Complementary between HK & DUNE to complete 3-flavor PMNS picture & beyond

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July 17, 2023
19th Rencontres du Vietnam @ IFIRSE

1. Introduction

- Motivations for determination of mass ordering, CP phase
- Parameter degeneracy

2. Sensitivity of T2HK & DUNE to N_ν=3 oscillation parameters

- Precision of Δm^2_{31} & θ_{23}
- Mass ordering
- Octant degeneracy
- CP

3. Sensitivity to scenarios beyond the 3-flavor PMNS picture

- ν_s, NSI, scalar NSI, long-range force, Non-unitarity, LIV

4. Conclusions

1. Introduction

Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

All 3 mixing angles have been measured (2012):

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8 \times 10^{-5} \mathrm{eV}^2$

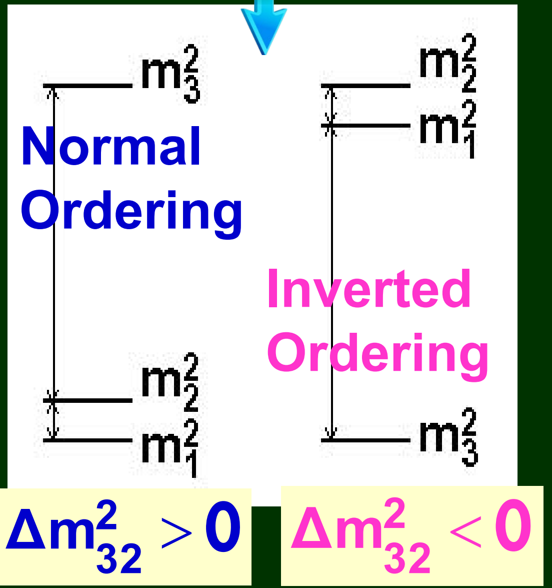
ν_{atm}+T2K +MINOS+NOvA (accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} \mathrm{eV}^2$

DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS+Nova etc → $\theta_{13} \cong \pi / 20$

Next things to do are to determine the following:

- sign(Δm^2_{31})
- $\pi/4-\theta_{23}$
- δ

Both mass patterns are allowed



- Motivation for determining mass ordering
  - (i) Guidelines for models (GUT etc.)
  - (ii) Influence on the measurement of CP phase
  - (iii) Implication for neutrinoless double β decay
- Motivation for determining the CP phase
  - (i) Guidelines for models (GUT etc.)
  - (ii) Leptogenesis?

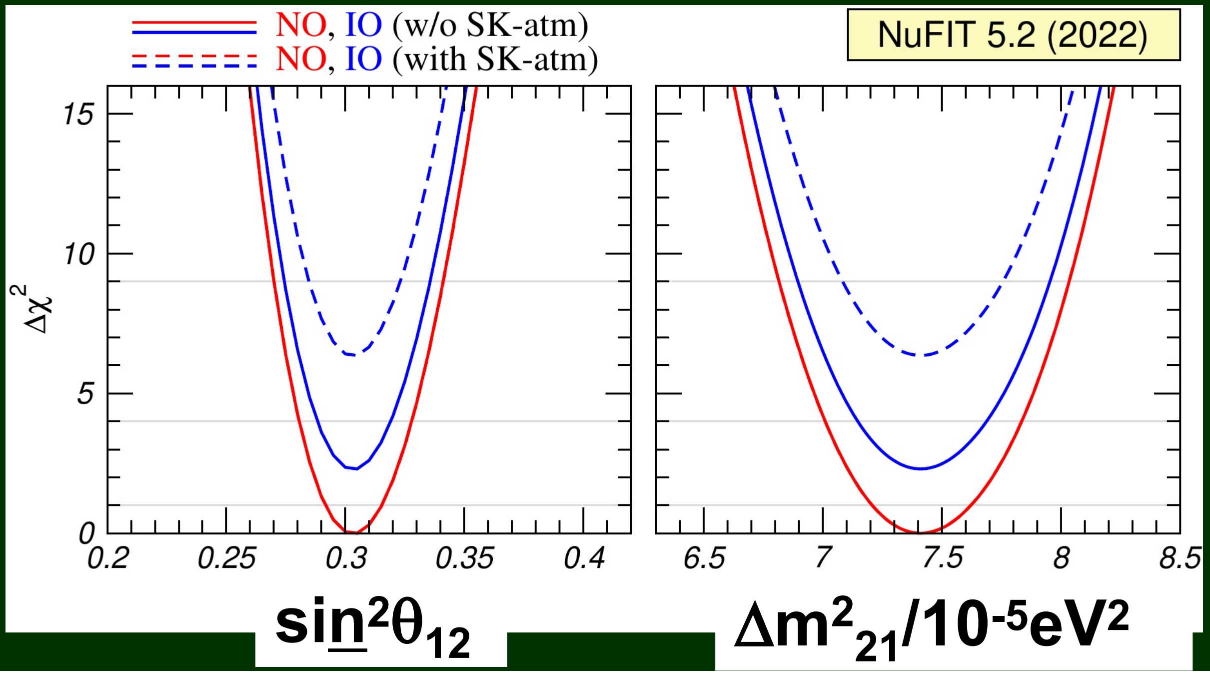
Status of 3ν fit (1)

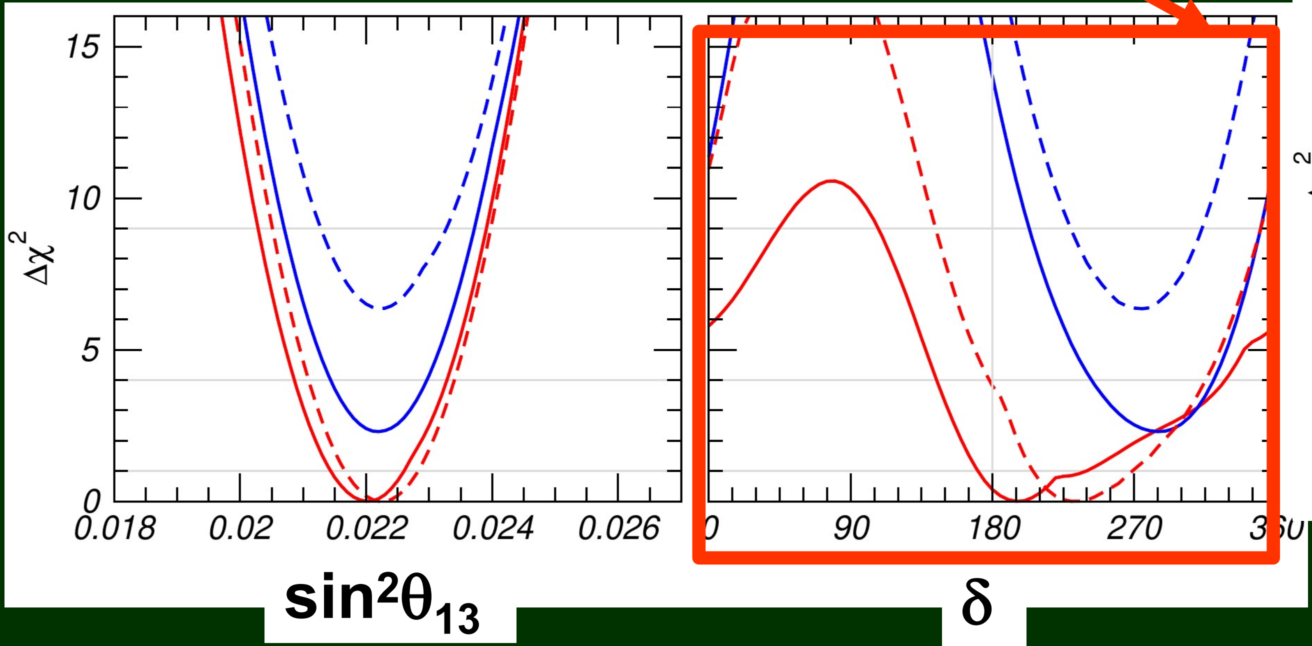
www.nu-fit.org
v5.2 (Nov. 2022)

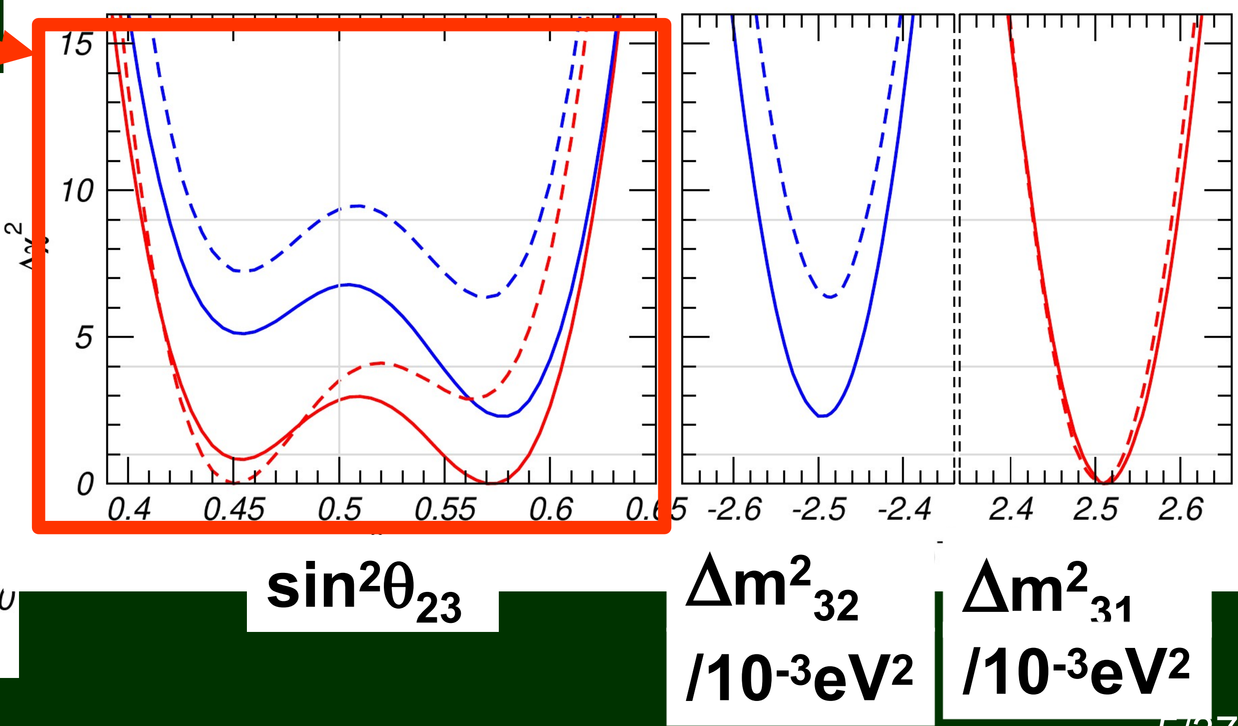
NO, δ~π seems to be preferred over IO, δ~3π/2

NO, IO (w/o SK-atm)
NO, IO (with SK-atm)

θ_{23} and δ have large errors



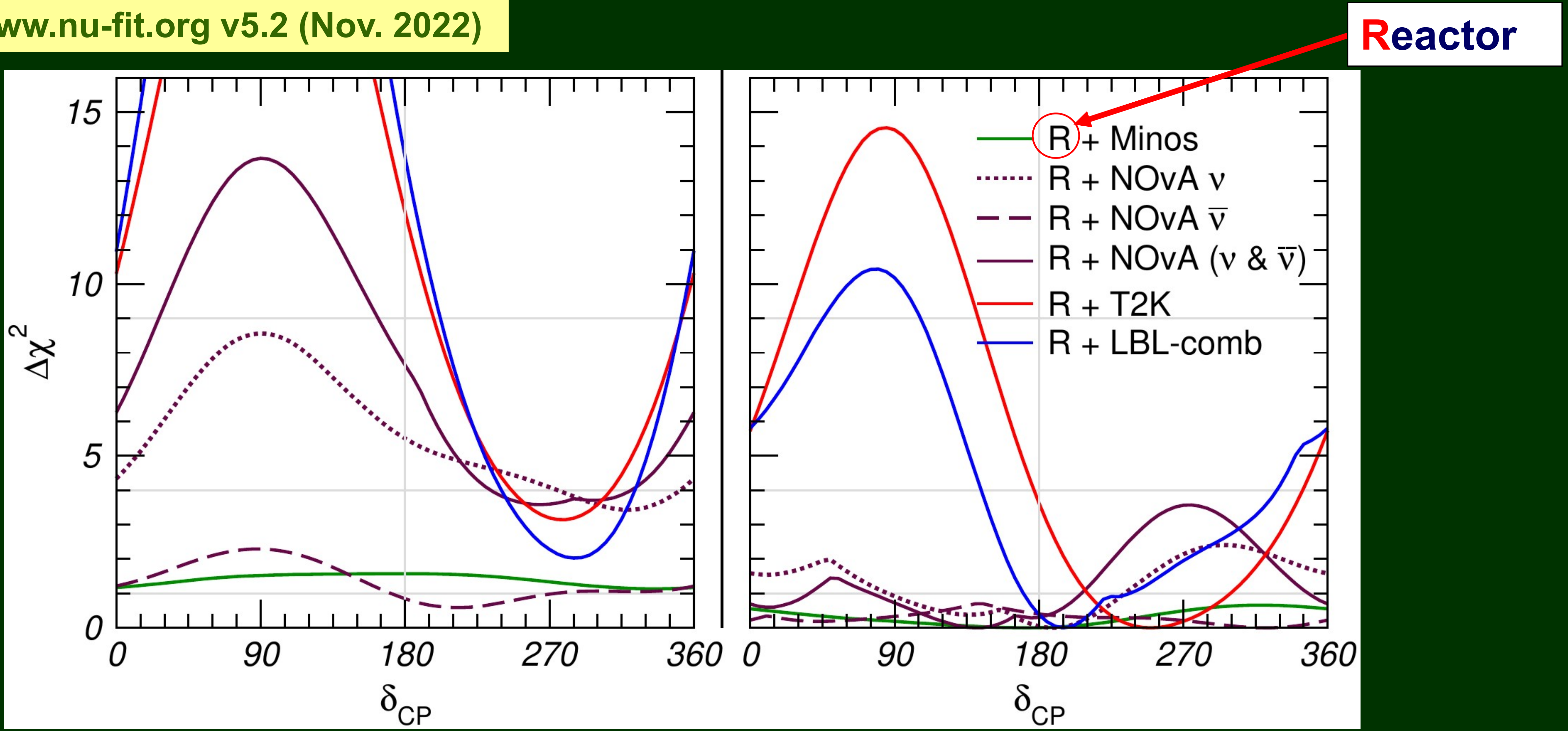




Status of 3ν fit (2)

Appearance data of LBL show us potential tension for NO, although T2K dominates over NOvA in statistics.

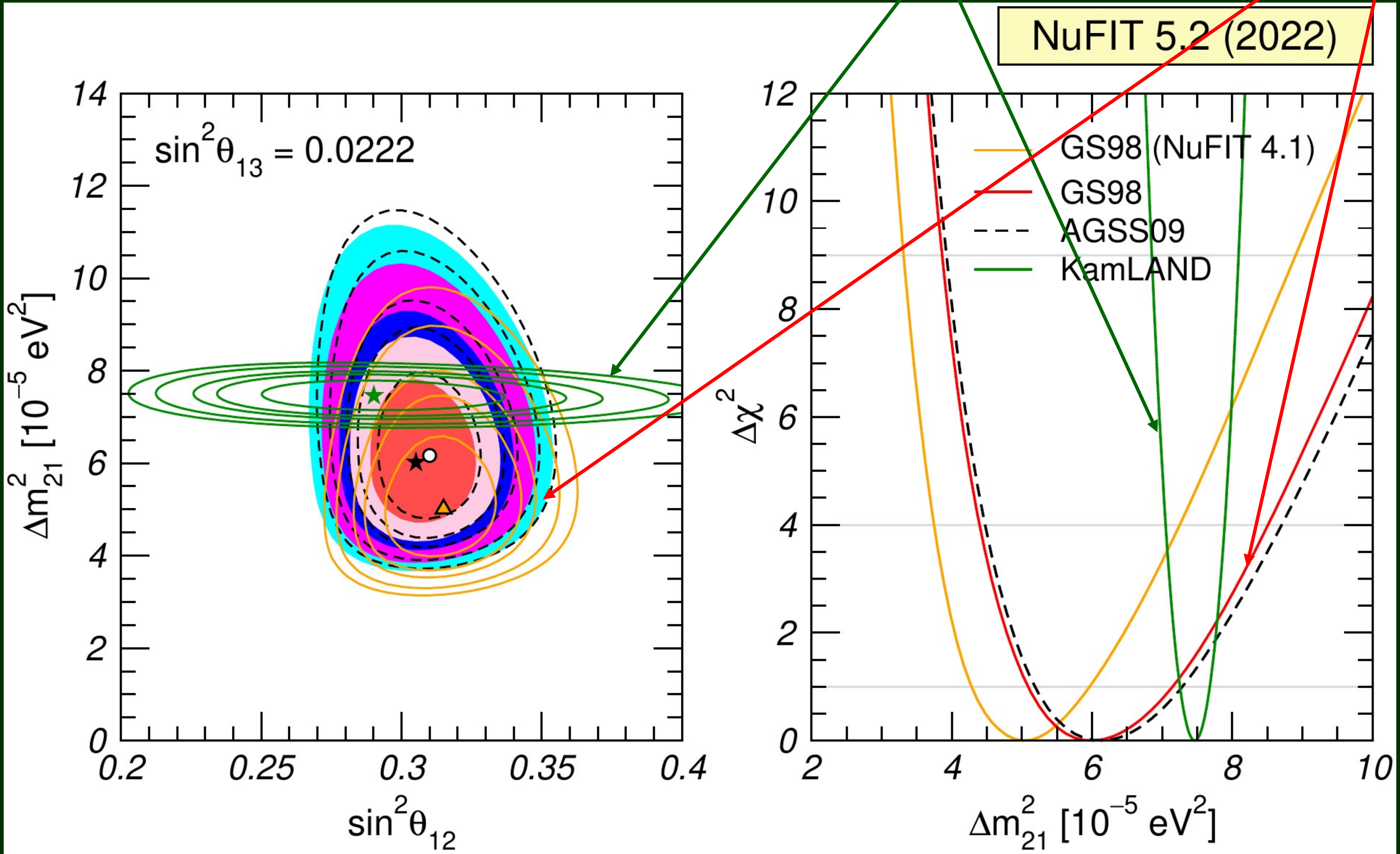
www.nu-fit.org v5.2 (Nov. 2022)



Status of 3ν fit (3)

www.nu-fit.org v5.2 (Nov. 2022)

Tension of Δm^2_{21} between solar ν and KamLAND remains.



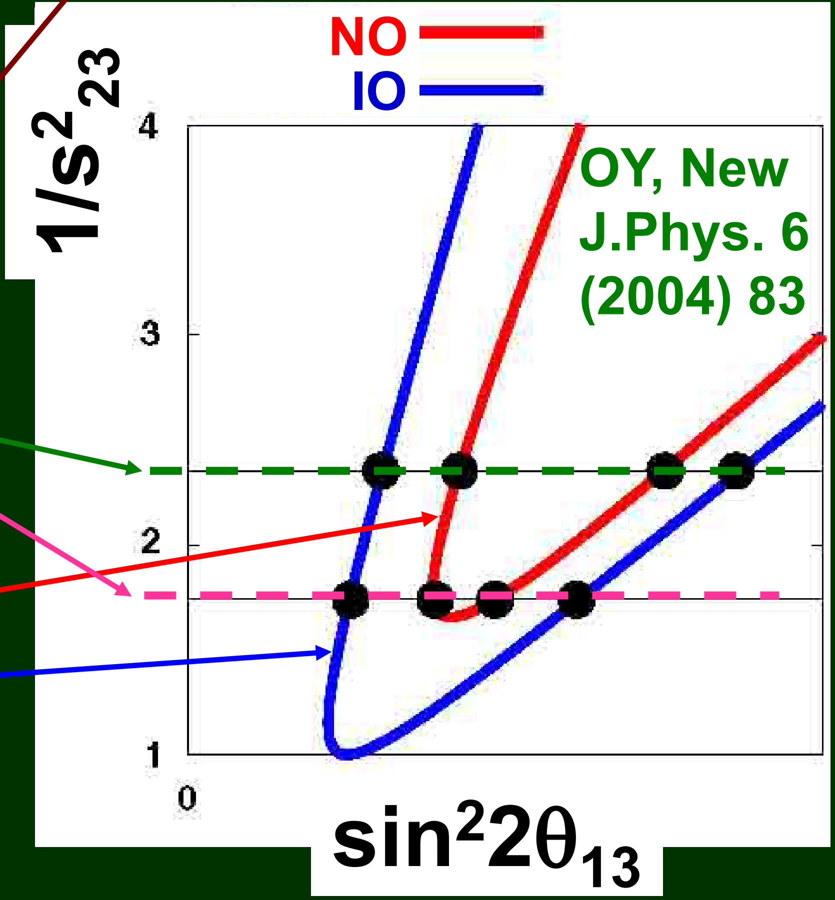
Tension may be a hint for **N**on **S**tandard **I**nteractions or **sterile neutrinos**.

● Parameter degeneracy

Even if we know $P \equiv P(\nu_\mu \to \nu_e)$ and $\bar{P} \equiv P(\overline{\nu_\mu} \to \overline{\nu_e})$ in LBL experiments with energy E and baseline L, δ cannot be uniquely determined because of the 8-fold **parameter degeneracy**.

