Tests and Assembly of the T2K Near Detector Upgrade

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on behalf of T2K collaboration

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Content

T2K experiment

Main goals

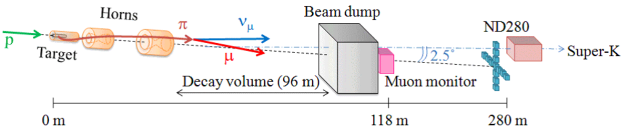
- Discovered appearance of $\nu_\mu \rightarrow \nu_e$ $\theta_{13}(2013)$, δ_{CP}
- Measurement of $\nu_\mu \rightarrow \nu_\mu$ θ_{23}, Δm^2_{32}

T2K upgrade $\rightarrow 3\sigma$C.L on δ_{CP}

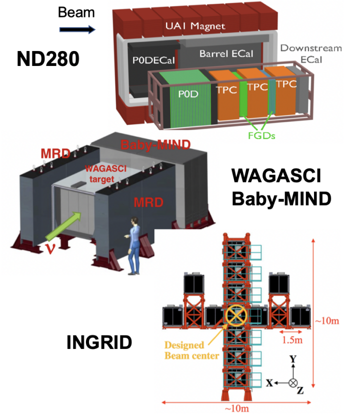
- Long-baseline (295 km) ν experiment in Japan from J-PARC(Tokai) to Super-K (Kamioka)

- p (30GeV) + graphite $\rightarrow \pi \rightarrow \mu + \nu_\mu(600MeV)$ - 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

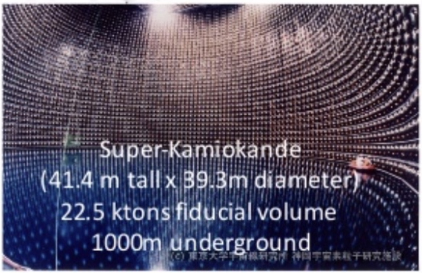


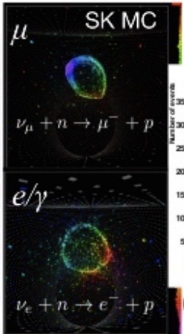
- **ND280 (2.5° off axis):** constrain flux and cross-section parameters
- **WAGASCI (1.5° off axis):** Measurements of ν interaction cross sections on water and carbon
- **INGRID (on axis):** Measurements of ν beam intensity & profile

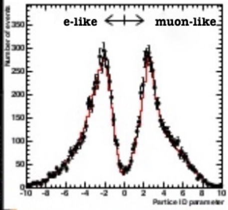


Far Detector

- **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

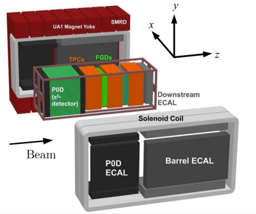


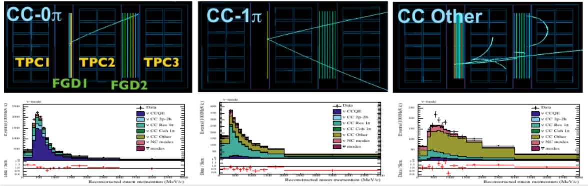




(atmospheric ν data)

Role of Near Detectors

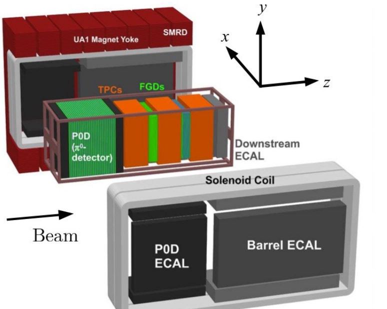




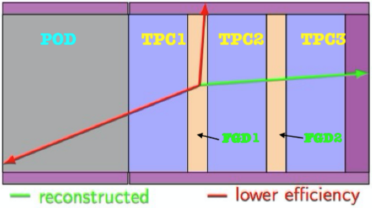
- Near Detector complex is 280m downstream of neutrino production point (target).
- Measurement of the interaction rates before oscillation
- Measurement of neutrino nucleus cross-section in several channels
- Strongly constrain the expected rates at Super-K for precision oscillation analyses

good acceptance for forward tracks

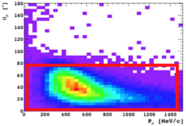
What ND280 cannot do?



