The T2K near detector upgrade

Dung Nguyen Thi, VNU-HUS, Hanoi, Vietnam [1]

on behalf of T2K collaboration

Neutrinos Physics, 17-23 July 2022, Quy Nhon, Vietnam

July 20, 2022

[1] Email: nguyenthidung.hus@vnu.edu.vn

Content

1. Physics Motivation
2. T2K Experiment
3. T2K Near Detector Upgrade status

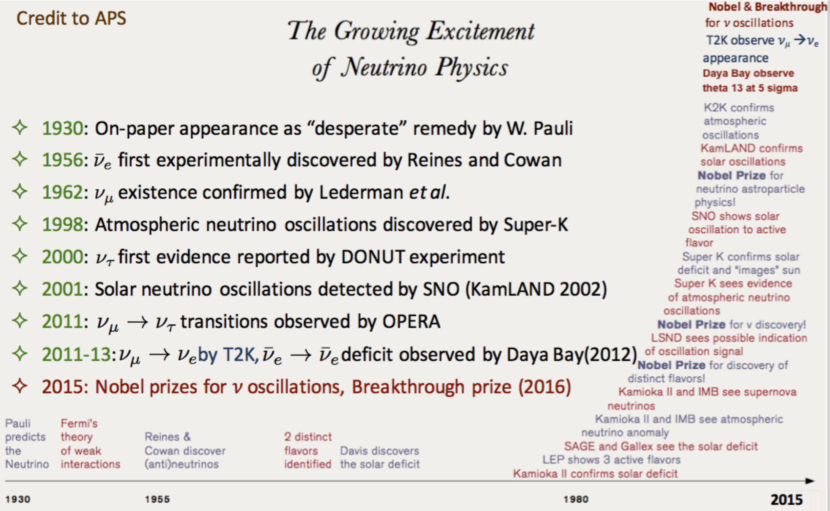
Content

Brief Neutrino History

Credit to APS

The Growing Excitement of Neutrino Physics

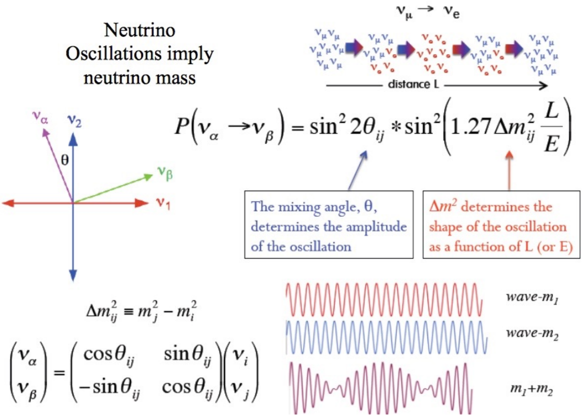
- 1930: On-paper appearance as "desperate" remedy by W. Pauli
- 1956: $\bar{\nu}_e$ first experimentally discovered by Reines and Cowan
- 1962: ν_μ existence confirmed by Lederman *et al.*
- 1998: Atmospheric neutrino oscillations discovered by Super-K
- 2000: ν_τ first evidence reported by DONUT experiment
- 2001: Solar neutrino oscillations detected by SNO (KamLAND 2002)
- 2011: $\nu_\mu \to \nu_\tau$ transitions observed by OPERA
- 2011-13: $\nu_\mu \to \nu_e$ by T2K, $\bar{\nu}_e \to \bar{\nu}_e$ deficit observed by Daya Bay(2012)
- 2015: Nobel prizes for ν oscillations, Breakthrough prize (2016)



Neutrino oscillations

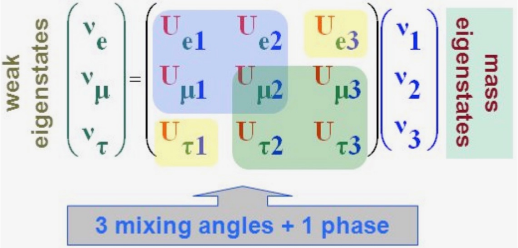
- Neutrino have mass and mixings:

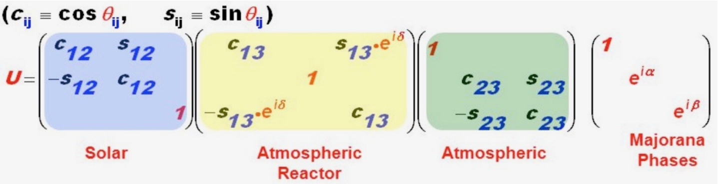
$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i$$



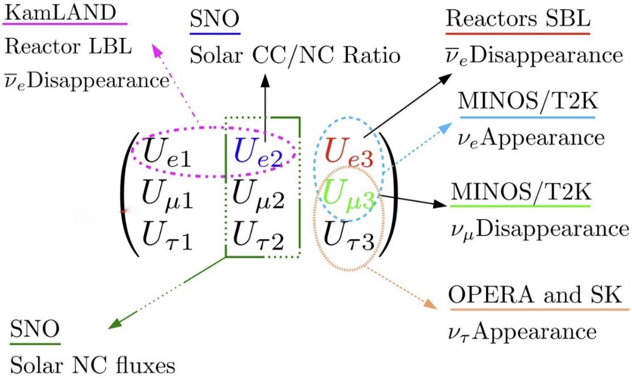
Neutrino oscillations

- Pontecovo - Maki - Nakagawa - Sakata (PMNS) matrix





Results are coming from the experiments



Measured oscillation parameters

$$\Delta m^2_{31} = \Delta m^2_{atm} \approx 2.56^{+0.03}_{-0.04} x 10^{-3} eV^2$$

$$\Delta m^2_{21} = \Delta m^2_{solar} \approx 7.5^{+0.22}_{-0.20} x 10^{-5} eV^2$$

$$sin^2\theta_{23}/10^{-1} \approx 5.66^{+0.16}_{-0.22}$$

$$sin^2\theta_{13}/10^{-2} \approx 0.093 \pm 0.008$$

$$sin^2\theta_{12}/10^{-1} \approx 3.18 \pm 0.16$$

The T2K results: Nature (2020) 580 339 - 344

$$P(\nu_\mu \to \nu_e) \sim sin^2(2\theta_{13}) sin^2(\theta_{23}) sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

