CP Violation in Neutrinos: An Experimental Point of View

Duyang Hongyue

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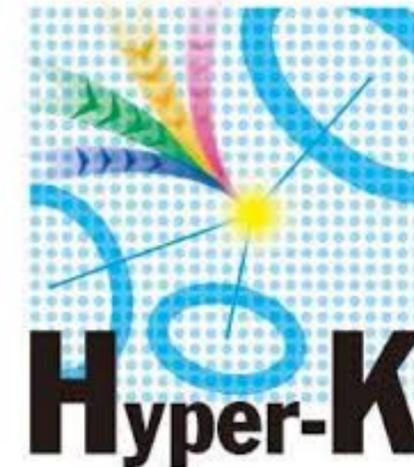
味物理前沿研讨会@三亚

2026-02-03

Outline

- Introduction: how to measure CPV in neutrinos?

- Current experiments:

  - NOvA

  - T2K

- Next generation experiments:

  - DUNE

  - Hyper-Kamiokande

- Novel ideas

- Summary

Claudio Giganti, Neutrino2024

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

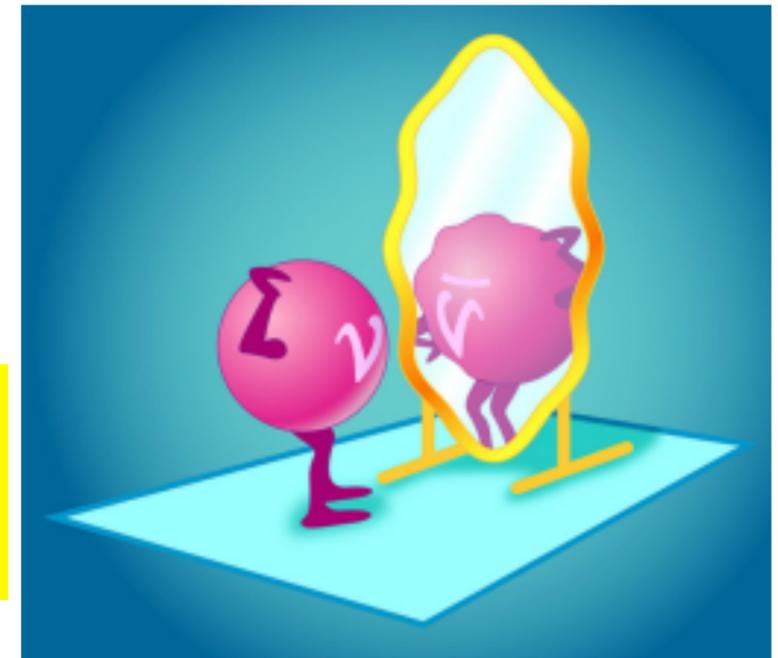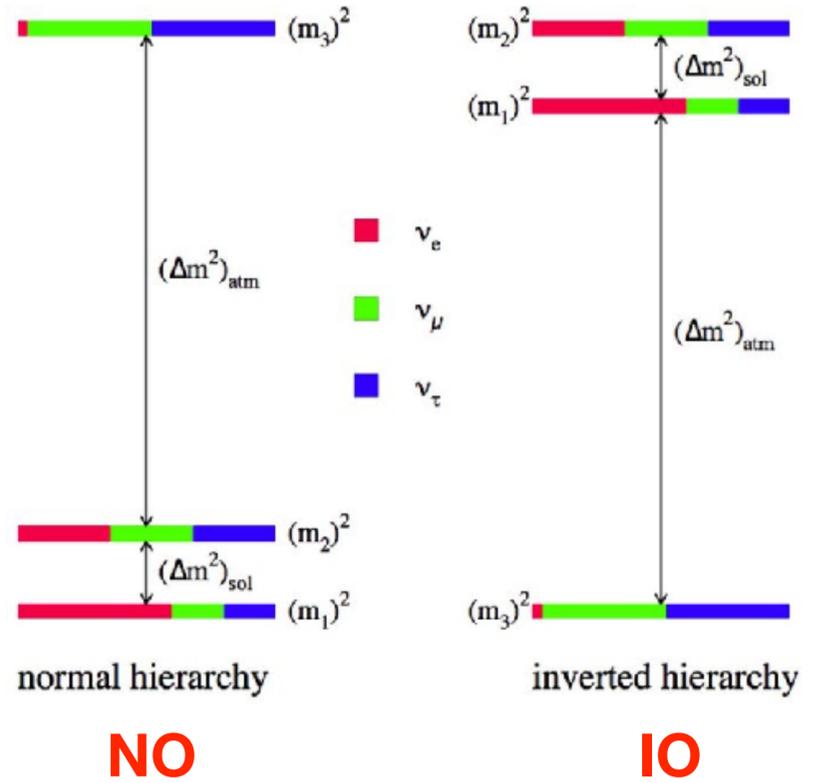| Atmospherics and LBL $\theta_{23} \sim 45°$ $\vert\Delta m^2_{32}\vert \sim 2.5 \times 10^{-3}$ eV^2	Reactors $\theta_{13} \sim 10°$ LBL θ_{13} and δ_{CP}	Solar and reactors $\theta_{12} \sim 35°$ $\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2

CP violation phase δ_{CP}: asymmetry between $\nu/\bar{\nu}$ oscillations

$$P(\nu_\mu \to \nu_e) \simeq 4\,s^2_{13}\,s^2_{23}\,\frac{\sin^2\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})^2}$$

$$+ \alpha^2\,c^2_{23}\,\sin^2 2\theta_{12}\,\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

$$+ 2\,\alpha\,s_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\frac{\sin(\hat{A}\Delta)}{\hat{A}}\,\frac{\sin\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})}\,\cos(\Delta + \delta_{CP}).$$

Introduction

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Atmospherics and LBL
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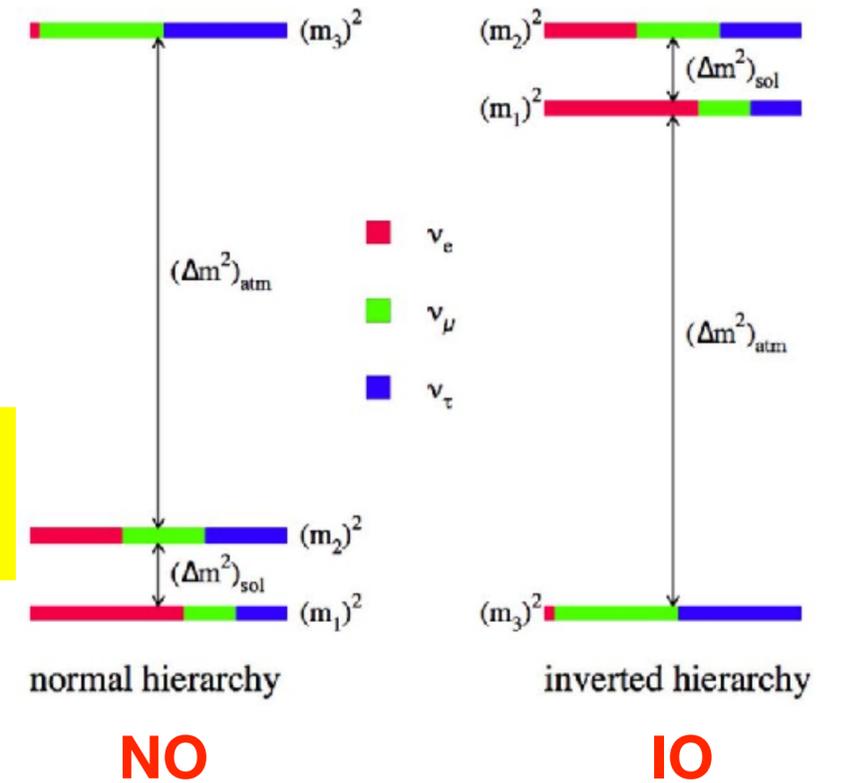$|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}$ eV^2

Reactors
$\theta_{13} \sim 10°$
LBL
θ_{13} and δ_{CP}

Solar and reactors
$\theta_{12} \sim 35°$
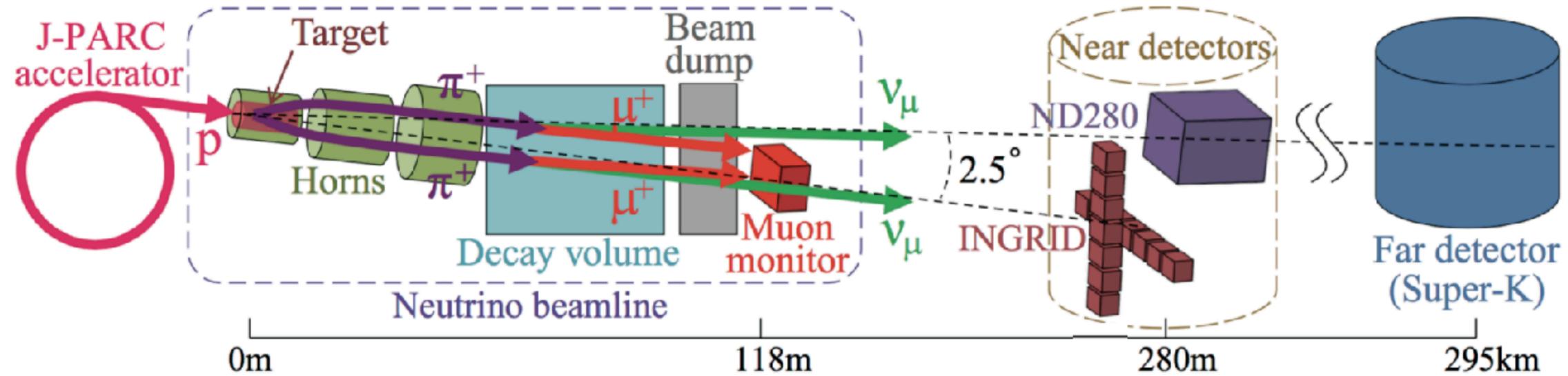$\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2

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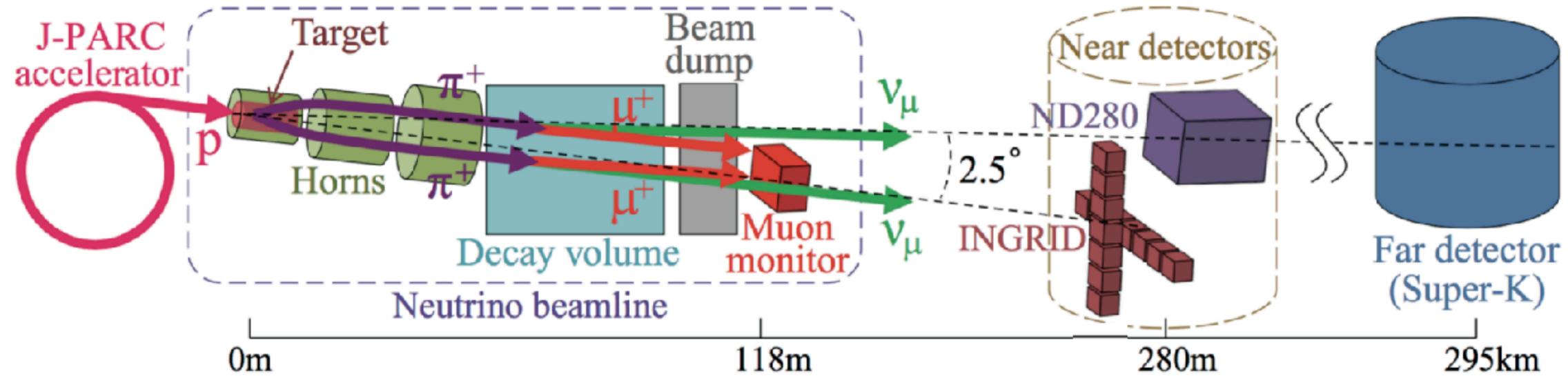
normal hierarchy   inverted hierarchy

NO   **IO**

The unknown neutrino mass ordering (MO) also contribute to $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ with matter effects.

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LBL
θ_{13} and δ_{CP}

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θ_{23} octant also affects the size of the asymmetry

NO   **IO**

normal hierarchy   inverted hierarchy

The unknown neutrino mass ordering (MO) also contribute to $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ with matter effects.
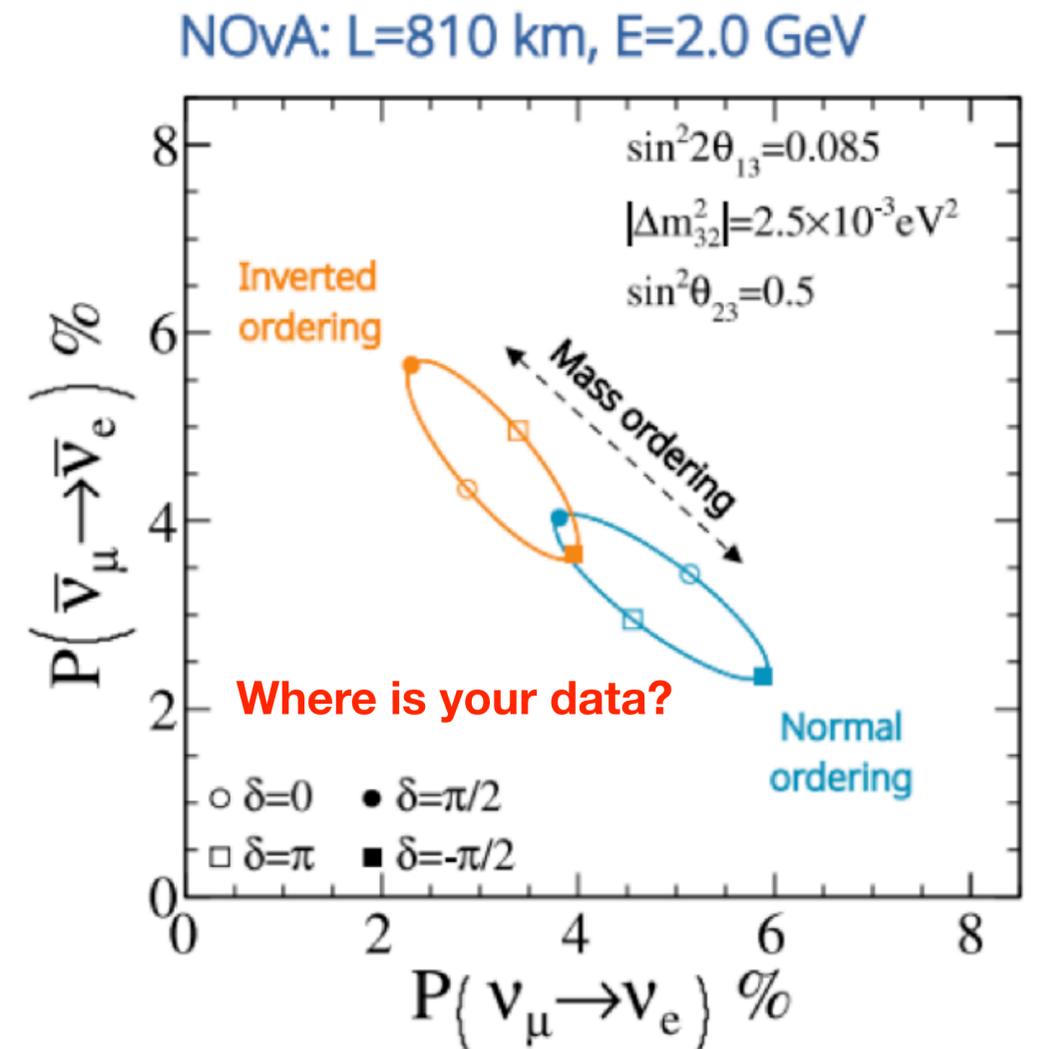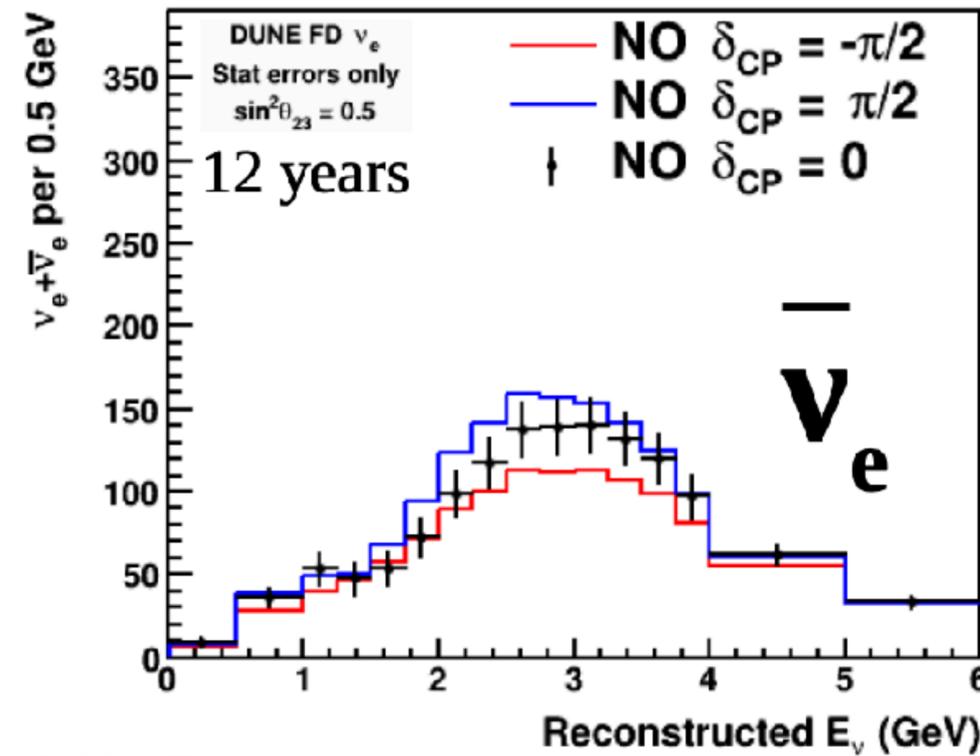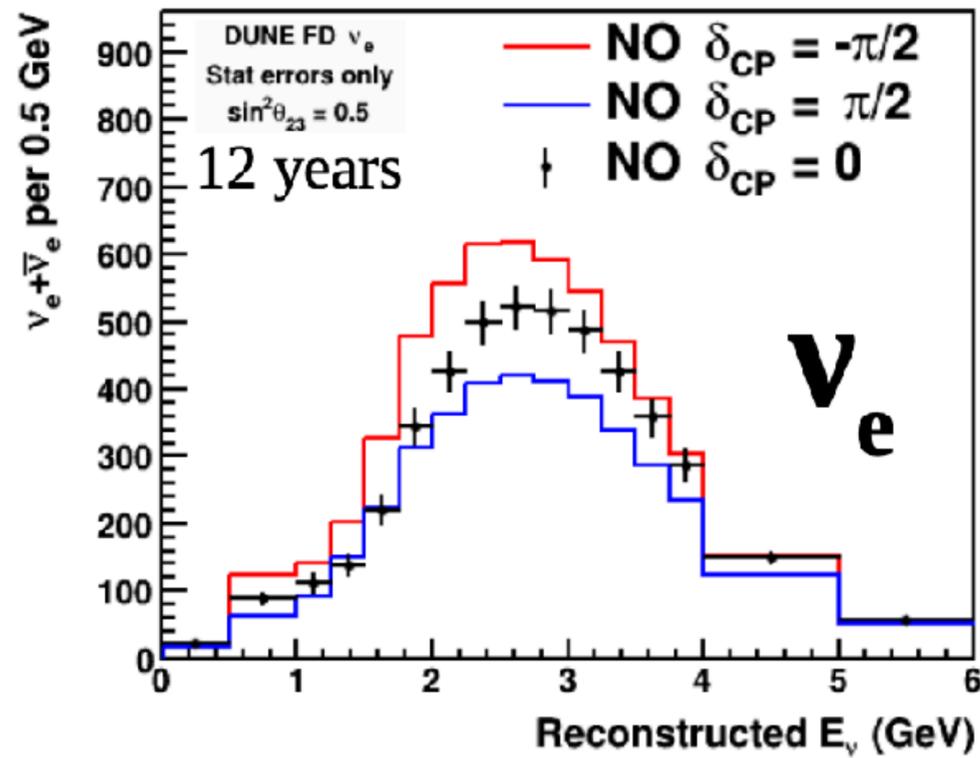
Accelerator-based Neutrino Oscillation Experiments

- Accelerators are capable of producing $\nu_\mu/\bar{\nu}_\mu$ beams.

- $\nu_e/\bar{\nu}_e$ appearance measurements offer sensitivity to δ_{CP}

- $\nu_\mu/\bar{\nu}_\mu$ disappearance measurements help constraining θ_{23}

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Detector requirements

- Near detectors to control flux/xsec systematics etc.

- Large-mass far detector for statistics

- Capability of flavor identification.

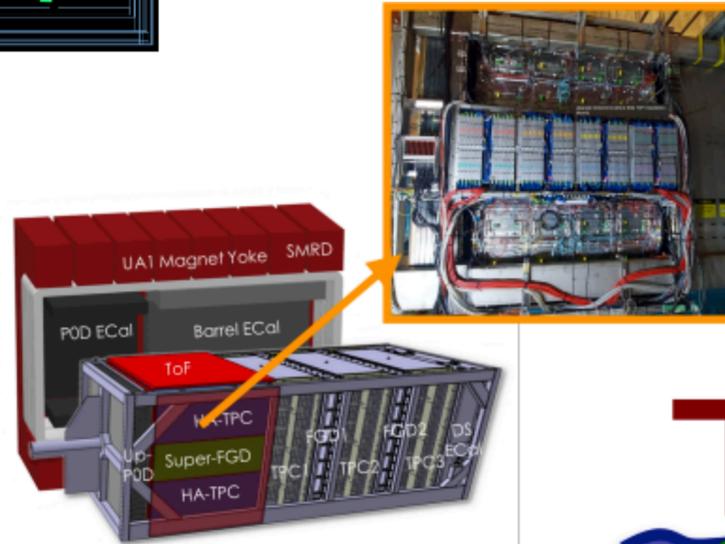# Accelerator-based Neutrino Oscillation Experiments

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Accelerator-based Neutrino Oscillation Experiments

Example of DUNE
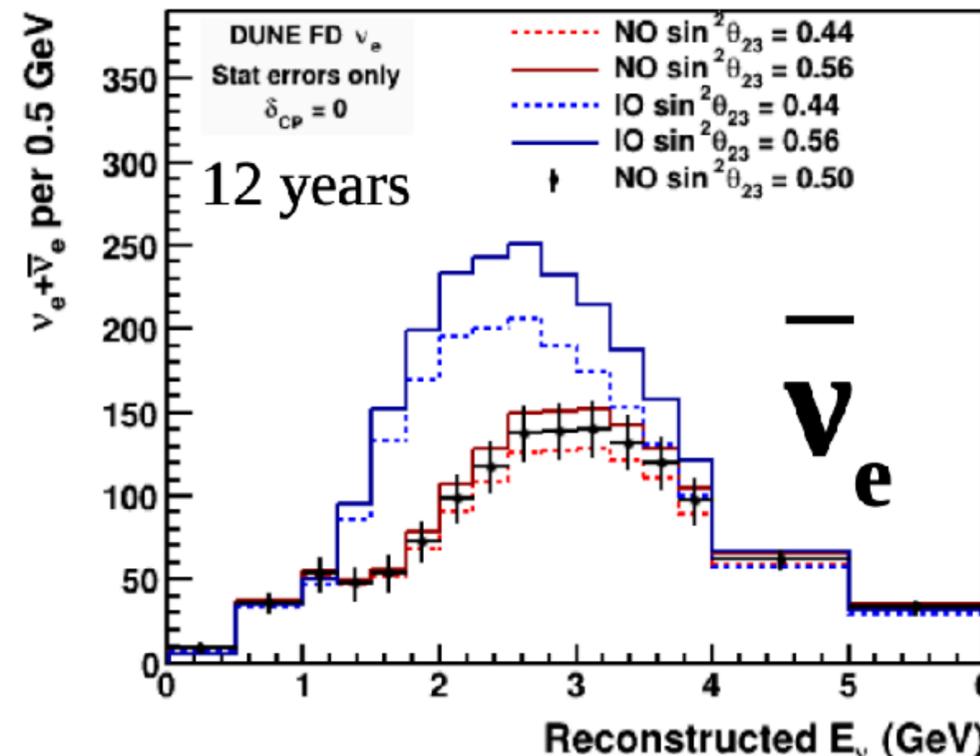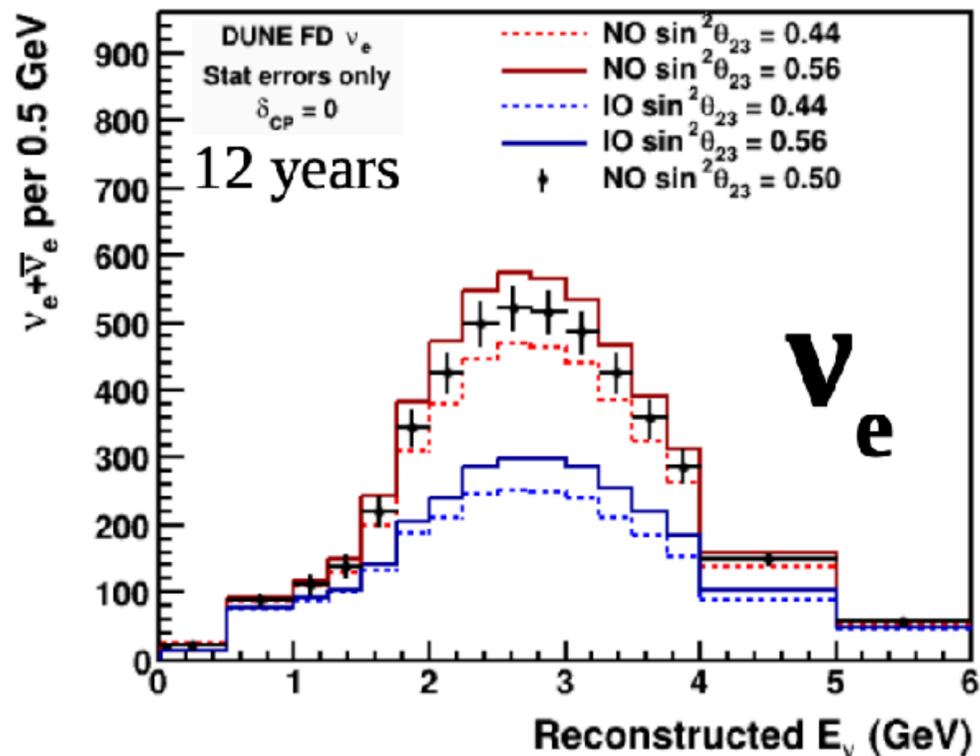
- Shape measurements help breaking the degenracy between δ_{CP}, MO and θ_{23}.

