CP violation in neutrino oscillations (lepton sector of SM)

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Neutrino oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

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

***U* parameterization:**
three mixing angles θ_{12} θ_{23} θ_{13}
CP violating phase δ_{CP}

Pontecorvo-Maki-Nakagawa-Sakata matrix

atmospheric — link between atmospheric and solar — solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

SuperK, K2K, MINOS, T2K, NOvA, IceCube

$\theta_{23} \sim 45^0$

$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times10^{-3}\,\mathrm{eV}^2$

T2K, NOvA — Daya Bay, RENO, Double Chooz

$\theta_{13} \approx 8.5^0$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

Solar experiments, SuperK, KamLAND

$\theta_{12} \approx 34^0$

$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times10^{-5}\,\mathrm{eV}^2$

two independent Δm^2

$m_\nu \neq 0$ ↓ NEW PHYSICS beyond STANDARD MODEL

Neutrino: open questions

Absolute scale of neutrino mass → β decay, $0\nu2\beta$ decay, astrophysics and cosmology

Neutrino nature: Dirac or Majorana → $0\nu2\beta$ decay

Neutrino mass ordering → astrophysics and cosmology, atmospheric and reactor neutrinos, accelerator (LBL experiments) neutrinos

CP violation → **accelerator neutrinos (LBL experiments)**

Precise measurement of oscillation parameters (θ_{23} = 45°?) → solar, atmospheric, reactor, accelerator (LBL experiments)

Sterile neutrinos → β decay, $0\nu2\beta$ decay, astrophysics and cosmology, atmospheric and reactor neutrinos, accelerator neutrinos

Neutrino interactions → atmospheric and reactor neutrinos, accelerator neutrinos

Neutrino: CPV and MO

- CP violation in lepton sector

Magnitude of CP violation in neutrino oscillations

$$J_{CP} = Im(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = Im(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2})$$
$$= \frac{1}{8}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta_{CP}$$

all mixing angles $\neq 0$ $\rightarrow$ $J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

Mixing matrix

neutrinos

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

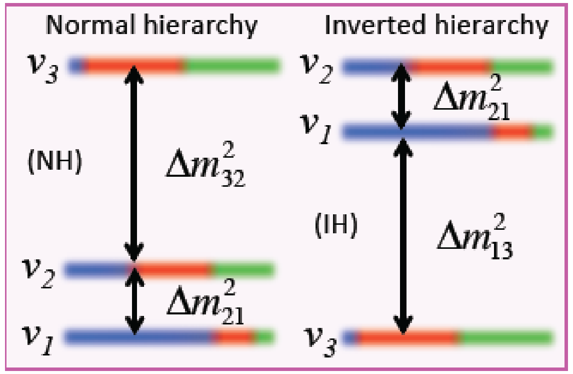
quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Quark sector: $J_{CP} \approx 3\times10^{-5}$

Lepton sector: $J_{CP} \simeq (0.03\text{-}0.04)\times\sin\delta_{CP}$

- Neutrino mass ordering (MO)

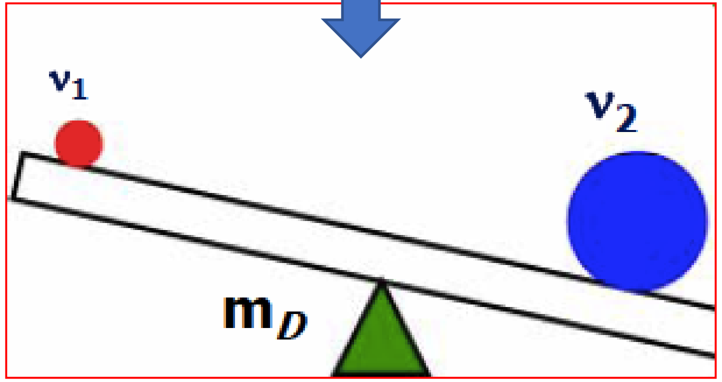


IO: $\Sigma m_i \approx 100\ meV$
NO: $\Sigma m_i \approx 60\ meV$

Why is CPV in lepton sector important?

SM cannot explain non-zero neutrino mass

See-saw model → ν mass



$$m_\nu \approx \frac{m_D^2}{M_R}$$

m_D ~ 100 GeV

$\nu_2 \to M_R \le 10^{14}$ GeV

Baryon Asymmetry of Universe (BAU)

$$Y_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

$$\frac{n_{\bar{B}}}{n_B} < 10^{-6}$$

CP violation in quark sector (K, B, D decays) too small to generate BAU

M.Gavela et al. Mod.Phys.Lett 9 (1994) 795

$$Y_B \sim J \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)}{M_W^6} \frac{(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_b^2 - m_d^2)}{(2\gamma)^9}$$

~10 orders below measured BAU value

See-saw model produces BAU by leptogenesis mechanism

M. Fukugita ,T. Yanagida, 1986

N_R decays → lepton asymmetry ε_1 → partially transformed into BAU

lepton asymmetry from N_R decays ε_1 must be > 10^{-6}

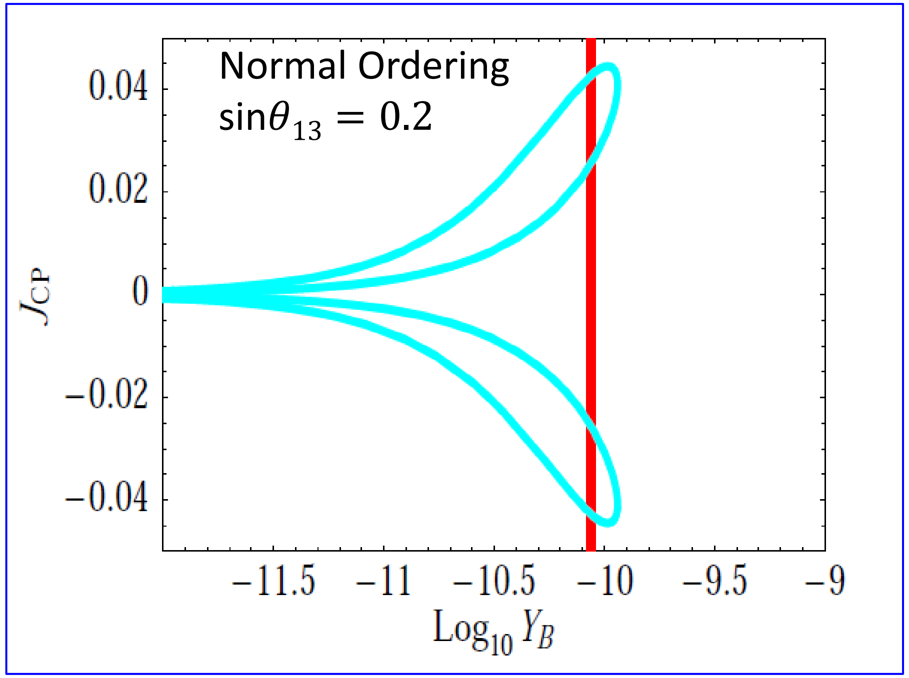
Baryon Asymmetry ↔ Neutrino Physics ??

CPV in PMNS ⟺ CPV in Leptogenesis ?

Type I See-saw model

SM + 3 heavy (RH) Majorana neutrinos N_1, N_2, N_3
with masses $M_1 << M_2 < M_3$
Leptogenesis takes place at temperatures $10^9\ GeV < T < M_1$

S.Petcov et al. Nucl.Phys. B774,2007, 1
S.Petcov et al. Phys.Rev. D75, 2007, 083511



$$Y_B \simeq 3 \times 10^{-13} |\sin \delta_{CP}| \left(\frac{\sin\theta_{13}}{0.2}\right)\left(\frac{M_1}{10^9 GeV}\right)$$

M_1 = (3-5)x10^{11} GeV

BAU can be reproduced, if

$|\sin\theta_{13}\sin\delta_{CP}| > 0.11$

Daya Bay: $\sin\theta_{13} = 0.15 \ \rightarrow \sin\delta_{CP} > 0.75$

⇓

$|J_{CP}| > 0.024$

CPV in PMNS ⟺ CPV in Leptogenesis ?

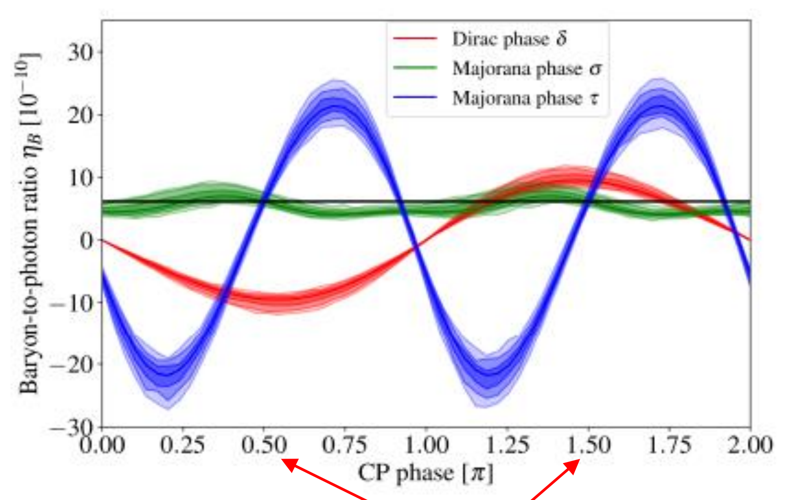
Type II See-saw model

SM + SU(2)$_L$ triplet scalars Δ: $\Delta^+, \Delta^{++}, \Delta^0$ B.Karmakar, A. Sil arXiv:1509.0790

$\delta_{CP} = 0, 2\pi$ excluded, close to $\frac{3}{2}\pi$ – *favoured, but exact value of* $\frac{3}{2}\pi$ – *excluded*

T.Rink et al., arXiv:2006.03021

Type I +II See-saw model



max CPV in oscillations

Oscillations **$0\nu2\beta$ decay**

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \times \mathrm{diag}(1, e^{i\sigma}, e^{i\tau})$$

How to search for CP violation?

