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# Present status and future prospects of neutrino oscillation experiments

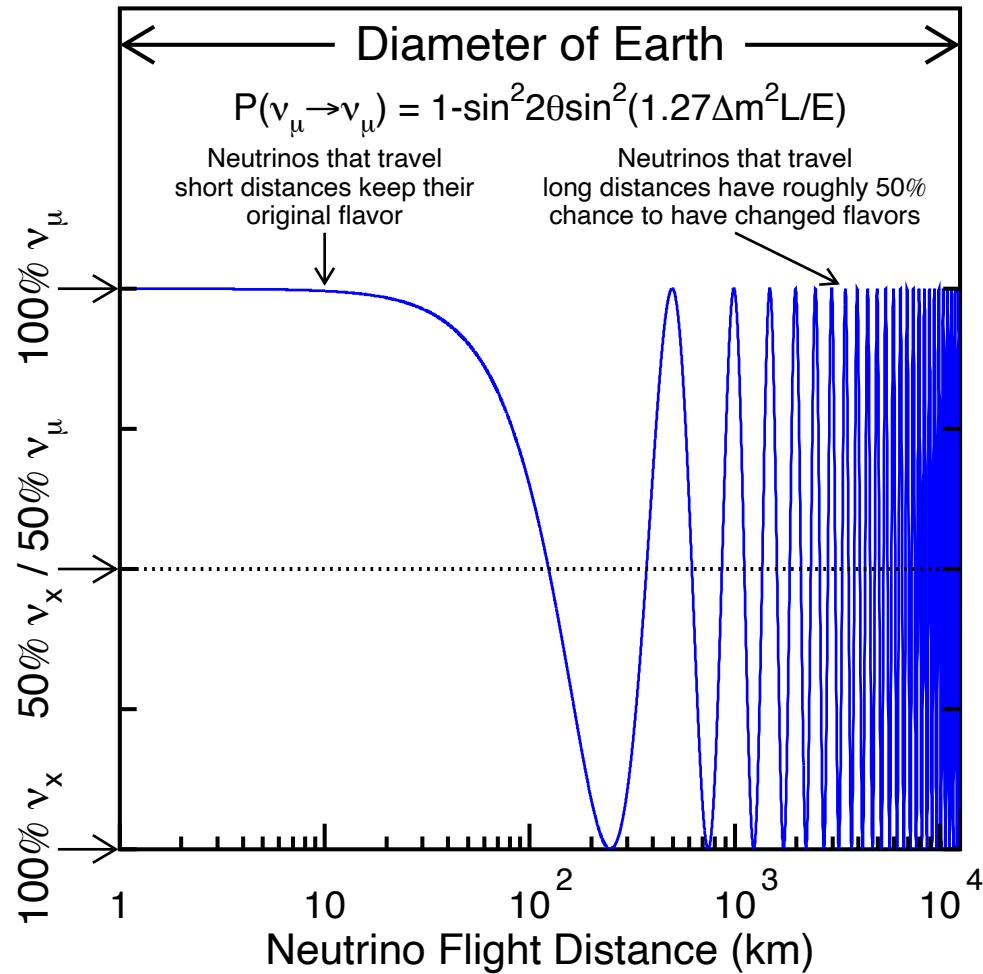
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MTTD 2023  
University of Silesia, Katowice, Poland  
Ustron, 17-22 September 2023

# Neutrino Oscillation



- Oscillation from one flavour to another
- Because flavour states and mass states are not same

$$|\nu_\alpha\rangle = U_{\alpha i} |\nu_i\rangle$$

U is the PMNS matrix

- The transition probability is given by

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

This talk: Present and future of 3 and 3+1 scenarios

# Oscillation in 3 flavour

In the standard three flavour framework

3 mixing angles and 1 phase:  $U^{3\nu} = R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_{CP}) R_{12}(\theta_{12})$

2 mass squared difference:  $\Delta m_{21}^2 = m_2^2 - m_1^2$ ,  $\Delta m_{31}^2 = m_3^2 - m_1^2$

Two intrinsic parameters: baseline L and energy E

Measurements of these parameters

Solar experiments:  $\theta_{12}$ ,  $\Delta m_{21}^2$

Atmospheric experiments:  $\theta_{23}$ ,  $\Delta m_{31}^2$

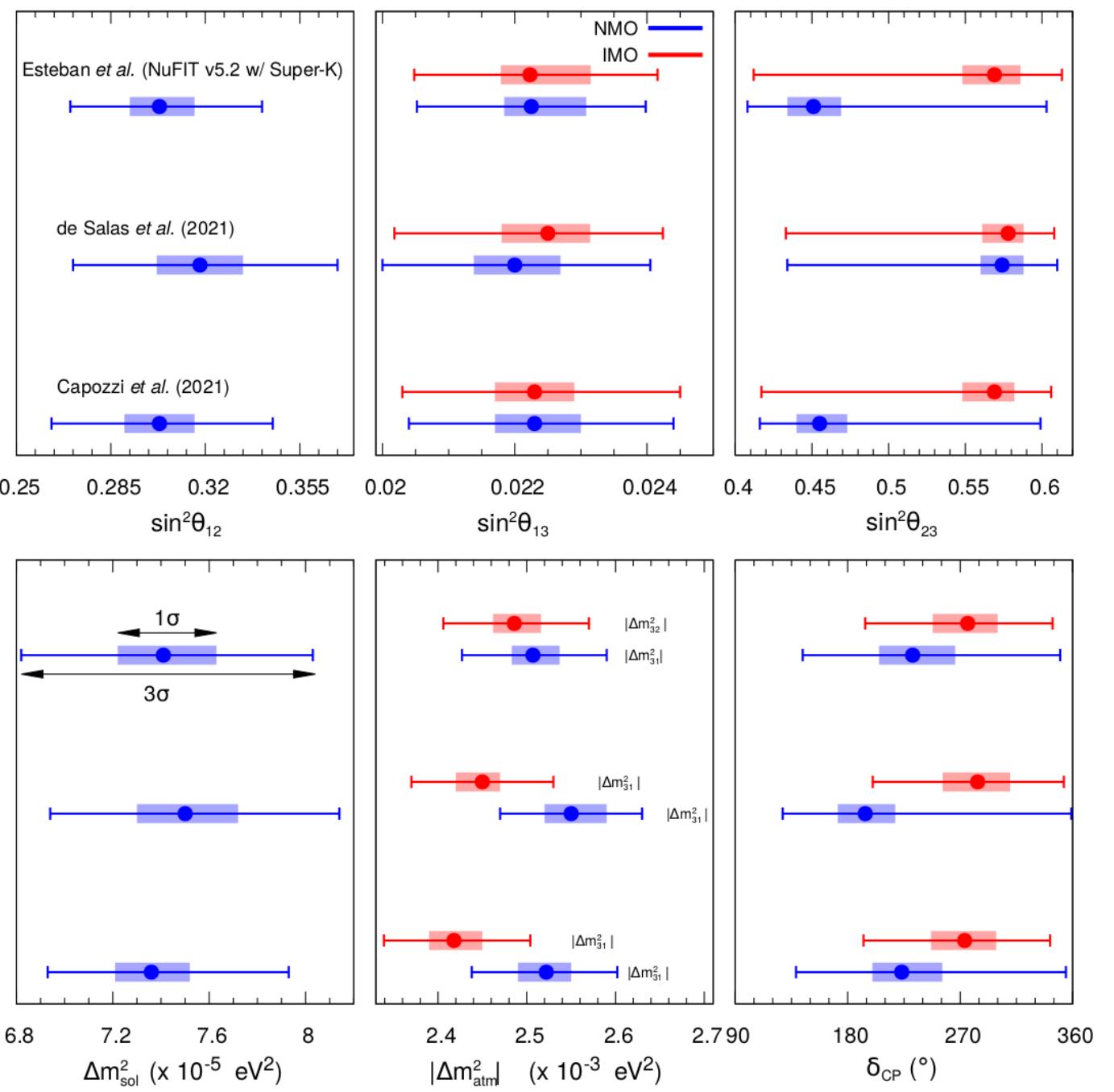
Reactor experiments:  $\theta_{13}$

Accelerator experiments:  $\delta_{CP}$ , sign of  $\Delta m_{31}^2$ , Octant of  $\theta_{23}$  ([this talk](#))

# Current Status

Global fit results from 3 independent groups

Top: Nufit  
Middle: Valencia  
Bottom: Bari



# Current Unknowns

Sign of  $\Delta m_{31}^2$  i.e.,

(i) Normal Ordering (NO) with  $\Delta m_{31}^2 > 0$

Or

(ii) Inverted ordering (IO) with  $\Delta m_{31}^2 < 0$

Octant of  $\theta_{23}$  i.e.,

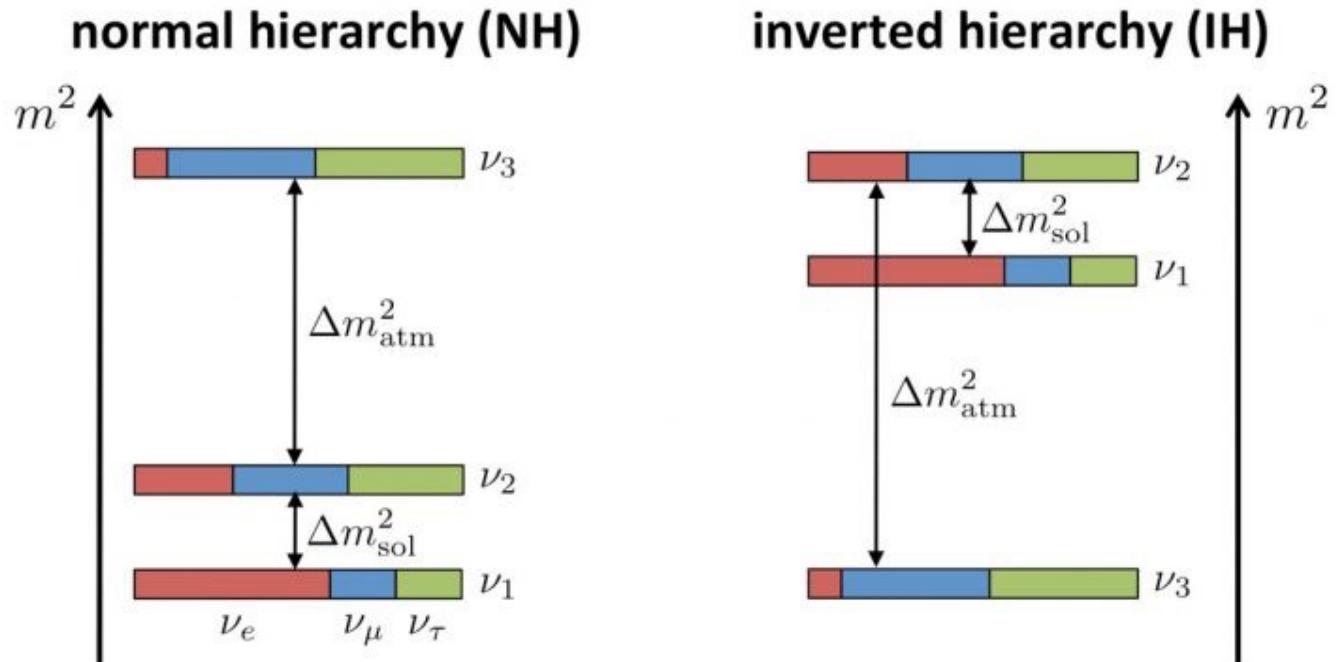
(i) Higher Octant (HO) with  $\theta_{23} > 45^\circ$

