

CP violation searches in neutrino oscillations

Christopher Mauger (T2K collaboration)

University of Pennsylvania

17 July 2023

Lepton-Photon 2023, Melbourne, Australia


Outline

- Introduction to neutrino oscillations and CP violation signatures
- T2K
- NOVA
- T2K upgrade
- Conclusions
- Plenary Talks tomorrow:
 - Theory challenges in neutrino physics (Stephen Parke)
 - Future Long-baseline neutrino experiments (Francesco Terranova)

Neutrino oscillation phenomena


Flavor eigenstates:

Flavor eigenstates created in
weak interactions


$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\nu_i\rangle, \text{ for } \alpha = e, \mu, \tau$$

where $|\nu_i\rangle$ mass eigenstates. Time evolution:

Propagates with free
particle Hamiltonian


$$|\nu_\alpha(t)\rangle = \sum_{i=1}^3 U_{\alpha i} \exp(-i\hat{H}t) |\nu_i\rangle$$

Survival Probability:

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = |\langle \nu_\alpha | \nu_\alpha(t) \rangle|^2$$

Neutrino oscillation physics

Two-Flavor Case:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{\nu_e \rightarrow \nu_e} = |\langle \nu_e | \nu_e(t) \rangle|^2 = 1 - \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$

$$\Delta m^2 = m_2^2 - m_1^2 \text{ (eV}^2\text{)}$$

L distance from production (km) or (m)

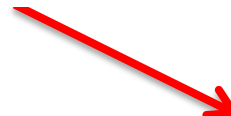
E energy of neutrino (GeV) or (MeV)

Dependence on L/E – generically true

Neutrino oscillation physics

Two-Flavor Case:

$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$: Size of difference of squared masses
drives the oscillation length –
important experimental consideration

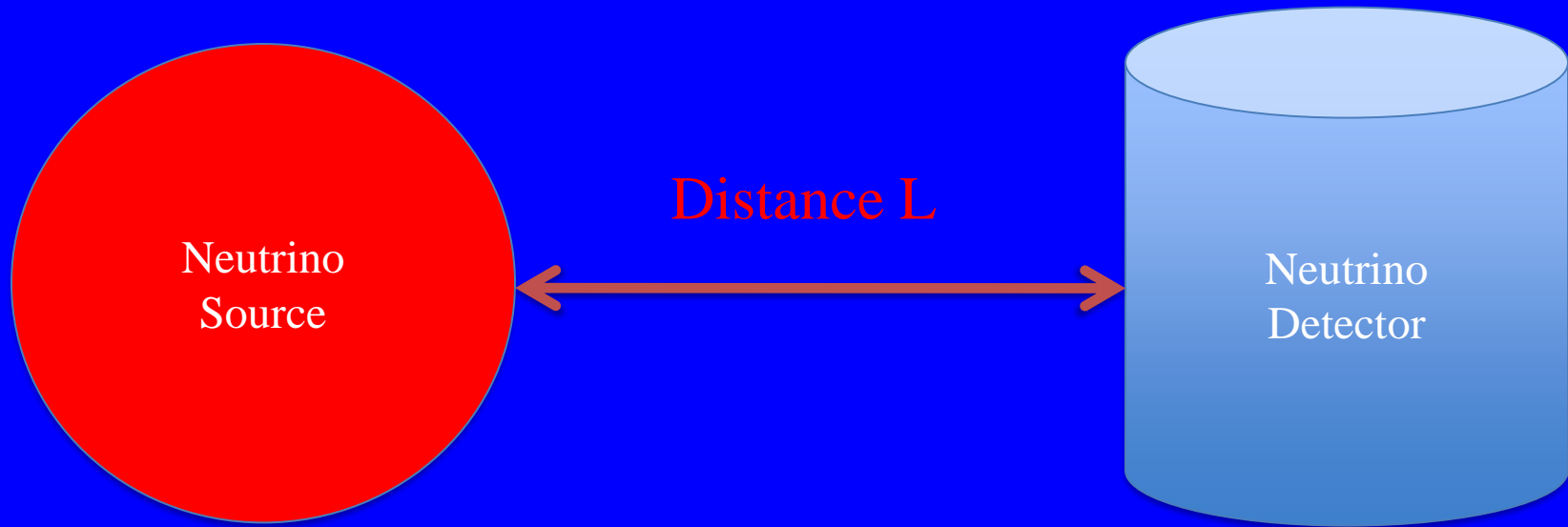
$$P_{\nu_e \rightarrow \nu_e} = |\langle \nu_e | \nu_e(t) \rangle|^2 = 1 - \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$


$$\Delta m^2 = m_2^2 - m_1^2 \text{ (eV}^2\text{)}$$

L distance from production (km) or (m)

E energy of neutrino (GeV) or (MeV)

What do we measure in experiments?



In experiments, we control L and E , nature gives us the mixing angle θ and the differences of squared masses Δm^2 .

We can fix L or E or have a spectrum of L 's and E 's.

Survival Probability

$$1 - \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L}{E} \right)$$

Three-flavor oscillations

- If all elements of U are real, no CP violation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- CP violation only manifest in neutrino oscillations if relative complex phase between elements of U
- Matrix often parameterized as follows:

$$s_{ij} = \sin \theta_{ij}, \quad c_{ij} = \cos \theta_{ij}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three-flavor oscillations

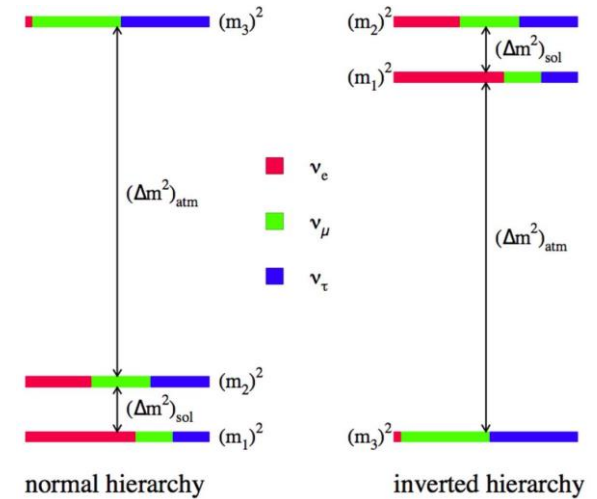
- Search for CP violation with neutrino oscillations is a comparison of flavor transformation probabilities, for example:

$$P(\nu_\mu \rightarrow \nu_e) \stackrel{?}{=} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- Six possible approaches, above the most common
- Why?
 - Want to identify the neutrino flavor – need charged current interactions
 - Want to produce high-flux beam
- Muon neutrino and anti-neutrino beams are the conventional choice – high fluxes of neutrinos or anti-neutrinos above both muon and electron CC threshold
- For \sim GeV neutrinos, oscillation lengths 100's of km – long-baseline neutrino oscillation experiments
- We fix L, determine E from data, fit to an oscillation hypothesis
- Determining E from data a key challenge at these energies

Three-flavor oscillations

- Three angles and two independent Δm^2
- All three angles have been measured, magnitudes of Δm^2 's and the sign of one Δm^2 have been measured
- Ambiguity of sign of one Δm^2 is the neutrino mass ordering problem

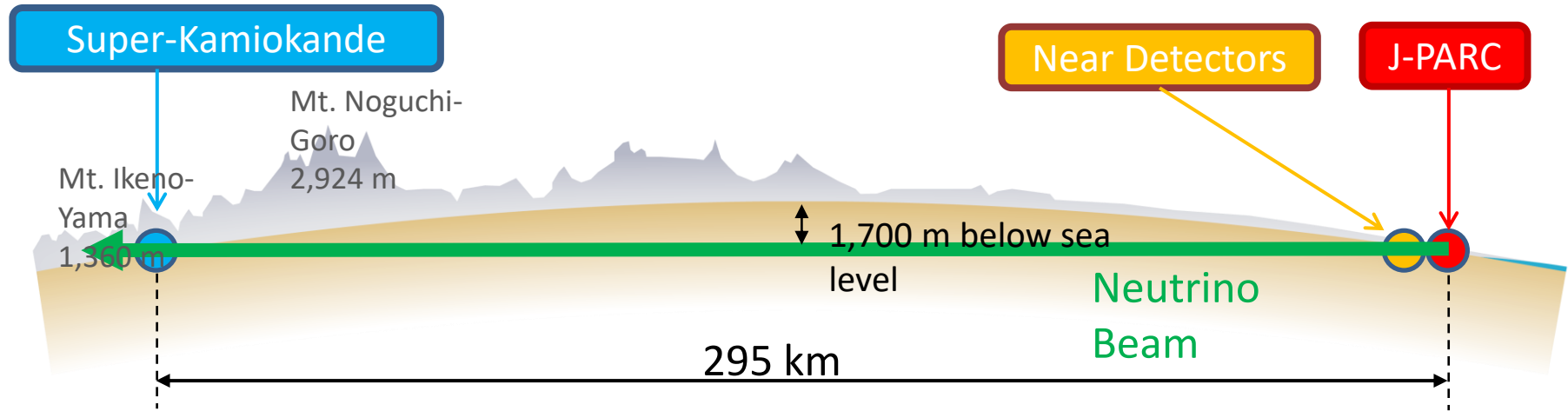


- Neutrinos pass through matter – lots of electrons, earth is not CP symmetric

$$\begin{aligned}
 P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &\approx \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}] \\
 &+ \alpha \frac{J_0 \sin \delta_{CP}}{A(1-A)} \sin \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] \\
 &+ \alpha \frac{J_0 \cos \delta_{CP}}{A(1-A)} \cos \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] \\
 &+ \alpha^2 \cos^2 \theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta_{31}) \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 \alpha &= \Delta m_{21}^2 / \Delta m_{31}^2 \\
 \Delta_{ij} &= \Delta m_{ij}^2 L / 4E \\
 A &= (-) 2\sqrt{2} G_F n_e E / \Delta m_{31}^2 \\
 J_0 &= \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13}
 \end{aligned}$$

T2K Experiment

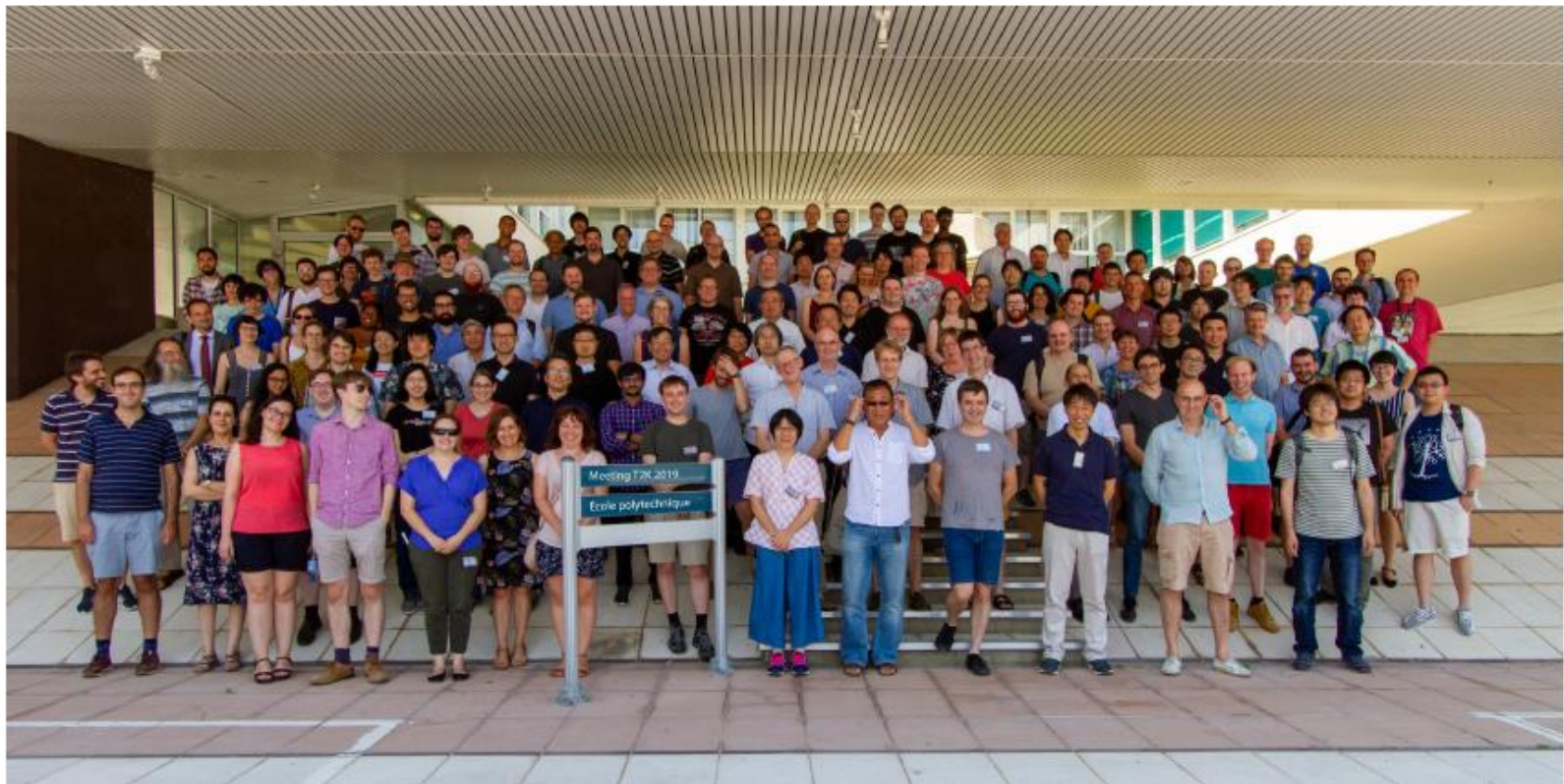


- Near Detector – detailed studies of neutrino and anti-neutrino beams in high flux environment
- Excellent forward-particle measurements
- Far detector – isotropic measurement of event signatures

