T2K Results and Plans

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Neutrino oscillations

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$
$\Delta m_{ij} = m_i^2 - m_j^2$

- Mixing between flavor eigenstates (interacting states) and mass eigenstates (propagating states) governed by Pontecorvo-Maki-Nakagawa-Sakata(PMNS) matrix

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

Atmospheric Accelerator	Reactor Accelerator	Solar Reactor
$\theta_{23} \sim 48°$	$\theta_{13} \sim 8°$	$\theta_{12} \sim 34°$
$\lvert\Delta m_{32}^2\rvert \sim 2.5\times10^{-3} eV^2$	$\delta_{CP} = ?$	$\Delta m_{21}^2 \sim 7.5\times10^{-5} eV^2$

Open questions

- Neutrino mass ordering
  - Normal($\Delta m^2_{32} > 0$) or inverted($\Delta m^2_{32} < 0$)
- θ_{23} octant
  - Upper($sin^2\theta_{23} > 0.5$) of lower($sin^2\theta_{23} < 0.5$) or $\theta_{23} = 45°$
- CP violation in neutrino sector
  - $\delta_{CP} \neq 0, \pi$ indicates $P(\nu_\alpha \to \upsilon_\beta) \neq P(\bar{\upsilon}_\alpha \to \bar{\upsilon}_\beta)$ in vacuum

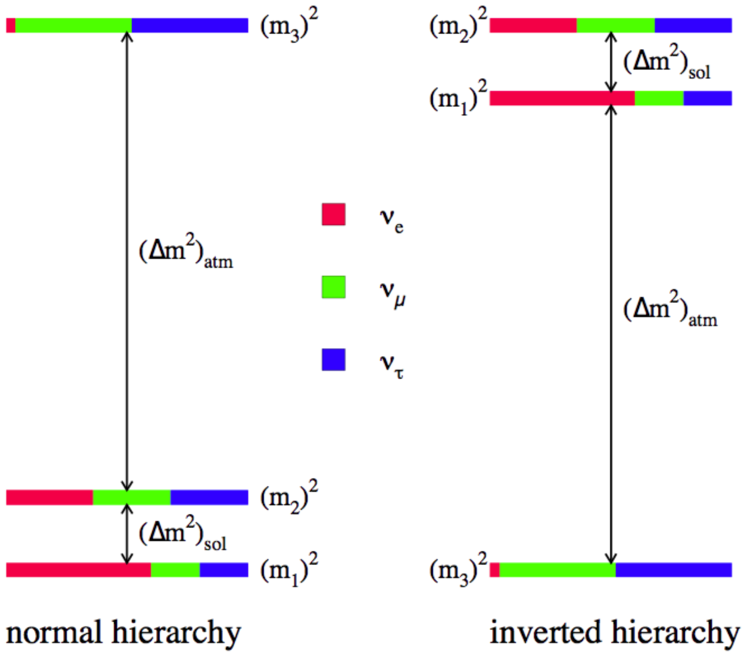


Figure from here

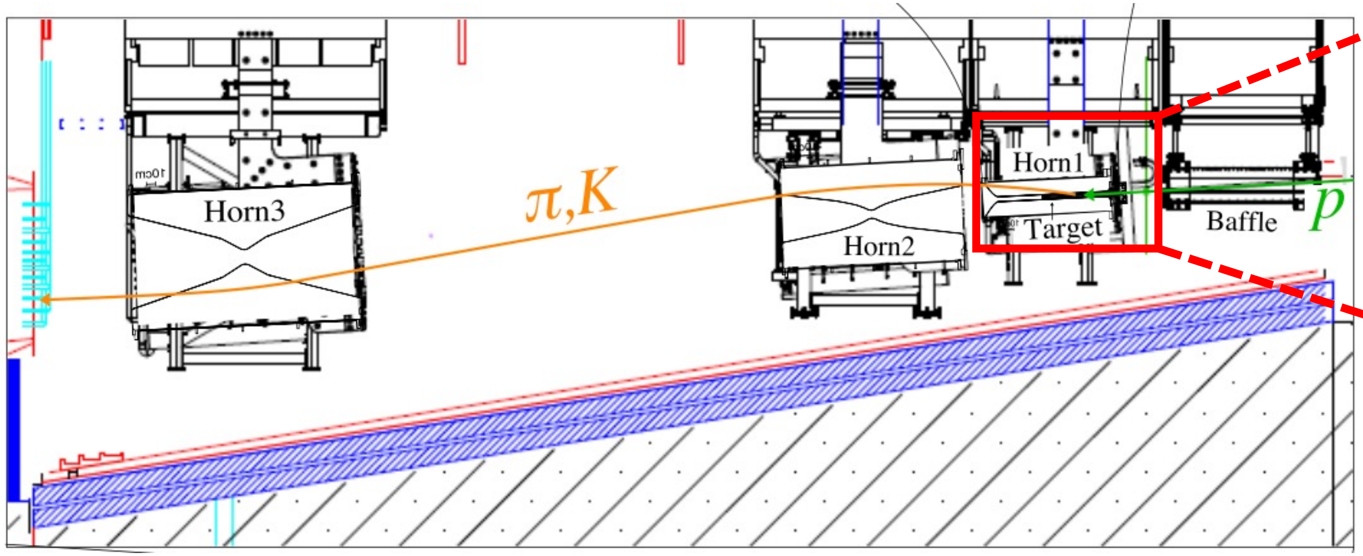
T2K is well sensitive to answer all three questions!

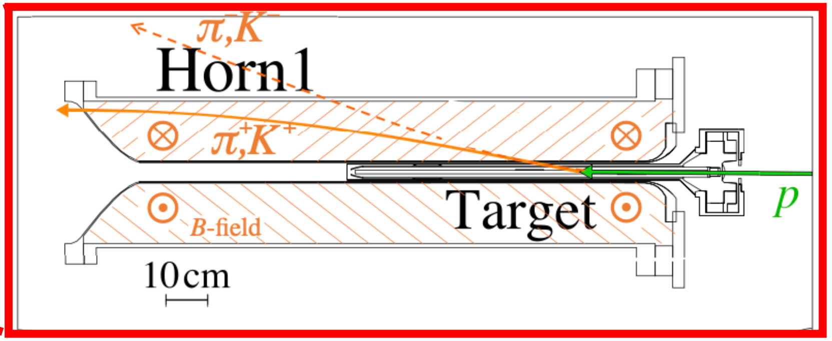
Tokai-to-Kamioka (T2K) experiment

- Study oscillation of neutrino beam from J-PARC
  - Intense ν or $\bar{\nu}$ beam from J-PARC neutrino beamline
  - Near(280 m)/far(295 km) neutrino detectors, ND280/Super-K

T2K neutrino beam

- 30 GeV protons strike the 90 cm long graphite target, producing π, K.
- Three magnetic horns selectively focus π^+, K^+ or π^-, K^- to produce ν or $\bar{\nu}$ beam (decay in-flight).





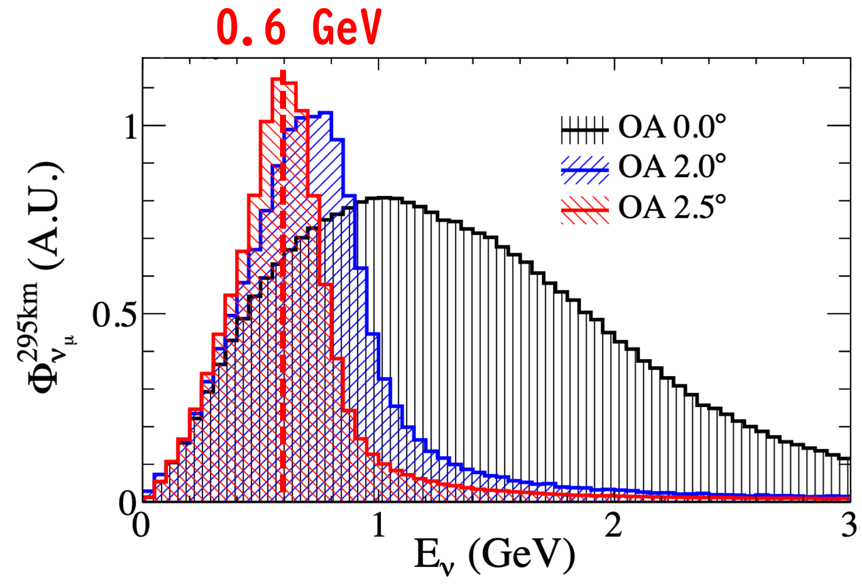
$$\pi^+ \to \mu^+ \upsilon_\mu$$

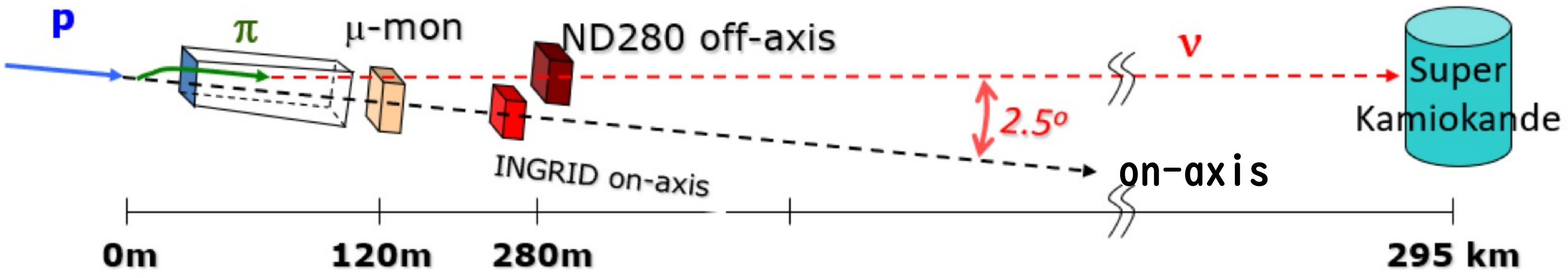
$$\pi^- \to \mu^- \bar{\nu}_\mu$$

Off-axis beam

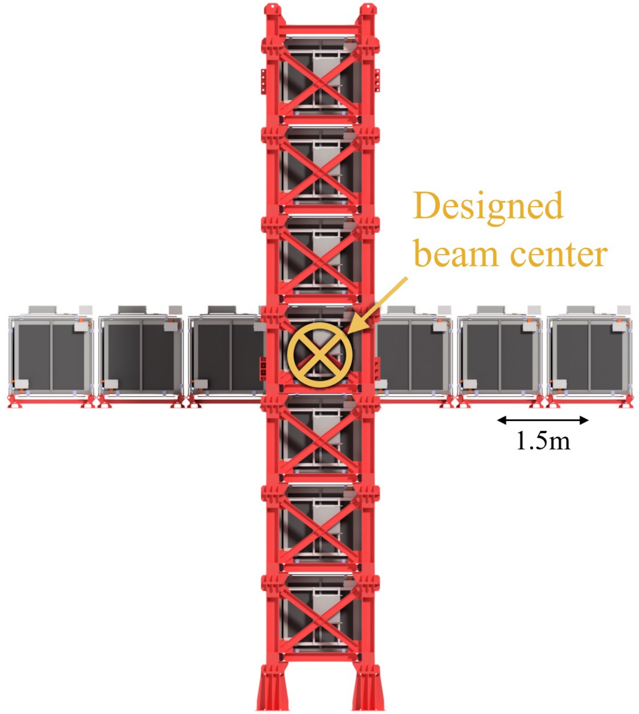
$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m_{23}^2 \frac{L}{E_\nu}\right)$$