($\sin^2 2\theta_{13}$, $1/s^2_{23}$) plane (P=const & $\bar{P}$=const gives a quadratic curve)

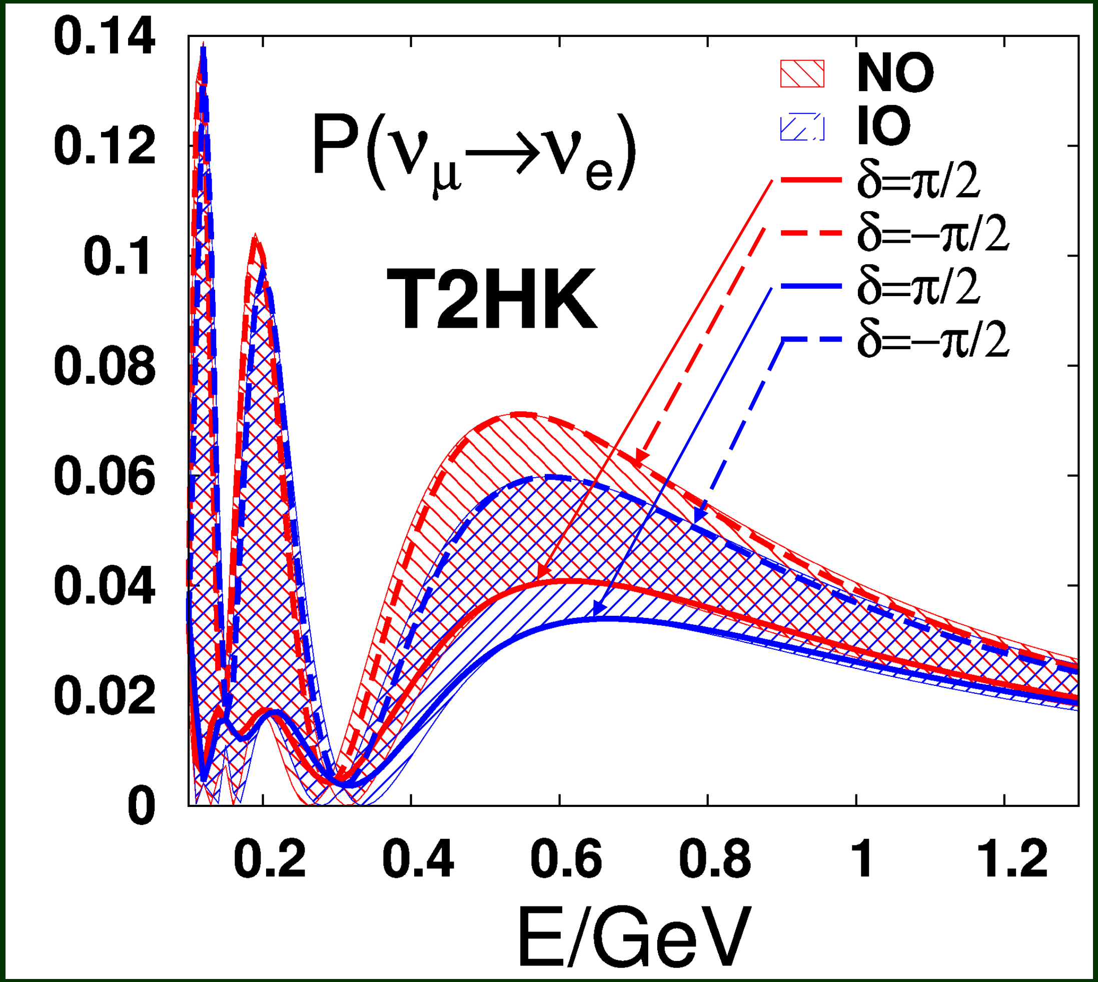
- **octant degeneracy** $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$ (Fogli-Lisi, '96)
- **intrinsic degeneracy** (δ, θ_{13}) (Burguet-Castell et al, '01)
- **sign degeneracy** $\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$ (Minakata-Nunokawa, '01)



● Understanding degeneracy by appearance probabilities

hierarchy - δ — Prakash, Raut, Sankar, PRD 86, 033012 (2012)

octant - δ — Agarwalla, Prakash, Sankar, JHEP 1307, 131 (2013)



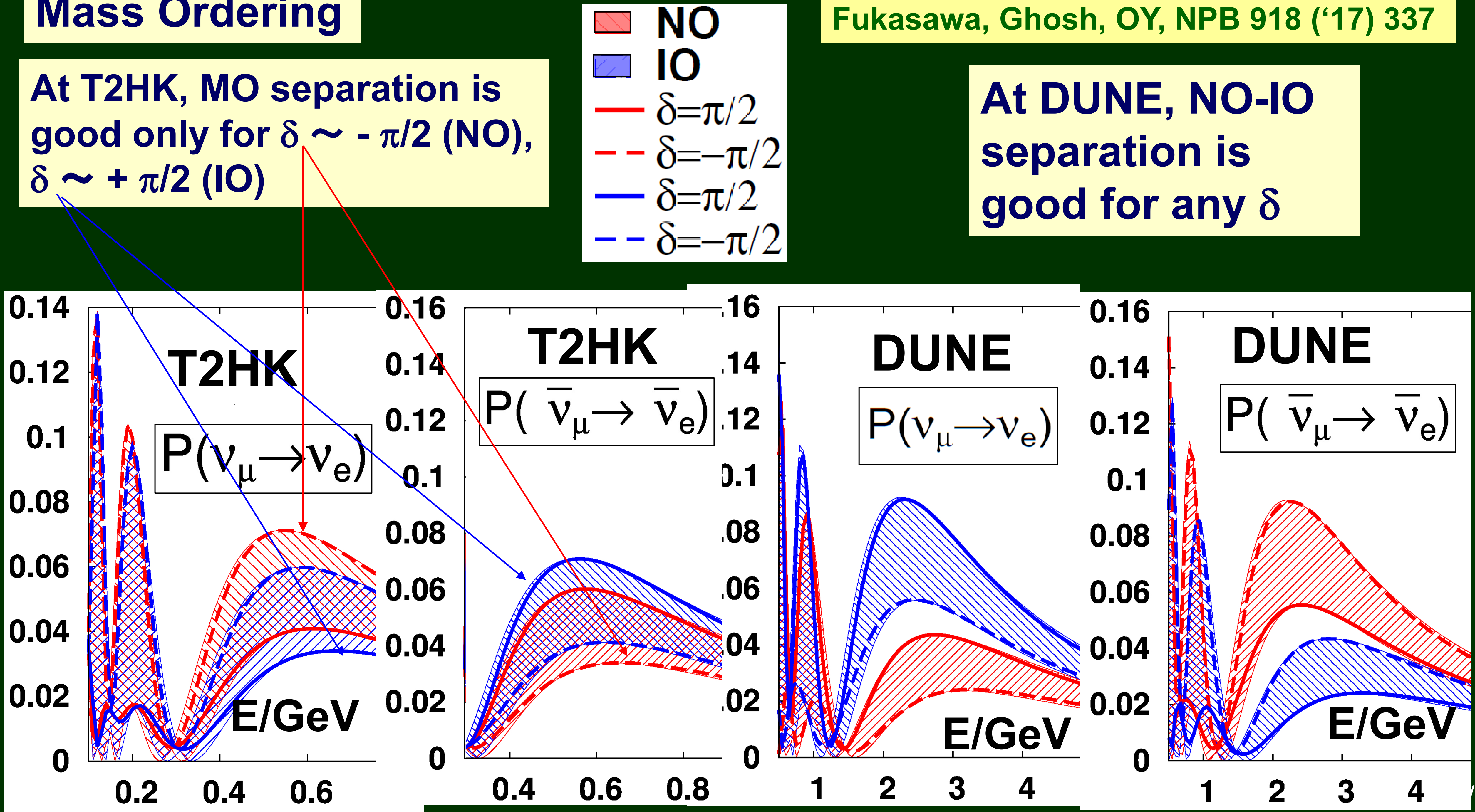
Due to uncertainty in δ, the appearance probabilities has finite width.
-> Each border is approximately realized for δ = +π/2 or -π/2

Mass Ordering

Fukasawa, Ghosh, OY, NPB 918 ('17) 337

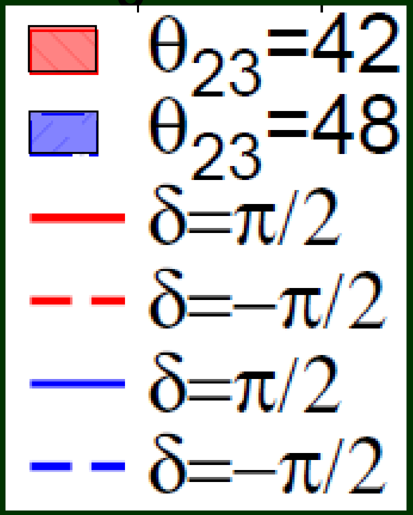
At T2HK, MO separation is good only for δ ~ - π/2 (NO), δ ~ + π/2 (IO)

At DUNE, NO-IO separation is good for any δ



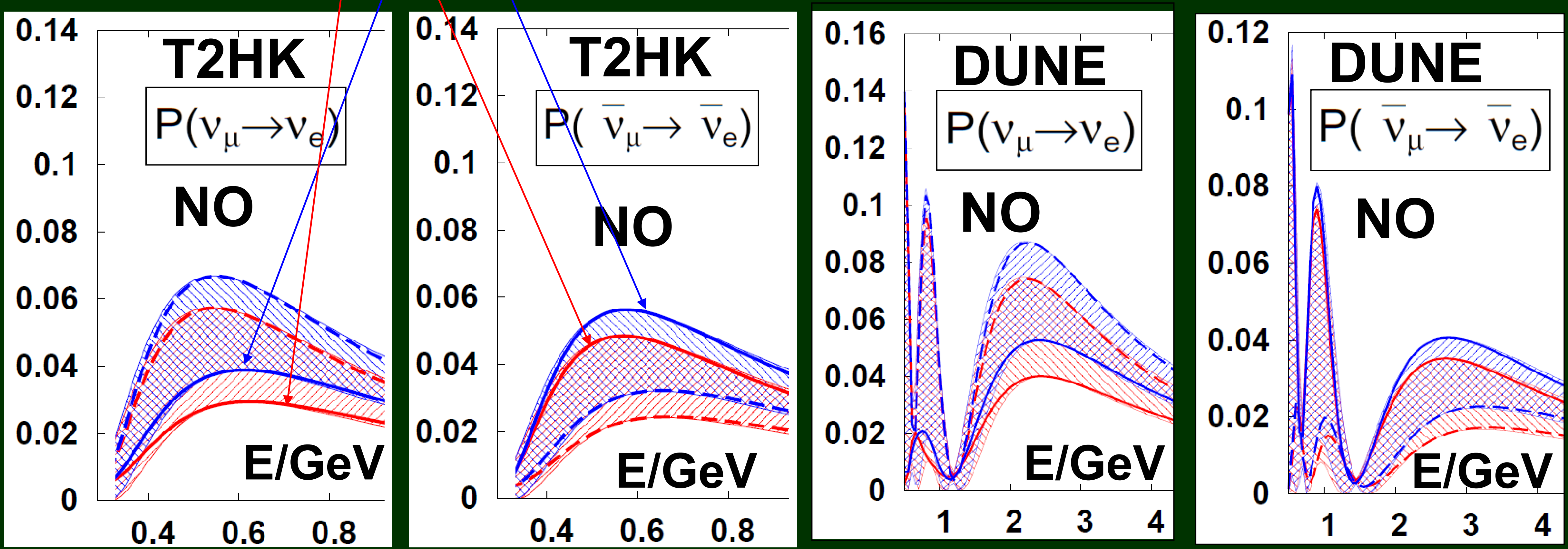
Octant

Fukasawa, Ghosh, OY, NPB 918 ('17) 337



At both T2HK & DUNE, HO-LO separation is possible w/ ν & $\bar{\nu}$ for most of δ

Unlike hierarchy degeneracy, δ=−π/2 lies on the same side for ν & $\bar{\nu}$



Complementarity of T2HK and DUNE

T2HK

pro: #(events) ($\propto L^{-2}$) is large

con: little matter effect

DUNE

pro: #(events) ($\propto L^{-2}$) is smaller

con: large matter effect

Matter effect becomes most conspicuous if $\Delta E\cos 2\theta = A$ is satisfied.

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

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A}$$

$$\Delta \tilde{E} \equiv \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2 \right]^{1/2}$$

$$A \equiv \sqrt{2} G_F n_e(x)$$

In this case, the baseline length L has to be large

$\rightarrow L > \pi / A \sim O(1000\text{km})$ → It is satisfied by DUNE but not by T2HK.

2. Sensitivity of T2HK & DUNE to N_ν=3 oscillation parameters

Uncertainty in matter density taken into account

Ghosh-OY, NPB 989 ('23) 116142

The parameters assumed here:

T2HK

187 kton fiducial volume

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

Total exposure: 2.7 x 10^{22} POT

DUNE

40 kt LiAr detector,

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

Total exposure: 1.1 X 10^{21} POT

Reference value:

$\theta_{23} = 42^\circ$ or 48°,

$\delta = -90^\circ$,

$\Delta m^2_{31} = 2.51\times10^{-3}\,\mathrm{eV}^2$,

$\Delta\rho/\rho$ = 0 , 5%, 10%

2.1 Precision to oscillation parameters

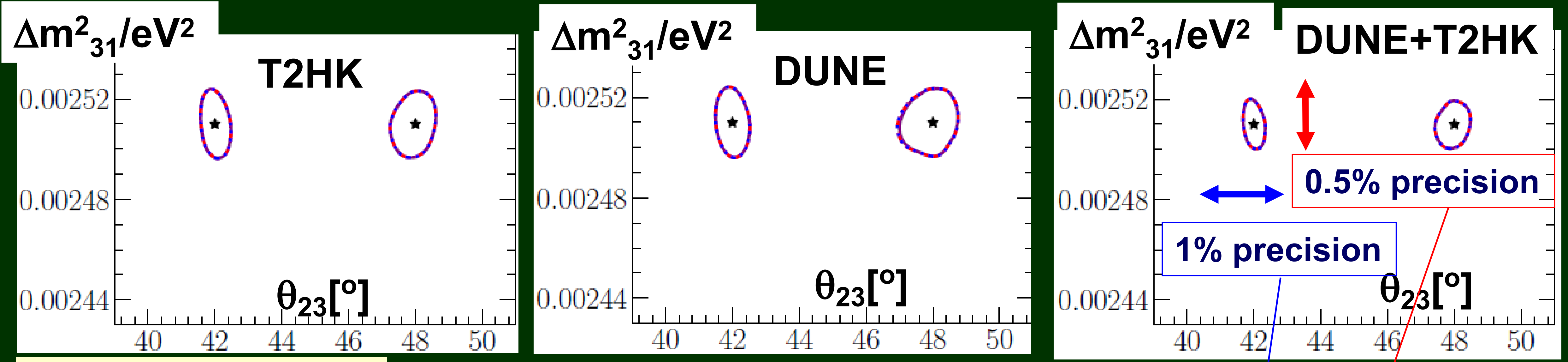
Ghosh-OY, NPB 989 ('23) 116142

Uncertainty in matter density taken into account

Precision of DUNE is slightly better than that of T2HK.
-> Combined precision is excellent.

Uncertainty in matter density has little effect
<- Major contribution comes from disappearance channel.

$\Delta\rho/\rho$=0%
$\Delta\rho/\rho$=5%
$\Delta\rho/\rho$=10%



$\Delta m^2_{31}/10^{-3}eV^2$ = (2.51+0.013-0.014)

θ_{23} = (42±0.5)°

(2.51+0.015-0.014)

(42±0.5)°

(2.51±0.01)

(42+0.4-0.3)°

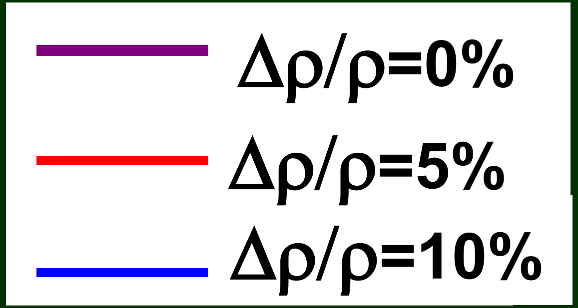
DUNE&T2HK vs Present status of global fit

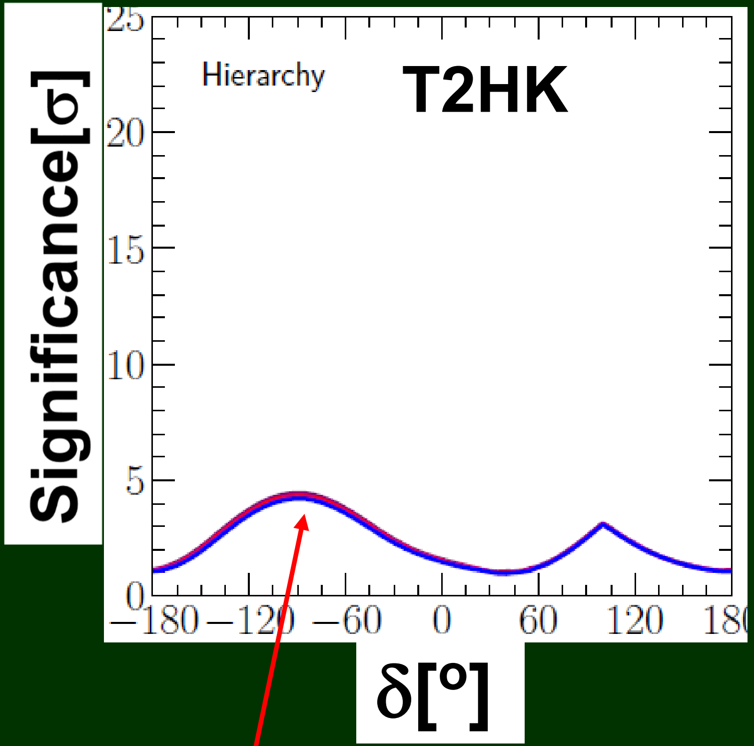
	Ref	$\Delta m^2_{31}/10^{-3}eV^2$	$\theta_{23}[^\circ]$
Global fit	www.nu-fit.org v5.2 (Nov. 2022)	$2.507^{+0.026}_{-0.027}$	$42.2^{+1.1}_{-0.9}$
Future exp	T2HK Ghosh-OY('23)	$2.510^{+0.013}_{-0.014}$	42.0 ± 0.5
	DUNE Ghosh-OY('23)	$2.510^{+0.015}_{-0.014}$	42.0 ± 0.5
	DUNE+T2HK Ghosh-OY('23)	2.510 ± 0.010	$42.0^{+0.4}_{-0.3}$

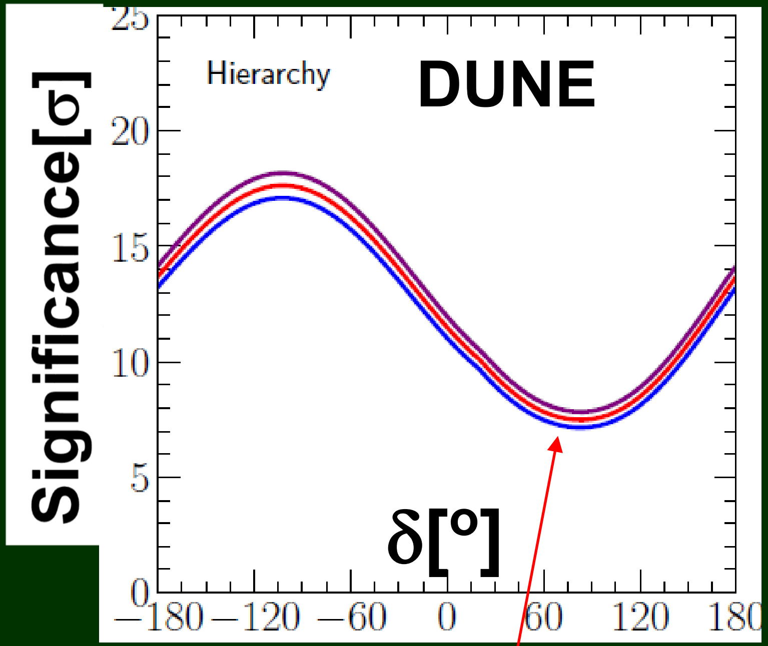
2.2 Sensitivity to Mass Ordering

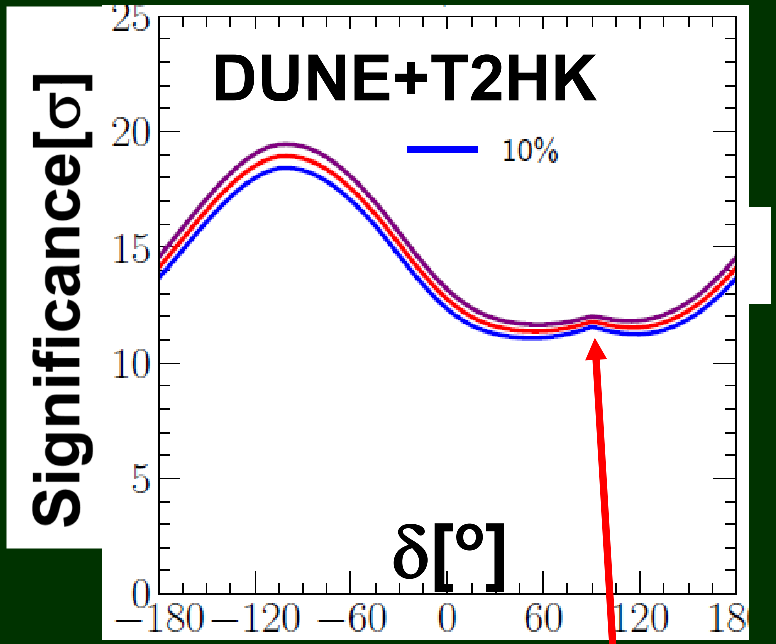
Ghosh-OY, NPB 989 ('23) 116142

Uncertainty in matter density has some effect on DUNE
<- DUNE has longer baseline L=1300km









