T2K Near Detector Upgrade

Yury Kudenko
INR RAS
(for the T2K Collaboration)

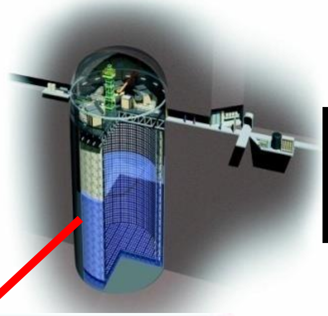
XII International Conference on New Frontiers in Physics
10-23 July 2023, OAC, Kolymbari, Crete, Greece

Long-Baseline Neutrino Oscillation Experiment

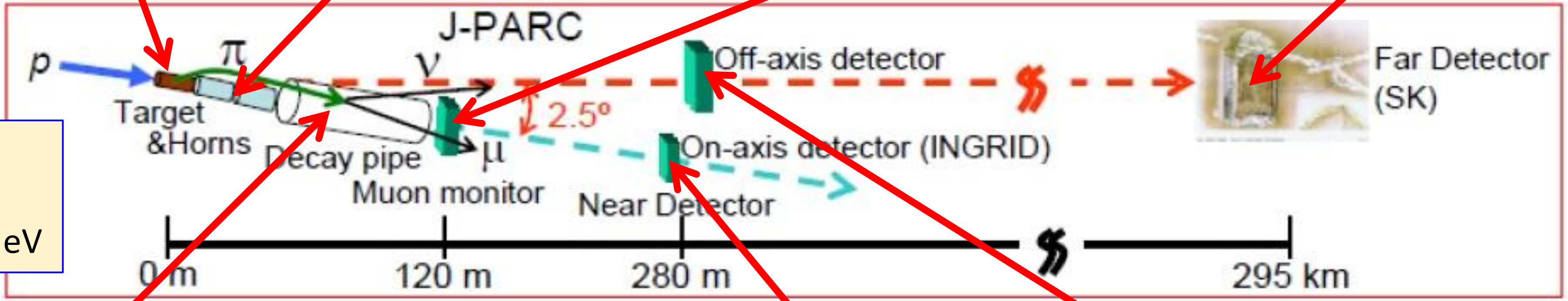
> 550 members
76 institutions
from 14 countries

Experiment T2K

T2K collects data since 2010



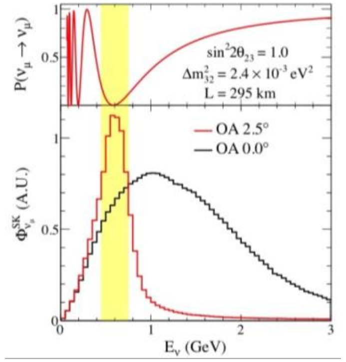
Far neutrino detector SuperKamiokande



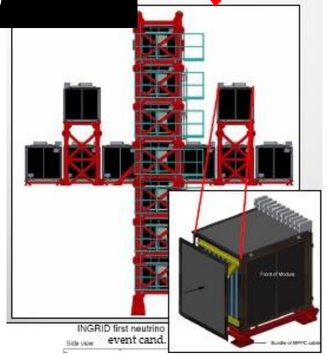
L = 295 km
Off-axis ν beam
Peak energy 600 MeV

Decay tunnel

Off-axis neutrino beam

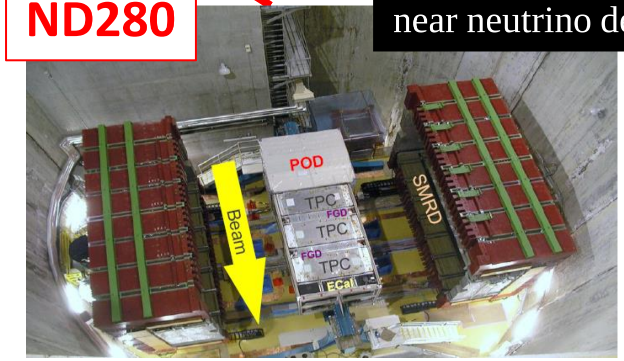


Neutrino monitor INGRID



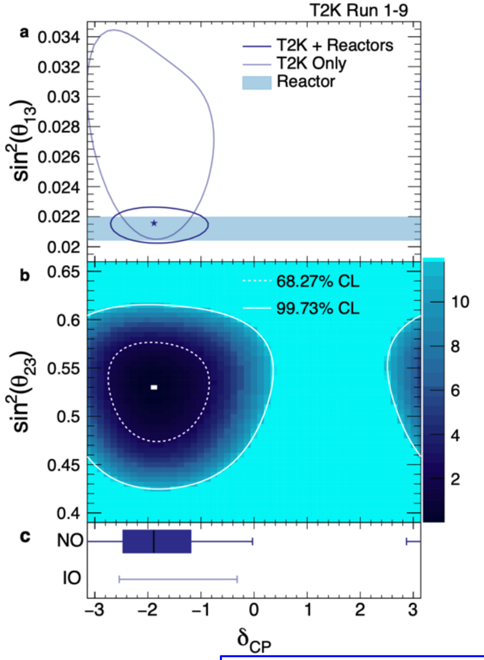
ND280

Off-axis near neutrino detector

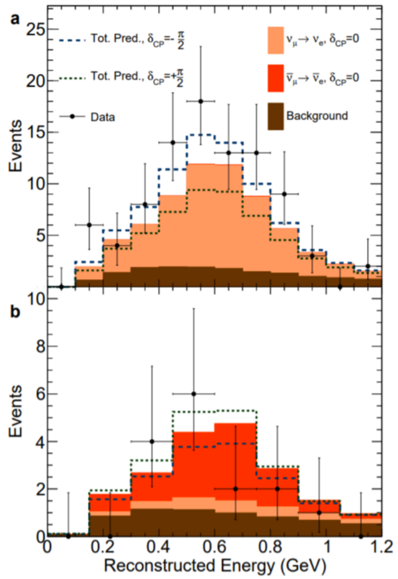


T2K Results

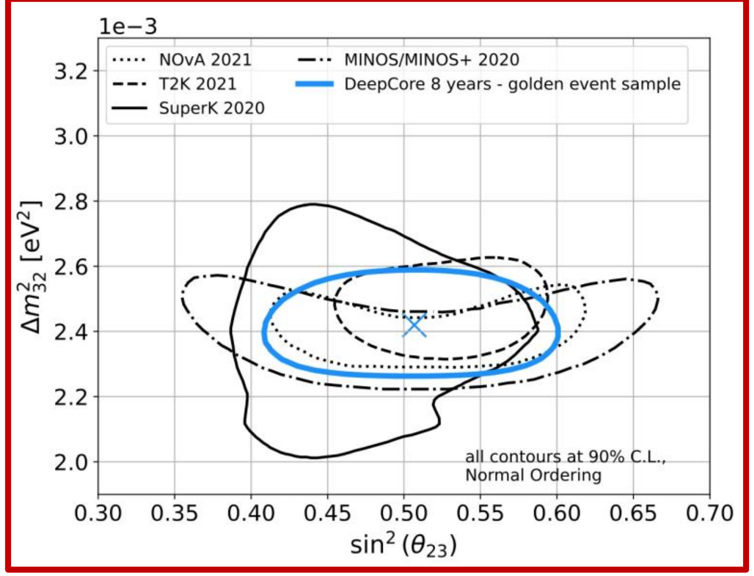
Constraints on CP violating parameter δ_{CP}



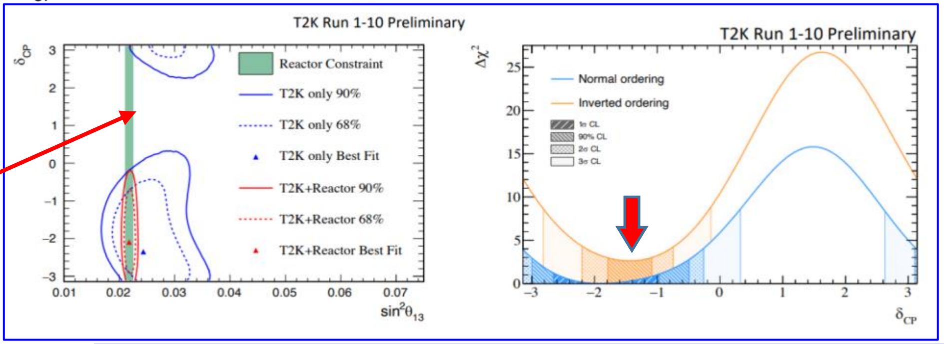
Number of observed electron neutrinos in the beam of the muon neutrinos



Oscillation parameters
$\sin^2(\theta_{23})$ and Δm^2_{32}
for normal mass hierarchy



Constraint on θ_{13} from reactor experiments Daya Bay, RENO, DChooz



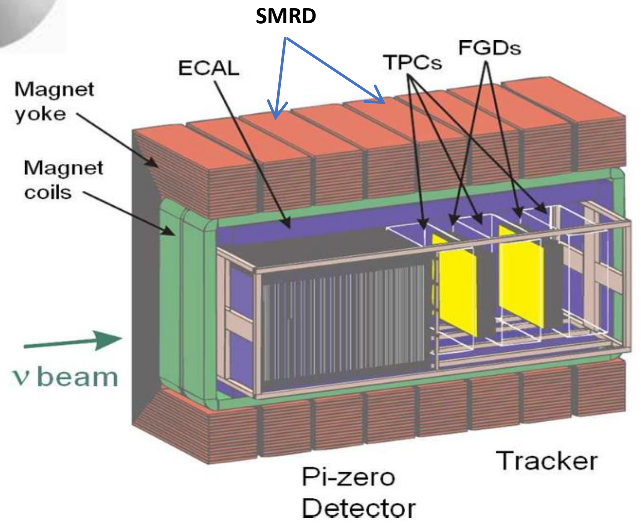
35% of δ_{CP} values excluded at 3σ marginalized over hierarchies
CP conserving values ($\delta_{CP} = 0, \pi$) excluded at >90%

