New Physics Tests with Long Baseline Neutrino Oscillations

Hiroshi Nunokawa

Department of Physics, Pontificia Universidade Católica do Rio de Janeiro, Brazil

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What are “Long Baseline” (LBL) Neutrino Oscillation Experiments?

No clear definition, but usually we refer to neutrino oscillation experiments which use neutrinos produced by accelerators with baseline larger than ~O(100) km

In this talk, I will restrict to experiments which satisfy this condition

Outline

- Brief introduction of neutrino oscillations which can be studied by long-baseline (LBL) neutrino experiments
- Current Status and Open Questions
- Brief review of sensitivities to oscillation parameters to be studied by near future LBL experiments, focusing on DUNE and Hyper-Kamiokande, within the standard 3 flavor framework
- New physics beyond SM (beyond masses and mixing of 3 active neutrinos) to be studied (mainly) by DUNE and HK
- Summary

I will focus more on phenomenological aspects, for experimental details, please see talks by Ettore Segreto for DUNE (Friday), Saul Cuen-Rochin for Hyper-K (yesterday), Pedro Ochoa for Short Baseline experiments (today)!

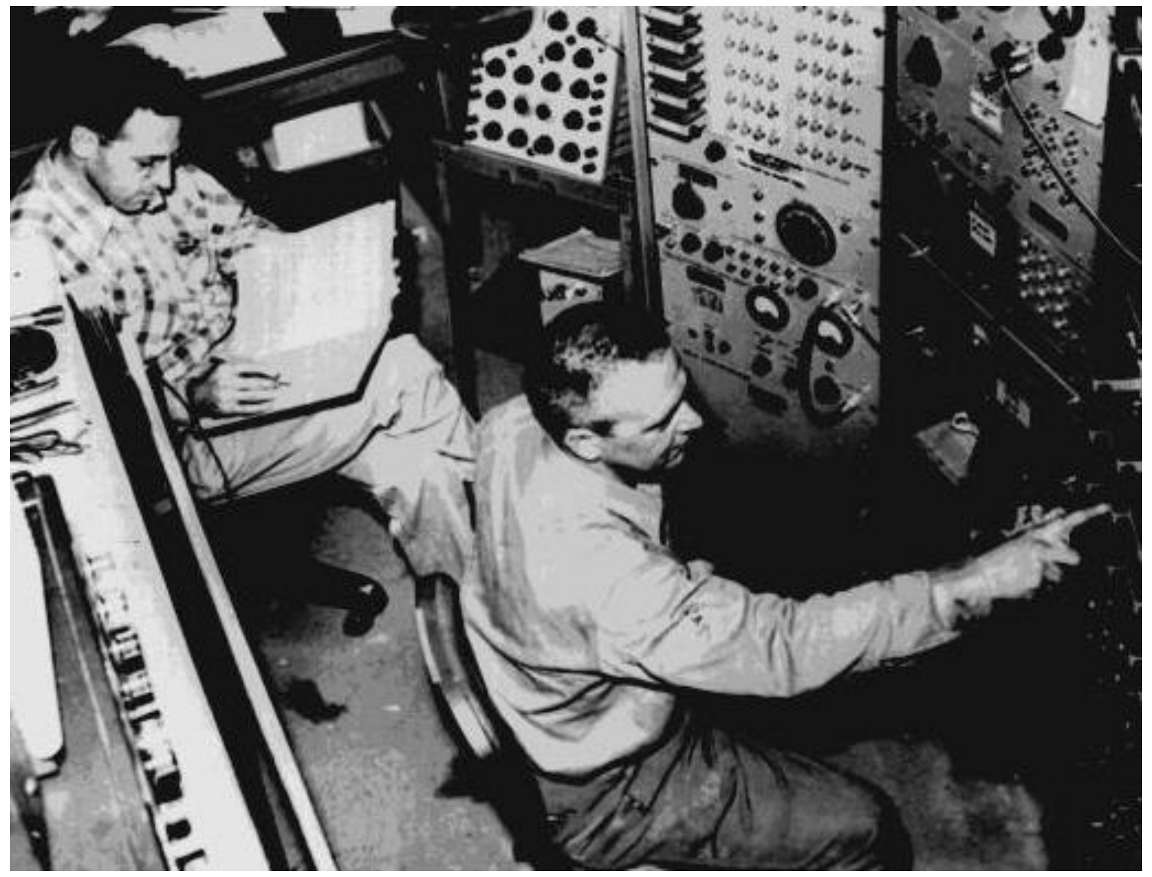
(Very) Brief review of Neutrino Oscillation

- from theory to experiment -

A bit of History

Neutrino was invented/introduced by W. Pauli in 1930 to explain the problem (of continuous spectra of emitted electrons) observed in beta decays

$${}^{A}_{Z}X \rightarrow {}^{\;\;A}_{Z+1}Y + e^- + \bar{\nu}_e$$



Discoverd/detected for the first time by Rines and Cowan in 1956 by using reactor neutrinos through the IBD (inverse beta decay) reaction

$$p + \bar{\nu}_e \rightarrow n + e^+$$


1995

Period (until 1998) after the first detection of neutrino

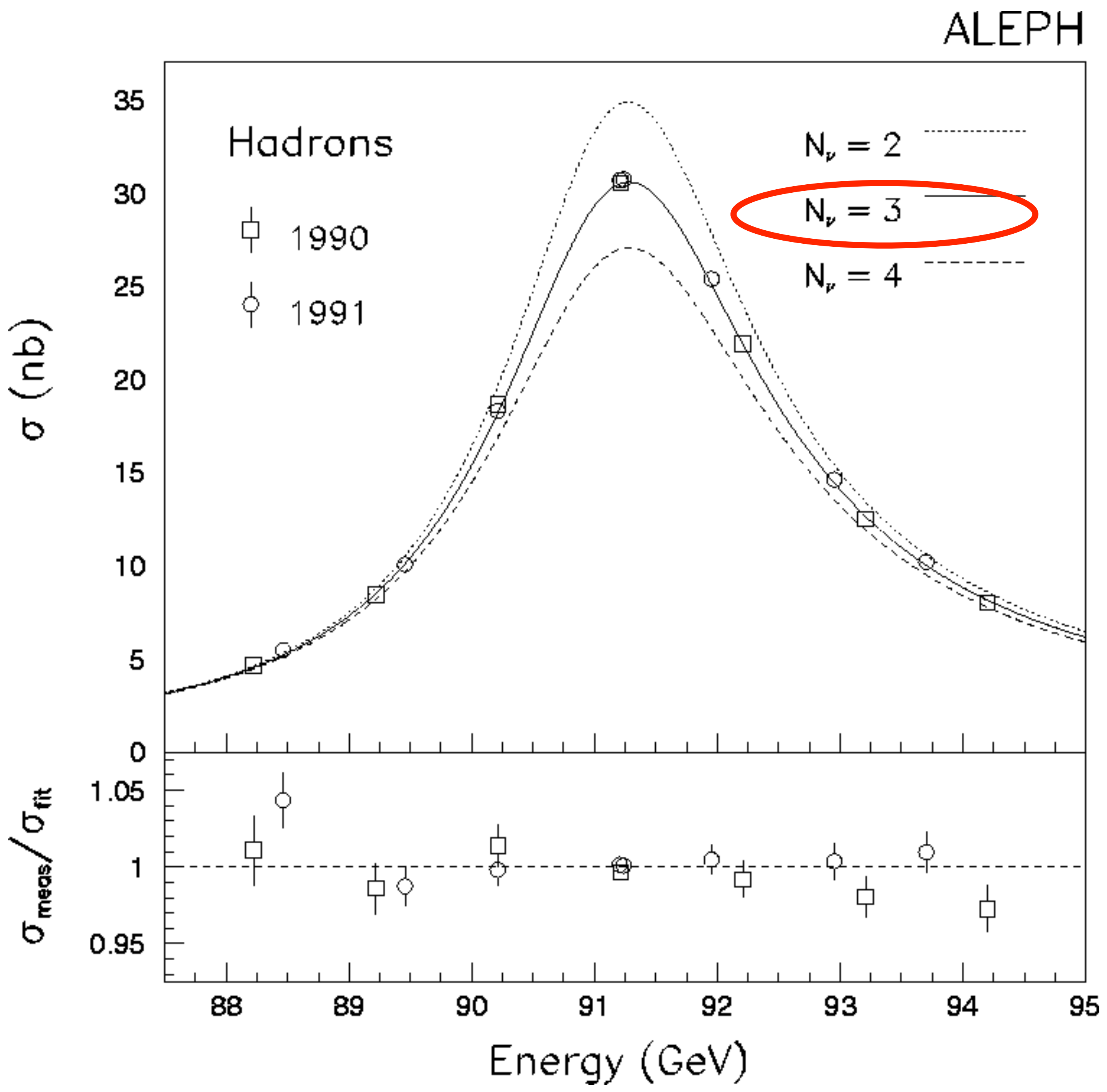
1956-1998 (~40 years): steady progress from both theoretical and experimental point of view

Theory: possibility of non-zero neutrino masses, concept of neutrino mixing, neutrino oscillation, nature of neutrino, Dirac or Majorana, etc

Experiments: detection of ν_μ , observations of neutrinos from various different sources, detection of supernova (SN1987A) neutrinos, solar neutrino problem, atmospheric neutrino anomaly, etc.

We know that there are three types (flavors) of “active” neutrinos associated to charged leptons, e, μ and τ

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix} \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$$



and their anti-particles or anti-neutrinos

$$\begin{pmatrix}\bar{\nu}_e\\ e^+\end{pmatrix} \begin{pmatrix}\bar{\nu}_\mu\\ \mu^+\end{pmatrix} \begin{pmatrix}\bar{\nu}_\tau\\ \tau^+\end{pmatrix}$$

LEP: $N_\nu = 2.984 \pm 0.012$

from the decay width of Z

see later for “sterile” neutrino(s)

During ~15 years of 1998 - 2012

Very Important Discovery in Neutrino Physics

Neutrino Oscillation!

During ~15 years of 1998 - 2012

Very Important Discovery in Neutrino Physics

Neutrino Oscillation!

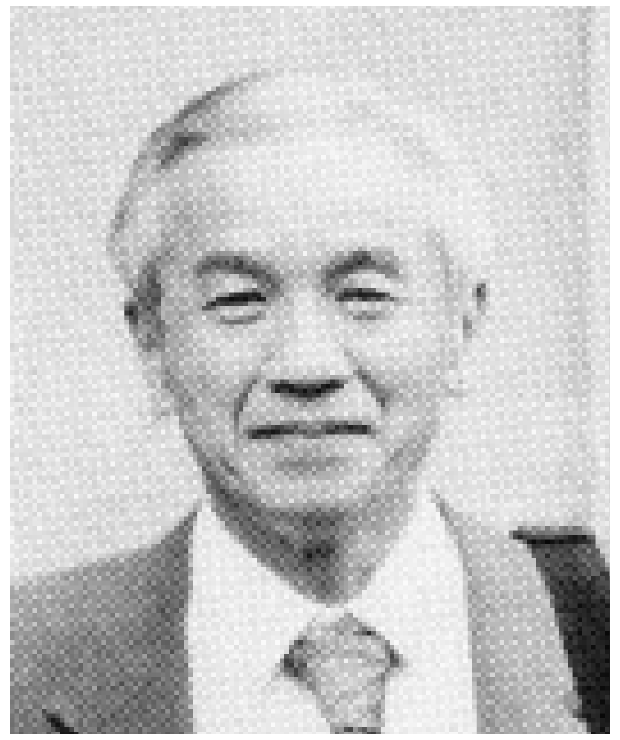
1998-2012: "Discovery" Phase (Era) of (several types of) neutrino oscillations

Brief Review of Neutrino Oscillation

from theory point of view

Mixing of Neutrinos


Z. Maki


M. Nakagawa


S. Sakata

1962

If neutrinos have non-zero different masses, assuming only 2 flavors

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

$m_1 \neq m_2$

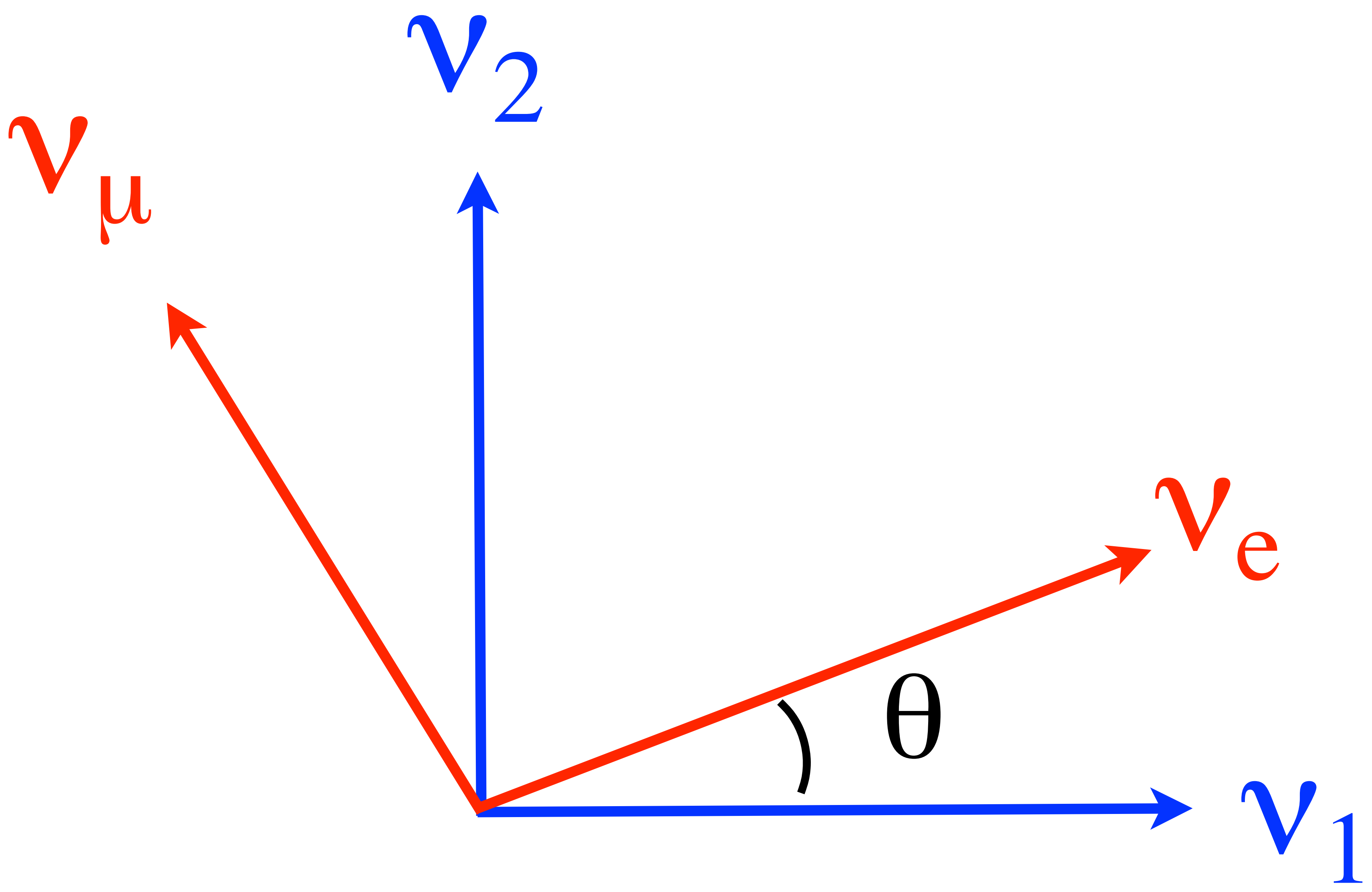
↑ **flavor eigenstates**

↑ **mass eigenstates**

θ **: mixing angle**

Prog.Theo.Phys. 28 (1962) 870

Mixing of Neutrinos



general neutrino state

$$|\nu\rangle = c_e|\nu_e\rangle + c_\mu|\nu_\mu\rangle$$

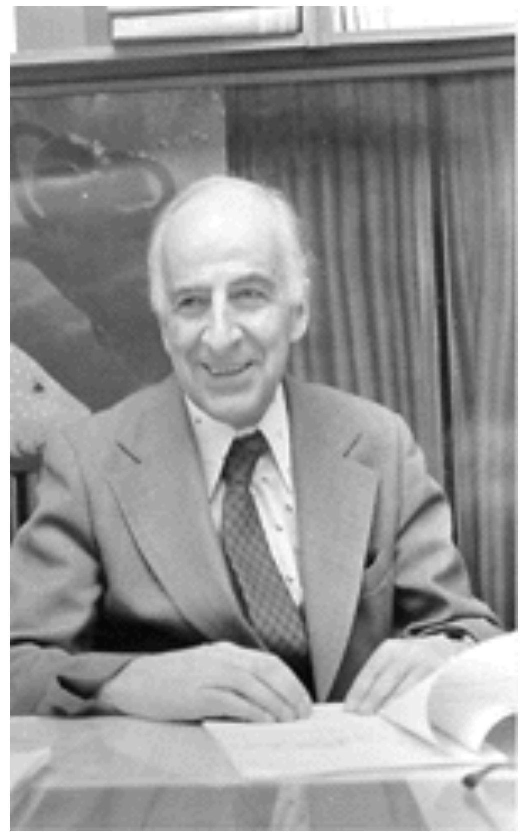
$$|\nu\rangle = c_1|\nu_1\rangle + c_2|\nu_2\rangle$$

general neutrino state

= a  **+ b** 

linear superposition (combination) of different flavors/masses (states)

Oscillation Probabilities for 2 flavors in vacuum



B. Pontecorvo

For ultra-relativistic neutrino, $E = \sqrt{p^2 + m^2} \sim p + \frac{m^2}{2p} \sim p + \frac{m^2}{2E}$

E: energy, p: momentum, m: mass of neutrino

For the case where the initial state is ν_μ

$$P(\nu_\mu \to \nu_e) = \left| \sin\theta\cos\theta e^{-\overset{\nu_1}{\boxed{i\frac{m_1^2}{2E}L}}} + \cos\theta(-\sin\theta)e^{-\overset{\nu_2}{\boxed{i\frac{m_2^2}{2E}L}}} \right|^2$$

$$= \boxed{\sin^2 2\theta} \sin^2\left[\frac{\Delta m^2}{4E}L\right]$$

: appearance probability

oscillation amplitude

$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta} \sin^2\left[\frac{\Delta m^2}{4E}L\right]$$

: survival (disappearance) probability

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

: mass squared difference

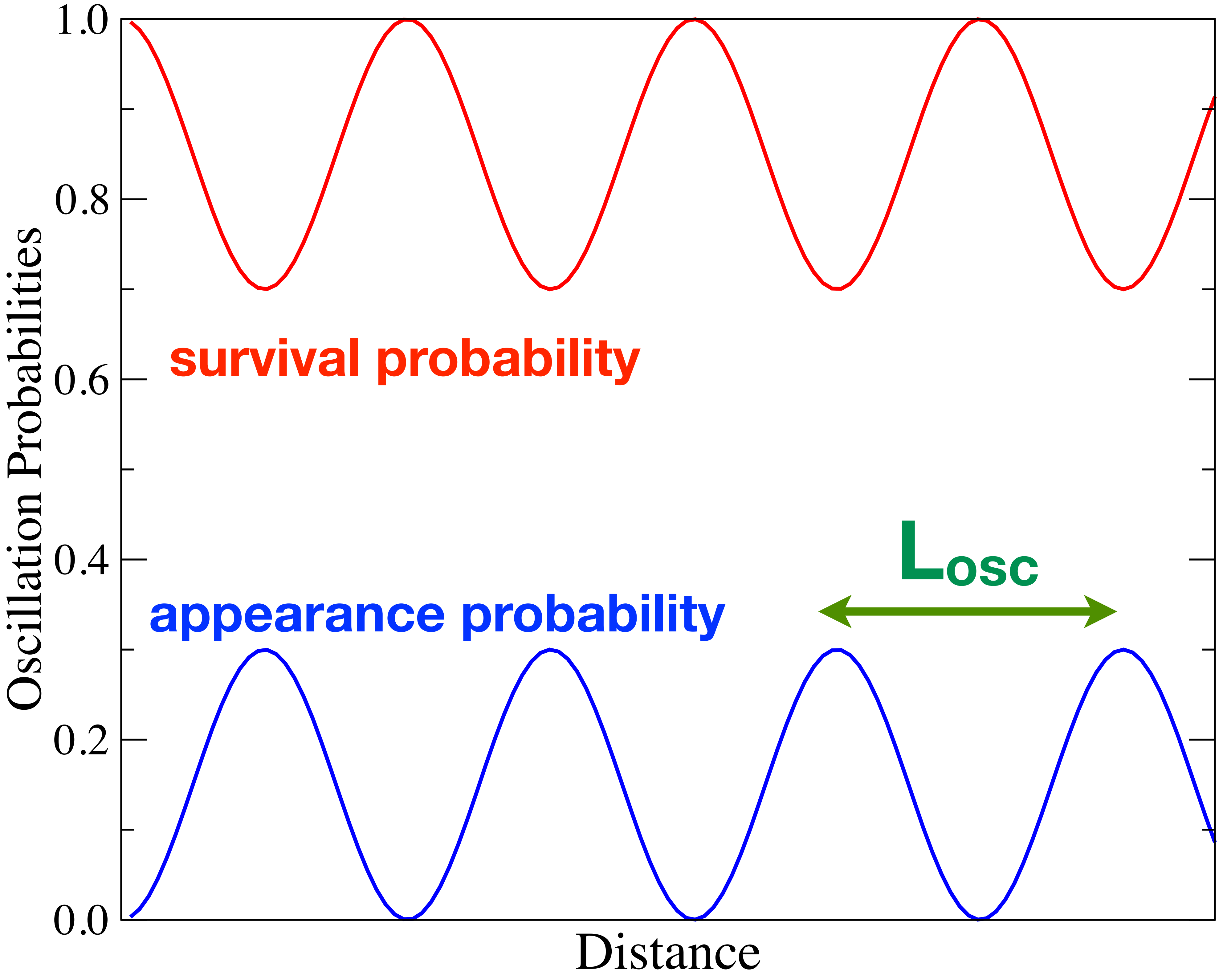
Oscillation Probabilities for 2 flavors in vacuum

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left[\frac{\Delta m^2}{4E}L\right]$$

appearance probability

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left[\frac{\Delta m^2}{4E}L\right]$$

survival probability

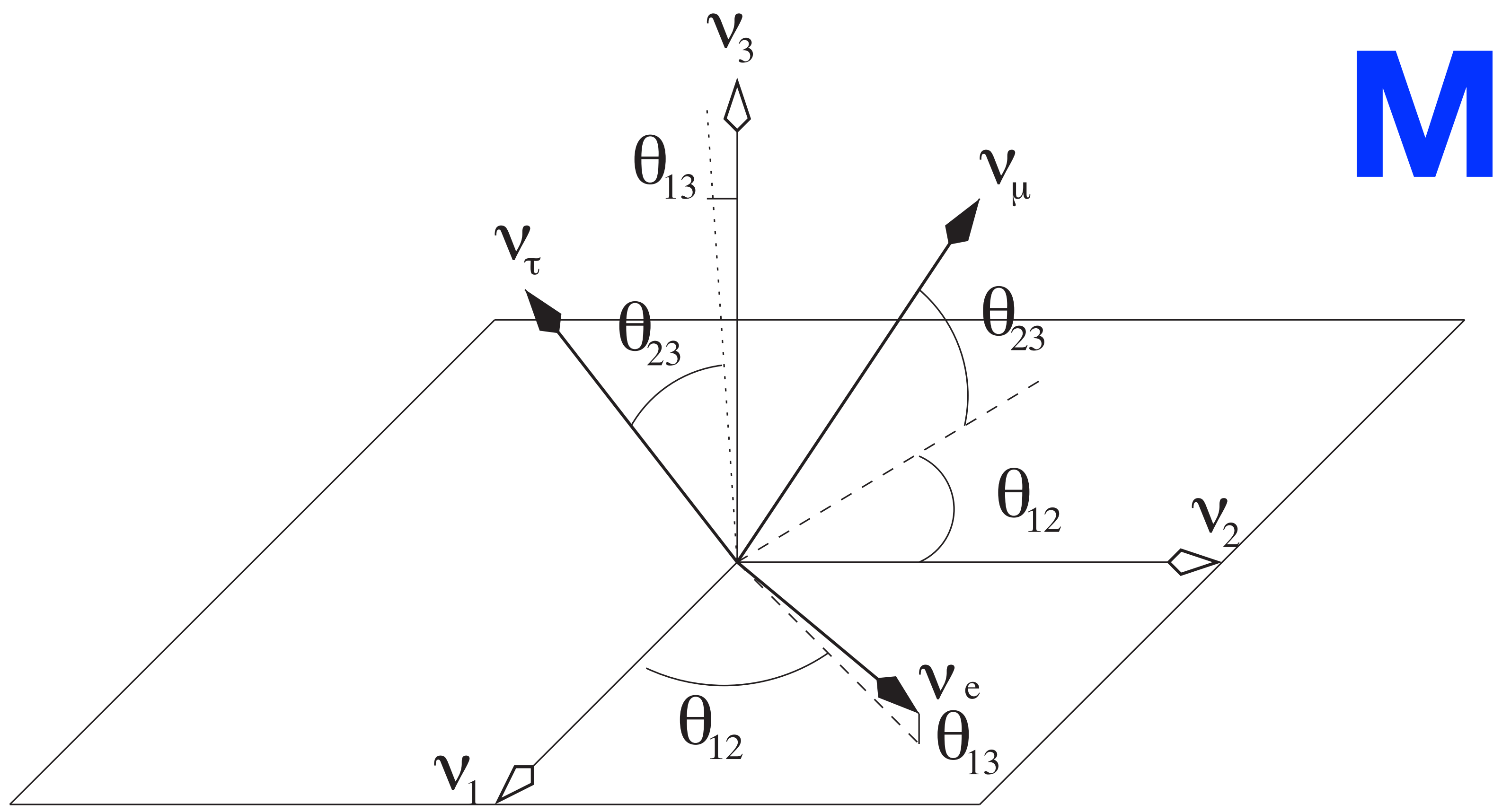


$$\boxed{L_{\rm osc} = \frac{4\pi E}{\Delta m^2} \simeq \frac{\pi}{1.27}\left[\frac{E}{\rm GeV\ (MeV)}\right]\left[\frac{\rm eV^2}{\Delta m^2}\right]\ \rm km\ (m)}$$

: oscillation length

ν oscillation is a powerful tool to probe (indirectly) very tiny neutrino masses

Mixing among 3 flavors of neutrinos



$\theta_{12}\ \theta_{23}\ \theta_{13}$ analogous to Euler angles

flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PNMS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

U$_{\mathrm{PMNS}}$: analogous to CKM matrix

$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Pontecorvo-**M**aki-
Nakagawa-**S**akata

atmospheric ν osc.

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

reactor ν osc.

solar ν osc.

For oscillation, 6 indep. parameters: 3 mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$,1 CP phase δ_{CP}

and 2 (indep.) mass squared differences $\Delta m^2_{21}, \Delta m^2_{31} (= \Delta m^2_{32} - \Delta m^2_{21})$

Neutrino Oscilltion Probabilities in Vacuum

$$P(\alpha \to \beta) = \left| \sum_j U^*_{\alpha j} U_{\beta j} e^{-i\frac{m_j^2}{2E}L} \right|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin^2\left(\frac{\Delta m^2_{ij}}{4E}L\right) + 2\sum_{i>j} \Im[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin\left(\frac{\Delta m^2_{ij}}{2E}L\right)$$

Oscillation probabilities depends on 6 oscillation parameters

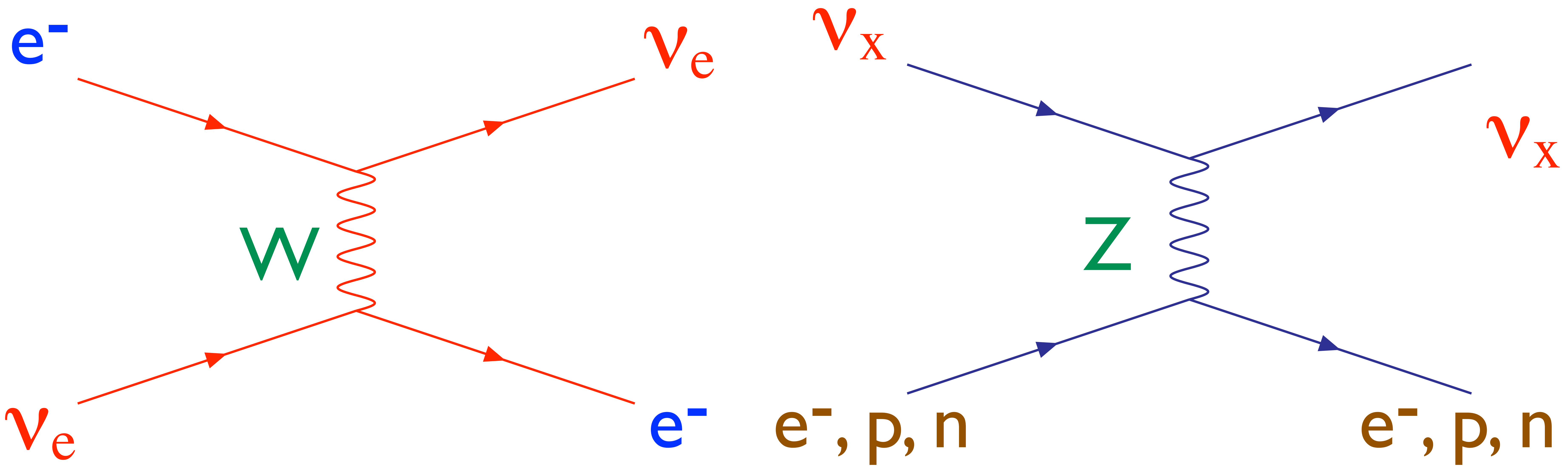
$$\Delta m^2_{21}, \Delta m^2_{31} (= \Delta m^2_{32} - \Delta m^2_{21})$$

$$\theta_{12}, \theta_{23}, \theta_{13}$$

$$\delta_{\text{CP}}$$

Interaction of neutrinos with matter

Charged Current (CC)   Neutral Current (NC)



$\nu_x = \nu_e, \nu_\mu, \nu_\tau$

Coherent Effect $\sim$ O(G_F)

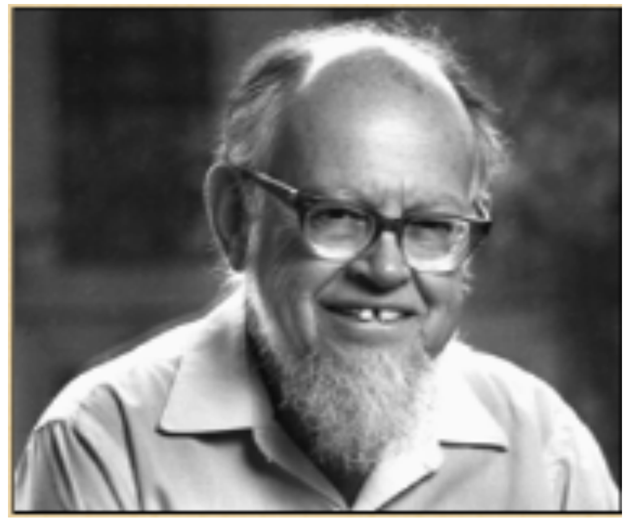
matter effect modifies the index of refraction for neutrinos

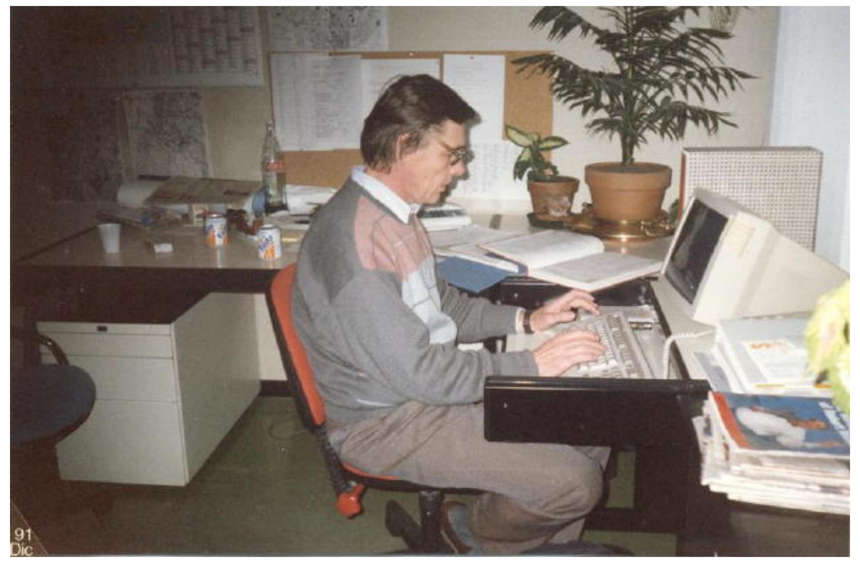
can modify drastically the oscillation probability

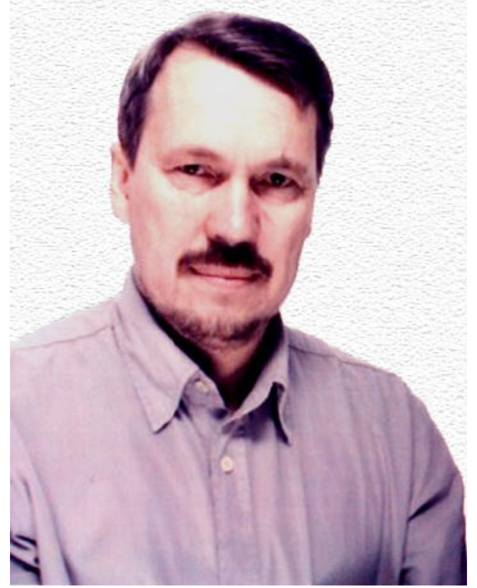
analogy: photon gain effective mass in matter

Neutrino Oscilltion in Matter

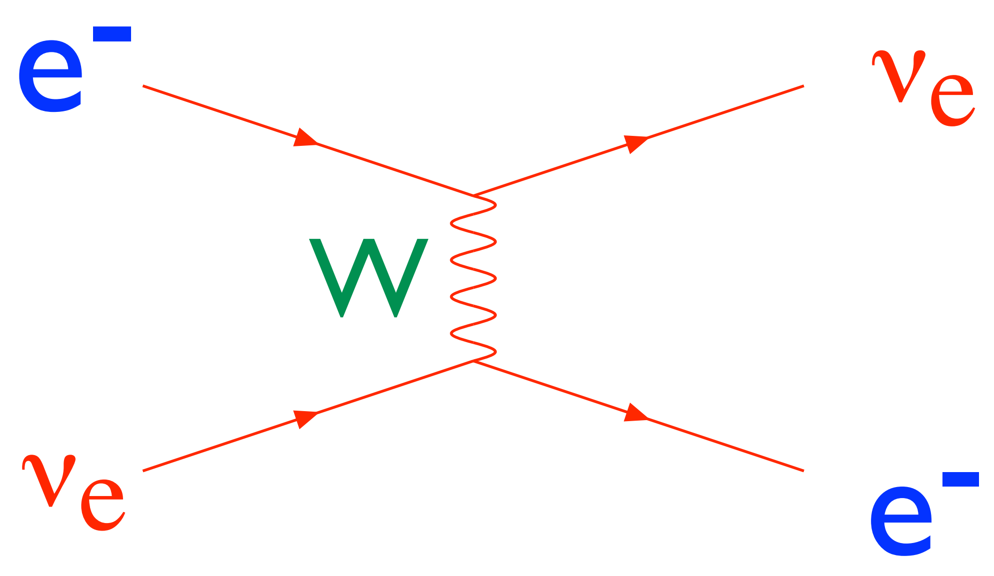
Mikheyev-Smirnov-Wolfenstein (MSW) Effect


L. Wolfenstein


S. P. Mikheyev


A. Yu. Smirnov

Charged Current



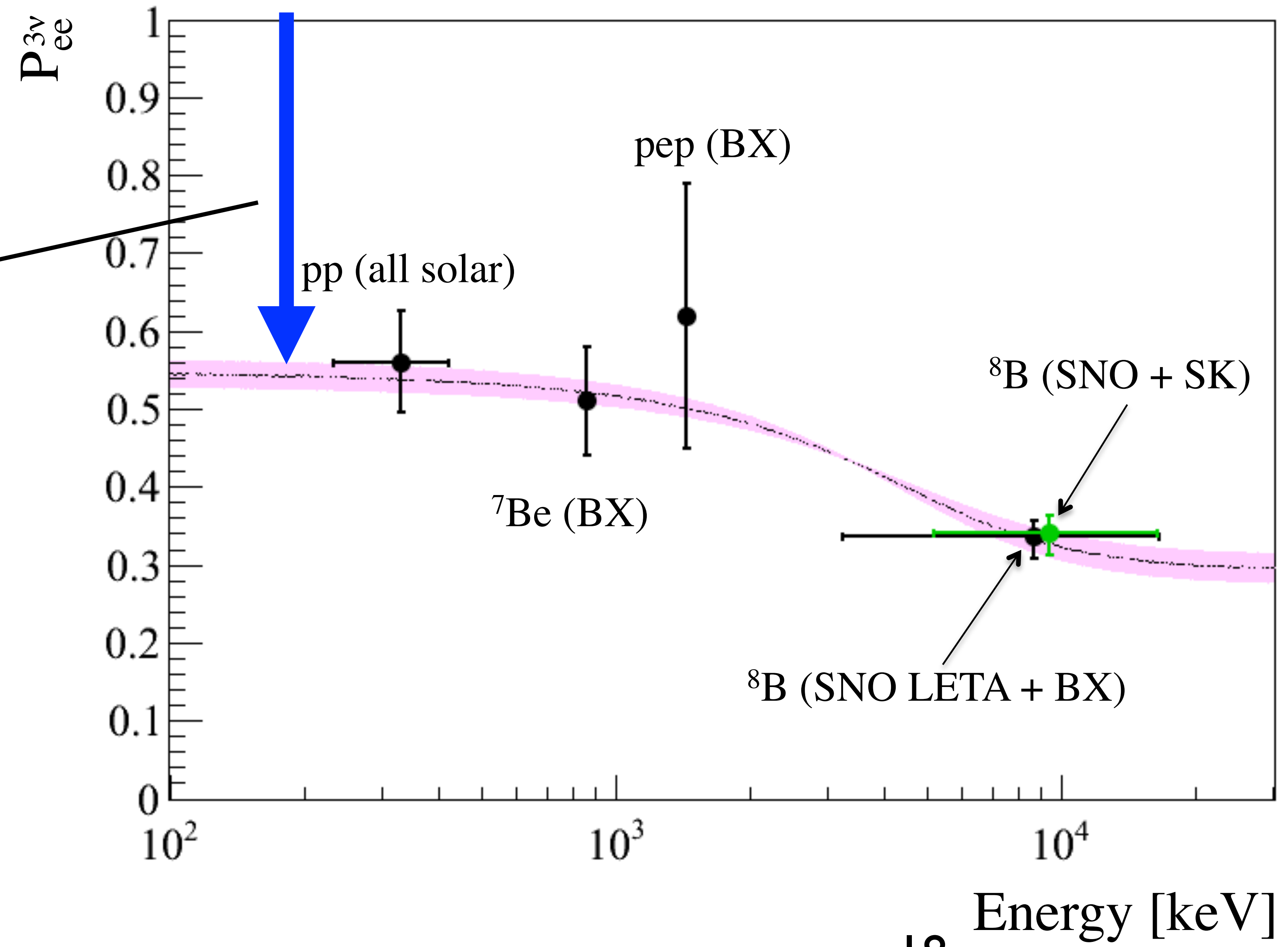
L. Wolfenstein, PRD17 (1978)2369

S.P.Mikheyev and A. Yu. Smirnov, Sov. J. Nucl. Phys. 42 (1985)913

Resonant Enhancement of Neutrino Oscillation in matter

Essential to solve Solar Neutrino Problem

Vacuum osc.