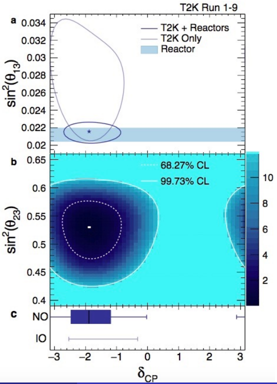
$$\mp \frac{1.27\Delta m^2_{21} L}{E} 8 J_{CP} sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - 4cos^2(\theta_{13}) sin^2(\theta_{23}) \times [1 - cos^2(\theta_{13}) sin^2(\theta_{23})] \times$$

$$sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

T2K improve the oscillation parameters

- $sin\theta_{23} = 0.03^{+0.03}_{-0.04}$ (both mass ordering)
- $\Delta m^2_{32} = 2.45 \pm 0.07 \times 10^{-3}$ (NO)
- $\Delta m^2_{13} = 2.43 \pm 0.07 \times 10^{-3}$ (IO)
- $\delta_{CP} = -1.89^{+0.7}_{-0.58} (-1.38^{+0.48}_{-0.54})$



Content

T2K experiment

Main goals

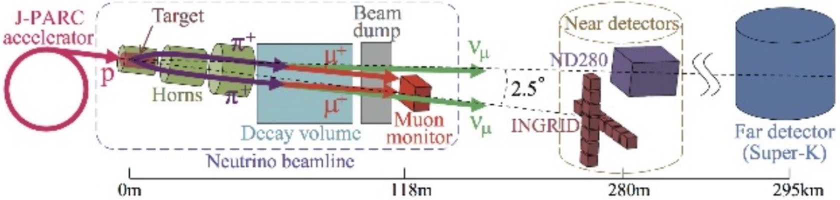
- Discovered appearance of $\nu_\mu \to \nu_e$ $\theta_{13}(2013)$, δ_{CP}
- Measurement of $\nu_\mu \to \nu_\mu$ θ_{23}, Δm^2_{32}

T2K upgrade $\to$ 3σC.L on δ_{CP}

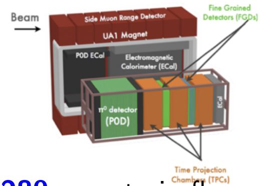
- Long-baseline (295 km) ν experiment in Japan from J-PARC(Tokai) to Super-K (Kamioka)

- p (30GeV) + graphite $\to \mu + \nu_\mu (\approx 600 MeV)$ - high intensity
- The MR beam power: from 500kW to 700kW(2022) and 1.3 MW (2028), 30×10^{20}POT (Proton On Target/year)

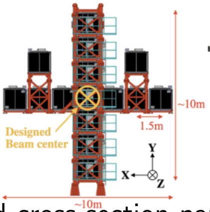
Near Detector



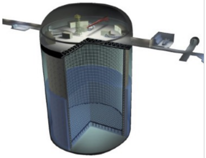
ND280



INGRID



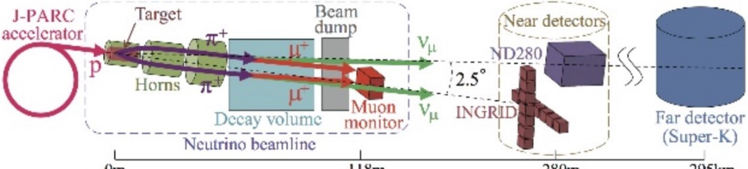
SK



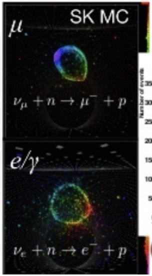
- **ND280:** constrain flux and cross-section parameters
- **INGRID:** Measure ν beam intensity & profile: 16 scintillator-stell interleaved modules (7.1 tons/each)

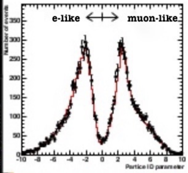
Far Detector, Super - Kamiokande

- Super-K is 2.5° off the beam's axis to achieve narrow band beam peaked at oscillation maximum (0.6GeV)



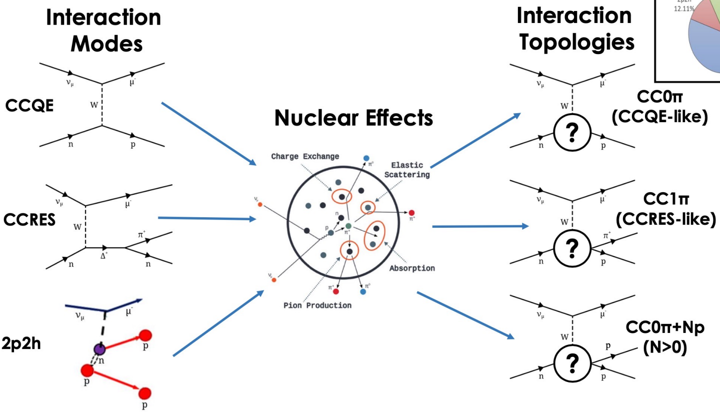
- Muon and electron are well-separated → identify ν_μ/ν_e with high purity