Atmospheric Neutrino Experiments

KM3NeT

IceCube
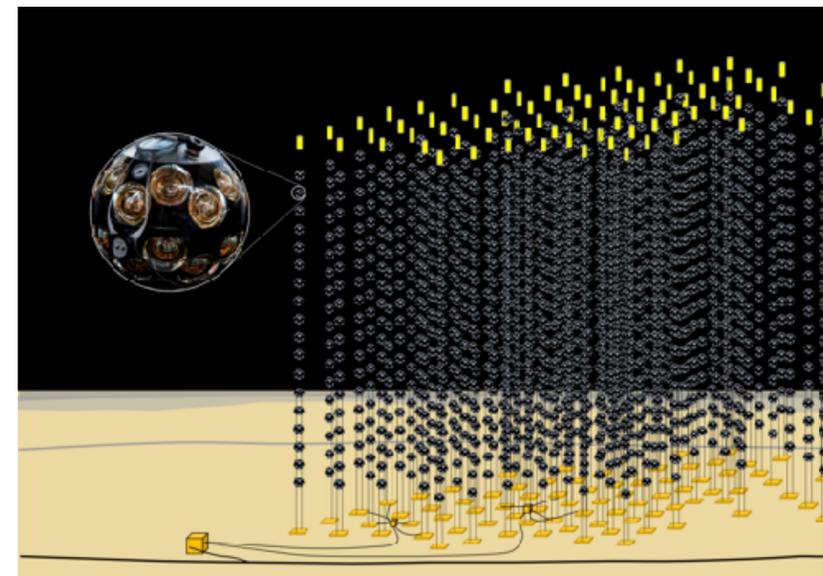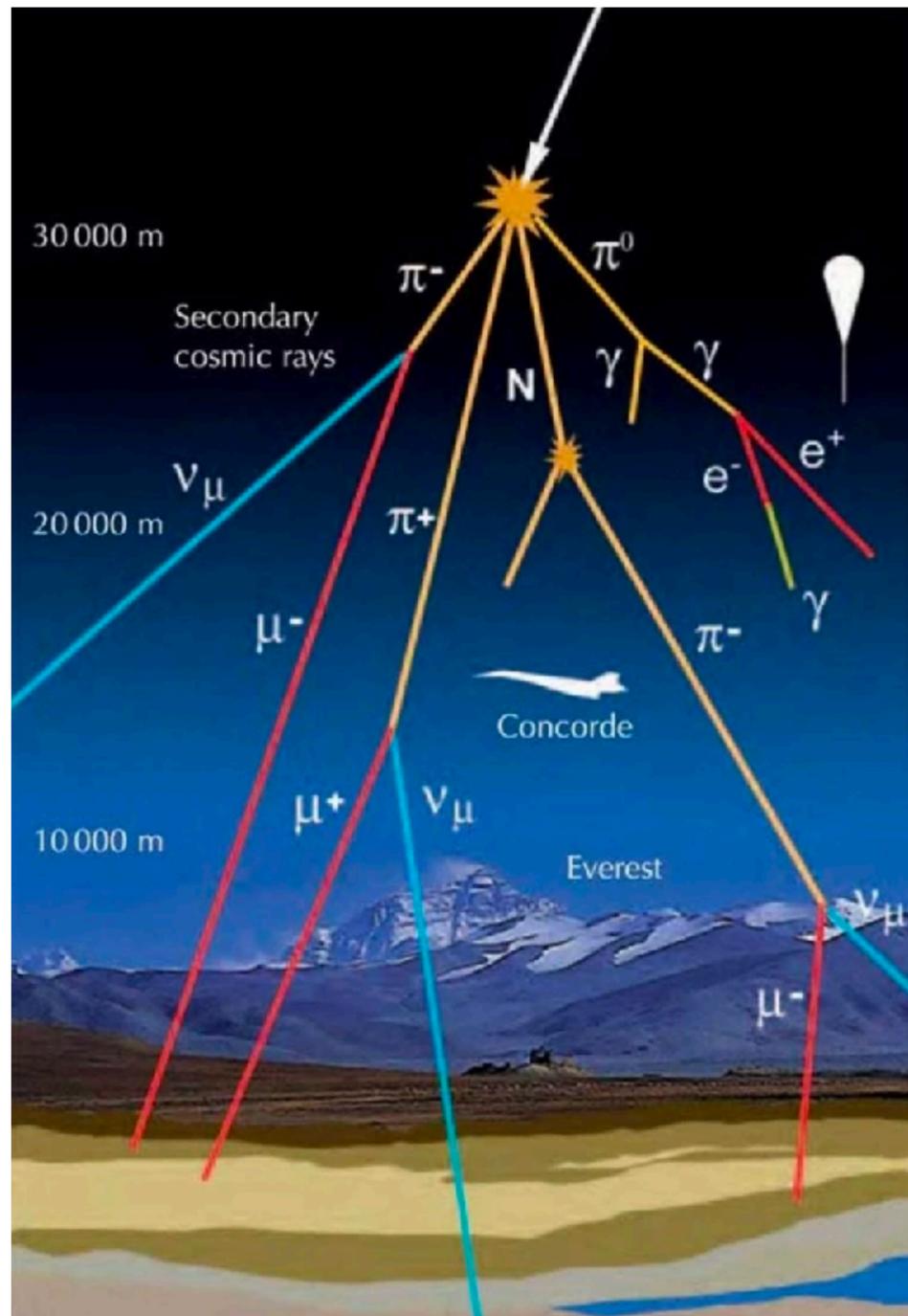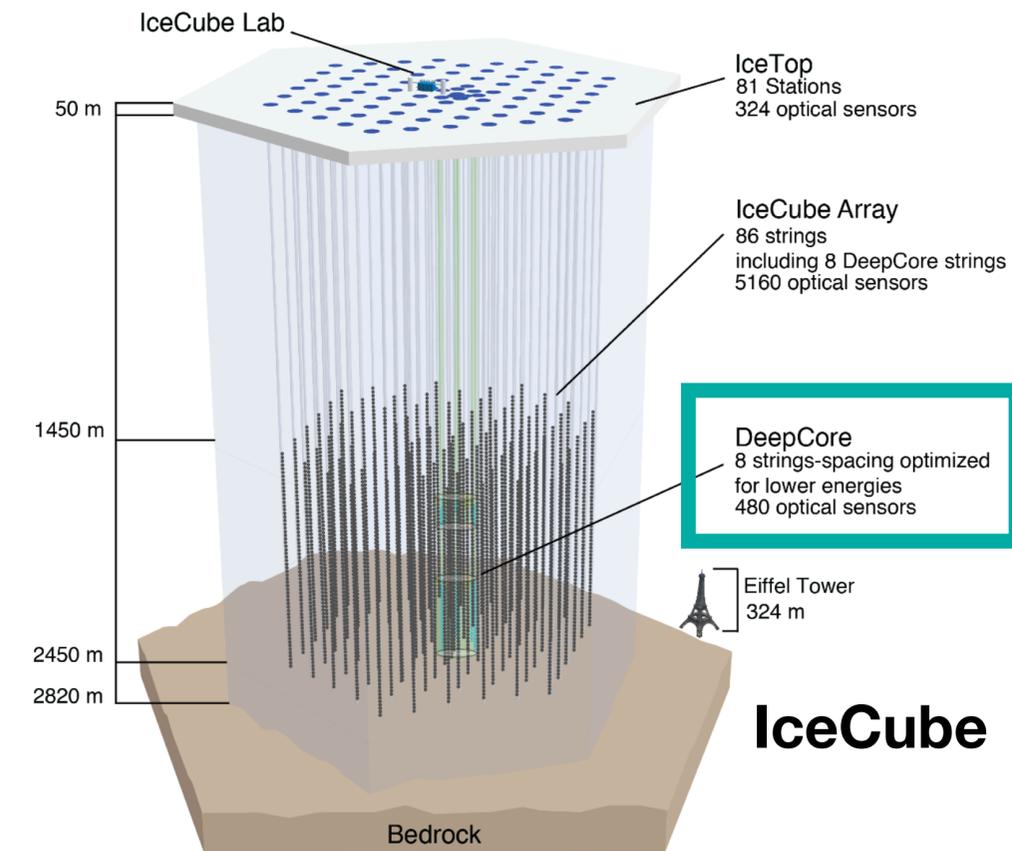
- Atmospheric neutrino experiments have limited CP sensitivity:

  - Both $\nu/\bar{\nu}$ in the flux with large uncertainties;

  - Difficult to identify $\nu/\bar{\nu}$ in massive water detectors.

- But offers MO measurement that is helpful to break the degeneracy between MO and CP.

  - T2K + Super-K; Hyper-K accelerator + atmospheric

Current Experiments

NOvA

Far Detector
14-kton
896 planes
344,064 channels
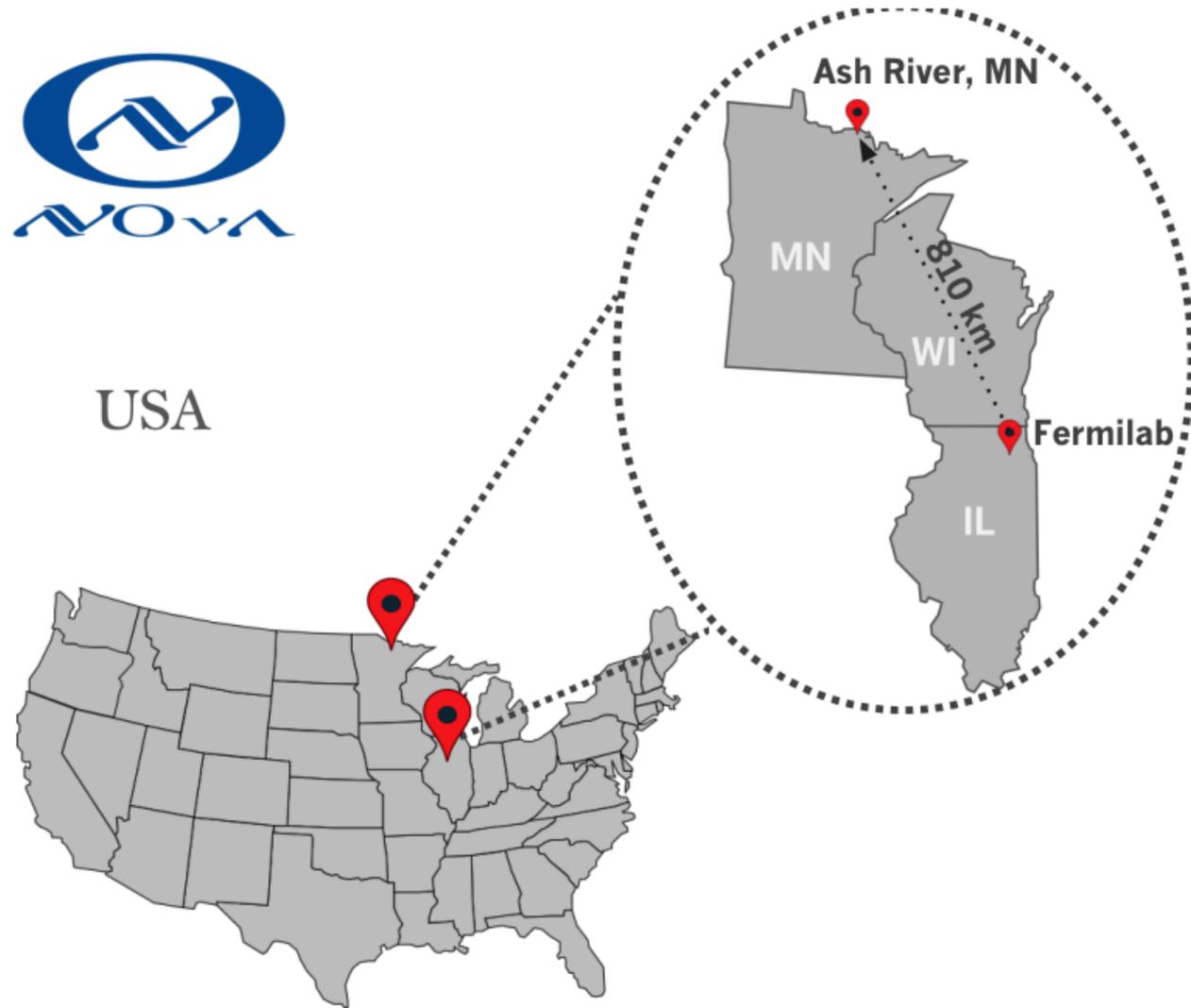
3D schematic of
NOvA particle detector
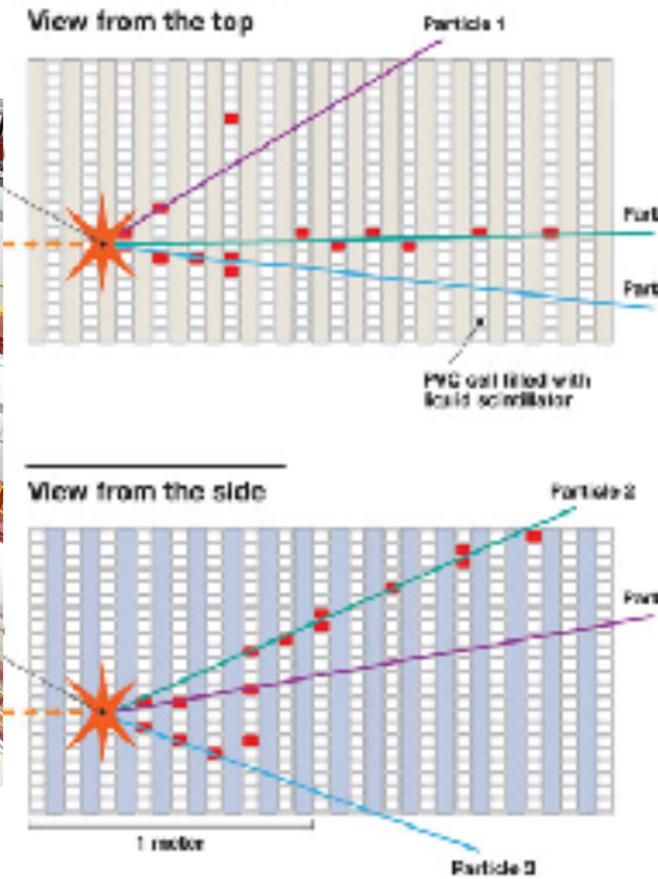
- 14 kton segmented LS detector.
- 810 km baseline.
- $\nu_\mu/\bar{\nu}_\mu$ flux peak at 2 GeV
- 290 ton ND for systematic cancellation.

ν_μ CC Signal

$\mu + p$

ν_e CC Signal

$e + p$

NC Signal or Background

$\pi^0 + \pi + p$

6
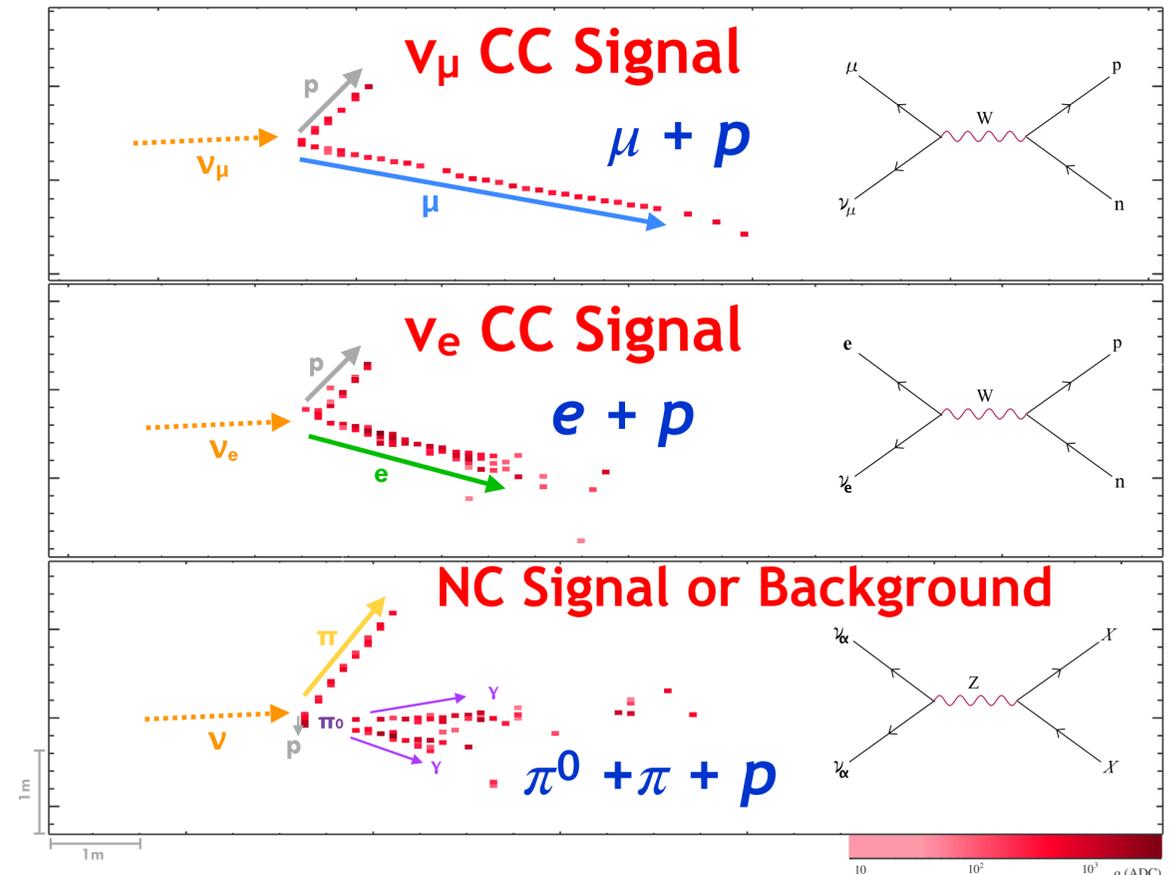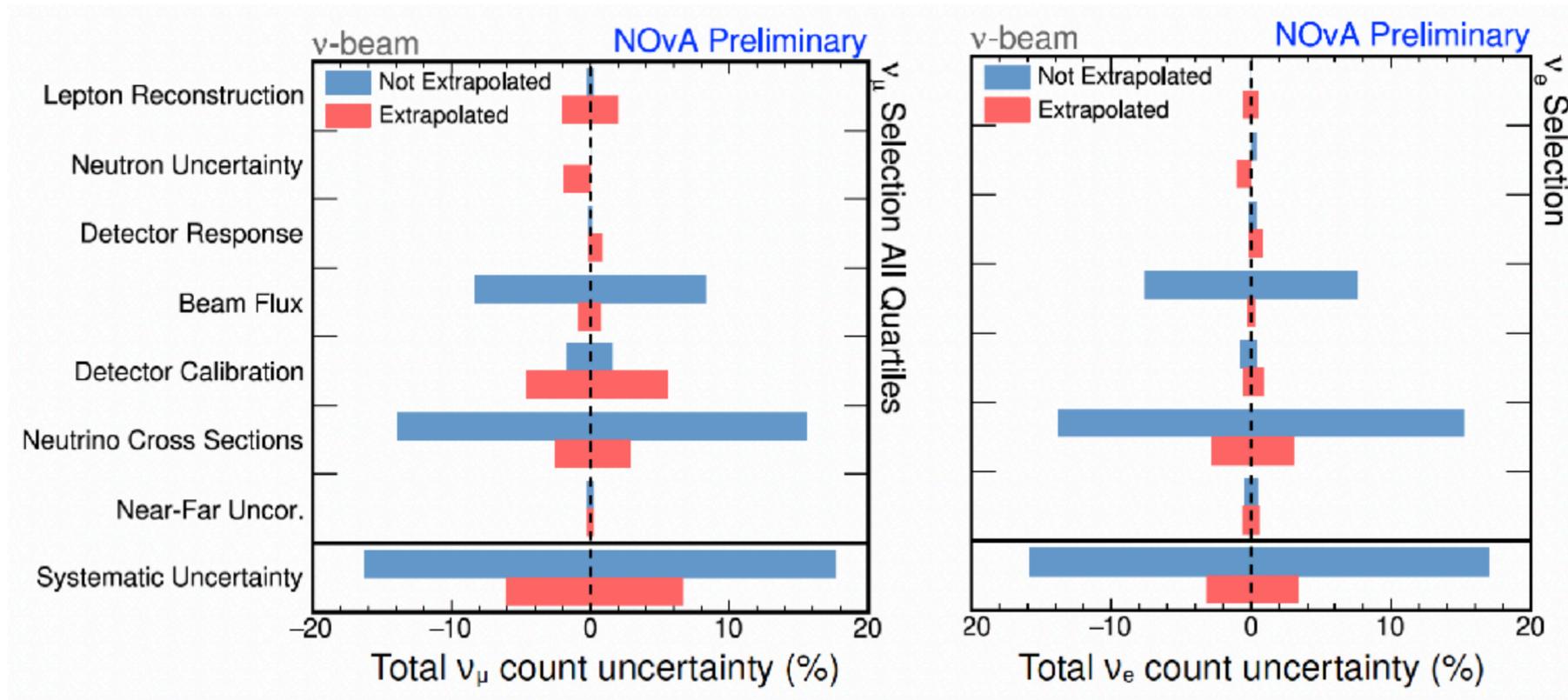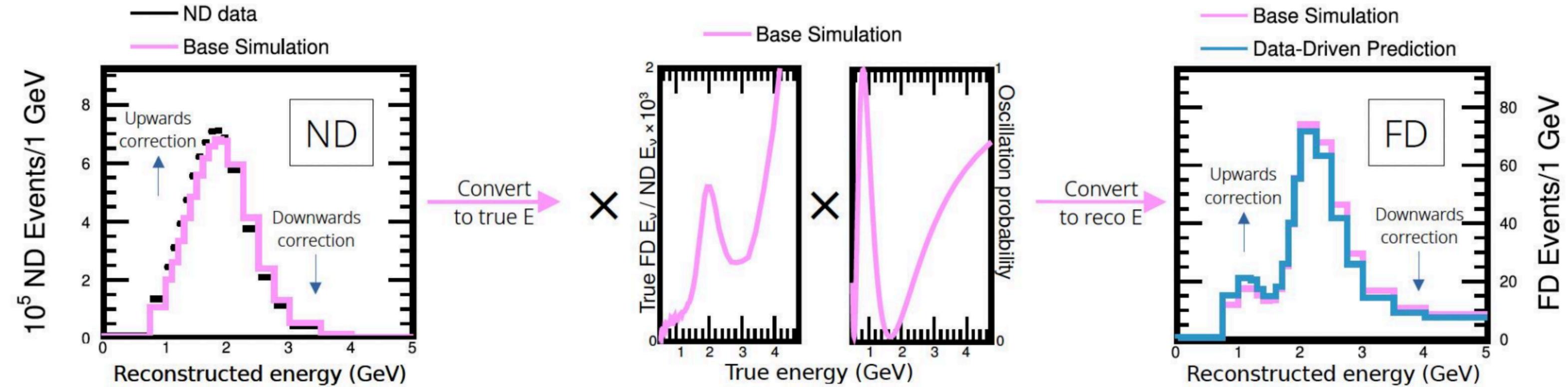
NOvA

- Both $\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance channels
- Similar far/near detectors allows for near-to-far extrapolation.
  - Systematic uncertainties largely reduced by near detector constraints.