Indication of maximal CP violation in neutrino oscillations $\delta_{CP} \sim -\pi/2$

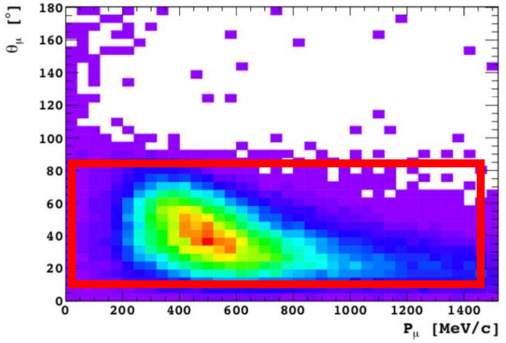
Normal mass ordering is preferred at 80% CL

T2K Near Detector ND280

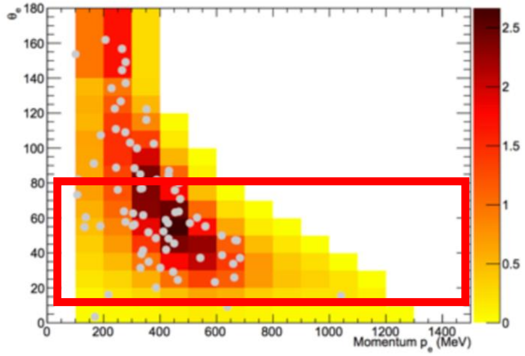
- Placed at 280 m from the target
- Measures the flux, flavor content, energy spectrum of the neutrino beam, studies neutrino-nucleus interactions



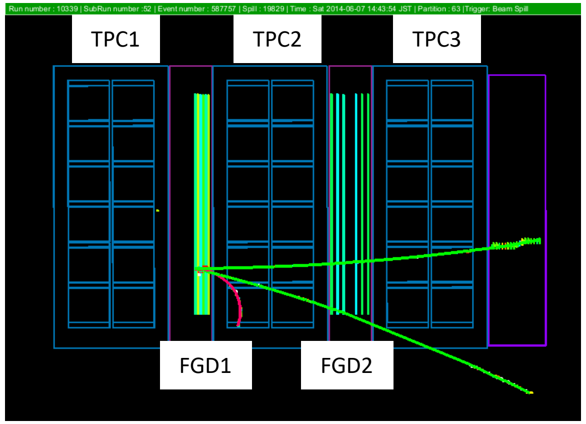
Muons in ND280:
- forward direction



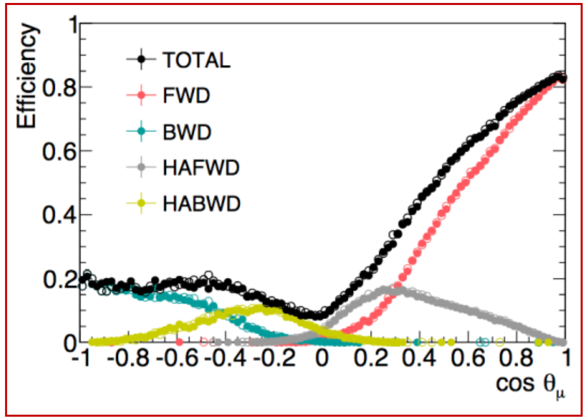
Electrons in SuperK:
- 4π acceptance



ν interaction in ND280



ND280
- Momentum threshold for protons 450 MeV/c (100 MeV kinetic energy);
- Non-CCQE interaction (2p2h, FSI) observed as CCQE;
- Acceptance for tracks in forward direction, SuperK - 4π acceptance;
- Larger oscillation systematic uncertainties due to tracks not measured by TPCs
- No capability to detect neutrons



Motivation for ND280 upgrade

- Uncertainties of current T2K oscillation measurements are dominated by statistics
- However, systematics will limit T2K (and HyperK) sensitivity in future

Post-fit errors of the most significant systematic parameters

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

The systematic error can be reduced by about 30% in the ND280 upgrade configuration

- Important to measure neutrino interactions in all phase space
- Precisely detect particles produced at any angle
- Reduce detection threshold, measure protons with low threshold
- Measure neutrons in anti-ν_μ interactions
- Reduce background, obtain better track identification using TOF
- Provide electron/gamma separation
- Reduce total systematics to ≤ 4% level for appearance modes

ND280 upgrade

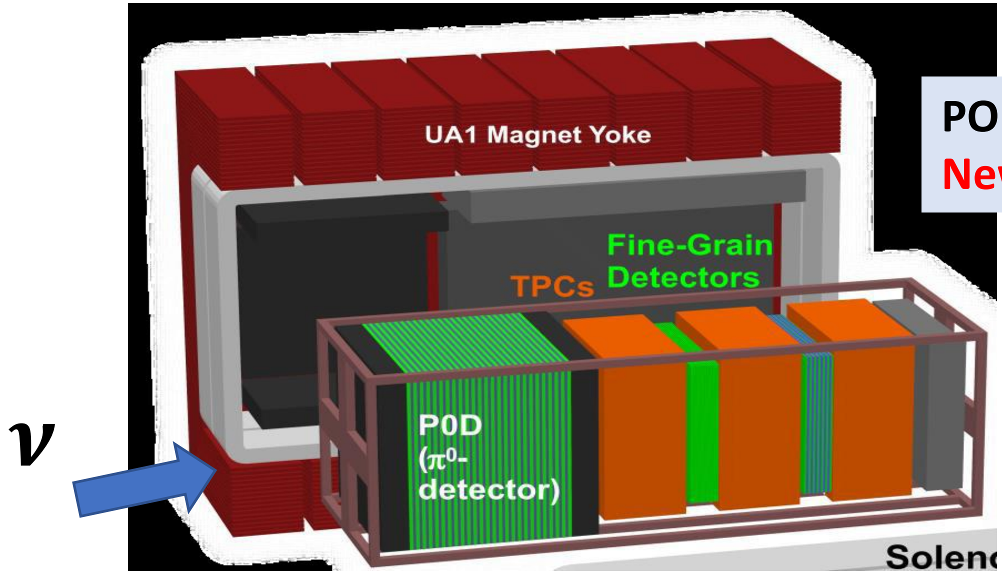
New upstream tracker:
- One 3D fine-grained scintillator target SuperFGD
- Two Horizontal TPCs
- TOF system around new tracker

- Fully active detector
- 4π acceptance for charged particles
- Detection of low energy protons and pions
- Electron/gamma separation
- Electron neutrino studies
- Detection of neutrons

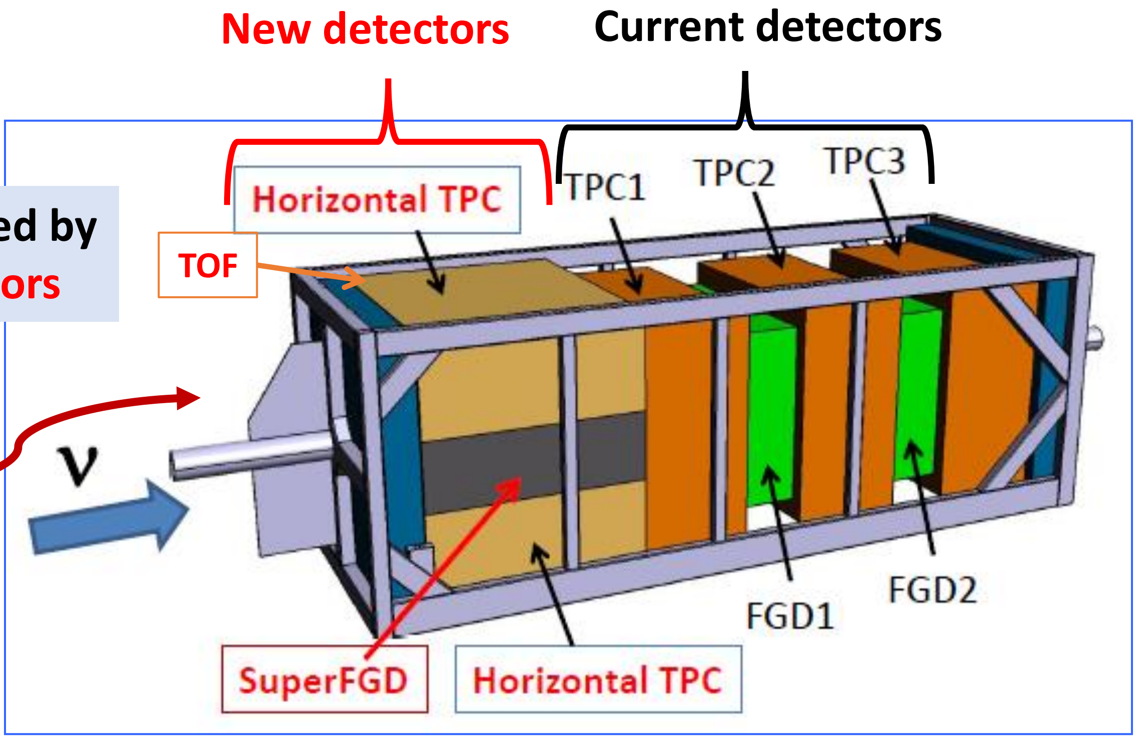
arXiv:1901.03750

T2K ND280 upgrade group:
120 participants from
29 institutions and 11 countries
including CERN

