Synergy of HK & DUNE

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1. Introduction

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

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

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- Mass ordering
- Octant degeneracy
- CP

3. Sensitivity of T2HK & DUNE to NSI

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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) → $\theta_{12} \cong \frac{\pi}{6}$, $\Delta m^2_{21} \cong 8\times10^{-5}\,\mathrm{eV}^2$

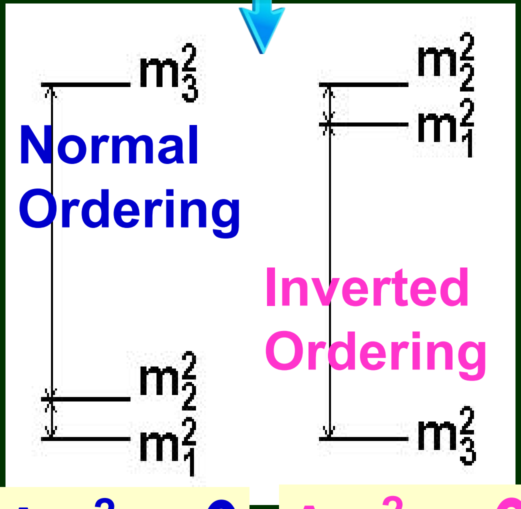
ν_{atm}+T2K +MINOS+NOvA (accelerators) → $\theta_{23} \cong \frac{\pi}{4}$, $|\Delta m^2_{32}| \cong 2.5\times10^{-3}\,\mathrm{eV}^2$

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

Next things to do are to determine the following:

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

Both mass patterns are allowed



$\Delta m^2_{32} > 0$ $\Delta m^2_{32} < 0$

- **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.)

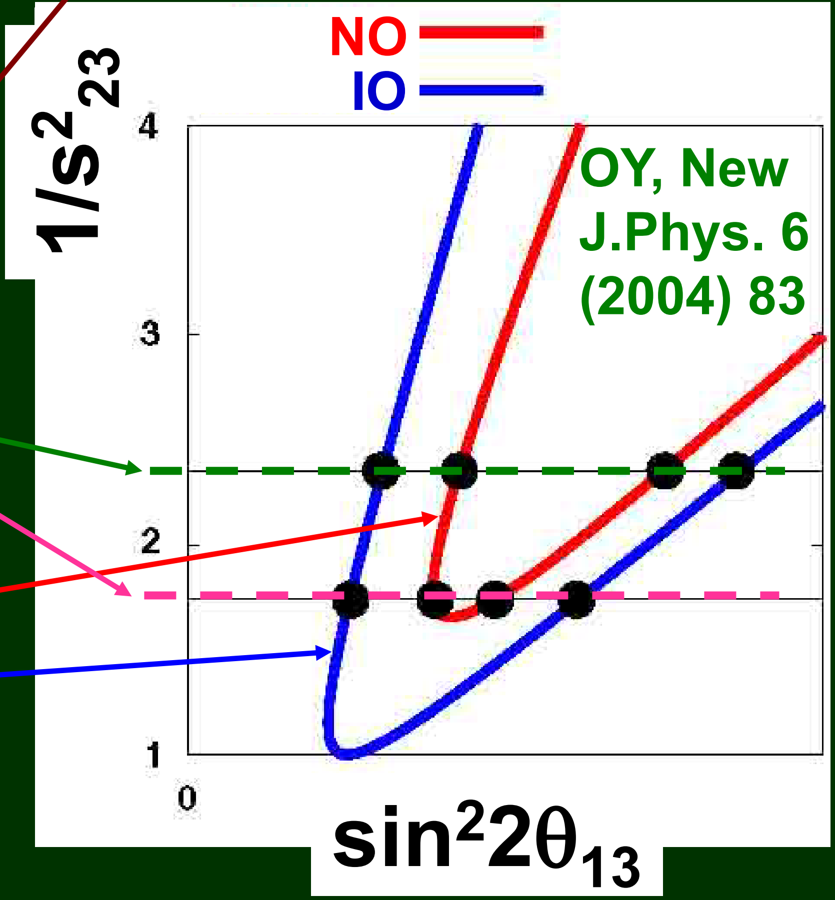
  (ii) Leptogenesis?