Golden channel for CP search: $\nu_\mu \to \nu_e$

Probability of $\nu_\mu \to \nu_e$ oscillation in matter

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E_\nu} \times \left[1 + \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] \\
& + 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} \\
& - 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}\sin\frac{\Delta m_{12}^2 L}{4E_\nu} \\
& + 4s_{12}^2 c_{13}^2(c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\frac{\Delta m_{12}^2 L}{4E_\nu} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E_\nu}\frac{aL}{4E_\nu}\sin\frac{\Delta m_{13}^2 L}{4E_\nu}(1-2s_{13}^2),
\end{aligned}
$$

leading term

- θ_{13}
- CP-even
- CP-odd
- Solar
- Matter

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

Matter effect

$$a[eV^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6\times10^{-5}\rho\left[g/cm^3\right]E_\nu[GeV]$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow a \to -a \qquad \delta \to -\delta$$

change sign for NH → IH

Search/measurement of CP violation

Long baseline accelerator experiments

Direct search: compare oscillation probabilities
muon neutrino → electron neutrino
and
muon antineutrino → electron antineutrino

CP asymmetry A_{CP}

Direct measurement →

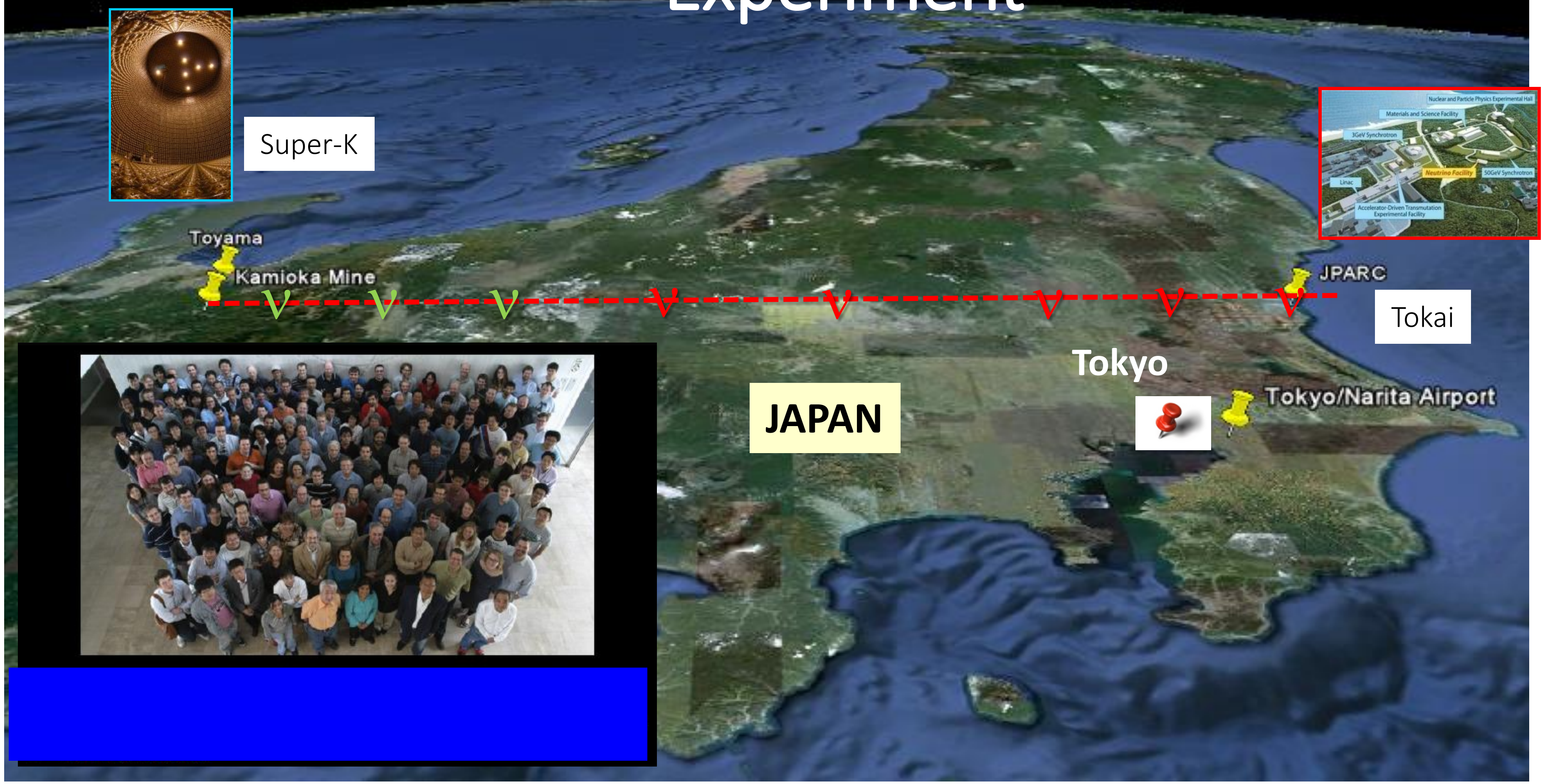
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$A_{CP} \neq 0$ → $\delta_{CP} \neq 0$ → CP violation

Sensitivity to CPV **increases** using the value of θ_{13} obtained in reactor experiments

Current experiments T2K and NOvA

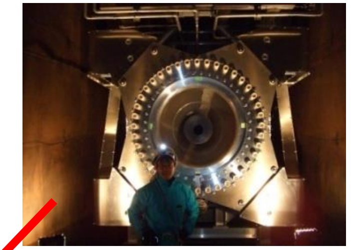
Long-Baseline Neutrino Oscillation Experiment

