



Neutrino oscillations: CP violation and mass ordering

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Standard Model: neutrinos are *massless* particles

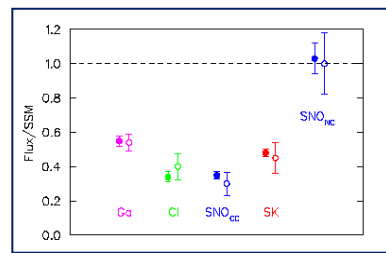
However, the *discovery of neutrino oscillations*



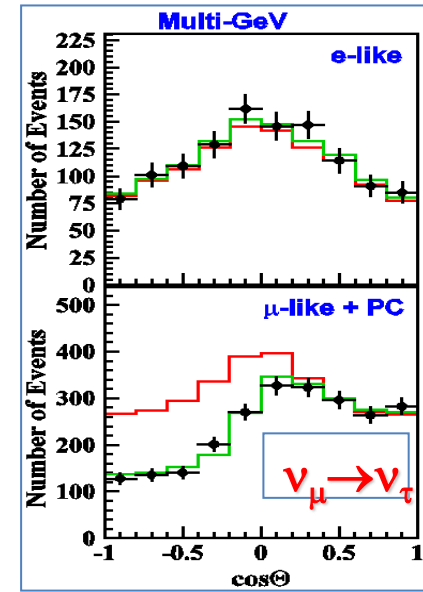
Лео́ну По́нтекову

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

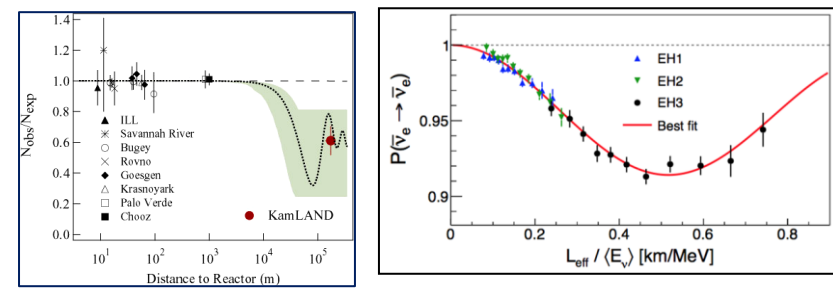
Solar ν



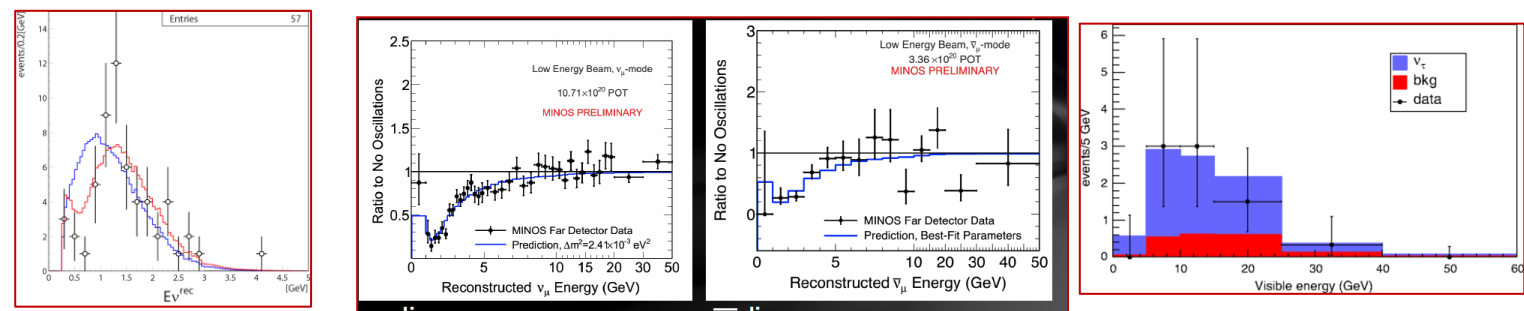
Atm ν



Reactor ν



Accelerator ν



$$K^0 \leftrightarrow \bar{K}^0$$
$$\nu \leftrightarrow \bar{\nu}$$



Neutrino oscillations and mixing

3 families

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

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

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

New
Physics



Neutrino: open questions

- 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** → atmospheric and reactor neutrinos, accelerator neutrinos (LBL experiments), $0\nu 2\beta$ decay, astrophysics and cosmology
- 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: CPV and Mass Ordering

- 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

talk L. Kolupaeva

quarks

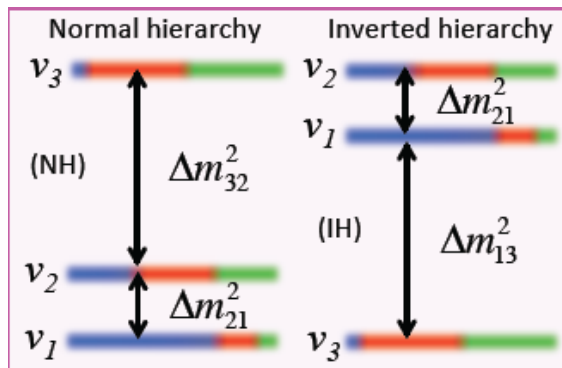
$$V_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

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

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

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

- Neutrino mass ordering (NMO)



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

Mass Ordering

NO or IO ?

Impact on

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



Why is CPV in lepton sector important?

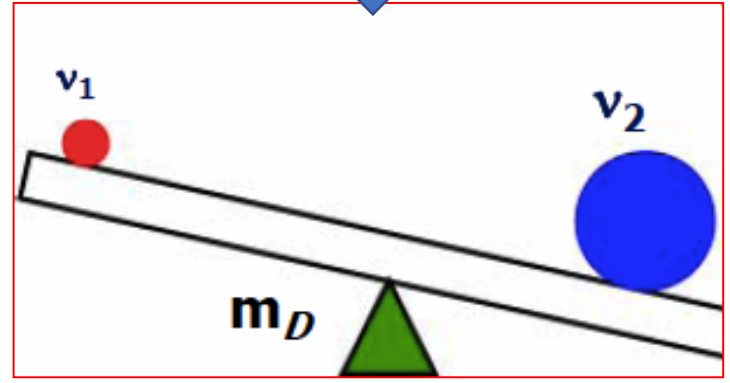
SM cannot explain non-zero neutrino mass
See-saw model

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 BAU value

See-saw model produces BAU by leptogenesis mechanism M. Fukugita, T. Yanagida, 1986

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

$$m_D \sim 100 \text{ GeV}$$
$$\nu_2 \rightarrow M_R \leq 10^{14} \text{ GeV}$$

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 \leftrightarrow Neutrino Physics ??



Golden channel for CPV and MO: $\nu_\mu \rightarrow \nu_e$

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

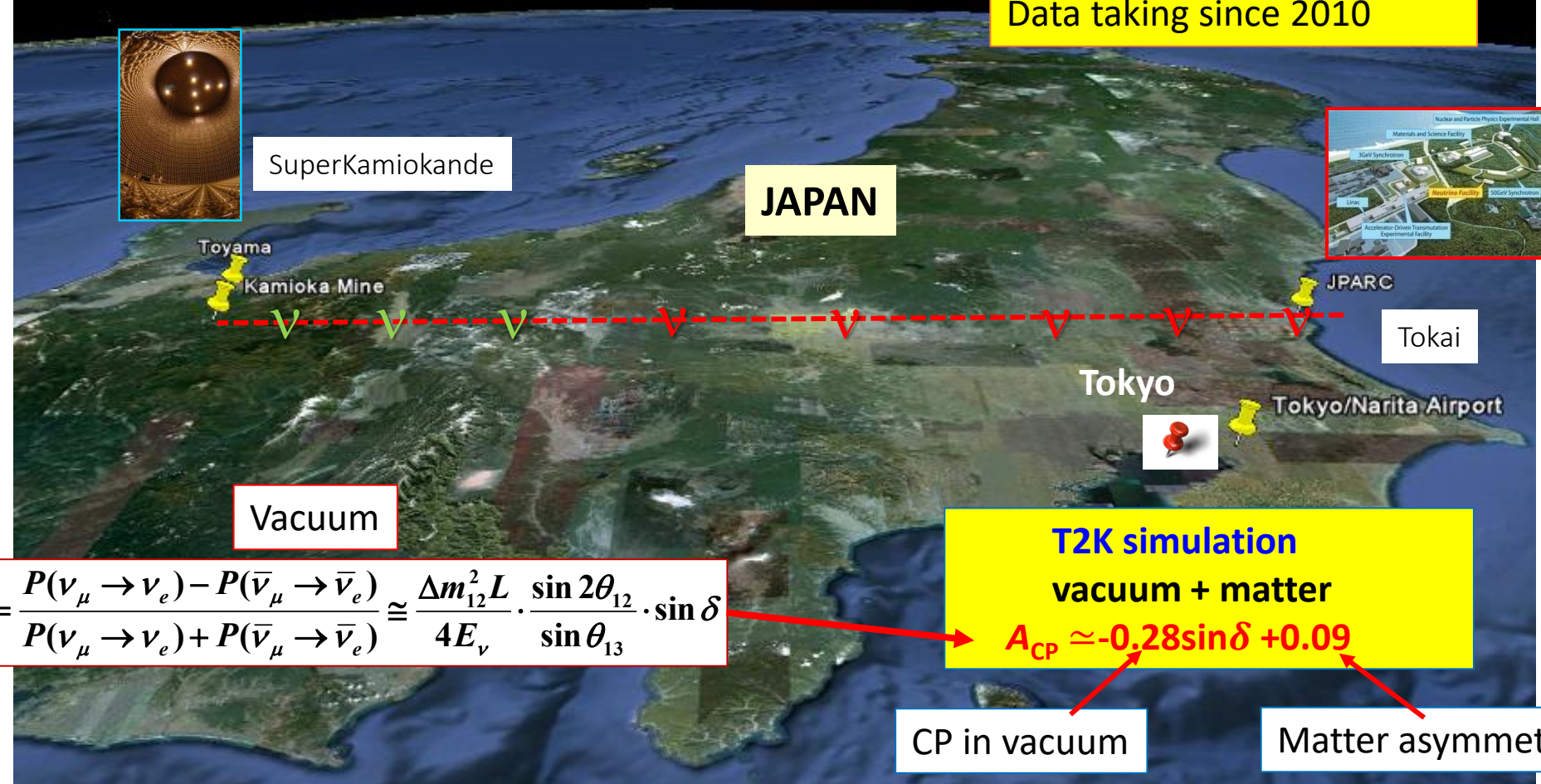
Sensitivity to CP phase increases using the value of θ_{13} obtained in reactor experiments

Recent results



~575 participants,
75 institutions, 14 countries
Russia: INR, JINR

$E_\nu \sim 0.6 \text{ GeV}$
Neutrino beam from J-PARC
Baseline = 295 km
Data taking since 2010