MSW effect (prediction)

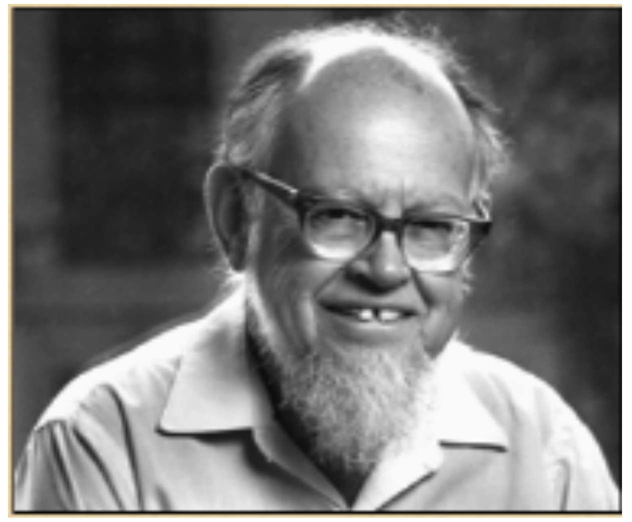
changes index of refraction

ν_e feels extra potential or gains effective mass

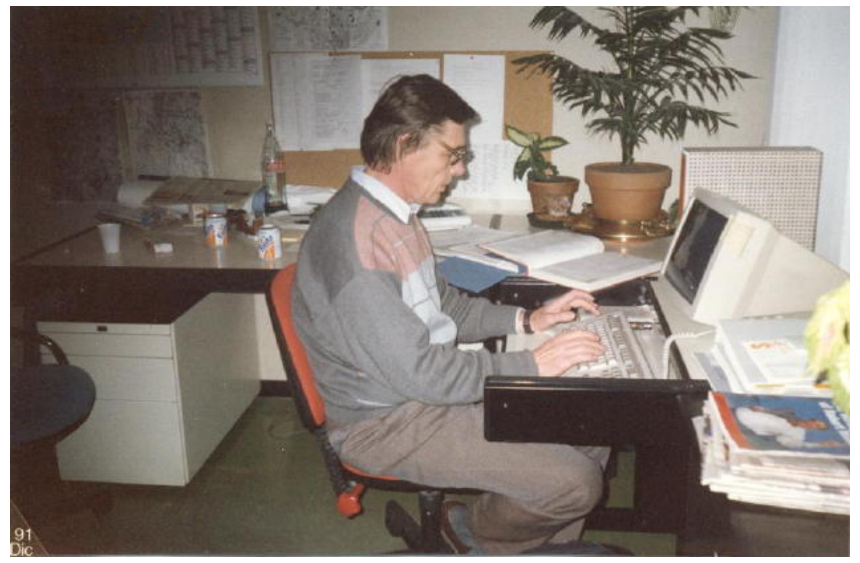
Bellini et a, Borexino, PRD89, 112007 (2014)

Neutrino Oscilltion in Matter

Mikheyev-Smirnov-Wolfenstein (MSW) Effect



L. Wolfenstein



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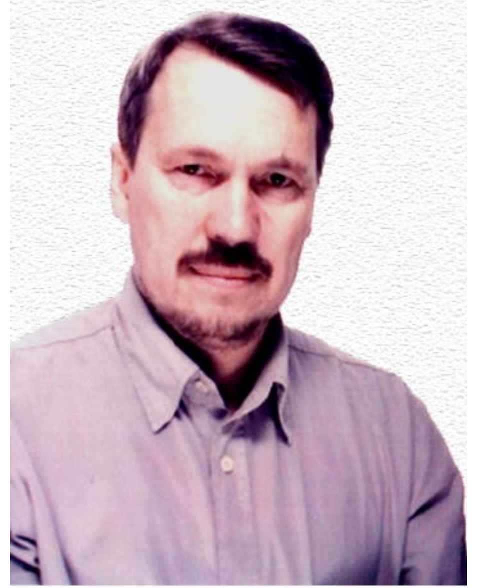

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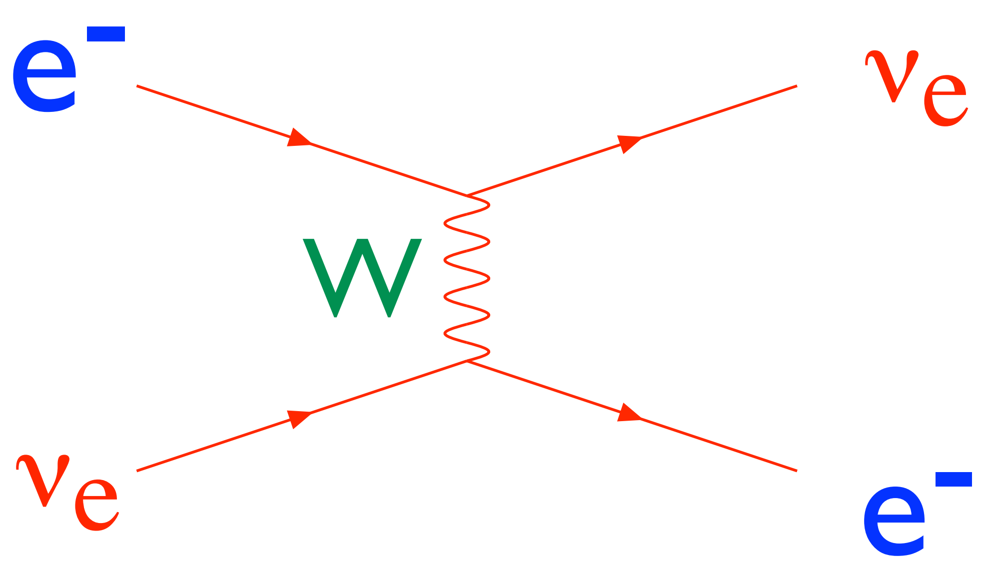

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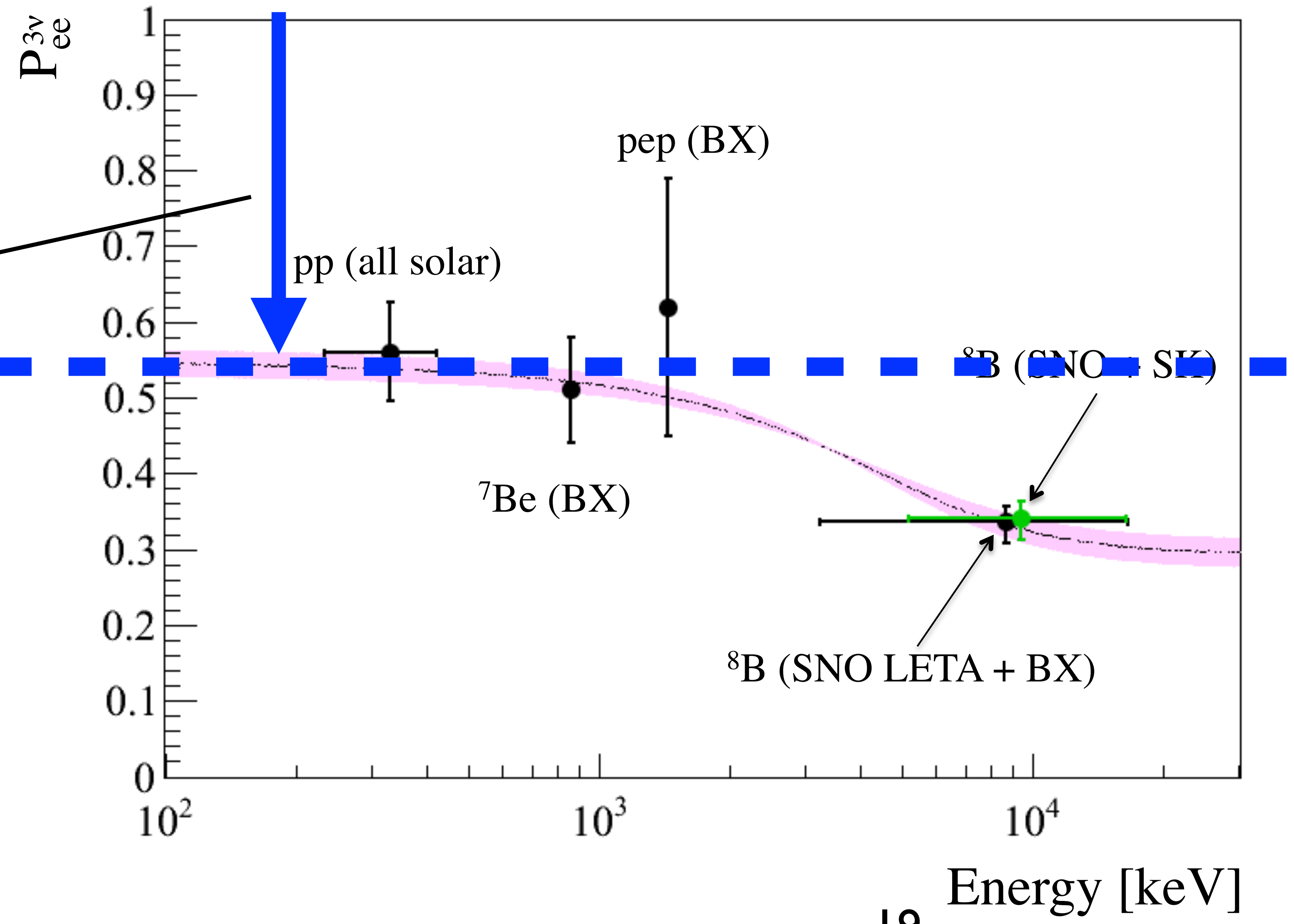

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Neutrino Oscilltion Probabilities in Matter

$$P(\alpha \to \beta) = \left| \sum_j U^*_{\alpha j} U_{\beta j} e^{-i\frac{m_j^2}{2E}L} \right|^2$$ (Oscilltion Probabilities in vacuum)

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin^2\left(\frac{\Delta m^2_{ij}}{4E}L\right) + 2 \sum_{i>j} \Im[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin\left(\frac{\Delta m^2_{ij}}{2E}L\right)$$

With constant matter density, we can compute oscillation probabililties in the same way by simply replacing the vacuum mixing matrix elements and mass squared differences to the effective ones in matter,

$$\boxed{U_{\alpha i} \to \widetilde{U}_{\alpha i}\ ,\ \Delta m^2_{ij} \to \widetilde{\Delta m^2_{ij}}}$$

Neutrino Oscilltion Probabilities in Matter

$$P(\alpha \to \beta) = \left| \sum_j \widetilde{U_{\alpha j}}^* \widetilde{U_{\beta j}} e^{-i \frac{\widetilde{m_j^2}}{2E} L} \right|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re[\widetilde{U_{\alpha i}}^* \widetilde{U_{\alpha j}} \widetilde{U_{\beta i}} \widetilde{U_{\beta j}}^*] \sin^2 \left(\frac{\widetilde{\Delta m_{ij}^2}}{4E} L \right) + 2 \sum_{i>j} \Im[\widetilde{U_{\alpha i}}^* \widetilde{U_{\alpha j}} \widetilde{U_{\beta i}} \widetilde{U_{\beta j}}^*] \sin \left(\frac{\widetilde{\Delta m_{ij}^2}}{2E} L \right)$$

With constant matter density, we can compute the probabililties in the same way by simply replacing the vacuum mixing matrix elements and mass squared differences to the effective ones in matter,

$$\boxed{U_{\alpha i} \to \widetilde{U}_{\alpha i} \; , \; \Delta m_{ij}^2 \to \widetilde{\Delta m_{ij}^2}}$$

Neutrino Evolution Equation in Matter

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{bmatrix} = H\begin{bmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{bmatrix}$$

G_F : Fermi Constant

N_e : Electron number density

$$H = U\begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{bmatrix}U^\dagger + \begin{bmatrix}\sqrt{2}G_F N_e & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

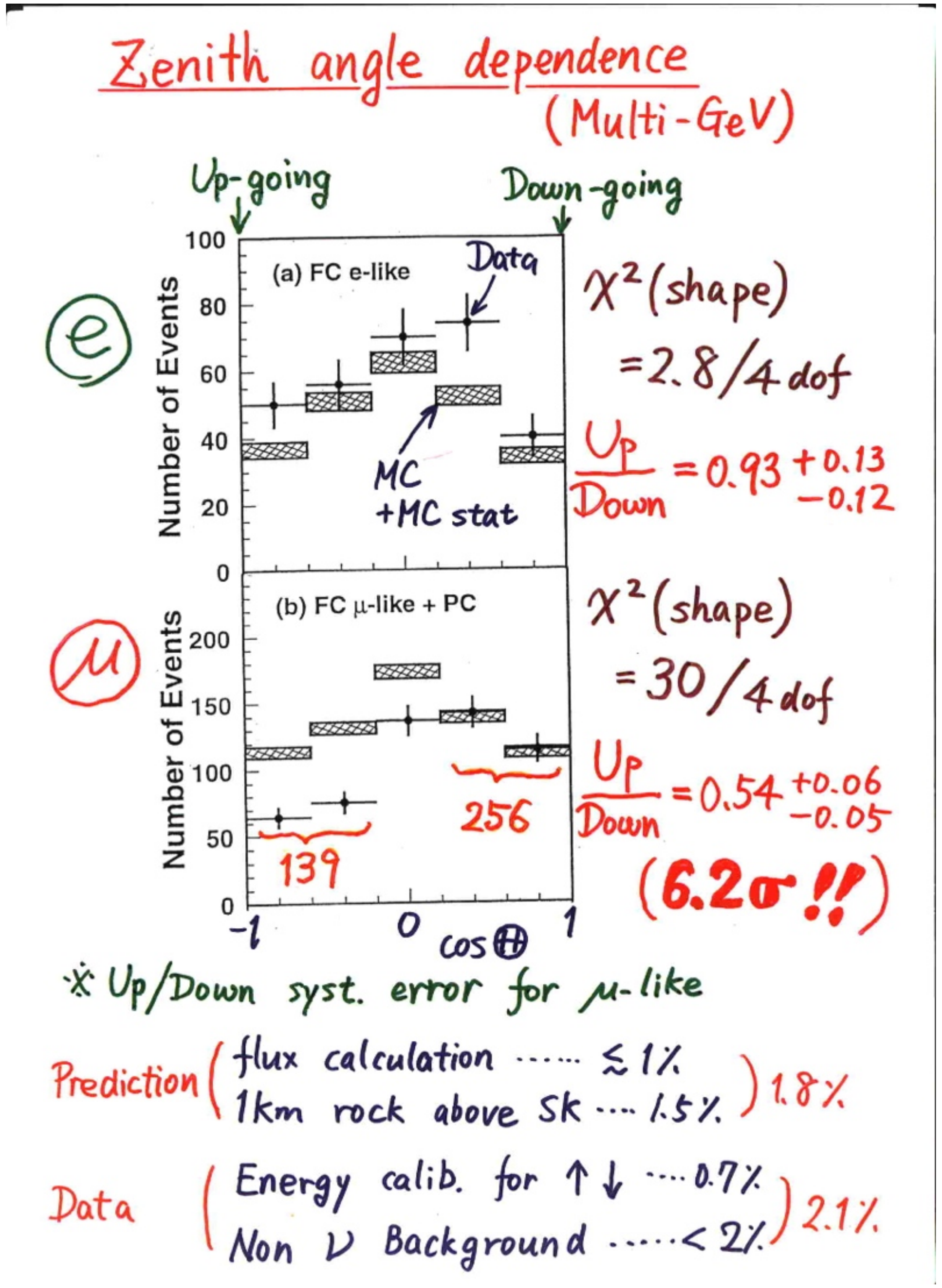
In general, for varying matter (electron) density profile, one needs to solve numerically the evolution equation, or diagonalize the Hamiltonian at each position, to compute the final oscillation probability

Discovery of Neutrino Oscillations

from experimental point of view

Discovery of Neutrino Oscillation in 1998

Announced in “Neutrino ’98” @Takayama, Japan



Zenith angle dependence

(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

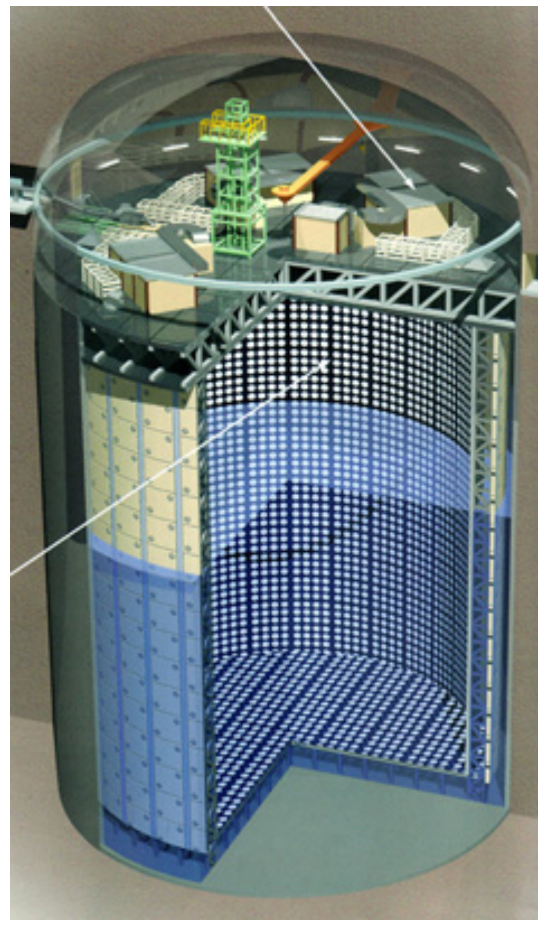
(6.2σ !!)

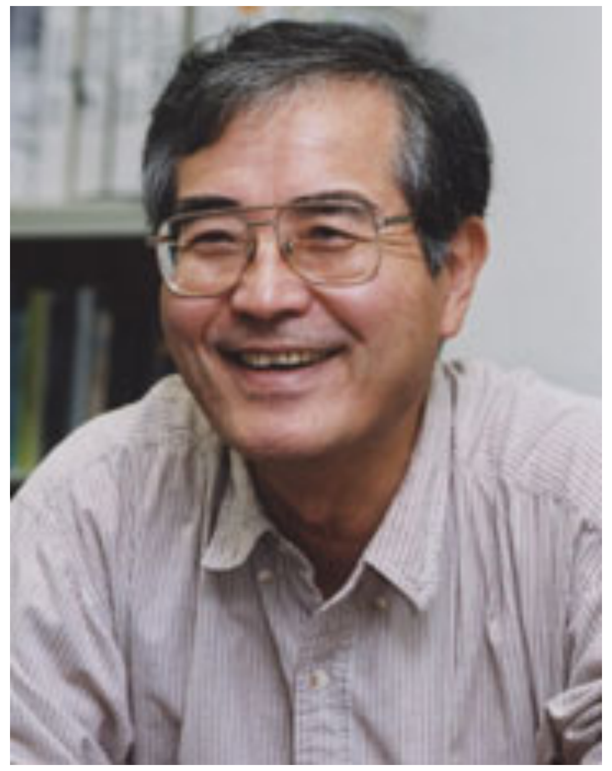
※ Up/Down syst. error for μ-like

Prediction (flux calculation ······ $\lesssim 1\%$; 1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑↓ ···· 0.7% ; Non ν Background ·····< 2%) 2.1%

T. Kajita





Y. Totsuka
(1942-2008)

Super-Kamiokande Collaboration

$$\nu_\mu \longleftrightarrow \nu_\tau$$

neutrinos change falvors !

$$\rightarrow m_\nu \neq 0$$

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

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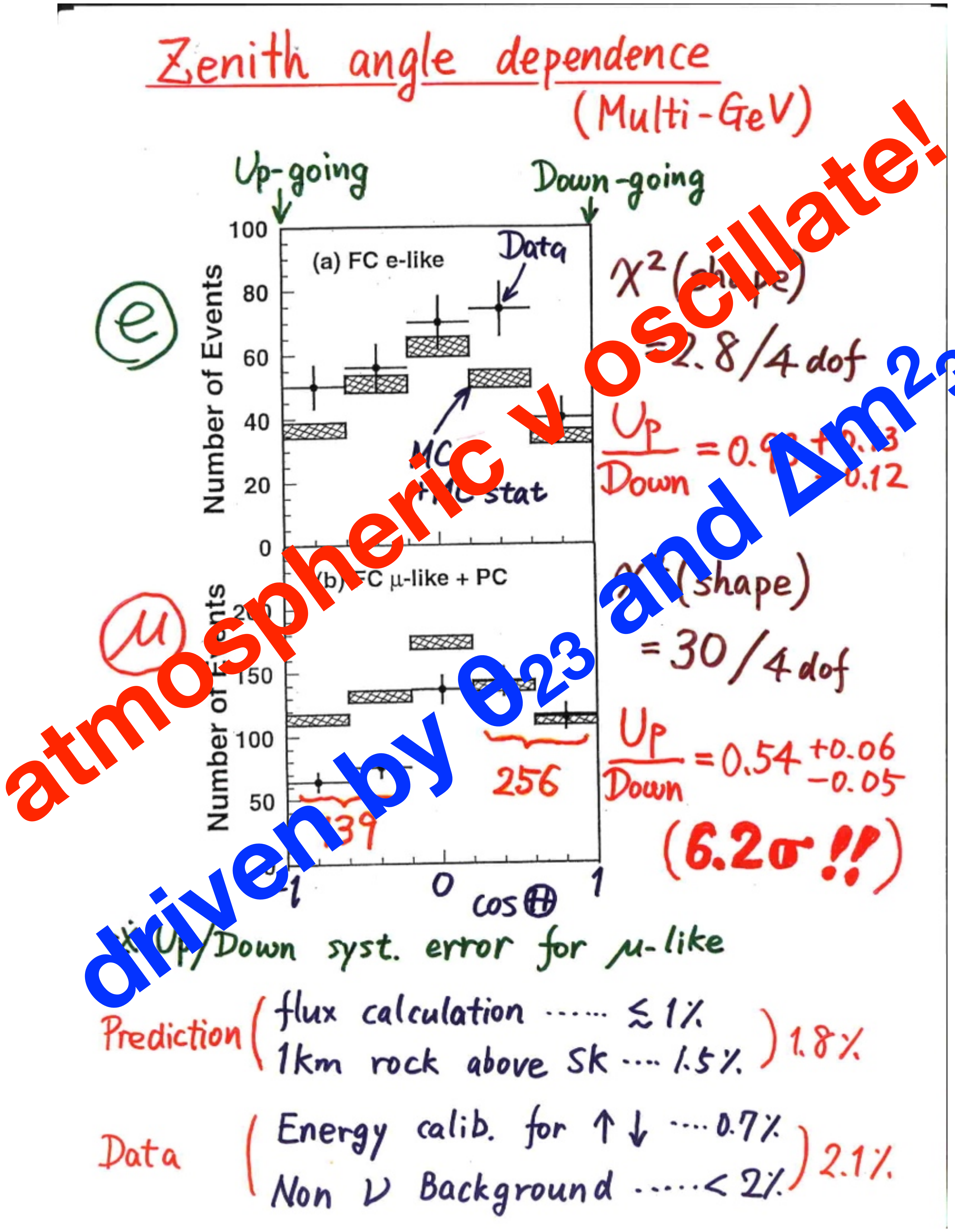

Zenith angle dependence (Multi-GeV)

(a) FC e-like

χ^2(shape) = 2.8/4 dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

(b) FC μ-like + PC

χ^2(shape) = 30/4 dof

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* Up/Down syst. error for μ-like

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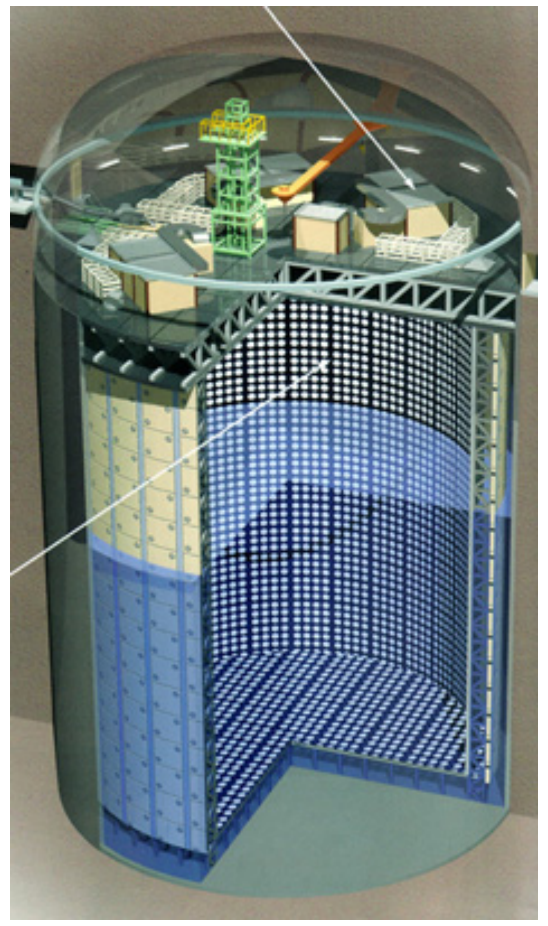
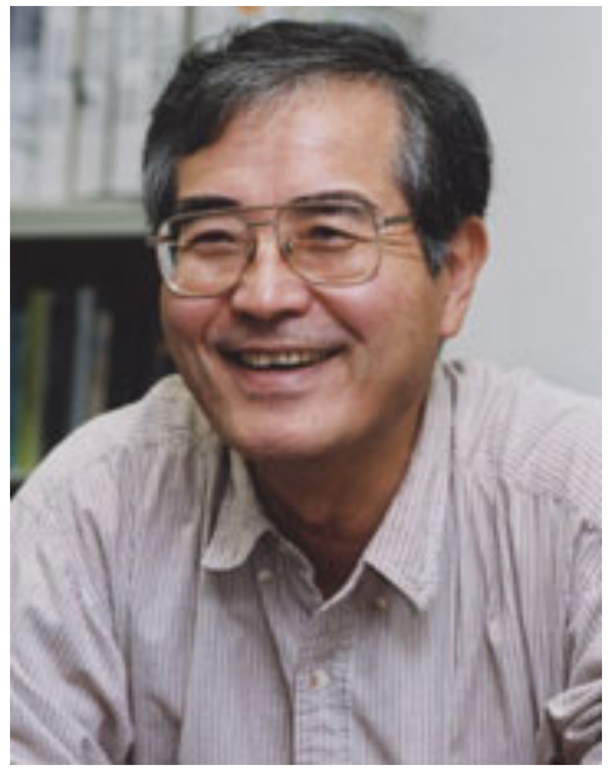
atmospheric ν oscillate!

driven by θ_{23} and Δm^2_{32}

T. Kajita





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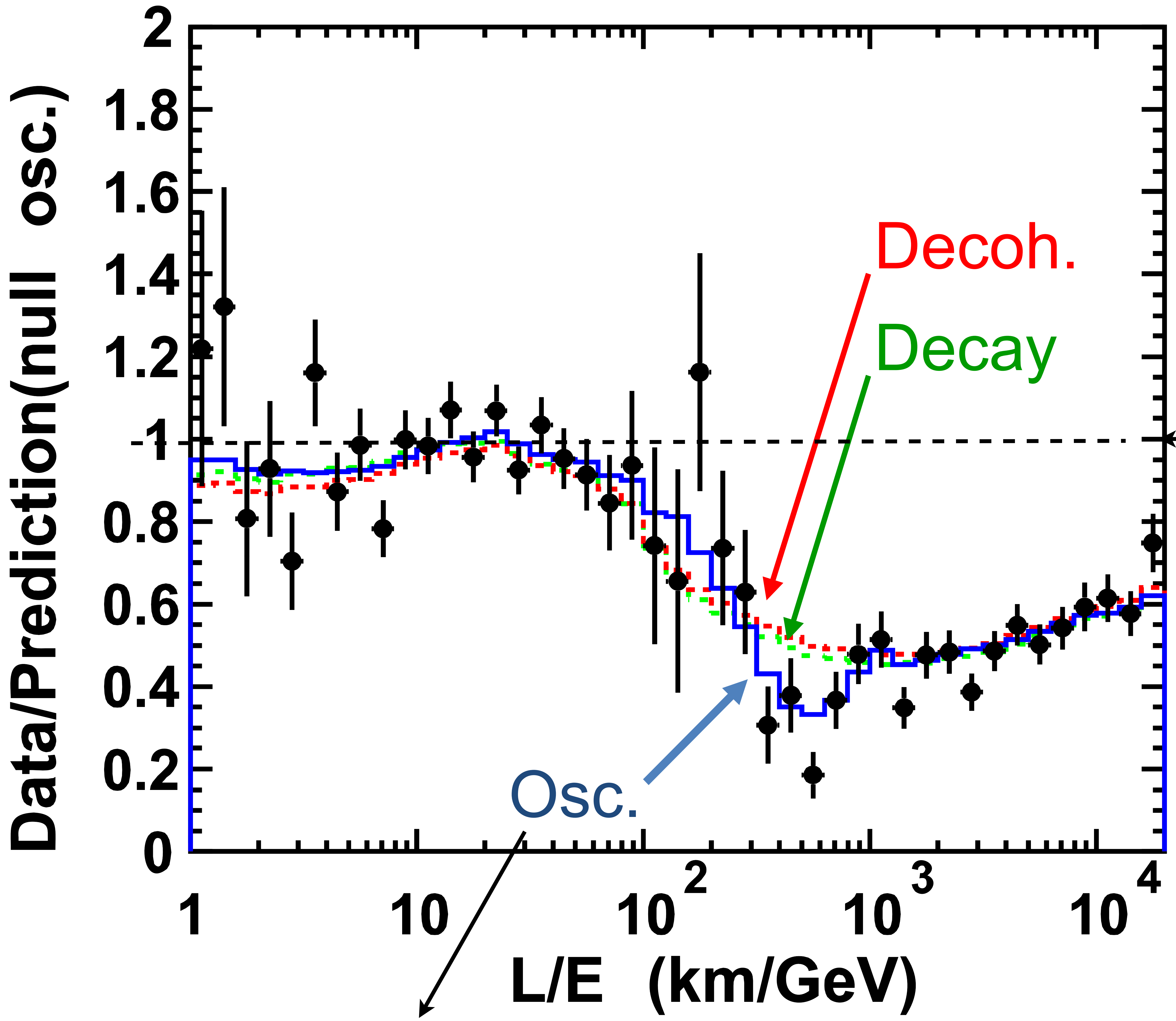
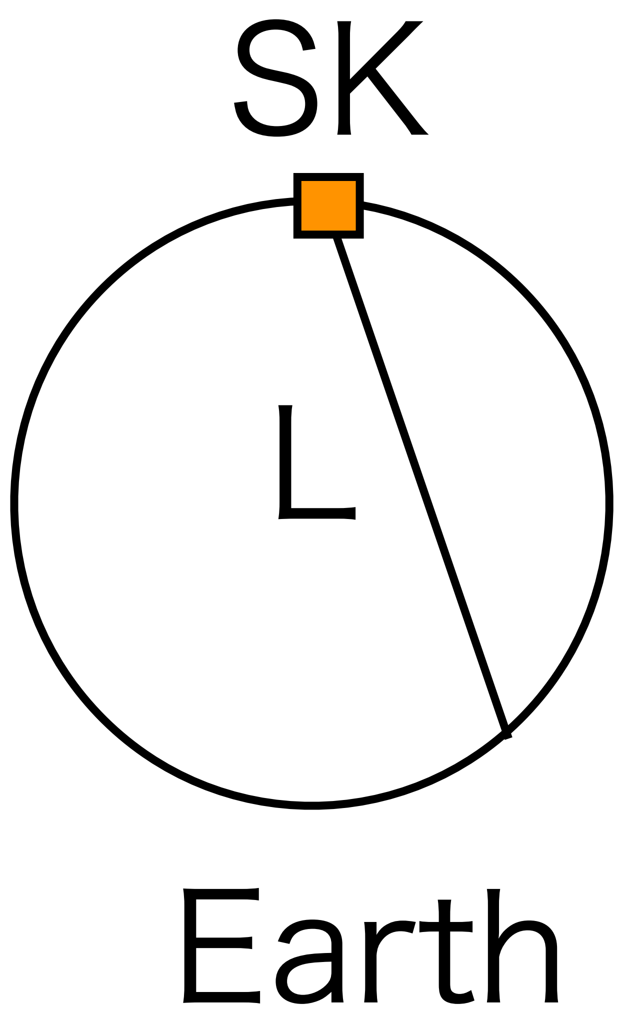
$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

L/E distribution of Super-Kamiokande Atmospheric Neutrinos



Ashie et al, PRL93, 101801 (2004)

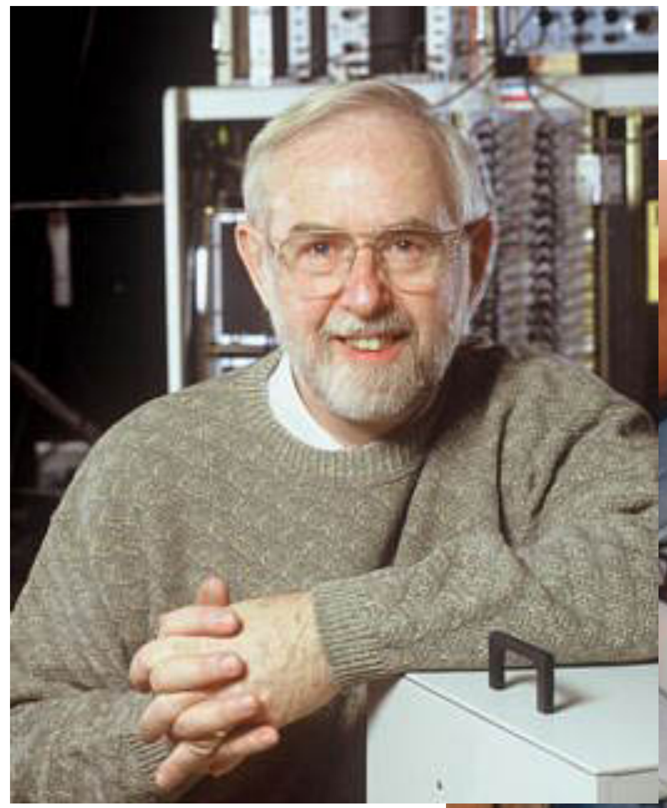


$$P(\nu_\mu \to \nu_\mu) = \sin^2 2\theta \sin\left(\frac{\Delta m^2}{4E} L\right)$$

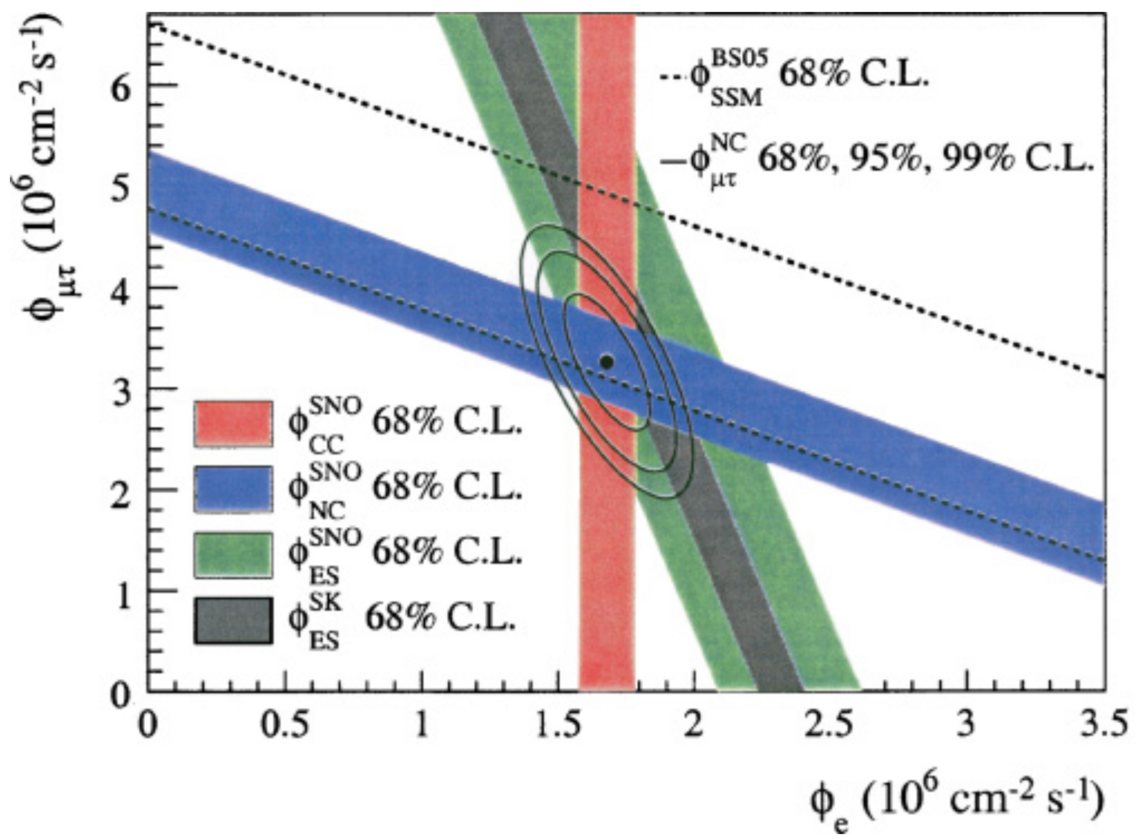
Solar neutrinos also oscillate!

$$\nu_e \longleftrightarrow \nu_{\mu,\tau}$$

A. McDonald



$$P(\nu_e \to \nu_e) \sim \sin^2\theta_{12}$$



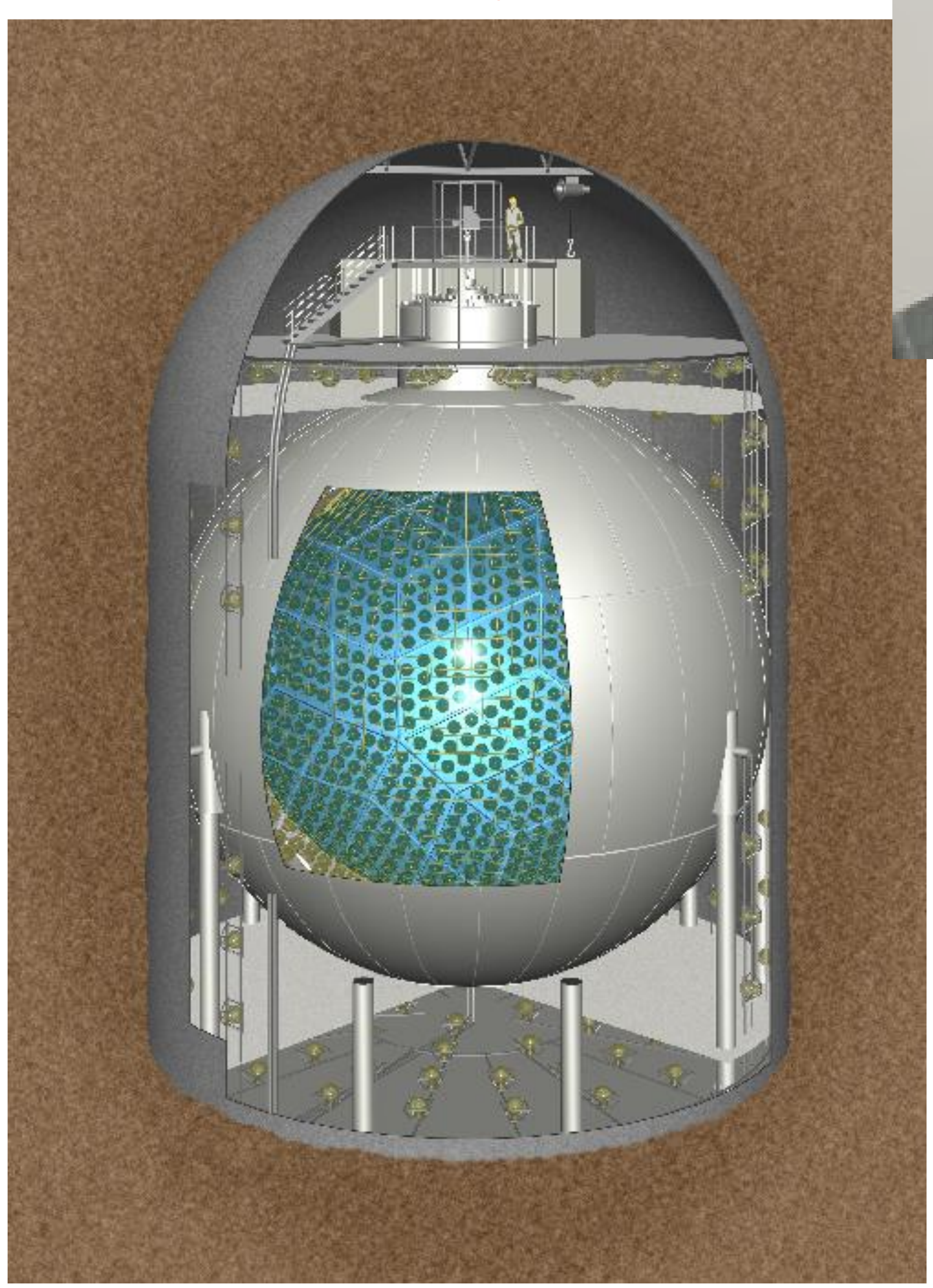
Aharmim et al, PRC72, 055502 (2005)

SNO

solar ν

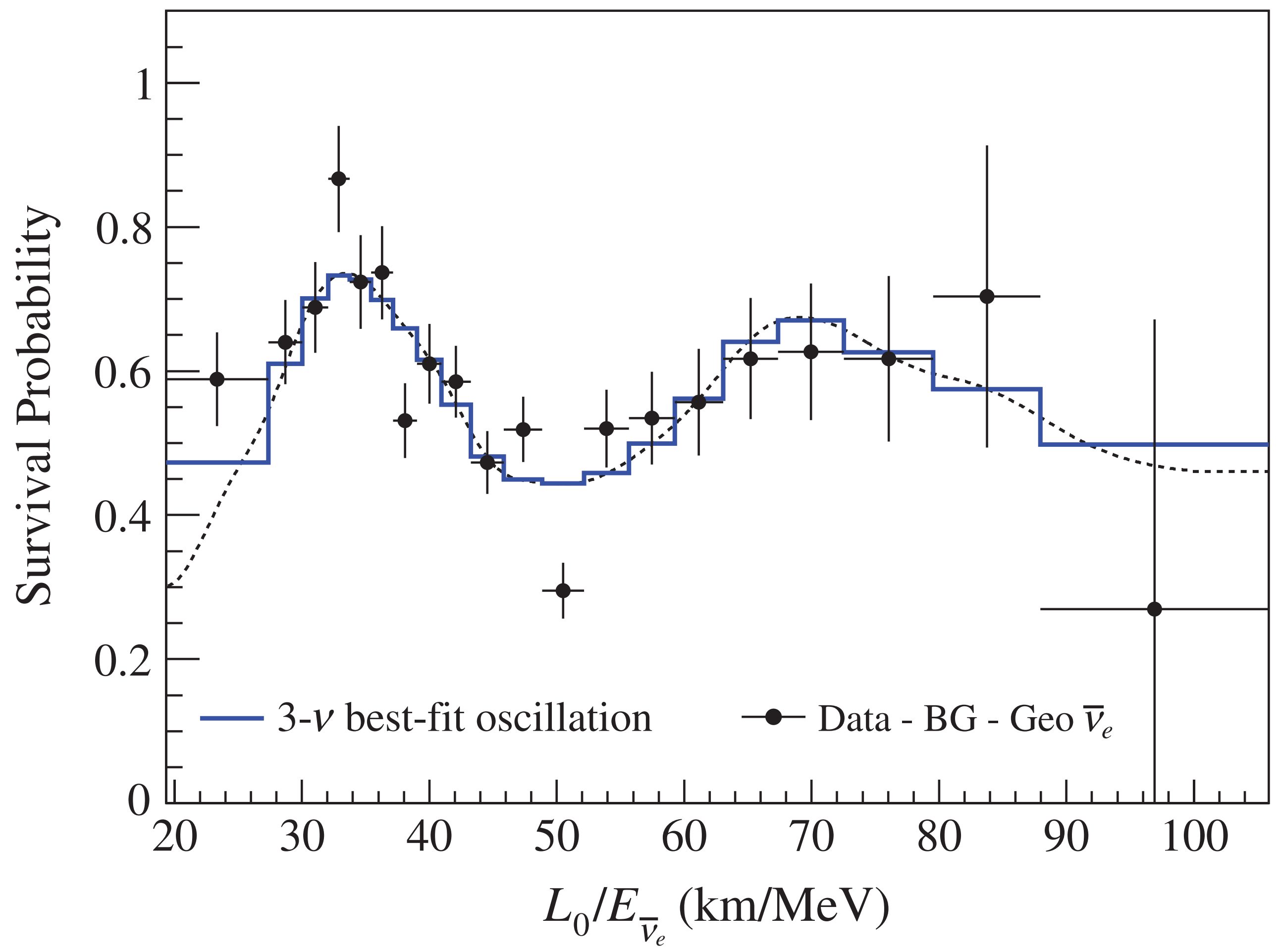
2002

A. Suzuki



KamLAND

reactor ν

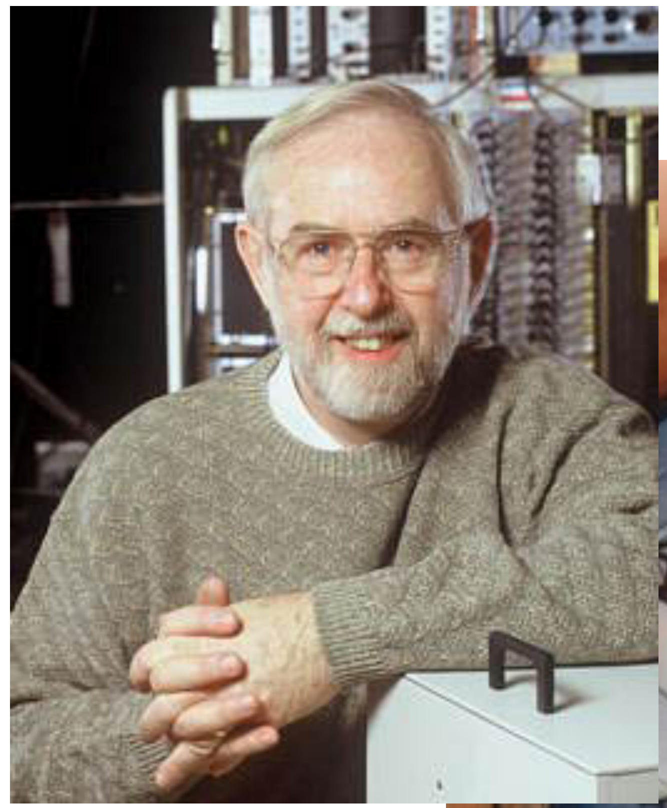


Gando et al, PRD88, 033001 (2013)

$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right)$$

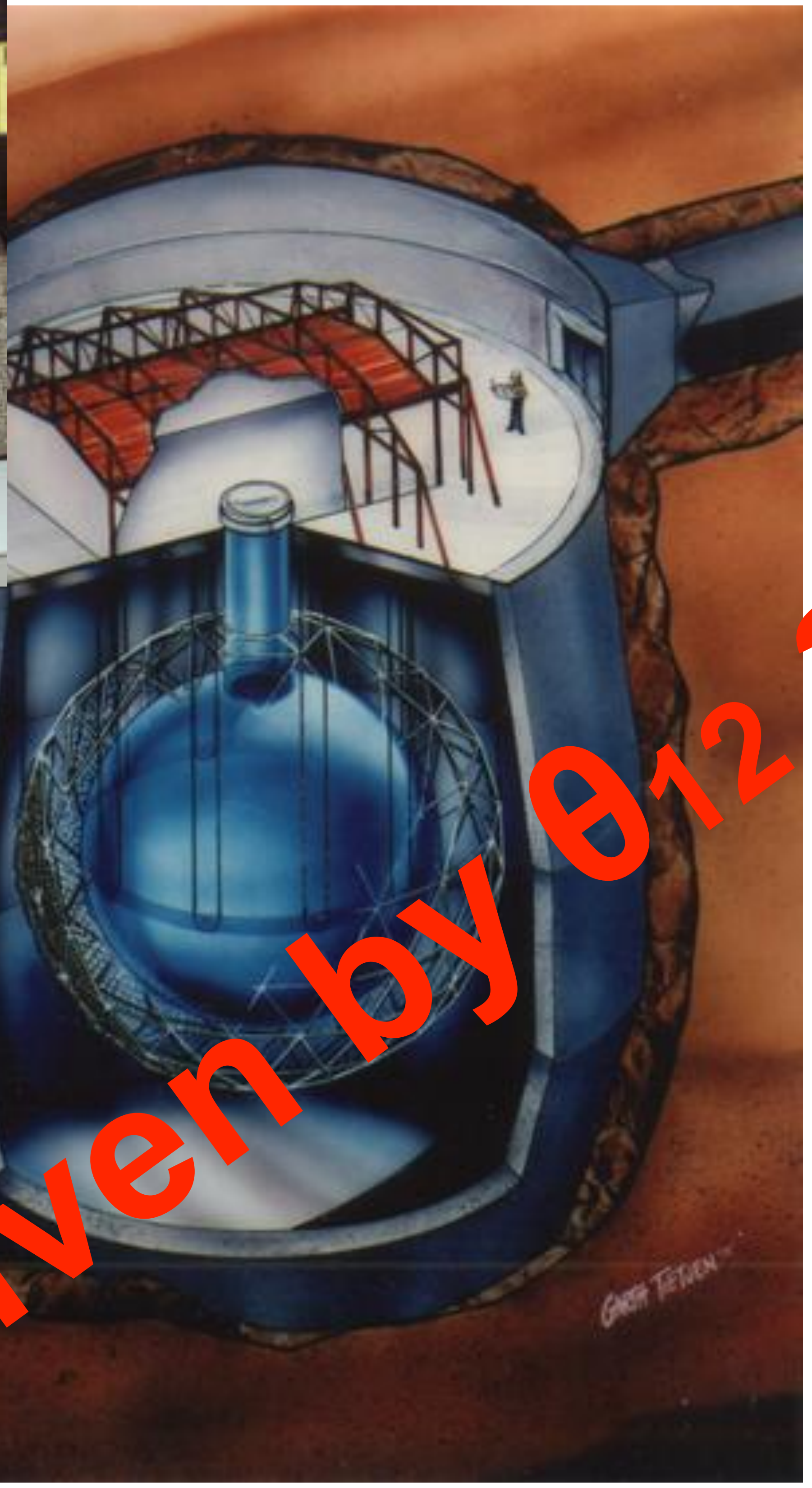
Solar neutrinos also oscillate!

