



Long baseline accelerator neutrino experiments

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Neutrino: open questions

Discovery of neutrino oscillations → non-zero neutrino mass → new physics beyond SM

- Absolute scale of neutrino mass** → β decay, $0\nu 2\beta$ decay, astrophysics and cosmology
- Neutrino nature: Dirac or Majorana** → $0\nu 2\beta$ 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 ($\theta_{23} = 45^\circ?$)** → solar, atmospheric, reactor, **accelerator (LBL experiments)**
- Sterile neutrinos** → β decay, $0\nu 2\beta$ decay, astrophysics and cosmology, atmospheric and reactor neutrinos, **accelerator neutrinos**
- Neutrino interactions** → atmospheric and reactor neutrinos, **accelerator neutrinos**



Neutrino oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

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

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

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

T2K, NOvA

Daya Bay, RENO
Double Chooz

Solar experiments, SuperK
KamLAND

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

$$|\Delta m_{32}^2| \cong |\Delta m_{31}^2| =$$

$$|\Delta m_{atm}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$$

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

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

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

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

$$\Delta m_{21}^2 = \Delta m_{sol}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

two independent Δm^2



Neutrino: CPV and MO

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

$$J_{CP} = \text{Im}(U_{e1}U_{\mu 2}U_{e2}^*U_{\mu 1}^*) = \text{Im}(U_{e2}U_{\mu 3}U_{e3}^*U_{\mu 2}^*)$$

$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

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

Mixing matrix

neutrinos

quarks

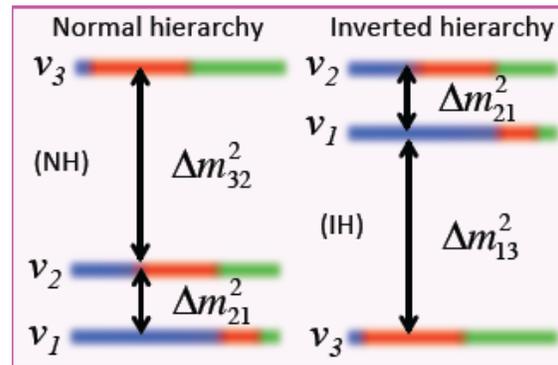
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

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

Quark sector: $J_{CP} \approx 3 \times 10^{-5}$

Lepton sector: $J_{CP} \sim 0.02 \times \sin\delta_{CP}$

- Neutrino mass ordering



IO: $\Sigma m_i \approx 100 \text{ meV}$
NO: $\Sigma m_i \approx 60 \text{ meV}$

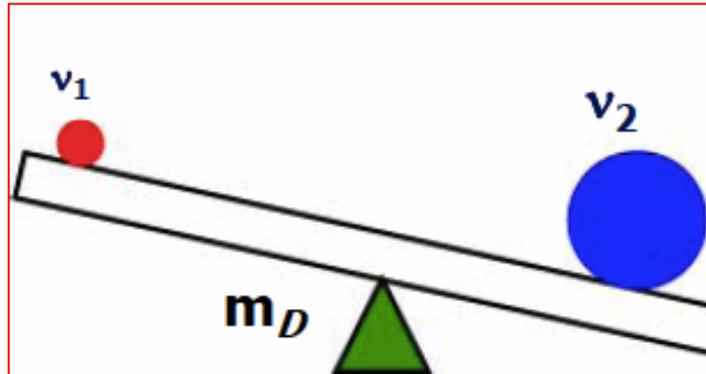


Why is δ_{CP} important?

Baryon Asymmetry of Universe (BAU)

SM cannot explain non-zero neutrino mass

See-saw model



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

$$m_D \sim 100 \text{ GeV}$$
$$v_2 \rightarrow M_R \sim 10^{14} \text{ GeV}$$

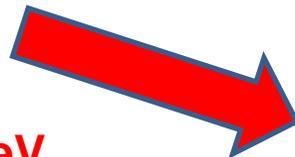
$$\eta = \frac{n_B - n_{\bar{B}}}{\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$
$$\frac{n_{\bar{B}}}{n_B} < 10^{-6}$$

**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 BAU value



**See-saw model produces BAU
by leptogenesis mechanism**



Leptogenesis

M. Fukugita and T. Yanagida, 1986

Leptogenesis: is a class of scenarios where the Universe baryon asymmetry ($Y_{\Delta B}$) is produced from a lepton asymmetry ($Y_{\Delta L}$) generated in the decays of the heavy $SU(2)$ singlet *seesaw* Majorana neutrinos.



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

Baryon Asymmetry \leftrightarrow Neutrino Physics ??

Observation of CP violation in neutrino oscillations would be an indication of leptogenesis as the explanation for BAU, ...but **no direct** relation between ϵ_1 and δ_{CP} established



Mass ordering

Mass Ordering

impact on

- Cosmology
- $0\nu 2\beta$ decay
- Direct mass measurement
- Cosmic neutrino background

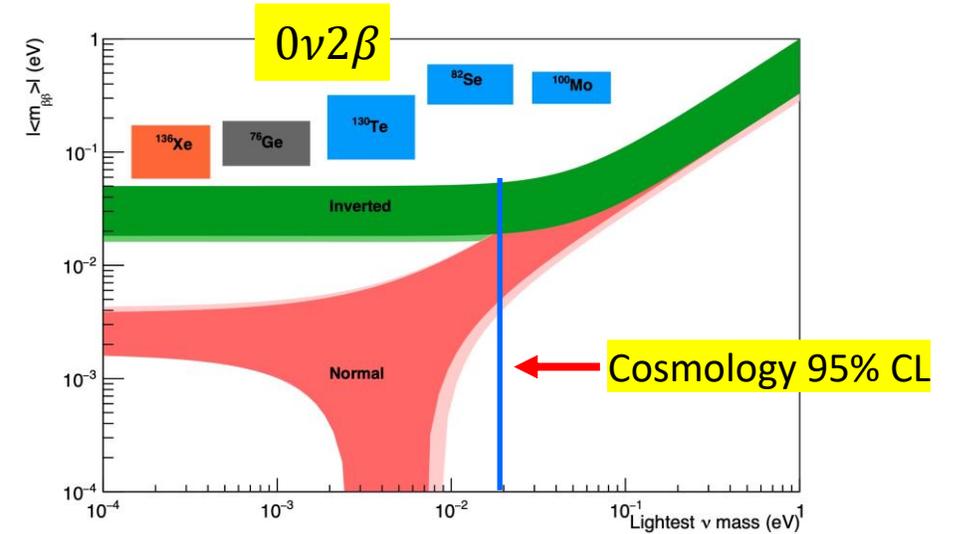
Cosmology (model dependent):

$\sum m_i < 0.12$ eV (CMB + BAO) \rightarrow close to IO: $\sum m_i \sim 100$ meV

$0\nu 2\beta$

Experiment: $m_{\beta\beta} < 36-156$ meV (90%CL)

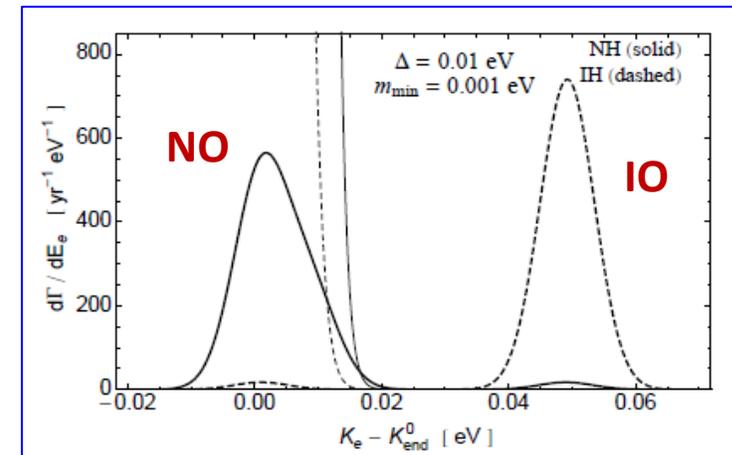
Theory IO: $m_{\beta\beta} \approx 20-50$ meV



CvB



A.J.Long et al. 1405.7654





How to search for CP violation and determine mass ordering?



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

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

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

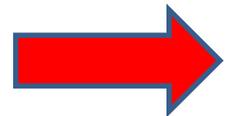
$$s_{ij} = \sin \theta_{ij}$$

$$c_{ij} = \cos \theta_{ij}$$

Matter effect

$$a [eV^2] = 2\sqrt{2} G_F n_e E_\nu = 7.6 \times 10^{-5} \rho \left[\frac{g}{cm^3} \right] E_\nu [GeV]$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



$$a \rightarrow -a \quad \delta \rightarrow -\delta$$

change sign for NH \rightarrow 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}

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

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

Sensitivity to CP phase increases using the value of θ_{13} obtained in reactor experiments



Current experiments T2K and NOvA



About 500 members
59 institutions
from 11 countries

Long-Baseline Neutrino Oscillation Experiment



Super-K

Toyama
Kamioka Mine



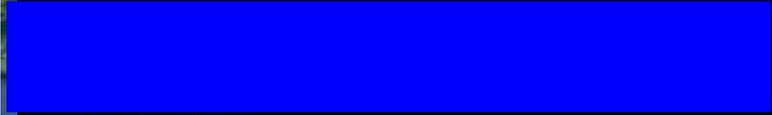
JPARC

Tokai

Tokyo

Tokyo/Narita Airport

JAPAN

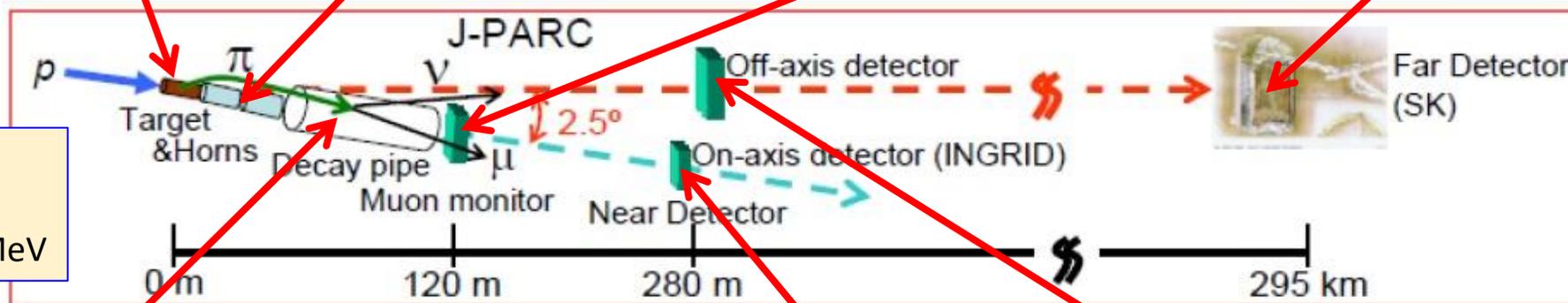
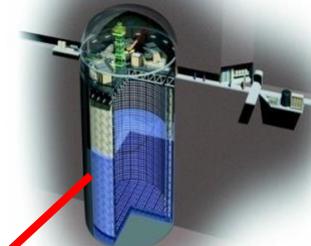




