CP symmetry measurement in neutrino oscillations in the T2K experiment

Marcela Batkiewicz-Kwaśniak
IFJ PAN

IFJ PAN Seminar
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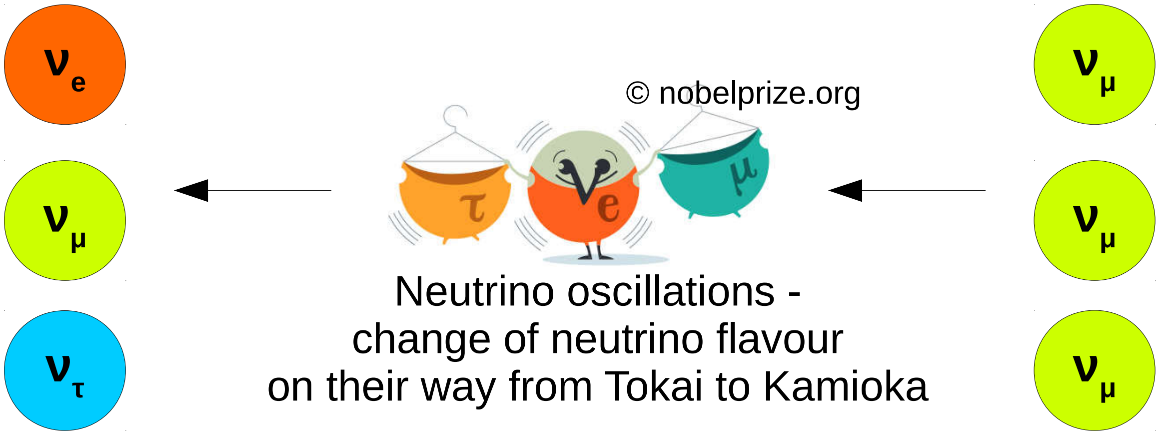
Overview

- Introduction
- Matter-antimatter imbalance
- Neutrino mixing and oscillations
- T2K experiment overview
- Analysis strategy
- T2K future
- IFJ involvement
- Summary

Introduction

- T2K (Tokai to Kamioka) experiment
  - long-baseline neutrino oscillation experiment
  - conducted in Japan by an international collaboration
  - recently provided the first constraint on δ_{CP} phase – parameter describing the charge-space (CP) symmetry conservation/violation



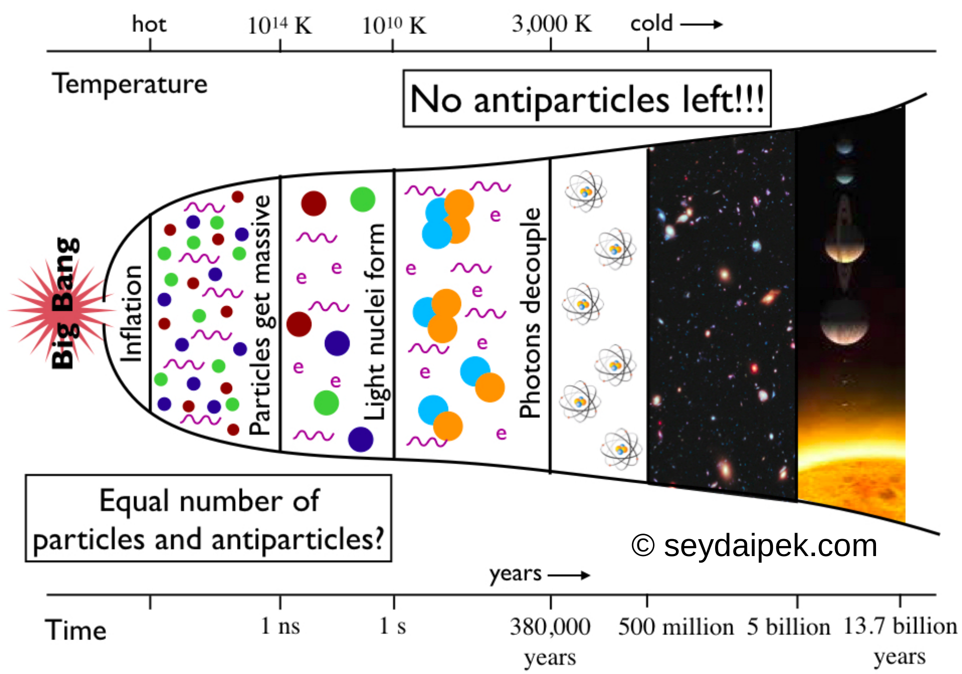
Neutrino oscillations -
change of neutrino flavour
on their way from Tokai to Kamioka

Neutrinos in Kamioka

Neutrinos produced in Tokai

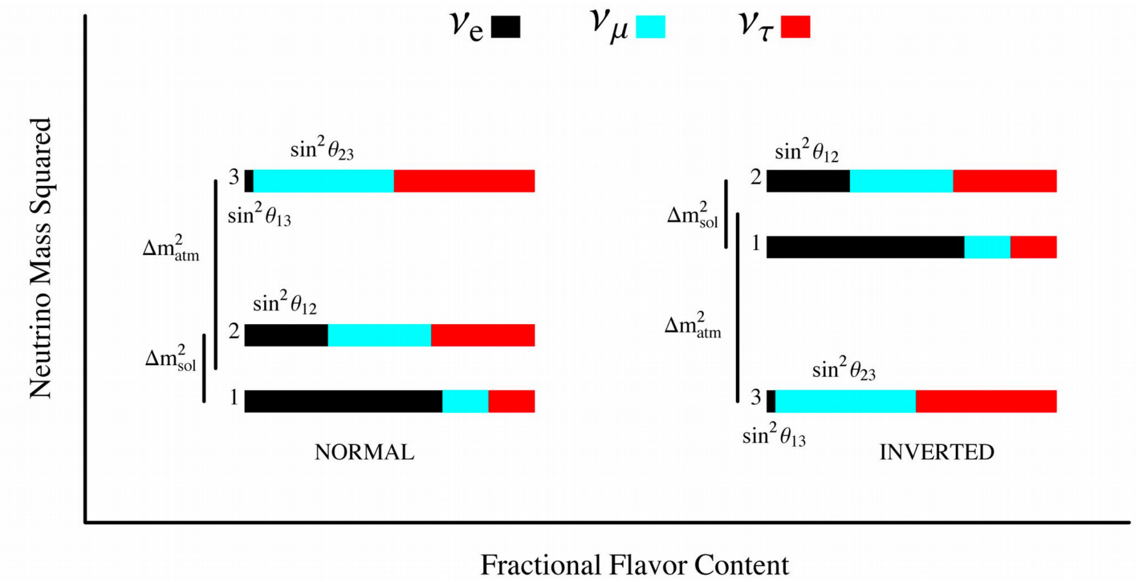
Matter-antimatter imbalance in the Universe

- The Universe is dominated by matter
- Sakharov conditions to explain matter-antimatter imbalance:
  - violation of C and CP symmetries
  - non-conservation of barion number B
  - interactions out of thermal equilibrium



- C violated observed in weak interaction
- CP violation in quark sector to small
- CP violation in lepton sector not conclusively observed so far
- Proton decay (B violation) searches ongoing

Neutrino mixing

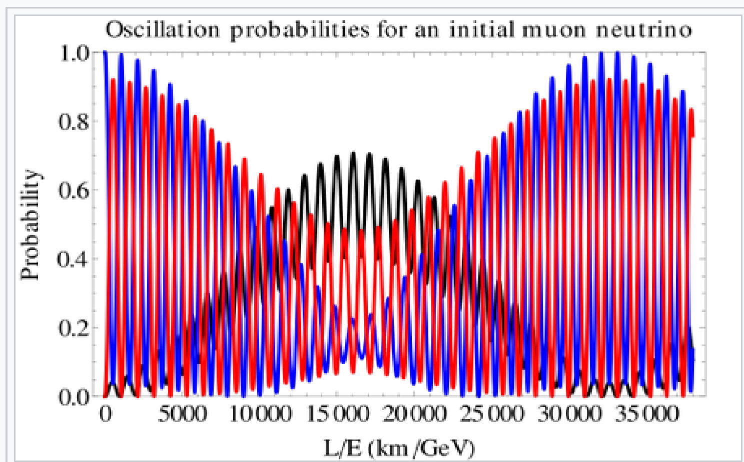


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

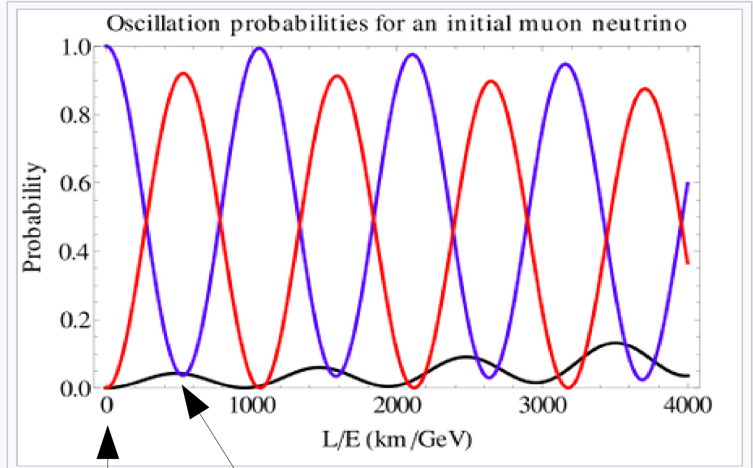
$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmosferic neutrino oscillation}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar neutrino oscillation}}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and $\delta = \delta_{CP}$.

Neutrino oscillations



Muon neutrino oscillations, long range[23]



Muon neutrino oscillations, short range[23]

usual near detector position

usual far detector position

Oscillation probabilities with CP violating term, but without matter effect, where:
E – neutrino energy
L – travelled distance
J_{CP} – Jarlskog invariant
(for quarks $J_{CP} = 3\times10^{-5}$)

$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP} = 0.033\sin\delta_{CP}$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times (1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

"-" for ν
"+" for $\bar{\nu}$

Neutrino oscillations parameters

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2$$
$$\sin^2(\theta_{23}) = 0.547 \pm 0.021 \quad \text{(Inverted order)}$$
$$\sin^2(\theta_{23}) = 0.545 \pm 0.021 \quad \text{(Normal order)}$$
$$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}\ \text{eV}^2 \quad \text{(Inverted order)}$$
$$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}\ \text{eV}^2 \quad \text{(Normal order)}$$
$$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$$
$$\delta,\ CP \text{ violating phase} = 1.36 \pm 0.17\ \pi \text{ rad}$$

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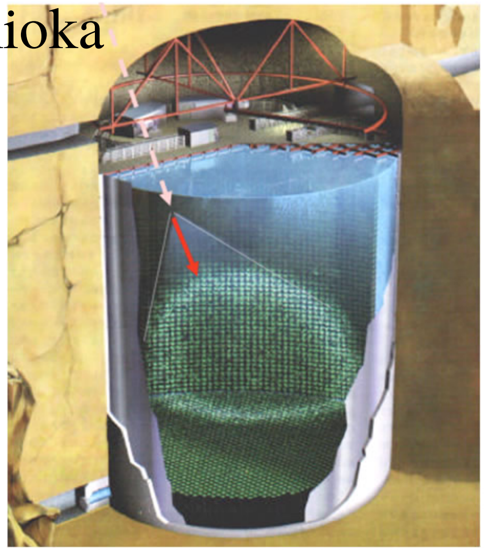
Unknowns:

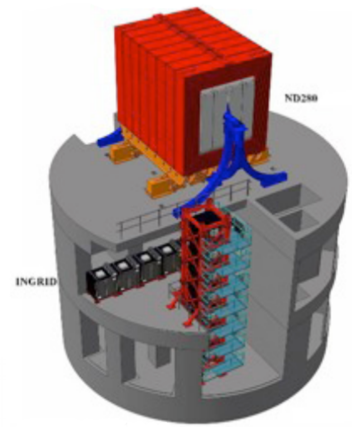
- is CP conserved (δ_{CP} = 0° or ±180°) or violated
- is θ_{23} < 45° (I octant) or > 45° (II octant)
- what is the mass ordering ($m_3 > m_2 > m_1$ – Normal Ordering or $m_2 > m_1 > m_3$ – Inverted Ordering)