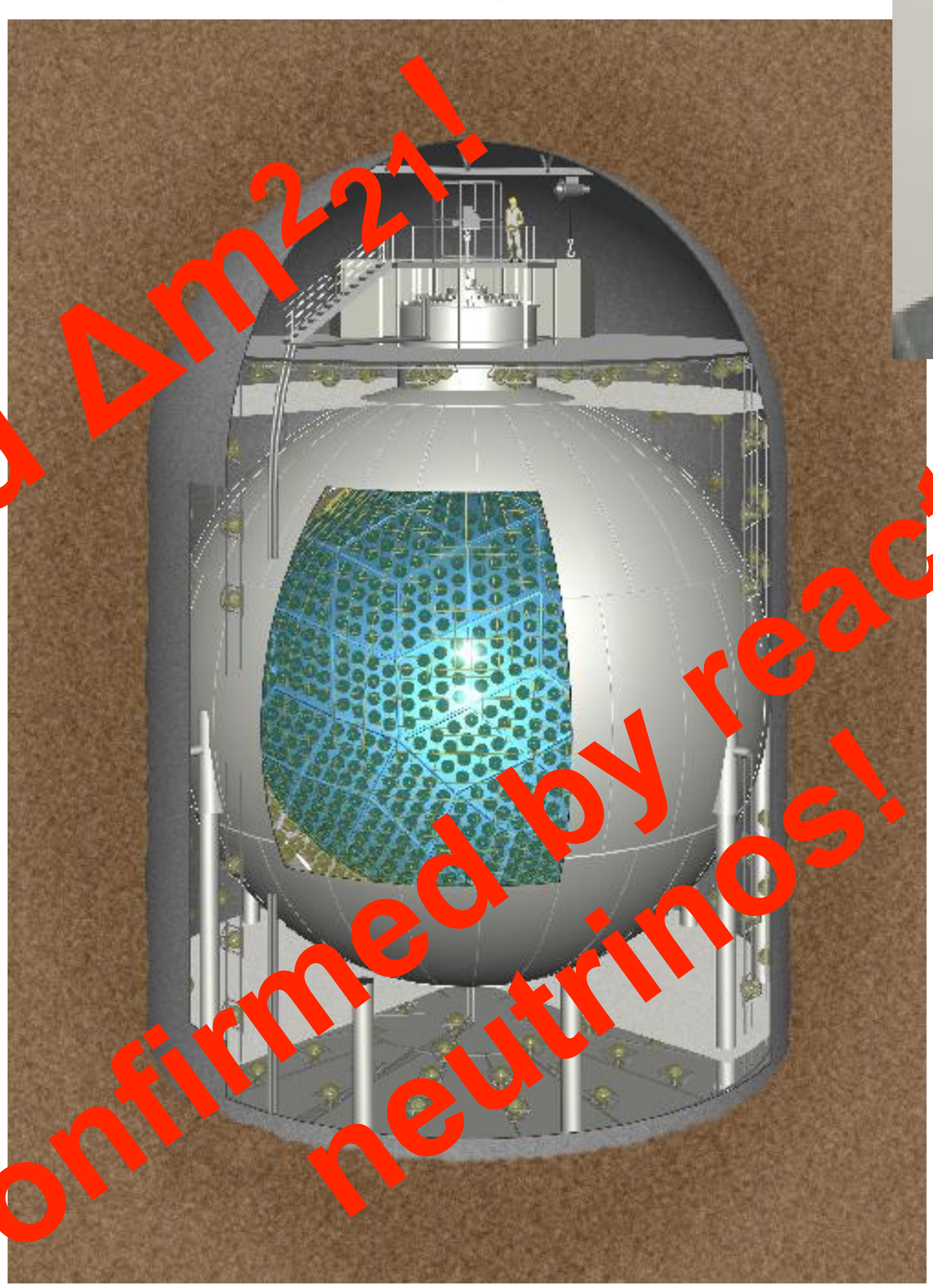
A. McDonald



$\nu_e \longleftrightarrow \nu_{\mu,\tau}$

A. Suzuki

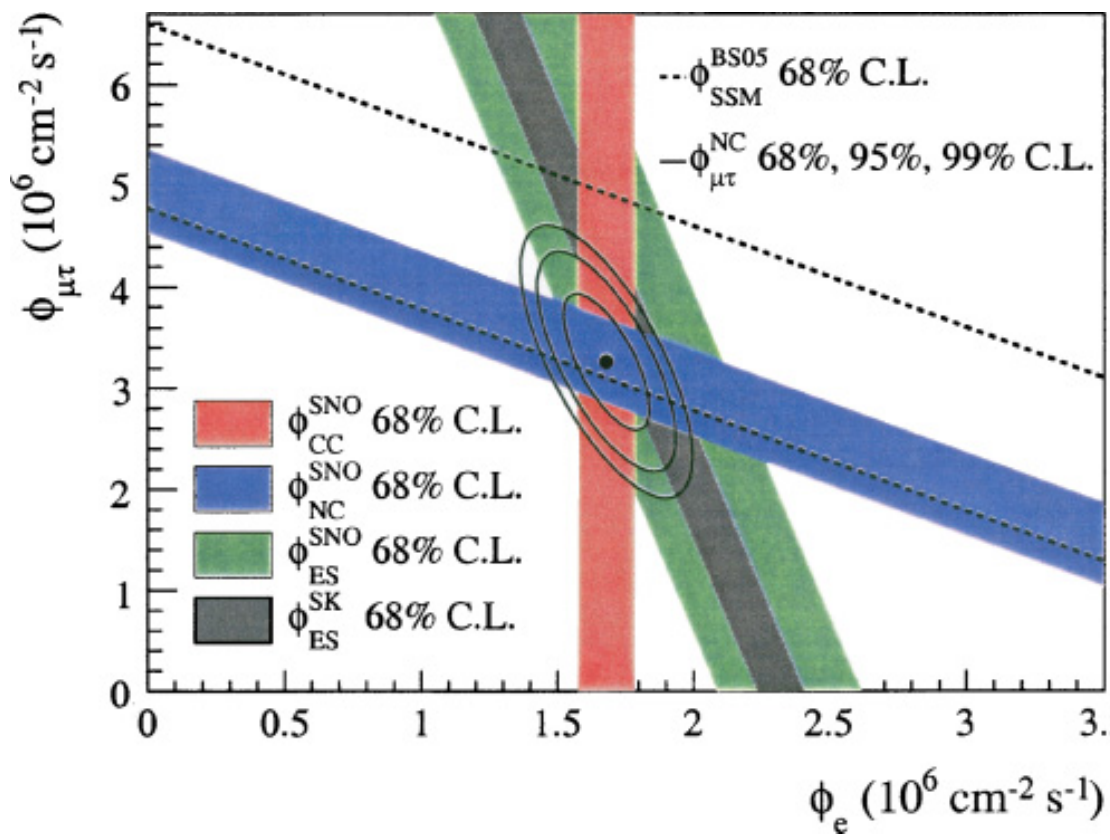




driven by θ_{12} and Δm^2_{21}!

confirmed by reactor neutrinos!

$$P(\nu_e \to \nu_e) \sim \sin^2\theta_{12}$$



Aharmim et al, PRC72, 055502 (2005)

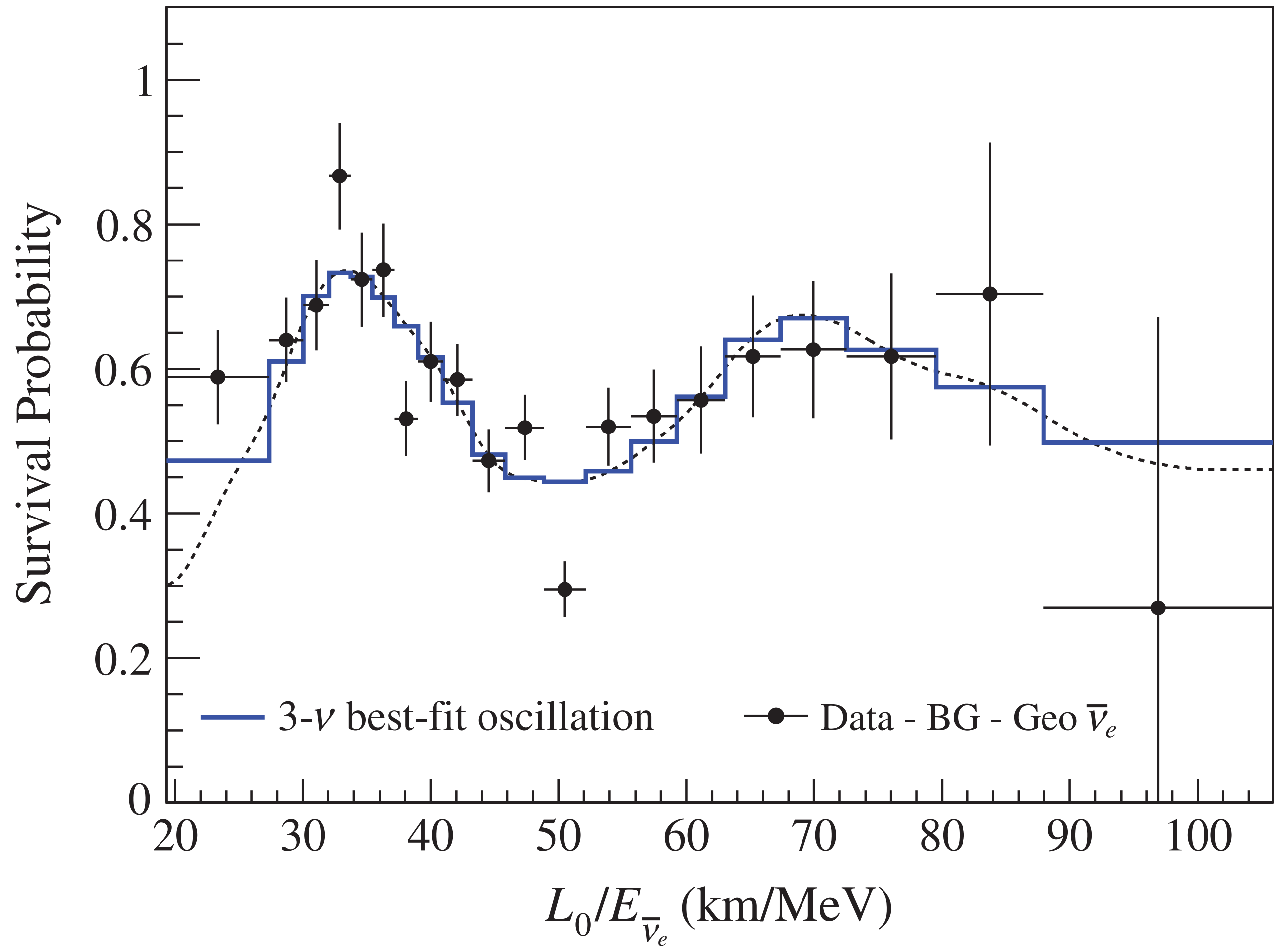
SNO

solar ν

2002

KamLAND

reactor ν

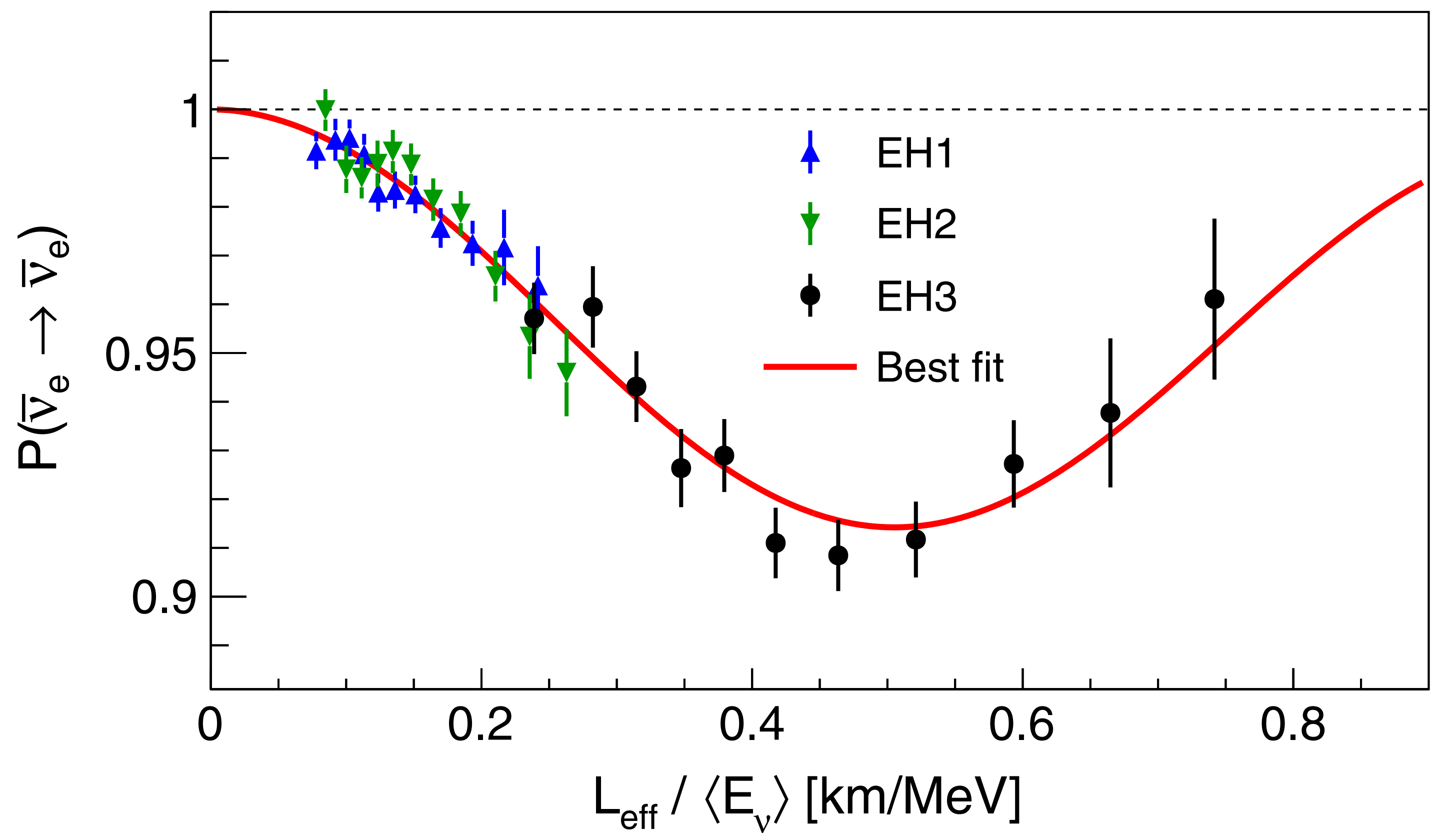


Gando et al, PRD88, 033001 (2013)

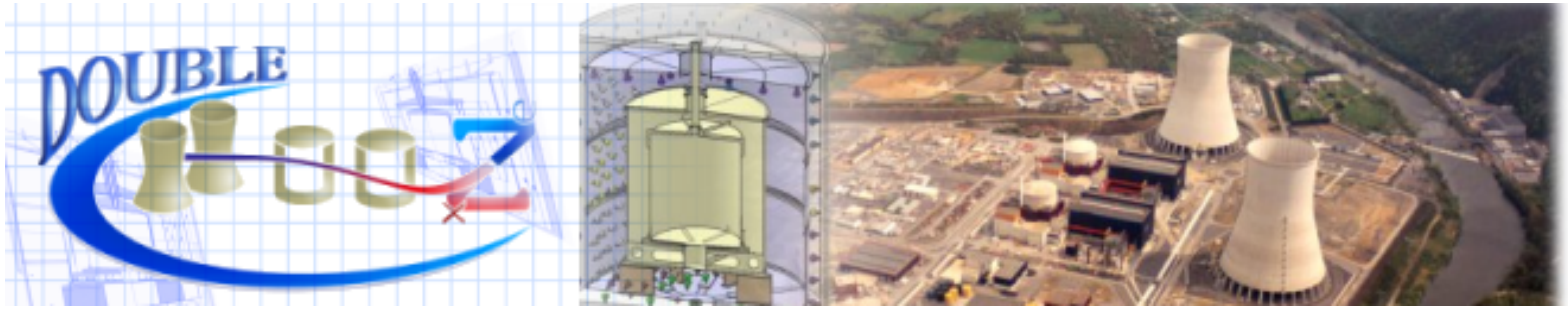
$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21}}{4E}L\right)$$

Another oscillation channel observed by reactor experiments

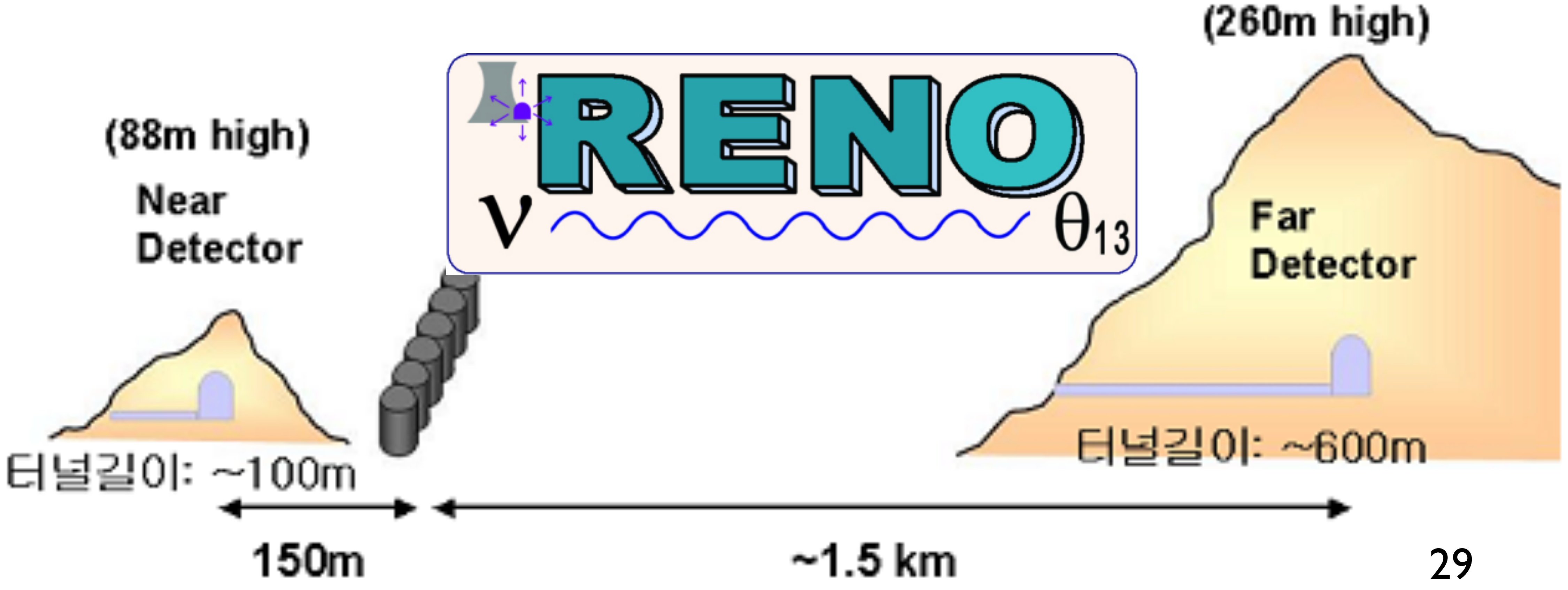
2011-2012 $P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31}}{4E} L \right)$



An et al, PRL108, 171803 (2012)



Abe et al, PRL108, 131801 (2012)



Ahn et al, PRL108, 191802 (2012)

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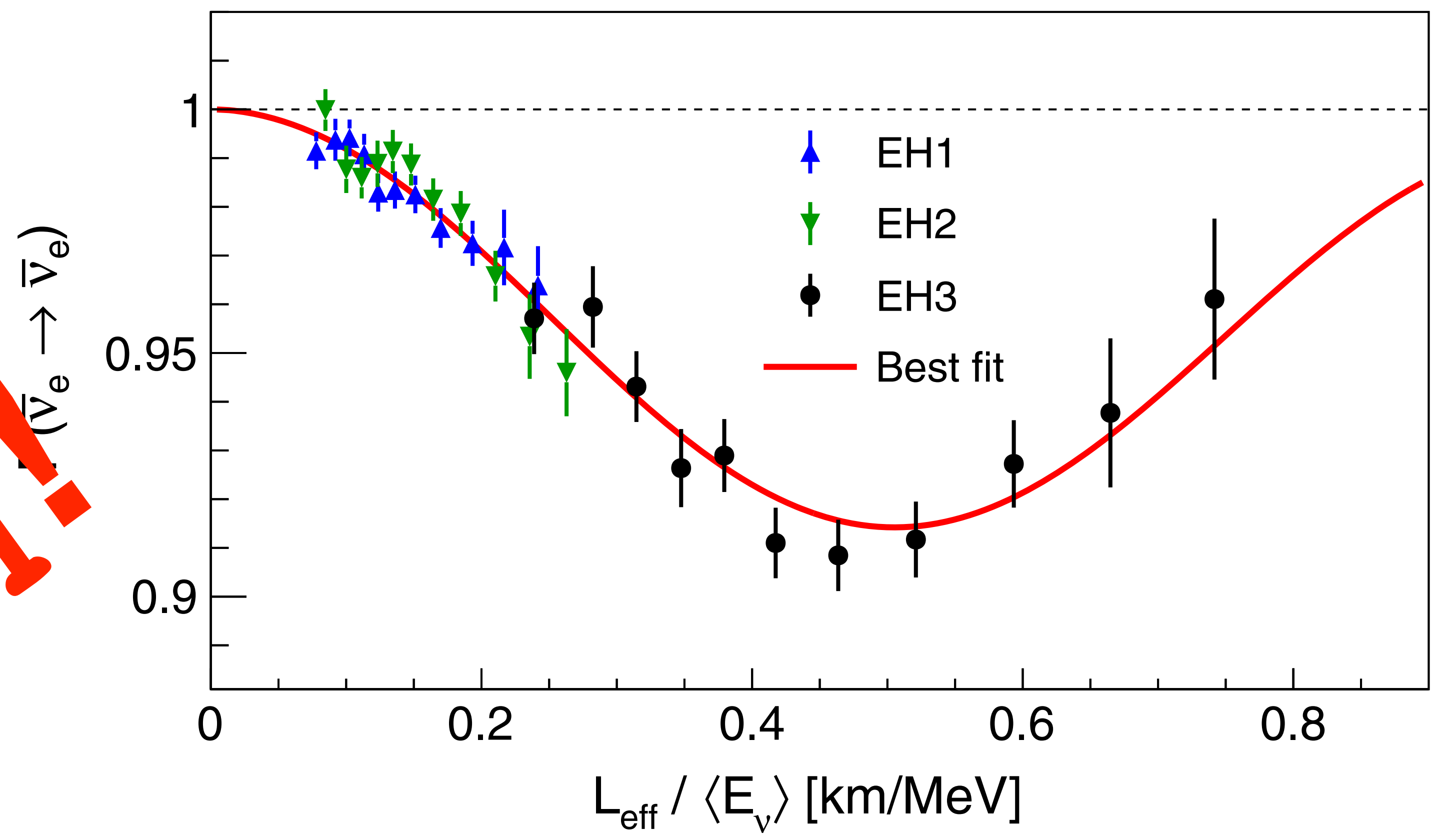


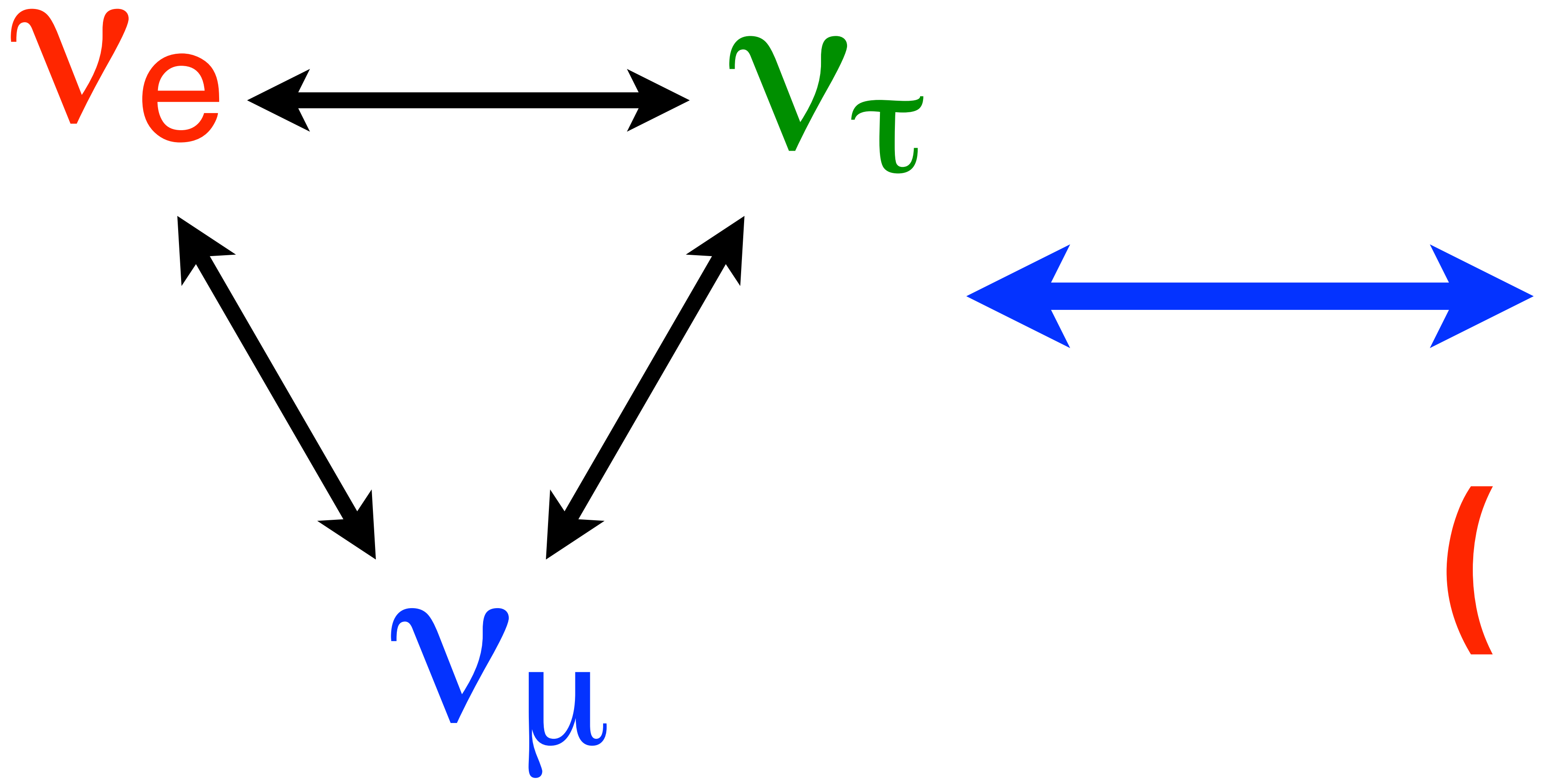
An et al, PRL108, 171803 (2012)

Abe et al, PRL108, 131801 (2012)

driven by θ_{13} and Δm^2_{31}!

Ahn et al, PRL108, 191802 (2012)

Neutrinos do Oscillate!



ν_e ν_τ

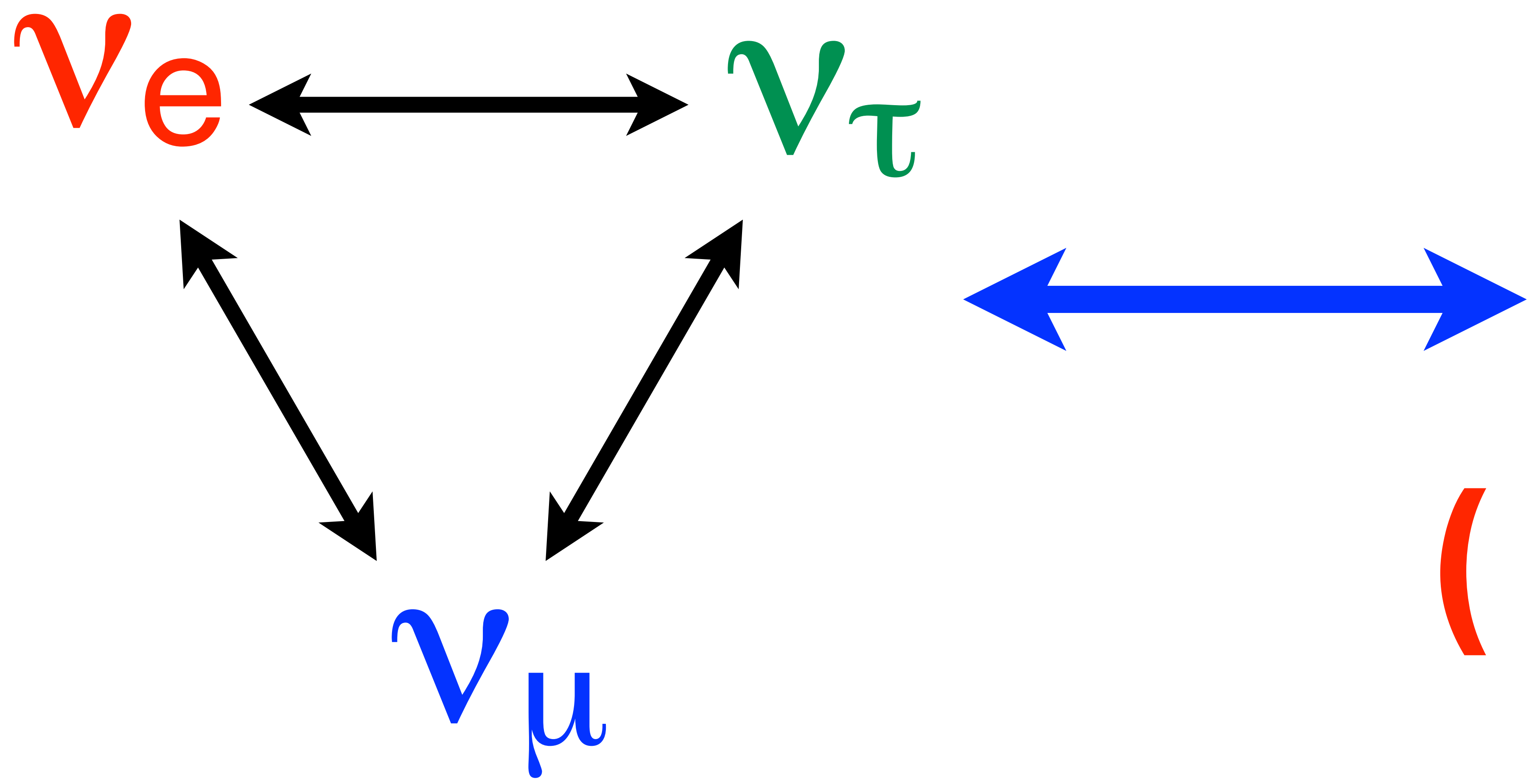
ν_μ

$m_\nu \neq 0$

(at least 2 neutrinos)

So What?

Neutrinos do Oscillate!



$m_\nu \neq 0$

(at least 2 neutrinos)

So What?

- Strong evidence of physics beyond the Standard Model
- It is likely that by studying phenomena related to tiny neutrino masses, we are probing some higher energy scales beyond SM, e.g., GUT scale, like the scenario suggested in the Seesaw Mechanism

Current Status and Open Questions

(in the context of LBL oscillation experiments)

Past and currently running “Long Baseline” ν oscillation experiments

- K2K (KEK to Kamioka) : Japan, 1999-2004, Baseline = 250km
- MINOS (Main Injector Neutrino Oscillation Search): USA, 2005-2016, Baseline = 735 km
- OPERA (Oscillation Project with Emulsion-tRacking Apparatus): CERN to Gran Sasso Laboratory, 2008-2012, Baseline = 730 km
- T2K (Tokai to Kamioka): Japan, 2009-present, Baseline = 295 km
- NOvA (NuMI Off-Axis ν_e Appearance, USA): 2014-present, Baseline = 810 km

So far, all of them showed results consistent with neutrino oscillation within the standard 3 flavor scheme, no strong disagreement among these experiments

Setup of Near-Far Detectors in LBL experiments

ν source

near detector
typically at L $\lesssim$ ~1km

far detector
L > O(100 km)

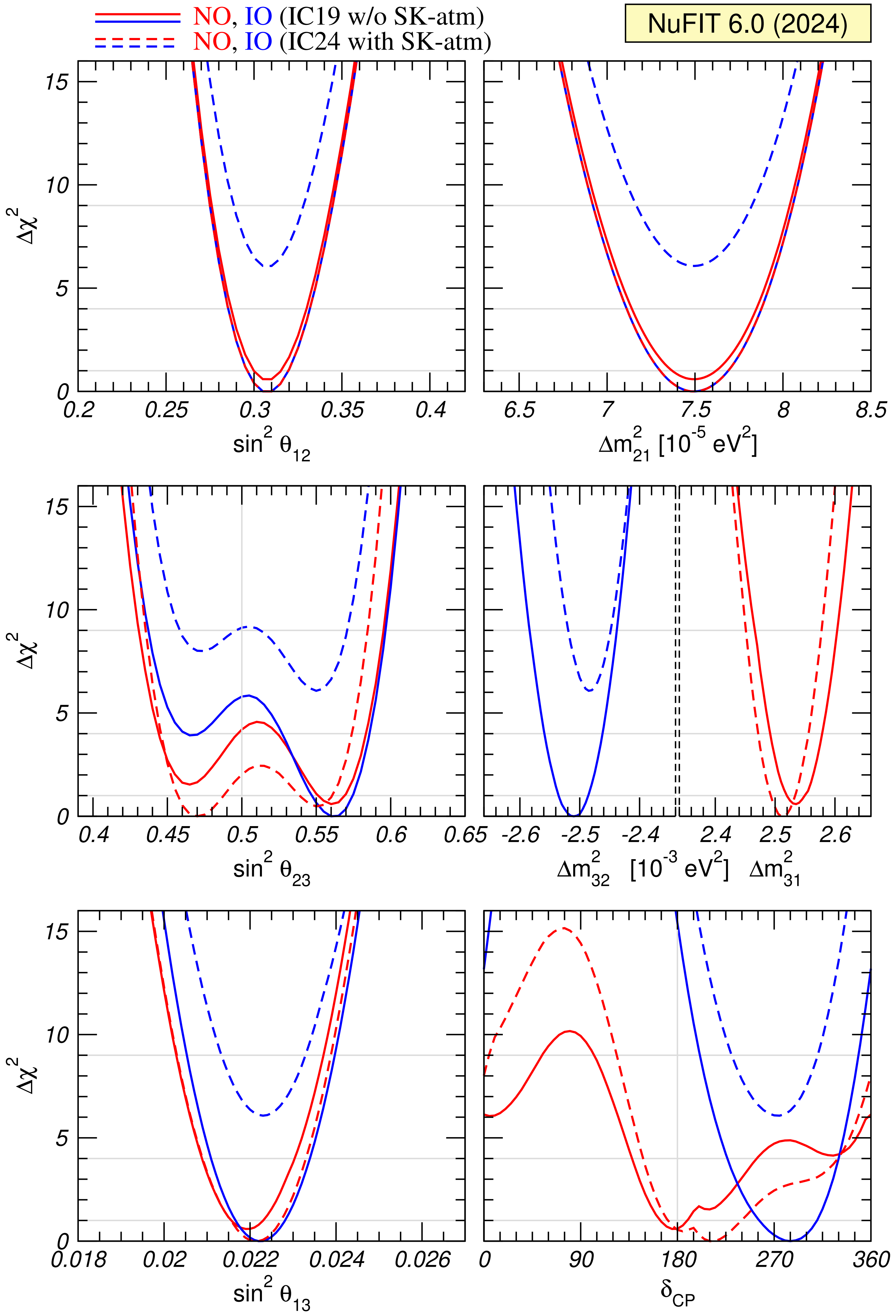
In LBL oscillation experiments, near detector (ND) is mandatory, or essential to predict “unoscillated” neutrino spetra at the far dector (FD), cancelling various systematic uncertainties

This near-far comparison allows us to perform precise analysis/study of oscillation (or effect of any new physics)

Therefore, in general, a LBL oscillation experiment comes with a “short baseline (~km)” experiment with its near detector, by which one can study also some physics (inculding some BSM physics) related to neutrinos

I will forcus mainly the oscillation related phenomena which can be studied by “near-far” comparison

Current allowed range of mixing parameters from Global Fit



Based on ν data coming from solar, atmospheric, reactor, accelerator ν expriments (no strong evidence of more than 3 flavors, except for some hints/indications)

1σ uncertainties of 6 mixing parameters

$\sin^2\theta_{ij}\ (ij = 12, 23, 23)$: ~ 3 - 4 %

Δm^2_{21} : ~3 %

$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

$|\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$: ~1%

$\delta_{\rm CP}$: ~30º (central value not so stable)

normal mass ordering ($\Delta m^2_{31} > 0$) is favored at ~2σ

See Mriam Tortola's talk for any details!

NuFit6.0 Esteban et la, arXiv:2410.05380

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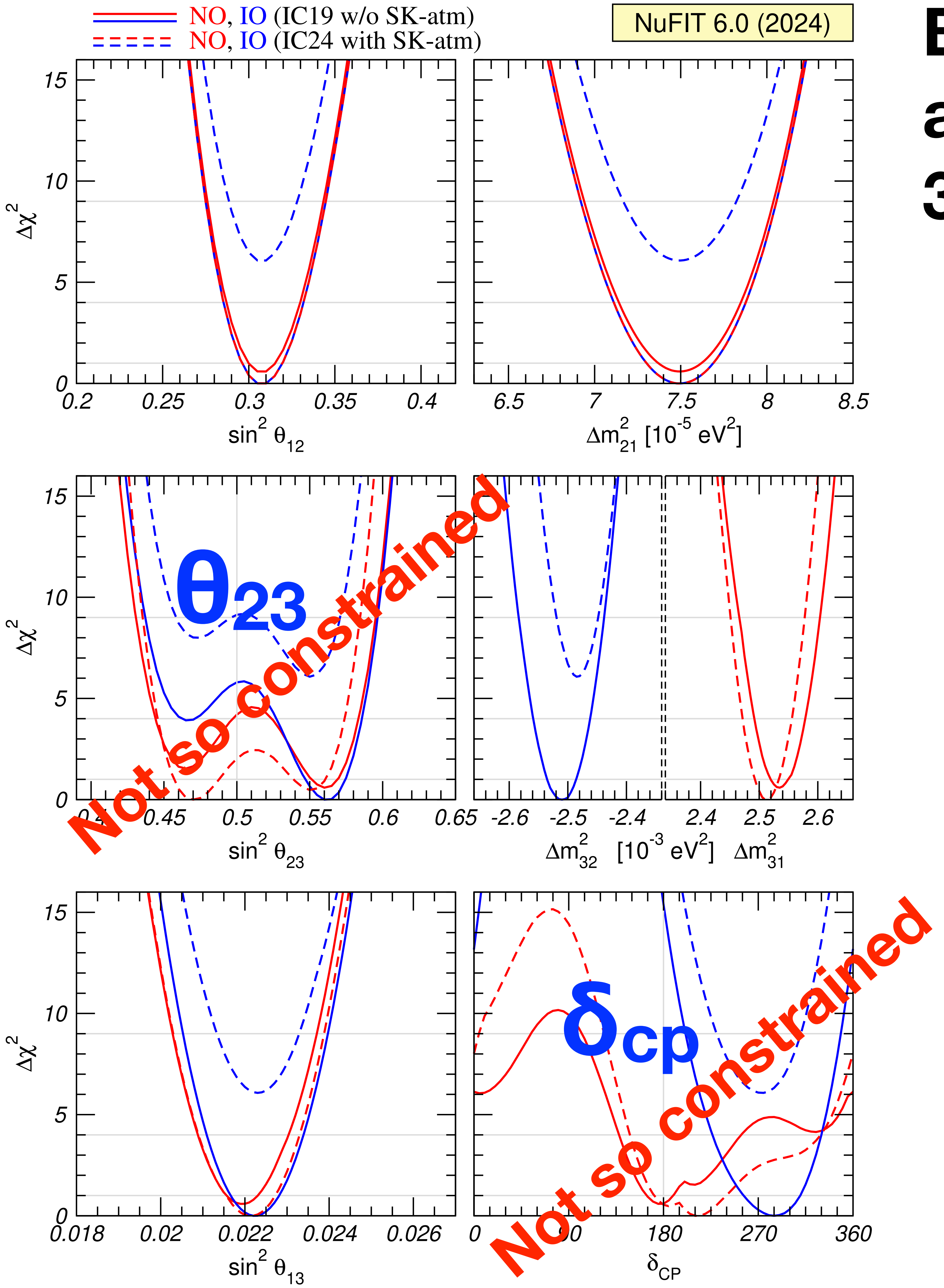

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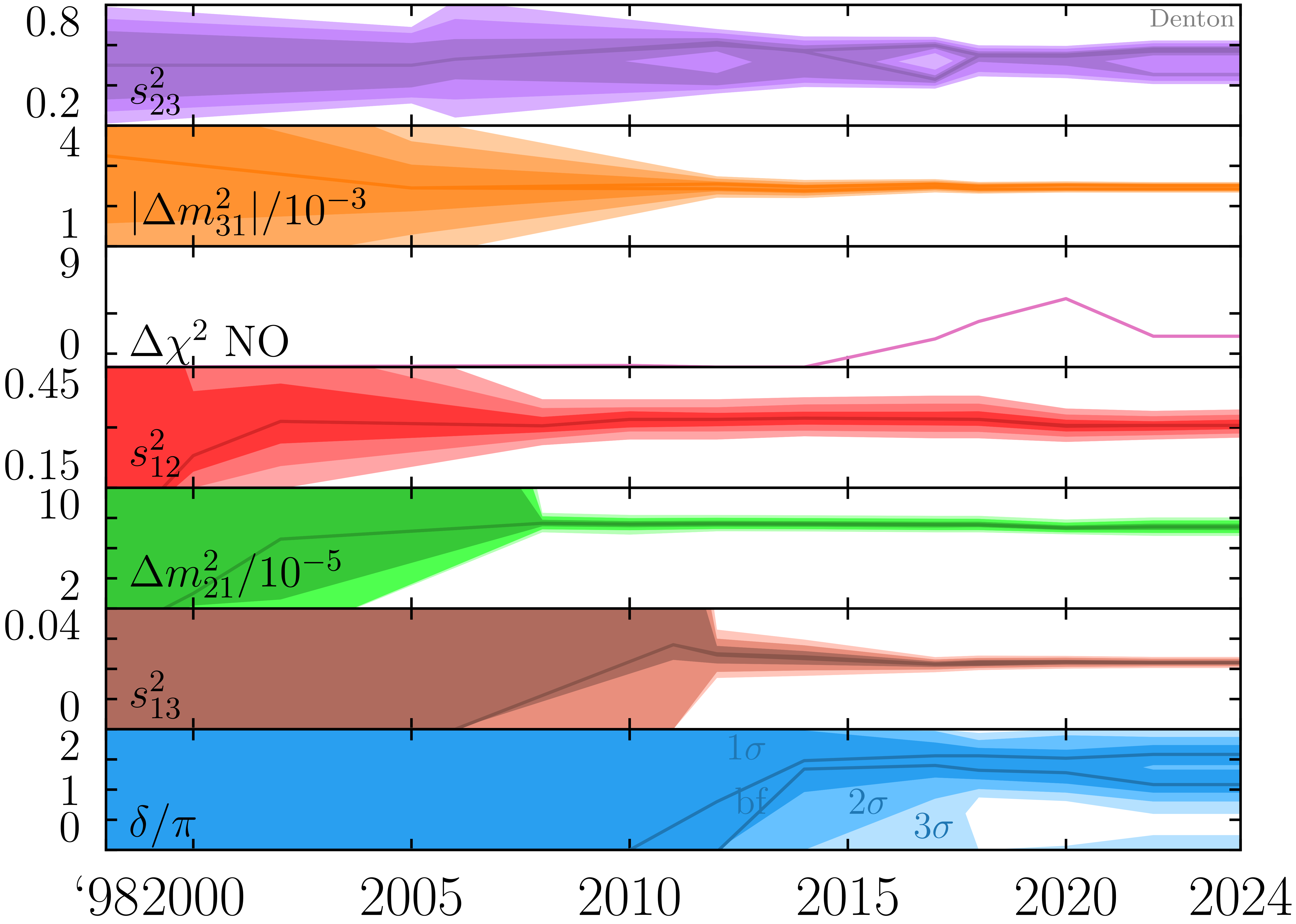
Time evolution of precision of our knowledge about mixing parameters



we are now in a “precision” era!