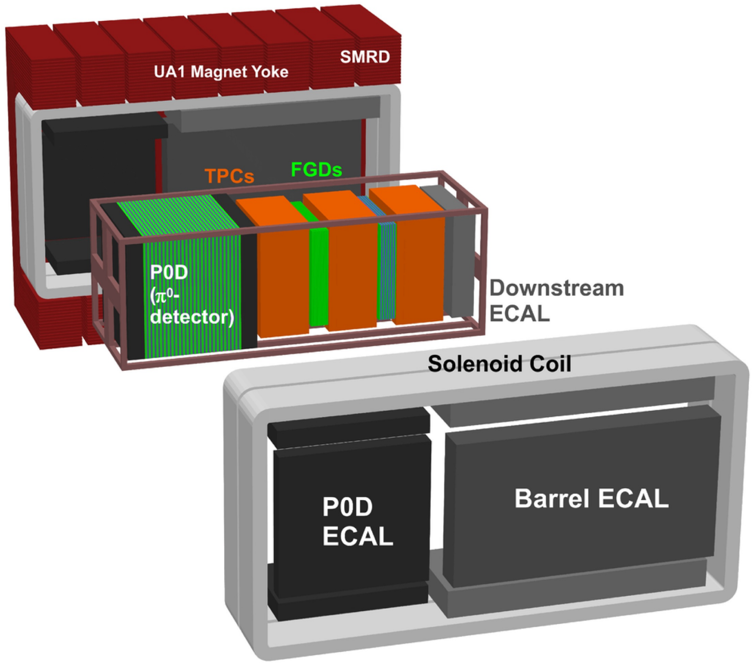
- T2K experiment
  - $L = 295\ km,\ \ \Delta m_{23}^2 \sim 2.4\times10^{-3} eV^2$
    → Oscillation maximum @ $E_\nu \sim 0.6\ GeV$
  - Off-axis angle = 2.5°
    - Select flux at the oscillation maximum
    - Reduce high energy ν backgrounds
    - CCQE is the dominant interaction





Near detectors





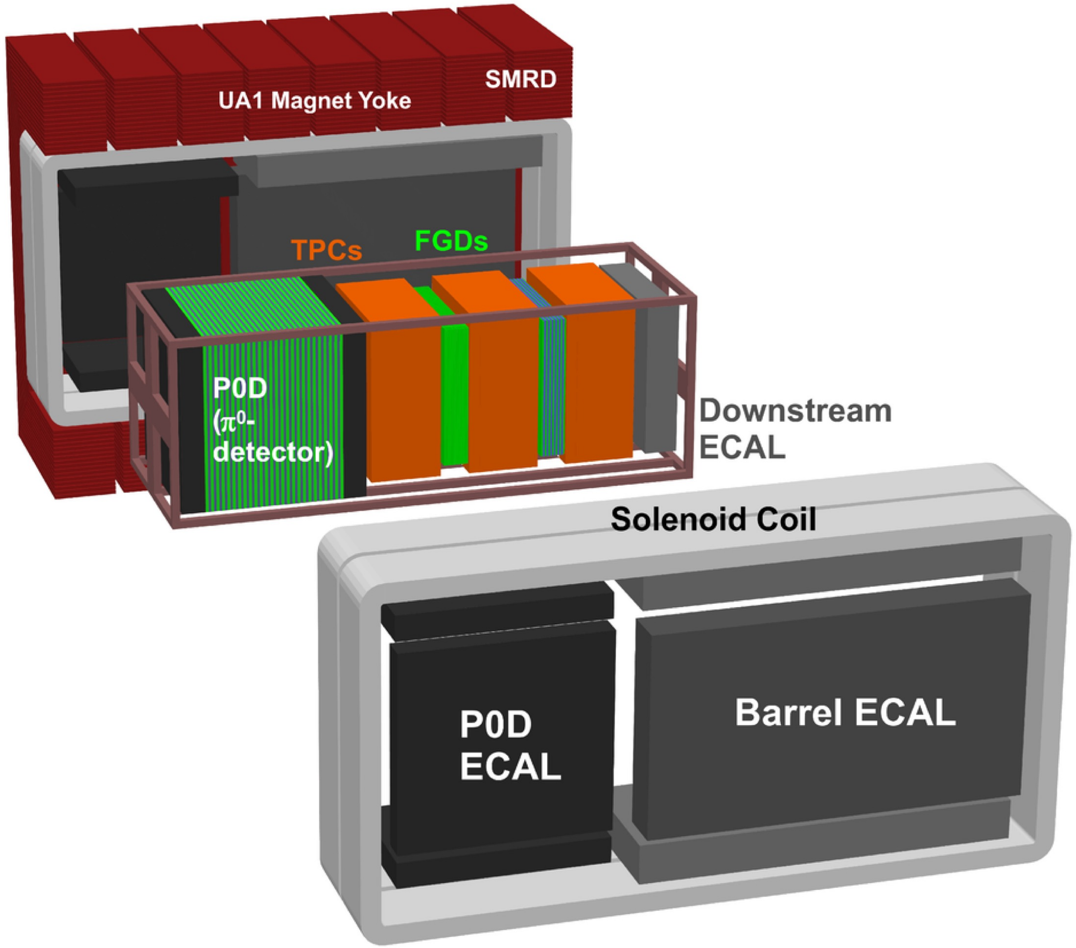
INGRID (on-axis)

- Beam monitor
  (direction and intensity)

ND280 (2.5° off-axis)

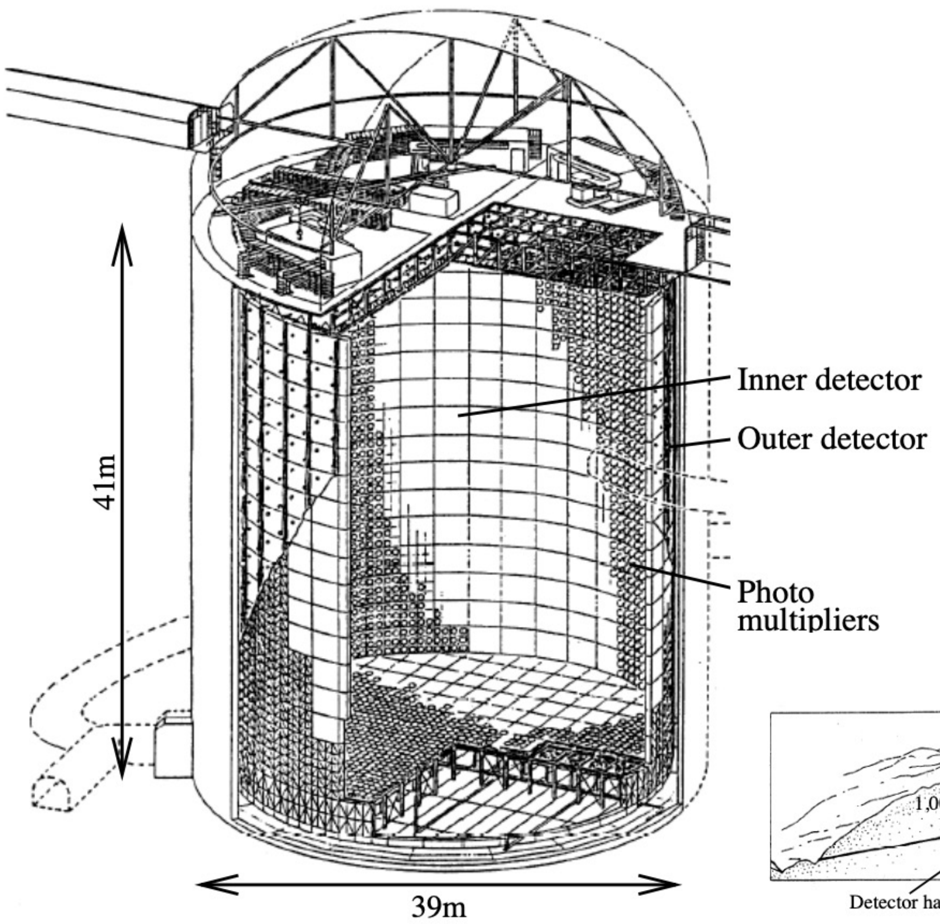
- constraints on
  beam flux and ν interactions
- ν cross section measurements

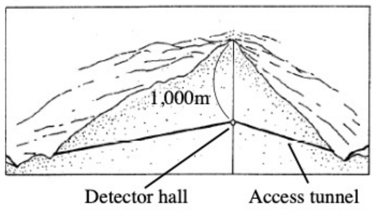
ND280 (2.5° off-axis)



- FGDs: Active scintillator + passive water targets
- Magnetized (0.2 T) for charge and momentum measurement with TPCs
- ECALs: Electromagnetic Calorimeters

Super-Kamiokande - the far detector



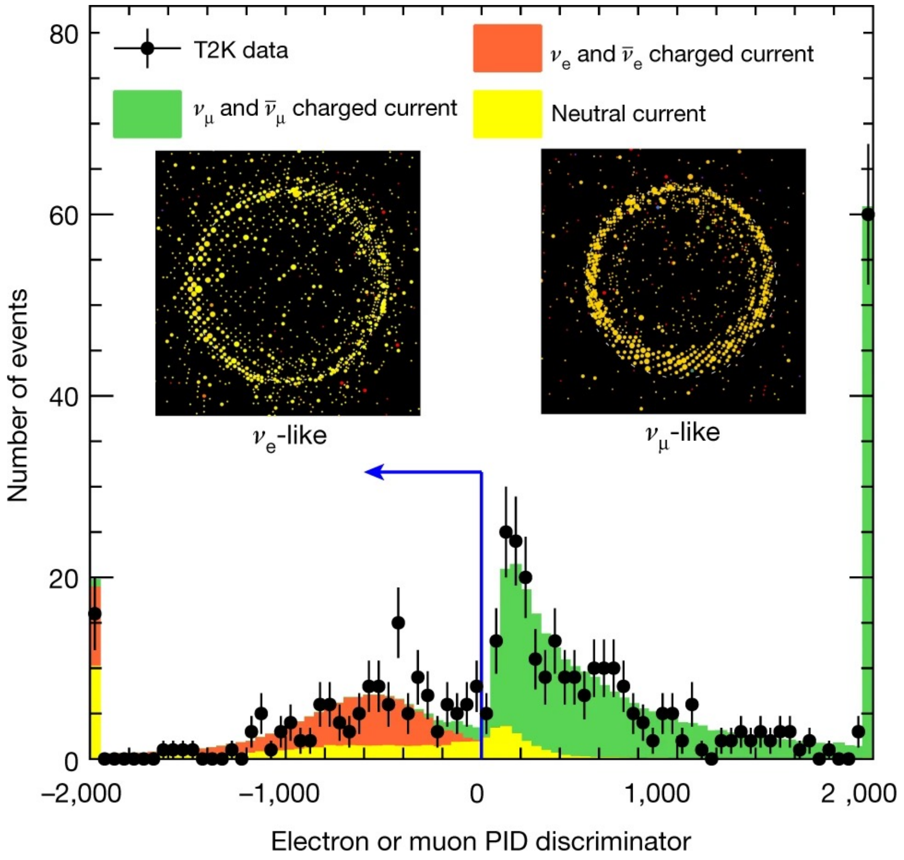


- 50 kton water Cherenkov detector
- 11000 20-inch PMTs
- Reconstruct neutrino energy from e/μ momentum and angle w.r.t beam

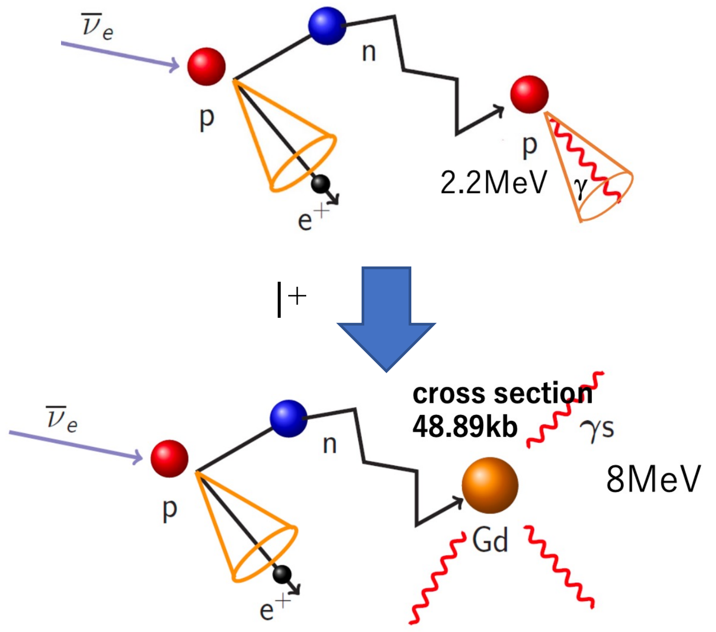
Super-Kamiokande – the far detector

- Good μ/e PID from ring shape

Adapted from Nature 580, 339-344 (2020)