T2K Collaboration



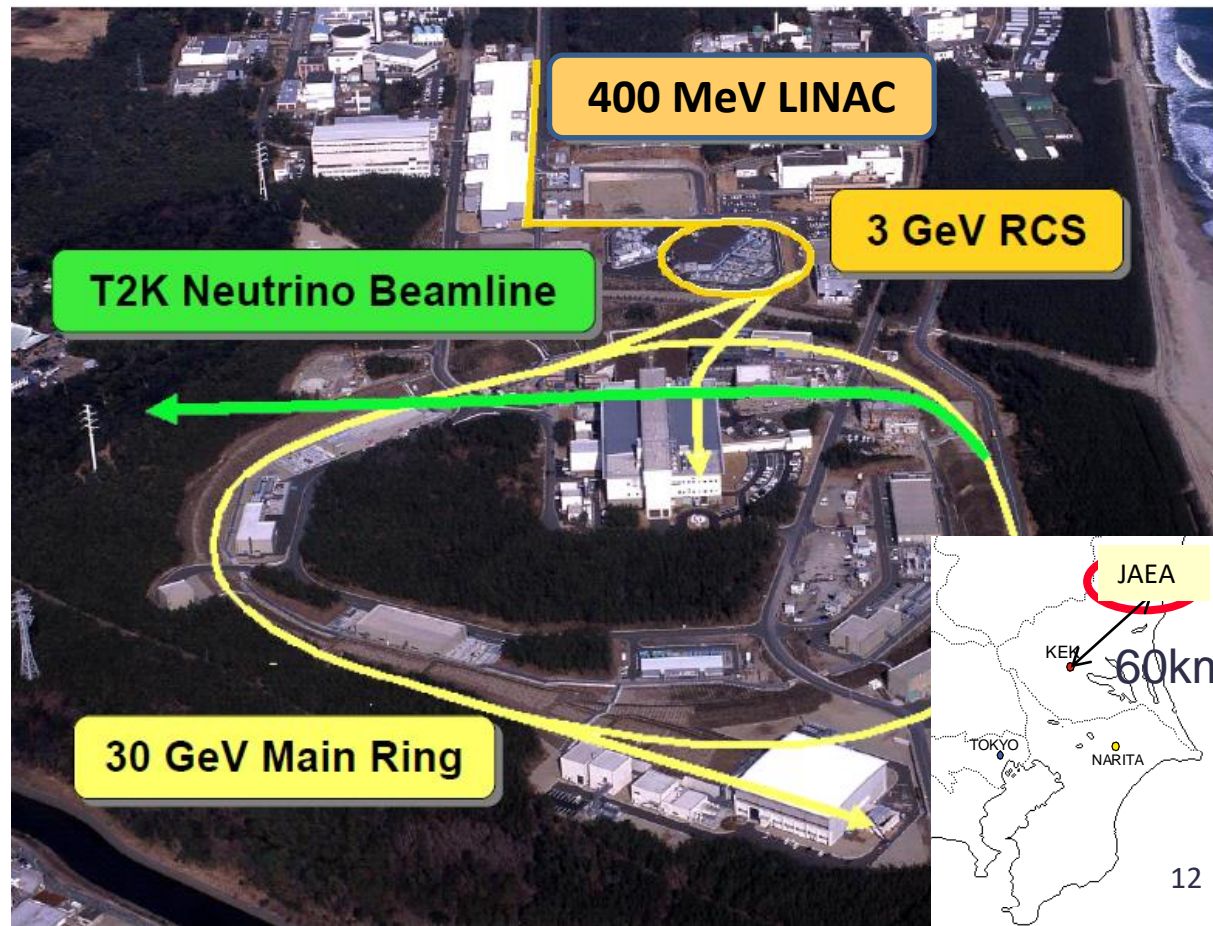
~500 members, 76 institutes, 13 countries (+CERN)



J-PARC

Japan Proton Accelerator Research Complex

- Located in Tokai-village, 60km N.E. of KEK
- Completed in 2009
- MR
 - 1567.5 m circum.
 - $T_p = 30\text{GeV}$
 - 8 bunch ($h\#=9$)
 - Rep cycle: 2.48sec – upgraded to 1.3 s
- Design goal
 - RCS: 1MW
 - MR: 750kW



Joint project of KEK & Japan Atomic Energy Agency (JAEA)

Muon Monitor

Horn

Beam monitors

Super-Conducting Magnets

30 GeV MR

Target

Decay Volume

Beam Dump

detector (from target)

Intensity, position profile

3 Horns w/ 250kA

Decay Volume

Beam dump

Graphite, Φ26 x 900 mm long

Helium cooling

110m length

proton beam

μ⁻

ν_μ

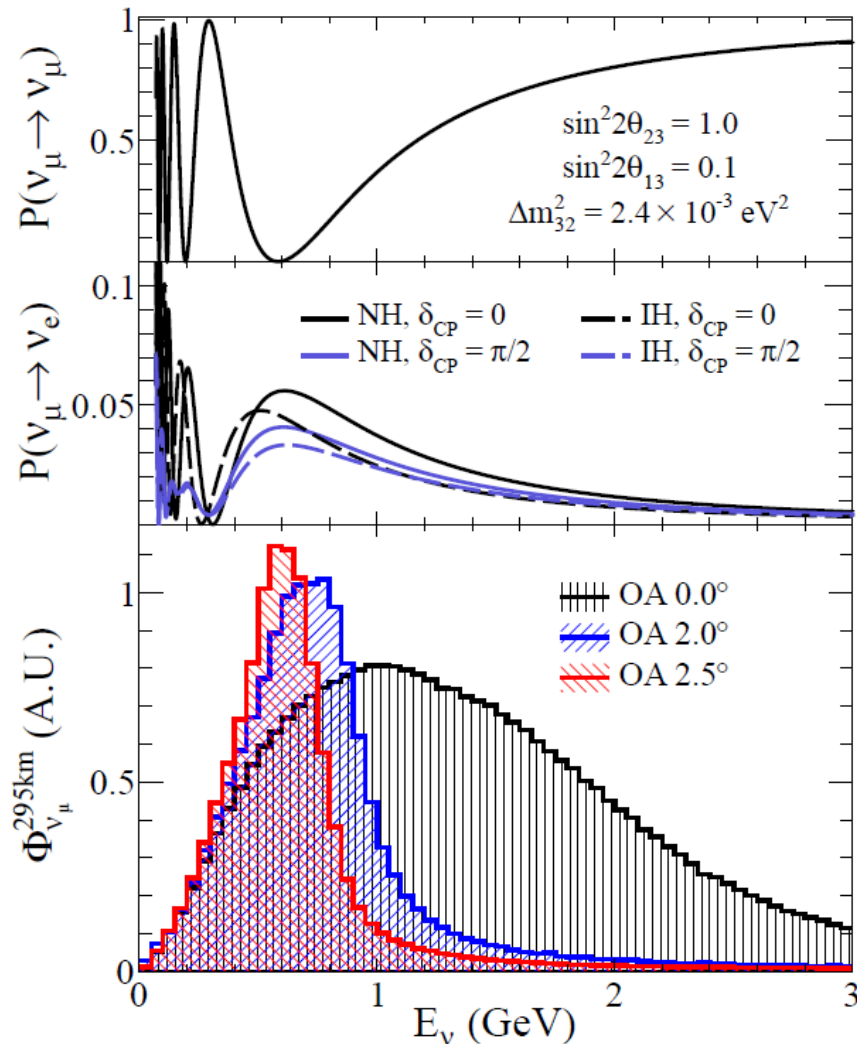
0 50 100 (m)

Main

N

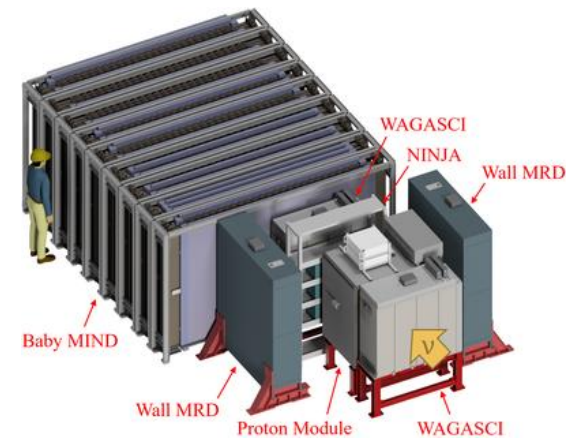
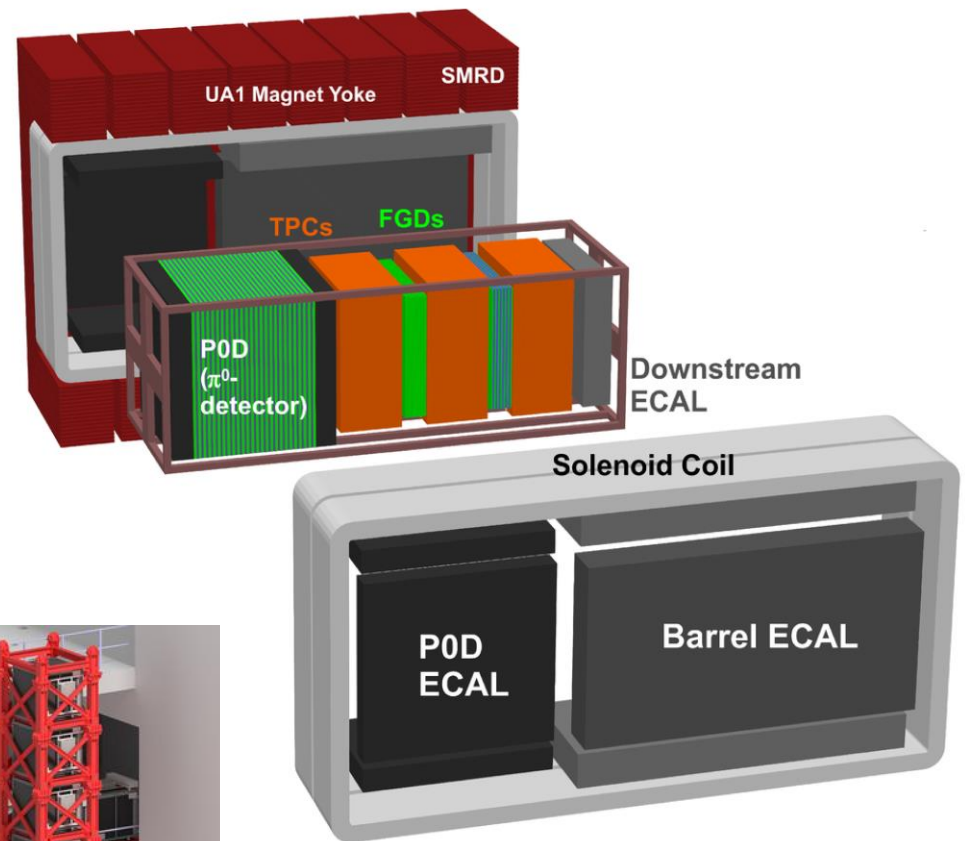
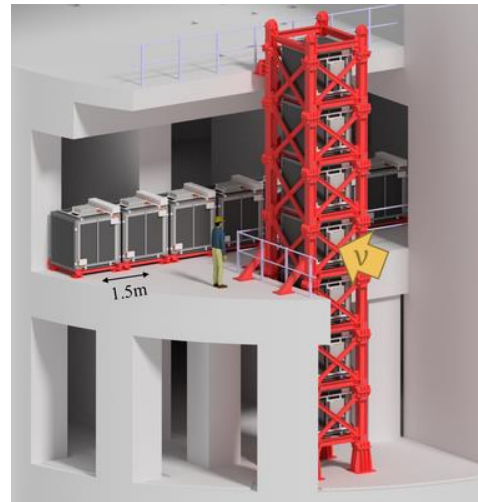
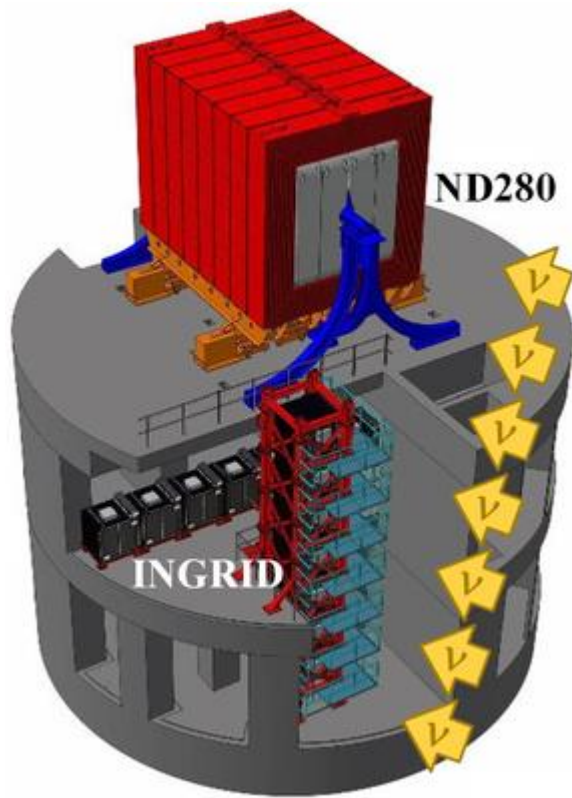
proton beam