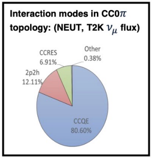




(atmospheric ν data)

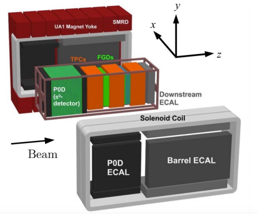
Physics Processes vs Event Topologies

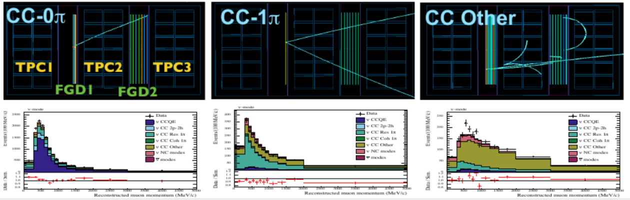




Content

Role of Near Detectors

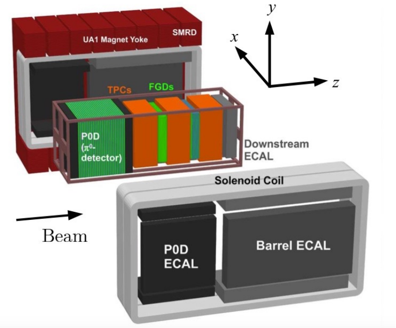


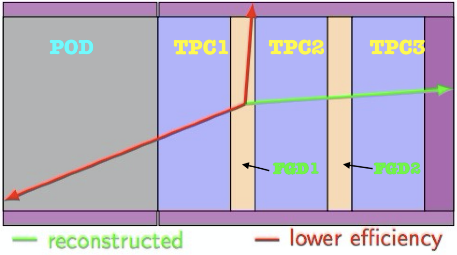


- Near Detector complex is 280m downstream of neutrino production point (target).
- Measurement of the interaction rates before oscillation
- Measurement of neutrino nucleus cross-section in several channels
- Strongly constrain the expected rates at Super-K for precision oscillation analyses

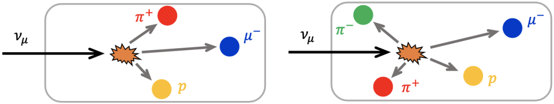
good acceptance only for forward tracks

Limitation of current ND280





- Small acceptance
- Low efficiency to reconstruct the hadronic part (π, p) of the interactions



Motivation of T2K near detector upgrade

- Control the systematic uncertainties associated with the ν production and detection
  - ↑ POT in T2K-II goal → ↓ Stat. error
  - Current sys. error $\nu_e(\bar{\nu}_e)$ event candidates is 8.8 (7.1%)
  - Near future: Suppression of sys. error becomes more important

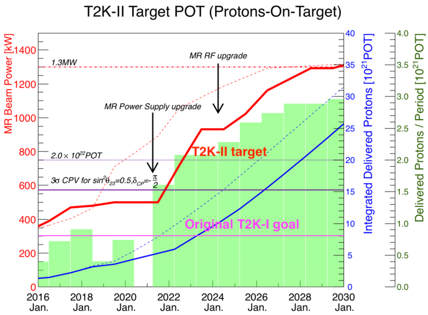
PRD 103, 112008 (2021) Fractional uncertainty on event rate in %

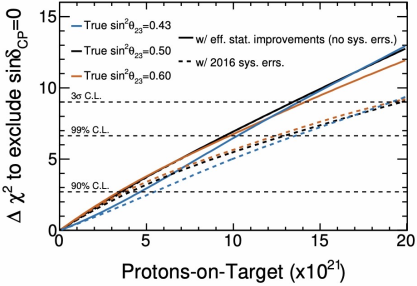
Error source	1-Ring μ FHC	1-Ring μ RHC	1-Ring e FHC	1-Ring e RHC	1-Ring e FHC 1 d.e.	1-Ring e FHC/RHC
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross-section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
SK Detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI + SI + PN	2.2	2.0	3.0	2.3	11.4	1.6
Nucleon Removal Energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All Systematics	5.1	4.5	8.8	7.1	18.4	6.0

- Dominant error is Flux (**Detector upgrade**) + Cross section (Interaction model) → aiming to **reduce overall error to 4%**

T2K Upgrade plan

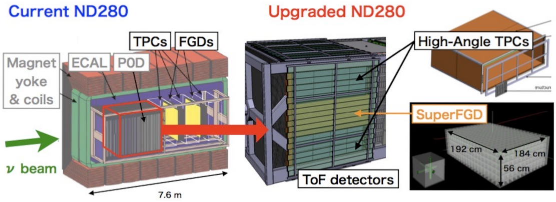
- T2K upgrade near detector: expected ↓ overall systematic uncertainty to 4%
- Goal of T2K upgrade is to accumulate enough POT → to exclude $\sin\delta_{CP}=0$ at 3σ
  an installation is expected in the first half of 2023