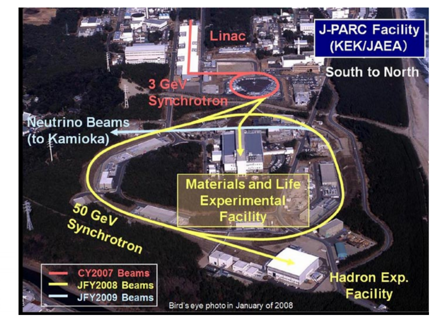
T2K experiment

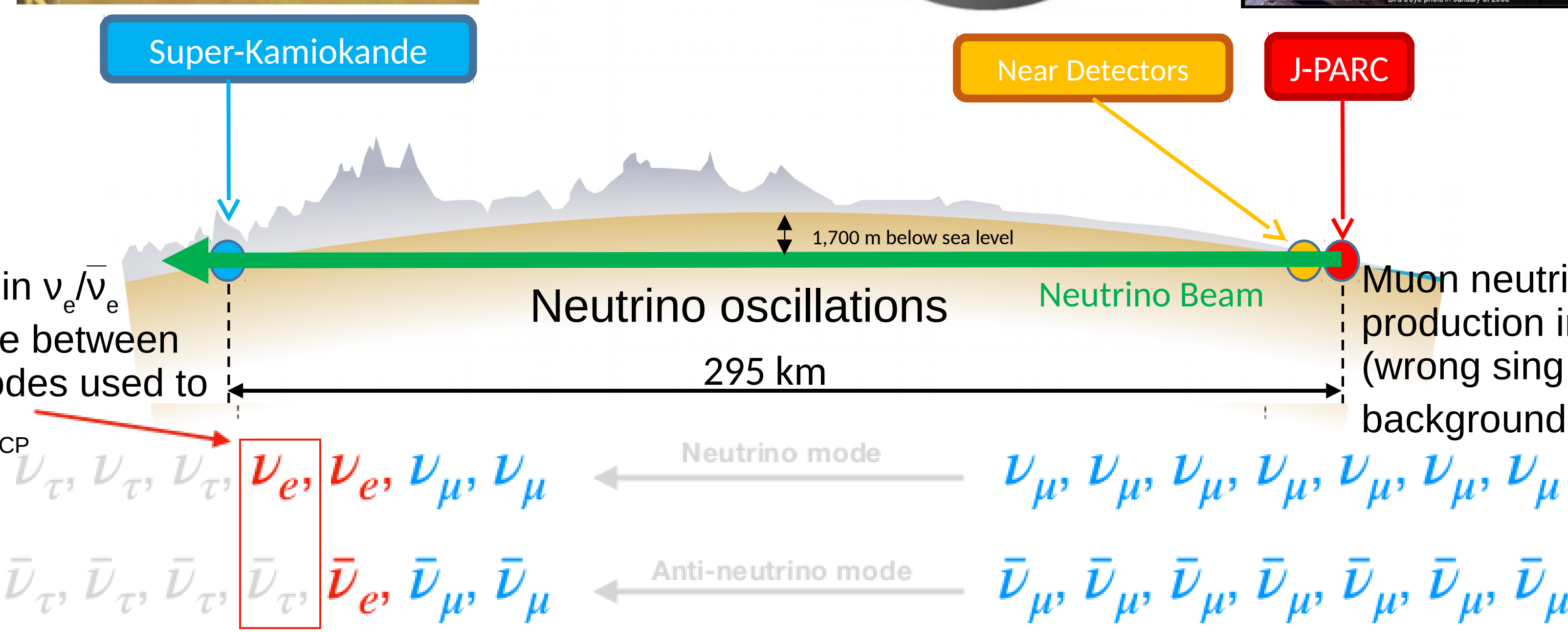
Far detector
in Kamioka



Accelerator complex and
near detectors in Tokai



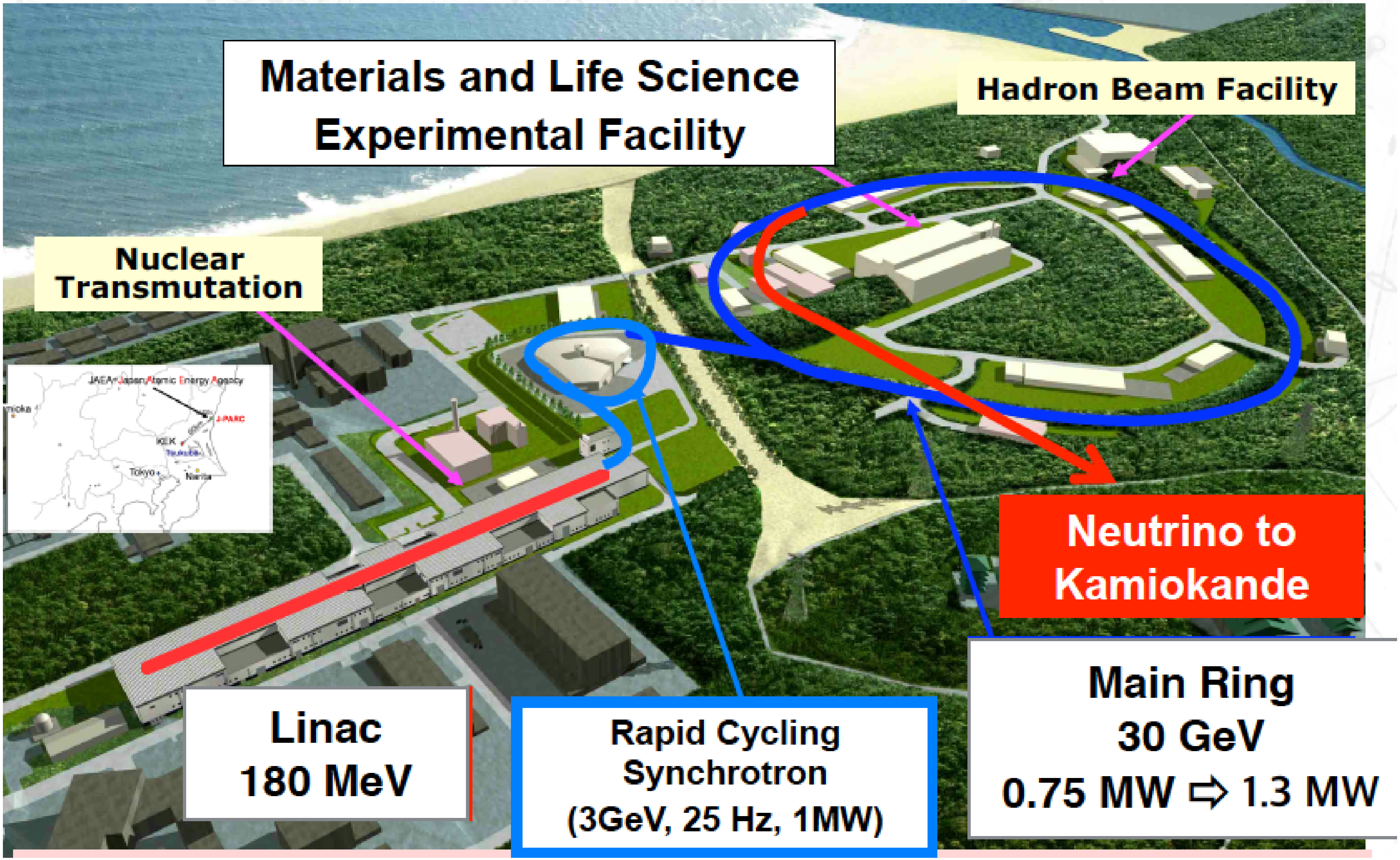




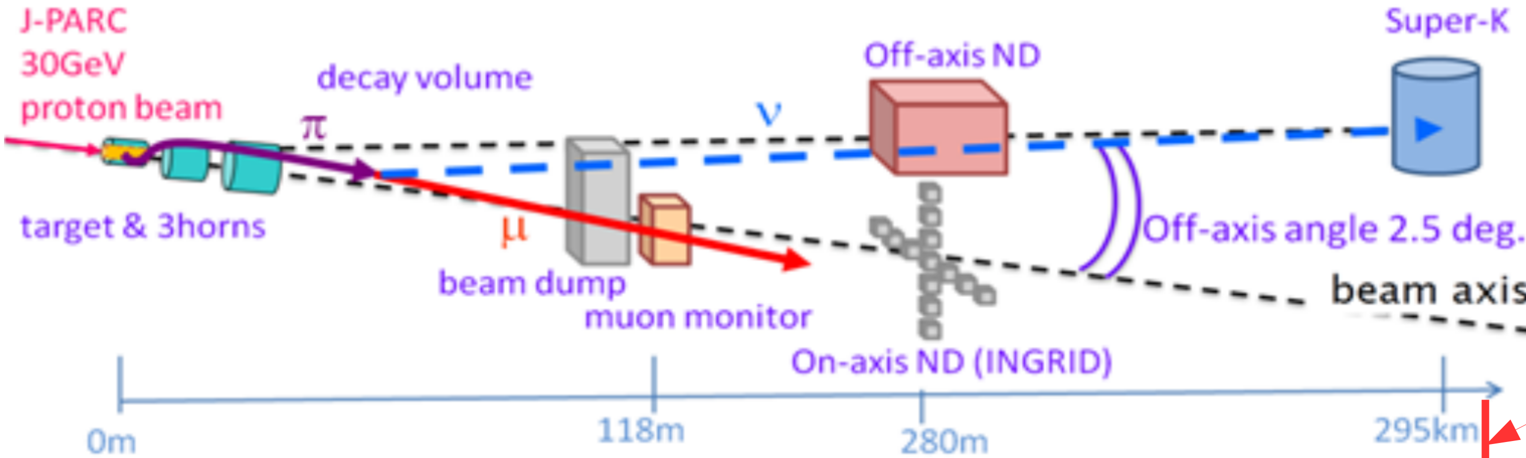
Difference in $\nu_e/\bar{\nu}_e$ appearance between ν and $\bar{\nu}$ modes used to measure δ_{CP}

Muon neutrino production in Tokai (wrong sing and ν_e background not shown)

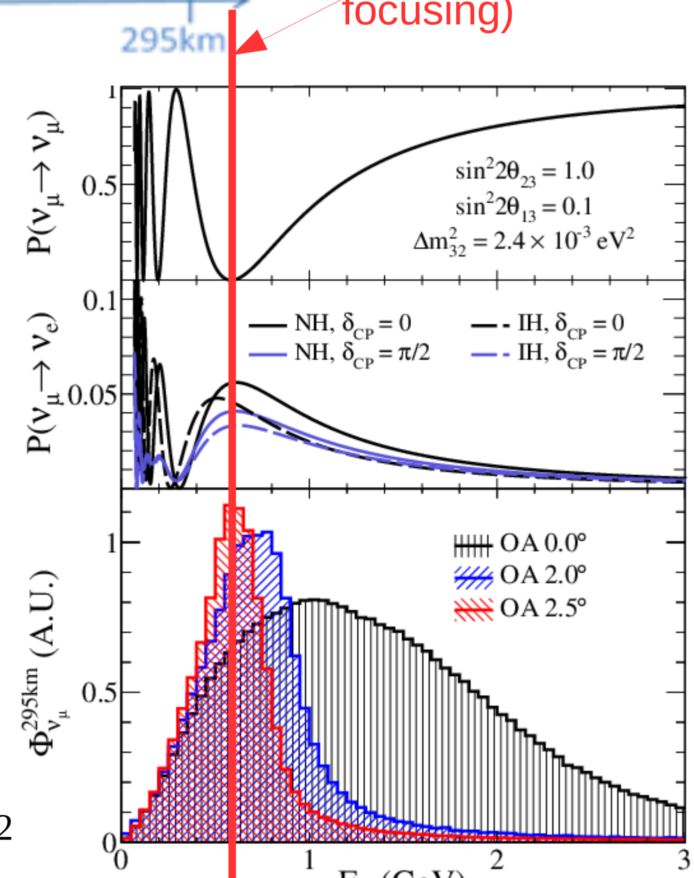
30 GeV proton beam production at J-PARC (Japan Proton Accelerator Research Complex)



Neutrino beam production



Off-axis angle chosen to maximise oscillation probability in SK (kinematical focusing)



$$p + C \to \pi^{+/-/0} + \ldots,\ K + \ldots$$

Neutrino mode – focus positive particles

$\pi^+ \to \mu^+ + \nu_\mu$

$K^+ \to \mu^+ + \nu_\mu\ (+\ \pi^0)$

Antineutrino mode – focus negative particles

$\pi^- \to \mu^- + \bar{\nu}_\mu$

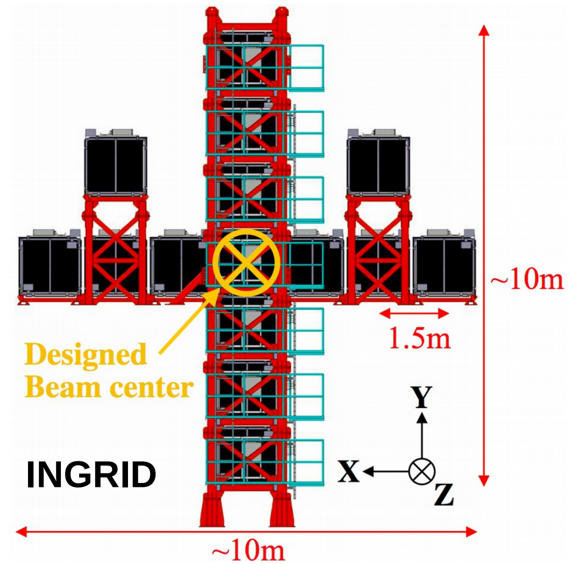
$K^- \to \mu^- + \bar{\nu}_\mu\ (+\ \pi^0)$

Background:

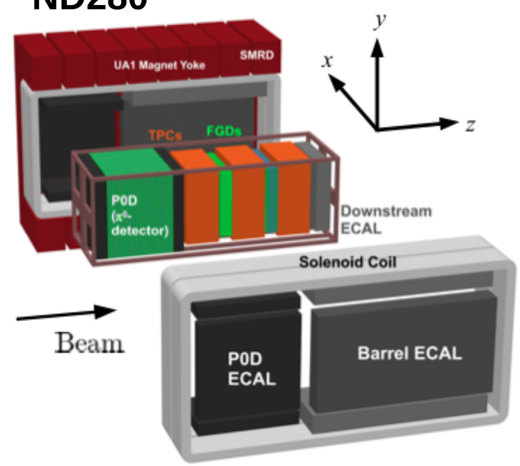
- wrong sign background
- muon decays: $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$
- kaon decays: $K^+ \to e^+ + \nu_e + \pi^0$ (~5% of decays)

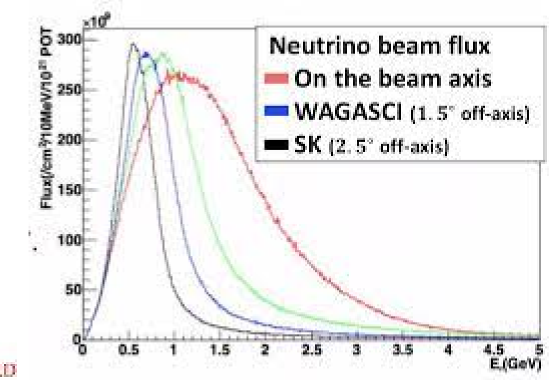
Near detectors

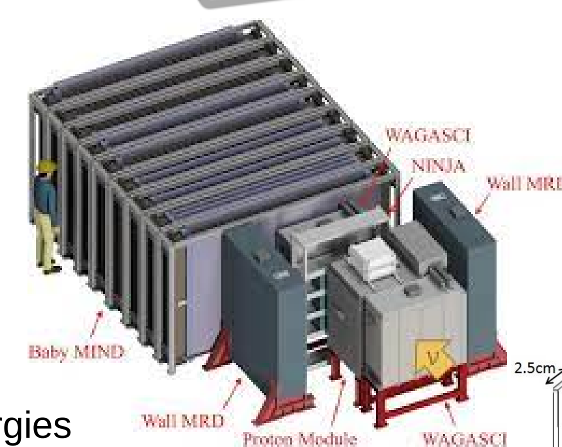
- INGRID (on-axis – 0°)
  - plastic scintillator, iron
  - not magnetized
  - beam position and intensity monitoring
- ND280 (off-axis – 2.5°)
  - plastic scintillator, water, iron, lead
  - time projection chambers
  - magnetized
  - beam content before oscillations
  - neutrino cross-sections
- WAGASCI – BabyMIND (off-axis – 1.5°)
  - plastic scintillator, water, iron
  - magnetized
  - neutrino cross-sections at different energies



ND280

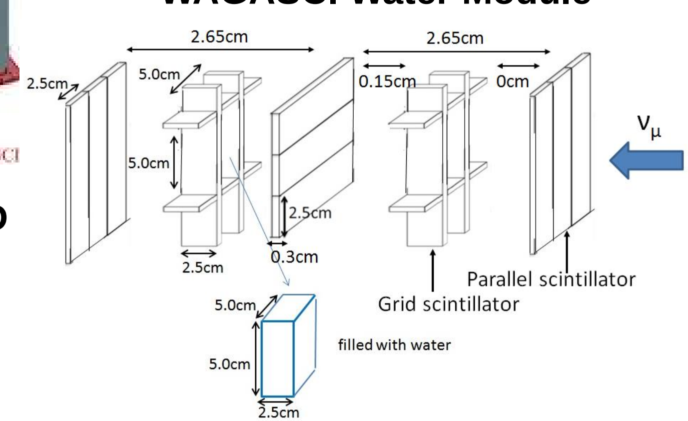




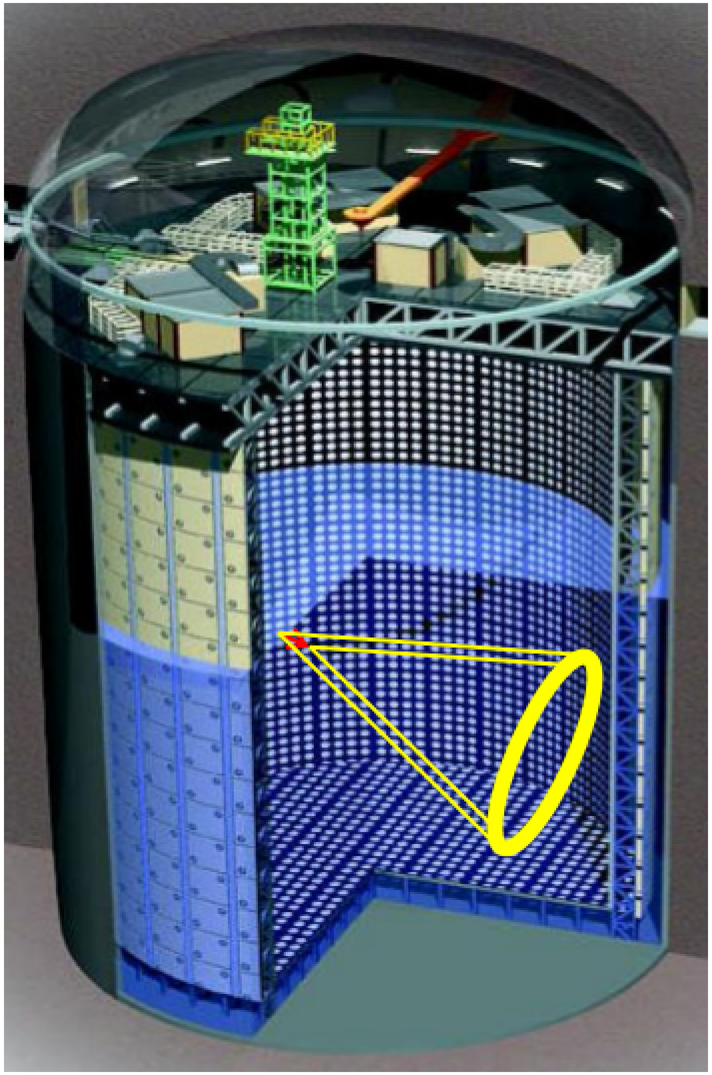


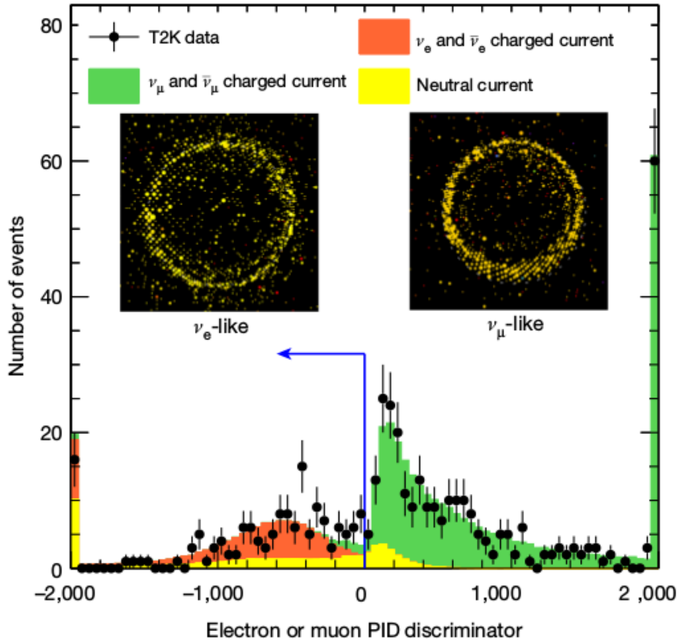
WAGASCI – BabyMIND

WAGASCI Water Module



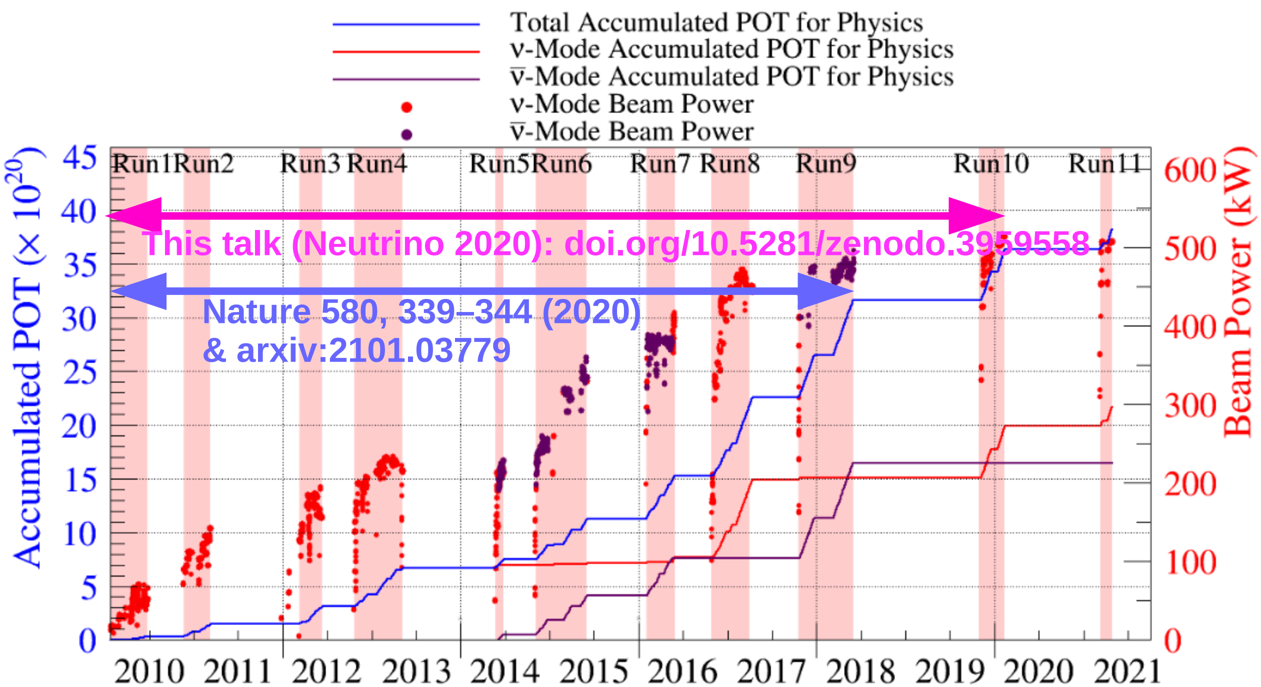
Super-Kamiokande far detector





- 50 kton water Cherenkov with ~13 000 photomultiplier tubes
- charged particle travelling faster than light in the medium → Cherenkov light production
- electron (small mass) → lots of scattering →fuzzy ring
- muon (bigger mass) → less scattering → sharp ring
- no magnetic field to distinguish particles from anti-particles
- previously clean water, now doped with Gd
- Gd emits light during deexcitation after neutron capture
- neutrons are mostly produced in $\bar{\nu}$ interactions (partial $\nu/\bar{\nu}$ distinction)

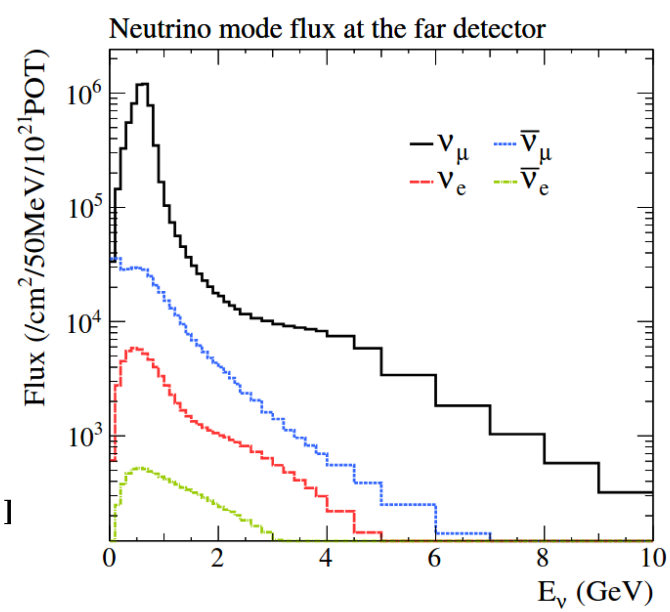
Data sample

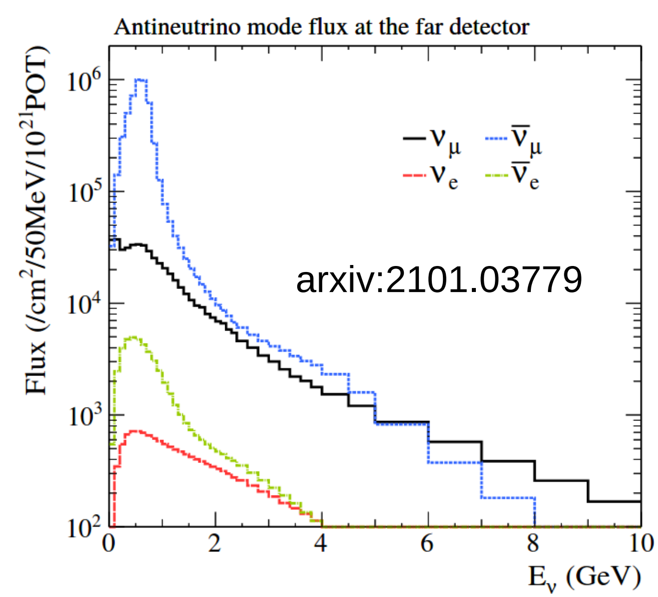


Nature results:
- ν mode: 1.49×10^{21} Protons On Target (POT)
- $\bar{\nu}$ mode: 1.64×10^{21} POT