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)

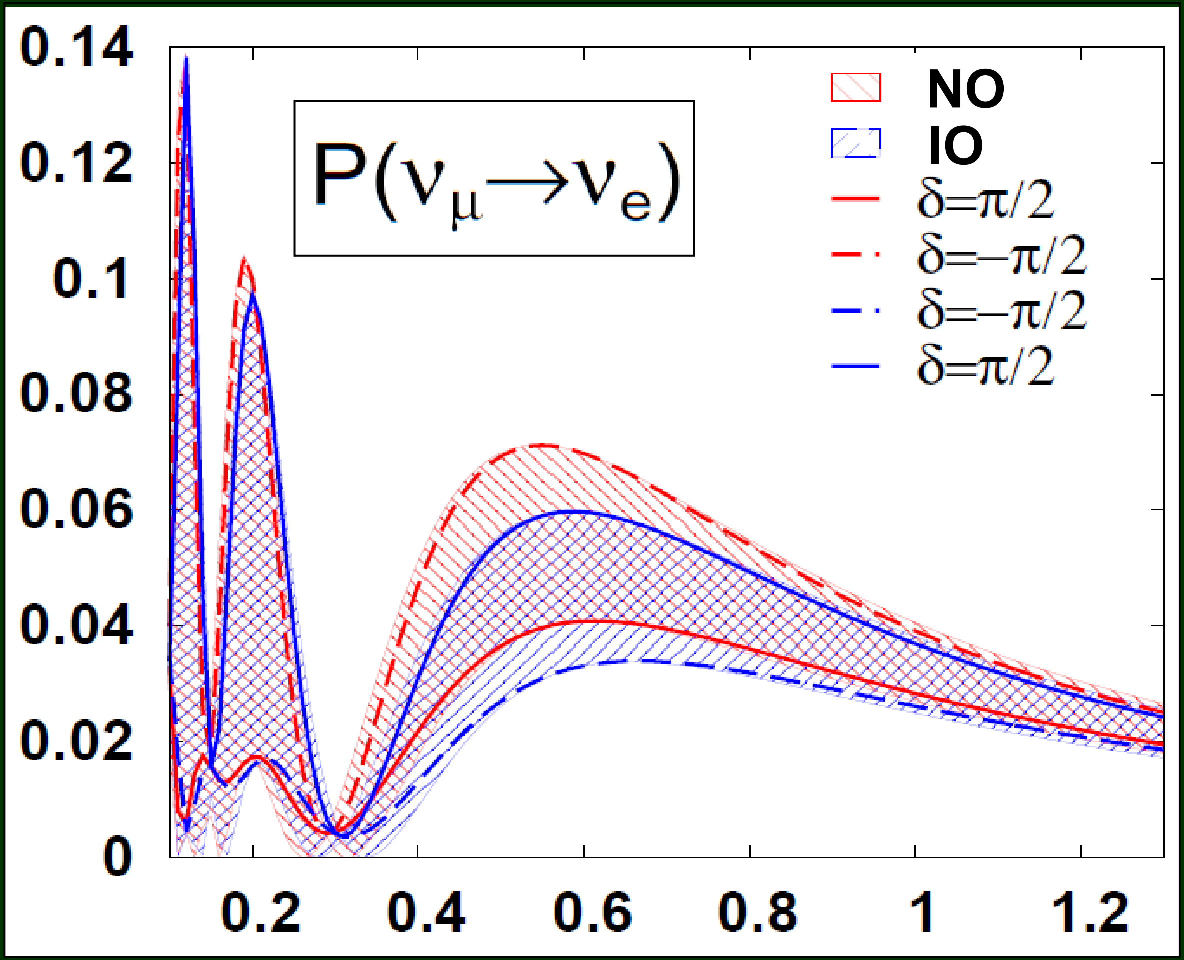
- **octant degeneracy** $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$
  (Fogli-Lisi, '96)
- **intrinsic degeneracy** (δ, θ_{13})
  (Burguet-Castell et al, '01)
- **sign degeneracy** $\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$
  (Minakata-Nunokawa, '01)