Or

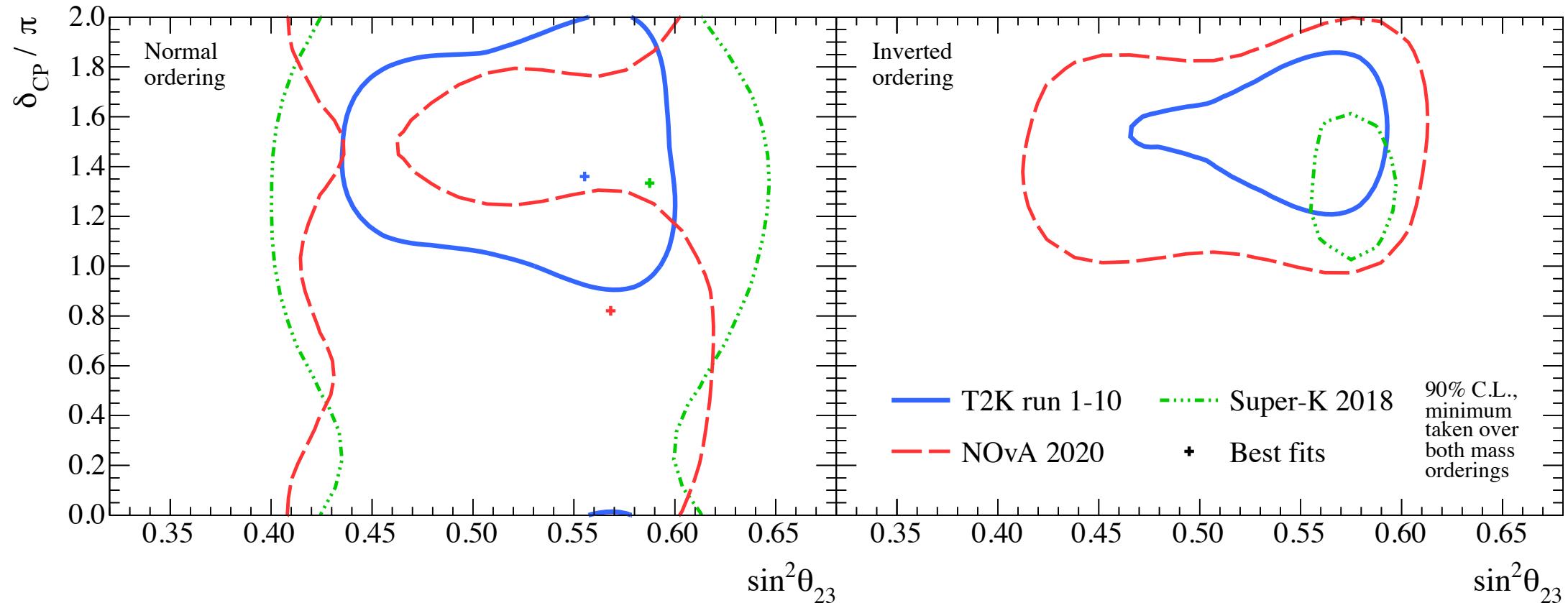
(ii) Lower Octant (LO) with  $\theta_{23} < 45^\circ$

Measurement of  $\delta_{CP}$

And also the precision of  $\Delta m_{31}^2$  and  $\theta_{23}$



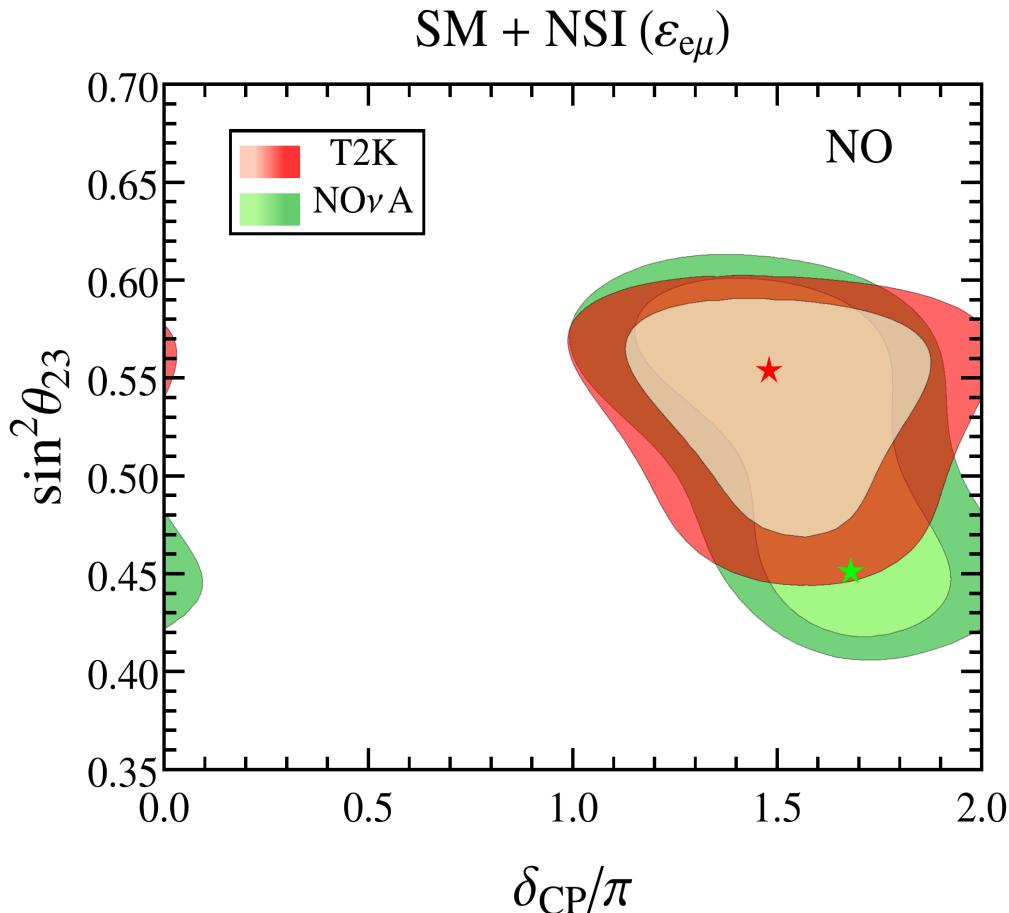
# Present: Results from T2K and NO $\nu$ A



Both prefers NO over IO and HO over LO

T2K prefers :  $\delta_{CP} = -90^\circ$  but NO $\nu$ A prefers  $180^\circ$  : Allowed region of T2K excluded by NO $\nu$ A → TENSION