Experiment T2K

T2K collects data since 2010

Far neutrino detector
SuperKamioKande

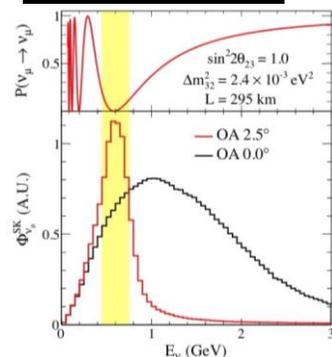


$L = 295 \text{ km}$
 Off-axis ν beam
 Peak energy 600 MeV

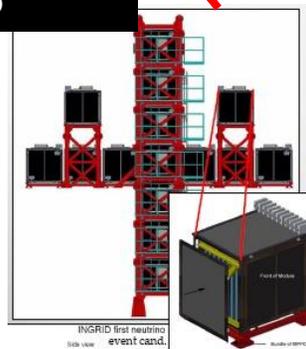
Decay tunnel



Off-axis neutrino beam

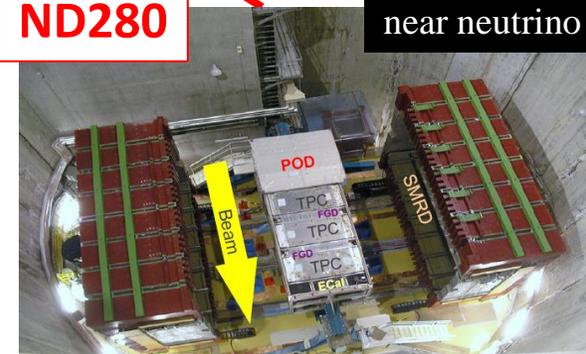


Neutrino monitor
INGRID



ND280

Off-axis near neutrino detector



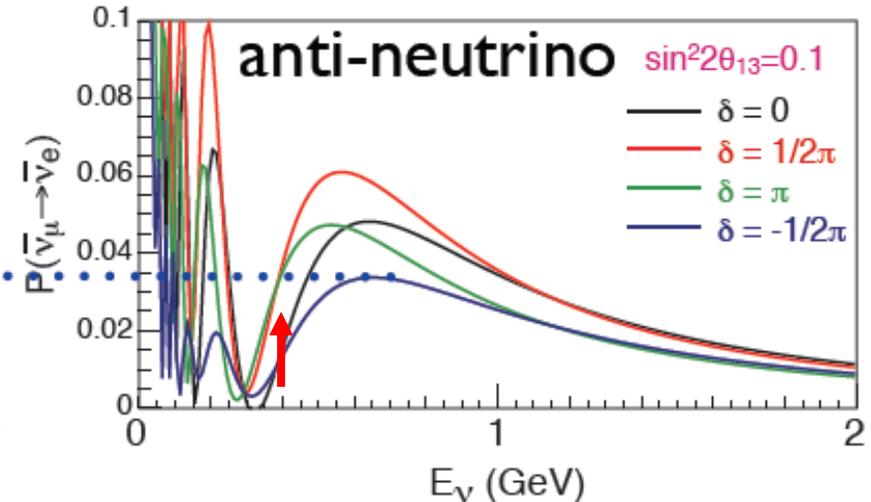
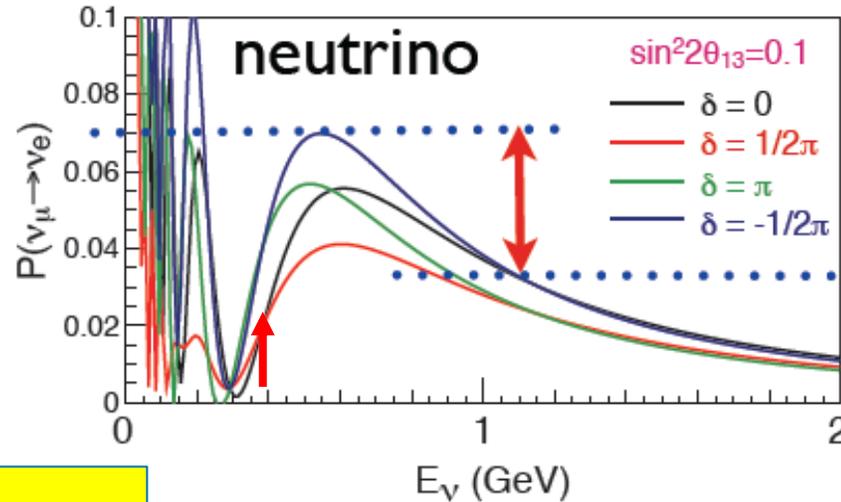


Search for CP violation in T2K

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

Normal hierarchy

T2K baseline = 295 km, $E_\nu(\text{peak}) = 600$ MeV



Experiment T2K:
 $E_\nu \sim 0.6$ GeV,
 baseline = 295 km

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

CP in vacuum

Matter asymmetry

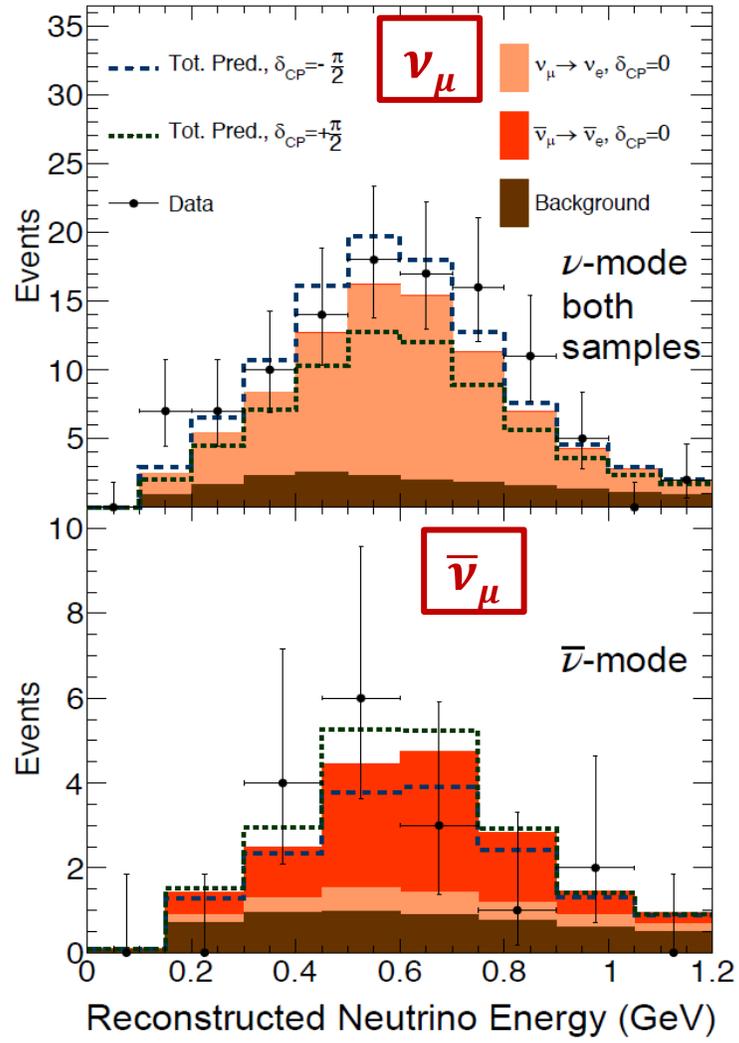
CP asymmetry in vacuum

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



ν_e and $\bar{\nu}_e$ appearance

T2K Run 1-10 Preliminary



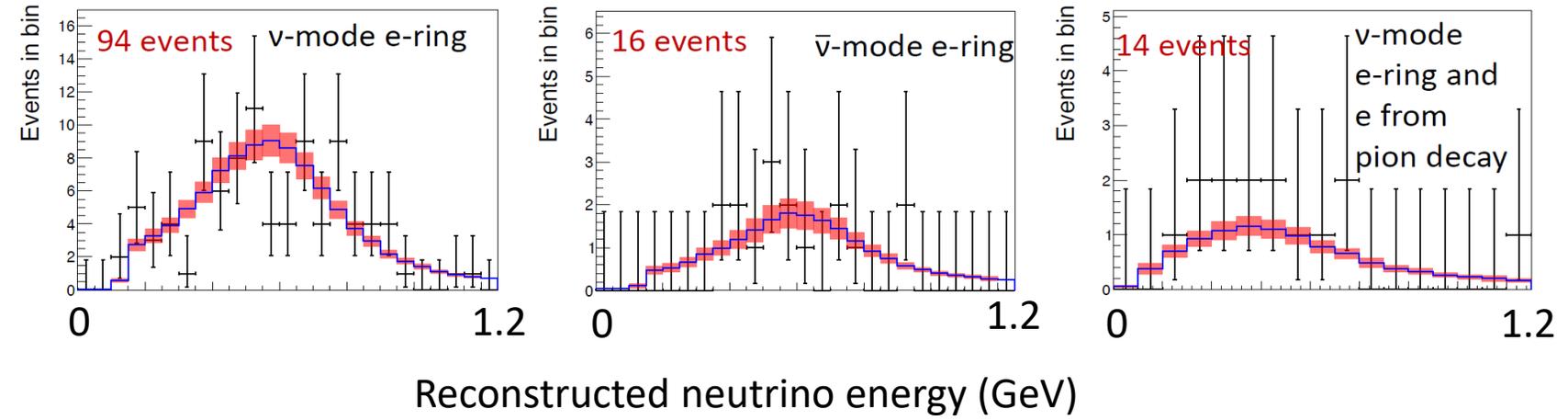
Number of protons on target (POT) →

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

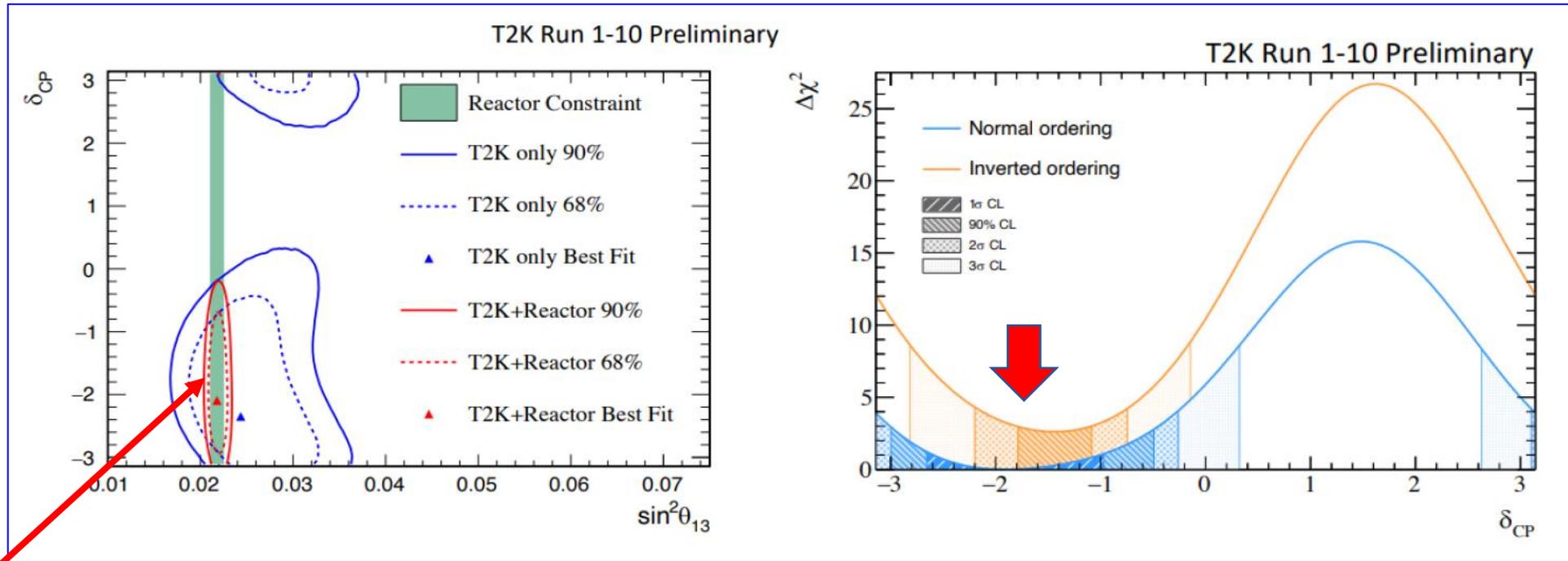
Accumulated number of electron neutrinos and antineutrinos





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 $>90\%$

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

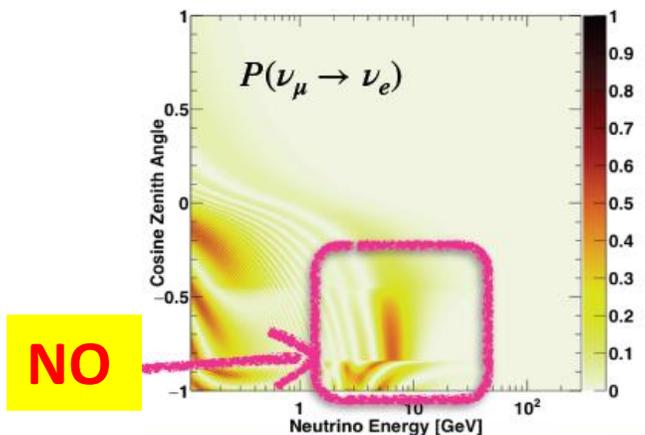
Normal mass ordering is preferred at 80% CL