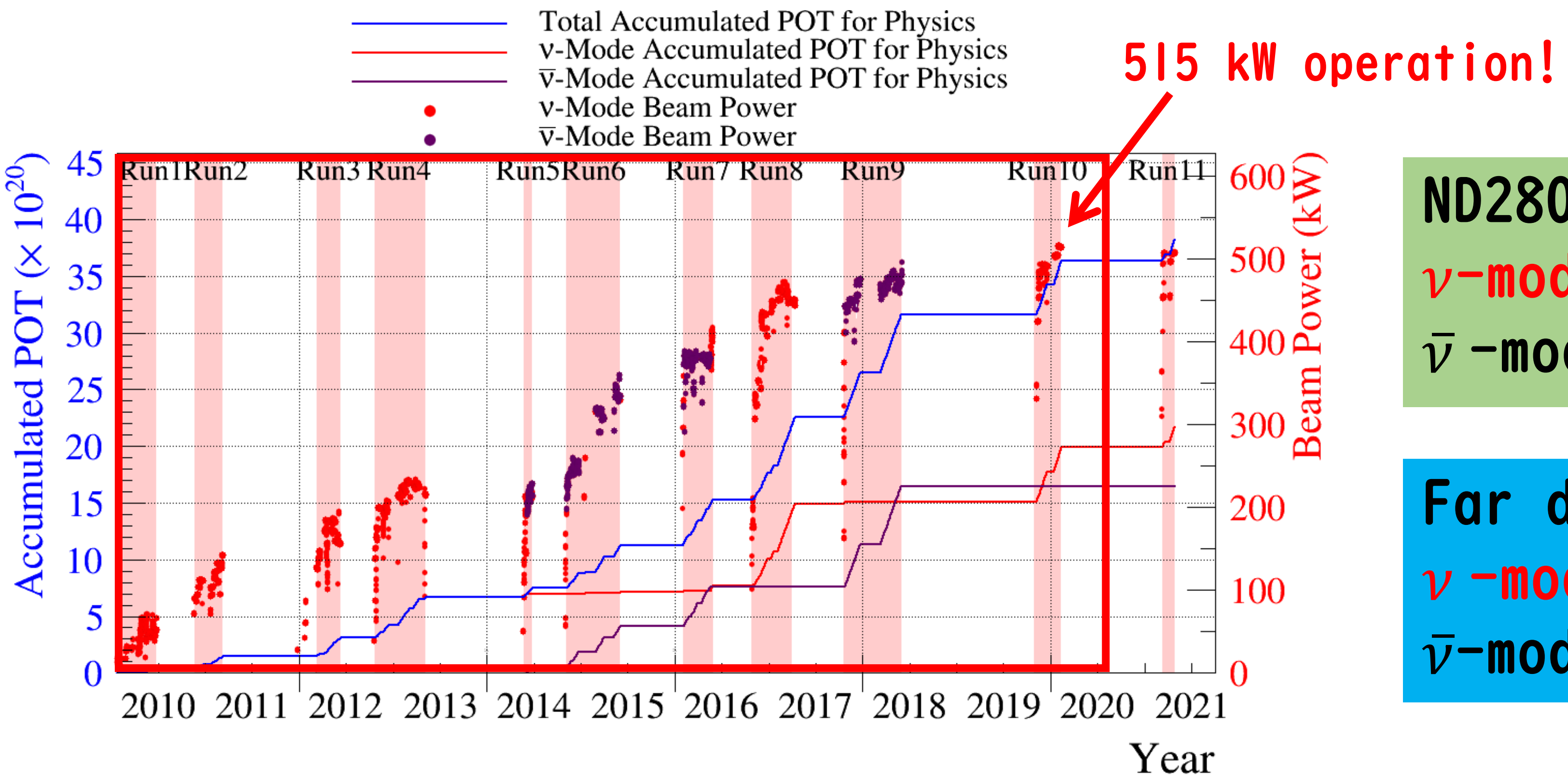
- Now loaded with Gd for improved neutron tagging



may provide wrong-sign background constraint in $\bar{\upsilon}_\mu$ and $\bar{\upsilon}_e$ samples

Dataset

- This talk (Run 1-10): 3.6×10^{21} protons on target (POT)
  - One more year of data available with Gd at SK (Run 11)



ND280

ν-mode: 1.39×10^{21} POT

$\bar{\nu}$-mode: 0.63×10^{21} POT

Far detector

ν-mode: 1.97×10^{21} POT

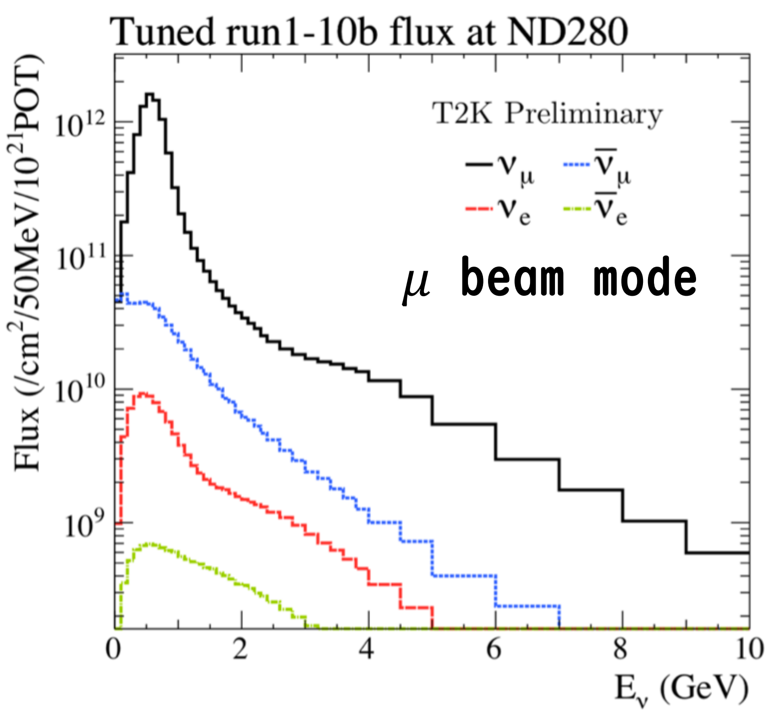
$\bar{\nu}$-mode: 1.63×10^{21} POT

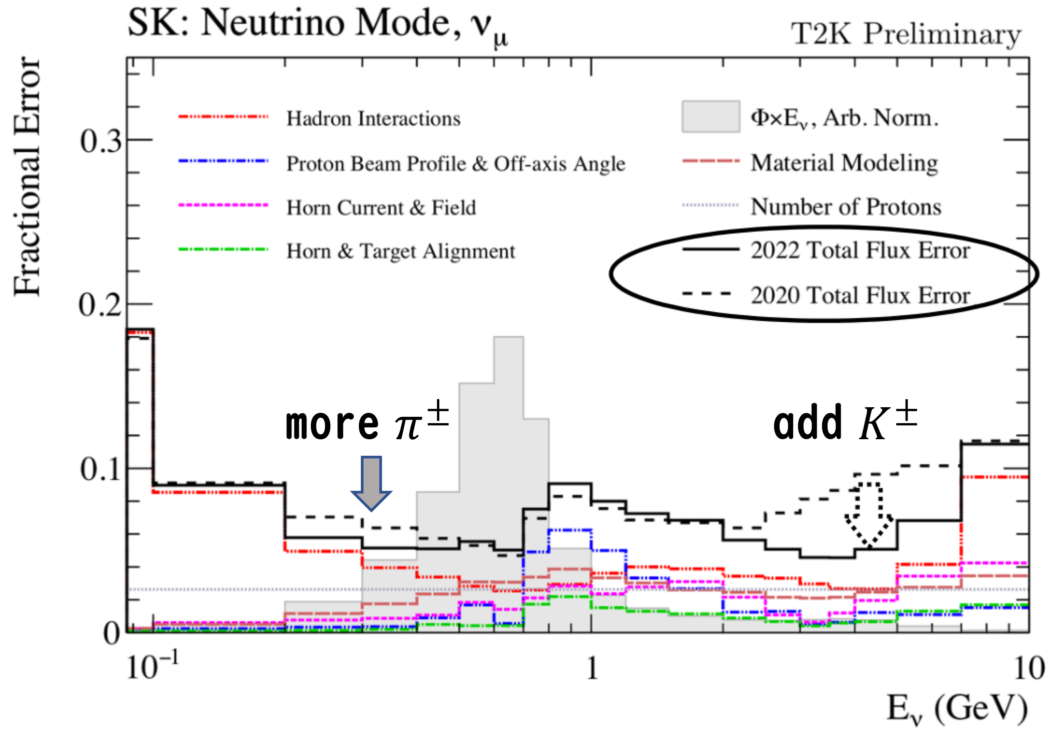
Data used for Oscillation analysis

- Beam monitors + INGRID + hadron production experiments
  → Neutrino flux prediction
- ND280 measurements + external measurements
  → Near detector fit: Neutrino flux x ν interaction
- 6 samples at Super-Kamiokande
  → Neutrino oscillation analysis

Neutrino flux prediction

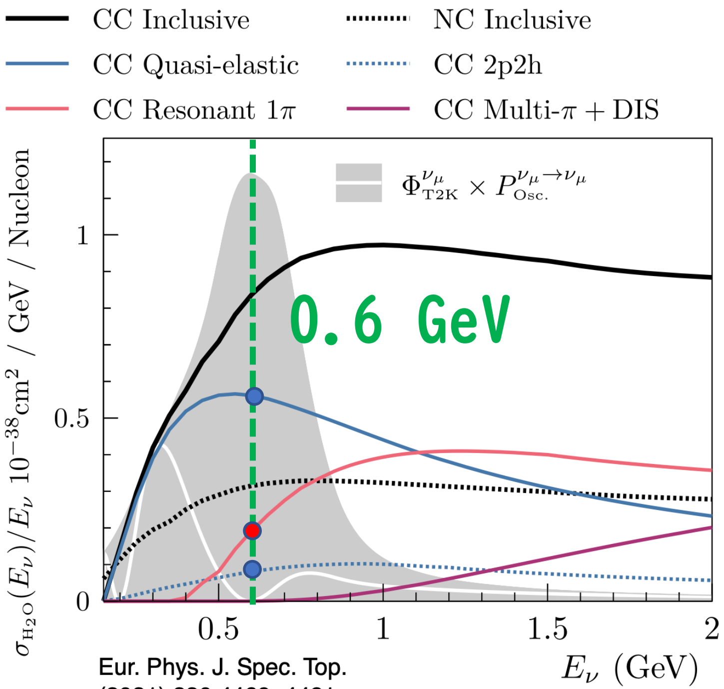
- Hadron production data from NA61/SHINE 2010 T2K replica target data (Eur. Phys. J. C79, 100) are adapted.
  - More statistics for $\pi^{\pm}$ production & add $K^{\pm}$ and proton data





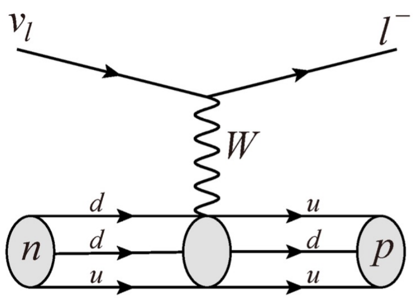
Neutrino interaction model

- CCQE: Spectral Function model
- CC Resonant: Rein-Sehgal model with RFG model
- CC 2p2h

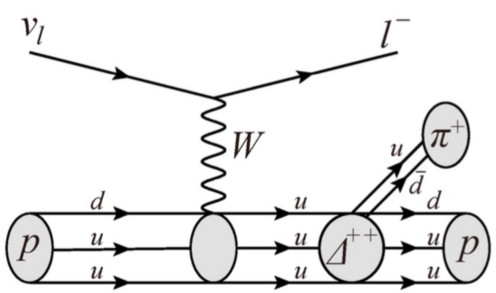


Eur. Phys. J. Spec. Top. (2021) 230:4469–4481

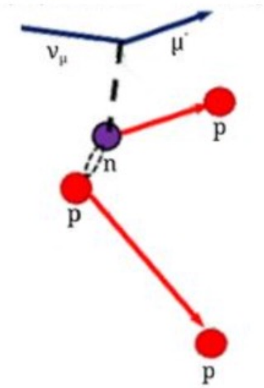
CCQE



CC Resonant

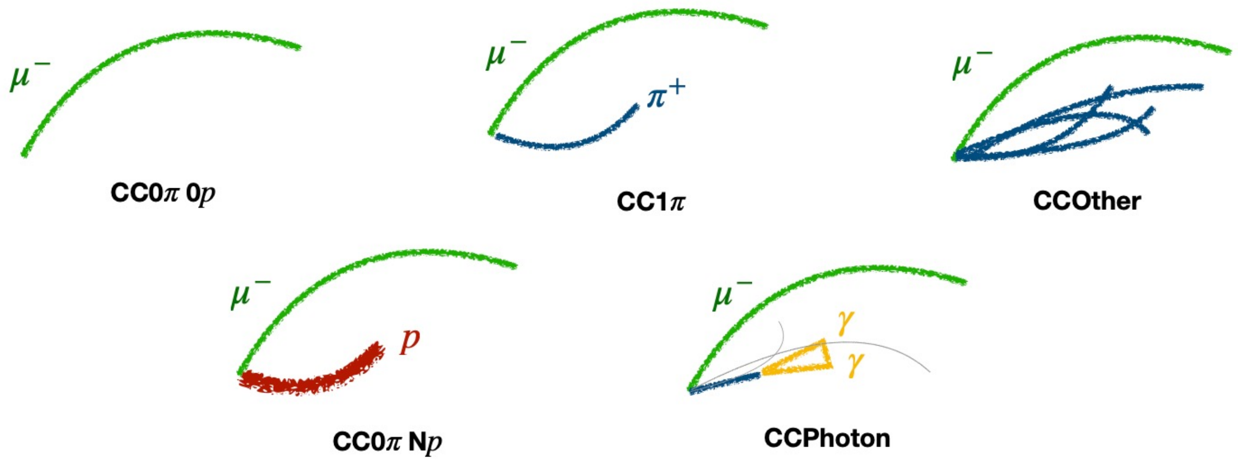


CC 2p2h



ND280 samples (ν beam mode)