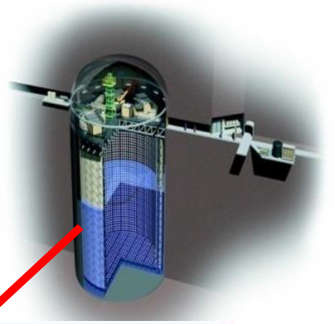


Experiment T2K

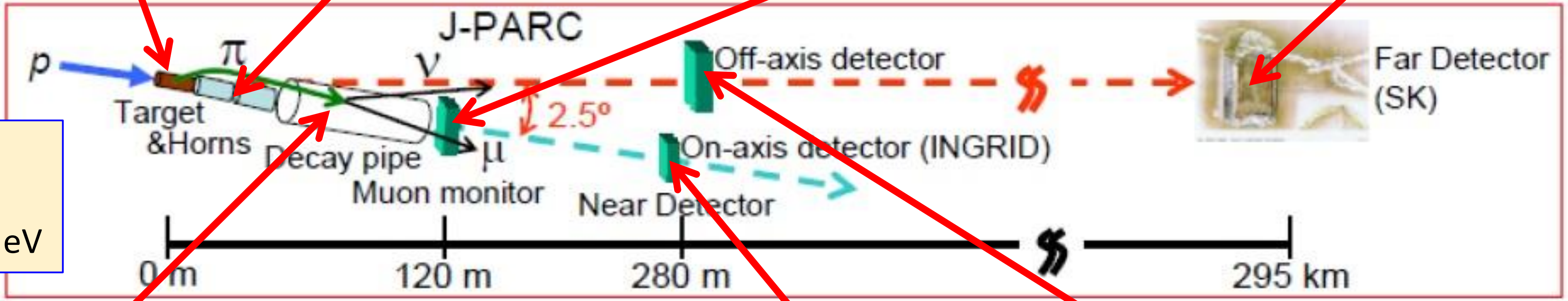
T2K collects data since 2010

Far neutrino detector
SuperKamiokande



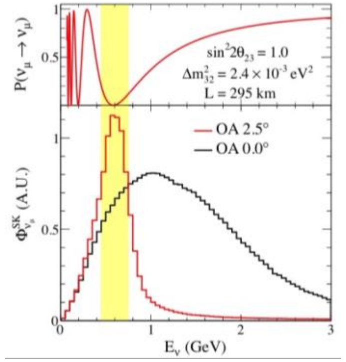


L = 295 km
Off-axis ν beam
Peak energy 600 MeV

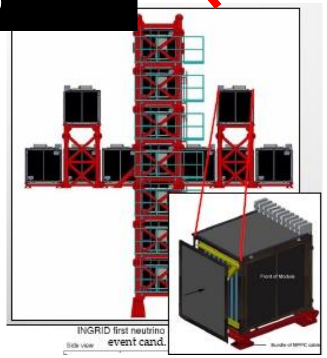


Decay tunnel

Off-axis neutrino beam

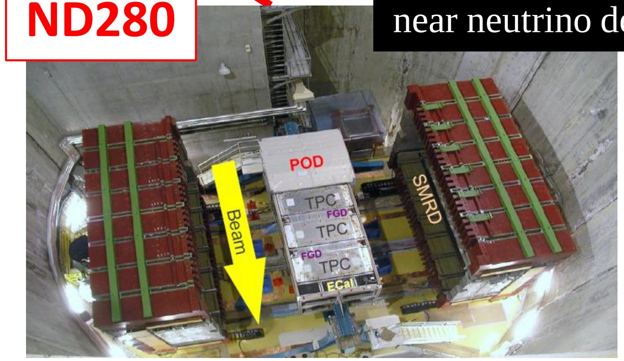


Neutrino monitor
INGRID



ND280

Off-axis
near neutrino detector

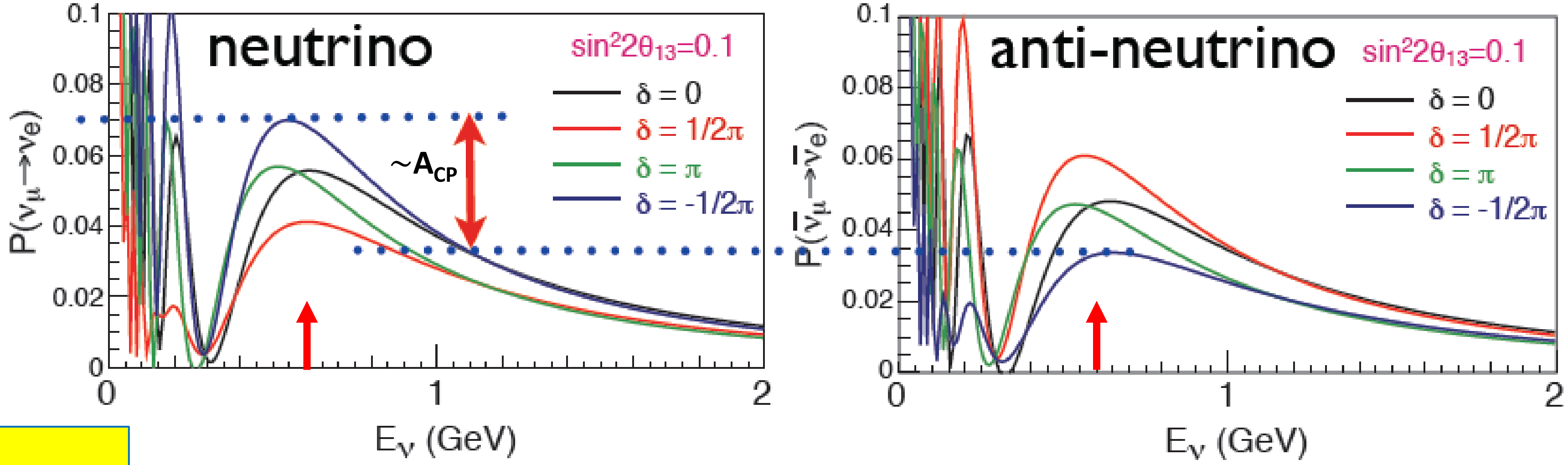


Search for CP violation in T2K

Measurements of oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

Normal hierarchy

T2K baseline = 295 km, E_ν(peak) = 600 MeV



Experiment T2K:
E_ν ~ 0.6 GeV,
baseline = 295 km

T2K simulation
vacuum + matter
$A_{CP} \simeq -0.28\sin\delta + 0.09$

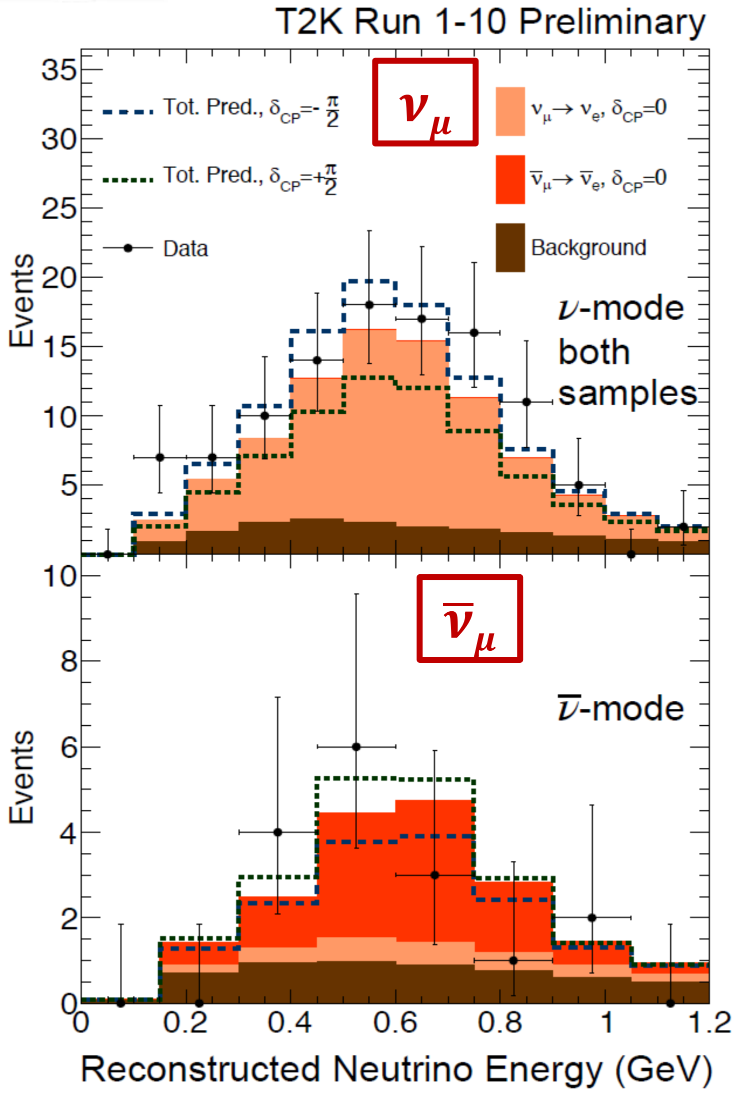
CP in vacuum

Matter asymmetry

CP asymmetry in vacuum

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta$$

ν_e and $\bar{\nu}_e$ appearance



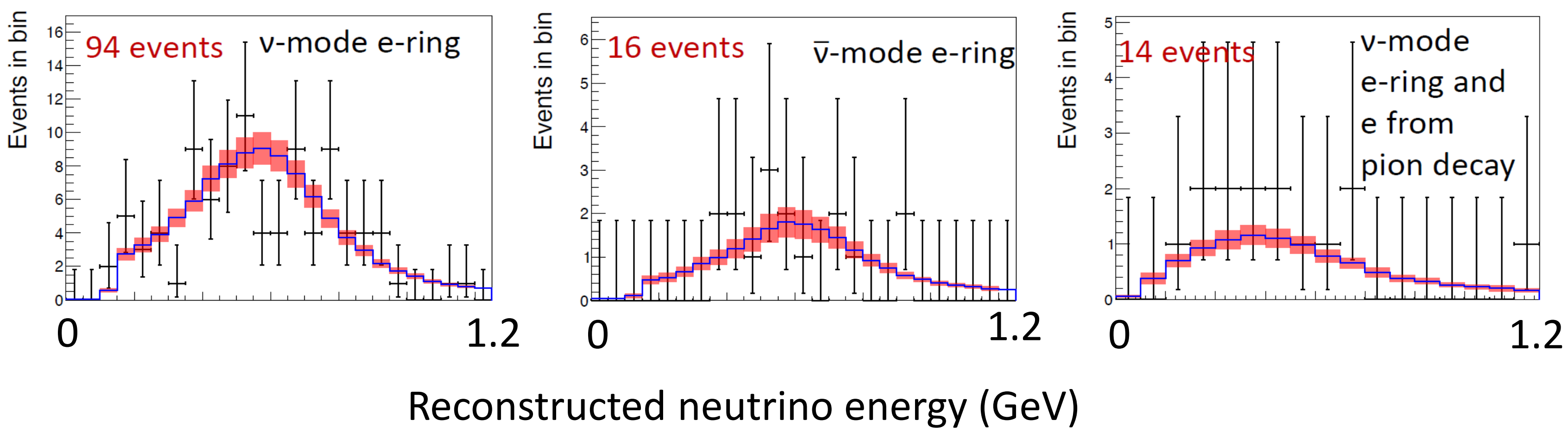
Number of protons on target (POT)

ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

Three samples with electron-like Cherenkov rings

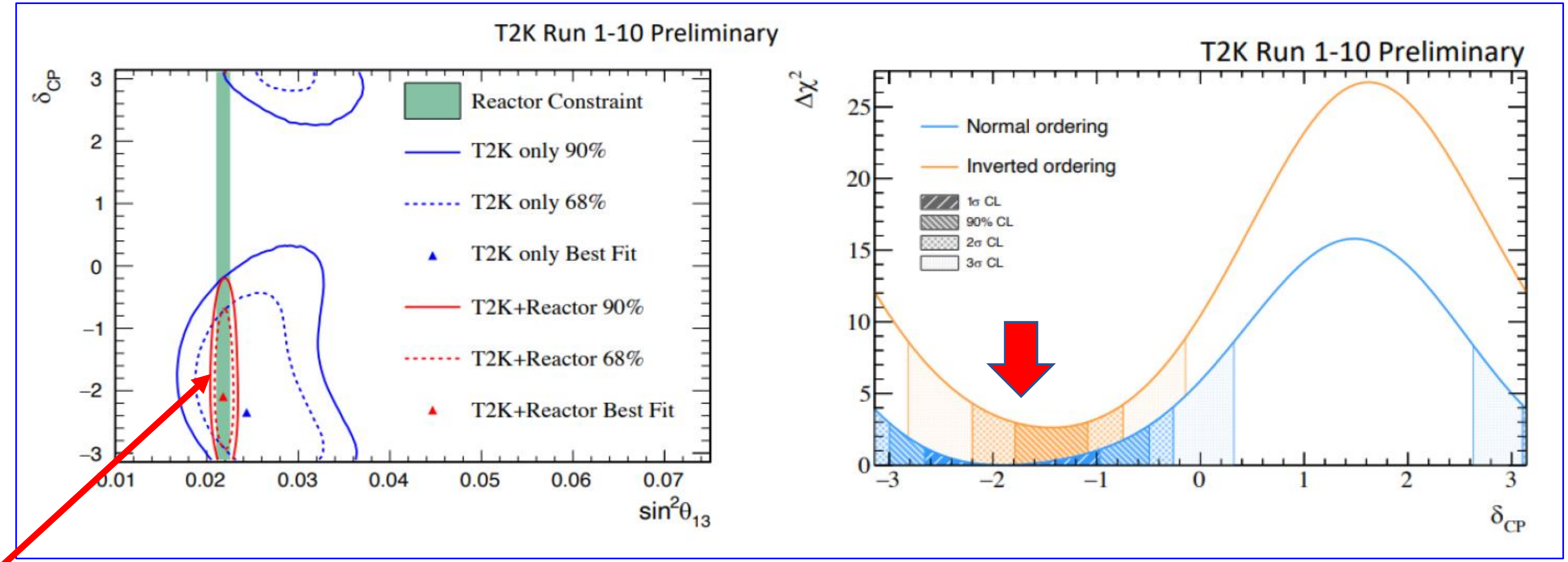
- Two (1 ν-mode and 1 $\bar{\nu}$-mode) with e-ring only targeting 0π events
- One in ν-mode with e-ring and e from π decay targeting 1π events

Accumulated number of electron neutrinos and antineutrinos



Hint of CP violation

L.Kormos, Nufact2022



Constraint on θ_{13} from reactor experiments Daya Bay, RENO, DChooz

35% of δ_{CP} values excluded at 3σ marginalized over hierarchies

CP conserving values ($\delta_{CP} = 0,\ \pi$) excluded at **about 2σ**

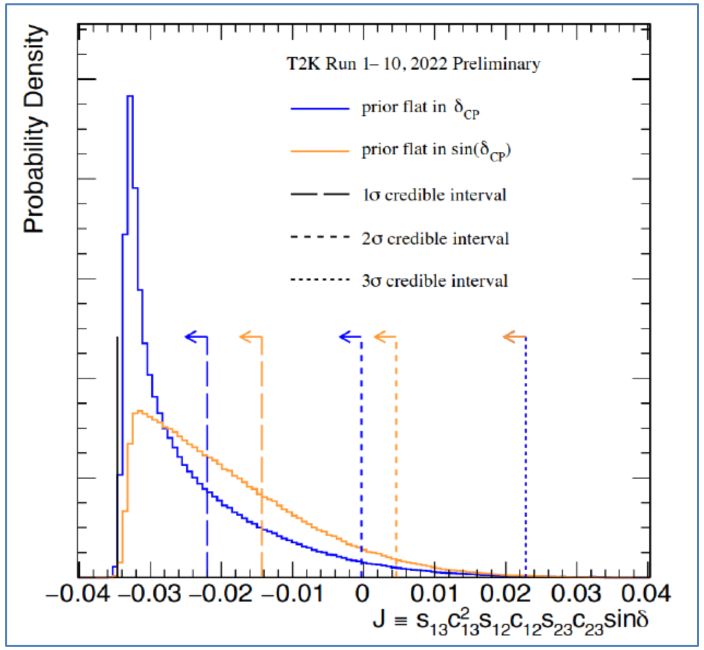
Best fit: $\delta_{CP} \sim -\pi/2$ → close to maximum CP violation