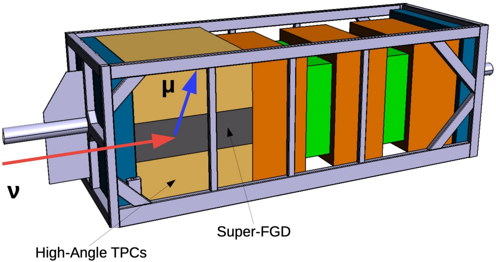




ND280 upgrade

POD → Super-FGD, 2 HA-TPCs, 6 ToF planes

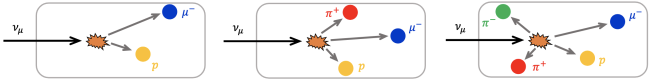




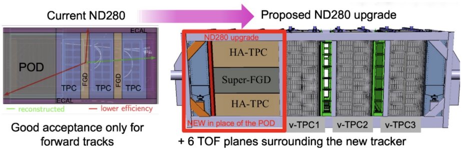
Super-FGD
→ improve the reconstruction hadronic part and low momentum leptons

2 HA-TPCs
→ improve the reconstruction high angle leptons

6 ToF planes
→ reduce background from the outside of SuperFGD

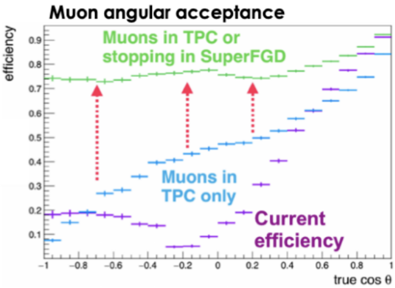


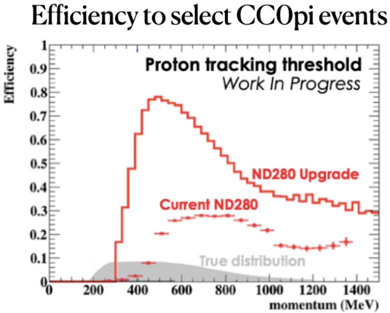
Efficiencies of ND280 upgrade



Efficiencies of ND280 upgrade:

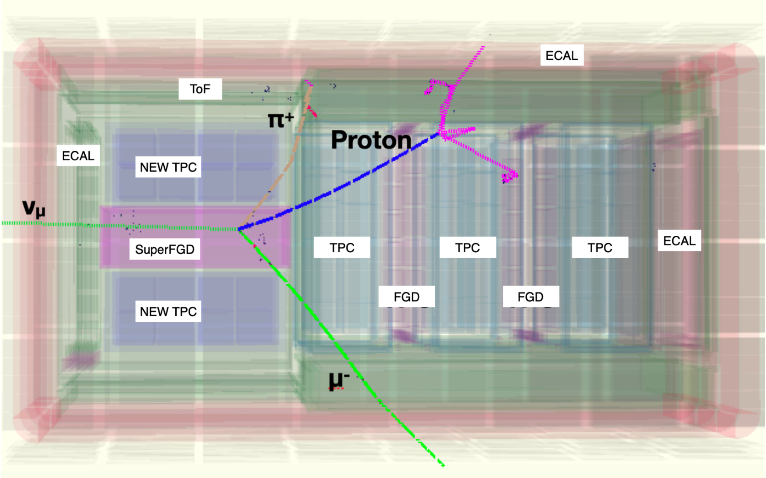
4π acceptance, high efficency of particle low momentum.





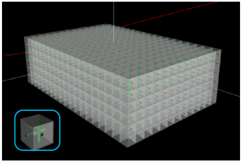
Event display in ND280 upgrade

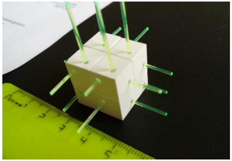
CC1π event: $\nu_\mu + N \rightarrow \pi^+ + p + \mu$

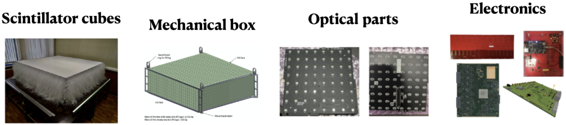


SuperFGD

- 2 million cubes 1x1x1 cm^3 plastic scintillator cubes with 3 holes
- Fully active target (200 x 180 x 60 cm^3)
- Active mass 2,2 tons
- $\sim$ 60 000 readout WLS and MPPC
- 3D reconstruction and high segmentation, 4π acceptance
- Good tracking, timing, PID



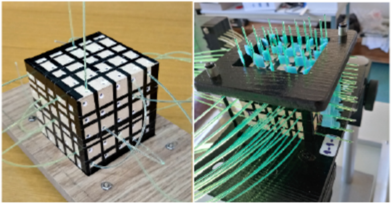




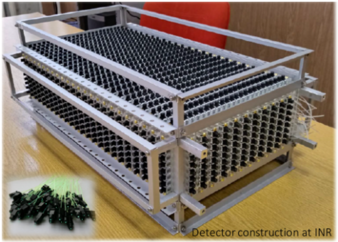
Prototypes test

Two prototypes 125 and 9216 cubes were tested at CERN (2017 , 2018)

5 x 5 x 5



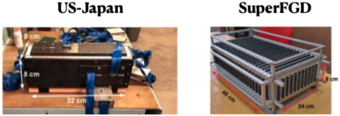
8 x 24 x 48



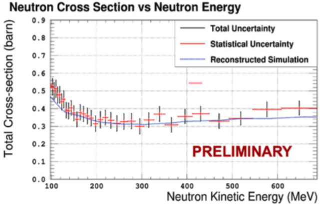
Test shows the upgrade achieving requirement

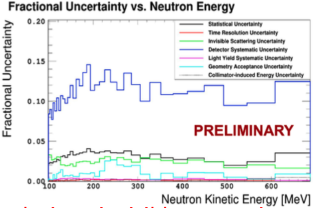
Neutron test beam in LANL

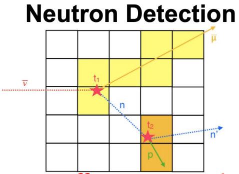
- 2 prototypes (Super-FGD and US-Japan) were tested in 2019 and 2020 in LANL