- Separate events by observed particles ($\pi^{\pm}$, p, γ)

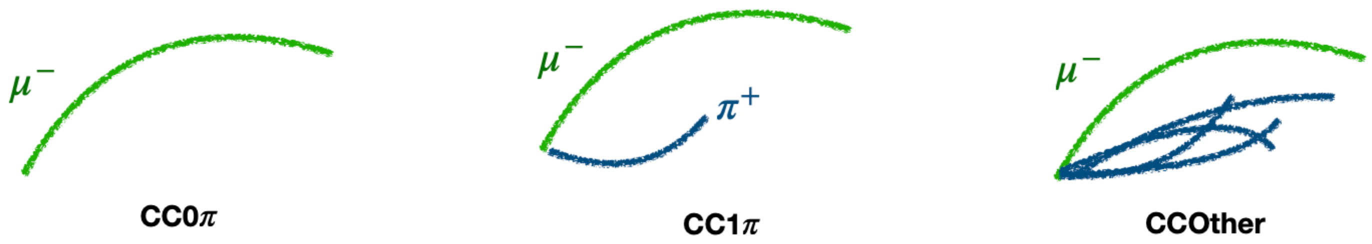


- 2 target materials: FGD1(C) and FGD2(C+O)

$5 \times 2 = 10$ samples

ND280 samples ($\bar{\nu}$ beam mode)

- Separate events by observed particles ($\pi^{\pm}$)

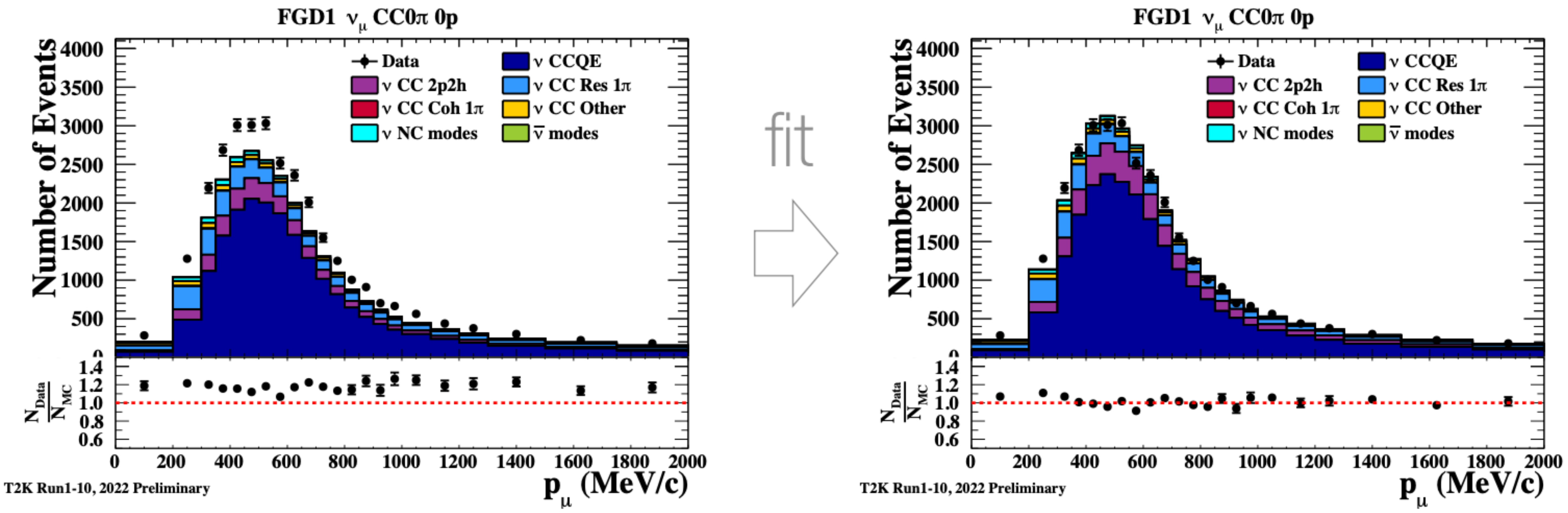


- Separate Right-sign (μ^+) and Wrong-sign (μ^-)
- 2 target materials: FGD1(C) and FGD2(C+O)

$3\times2\times2 = 12$ samples

ND280 fit

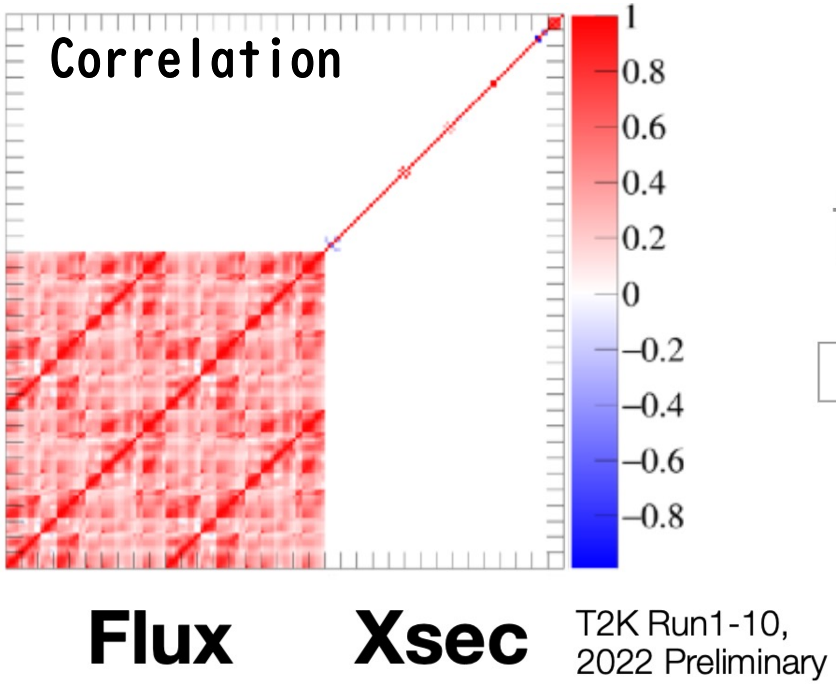
- Tuning the beam flux and neutrino interaction models with ND280 data.



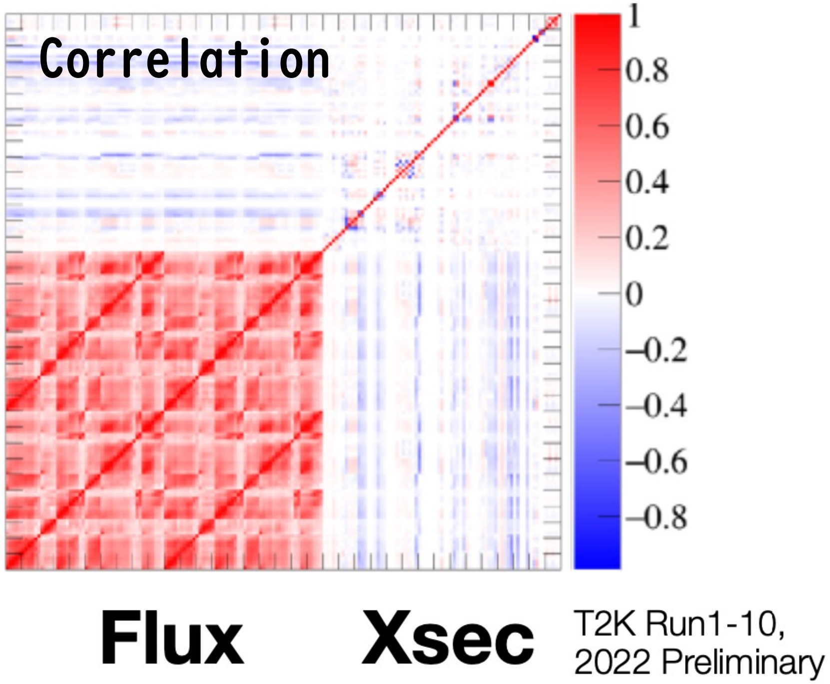
ND280 fit p-value: 10.9% (>5% threshold)

ND280 fit

- Fit result with correlated beam flux x neutrino cross section propagated to far detector analysis via covariance matrix.

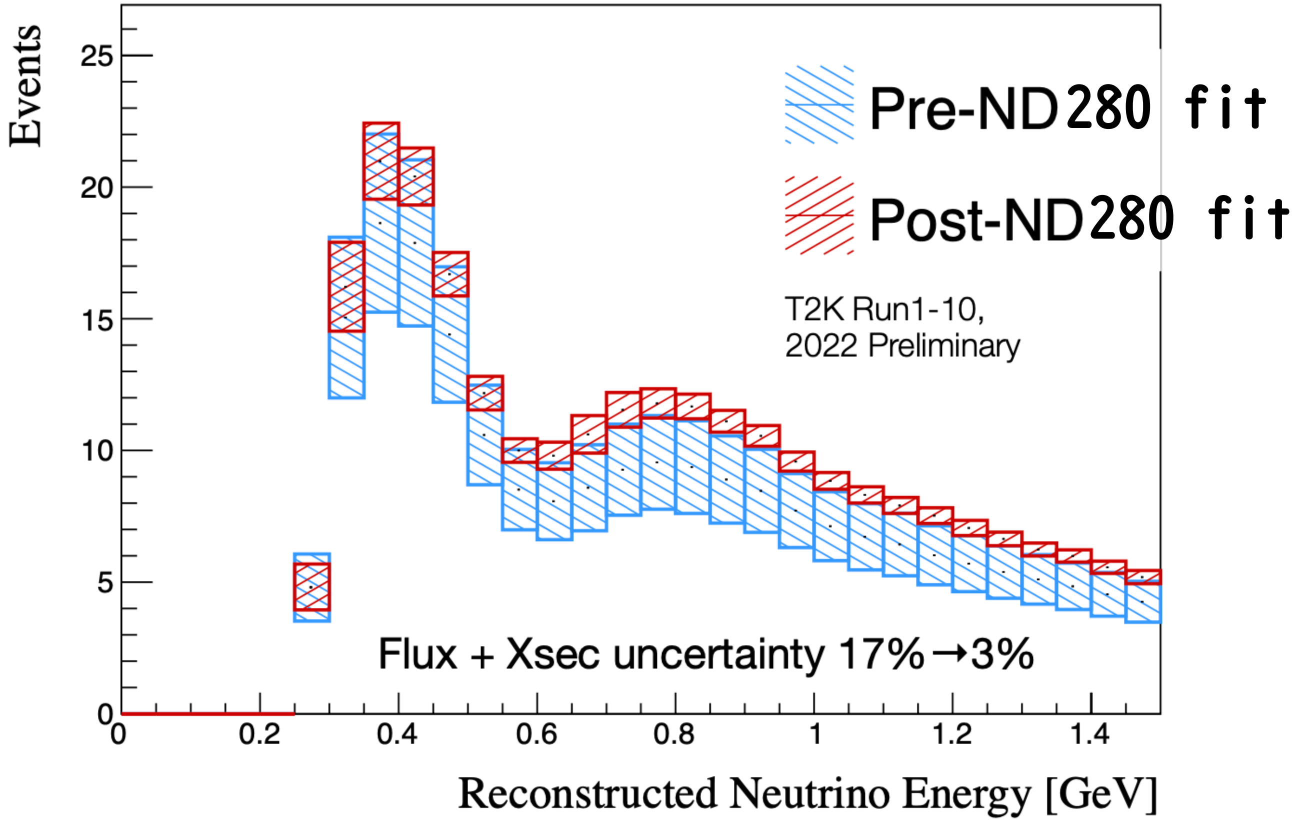


fit



ND280 fit

- Total systematic uncertainty on # of 1 Ring μ events at Super-Kamiokande (ν beam mode)