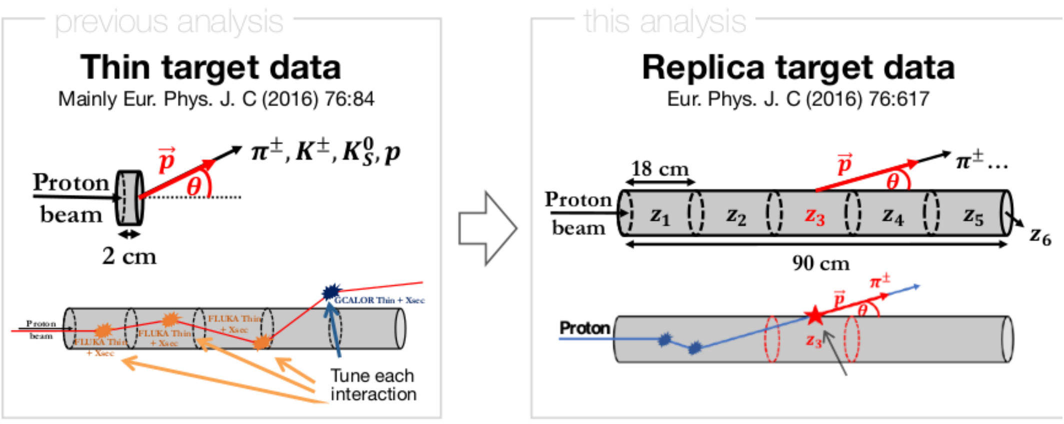
This talk (Neutrino 2020):
- ν mode: 1.97×10^{21} Protons On Target (POT)
- $\bar{\nu}$ mode: 1.64×10^{21} POT

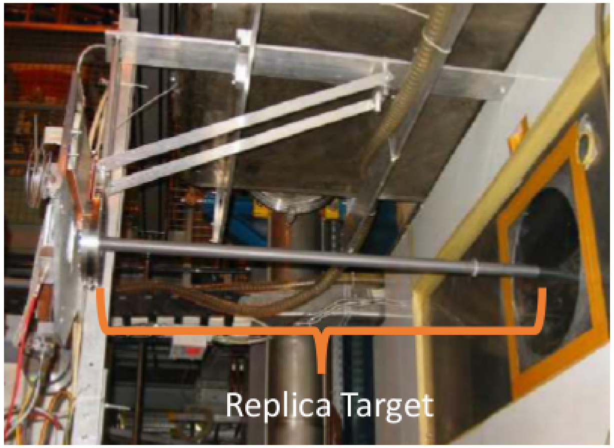
Stable operation up to 515 kW in Run 10!



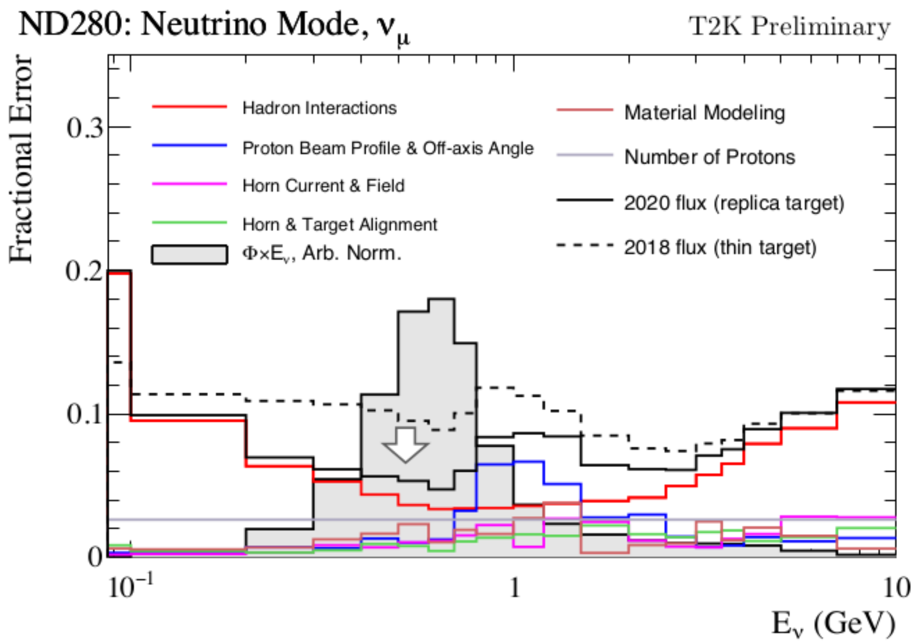


Neutrino production modelling



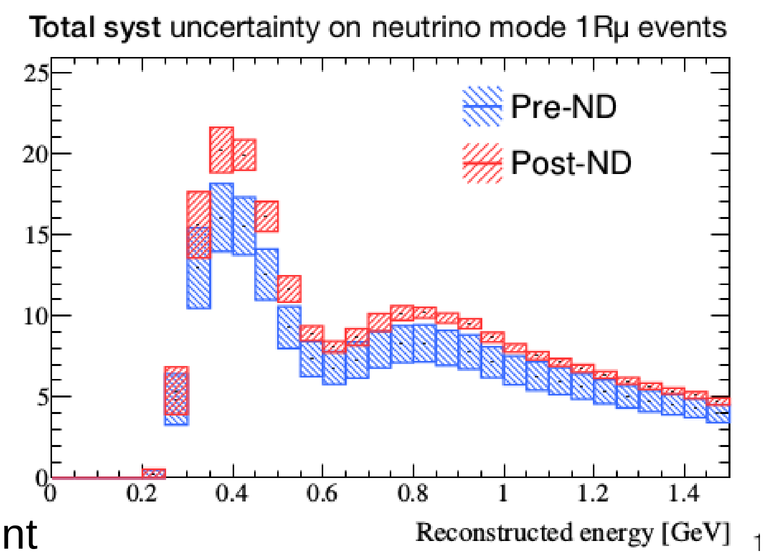


- T2K proton target – 90 cm long graphite rod
- NA61/SHINE experiment measurement of particles produced in thin (2 cm long) graphite target and in the replica target
- Interactions in the target simulated in FLUKA and tuned to the NA61/SHINE results
- Significant reduction of the flux uncertainty (8%→5%) after including replica target results
- Beam monitoring:
  - Muon monitor
  - INGRID

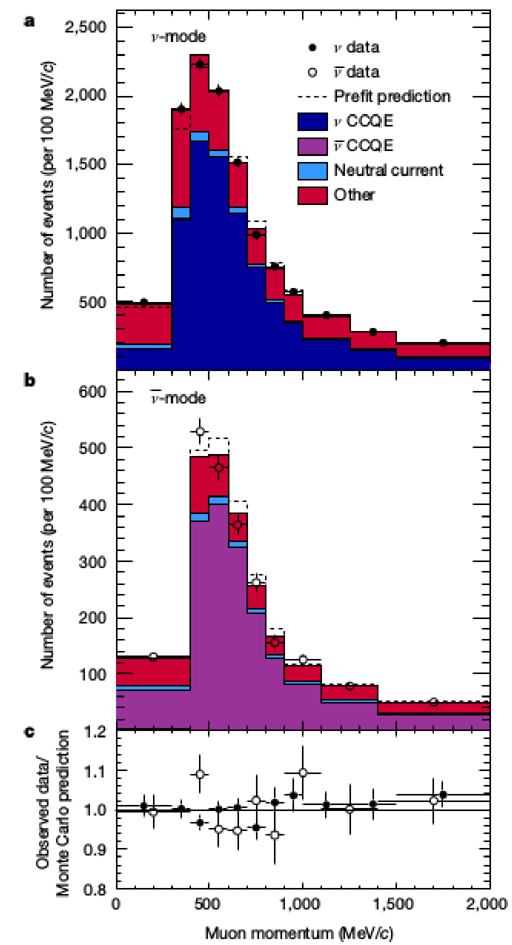


Neutrino flux & interaction modelling vs near detector measurements

- ND280 detector
  - magnetized detector → separation of ν and $\bar{\nu}$ interactions
  - TPC → good particle identification; momentum and angle measurement
  - neutrino flux measurement at the same off-axis angle as SK → measurement of intrinsic ν_e and wrong sing background
  - many cross-section results:
    - CC0π, CC1π, CCNπ
    - interactions on C and O
    - ν_μ vs ν_e interactions
    - ν vs $\bar{\nu}$ interactions

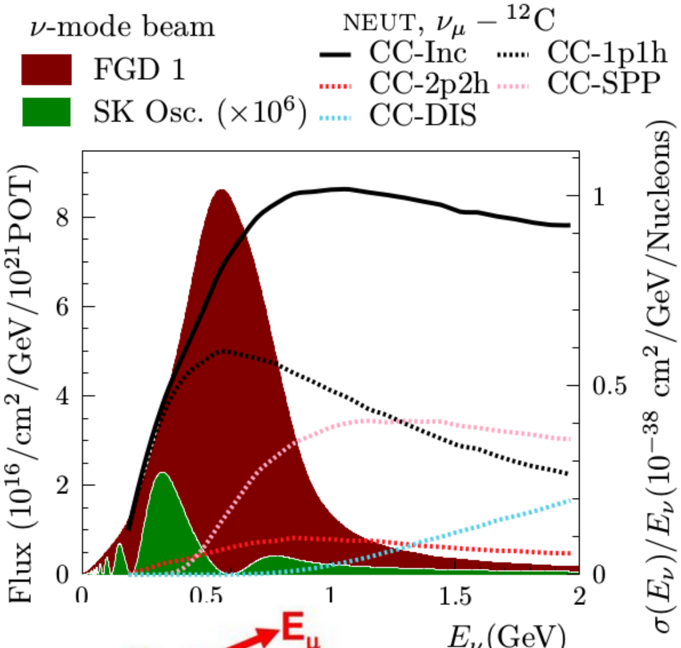


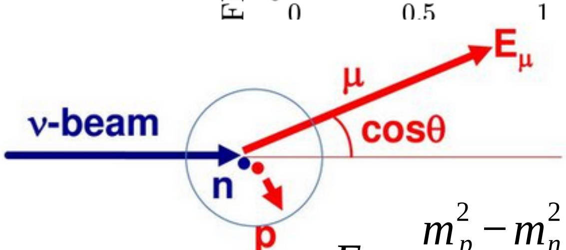
Model tuning to ND280 data



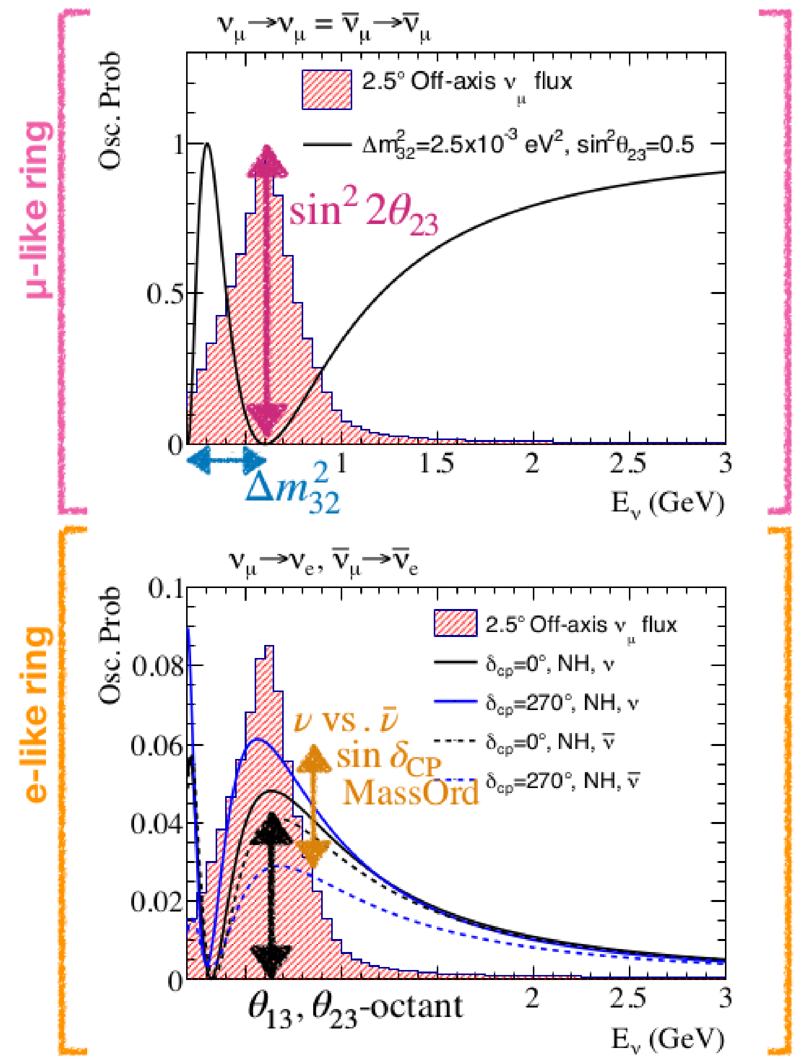
- INGRID and WAGASCI-BabyMIND
  - cross-section for different off-axis angles → for different neutrino energy spectra