NOvA
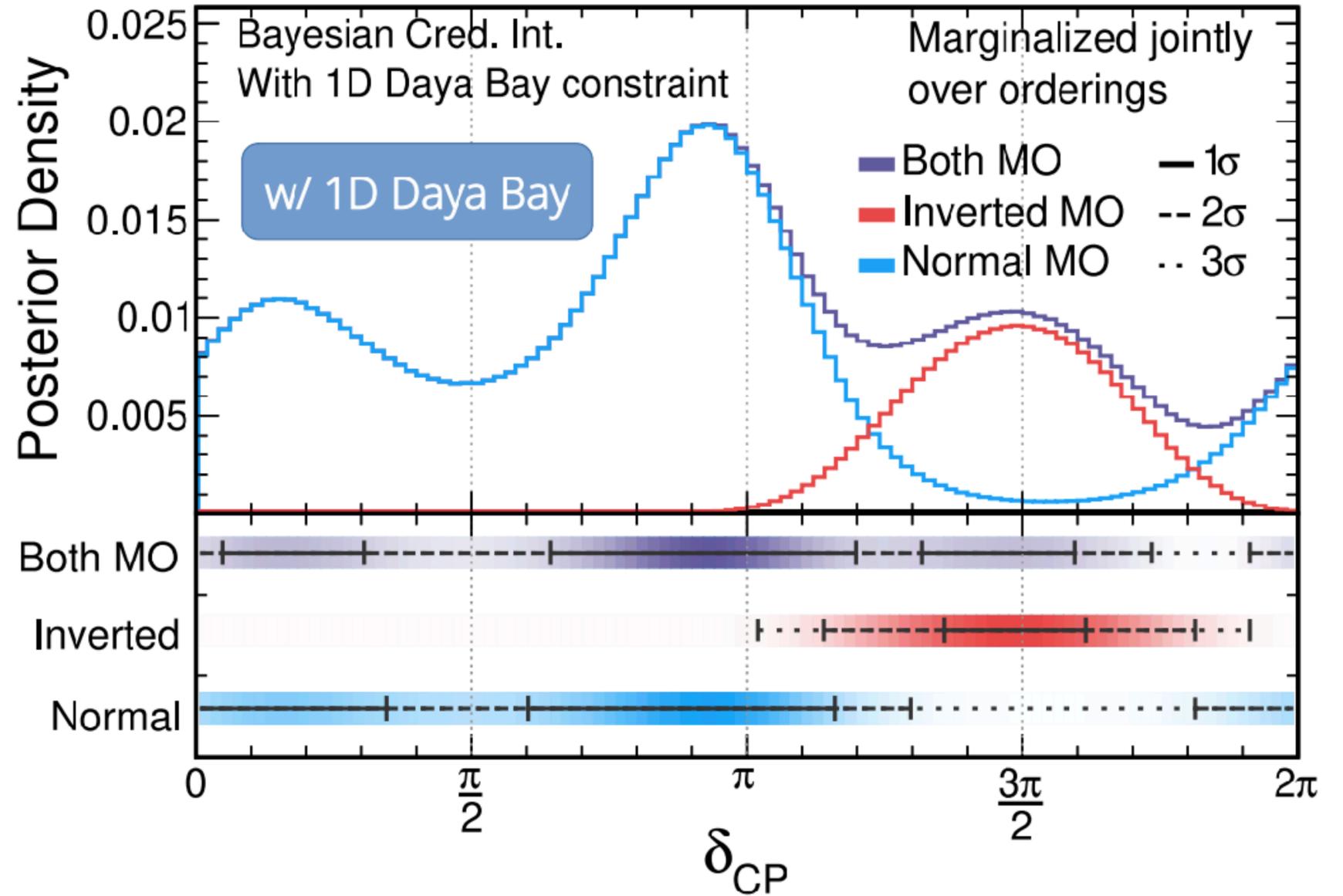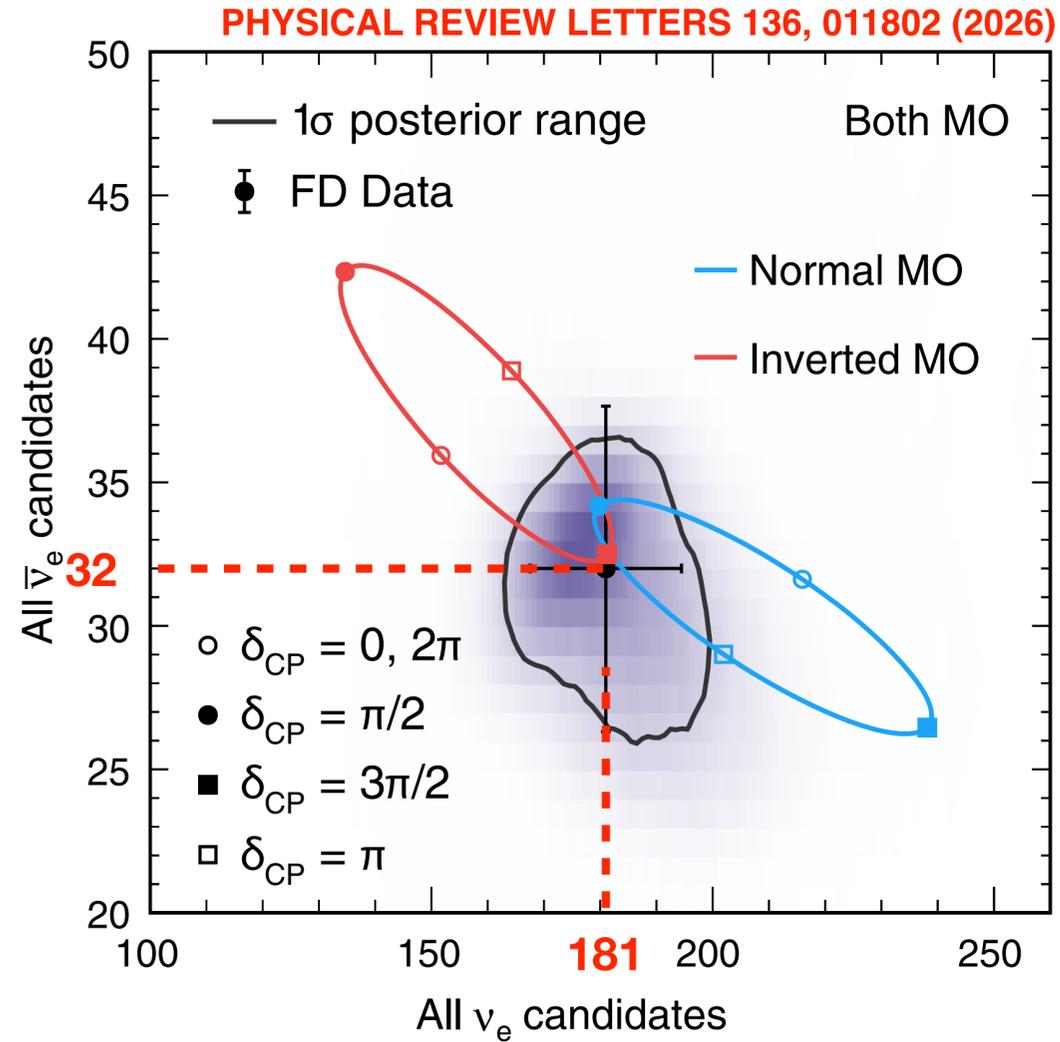
- 10 years of data published in 2026.

- Degeneracy between CP and MO:

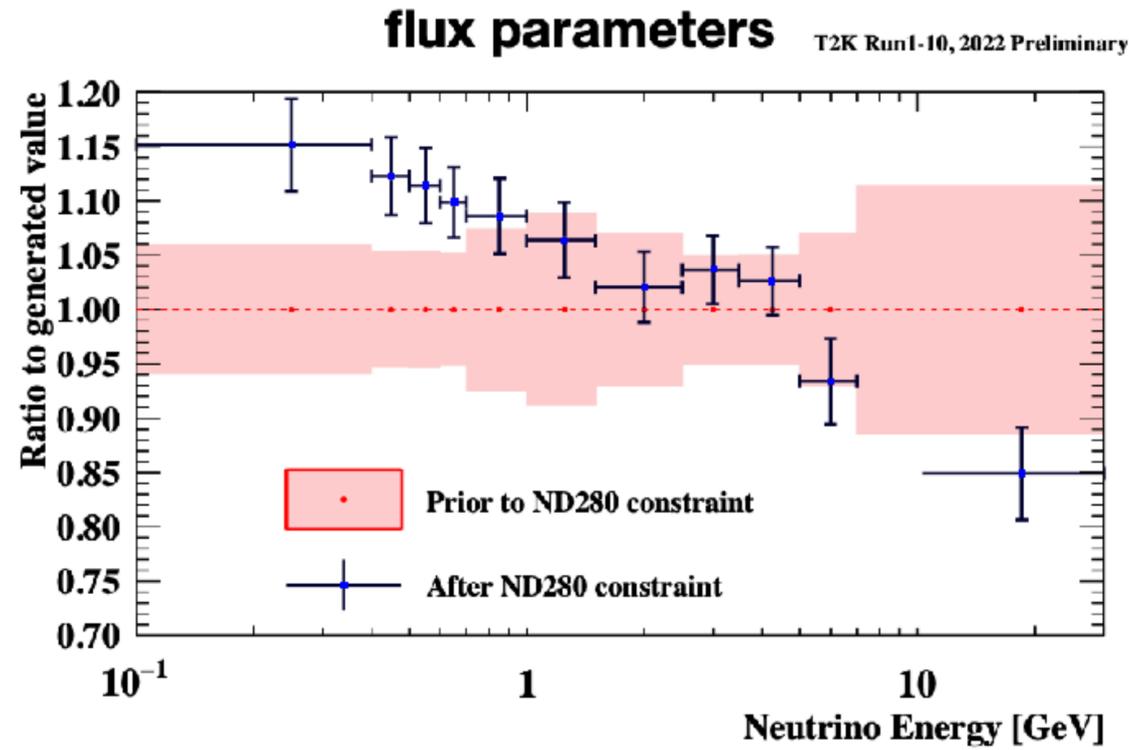 - Best fit values: $\delta_{CP} = \pi$ in NO, no exclusion of $\pi/2$ or $3\pi/2$, but $3\pi/2$ in IO

T2K

TPC1 TPC2 TPC3
FGD1 FGD2

e-like

μ-like
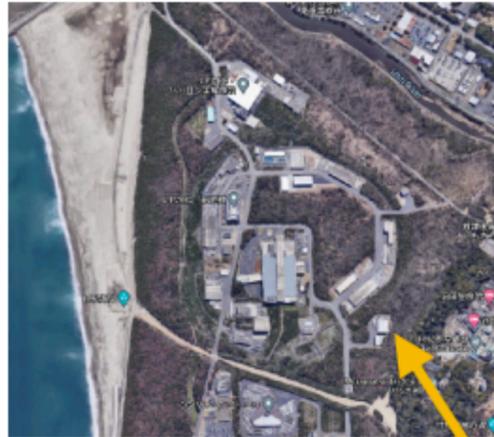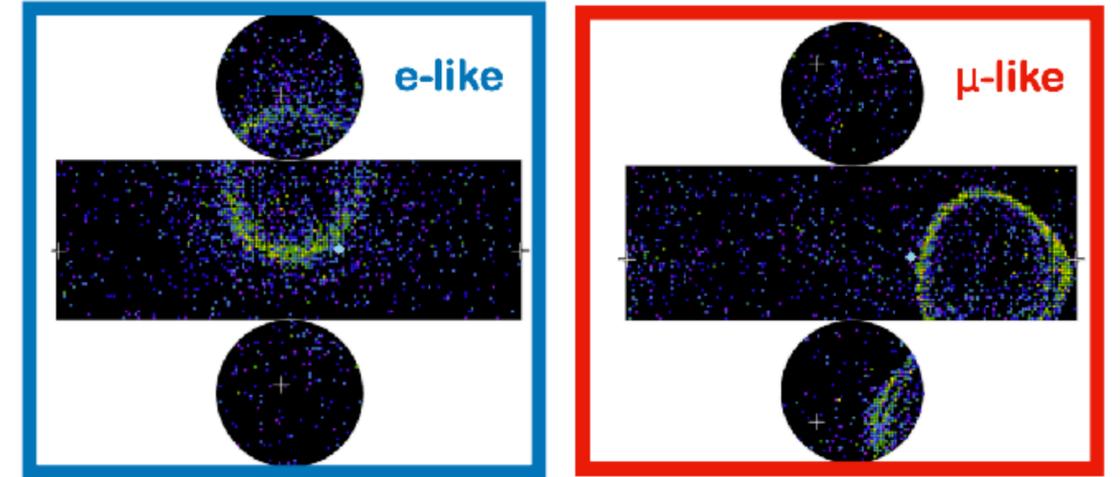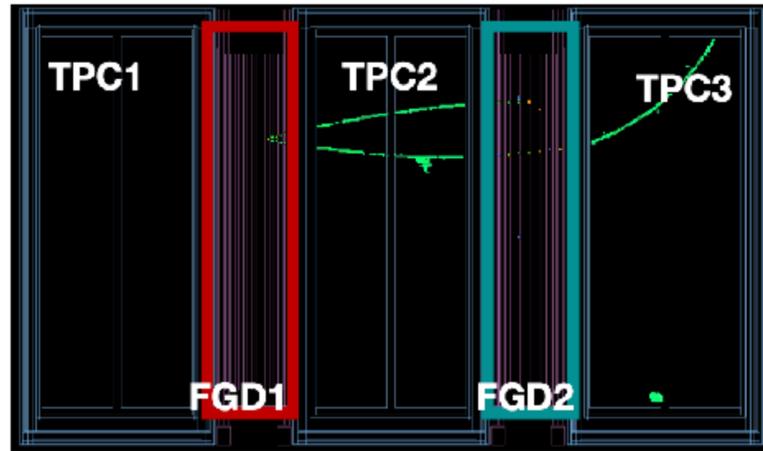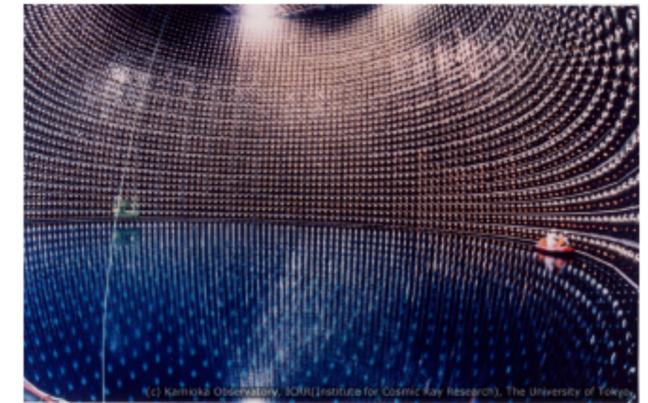
J-PARC ND280

Super-Kamiokande

Mt. Ikeno
1,360 m

ν_μ ν_μ ν_e

Tokai

295 km

Kamioka

OA 0.0°
OA 2.0°
OA 2.5°

$\Phi_{\nu_\mu}^{295km}$ (A.U.)

E_ν (GeV)

T2K

flux parameters — T2K Run1-10, 2022 Preliminary

CCQE x-sec parameters — T2K Run1-10, 2022 Preliminary
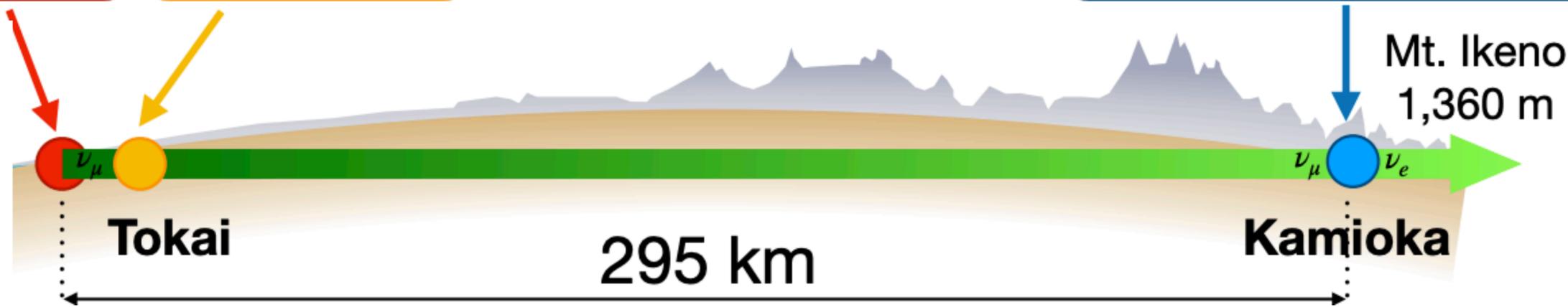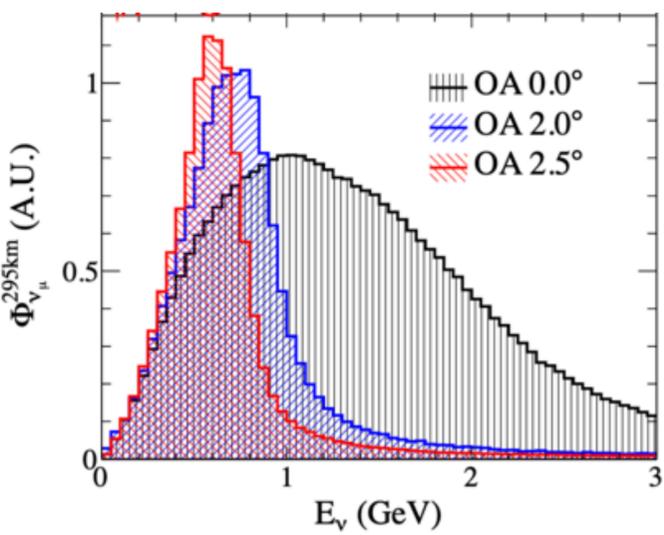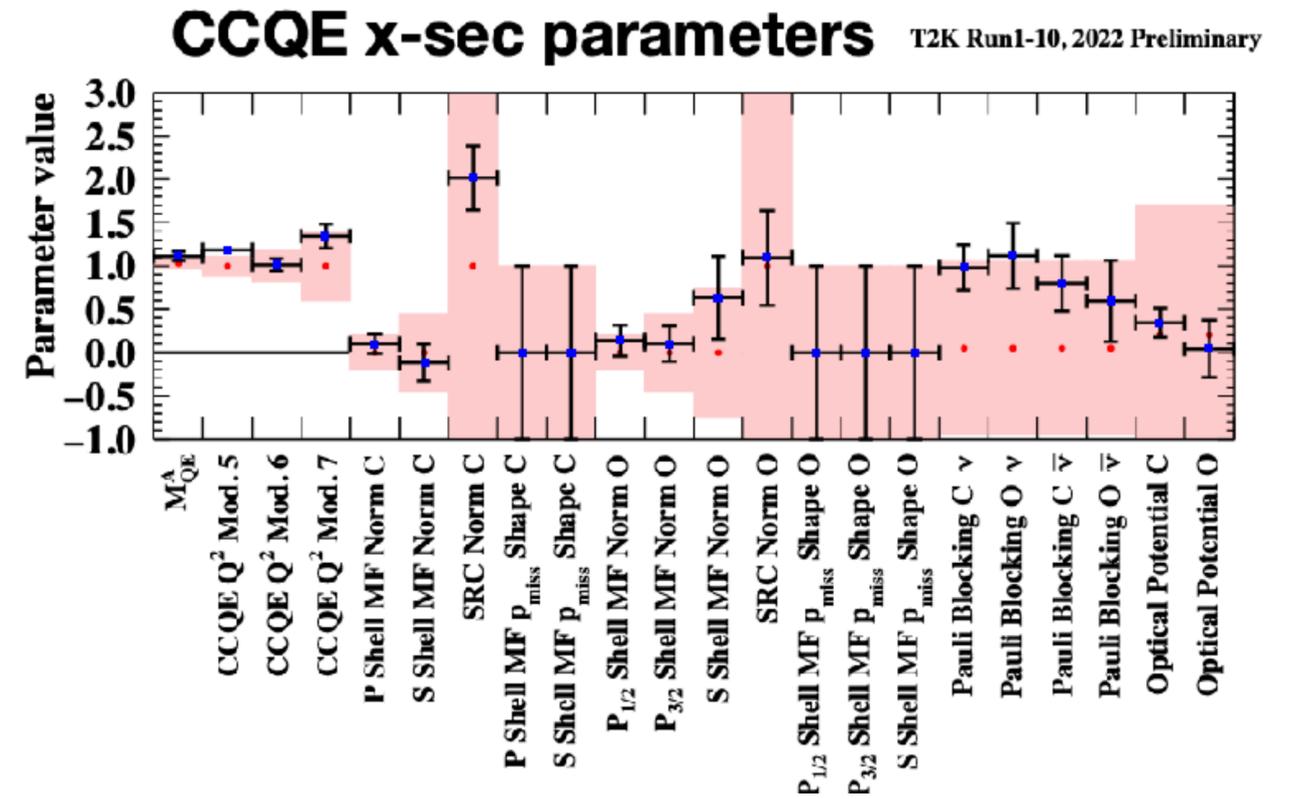
- Flux, cross-section uncertainties reduced by near-detector fit.

- Correlate flux and cross-section to predict expected spectra at the Far Detector

T2K Run 1–10, 2022 preliminary

T2K
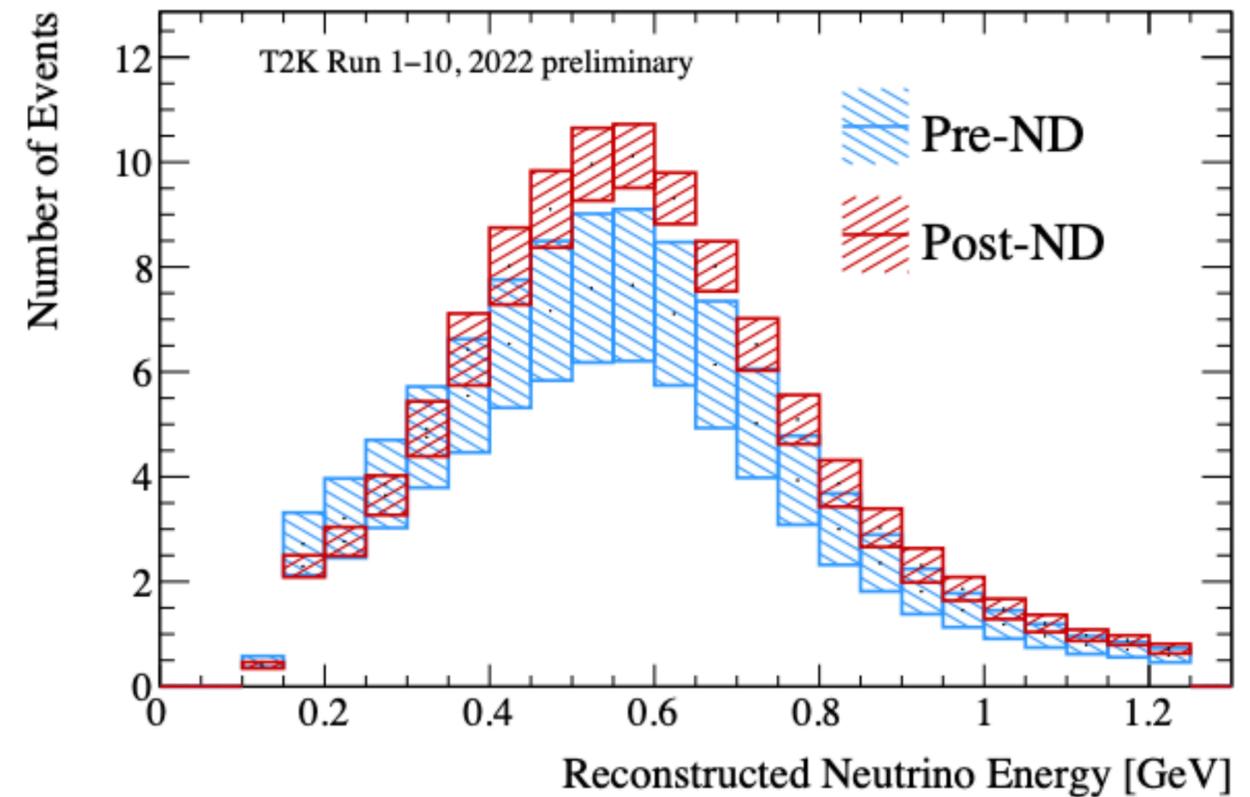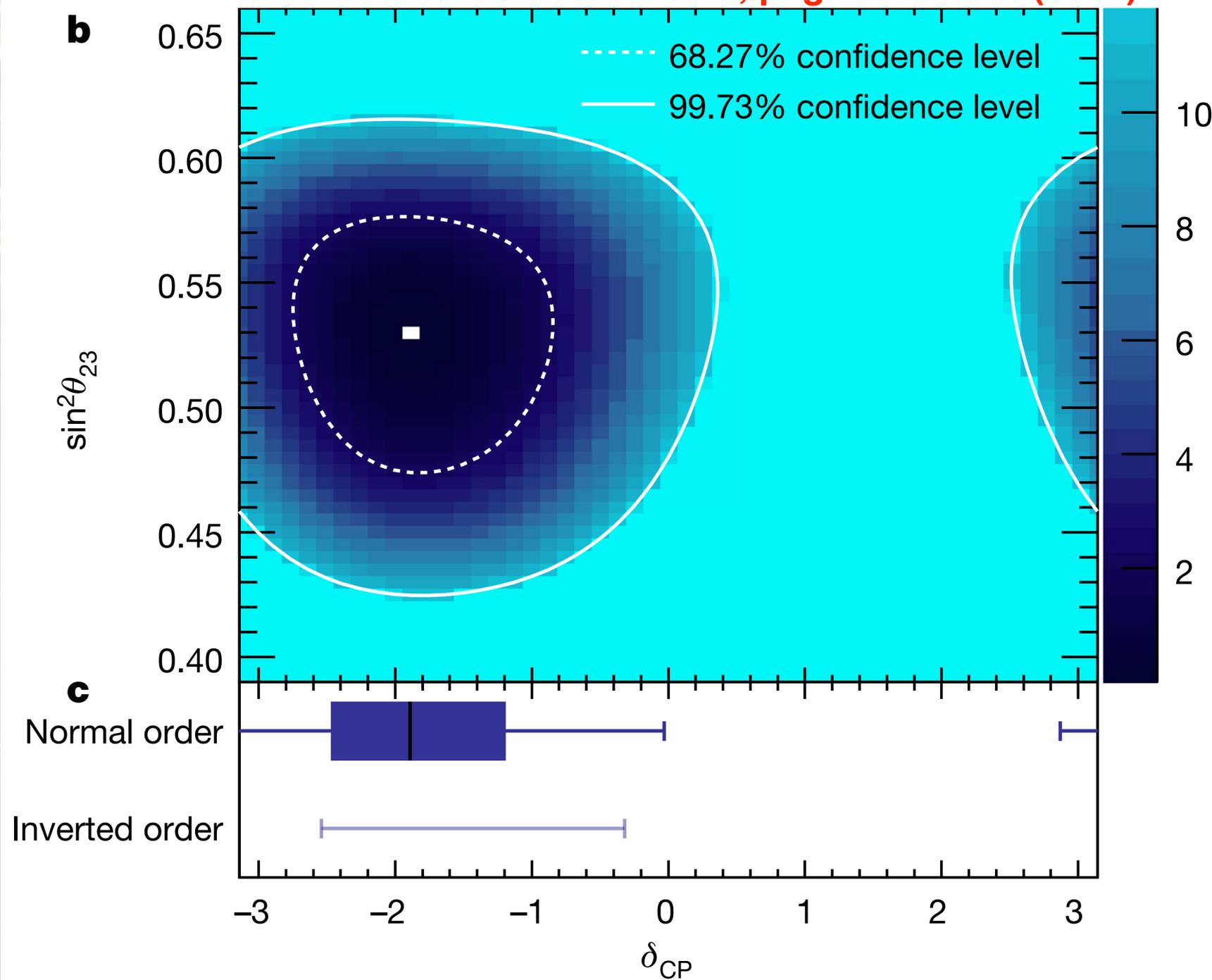
- Prefer near-maximum CP violation in NO.