Mass ordering: SuperKamiokande + T2K

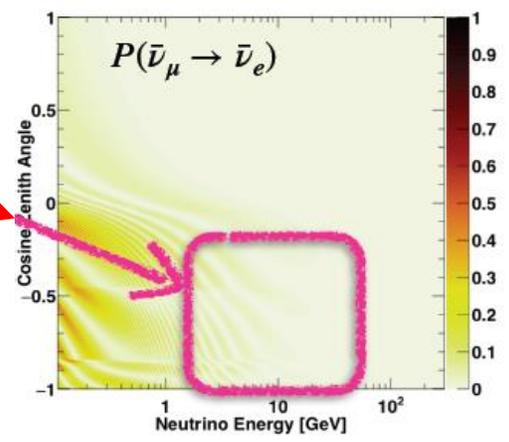
M.Pasiadala-Zezula, ICHEP2022

SuperKamiokande

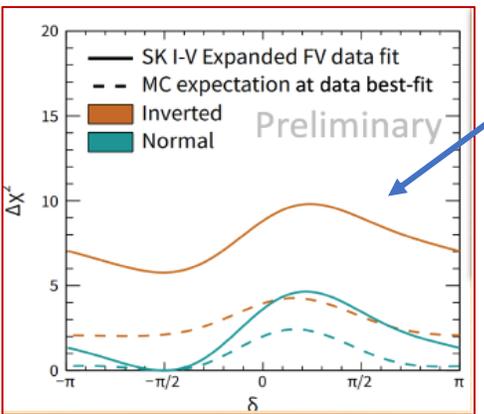


NO

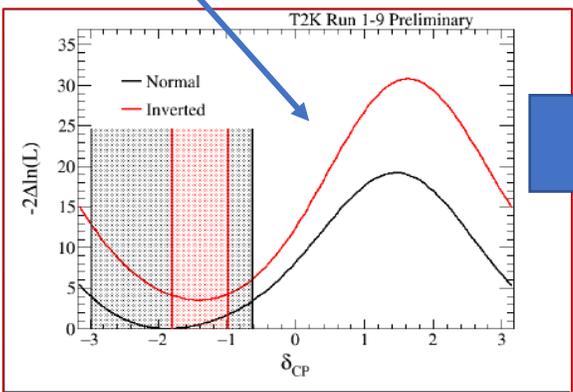
In case of IO:
resonance for
 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



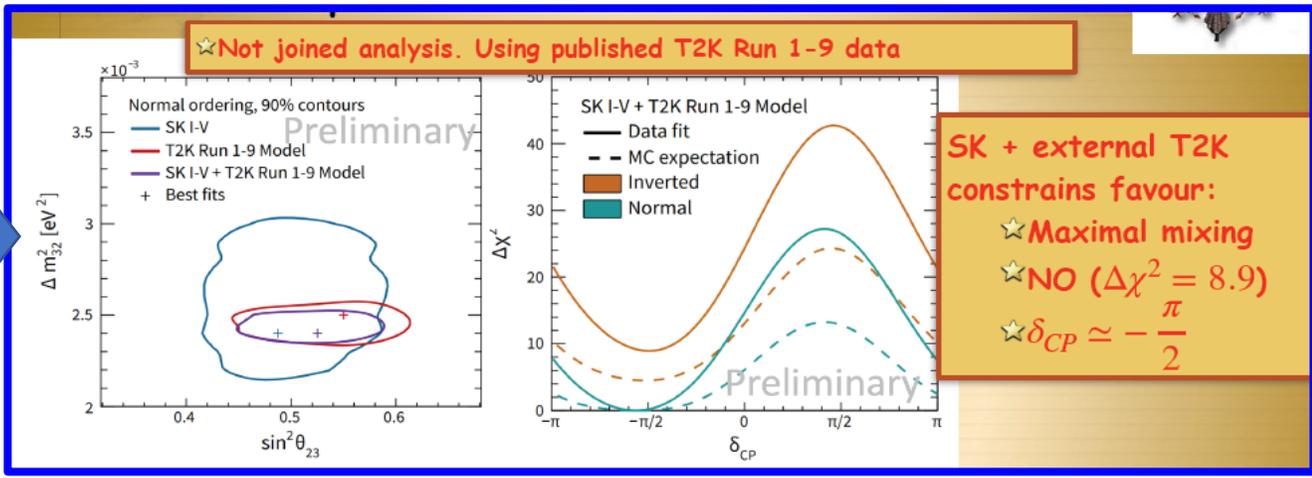
SuperKamiokande:
atmospheric neutrino
sensitive to
mass hierarchy
due to matter effect



SuperK is sensitive to **MO**
T2K is sensitive to **CP**



Joint analysis SuperK+T2K increases sensitivity to MH



SK + external T2K
constrains favour:

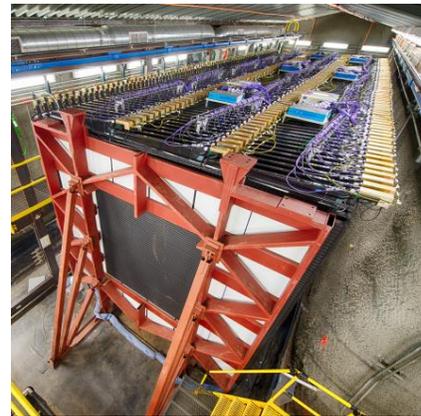
- ★ Maximal mixing
- ★ NO ($\Delta\chi^2 = 8.9$)
- ★ $\delta_{CP} \simeq -\frac{\pi}{2}$



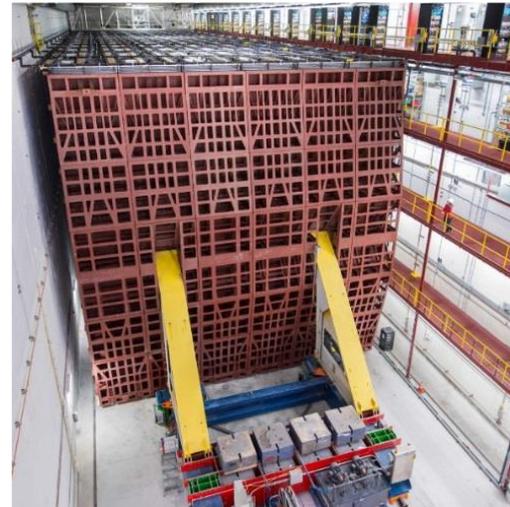
Experiment NOvA



Near Detector



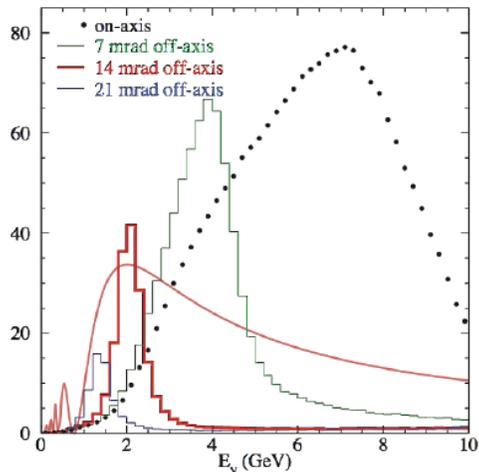
Far Detector



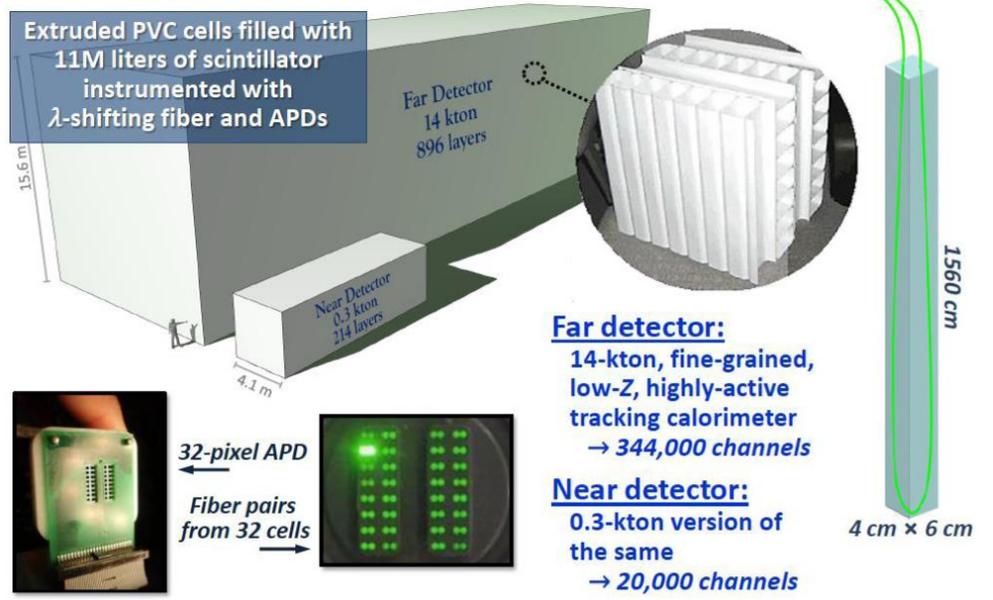
Taking data since Summer 2014
Study of $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations