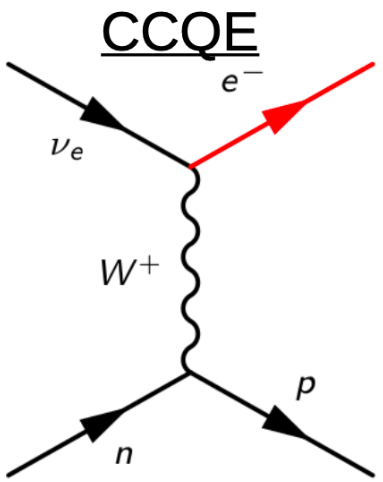


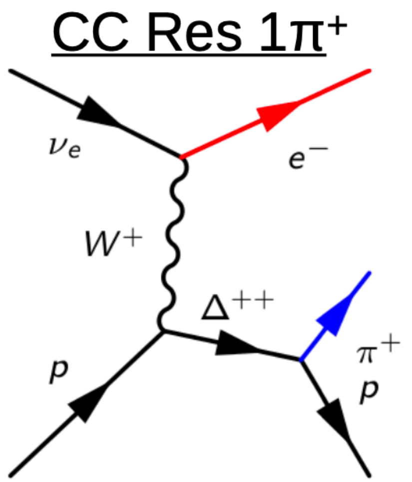
Super-K: Single ring samples

- Nominal event selection targets CCQE events, by selecting events with one ring e-like (1Re) or one ring μ-like (1Rμ).
- One additional sample in ν beam mode targets CC1πν_e events, tagging Michel electron (M.e) from pion decay.

5 samples

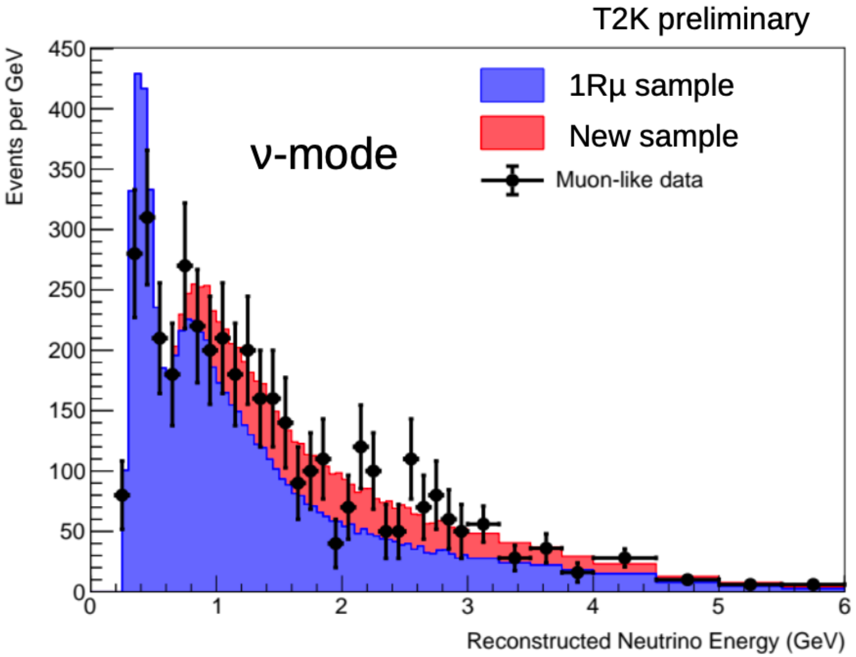
	e-like	μ-like
ν beam	1Re + 0 M.e	1Rμ + 0/1 M.e
	1Re + 1 M.e	
$\bar{\nu}$ beam	1Re + 0 M.e	1Rμ + 0/1 M.e

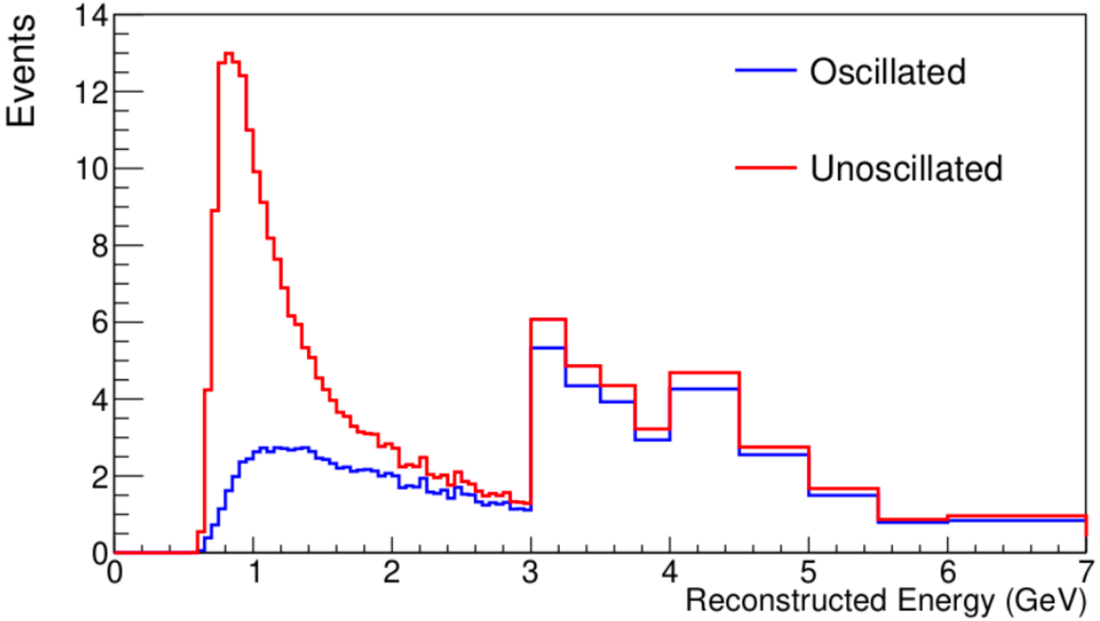




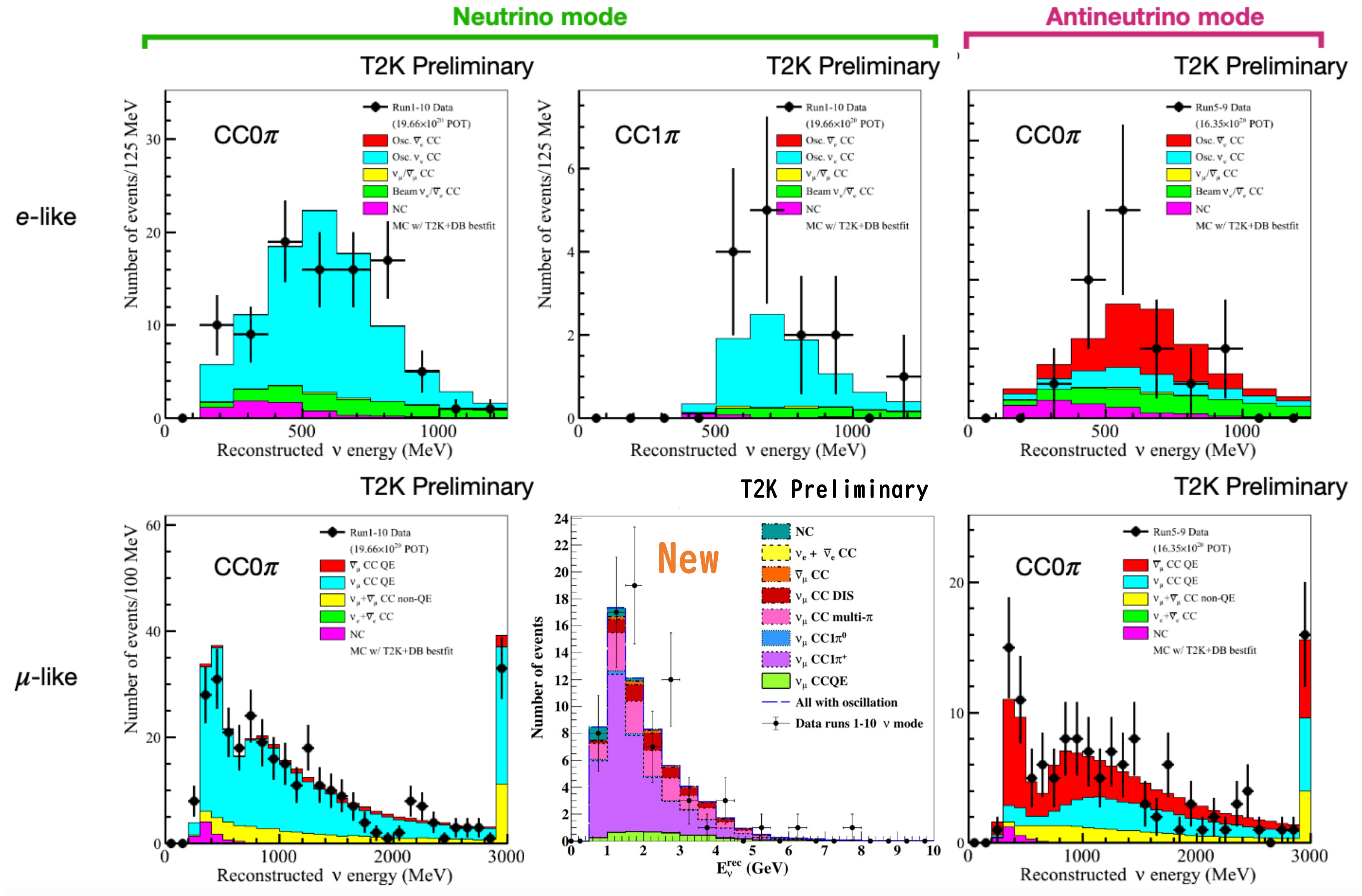
Super-K: new sample

- is targeting ν_μ CC1π^+ interactions in ν beam mode
- Combination of "1Rμ + 2 M.e" and two ring μ-like (2Rμ)
- Increase ν-mode μ-like statistics by ~30%





Super-K samples



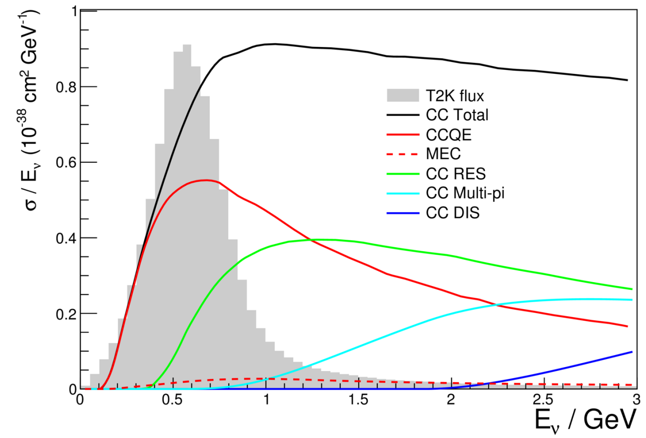
Super-K samples

ν -mode: 1.97×10^{21} POT
$\bar{\nu}$-mode: 1.63×10^{21} POT

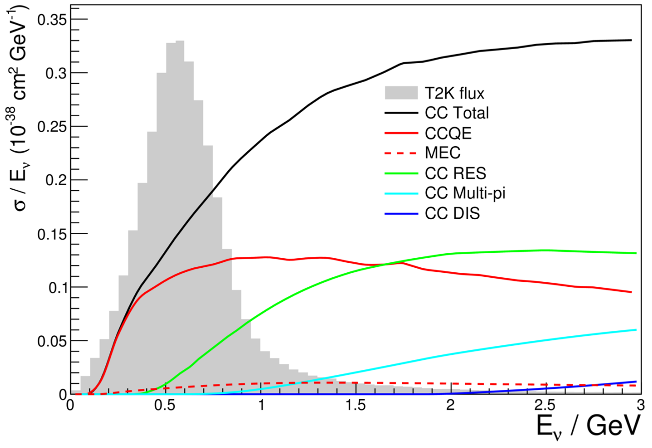
Mode	Sample	δ=-π/2 MC	δ=0 MC	δ=π/2 MC	δ=π MC	Data
ν	1Re	102.7	86.7	71.1	87.1	**94**
	1Re CC1π⁺	10.0	8.7	7.1	8.4	**14**
	1Rμ	379.1	378.3	379.1	380.0	**318**
	MRμ CC1π⁺	116.5	116.0	116.5	117.0	**134**
$\bar{\nu}$	1Re	17.3	19.7	21.8	19.4	**16**
	1Rμ	144.9	144.5	144.9	145.3	**137**