- CP conservation excluded by ~3σ in NO.

T2K
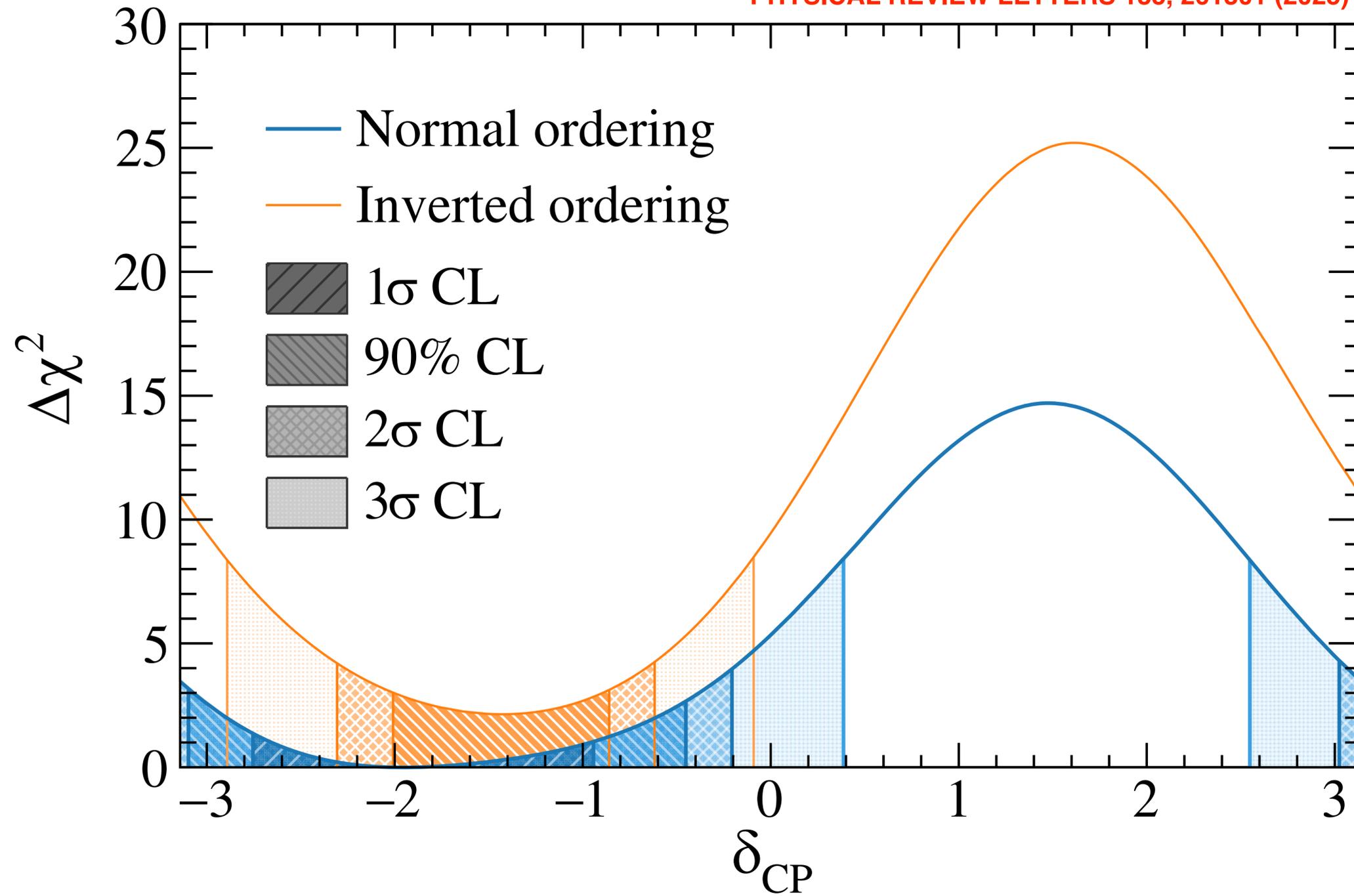
- 2025 update with additional event sample ($\nu_\mu CC1\pi^+$) and improved systematics.

NOvA+T2K

Neutrino flux
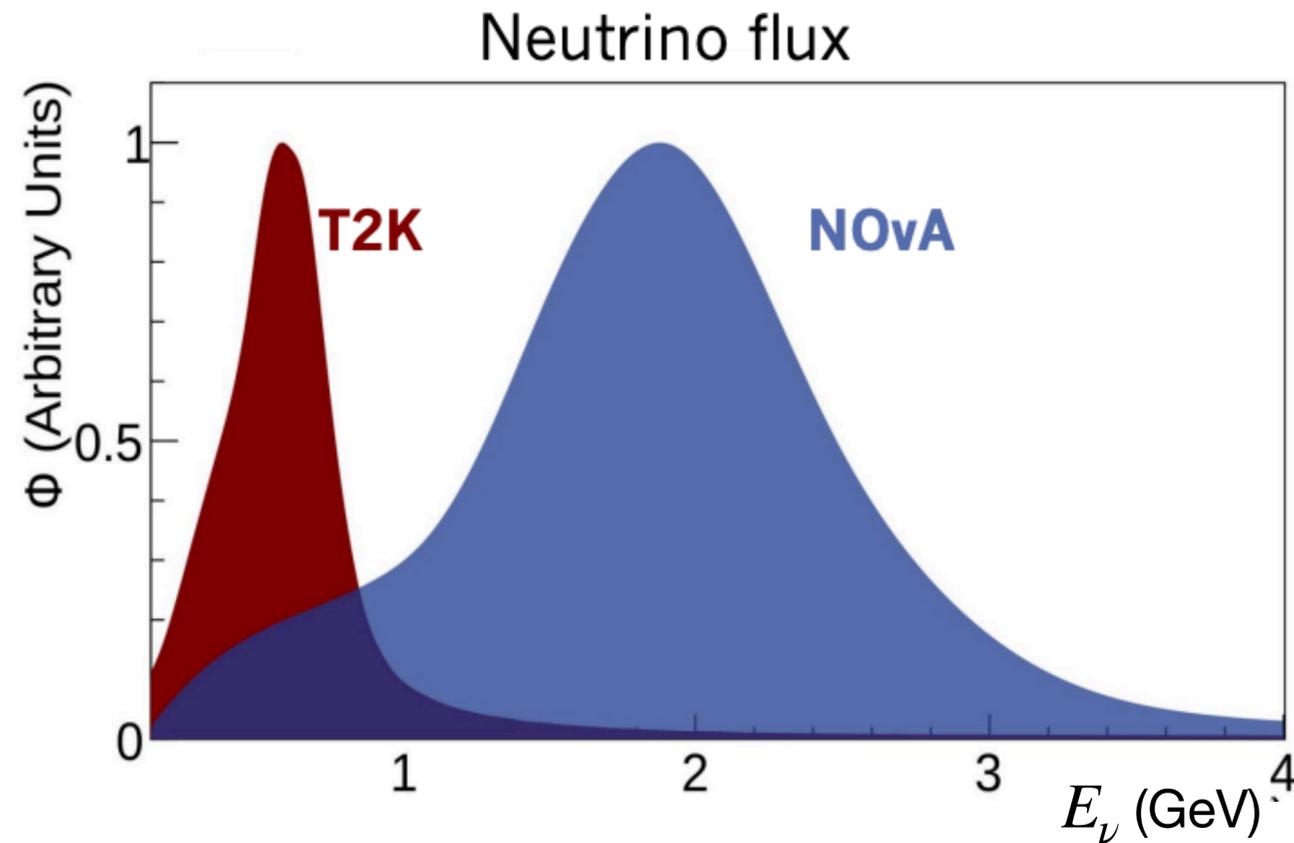
	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	~ ±9%	~ ±19%
CP effect*	~ ±30%	~ ±25%

*calculated at beam peak energy

- NOvA and T2K are complimentary:

  - NOvA: higher energy, longer baseline, larger matter effects: more sensitive to MO;

  - T2K: lower energy, shorter baseline, smaller matter effects: more focus on CP.

  - Different interaction channels, final-state topologies etc.

NOvA+T2K

T2K: L=295 km, E=0.6 GeV

$\sin^2 2\theta_{13} = 0.085$

$|\Delta m^2_{32}| = 2.5 \times 10^{-3} eV^2$

$\sin^2 \theta_{23} = 0.5$

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

$P(\nu_\mu \rightarrow \nu_e)$ %

δCP phase

○ δ=0   ● δ=π/2
□ δ=π   ■ δ=-π/2

NOvA: L=810 km, E=2.0 GeV

$\sin^2 2\theta_{13} = 0.085$

$|\Delta m^2_{32}| = 2.5 \times 10^{-3} eV^2$

$\sin^2 \theta_{23} = 0.5$

Inverted ordering

Mass ordering

Normal ordering

○ δ=0   ● δ=π/2
□ δ=π   ■ δ=-π/2
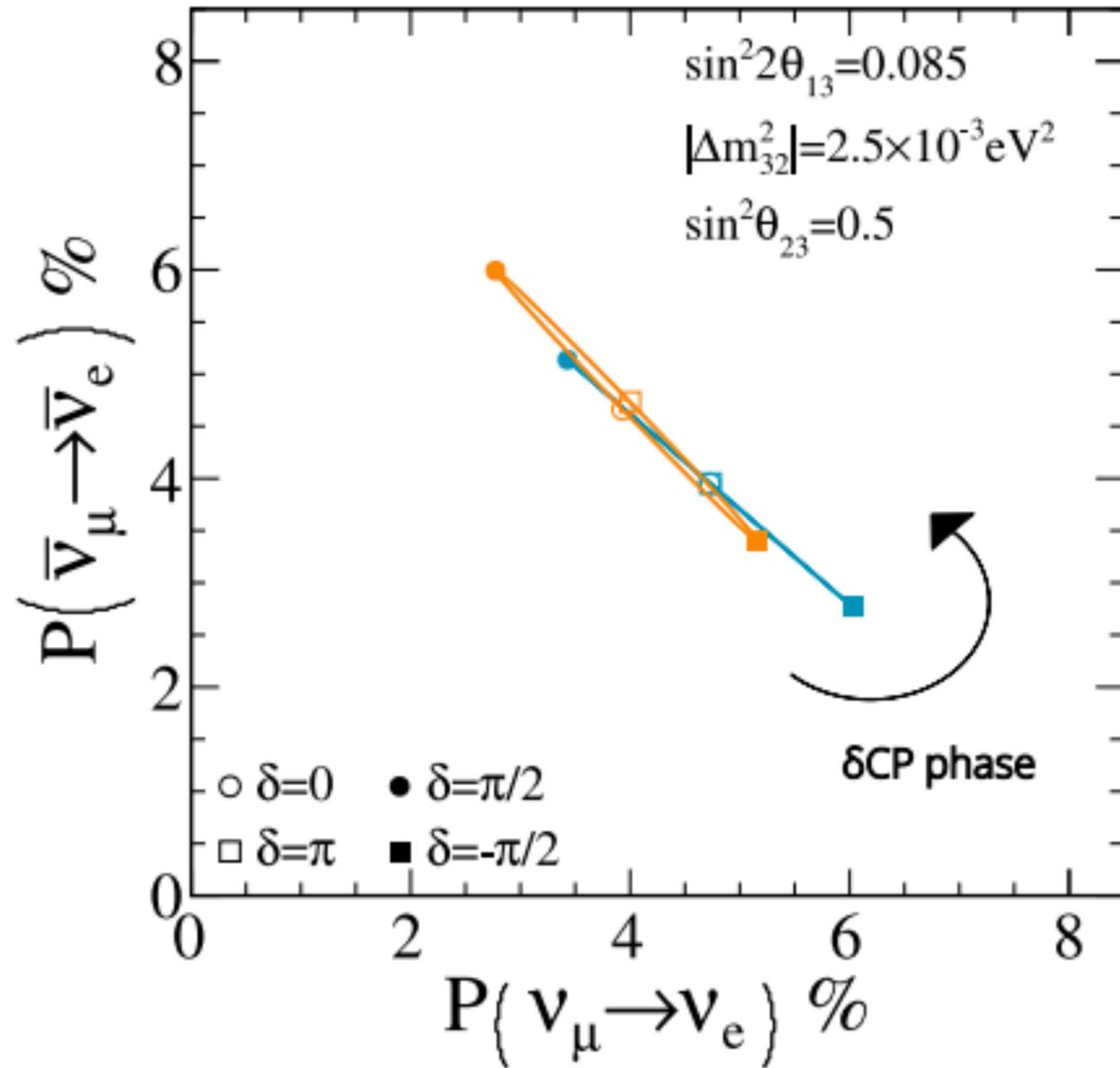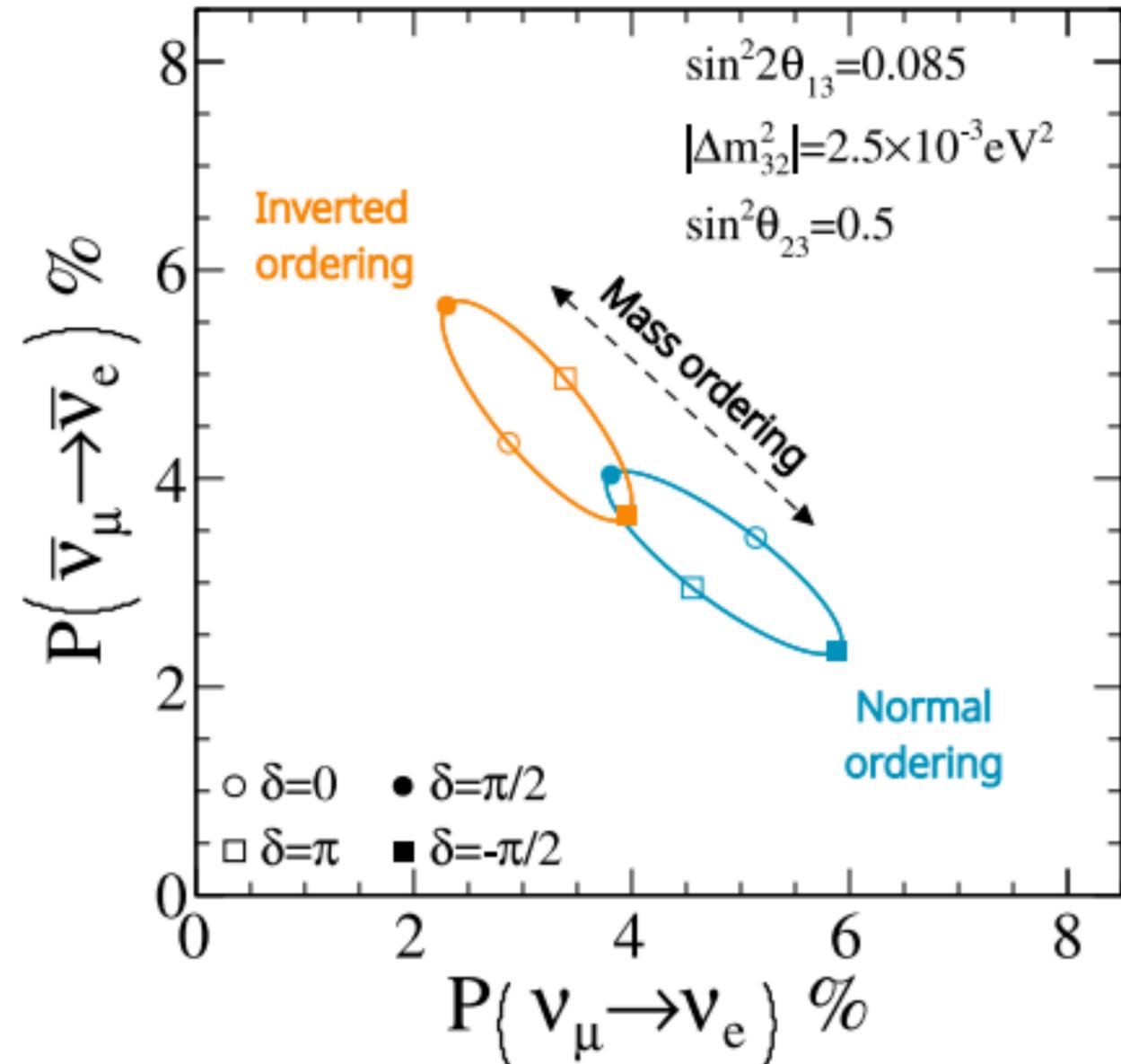
- Different experimental configurations help breaking the degeneracy.

14
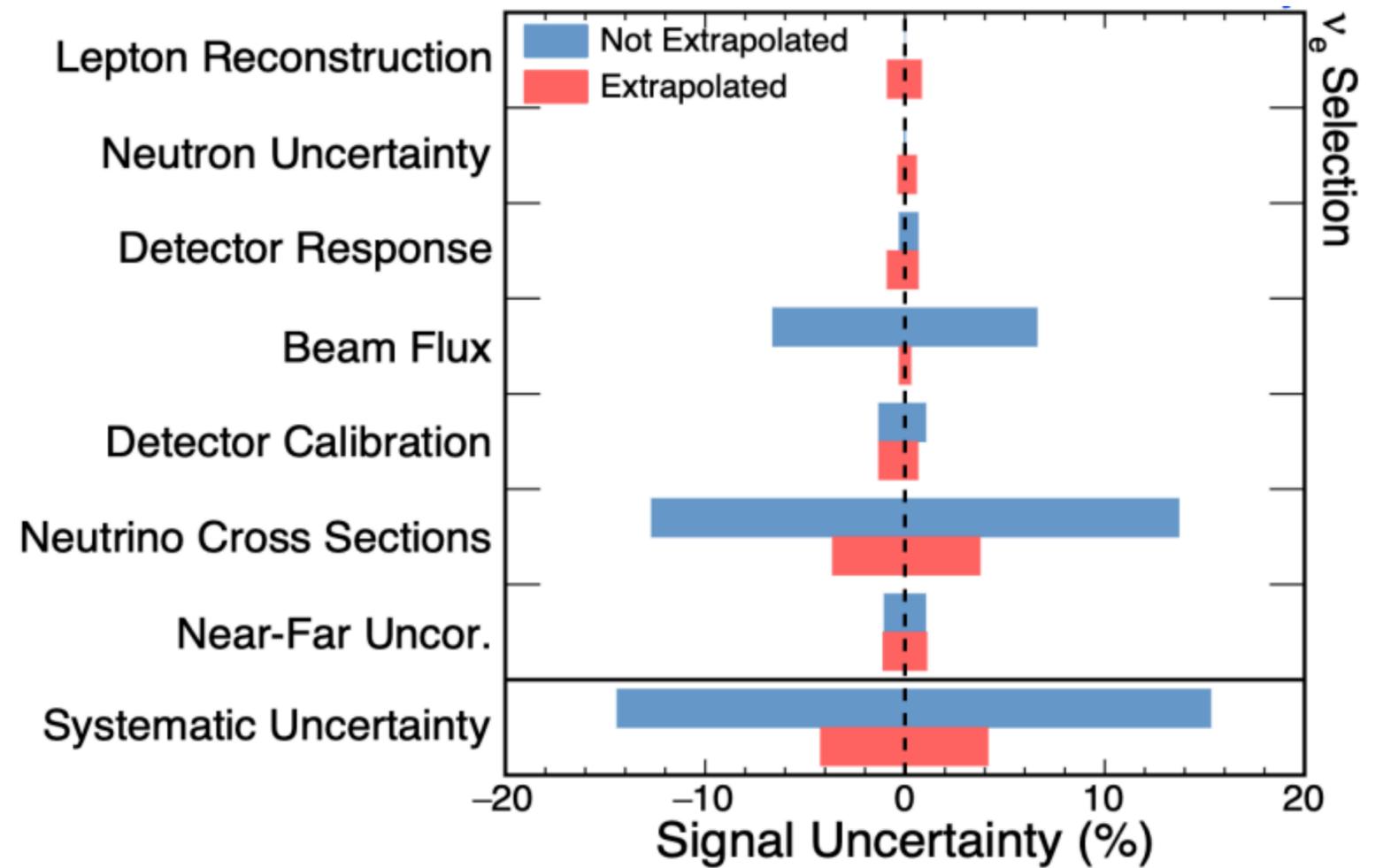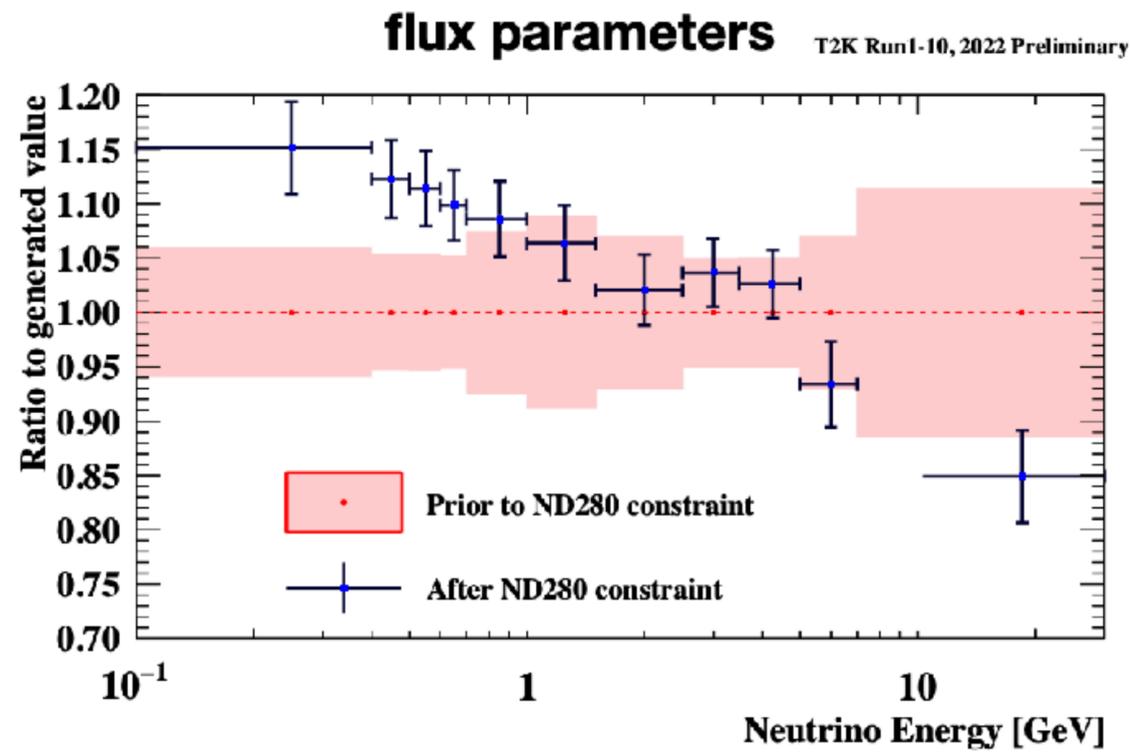
NOvA+T2K

- NOvA and T2K are share systematic uncertainty sources:
  - Flux uncertainties from hadron production modeling etc.
  - Neutrino cross sections (ν-CH, ν-H_2O).
- A joint analysis is more powerful than global fit.