● Understanding degeneracy by appearance probabilities

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

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



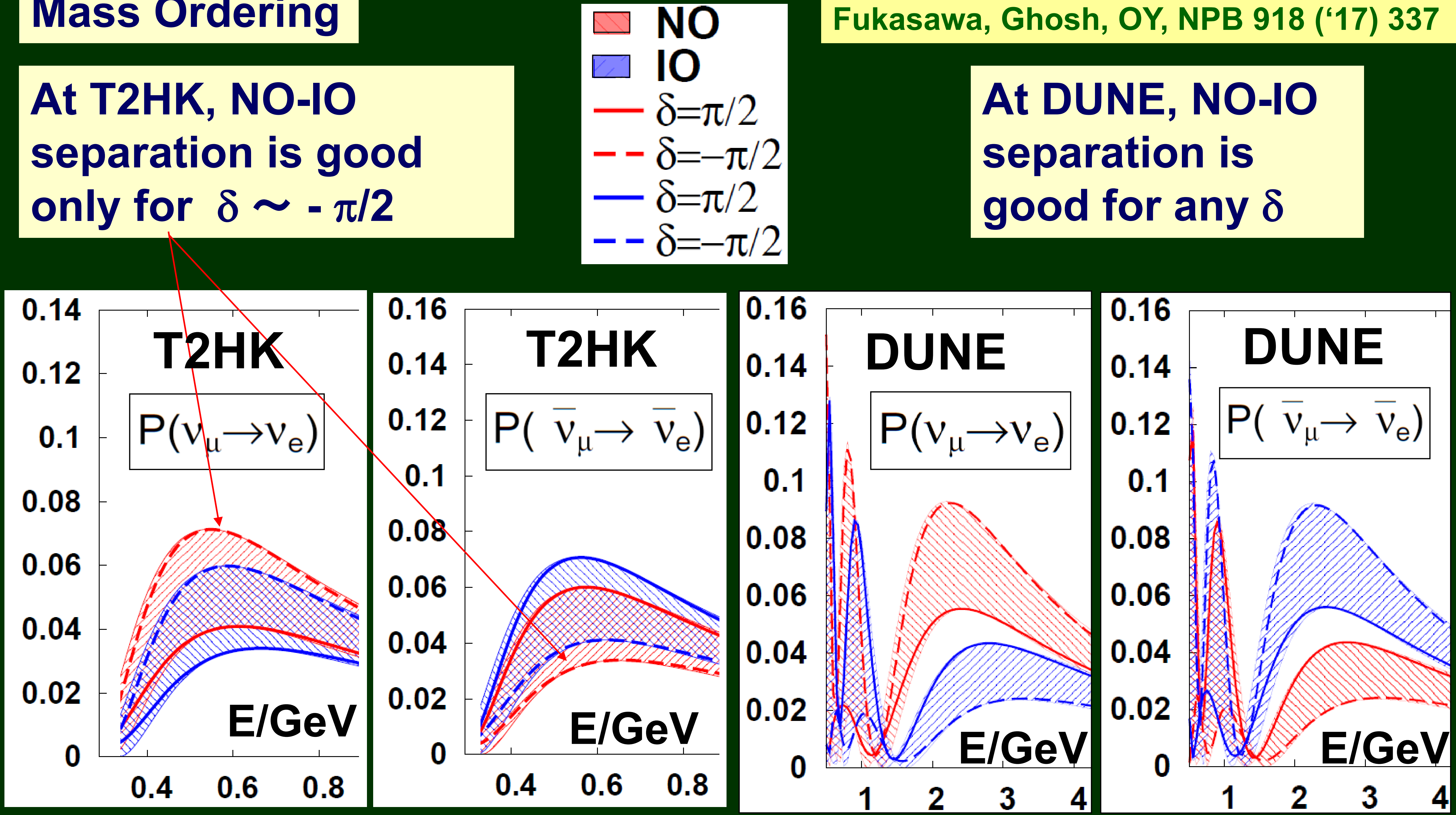
Due to uncertainty in δ, the appearance probabilities has finite width.
-> Each border is approximately realized for $\delta = +\pi/2$ or $-\pi/2$