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

Neutrino beam



NOvA detectors





ν_e and $\bar{\nu}_e$ appearance

nu beam: 1.36×10^{21} POT

anti-nu beam: 1.25×10^{21} POT

A.Mislivec, FPCP2021

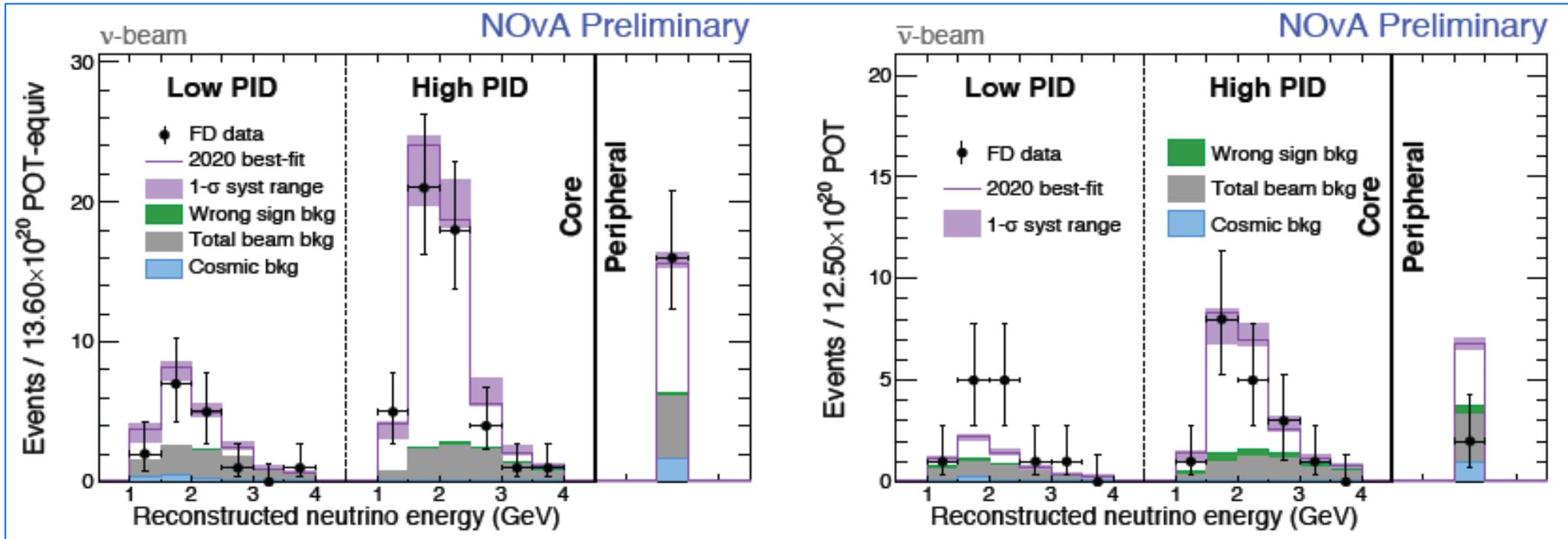
ν_e

Far detector

$\bar{\nu}_e$

Total observed ν_e events	82
Total background	27

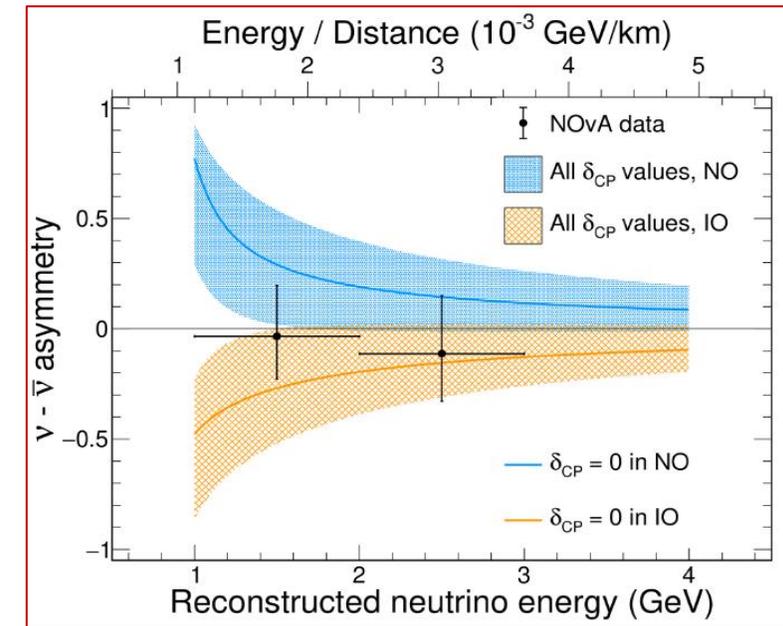
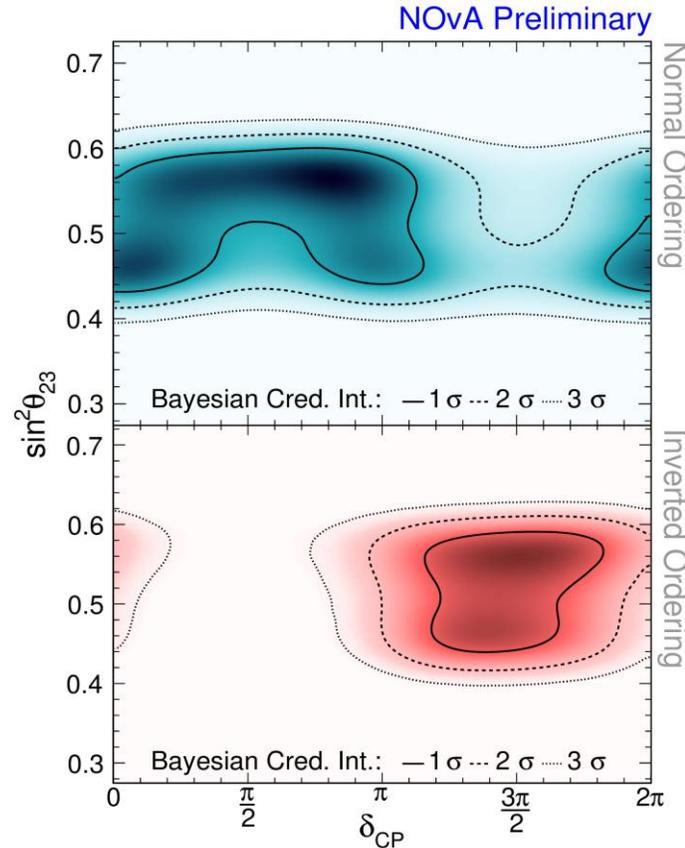
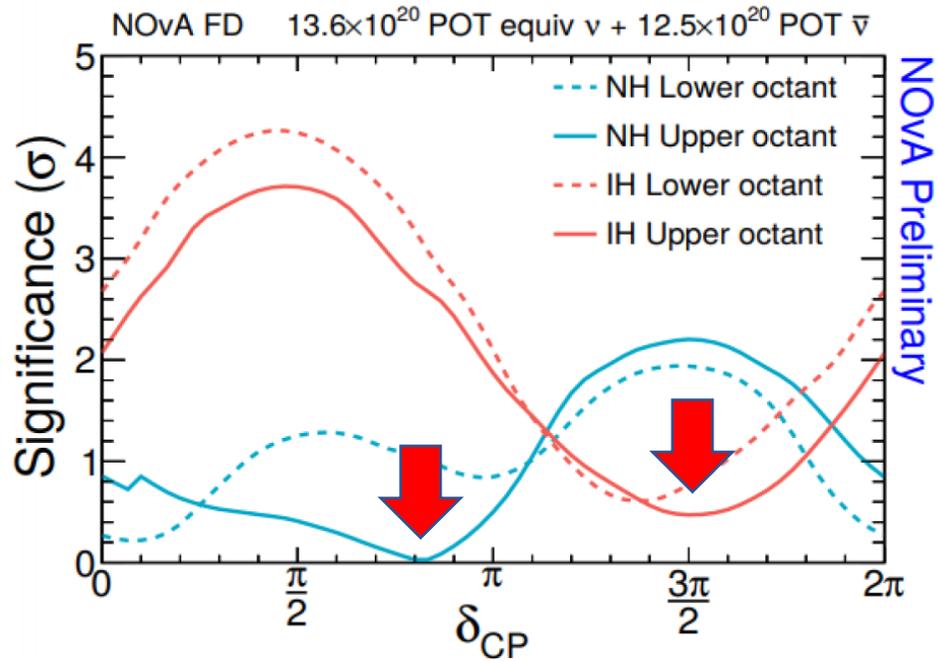
Total observed $\bar{\nu}_e$ events	33
Total background	14.0





NOvA: search for CP violation

R.Sharma, NuFact2022



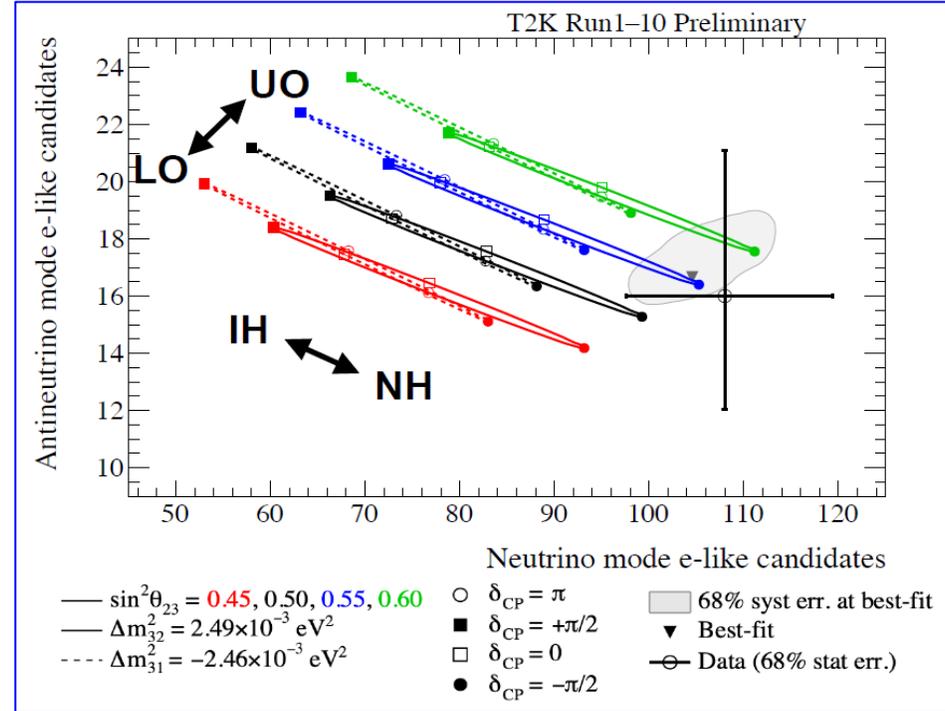
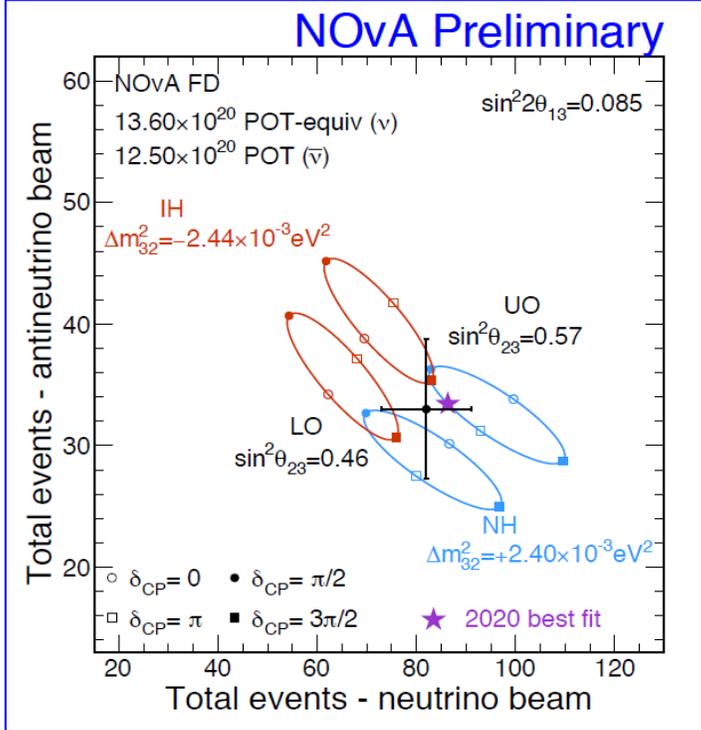
No significant CP asymmetry was observed

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



CP: T2K and NOvA

T2K Preliminary



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

T2K →

NOvA →

$\delta = -\pi/2$ 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 $> 3\sigma$
 Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

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



CP: T2K and NOvA

T2K and NOvA data: *mild tension*

Normal Ordering

- 1σ overlap for some regions

Inverted Ordering

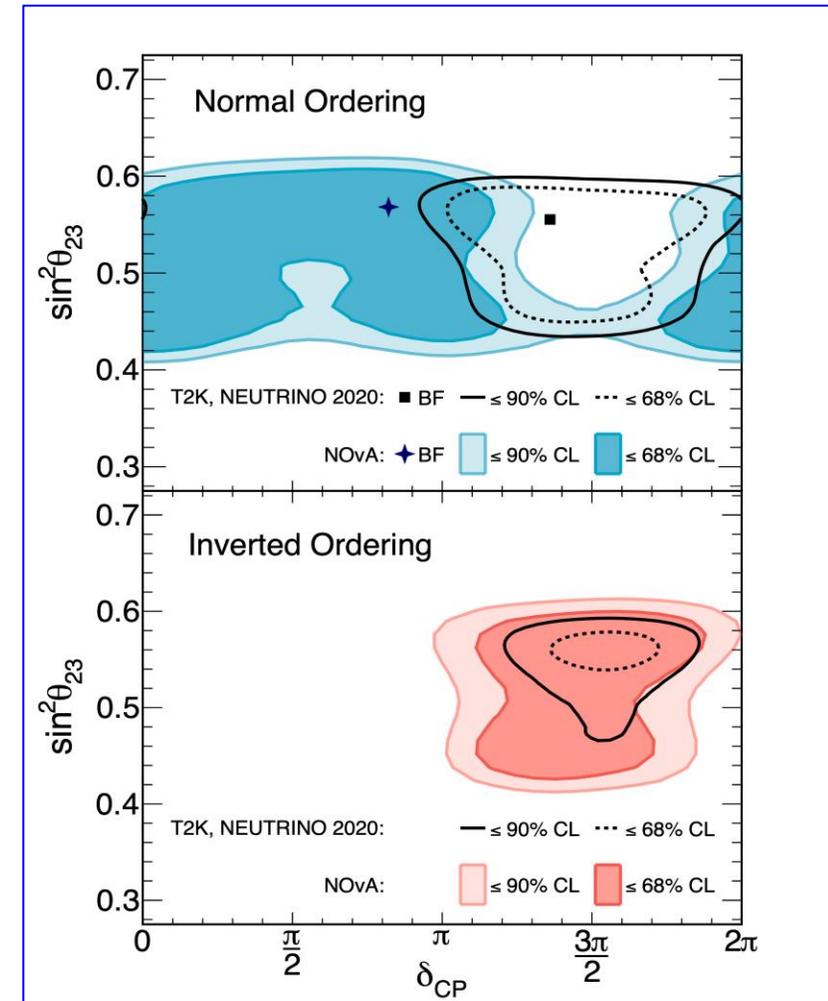
- very similar allowed regions

T2K- NOvA joint analysis in progress:
different baselines, energies,
detector technologies