T2K Neutrino Fluxes



- T2K is an off-axis experiment – focus on neutrino energies relevant to oscillation physics
- Determining true neutrino energy is the crucial challenge
- Higher energy neutrinos generate feed-down background that can hide the oscillation signal

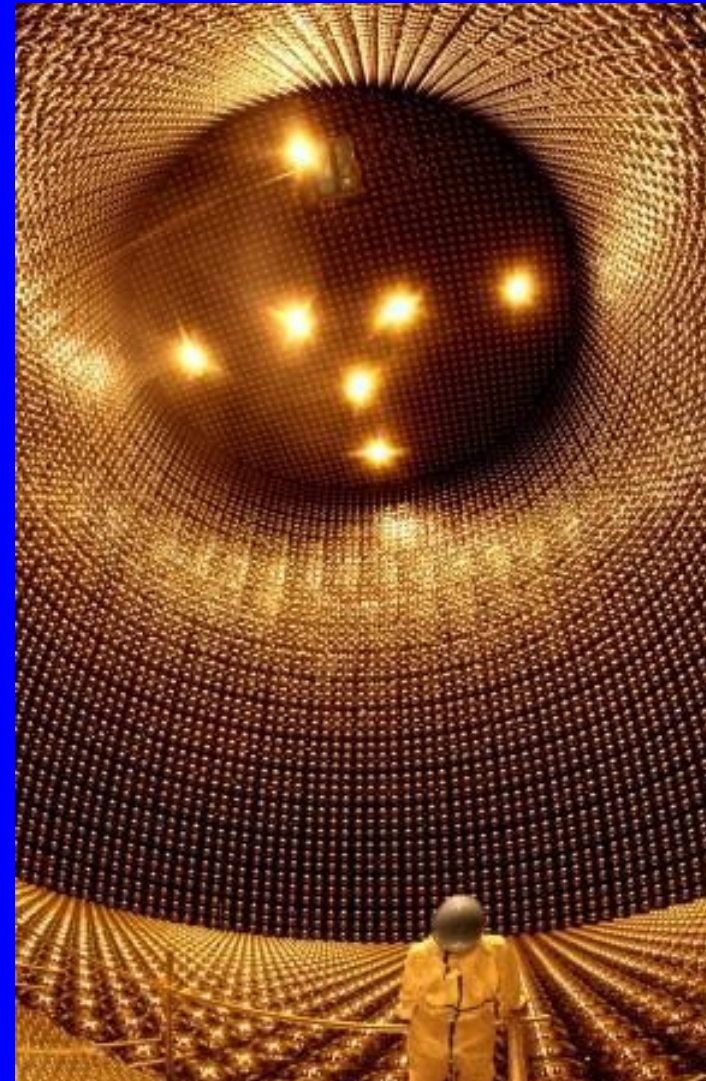
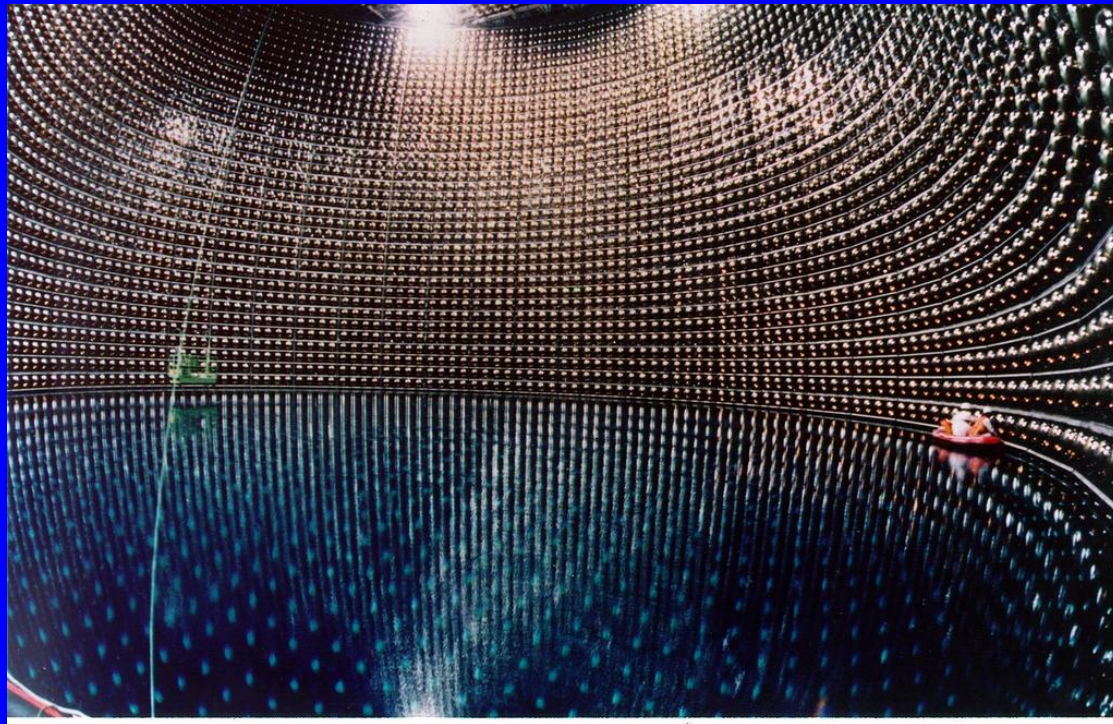
T2K Near Detector



- Detailed measurements of neutrino interactions of the on and off-axis neutrino fluxes
- ND data employed to constrain neutrino interaction models

Super-Kamiokande Detector

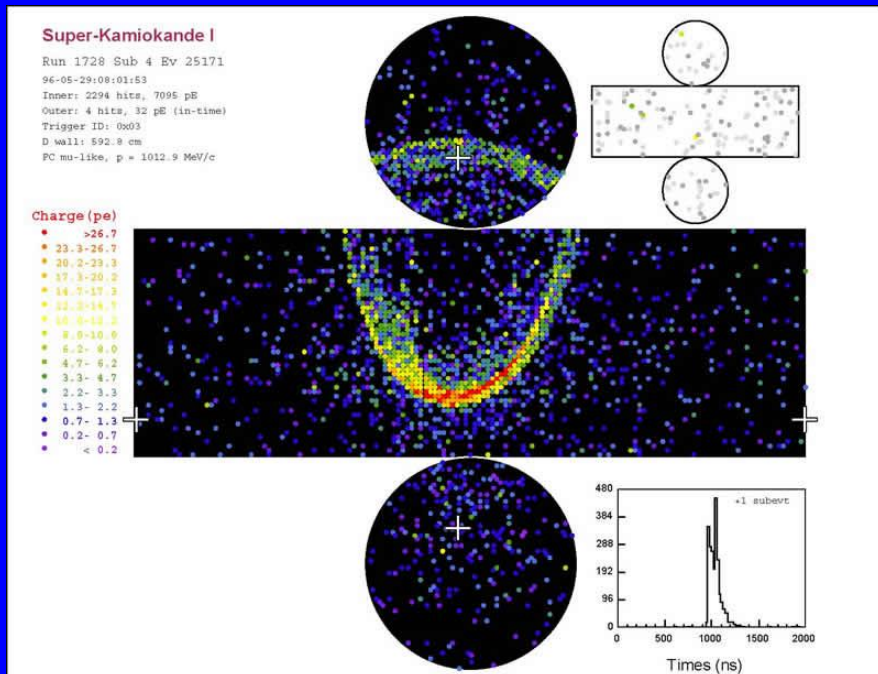
- 13,000 photomultiplier tubes (PMTs) in a 50 kt water tank
- Excellent electron-muon flavor discrimination



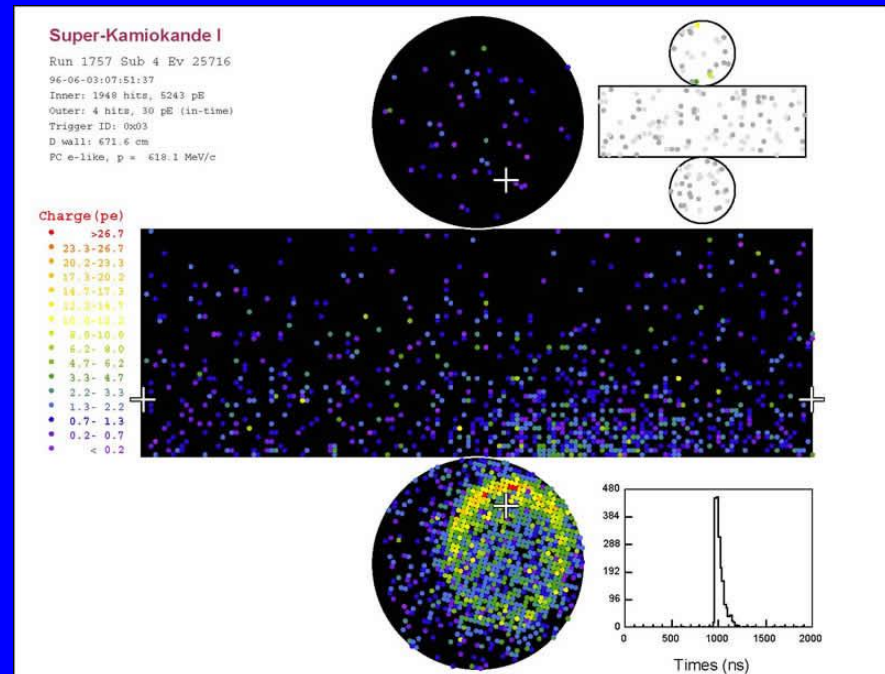
Distinguish showering vs. non-showering events – flavor identification

- By detecting Cherenkov light, Super-Kamiokande can distinguish the patterns of showering vs. non-showering events
- Electrons will create showering events (charged-current ν_e)
- Muons will create non-showering events (charged-current ν_μ)