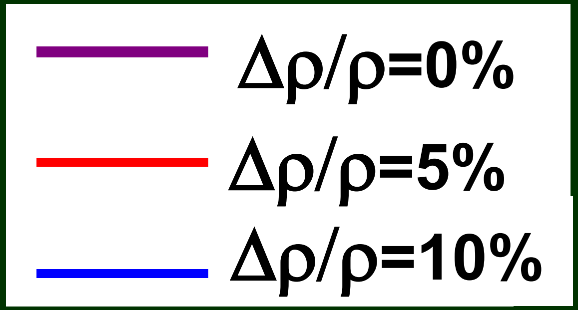
Sensitivity of T2HK is poor except for $\delta \sim -\pi/2$

Sensitivity of DUNE is excellent for any δ

Synergy of T2HK+DUNE at $\delta = \pi/2$: If MO is known from DUNE → Sensitivity of T2HK is improved

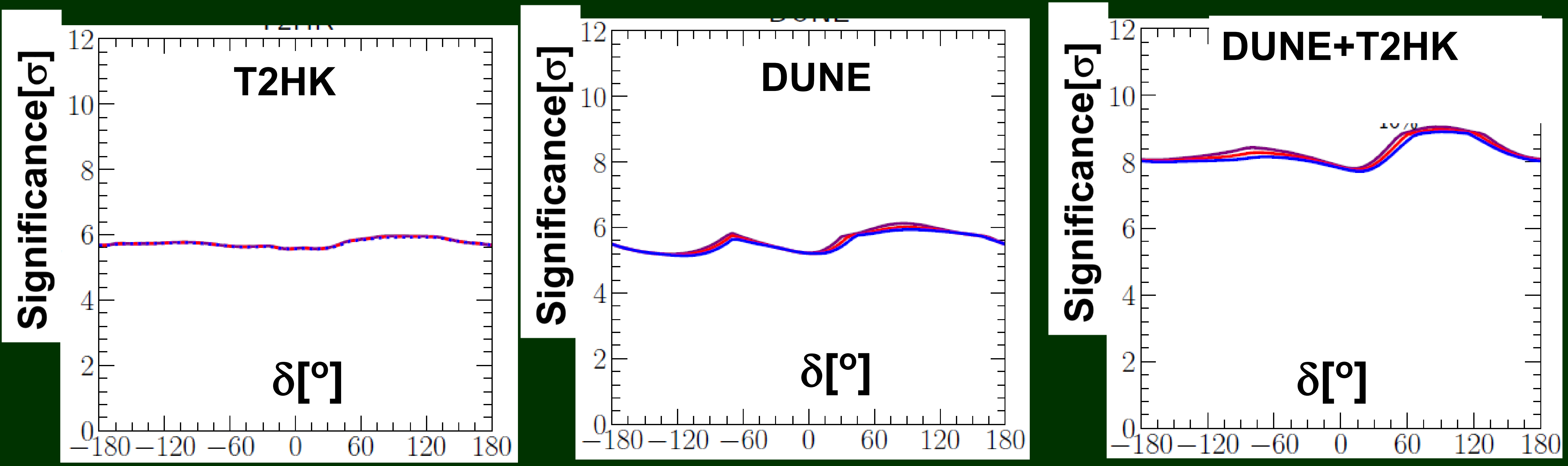
2.3 Sensitivity to Octant degeneracy

Ghosh-OY, NPB 989 ('23) 116142



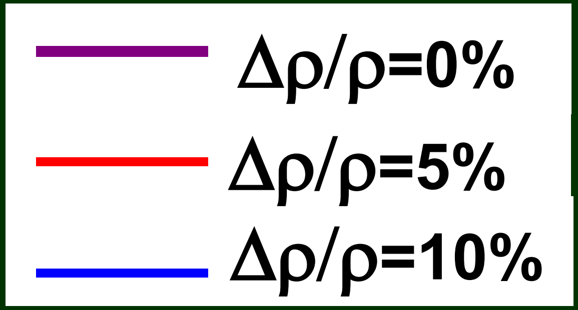
HO-LO Separation is possible for T2HK & DUNE w/ ν & $\overline{\nu}$ for most of δ

$$\theta_{23} = 42^\circ$$



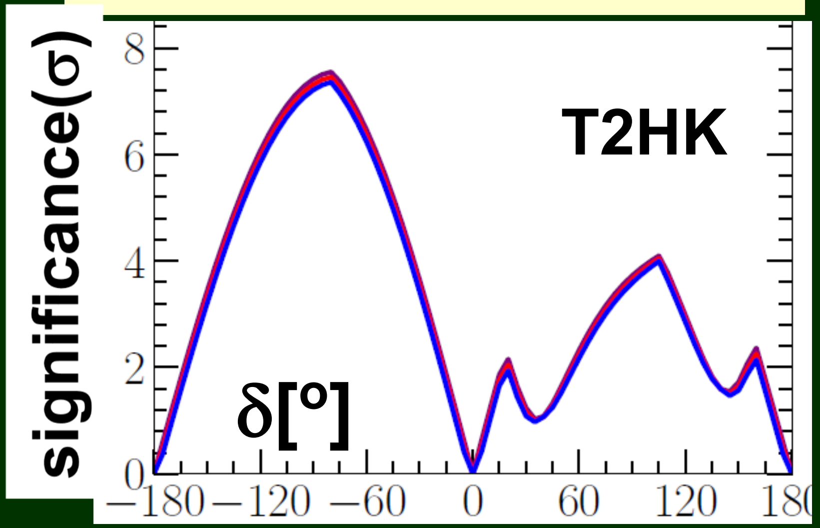
2.4 Sensitivity to CP(1)

Ghosh-OY, NPB 989 (‘23) 116142

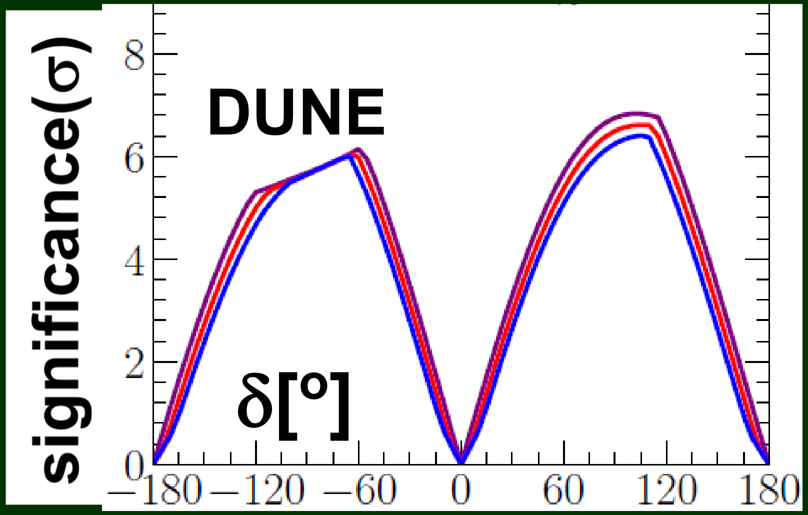


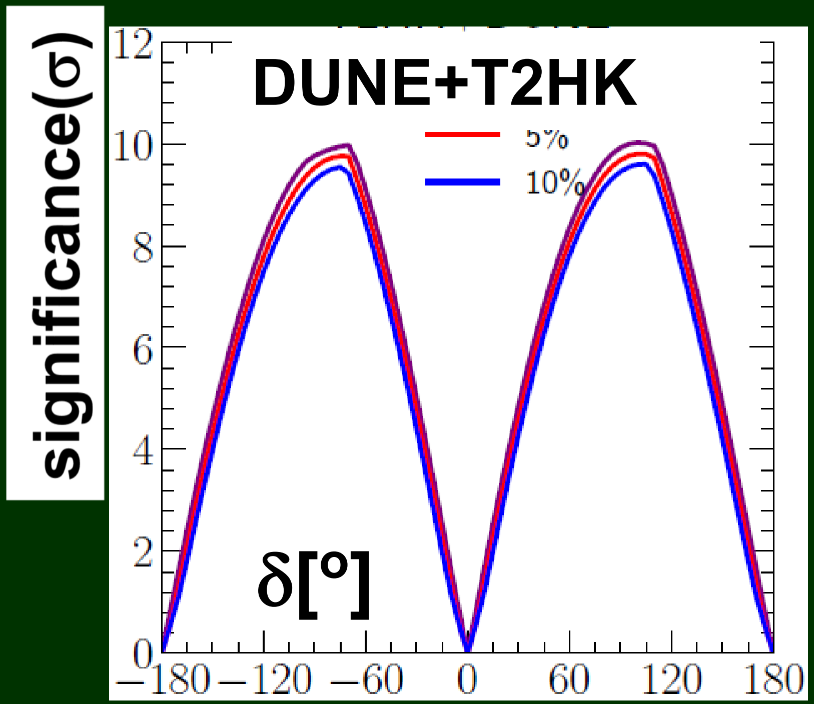
Uncertainty in matter density has some effect on DUNE.
<- DUNE has longer baseline L=1300km
However even with $\Delta\rho/\rho$=10%, the sensitivity is excellent.

Sensitivity of **T2HK** is poor for (NO, δ = + π/2) & (IO, δ = - π/2)



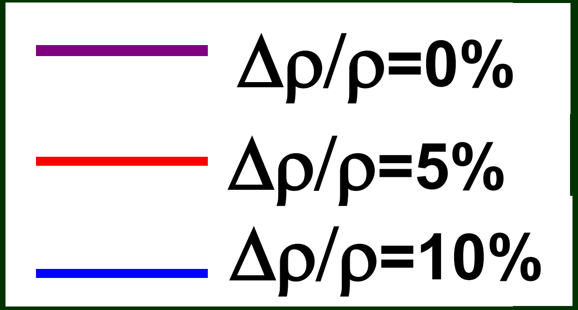
Sensitivity of **DUNE** is excellent for |sinδ|=1 for both mass hierarchy





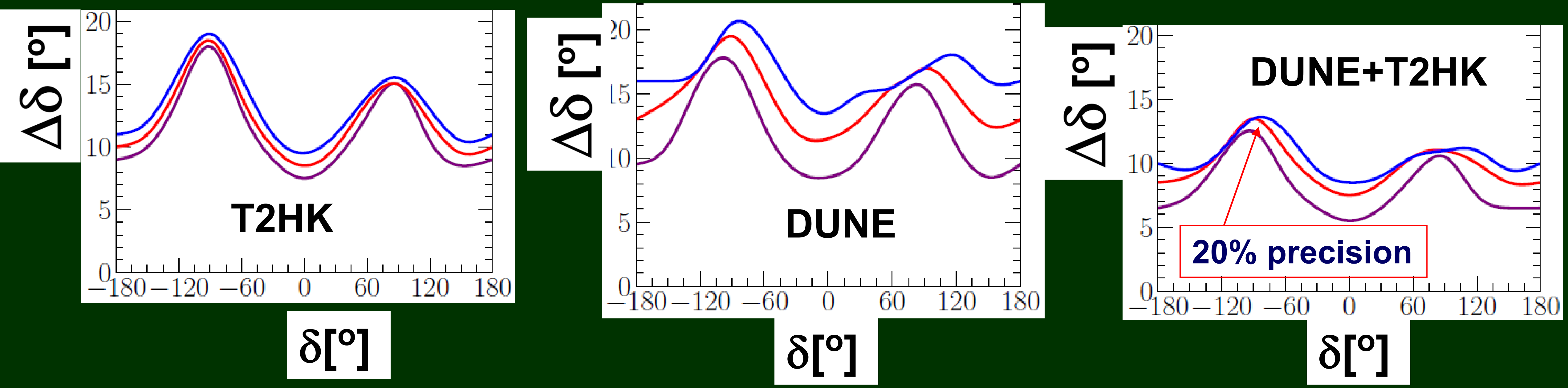
2.4 Sensitivity to CP(2)

Ghosh-OY, NPB 989 ('23) 116142



Uncertainty in matter density has some effect on the precision $\Delta\delta$ both for T2HK & DUNE.

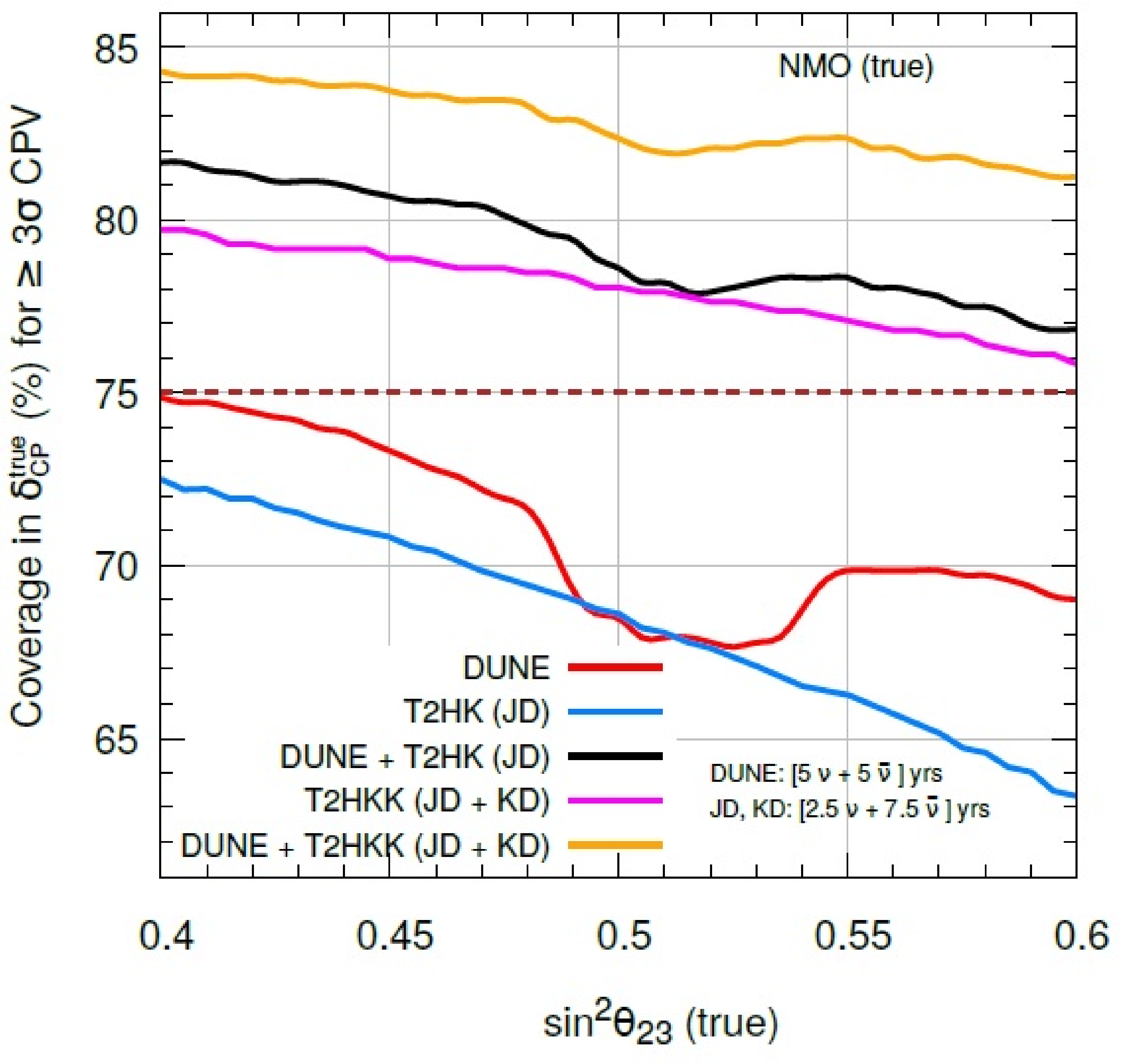
$\Delta\delta/\delta$ has mild dependence on δ but not much.



2.4 Sensitivity to CP(3)

Agarwalla, Das, Giarnetti, Meloni, Singh, 2211.10620 [hep-ph]

Coverage in δ (= the range of δ for which leptonic CPV can be established at 3σ) is the largest by combining T2HKK & DUNE.



For details, see talk by Masoom Singh on July 19.

3. Sensitivity to scenarios beyond the 3-flavor PMNS picture

Scenarios suggested by experiments:

- 3.1 sterile ν ⇐ LSND/MiniBooNE, Reactor/Gallium ν anomaly
- 3.2 NSI ⇐ Tension of Δm^2_{21} between solar ν and KamLAND

Scenarios which are not suggested by experiments:

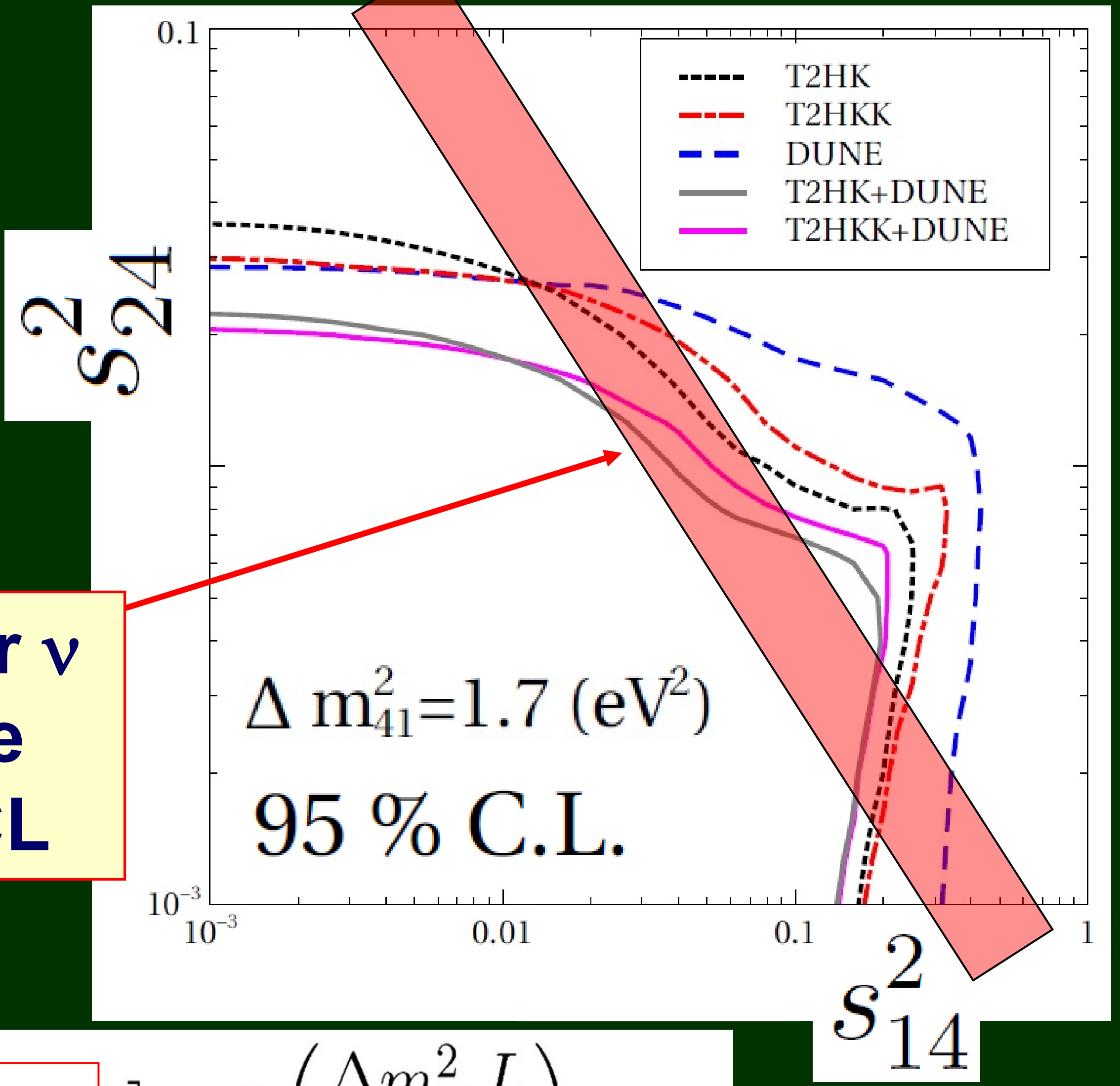
- 3.3 Scalar NSI
- 3.4 Flavor-dependent long-range interactions
- 3.5 Non-unitarity
- 3.6 Lorentz Invariance Violation

⇐ No affirmative hints for these, but discovery of these would give a clue for Physics Beyond the Standard Model

3.1 Sensitivity of T2HK & DUNE to Sterile ν

Choubey, Dutta, Pramanik, Eur.Phys.J.C78('18)4, 339

(1) Accelerator ν (T2HK, T2HKK, DUNE)



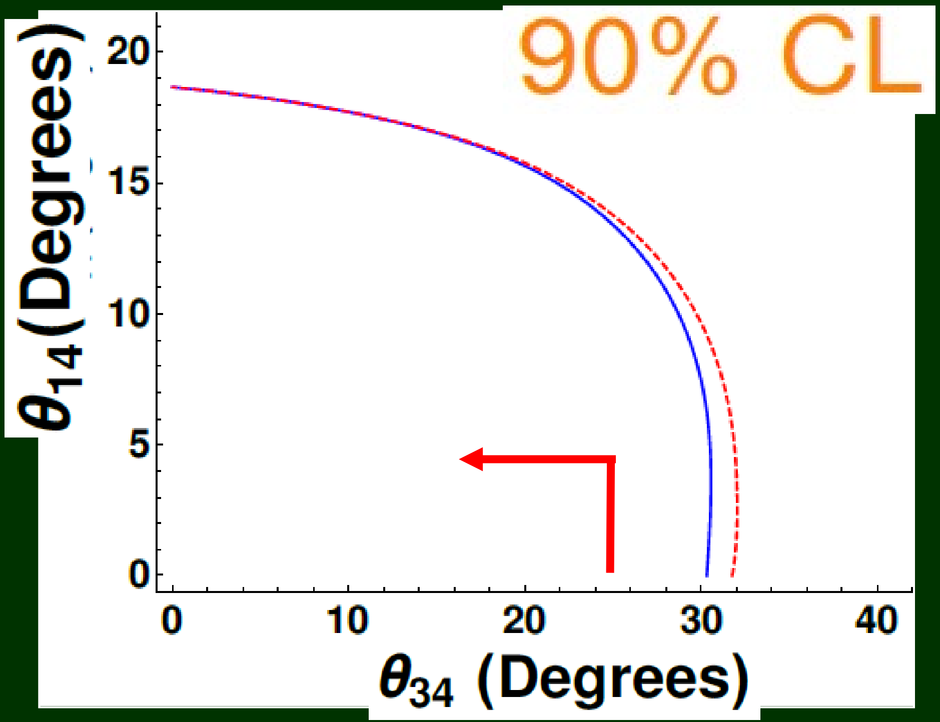
Combined accelerator ν can cover some of the LSND region @ 90%CL