Event reconstruction in SK





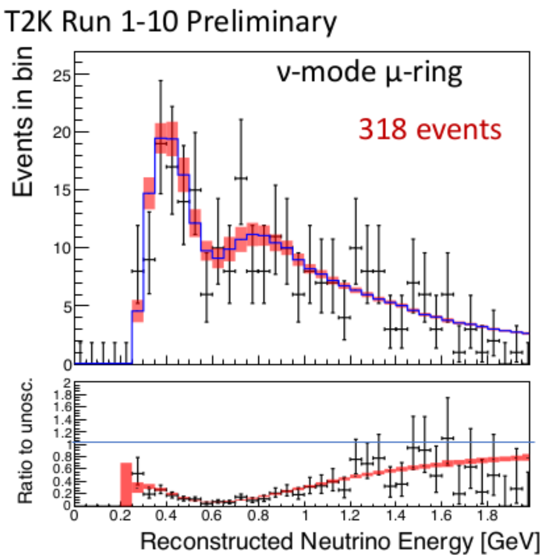
$$E_\nu = \frac{m_p^2 - m_n^2 - m_l^2 + 2 m_n E_l}{2\left(m_n - E_l + p_l \cos\theta_l\right)}, E_l = \sqrt{m_l^2 + p_l^2}$$

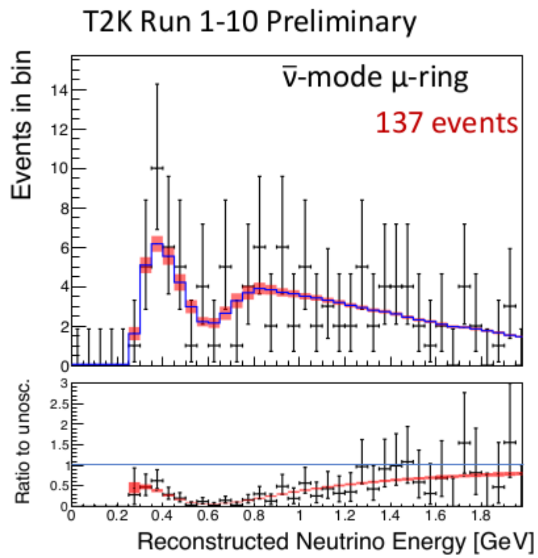


Nuclear effects important for energy reconstruction:

- non-zero momenta of nucleons bound in nuclei
- interaction on two nucleons (2p-2h)

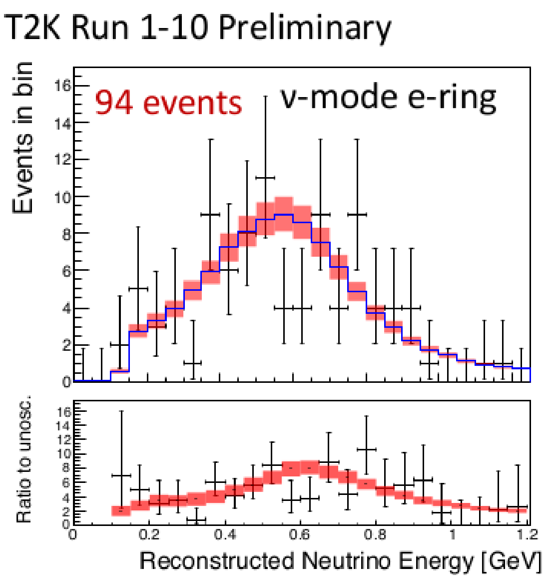
Even reconstruction in SK

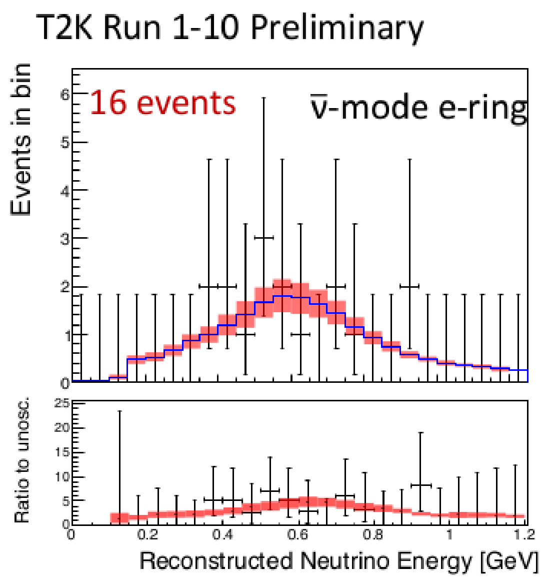


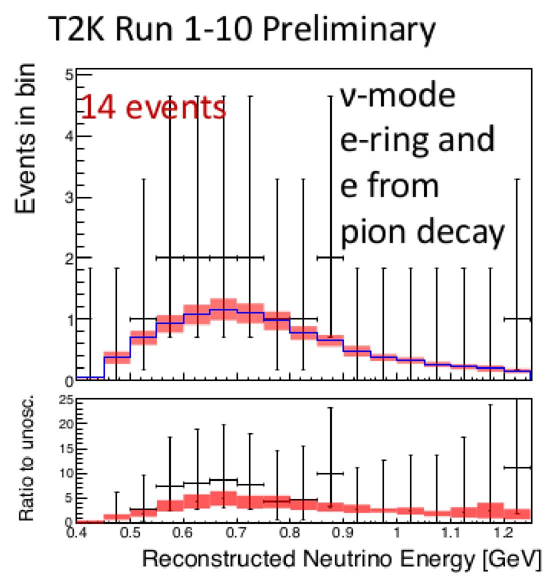


5 samples in SuperK:

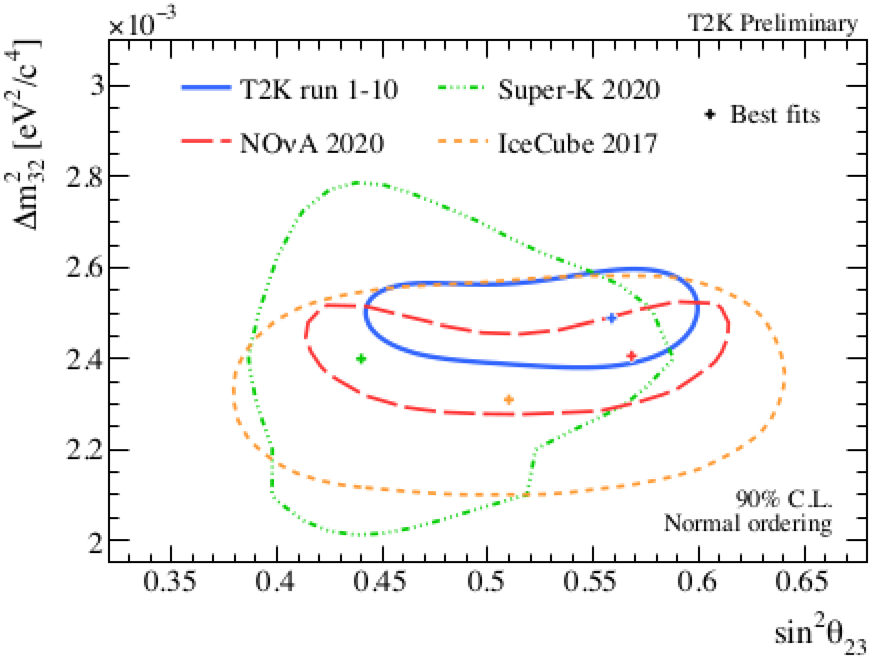
- **μ disappearance:**
  1) 1 μ-like ring in ν-mode
  2) 1 μ-like ring in ν̄-mode
- **e appearance:**
  3) 1 e-like ring in ν-mode
  4) 1 e-like ring in ν̄-mode
  5) 1 e-like ring + 1 decay-e ring in ν-mode
     decay-e from $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  - no decay-e sample in ν̄-mode because π^- mostly absorbed before decay

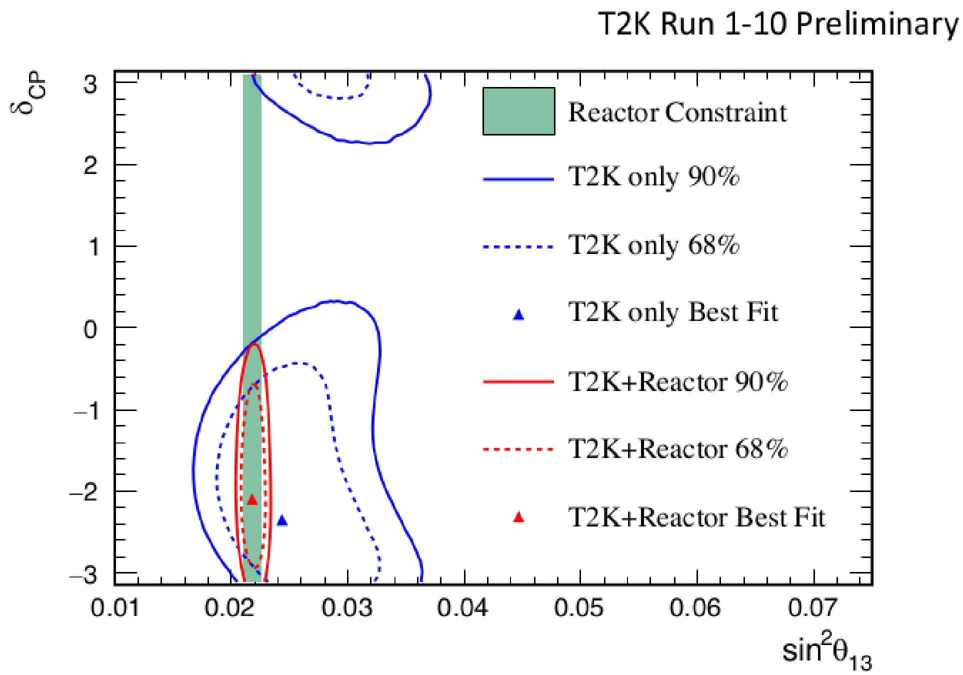






Neutrino oscillation parameters

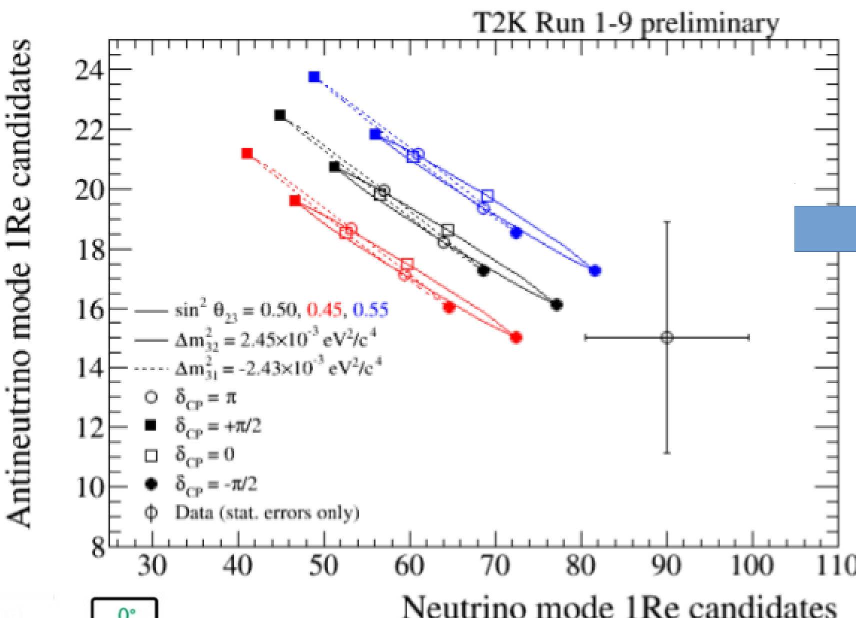


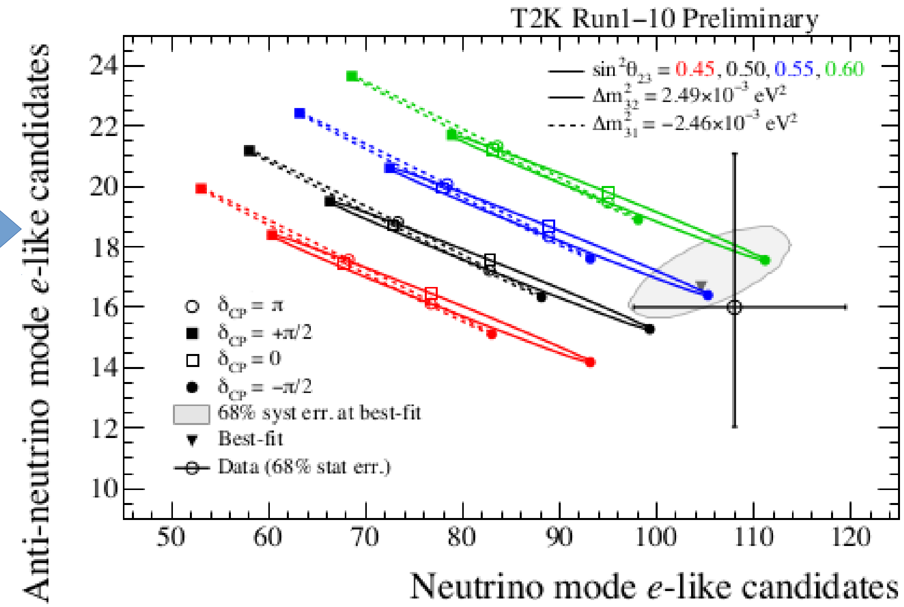


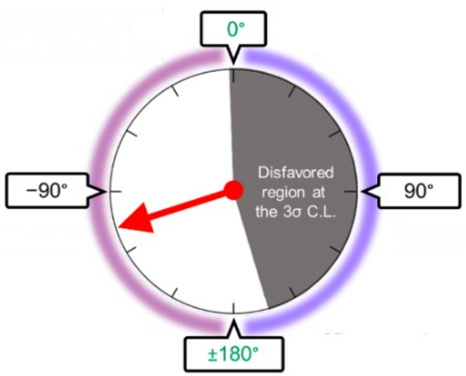
T2K provides the world's best measurement on θ_{23} parameter.