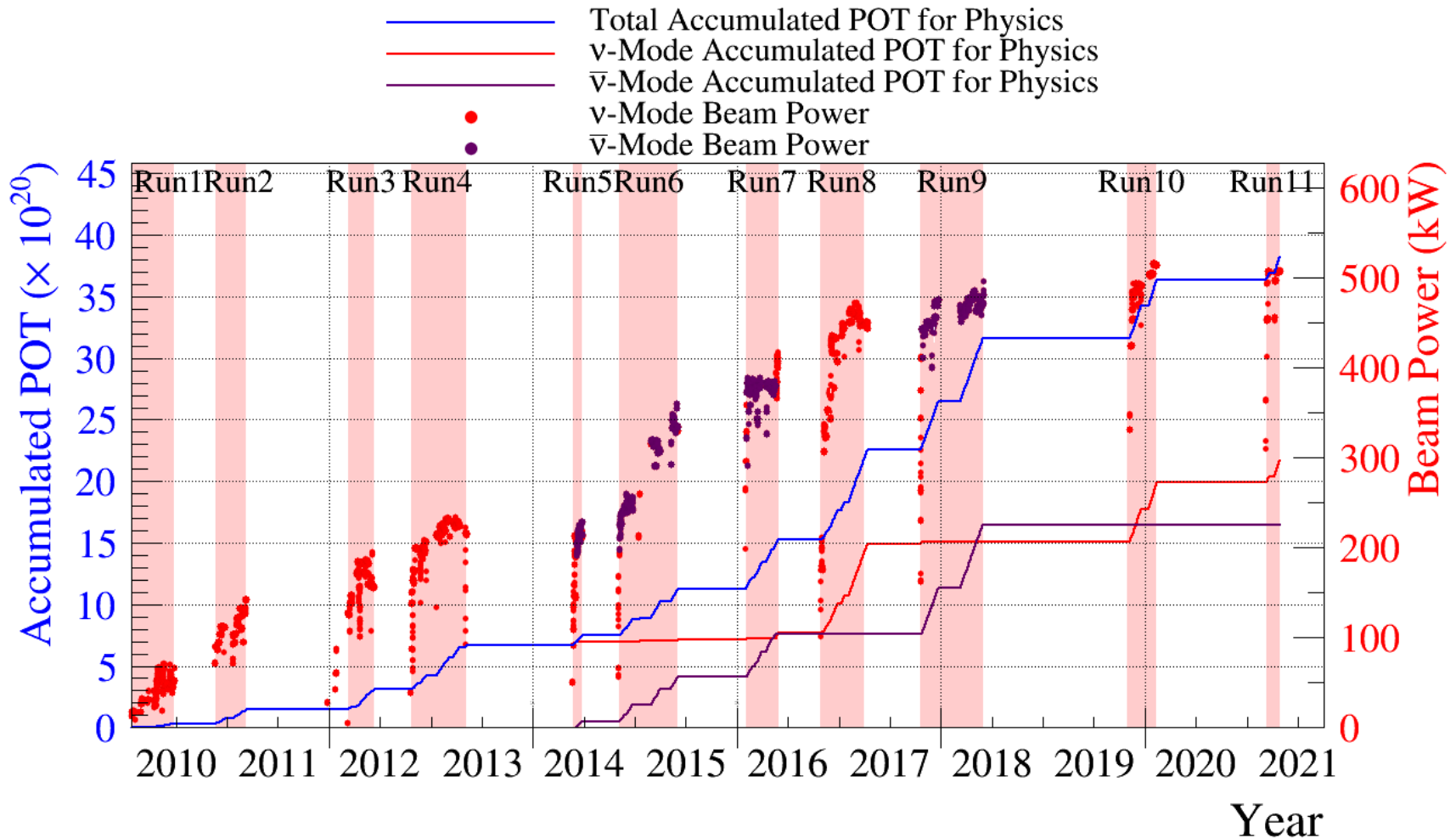
non-showering



showering



Protons on Target



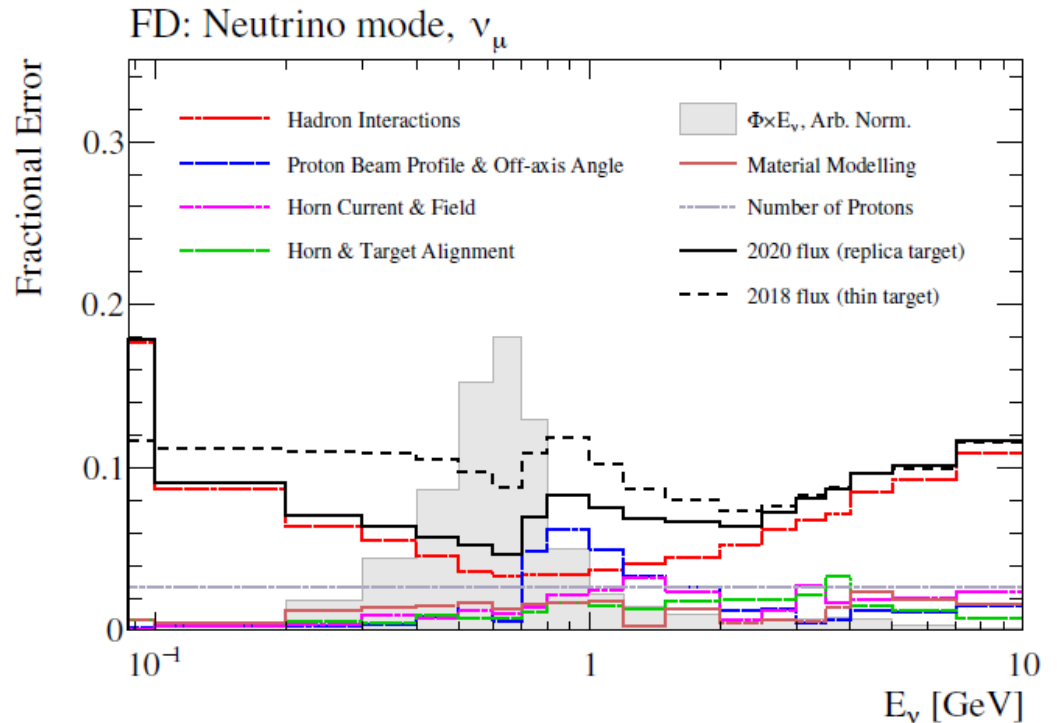
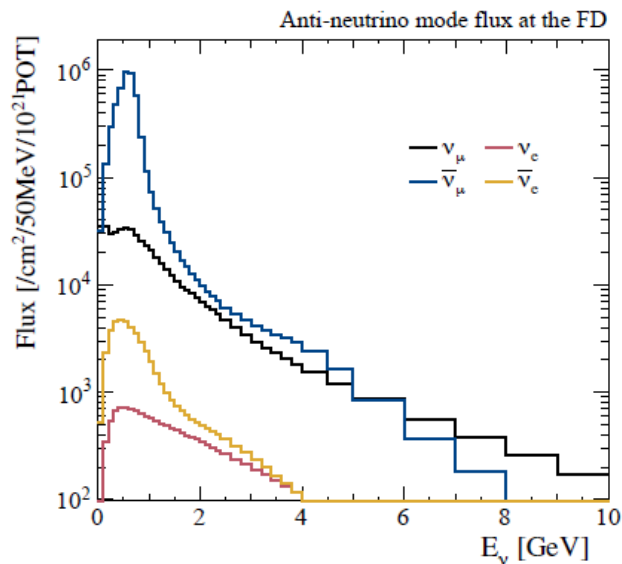
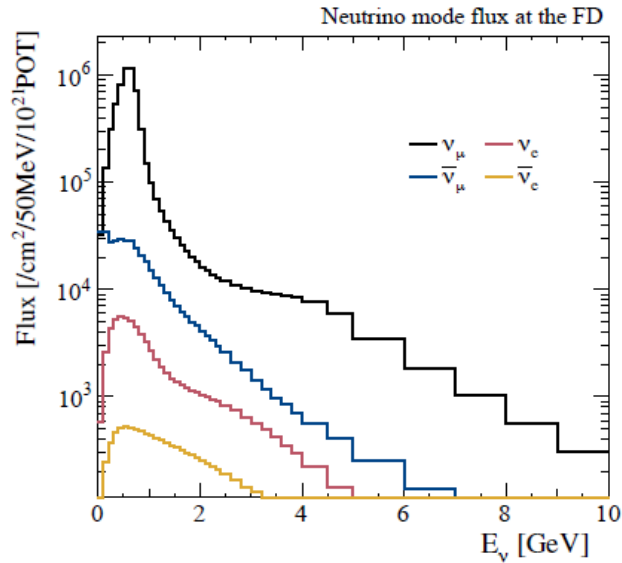
- ND280 (Runs 2-9); INGRID, Super-Kamiokande (Runs 1-10)

Analysis Strategy

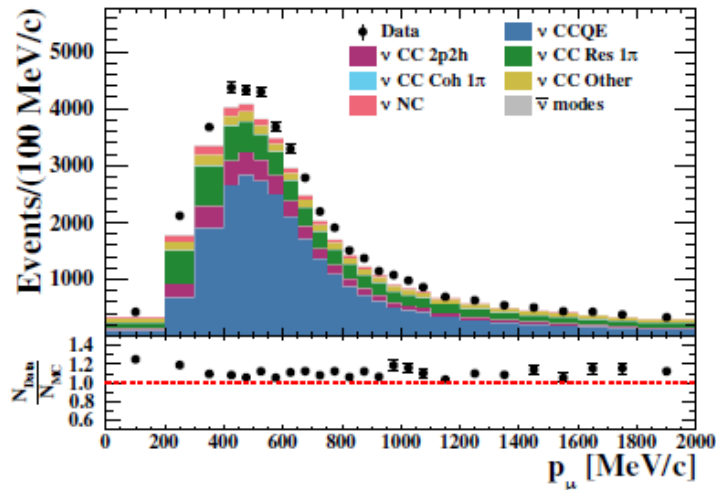
- Neutrino flux
 - Beamline monitors
 - External measurements
 - Detailed simulation
- Unoscillated flux and cross section
 - Detailed ND280 measurements
 - External constraints
 - Detailed neutrino interaction simulation
- Oscillated flux
 - Five far detector samples exploring electron neutrino appearance and muon neutrino disappearance
 - Near detector fits crucial for robust and precise determination of neutrino energy

Neutrino Flux

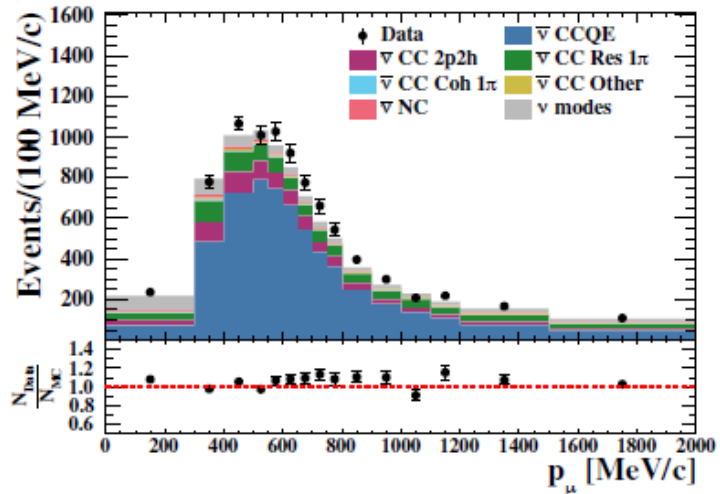
- Many improvements in modeling
- 2020 NA61/SHINE data with T2K replica target



Near Detector Measurements



(a) FGD1 ν -mode ν_μ CC 0π

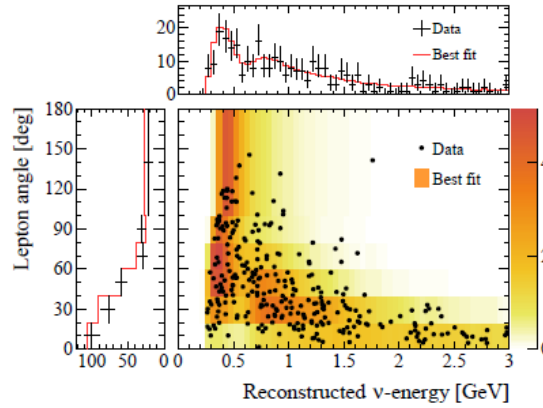


(b) FGD2 $\bar{\nu}$ -mode $\bar{\nu}_\mu$ CC 0π

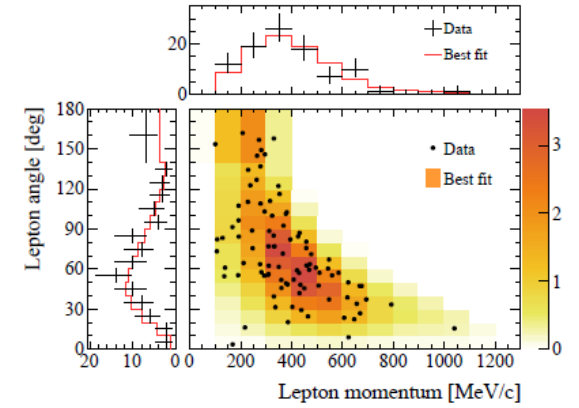
- Detailed measurements of 18 samples at the near site used to tune the neutrino interaction model

Far Detector Samples

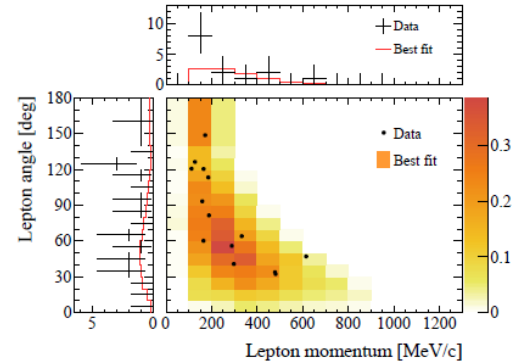
- Selection of 1-ring events consistent with quasi-elastic topology – better neutrino energy determination
- Three neutrino-mode and two anti-neutrino-mode samples included