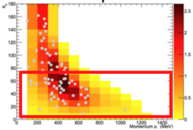
- Small acceptance
- Low efficiency to reconstruct the hadronic part (π, p) of the interactions
- No capacity to detect neutrons

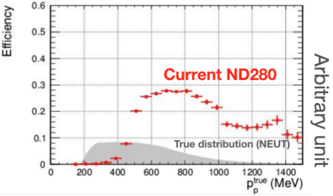


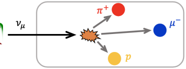
Muons at ND280:
- forward direction

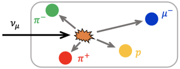


Electrons at SuperK:
- 4π acceptance









Motivation of T2K near detector upgrade

- Control the systematic uncertainties associated with the ν production and detection
  - $\uparrow$ POT in T2K-II goal $\rightarrow \downarrow$ Stat. error
  - $\downarrow$ sys. error $\nu_e(\bar{\nu}_e)$ event candidates
  - Near future: Suppression of sys. error becomes more important

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation	3.1	2.4
$(0.6 < E_\nu < 0.7$ GeV$)$		
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

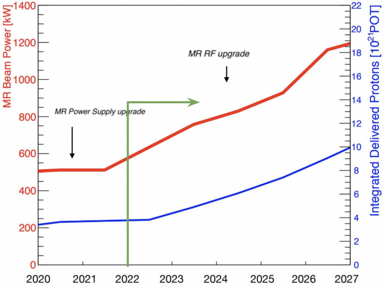
- The systematic error can be reduced by about 30% in the ND280 upgrade configuration

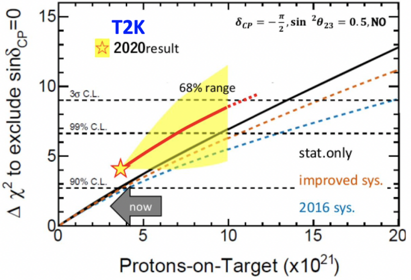
T2K Upgrade plan

- T2K upgrade near detector: expected ↓ systematic uncertainty to 4%

Beam upgrade up to $\sim$ 1.3MW

accumulate enough POT $\rightarrow$ to exclude $\sin\delta_{CP} = 0$ at 3σ



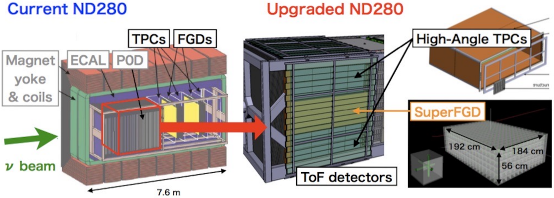


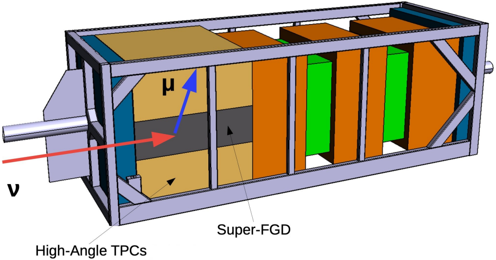
See Y. Sato and C. Naseby's talk

The upgrade ND280 begin collecting neutrino data in November 2023

ND280 upgrade

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





Super-FGD

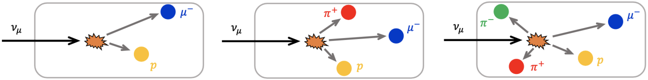
→ improve the reconstruction hadronic part and low momentum leptons

2 HA-TPCs

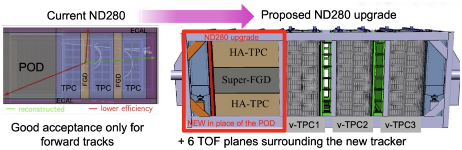
→ improve the reconstruction high angle leptons

6 ToF planes

→ reduce background from the outside of SuperFGD

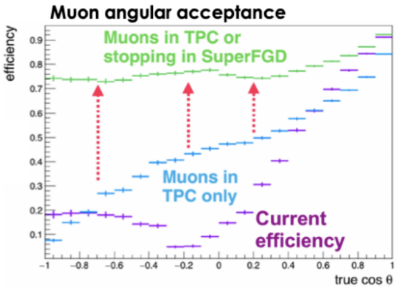


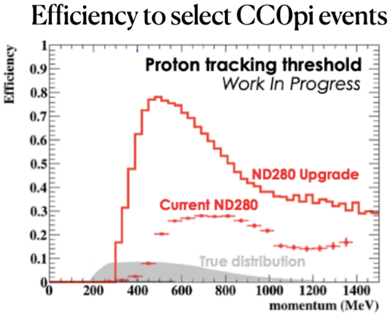
Efficiencies of ND280 upgrade



Efficiencies of ND280 upgrade:

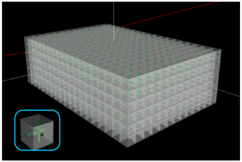
4π acceptance, high efficency of particle low momentum.