SuperKamiokande

JAPAN



Vacuum

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

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

CP in vacuum

Matter asymmetry



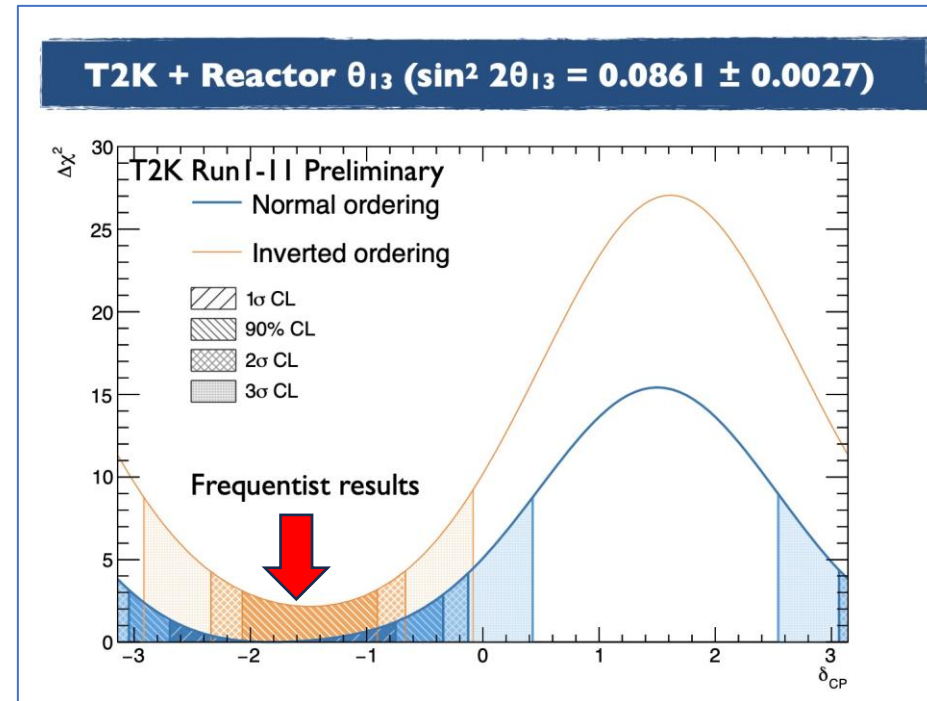
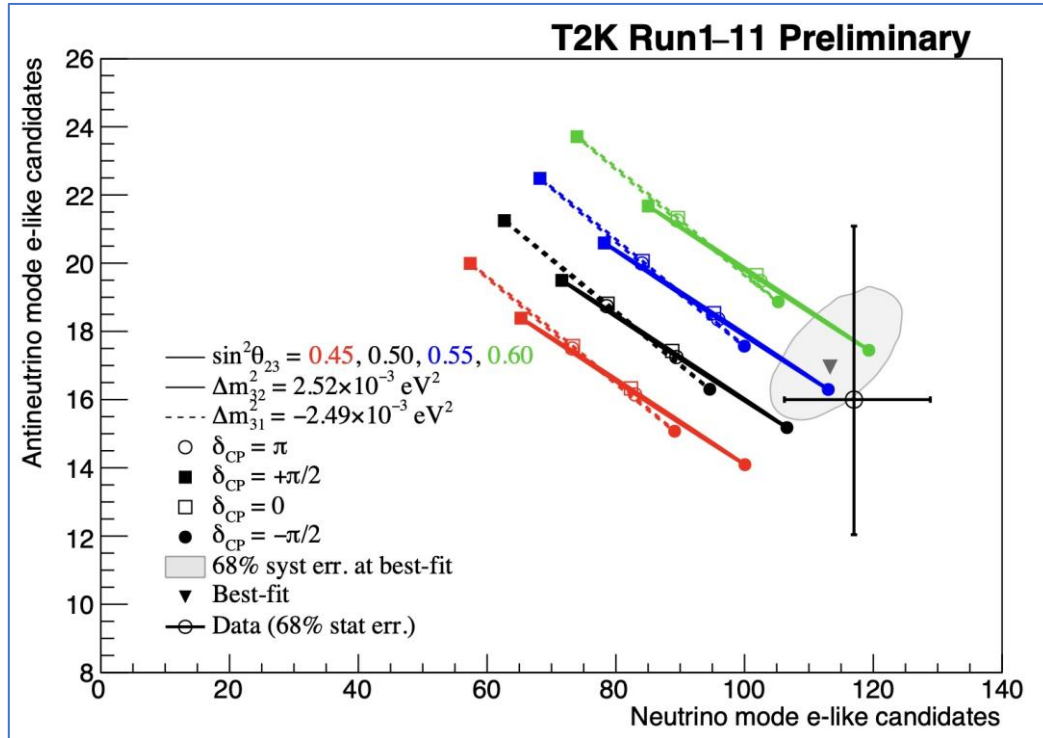
T2K: hint of CP violation

T.Leplumey, talk at 21 Rencontres du Vietnam

ν - mode: 21.4×10^{20} POT

$\bar{\nu}$ - mode: 16.3×10^{20} POT

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

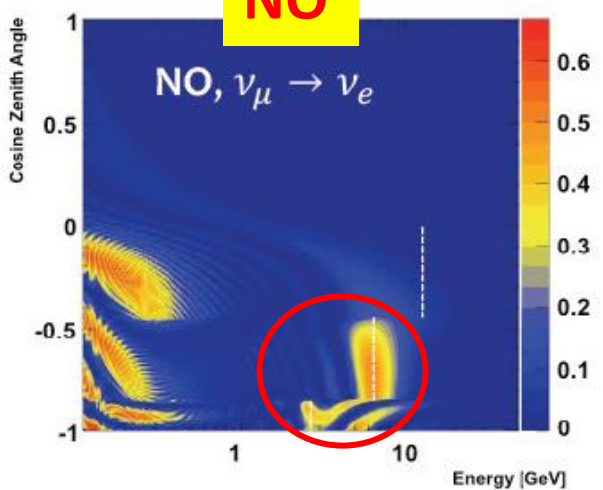
Normal mass ordering is preferred at 80% CL



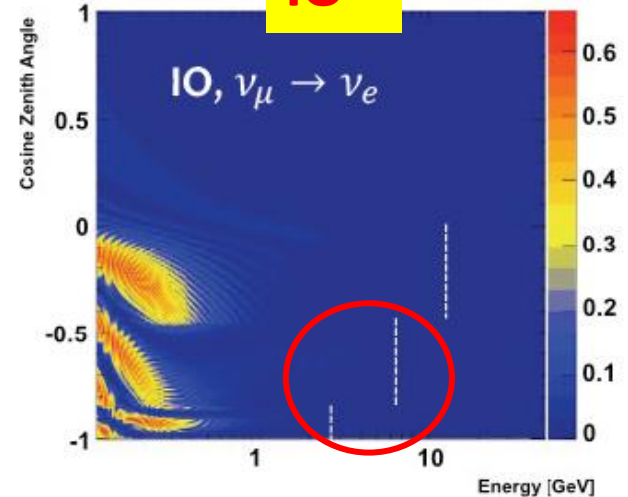
Mass ordering: SuperKamiokande + T2K

SuperKamiokande

NO



IO

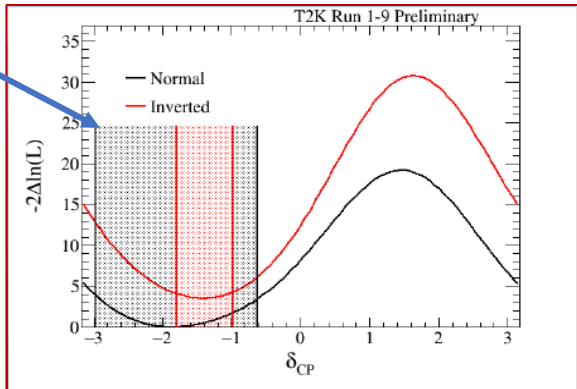
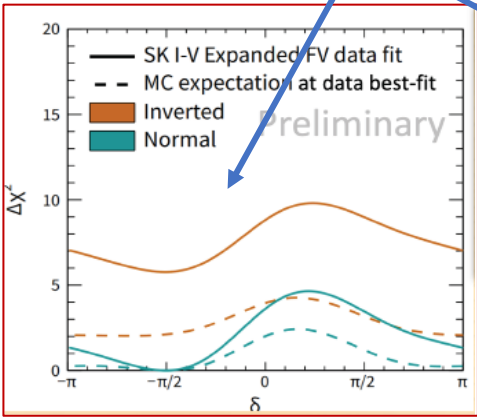


SuperKamiokande

- Atmospheric neutrino sensitive to mass ordering due to matter effect
- MSW resonance at ~ 10 GeV

$$2\sqrt{2}G_F N_e E_\nu = \Delta m_{31}^2 \cos 2\theta_{13}$$

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



Joint analysis SuperK+T2K

- increases sensitivity to MO
- slightly increases sensitivity to CPV

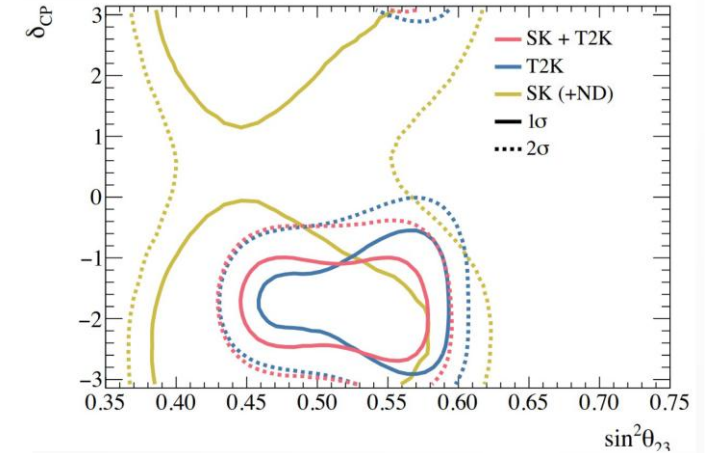
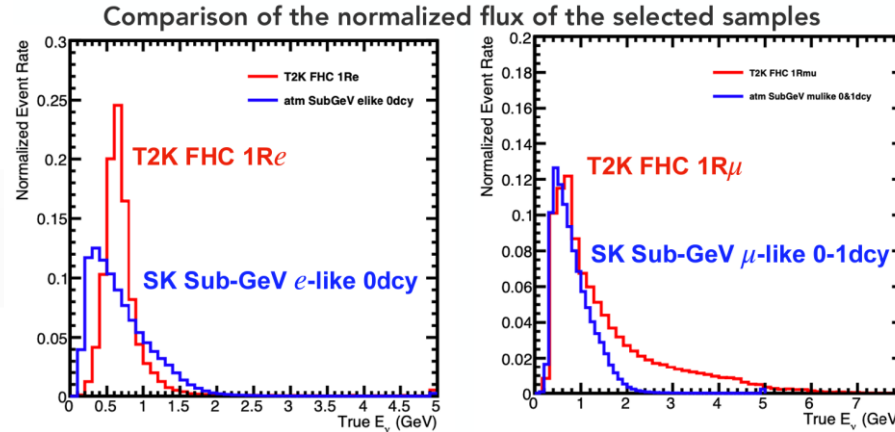