Increase sensitivity to
 δ_{CP} and mass ordering

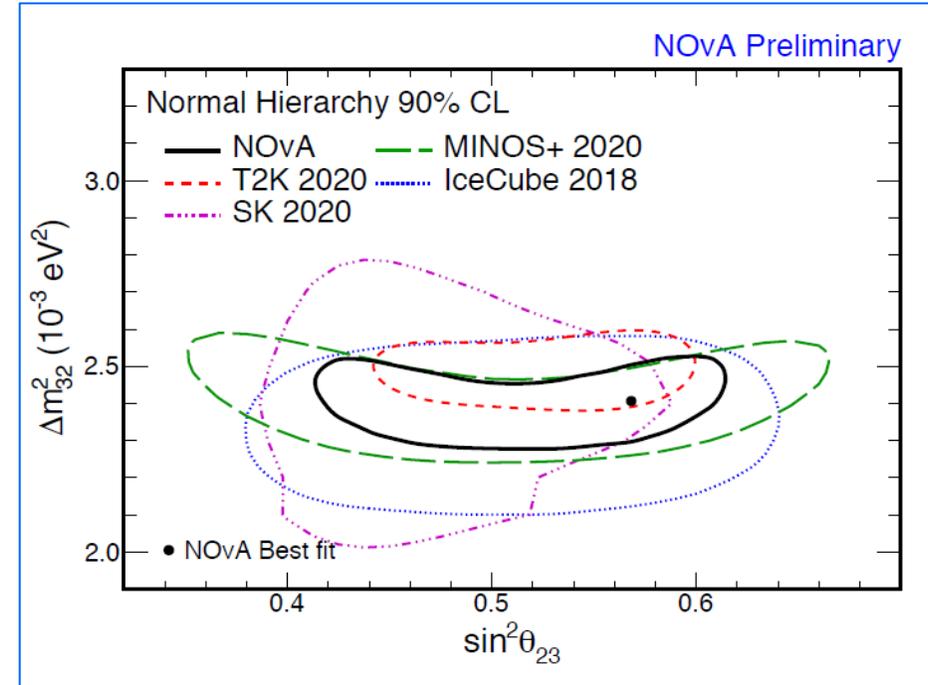
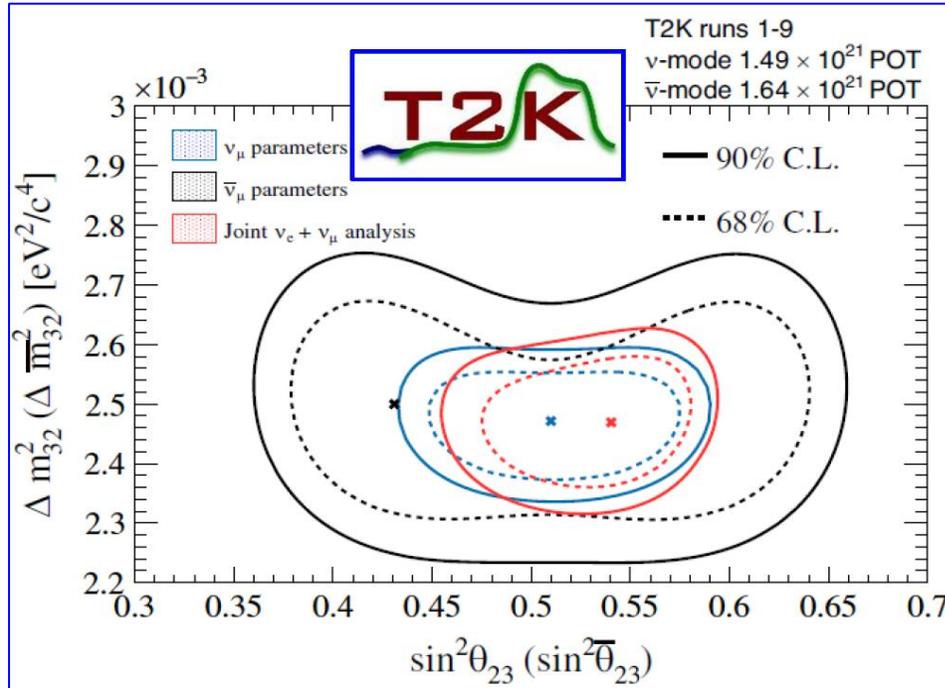
Result is expected in 2022





“Atmospheric” parameters

$\nu_\mu \rightarrow \nu_\mu$ oscillations



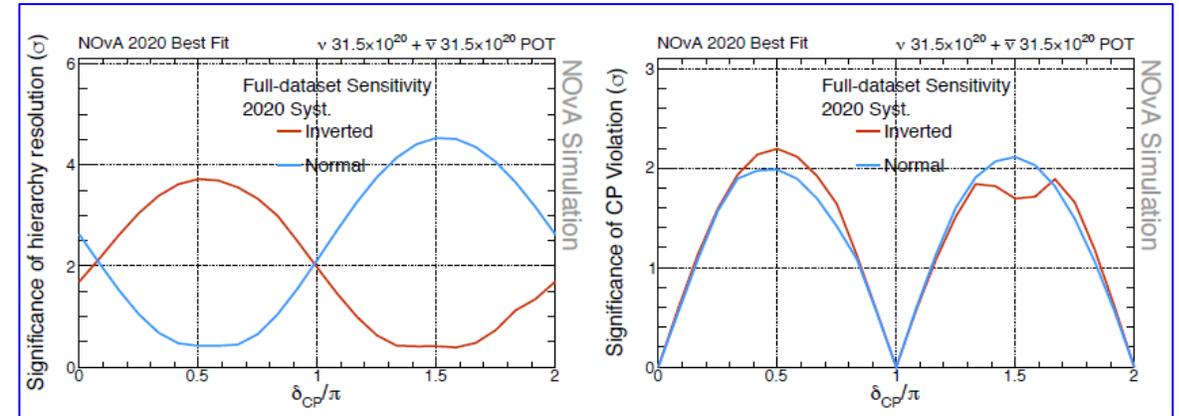
Consistent results of disappearance measurements of $\sin^2\theta_{23}$ and Δm_{32}^2 in several experiments: NOvA, T2K, SuperKamiokande, MINOS, IceCube



Perspectives for CP of T2K and NOvA

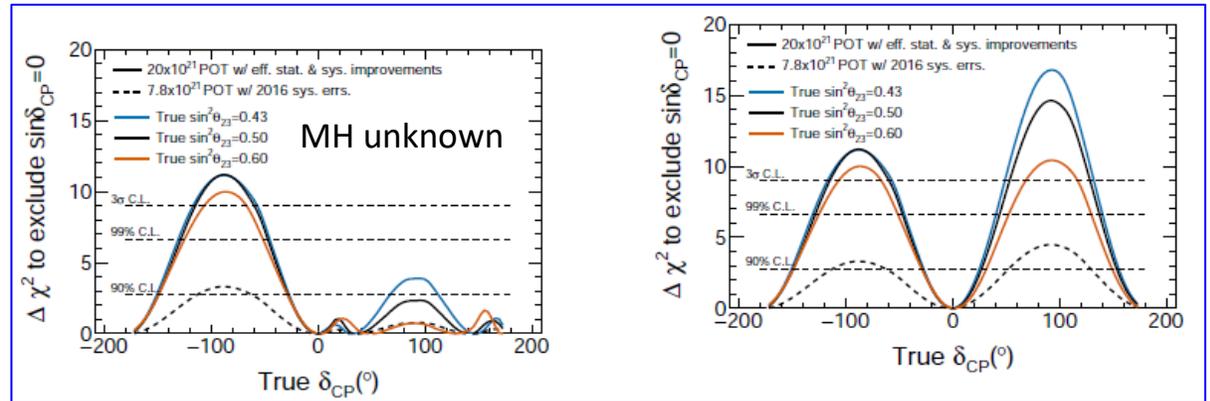
NOvA:

- Increase statistics by ~ 2.5 times of current data
- Can reach 3σ sensitivity to mass hierarchy and $>2\sigma$ to CP violation



T2K:

- JPARC beam upgrade
- ND280 upgrade
- Increase statistics by 2.0-2.5 times of current data
- Can reach 3σ sensitivity to CP, if maximal violation





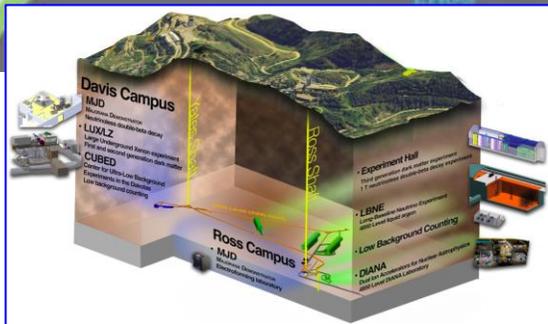
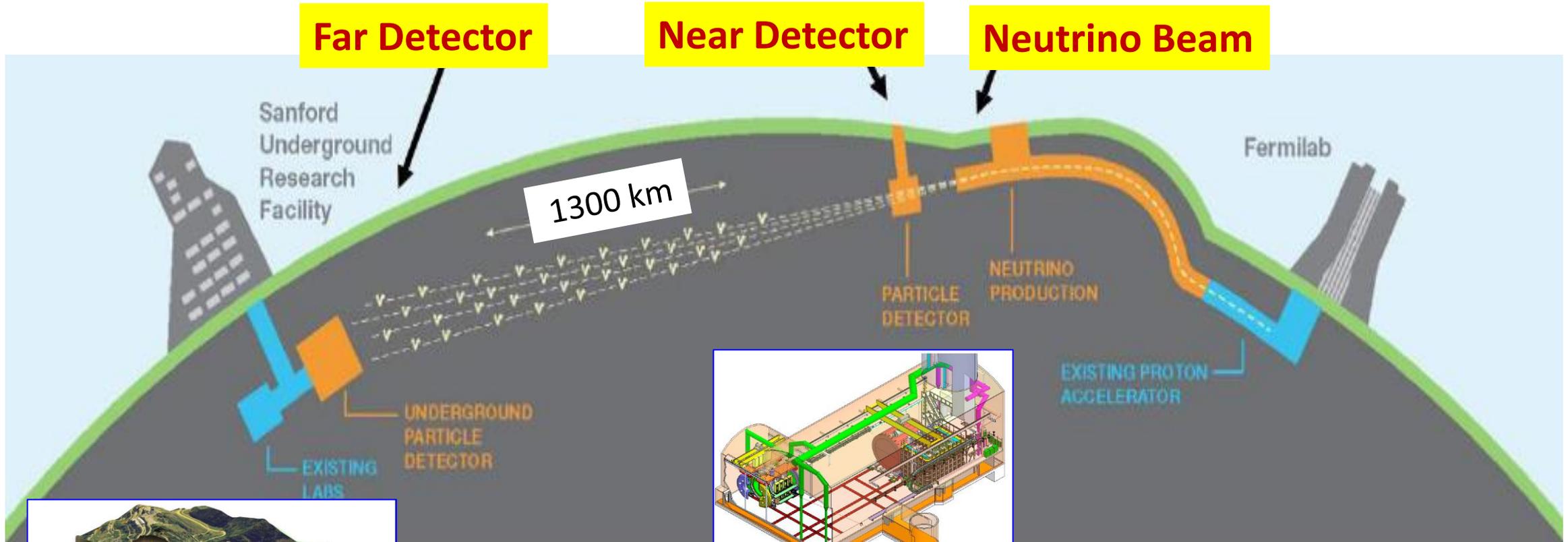
Future projects DUNE and Hyper-Kamiokande