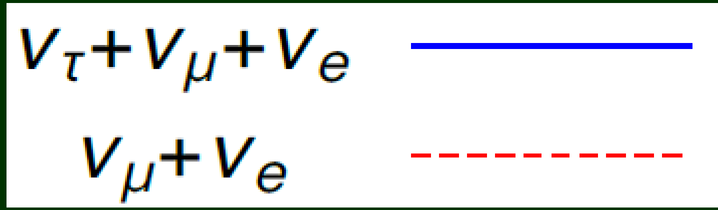
$$P(\nu_\mu \to \nu_e) = 4\mathrm{Re}\left[U_{e3}U^*_{\mu 3}(U^*_{e3}U_{\mu 3} + U^*_{e4}U_{\mu 4})\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$

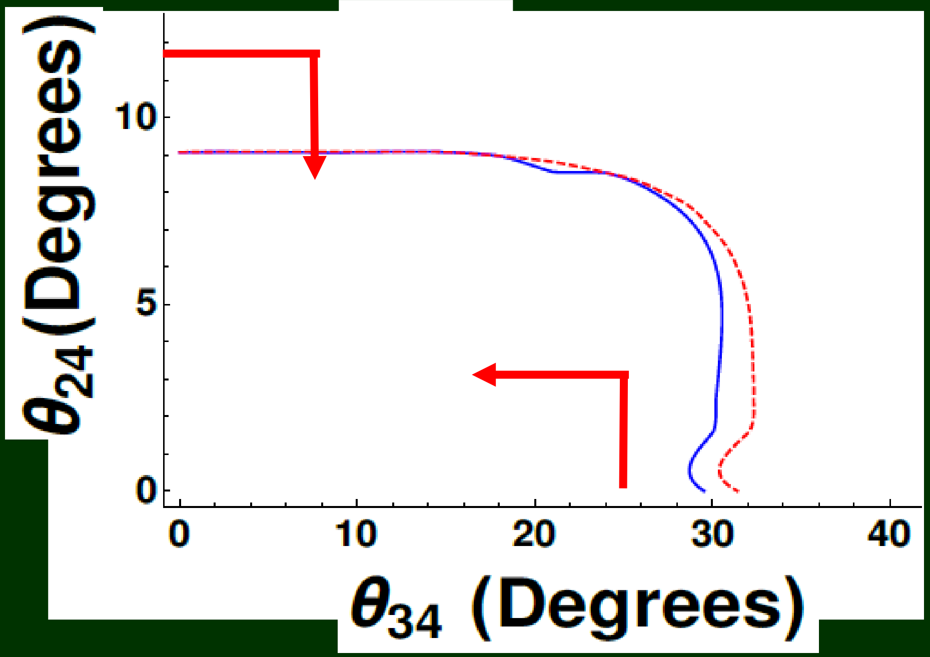
(2) Accelerator ν (DUNE w/ ν_τ)

Ghoshal-Giarnetti-Meloni, JHEP 12 (2019) 126

$\Delta m_{41}^2 = 1.0\ \mathrm{eV}^2$



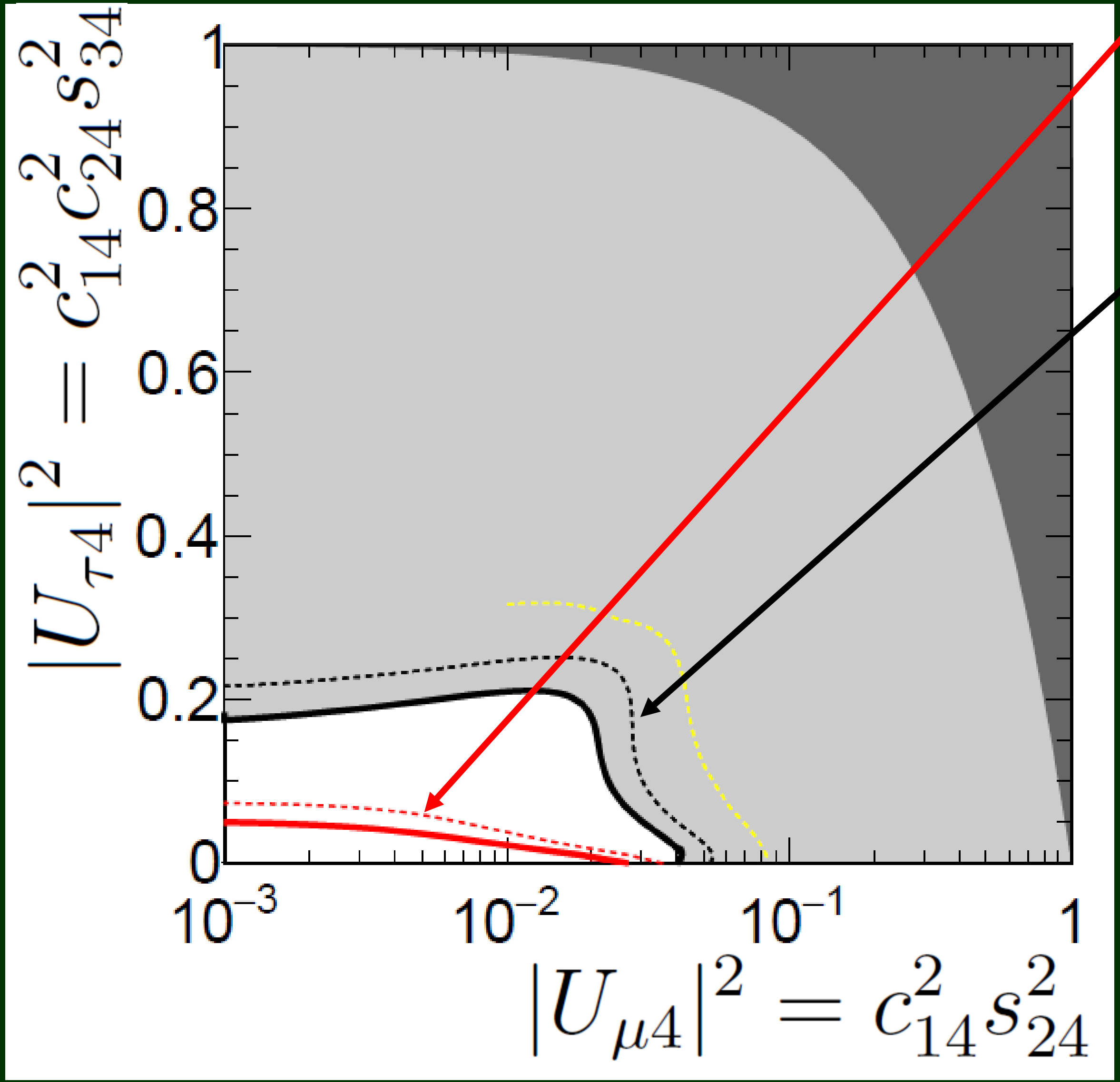




Accelerator ν has better (worse) sensitivity to θ_{24} (θ_{34}) than ν_{atm} (depicted by ↰)

(3) HK ν_{atm}

HK, arXiv:1805.04163v2



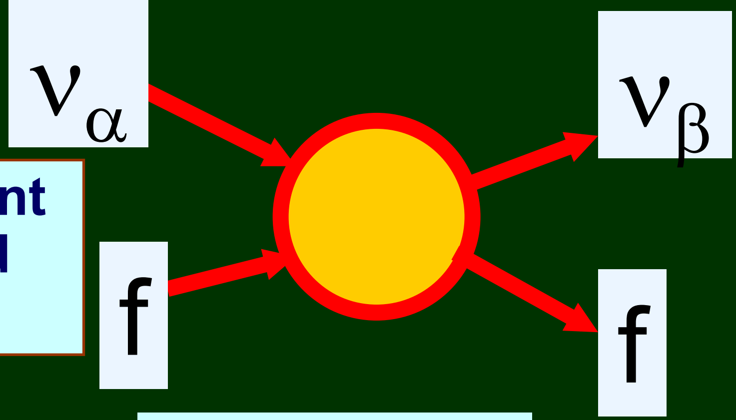
HK Sensitivity to θ_{34} (θ_{24}) is (is not much) improved compared to SK: 90% CL (solid) 99% CL (dashed)

3.2 Sensitivity of T2HK & DUNE to NSI

Phenomenological New Physics considered here: 4-fermi Non Standard Interactions:

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha \gamma^\mu \nu_\beta\, \bar{f}\gamma_\mu f'$$

neutral current non-standard interaction



f = e, u or d

Modification of matter effect

$A \equiv \sqrt{2} G_F N_e$ $\quad N_e \equiv$ electron density

$$\mathcal{A} \equiv \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} \epsilon_{ee}^f & \epsilon_{e\mu}^f & \epsilon_{e\tau}^f \\ \epsilon_{\mu e}^f & \epsilon_{\mu\mu}^f & \epsilon_{\mu\tau}^f \\ \epsilon_{\tau e}^f & \epsilon_{\tau\mu}^f & \epsilon_{\tau\tau}^f \end{pmatrix}$$

NP

Tension of Δm^2_{31} between solar ν and KamLAND may be accounted for by NSI.

CP-conserving Global fit (except T2K & NOvA appearance data) of NSI: Terrestrial ν basis

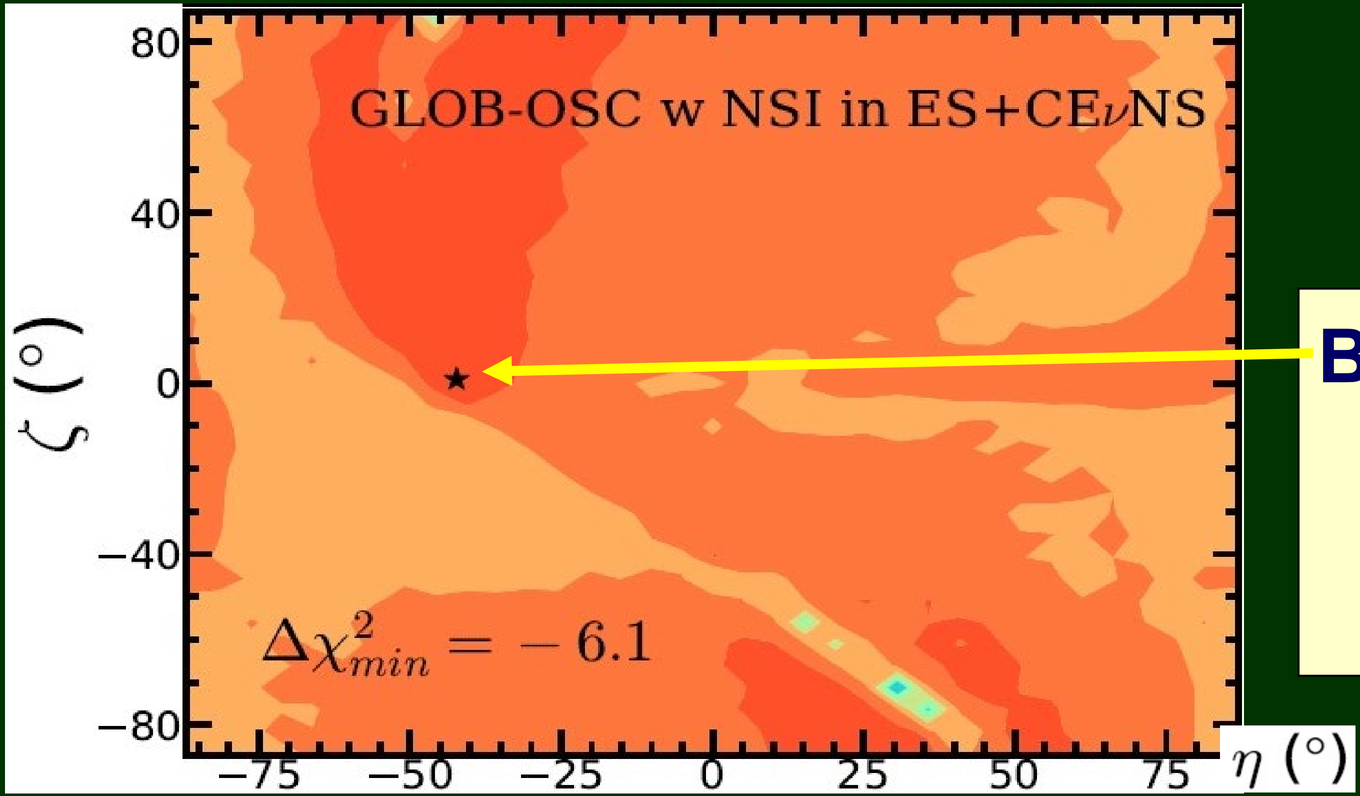
Coloma et al. arXiv:2305.07698v1 [hep-ph]

$$\mathcal{E}_{\alpha\beta}(x) = \varepsilon_{\alpha\beta}\left[\xi^e + \xi^p + Y_n(x)\xi^n\right] = \sqrt{5}\left[\cos\eta\left(\cos\zeta + \sin\zeta\right) + Y_n(x)\sin\eta\right]$$

$$= \sqrt{5}\left[\cos\eta' + Y_n(x)\sin\eta'\right]\varepsilon'_{\alpha\beta}$$

$$\tan\eta' \equiv \tan\eta \,/\, \left(\cos\zeta + \sin\zeta\right)$$

$$\varepsilon'_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}\sqrt{1 + \cos^2\eta\,\sin(2\zeta)}$$



To simplify the analysis, no extra CP phase are taken into account.

Best fit: $\zeta \sim 0$

$\eta \sim -43.6^{o} = \arctan(-1/Y_n)$

→ $\varepsilon_{\alpha\beta} \sim 0$

Before the work 1805.04530, fit only for the cases tanη=1/2 ($\varepsilon_{\alpha\beta}^d$=0; η=26.6°) and tanη=2 ($\varepsilon_{\alpha\beta}^u$=0; η=64.4°) were known.

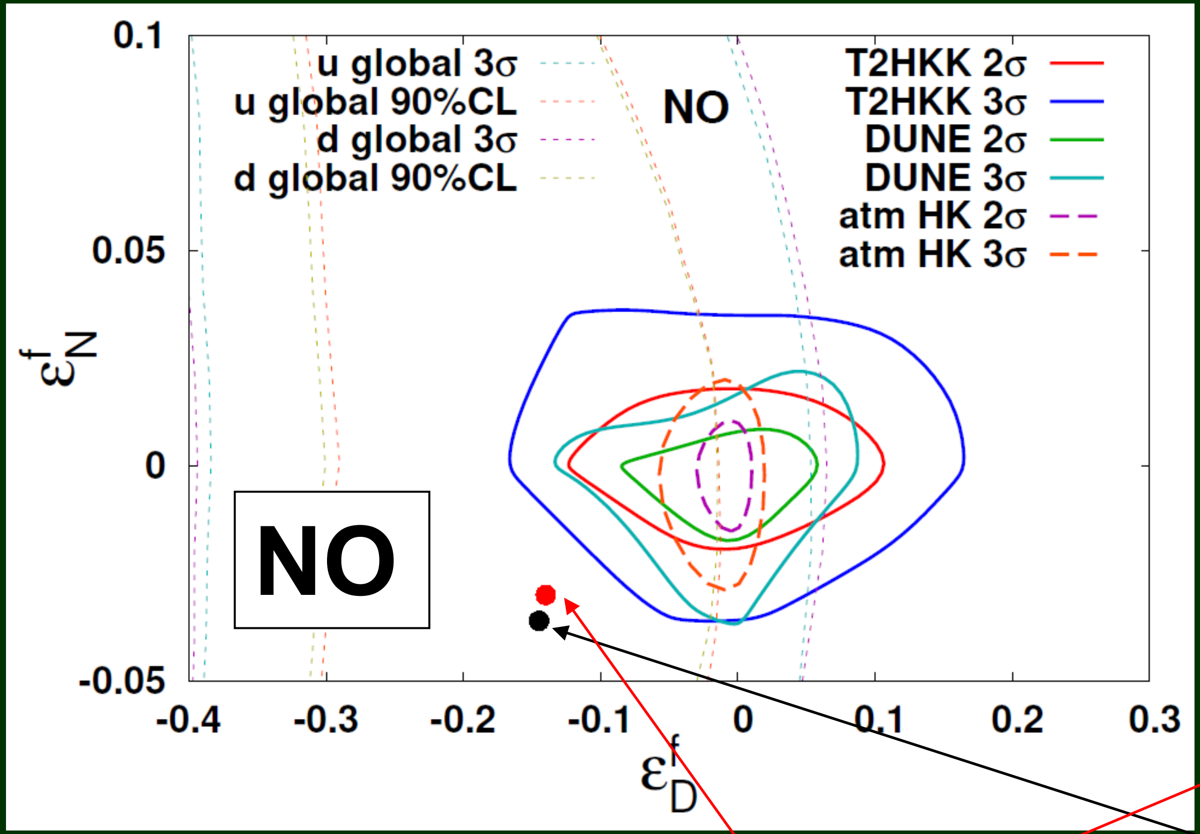
→On the next page, significance of NSI at DUNE, ν_{atm}@HK, T2HKK (possible extension of T2HK) is compared only the case for tanη=1/2 (ε^d=0; η=26.6°) and tanη=2 (ε^u=0; η=64.4°), assuming old design of HK (0.56 Mton fiducial volume x 12 yrs).

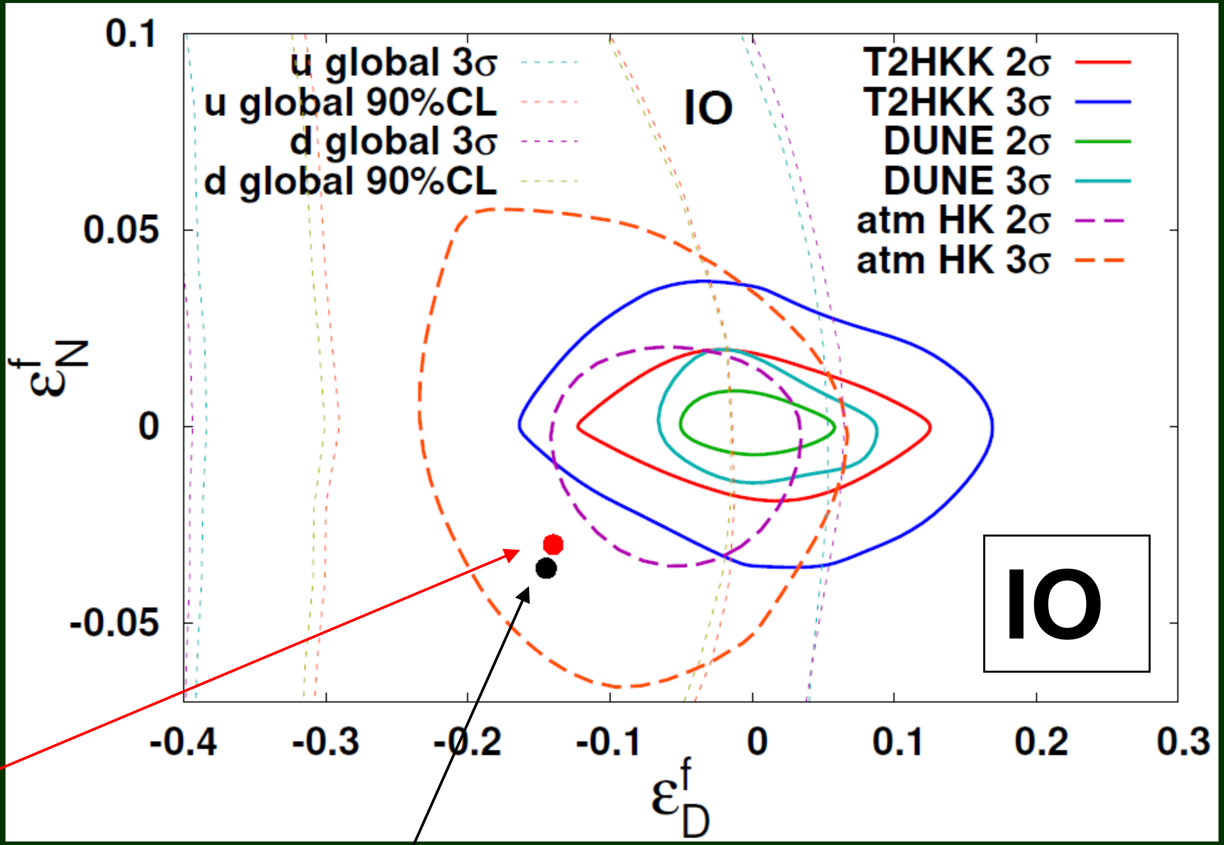
→After the work 1805.04530, the best fit is $\eta \sim \arctan(-1/Y_n) = -43.6°$, and LBL experiments are useless for this value because $\varepsilon_{\alpha\beta} \sim 0$.

→ Do the CP phases of $\varepsilon_{\alpha\beta}$, which were ignored in the analysis, change the best fit point $\eta \sim -43.6°$?