Normal mass ordering is preferred at 80% CL

CP violation: J_{CP}

PMNS parametrization independent metric for CPV

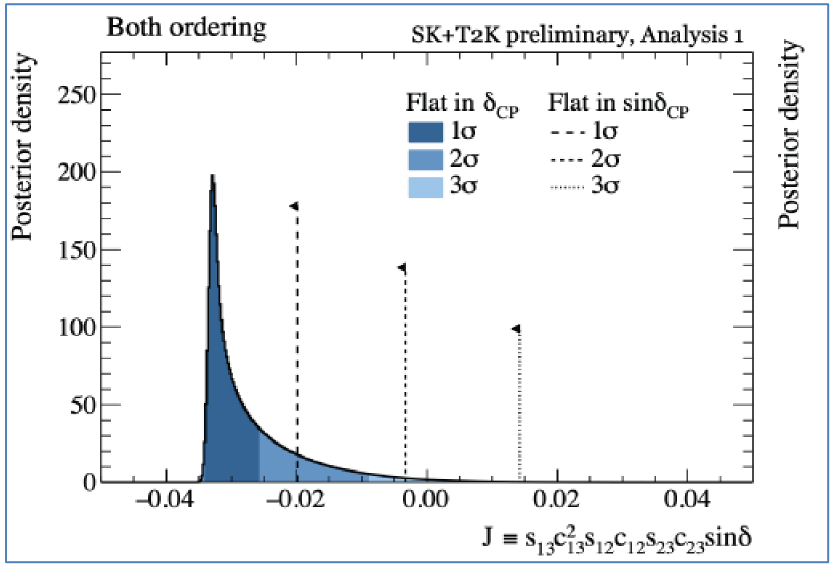
T2K



CP-conservation (J_{CP}=0) excluded at:
- 2σ for a flat prior in δ_{CP}
- 90% for a flat prior in $\sin\delta_{CP}$

T.Holney, talk at Neutrino Telescopes2023

T2K + SuperK joint analysis

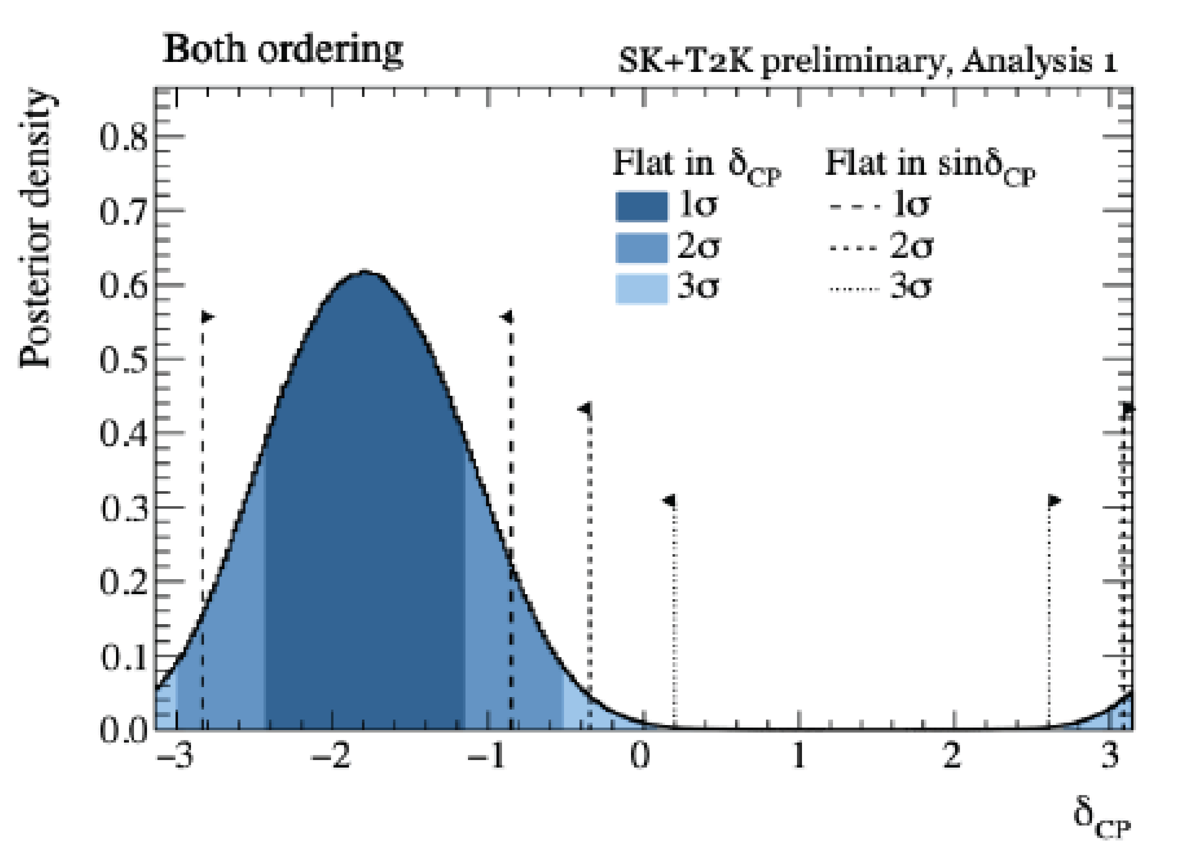


CP-conservation (J_{CP}=0) excluded at 2σ

CPV: T2K+SuperK

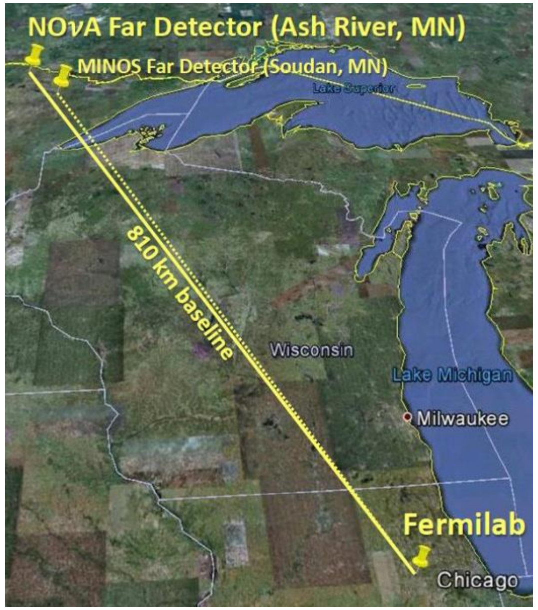
T2K + SuperK joint analysis

A.Blanchet, talk at Neutrino Telescopes2023

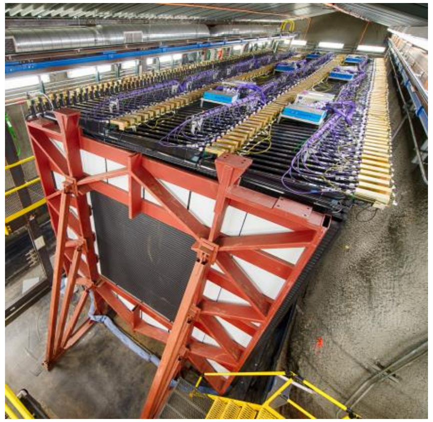


- Improved δ_{CP} constraints
- CP conservation is excluded at around 2σ with θ_{13} from rector experiments applied