LBNF/DUNE

USA, Fermilab

>1400 collaborators from 200 institutions

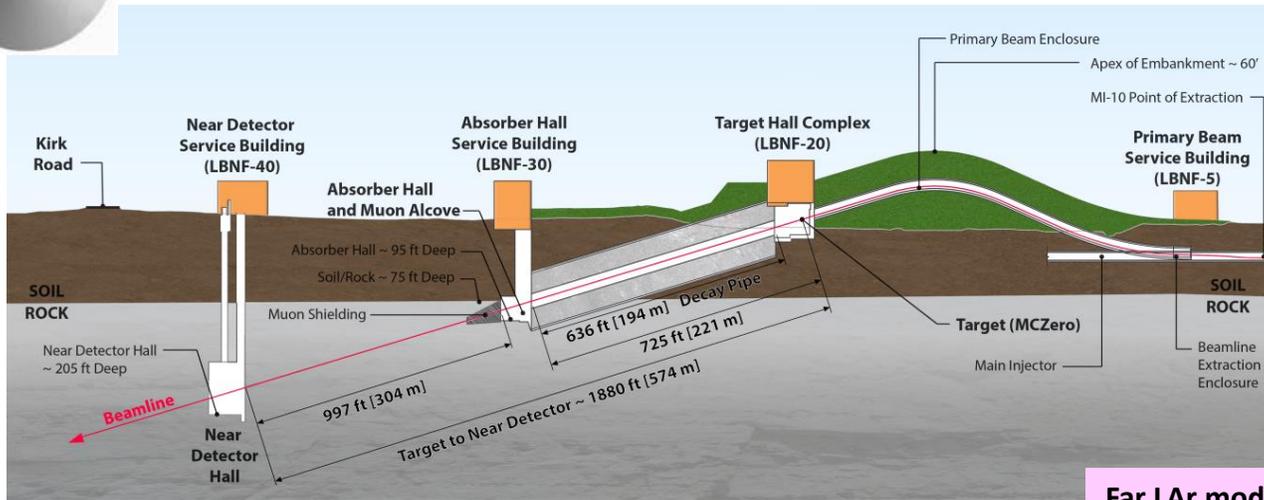


Phase I: 2x17kt modules in late 2020s, ND, proton beam 1.2 MW by 2031

Phase II: 4x17 kt modules, ND, proton beam 1.2 → 2.4 MW



LBNF/DUNE

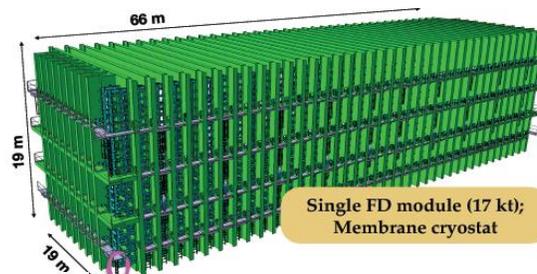


$E_p = 60-120 \text{ GeV}$
 Beam power 1.2 -> 2.4 MW
 On axis neutrino beam
 $E_\nu \sim 1-6 \text{ GeV}$
 L=1300 km from FNAL to SURF, S.Dakota

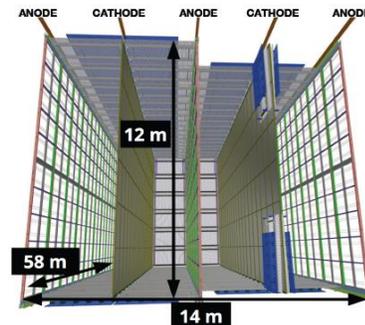
Near Detector Complex:
 LAr, GAR, SAND (tracker, Ecal)

Far detector: 4 modules, total mass $\sim 70 \text{ kt}$
 fiducial 40 kt (4 x 10kt) LAr TPC
 1.5 km underground

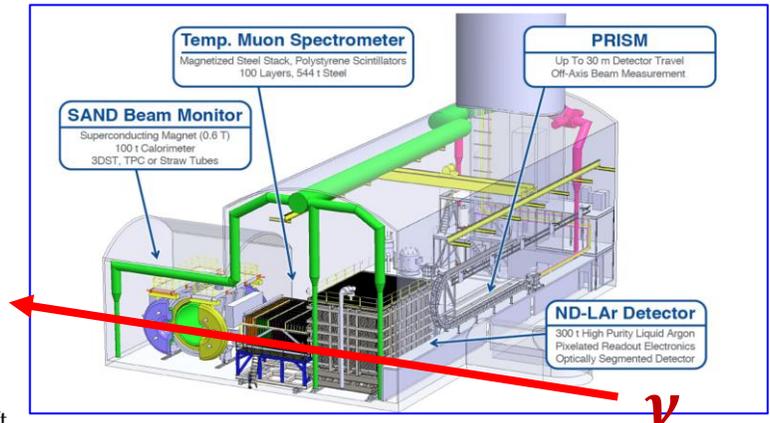
Far LAr module



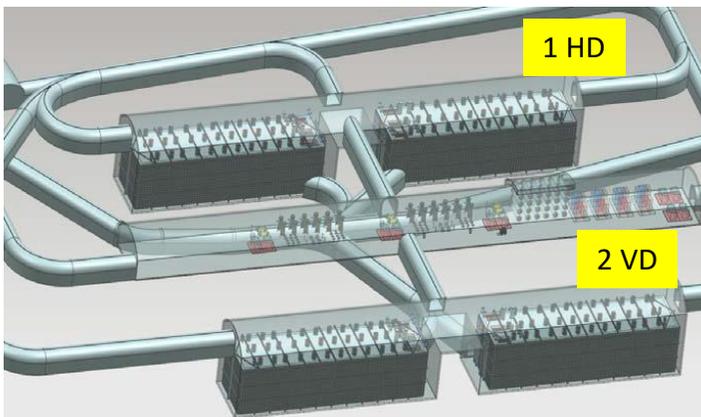
Single FD module (17 kt); Membrane cryostat