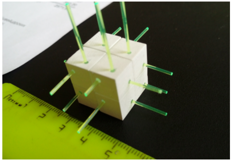




SuperFGD

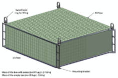
- 2 million cubes 1x1x1 cm^3 plastic scintillator cubes with 3 holes
- Fully active target (200 x 180 x 60 cm^3)
- Active mass 2,2 tons
- $\sim$ 60 000 readout WLS and MPPC
- 3D reconstruction and high segmentation, 4π acceptance
- Good tracking, timing, PID





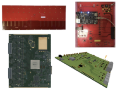
Scintillator cubes

Mechanical box



Optical parts

Electronics

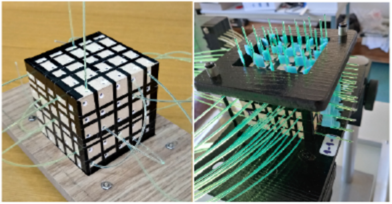


Prototypes test beam at CERN

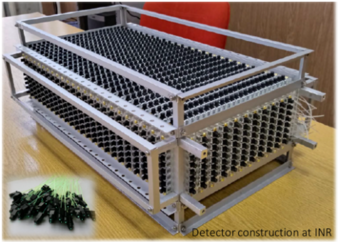
Two prototypes 125 and 9216 cubes were tested at CERN (2017 , 2018)

NIMA 936 (2018), JINST 15, 12 (2020), JINST 18 (2023) P01012

5 x 5 x 5



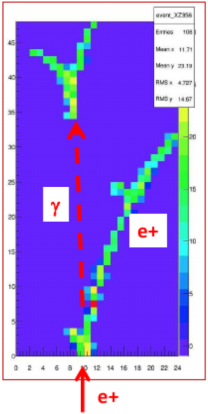
8 x 24 x 48



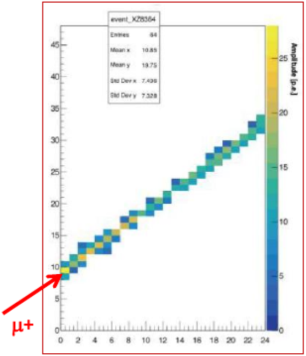
Test shows the upgrade achieving requirement

SuperFGD test beam events

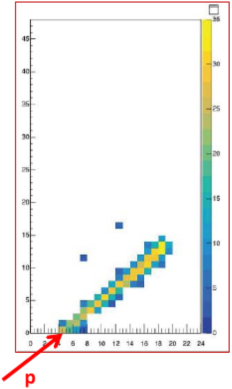
Positron, 1 GeV, B = 0.2 T



Muon, 5 GeV, 45 deg



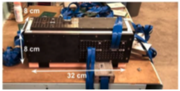
Stopped proton, 0.5 GeV, 45 deg



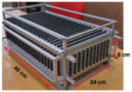
Neutron test beam in LANL

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

US-Japan

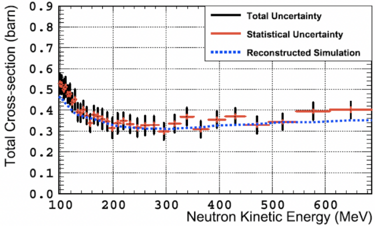


SuperFGD

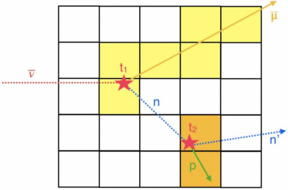


- Neutron beam energy ranges from 0 to 800 MeV
- Measurement of the total neutron-CH cross section