Current ND280 complex



POD replaced by
New Detectors

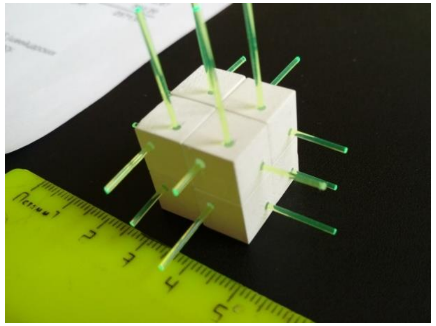


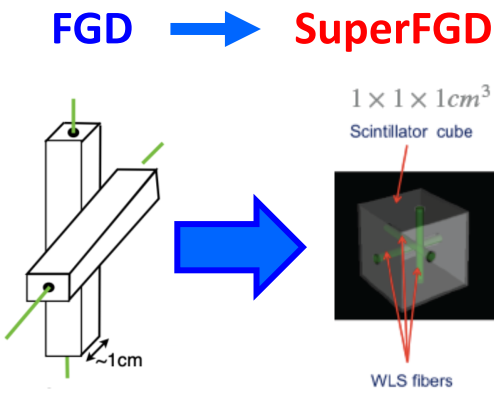
SuperFGD

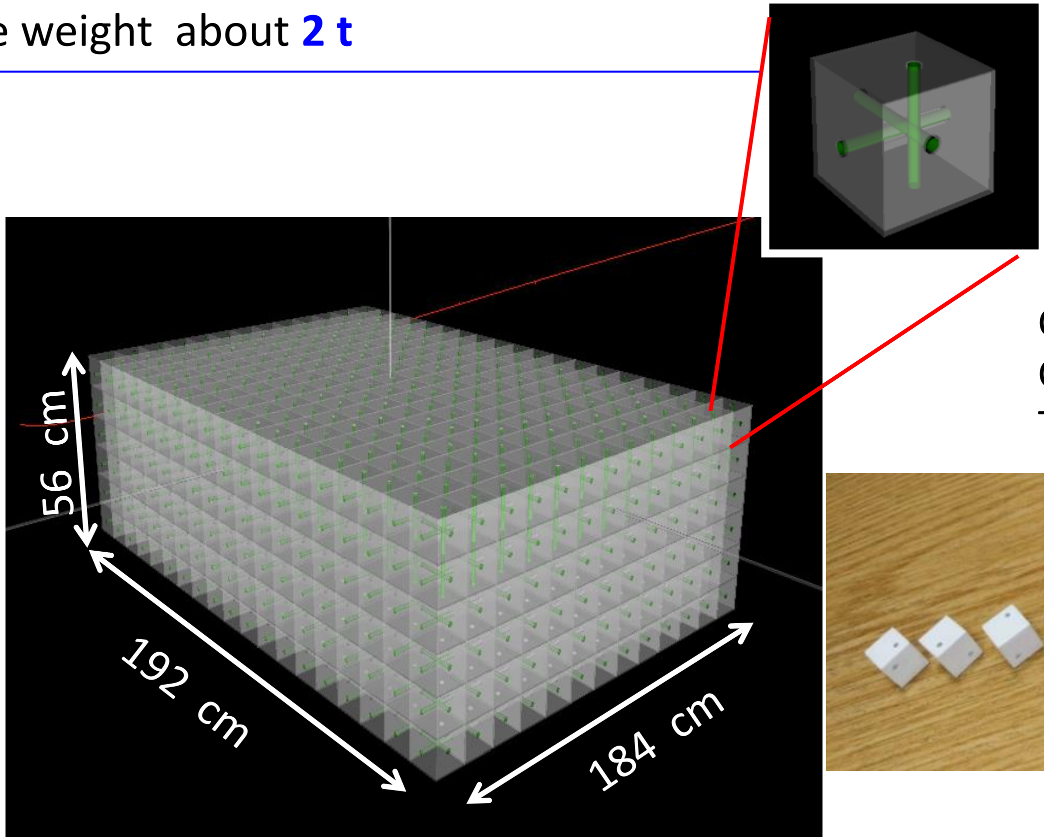
JINST 13 (2018) 02006

- Volume ~192 x 184 x 56 cm^3
- **~2 x 10^6** scintillator cubes , each 1 x 1 x 1 cm^3
- Each cube has 3 orthogonal holes of 1.5 mm diameter
- 3D (x,y,z) WLS readout
- About **60000** readout WLS/MPPC channels
- Total active weight about **2 t**

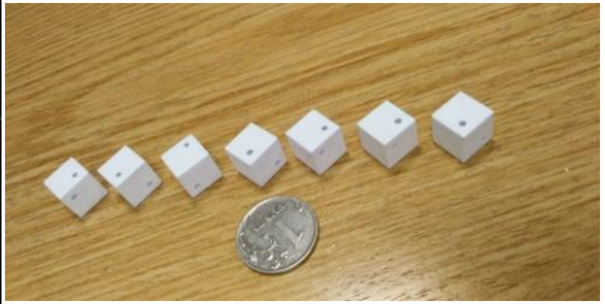
Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout

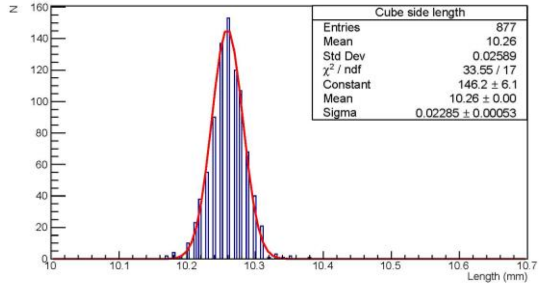






Cubes produced by injection molding
Covered by chemical reflector
Tolerance (each side) about 30 microns



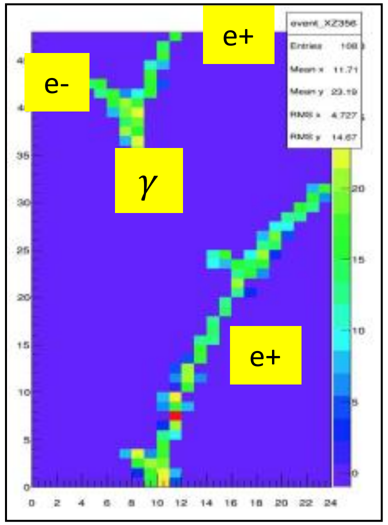


Performance in beam tests (I)

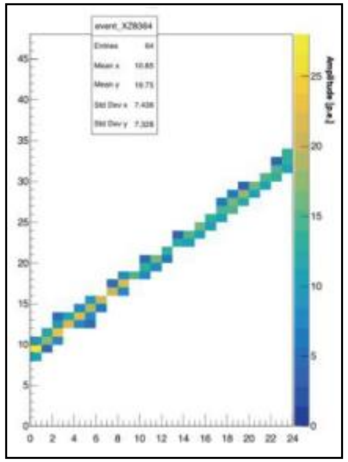
SFGD prototypes were tested:
- with charged particles beams (e, μ, π, p) at CERN
- with neutron beam at LANL

JINST 15 (2020) 12, P12003

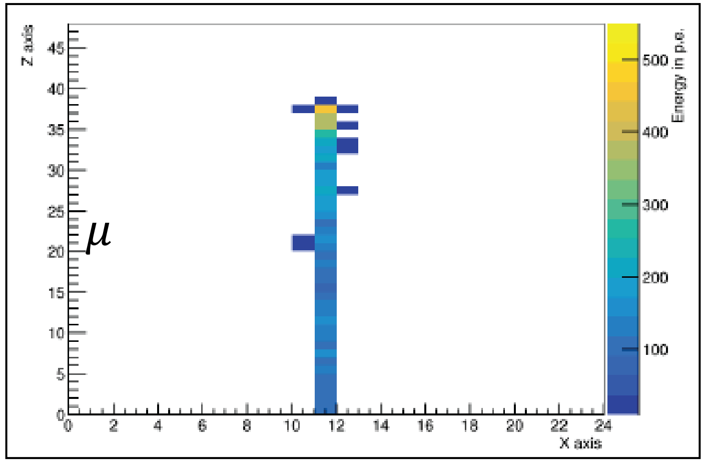
e+, B=0.2T

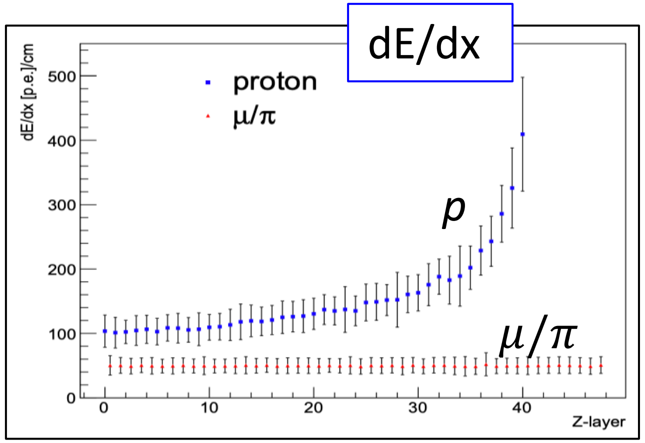


Muons



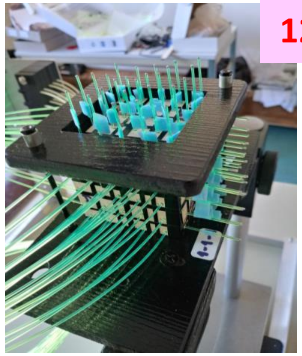
Stopped protons





Parameters of the SFGD prototype
obtained in the beam tests at CERN:
- Light yield of one cube 50-60 p.e./MIP, 1 fiber readout
- Light yield of one cube 150-180 p.e./MIP
  for sum of 3 orthogonal fibers
- Time resolution ~1 ns for MIP and 1 fiber readout
- Dark rate of MPPCs:
  50-70 kHz (th=0.5 p.e.), 0.5 kHz (th=1.5 p.e.)