●Comparison of sensitivity T2HKK, DUNE, ν_{atm}@HK

Ghosh & OY, MPL A35 ('20) 17, 2050142





Best fit point of glolal analysis for tanη=1/2 (ε^d=0; η=26.6°)

Best fit point of glolal analysis for tanη=2 (ε^u=0; η=64.4°)

In the case of NO, ν_{atm}@HK is the best

In the case of IO, DUNE is the best

3.3 Sensitivity of T2HK & DUNE to Scalar NSI

Medhi, Devi, Dutta, JHEP 01 (2023) 079

$$\mathcal{L}_{\text{eff}}^{\text{S}} = \frac{y_f y_{\alpha\beta}}{m_\phi^2}(\bar{\nu}_\alpha \nu_\beta)(\bar{f} f)$$

$$\mathcal{H} \approx E_\nu + \frac{(M + \delta M)(M + \delta M)^\dagger}{2E_\nu} \pm V_{\text{SI}}$$

$$\delta \widetilde{M} \equiv \sqrt{\Delta m_{31}^2} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}$$

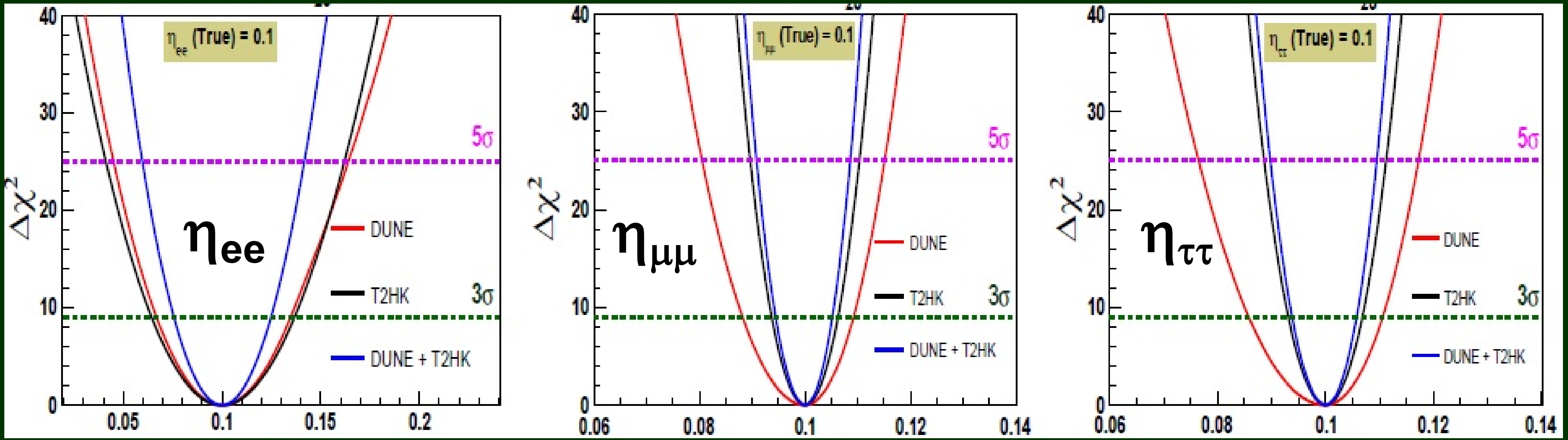
To simplify the analysis, only three cases were considered:

$\delta \widetilde{M} \propto$ **diag(η_{ee},0,0), diag(0,$\eta_{\mu\mu}$,0), diag(0,0,$\eta_{\tau\tau}$)**

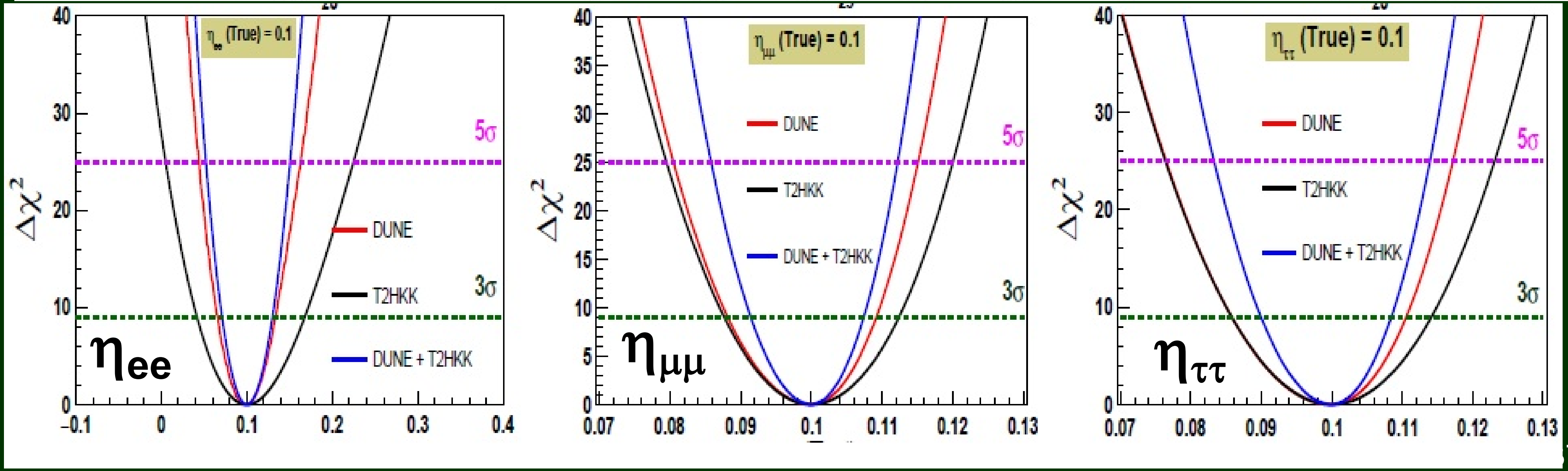
Reference value: NO, $\theta_{23} = 47^o$, $\delta = -90^o$, $\eta_{\alpha\alpha} = 0.1$ ($\alpha = e, \mu, \tau$)

Medhi, Devi, Dutta, JHEP 01 (2023) 079

T2HK & DUNE



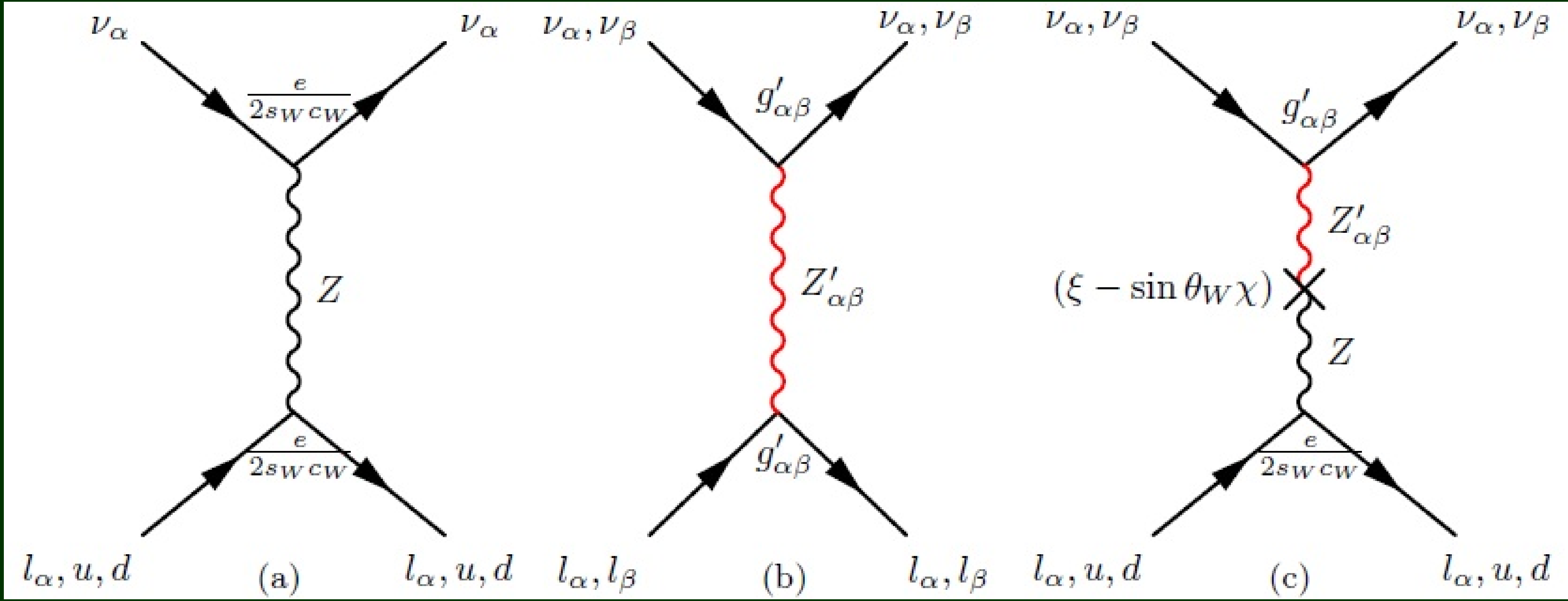
T2HKK & DUNE



3.4 Sensitivity of T2HK & DUNE to Flavor-dependent long-range neutrino interactions

Singh, Bustamante, Agarwalla, 2305.05184 [hep-ph]

A possible flavor dependent long-range force, mediated by a very light gauge boson, between neutrinos and astrophysical objects (Earth, Moon, Sun, Milky Way, the cosmological distribution of matter in the local Universe) is considered.



Singh, Bustamante, Agarwalla, 2305.05184 [hep-ph]

$$\mathbf{H} = \mathbf{H}_{\text{vac}} + \mathbf{V}_{\text{mat}} + \mathbf{V}_{\alpha\beta}$$

$$\mathbf{H}_{\text{vac}} = \frac{1}{2E}\mathbf{U}\ \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)\ \mathbf{U}^\dagger$$

$$\mathbf{V}_{\text{mat}} = \text{diag}(V_{\text{CC}}, 0, 0)$$

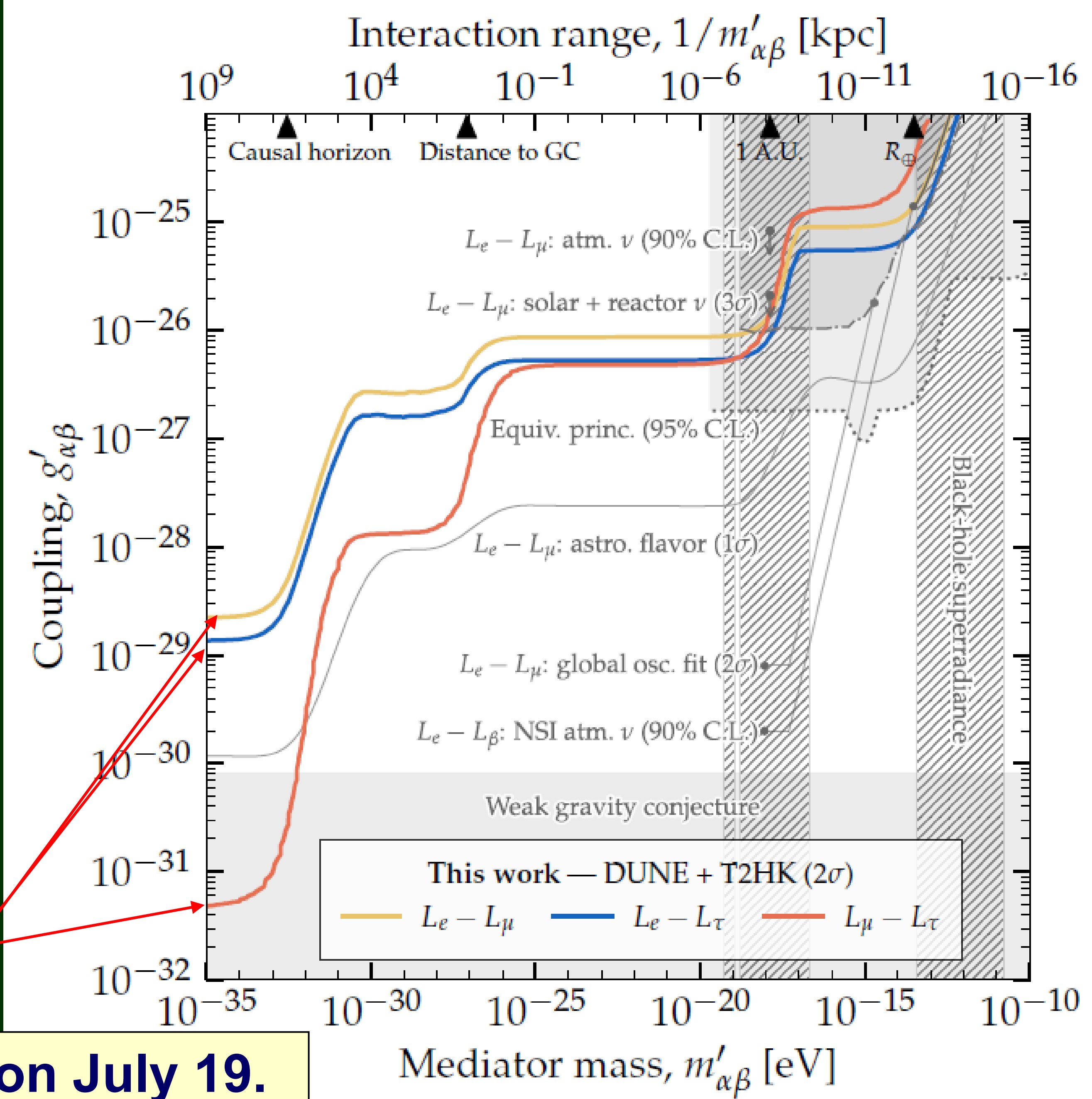
$$\mathbf{V}_{\alpha\beta} = \begin{cases} \text{diag}(V_{e\mu}, -V_{e\mu}, 0), & \text{for } \alpha, \beta = e, \mu \\ \text{diag}(V_{e\tau}, 0, -V_{e\tau}), & \text{for } \alpha, \beta = e, \tau \\ \text{diag}(0, V_{\mu\tau}, -V_{\mu\tau}), & \text{for } \alpha, \beta = \mu, \tau \end{cases}$$

$$V_{\alpha\beta} = V_{\alpha\beta}^{\oplus} + V_{\alpha\beta}^{☾} + V_{\alpha\beta}^{\odot} + V_{\alpha\beta}^{\text{MW}} + V_{\alpha\beta}^{\text{cos}}$$

$$V_{\alpha\beta} \propto \frac{1}{r}\exp\left(-r m'_{\alpha\beta}\right)$$

very light

T2HK + DUNE gives strong bound

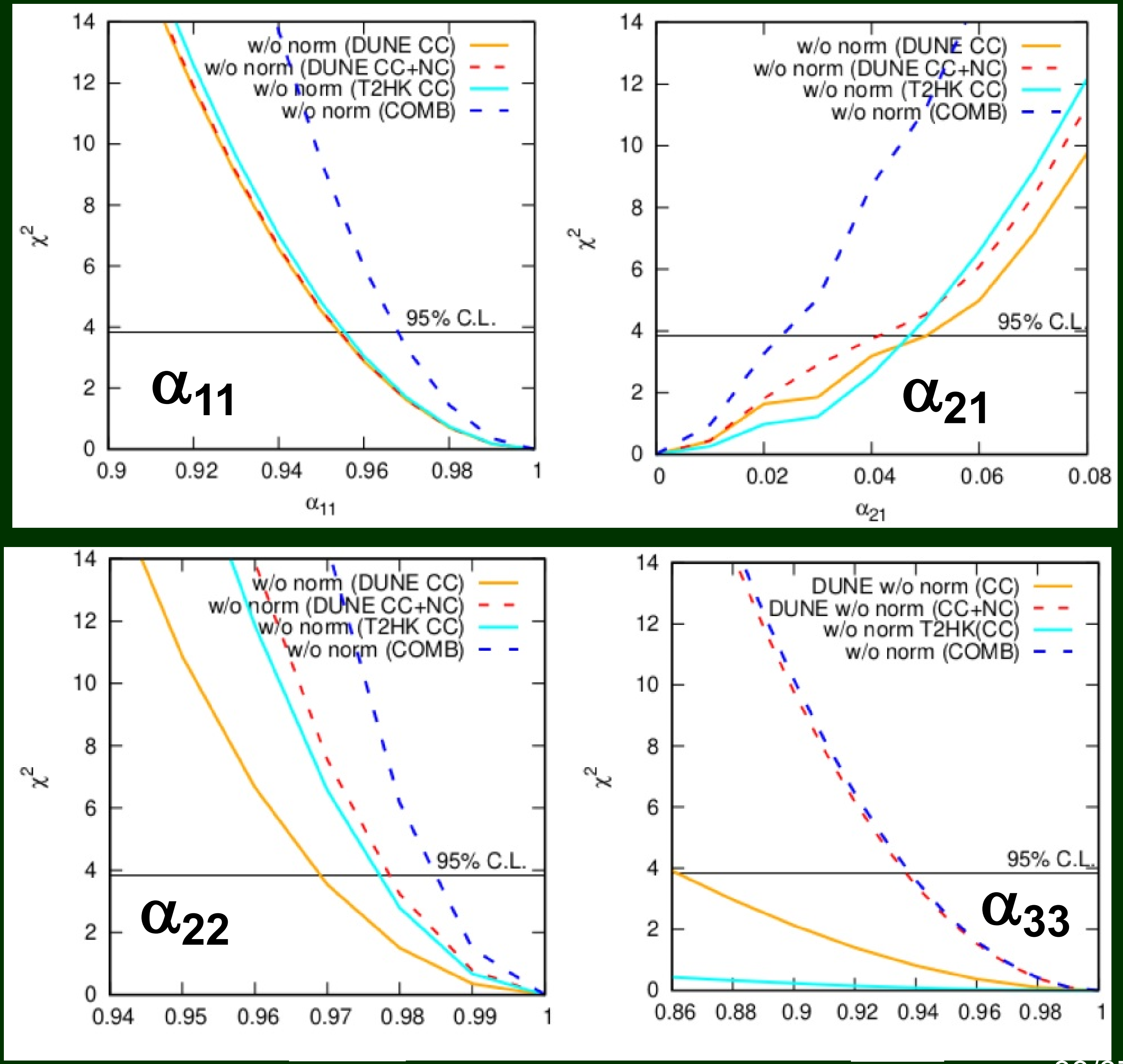


For details, see talk by Masoom Singh on July 19.

3.5 Sensitivity of T2HK & DUNE to Non-unitarity

Dutta, Roy, J.Phys.G 48 (2021) 4, 045004

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



Sensitivity of T2HK & DUNE is comparable except for α_{33}.

See also talk by Sudipta Das on July 19.

3.6 Sensitivity of T2HK & DUNE to Lorentz Invariance Violation

Agarwalla, Das, Sahoo, Swain, 2302.12005 [hep-ph]

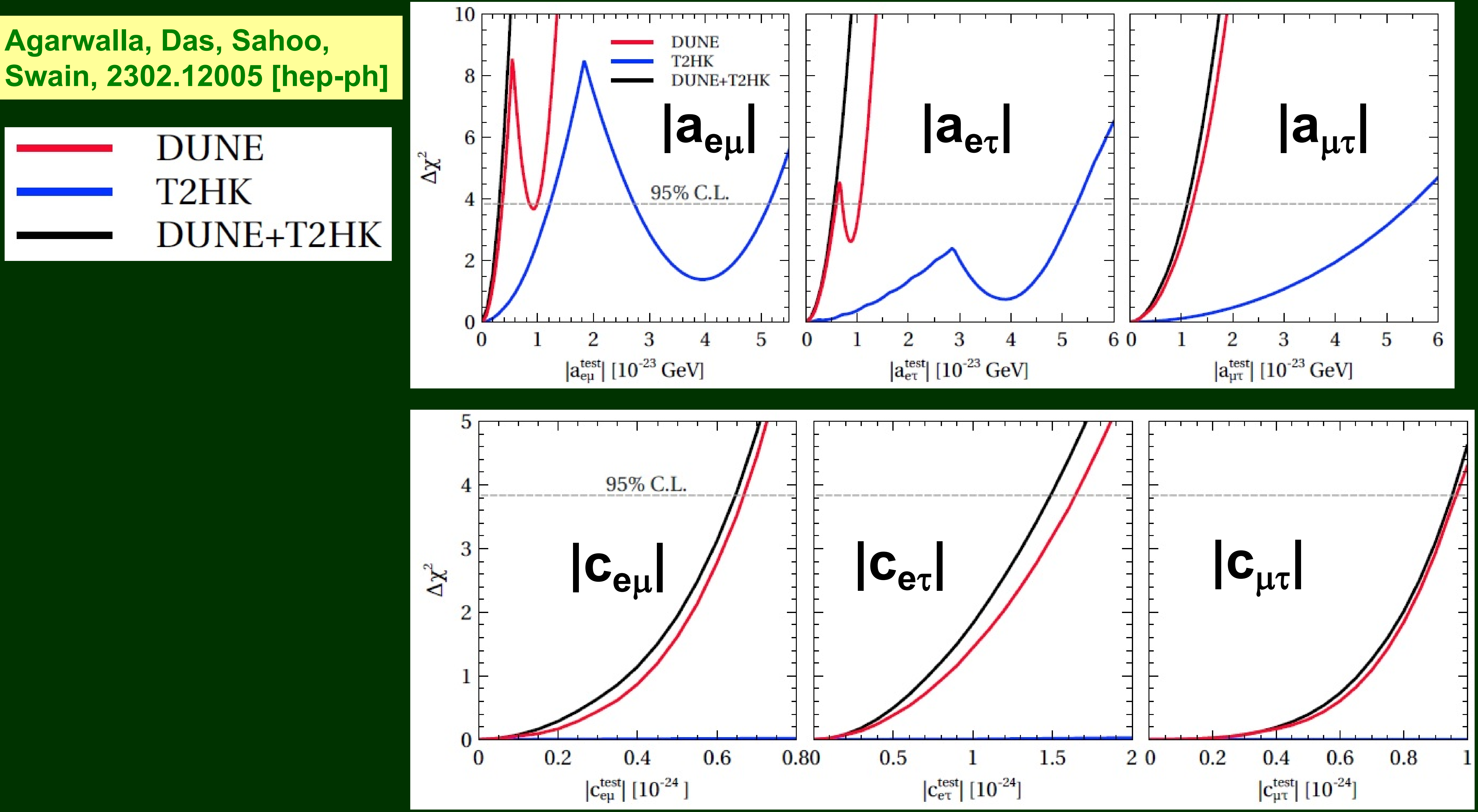
$$H = UMU^\dagger + V_e + H_{\rm LIV}$$

$$H_{\rm LIV} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^\star_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^\star_{e\tau} & a^\star_{\mu\tau} & a_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^\star_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^\star_{e\tau} & c^\star_{\mu\tau} & c_{\tau\tau} \end{pmatrix}$$

independent of energy & matter density

proportional to energy

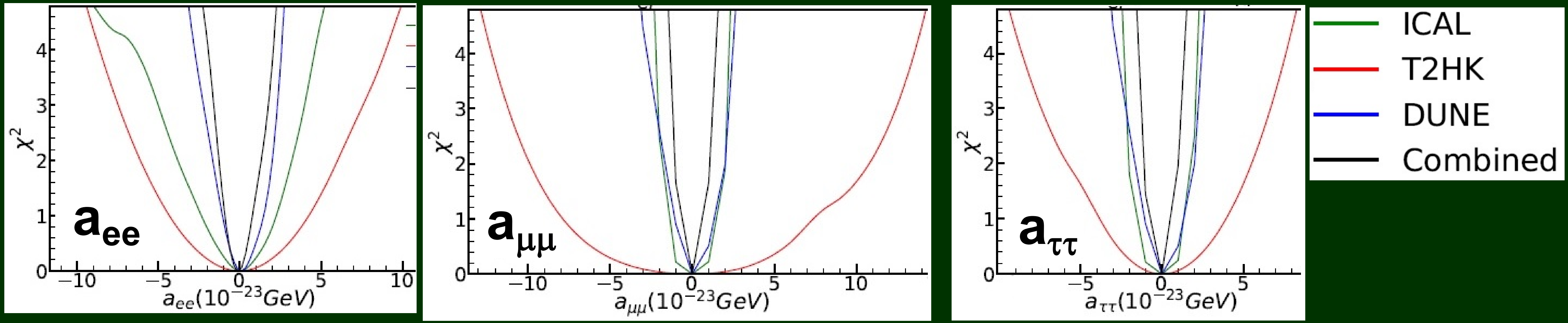
Agarwalla, Das, Sahoo, Swain, 2302.12005 [hep-ph]