Physics Letters B 840 (2023) 137843



Neutron Detection

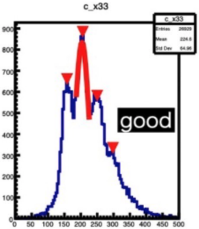


- Access to neutron kinematic is crucial to understanding better anti-neutrino CCQE and 2p2h interactions

SuperFGD assembly

- Super FGD assembly has been completed at J-PARC in April
- Super FGD electronic had been successully tested

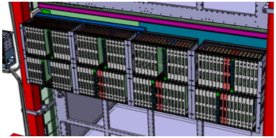
- The box was closed (27th Dec)
- Transferred to miniBabyBasket (11th Jan)
- Fiber and MPPC board installation ongoing



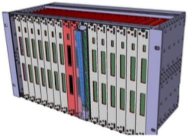
cables was attached and connection test with commercial electronics.

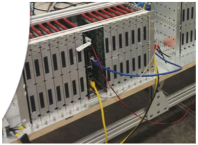
SuperFGD electronics

Super-FGD electronics
2 frames hosting 8 crates each



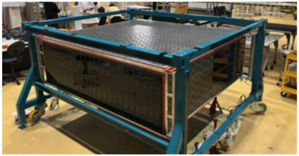
Each crate: 16 FEBs, 1 OCB, 1 Backplane

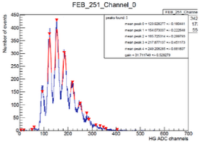




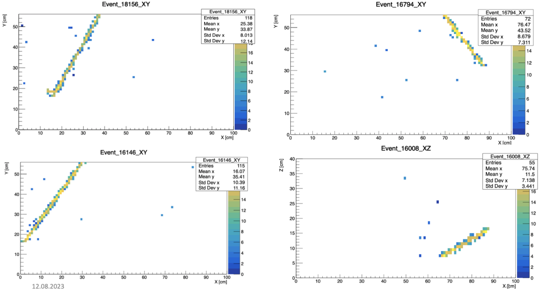
- 243 FEBs produced (221 needed to instrument all channels)
  $\rightarrow$ 210 passed QA/QC
- Mechanics for the frames, crates, cooling bars and cooling plates have been produced, tested and already to ship to J-PARC
- OCB and Blackplanes (16 neeed for each) are being produced in US and shipped to Geneva
- Ready for shipment to JPARC to start sFGD commissioning on surface

SuperFGD first cosmics





- MCB v1/2
- OCB
- Backplane v1
- 3 FEBs v2
- Pusle generator
- LED driver
- SFGD

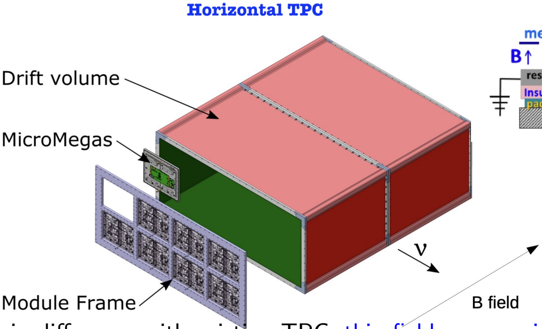


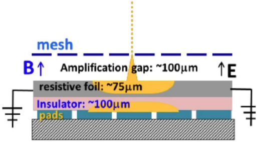
12.08.2023

- cosmic events have been observed with 3 crates - 42 FEBs - 10752 channels, MCB v1

- Super-FGD installation at the end of September
- Installation of the electronics in the first half of October

High Angle-TPC





Resistive Micromegas

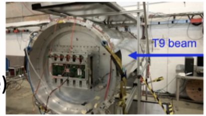
- Main difference with existing TPC: thin field cage, resistive Micromegas module (ERAM modules) with better spatial resolution
- 2 Field Cages, central cathode plan, 16 ERAM modules readout at the two opposite Anodes.
- Main purpose: 3D, PID by measuring momentum and deposit charge
- HA-TPC requirement:
  - 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**

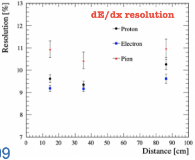
High Angle TPCs performance

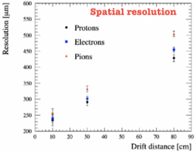
❑CERN 2018

✓ 1.5 m drift distance;
e, π, p (0.5-2GeV)
MM0-DLC1 (HARP field cage)