SFGD prototypes



125 cubes

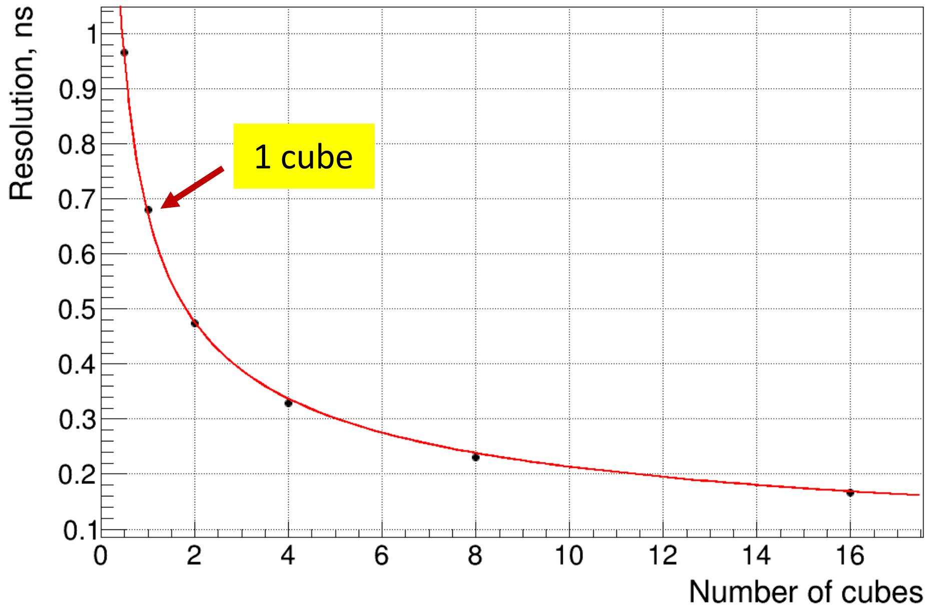
9216 cubes
1728 Y11 WLS fibers
and MPPCs

2048 cubes

Performance in beam tests (II)

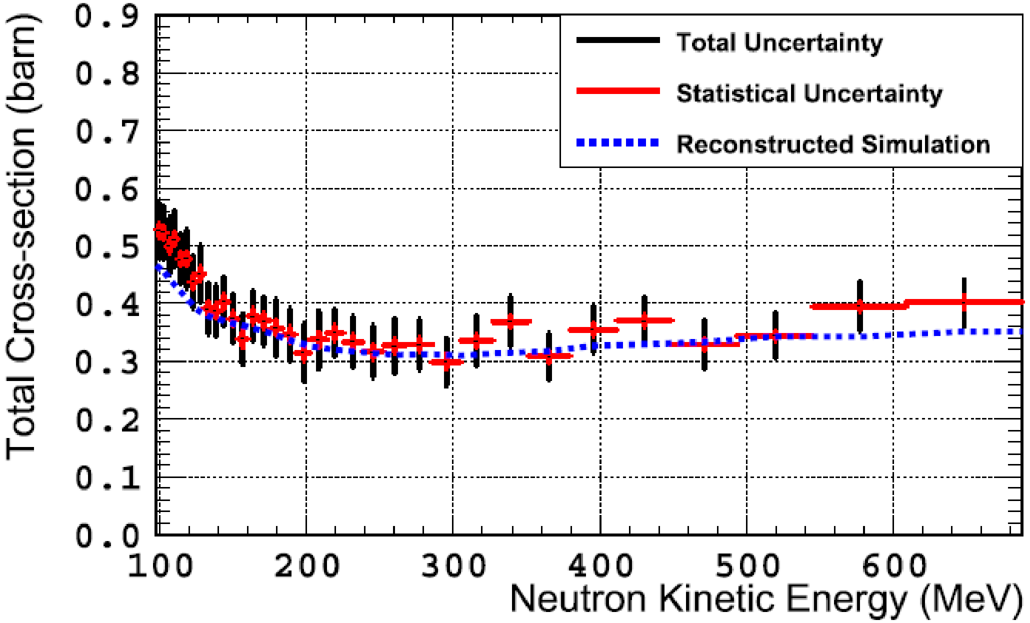
JINST 18 (2023) P01012

SuperFGD time resolution for a MIP



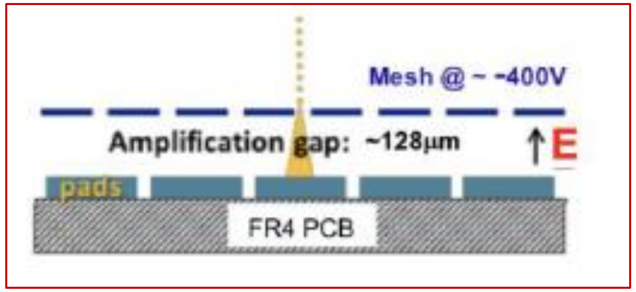
PLB 840 (2023) 137843

Neutron cross-section measurements at LANL with SuperFGD prototypes

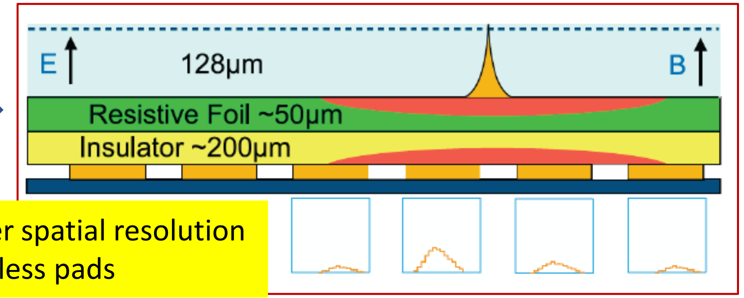


High-Angle TPC

Standard Bulk MicroMegas



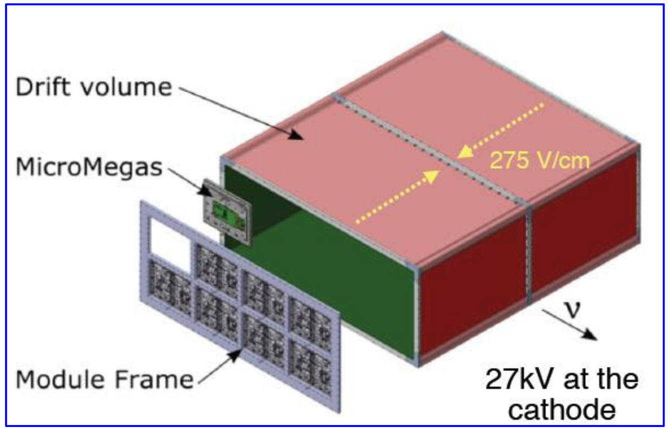
Resistive MicroMegas (RMM)

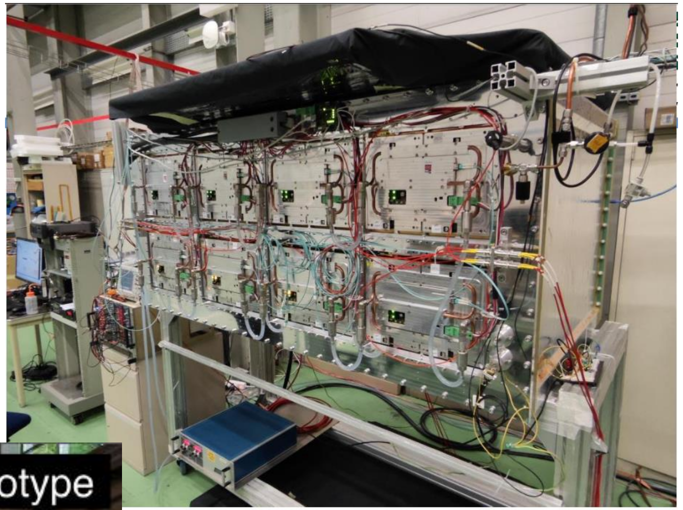


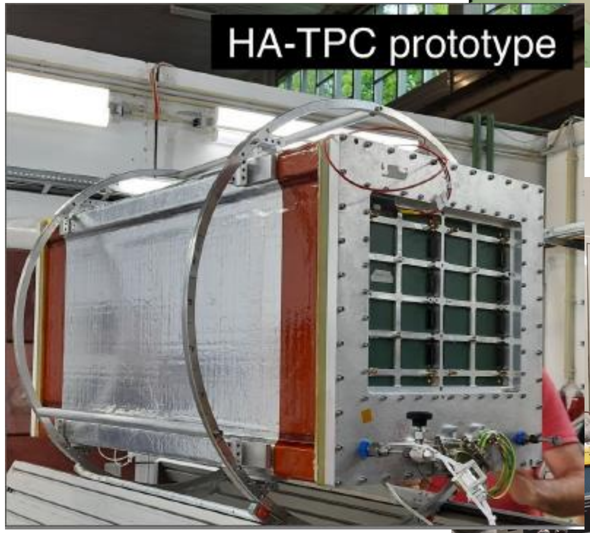
Better spatial resolution with less pads