CP: Joint SuperK/T2K analysis

Phys.Rev.Lett. 134 (2025) 1, 011801

T2K: 3.6×10^{21} POT

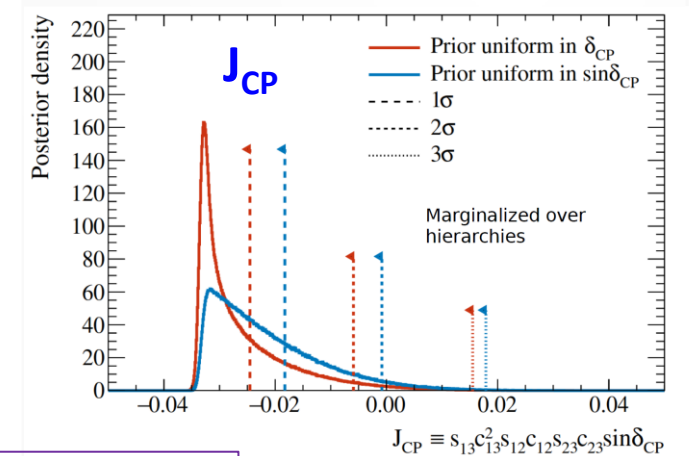
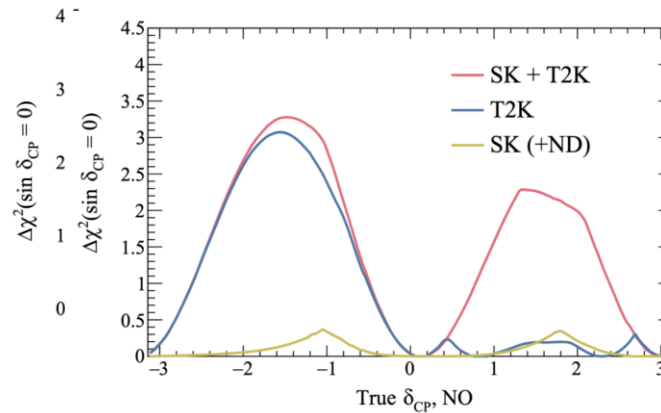
Data corresponding to Super-K 2019 analysis (prior to Gd doping) and T2K 2020 oscillation analysis (no multi-ring far detector sample, older systematics implementation).



Two experiments share the same detector (SK)
 Samples from the two sources have overlap energy range and among which, share similar selection cuts

- T2K ND can be utilized to constrain the xsec uncertainties for samples of the same energy range

Increase of statistics



SuperK+T2K analysis:

- excludes CP conservation at 2.0σ in IO, $\delta_{CP} = \pi$ still within 2σ in NO
- prefers maximal CP violation, $\delta_{CP} \sim -\pi/2$ in both MO
- preferred NO at 1.2σ CL (about 90%)



Experiment NOvA

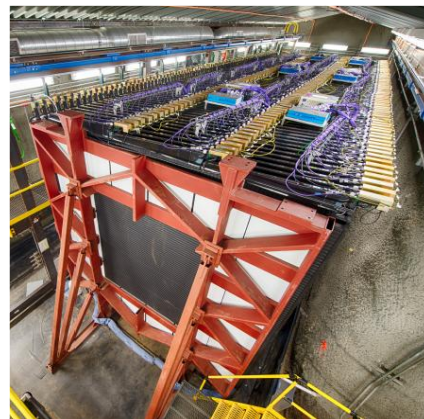
NOvA (USA)

Taking data since Summer 2014

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



Near Detector



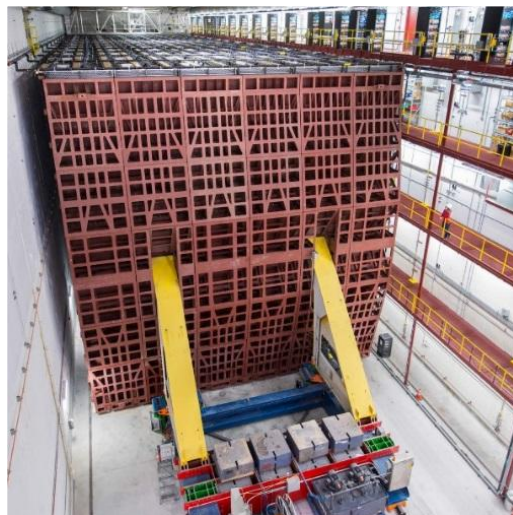
Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter

Protons on target

ν : 13.6×10^{20} POT

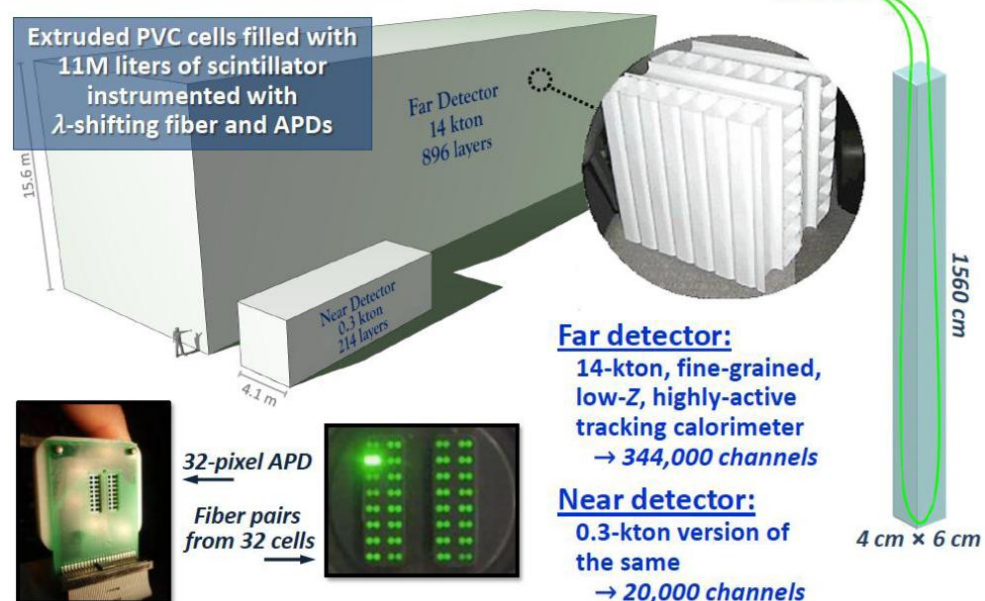
$\bar{\nu}$: 12.5×10^{20} POT

Far Detector



NOvA detectors

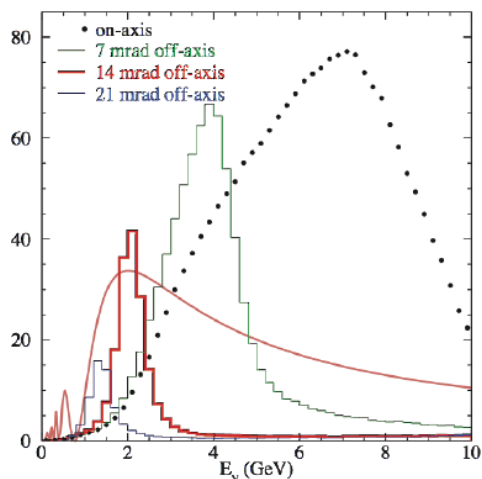
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ -shifting fiber and APDs



Far detector:
14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ 344,000 channels