# Possible solution to the TENSION



A solution was proposed by 2 PRL articles

By introducing non-standard interaction in neutrino propagation

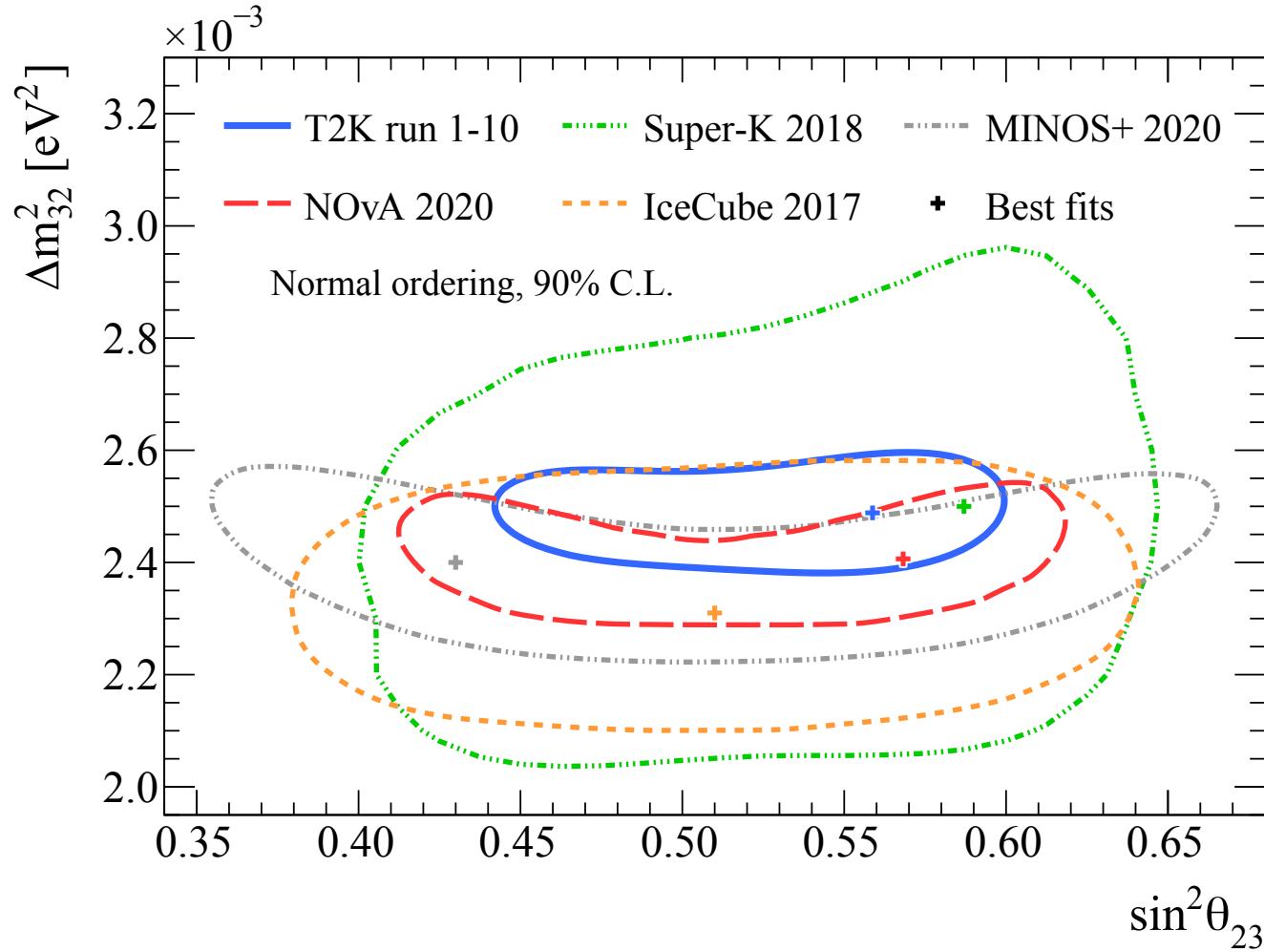
The  $\delta_{CP}$  TENSION is solved

BUT now T2K prefers HO and NO $\nu$ A prefers LO → NEW TENSION

S. S. Chatterjee and A. Palazzo, Phys. Rev. Lett. 126}(2021), 051802, 2008.04161

P. B. Denton, J. Gehrlein and R. Pesets, Phys. Rev. Lett. 126 (2021), 051801, 2008.01110

# Present: Continue



Precision has improved since 2018

# Future

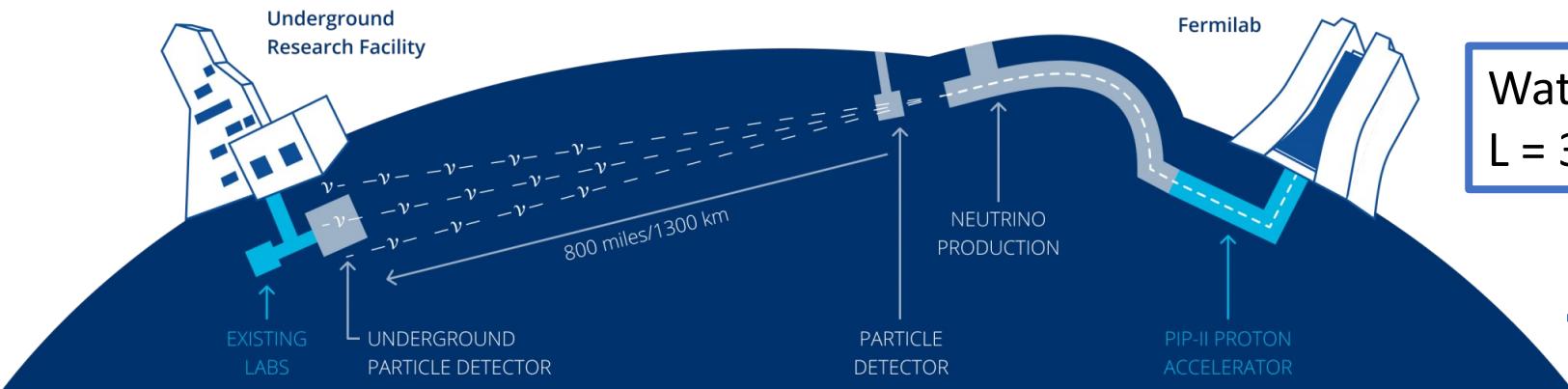
3 major experiments: T2HK, DUNE and ESSnuSB



WC 374 kt  
295 km



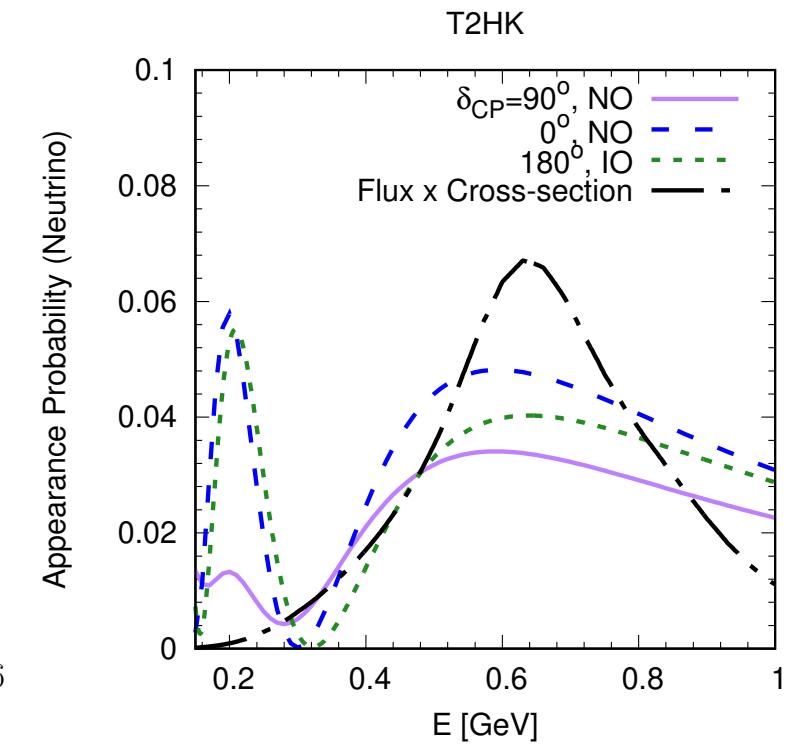
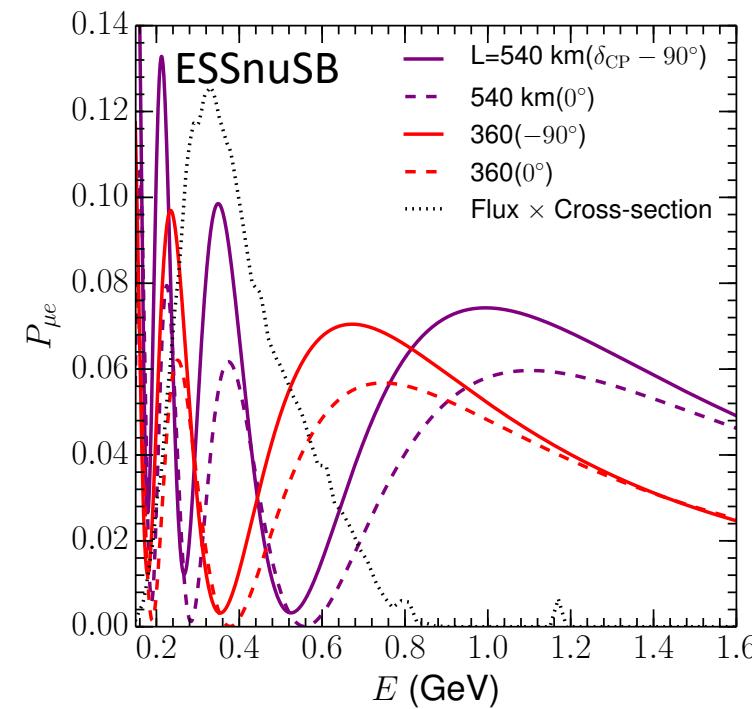
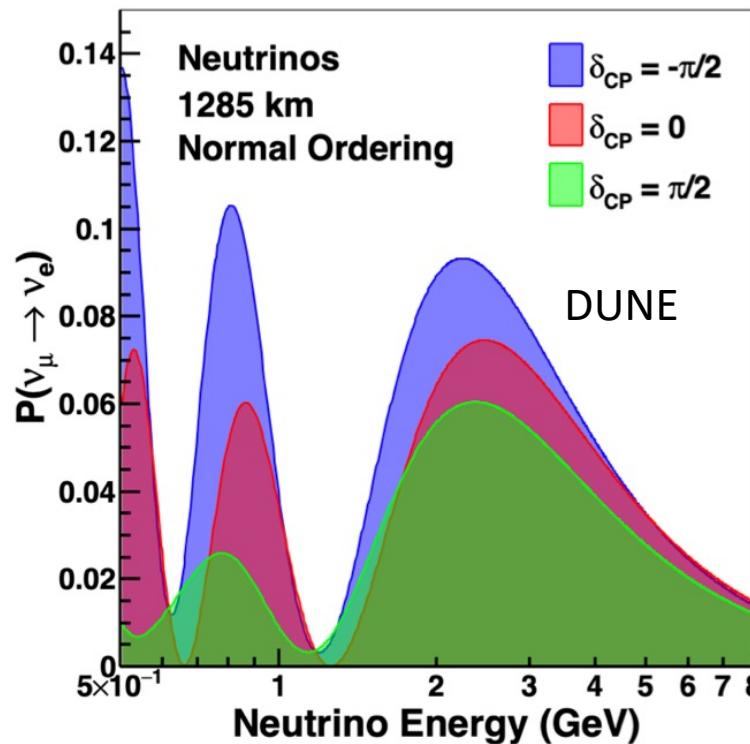
Water Cerenkov (WC) Far detector of 540 kt  
L = 360 km