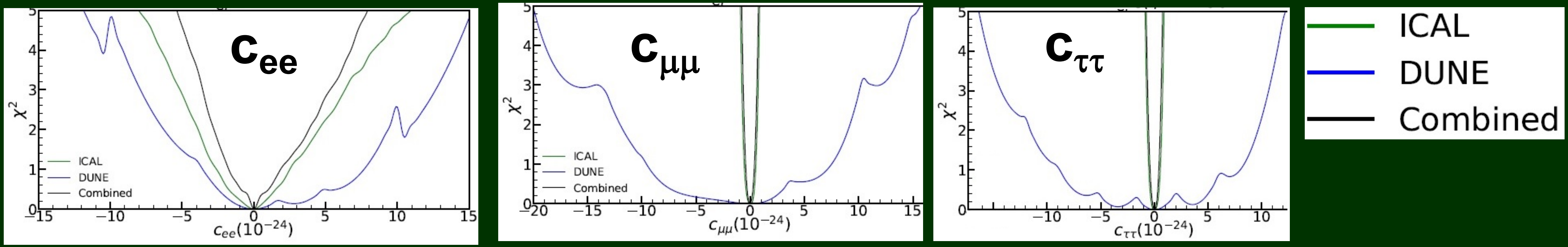
For details, see talk by Sadashiv Sahoo on July 19.

Raikwala, Choubey, Ghosh, 2303.10892v1 [hep-ph]

Sensitivity to $a_{\alpha\alpha}$ (independent of E): ICAL > DUNE > T2HK



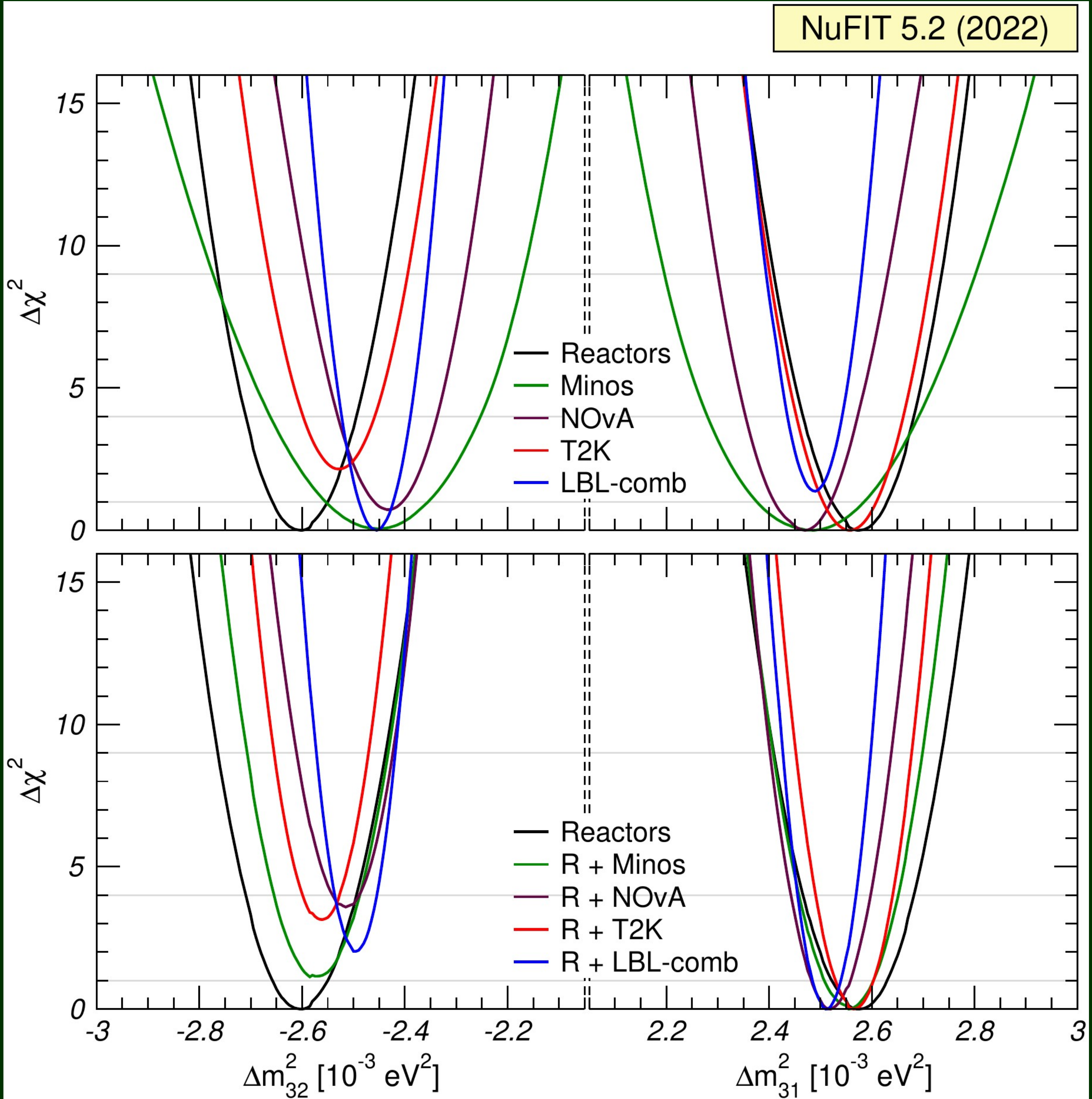
Sensitivity to $c_{\alpha\alpha}$ (proportional to E): ICAL >> DUNE >> T2HK



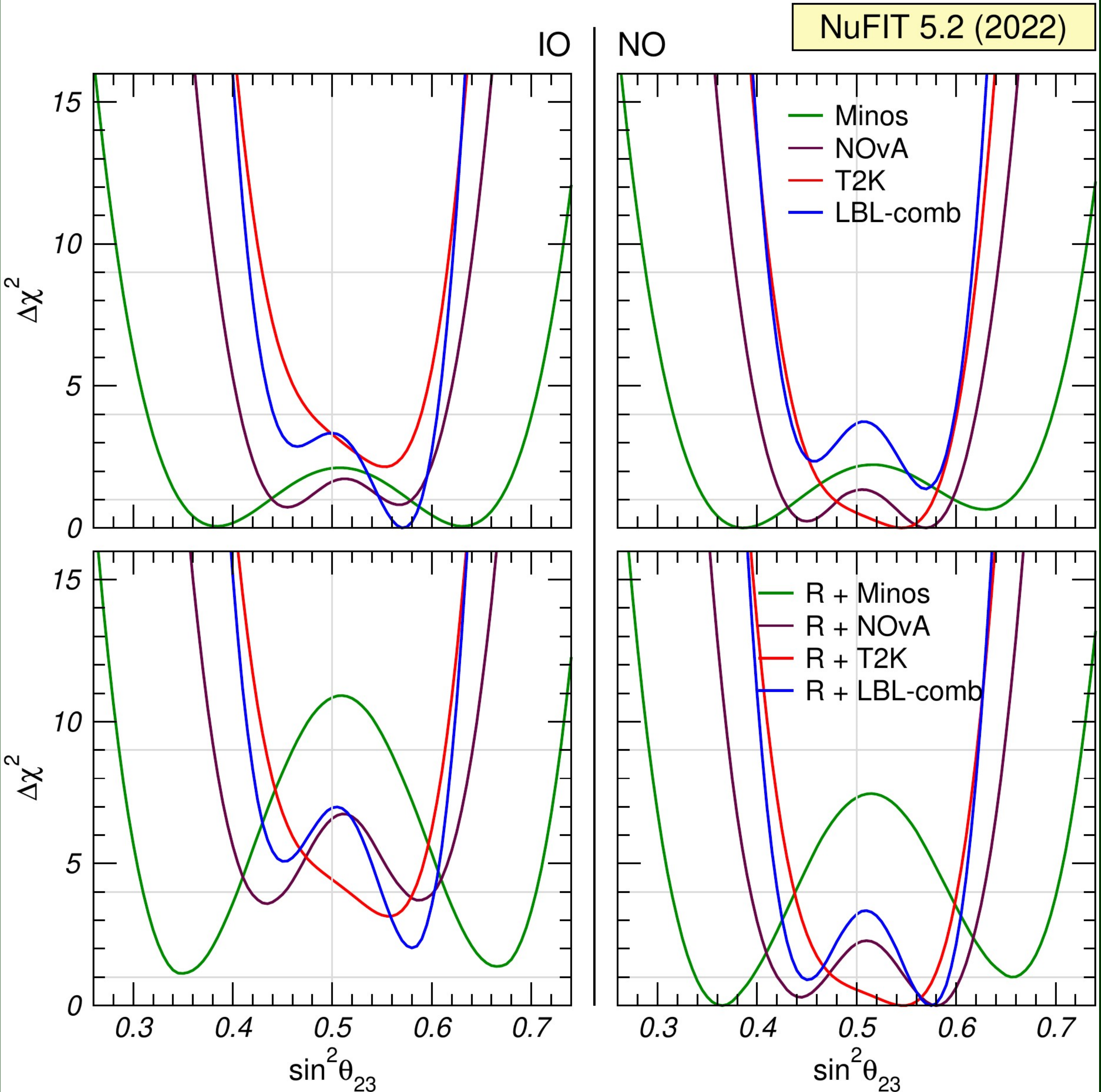
4. Conclusions

- Precision measurements of mixing angles, mass ordering and CP phase are important for research on Physics Beyond SM.
- Resolution of parameter degeneracy can be possible by combining ν & $\bar{\nu}$ at T2HK & DUNE.
- Measurements of anti-neutrino appearance are in general important to lift degeneracy.
- T2HK+DUNE gives us excellent precision in θ_{23} (1%), Δm_{32}^2 (0.5%), δ (20%).
- HK+DUNE have some sensitivity to scenarios beyond std PMNS (ν_s, scalar NSI, long-range force, Lorentz Invariance Violation, etc).
- For the best fit η=-43.6°, LBL has no sensitivity to NSI, which is suggested by the solar ν tension.

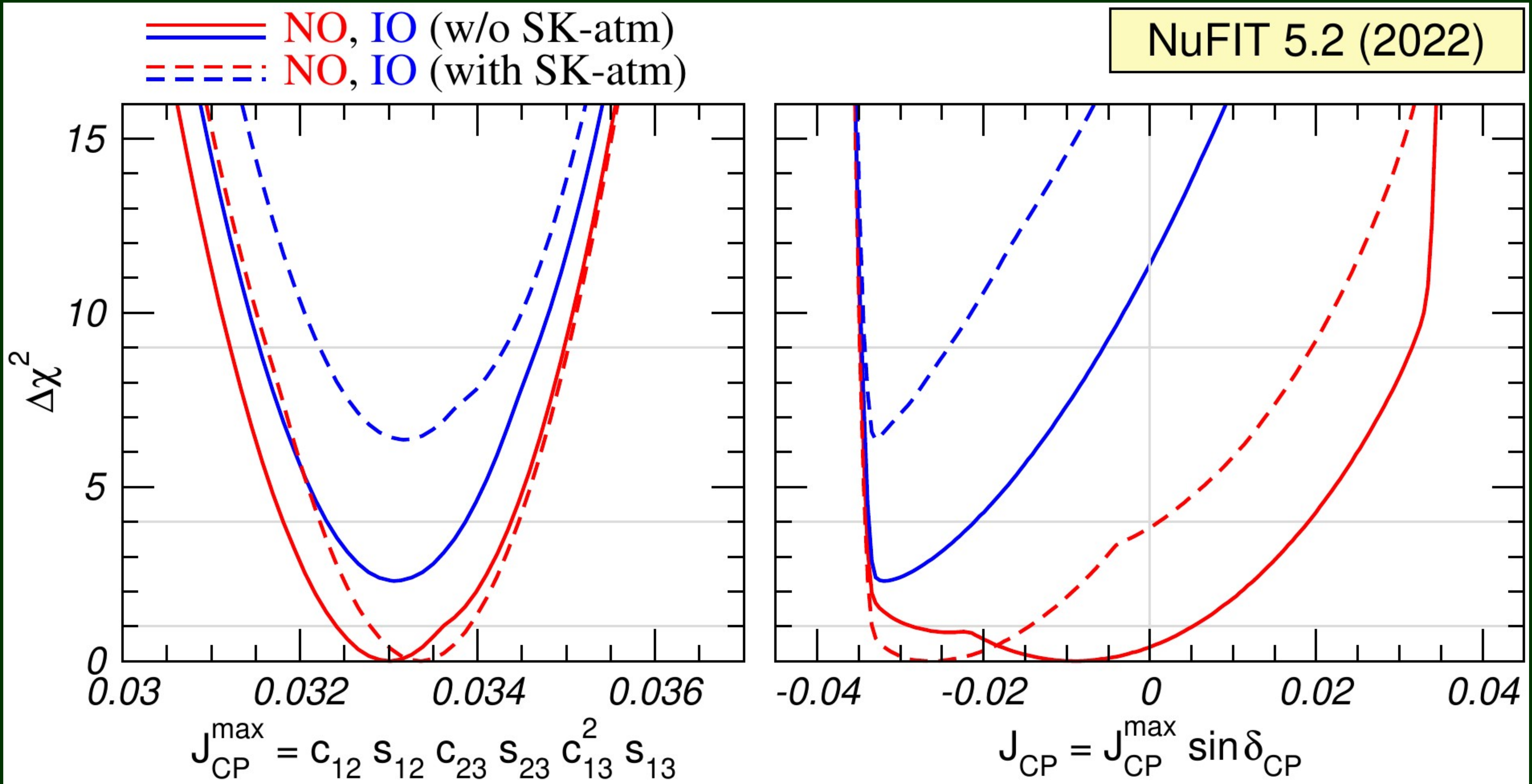
Backup slides



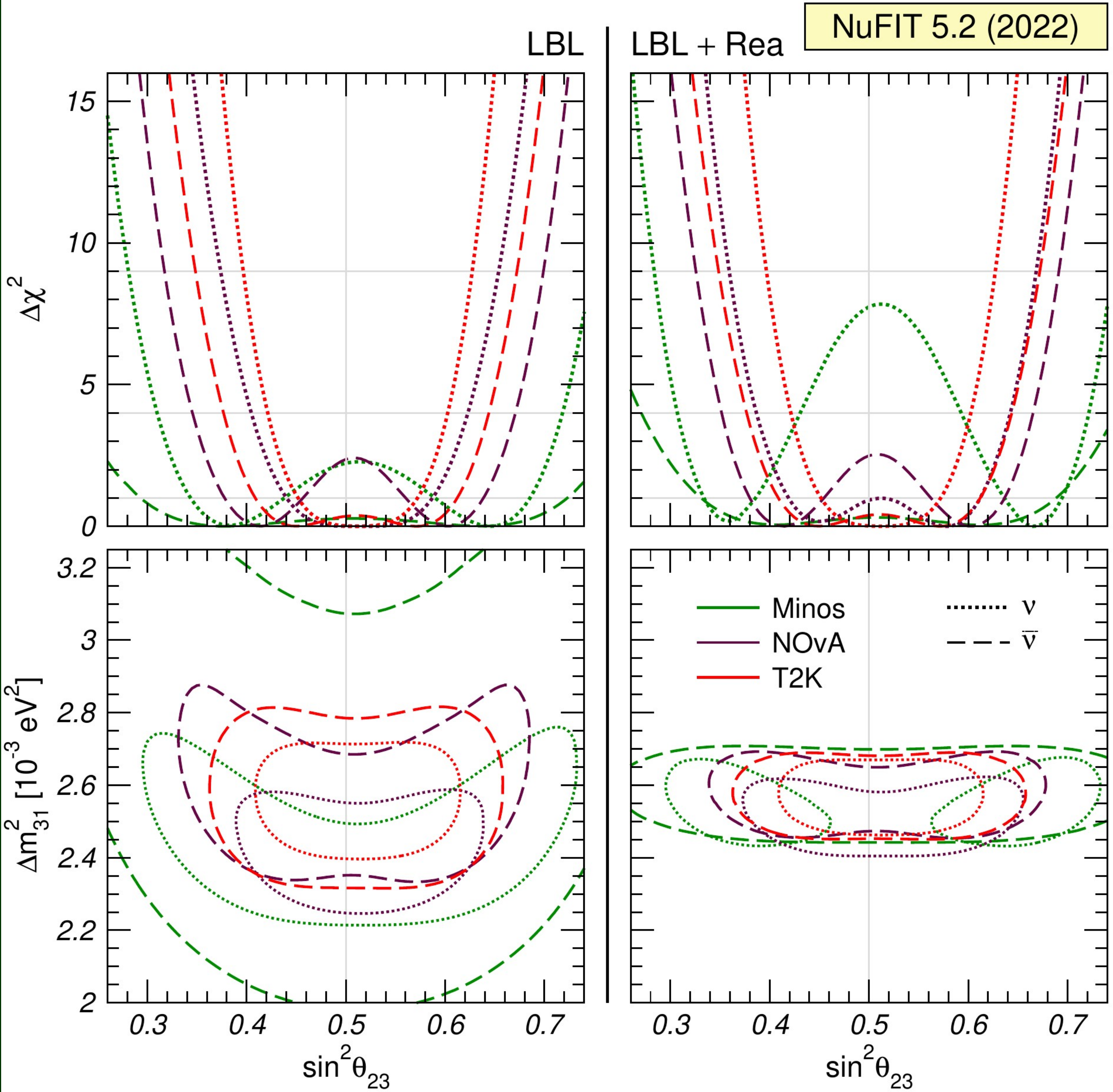
NuFIT 5.2 (2022)
Reactors
Minos
NOvA
T2K
LBL-comb
R + Minos
R + NOvA
R + T2K
R + LBL-comb
$\Delta\chi^2$
Δm^2_{32} [10^{-3} eV^2]
Δm^2_{31} [10^{-3} eV^2]



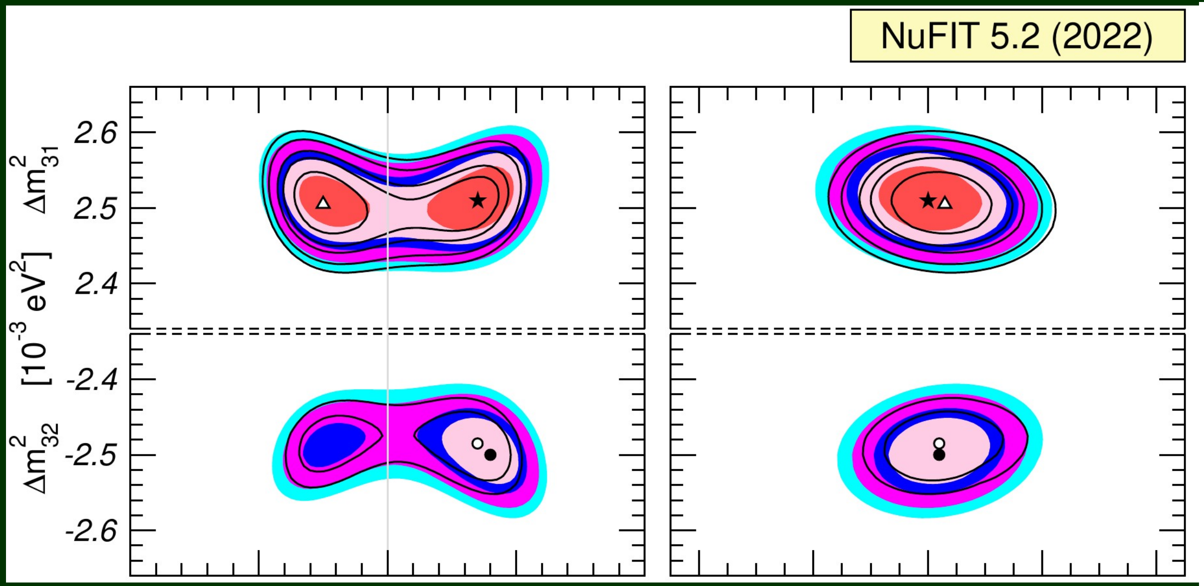
NuFIT 5.2 (2022)
IO
NO
Minos
NOvA
T2K
LBL-comb
R + Minos
R + NOvA
R + T2K
R + LBL-comb
$\Delta\chi^2$
$\sin^2\theta_{23}$
0
5
10
15
0.3
0.4
0.5
0.6
0.7