- Neutron beam energy ranges from 0 to 800 MeV
- Access to neutron kinematic is crucial to understanding better anti-neutrino CCQE and 2p2h interactions







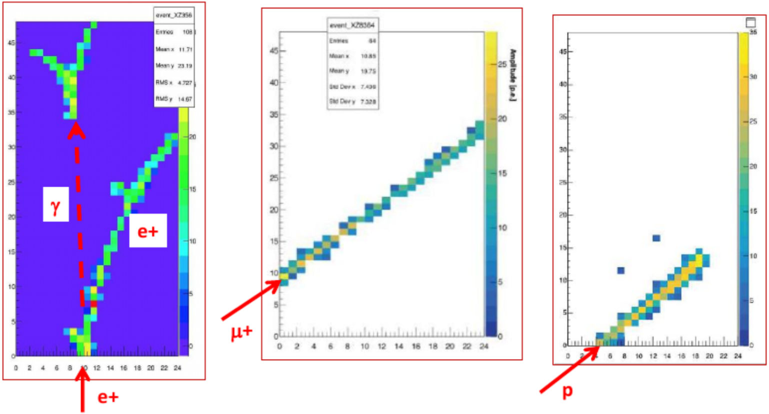
Source of uncertainties: time resolution, invisible scattering, detector effect, geometric acceptace, collimator-induced energy

SuperFGD test beam events

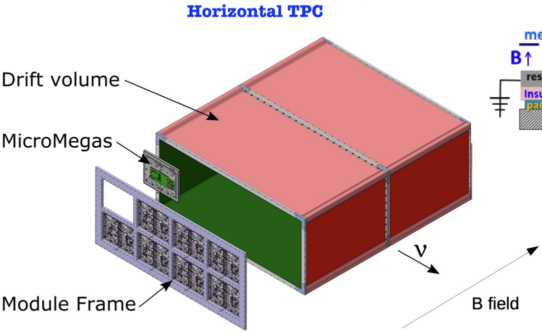
Positron, 1 GeV, B = 0.2 T

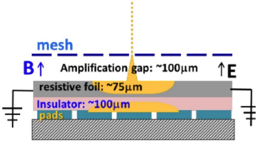
Muon, 5 GeV, 45 deg

Stopped proton, 0.5 GeV, 45 deg



High Angle - TPC



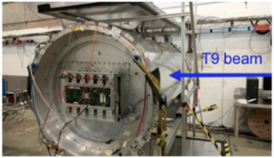


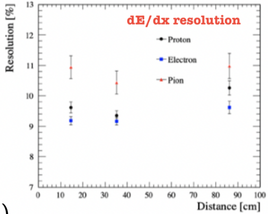
Resistive Micromegas

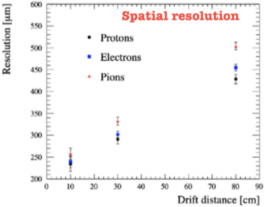
- Main difference with existing TPC: thin field cage, resistive Micromegas module
- Main purpose
  - High-resolution tracking (3D reconstruction) of charged particles
  - Particle identification (charge and momentum measurements)
- HA-TPC requirement:
  - To distinguish between μ/e at 3σ level $\rightarrow$ **energy resolution $\leq$ 10%**
  - Momentum resolution $\leq$ 10% at 1 GeV/c $\rightarrow$ **spatial resolution $\leq$ 0.8 mm**

High Angle - TPCs performance

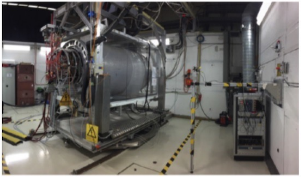
- CERN 2018 (Nucl. Instrum. Meth.V. 957, (2020) **Achieve requirements**
  1.5 m drift distance; MM0-DLC1 (HARP field cage); e, π, p (0.5-2GeV); Spatial resolution is 300 μm at 30 cm drift distance; dE/dx $\sim$ 10% for a MIP for 35 cm track length

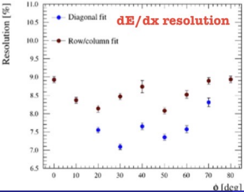


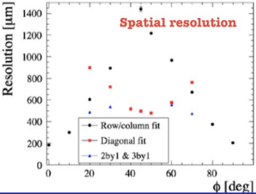




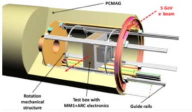
- DESY 2019 (arXiv:2106.12634)
  0.15 m drift distance; MM1-DLC1; e (0.5-5GeV); Spatial resolution is 600 μm; dE/dx $\sim$ 9% for all angles

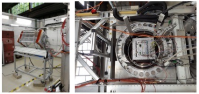






DESY 2021 test beam results

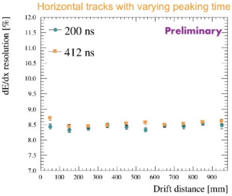


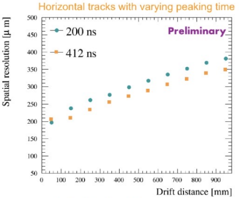


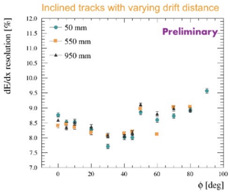
4 GeV e-; 1 m drift distance

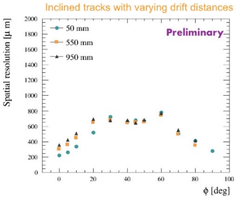
In order to ensure that setup satisfies the ND280 upgrade requirements the test beam intended to:

- test the setup stability
- characterize the charge spreading and study resistive foil uniformity.
- measure spatial and energy resolution;

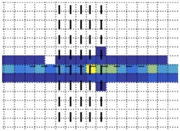




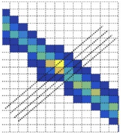




Horizontal track



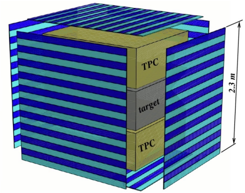
Inclined track

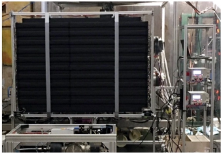


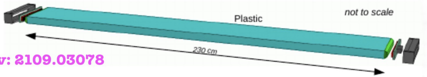
Fullfill the requirements: dE/dx resolution < 10% and spatial resolution < 0.8mm

Time of Flight detectors

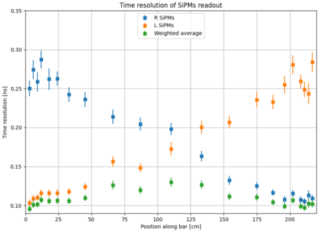
Goals: Identification of the direction of the track using time stamp → veto the bkg from outside of SuperFGD

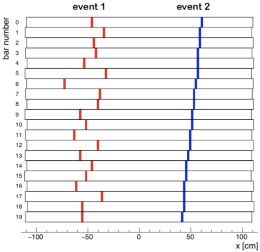






arXiv: 2109.03078





- 6 ToF modules will fully cover 2 HA- TPC and Super-FGD
- Each module 2.4 x 2.2 m^2 consists of 20 scintillator bars
- Readout of 8 MPPC/side (16 MPPC/bar) and total 236 readouts.

time resolution is 0.14 ns

ND280 upgrade physics studies

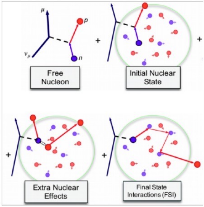
Flux model · Detector model · Neutrino interaction model · Oscillation Probability

$$N^{ND}_{\nu_\alpha}(E_\nu) = \boxed{\Phi^{ND}_{\nu_\alpha}(E_\nu)} \times \boxed{\epsilon^{ND}(E_\nu)} \times \boxed{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

$$N^{FD}_{\nu_\beta}(E_\nu) = \boxed{\Phi^{FD}_{\nu_\beta}(E_\nu)} \times \boxed{\epsilon^{FD}(E_\nu)} \times \boxed{\sigma^{FD}_{\nu_\beta}(E_\nu)} \times \boxed{P_{\nu_\alpha \to \nu_\beta}(E_\nu)}$$

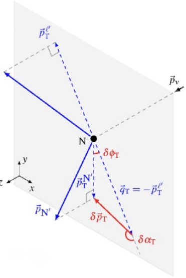
Upgrade → access to reconstruct in hadronic part of the final state → new, more powerful variables: $\delta p_T, \delta\alpha, E_{vis}$

Nuclear effects are the main source of E_ν uncertainty



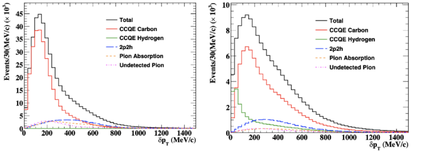
- Fermi motion
- Removal energy
- Final State Interactions
- Non quasi-elastic event without pion in final state (2p2h, pion, absorption, undetected pion)

arXiv:2108.11779



- missing momentum $\delta p_T = |p_T^\mu - p_T^{p(b)}|$
- Transverse boosting angle $\delta\alpha$
- Visible energy $E_{vis} = E_\mu + T_{p(n)}$ where $T_{p(n)}$ kinetic

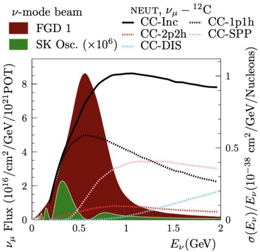
Future OA for ND280 upgrade
→ multidimensional fit μ + hadron kinematics



- δp_T: Fermi motion, 2p2h, seperate CCQE/non-CCQE
- $\delta\alpha$ shape sensitive to FSI
- E_{vis}: Nuclear removal energy

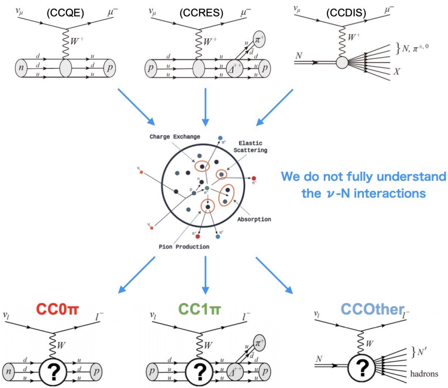
Constraints by NDs on ν-N interaction model

The oscillation probability depends on E_ν



$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

Reconstructed E_ν from outgoing tracks



We do not fully understand the ν-N interactions

E_ν reconstruction accuracy highly depends on the interaction types. We are working on it with ND.

Conclusion

- T2K upgrade goal is 3σ significance to CP violation
  - Beam power is expected to increase from 0.5 MW to 1.3 MW (30×10^{20}POT/year)
- ND280 upgrade intended to reduce total systematics
  - ND280 upgrade is in the preparation stage, and an installation is expected in the first half of 2023
  - Super-FGD: more massive (2.2t), more statistics
  - Super-FGD and HA-TPCs performance was tested and simulation and reconstruction procedures are currently under development
  - ND280 upgrade program shows the impressive ability to constrain key systematic uncertainties.