Liquid argon TPC of 40 kt  
L = 1300 km

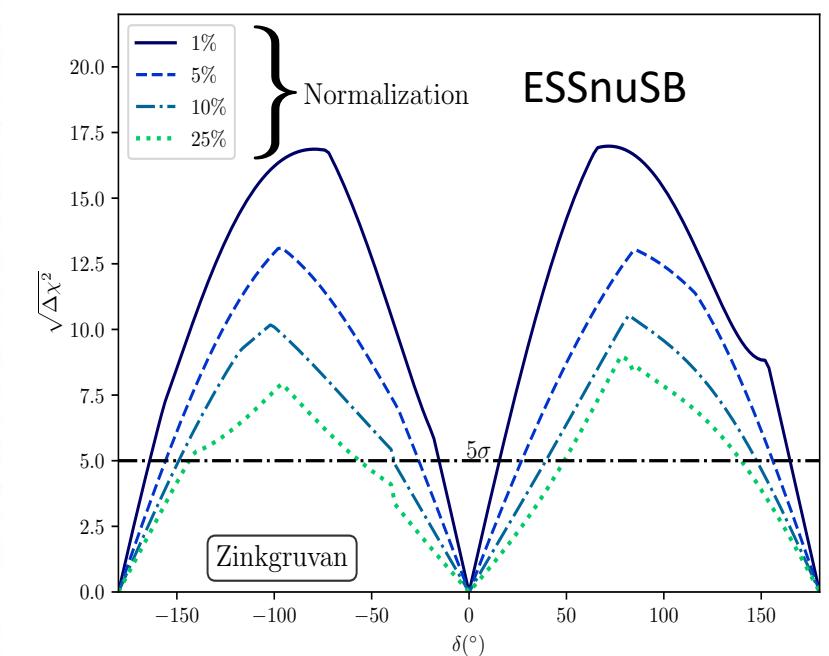
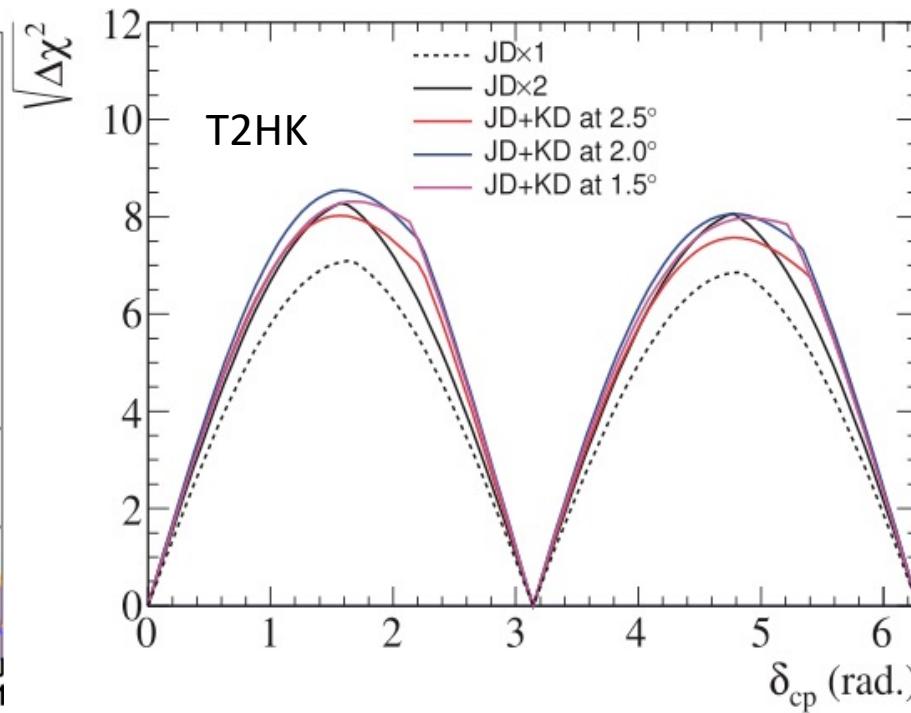
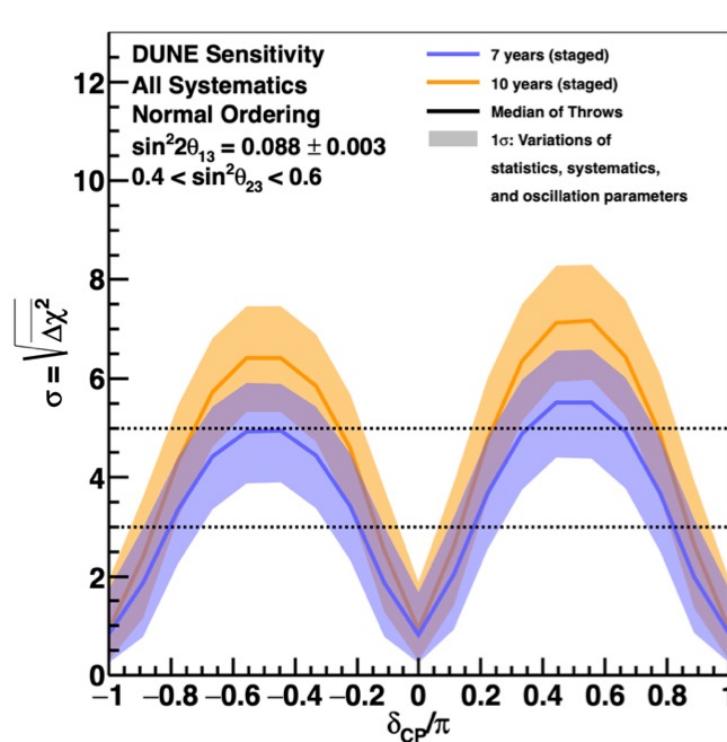
# Probability and Flux

- DUNE: First Maximum at 2.5 GeV
- T2HK: First Maximum at 0.6 GeV
- ESSnuSB: First Minimum at 0.35 GeV (360 km)



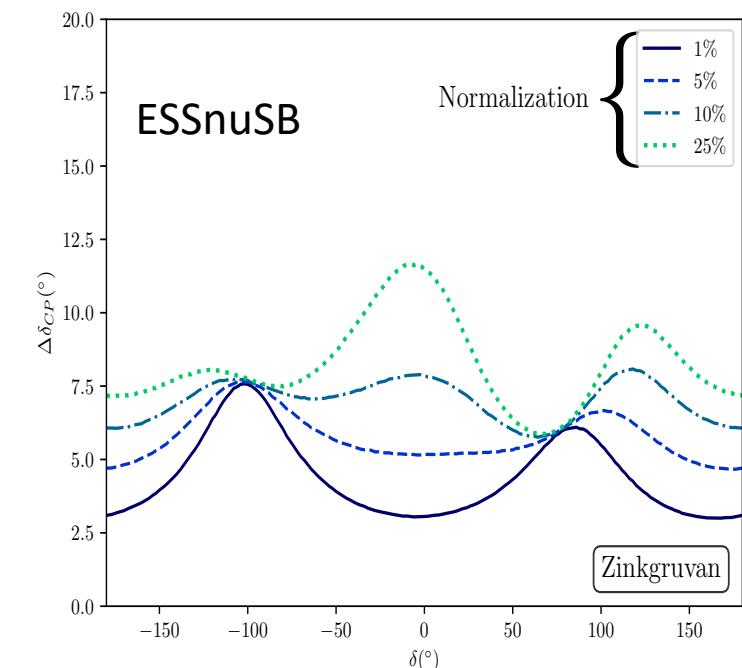
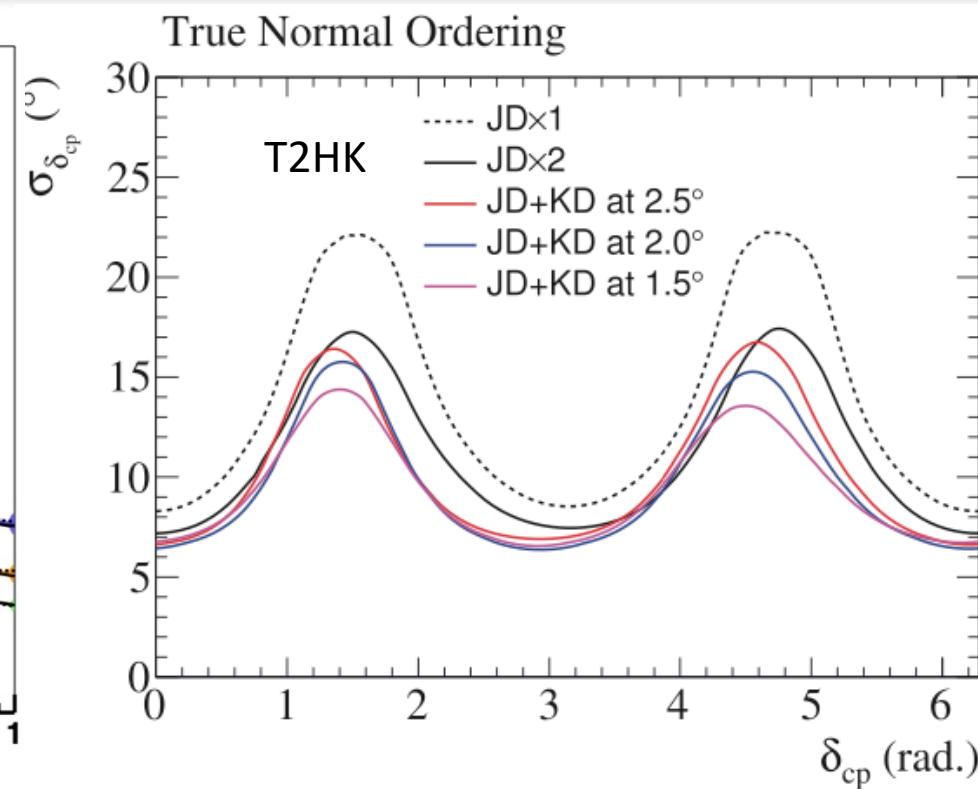
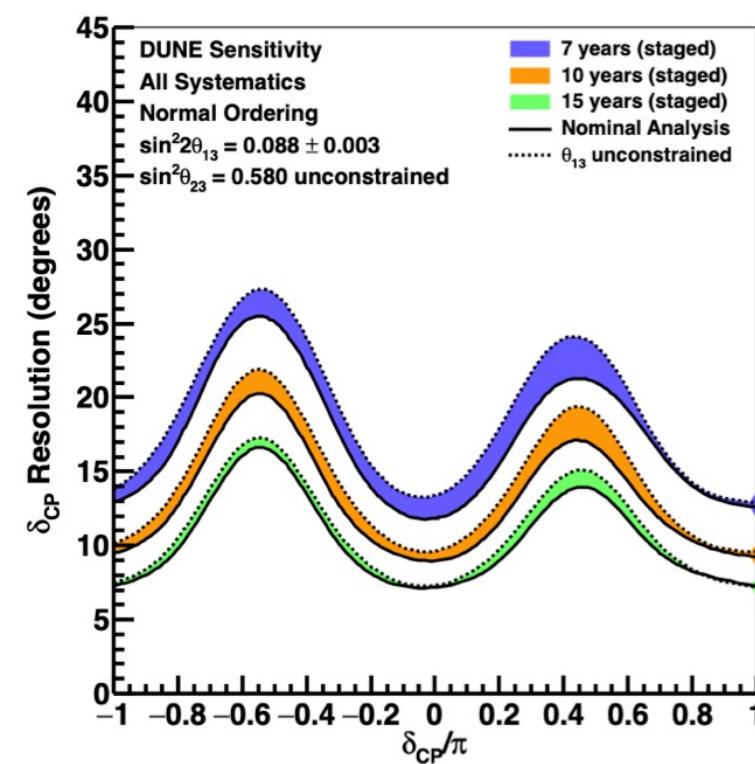
# CP Violation