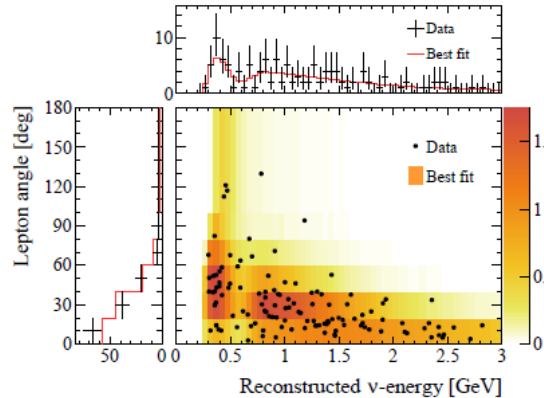
(a) ν -mode $1R\mu$



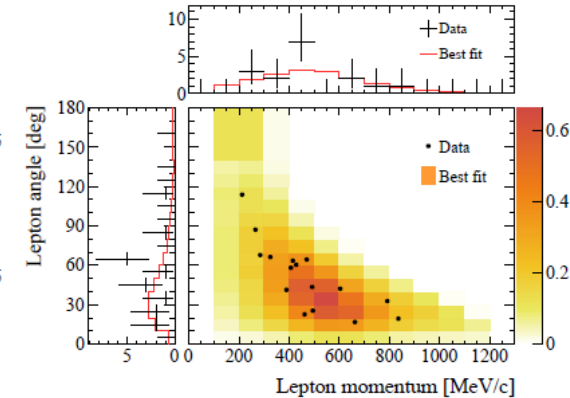
(b) ν -mode $1Re$



(c) ν -mode $1Re1de$



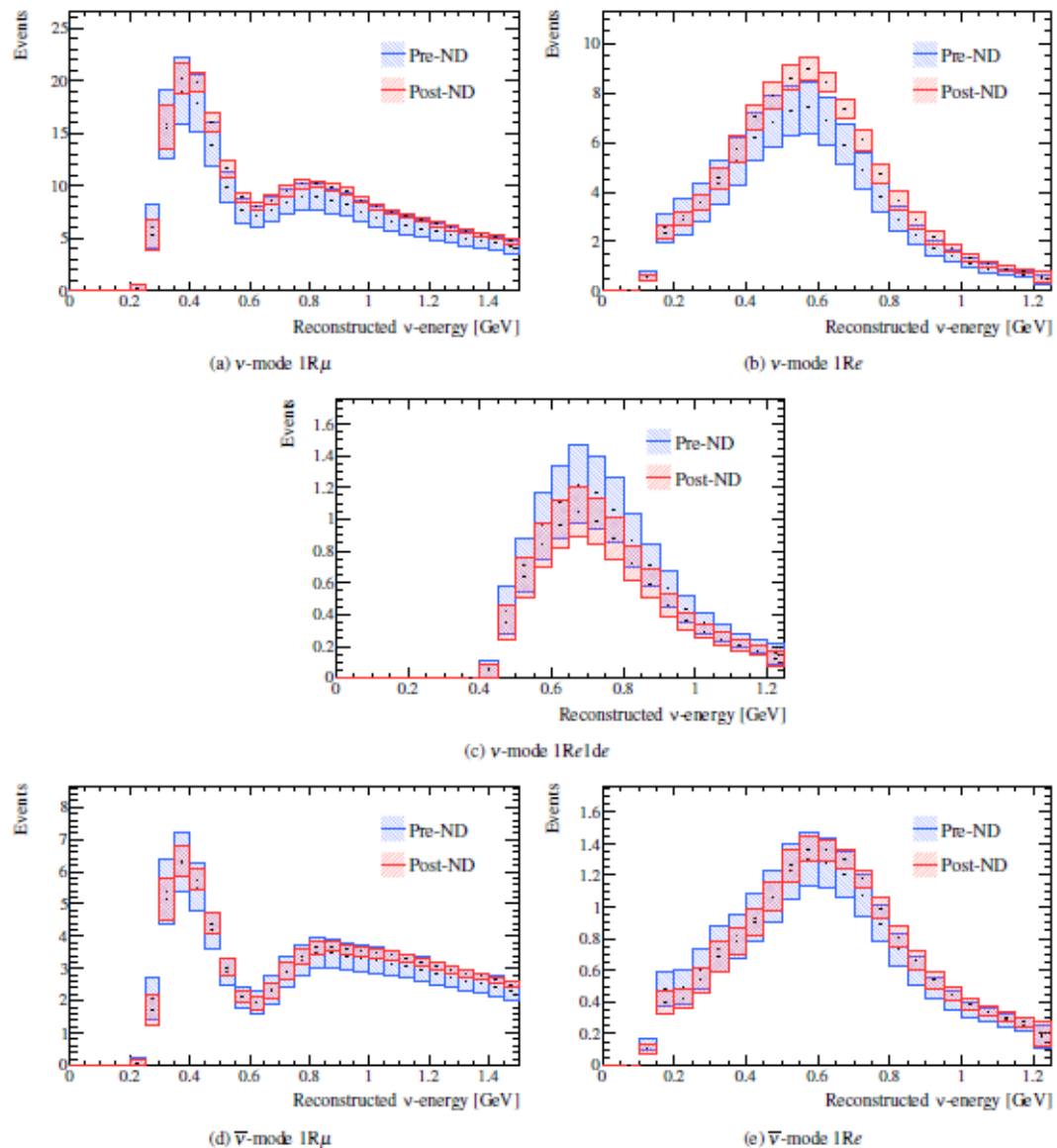
(d) $\bar{\nu}$ -mode $1R\mu$



(e) $\bar{\nu}$ -mode $1Re$

Sample		True δ_{CP} (rad.)				Data
		$-\pi/2$	0	$\pi/2$	π	
$1R\mu$	ν -mode	346.61	345.90	346.57	347.38	318
	$\bar{\nu}$ -mode	135.80	135.45	135.81	136.19	137
$1Re$	ν -mode	96.55	81.59	66.89	81.85	94
	$\bar{\nu}$ -mode	16.56	18.81	20.75	18.49	16
$1Re1de$	ν -mode	9.30	8.10	6.59	7.79	14

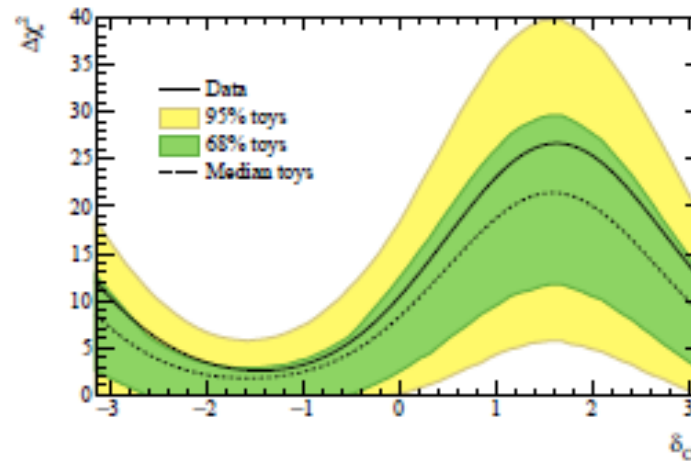
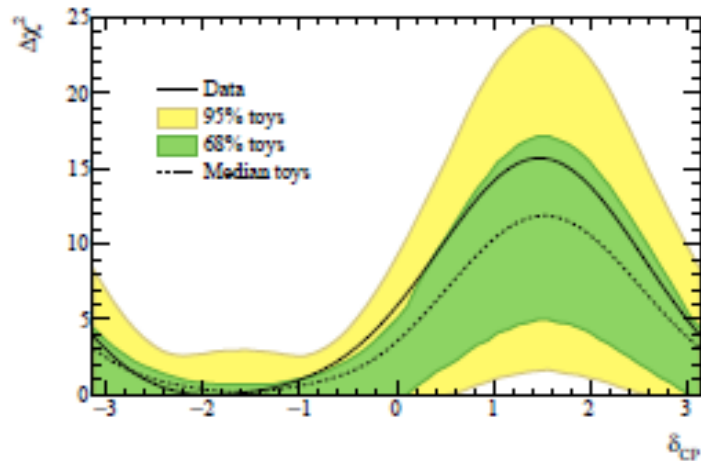
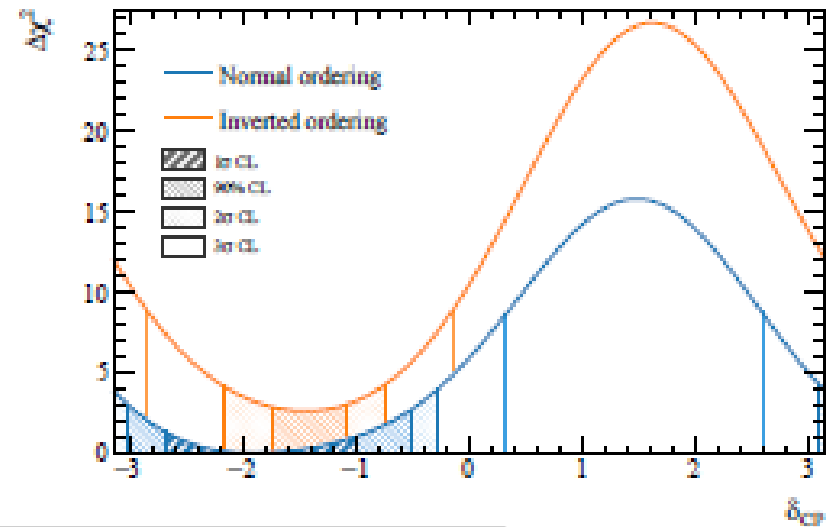
Impact of near detector analysis



- Uncertainty on neutrino energy reconstruction significantly reduced – near detector measurements reduce systematic uncertainties and improve the quality of far detector predictions

Measurement of CP-violating phase

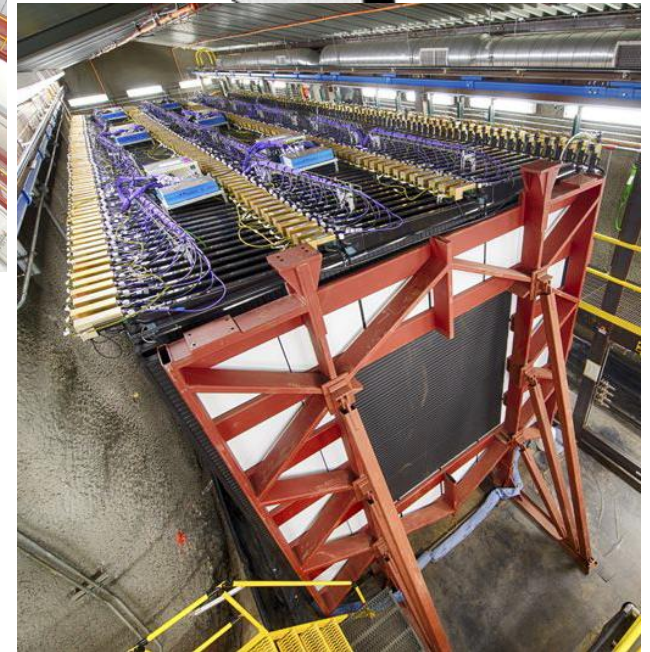
- Right: T2K results with frequentist analysis
 - Disfavor at 3σ , most values of $\delta > 0$
 - No CP violation disfavored at $>2\sigma$
 - Uses reactor θ_{13} constraint – see next talk by Liang Zhan
- Below: Comparison of data fit with toy MCs produced for $\delta = -\pi/2$



- T2K talk: Henry Israel, Neutrino Session 18 July, WAGASCI: John Nugent (poster)
- HK: Paul Soler Neutrino Session 19 July

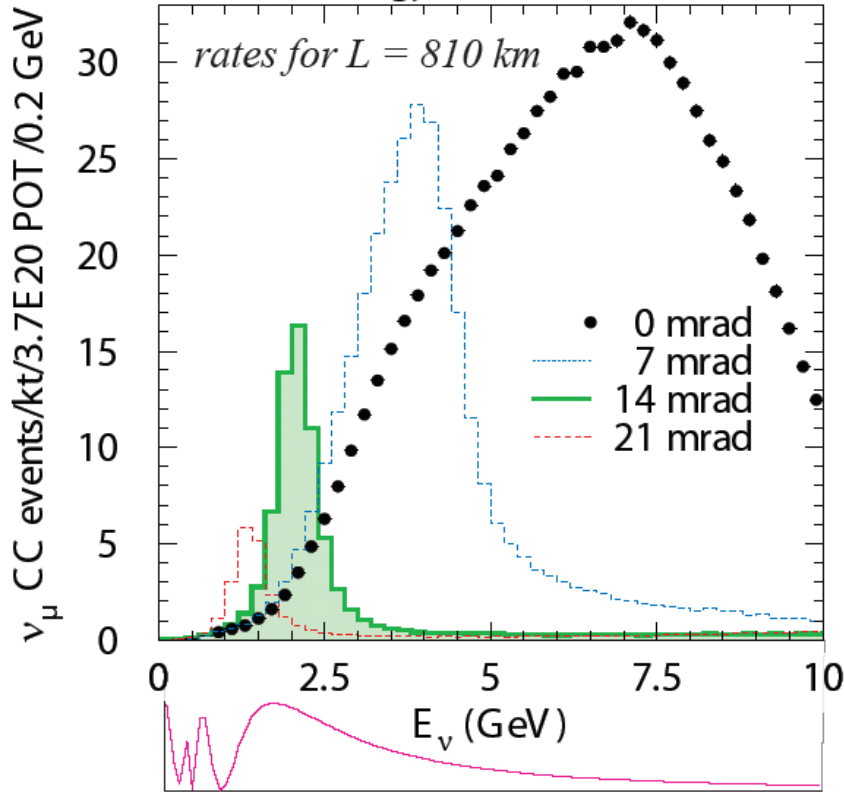
NOVA Experiment

- NOVA information from: A. Norman, DPF 2009; K. Sutton, NNN21 (2022); PRD 106, 032004 (2022)
- Off-axis long-baseline neutrino oscillation experiment FNAL to Ash River, Minnesota
- Functionally identical near and far detectors
 - Scintillator tracking calorimeters – PVC cells filled with liquid scintillator
 - ND – 300 tons, 1 km
 - FD – 14 kt, 810 km
- Neutrino and anti-neutrino data – plan to double the data-set between now and turnoff (2026 or 2027 – depends on DUNE)

