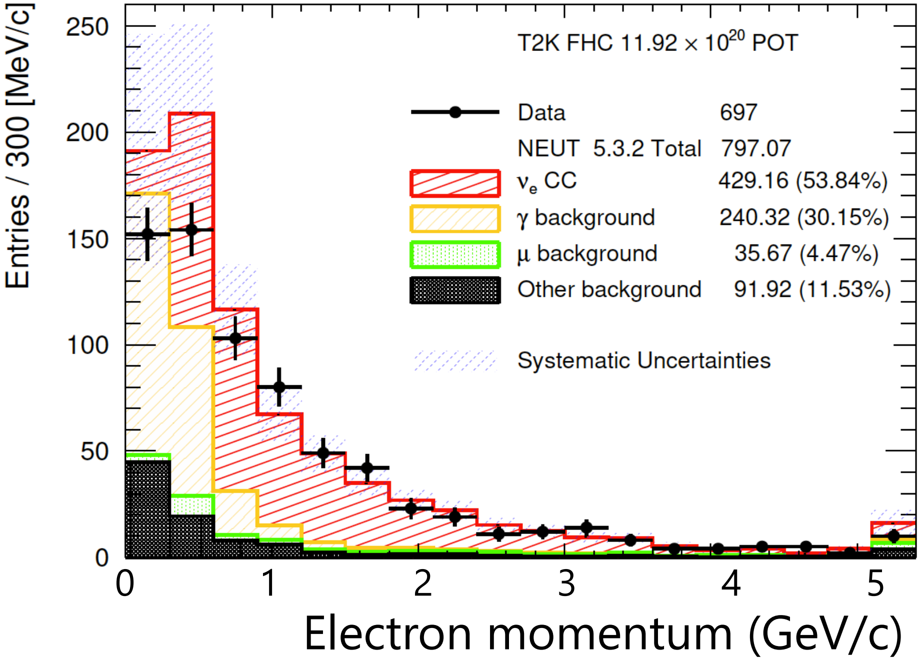


ν_e measurement with Super-FGD

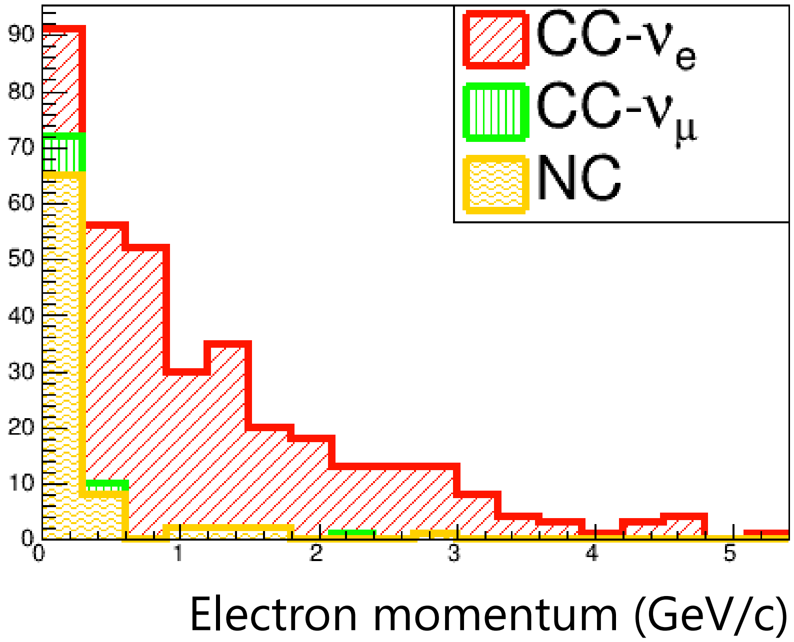
- γ-ray backgrounds for the ν_e measurement can be reduced looking at the conversion point.
- ν_e cross section can be precisely measured.