NOvA+T2K
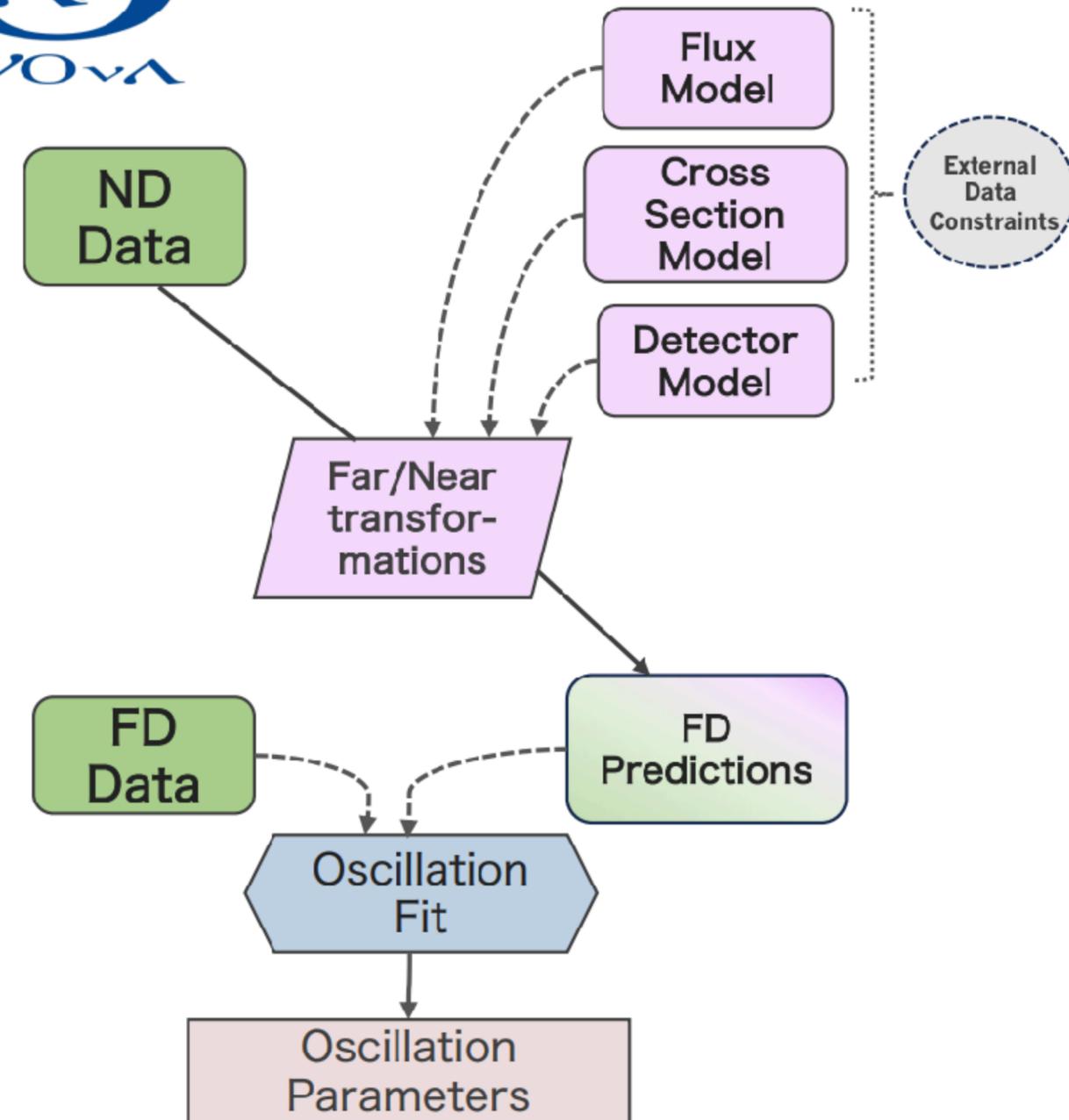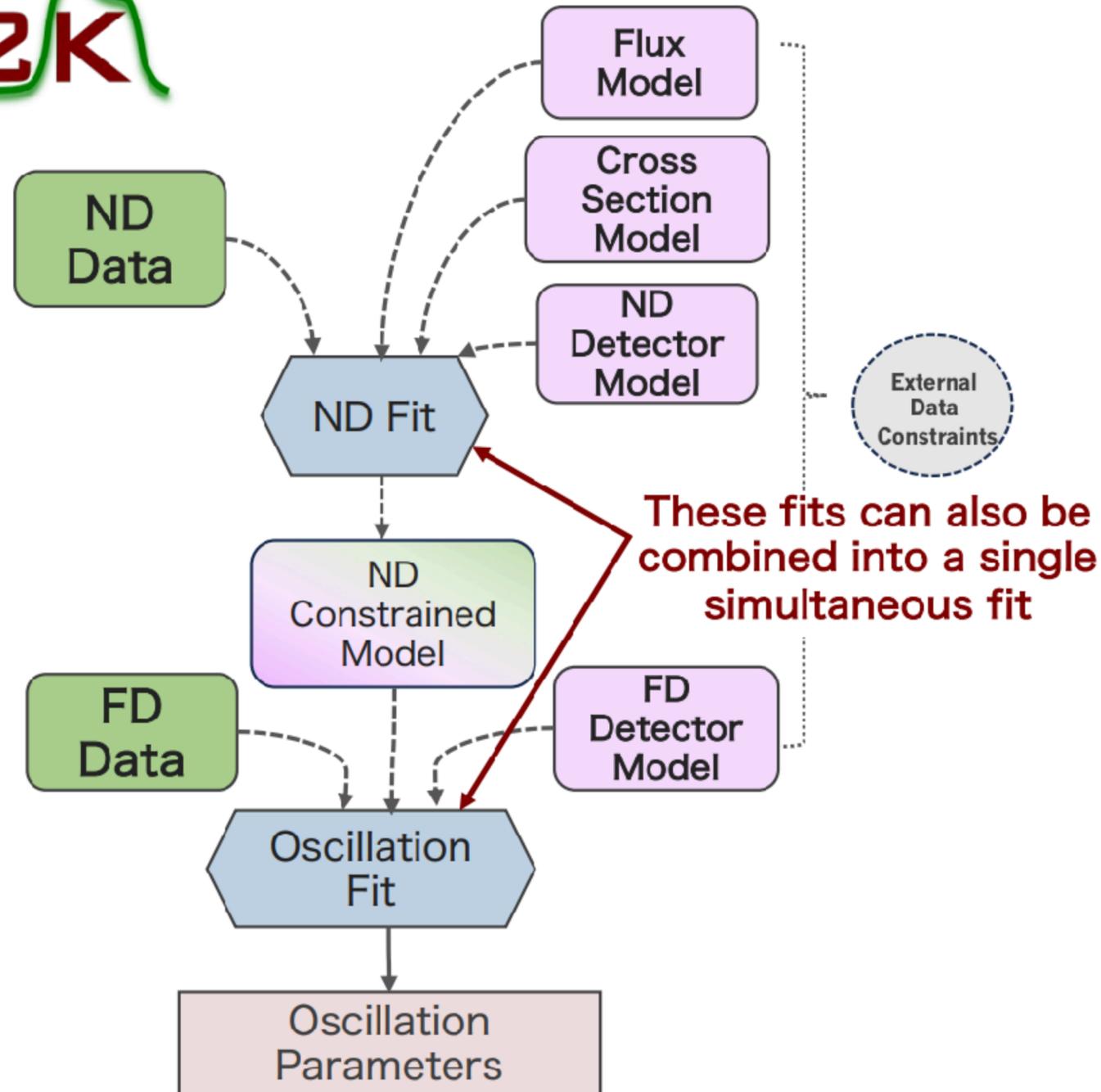
- NOvA and T2K have very different detector technologies, and as a result, very different analysis approaches

NOvA+T2K

a

$\bar{\nu}_e$ candidates

40

30

NOvA

— Normal
— Inverted
● Data

60   80   100   120

ν_e candidates

b

T2K

$\bar{\nu}_e$ candidates

20

10

■ $\delta_{CP} = -\pi/2$
▲ $\delta_{CP} = 0$
△ $\delta_{CP} = \pi/2$
□ $\delta_{CP} = \pi$

60   80 $\frac{2}{32}$ 100   120

ν_e candidates
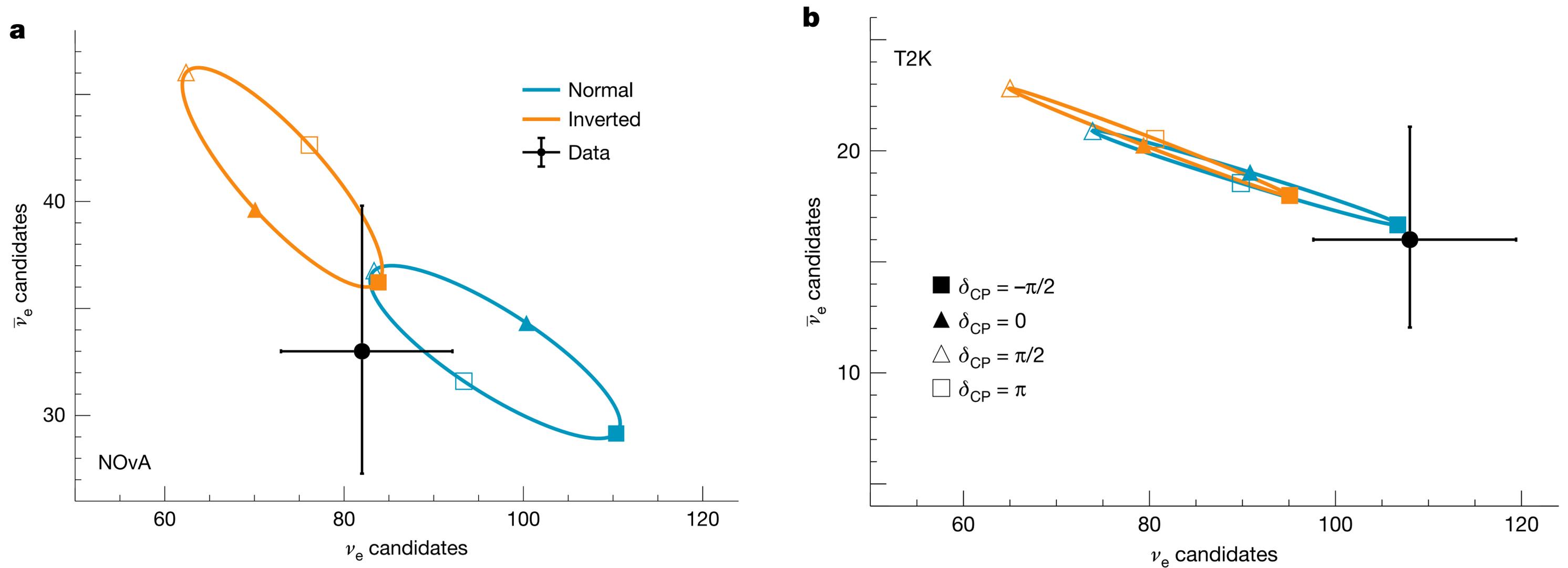
- NOvA and T2K data show different preferences in δ_{CP}

ν_e

ν_e

NOvA+T2K
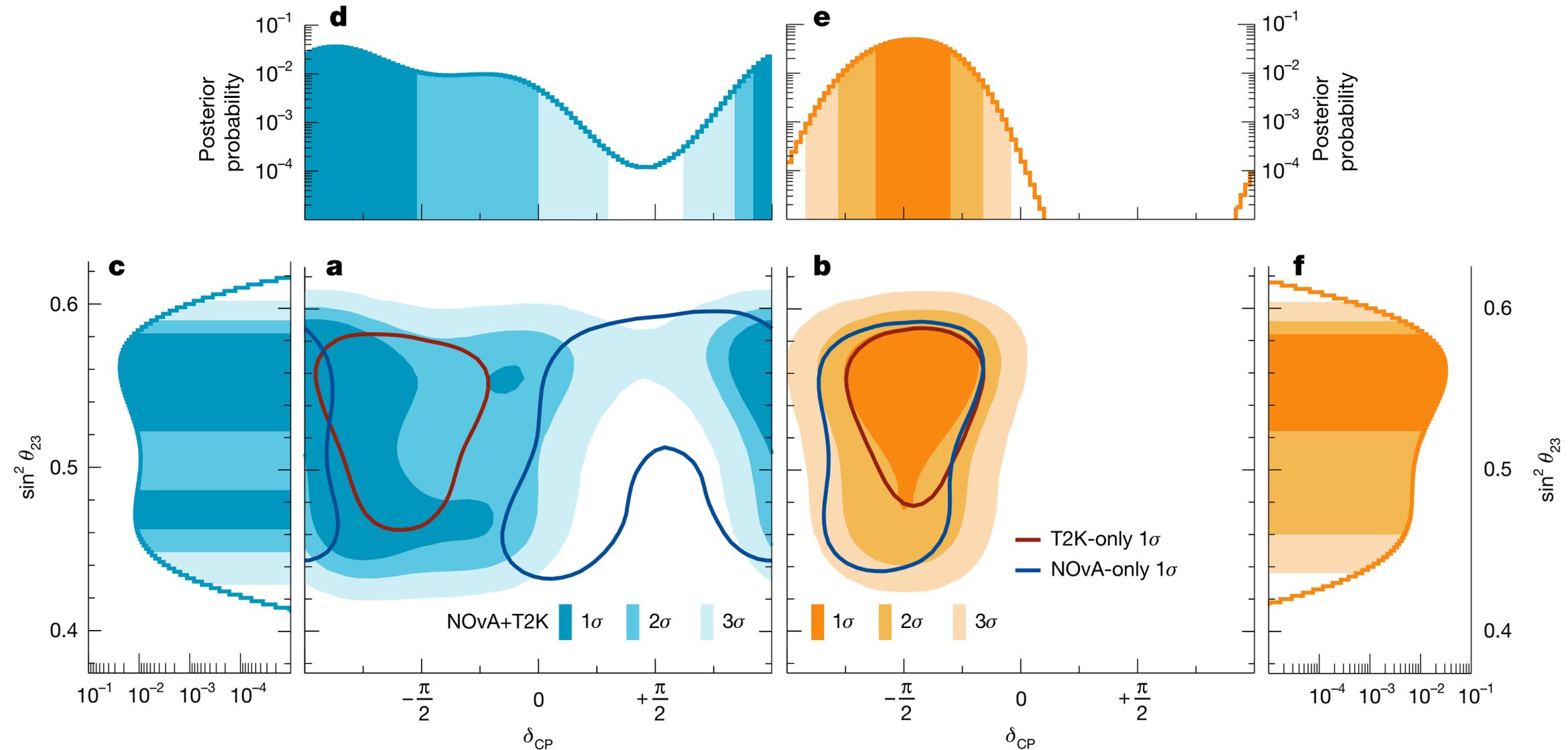
Fig. 3 | Constraints on $\sin^2\theta_{23}$ and δ_{CP}. Marginalized posterior probabilities and 1D or 2D Bayesian credible regions of $\sin^2\theta_{23}$ and δ_{CP} in the case of the normal (blue, left side) and inverted (orange, right side) neutrino mass ordering with the reactor constraint applied. Shaded areas correspond to 1σ, 2σ and 3σ credible regions. **a,b**, The 2D panels of $\sin^2\theta_{23}$ vs δ_{CP} (**a,b**) are overlaid with 1σ credible regions from the T2K-only (dark red) and NOvA-only (dark blue) data fits assuming normal (**a**) and inverted ordering (**b**). **c–f**, The 1D panels show the posterior probabilities of $\sin^2\theta_{23}$ (**c**) and δ_{CP} (**d**) in the normal ordering, and δ_{CP} (**e**) and $\sin^2\theta_{23}$ (**f**) in the inverted ordering.

- Joint NOvA and T2K analysis prefers $\delta_{CP} = -\dfrac{\pi}{2}$ in IO, but not in NO.

Next Generation Experiments

DUNE

LArTPC Event Display

Flux at ND
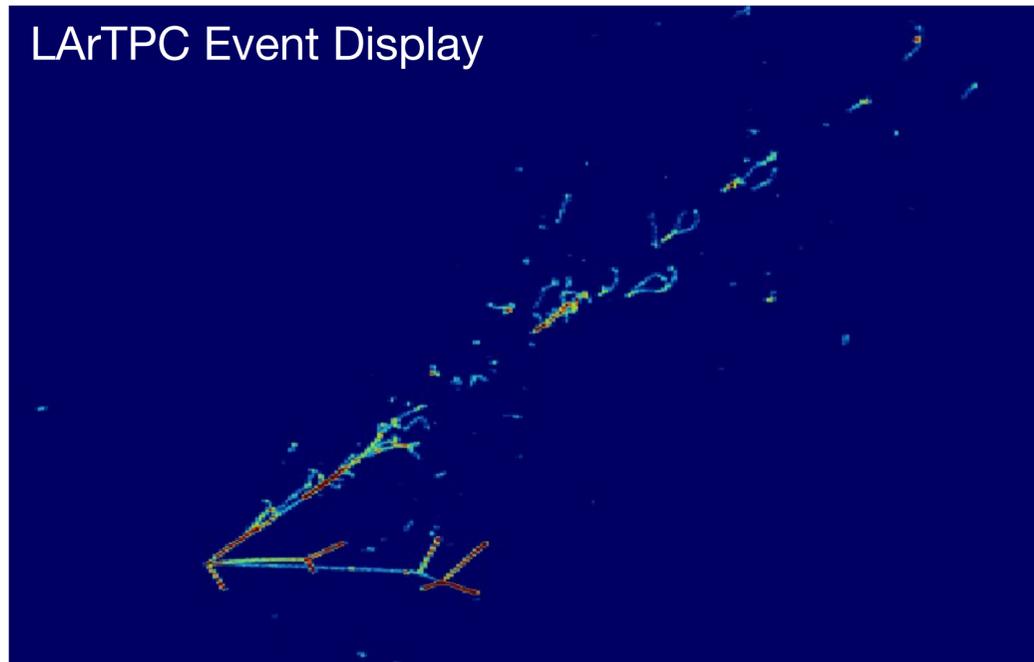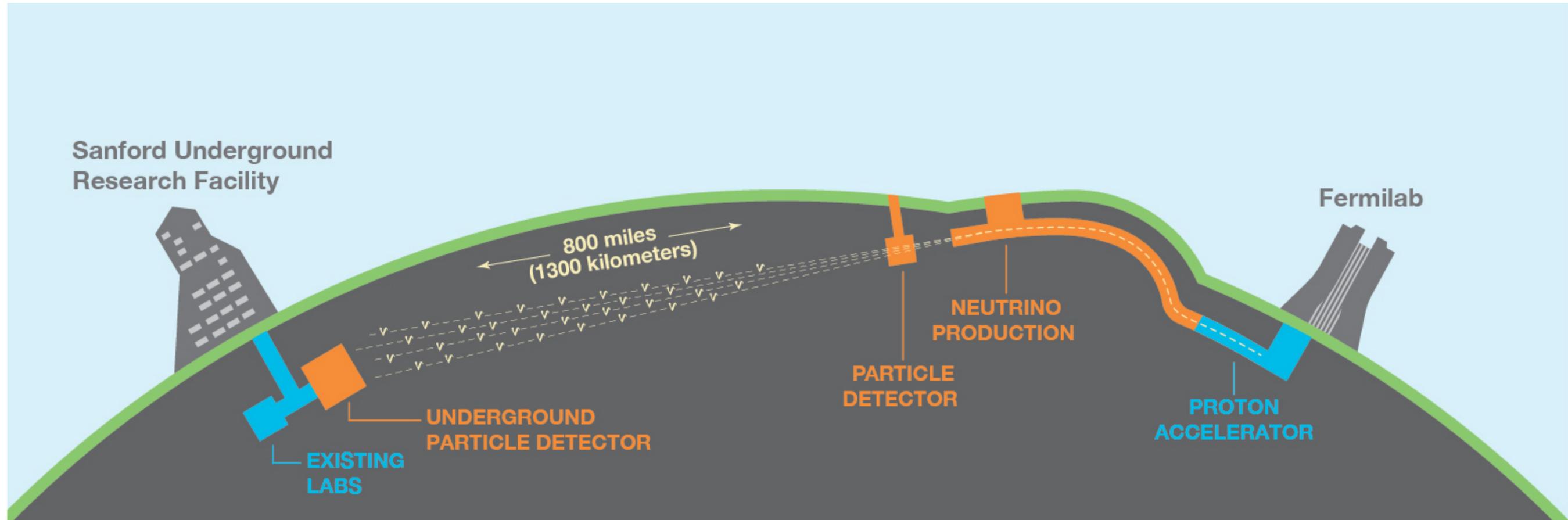
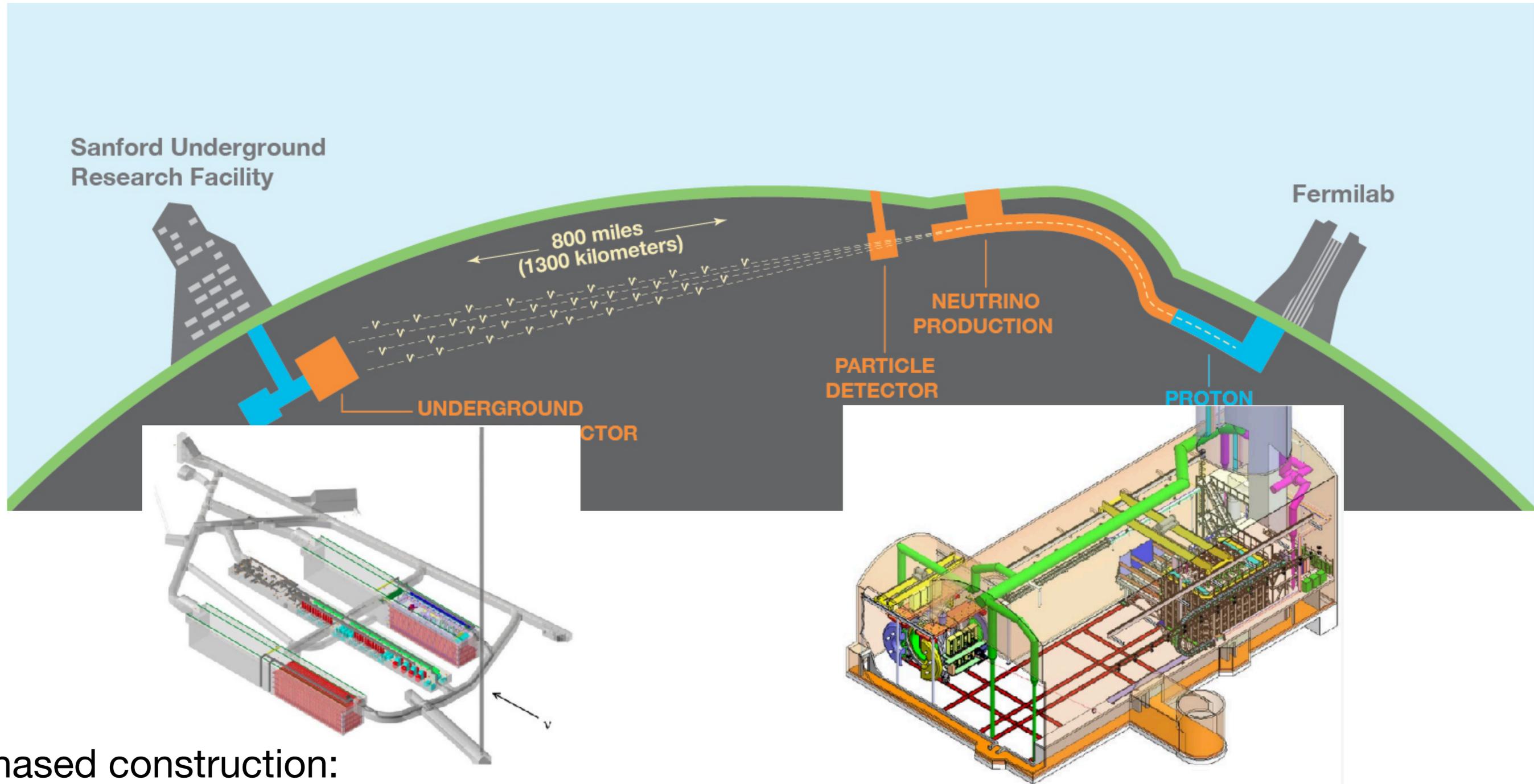- Designed with 40kton LArTPC for accurate reconstruction and PID.
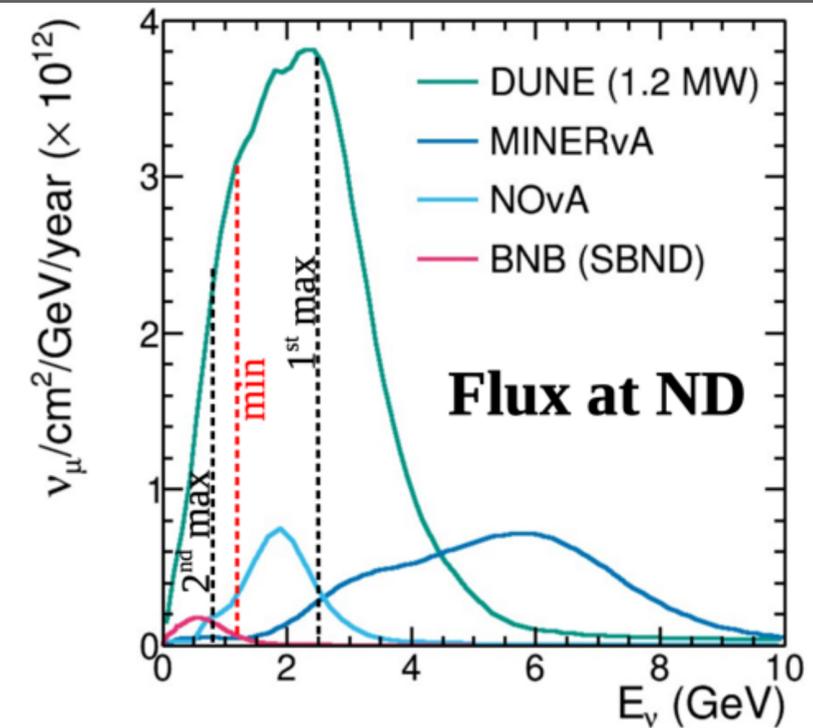
- Wide band neutrino flux covering 1st and 2nd oscillation maxima.