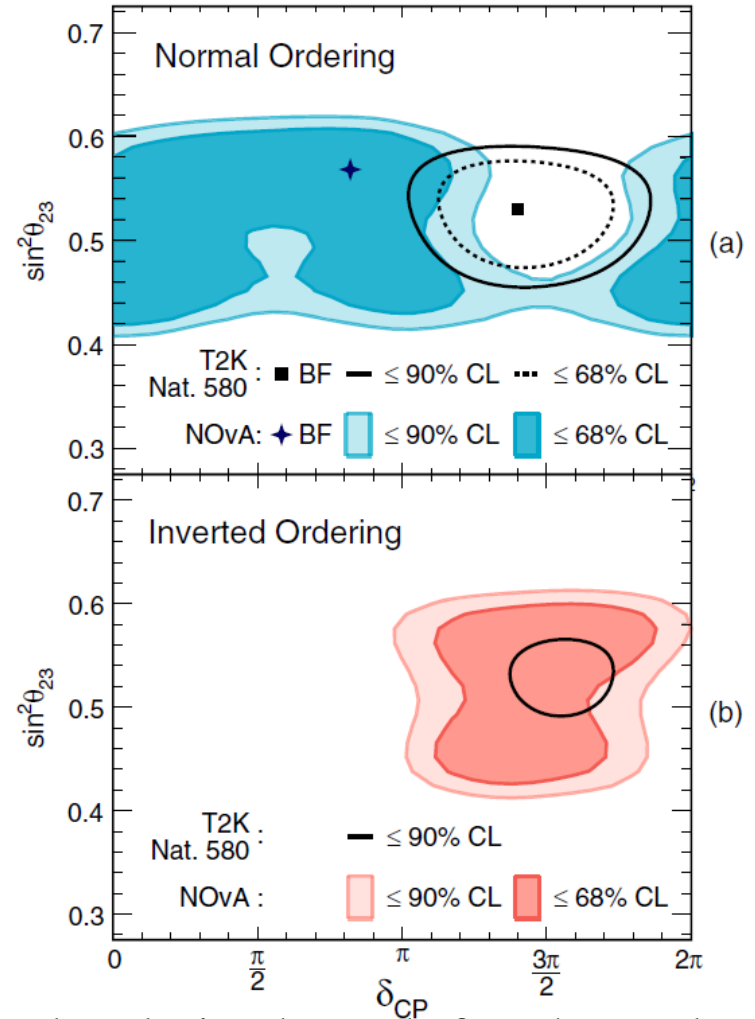


NOVA Experiment

Medium Energy NuMI Beam Tune



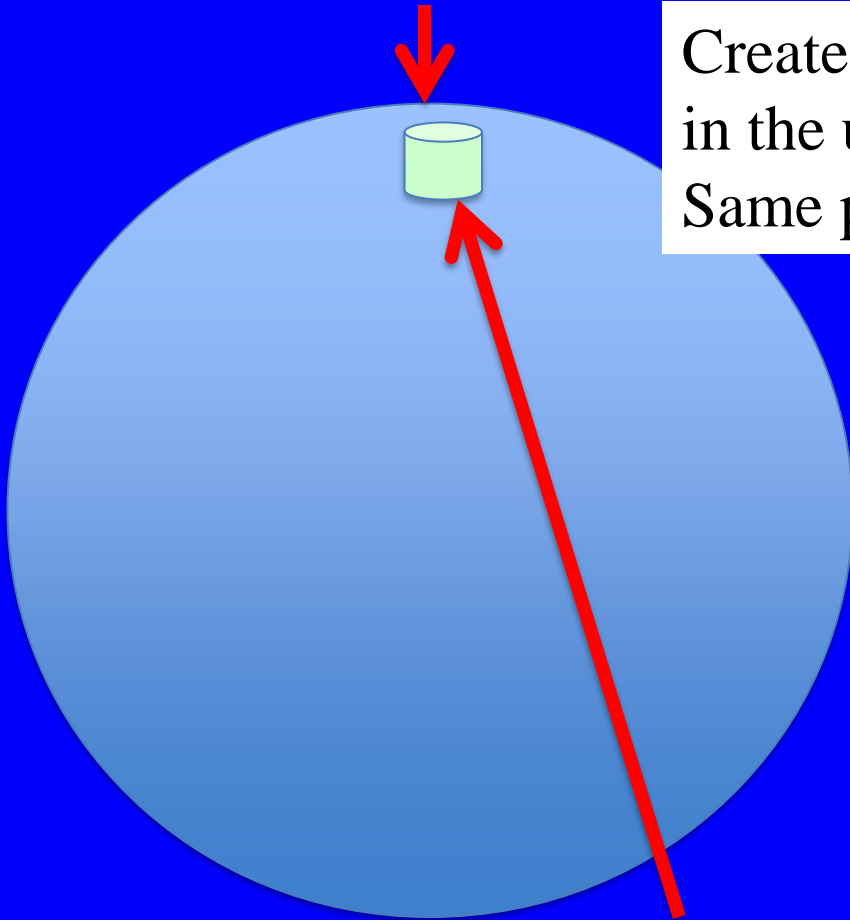
- Off-axis 14 mrad beam – neutrino energies concentrated on first oscillation maximum
- Some discrepancy between T2K and NOVA results
- T2K + NOVA collaborations conducting a combined analysis – began before the pandemic
- Treatment of systematics, neutrino interaction model require a lot of work
- Hopeful for results soon
- NOVA talk: Liudmila Kolupaeva Neutrino Session 19 July
- T2K/NOVA discrepancy: Rukmani Mohanta Neutrino Session 18 July



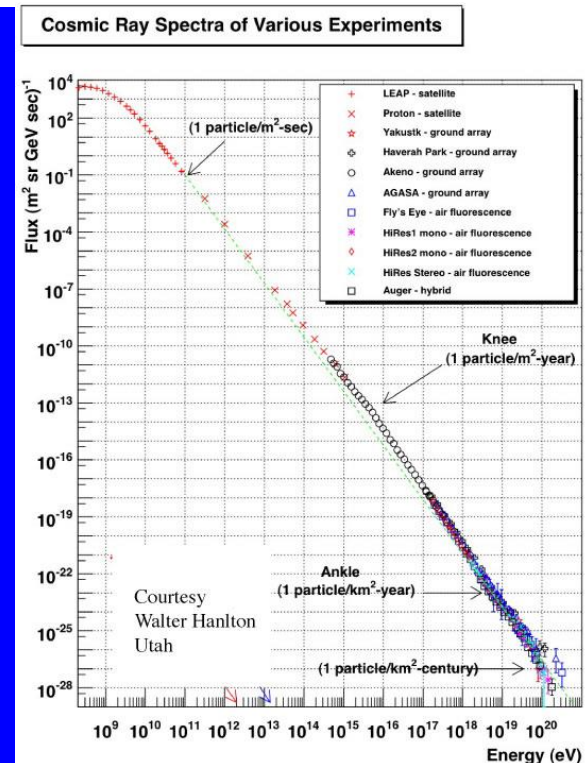
Atmospheric Neutrinos – muon and electron neutrino flavors

Neutrinos from just above the detector – small L

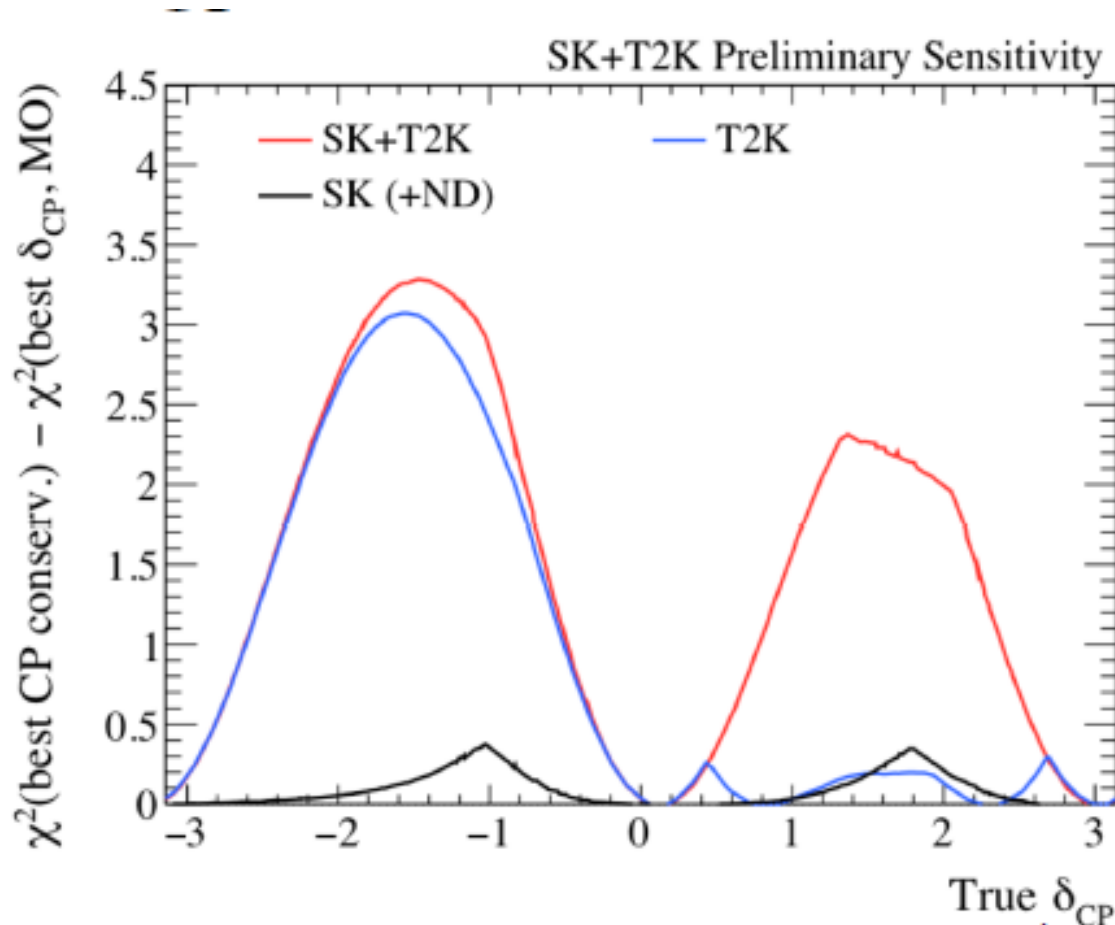
Created via cosmic ray interactions
in the upper atmosphere $\sim 10\text{km}$
Same processes make neutrino beams



Neutrinos from other side of earth – big L

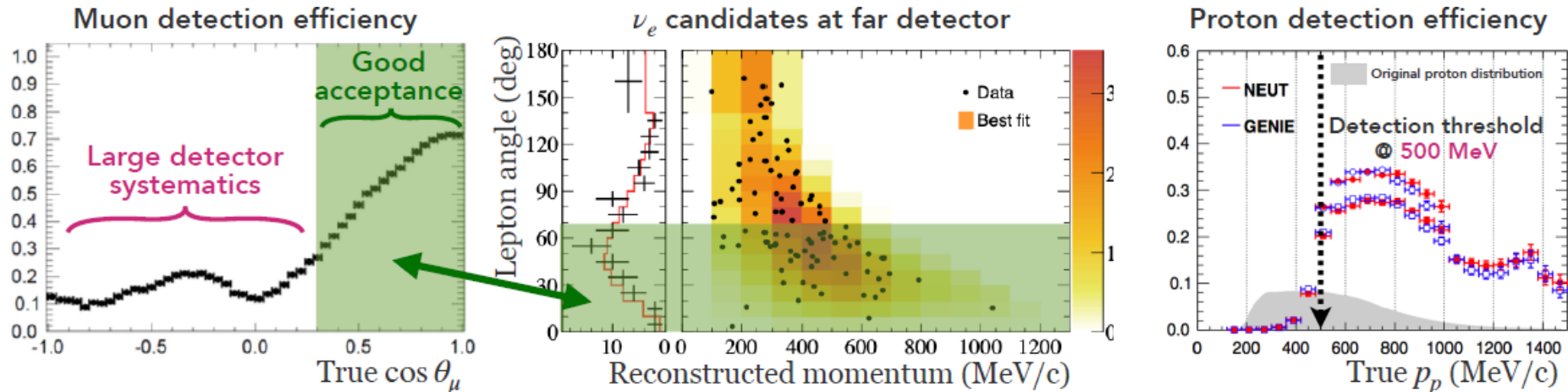


Super-Kamiokande – T2K joint analysis



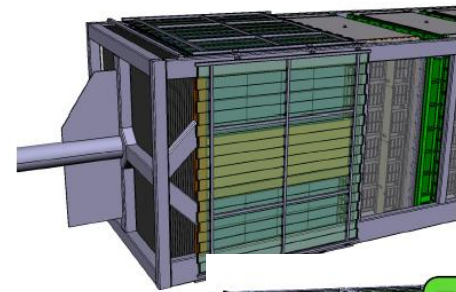
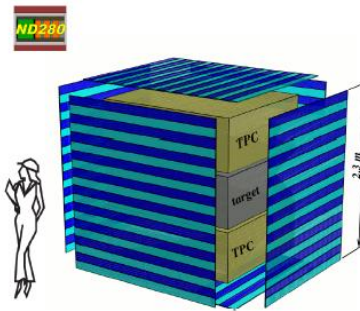
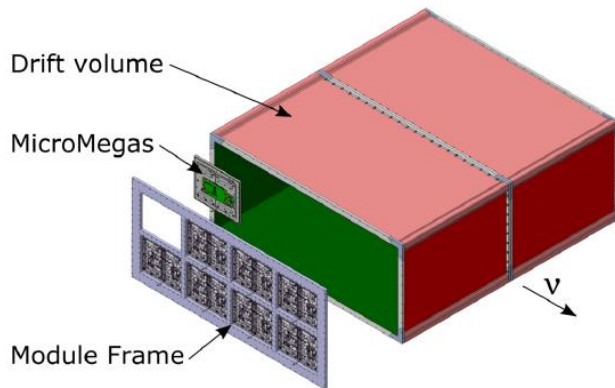
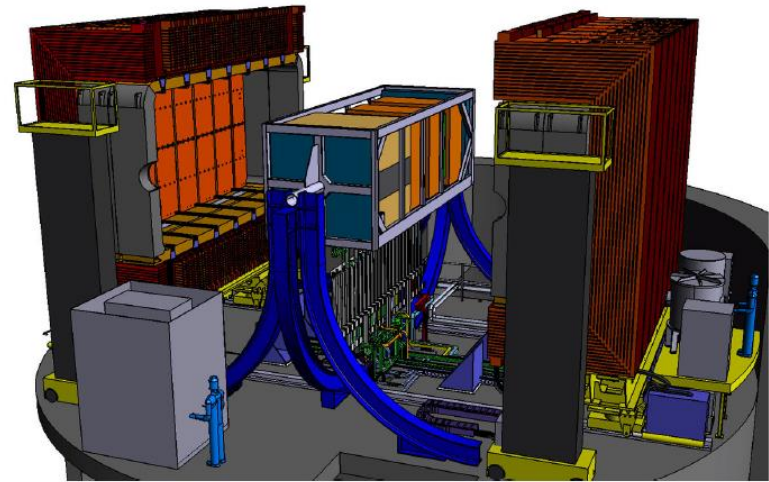
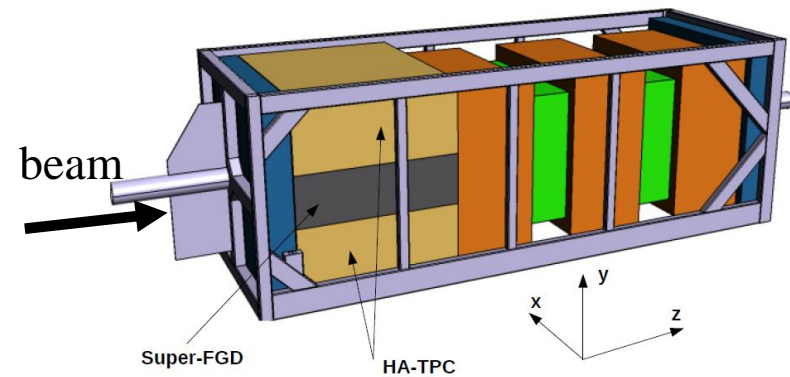
- T2K sensitive to CP violation – weak sensitivity to mass ordering
- SK sensitive to mass ordering – weak sensitivity to CP violation
- Combined analysis underway
- Treatment of combined systematics crucial
- Above for Normal Ordering