- ESSnuSB > T2HK > DUNE
- Effect of 2<sup>nd</sup> oscillation maximum enhances CP sensitivity of ESSnuSB
- For T2HK high CP sensitivity is due to large statistics



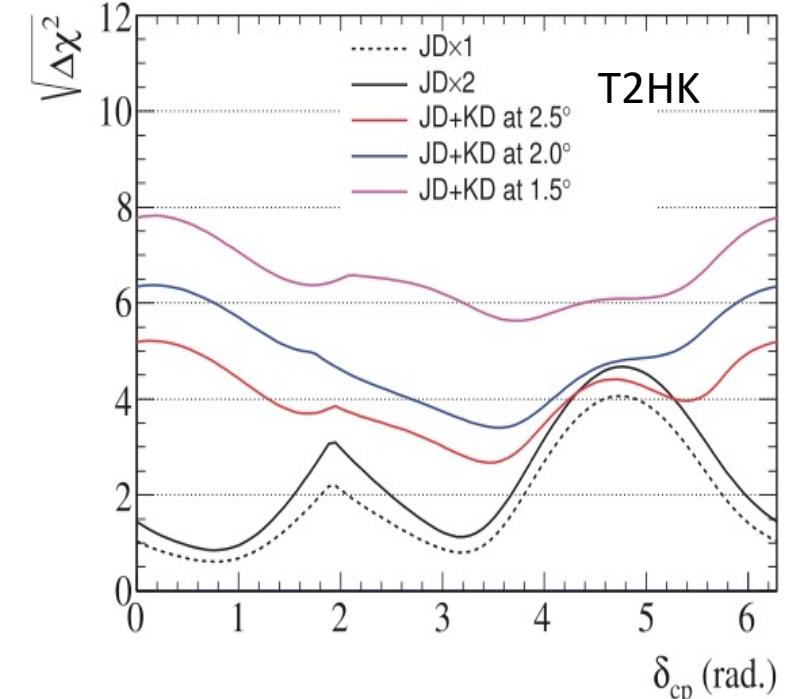
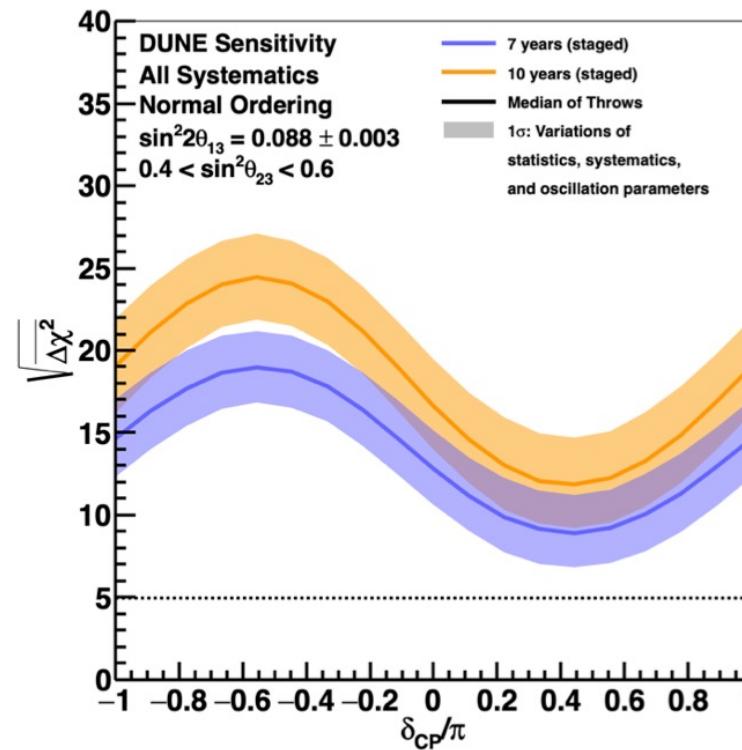
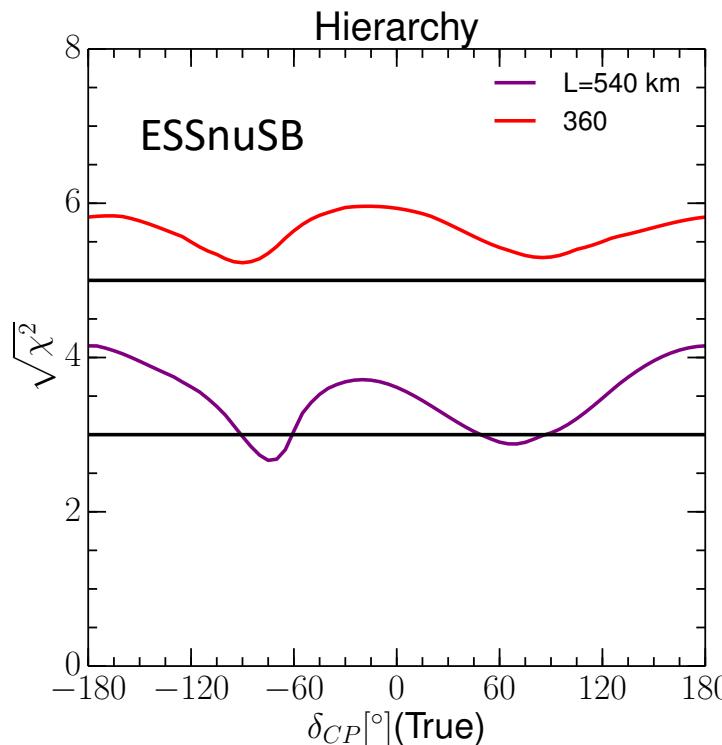
## CP Precision

- ESSnuSB > T2HK > DUNE
- Effect of 2<sup>nd</sup> oscillation maximum enhances CP sensitivity of ESSnuSB
- For T2HK high CP sensitivity is due to large statistics



# Mass Ordering

- DUNE > T2HK ~ ESSnuSB
- Large matter effect enhances hierarchy sensitivity of DUNE
- Sensitivity of T2HK and DUNE are limited



# Sterile Neutrino

- SU(2) singlet
- No Standard Model (SM) interactions
- Active neutrinos ( $\nu_e, \nu_\mu, \nu_\tau$ ) can oscillate into sterile neutrinos ( $\nu_s$ )

# 3+1 Scenario

$$U_{PMNS}^{4\nu} = R(\theta_{34}, \delta_{34}) R(\theta_{24}, \delta_{24}) R(\theta_{14}, 0) U_{PMNS}^{3\nu}$$

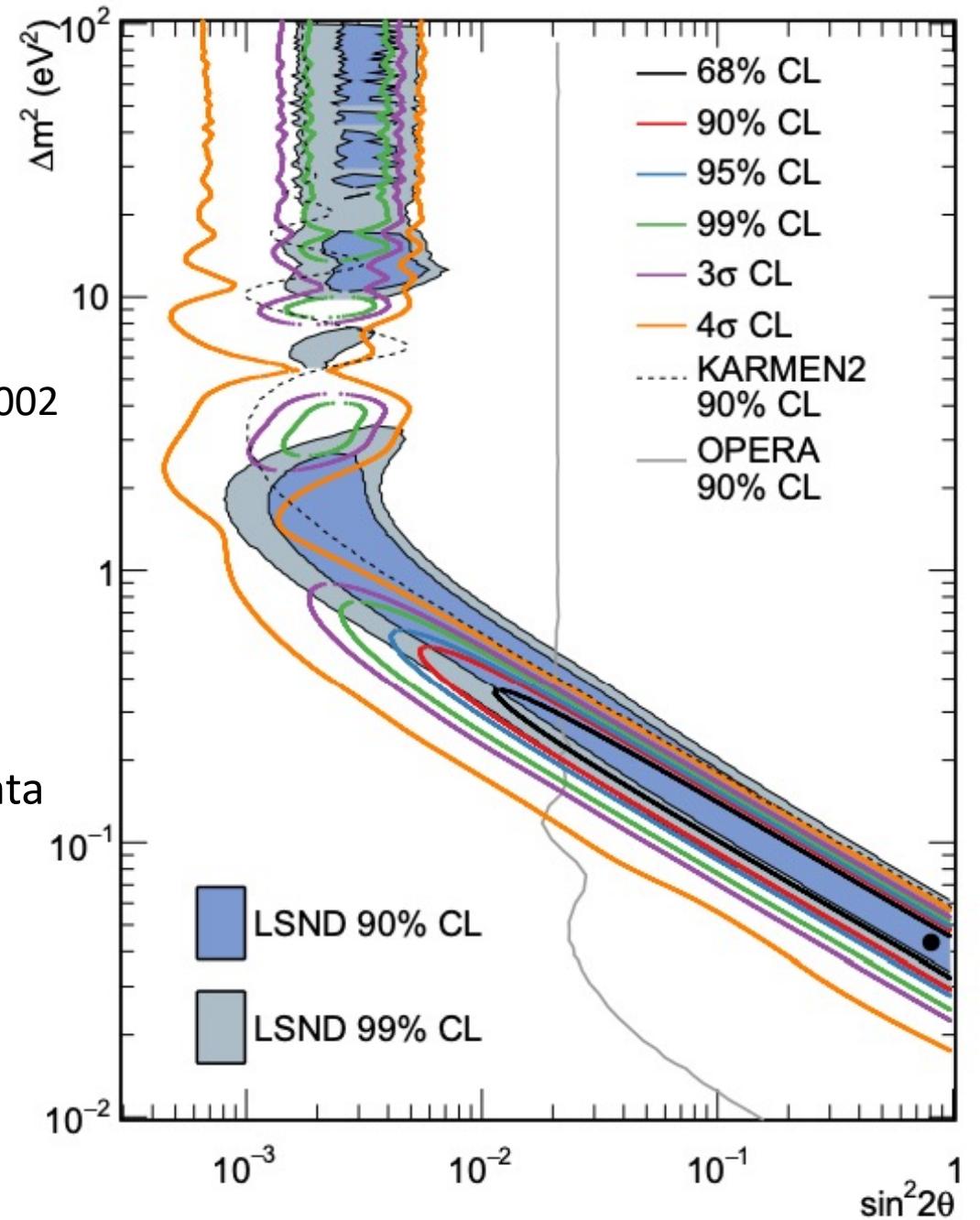
$$P_{\mu e} = s_{24}^2 \sin^2 2\theta_{14} \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{24} \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