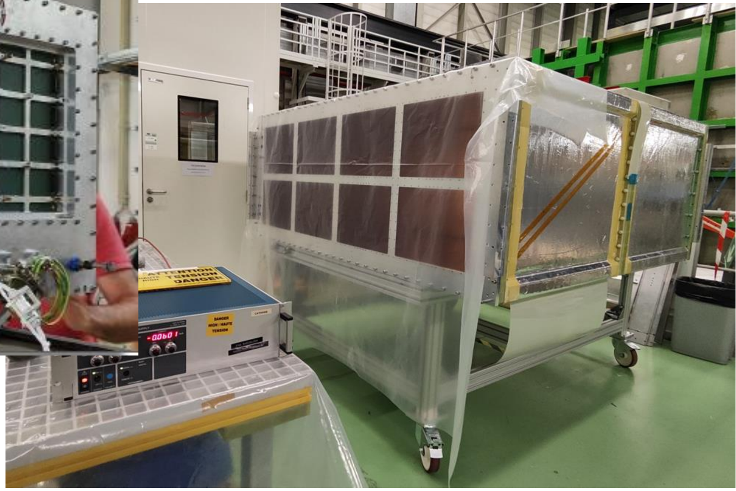
The field cage is a layer of solid insulator laminated on a composite material
→ dead space minimized, tracking volume maximized

Parameter	Value
Overall x × y × z (m)	2.0 × 0.8 × 1.8
Drift distance (cm)	90
Magnetic Field (T)	0.2
Electric field (V/cm)	275
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2
Drift Velocity $cm/\mu s$	7.8
Transverse diffusion ($\mu m/\sqrt{cm}$)	265
Micromegas gain	1000
Micromegas dim. z×y (mm)	340 × 410
Pad z × y (mm)	10 × 11
N pads	36864
el. noise (ENC)	800
S/N	100
Sampling frequency (MHz)	25
N time samples	511







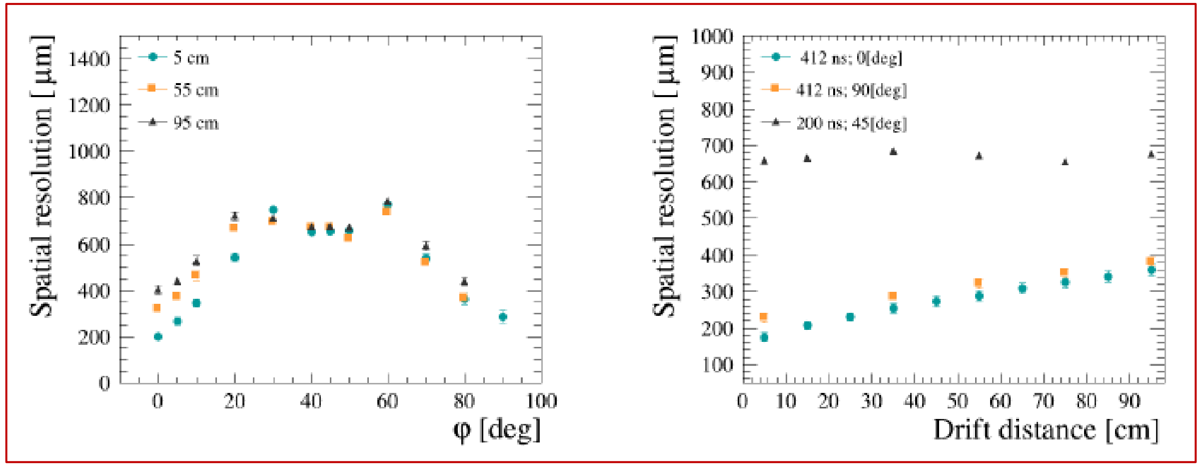


Performance of HA-TPC

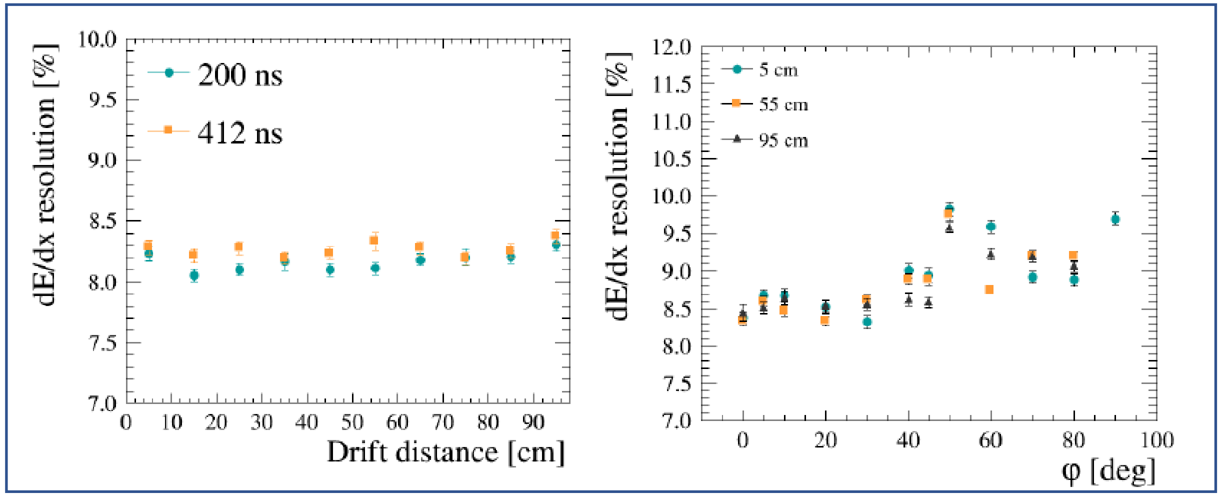
Test with electron beam at DESY

NIM 1052 (2023) 168248

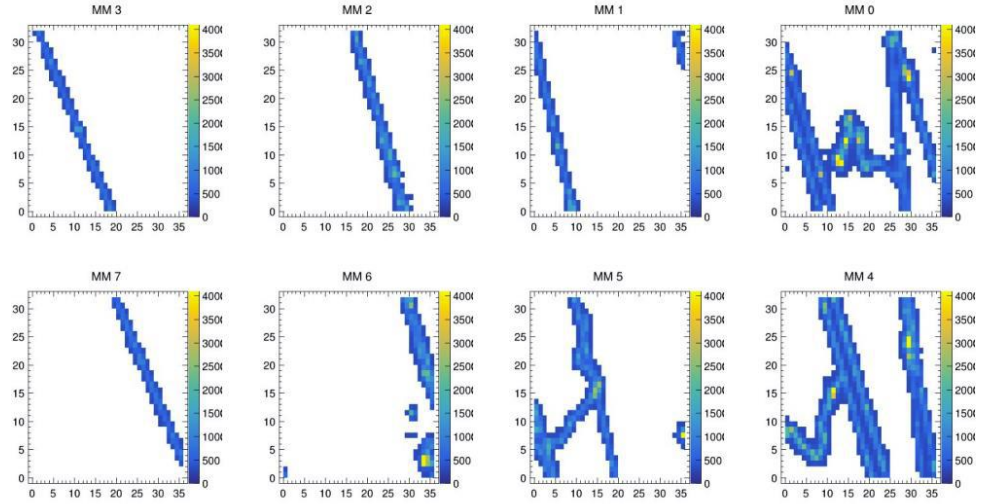
Spatial resolution for a hit < 0.8 mm



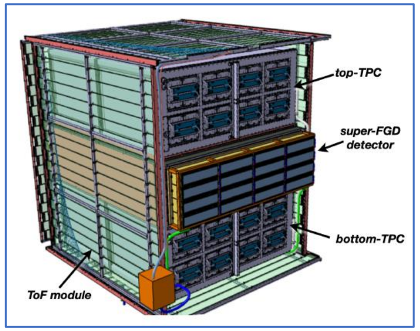
dE/dx resolution < 10%



Cosmic test at CERN



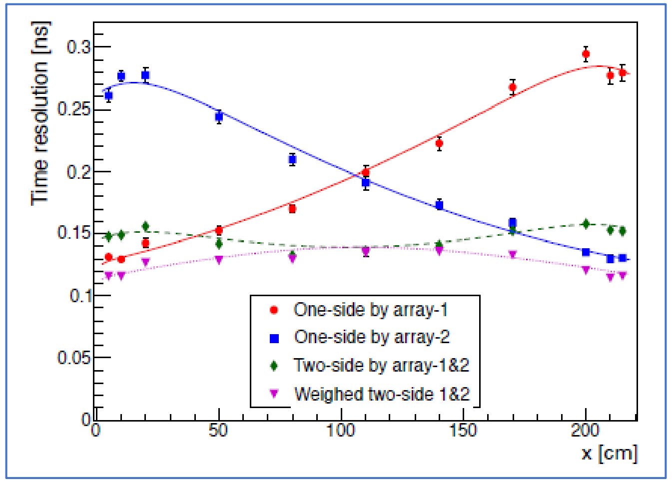
TOF Detector



TOF covers 2 HA-TPCs and SuperFGD
- 6 modules, each comprised of
  20 plastic scintillator bars
- One bar: 220 x 12 x 1 cm3
- Both ends readout by 8 SiPMs on each end