NIMA 957 (2020) 163286



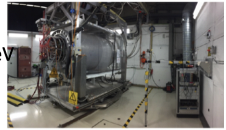


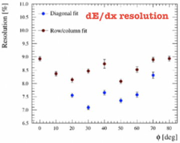


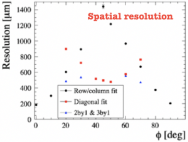
❑DESY 2019

✓ 0.15 m drift distance; e- 4GeV
MM1-DLC1;

NIMA 1025 (2022) 166109



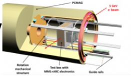


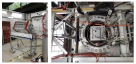


❑DESY 2021

✓ 1 m drift distance; e- 4GeV

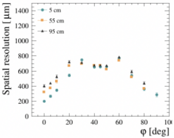
NIMA 1052 (2023) 168248



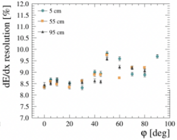


4 GeV e-; 1 m drift distance

Spatial Resolution



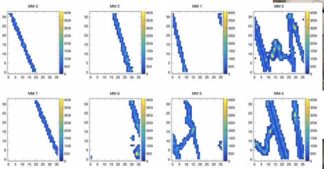
dEdx Resolution

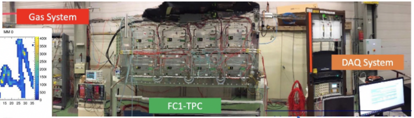


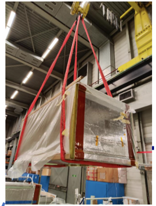
Achieved spatial resolution better than 800 μm and dE/dx resolution better than 10%.

Fulfills the requirements

High Angle TPC

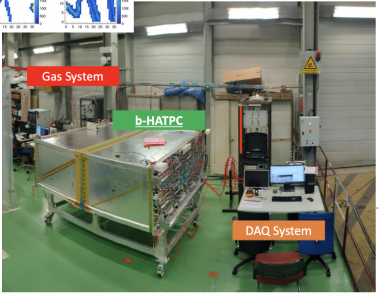






FC2 arrival at CERN
June 2023

- ✓ 2 Field cages has been assembled at CERN
- ✓ The TPC has been tested with cosmic
- ✓ Running stably and good data quality

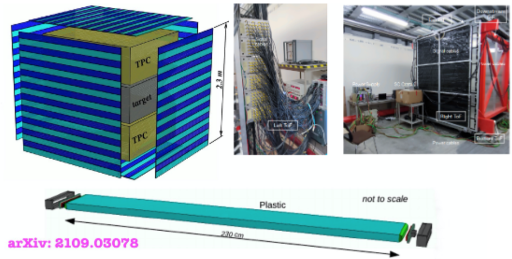


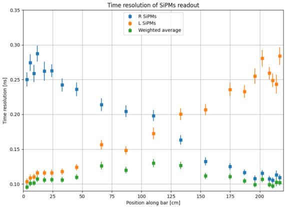
Vertical assembly FC1+FC2

Shipment of Bottom TPC to JPARC in August
so that installation can be done in early September

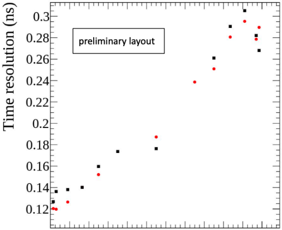
Time of Flight detectors

Main Goals: + Identification of the direction of the track using time stamp
→ veto the bkg from outside of SuperFGD
+ Improvement of particle identification using timing





- 6 ToF modules cover 2 HA-TPC and Super-FGD
- Each module 2.4 x 2.2 m^2 consists of 20 sci bars
- Both ends readout by 8 SiPM on each end (total 236 readouts).



Time resolution from SAMPIC (Federico)