Near detector:
0.3-kton version of the same
→ 20,000 channels

Neutrino beam





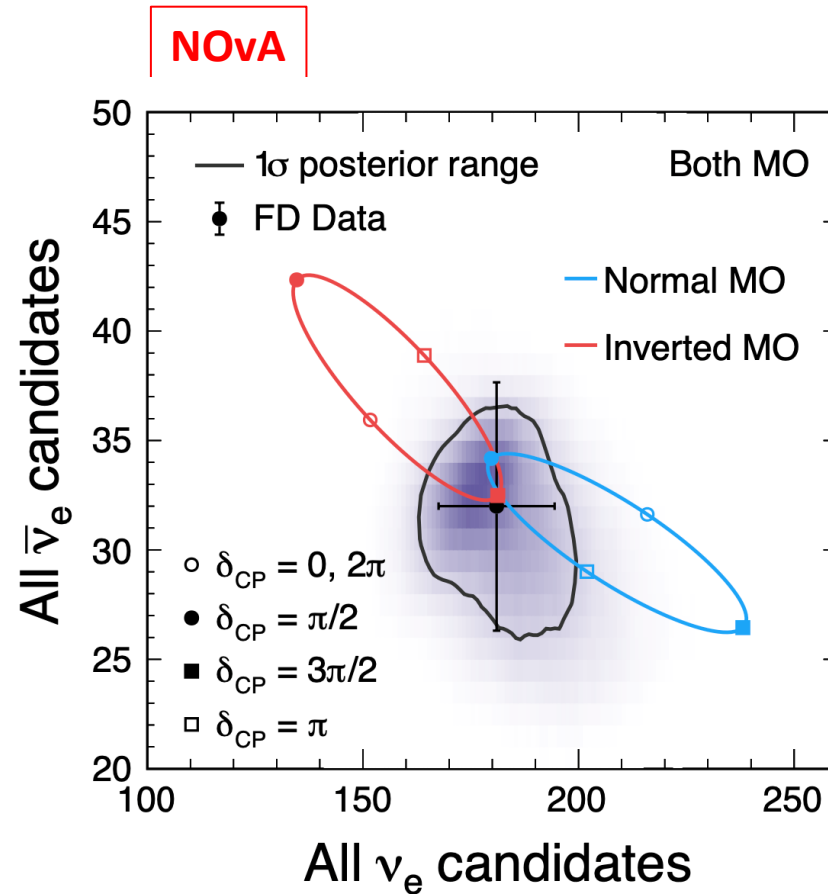
NOvA: CPV result

Phys.Rev.Lett. 136 (2026) 1, 011802

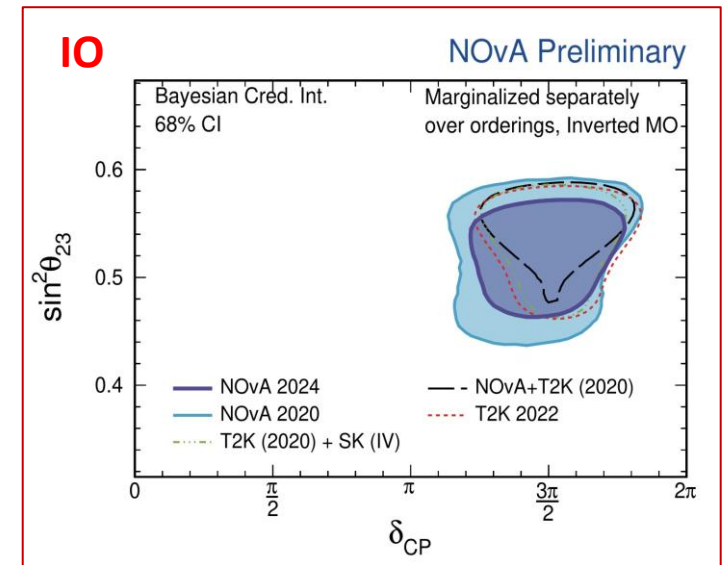
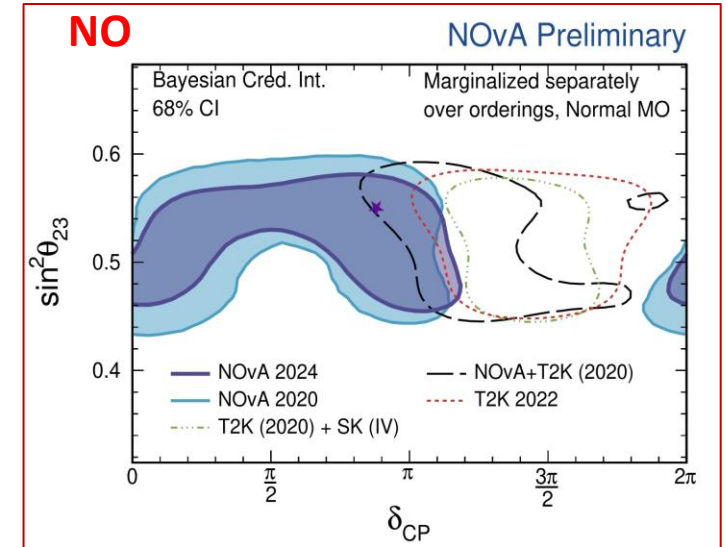
Protons on target
in 2014-2023
 ν : 26.61×10^{20} POT
 $\bar{\nu}$: 12.5×10^{20} POT



384	ν_μ	11.3 background
106	$\bar{\nu}_\mu$	1.7 background
181	ν_e	61.7 background
32	$\bar{\nu}_e$	12.2 background



Data are in the region where
CP violation and matter effect degenerate

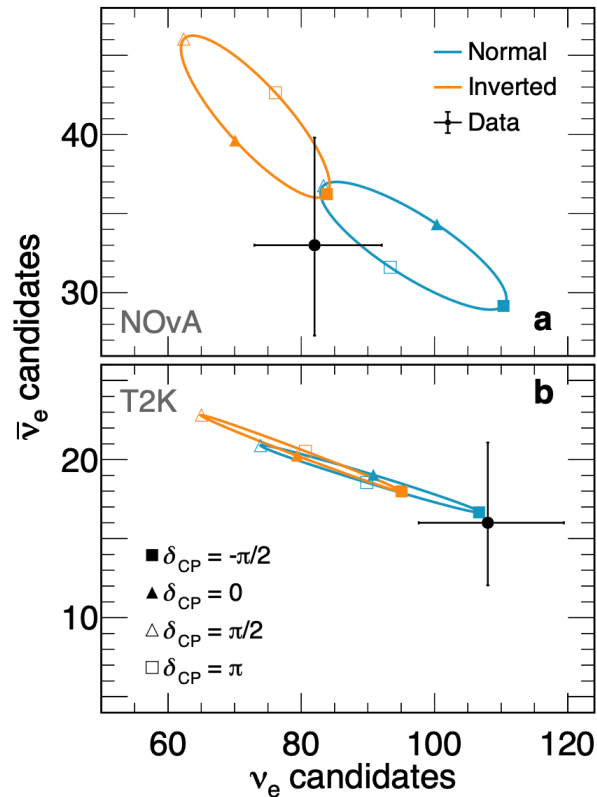




T2K and NOvA joint analysis

Nature 646 (2025) 8086, 818-824

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



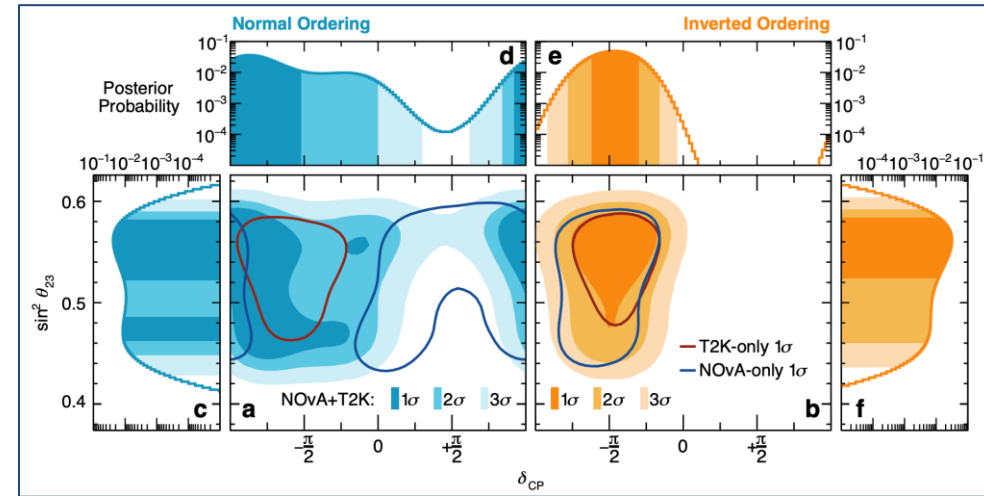
T2K and NOvA data: *mild tension*

Normal Ordering

- 1σ overlap for some regions

Inverted Ordering

- **very similar allowed regions**



Main results of joint analysis

- Smallest uncertainty on $|m_{32}^2|$, error about 1.5%
- For both mass ordering $\delta_{CP} = +\frac{\pi}{2}$ excluded at $>3\sigma$
- CP conservation excluded at $>3\sigma$ for IO

Future prospects



LBNF/DUNE

Fermilab, USA

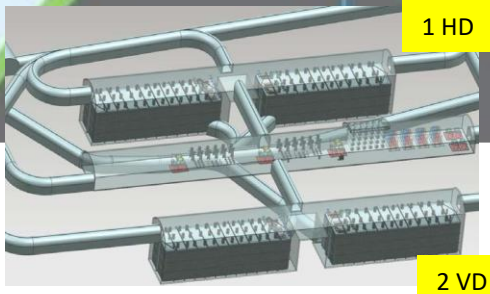
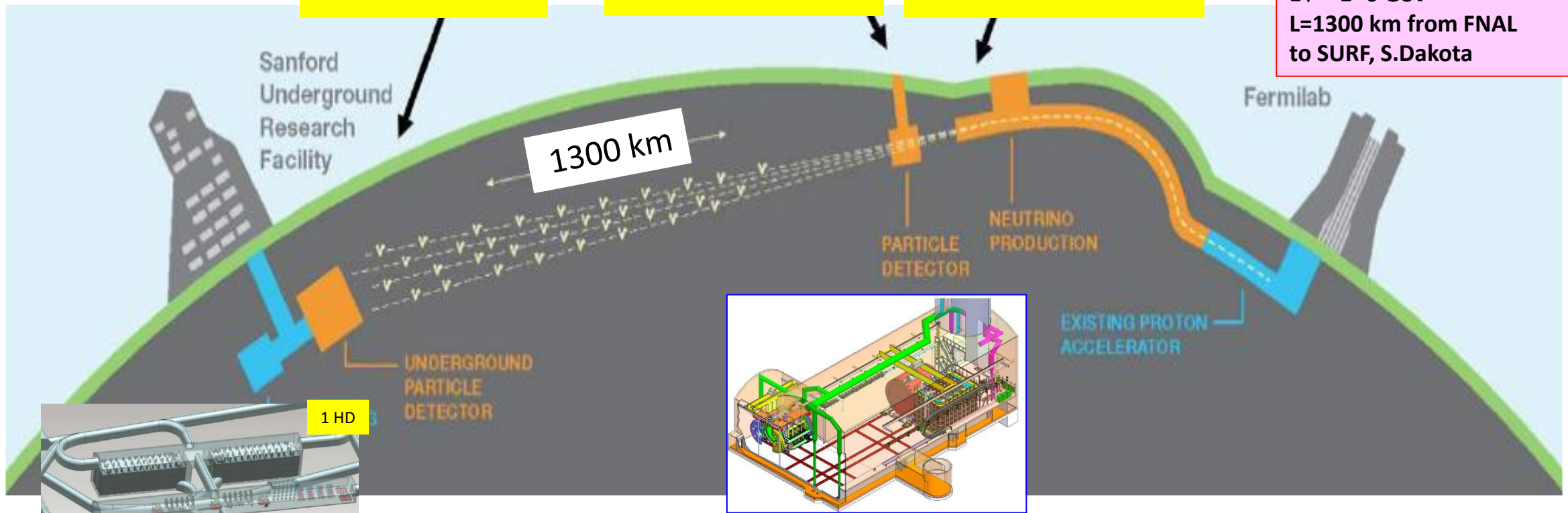
>1400 collaborators from ~200 institutions

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

Far Detector

Near Detector

Neutrino Beam



Phase I: LAr TPC 2x17kt modules in late 2020s, ND, proton beam 1.2 MW by 2031
Phase II: Lar 4x17 kt modules, ND, proton beam 1.2 → 2.4 MW