Motivation for the T2K Near Detector Upgrade

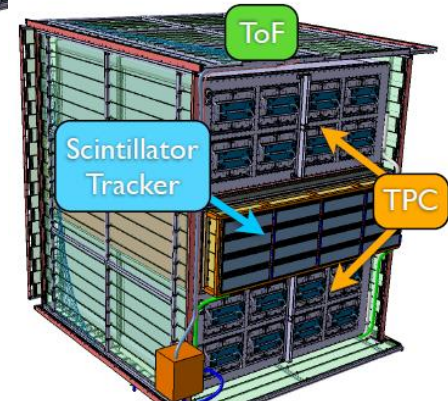


- Current ND280
 - Limited acceptance for large angles
 - High detection threshold for protons
 - No neutron information
- Improvements yield improvements in neutrino energy determination

Overview of the Upgrade Detector

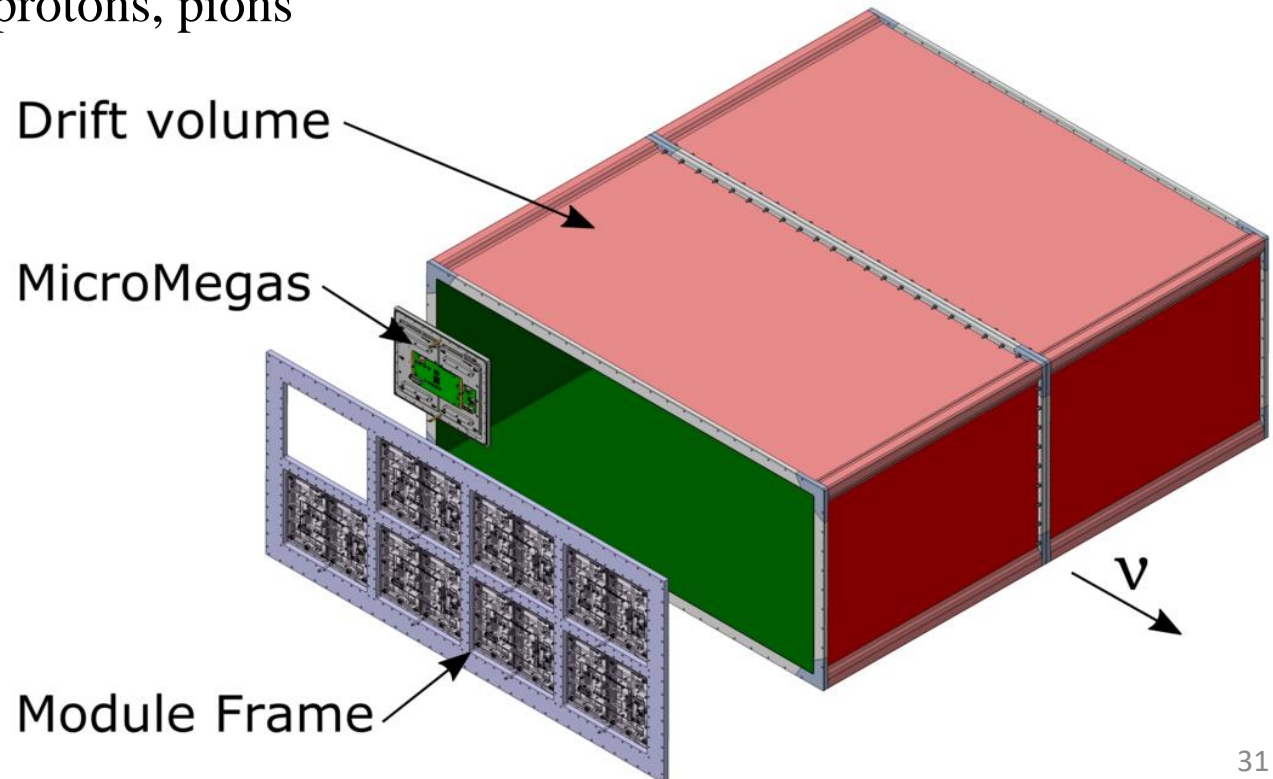
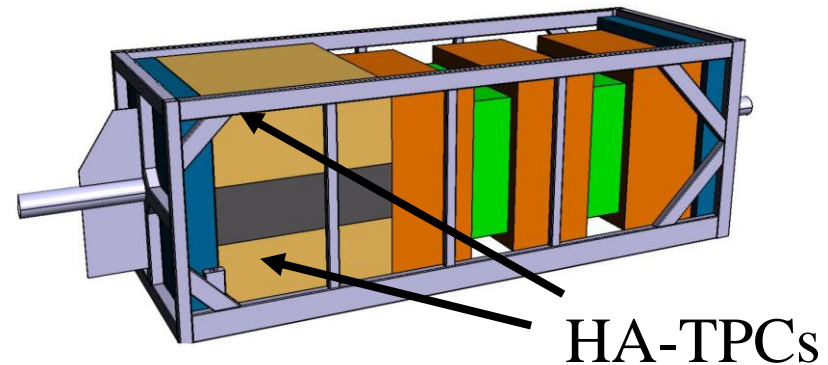


- Super Fine-Grained Detector (SFGD)
 - Primary target – solid scintillator detector composed of 1-cm cubes
 - Groups on 3 continents contributing to this detector
- High-Angle Time-projection chambers (HA-TPC)
- Time of flight detectors (ToF)

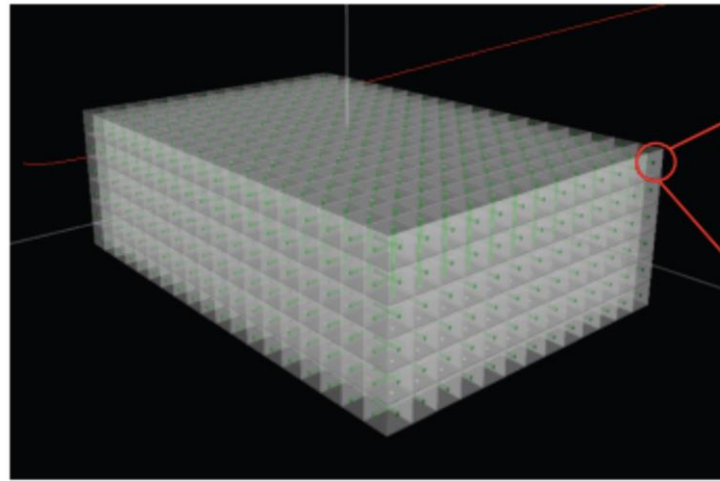


High Angle Time-Projection Chambers

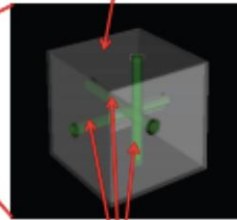
- High resolution tracking and particle ID
- Minimized dead space
- Employs resistive MicroMegas
- Transverse to primary neutrino target for exceptional high-angle efficiency
- Dimensions: 187cm x 200cm x 82cm
- Prototypes run at CERN and DESY: muons, electrons, protons, pions



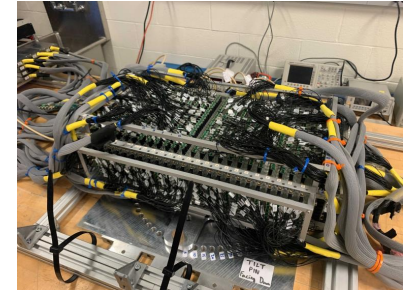
Super Fine-Grained Detector: SFGD



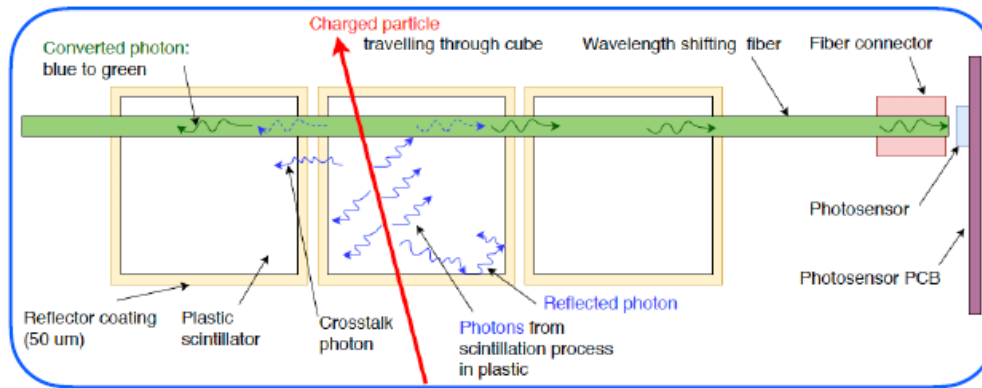
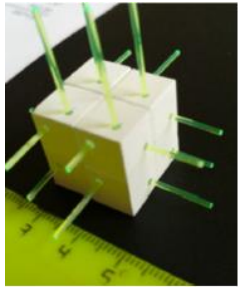
Scintillator cube



WLS fibers



Prototypes

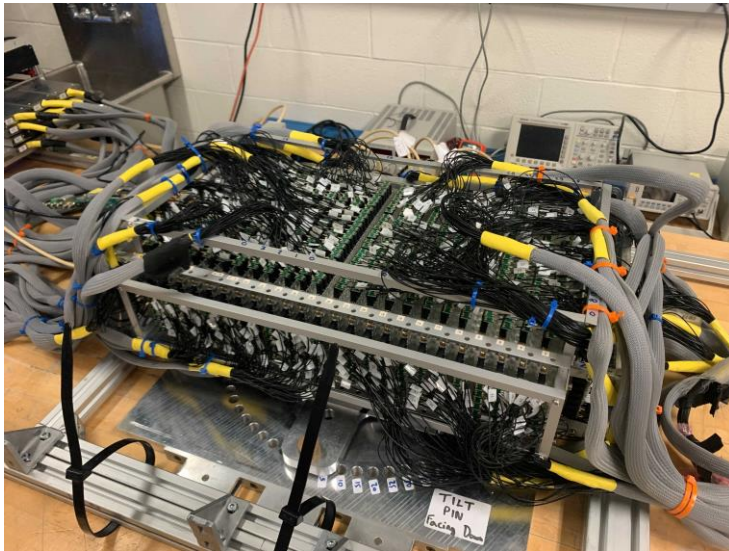


1x1x1 cm³ cubes
 Polystyrene scintillator
 1.5% paraterphenyl
 0.01% POPOP
 Chemical etched reflector
 WLS fiber Kuraray Y11
 2-clad (Ø=1mm)

- 3D-array of 1-cm scintillator cubes (184x192x56)
- Fibers run the length (or width or height) of the detector – 3-fibers in each cube
- Low-occupancy experiment – 3D view of events (4π – like acceptance)
- Prototype detectors – neutron measurements

Prototypes

Tests in charged particle and neutron beams

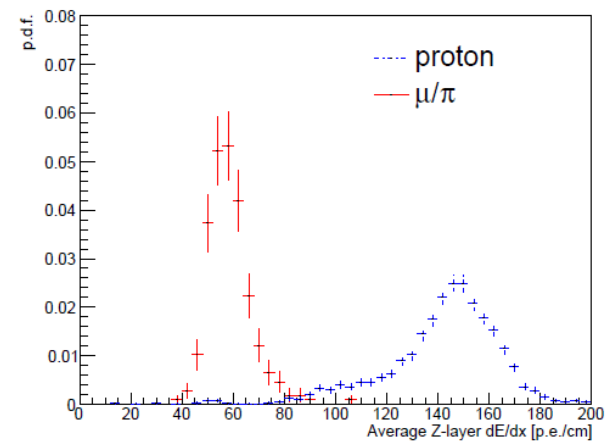
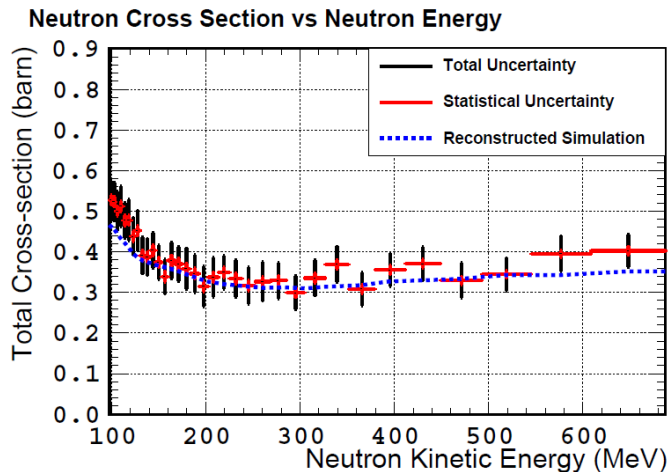