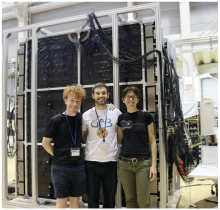
time resolution is 0.13 ns

ToF transportation and commissioning on surface

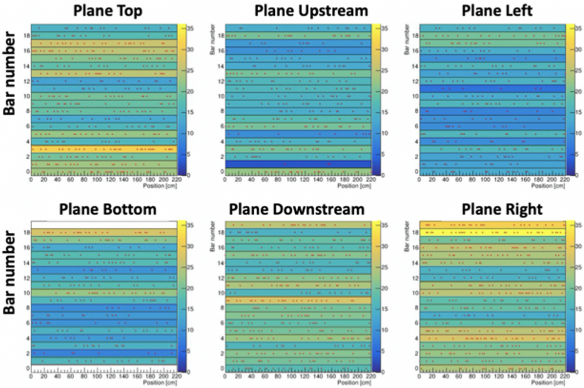
Transport

ToF@JPARC on 22/6

Commissioning on surface

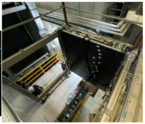


TOF Events display



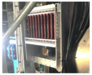
- ToF detector shiped on June 8th visa plane and arrived at JPARC on June 22nd.
- DAQ and SC system fully connected and commissioned successfully the whole ToF planes
- Event display show the reconstructed position in all bars.

Installation of Upstream, Bottom planes of ToF in ND280 detector

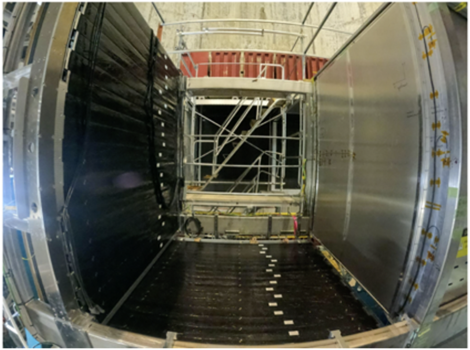


ToF rack

SC crate



Cabling



Installation of U and B planes in ND280 basket

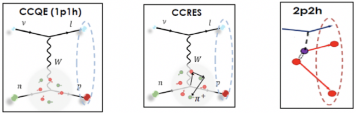
- the U, B planes installed perfectly in ND280 detector.
- Installation of last 4 planes after top HATPC
- ToF hardward is ready for beam in November

ND280 upgrade physics studies: E_ν reconstruction

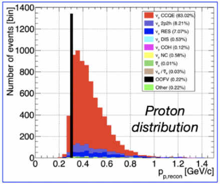
See L. Munteanu's talk

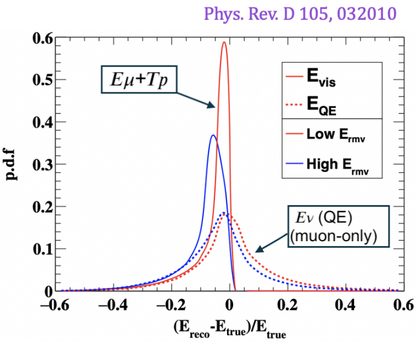
$$\nu_\mu + n \longrightarrow \mu^- + p$$

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



Proton momentum distribution from ν_μCC 1muon+1proton selection





No detector smearing

- **SuperFGD provides reconstruction of the neutrino energy by measuring both the muon and proton energies**
- **More precise $E\nu$ reconstruction, more sensitive to oscillation physics**

Detection of neutron

Antineutrino CCQE

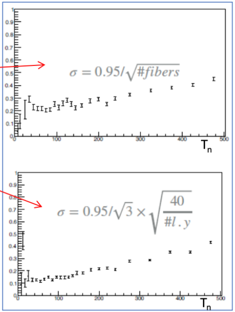
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

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

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

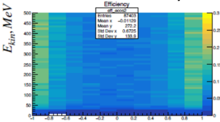
Detection of neutrons by time-of-flight

arXiv:1912.01511

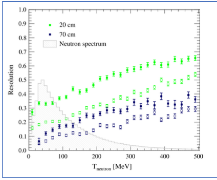


Monte Carlo study

Detection efficiency

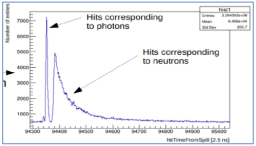


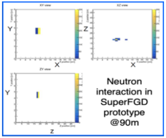
Energy resolution



PLB 840 (2023) 137843

Beam tests with neutrons of SFGD prototype at LANL





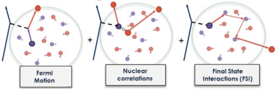
Improved Observables: Transverse Kinematic Imbalance

Flux model | Detector model | Neutrino interaction model | Oscillation Probability

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

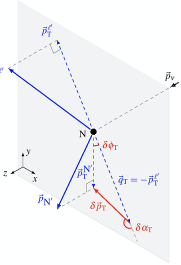
$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