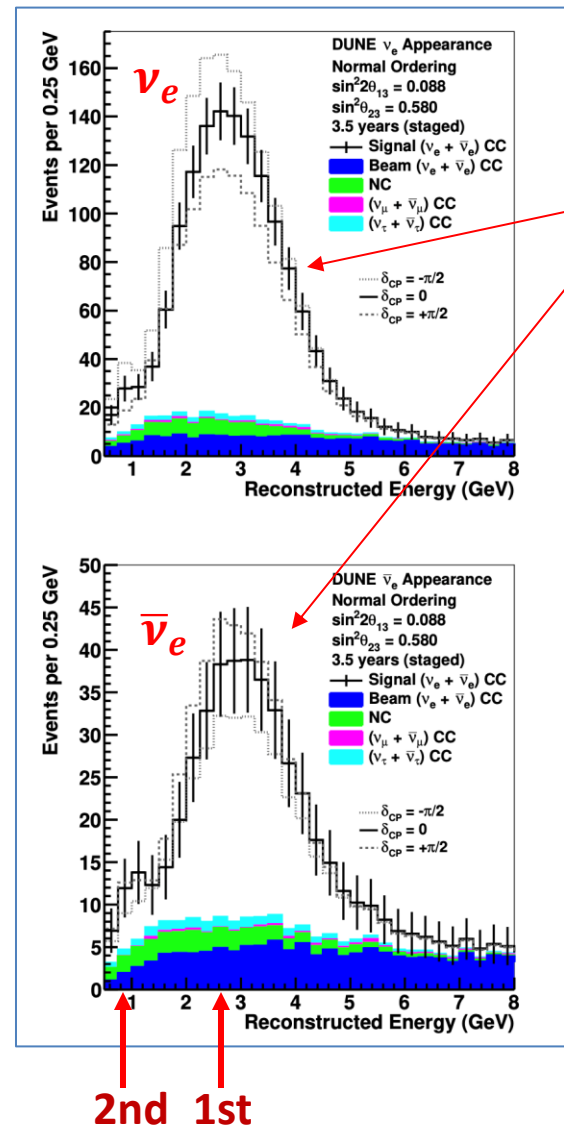
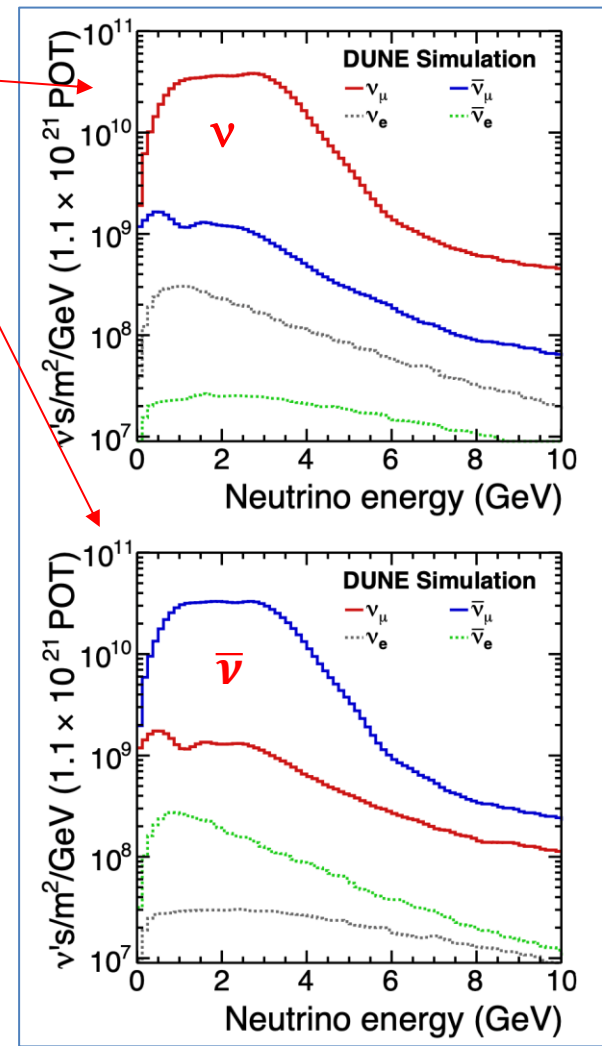
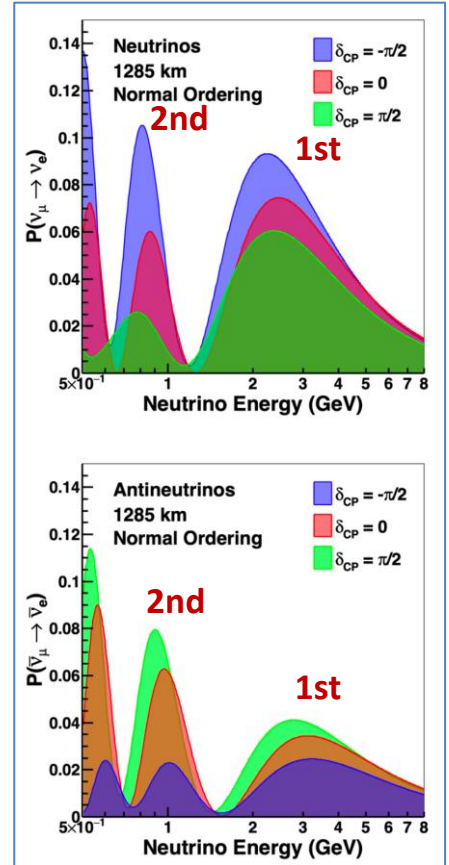


DUNE: neutrino spectra

DUNE Collaboration
 Eur.Phys.J.C 80 (2020) 10, 978

- Un-oscillated flux at Far Detector
- Broad band beam

$$A_{CP} (2^{nd}) \approx 3A_{CP} (1^{st})$$



Electron neutrino and antineutrino spectra after 3.5 y of data taking

DUNE baseline 1300 km
 1st oscillation maximum $E_\nu \approx 2.6$ GeV
 2nd oscillation maximum $E_\nu \approx 0.86$ GeV



DUNE: CP sensitivity

DUNE Collaboration
Eur.Phys.J.C 80 (2020) 10, 978

DUNE, staged approach:

Start of beam:

- 3 FD modules, fiducial mass 20 kt, 1.2 MW

After one year:

- 3 modules, fiducial mass 30 kt

After three years:

- 4 modules, fiducial mass of 40 kt

After six years:

- Upgrade to 2.4 MW beam

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

Sensitivity to δ_{CP}

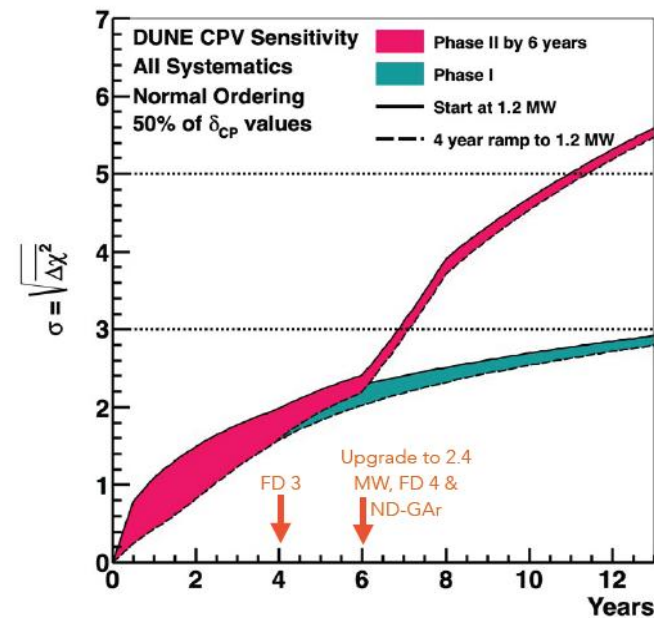
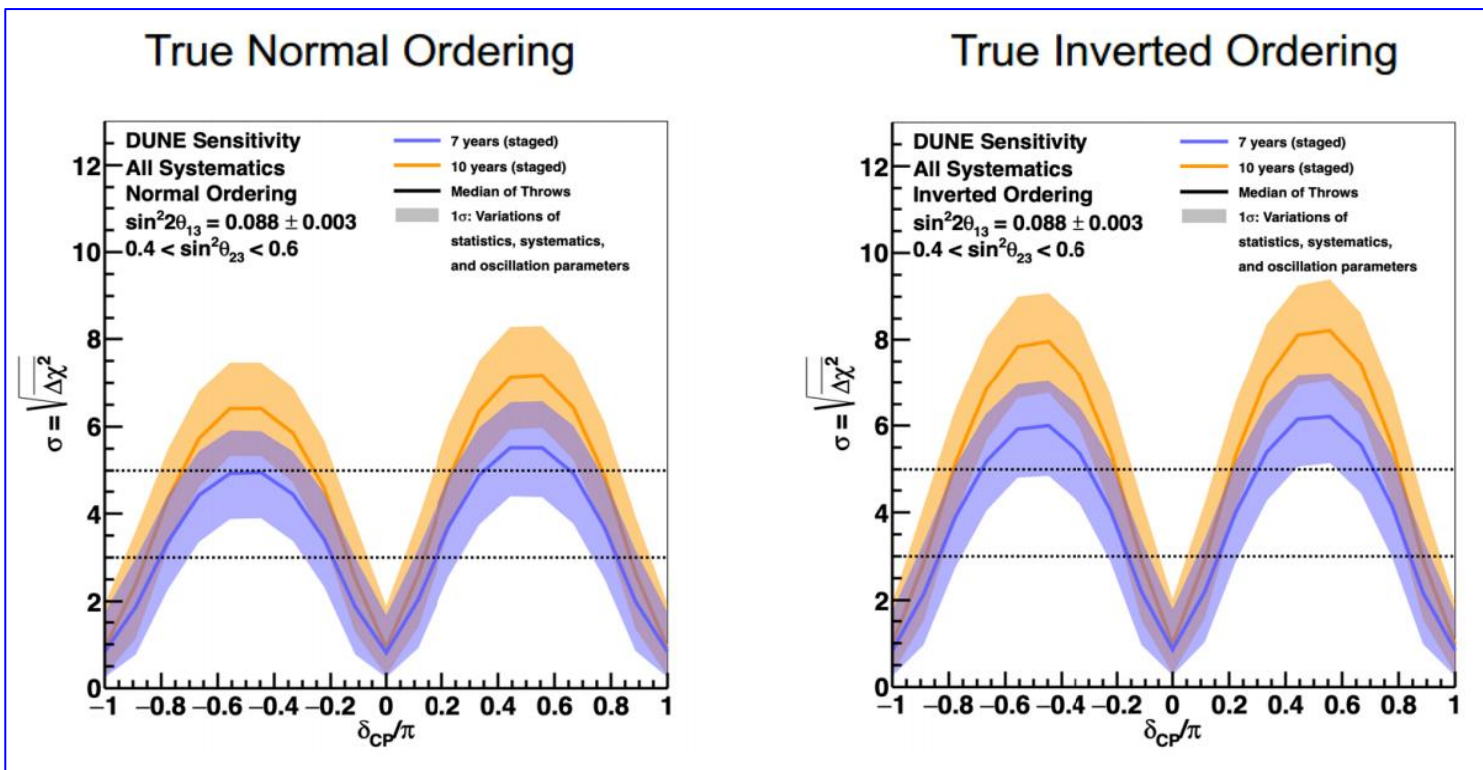
- 7 years data taking