# LSND and MiniBooNE

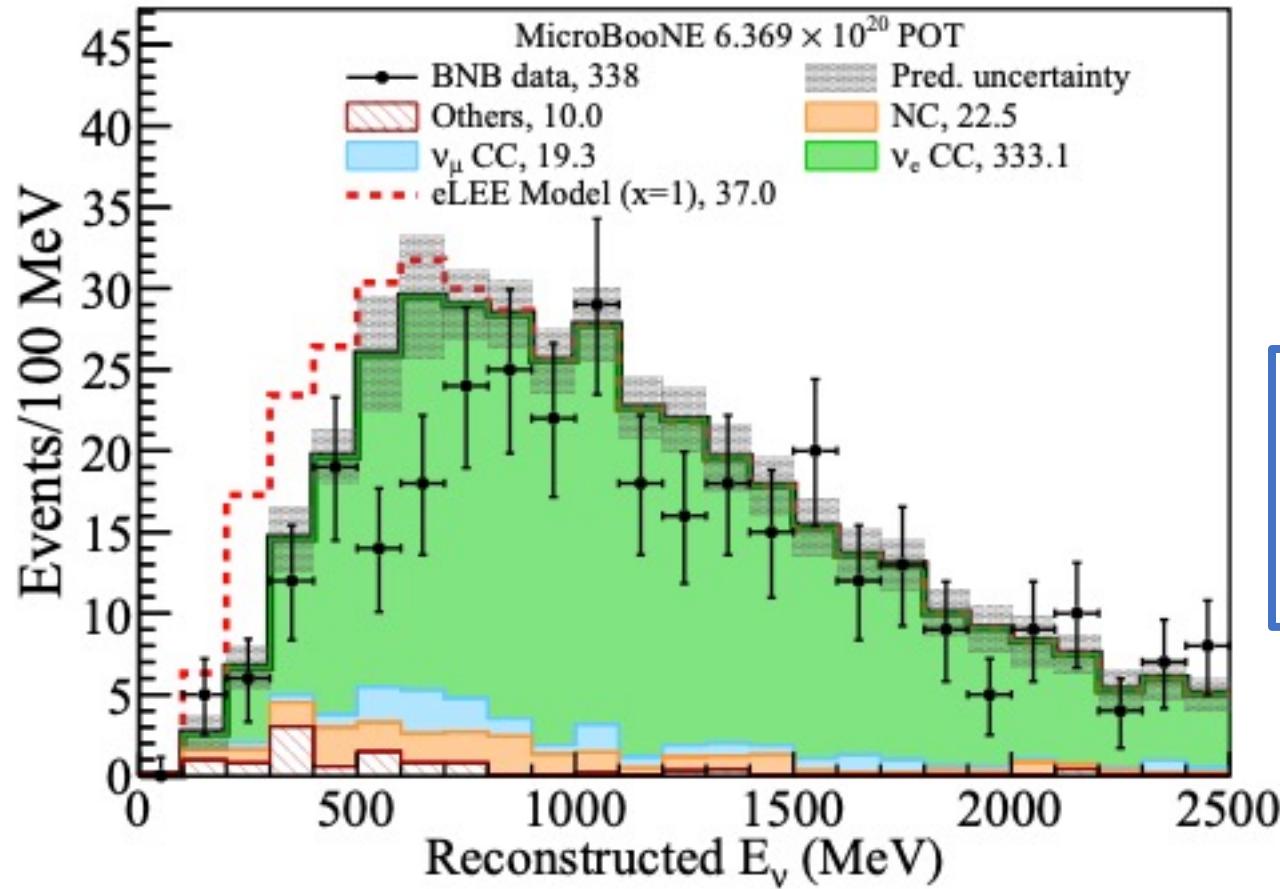
A. A. Aguilar-Arevalo et al. [MiniBooNE], Phys. Rev. D 103 (2021), 052002

- They saw a positive signal for a 4th neutrino
- $4.8\sigma$  Excess of electron like events in the MiniBooNE data



# MicroBooNE

P. Abratenko et al. [MicroBooNE], Phys. Rev. Lett. 128 (2022), 241801



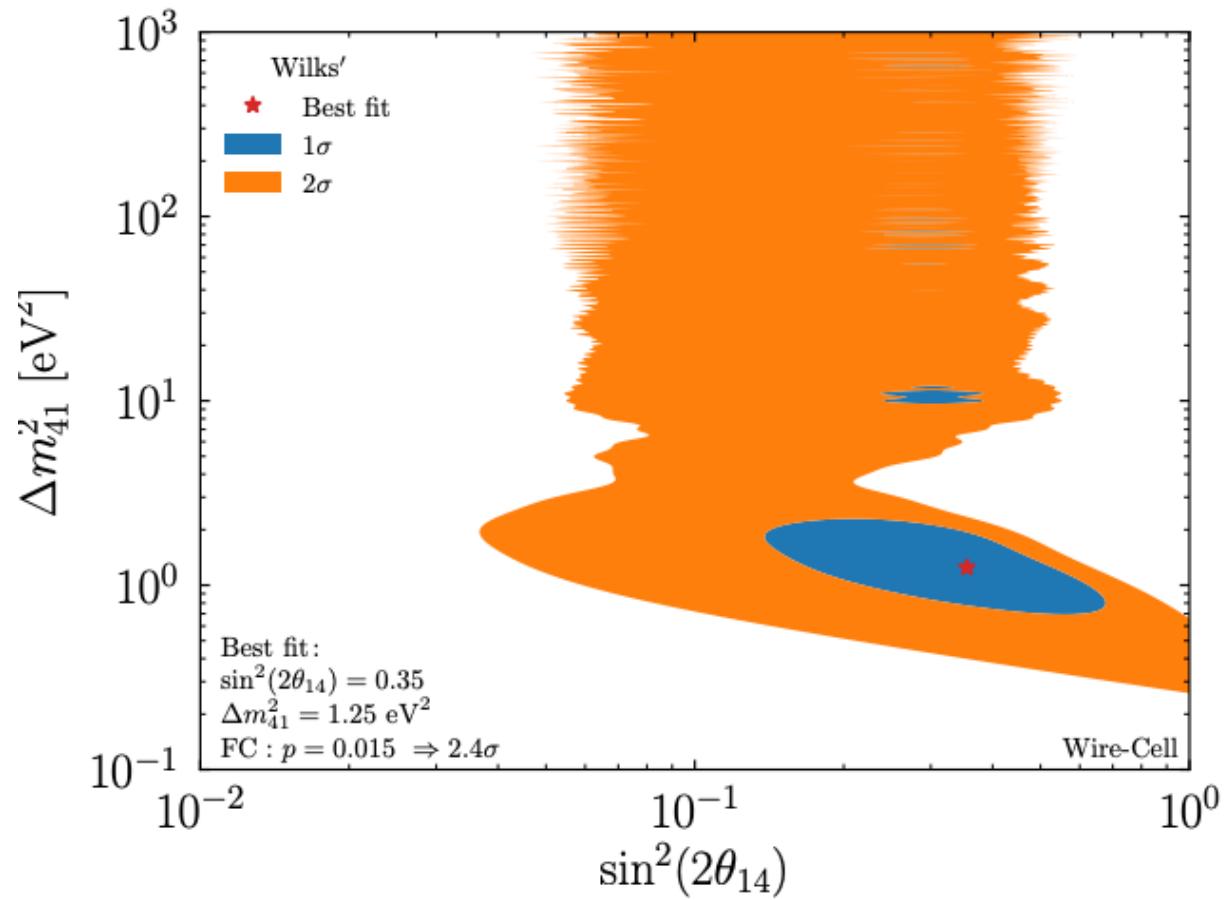
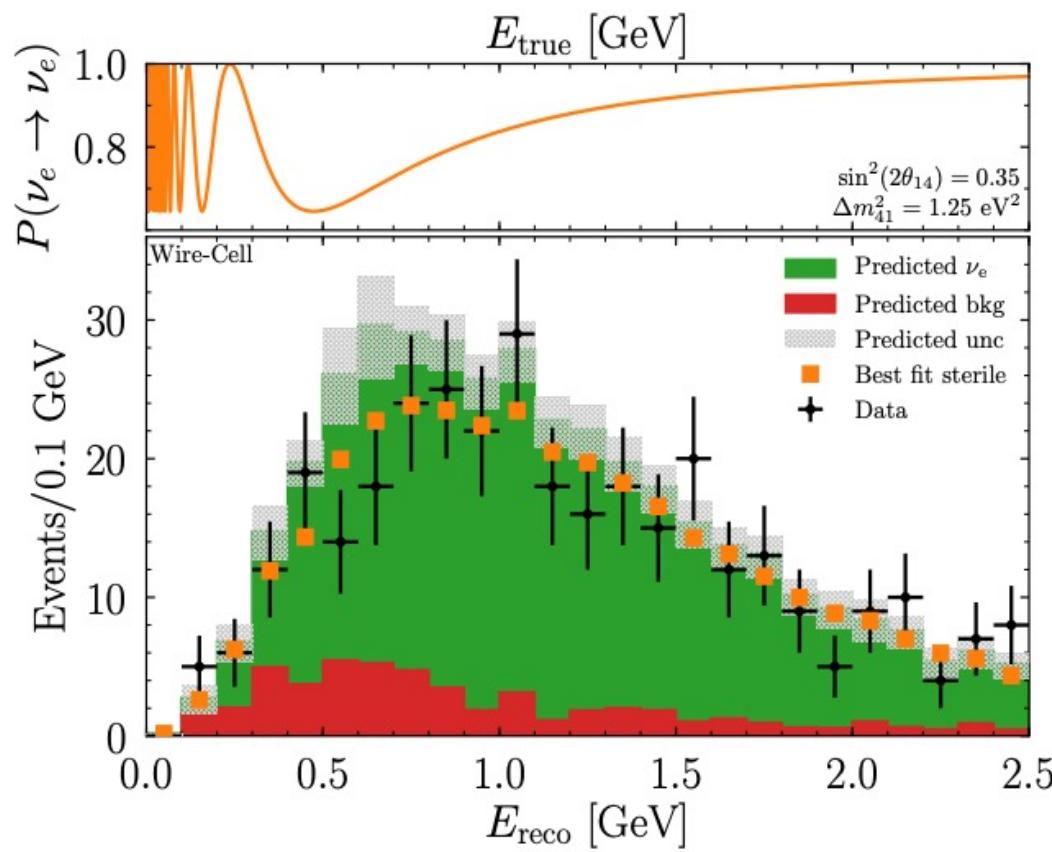
Updated version of MicroBooNE