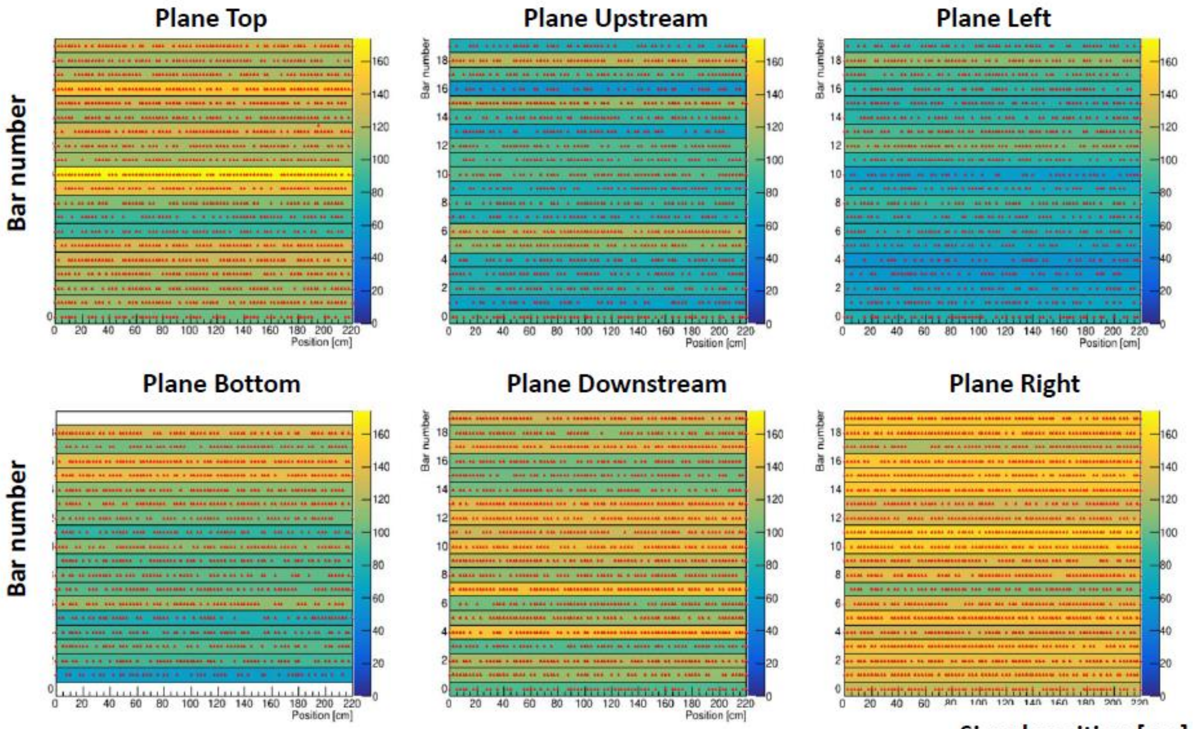
Main Goals:
- Precise measurement of the crossing time of charged particles
- Separate inward going background
- Cosmic trigger for the calibration of Super-FGD and HA-TPCs
- Improvement of particle identification using timing

JINST 17 (2022) 01, P01016



Excellent time resolution of about 130 ps

TOF Event Display

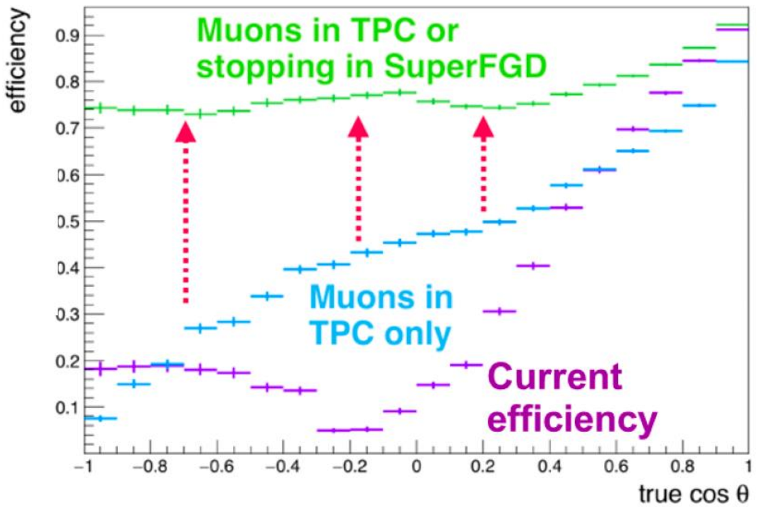


Features of upgraded ND280

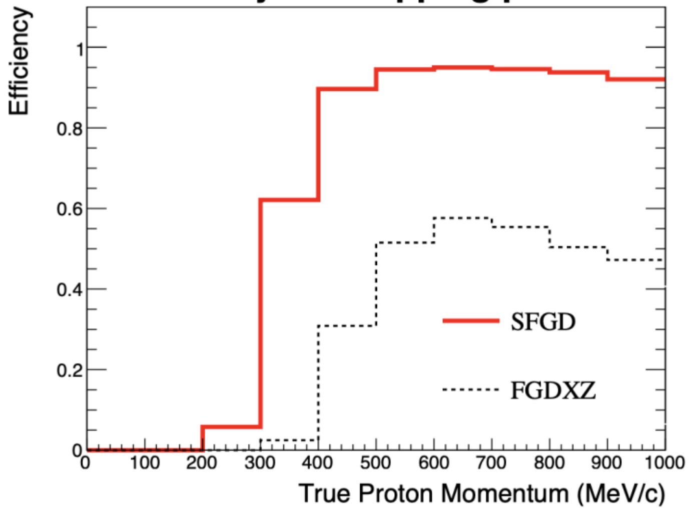
Current ND280 ⇒ ***Upgraded ND280***

- SuperFGD and HA-TPC improve acceptance for high angle and backward tracks
- SuperFGD provides a high precision probe of the nuclear effects responsible for some of the dominant systematics in neutrino oscillation analyses → reduced systematics
- High granularity of SuperFGD → detection of short proton tracks which is very important for T2K analysis
- SuperFGD provides reconstruction of the neutrino energy by time-of-flight
- TOF Detector separates background from outside SuperFGD and HA-TPC

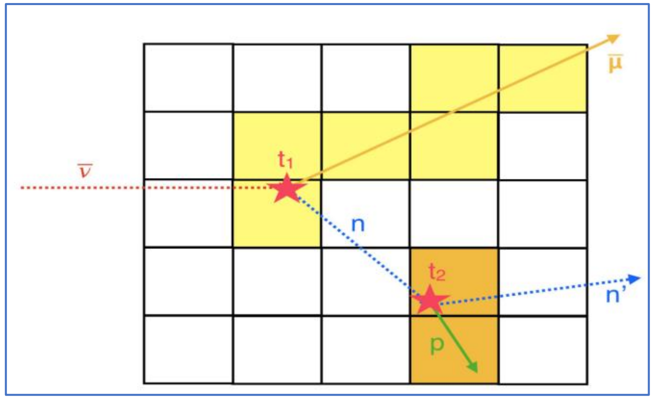
High angle acceptance



Efficiency for stopping protons



Neutron detection by TOF



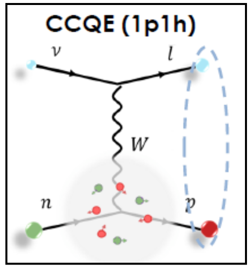
Neutrino energy reconstruction

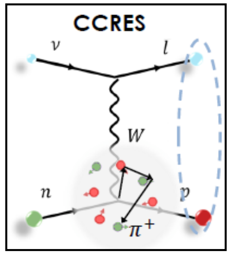
Muon neutrino CC0π

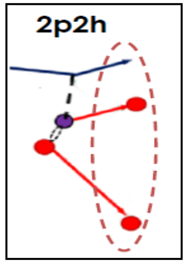
$$\nu_\mu + n \longrightarrow \mu^- + p$$