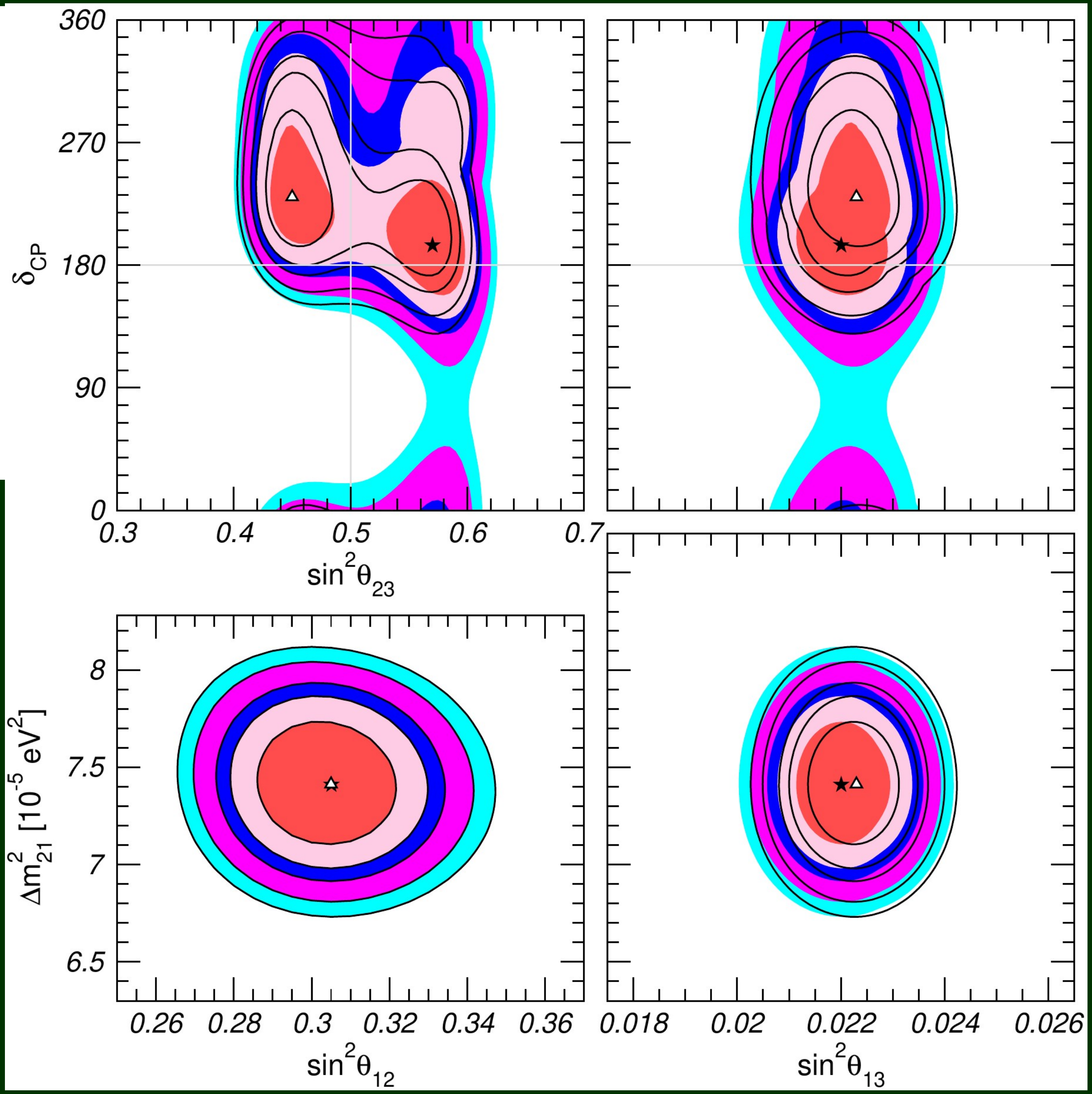


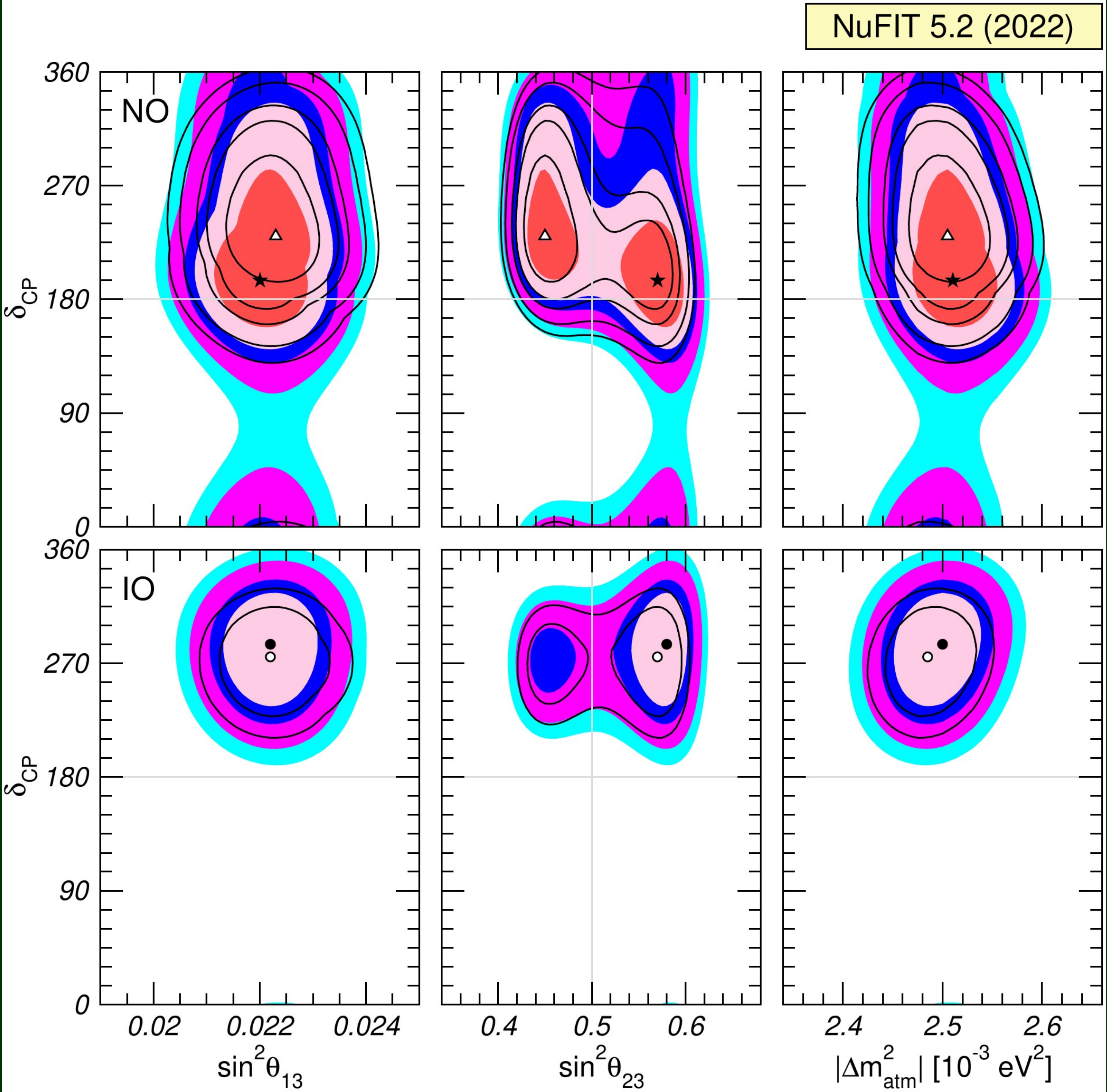
NO, IO (w/o SK-atm)
NO, IO (with SK-atm)
NuFIT 5.2 (2022)
15
10
5
0
$\Delta\chi^2$
0.03
0.032
0.034
0.036
$J_{CP}^{max} = c_{12}\, s_{12}\, c_{23}\, s_{23}\, c_{13}^2\, s_{13}$
-0.04
-0.02
0
0.02
0.04
$J_{CP} = J_{CP}^{max} \sin\delta_{CP}$

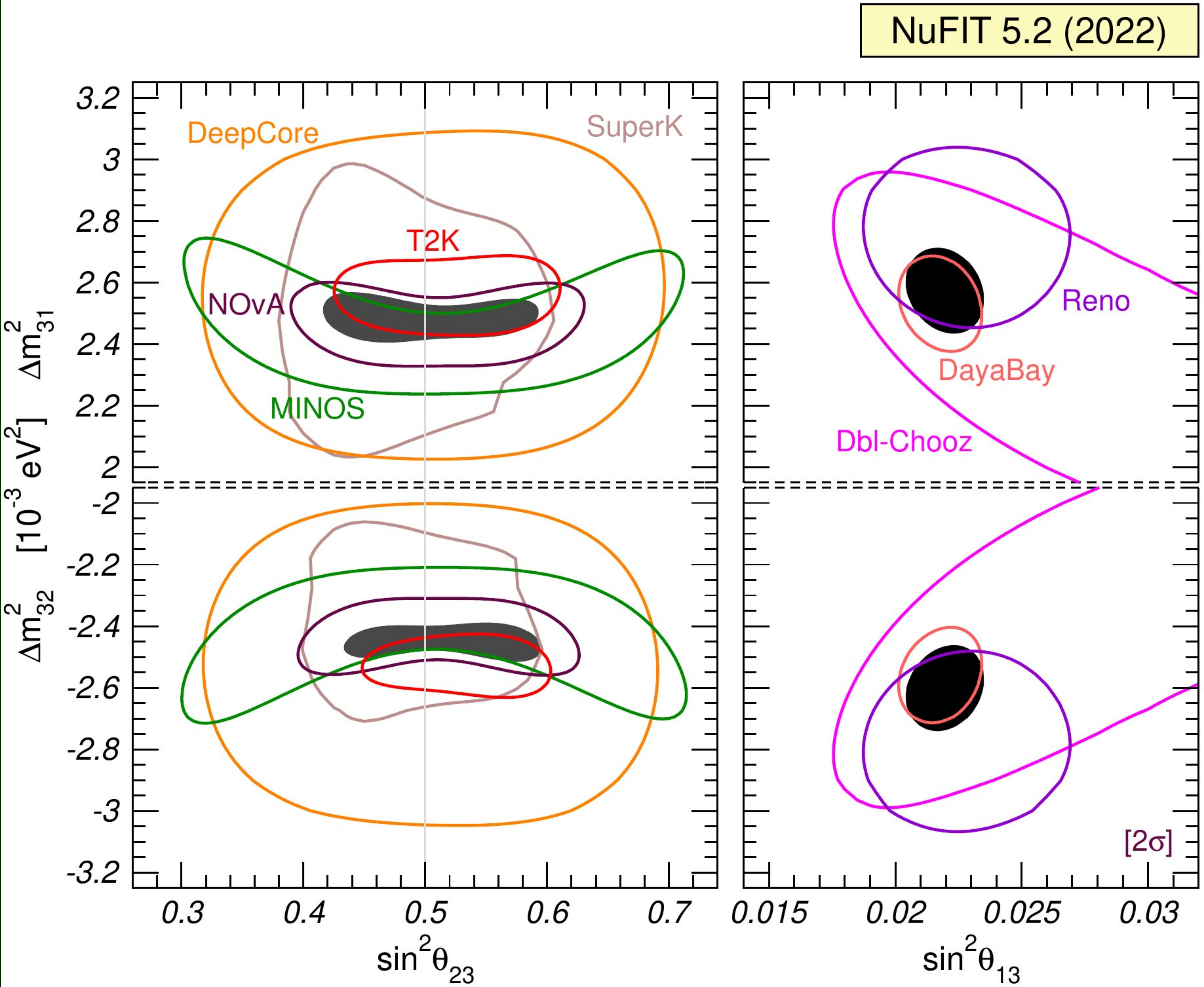


NuFIT 5.2 (2022)
LBL
LBL + Rea
$\Delta\chi^2$
15
10
5
0
3.2
3
2.8
2.6
2.4
2.2
2
Δm^2_{31} [10^{-3} eV^2]
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
Minos
NOvA
T2K
ν
$\bar{\nu}$


NuFIT 5.2 (2022)
Δm^2_{31}
Δm^2_{32}
$[10^{-3}\ \mathrm{eV}^2]$
2.6
2.5
2.4
-2.4
-2.5
-2.6


δ_{CP}
360
270
180
90
0
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
$\Delta m^2_{21}\ [10^{-5}\ \mathrm{eV}^2]$
8
7.5
7
6.5
0.26
0.28
0.3
0.32
0.34
0.36
$\sin^2\theta_{12}$
0.018
0.02
0.022
0.024
0.026
$\sin^2\theta_{13}$


NuFIT 5.2 (2022)
NO
IO
δ_{CP}
360
270
180
90
0
0.02
0.022
0.024
0.4
0.5
0.6
2.4
2.5
2.6
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
$|\Delta m^2_{atm}|$ [10^{-3} eV^2]


NuFIT 5.2 (2022)
DeepCore
SuperK
T2K
NOvA
MINOS
Reno
DayaBay
Dbl-Chooz
[2σ]
Δm^2_{31} [10^{-3} eV^2] Δm^2_{32}
$\sin^2\theta_{23}$
$\sin^2\theta_{13}$
3.2
3
2.8
2.6
2.4
2.2
2
-2
-2.2
-2.4
-2.6
-2.8
-3
-3.2
0.3
0.4
0.5
0.6
0.7
0.015
0.02
0.025
0.03

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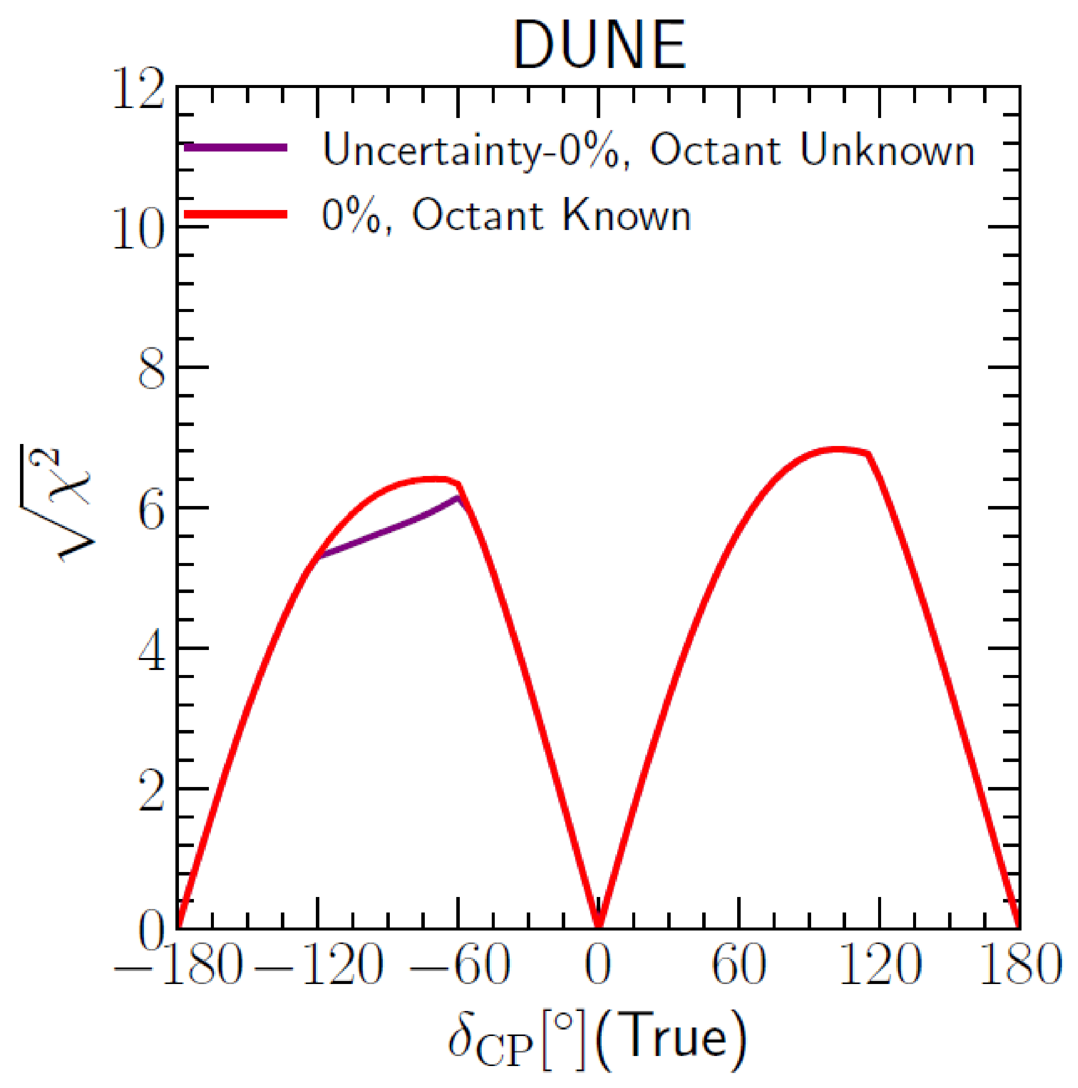

octant degeneracy at DUNE

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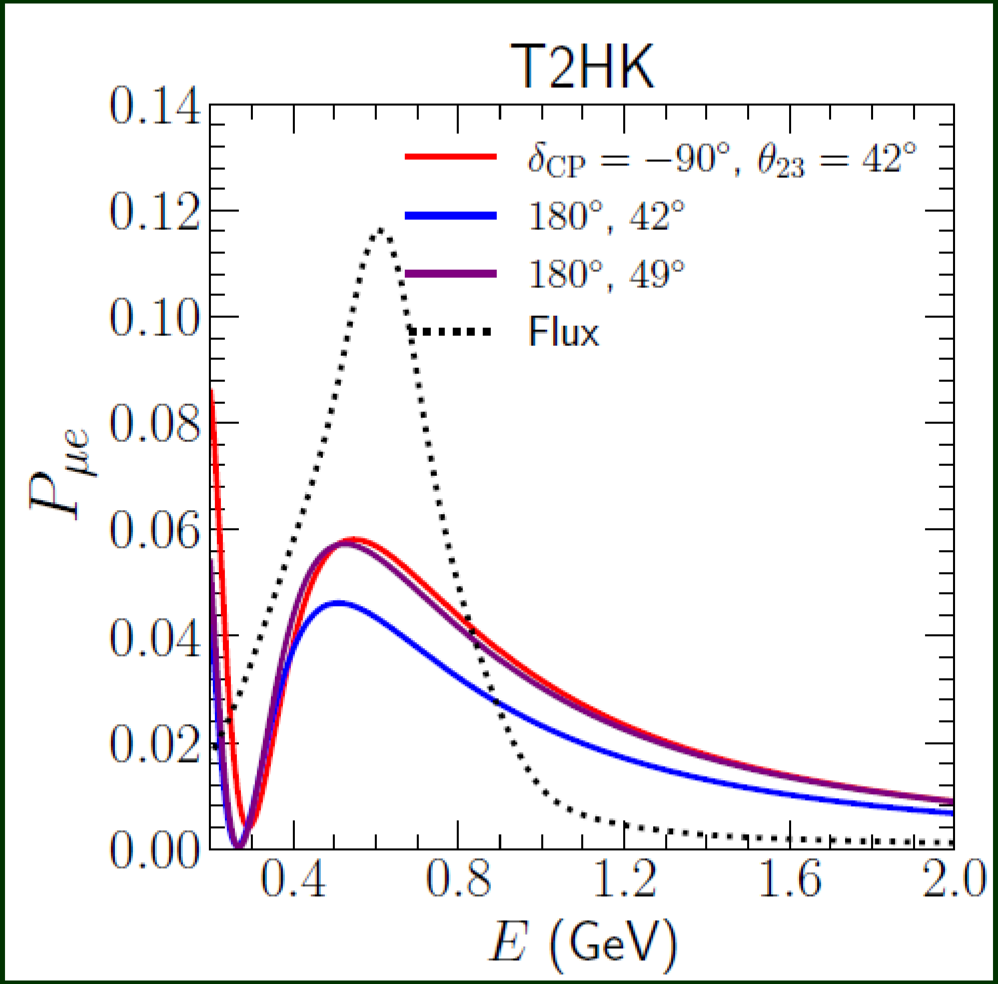