← SFGD Prototype (8x24x48):

- Charged particle beam at CERN
- Neutron beam at LANL

US-Japan Prototype (8x8x32) →

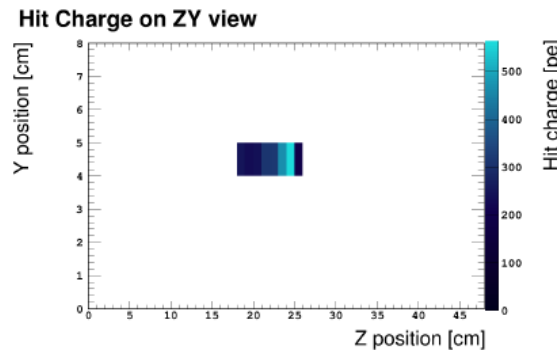
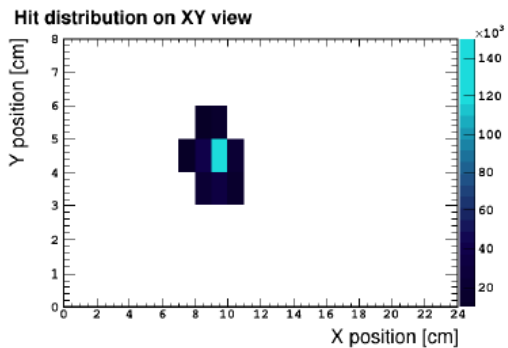
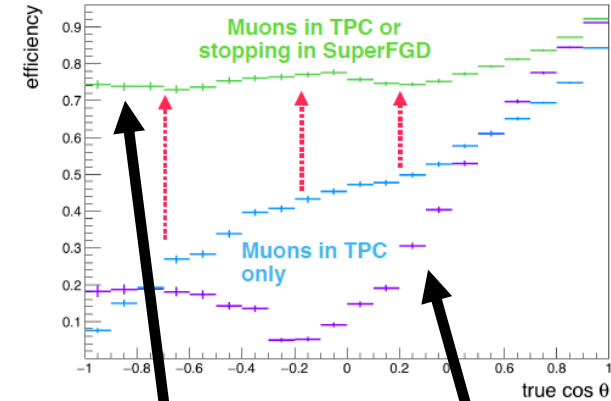
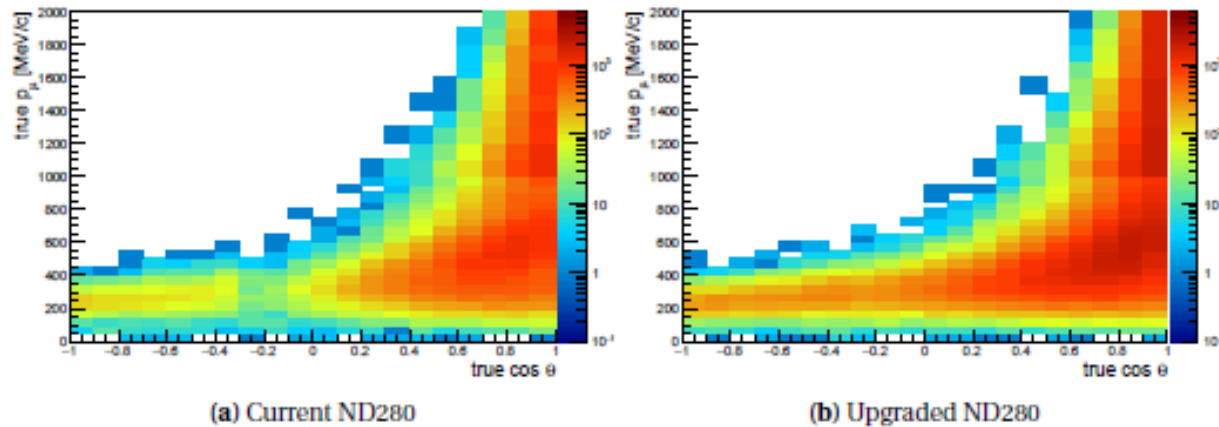
- Neutron beam at LANL



<https://arxiv.org/abs/2207.02685>

A. Blondel et al 2020 JINST 15 P12003

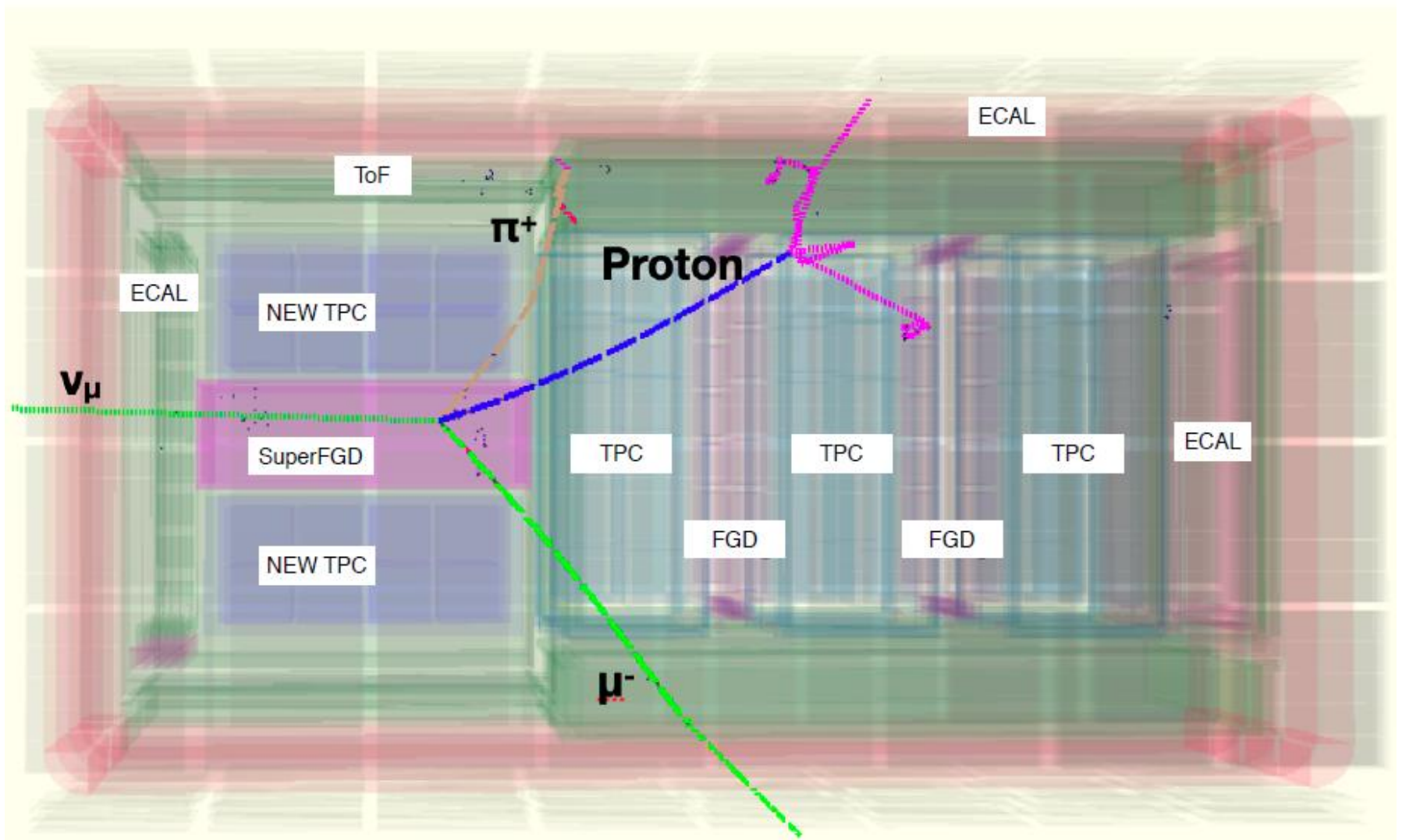
Performance and Capabilities of Upgraded Detector



Neutron detection capability demonstrated in the SFGD prototype
 ~170 MeV KE neutron from prototype run at LANSCE
 Time-of-Flight measurement of neutrons from neutrino interactions enabled

- Greatly improved performance for transverse particles
- Excellent neutron detection *and* neutron measurement of kinetic energy via time of flight *within* the SFGD
- Momentum by range – 3% for stopping muons

Simulated Event in Upgraded ND



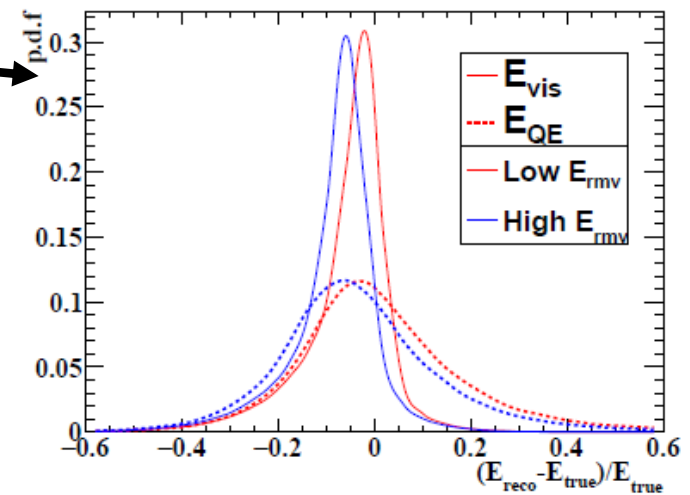
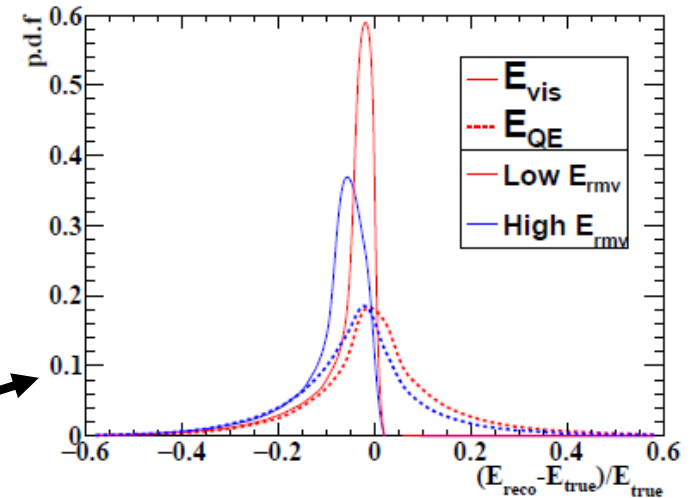
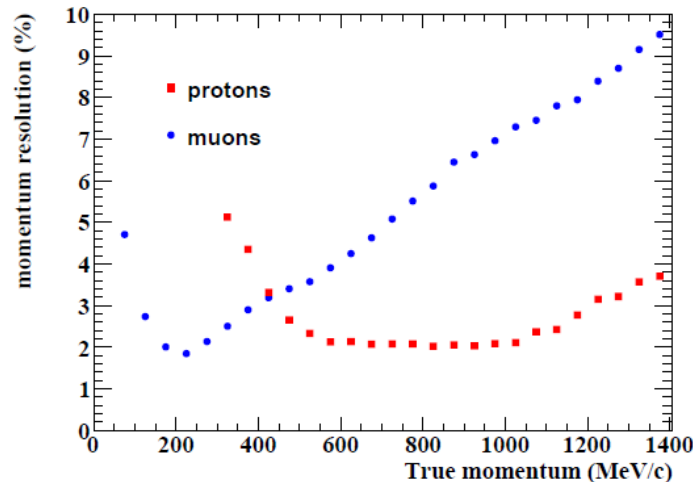
Summary

- Neutrino oscillation experiments are an excellent laboratory with which to explore leptonic CP violation
- Long-baseline experiments are required due to the neutrino oscillation lengths relevant for neutrino beams above muon and electron CC production thresholds
- Strong evidence for CP violation now exists from T2K
- Look forward to an exciting future ahead
- Thank you very much to the organizers for the invitation to your beautiful city and stimulating conference!

Reconstructed – True Neutrino Energy:

Full kinematics give window to nucleon state

- Improved proton reconstruction performance – higher precision neutrino energy reconstruction
- Solid lines – reconstruct neutrino energy with both muons and protons
- Dotted lines – reconstruct neutrino energy with only muons (employ quasi-elastic assumption)
- Red and blue are different hypotheses of true nucleon removal energy
- Upper plot – perfect reconstruction
- Lower plot – anticipated reconstruction resolutions with SFGD ($< 5\%$ on neutrino energy)
- Proton and muon momentum resolutions assumed in the calculations



Phys. Rev. D 105, 032010

Transverse kinematic imbalance isolates different neutrino interaction modes

- Contribution of different neutrino interaction mode for charged current, zero pion events
- Low kinematic imbalance region probes Fermi motion
- High imbalance region probes final state interactions and correlated nucleon states
- Very low imbalance region in anti-neutrinos probes interactions on hydrogen