DUNE
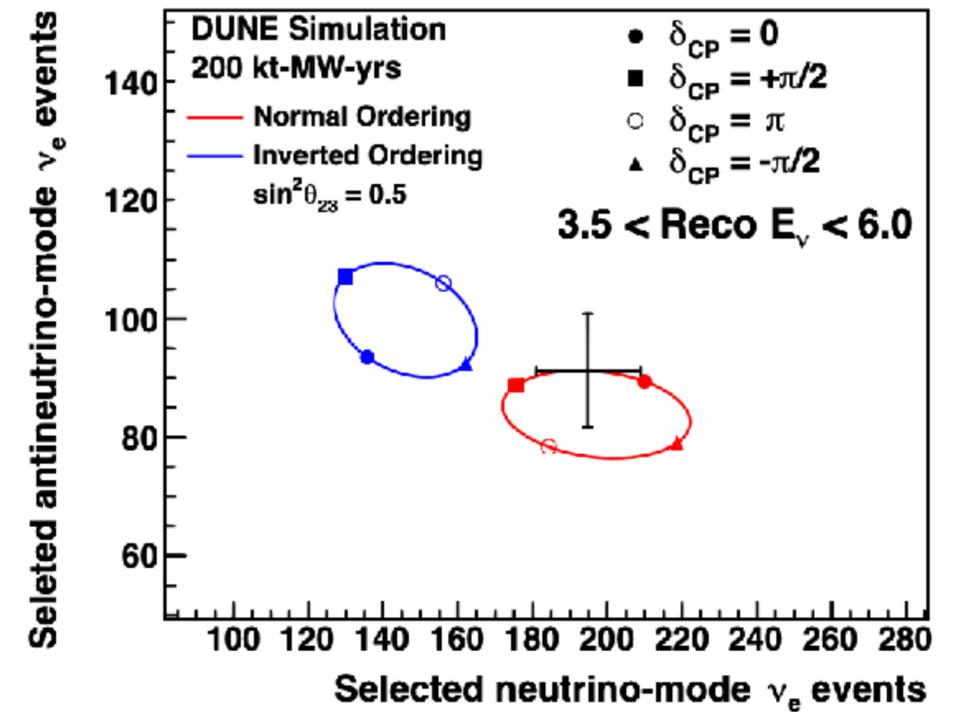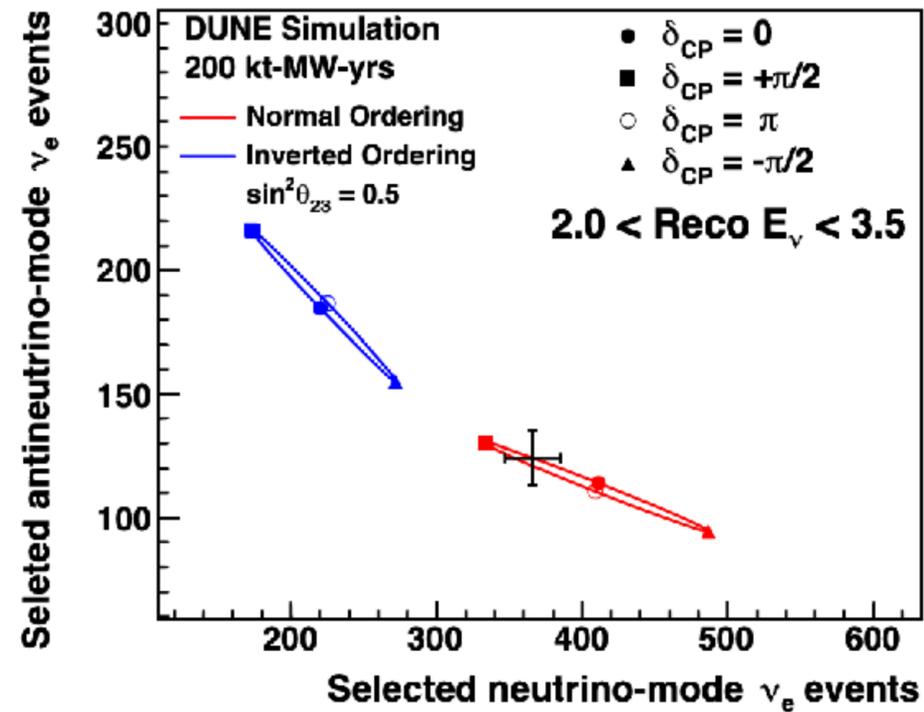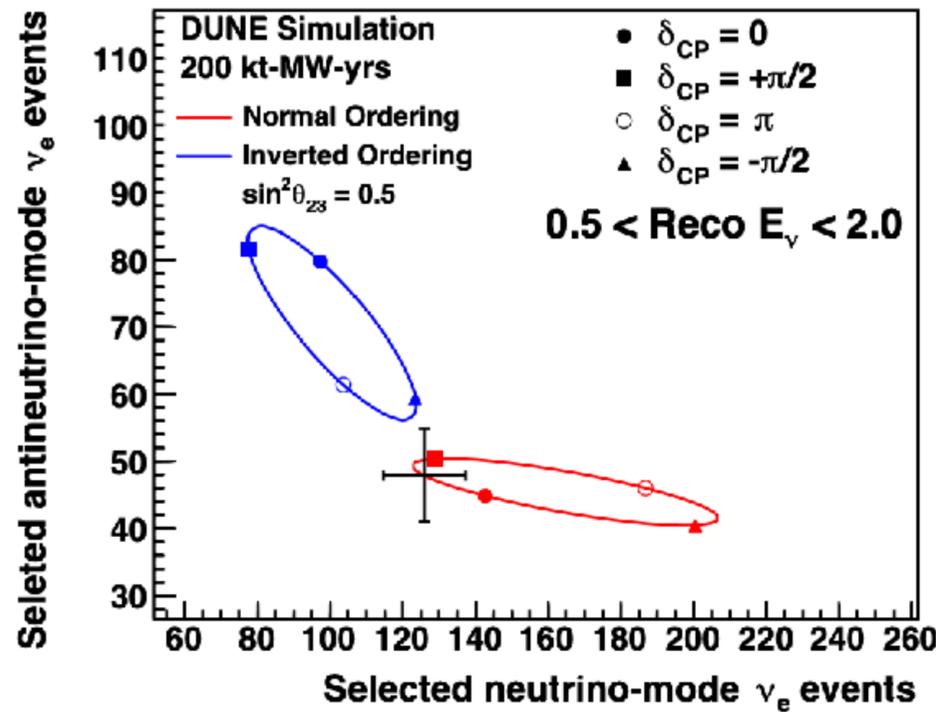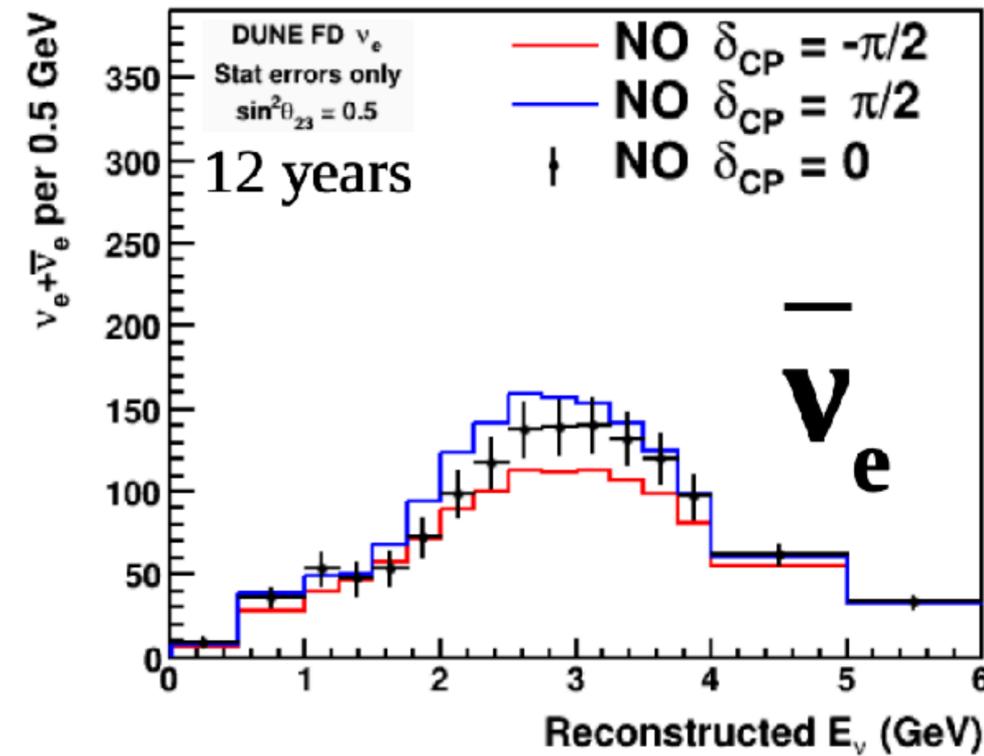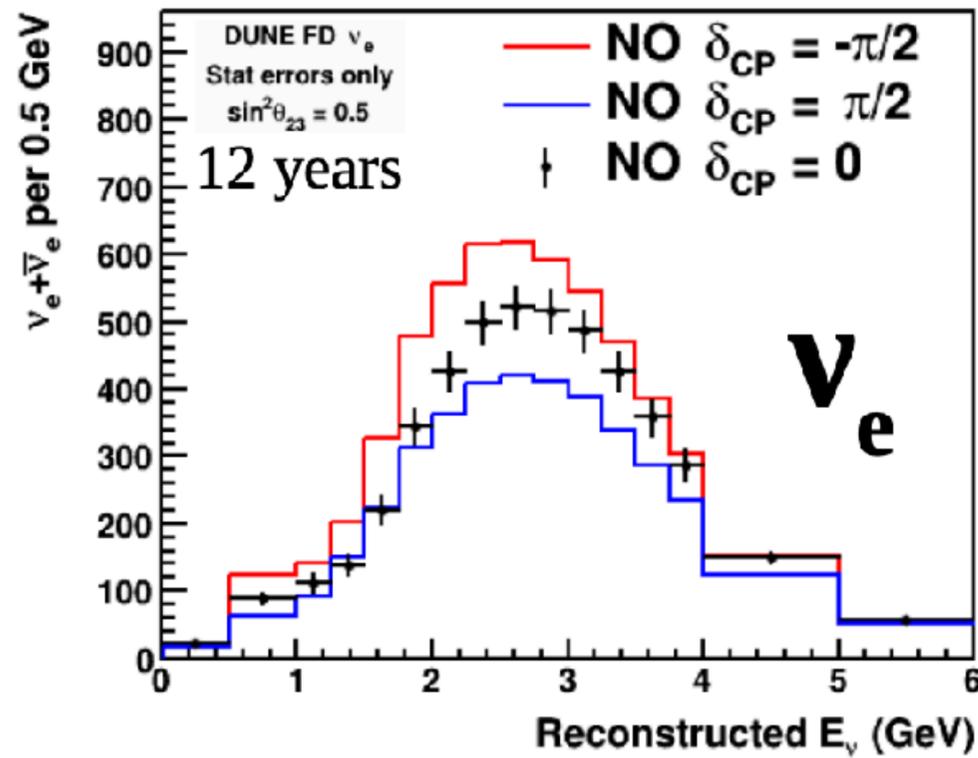
- The DUNE flux covers two oscillation maximums, allowing shape measurement to break the degeneracy.
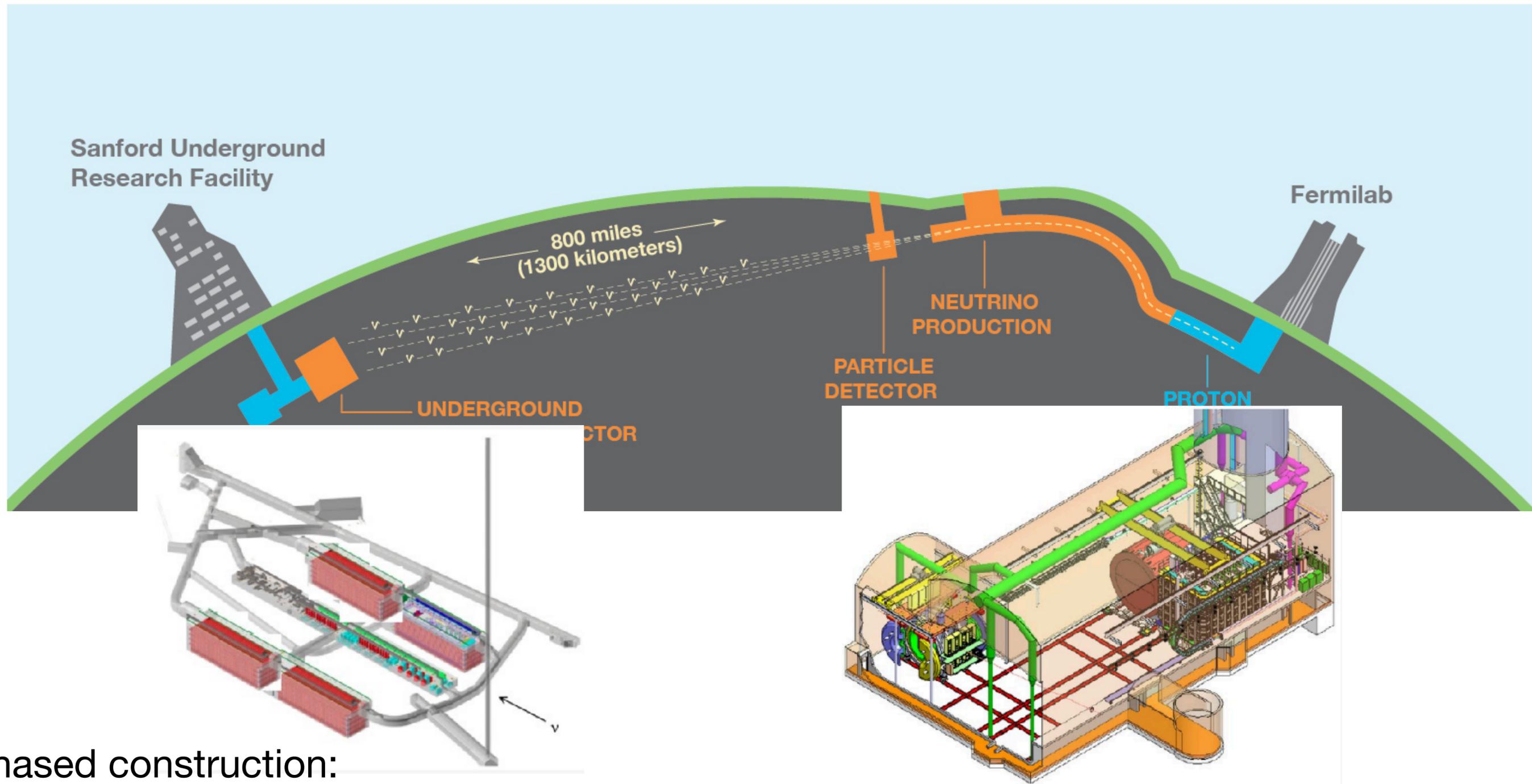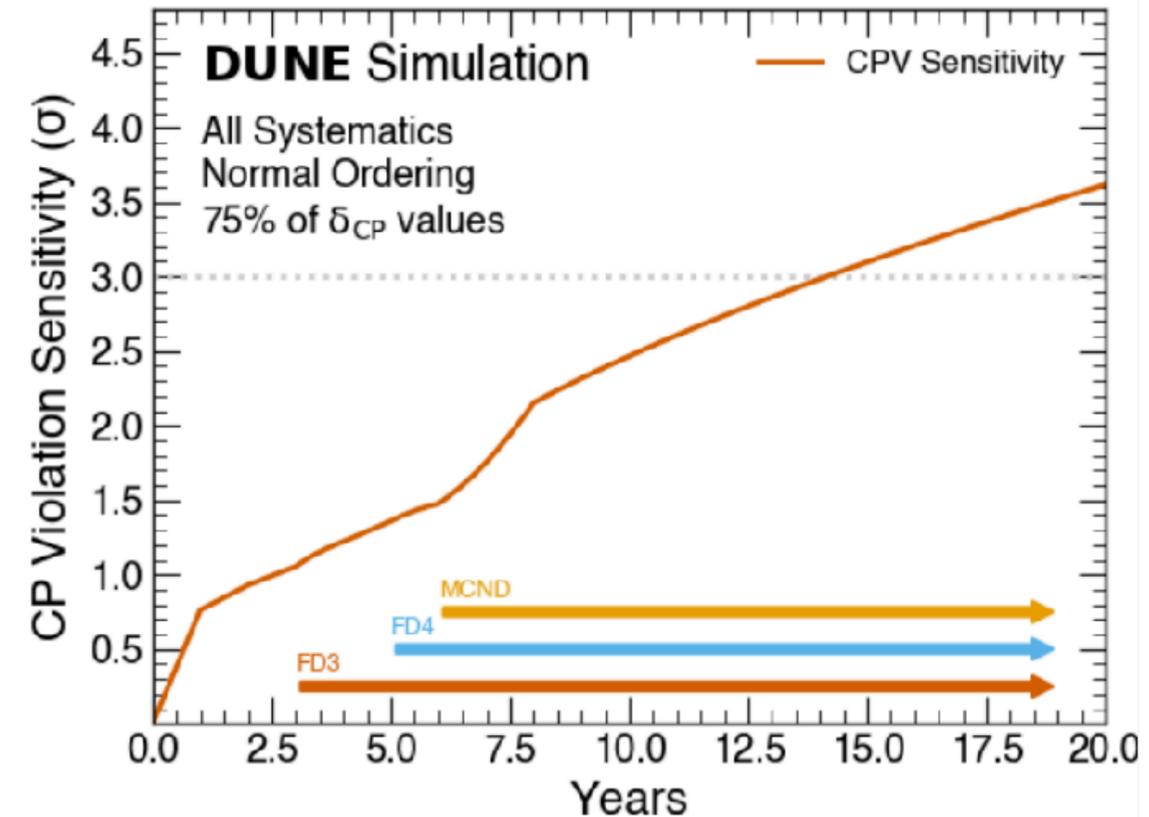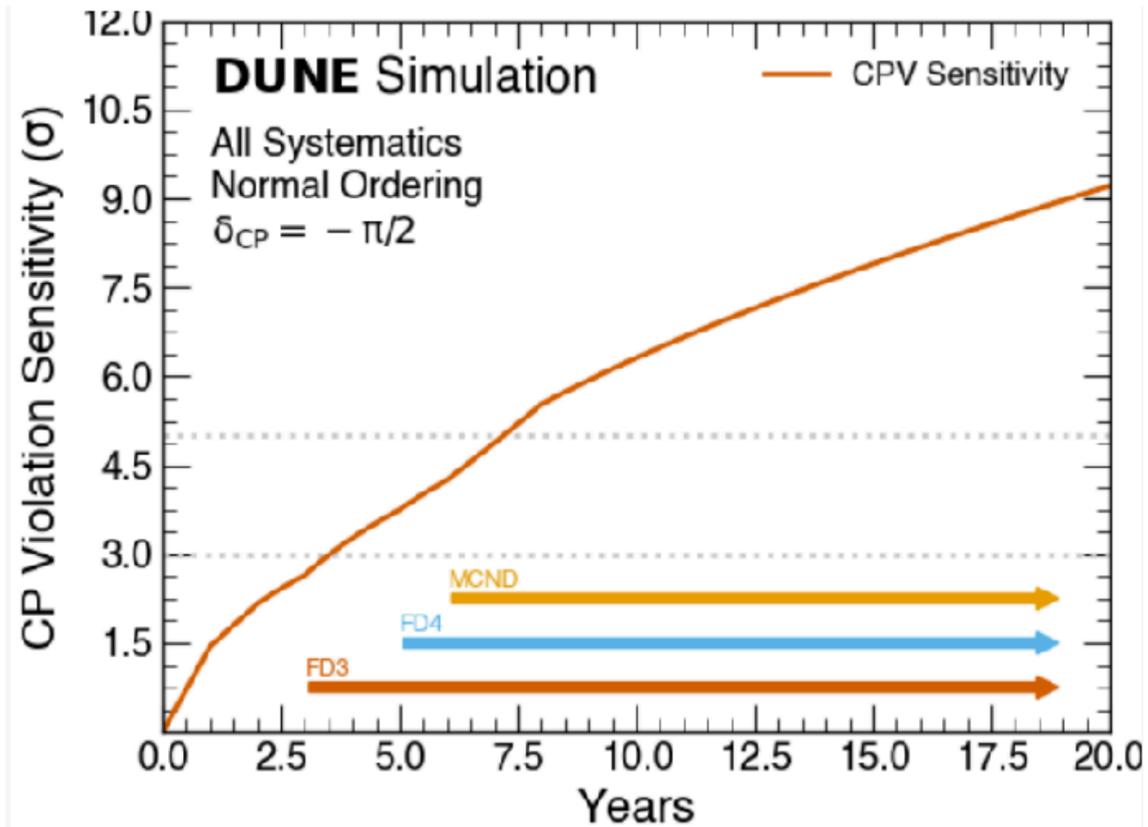
DUNE

- Phased construction:

  - Phase I: 2 LArTPC modules (17 kton each), 1.2 MW beam, LArTPC + SAND ND, finish by 2031;

  - Phase II: 2 additional modules, > 2 MW beam, ND upgrade.

DUNE

- Phased construction:

  - Phase I: 2 LArTPC modules (17 kton each), 1.2 MW beam, LArTPC + SAND ND, finish by 2031;

  - Phase II: 2 additional modules, > 2 MW beam, ND upgrade.

DUNE

- if $\delta_{CP} = -\pi/2$, >3σ CPV sensitivity in 3.5 years

- Over 75% of δ_{CP} values at >3σ in the longer term.

- Ultimate precision 6-16° in δ_{CP}
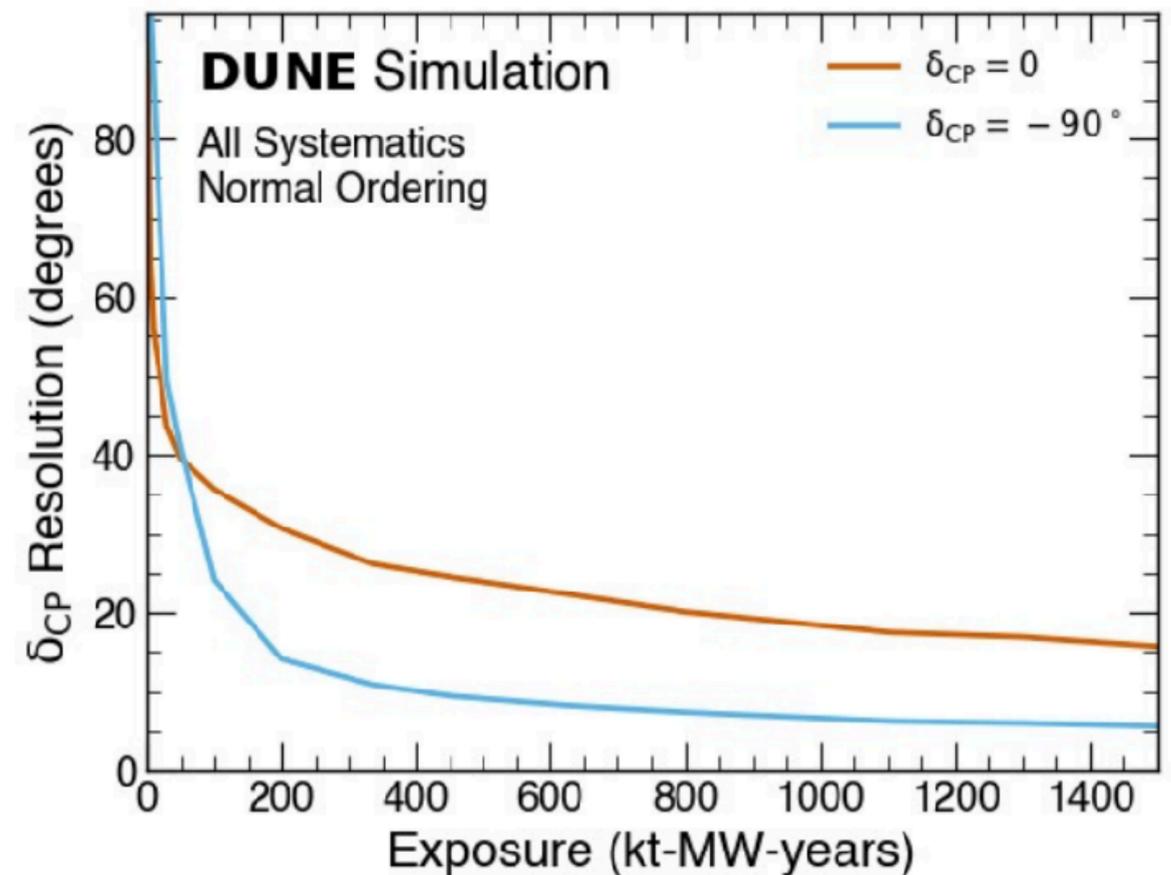
Hyper-Kamiokande

- 258 kton water-Cherenkov detector (8 X Super-K)

- 295 km baseline length.

- 1.3 MW neutrino beam.

- Small matter effect and large CPV effect.