Reactor experiments are not sensitive to δ_{CP} parameter, but are much more sensitive to θ_{13} angle. T2K is consistent with their results and uses it to constrain other parameters (e.g. θ_{23} and δ_{CP}).

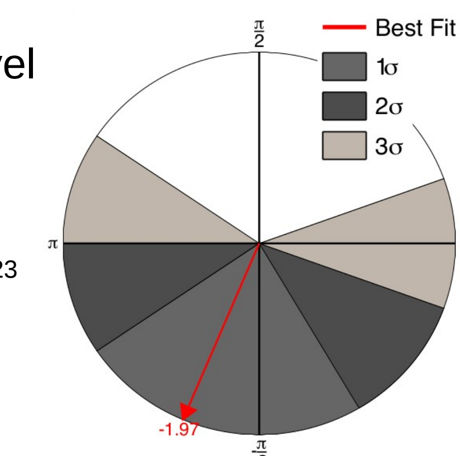
ν_e vs $\bar{\nu}_e$ appearance







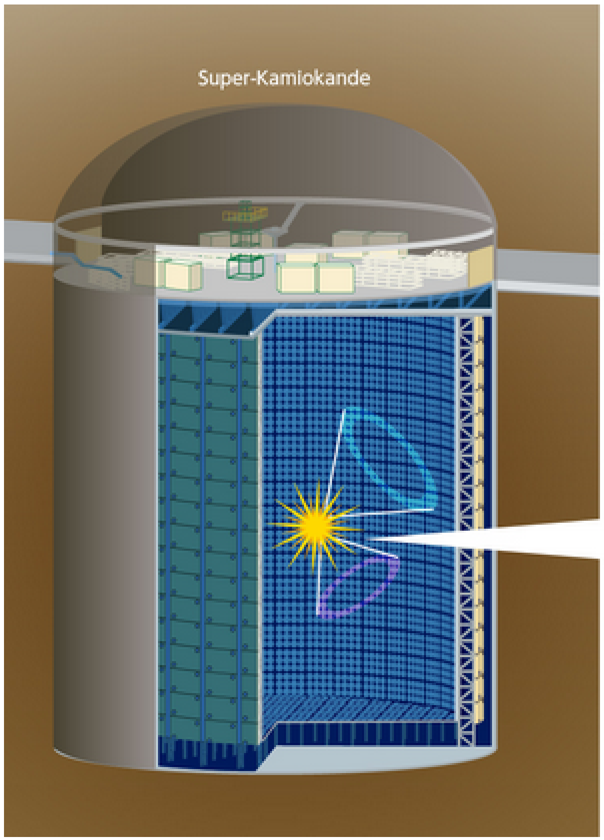
- Large range of δ_{CP} values around $+\pi/2$ rejected at 3σ level
- Best fit close to maximal CP violation near $-\pi/2$
- CP conservation (δ_{CP} = 0 or π) excluded at 90% CL
- Weak preference for Normal Ordering and II octant for θ_{23}
- Looser constraint after adding Run 10 data
  → Previously data exceeded projected CP violation, probably because of statistical fluctuation

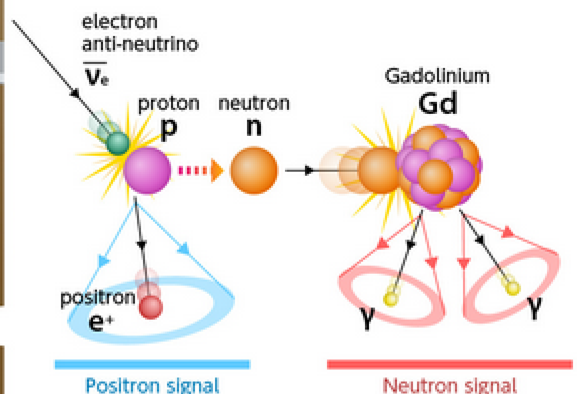


T2K future

- T2K phase II → 2023
  - neutrino beam upgrade
  - ND280 near detector upgrade
  - Super-Kamiokande + Gd
- Hyper-Kamiokande → 2027
  - Intermediate Water Cherenkov Detector
  - Hyper-Kamiokande far detector

Super-Kamiokande with Gadolinium





- Gadolinium adding already started
- It will enhance $\nu/\bar{\nu}$ discrimination
- and improve SK ability to observe Supernova Relic Neutrinos
- 0.1% Gd → 90% neutron capture efficiency

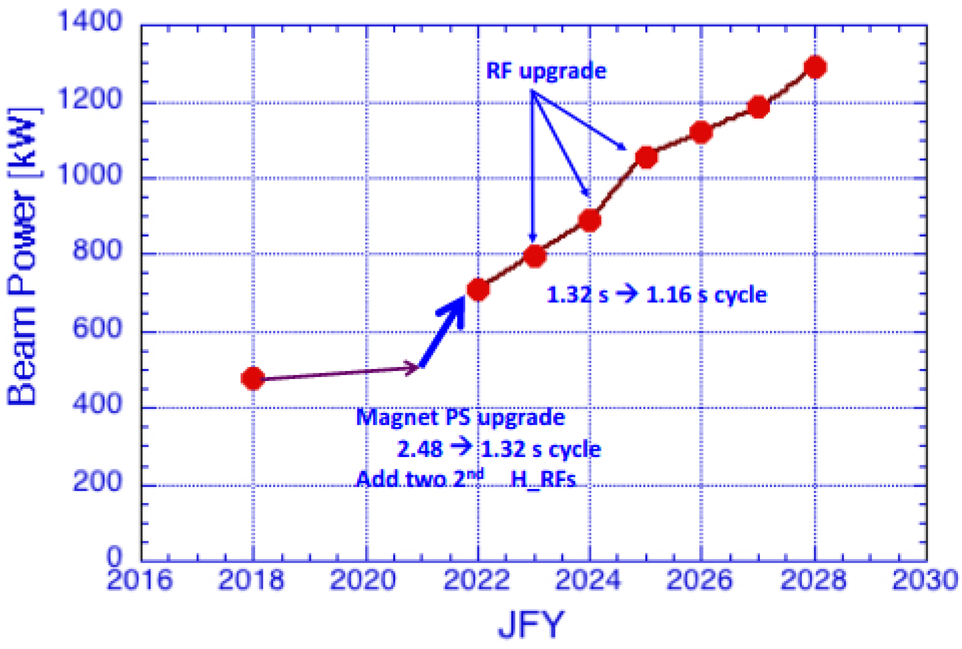
Tank refurbishment in 2018 to stop water leakage

Accelerator and neutrino beamline upgrade

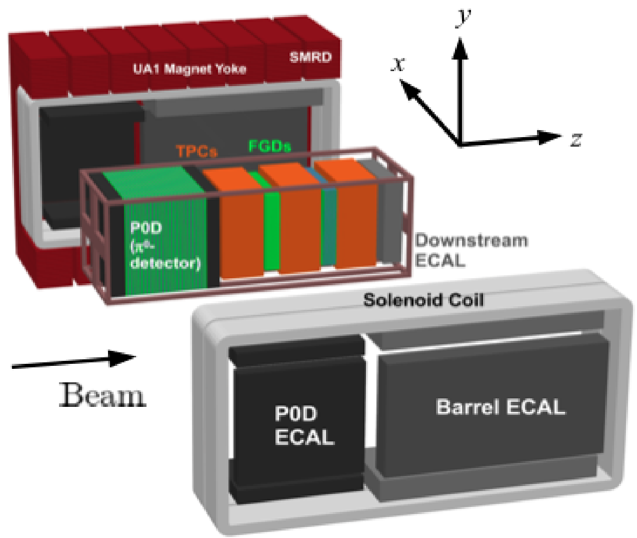
Proton beam power upgrade
+ increase of the horn current:
250 kA → 320 kA
→decrease of wrong sign background

	Cycle time [s]	Protons per pulse	Beam power
Now	2.48	2.6×10^{14}	~500 kW
Goal	1.16	3.2×10^{14}	1.3 MW

Requirements:
- upgrade of the Main Ring power supplies
- upgrade of the focusing horn power supplies
- enhancement of the cooling capacity of the graphite target, the magnetic horns and the beam dump
- disposal of a larger amount of irradiated cooling water



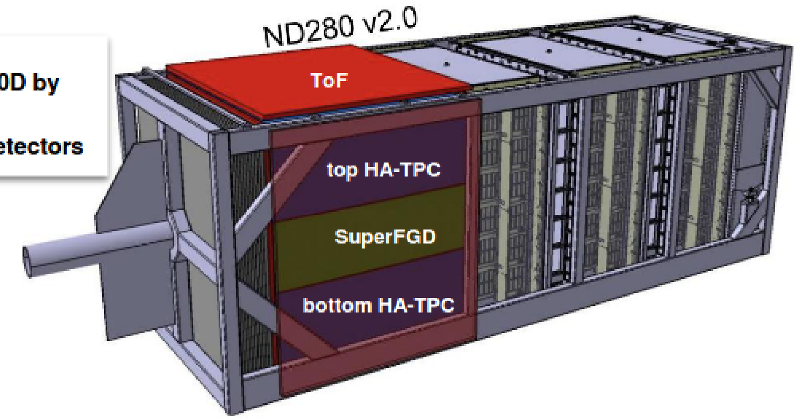
ND280 upgrade



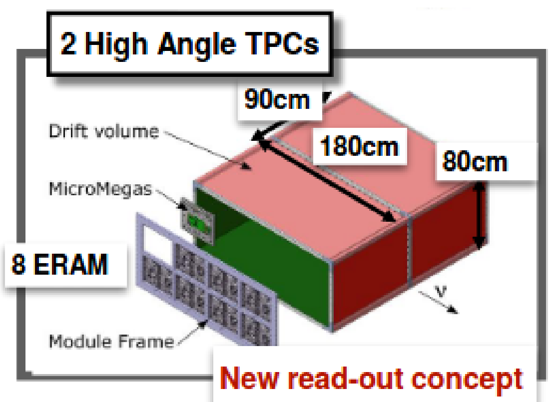
Upgrade

Replace P0D by

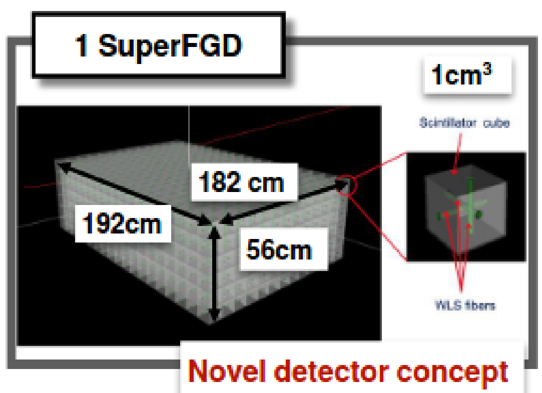
new subdetectors



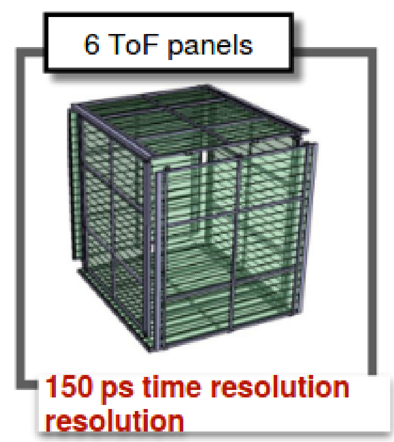
Planned to finalise by the end of 2022



NIM A 957 163286 (2020)