Denton et la (SNOWMASS Report), arXiv:2212.00809, updated in 2024 by P. Denton

Best Fitted values of mixing parameters from PDG2024

$$\sin^2\theta_{12} = 0.307 \pm 0.013 \qquad \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2\theta_{13} = (2.19 \pm 0.07) \times 10^{-2}$$

Normal Order

$$\Delta m^2_{32} = (2.455 \pm 0.028) \times 10^{-3}\ \mathrm{eV}^2 \qquad \sin^2\theta_{23} = 0.558^{+0.015}_{-0.021}$$

Inverted Order

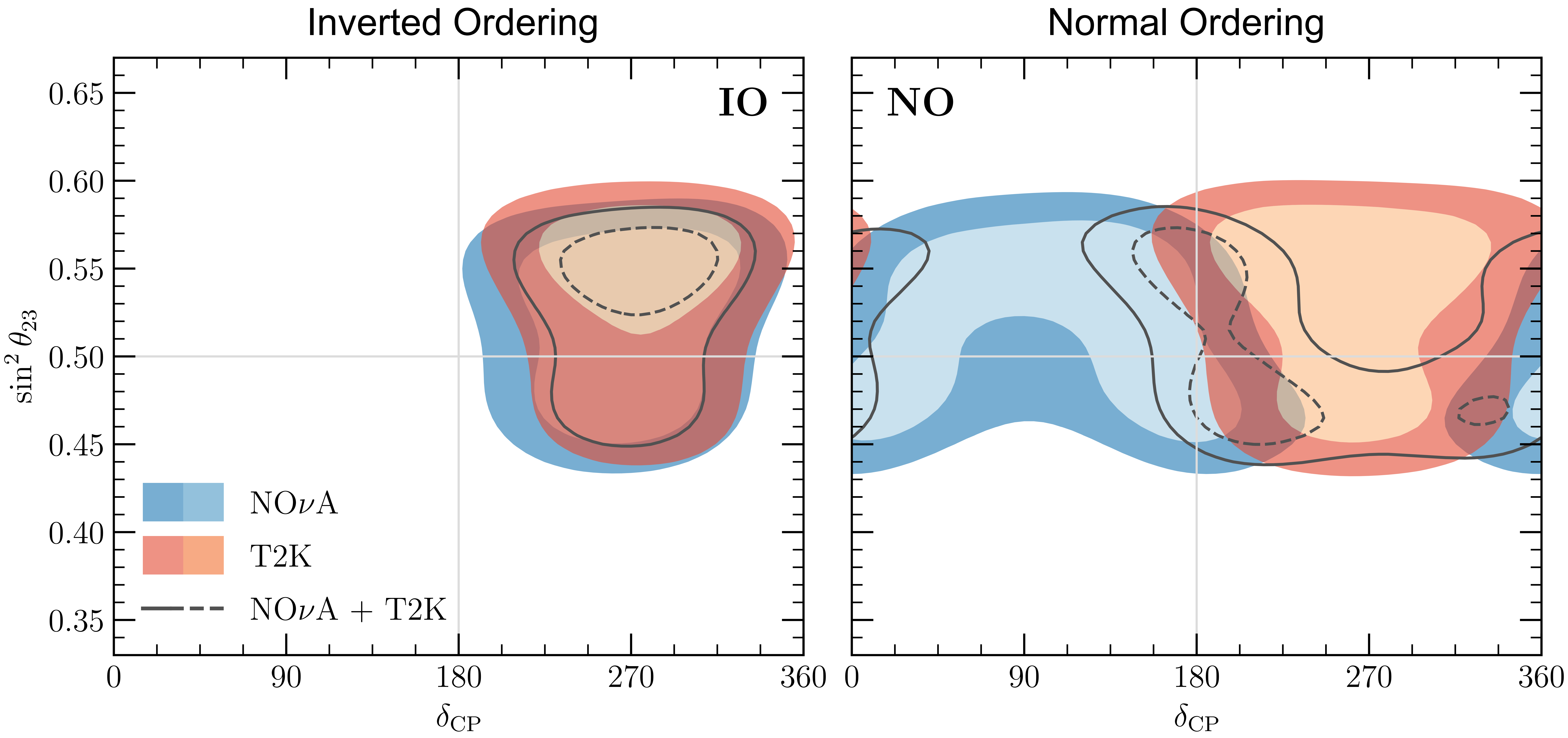
$$\Delta m^2_{32} = (-2.529 \pm 0.029) \times 10^{-3}\ \mathrm{eV}^2 \quad \sin^2\theta_{23} = 0.553^{+0.016}_{-0.024}$$

$$\delta_{CP} = 1.19 \pm 0.22\pi\ \text{rad}$$

~ a few % precisions, except for CP phase and Mass Ordering

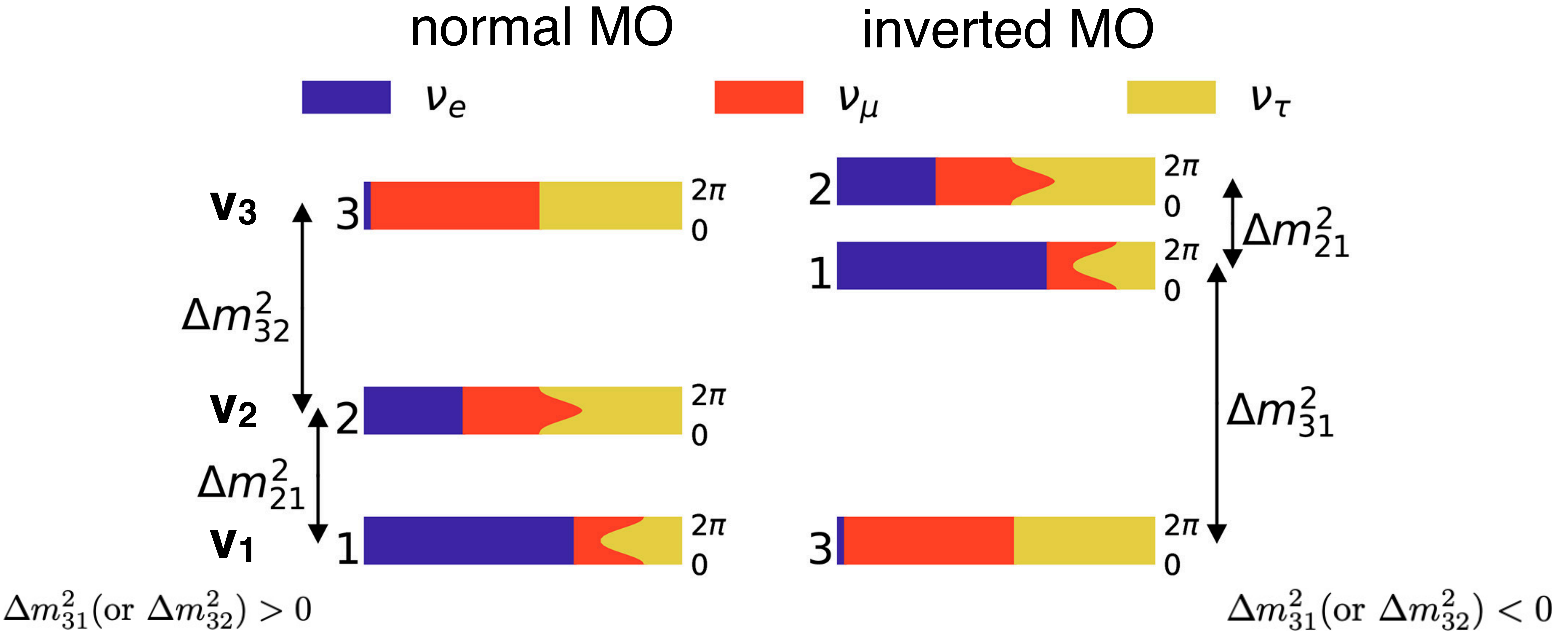
S. Navas et al. (PDG2024),Phys. Rev. D 110, 03001 (2024)

We do not know very well the value of CP phase



NuFit6.0 Esteban et la, arXiv:2410.05380

We still do not know the neutrino mass ordering (MO)



Salas et al, Front.Astron.Space.Sci 5, 36(2018)

Normal MO is currently favored only at ~ 2-3σ, not yet conclusive

Open Questions in Neutrino Sector

- **Why neutrino masses are very small? How to understand mixing pattern?**
- **Neutrinos are Dirac or Majorana particles?**
- **Is CP (Charge Conjugation) symmetry violated?**
- **Mass Ordering (MO), Normal or Inverted?**
- **Octant of θ_{23}, larger than $\pi/4$ or not?**
- **Are there more than 3 neutrinos (sterile ν) ?**
- **Do neutrinos have some new BSM (Beyond Standard Model) properties such as non-standard interactions (NSI), magnetic moment, instabilities (decay), decoherence, etc?**

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- **Do neutrinos have some new BSM (Beyond Standard Model) properties such as non-standard interactions (NSI), magnetic moment, instability (decay), decoherence, etc?** ← **JUNO/HK/DUNE**

So far, in neutrino sector, there is no strong evidence of new physics beyond SM (beyond mass and mixing), apart from some indication/hint like LSND anomaly, or some mild "tension" between some experiments

So we need to look for hint for new physics in future experiments, in particular, in the context of new oscillation experiments, JUNO, Hyper-Kamiokande and DUNE

Near Future Long-Baseline Neutrino Oscillation Experiments: Hyper-Kamiokande and DUNE

Please also see talks by

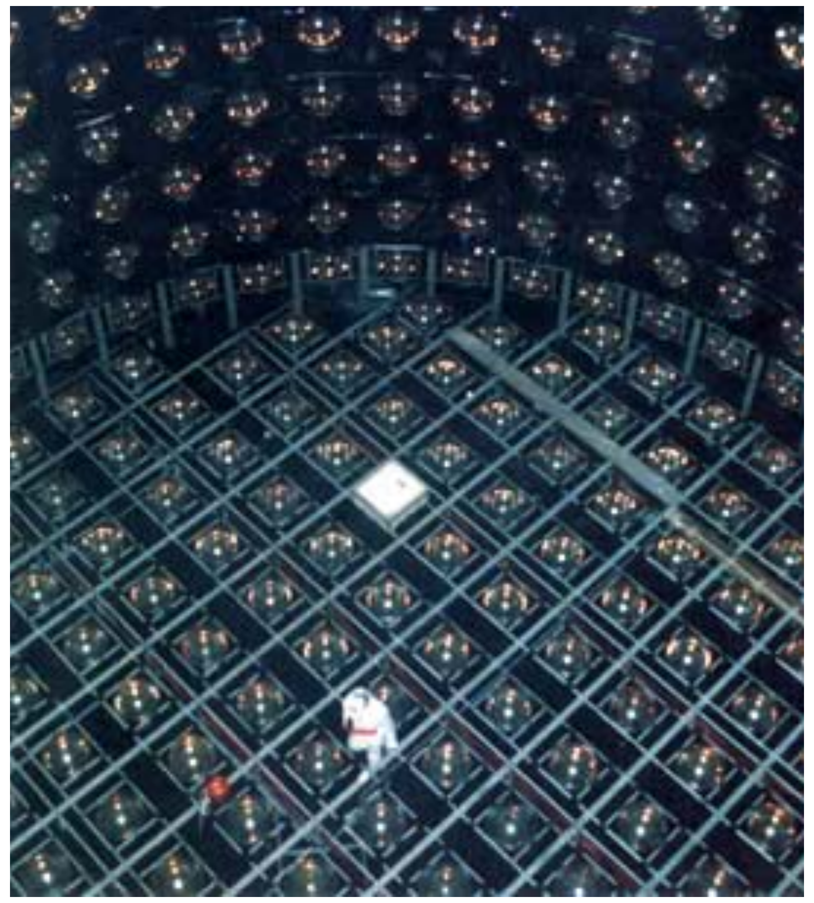
Saul Cuen-Rochin for Hyper-Kamiokande (yesterday)

Pedro Ochoa Ricoux for Short Baseline Oscillation Experiments (today)

Ettore Segreto for DUNE (Friday)

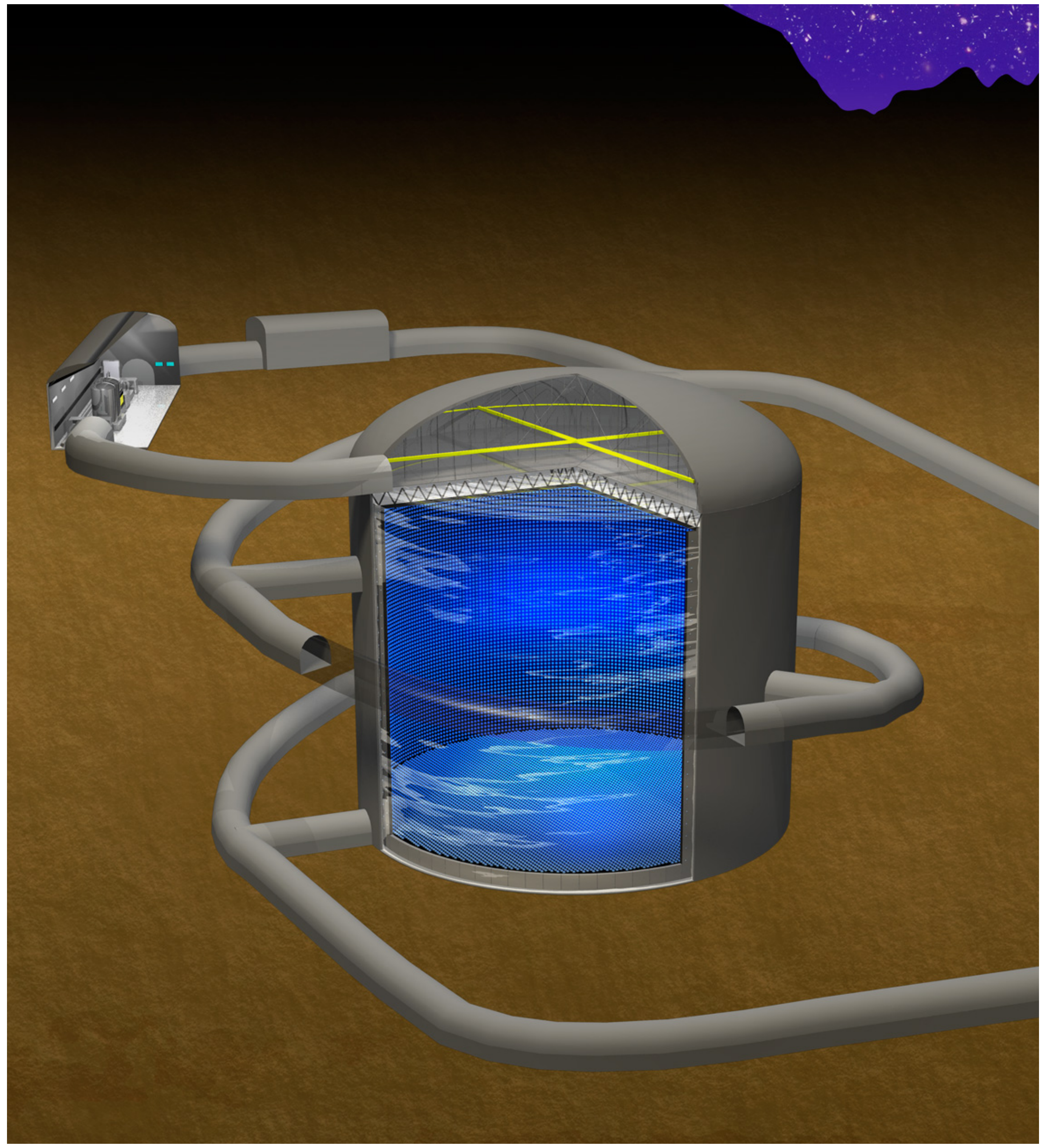
Hyper-Kamiokande

3rd Generation Water Cherenkov Detector in Kamioka



Kamiokande (1983-1996)
0.68 kton, Detection of
Neutrinos from SN1987A

Super-Kamiokande (1996-ongoing):
22.5 kton, Discovery of Neutrino Oscillation
in 1998



Hyper-Kamiokande (will start in 2027)
188 kton (~8 times SK)
Observation of CP violation, Nucleon Decay,
Supernova, New Physics?

Hyper-Kamiokande is in the Construction Phase

Expected to start data taking in 2027

Cavern now excavated to 37m depth (over halfway)

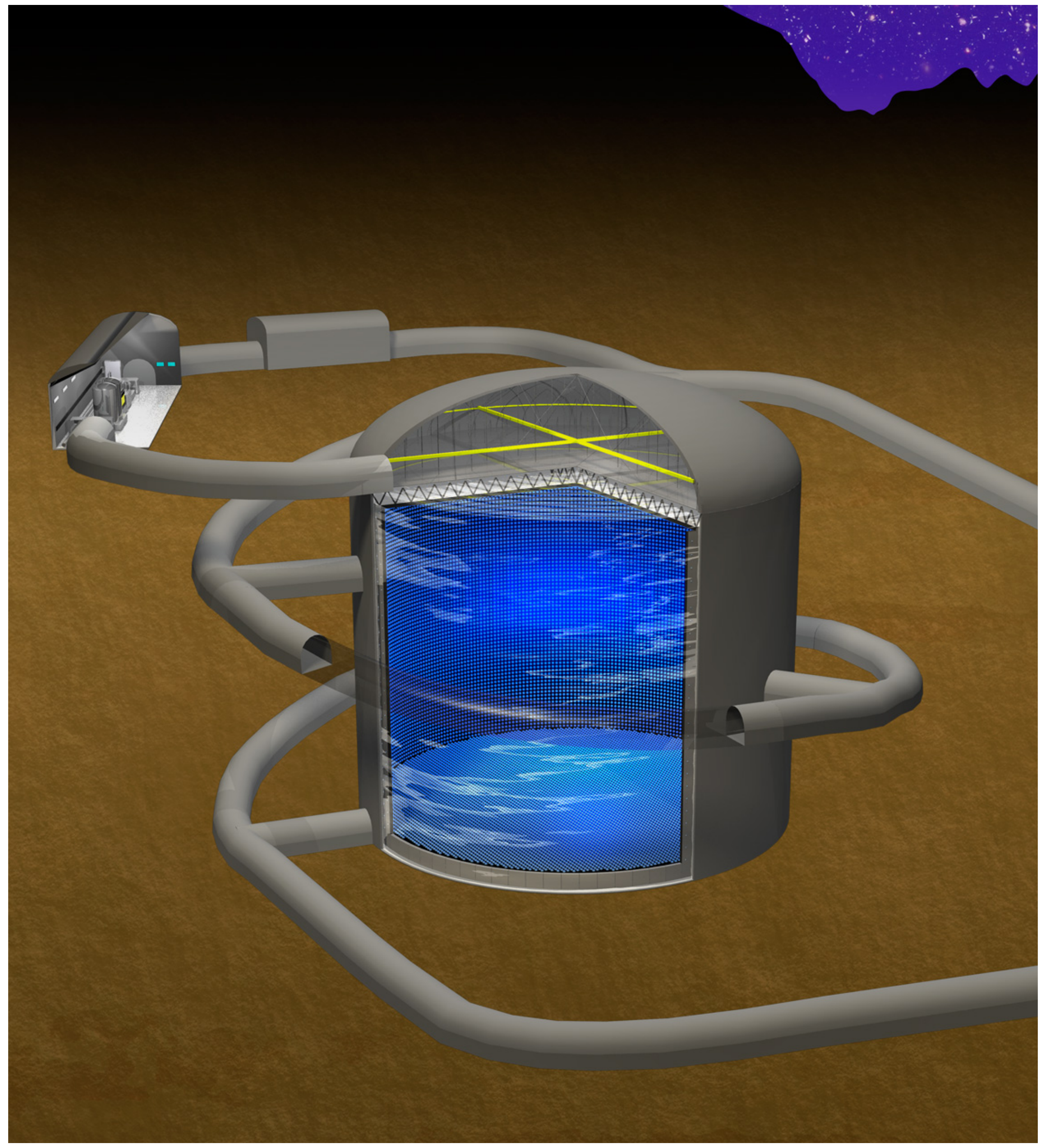
Photograph taken
June 2024

22

Slide shown by Jeanne Wilson @ NOW2024 workshop (September 2024)

Experimental Setup of HK's LBL Oscillation Study by using JPARC Neutrino Beam

L = 295 km

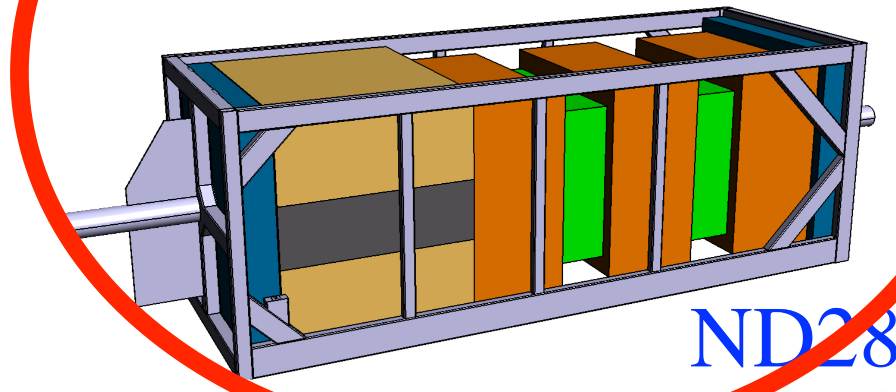


$\nu_e/\bar{\nu}_e$

$\nu_\mu/\bar{\nu}_\mu$

near detector

L = 280 m



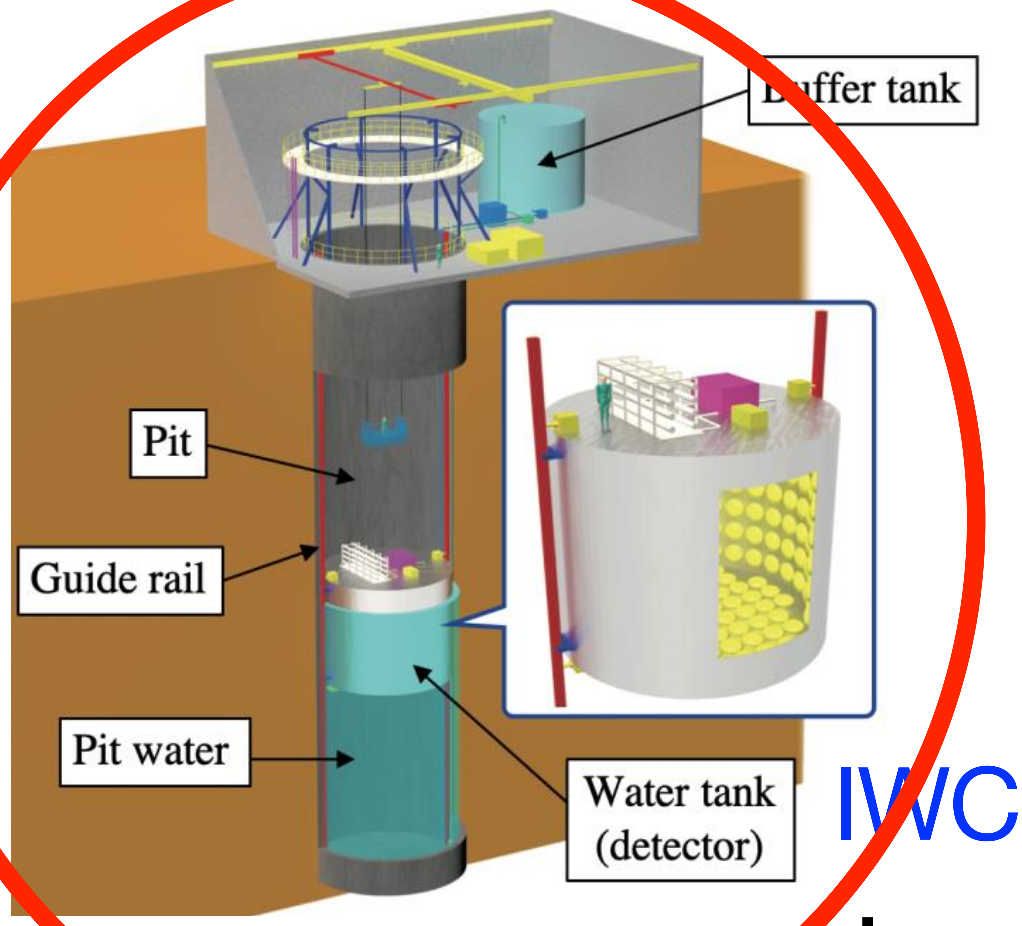
ND280

$\nu_\mu/\bar{\nu}_\mu$

J-PARC

1.3 MW ν beam

based on off-axis (2.5°) beam



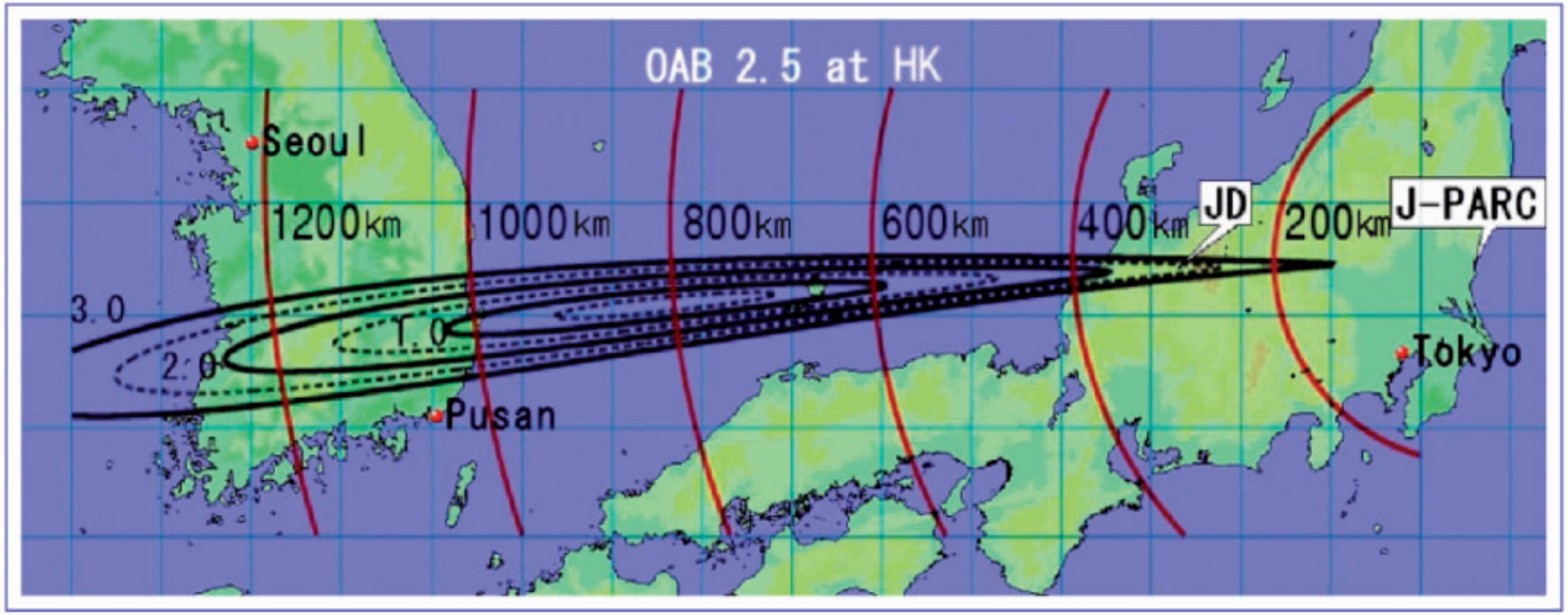
IWCD

L = ~1km

near detector

often called "T2HK" (Tokai to HK) experiment/setup (not an official name)

Possibility to construct another identical detector in Korea with a baseline ~ 1000 km, is under consideration/discussion



map showing baseline and off-axis angles of the beam from J-PARC

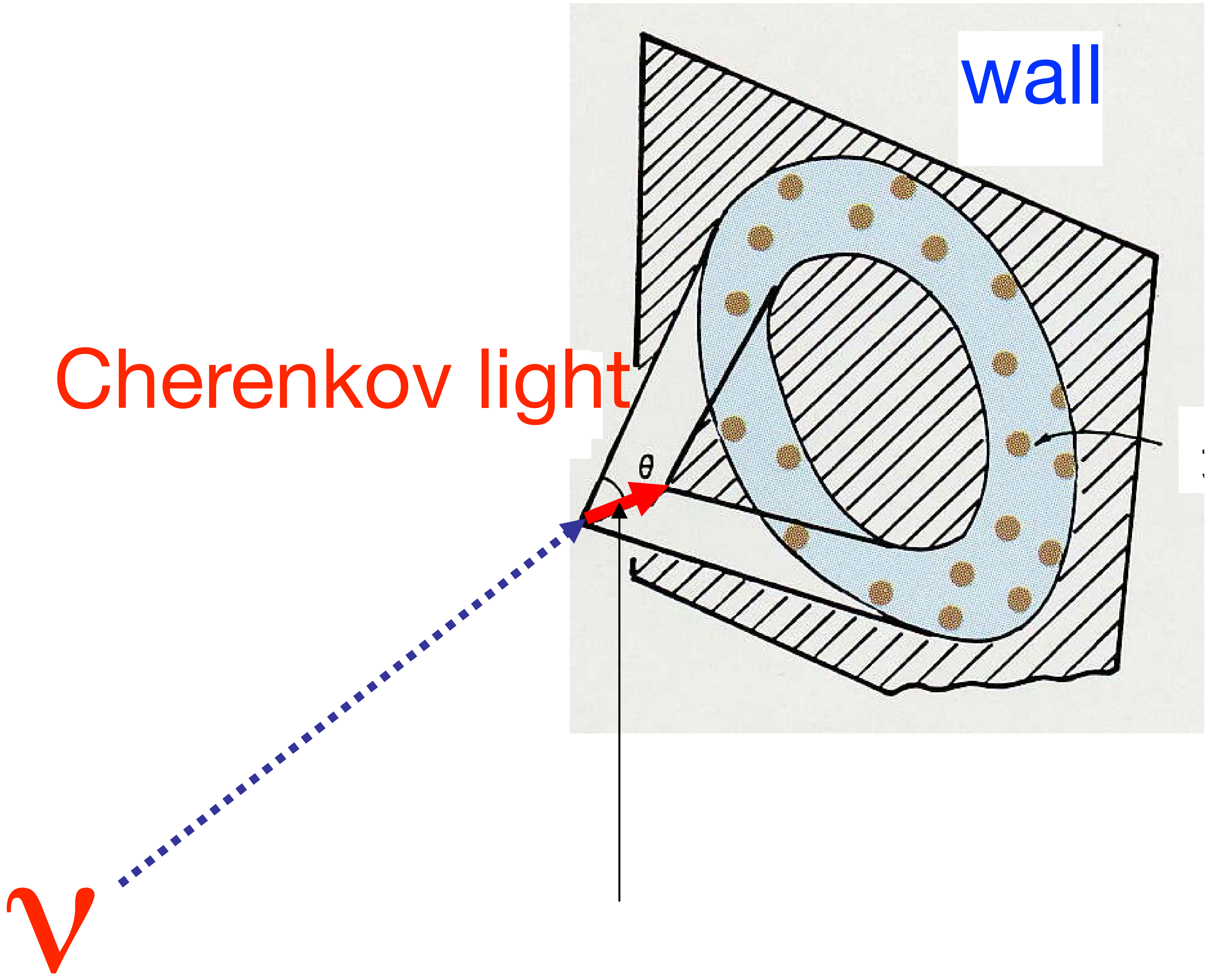
This setup is often called “T2HKK” (Tokai to HK and Korea), not an official name

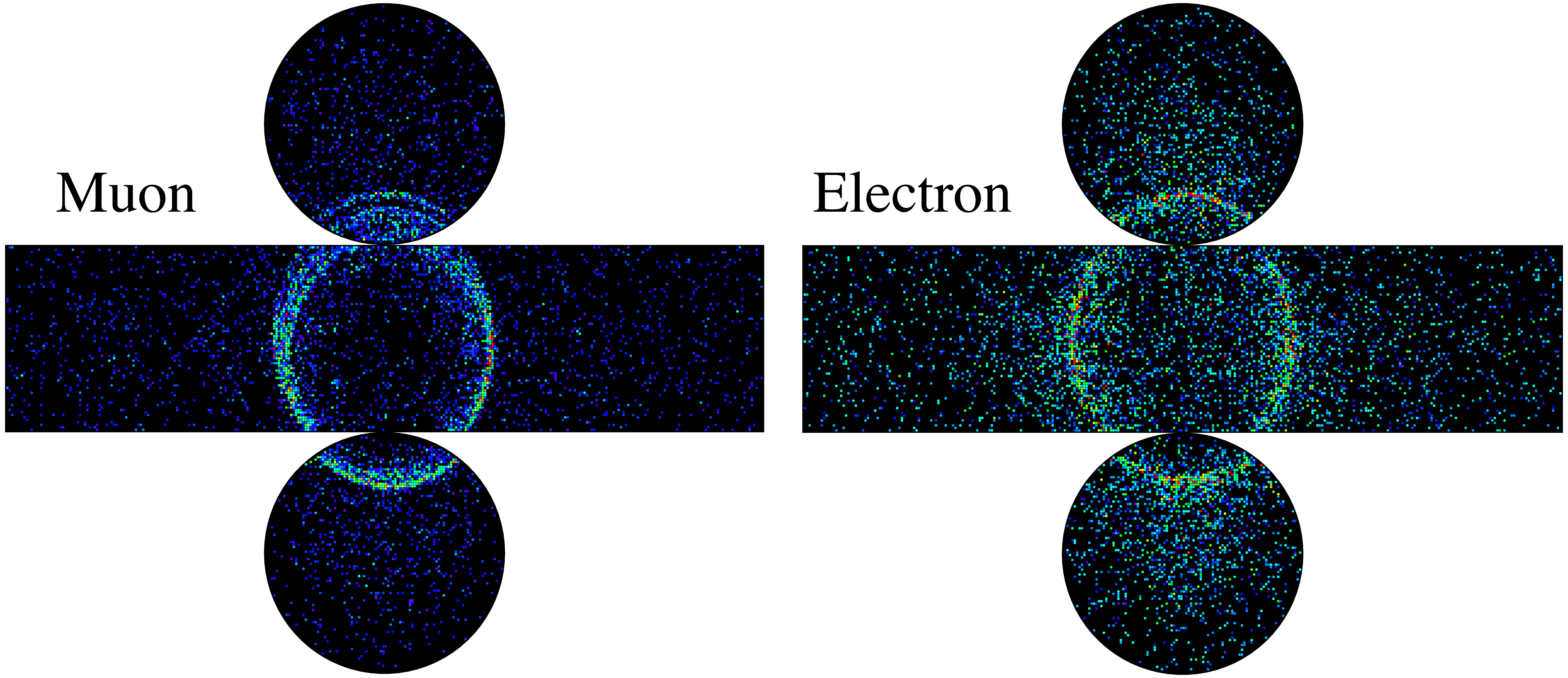
ν_μ and ν_e can be distinguished in the Water Cherenkov detector

$$n+\nu_\mu \rightarrow p+\mu^-$$

$$n+\nu_e \rightarrow p+e^-$$

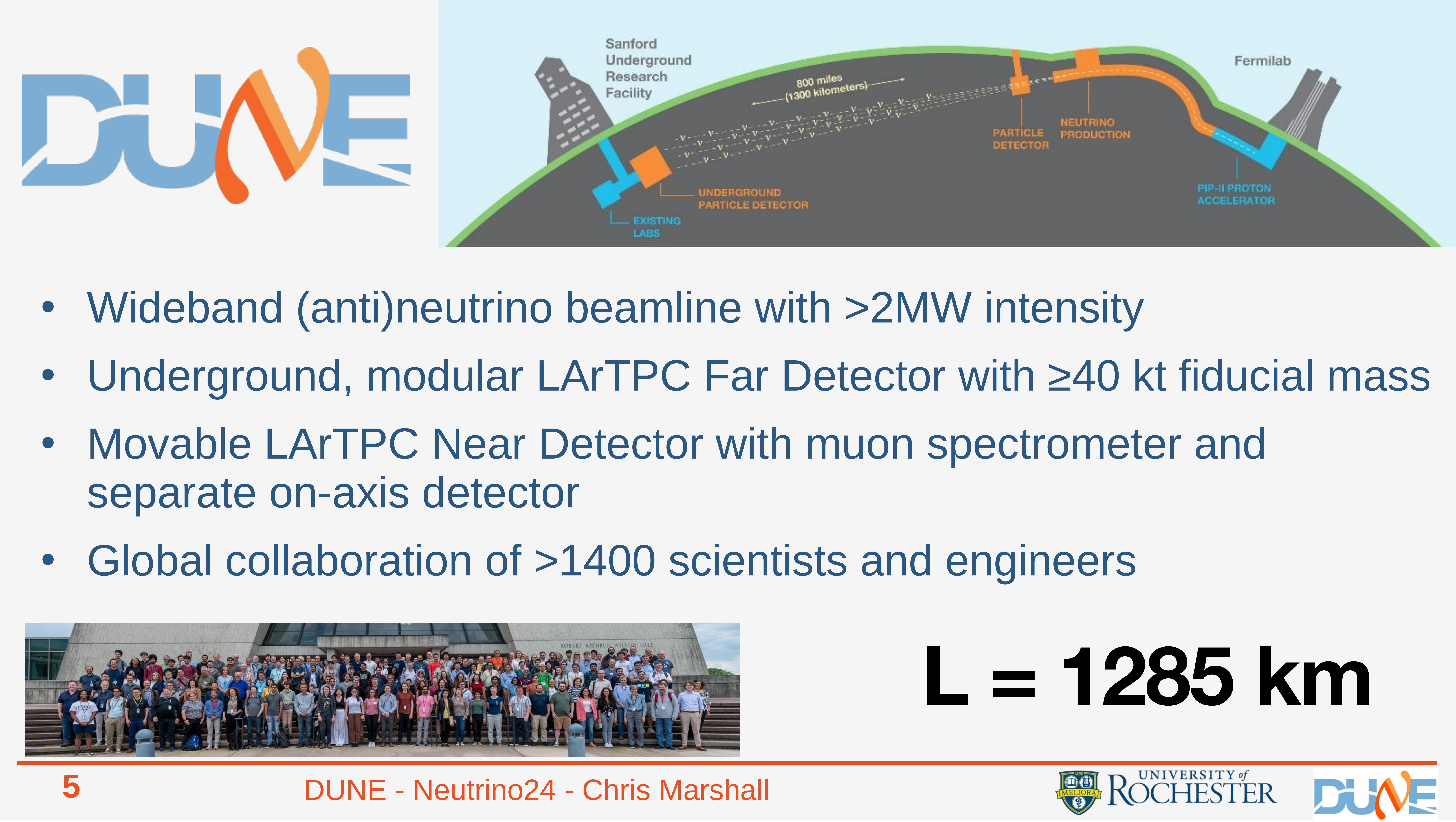
Charged Current Interaction





if v_{pamticle} > speed of light in matter = c/n (n=1.33 for water)

DUNE (Deep Underground Neutrino Experiment) Project



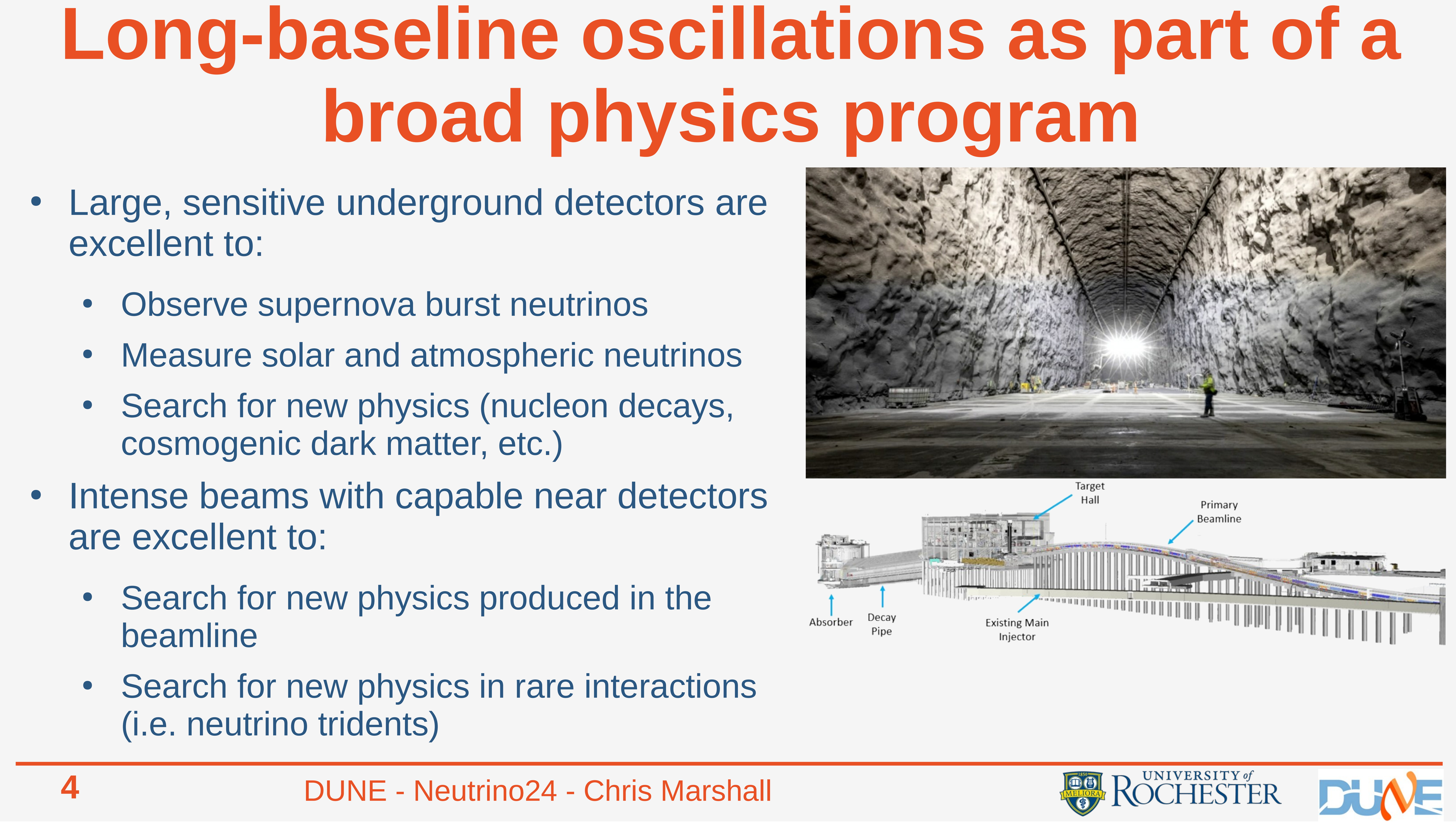
- Wideband (anti)neutrino beamline with >2MW intensity
- Underground, modular LArTPC Far Detector with ≥40 kt fiducial mass
- Movable LArTPC Near Detector with muon spectrometer and separate on-axis detector
- Global collaboration of >1400 scientists and engineers

L = 1285 km

See the talk by Ettore Segreto

Talk by C. Marshall @ Neutrino 2024

DUNE (Deep Underground Neutrino Experiment) Project



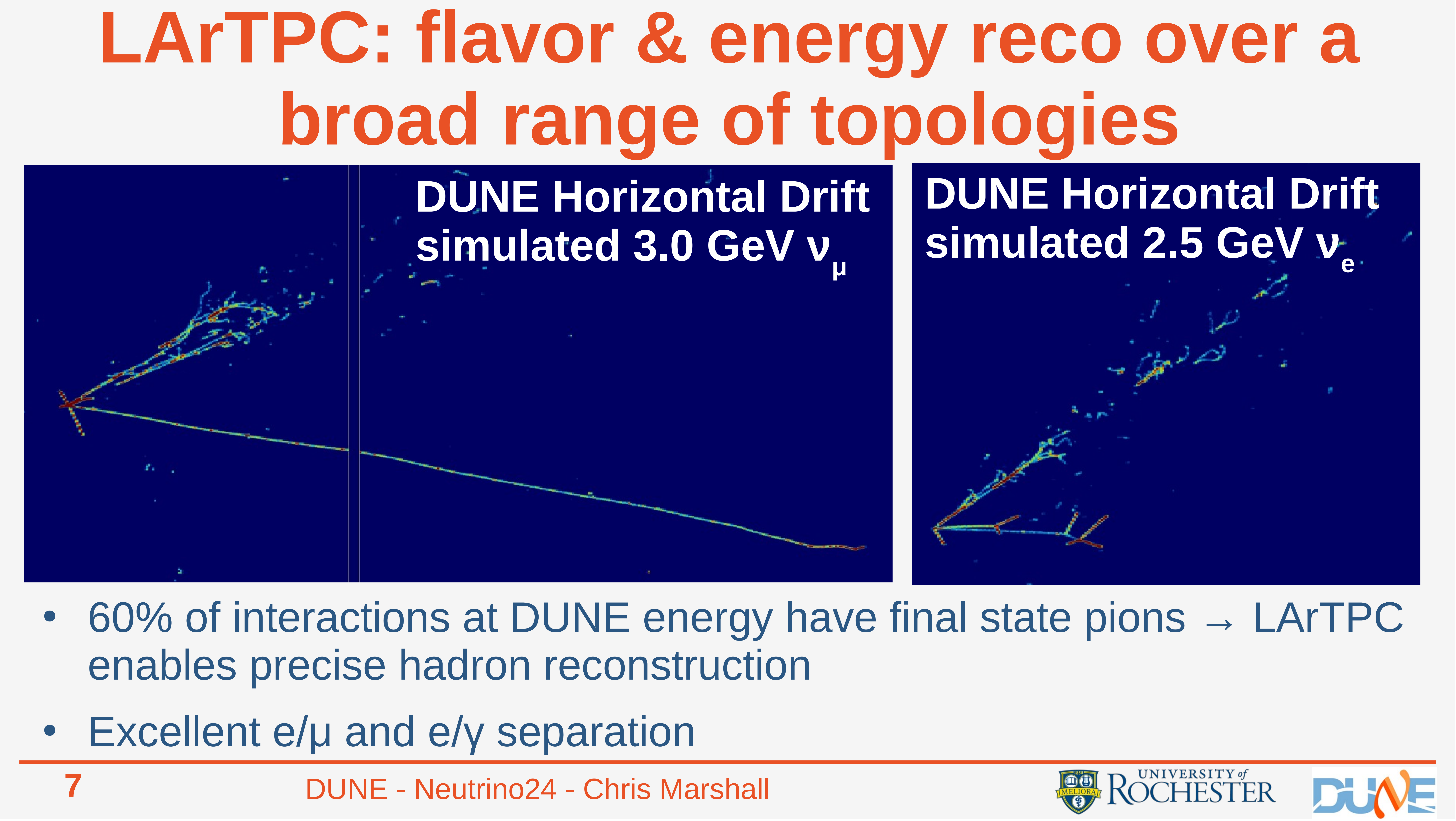
Long-baseline oscillations as part of a broad physics program

- Large, sensitive underground detectors are excellent to:
  - Observe supernova burst neutrinos
  - Measure solar and atmospheric neutrinos
  - Search for new physics (nucleon decays, cosmogenic dark matter, etc.)
- Intense beams with capable near detectors are excellent to:
  - Search for new physics produced in the beamline
  - Search for new physics in rare interactions (i.e. neutrino tridents)

4 DUNE - Neutrino24 - Chris Marshall

Talk by C. Marshall @ Neutrino 2024

DUNE detector is based on Liquid Argon Time Projection Chamber



LArTPC: flavor & energy reco over a broad range of topologies

DUNE Horizontal Drift simulated 3.0 GeV ν_μ

DUNE Horizontal Drift simulated 2.5 GeV ν_e

- 60% of interactions at DUNE energy have final state pions → LArTPC enables precise hadron reconstruction
- Excellent e/μ and e/γ separation

7 DUNE - Neutrino24 - Chris Marshall

Talk by C. Marshall @ Neutrino 2024

Test of CP Violation by Long-Baseline Neutrino Oscillation Experiments

Test of CP (Charge Conjugation) Symmetry

One of the fundamental symmetries in Nature

May shed some light on matter-antimatter asymmetry in the Universe

studying oscillation between muon and electron neutrinos is the easiest way

$$\begin{tikzcd}
\nu_\mu \to \nu_e \arrow[r, Leftrightarrow, "\mathrm{CP}"] \arrow[d, Leftrightarrow, "T"'] & \bar{\nu}_\mu \to \bar{\nu}_e \arrow[d, Leftrightarrow, "T"] \\
\nu_e \to \nu_\mu \arrow[r, Leftrightarrow, "\mathrm{CP}"'] & \bar{\nu}_e \to \bar{\nu}_\mu
\end{tikzcd}$$

Compare oscillation probabilities of CP conjugate channels

Note: if CP is violated, T (time reversal) is also violated due to CPT invariance

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

$$P(\nu_\mu \to \nu_e) = \left| \underset{\nu_1}{U_{e1}U^*_{\mu 1}e^{-i\frac{m_1^2}{2E}L}} + \underset{\nu_2}{U_{e2}U^*_{\mu 2}e^{-i\frac{m_2^2}{2E}L}} + \underset{\nu_3}{U_{e2}U^*_{\mu 2}e^{-i\frac{m_2^2}{2E}L}} \right|^2$$

$$\approx \left| \sqrt{P_{\text{atm}}}e^{-i(\Delta_{32}+\delta_{\text{CP}})} + \sqrt{P_{\text{sol}}} \right|^2$$

HN, Parke & Valle, arXiv:0710.0554 [hep-ph]

$$= P_{\text{atm}} + \underbrace{2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{sol}}}\cos(\Delta_{32} + \delta_{\text{CP}})}_{\text{interference term}} + P_{\text{sol}}$$

where $\Delta_{ij} \equiv \dfrac{\Delta m^2_{ij}}{4E}L$

$\sqrt{P_{\text{sol}}} \equiv \cos\theta_{23}\cos\theta_{13}\sin 2\theta_{12}\sin\Delta_{21}$

solar term

$\sqrt{P_{\text{atm}}} \equiv \sin\theta_{23}\sin 2\theta_{13}\sin\Delta_{31}$

atmospheric term

for $\bar{\nu}_\mu \to \bar{\nu}_e$ we should consider $U \to U^*$ or $\delta_{\text{CP}} \to -\delta_{\text{CP}}$

For HK (or DUNE), $\sin\Delta_{21} \sim \Delta_{21}(\sim |\Delta_{31}|/30)$ ⟶ osc. is driven by $\Delta m^2_{32} \sim \Delta m^2_{31}$

In matter, mixing parameters get modified $\theta_{ij} \to \theta^{\text{m}}_{ij},\ \Delta_{ij} \to \Delta^{\text{m}}_{ij}$ **but the same formula applies**

Observation of CP Violation (CPV) in vacuum

$$\boxed{\Delta P_{\rm CPV} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin\Delta_{12} \sin\Delta_{23} \sin\Delta_{31},}$$

where $\Delta_{ij} \equiv \dfrac{\Delta m^2_{ij}}{2E} L$

$$\boxed{J_{\alpha\beta} \equiv \Im[U_{\alpha 1} U^*_{\alpha 2} U_{\beta 1} U^*_{\beta 2}] = \pm J_\nu, \quad J_\nu \equiv s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \boxed{\sin\delta_{\rm CP},}}$$