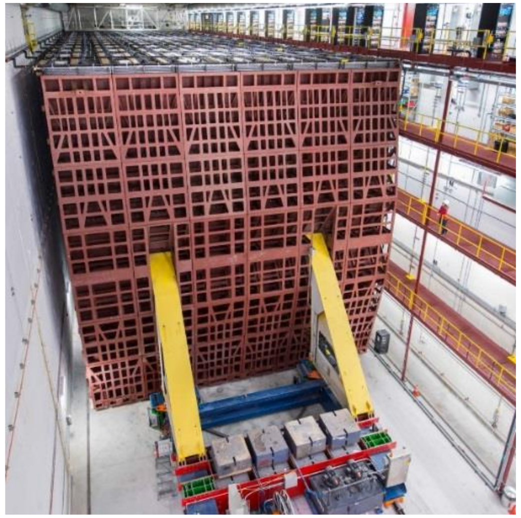
Experiment NOvA



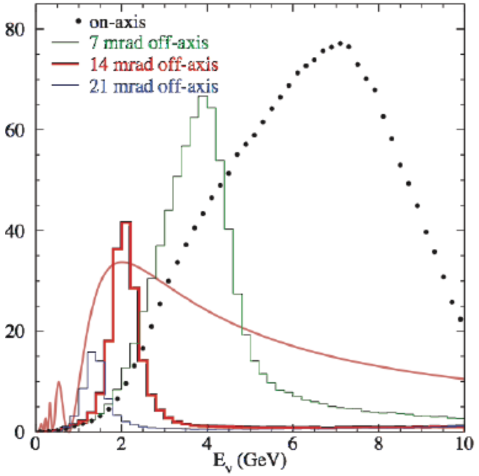
Near Detector



Far Detector



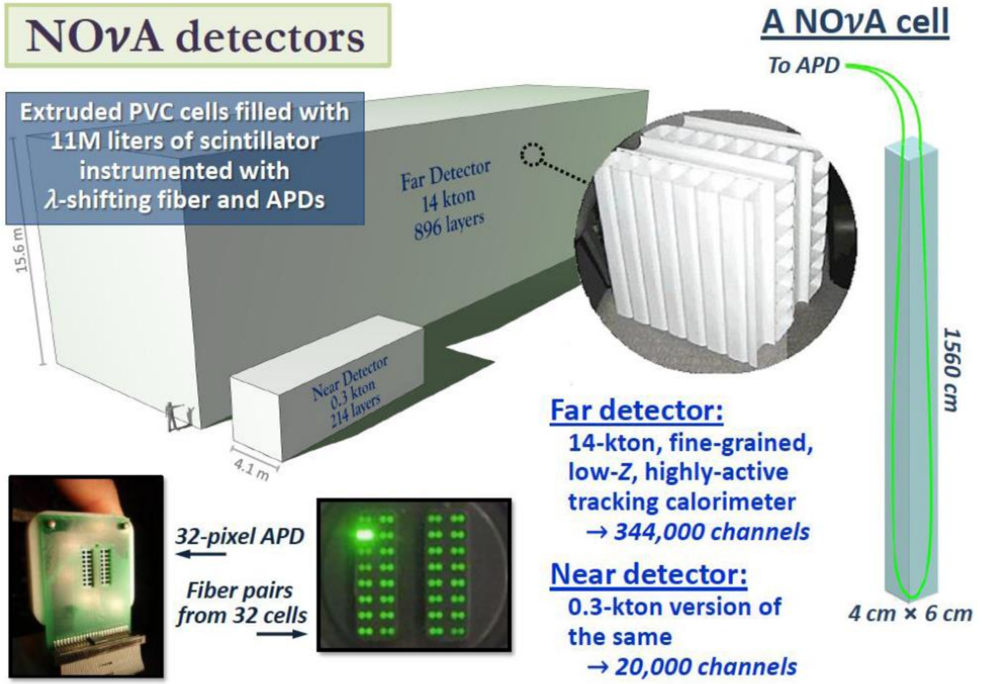
Neutrino beam



Taking data since Summer 2014

Study of $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations

Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter



ν_e and $\bar{\nu}_e$ appearance

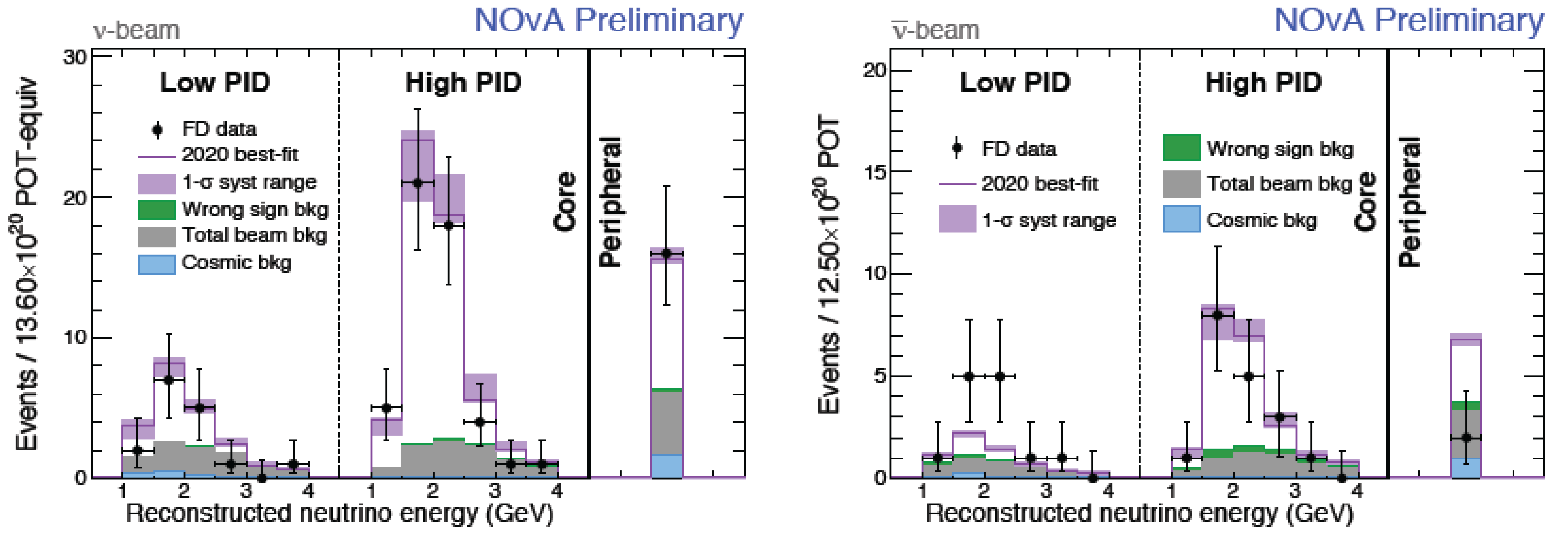
nu beam: 1.36x10[21] POT   anti-nu beam: 1.25x10[21] POT

A.Aurisano, Nufact2023

ν_e **Far detector** $\bar{\nu}_e$

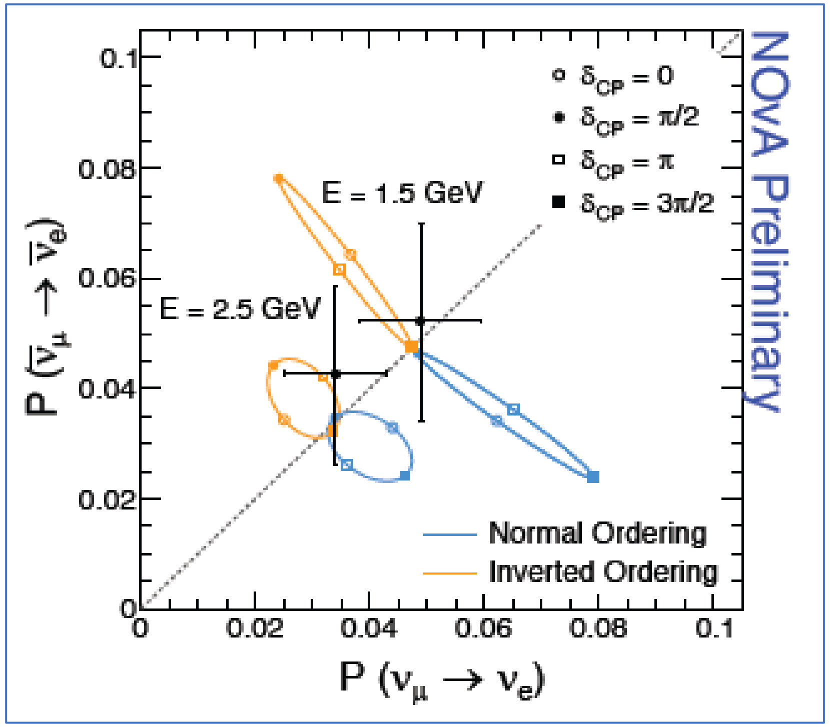
Total observed ν_e events	82
Total background	26.8

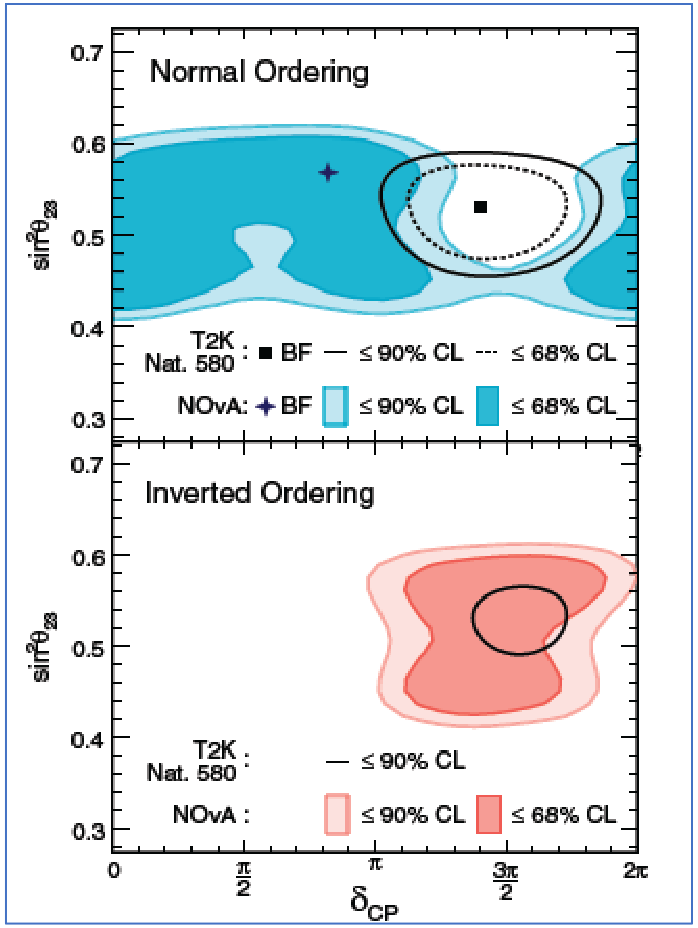
Total observed $\bar{\nu}_e$ events	33
Total background	14.0



NOvA: search for CP violation

M.Frank, EPS-HEP 2023





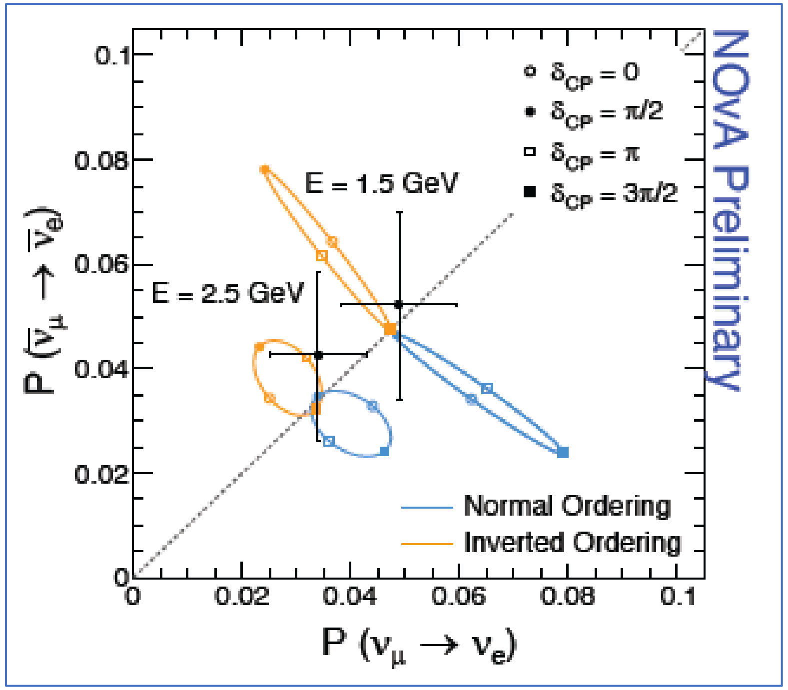
Normal ordering
Disfavor $\delta = 3\pi/2$ at $\sim 2\sigma$