MC: $sin^2\theta_{23} = 0.561,\ \Delta m^2_{32} = 2.49\times10^{-3}\ eV^2c^{-4},$
$sin^2\theta_{13} = 0.022,$ Normal mass ordering

υ cross sections



$\bar{\upsilon}$ cross sections



Oscillation analysis result: Atmospheric parameters

- $\nu_\mu(\bar{\nu}_\mu)$ disappearance sensitive to $sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \boxed{sin^2(2\theta_{23})} sin^2\left(1.27 \boxed{\Delta m^2_{23}} \frac{L}{E_\nu}\right)$$

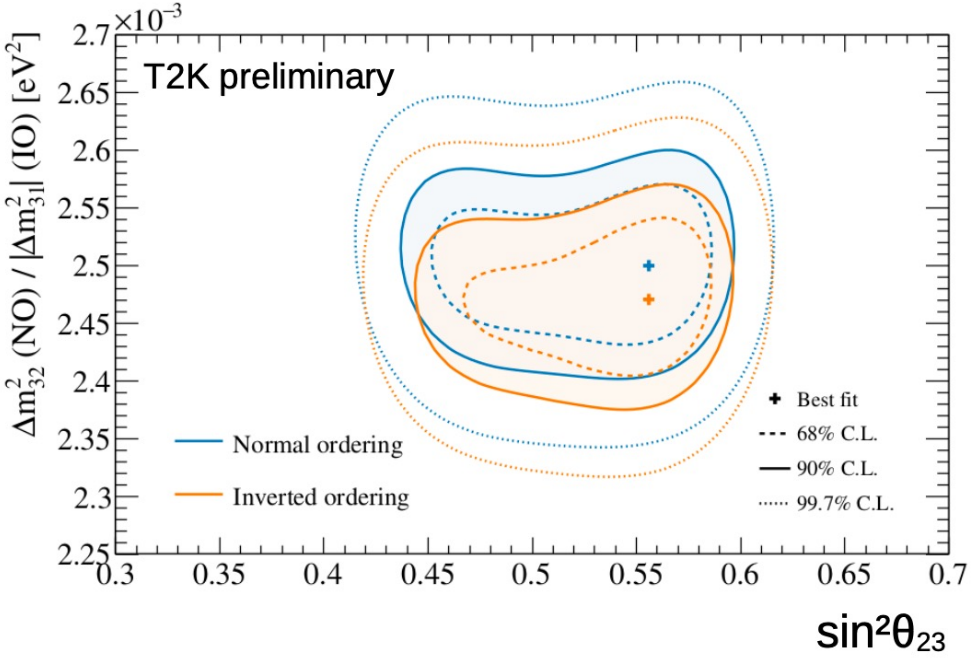
- $\nu_e(\bar{\nu}_e)$ appearance sensitive to θ_{23} octant

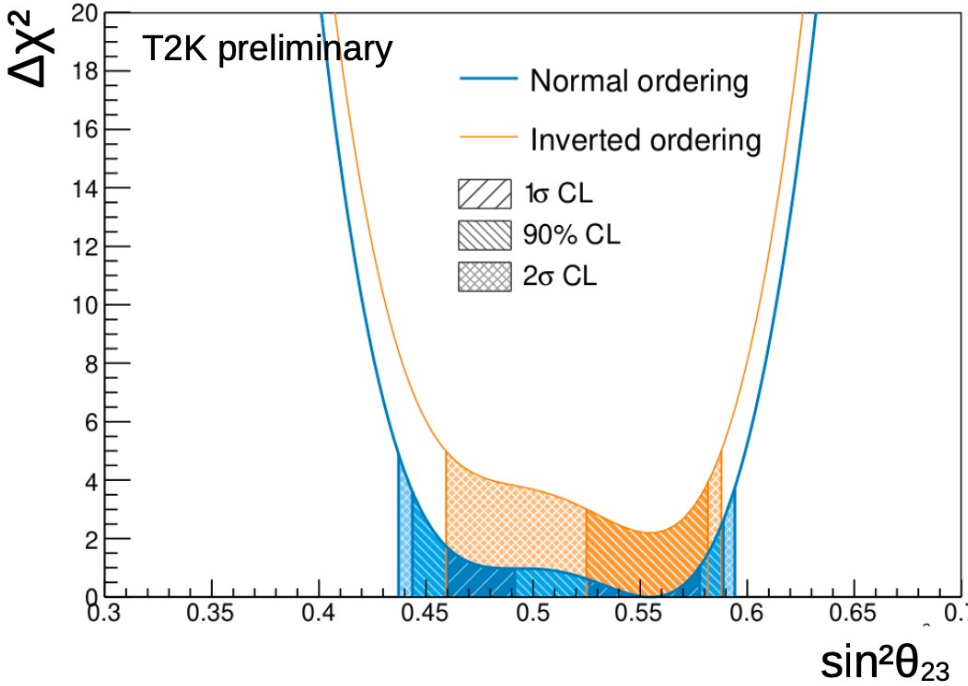
$$P(\nu_\mu \to \nu_e) \sim \boxed{sin^2(\theta_{23})} sin^2(2\theta_{13}) sin^2\left(1.27 \Delta m^2_{23} \frac{L}{E_\nu}\right) + (\text{CPV term}) + (\text{matter term}) + \cdots$$

Atmospheric parameters are important to δ_{CP} measurement

Oscillation analysis result: Atmospheric parameters

- Best fit in the upper octant
- Lower octant still allowed at the 68% CL level

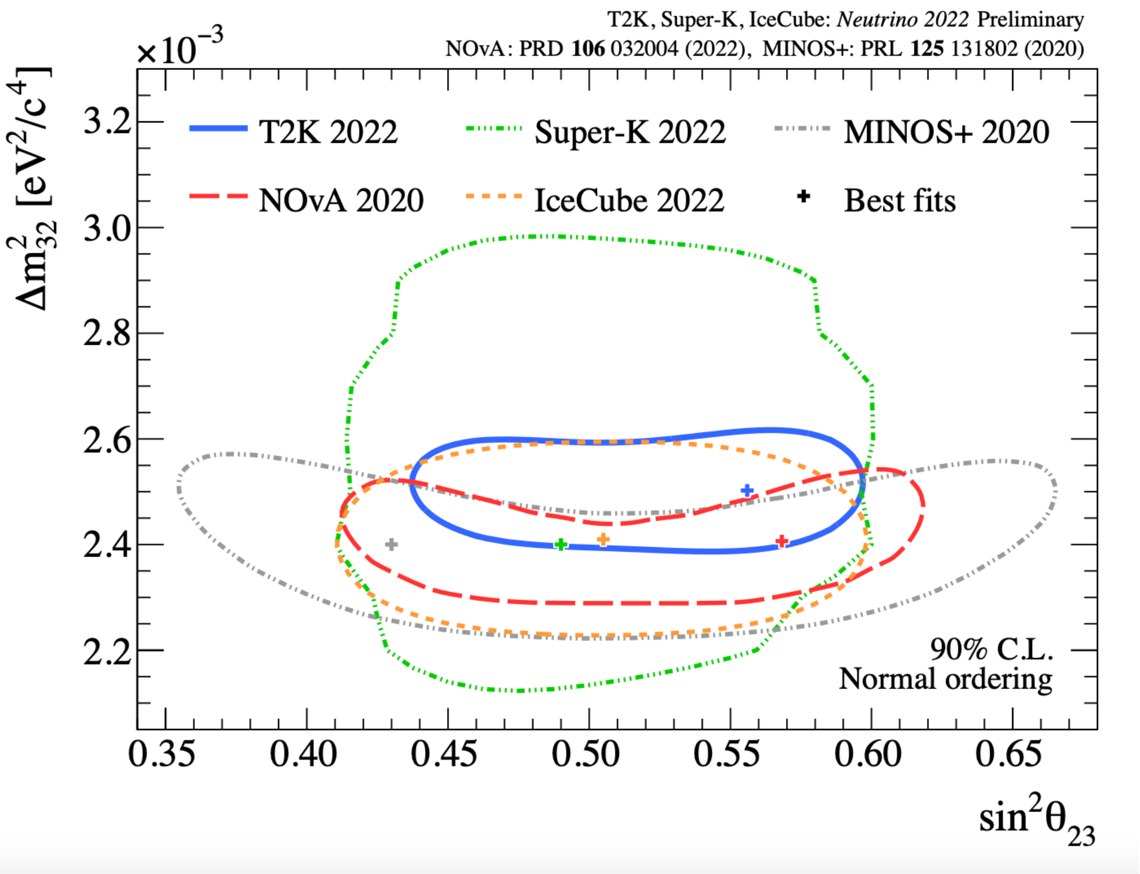




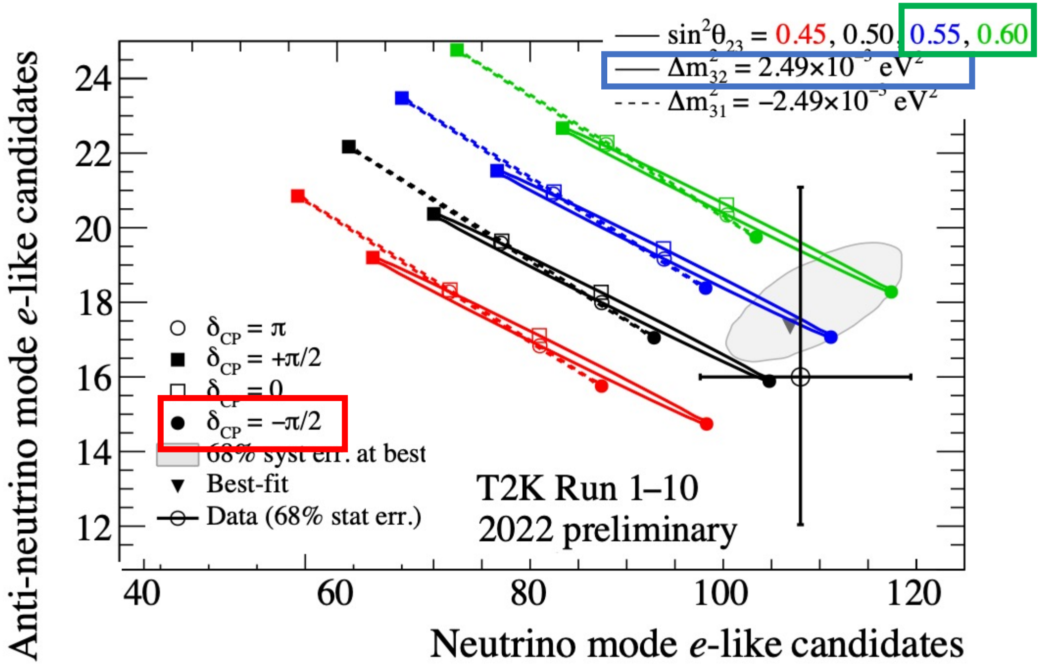
Using θ_{13} constraint from reactor experiments: $sin^2 2\theta_{13} = 0.0861 \pm 0.0027$

Oscillation analysis result: Atmospheric parameters

- World-leading measurement of atmospheric parameters



Oscillation analysis result: Constraints of δ_{CP}



Octant

Mass ordering: Posterior prob.	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IO ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.00

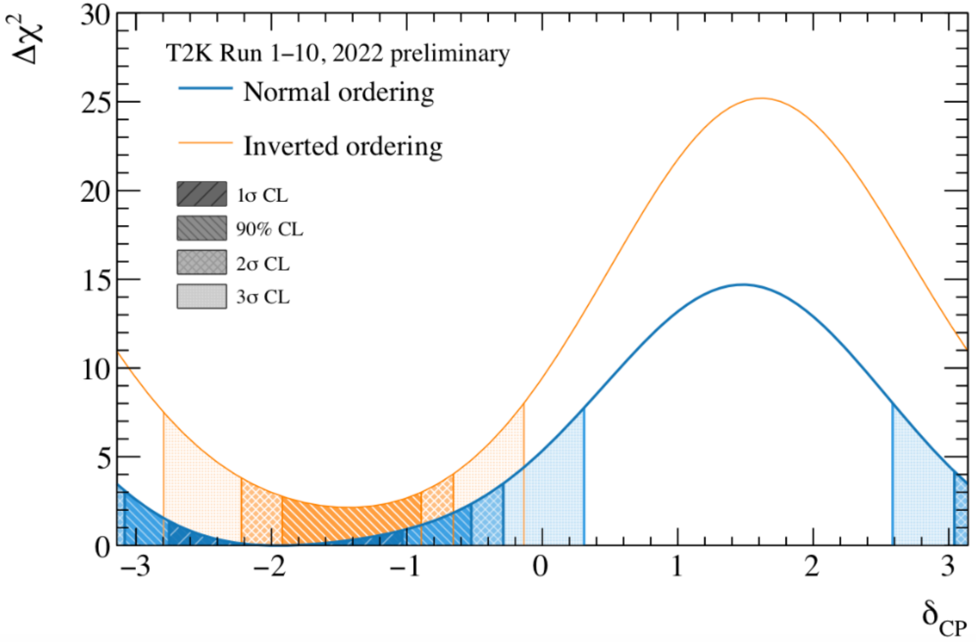
- Best-fit δ_{CP} around maximal CP-violation, $-\frac{\pi}{2}$
- Weak preference for Normal mass ordering with Bayes factor 2.8
- Weak preference for upper octant ($sin^2\theta_{23} > 0.5$) with Bayes factor 3.0

Other oscillation parameters ($\theta_{23}, \Delta m^2_{32}$) are important for δ_{CP} measurement.