+(-) sign is for cyclic (anti-cyclic) permutation of α, β = e, μ, τ

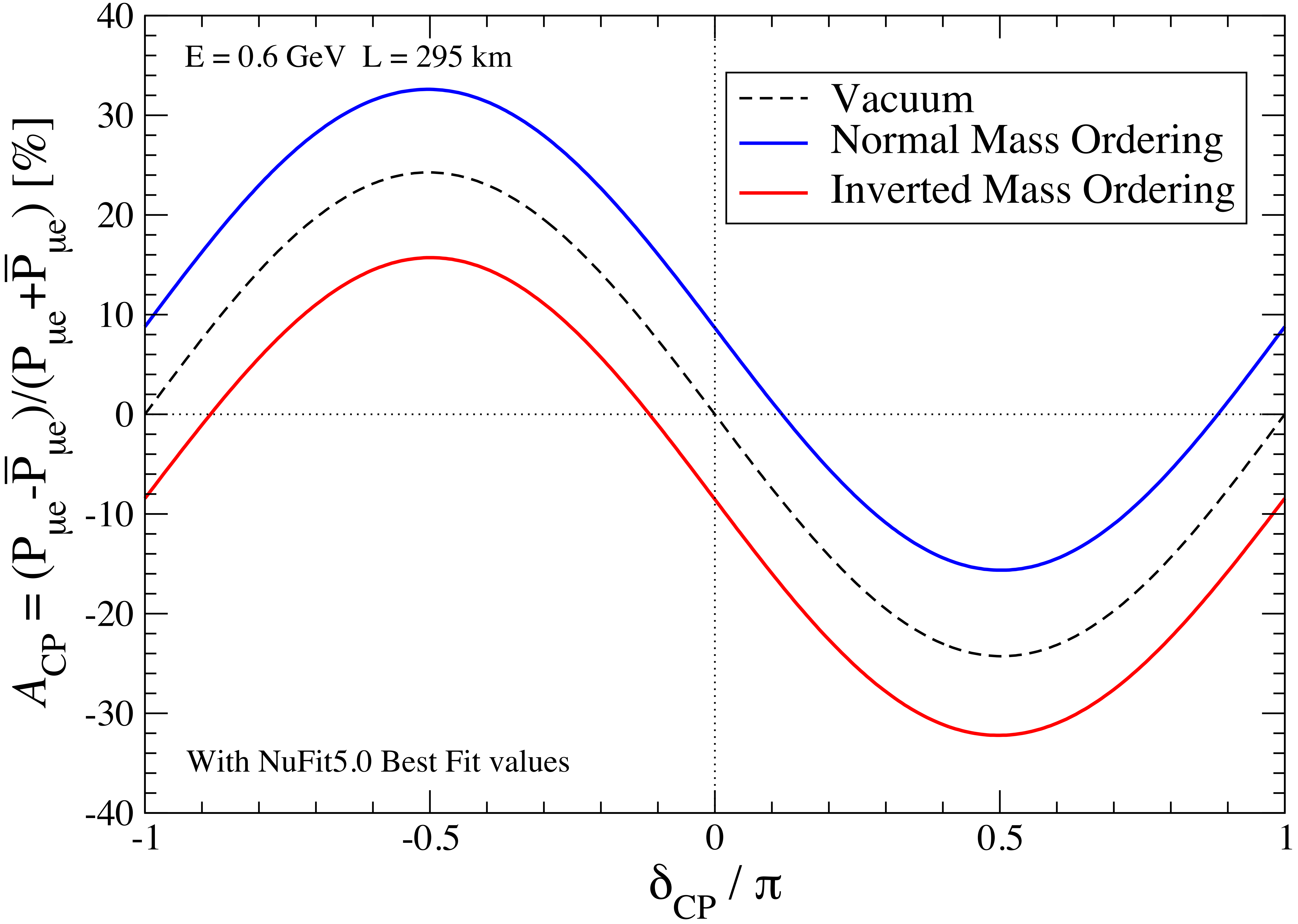
parametrization independent measure of CPV (Jarlskog invariant)

from current data, $J^{\rm max}_\nu = J_\nu(\sin\delta_{\rm CP} = 1) \simeq 0.033$

CPV ⟷ all ν masses must be non-degenerate, all $\theta_{12}, \theta_{23}, \theta_{13} \neq 0$ and $\sin\delta_{\rm CP} \neq 0$

CP asymmetry $A_{\rm CP} \equiv \dfrac{[P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)]}{[P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)]} \propto \sin\delta_{\rm CP}$ **would be useful**

CP asymmetry $A_{\rm CP} \equiv \frac{[P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)]}{[P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)]} \propto \sin\delta_{\rm CP}$



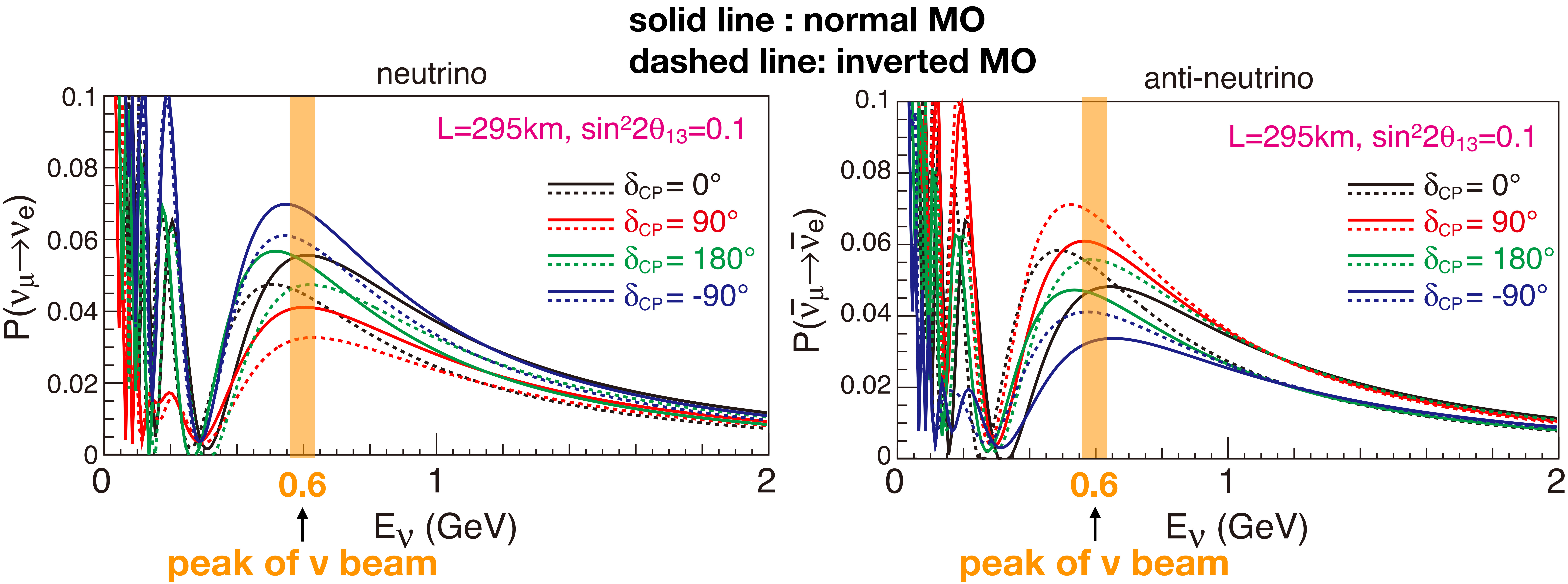
CP asymmetry can be as large as ~30%

matter effect (predictable)

Due to matter effect, $A_{\rm CP} \neq 0$ **even for** $\sin\delta_{\rm CP} = 0$

CP asymmetry could, in principle, tell us the presence of CPV in the lepton sector even if some unknown new physics (NSI, non-unitarity, etc) is the source of CPV!

Appearance Probabilities for T2HK (Tokai to Hyper-K)



solid line : normal MO
dashed line: inverted MO

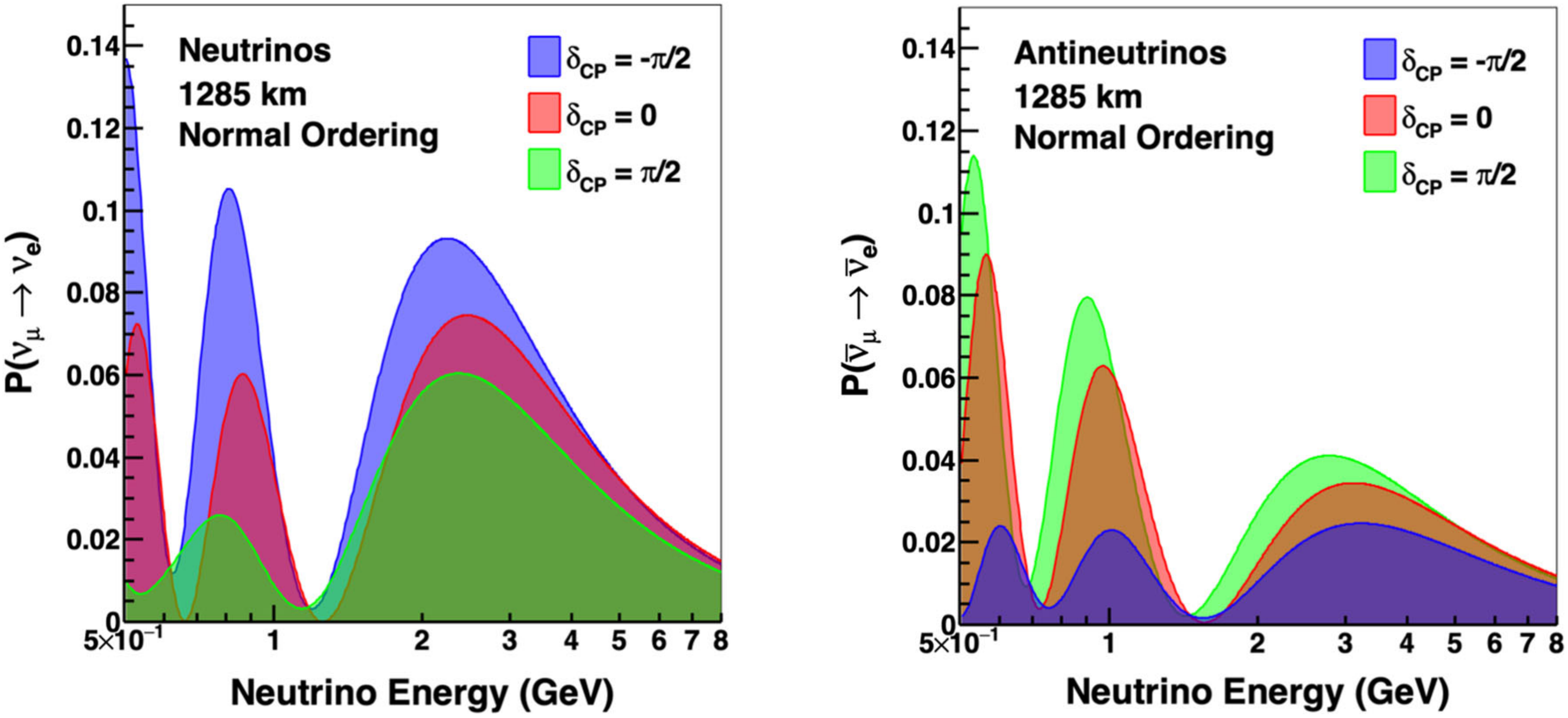
peak of ν beam

peak of ν beam

HK Design Report, arXiv:1805.04163v2 [hep-ex]

CP phase affects oscillation amplitudes and also positions of the peaks and dips of oscillations

Appearance Probabilities for DUNE (L ~ 1300 km)

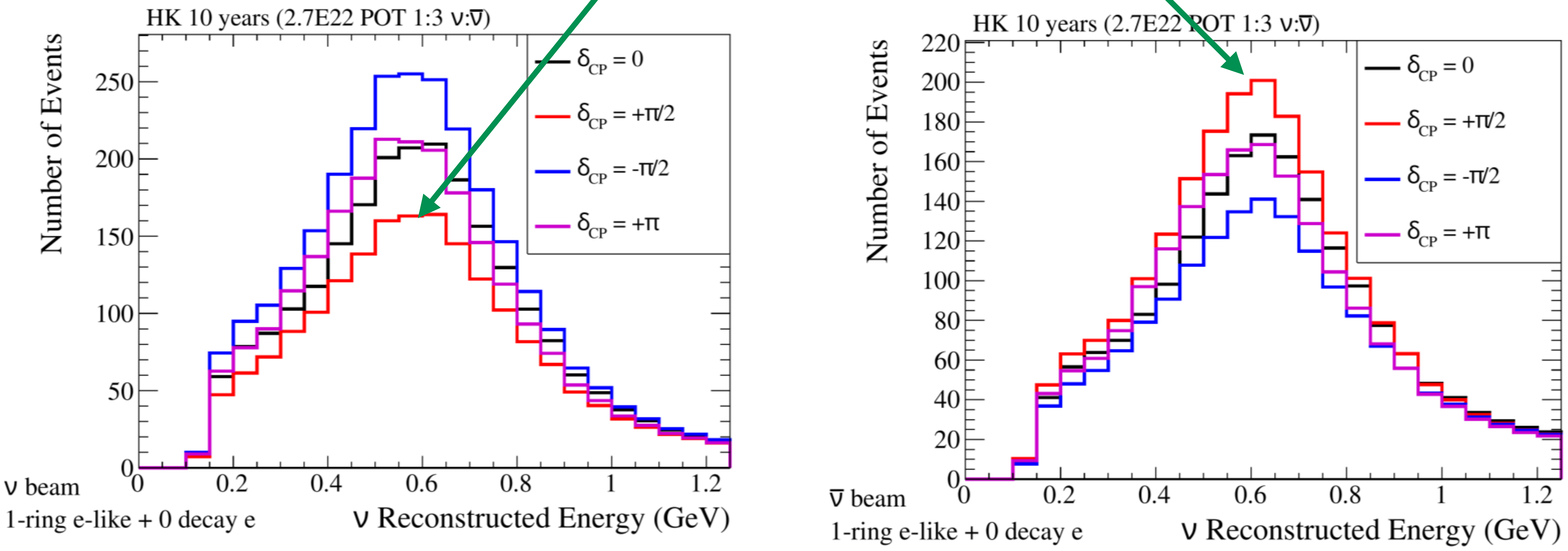


Abi et al, Eur. Phys. J. C80, 978 (2020)

Large differences in probability for neutrino and anti-neutrinos comes mainly from the matter effect

Expected Event Number Distributions at Hyper-K

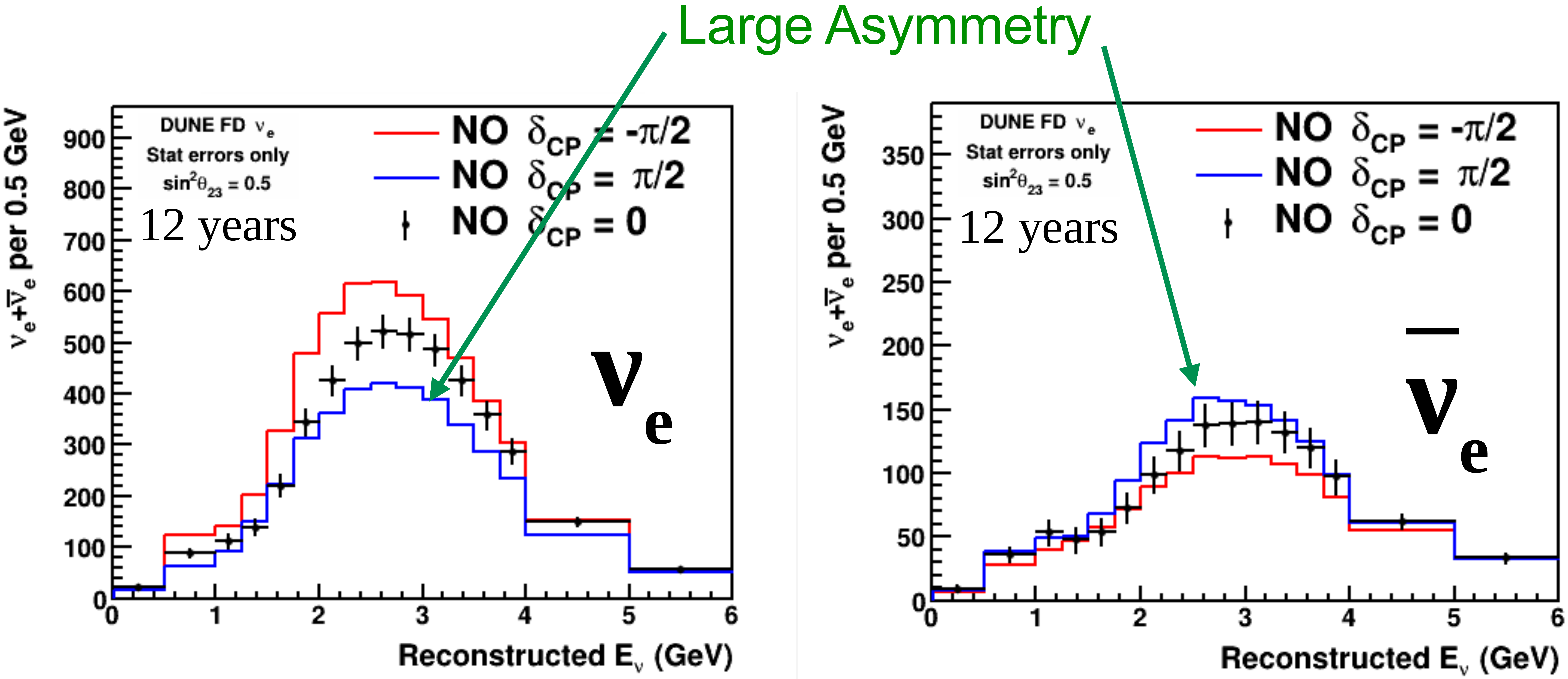
Large Asymmetry



Neutrino

Anti-Neutrino

Expected Event Number Distributions at DUNE



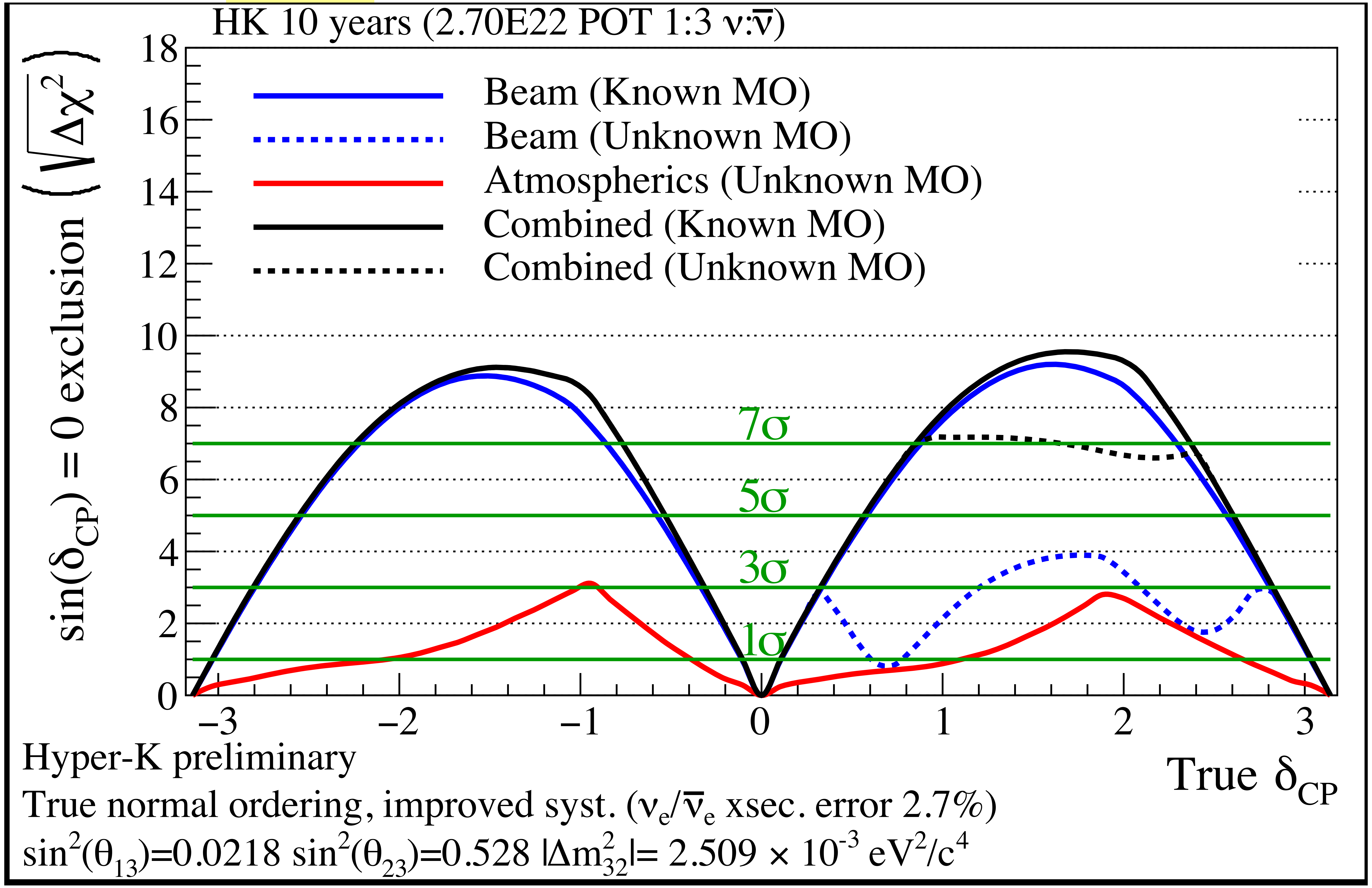
Large Asymmetry

Neutrino

Anti-Neutrino

HK's ability to exclude the CP conserving case $\sin\delta_{\rm CP} = 0$

Assumption: True Mass Ordering = Normal Ordering



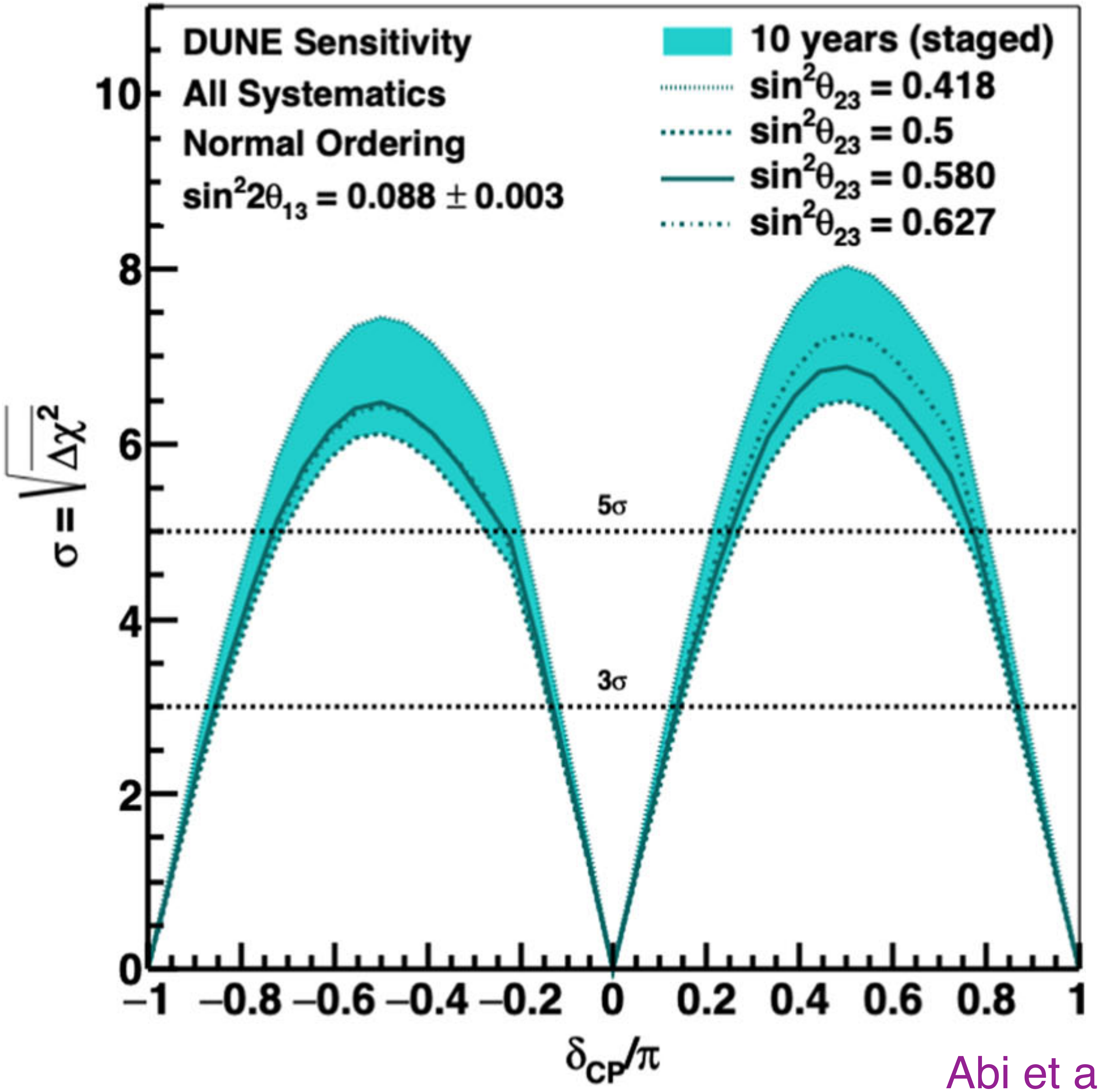
J. Wilson @NOW 2024 Workshop

T2K+NOvA may reach at most ~3σ for some values of CP phase

↓

Significant Improvement

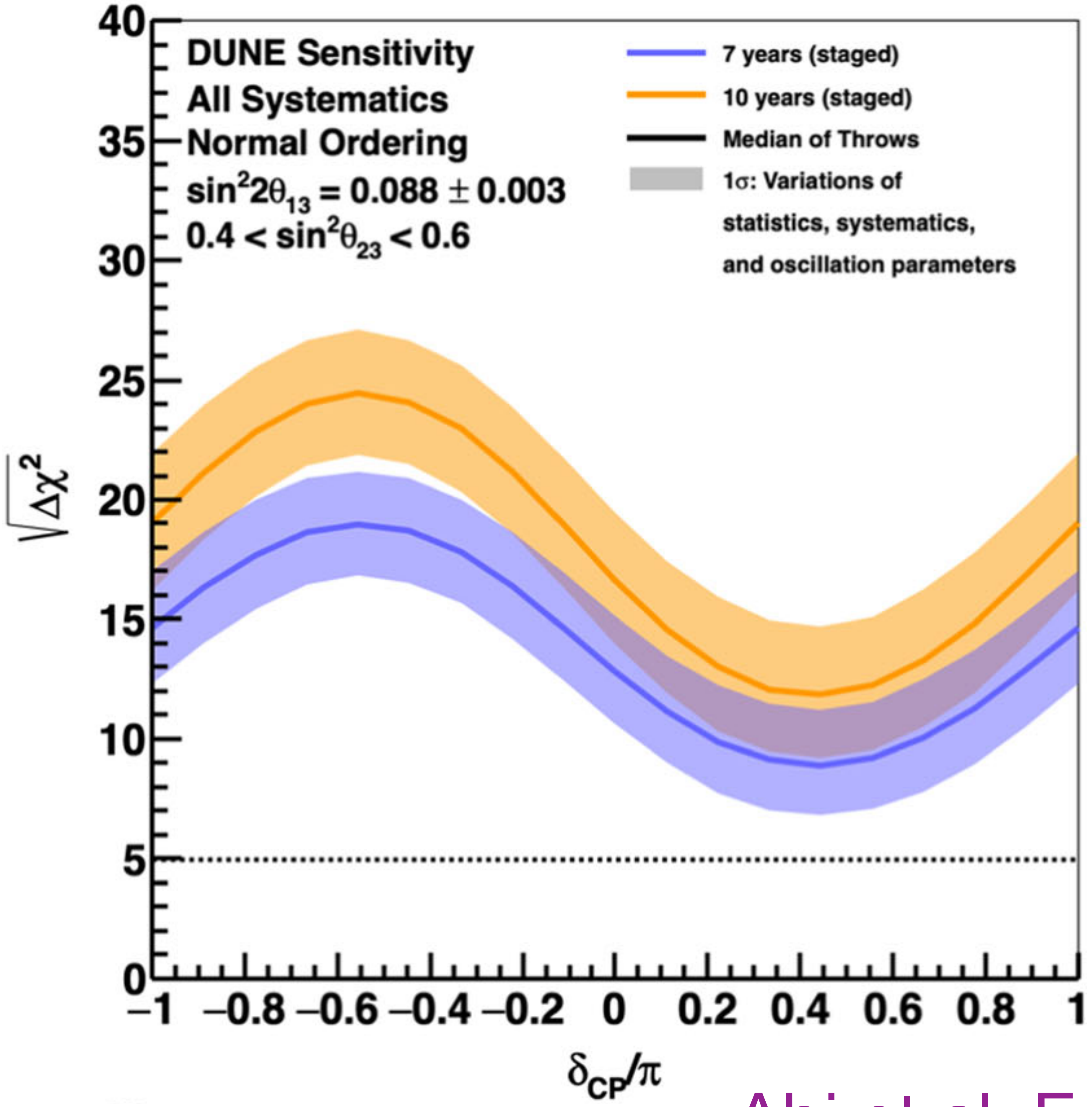
DUNE's ability to exclude the CP conserving case $\sin\delta_{\mathrm{CP}} = 0$



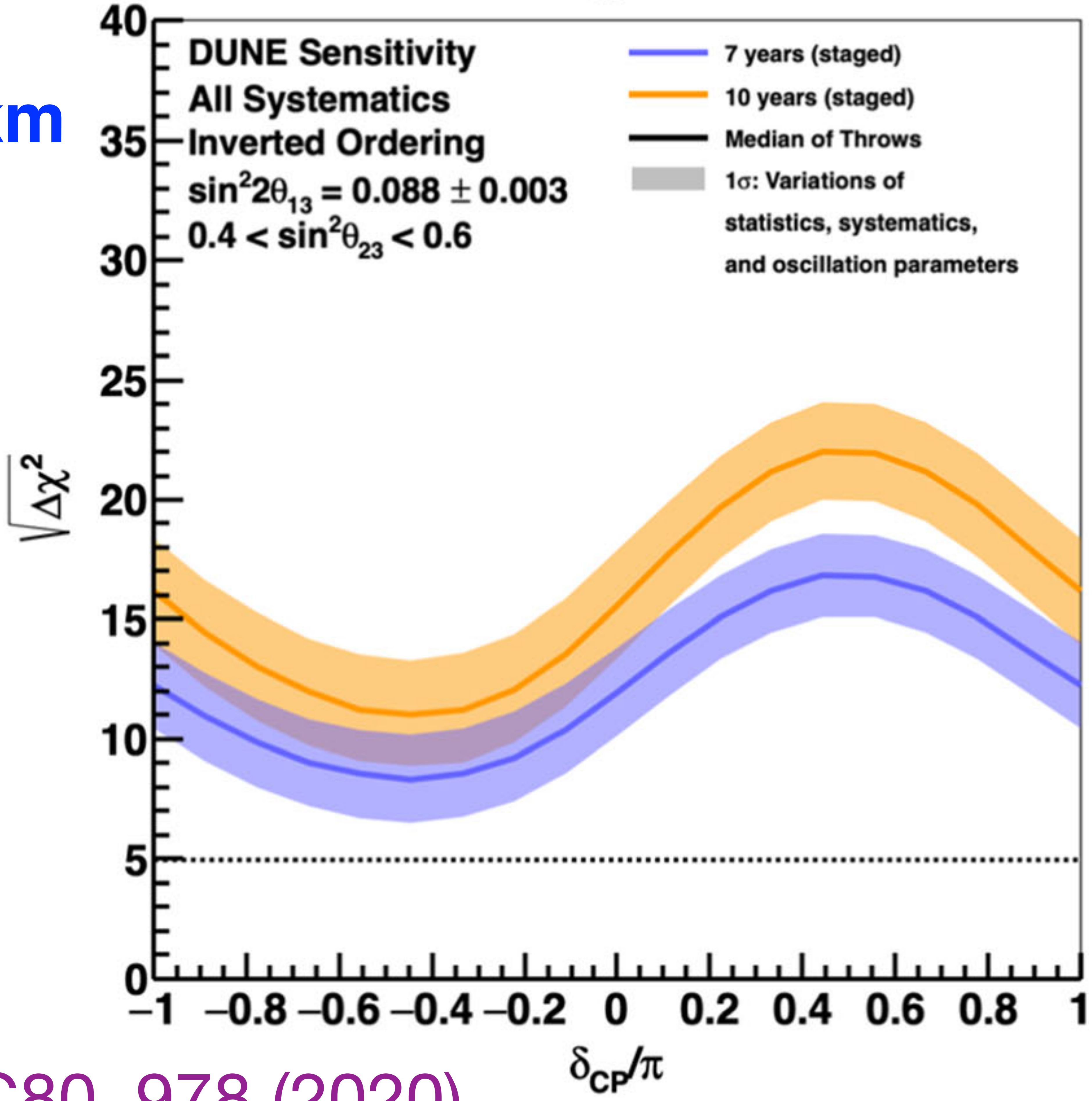
Abi et al, Eur. Phys. J. C.80, 978 (2020)

Determination Neutrino Mass Ordering by Long-Baseline Neutrino Oscillation Experiments

HK LBL is not powerful, but DUNE LBL is quite powerful to determine MO thanks to the larger matter effect due to longer baseline!



L ~ 1300 km



Abi et al, Eur. Phys. J. C80, 978 (2020)

DUNE alone can determine MO at more than 5σ !

Test of New Physics by Long-Baseline Neutrino Oscillation Experiments

New Physics = neutrino property beyond the standard framework of 3 massive neutrinos

For some New Physcs effects which can be studied in coherent neutrino-nucleus elastic scattering, see the talk by Diego Aristizábal (Friday) !

Effect of New Physics is not expected to be so large

Current Situation: Apart from some experimental data (such as LNSD), almost all the data can be explained quite well by neutrino oscillations (induced by masses and mixing) in the standard 3 flavor framework.

In general, if there is some new physics effect, such effect should not be so large or should be subdominant

More precision is needed!

Examples of “New Physics” effect which can manifest in LBL neutrino oscillations

NSI (Non-standard Interactions) of neutrinos

Presense of extra (sterile) neutrino

Decay of neutrinos due to New Physics

Violation of unitarity, or non-unitarity

Decoherence effect

Lorentz Violation, and so on

Examples of "New Physics" effect which can manifest in LBL neutrino oscillations

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Decoherence effect

Lorentz Violation, and so on

Phenomenological Approache

In most cases, New Physics (NP) effects can be manifested or parameterized by some effective NP parameters, in model independent (or less model dependent) way, which allows us to take phenomenological approache without explicitly considering some specific models

In this presentation, I will follow this approach, focusing on phenomenological aspects/consequences

Test for NSI (Non-Standard Interactions) of neutrinos with matter in long baseline oscillation experiments

Non-Standard Interactions (NSI) of Neutrinos

NSI can be generally described by

$$\mathscr{L}_{\text{NSI, CC}} = -2\sqrt{2}G_F \sum_{f,f'\alpha,\beta} \varepsilon^{ff',P}_{\alpha\beta}(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f}\gamma^\mu P f') + \text{h.c.}$$: CC NSI

Strongly contained by meson/muon decays

$$\mathscr{L}_{\text{NSI, NC}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f}\gamma^\mu P f) + \text{h.c.}$$: NC NSI

where $\alpha, \beta = e, \mu, \tau,$ *f, f'* = SM charged fermions, ℓ = SM charged leptons

$$\varepsilon^{f,V}_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} + \varepsilon^{f,R}_{\alpha\beta}, \ \varepsilon^{f,A}_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} - \varepsilon^{f,R}_{\alpha\beta}$$ (vector and axial NSI coefficients)

we define the effective NSI parameters as

$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^f_{\alpha\beta}\frac{N_f}{N_e} = \sum_{f=e,u,d} (\varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta})\frac{N_f}{N_e} \simeq \varepsilon^e_{\alpha\beta} + 3\varepsilon^u_{\alpha\beta} + 3\varepsilon^d_{\alpha\beta}$$ for Earth matter

Neutrino Evolution Equation in Matter with NSI effect

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

$$H = U\begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m_{21}^2}{2E} & 0\\ 0 & 0 & \frac{\Delta m_{31}^2}{2E}\end{bmatrix}U^\dagger + \sqrt{2}G_F N_e\begin{bmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{\mu e}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{\tau e}^* & \varepsilon_{\tau\mu}^* & \varepsilon_{\tau\tau}\end{bmatrix}$$

G_F : Fermi Constant

N_e : Electron number density

Neutrino Evolution Equation in Matter with NSI effect

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

Off diagonal elements, $\varepsilon_{\alpha\beta}\,(\alpha \neq \beta)$, can induce additional mixing(-like) effects

Im[$\varepsilon_{\alpha\beta}$] is a new source of CP violation

$$H = U\begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{bmatrix}U^\dagger + \sqrt{2}G_F N_e\begin{bmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{\tau e} & \varepsilon^*_{\tau\mu} & \varepsilon_{\tau\tau}\end{bmatrix}$$

Diagonal elements, $\varepsilon_{\alpha\alpha}$, can induce new potential and modify the resonance condition

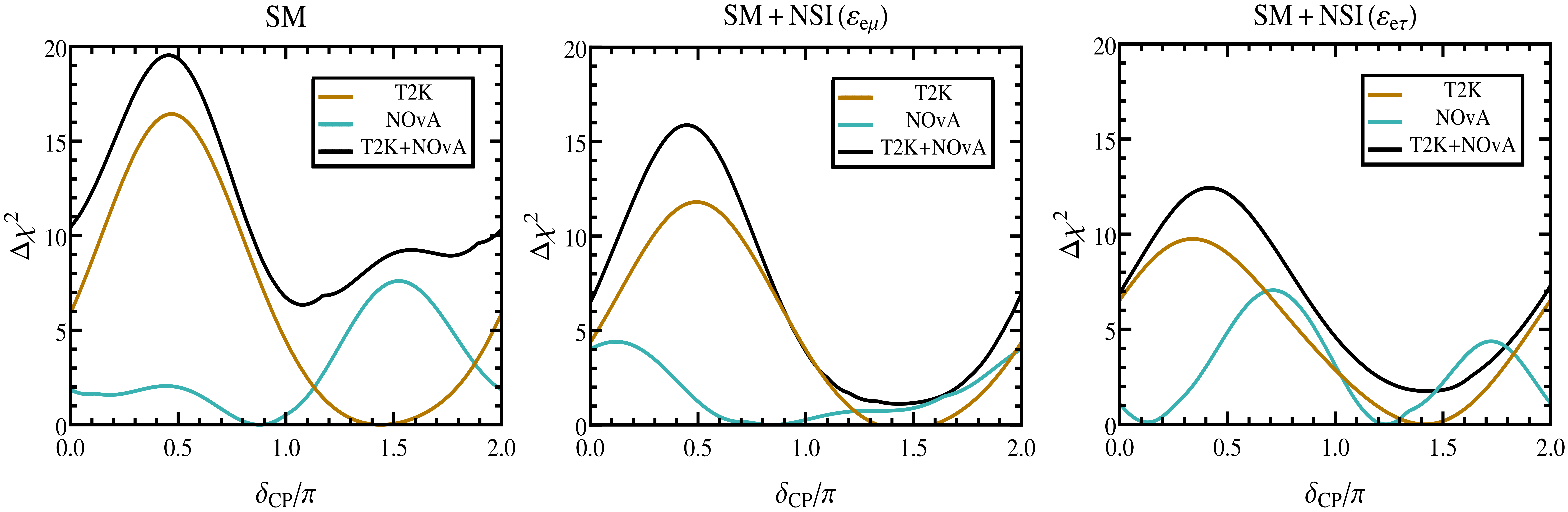
G_F : Fermi Constant

N_e : Electron number density

Some indication (hint) of NSI?

For Normal Ordering, T2K and NOvA results are in some tension with each other which could be alleviated if we include NSI effect

some tension (mismatch) of preferred value of CP phase between T2K and NOvA

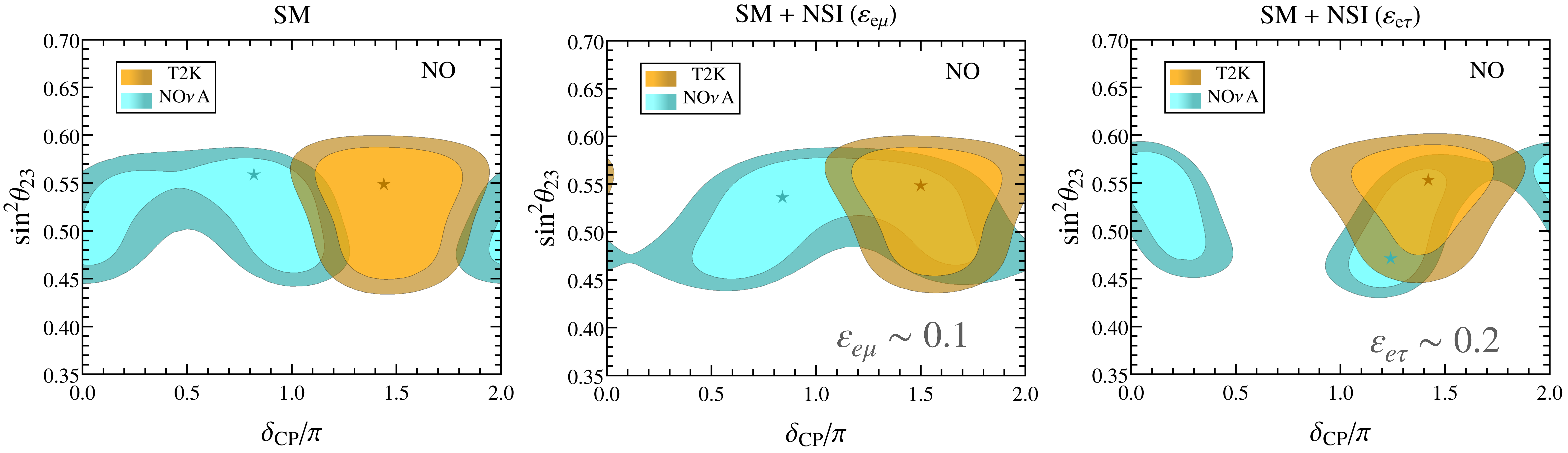


S. S. Chatterjee and A. Palazzo, arXiv:2409.10599 [hep-ph]

Some indication (hint) of NSI?