- 10 years data taking

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

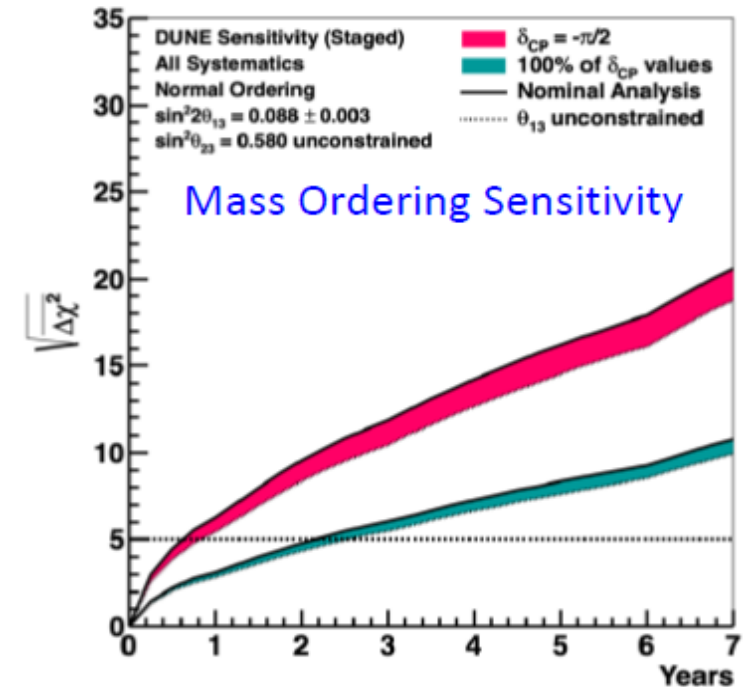
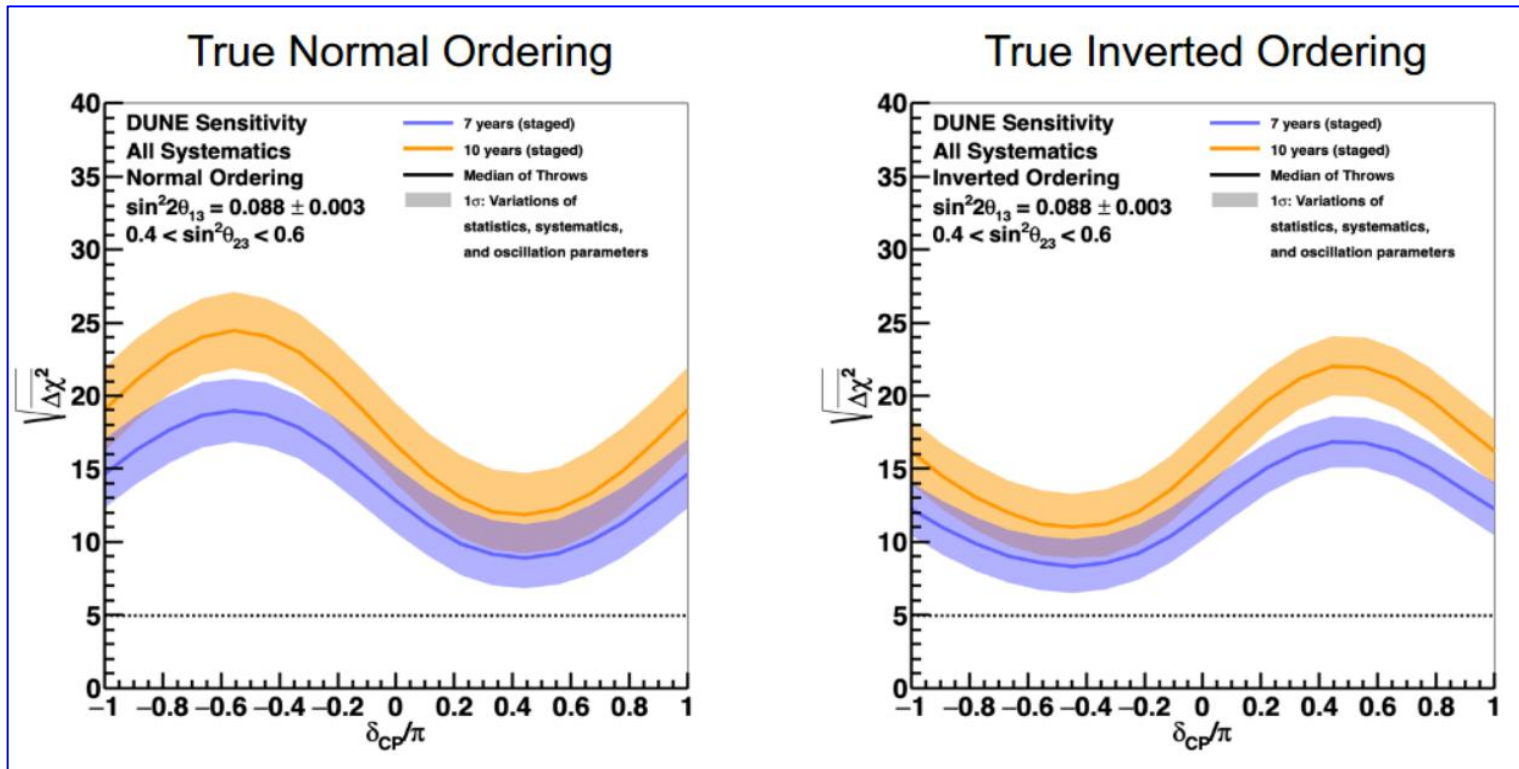




DUNE: Mass Ordering

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

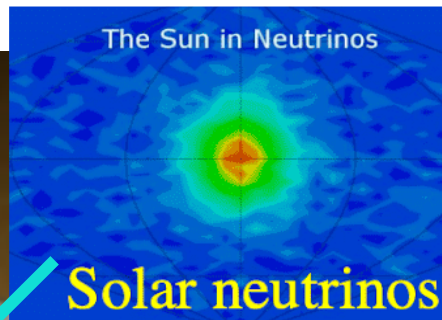
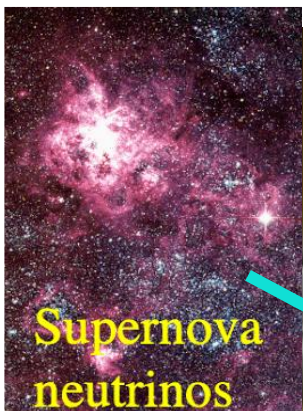
> 5 σ discovery
for all possible δ_{CP} values
after 3-4 years of data taking





Hyper-Kamiokande

Japan. Project approved in 2020, construction begun in 2021, operation starts in 2028
>650 members, 106 institutions, 22 countries



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

Water Cherenkov detector

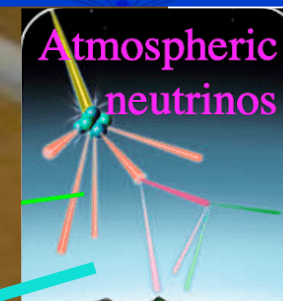
71 m (height) x 68 m (diameter)
Total mass about 260 kt

Inner Detector:

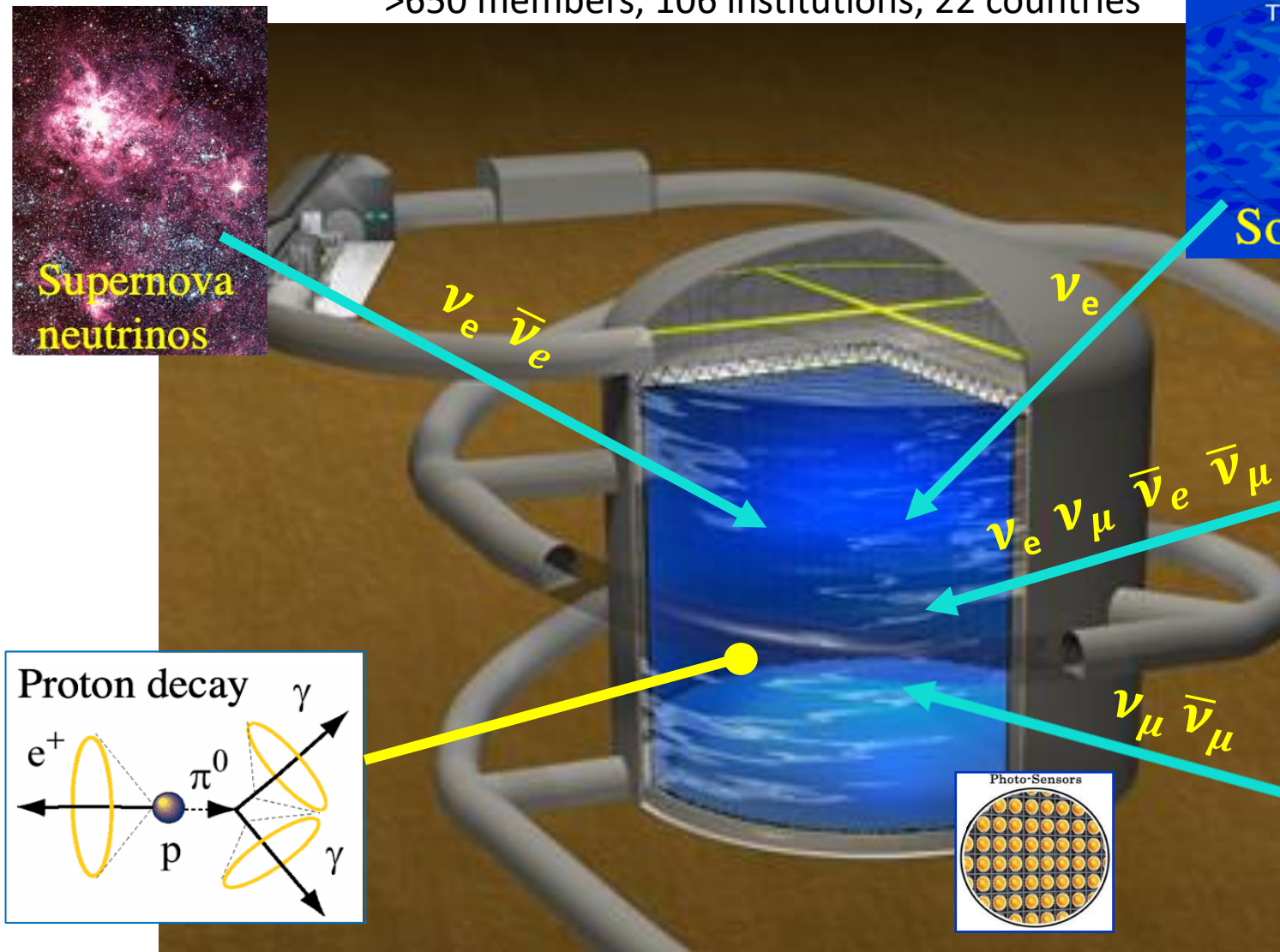
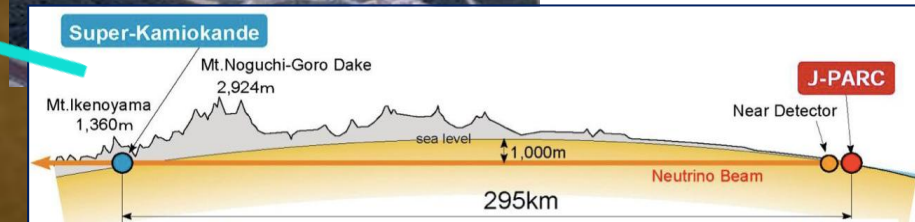
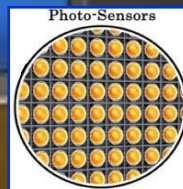
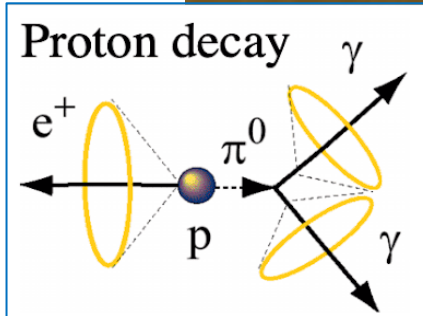
20000 50 cm PMTs + mPMTs