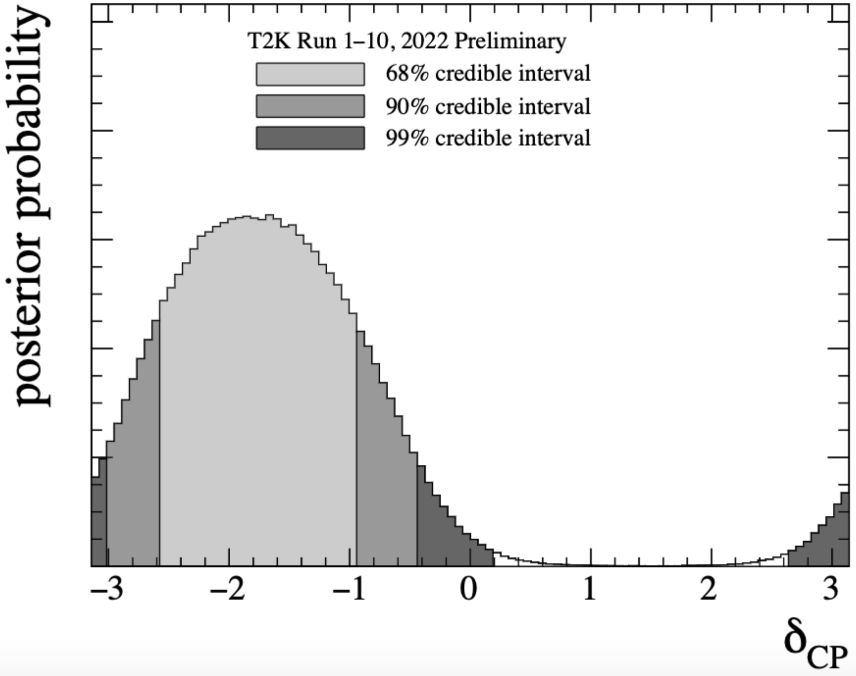
Oscillation analysis result: Constraints of δ_{CP}

- Large region excluded by 3δ, and CP-conserving values($\delta = 0$ and $\delta = \pi$) excluded by 90% C.L.

Frequentist (with Feldman-Cousins)



Bayesian (Marginalized over MO)

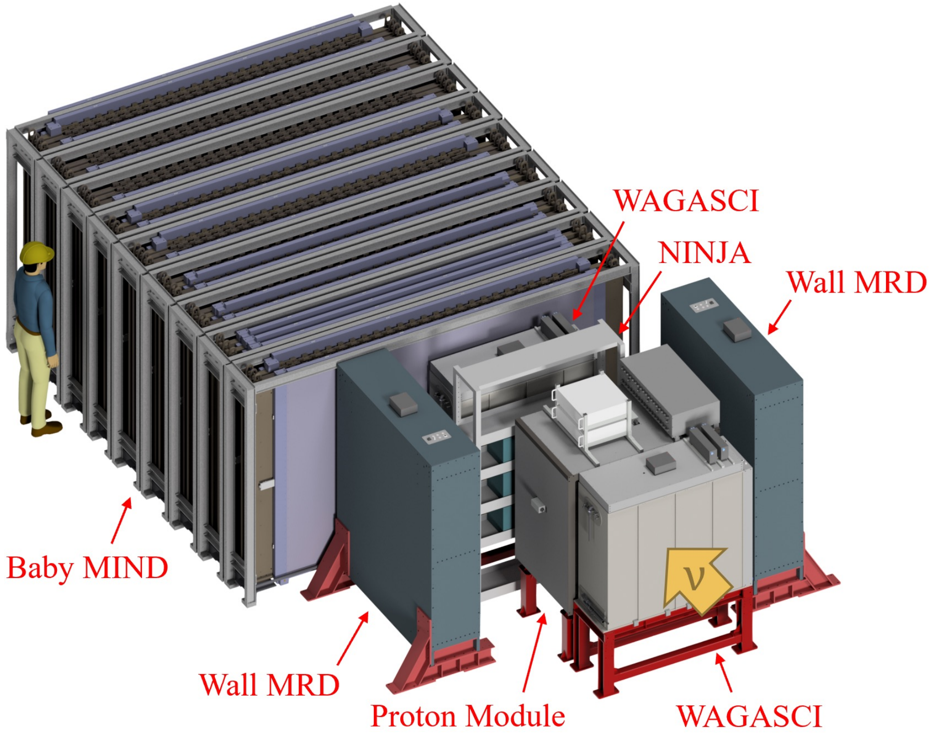


Using θ_{13} constraint from reactor experiments: $sin^2 2\theta_{13} = 0.0861 \pm 0.0027$

Future

Future: cross-section measurements

- New set of detectors at 1.5 degree off-axis:
  - Neutrino energy peaked around 0.86 GeV
  - Start operation in 2019

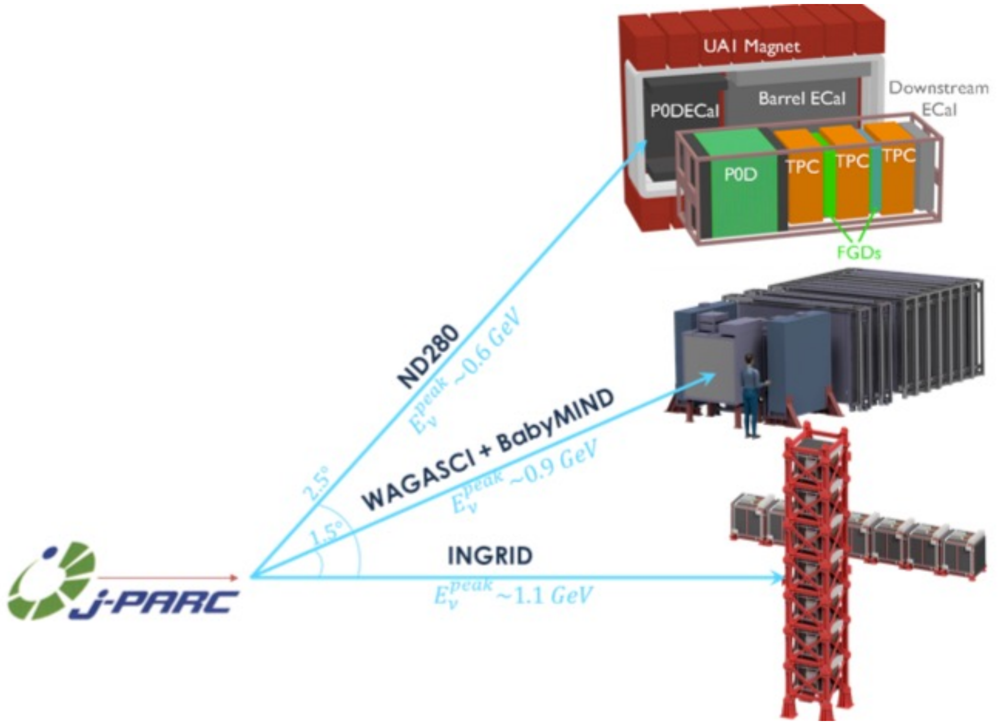


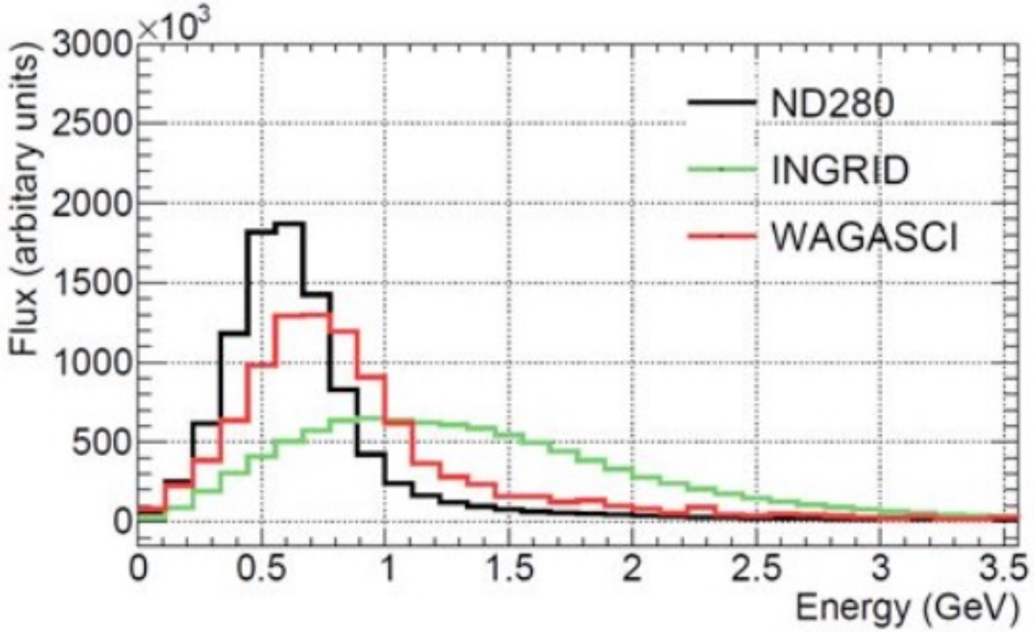
Neutrino target detectors
- WAGASCI (H_2O)
- Proton Module (CH)

Muon Range Detectors
- Baby MIND: μ^-/μ^+ PID
- Wall MRD

Future: cross-section measurements

- “joint” measurements between on/off/another-off axes
  - Direct probes of E_ν dependence
  - Full correlations between on/off/another-off axis results