- Aiming for operation in 2028.
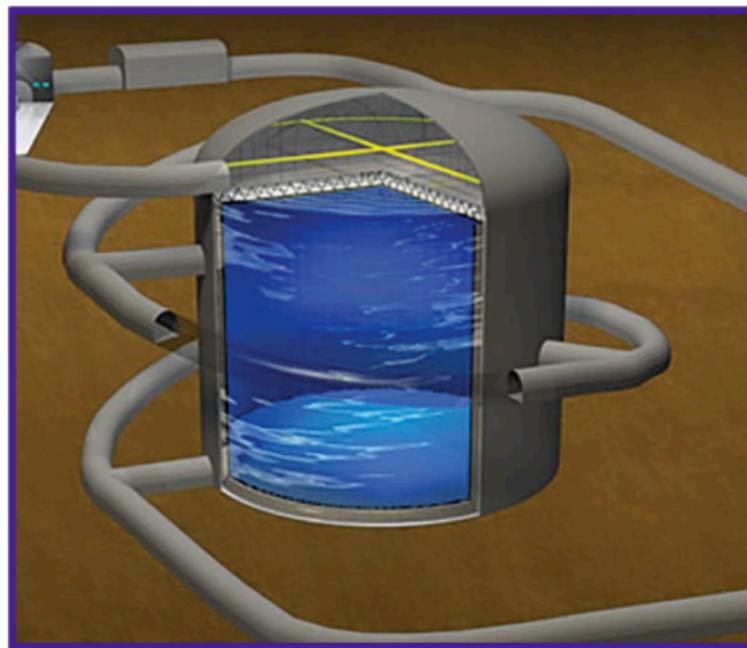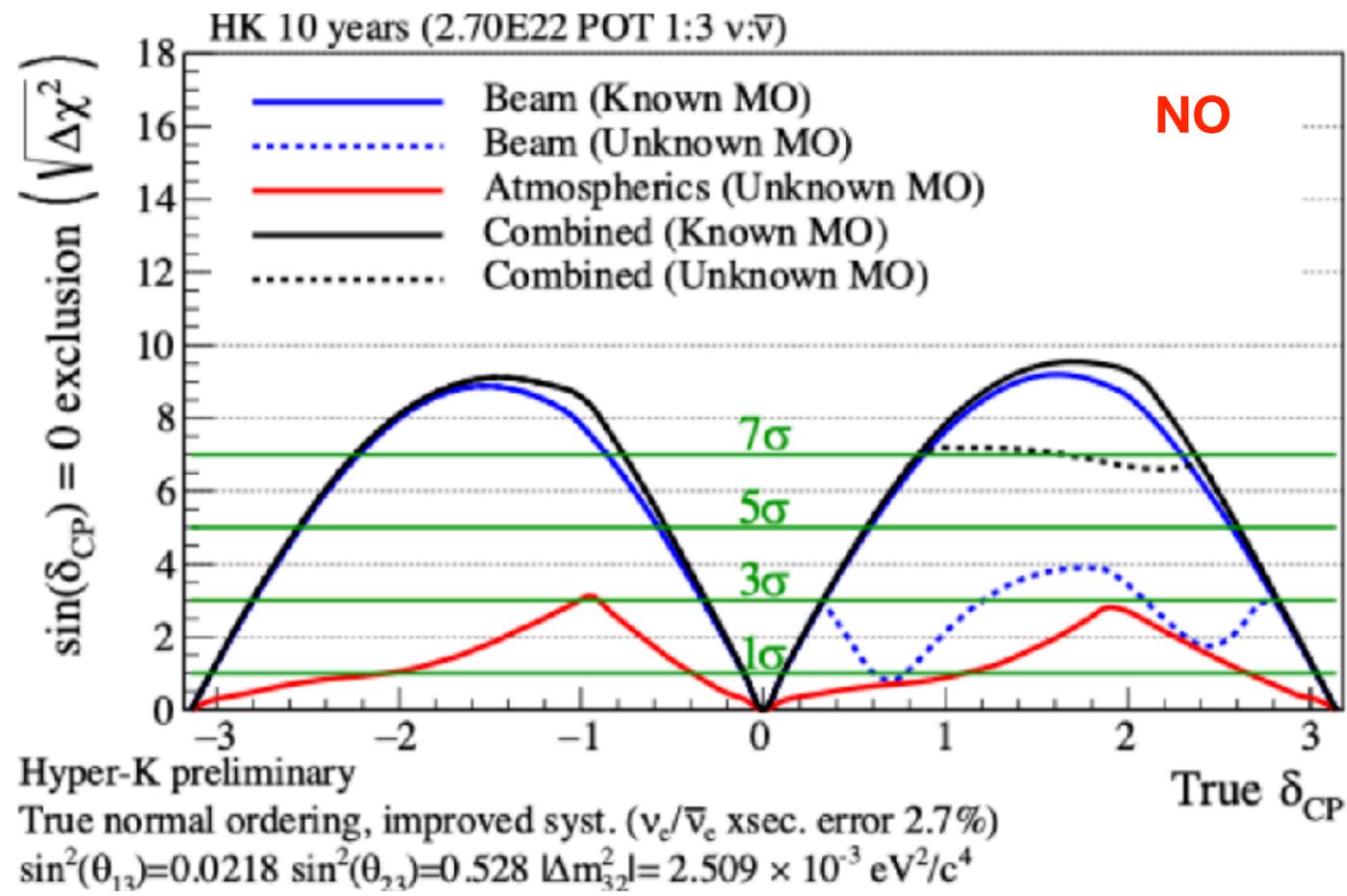

Charlie Nasty, Nufact 2023
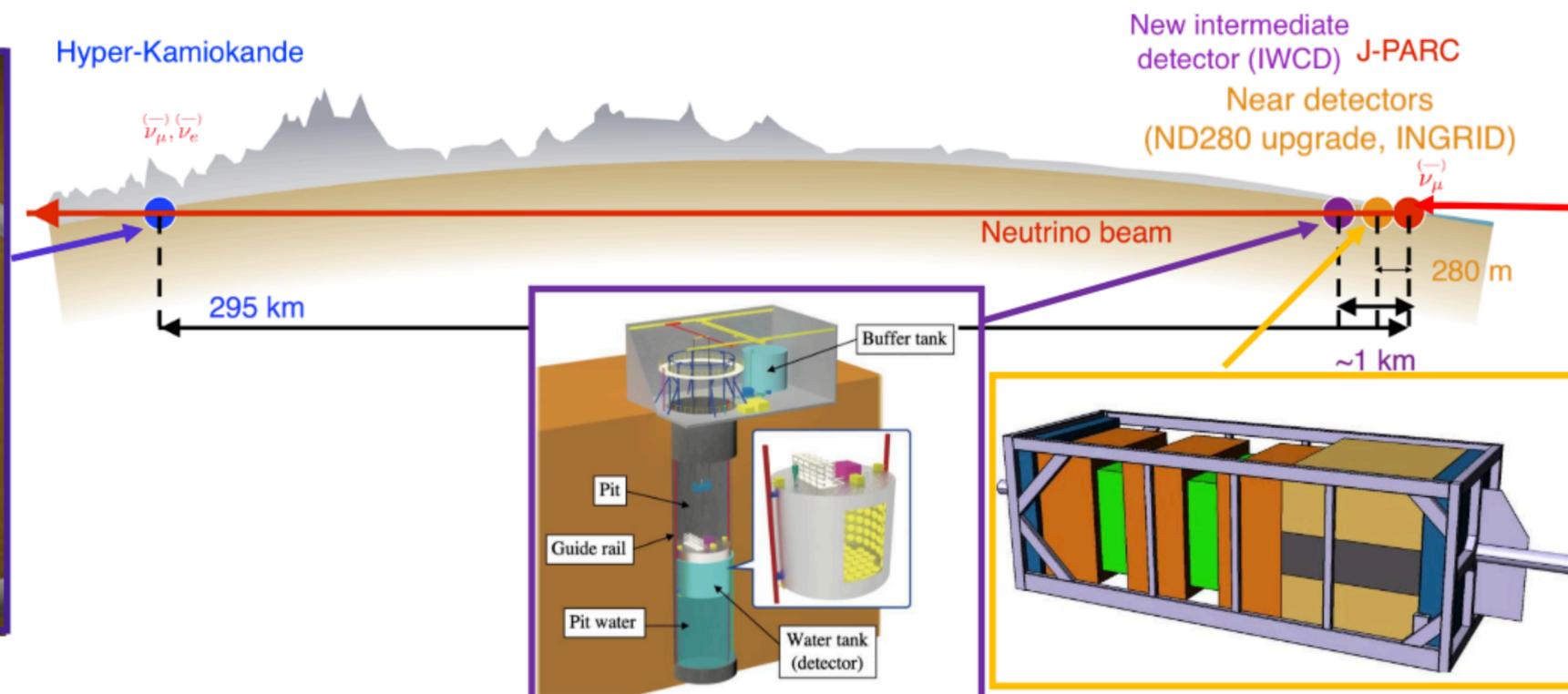
Hyper-Kamiokande
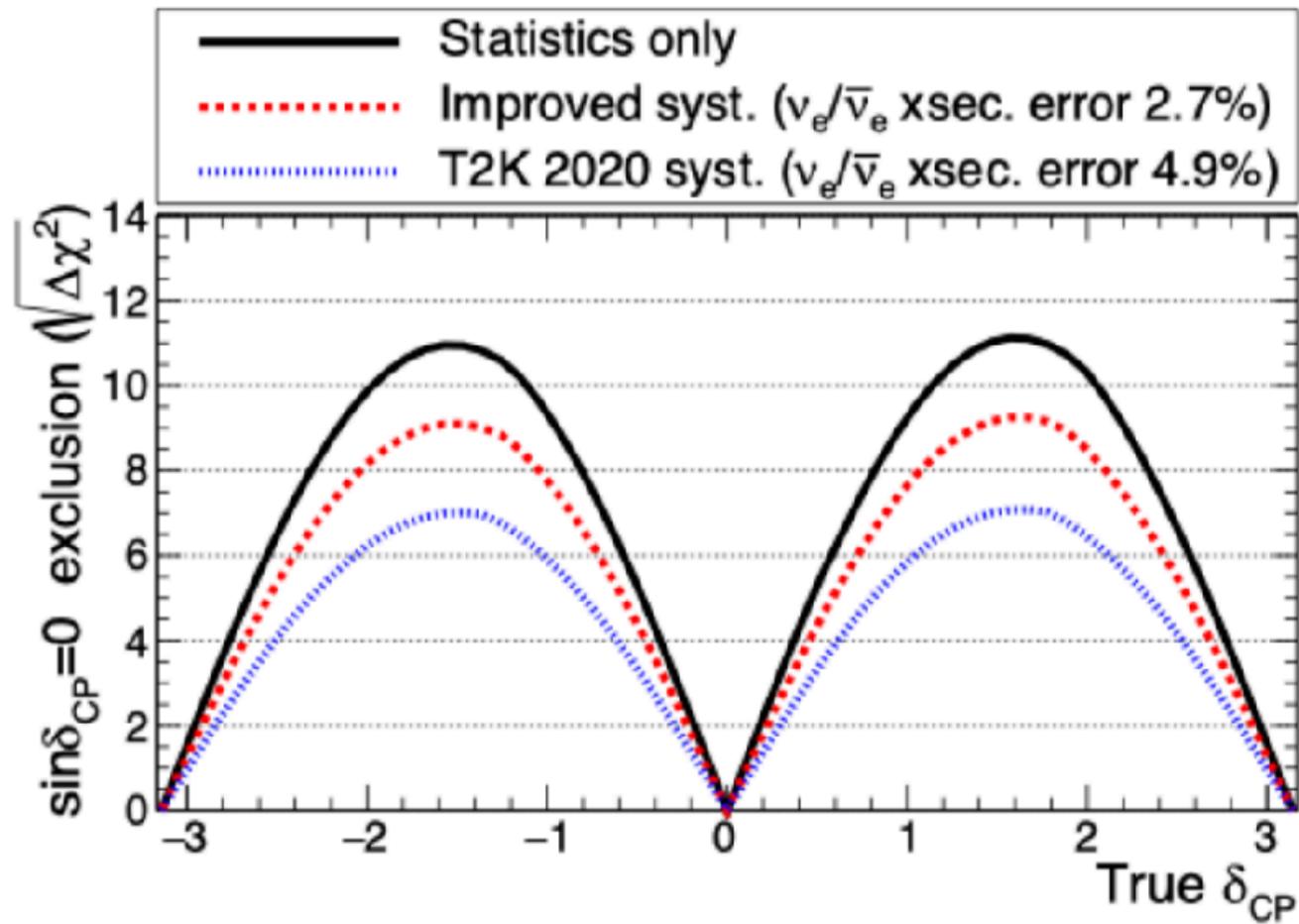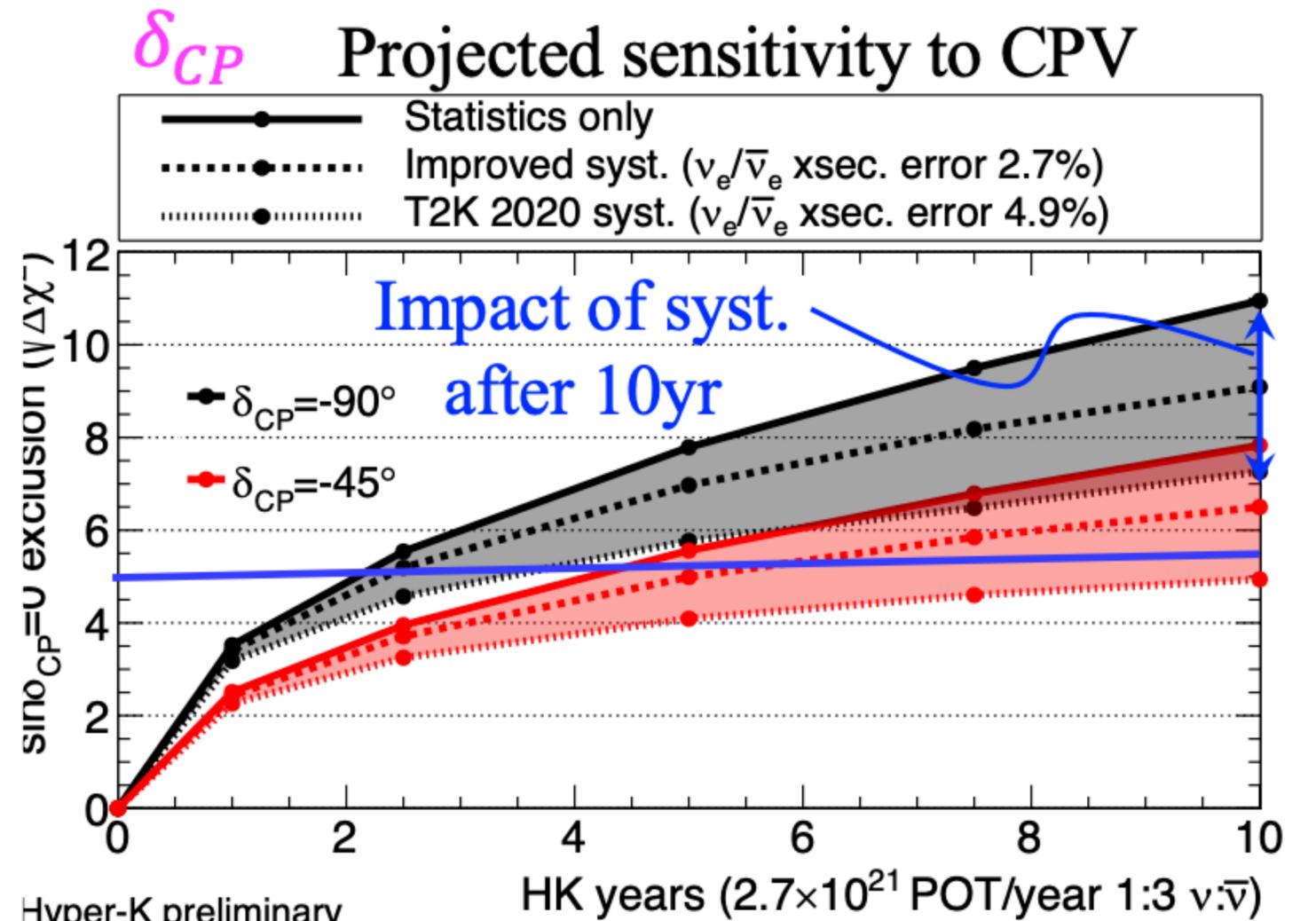
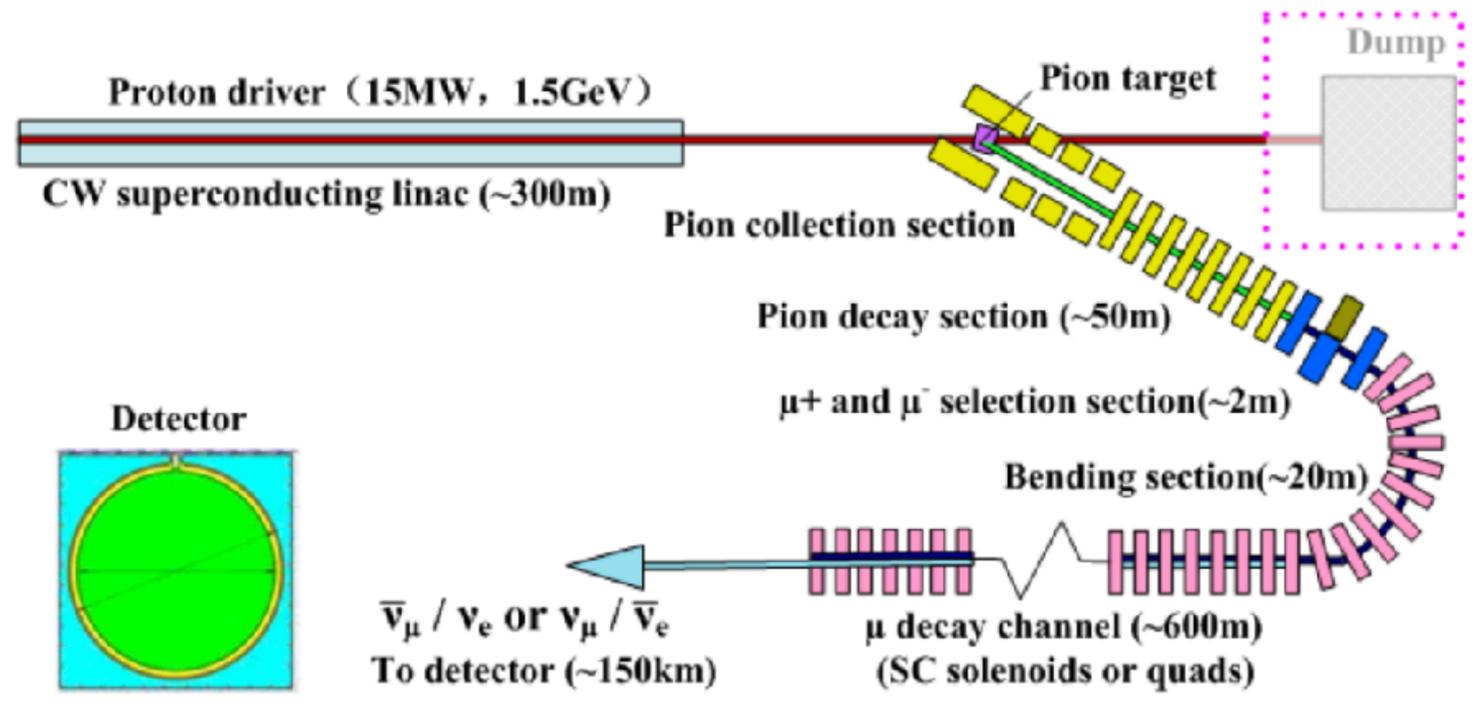- Assuming MO is known, 5σ in 3 years with maximum CPV, exclude 50% CP with 5σ in 5 years.

Hyper-Kamiokande
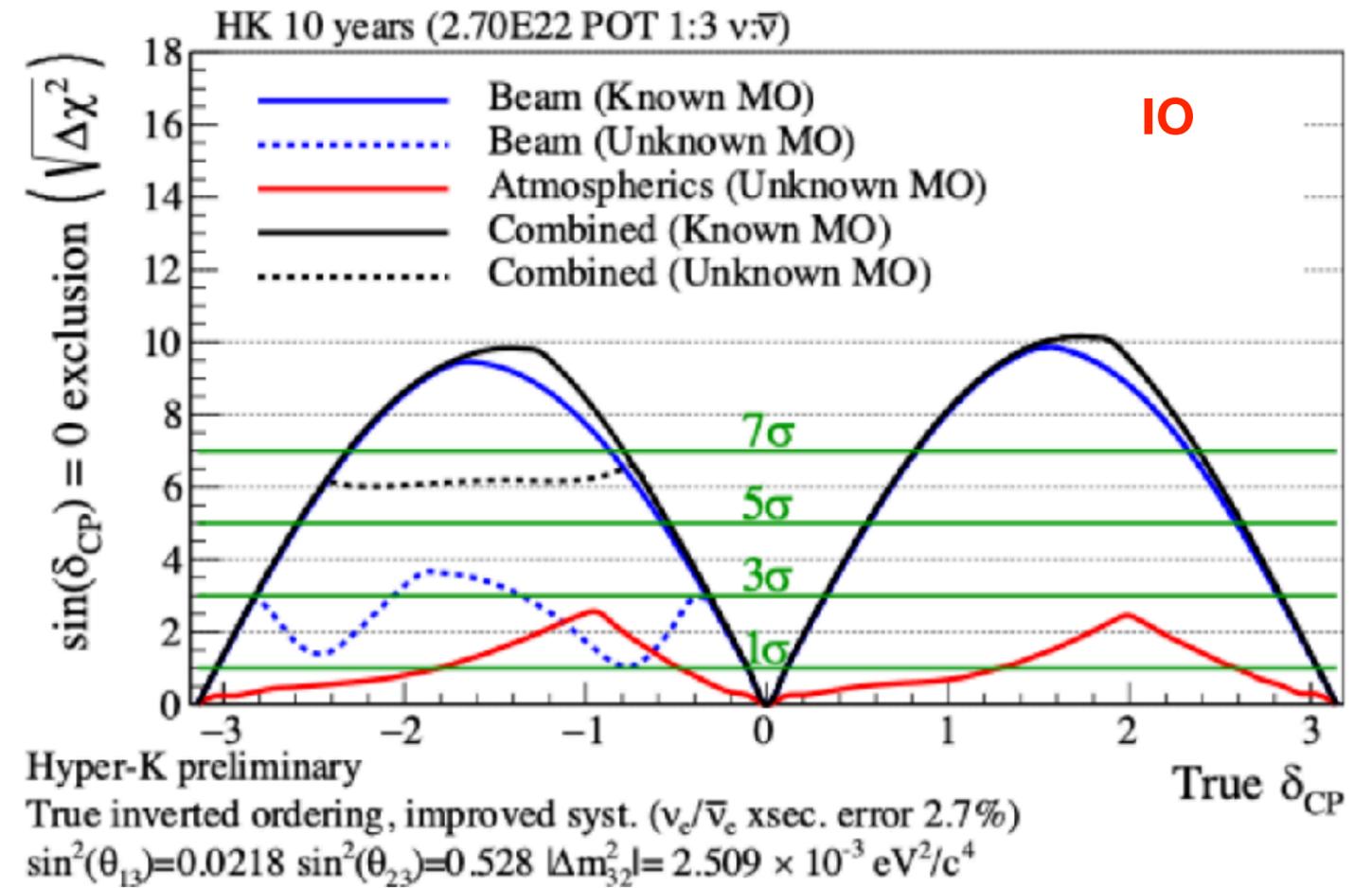
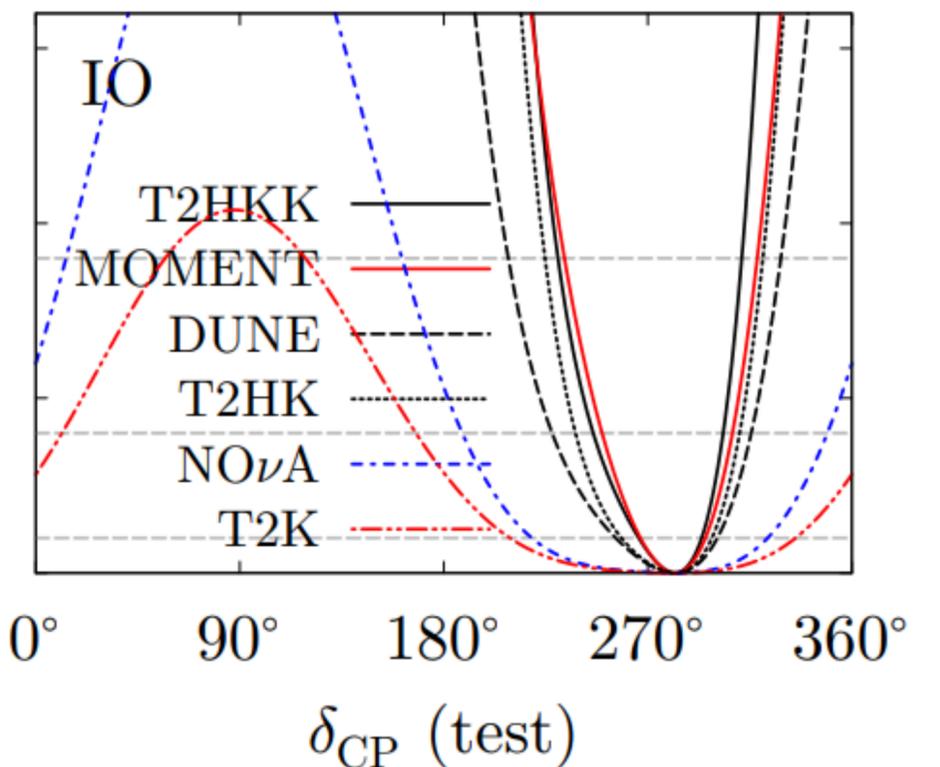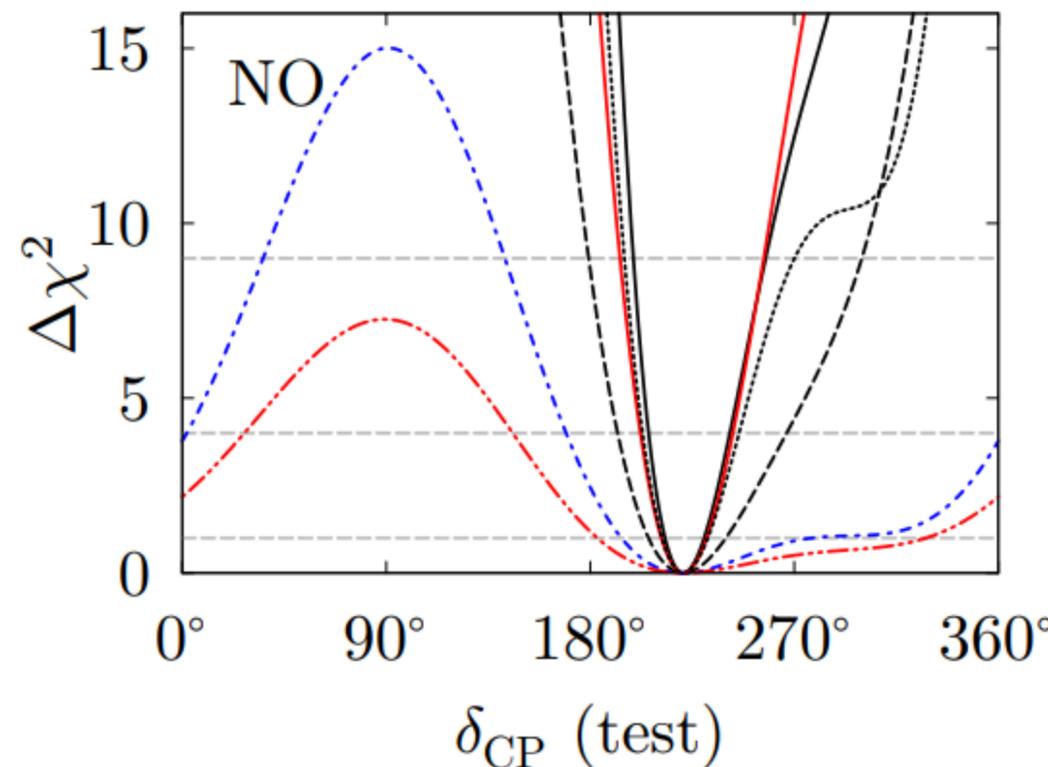- Atmospheric neutrinos can help if MO is not known.