either consistent with or modestly lower than the nominal  $\nu_e$  rate expectations

no excess of  $\nu_e$  events is observed.

No Evidence for  $\nu_\mu \rightarrow \nu_e$

# An interesting article using MicrBooNE data

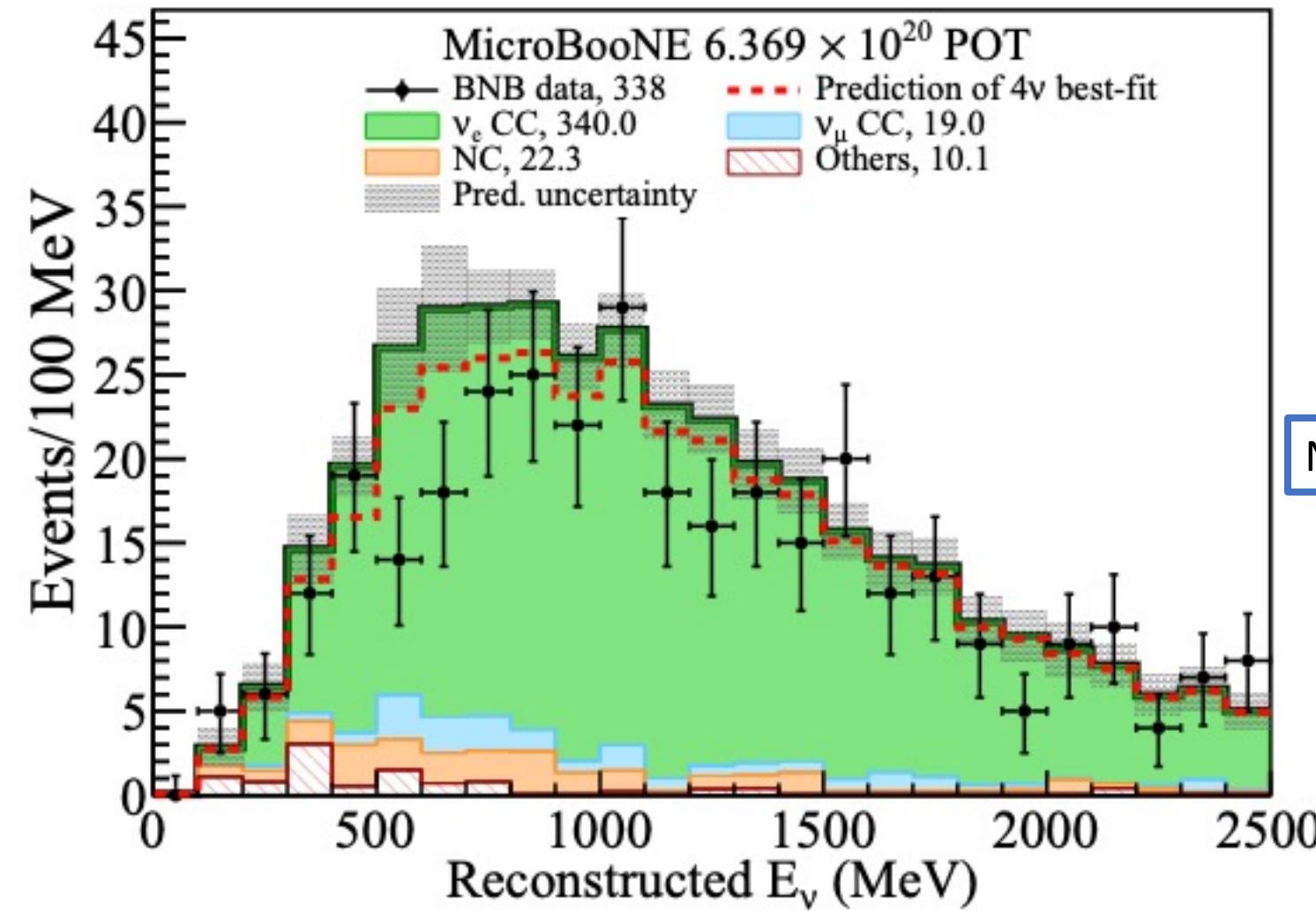


No Evidence for  $\nu_\mu \rightarrow \nu_e$  but  
found evidence for  $\nu_e \rightarrow \nu_e$  at  $2.4\sigma$

P. B. Denton, Phys. Rev. Lett. 129 (2022), 061801

# Reply by MicroBooNE

P. Abratenko et al. [MicroBooNE], Phys. Rev. Lett. 130 (2023), 011801



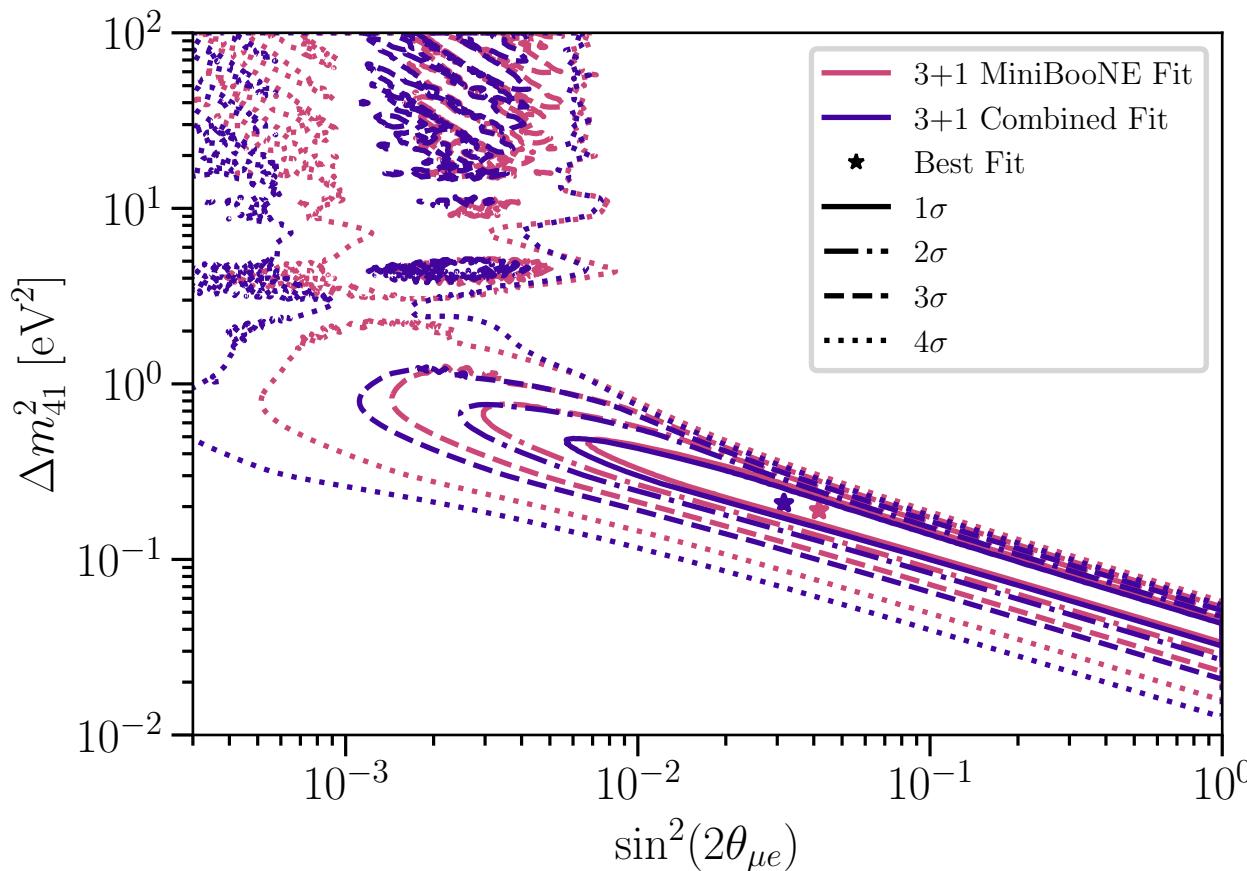
Performs a combined analysis:

$$\nu_e \text{ CC: } \nu_\mu \rightarrow \nu_e + \nu_e \rightarrow \nu_e$$

No evidence of light sterile neutrino oscillations

# MiniBooNE + MicroBooNE

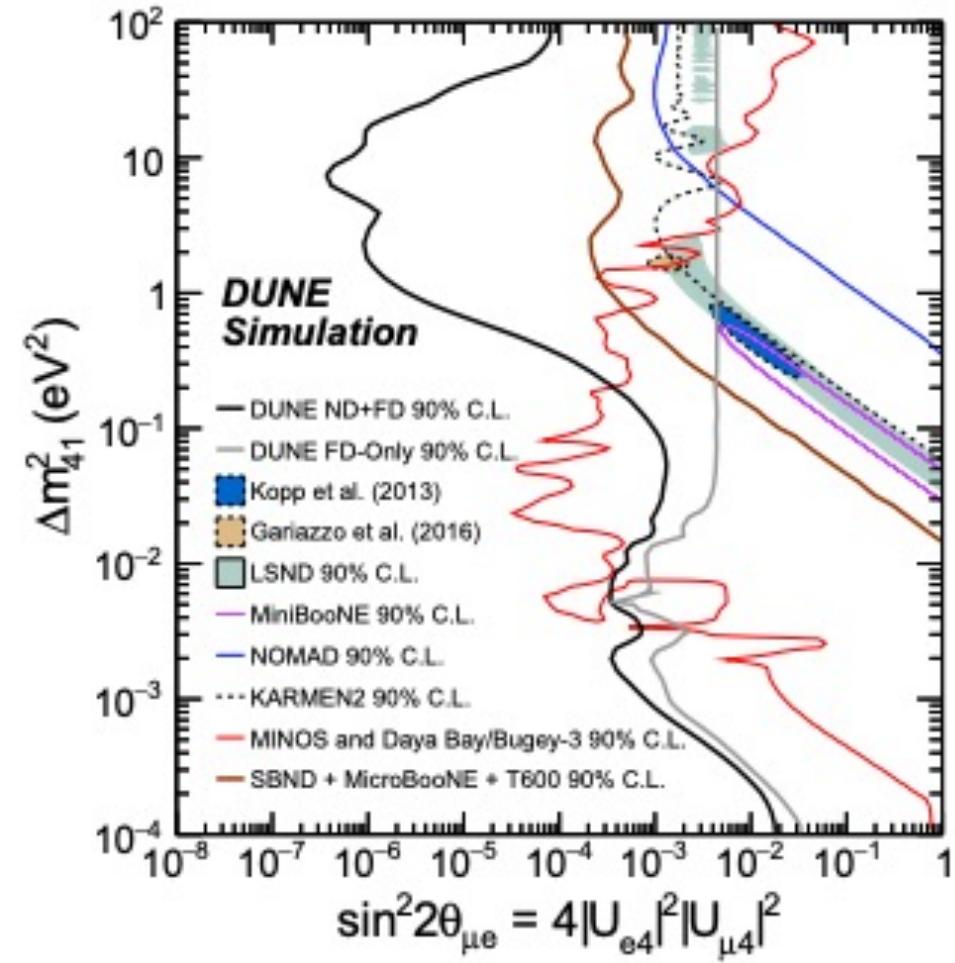
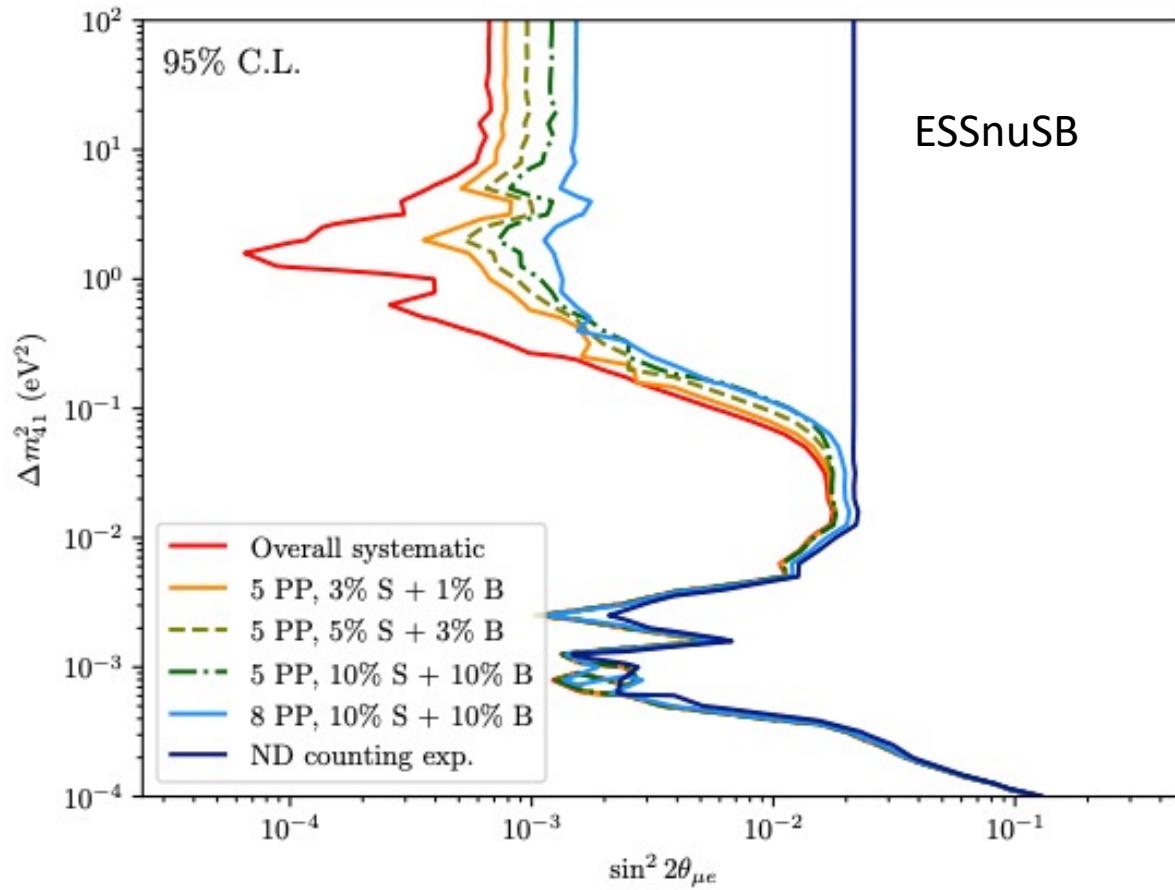
A. A. Aguilar-Arevalo et al. [MiniBooNE], Phys. Rev. Lett. 129 (2022), 201801



Present Satuts

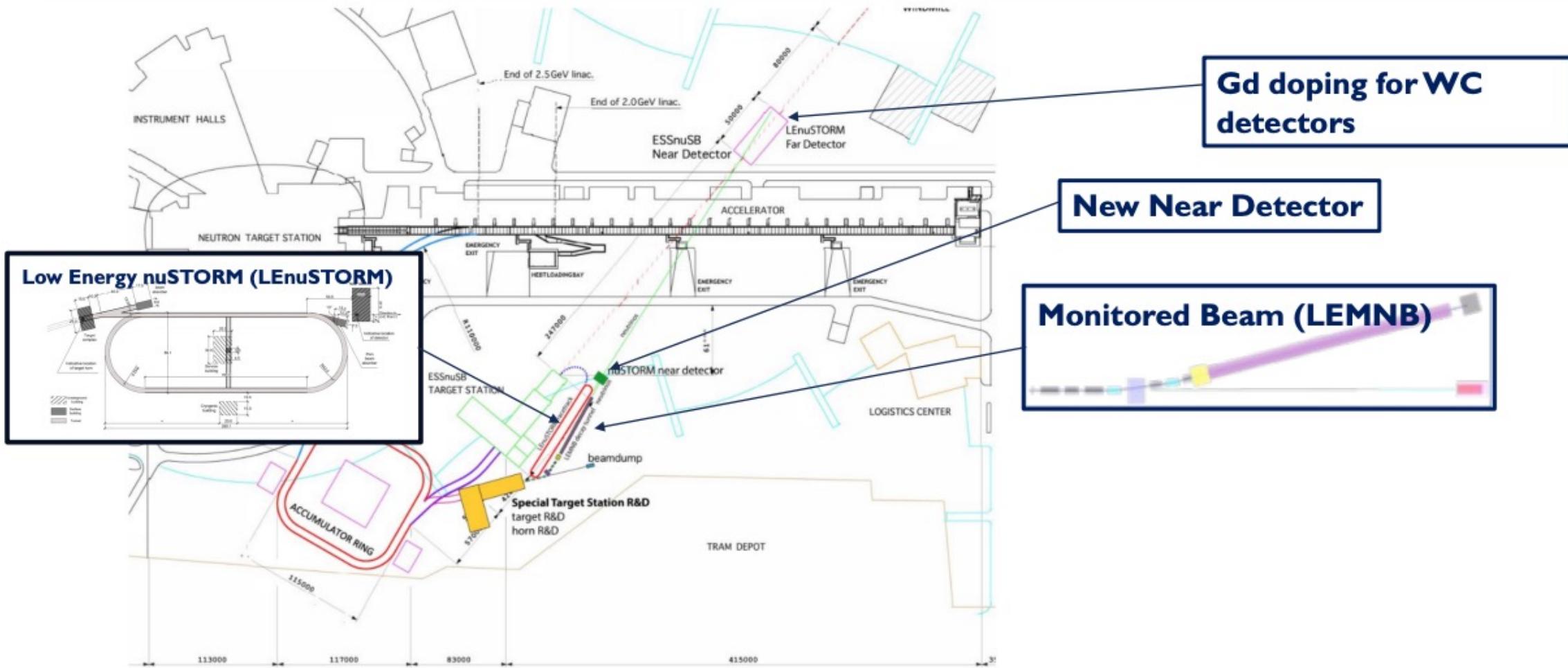
The data prefer the 3+1 model with  $3.4\sigma$  preference

# Future limits



Stringent bound can be obtained in future combining FD and ND

# Future plans for ESSnuSB: ESSnuSB+



Will improve the sensitivity for 3 flavour and 3+1 scenario further

A. Alekou et al. [ESSnuSB], Universe 9 (2023), 347

# Other new physics

Apart from 3+1 scenario, there are many new physics scenarios that are being studied at this moment

- Non-standard neutrino interactions (mediated by vector and scalar field): [2112.04876](#), [2308.10789](#)
- Violation of Lorentz invariance: [2303.10892](#), [2303.10892](#)
- Neutrino decay (visible and invisible): [2010.16334](#)
- And many more

# Summary

Exciting time for neutrino oscillation physics

- Present experiments are providing hints for the current unknowns
- Future experiments will establish these hints on a firm footing
- Important to look for new physics scenarios including 3+1 scenario

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Thank You