NO: NOvA best fit:
$\delta_{CP} = 0.82\pi$

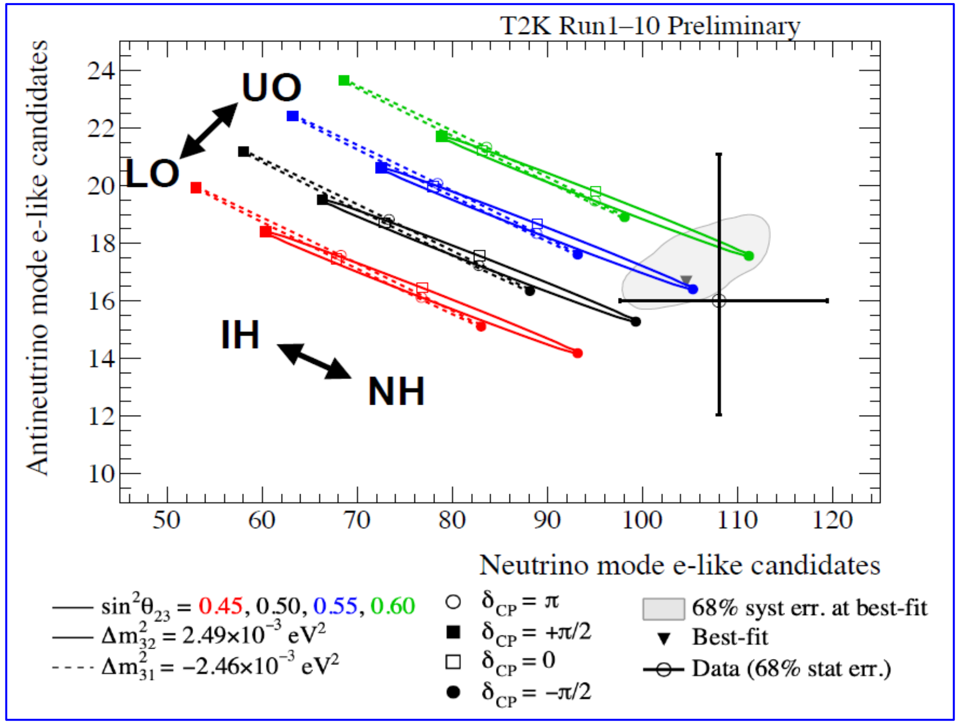
Inverted ordering
Exclude $\delta = \pi/2$ at > 3σ

- Weak preference for normal ordering
- No significant CP asymmetry was observed

CP: T2K and NOvA



T2K Preliminary



NOVA ($\nu+\bar{\nu}$) prefers:
NO
CP conservation
octants ~degenerate

T2K →

$\delta = -\pi/2$ favored
Large range of values of δ around $+\pi/2$ excluded at 99.7%

Best fit $\delta = 0.82\pi$
Exclude IH $\delta = \pi/2$ at > 3σ
Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

NOvA →

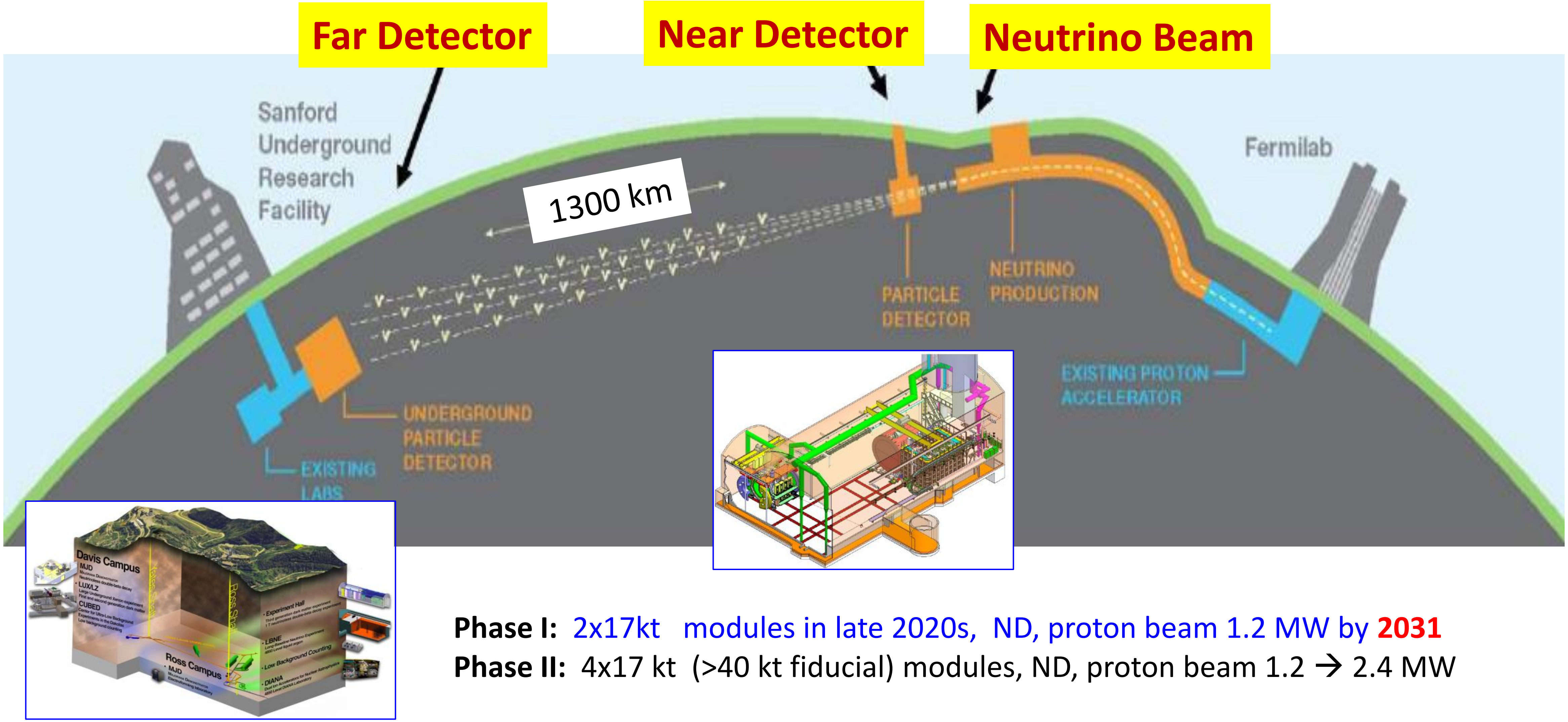
T2K ($\nu+\bar{\nu}$) prefers:
NO
$\delta \sim 3\pi/2$ (~max CPV)
2nd octant

Future projects
DUNE and Hyper-Kamiokande

LBNF/DUNE

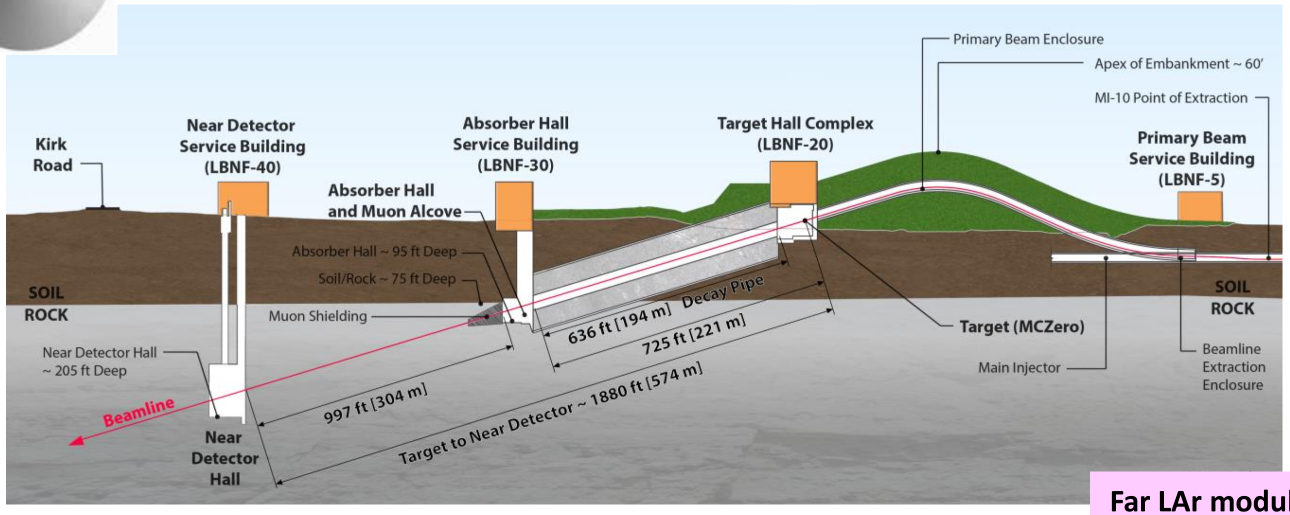
USA, Fermilab

>1400 collaborators from 200 institutions



Phase I: 2x17kt modules in late 2020s, ND, proton beam 1.2 MW by **2031**
Phase II: 4x17 kt (>40 kt fiducial) modules, ND, proton beam 1.2 → 2.4 MW

LBNF/DUNE



E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
Eν ~ 1- 6 GeV
L=1300 km from FNAL to SURF, S.Dakota

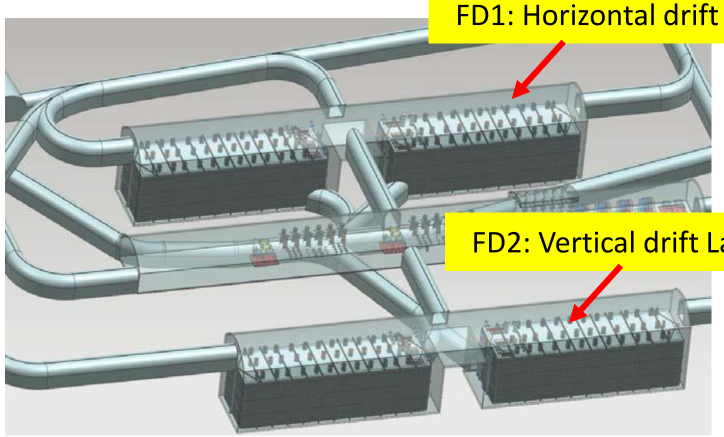
Near Detector Complex:
LAr, GAr, SAND (tracker, Ecal)

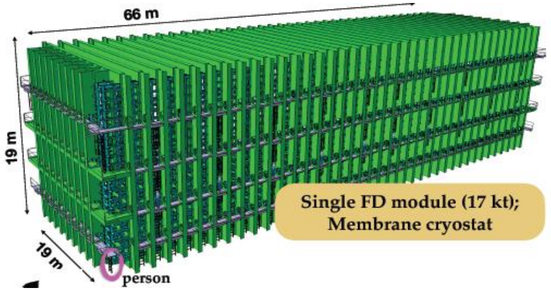
Far LAr module

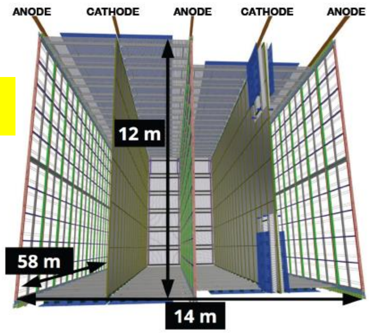
Far detector: 4 modules, total mass ∽70 kt
fiducial 40 kt (4 x 10kt) LAr TPC
1.5 km underground