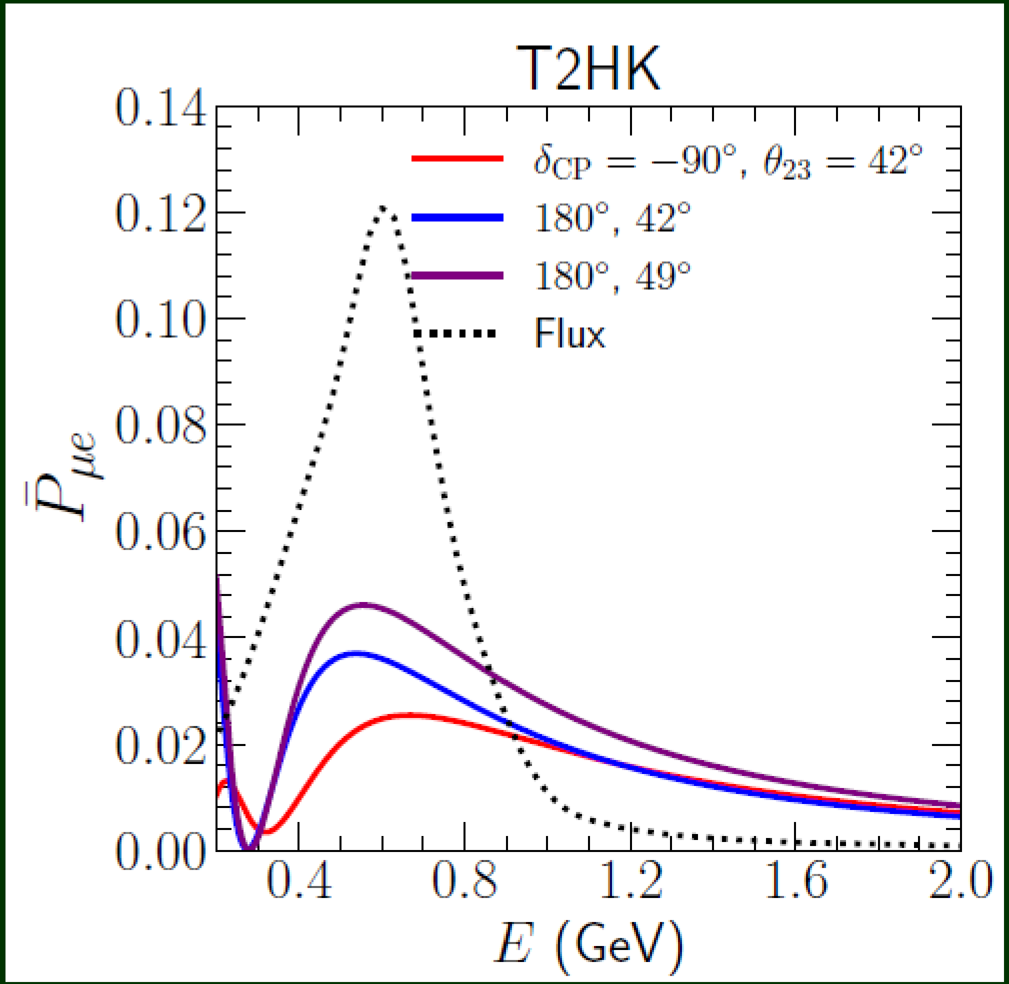

Probability vs octant degeneracy at T2HK

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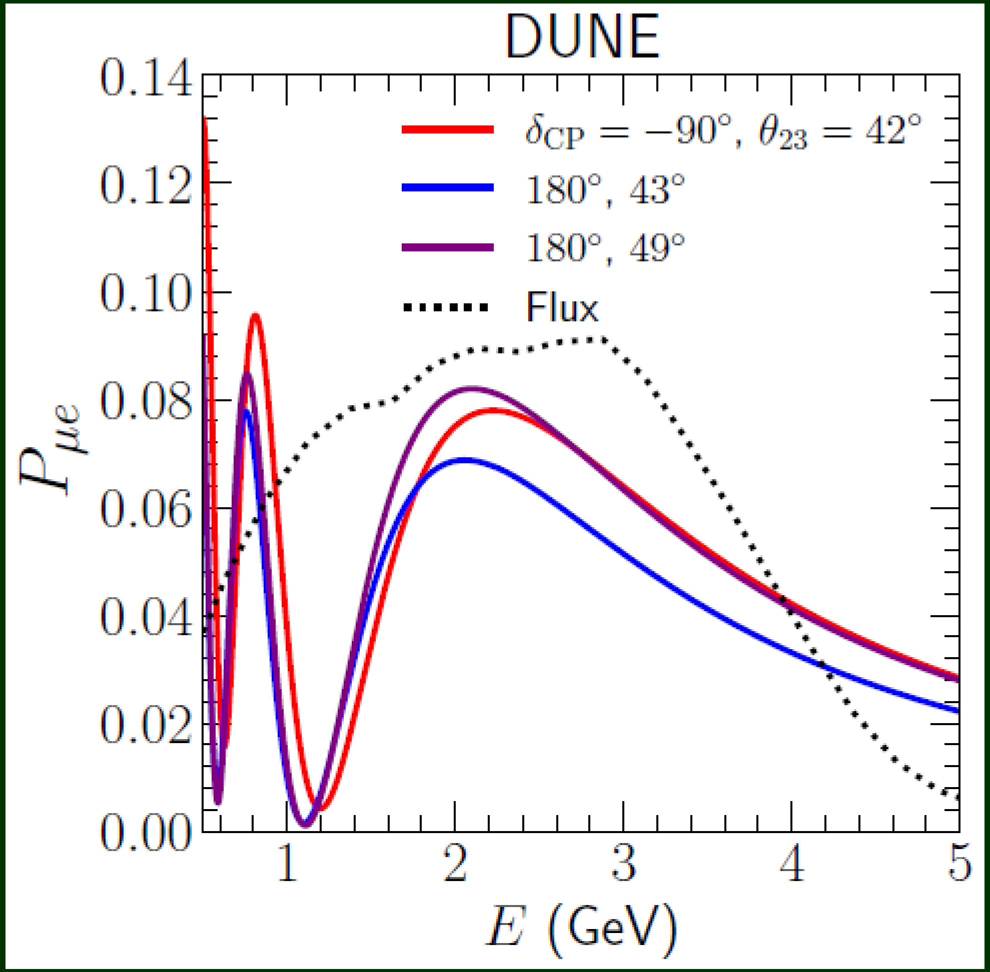

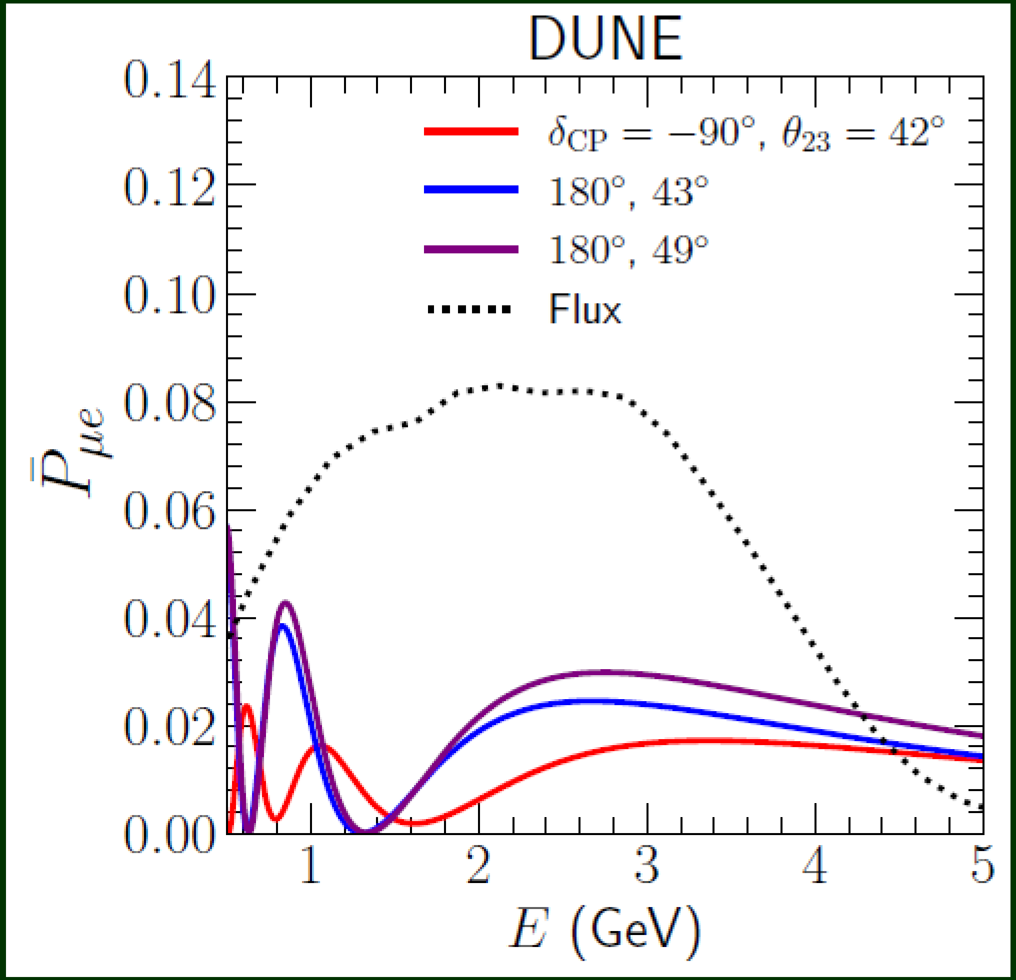

Probability vs octant degeneracy at DUNE

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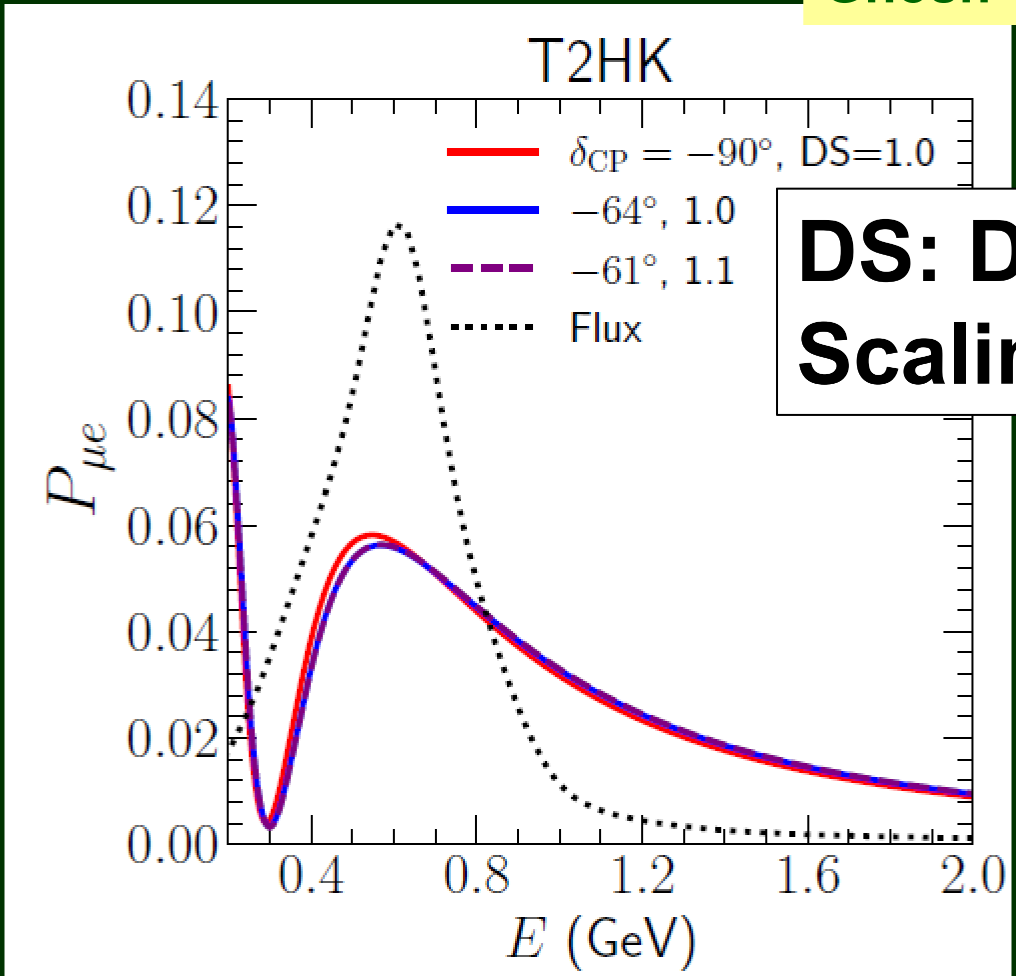
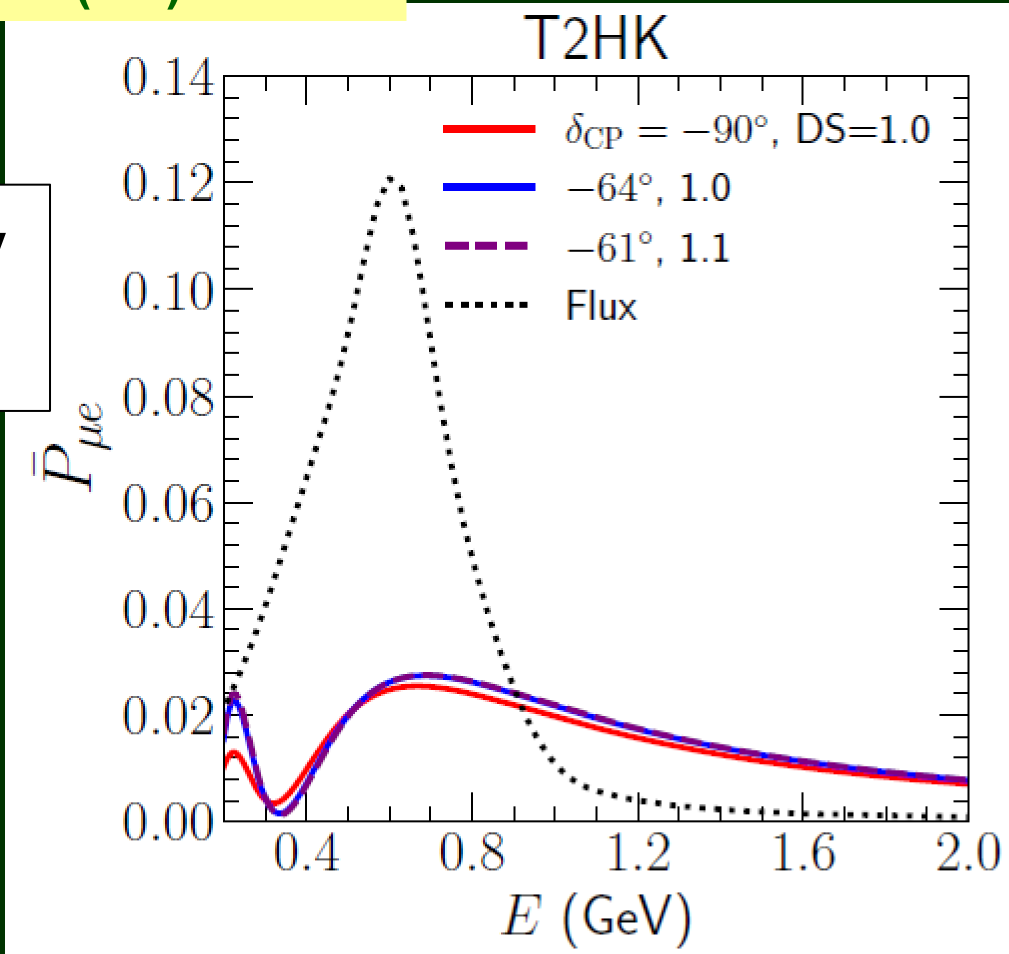


DS: Density Scaling



For T2HK, (δ, DS)=(-64°, 1.0) is degenerate with (-61°, 1.1).
For δ(true) = -90°, (δ(test),DS(test)) = (-61°, 1.0) is excluded but (δ(test),DS(test)) = (-61°, 1.1) is allowed.

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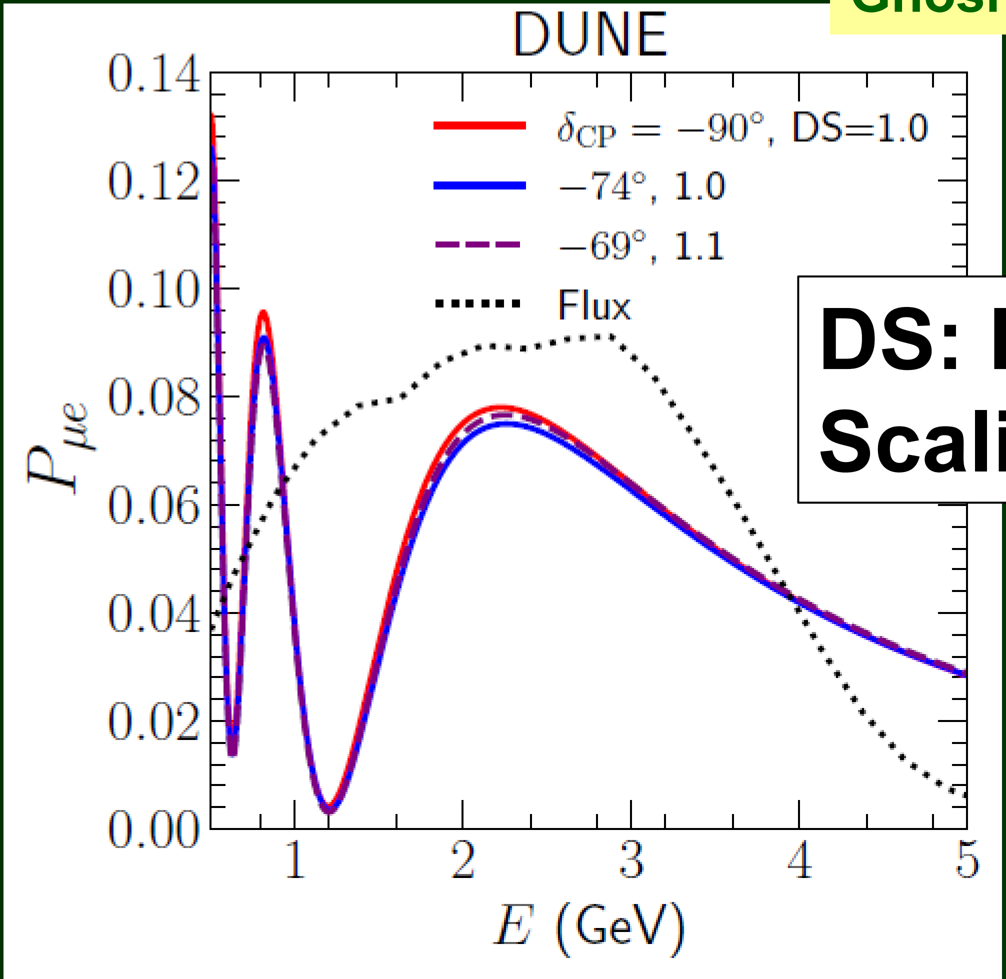
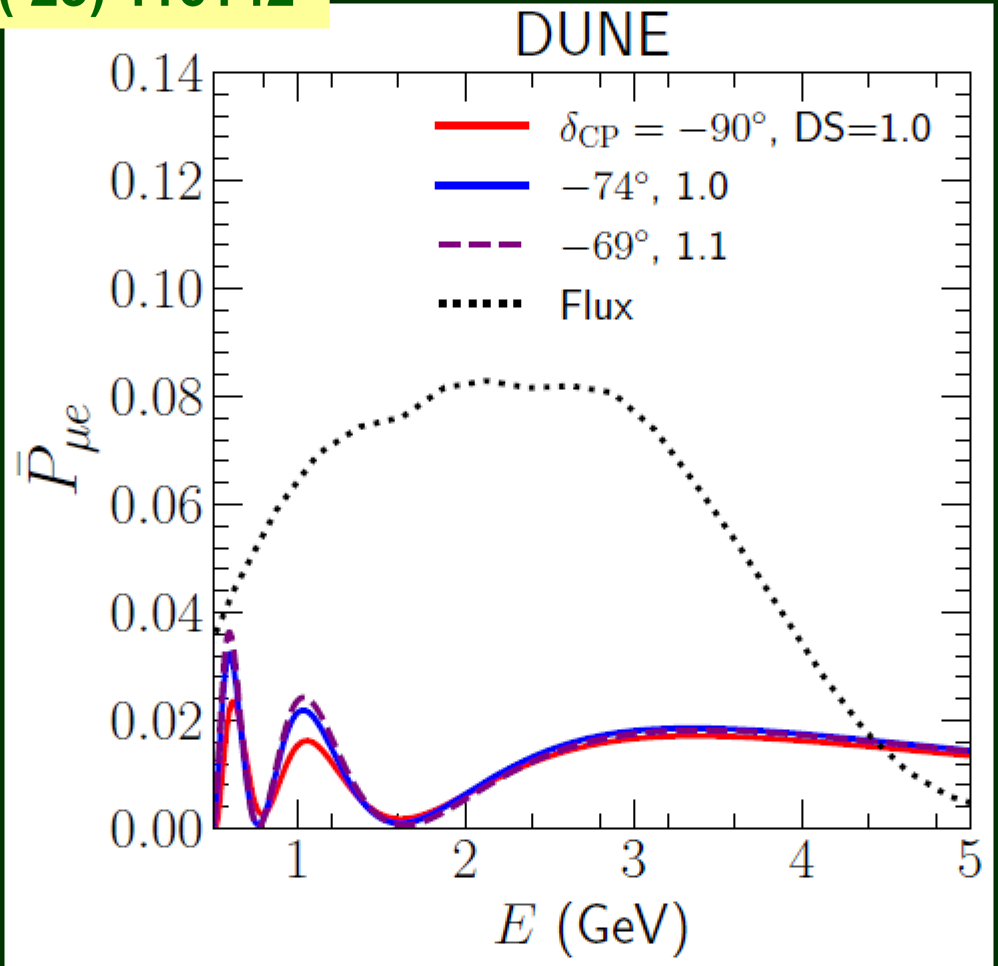


DS: Density Scaling



For DUNE, (δ, DS)=(-74°, 1.0) is degenerate with (-69°, 1.1). For δ(true) = -90°, (δ(test),DS(test)) = (-69°, 1.0) is excluded but (δ(test),DS(test)) = (-69°, 1.1) is allowed.