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

Nuclei smearing and bias E_ν



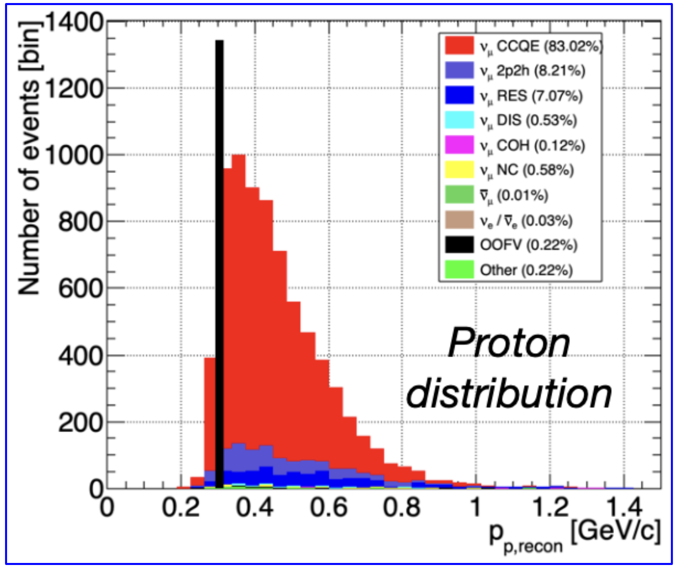


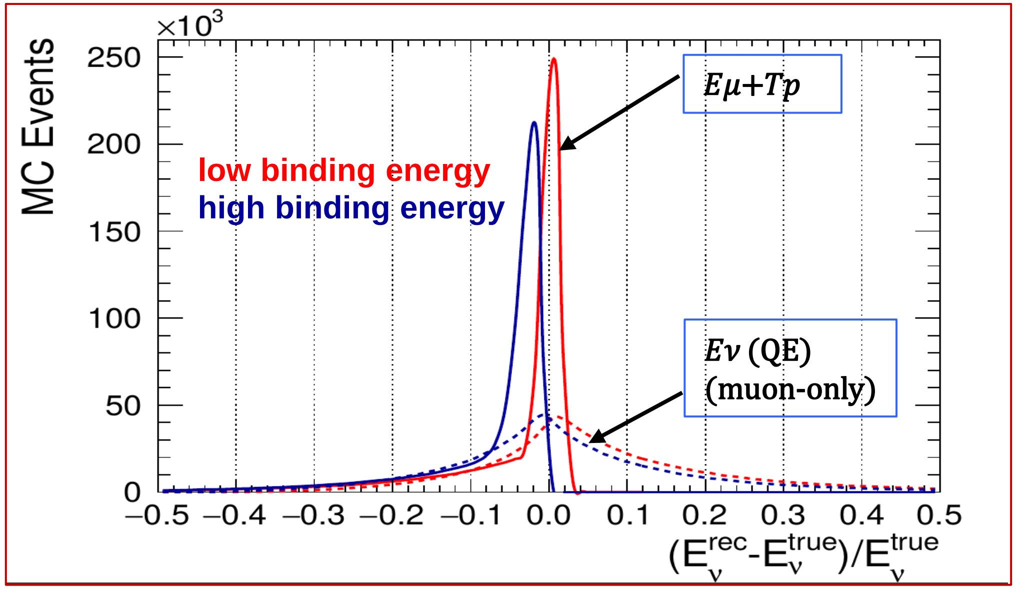


S.Dolan, talk at HEP-EPS 2021

- **Current ND280 uses only muons for reconstruction of the neutrino energy**
- **SuperFGD provides reconstruction of the neutrino energy by measuring both the muon and proton energies**
- **More precise *Eν* reconstruction, more sensitive to oscillation physics**

Proton momentum distribution from ν_μCC 1muon+1proton selection





No detector smearing

Detection of neutrons

Antineutrino CCQE

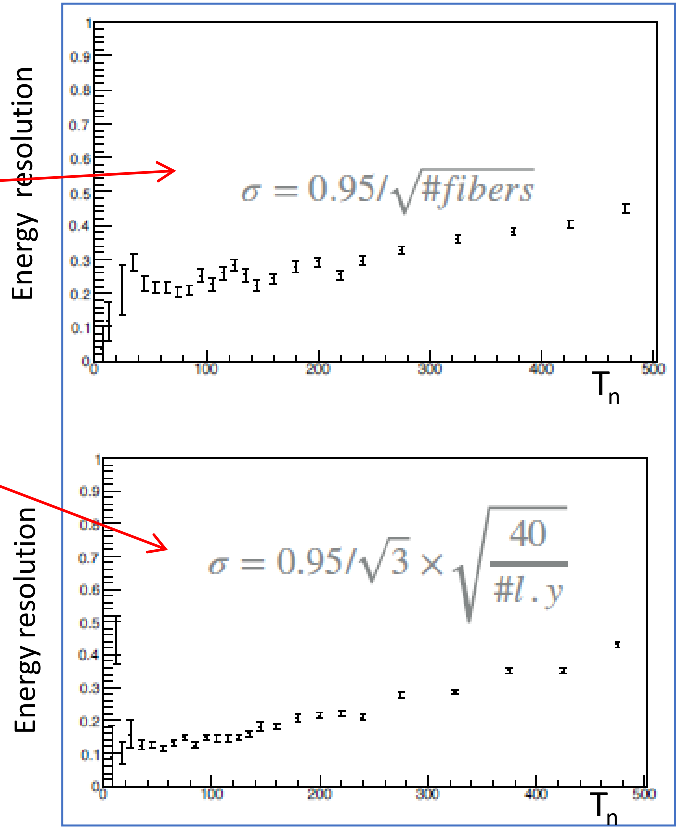
Detection of neutrons by time-of-flight

arXiv:1912.01511

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

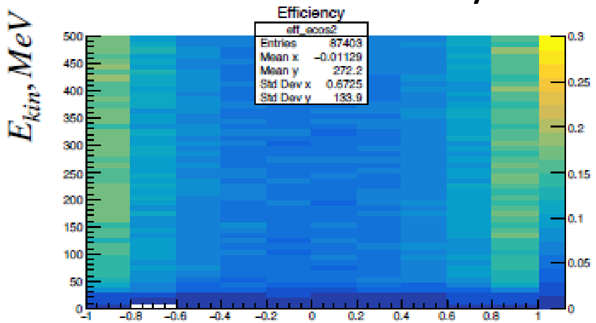
$$\sigma_t = 0.95ns / \sqrt{\#\ fibers}$$

$$\sigma_t = \frac{0.95ns}{\sqrt{3}} \sqrt{\frac{40}{l.y.}}$$

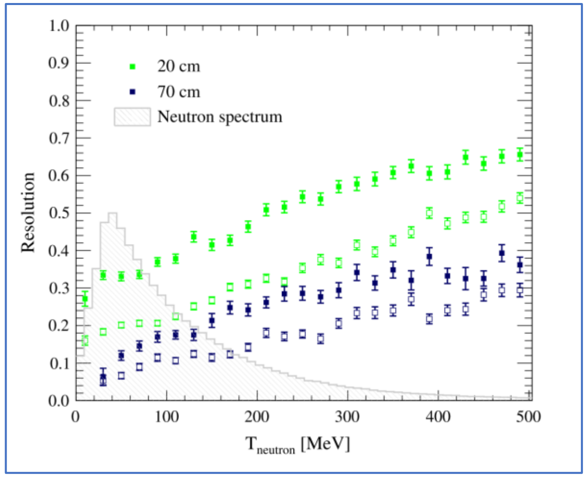


Monte Carlo study

Detection efficiency

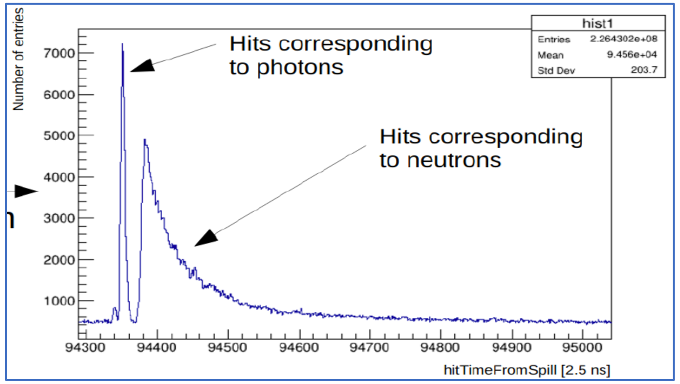


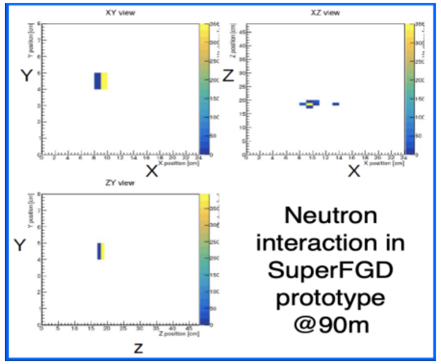
Energy resolution



PLB 840 (2023) 137843

Beam tests with neutrons of SFGD prototype at LANL

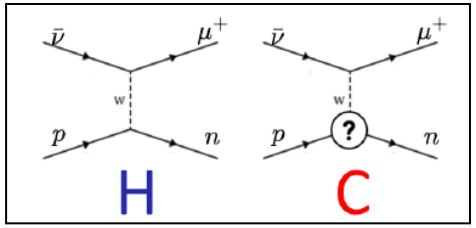




Anti-neutrino energy reconstruction

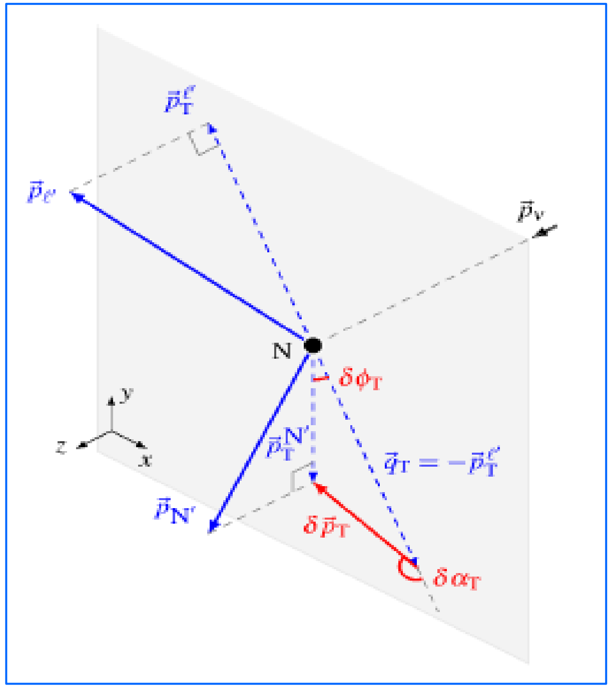
Muon antineutrino CCQE

$$\bar{\nu}_\mu + p \longrightarrow \mu^+ + n$$



Transverse kinematic imbalance

X.-G.Lu et al, arXiv:1512.05548

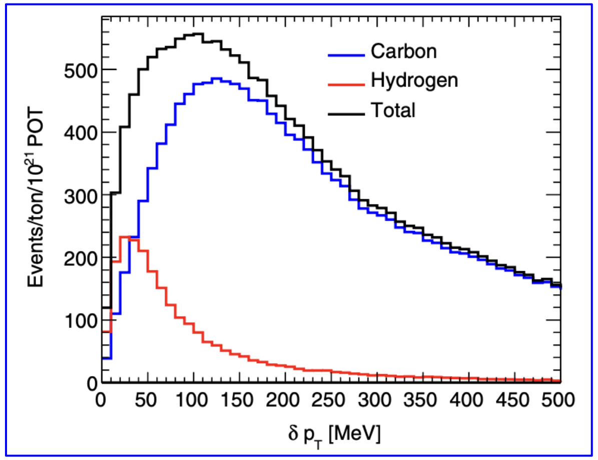


$$\delta p_T = |\vec{p}_T^{\,l} + \vec{p}_T^{\,n}|$$

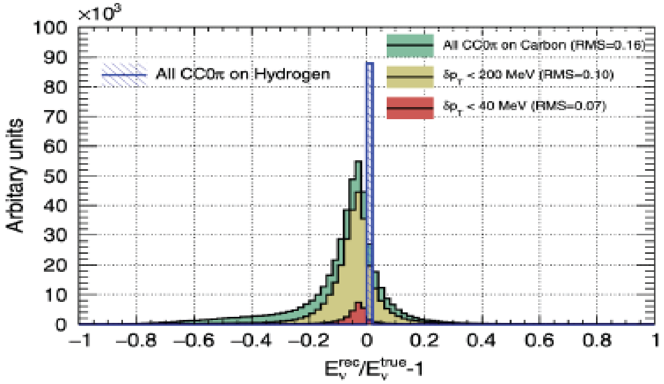
Transverse kinematic imbalance due to Fermi motion, FSI, 2p2h, pion absorption…