Nuclear effects are the main source of E_ν uncertainty



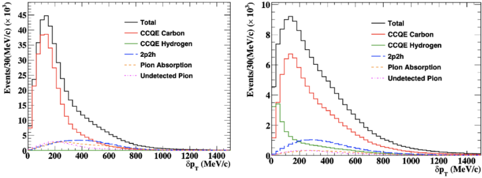
Upgrade → access to reconstruct in hadronic part of the final state → new, more powerful variables: $\delta p_T, \delta\alpha, E_{vis}$

for free proton $\delta p_T = 0$
(No nuclear effect)



- missing momentum $\delta \vec{p}_T = \vec{p}^{\,T}_\mu + \vec{p}^{\,T}_p$
- Transverse boosting angle $\delta\alpha$
- Visible energy $E_{vis} = E_\mu + T_{p(n)}$ where $T_{p(n)}$ kinetic energy

Phys. Rev. D 105,032010



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

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 completing assembly and test stage, and begin collecting neutrino data in November 2023
    - ND280 upgrade's low detection thresholds and full polar angle coverage will enable T2K to probe the complete final state of neutrino-nucleus interactions.
    - ND280 upgrade program shows the impressive ability to constrain key systematic uncertainties.

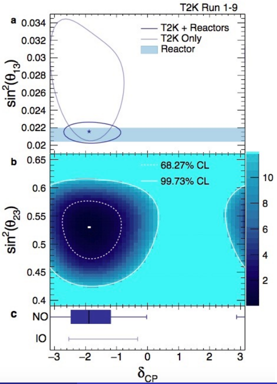

THANK YOU

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

$$P(\nu_\mu \to \nu_e) \sim sin^2(2\theta_{13}) sin^2(\theta_{23}) sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$
$$\mp \frac{1.27\Delta m^2_{21} L}{E} 8 J_{CP} sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$
$$P(\nu_\mu \to \nu_\mu) \sim 1 - 4cos^2(\theta_{13}) sin^2(\theta_{23}) \times [1 - cos^2(\theta_{13}) sin^2(\theta_{23})] \times$$
$$sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$

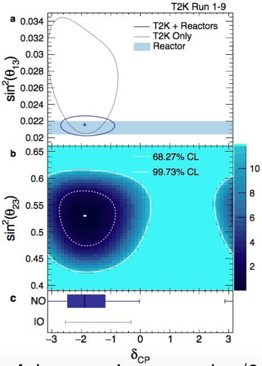
T2K improve the oscillation parameters

- $sin\theta_{23} = 0.03^{+0.03}_{-0.04}$ (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)
- $\delta_{CP} = -1.89^{+0.7}_{-0.58} (-1.38^{+0.48}_{-0.54})$



T2K Results

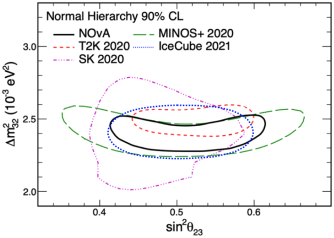
Constraint CP violating parameter δ_{CP}

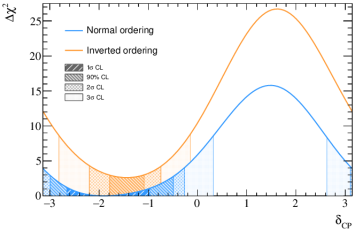


- A large region around $\pi/2$ is excluded to 3 σ in both mass orderings. CP conserving values are exclued at the 90 % CL
- Indication of maximal CP violation in neutrino oscillations $\delta_{CP} \sim -\pi/2$