JINST 13, P02006 (2018)
JINST 15 P12003 (2020)

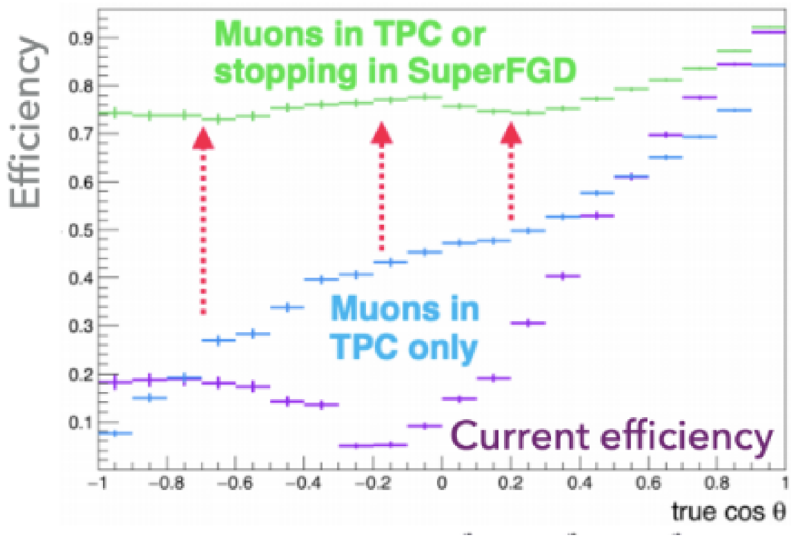


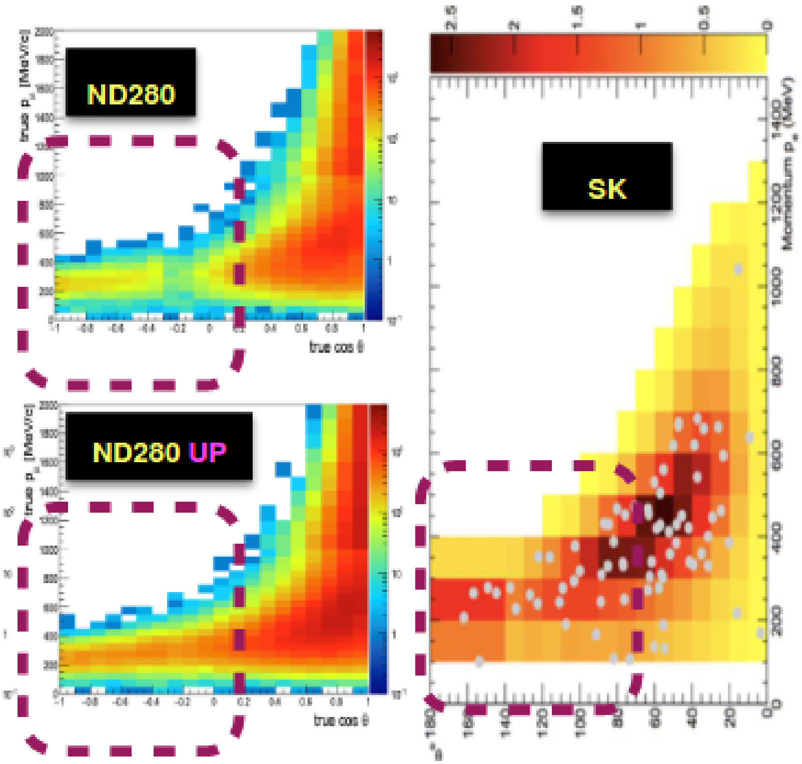
JPS Conf. Proc. 27, 011005 (2019)

ND280 upgrade

- Lower energy threshold
- High and flat angular acceptance
- Larger target mass (for tracker part)

Ready for data taking
at the beginning of 2023

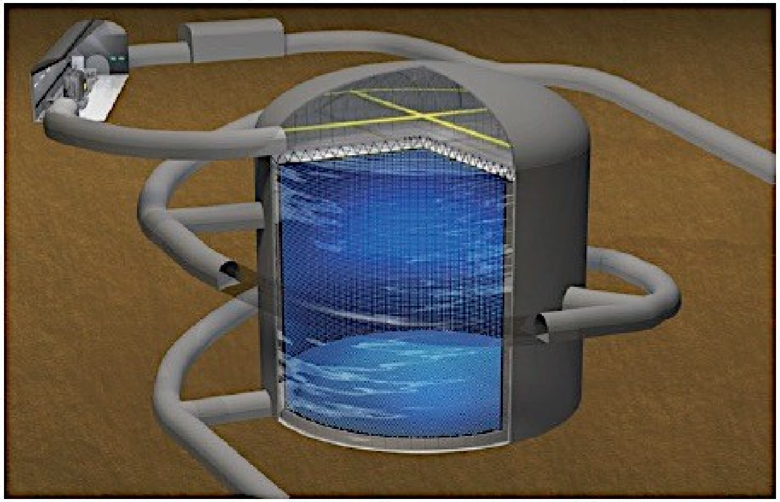




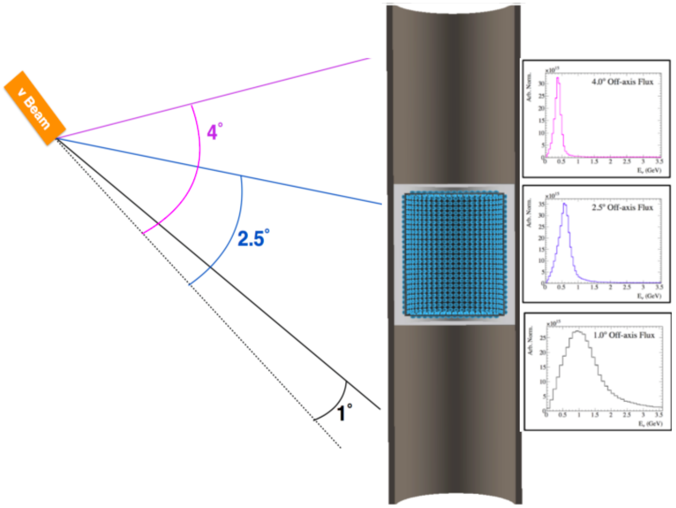
Hyper-Kamiokande

- Tunnel excavation work for HK already started
- Planned data taking in 2027
- Confirmation on 5σ level if CP is conserved or violated in neutrino oscillations thanks to larger statistics and smaller systematic errors

Hyper-Kamiokande detector



	SK	HK
Site depth	Mozumi (1000m)	Tochibora (650m)
# PMT	11,129	40,000
Photo-coverage	40 %	40% (x2 QE)
Mass Fiducial mass	50 ktons 22.5 ktons	260 kkons 188 ktons



Intermediate Water Cherenkov Detector

IFJ involvement

- T2K team in IFJ PAN
  - physicists: Agnieszka Zalewska, Jan Kisiel, Tomasz Wąchała, Marcela Batkiewicz-Kwaśniak
  - engineers: Jacek Świerblewski, Jerzy Michałowski, Henry Przybilski

MicroMegas stiffeners production in IFJ DAI

IFJ team activities in:

- T2K & T2KII
  - neutrino interaction studies: CC0π on lead, CCπ^0 on CH
  - responsible for FGD detector (together with other Polish groups)
  - ND280 run coordinator position
  - design & production of TPC end plates and MicroMegas stiffeners for the upgraded ND280 detector
  - members of committees and co-conveners of working groups:
    reconstruction, NC/ν_e/π^0 cross-section sub-group (up to 2020), public webpage
    ND280 upgrade mechanical integration, technical board, safety committee
- Hyper-K
  - members of Outreach Committee & Speakers Board

Summary

- T2K provided the first 3σ constraints on possible δ_{CP} values
- Exclusion of CP conservation in neutrino oscillations at 90% CL
- Weak preference for Normal Ordering and II octant for θ_{23}
- Ongoing works towards T2KII and Hyper-Kamiokande

Backup

Neutrino oscillations formula

Two flavour approximation:

$$P_{\mu e} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

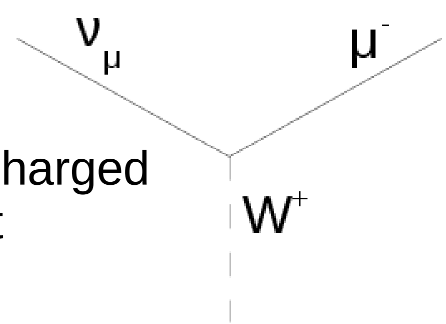
Three flavour oscillations with mass and CP term:

$$\begin{cases} P_{\mu e} \simeq \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)^2}}_{C_0} + \underbrace{\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\left(\hat{A}\Delta\right)}{\hat{A}^2}}_{C_1} \\ \underbrace{+\alpha\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}\sin(\Delta)\frac{\sin\left(\hat{A}\Delta\right)}{\hat{A}}\frac{\sin\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)}}_{C_-}\sin\delta_{CP} \\ \underbrace{+\alpha\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}\cos(\Delta)\frac{\sin\left(\hat{A}\Delta\right)}{\hat{A}}\frac{\sin\left[\left(1-\hat{A}\right)\Delta\right]}{\left(1-\hat{A}\right)}}_{C_+}\cos\delta_{CP} \end{cases}$$

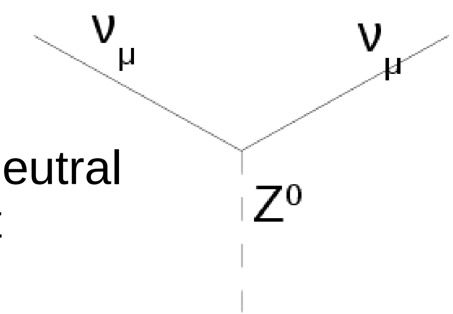
$$\Delta m^2_{ij} \equiv m^2_i - m^2_j, \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}, \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$\hat{A} \equiv \frac{A}{\Delta m^2_{31}}, \qquad A = \pm 2\sqrt{2} G_F N_e E.$$