THANK YOU

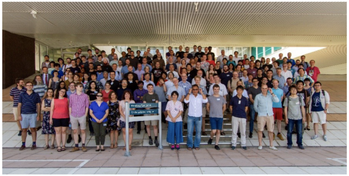
T2K collaboration

The T2K Collaboration (2022)

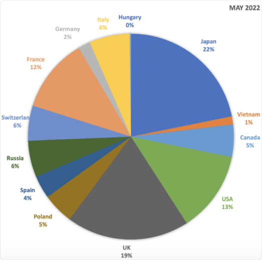
~528 members, 76 Institutes, 14 countries

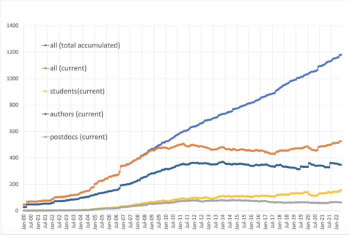
Asia	109
Japan	103
Vietnam	6

Americas	84
Canada	24
USA	60



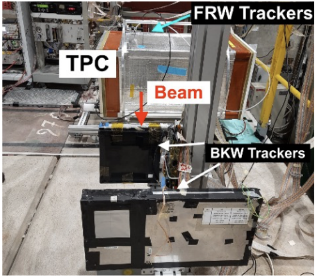
Europe	279
France	55
Germany	9
Hungary	1
Italy	30
Poland	23
Russia	27
Spain	17
Switzerland	26
UK	91



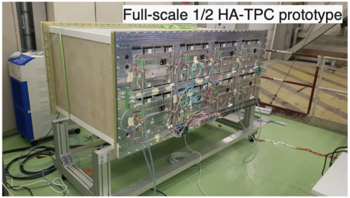


HA-TPCs performance

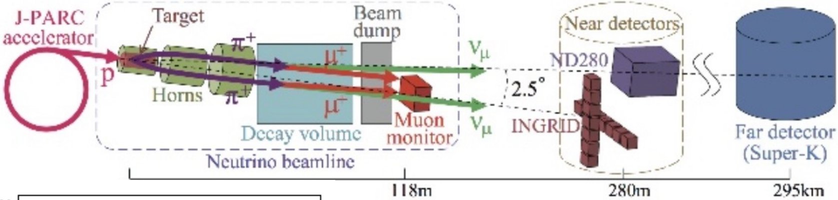
- **CERN November 2021**
  μ beam; the same TPC as for DESY 2021 + TRK; no mag. field

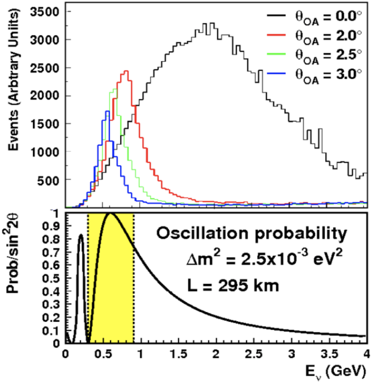


- **CERN May 2022** (rescheduled for December)
  Test of the one-half of HA-TPF (final desgin)



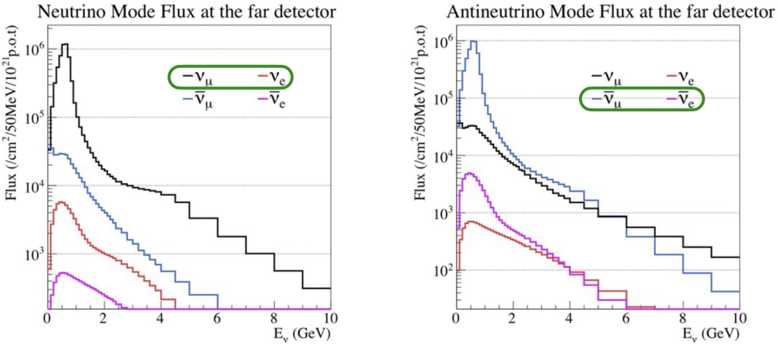
Beam direction - Oscillation probability

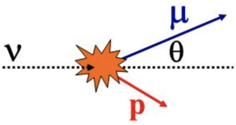




- Oscillation probability is maximum at 2.5° (off-axis) with narrow ν energy band peaking at 0.6 MeV
- Sensitive to the beam direction and its stability

Flux, Spectrum and Intrinsic ν_e



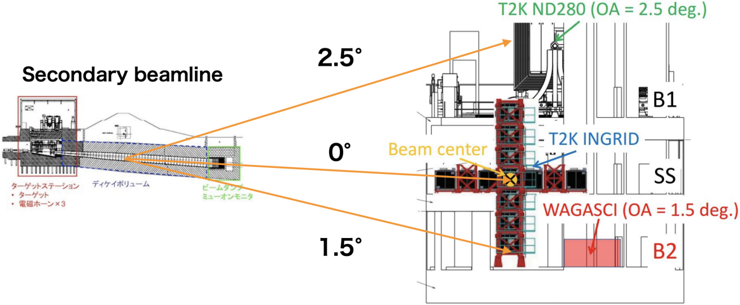


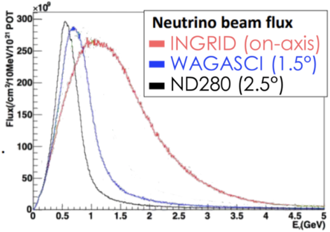
- Main interaction at T2K: CCQE
- can reconstructed ν energy and scattering angle θ
- p and $\cos\theta_c$ distribution measured by ND are used to constrain flux and spectrum