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

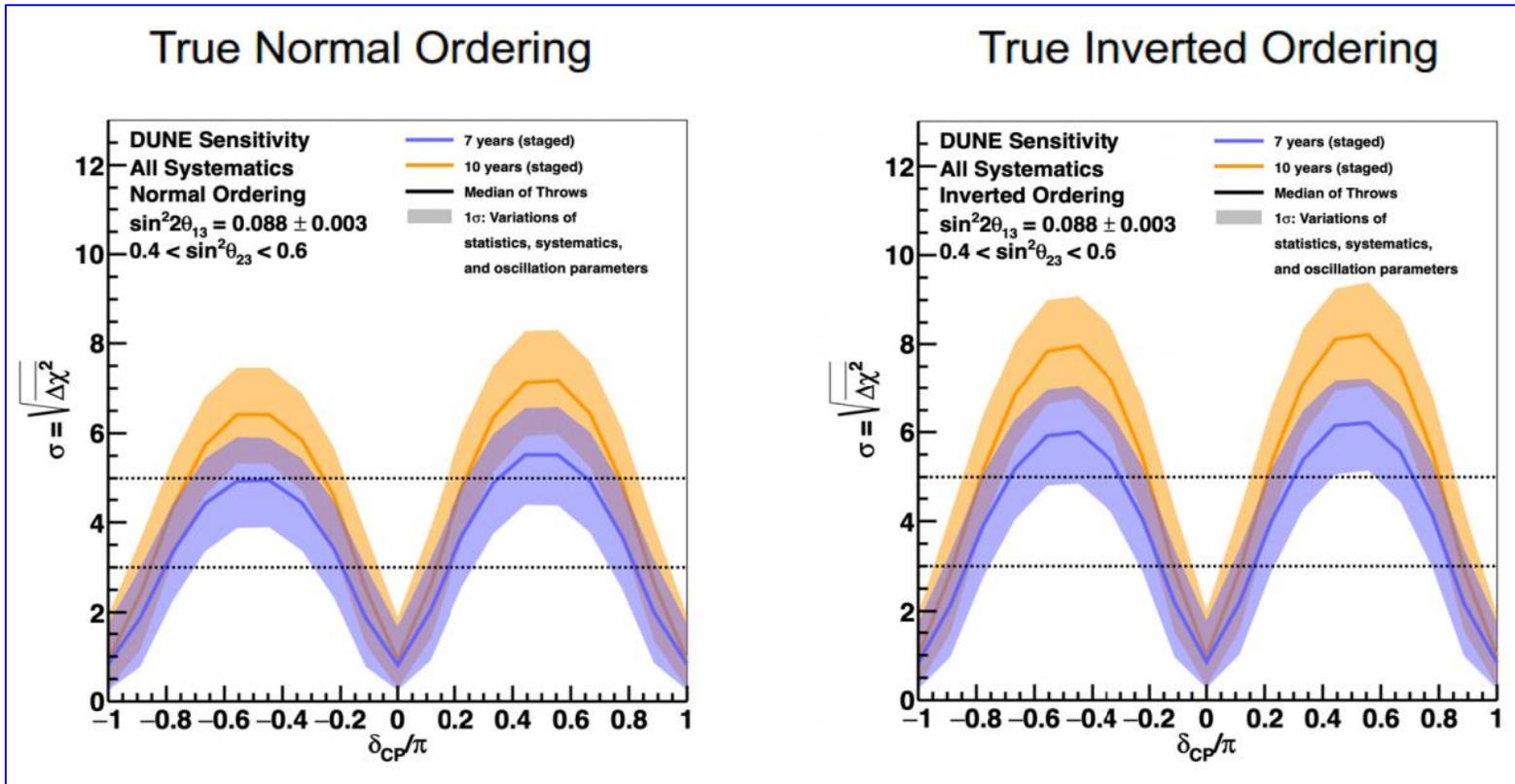
Sensitivity to δ_{CP}

- 7 years data taking
- 10 years data taking

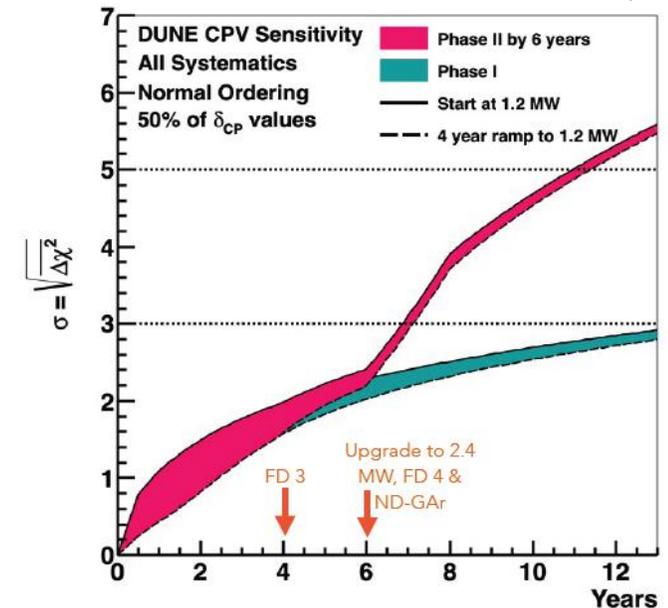
$$\nu : \bar{\nu} = 50\% : 50\%$$

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

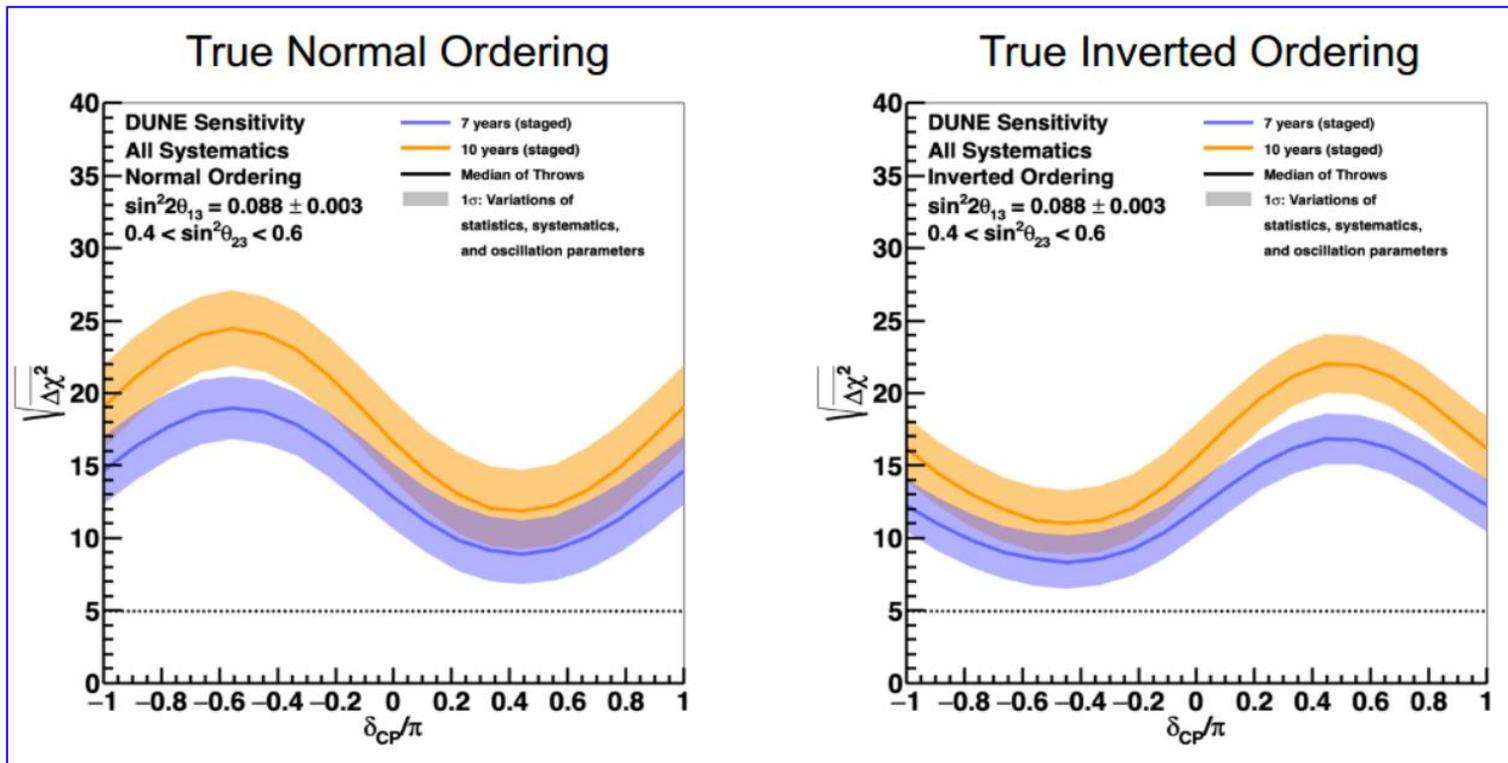




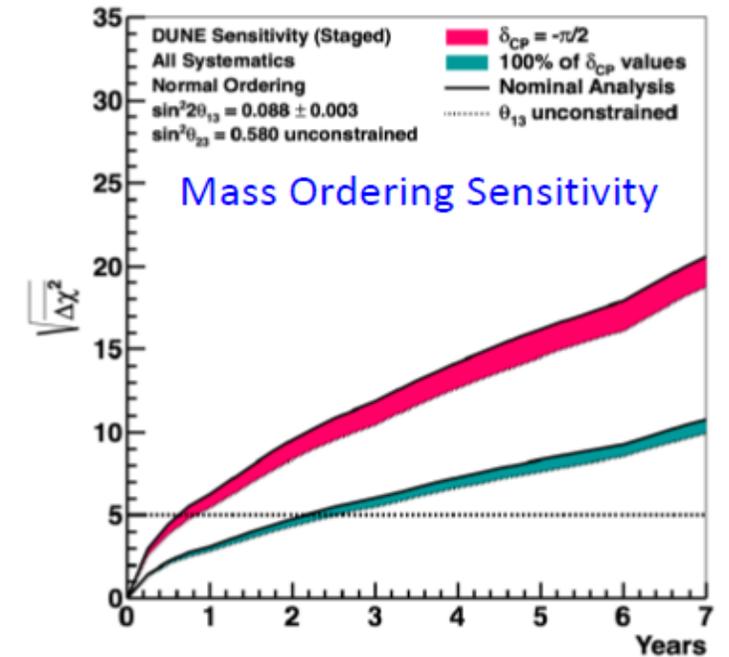
DUNE: Mass Ordering

$$\nu : \bar{\nu} = 1:1$$

DUNE Collaboration, 2006.16043



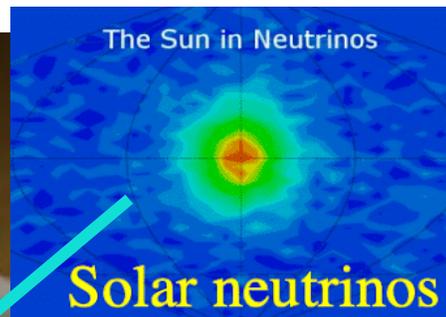
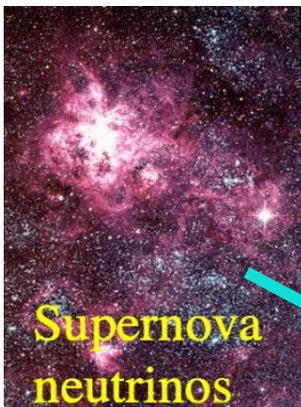
> 5 σ discovery
for all possible δ_{CP} values
after 7 years of data taking





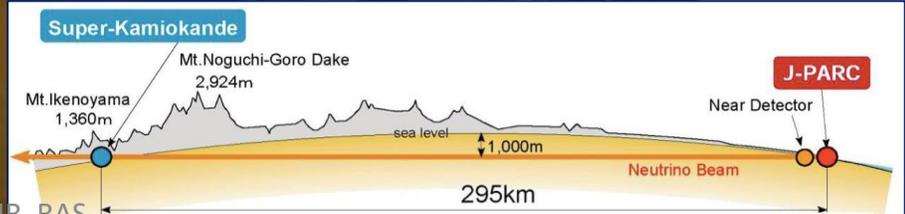
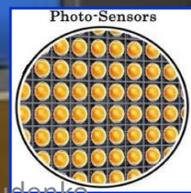
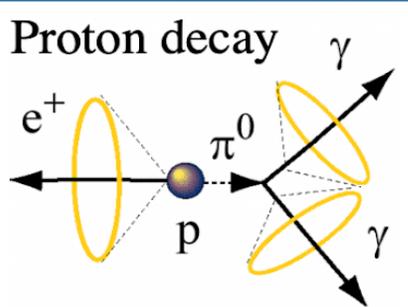
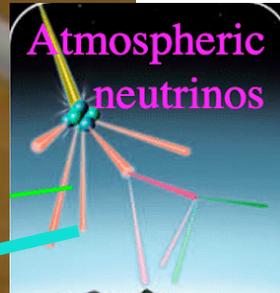
Hyper-Kamiokande

Japan. Project approved in 2020, construction begun in 2021, operation starts in 2027
500 collaborators, 99 institutions, 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



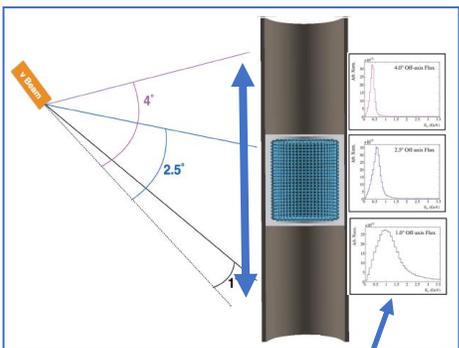


Near Detectors

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

J-RARC beam
30 GeV
1.3 MW

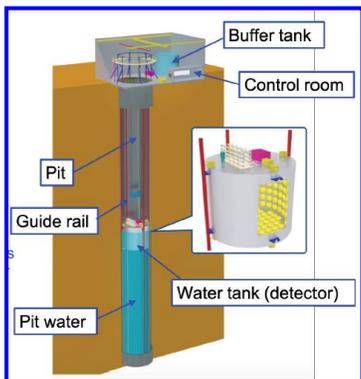
IWCD: Movable water Cherenkov detector



Neutrino spectra

~1 km from target

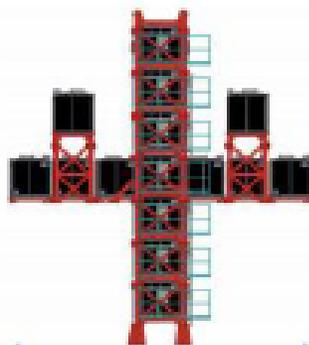
IWCD



IWCD: ~1 kT water Cherenkov detector multi-PMT modules

280 m from target

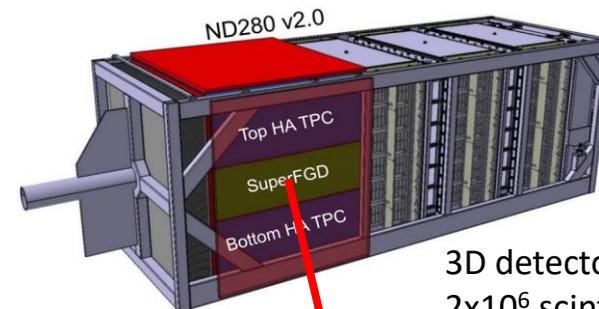
INGRID



Neutrino on/off axis beam monitor

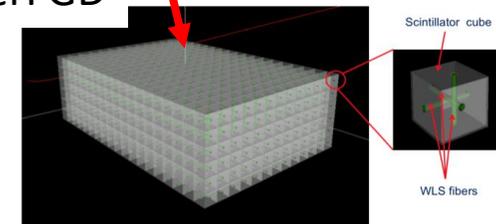
ND280

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

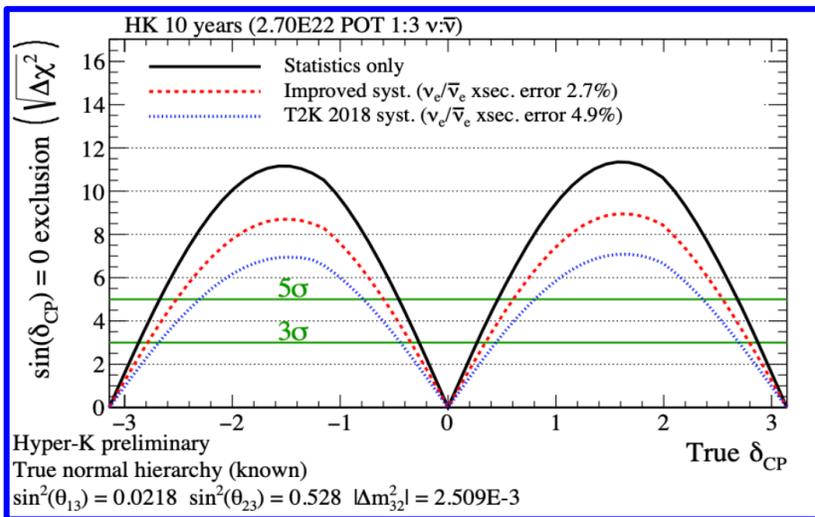
arXiv:1805.04163

Projected HyperK sensitivity to CP violation

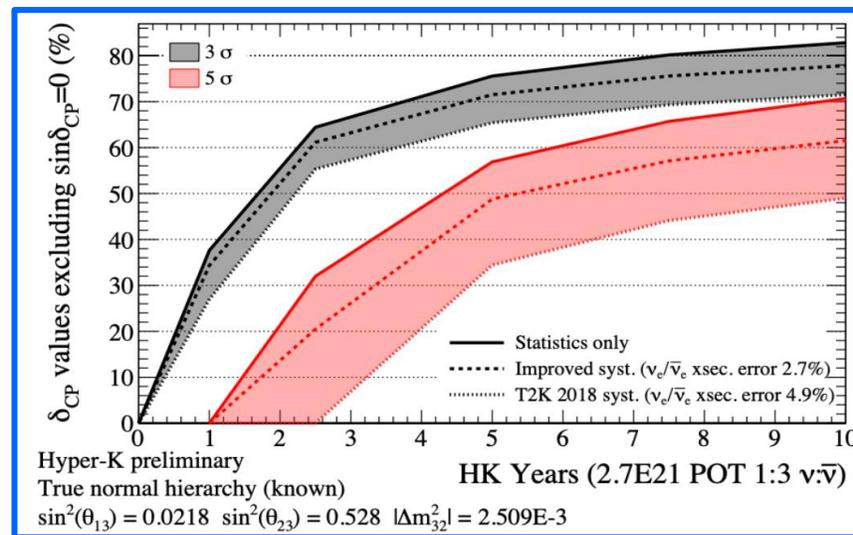
- 10 years of data taking,
- 1.3 MW beam power $\rightarrow 2.7 \times 10^{22}$ POT