For Normal Ordering, T2K and NOvA results are in some tension with each other which could be alleviated if we include NSI effect

Including NSI, T2K and NOvA data indicate the similar values of CP phase

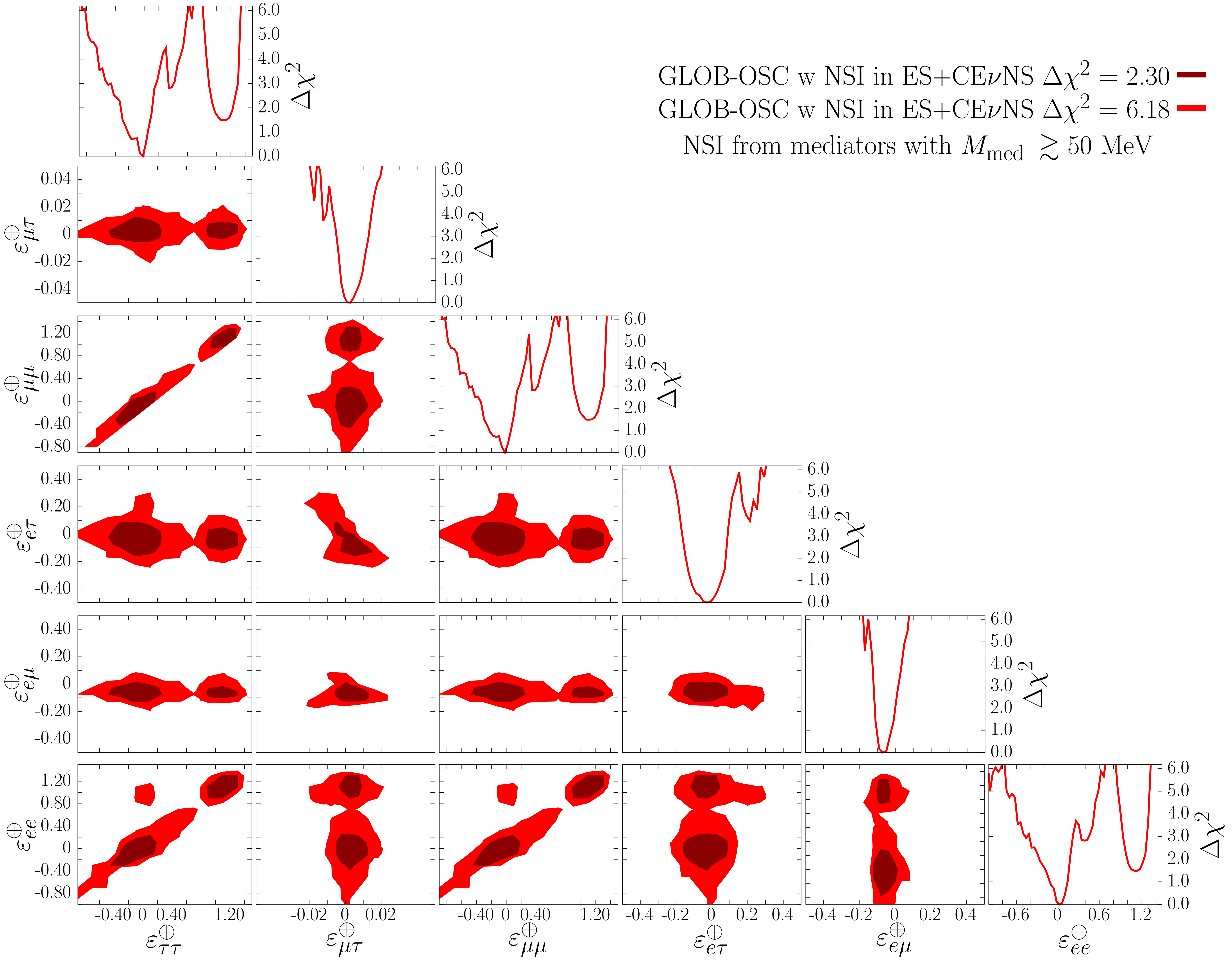


non-zero NSI is favored at ~2σ

S. S. Chatterjee and A. Palazzo, arXiv:2409.10599 [hep-ph]

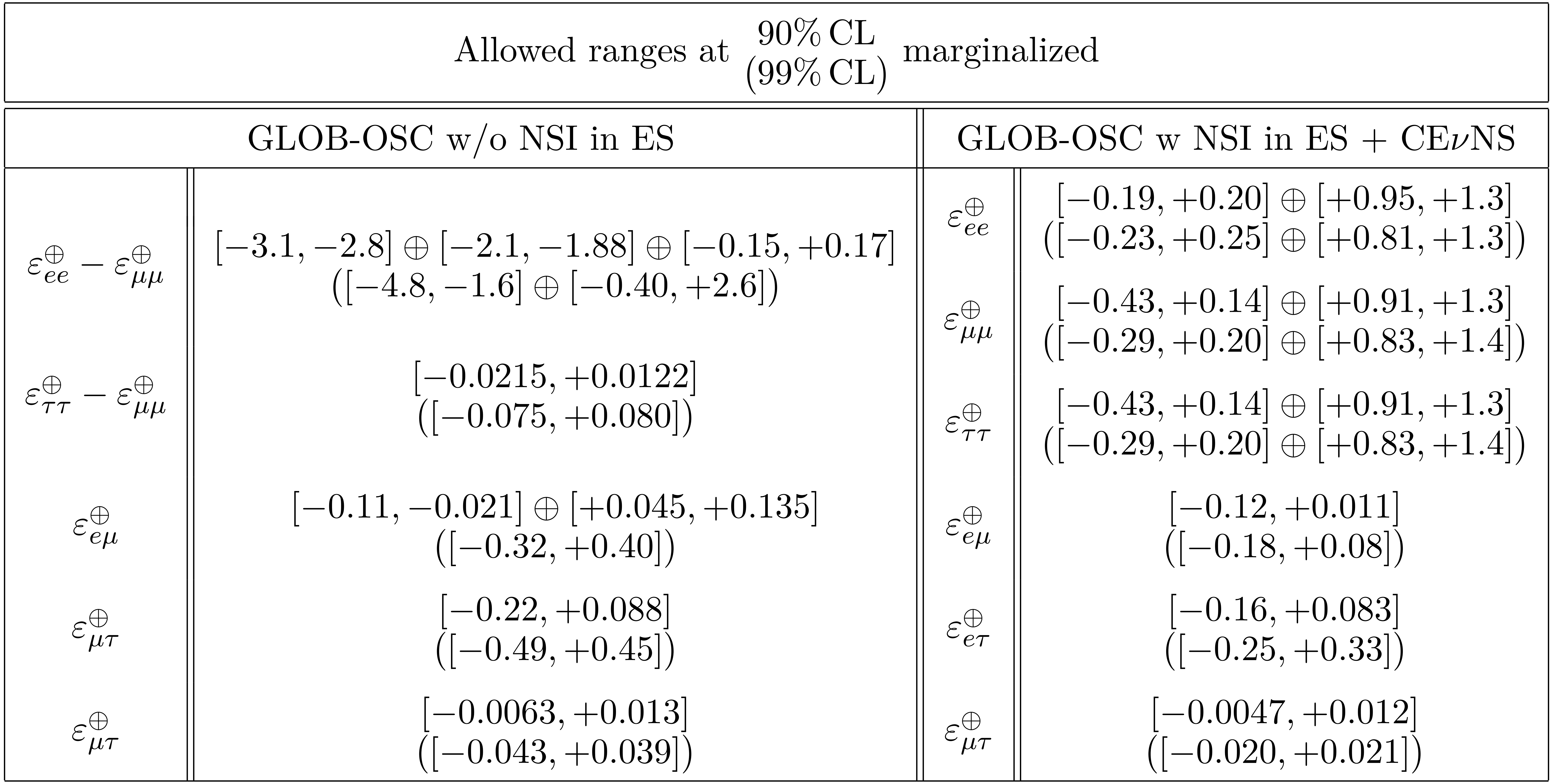
See also Denton et al, PRL126, 051801 (2021) [arXiv: 2008.01110 [hep-ph]]

Current Bounds on the effective NSI in Earth Matter relevant for LBL experiments



Coloma et al, JHEP08, 032 (2023) [arXiv:2305.07698 [hep-ph]]

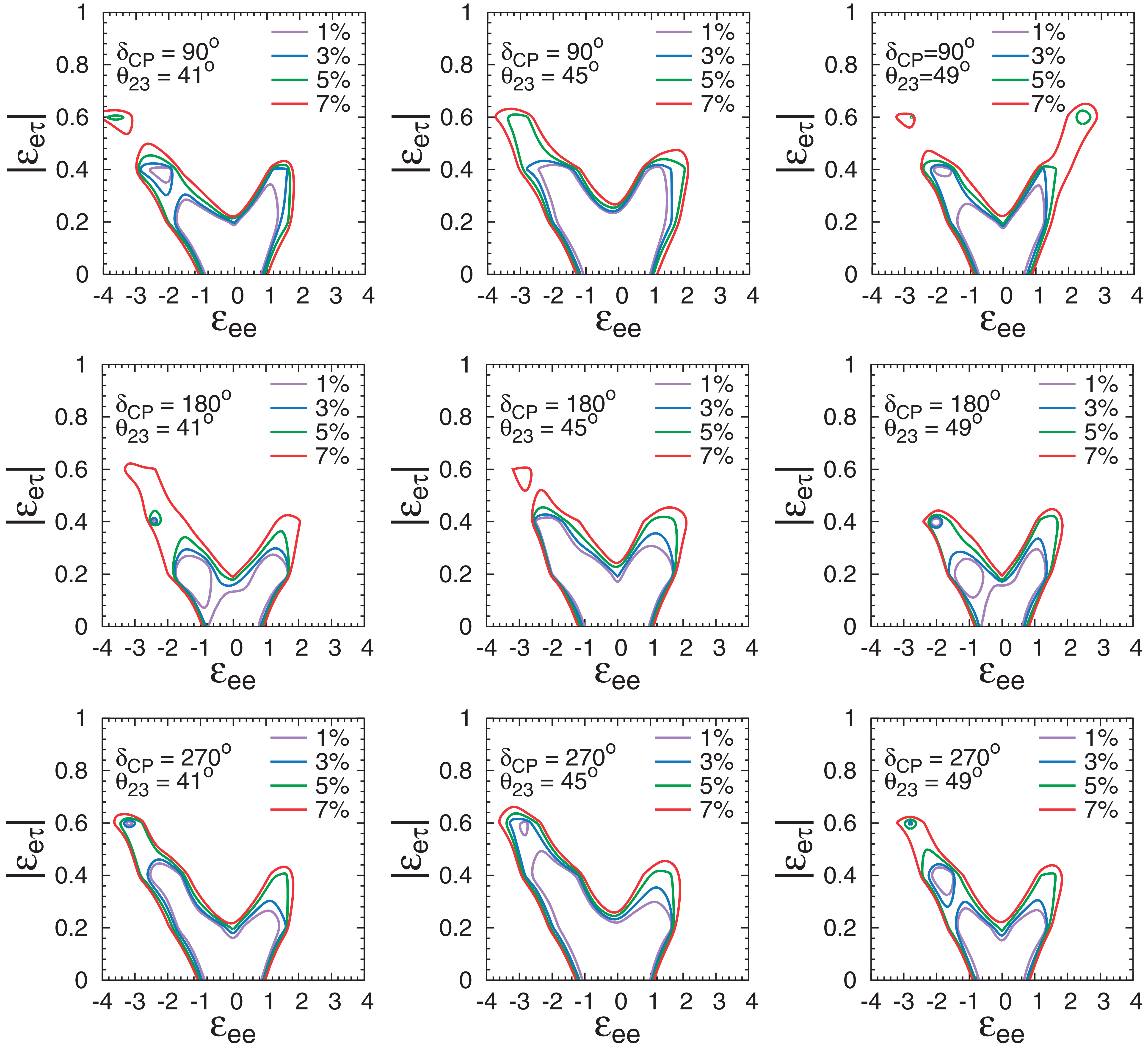
Current Bounds on the effective NSI in Earth Matter relevant for LBL experiments



Allowed ranges at $\begin{matrix}90\%\ \mathrm{CL} \\ (99\%\ \mathrm{CL})\end{matrix}$ marginalized			
GLOB-OSC w/o NSI in ES		GLOB-OSC w NSI in ES + CEνNS	
$\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu}$	$[-3.1, -2.8] \oplus [-2.1, -1.88] \oplus [-0.15, +0.17]$ $([-4.8, -1.6] \oplus [-0.40, +2.6])$	$\varepsilon^{\oplus}_{ee}$	$[-0.19, +0.20] \oplus [+0.95, +1.3]$ $([-0.23, +0.25] \oplus [+0.81, +1.3])$
		$\varepsilon^{\oplus}_{\mu\mu}$	$[-0.43, +0.14] \oplus [+0.91, +1.3]$ $([-0.29, +0.20] \oplus [+0.83, +1.4])$
$\varepsilon^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu}$	$[-0.0215, +0.0122]$ $([-0.075, +0.080])$	$\varepsilon^{\oplus}_{\tau\tau}$	$[-0.43, +0.14] \oplus [+0.91, +1.3]$ $([-0.29, +0.20] \oplus [+0.83, +1.4])$
$\varepsilon^{\oplus}_{e\mu}$	$[-0.11, -0.021] \oplus [+0.045, +0.135]$ $([-0.32, +0.40])$	$\varepsilon^{\oplus}_{e\mu}$	$[-0.12, +0.011]$ $([-0.18, +0.08])$
$\varepsilon^{\oplus}_{\mu\tau}$	$[-0.22, +0.088]$ $([-0.49, +0.45])$	$\varepsilon^{\oplus}_{e\tau}$	$[-0.16, +0.083]$ $([-0.25, +0.33])$
$\varepsilon^{\oplus}_{\mu\tau}$	$[-0.0063, +0.013]$ $([-0.043, +0.039])$	$\varepsilon^{\oplus}_{\mu\tau}$	$[-0.0047, +0.012]$ $([-0.020, +0.021])$

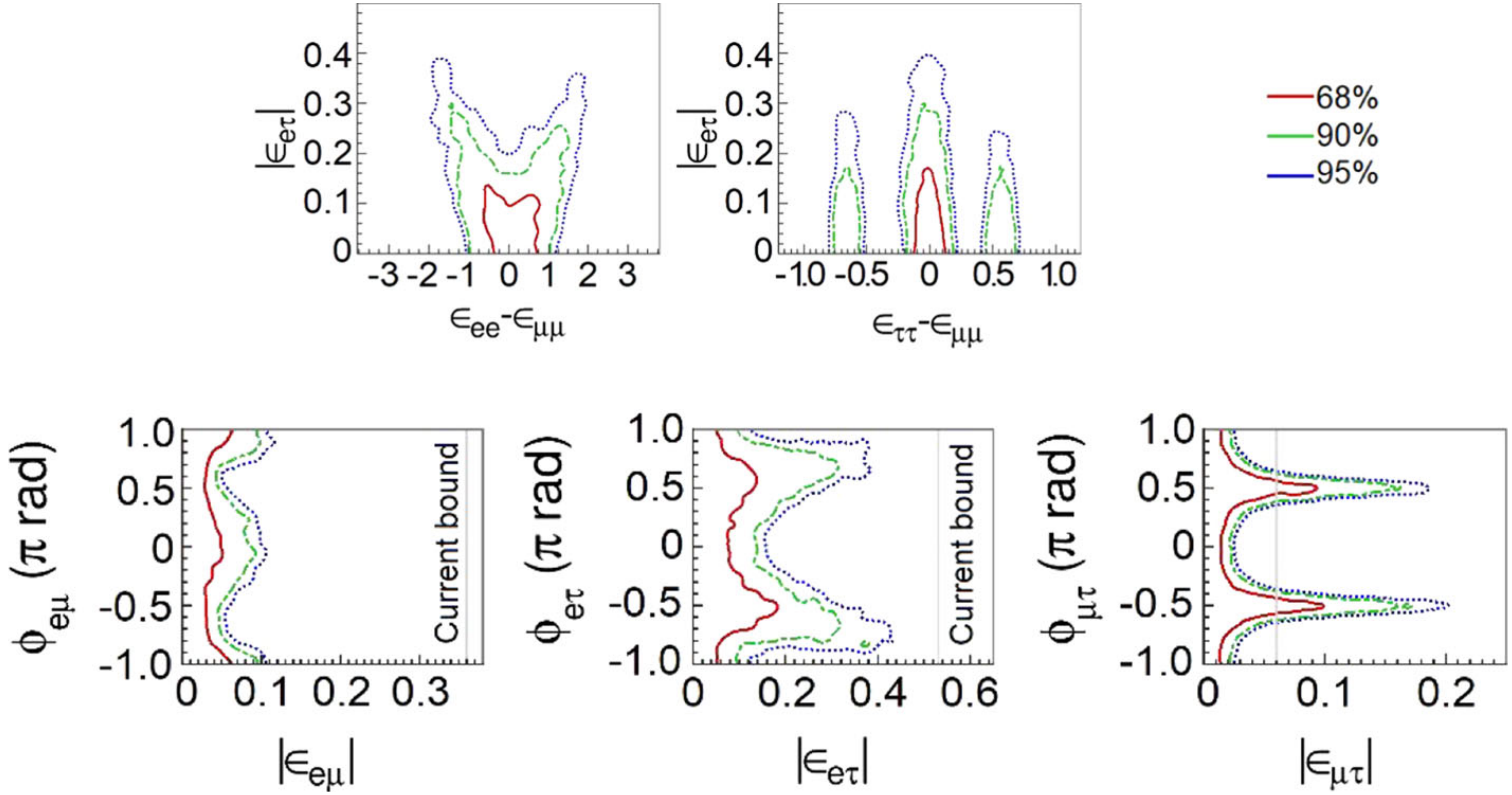
Coloma et al, JHEP08, 032 (2023) [arXiv:2305.07698 [hep-ph]]

Expected sensitivity to constrain NSI by Hyper-K + another detector at Korea



Abe et al, PTEP 2018, 063C01 [arXiv:1611.06118 [hep-ex]]

Expected sensitivity to constrain NSI by DUNE



Abi et al (DUNE Collab.), Eur. Phys. J. C81, 322 (2021) [arXiv:2008.12769 [hep-ex]]

Some remarks for NSI in LBL experiments

To enhance sensitivities to NSI, synergy among different experiments, Hyper-K, DUNE, JUNO, solar, atmospheric neutrinos, etc, would be important

If the hint for non-zero NSI implied by T2K+NOvA results is true, with much larger statistics, Hyper-K and DUNE are expected to confirm (or exclude) such a scenario

Interesting difference between Hyper-K and DUNE
- **Hyper-K: small matter (NSI) effect (L = 295km)**
- **DUNE: larger matter (NSI) effect (L = 1285 km)**

Test for sterile neutrinos in long baseline neutrino oscillation experiments

Neutrino Evolution Equation for 3+1 model

Let us consider so called 3+1 (3 active + 1 sterile neutrinos) model

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = (H_0 + V_m)\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix}$$

$$V_m = \begin{bmatrix}V_e + V_n & 0 & 0 & 0\\ 0 & V_n & & 0\\ 0 & 0 & V_n & 0\\ 0 & 0 & 0 & 0\end{bmatrix}$$

$$V_e \equiv \sqrt{2}G_F n_e,\ V_n \equiv -\frac{\sqrt{2}}{2}G_F n_e,$$

$$H_0 = U_{3+1}\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0\\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E}\end{bmatrix}U^\dagger_{3+1}$$

$$U_{3+1} \equiv R_{34}(\theta_{34})R_{24}(\theta_{24},\delta_{24})R_{14}(\theta_{14},\delta_{14})R_{23}(\theta_{23})R_{13}(\theta_{13},\delta_{13})R_{12}(\theta_{12})$$

What is the qualitative impact of sterile neutrino?

1) Further reduction of (active) neutrinos in the disappearance mode

$\nu_\mu \rightarrow \nu_\mu$ can occur or be induced through the mixing θ_{24}

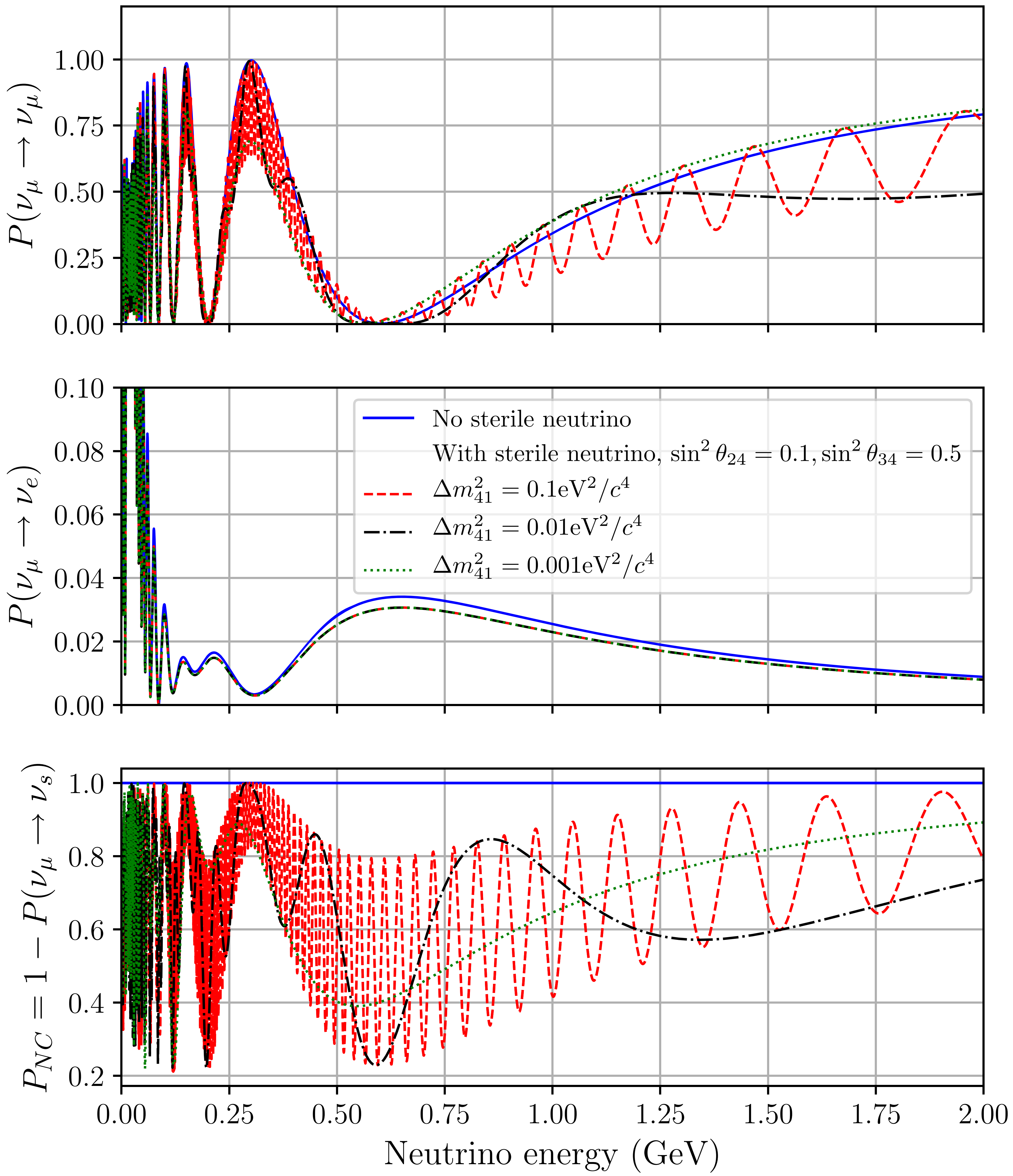
2) Additional (new) contribution in the appearance mode through the oscillation due to mixing and new mass eigenstate (mass squared differences)

$\nu_\mu \rightarrow \nu_e$ can occur or be induced through the simultaneous presence of mixing θ_{24} and θ_{14}

3) Reduction of NC (neutral current) induced events due to oscillation of active neutrinos into sterile ones

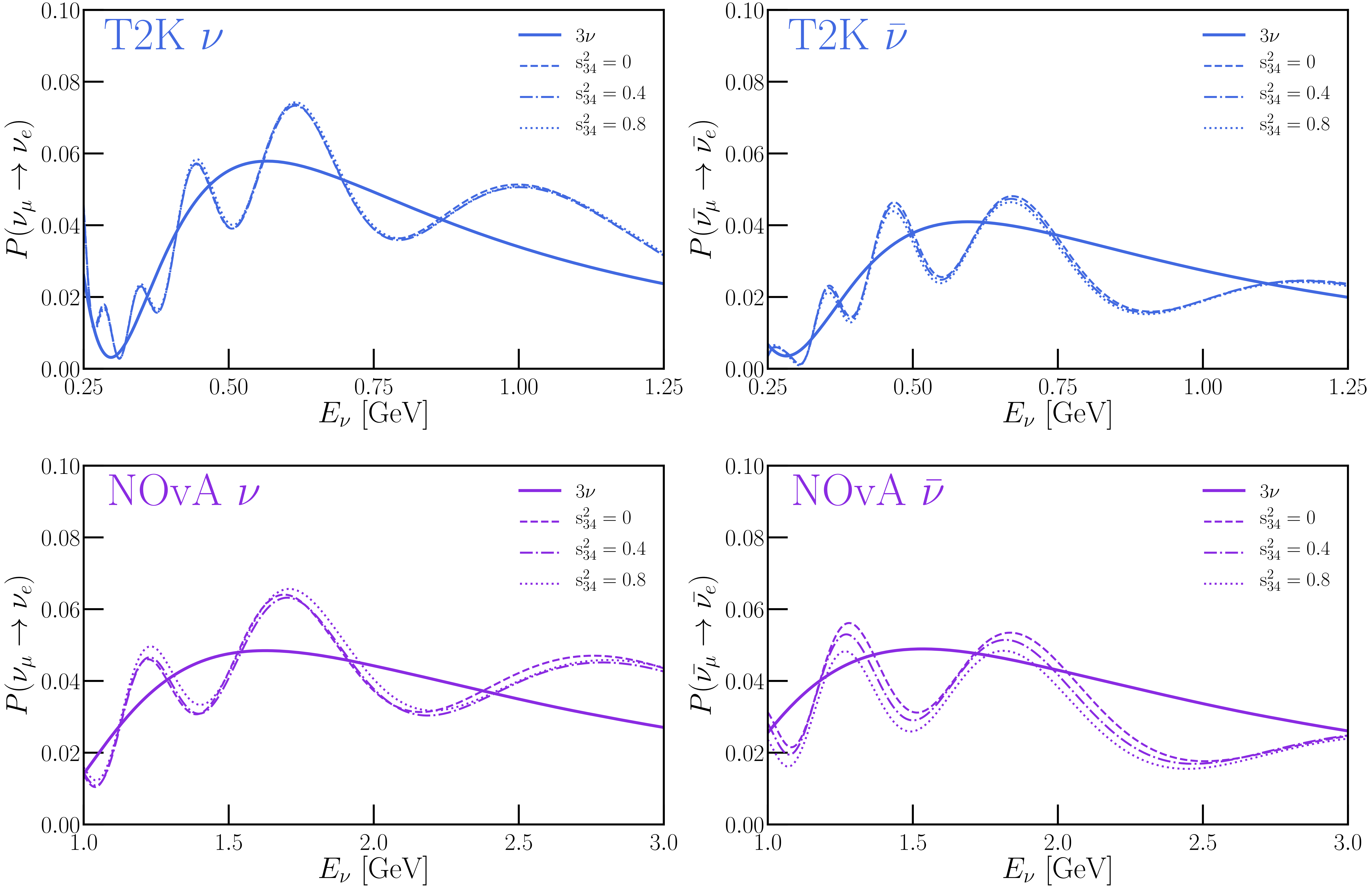
$\nu_\mu \rightarrow \nu_s$

Some example of oscillation probabilities in the 3+1 model for L = 295km (T2K/HK)



Abe et al (T2K Collab.), PRD99, 071103(R) (2019) [arXiv:1902.06529 [hep-ex]]

Some example of oscillation probabilities in the 3+1 model for L = 295/810 km for T2K/NOvA



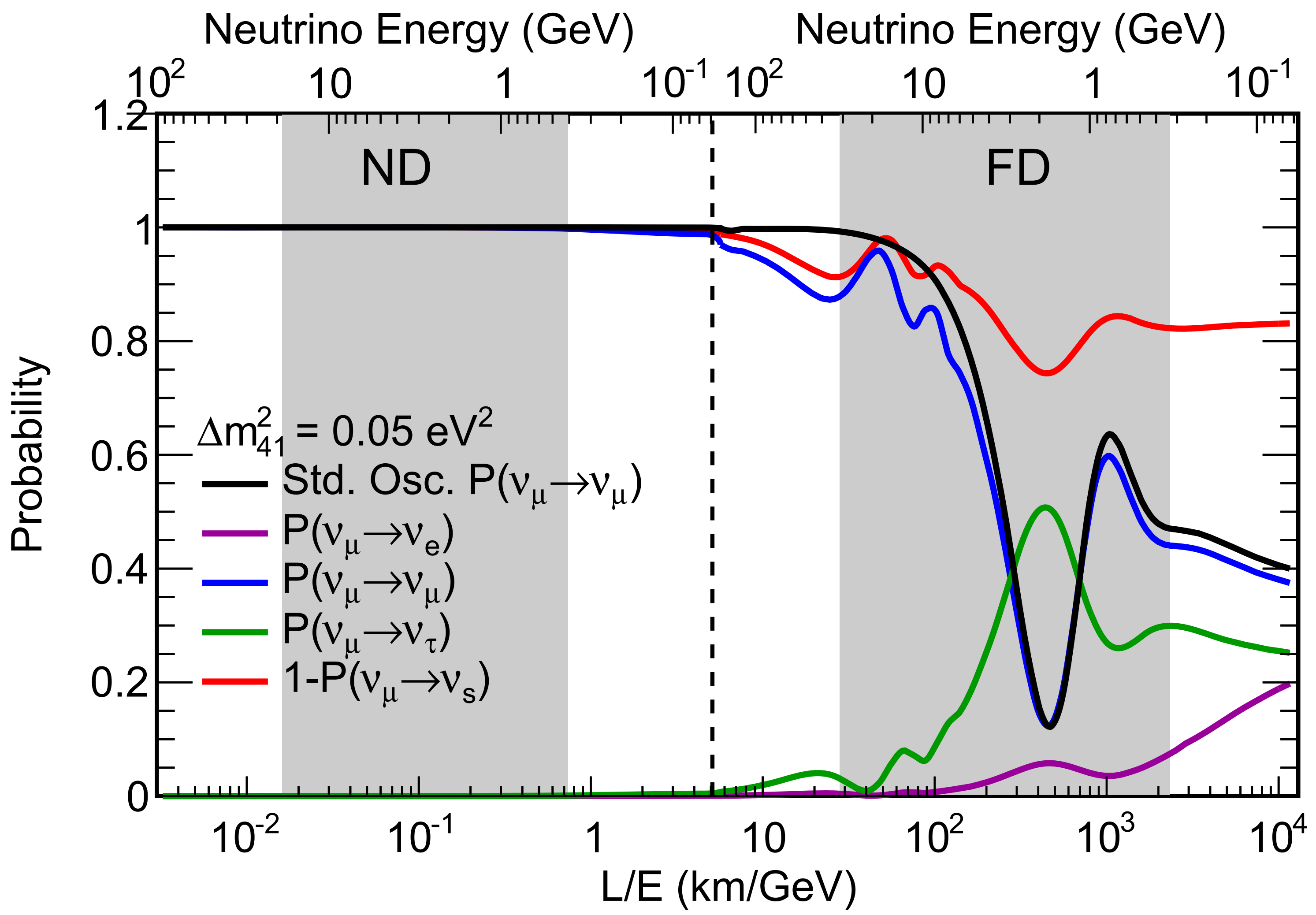
For Inverted Mass Ordering

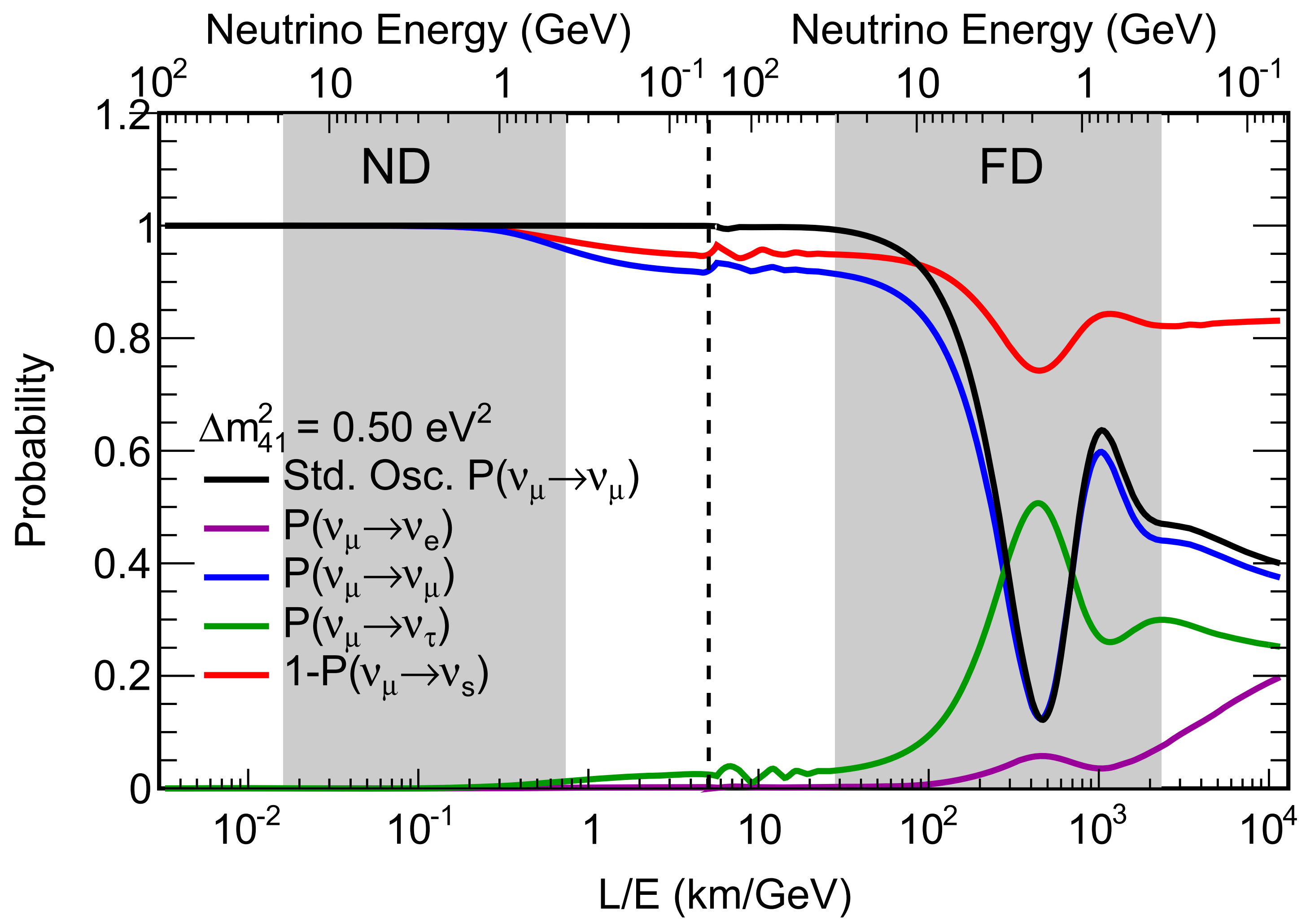
$$\Delta m^2_{31} = -2.39 \times 10^{-3}\ \text{eV}^2$$

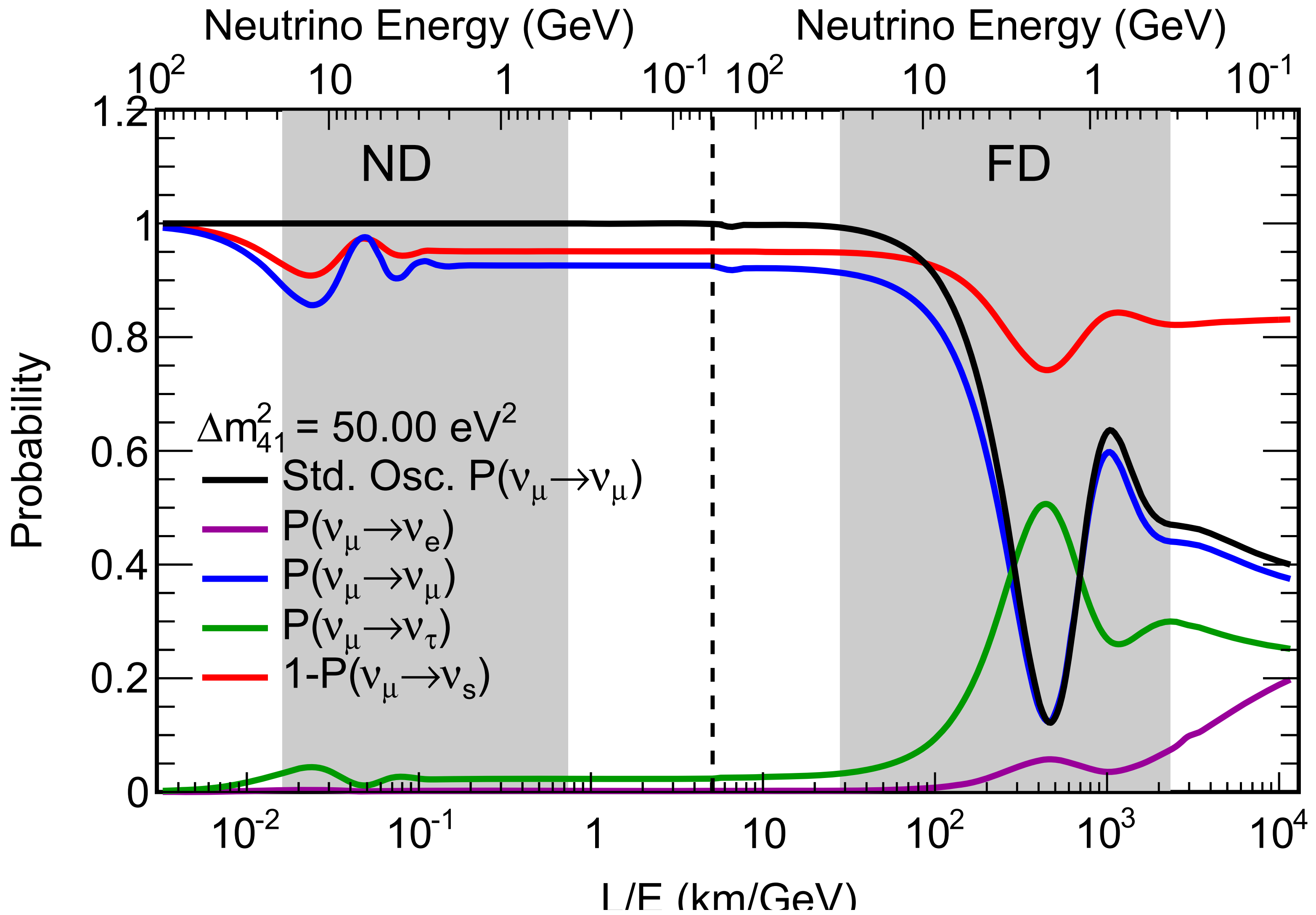
$$\Delta m^2_{41} = -0.011\ \text{eV}^2$$

Gouvea, Sahches and Kelly, PRD 106, 055025 (2022) [arXiv:2204.09130 [hep-ph]]

Some example of oscillation probabilities in the 3+1 model for L = 1285km (DUNE)

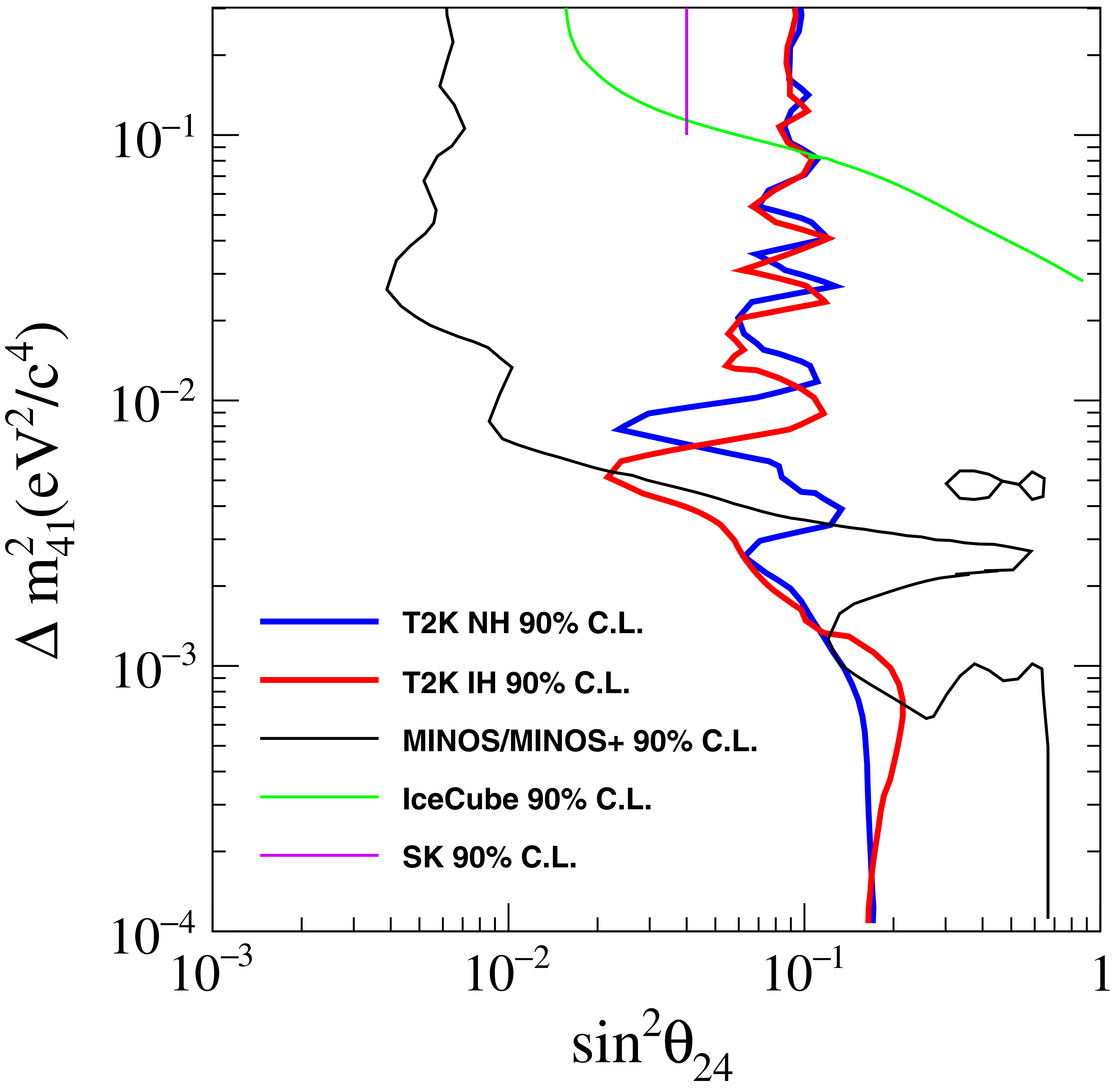






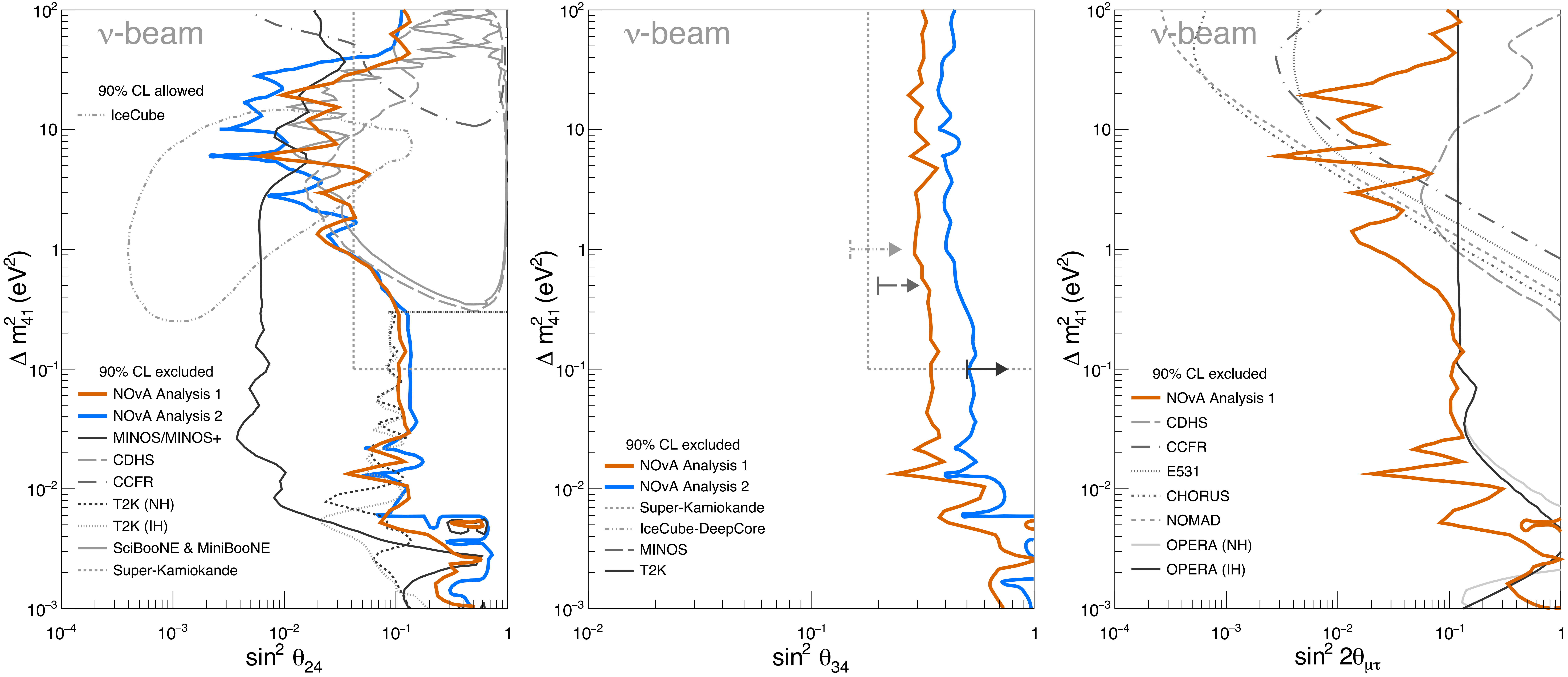
Abi et al (DUNE Collab.), Eur. Phys. J. C81, 322 (2021) [arXiv:2008.12769 [hep-ex]]

Current Bounds for light sterile neutrinos by T2K



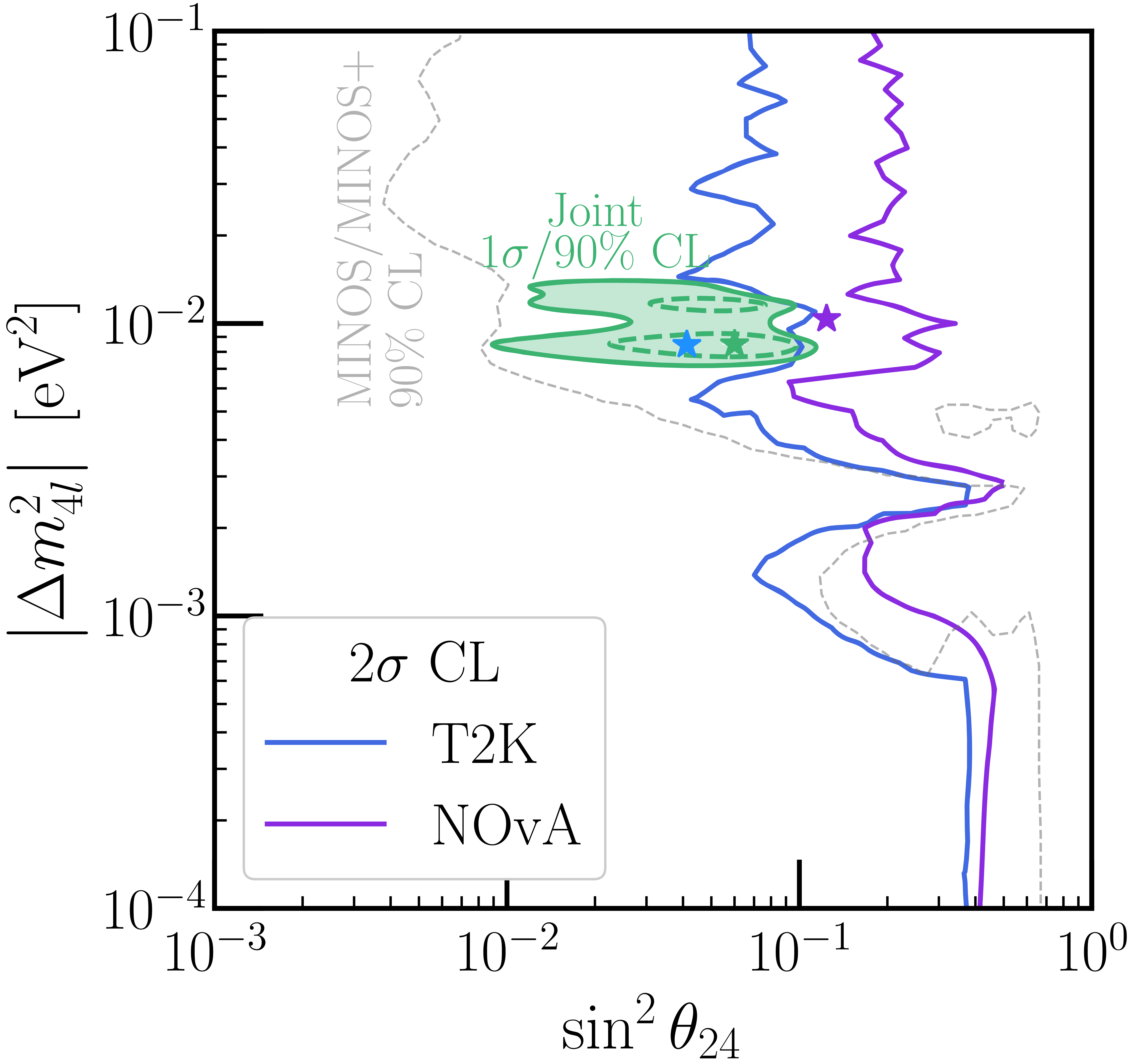
Abe et al (T2K Collab.), PRD99, 071103(R) (2019) [arXiv:1902.06529 [hep-ex]]