FD1: Horizontal drift LAr TPC

FD2: Vertical drift Lar TPC

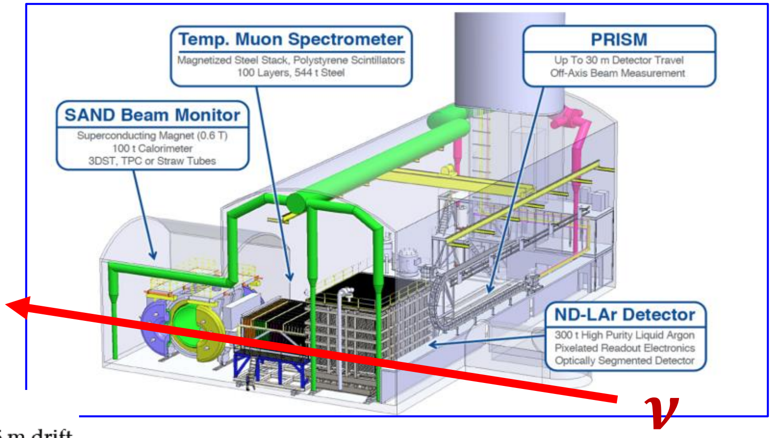






12 m x 14 m x 58 m active volume
Each Anode-Cathode chamber has 3.5 m drift
Cathode at -180 kV

150 Anode Plane Assemblies (APAs) with 384,000 readout wires
Anode planes have wrapped wires (readout on both sides)
6000 photon detection system (PDS) channels for light readout



574 m from target
- Characterization of ν beam
- Constraining of cross-section
- Systematics uncertainties

DUNE: CP sensitivity

DUNE Collaboration, 2006.16043

Staging approach

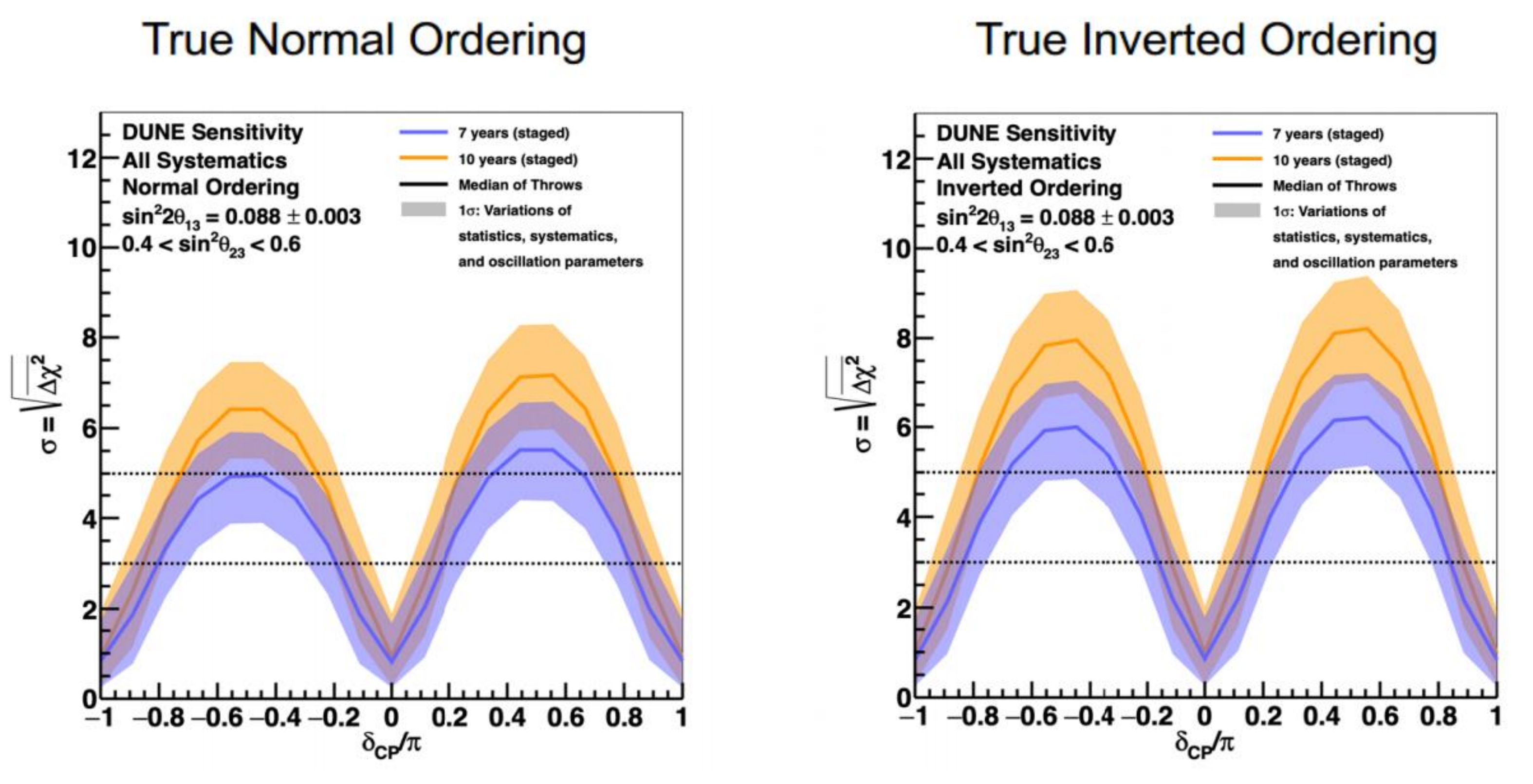
Sensitivity to δ_{CP}

- 7 years data taking
- 10 years data taking

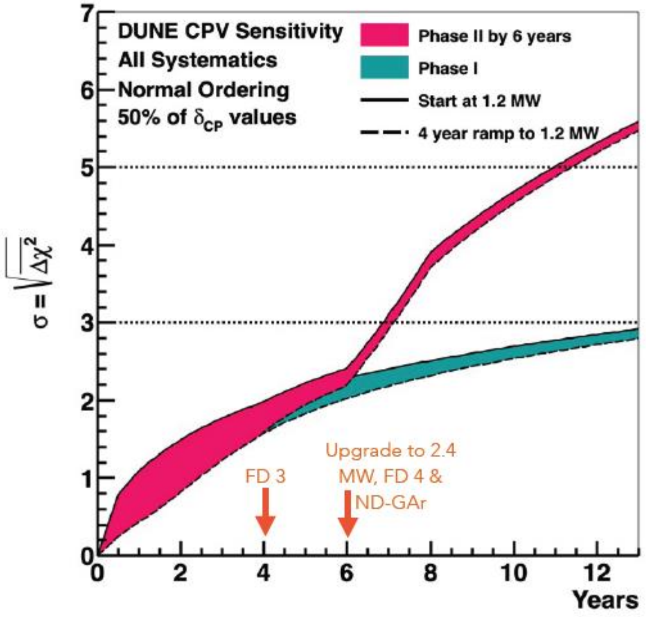
$\nu : \bar{\nu}$ = 50% : 50%

3.5 years, staged exposure

Sample	Expected Events			
	$\delta_{CP} = 0$		$\delta_{CP} = -\frac{\pi}{2}$	
	NH	IH	NH	IH
ν mode				
Oscillated ν_e	1155	526	1395	707
$\bar{\nu}$ mode				
Oscillated ν_e	81	39	95	53
Oscillated $\bar{\nu}_e$	236	492	164	396



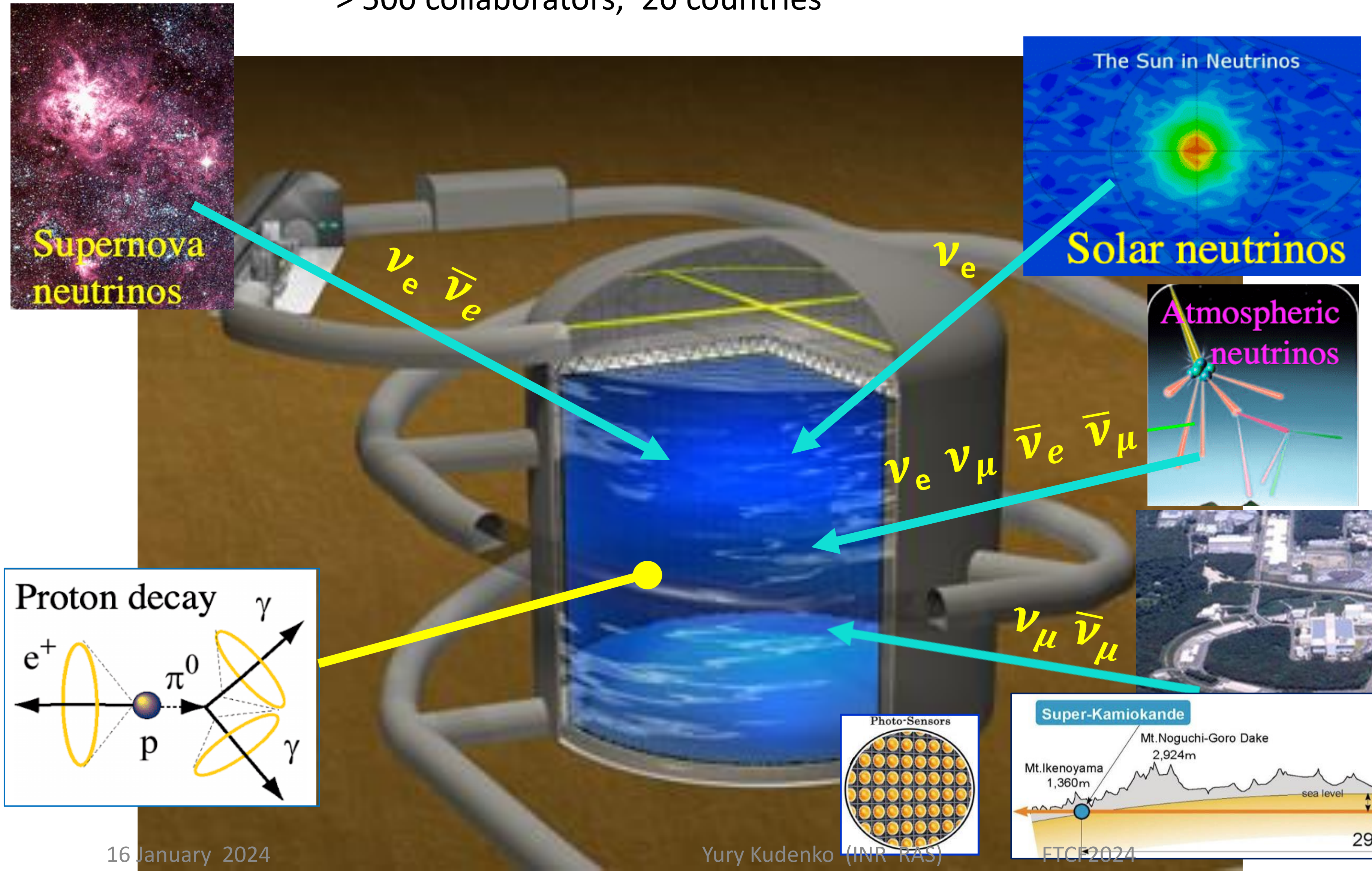
A.Booth, ICHEP2022



Hyper-Kamiokande

Japan. Project approved in 2020, construction begun in 2021, operation should start in 2027