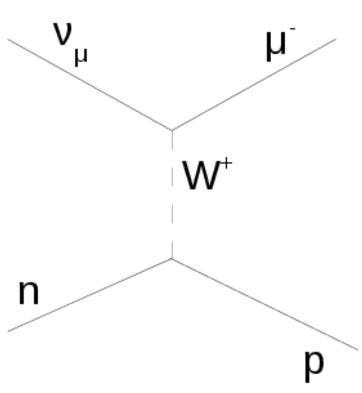
Neutrino interaction types



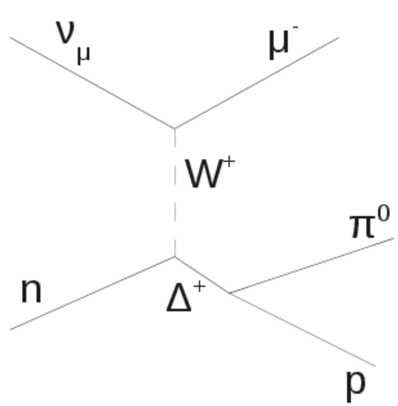
CC – charged current



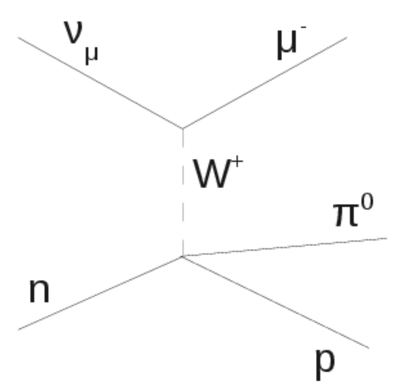
NC – neutral current



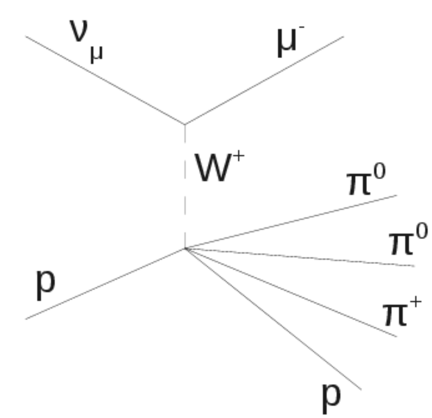
CCQE – CC quasi elastic



RES – resonant pion production

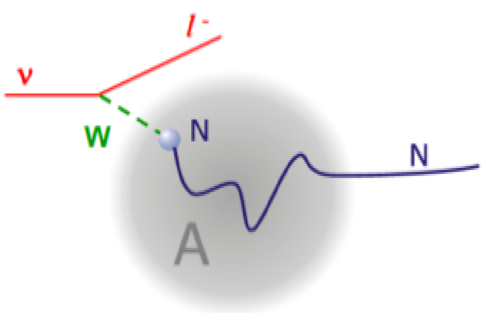


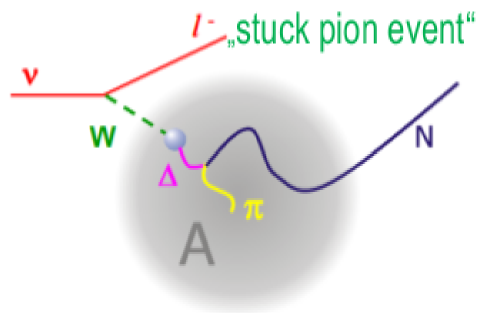
non resonant pion production

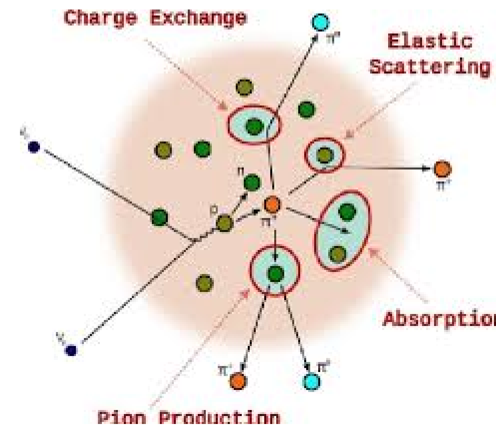


DIS – deep inelastic scattering

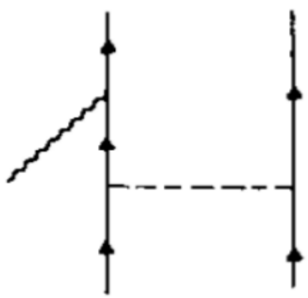
Neutrino-nucleus interaction



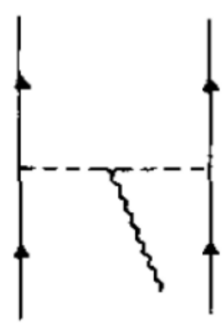


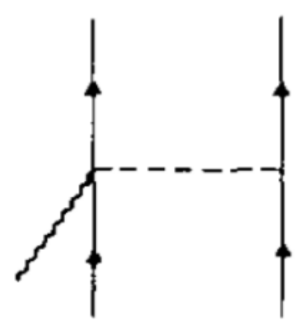


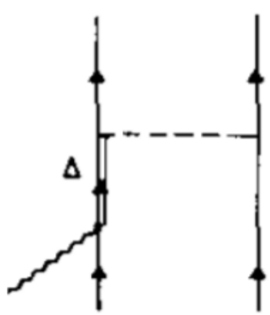
Nucleon-Nucleon correlations



Meson Exchange Currents (MEC)

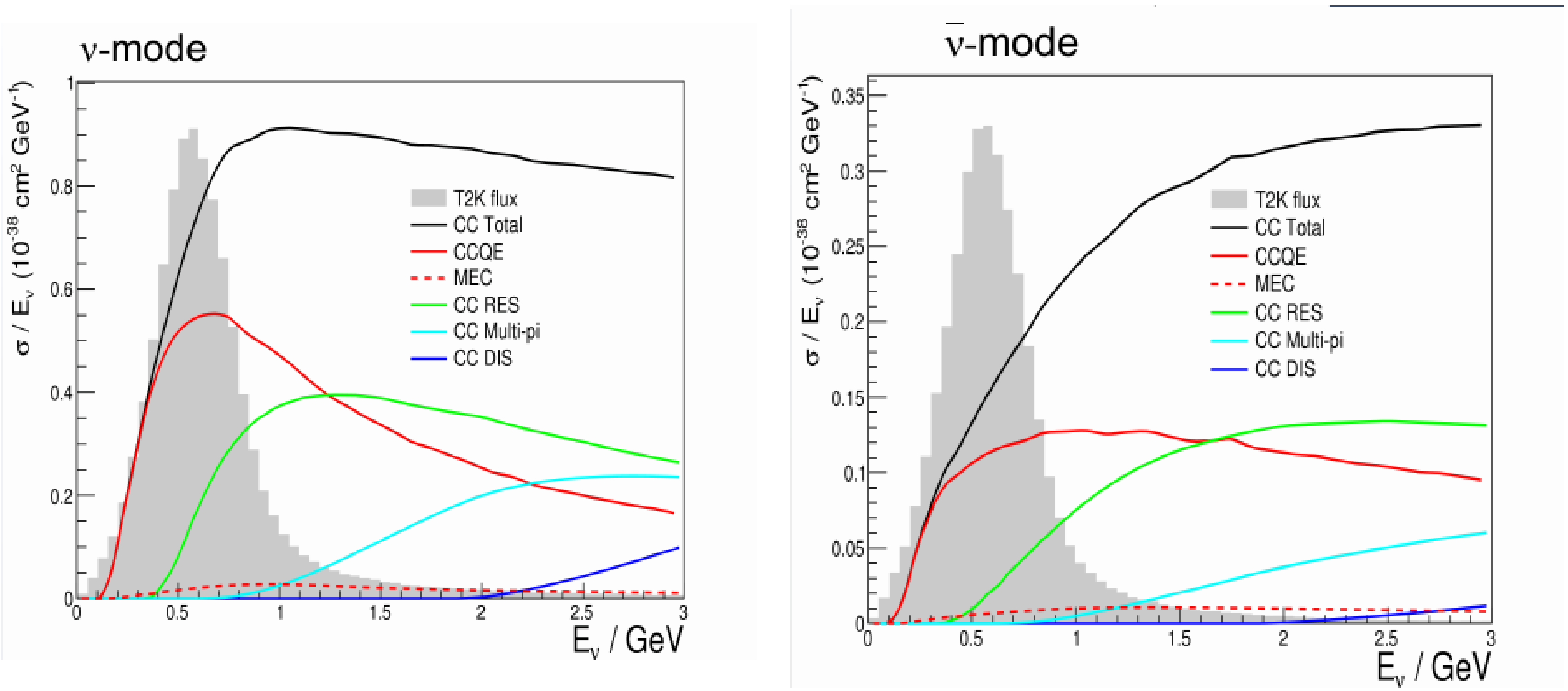






Pion in flight   Contact   Delta

Neutrino interactions cross-sections



Systematic uncertainties

T2K Preliminary

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
$\mathrm{BG}_A^{\mathrm{RES}}$ low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Systematic uncertainties

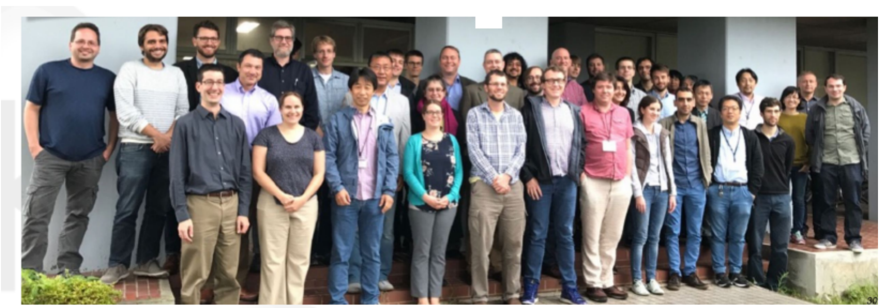
Before ND fit T2K Preliminary

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	5.1	4.7	4.8	4.7	4.9	2.7
Cross-section (all)	10.1	10.1	11.9	10.3	12.0	10.4
SK+SI+PN	2.9	2.5	3.3	4.4	13.4	1.4
Total	11.1	11.3	13.0	12.1	18.7	10.7

After ND fit T2K Preliminary

Error source (units: %)	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

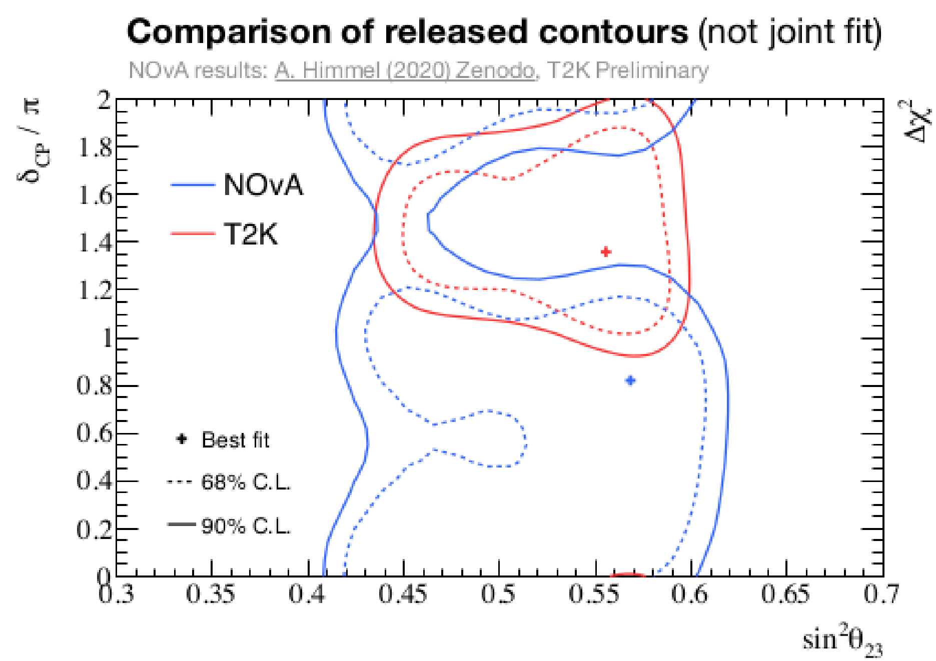
T2K + Nova



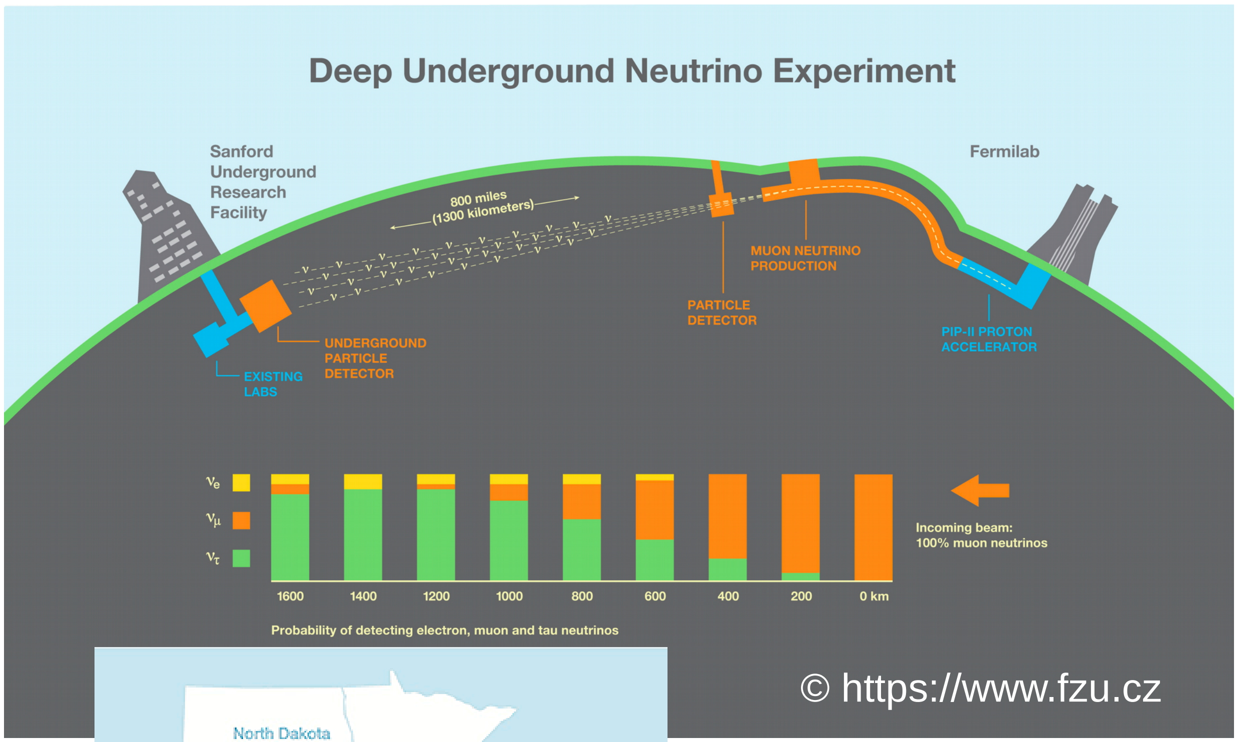
- Several workshops since 2017
- Challenges and chances:
  - Different experimental setups
  - Different peak energy
  - Different analysis

Joint T2K-NOvA analysis effort:

- Potential to further improve CP violation mass ordering sensitivity. Complementarity of the two experiments:
  - T2K practically insensitive to mass ordering (baseline too short) but more sensitive to CP violation
  - NovA sensitive to mass ordering due to its 860 km baseline. Less sensitive to CP violation.



DUNE experiment



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Planned project timeline

July 2017
Groundbreaking for LBNF/DUNE

Sept. 2018
First ProtoDUNE detector online at CERN

Jan. 2019
Pre-excavation work begins in South Dakota

Nov. 2019
LBNF/DUNE site preparation starts at Fermilab

2021
Begin main cavern excavation in South Dakota

2024
Begin installing the first DUNE detector

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