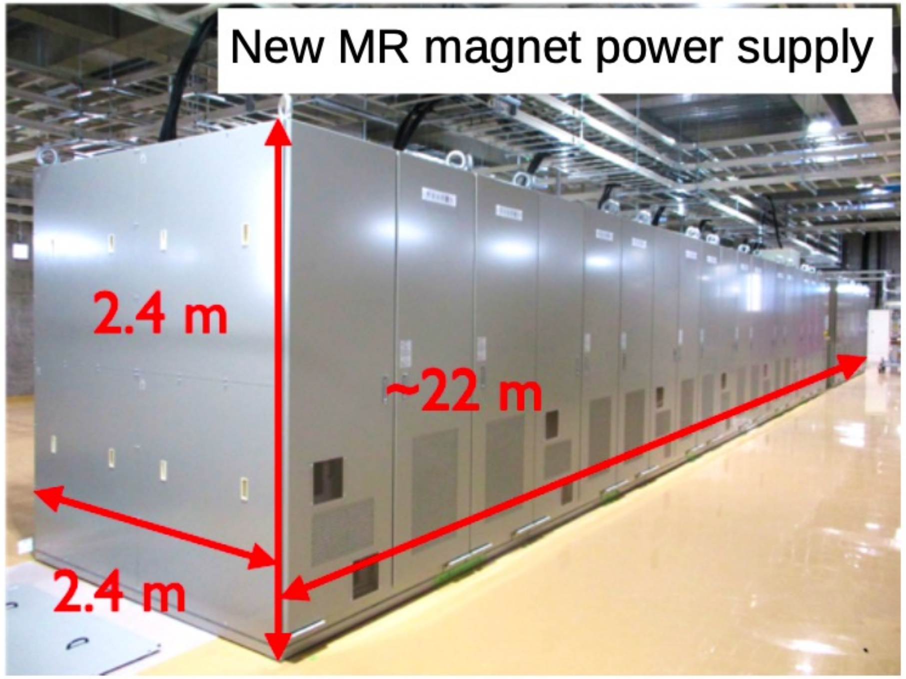


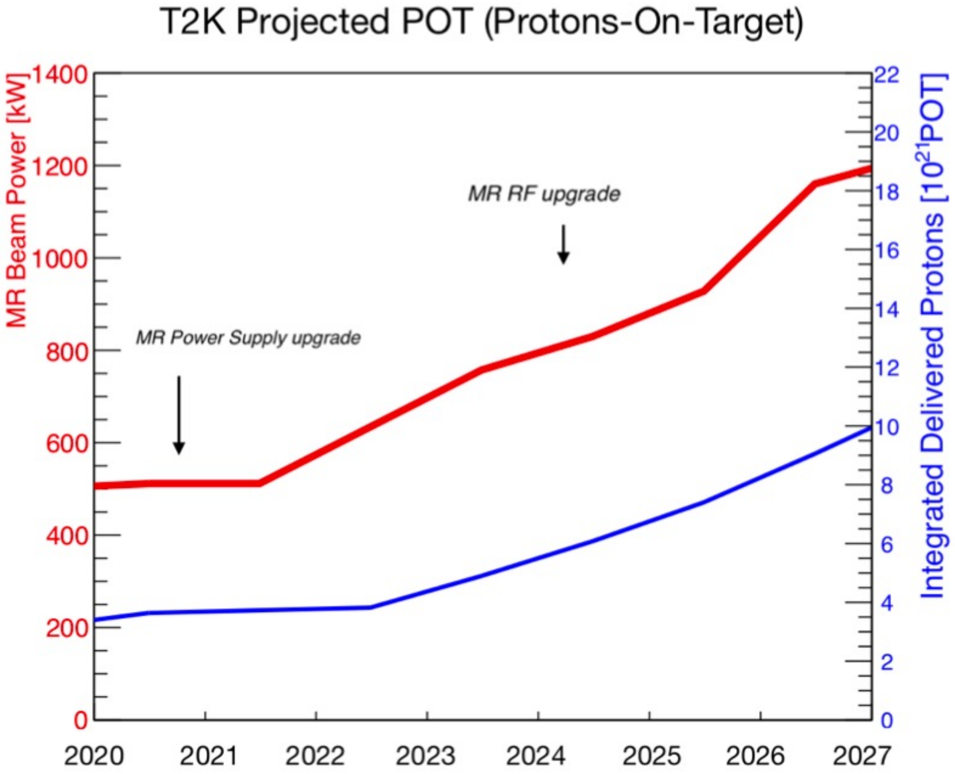
Future: T2K-II

- T2K was originally approved to collect 7.8×10^{21} POT.
- Proposal to extend the run until 2026
  - Thanks to J-PARC beam upgrade, we may be able to accumulate neutrino data beyond the approved POT by 2026.
- As statistical errors become smaller, reducing systematic errors becomes more important.
  - ND280 upgrade increased ability to study neutrino interactions.

Future: J-PARC Beam upgrade

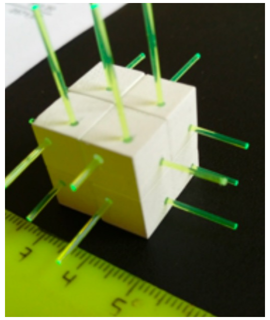
- Main ring power supply upgrade was completed!
- Expect a beam power above 1 MW by 2027

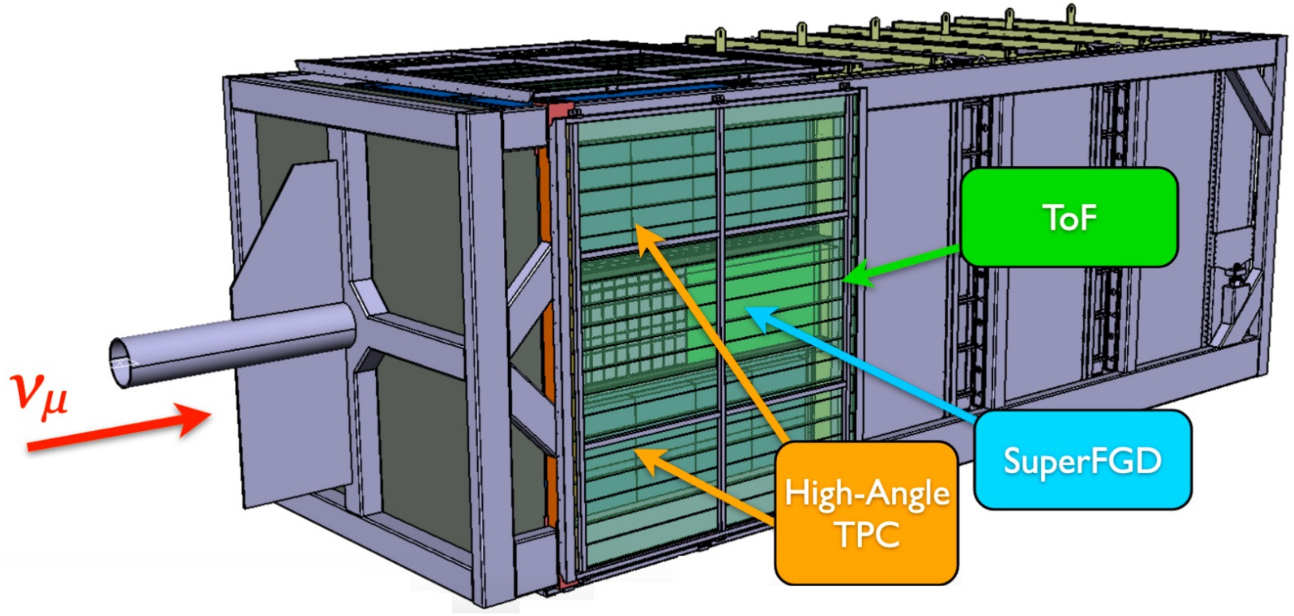


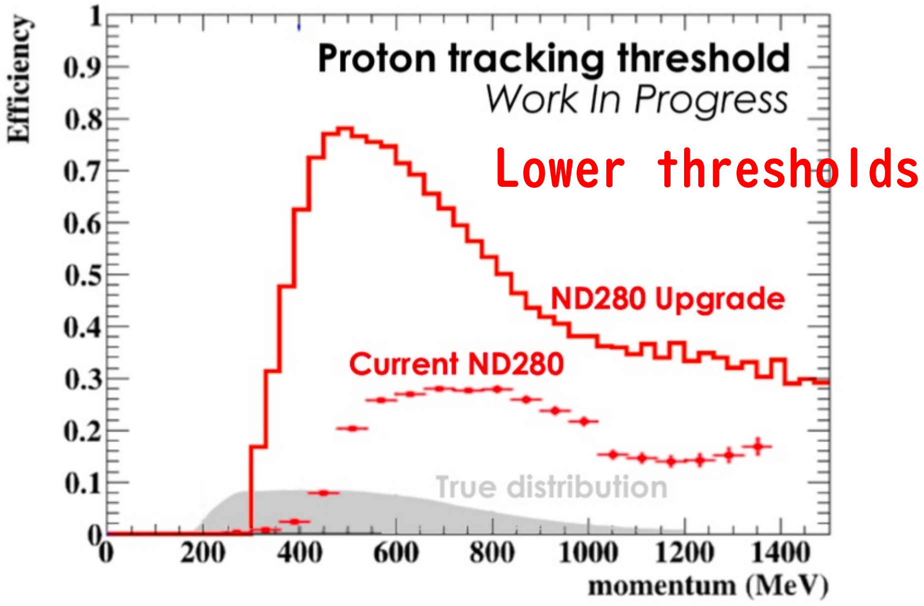


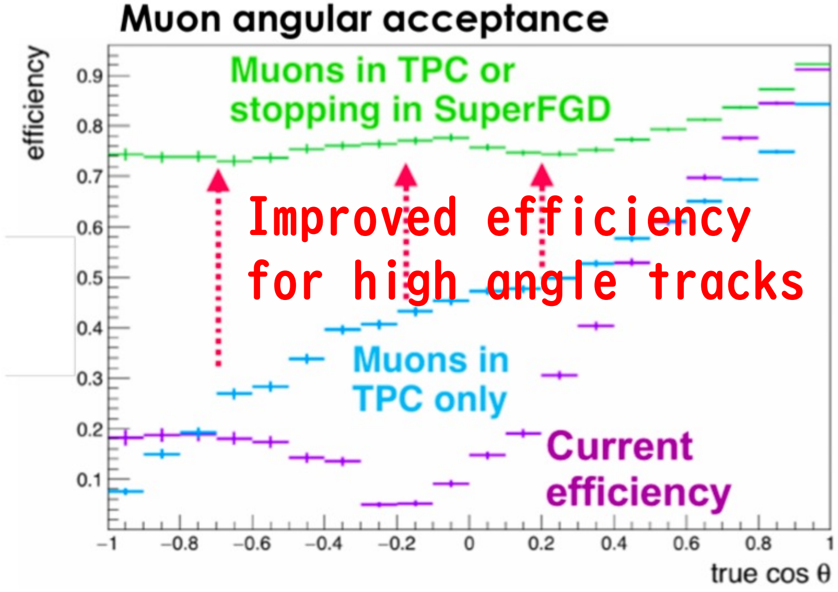
Future: ND280 upgrade

- New subdetectors
  - SuperFGD: 2×10^6 1cm-cubes
  - High-Angle TPC
  - Time-Of-Flight detector



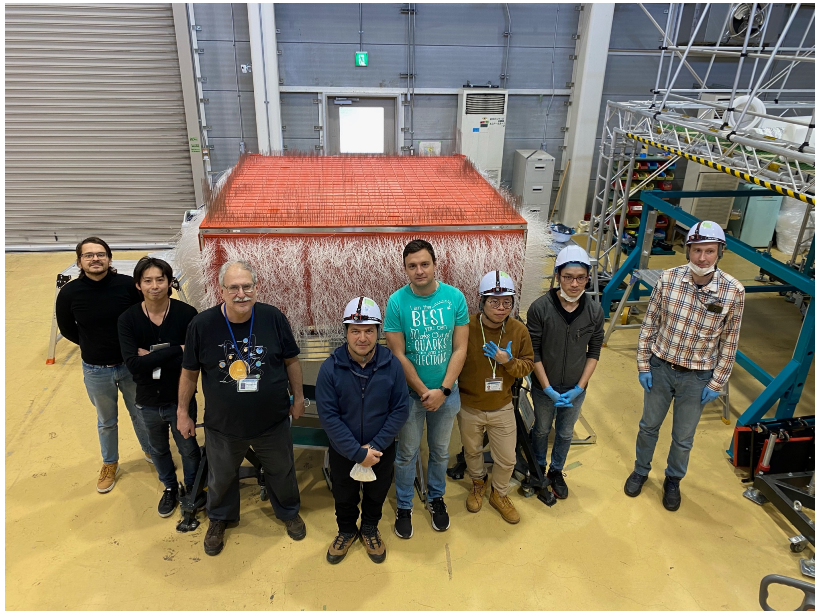






Future: ND280 upgrade

SuperFGD
in assembling @ J-PARC



High-Angle TPC
MicroMegas test @ CERN

ToF
assembled @ CERN

Expect to start data taking in 2023!

Summary

- New T2K neutrino oscillation result is achieved with 3.6×10^{21} POT of data.
- CP conservation ($\delta_{CP} = 0, \pi$) is excluded by 90% C.L.
- Weak preference of upper octant θ_{23} and normal mass ordering.

- J-PARC accelerator upgrade and ND280 upgrade enable higher beam intensity and increased ability to study neutrino interactions.
- Stay tuned for the exciting results in the near future!