> 500 collaborators, 20 countries



Physics program:
- Search for CP violation
- Neutrino oscillations
- Proton decay
- Neutrino astrophysics

Water Cherenkov detector

71 m (height) x 68 m (diameter)

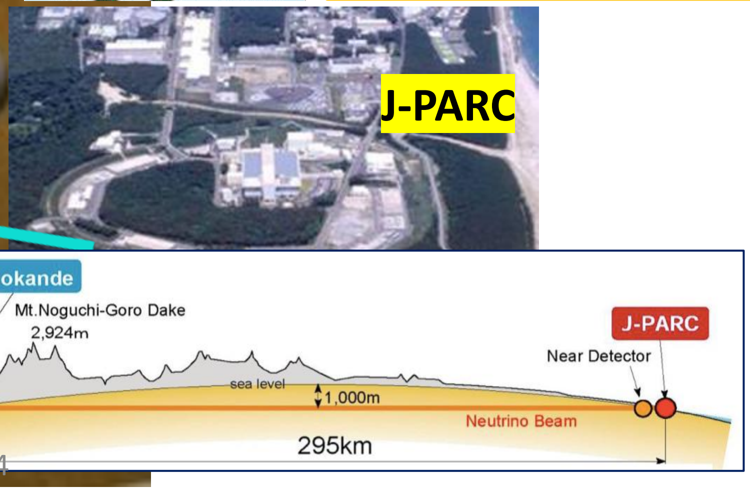
Total mass about 260 kt

Inner Detector:

20000 50 cm PMTs + mPMTs

Outer Detector:

8000 7.5 cm PMTs + WLS plates



Near Detectors

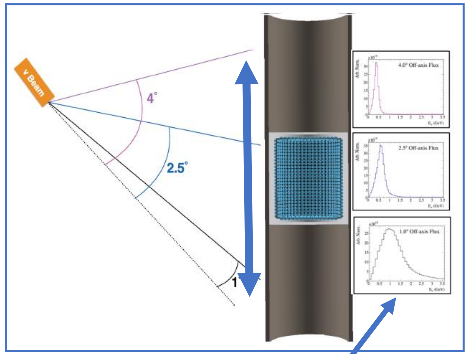
- **measure and control neutrino beam before oscillations**
- **neutrino cross sections**
- **systematics**

J-RARC beam
30 GeV
1.3 MW

New ND **~1 km from target**

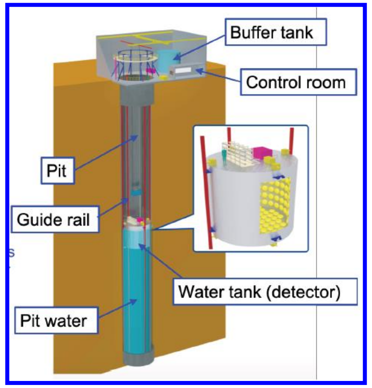
Existing (T2K+upgrade) ND **at 280 m from target**

IWCD: Movable water Cherenkov detector



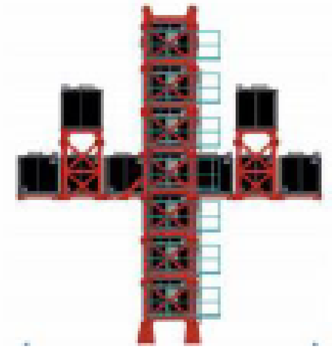
Neutrino spectra

IWCD



IWCD
~1 kt water Cherenkov detector
Photocesors: muli-PMT modules

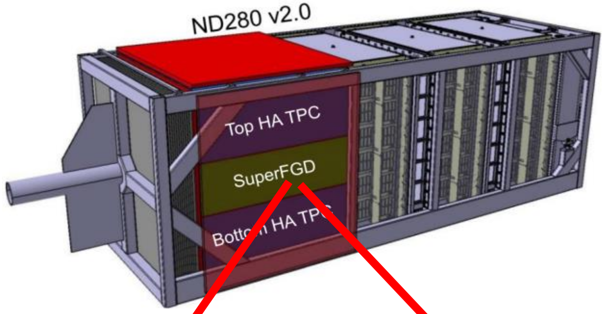
INGRID



Neutrino on/off axis beam monitor

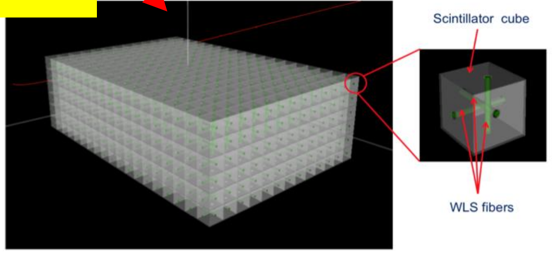
ND280 upgraded

Magnetized off-axis detector



3D detector SuperFGD: 2×10^6 scintillator cubes each of $1 cm^3$ with WLS readout

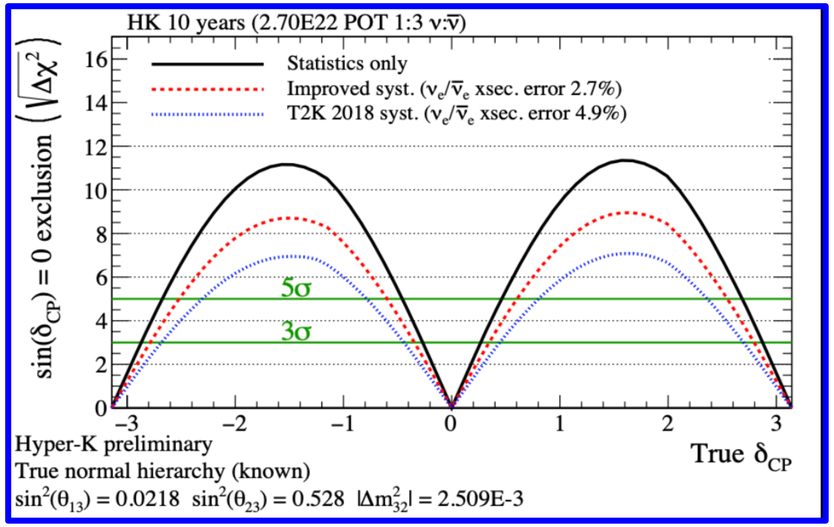
SuperFGD



Sensitivity to CP violation

arXiv:1805.04163

Projected HyperK sensitivity to CP violation

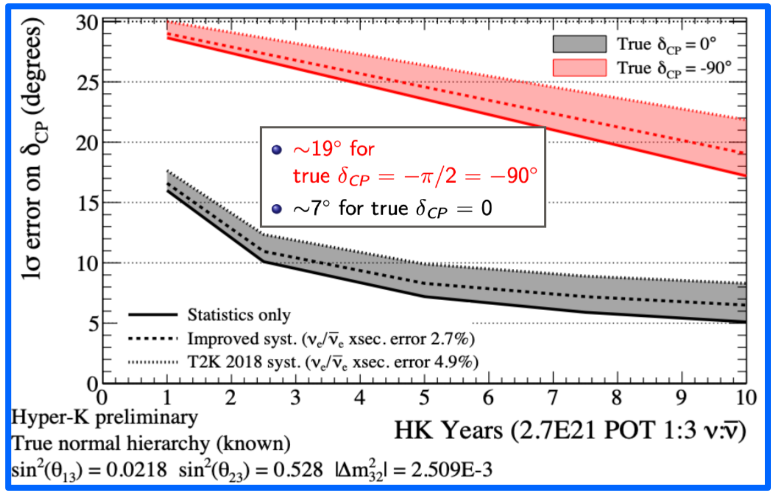


- 10 years of data taking,
- 1.3 MW beam power → 2.7×10^{22} POT

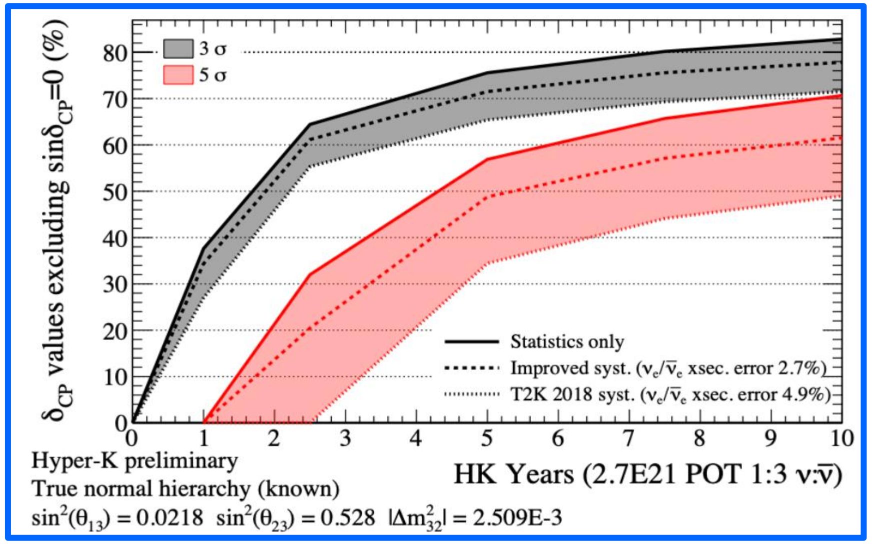
Expected number of events at HyperK for $\nu_e : \bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = 0$

2300 ν_e 1300 $\bar{\nu}_e$

Measurement of δ_{CP}



Exclusion of CP conservation



Conclusion

- **Search for CP violation in lepton (neutrino) sector of SM is one of main goals of neutrino physics**

- **CP asymmetries in neutrino mixing at low energy and in leptogenesis at high energy are linked in some scenarios**

- **T2K excludes CP conservation at about 2σ and favors near-maximal CP violation**

- **NOvA: no strong CP asymmetry observed**

- **DUNE and Hyper-Kamiokande aimed at the discovery of CP violation and δ_{CP} measurement**

Thank you very much for your attention