For free proton $\delta p_T = 0$

Very low δp_T – signature of neutrino interaction with hydrogen

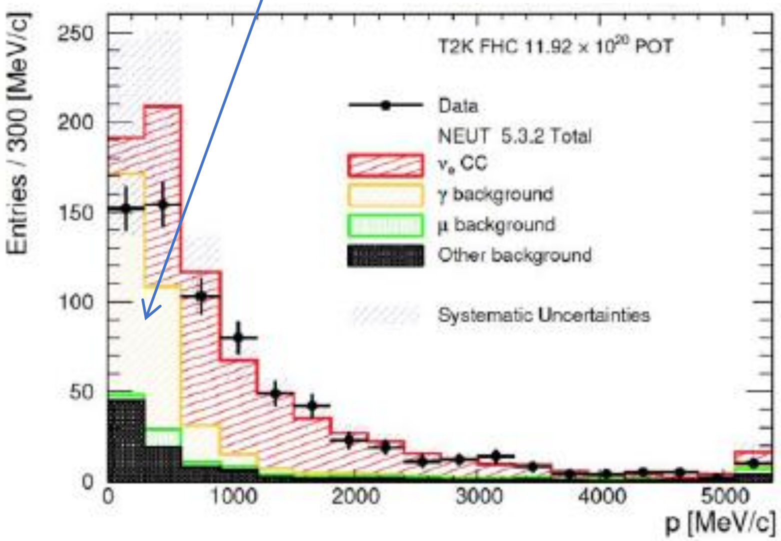


Improvement in reconstruction of $E_{\bar{\nu}}$ using detected neutron

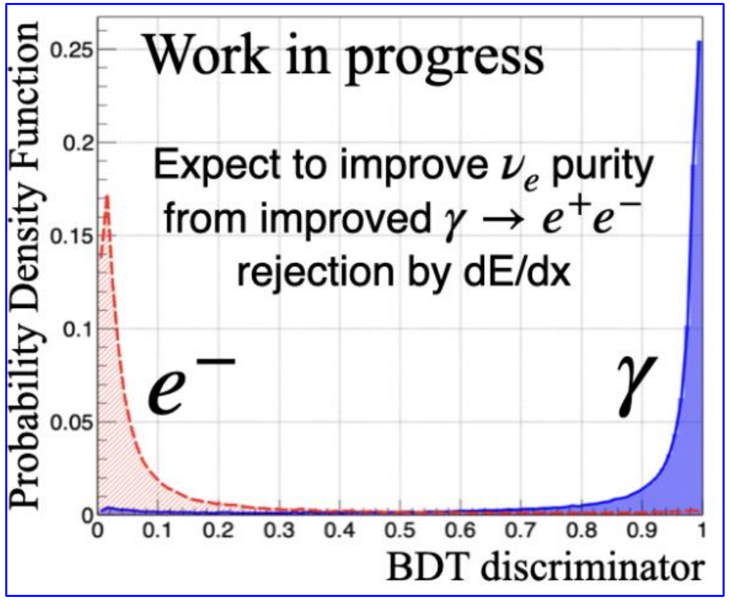


ν_e constraints

ND280: large contributions from photons in ν_e spectrum



SuperFGD: expected excellent electron/photon separation



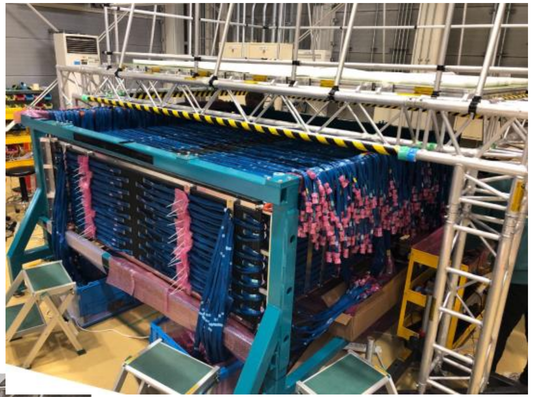
Understanding of difference between $\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$, $\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_\mu)$ - crucial for a search for **CP violation** in neutrino oscillations and measurements of **oscillation parameters**

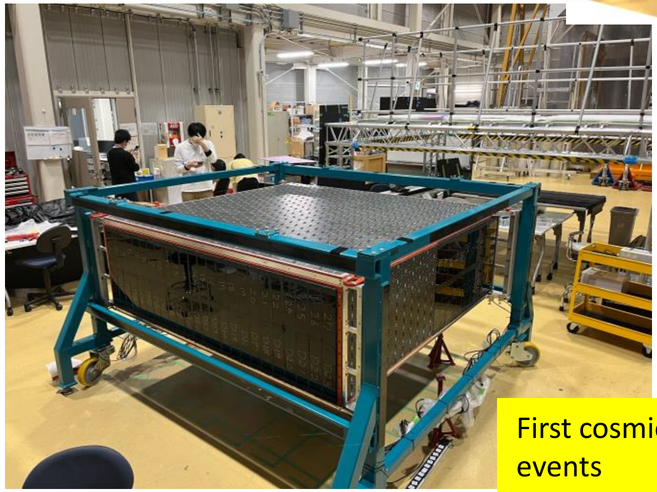
Measurement of double ratio:

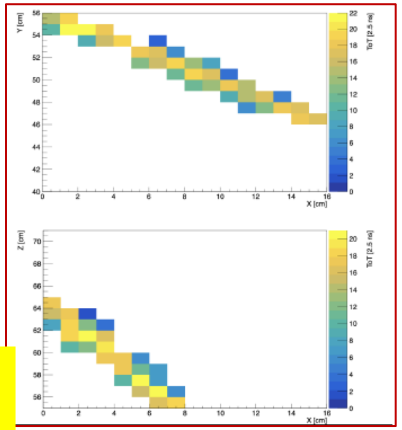
$$[\sigma(\nu_\mu)/\sigma(\nu_e)] / [\sigma(\bar{\nu}_\mu)/\sigma(\bar{\nu}_e)]$$

Status of ND280 upgrade

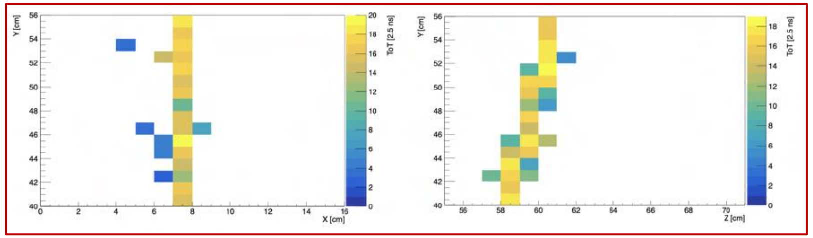
SuperFGD at J-PARC,
electronics installation,
calibration,
tests with cosmic muons
on surface





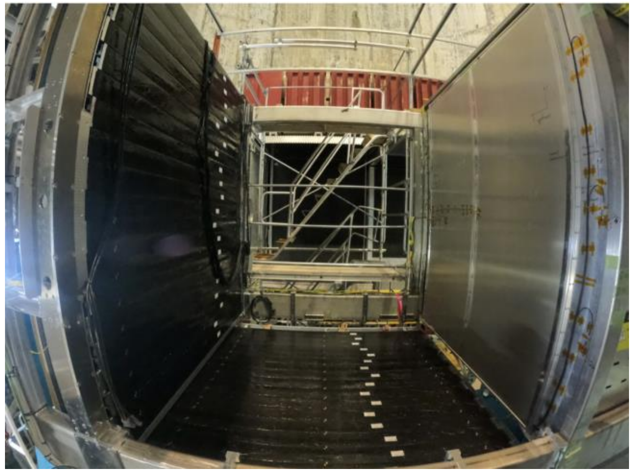


First cosmic
events



Bottom TPC is assembled at CERN.
To be delivered to J-PARC
in August 2023

TOF detector at J-PARC.
2 modules installed into
the Near Detector pit



The upgraded ND280 is to begin collecting neutrino data in November 2023

Conclusion

- Ambitious upgrade of T2K near detector ND280 is in progress
- Reduction of T2K systematic uncertainties – crucial for CP-violation search and oscillation measurements
- Rich neutrino interaction physics
- Upgraded ND280 detector is to take neutrino data in November 2023

Thank you very much for your attention