Current Bounds for light sterile neutrinos by NOvA



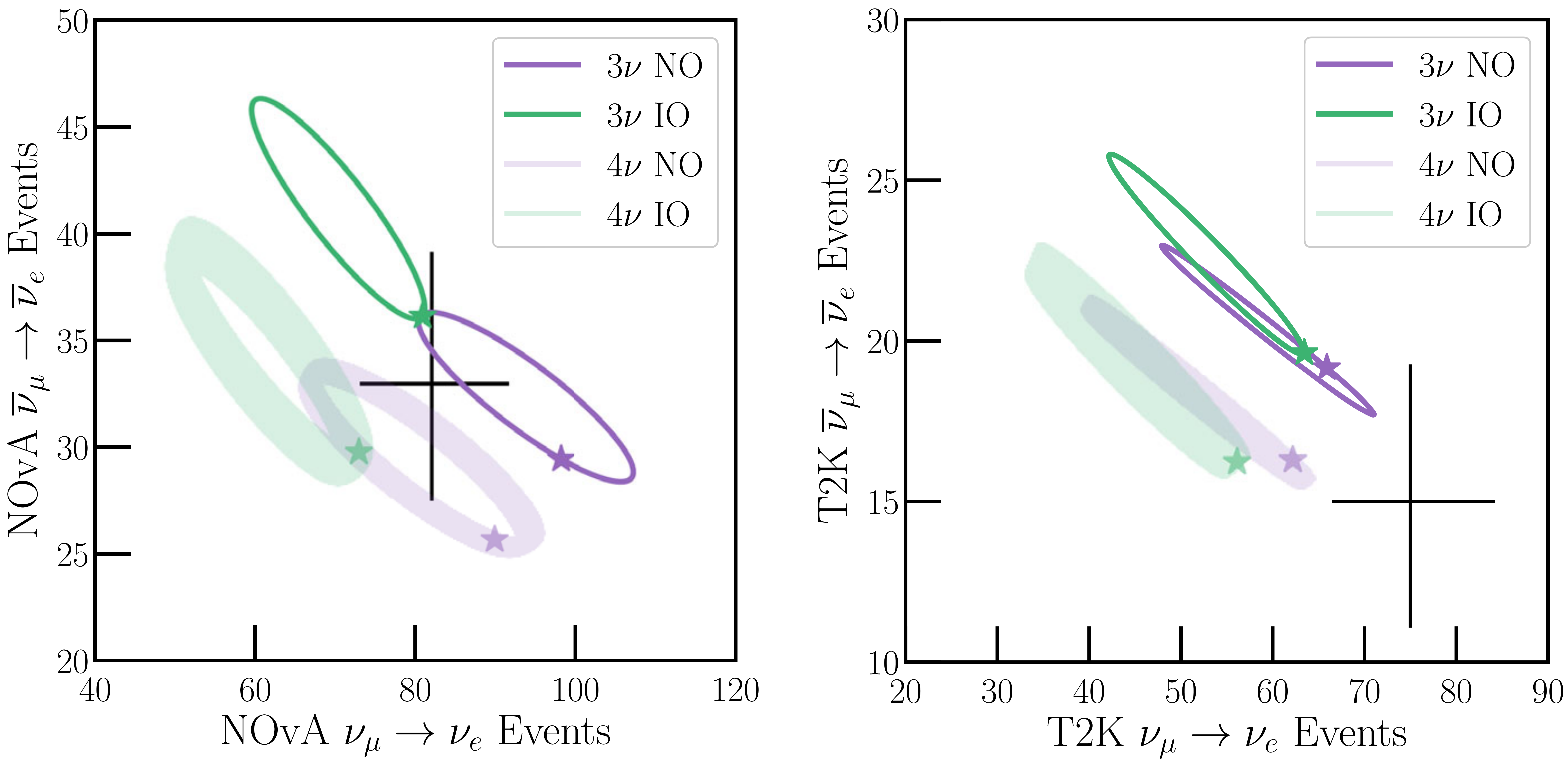
Acero et al (NOvA Collab.), arXiv:2409.04553 [hep-ex]]

Light Sterile Neutrino favored by NOvA and T2K



Gouvea, Sahches and Kelly, PRD 106, 055025 (2022) [arXiv:2204.09130 [hep-ph]]

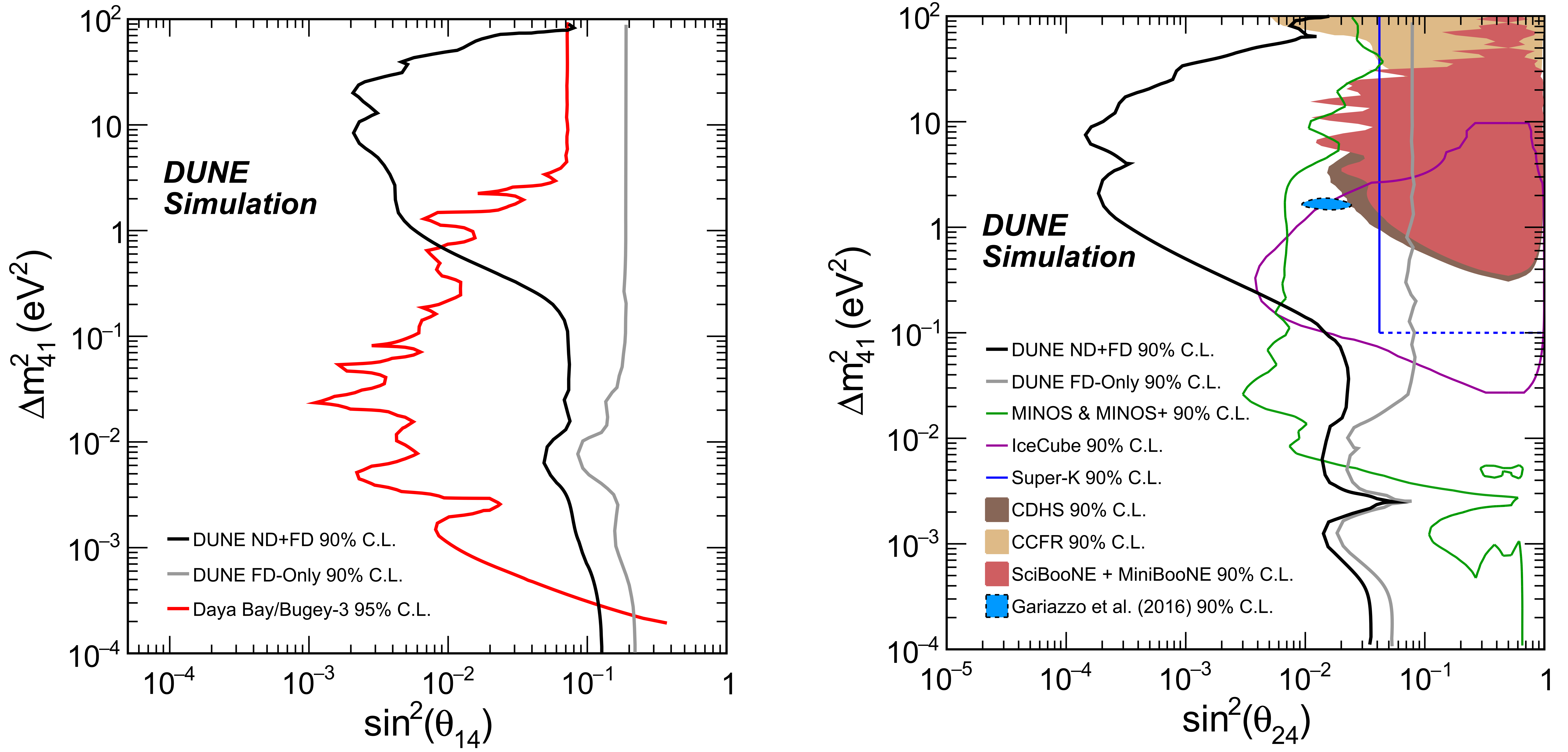
Light Sterile Neutrino favored by NOvA and T2K



Tension between NOvA and T2K can be somewhat (~2σ) alleviated by adding 1 sterile neutrino, or by 3+1 model

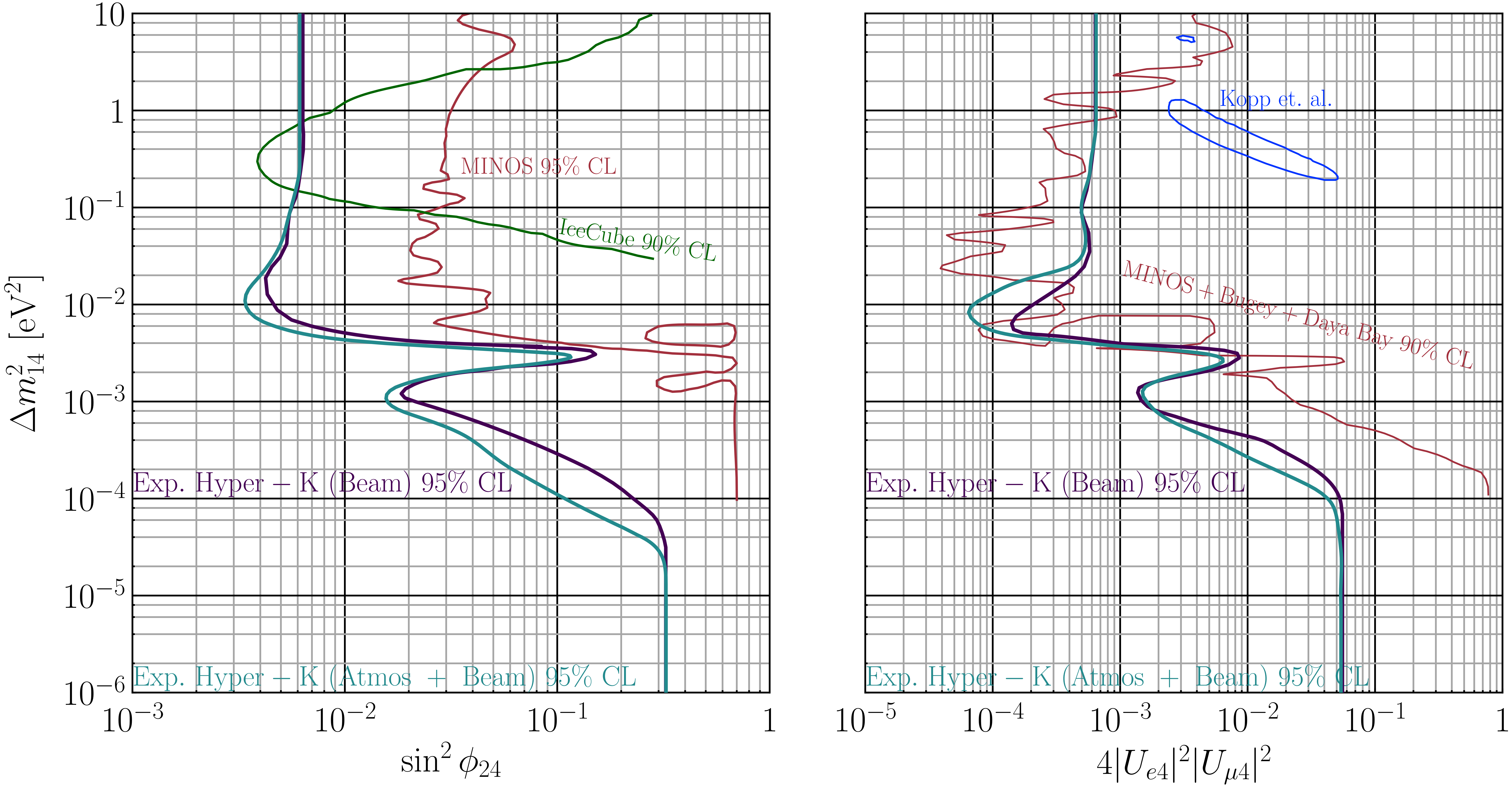
Gouvea, Sahches and Kelly, PRD 106, 055025 (2022) [arXiv:2204.09130 [hep-ph]]

Test of Sterile Neutrino by DUNE



Abi et al (DUNE Collab.), Eur. Phys. J. C81, 322 (2021) [arXiv:2008.12769 [hep-ex]]

Test of Light Sterile Neutrino by Hyper-K



Kelly, PRD95, 115009 (2017) [arXiv:1703.00448 [hep-ph]]

Some remarks for sterile neutrino in LBL experiments

Hyper-K and DUNE, with much larger statistics, would improve the current bounds

If the hint for the presence of sterile neutrino implied by T2K+NOvA results is true, with much larger statistics, Hyper-K and DUNE are expected to confirm (or exclude) such a scenario

Test of Neutrino Decay in LBL experiments

Invisible Decay

For simplicity, let us consider “invisible” decay mode like

$$\nu_i \to \nu_s + \chi \qquad \text{(i = 1, 2 or 3)}$$

where one of the mass eigenstates $\nu_i \; (i = 1, 2 \, \text{or} \, 3)$ decays into sterile neutrino plus some massless particle which would also be non-detectable

Then energy eigen value is given by,

$$E_i = \frac{m_i^2}{2E} - i\frac{\Gamma_i}{2} \qquad \frac{1}{\Gamma_i} = \frac{E}{m_i}\tau_i$$: Lorentz dilated life time

Neutrino Evolution Equation in Matter with decay effect

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

$$H = U\frac{1}{2E}\left(\begin{bmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{bmatrix} - i\frac{m_3}{\tau_3}\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}\right)U^\dagger + \sqrt{2}G_F n_e\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

assuming that ν_3 can decay into sterile state ν_s like $\nu_3 \rightarrow \nu_s + \chi$

G_F : Fermi Constant

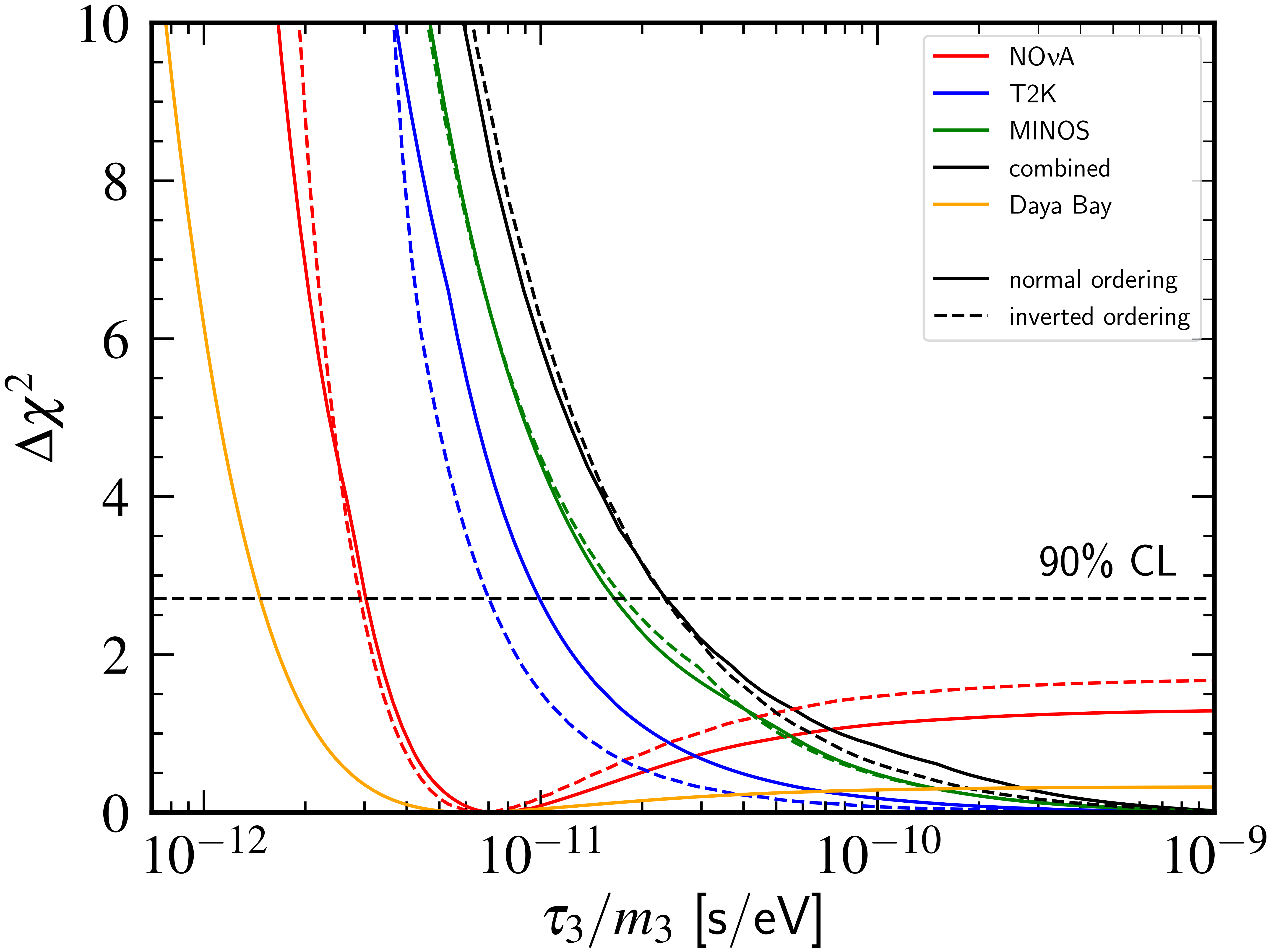
n_e : Electron number density

Roughly speaking, the large decay effect is expected if τ/m is ~L/E or

For exemple, if ~L/E is 1000km/1GeV,

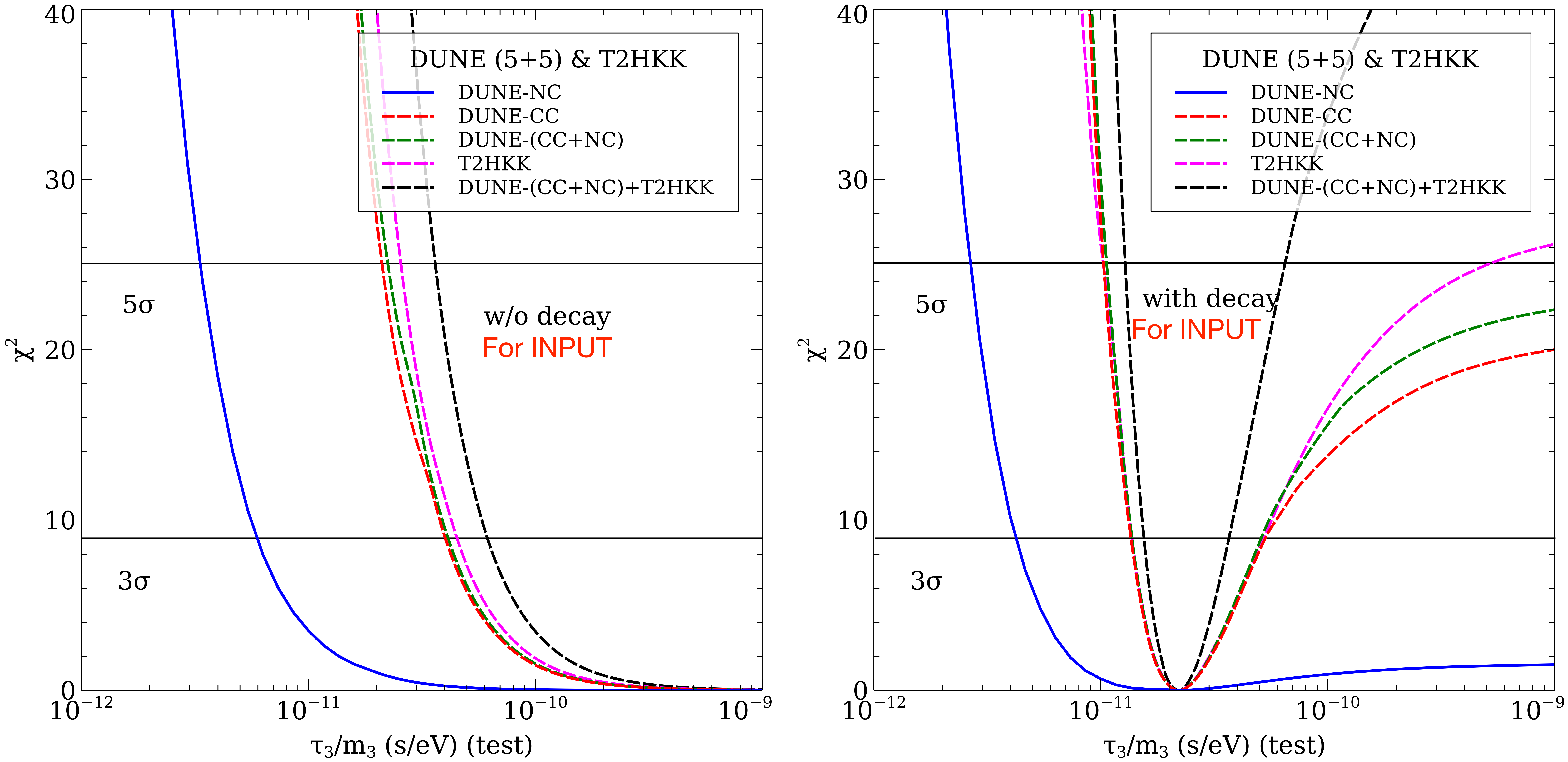
$$\frac{\tau}{m} = \frac{L}{E} \sim \frac{10^3\text{km}}{1\,\text{GeV}} \sim 3.3 \times 10^{-12}\,\frac{\text{s}}{\text{eV}}$$

Current bounds by NOvA/T2K/MINOS and Daya Bay



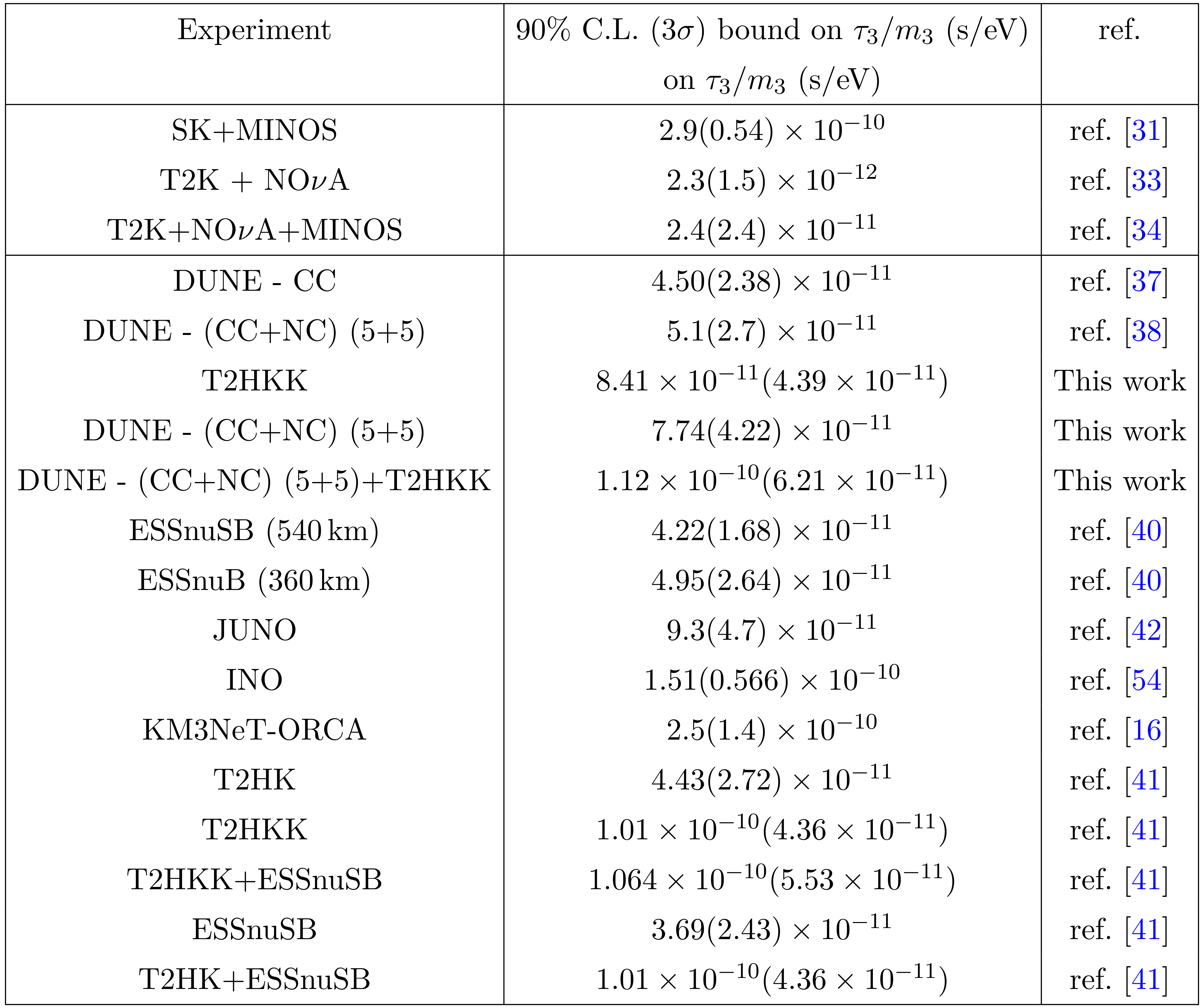
Ternes & Pagliaroli, PRD109, L071701 (2024) [arXiv: 2401.14316 [hep-ph]]

Expected sensitivity by DUNE and T2HKK



Dey & Dutta, JHEP09, 035 (2024) [arXiv: 2402.13235 [hep-ph]]

Expected sensitivity by DUNE and T2HKK

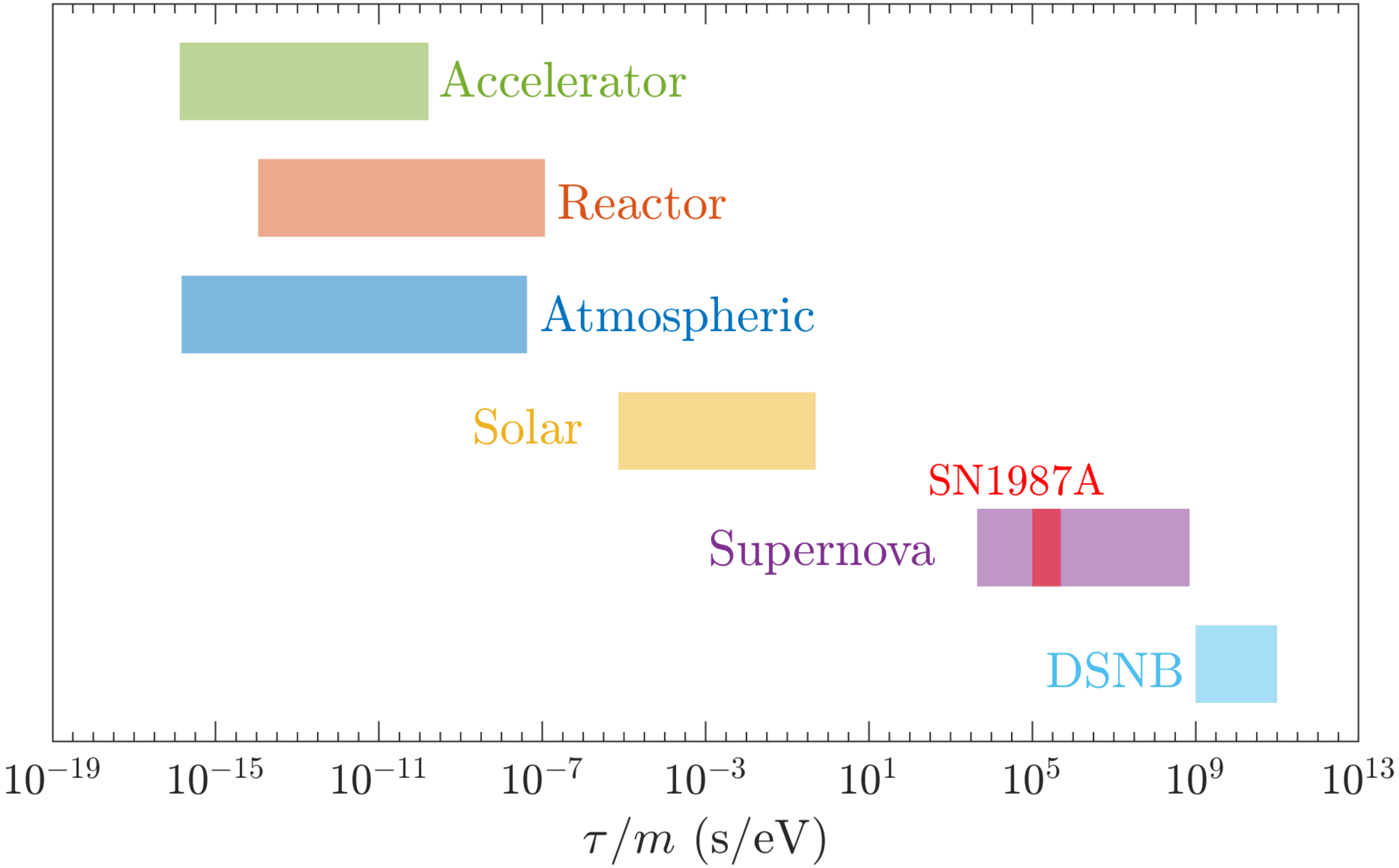


Experiment	90% C.L. (3σ) bound on τ_3/m_3 (s/eV) on τ_3/m_3 (s/eV)	ref.
SK+MINOS	$2.9(0.54) \times 10^{-10}$	ref. [31]
T2K + NOνA	$2.3(1.5) \times 10^{-12}$	ref. [33]
T2K+NOνA+MINOS	$2.4(2.4) \times 10^{-11}$	ref. [34]
DUNE - CC	$4.50(2.38) \times 10^{-11}$	ref. [37]
DUNE - (CC+NC) (5+5)	$5.1(2.7) \times 10^{-11}$	ref. [38]
T2HKK	$8.41 \times 10^{-11}(4.39 \times 10^{-11})$	This work
DUNE - (CC+NC) (5+5)	$7.74(4.22) \times 10^{-11}$	This work
DUNE - (CC+NC) (5+5)+T2HKK	$1.12 \times 10^{-10}(6.21 \times 10^{-11})$	This work
ESSnuSB (540 km)	$4.22(1.68) \times 10^{-11}$	ref. [40]
ESSnuB (360 km)	$4.95(2.64) \times 10^{-11}$	ref. [40]
JUNO	$9.3(4.7) \times 10^{-11}$	ref. [42]
INO	$1.51(0.566) \times 10^{-10}$	ref. [54]
KM3NeT-ORCA	$2.5(1.4) \times 10^{-10}$	ref. [16]
T2HK	$4.43(2.72) \times 10^{-11}$	ref. [41]
T2HKK	$1.01 \times 10^{-10}(4.36 \times 10^{-11})$	ref. [41]
T2HKK+ESSnuSB	$1.064 \times 10^{-10}(5.53 \times 10^{-11})$	ref. [41]
ESSnuSB	$3.69(2.43) \times 10^{-11}$	ref. [41]
T2HK+ESSnuSB	$1.01 \times 10^{-10}(4.36 \times 10^{-11})$	ref. [41]

Dey & Dutta, JHEP09, 035 (2024) [arXiv: 2402.13235 [hep-ph]]

But accelerator would not provide the best bound

typical sensitivities to the lifetime to mass ratio for neutrino from different sources



Ivanez-Ballestero & Volpe, PLB847, 138252 (2023) [arXiv: 2307.03549 [hep-ph]]

Larger the L/E, in general, provides better sensitivity

However, solar/supernova neutrinos can not provide good sensitivity to the decay of ν_3

Some remarks for neutrino decay in LBL experiments

Hyper-K and DUNE, with much larger statistics, would improve the current bounds for some decay modes

Test of Unitarity in LBL experiments

Unitarity Test

For 3 flavor of mixed neutrinos

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

mixing matrix U is unitary if

$$UU^\dagger = U^\dagger U = 1$$

9 indep. eqs.

$$|U_{\alpha1}|^2 + |U_{\alpha2}|^2 + |U_{\alpha3}|^2 = 1 \quad (\alpha = e, \mu, \tau)$$

or

$$|U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2 = 1 \quad (i = 1, 2, 3)$$

normalization

(3 eqs.)

$$U_{\alpha1}U^*_{\beta1} + U_{\alpha2}U^*_{\beta2} + U_{\alpha3}U^*_{\beta3} = 0 \quad (\alpha, \beta = e, \mu, \tau, \alpha \neq \beta)$$

or

$$U_{ei}U^*_{ej} + U_{\mu i}U^*_{\mu j} + U_{\tau i}U^*_{\tau j} = 0 \quad (i, j = 1, 2, 3, i \neq j)$$

closure
of unitarity
triangle
(6**R** eqs.)

Unitarity Test

Where the Non-Unitarity (NU) effect can manifest?

See e.g. Antusch et al, JHEP10, 084 (2006)

- **Decay Processes**
  - W decay
  - Invisible Z decay
  - Universality test
  - Rare charged lepton decay
- **Neutrino Oscillation**
  - Disappearance mode
  - Appearance mode

In this talk we focus on
NU effect for oscillation

Non-Unitarity implies the presence of extra neutrino state(s)

Let us consider n extra sterile sates

$$U_{(3+n)\times(3+n)} = \begin{bmatrix} U_{3\times3} & W \\ Z & V \end{bmatrix}$$

$$U^{\dagger}_{(3+n)\times(3+n)} U_{(3+n)\times(3+n)} = U_{(3+n)\times(3+n)} U^{\dagger}_{(3+n)\times(3+n)} = 1$$

then we expect that $U^{\dagger}_{3\times3} U_{3\times3} \neq 1,\ U_{3\times3} U^{\dagger}_{3\times3} \neq 1$

Non-unitarity can be parametrized as follows

Miranda et al, PRL117, 061804 (2016)

$$U = \begin{bmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{bmatrix} U_0$$

α_{ii} : real

α_{ij} $(i \neq j)$: complex

$\alpha_{ii} \sim 1, \ |\alpha_{ij}|(i \neq j) \ll 1$

non-unitary if the triangular α matrix is not 𝟙

standard 3x3 unitary matrix

$\alpha_{ij} \neq \delta_{ij}$ implies unitarity violation

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = \alpha_{11}^2$$
$$|U_{\mu 1}|^2 + |U_{\mu 2}|^2 + |U_{\mu 3}|^2 = \alpha_{22}^2 + |\alpha_{21}|^2$$
$$|U_{\tau 1}|^2 + |U_{\tau 2}|^2 + |U_{\tau 3}|^2 = \alpha_{33}^2 + |\alpha_{32}|^2 + |\alpha_{31}|^2$$

normalization (if =1 or not?)

$$U_{e1}^* U_{\mu 1} + U_{e2}^* U_{\mu 2} + U_{e3}^* U_{\mu 3} = \alpha_{11}\alpha_{21}$$
$$U_{e1}^* U_{\tau 1} + U_{e2}^* U_{\tau 2} + U_{e3}^* U_{\tau 3} = \alpha_{11}\alpha_{32}$$
$$U_{\mu 1}^* U_{\tau 1} + U_{\mu 2}^* U_{\tau 2} + U_{\mu 3}^* U_{\tau 3} = \alpha_{21}^*\alpha_{31} + \alpha_{22}^*\alpha_{32}$$

closure (of the unitarity triangle)

(if = 0 or not?)

Cauchy-Schwartz Inequalities

If U = U_{3x3} is a part of complete unitary matrix $U_{(3+n)x(3+n)}$ elements of U must satisfy the following conditions

closure relations

$$\left|\sum_{i=1}^{3} U_{\alpha i}U_{\beta i}^{*}\right|^{2} \leq \left(1-\sum_{i=1}^{3}|U_{\alpha i}|^{2}\right)\left(1-\sum_{i=1}^{3}|U_{\beta i}|^{2}\right)$$

This condition is important to constrain the closure relations or off diagonal elements $\alpha_{ij}\,(i \neq j)$

Remark: some works do not (intentionally) take into account this condition

Neutrino Evolution Equation in Matter with Non-Unitarity effect

$$i\frac{d}{dx}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = H\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

$$H = \begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m_{21}^2}{2E} & 0\\ 0 & 0 & \frac{\Delta m_{31}^2}{2E}\end{bmatrix} + \sqrt{2}G_F U^\dagger \begin{bmatrix}N_e - N_n/2 & 0 & 0\\ 0 & -N_n/2 & 0\\ 0 & 0 & -N_n/2\end{bmatrix} U$$

G_F : Fermi Constant

$N_e(N_n)$: Electron (neutron) number density

Neutrino Evolution Equation in Matter with Non-Unitarity effect

$$i\frac{d}{dx}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} = H\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Off diagonal elements, $\alpha_{ij}\,(i \neq j)$, can induce additional mixing(-like) effects

Im[α_{ij}] is a new source of CP violation

$$H = \begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E} & 0\\ 0 & 0 & \frac{\Delta m^2_{31}}{2E}\end{bmatrix} + \sqrt{2}G_F U^\dagger \begin{bmatrix}N_e - N_n/2 & 0 & 0\\ 0 & -N_n/2 & 0\\ 0 & 0 & -N_n/2\end{bmatrix} U$$

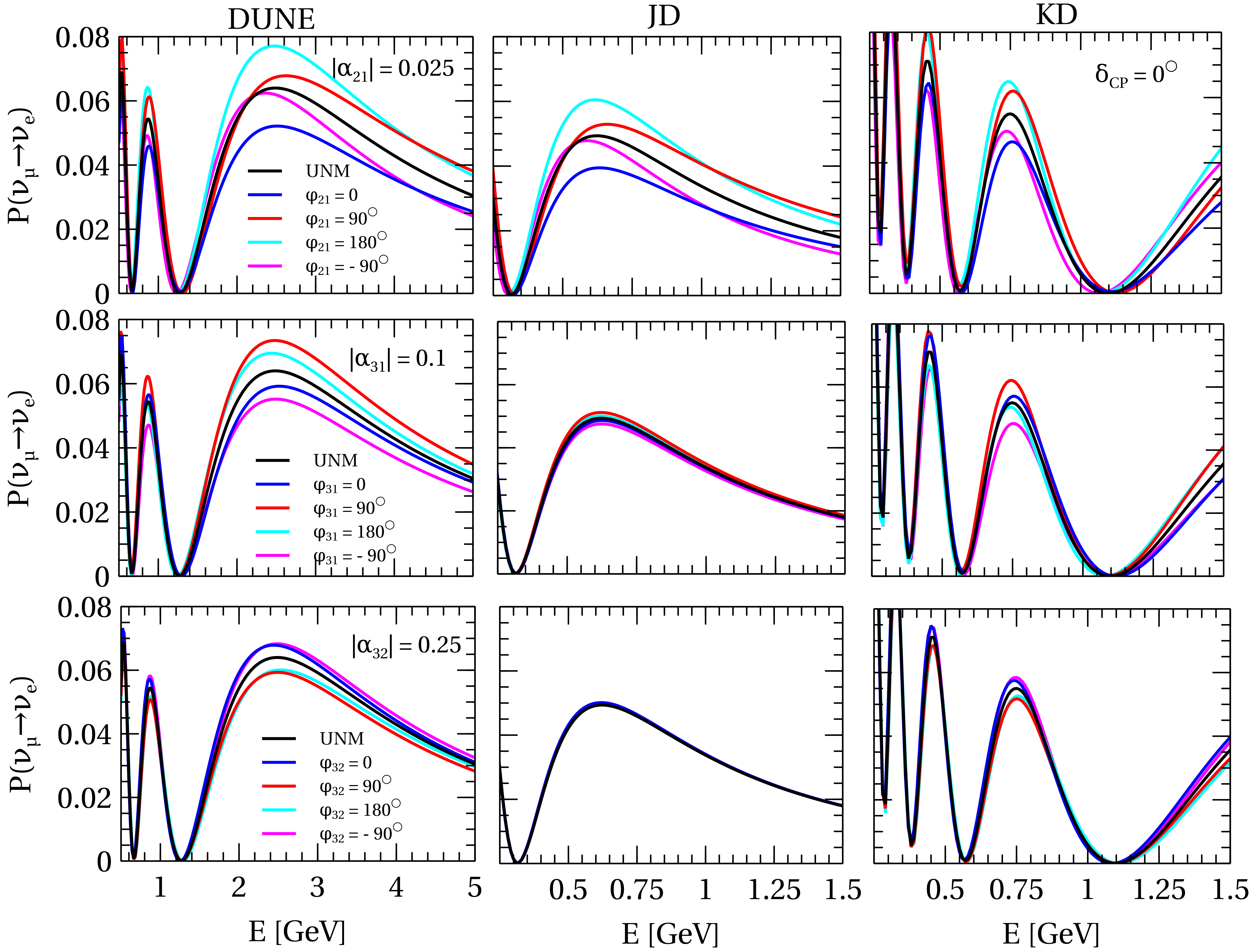
Diagonal elements, α_{ii} , if different from 1, can modify the resonance condition

G_F : Fermi Constant

$N_e(N_n)$: Electron (neutron) number density

Some example of oscillation probabilities with Non-Unitarity effects for LBL experiments

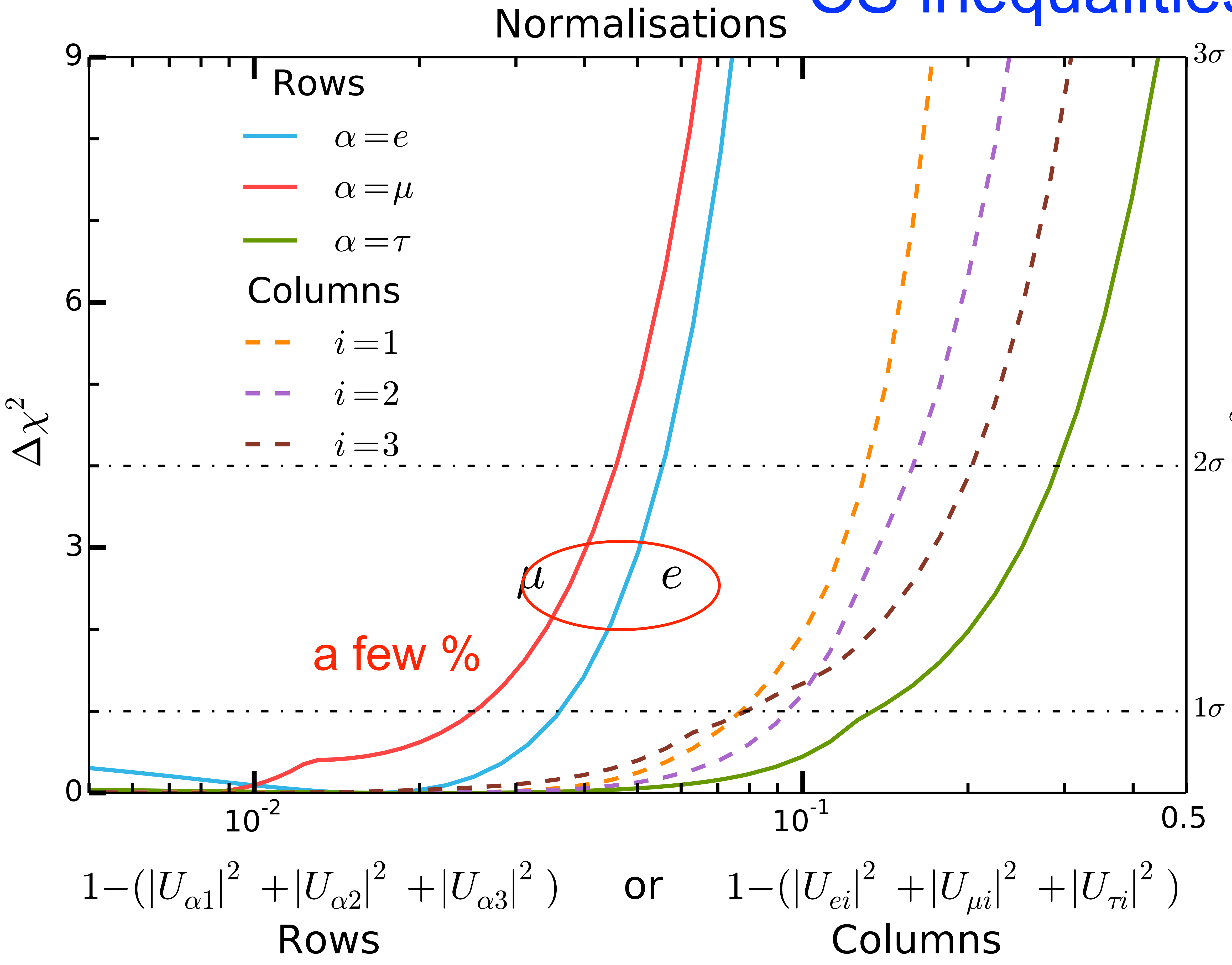
L = 1300 km L = 295 km L = 1100 km



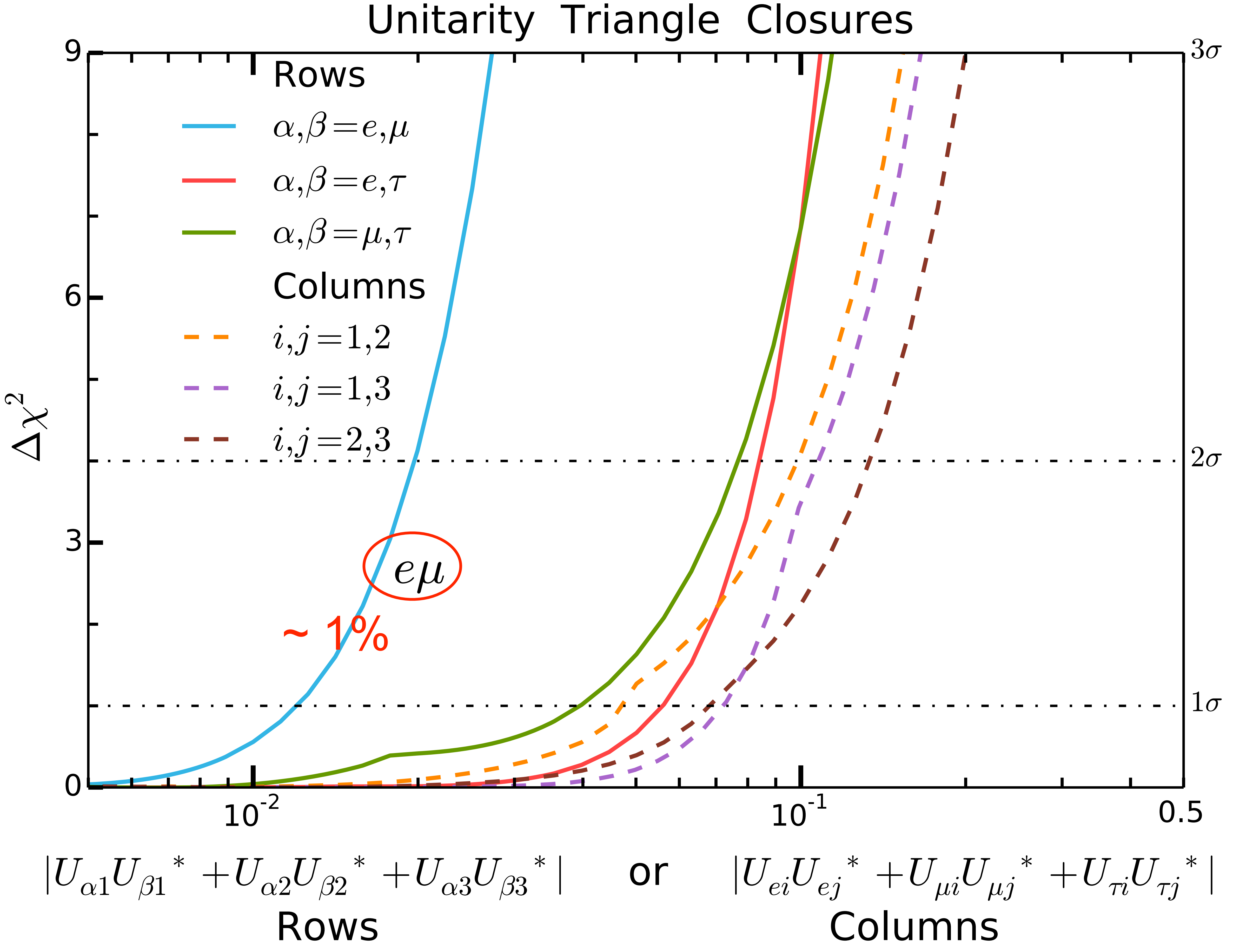
Agarwalla et al, JHEP07, 121(2022) [arXiv:2111.00329 [hep-ex]]