Current ND280



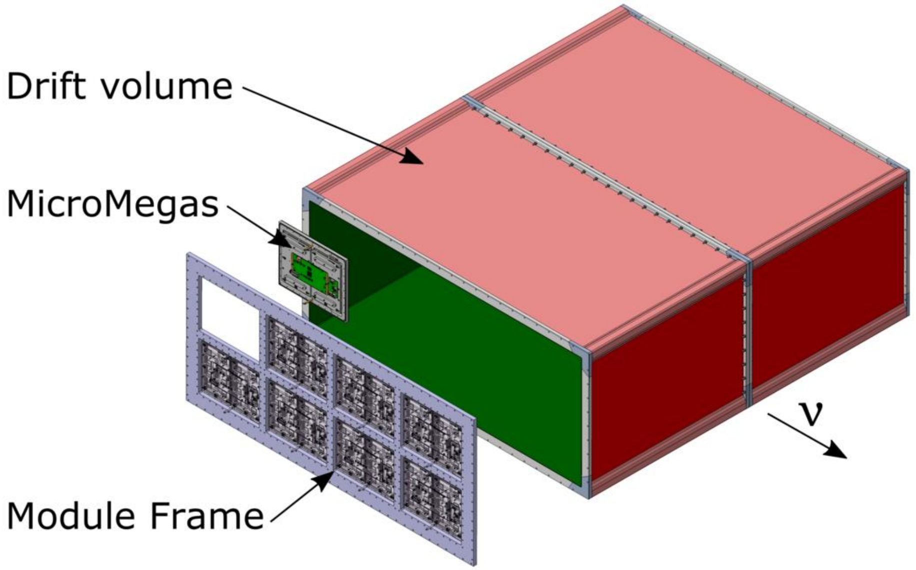
Upgraded ND280 (preliminary)



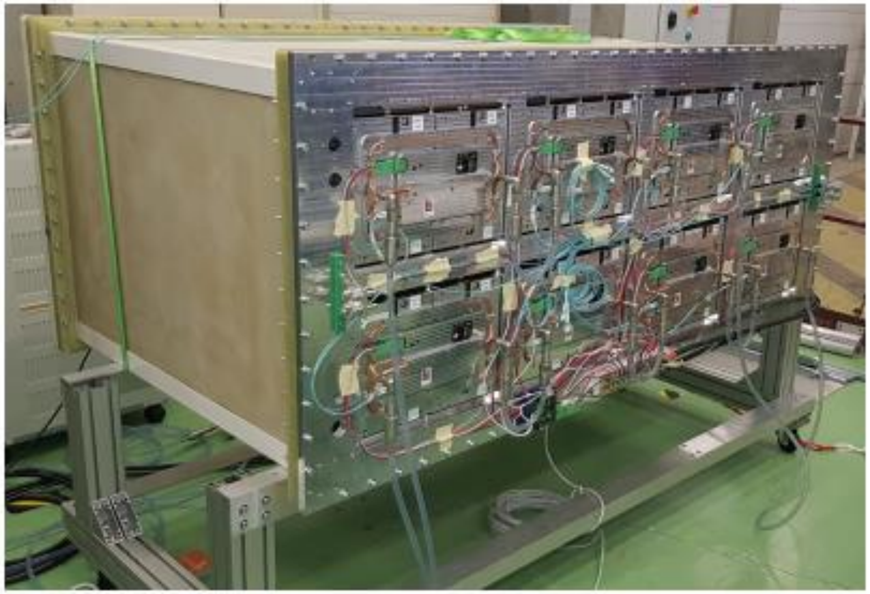
High-angle TPC

- New TPCs will be placed top and bottom of Super-FGD in addition to the downstream one.
- Measure the large-angle scattered particles precisely.