Outer Detector:

~4000 7.5 cm PMTs + WLS plates



J-PARC





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

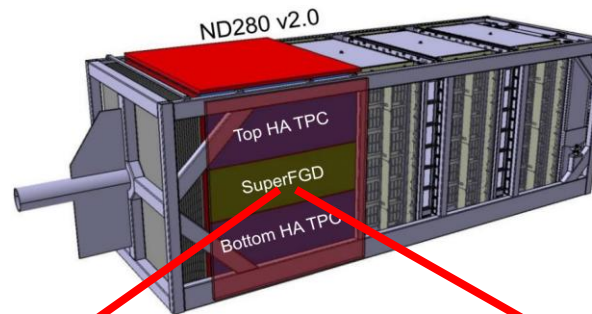
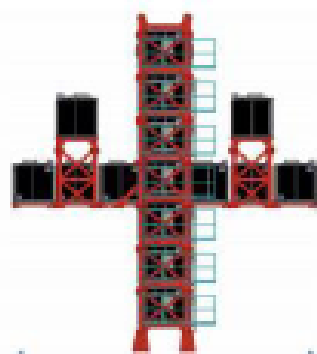
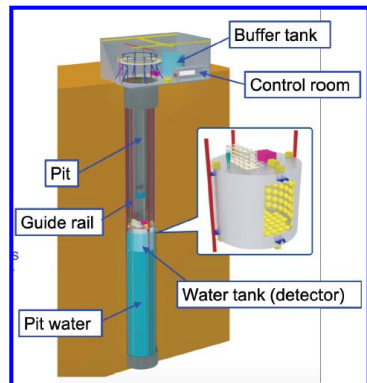
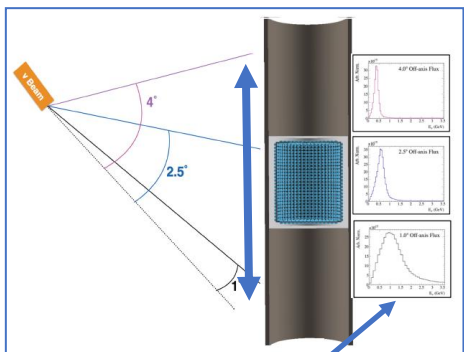
IWCD

INGRID

ND280 upgraded

Magnetized off-axis detector

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



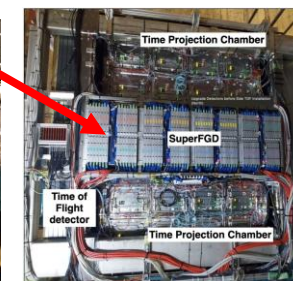
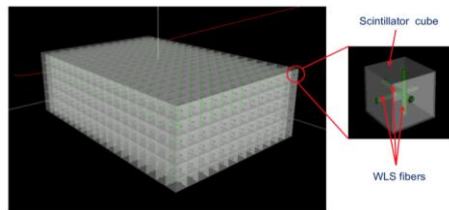
Constructed by
 Russia (INR, JINR, LPI), Japan, US,
 Switzerland, France, Spain

Neutrino spectra

IWCD
 1 kt water Cherenkov detector
 Photocensors:
 multi-PMT modules

Neutrino on/off axis beam monitor

SuperFGD

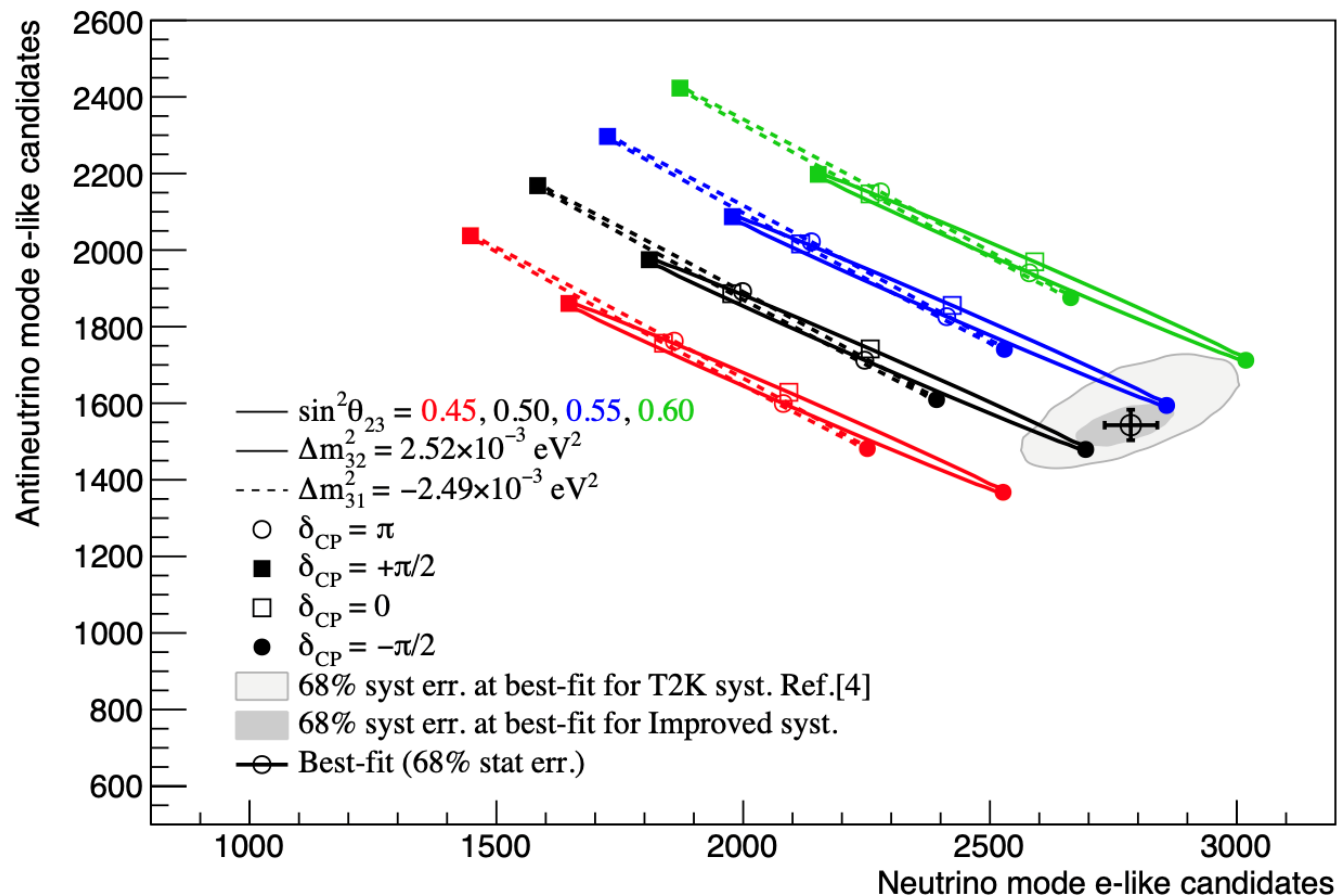




HyperK: ν_e and $\bar{\nu}_e$ events

10 years of data taking

Expected number of events at HyperK
for $\nu_e:\bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = -\pi/2$
 $\sim 2800 \nu_e$ $\sim 1500 \bar{\nu}_e$

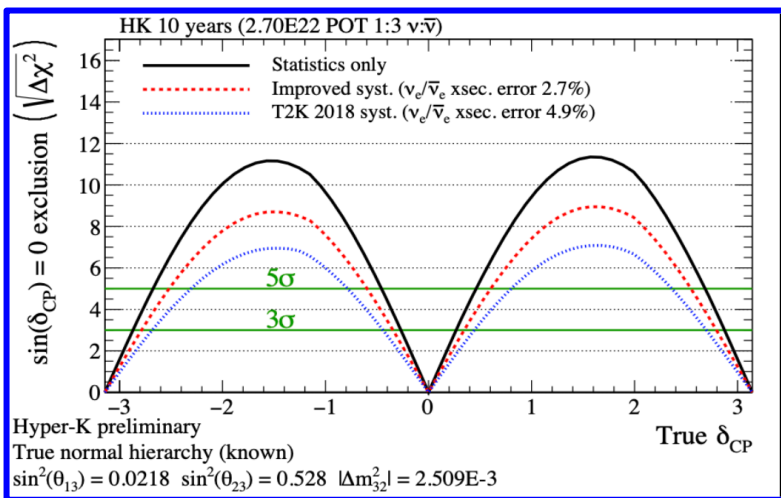




Sensitivity to CPV

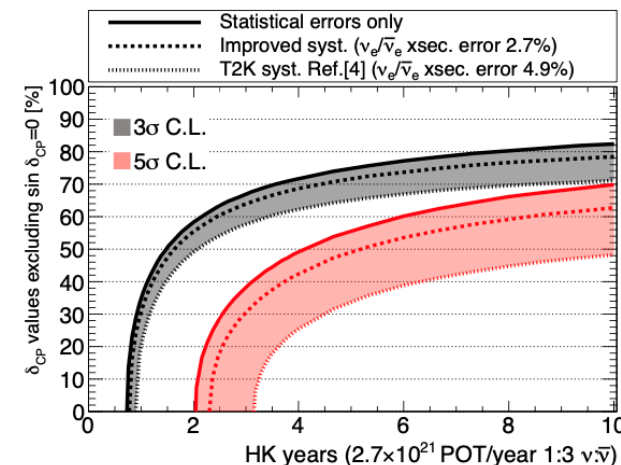
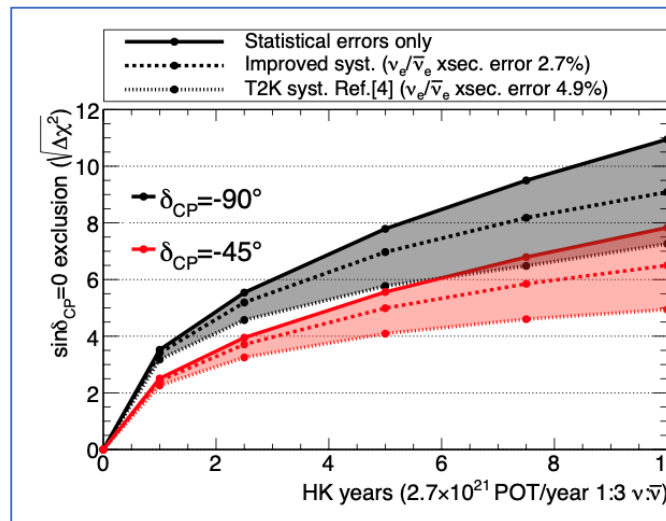
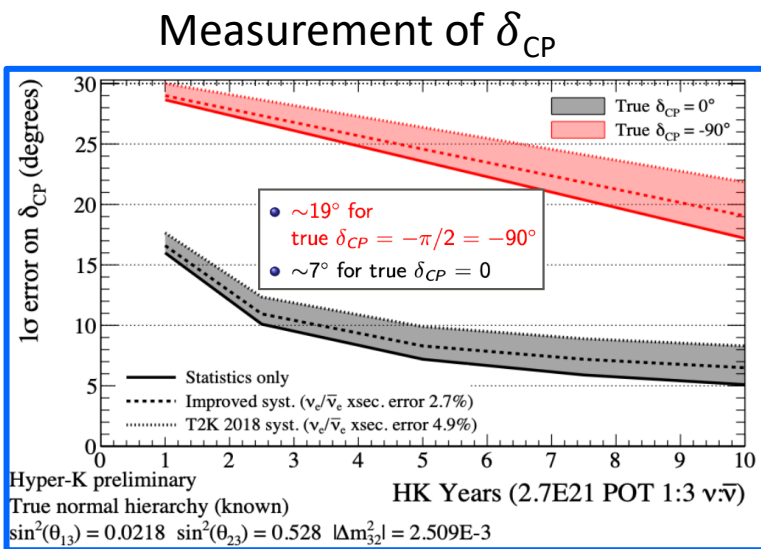
Projected HyperK sensitivity to CP violation