Current (around ~2016) limits on Non-Unitarity

CS inequalities considered



a few %



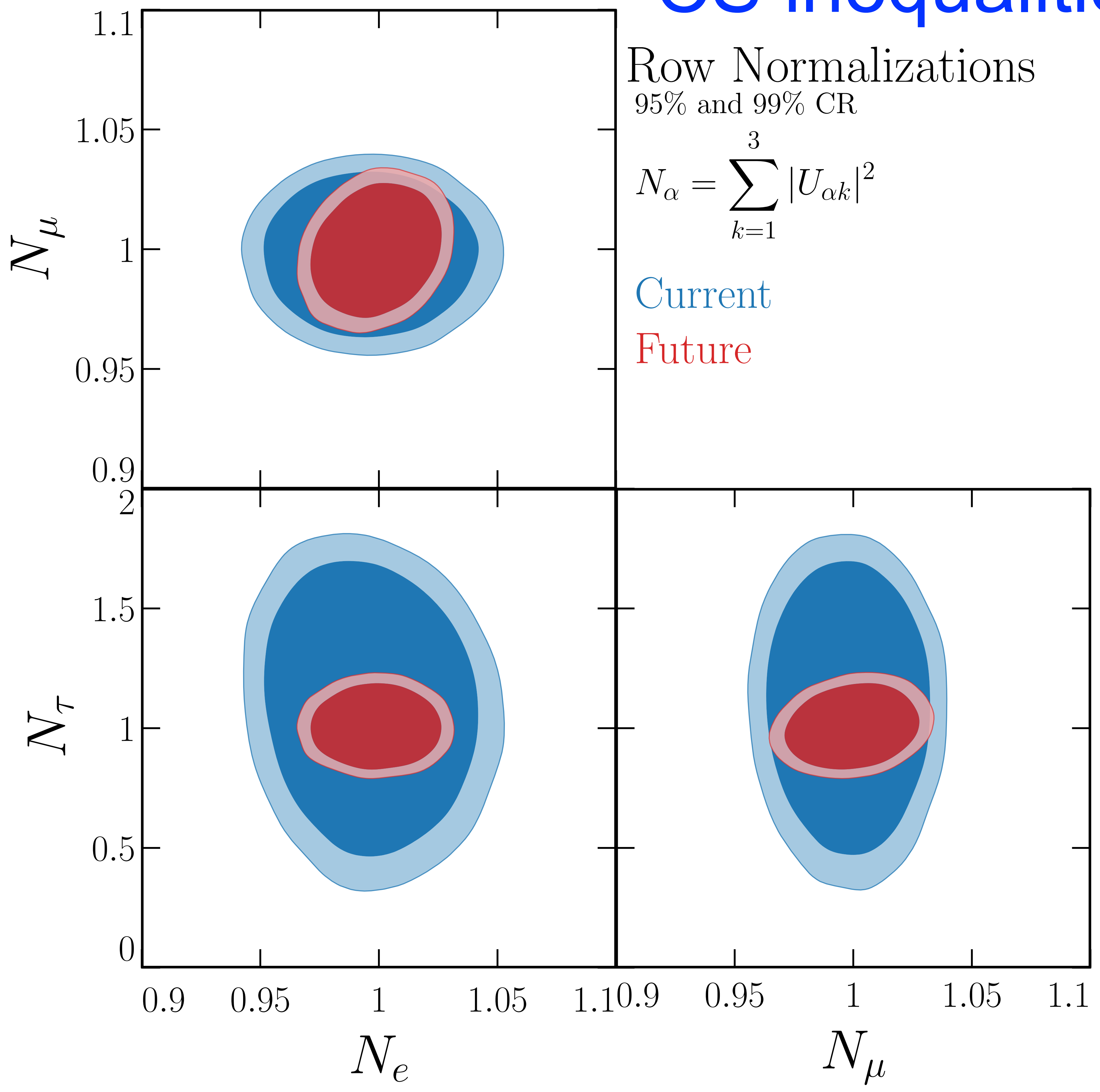
~ 1%

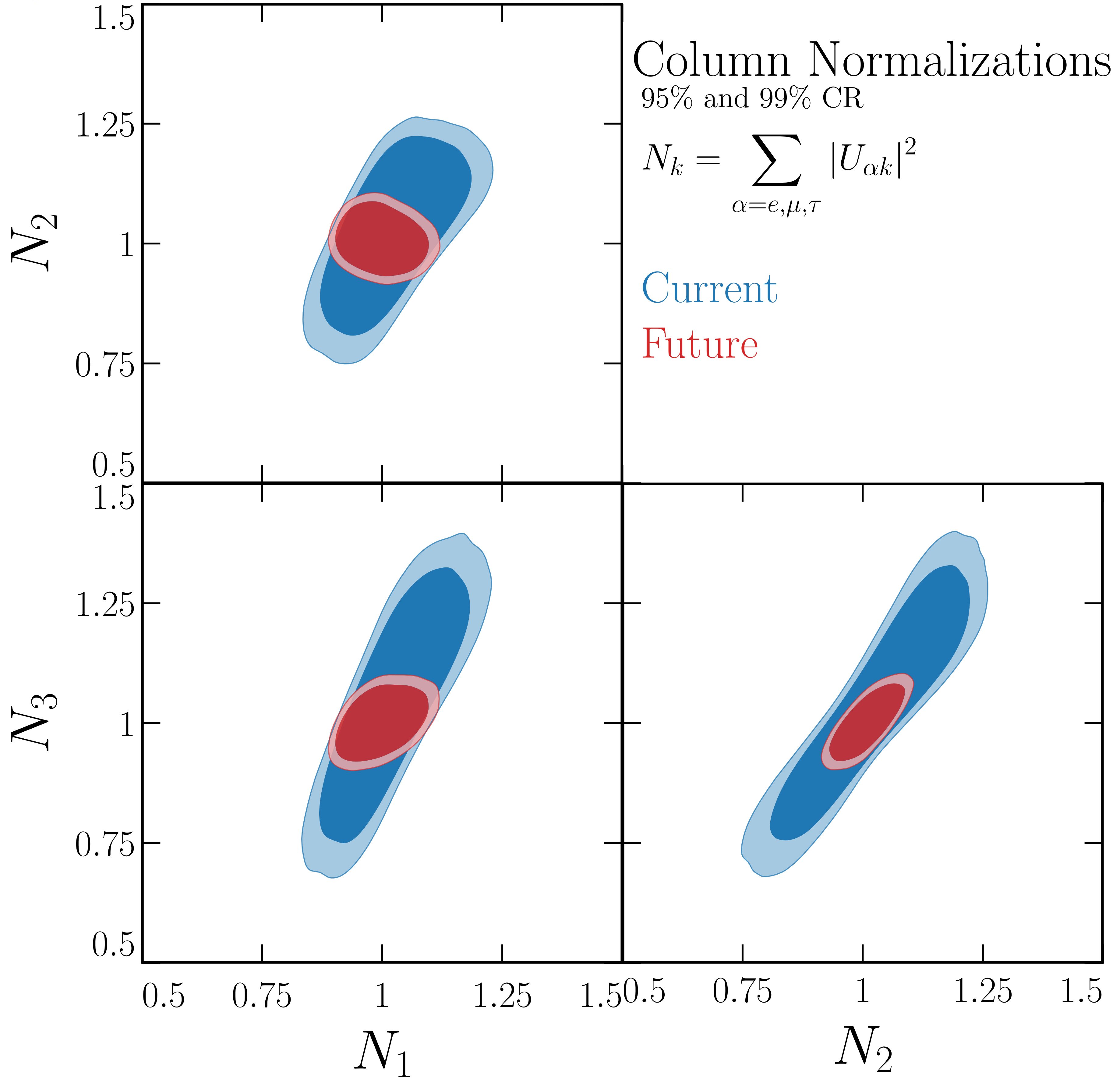
normalization bounds are limited by flux uncertainty

Parke and Ross-Lonergan, PRD93, 113009 (2016)

Current and Future bounds on Non-Unitarity for Normalizations

CS inequalities not considered





$N_\alpha \equiv |U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 + |U_{\alpha 3}|^2 (\alpha = e, \mu, \tau)$

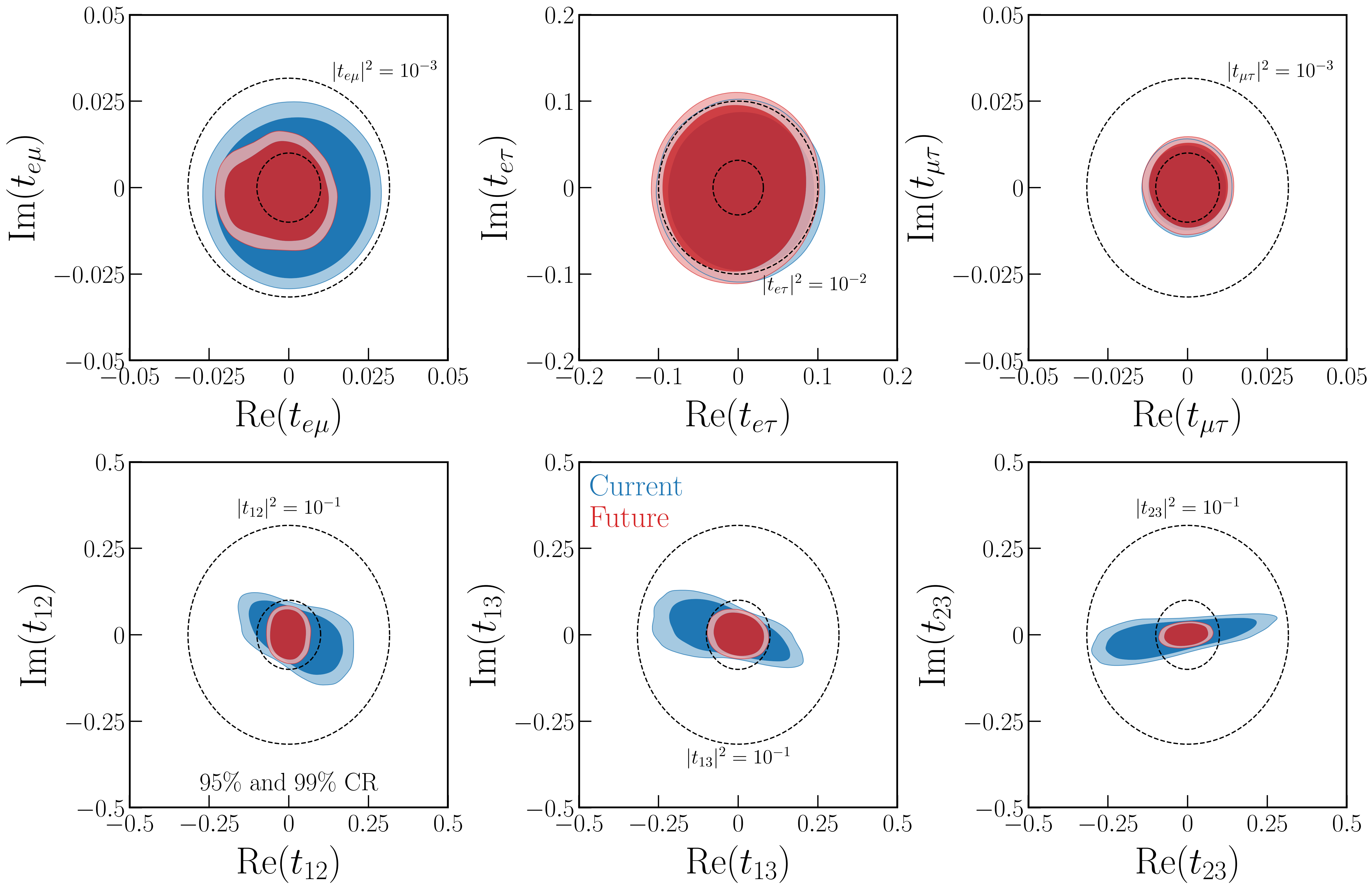
$N_k \equiv |U_{ek}|^2 + |U_{\mu k}|^2 + |U_{\tau k}|^2 (k = 1,2,3)$

Future case includes JUNO, HK, DUNE and IceCube (upgrade)

Ellis et al., JHEP12.068 (2020) [arXiv:2008.01088 [hep-ph]]

Current and Future bounds on Non-Unitarity for Closures

CS inequalities not considered



$$t_{\alpha\beta} \equiv U^*_{\alpha 1} U_{\beta 1} + U^*_{\alpha 2} U_{\beta 2} + U^*_{\alpha 3} U_{\beta 3} \; (\alpha, \beta = e, \mu, \tau, \alpha \neq \beta)$$

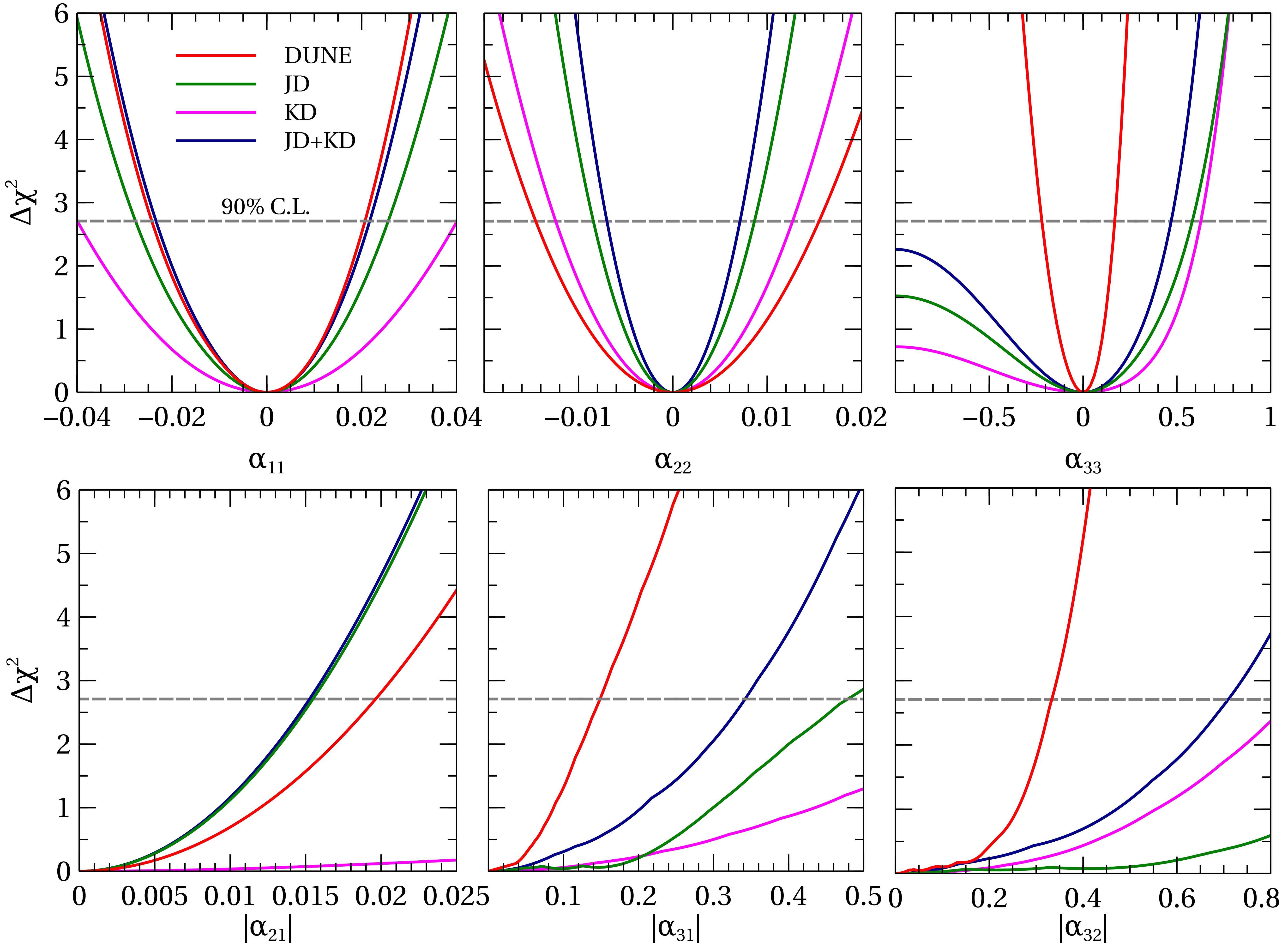
$$t_{ij} \equiv U^*_{ei} U_{ej} + U^*_{\mu i} U_{\mu j} + U^*_{\tau i} U_{\tau j} \; (i, j = 1,2,3, i \neq j)$$

Future case includes JUNO, HK, DUNE and IceCube (upgrade)

Ellis et al., JHEP12.068 (2020) [arXiv:2008.01088 [hep-ph]]

Future bounds on Non-Unitarity by DUNE, T2HK, T2HKK

CS inequalities not considered



JD = T2HK (295 km)

KD = HK detector in Korea only (1100km)

Agarwalla et al, JHEP07, 121(2022) [arXiv:2111.00329 [hep-ex]]

Some remarks for Unitarity test in LBL experiments

Hyper-K and DUNE (JUNO), with much larger statistics, would improve the current bounds

But, in my opinion, to improve more bounds on Non-Unitarity, the most important/crucial systematics are uncertainties on flux and the detection cross sections as they affect directly the normalization relations (and also closure relations through CS inequalities), therefore, they must be improved!

See C.S. Fong, HN, Minakata, JHEP02, 114(2017) [arXiv:1609.08623 [hep-ph]]

Summary

- **1. In last ~25 years, neutrino oscillation is very well established and we are now in the era of precision neutrino physics where long-baseline (LBL) oscillation experiments are playing important roles**
- **2. But there are still several fundamental open questions which can be studied by the future LBL experiments**
- **3. Near future LBL experiments like Hyper-K and DUNE can address the questions related to CP phase, θ_{23} and Δm^2_{32} (related to MO)**
- **4. LBL experiments will be study further new physics effects coming from NSI, sterile neutrino, decay, decoherence, etc**
- **5. We are looking forward to have very interesting and important progress in the coming decade!**

Concluding Remarks

- During ~15 years of 1998 - 2012

  - discovery phase in neutrino physics-

- ~2013 - present: Steady progress (precision era) but no big new discovery (not yet) related to neutrino

- 2025 - future: Operation of new generation experiments, JUNO, Hyper-K, DUNE, etc,

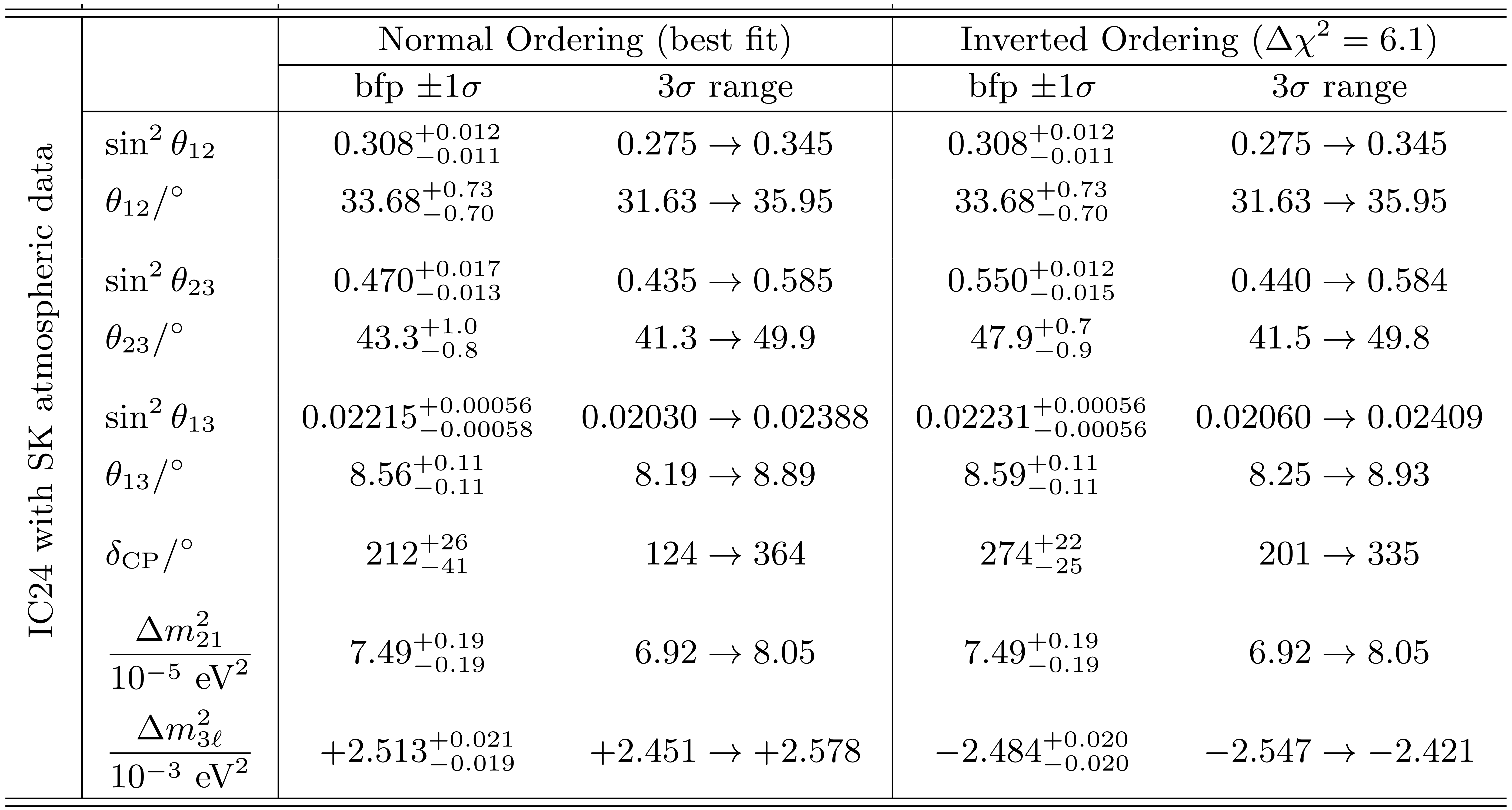
  New Discovery, some surprise?

Thank you very much for your attention!

¡Muchas gracias por su atención!

Backup Slides

Current allowed range of mixing parameters from Global Fit



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
	$\delta_{\rm CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

NuFit6.0, Esteban et la, arXiv: 2410.05380

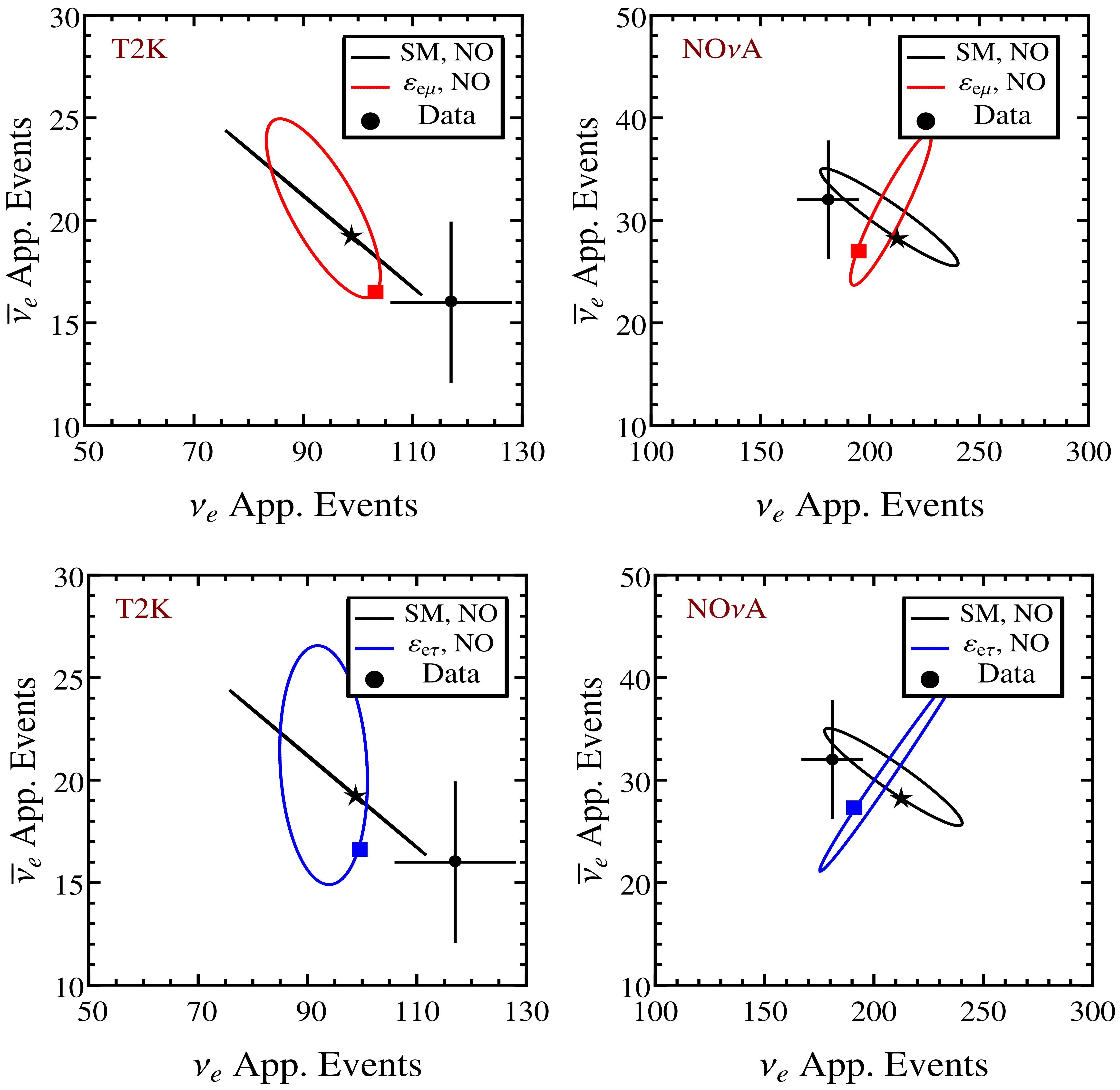
Roughly, 1σ uncertainties of $\sin^2\theta_{ij}\ (ij = 12, 23, 23)$ is ~3 - 4 %

Δm^2_{21} is ~3 % $|\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$ is ~1% $\delta_{\rm CP}$ is ~30-40^{o}

Neutrino Physics is in a Precision Era !

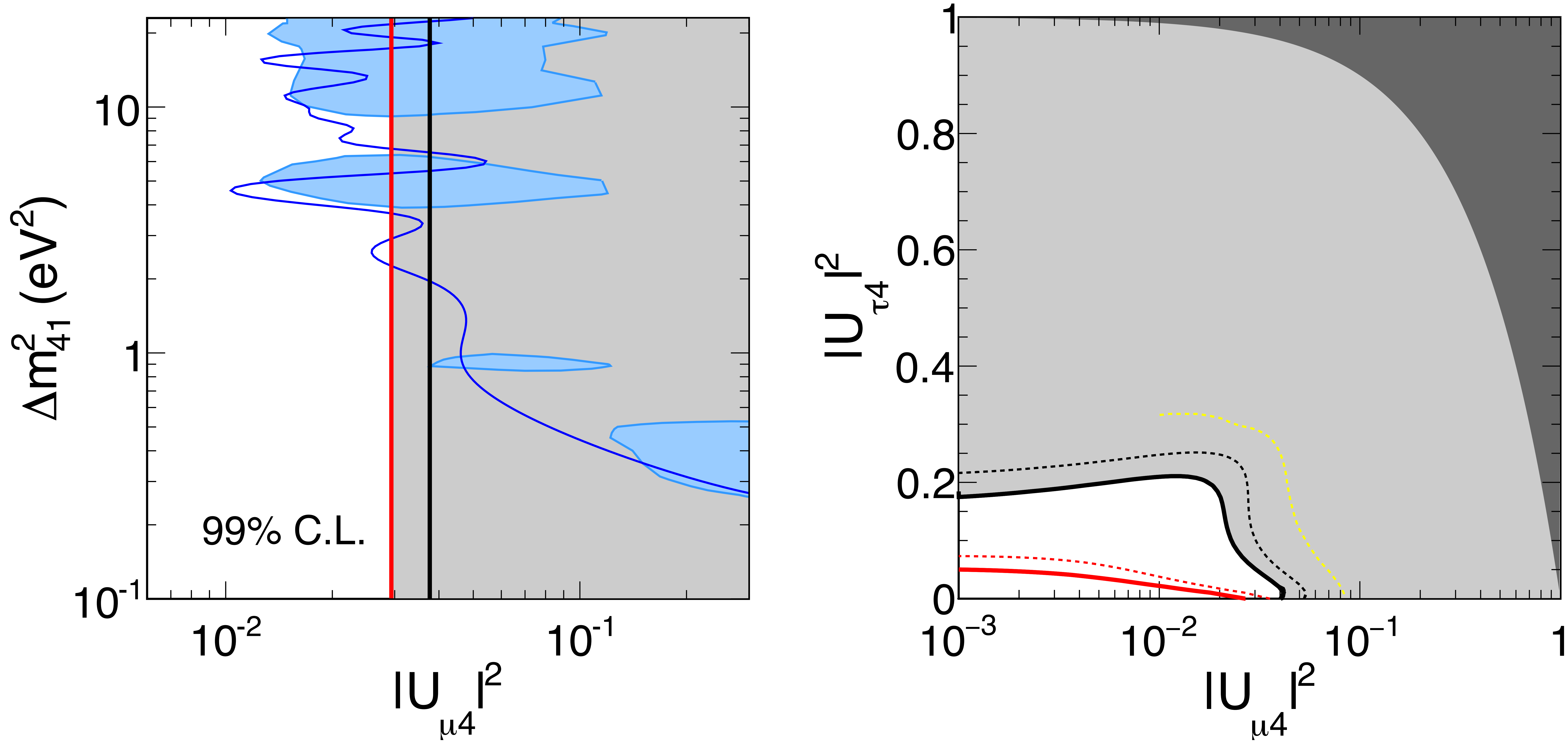
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{\mathrm{i}\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-\mathrm{i}\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\mathrm{e}^{\mathrm{i}\delta} & c_{23}c_{13} \end{bmatrix}$$



S. S. Chatterjee and A. Palazzo, arXiv:2409.10599 [hep-ph]

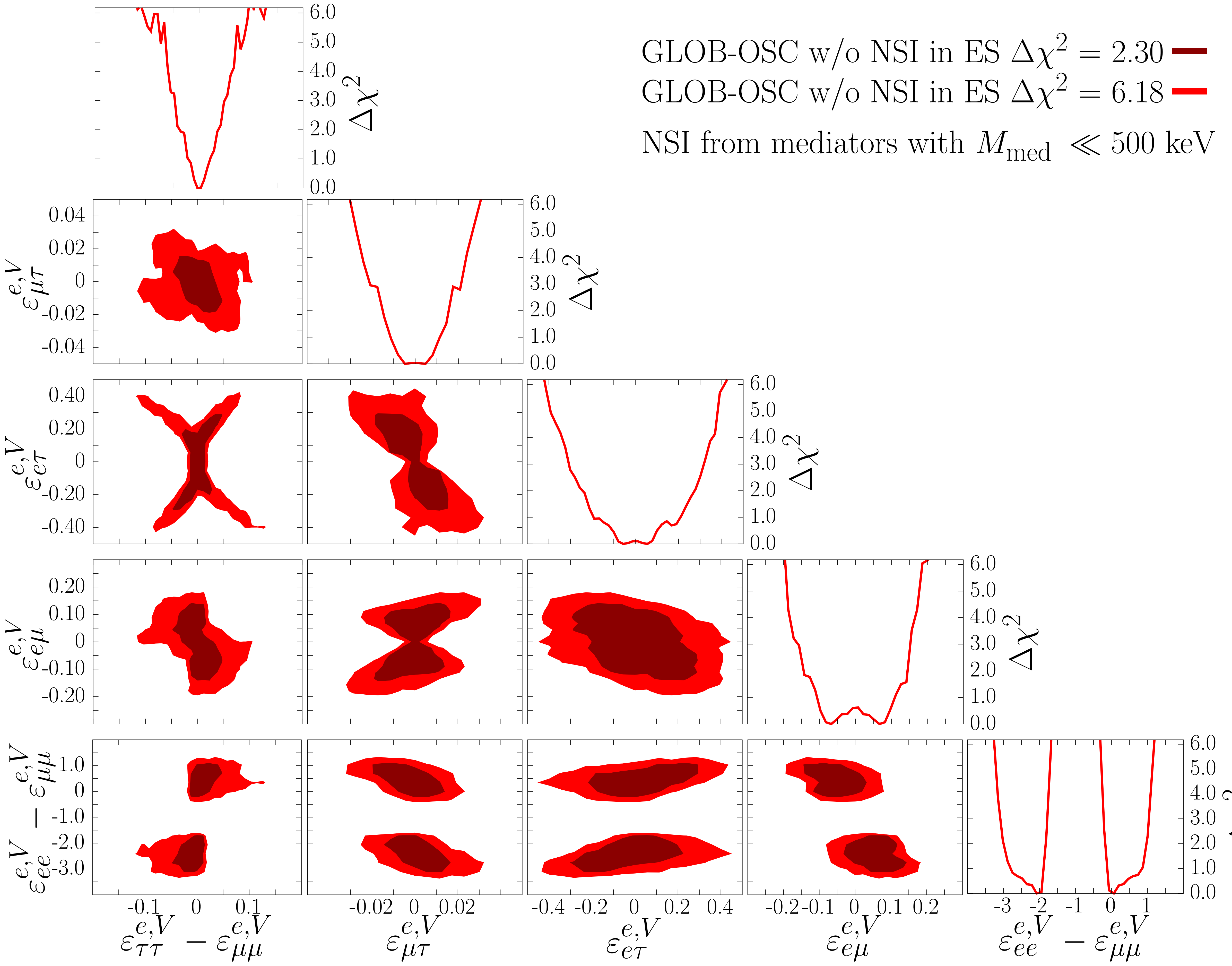
Test of Sterile Neutrino by Hyper-K

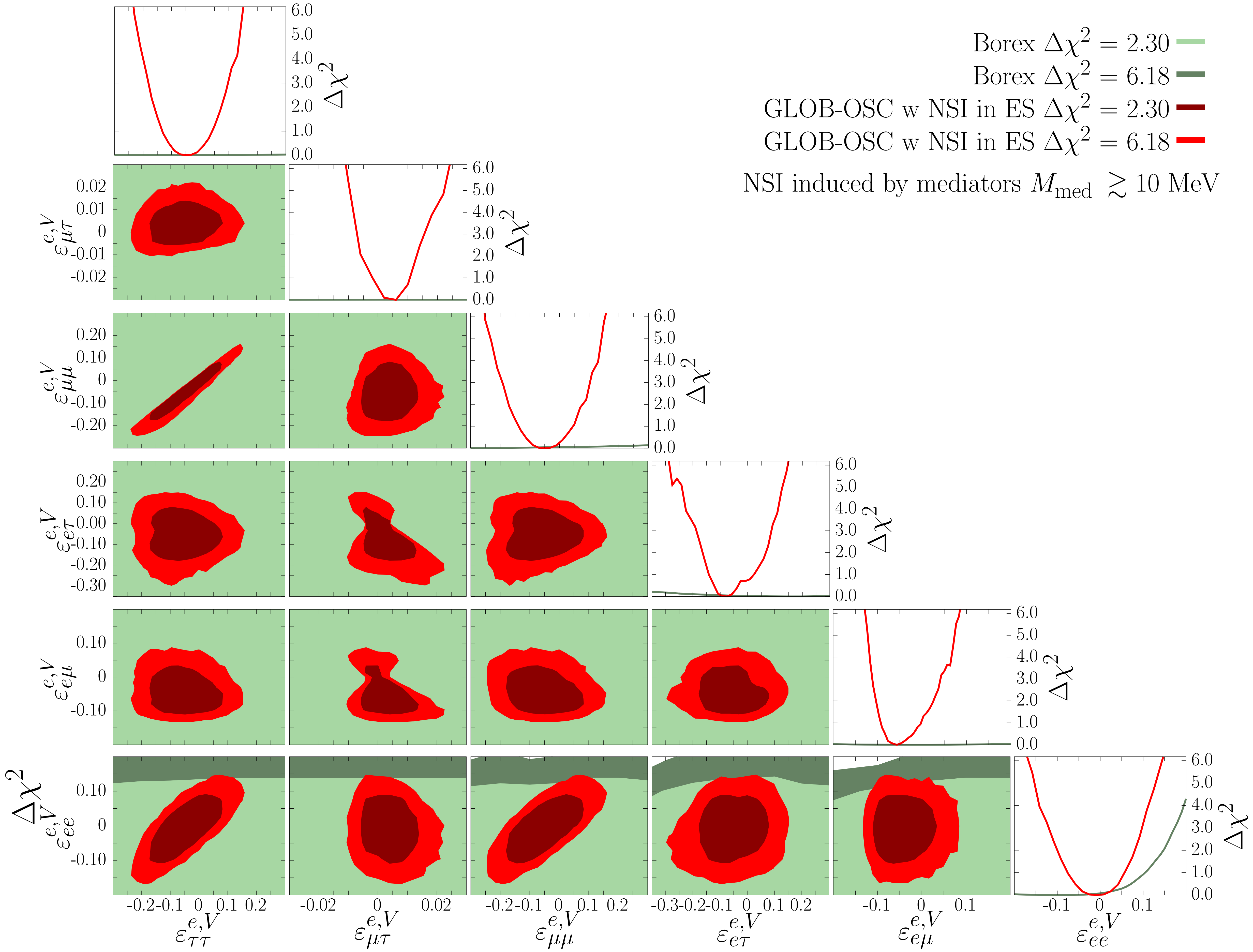


Abe et al (HK Collab.), Design Report [arXiv:1805.04163v2 [hep-ex]]

FIG

Current Bounds on NSI with electrons (by Global Analysis)





Coloma et al, JHEP08, 032 (2023) [arXiv:2305.07698 [hep-ph]]

Current Bounds on NSI with electrons (by Global Analysis)

	Allowed ranges at 90% CL (marginalized)			
	Vector $(X = V)$		Axial-vector $(X = A)$	
	Borexino	GLOB-OSC w NSI in ES	Borexino	GLOB-OSC w NSI in ES
$\varepsilon_{ee}^{e,X}$	$[-1.1, +0.17]$	$[-0.13, +0.10]$	$[-0.38, +0.24]$	$[-0.13, +0.11]$
$\varepsilon_{\mu\mu}^{e,X}$	$[-2.4, +1.5]$	$[-0.20, +0.10]$	$[-1.5, +2.4]$	$[-0.70, +1.2]$
$\varepsilon_{\tau\tau}^{e,X}$	$[-2.8, +2.1]$	$[-0.17, +0.093]$	$[-1.8, +2.8]$	$[-0.53, +1.0]$
$\varepsilon_{e\mu}^{e,X}$	$[-0.83, +0.84]$	$[-0.097, +0.011]$	$[-0.79, +0.76]$	$[-0.41, +0.40]$
$\varepsilon_{e\tau}^{e,X}$	$[-0.90, +0.85]$	$[-0.18, +0.080]$	$[-0.81, +0.78]$	$[-0.36, +0.36]$
$\varepsilon_{\mu\tau}^{e,X}$	$[-2.1, +2.1]$	$[-0.0063, +0.016]$	$[-1.9, +1.9]$	$[-0.79, +0.81]$

Coloma et al, JHEP08, 032 (2023) [arXiv:2305.07698 [hep-ph]]

Current Bounds on NSI with quarks (by Global Analysis)

	Allowed ranges at 90% CL (marginalized)	
	GLOB-OSC	
	LMA	LMA $\oplus$ LMA-D
$\varepsilon^{u,V}_{ee} - \varepsilon^{u,V}_{\mu\mu}$	$[-0.063, +0.36]$	$[-1.1, -0.79] \oplus [-0.063, +0.36]$
$\varepsilon^{u,V}_{\tau\tau} - \varepsilon^{u,V}_{\mu\mu}$	$[-0.0053, +0.017]$	$[-0.021, +0.018]$
$\varepsilon^{u,V}_{e\mu}$	$[-0.057, +0.013]$	$[-0.057, +0.061]$
$\varepsilon^{u,V}_{e\tau}$	$[-0.076, +0.11]$	$[-0.12, +0.11]$
$\varepsilon^{u,V}_{\mu\tau}$	$[-0.0077, +0.0042]$	$[-0.0077, +0.0083]$
$\varepsilon^{d,V}_{ee} - \varepsilon^{d,V}_{\mu\mu}$	$[-0.069, +0.38]$	$[-1.3, -0.91] \oplus [-0.072, +0.38]$
$\varepsilon^{d,V}_{\tau\tau} - \varepsilon^{d,V}_{\mu\mu}$	$[-0.0058, +0.018]$	$[-0.029, +0.019]$
$\varepsilon^{d,V}_{e\mu}$	$[-0.058, +0.014]$	$[-0.058, +0.098]$
$\varepsilon^{d,V}_{e\tau}$	$[-0.079, +0.11]$	$[-0.16, +0.11]$
$\varepsilon^{d,V}_{\mu\tau}$	$[-0.0087, +0.0051]$	$[-0.0087, +0.015]$

	Allowed ranges at 90% CL (marginalized)
	GLOB-OSC+CEνNS
	LMA $=$ LMA $\oplus$ LMA-D
$\varepsilon^{u,V}_{ee}$	$[-0.038, +0.034] \oplus [+0.34, +0.42]$
$\varepsilon^{u,V}_{\mu\mu}$	$[-0.046, +0.031] \oplus [+0.35, +0.42]$
$\varepsilon^{u,V}_{\tau\tau}$	$[-0.046, +0.033] \oplus [+0.35, +0.42]$
$\varepsilon^{u,V}_{e\mu}$	$[-0.044, +0.0049]$
$\varepsilon^{d,V}_{e\tau}$	$[-0.079, +0.11]$
$\varepsilon^{u,V}_{\mu\tau}$	$[-0.0064, 0.0053]$
$\varepsilon^{d,V}_{ee}$	$[-0.036, +0.031] \oplus [+0.30, +0.39]$
$\varepsilon^{d,V}_{\mu\mu}$	$[-0.040, +0.038] \oplus [+0.31, +0.39]$
$\varepsilon^{d,V}_{\tau\tau}$	$[-0.041, +0.043] \oplus [+0.31, +0.39]$
$\varepsilon^{d,V}_{e\mu}$	$[-0.054, +0.0045]$
$\varepsilon^{d,V}_{e\tau}$	$[-0.051, +0.11]$
$\varepsilon^{d,V}_{\mu\tau}$	$[-0.0075, +0.0046]$

Coloma et al, JHEP08, 032 (2023) [arXiv:2305.07698 [hep-ph]]

How to parametrize the Non-Unitary mixing matrix?

How many free parameters (for oscillation) we have for U if Unitarity is not assumed?

18 - 3 - 2 = 13 free parameters

3 phase can be removed by redefinition of charged lepton fields

2 Majorana phases

by relaxing normalisation (3) and closure (6) conditions

or 4 + 9 = 13 free parameters

Non-Unitarity U can be parametrised, e.g., as,

$$U = \begin{bmatrix} |U_{e1}| & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}|e^{i\phi_{e3}} \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}|e^{i\phi_{\tau2}} & |U_{\tau3}|e^{i\phi_{\tau3}} \end{bmatrix}$$

Phenomenological “equivalence” between NSI and Non-unitarity

production and detection NSI can be mapped NU effect as

$$\varepsilon^{s*}_{\beta\alpha} = \varepsilon^{d}_{\alpha\beta} = \alpha_{ij}\ (\alpha, \beta = e, \mu, \tau \rightarrow i, j = 1{,}2{,}3)$$

propagation NSI can be mapped NU effect as

$$\varepsilon_{ee} = -(1-\alpha_{11}), \quad \varepsilon_{\mu\mu} = -(1-\alpha_{22}), \quad \varepsilon_{\tau\tau} = -(1-\alpha_{33}),$$

$$\varepsilon_{e\mu} = \alpha^{*}_{21}/2, \quad \varepsilon_{e\tau} = \alpha^{*}_{31}/2, \quad \varepsilon_{\mu\tau} = \alpha^{*}_{32}/2$$

Blennow et al, JHEP04, 153(2017) [arXiv:1609.08637 [hep-ph]]