Schematic view



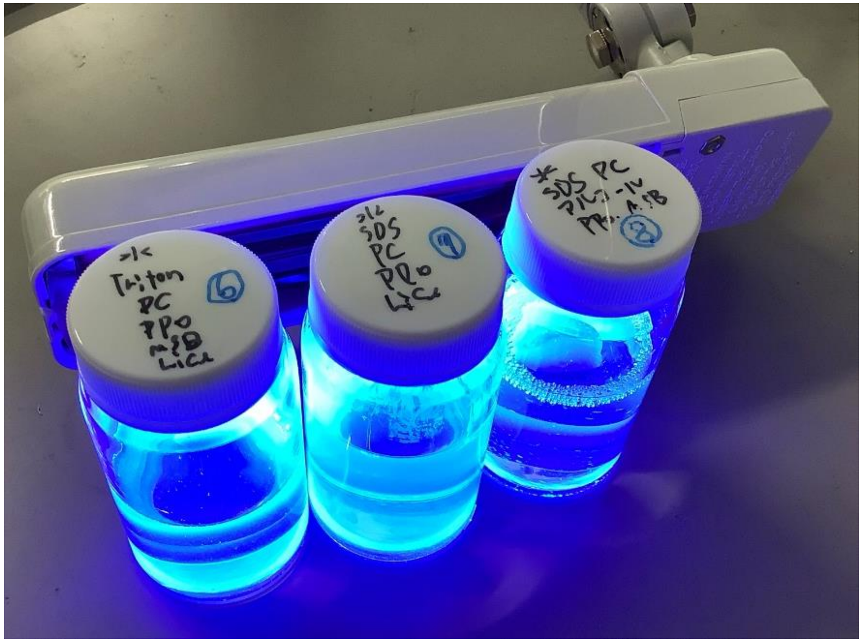
Mock up



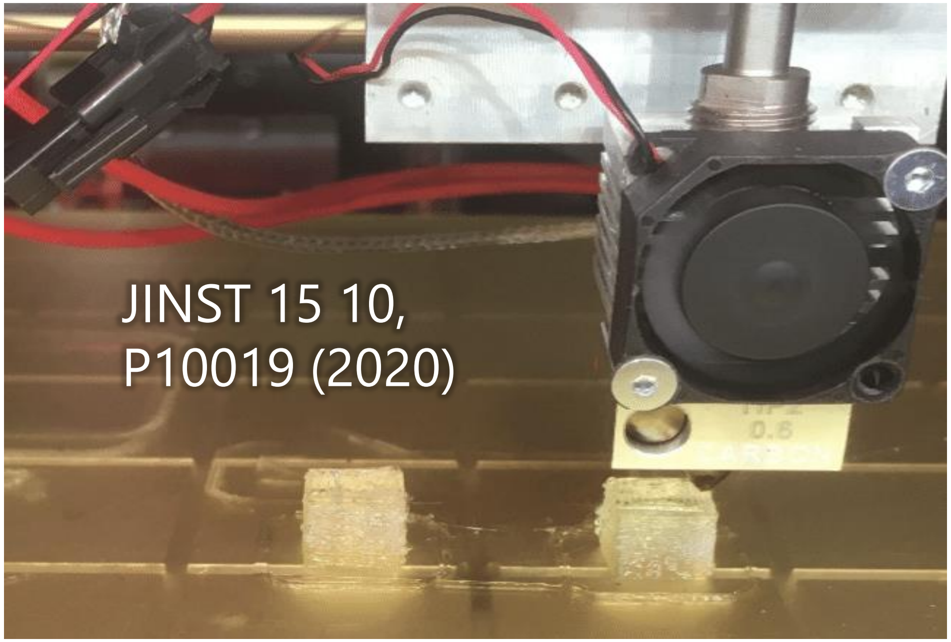
ND280 upgrade++

- Remaining weak point of ND280 is that it cannot precisely measure the neutrino-water cross section.
- Discussing the further upgrade for Hyper-Kamiokande experiment with new technologies.
  - Water-based liquid scintillator
  - 3D printed scintillator

Water-based liquid scintillator



3D printed scintillator



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Summary

- Near detector plays essential role in the long-baseline neutrino oscillation experiments.
- There are three kinds of near detectors in T2K.
  - INGRID
  - ND280
  - WAGASCI-BabyMIND
- They have significantly reduce the systematic error in the T2K oscillation analysis.
- Upgrade of ND280 is ongoing for more precise measurements of neutrino interactions.