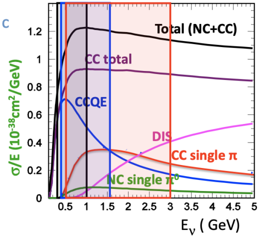
$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e\cos\theta_e)}$$

Detectors at ND280

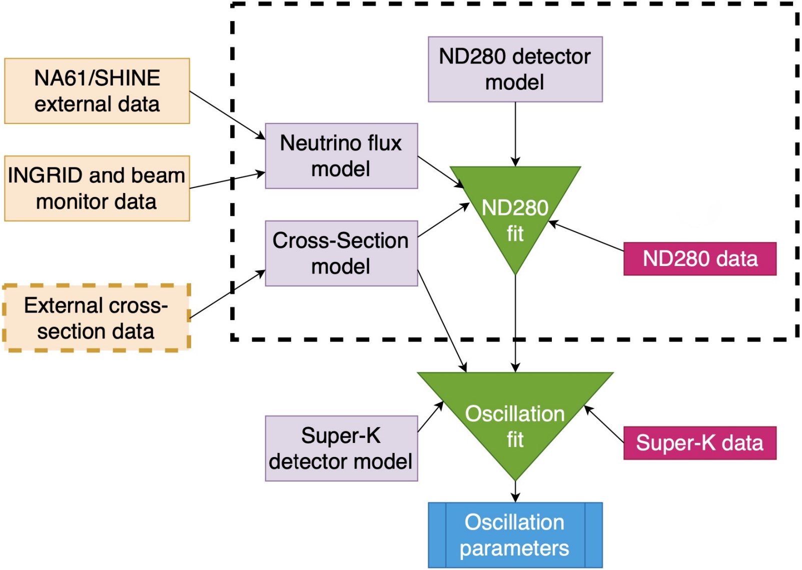
Precise measurement of neutrino-nucleus interactions



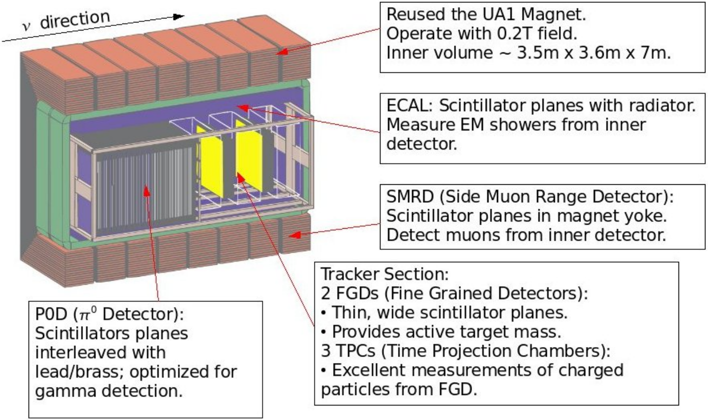




Constraints by NDs in ν oscillation fit

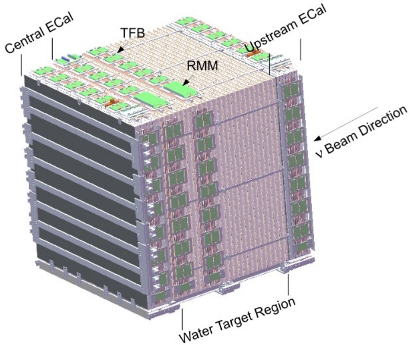


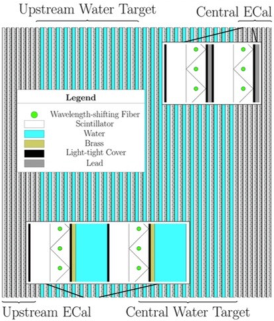
Current ND280



- FGD: ν target scintillator bar along XY to mesure interaction point
- TPC: to measure momentum & to identify particles from target

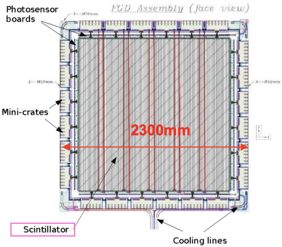
P0D Detector

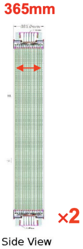


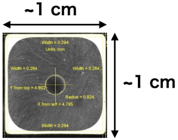


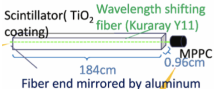
FGD Detector

- Fine-grained active scintillator (CH) target
- Particle tracking for detection of vertex



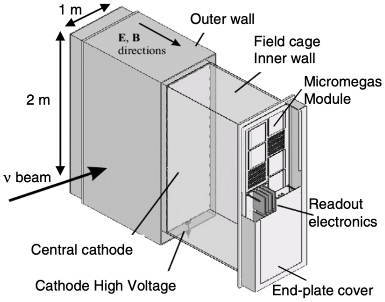


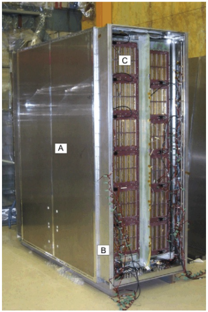




- Plastic FGD (FGD1) with 15 XY modules
- Water FGD (FGD2) with 7 XY modules & 6 water layers (2.5cm)

TPC Detector





- 3D tracking gas detector for charged particles
- Momentum measurement by trajectory & PID by energy deposit