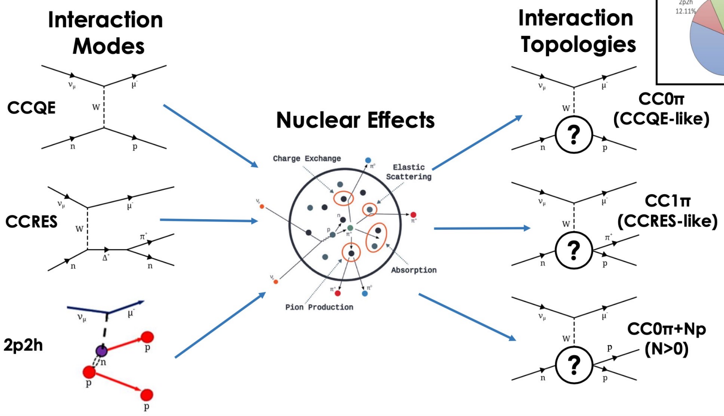
Δm^2_{32} **and** θ_{23} for NH

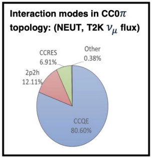
Normal ordering prefered at 80.8% CL





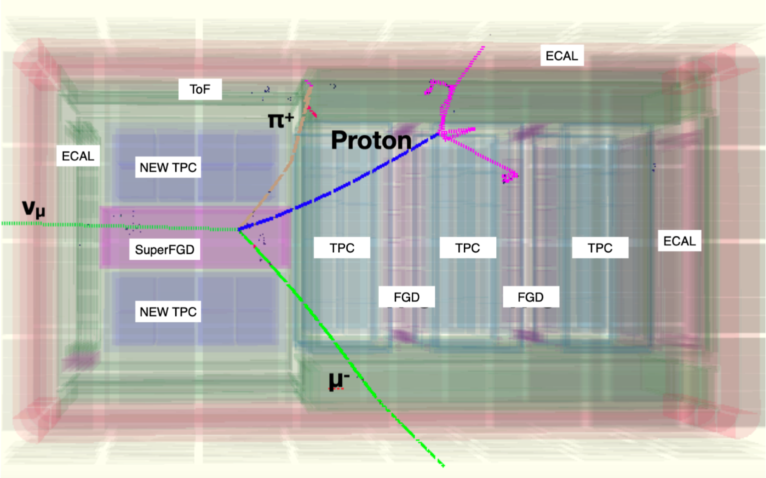
Physics Processes vs Event Topologies



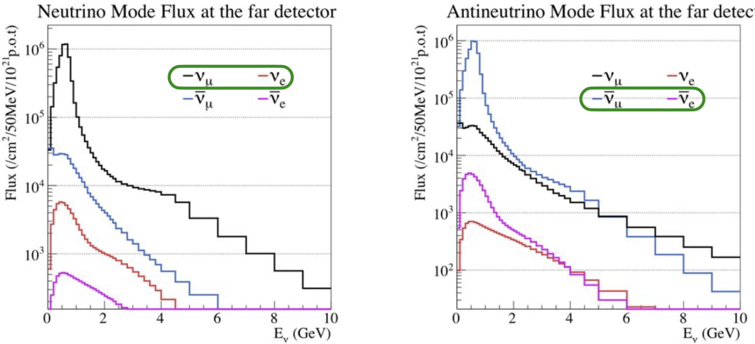


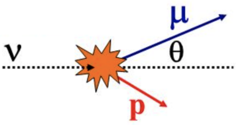
Event display in ND280 upgrade

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



Flux, Spectrum and Intrinsic ν_e



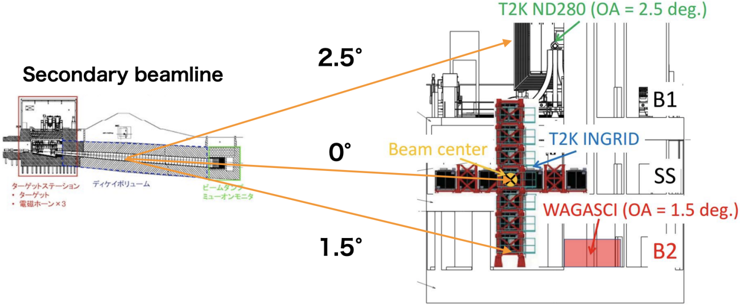


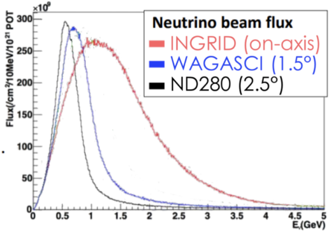
- Main interaction at T2K: CCQE
- can reconstructed ν energy and scattering angle θ
- p and $\cos\theta_c$ distribution measured by ND are used to constrain flux and spectrum

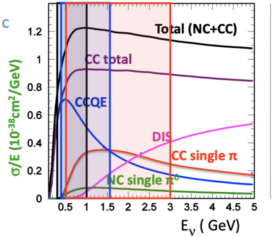
$$E_\nu^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e\cos\theta_e)}$$

Detectors at ND280

Precise measurement of neutrino-nucleus interactions







Constraints by NDs in ν oscillation fit