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

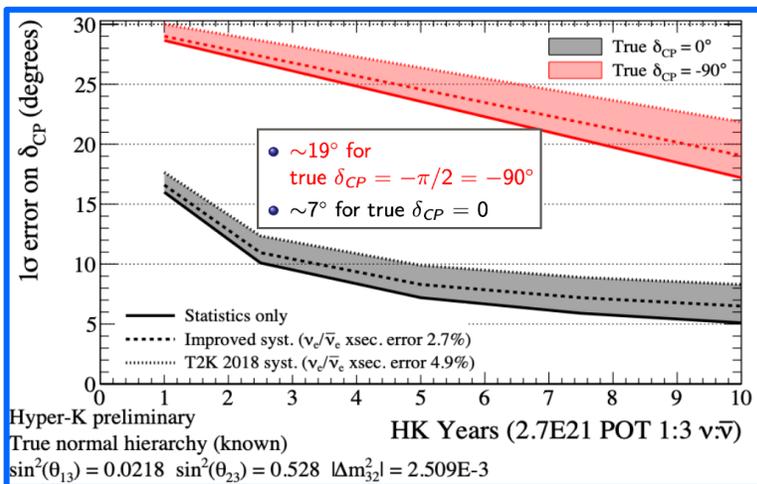
2300 ν_e **1300 $\bar{\nu}_e$**



Exclusion of CP conservation



Measurement of δ_{CP}

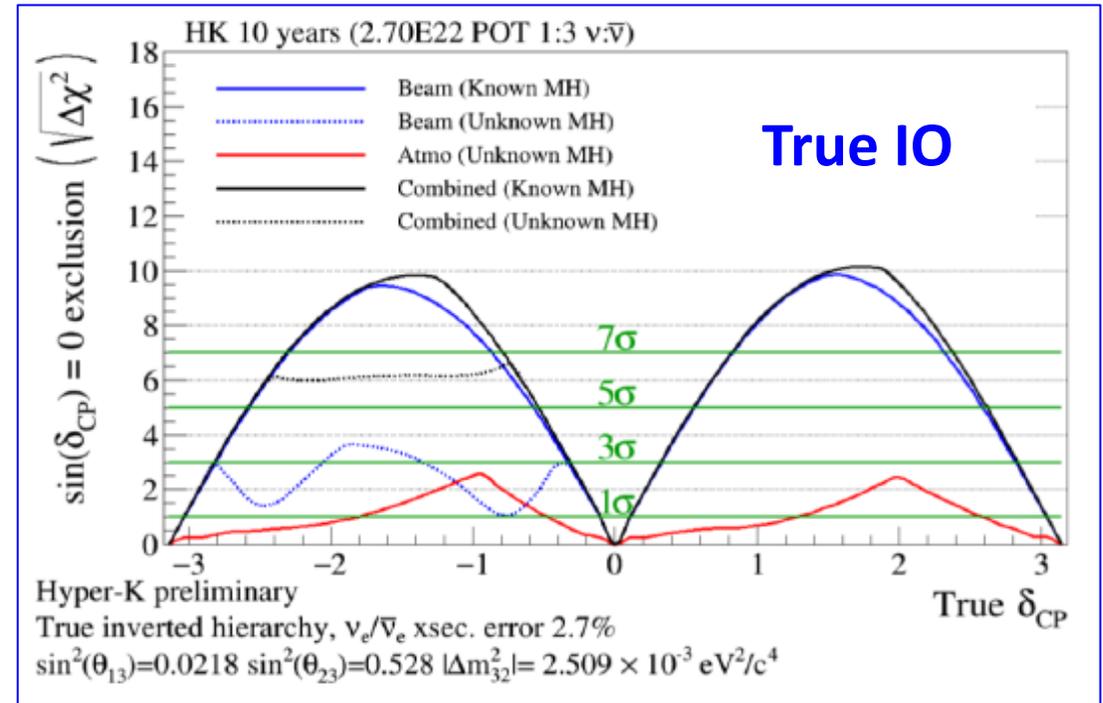
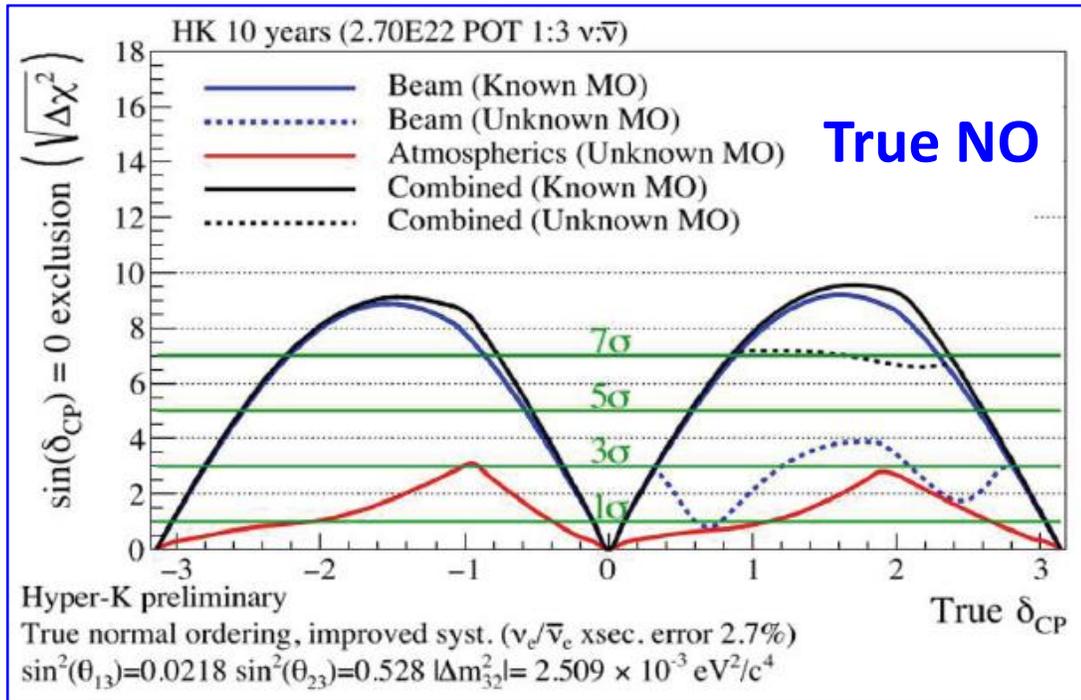




Hyper-Kamiokande: beam + atm ν 's

HyperK \rightarrow very good sensitivity to CP violation using only **beam neutrinos**... if MO known
Beam + atmospheric neutrinos \rightarrow HyperK CP sensitivity recovered regardless of true MO

Mass ordering: — known unknown

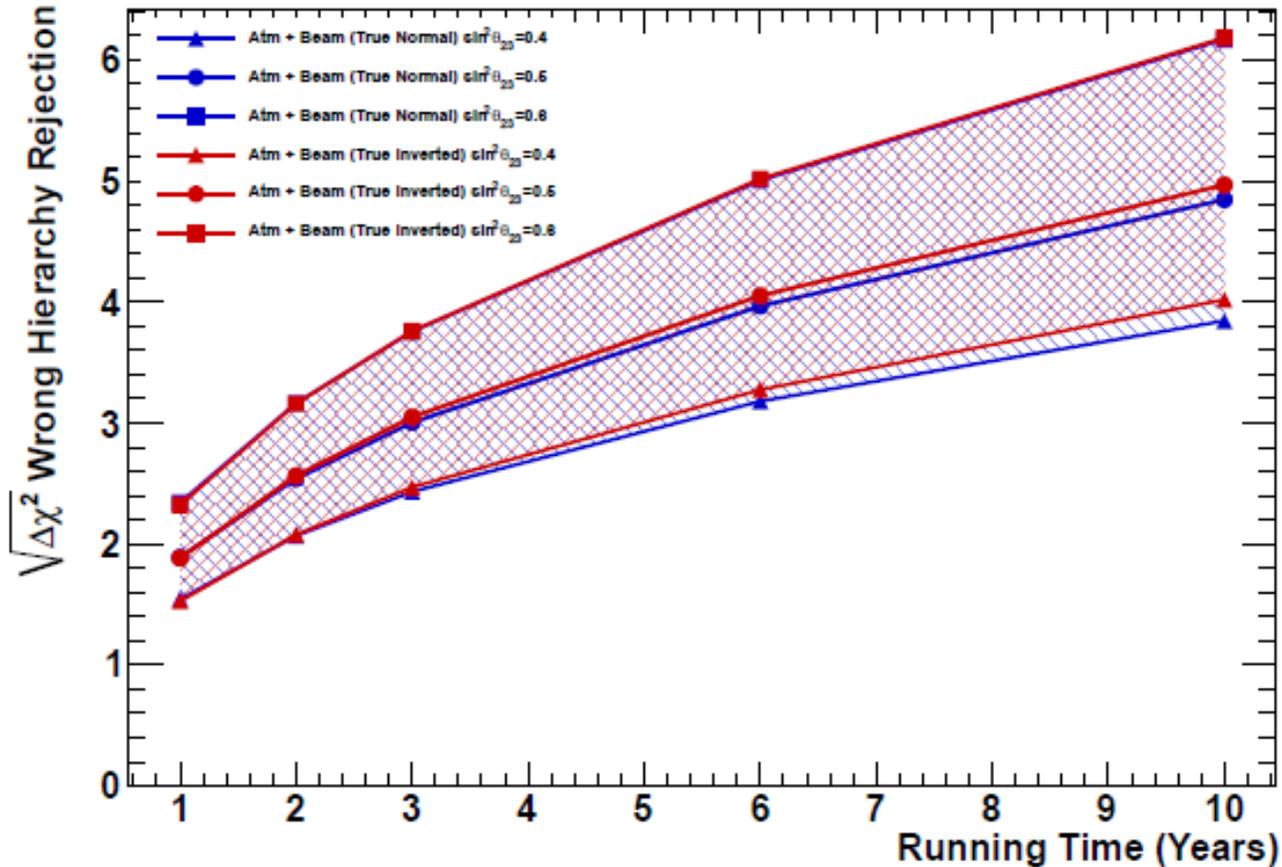




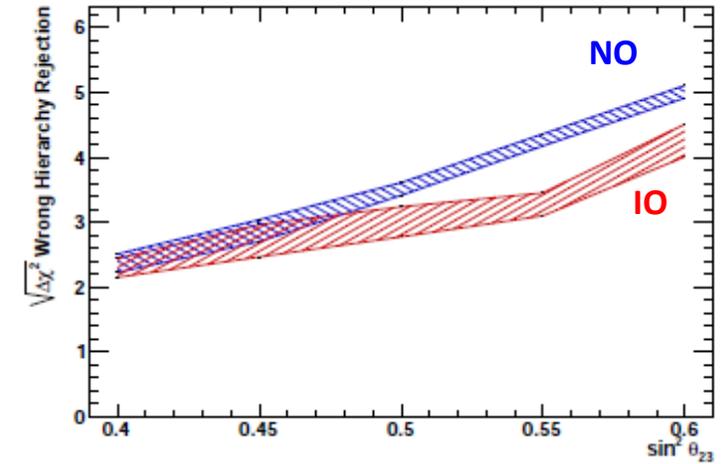
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande Proto-Collaboration,
arXiv:1805.04163



HyperKamiokande, atm neutrinos



	$\sin^2 \theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ



Conclusion

Neutrino is a unique instrument for research on Physics Beyond SM
LBL accelerator experiments play an important role in study of BSM physics

- **T2K** excludes CP conservation at 90% CL and favors near-maximal CP violation
- **NOvA**: no strong CP asymmetry observed
- **Both experiments** prefer the normal mass ordering
- **Joint T2K/NOvA** analysis with different baselines, energies and detectors is expected to improve sensitivity to δ_{CP} and mass ordering
- **DUNE** and **Hyper-Kamiokande** have broad and complementary experimental programs focusing primarily on the discovery of CP violation, δ_{CP} measurement, and determination of the neutrino mass ordering

Thank you very much for your attention

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