Novel Ideas

Possible Accelerator Neutrino Experiments in China
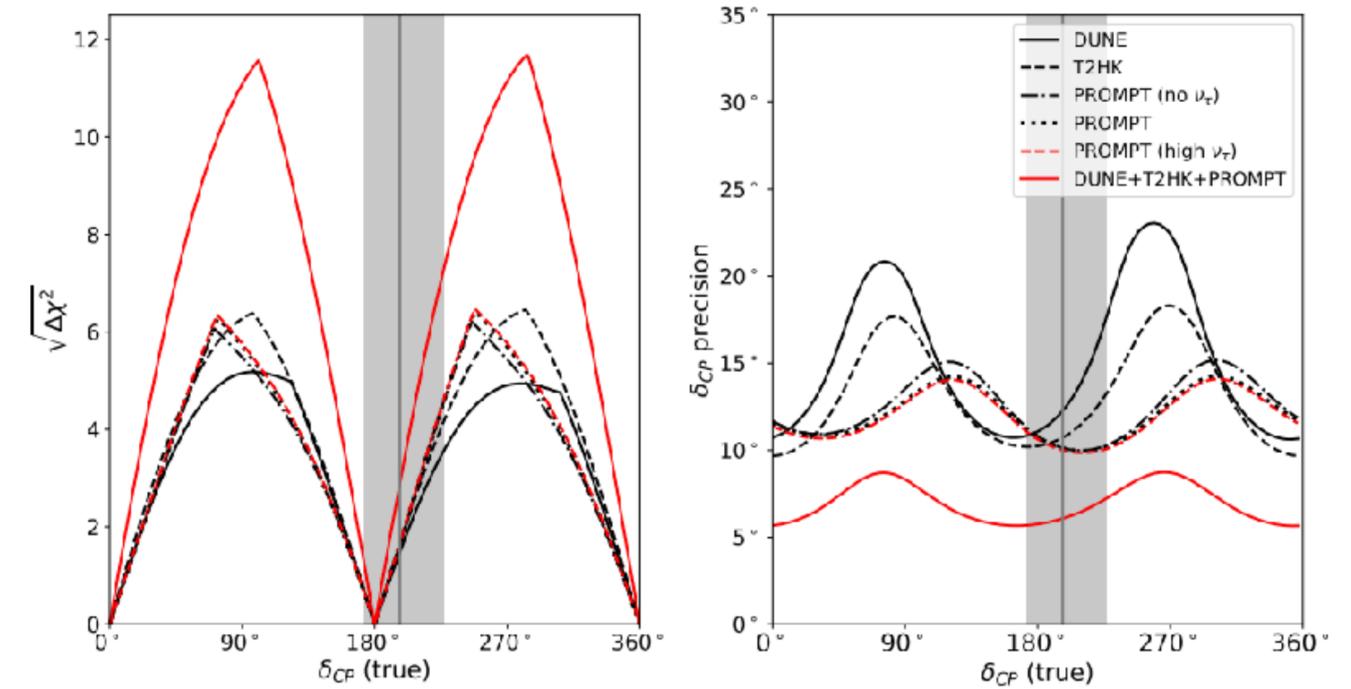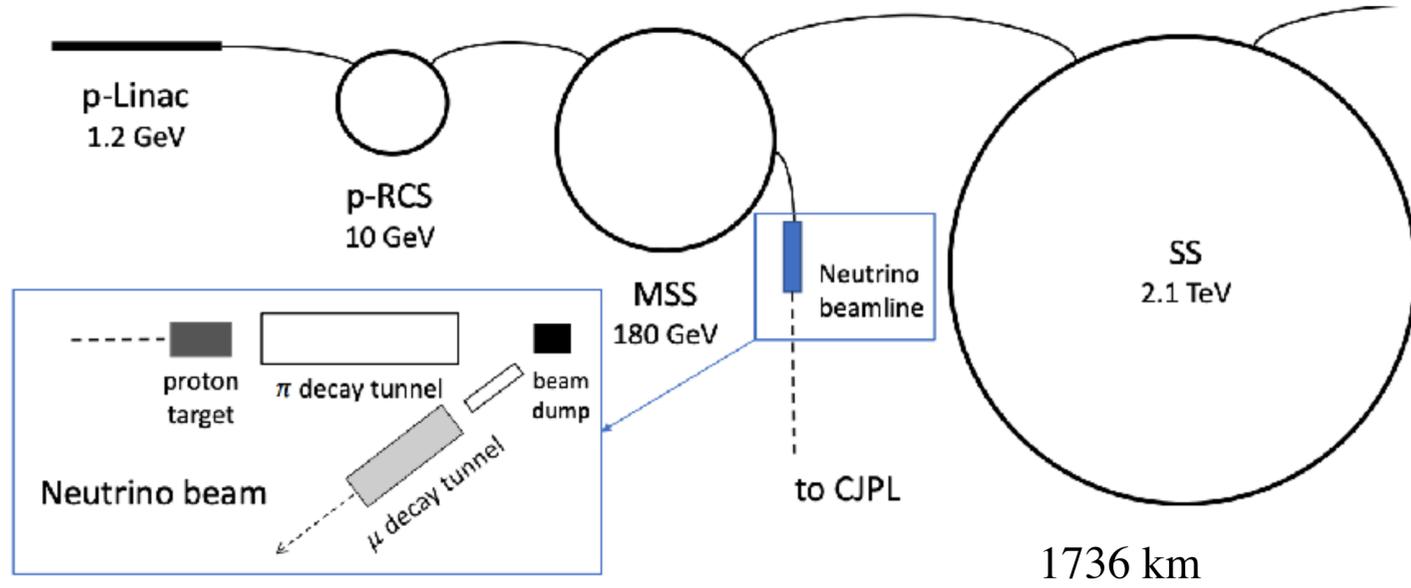

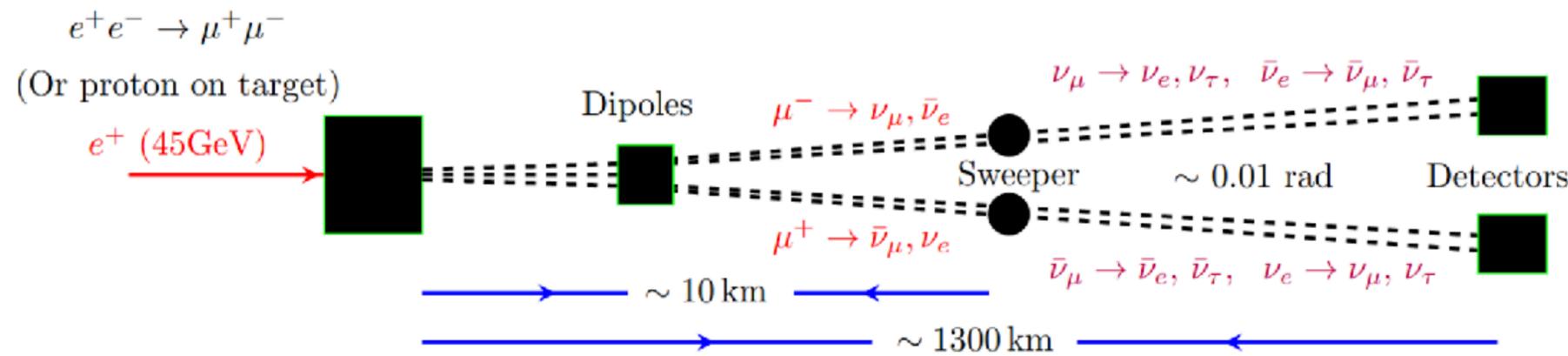MOMENT: a muon-decay medium-baseline neutrino beam facility

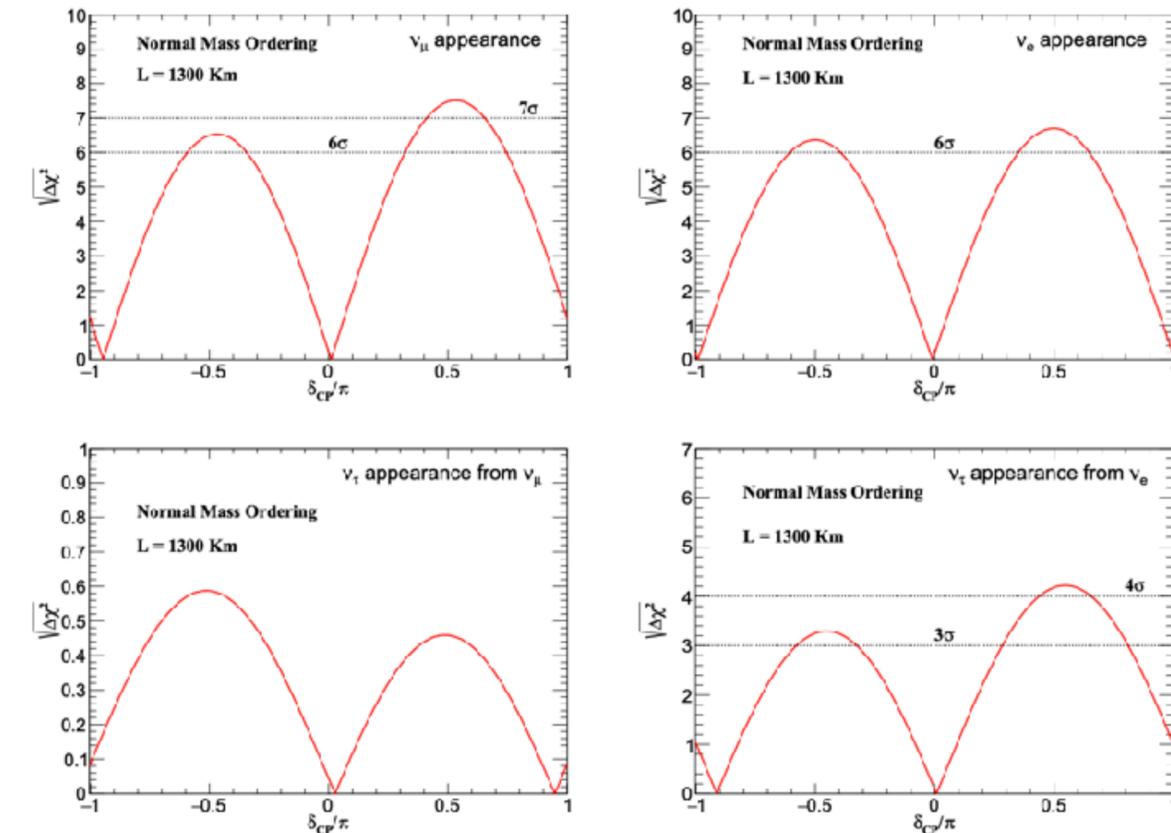MOMENT sensitivity to δ_{CP}
arXiv:1909.01548v

Possible Accelerator Neutrino Experiments in China

"PROMPT": Tang et al., Commun.TheorPhys. 74 (2022) 3, 035201

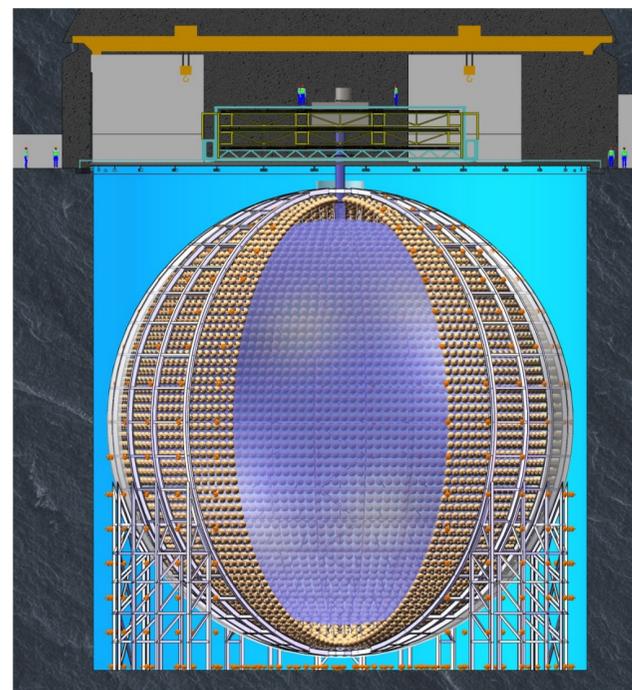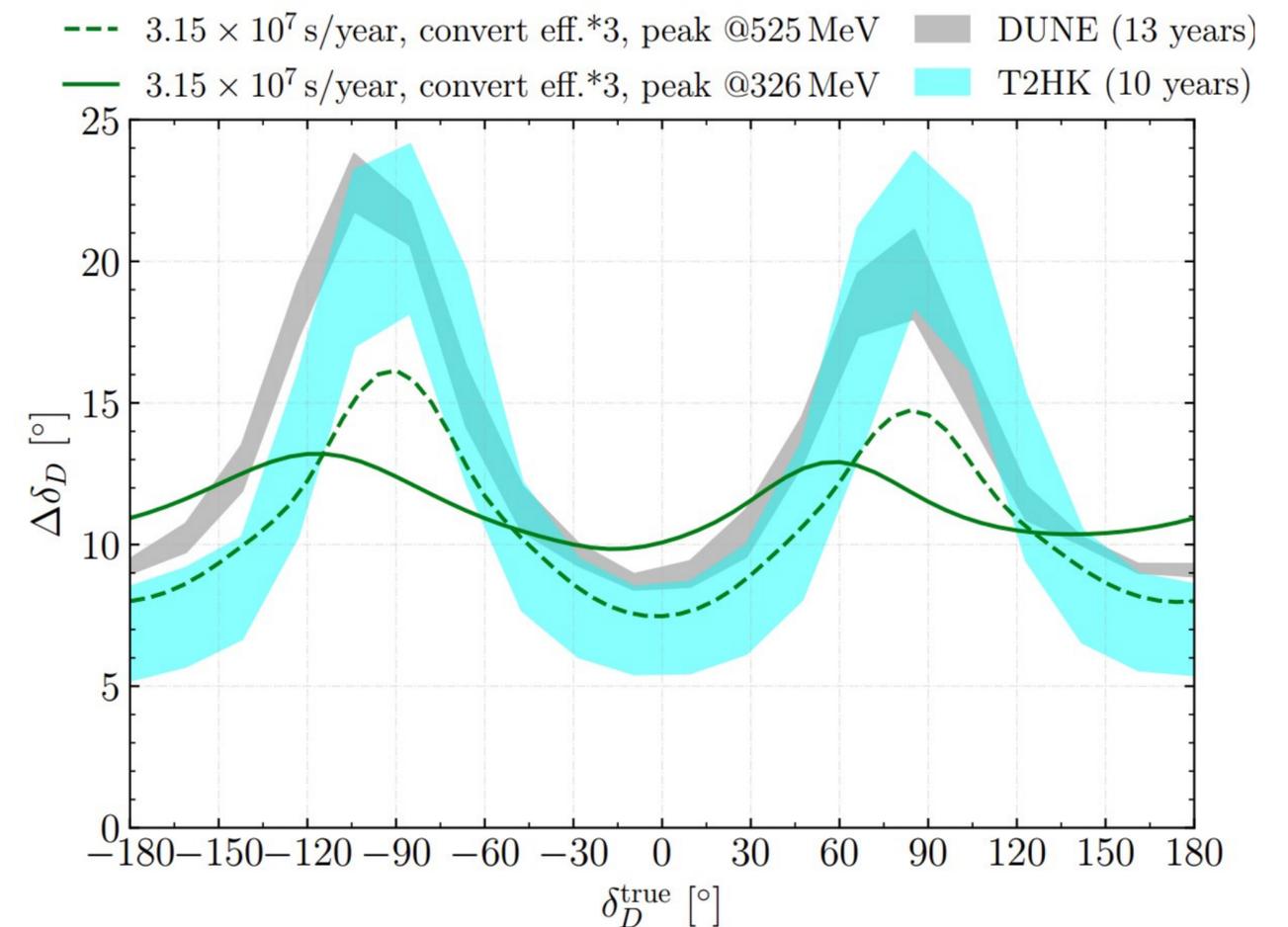Li et al., *Commun.Phys.* 7 (2024) 1, 137

HIAF + JUNO

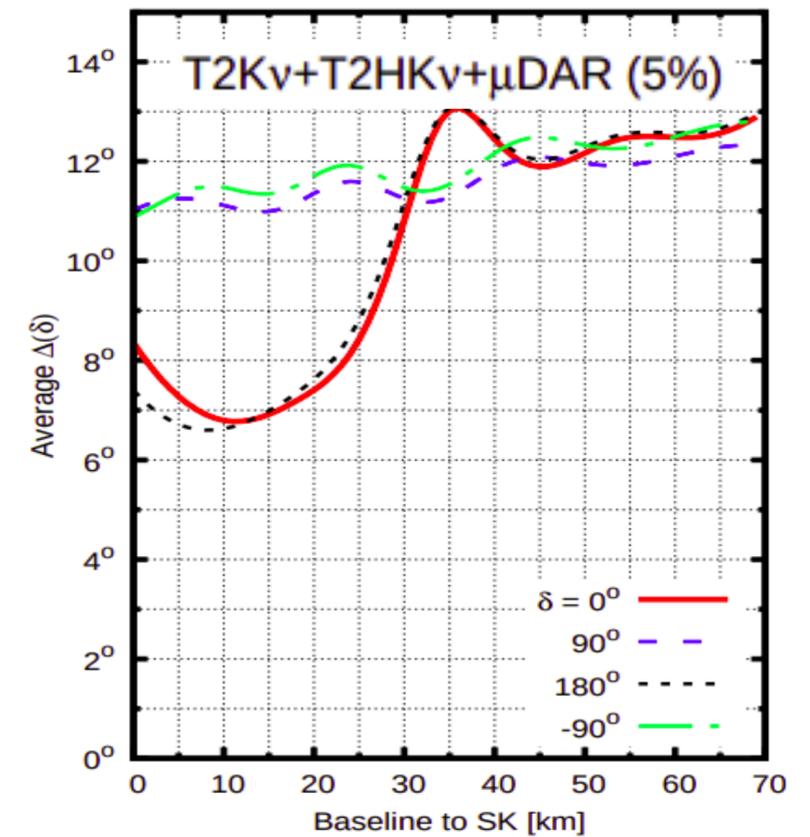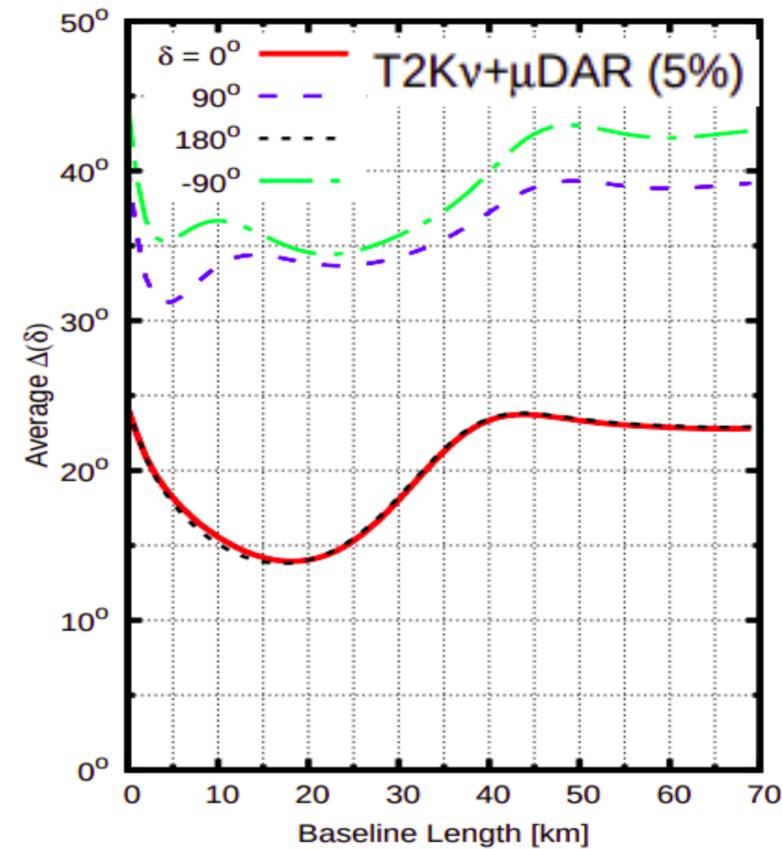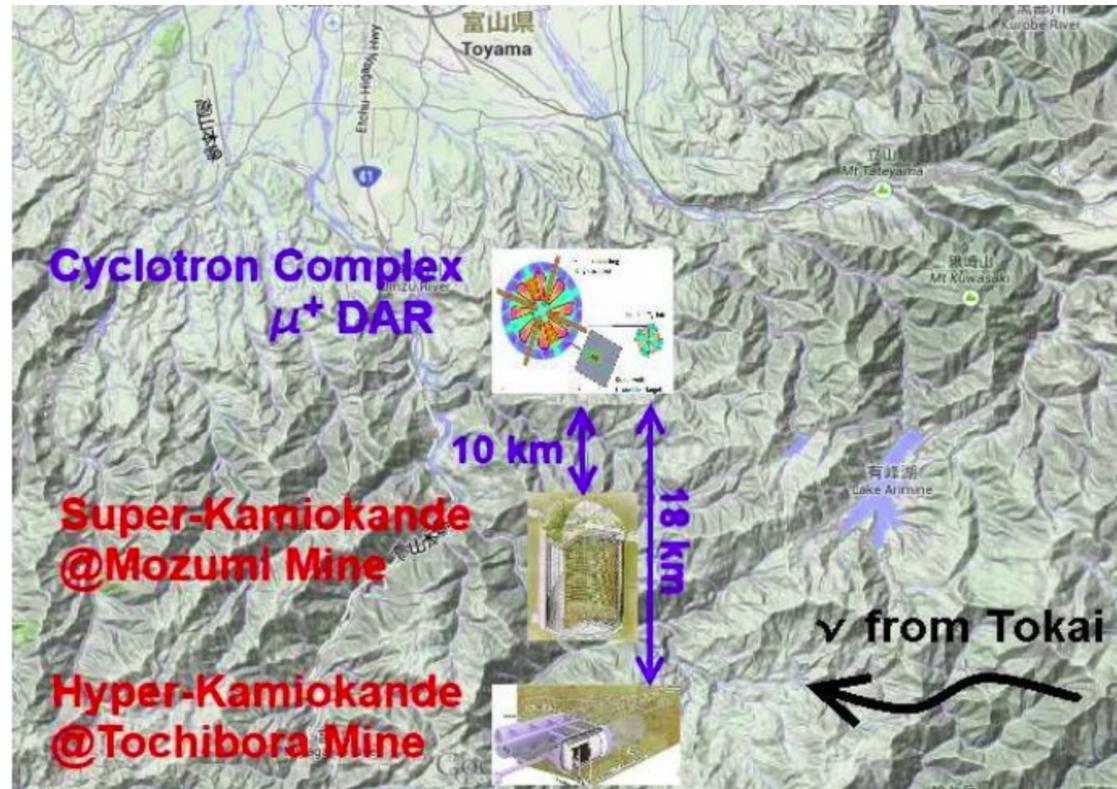|	Beam Power (MW)	Beam Energy (GeV)	Flux Intensity (ppp)	Frequency (Hz)	Duty Factor	POT/year
T2HK	1.3	30	$3.2*10^{14}$	0.86	0.32	$2.7*10^{21}$
DUNE	1.2	120	$7.5*10^{13}$	0.83	0.56	$1.1*10^{21}$
HIAF_U	4.8	25	$4*10^{14}$	3	1	$3.8*10^{22}$

Baseline ~ 260 km

Idea by Shaofeng Ge

- Neutrino beam can be optimized to reduce uncertainty at maximum CPV.

Muon Decay at Rest (μDAR)

Shaofeng Ge, *Nuovo Cim.C* 47 (2024) 6, 365

- Combine traditional accelerator ν_μ with $\bar{\nu}_\mu$ from muon decay at rest ($\mu^+ \to e^+ \bar{\nu}_\mu \bar{\nu}_e$)

  - Accelerator remains in neutrino mode with higher efficiency

  - Well-predicted $\bar{\nu}_\mu$ flux from μDAR

- Very different energy/baseline break degeneracy.

- Could improve precision for DUNE and Hyper-K.

Summary

- Current data is still not sufficient to claim neutrino CPV.

- DUNE/Hyper-K have very good opportunities to solve neutrino CPV is nature is kind.

- New ideas keep emerging.