Hyper-Kamiokande, EPJ C86 (2026) 2, 170



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

Exclusion of CP conservation

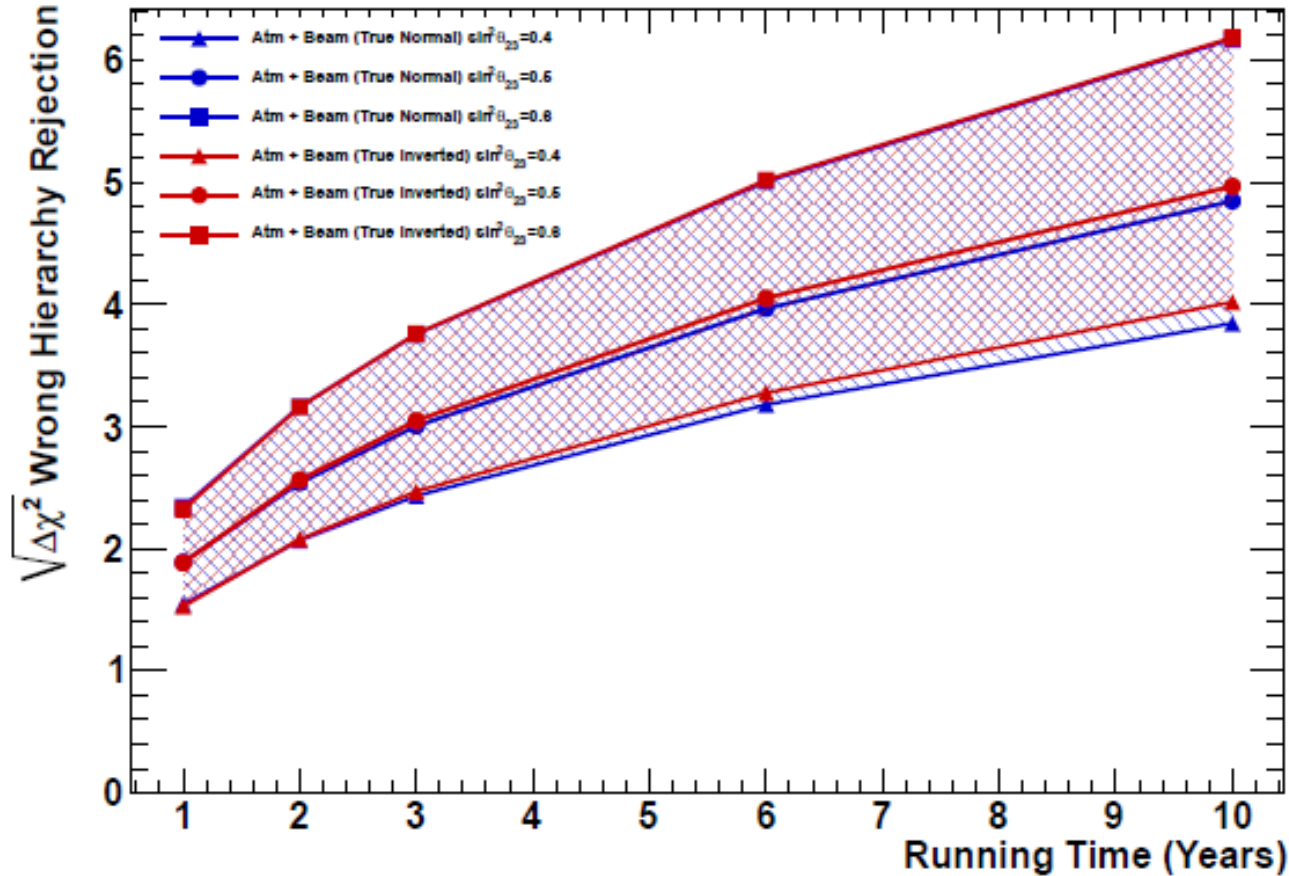




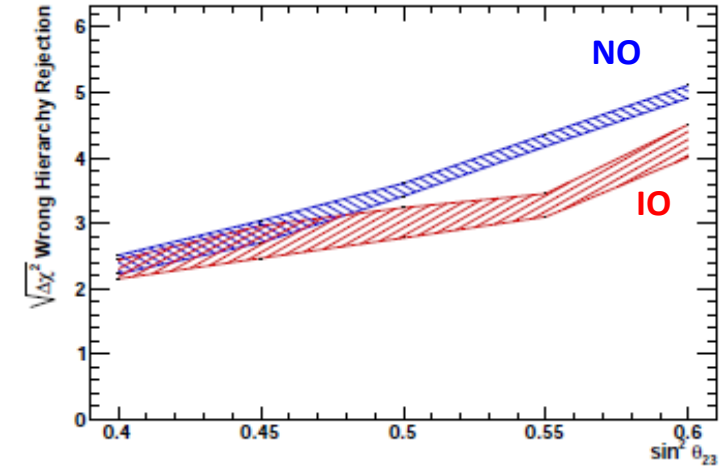
Hyper-Kamiokande: Mass Ordering

HyperKamiokande 10 years of data taking

Hyper-Kamiokande, EPJ C86 (2026) 2, 170



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

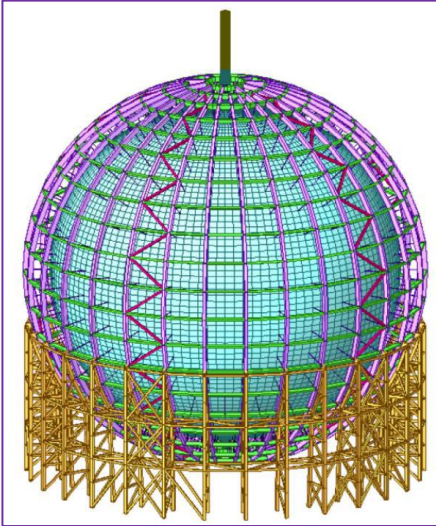


JUNO: Mass Ordering

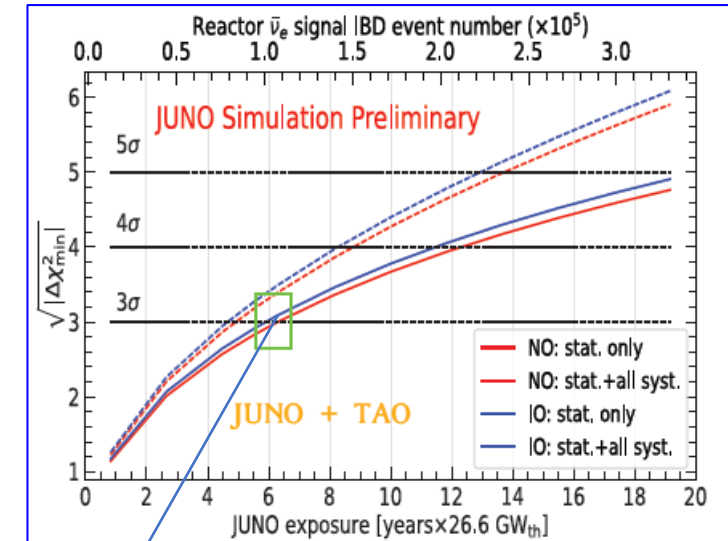
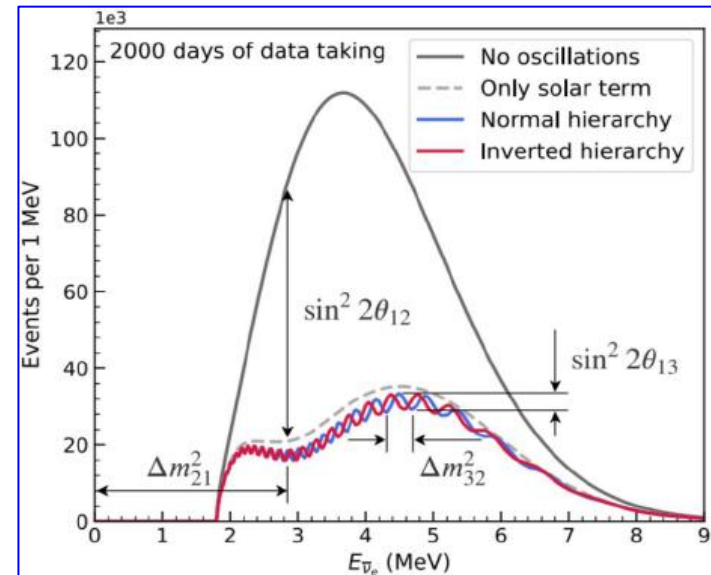
Reactor experiment JUNO, China

Chin.Phys.C 46 (2022) 12, 123001

talk D.Dolzhikov



JUNO detects the mass hierarchy directly by the phase shift in the oscillation pattern in a 20kton scintillator detector. Energy resolution is 3% at 1 MeV and nonlinearity < 1%



3σ within 6 years of data taking

JUNO begun data taking in 2025

20 kt liquid scintillator detector
20k - 50 inch PMT; 25.6k - 3 inch PMT
Baseline 53 km, 650 m overburden



Conclusion/Perspectives

Neutrino is a unique laboratory to study Physics Beyond SM

- **CP violation** and **Mass Ordering** – primarily targets of current and near future long baseline accelerator and reactor experiments
- Current experiments **T2K** and **NOvA** are taking data and will obtain new results on **CPV**
- **T2K** → maximal **CPV** for both **MO**, **NOvA** → maximal **CPV** for **IO**
- **HyperKamiokande** and **DUNE** will start data taking about 2028 and 2031, respectively
First results on **CPV** and **MO** are expecting in early **2030**
- **JUNO** begun collecting data and can determine **MO** with **3σ** in about **5 years**

Very exiting physics ahead of us !

Thank you for your attention