Mass Ordering

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

At T2HK, NO-IO separation is good only for $\delta \sim -\pi/2$

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

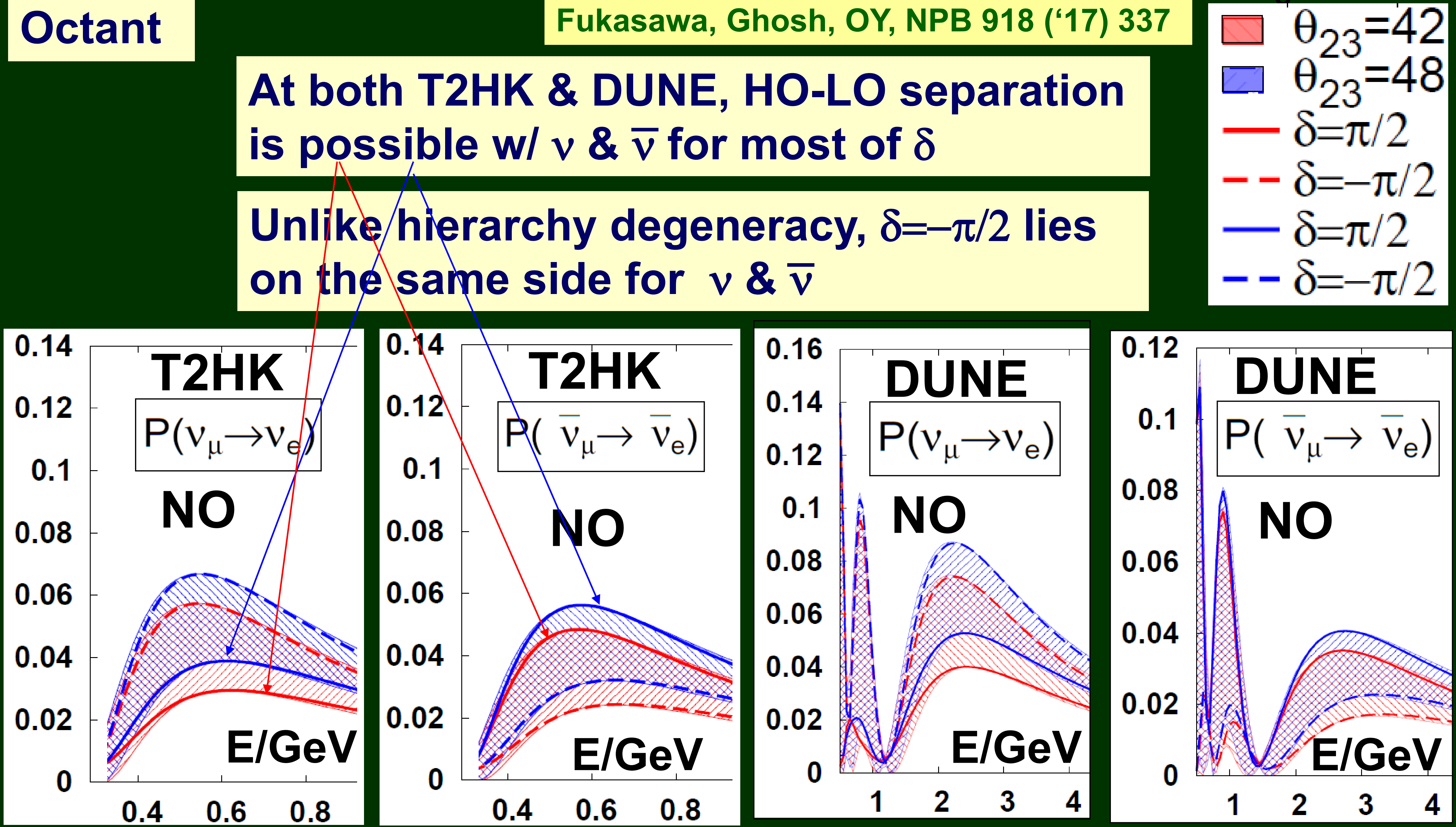


Octant

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, $\delta=-\pi/2$ lies on the same side for ν & $\bar{\nu}$



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

Uncertainty in matter density taken into account

Ghosh-OY (to appear soon)

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:

θ_{23} = 42° or 48°,

δ = -90°,

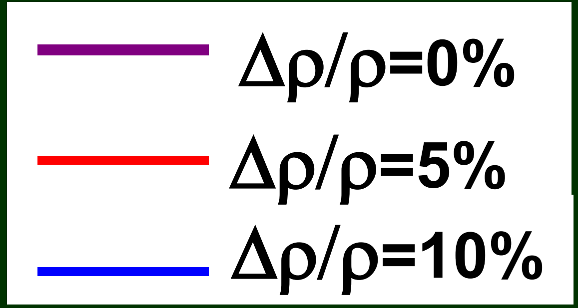
Δm^2_{31} = 2.51x10^{-3}eV^2,

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

2.1 Precision to oscillation parameters

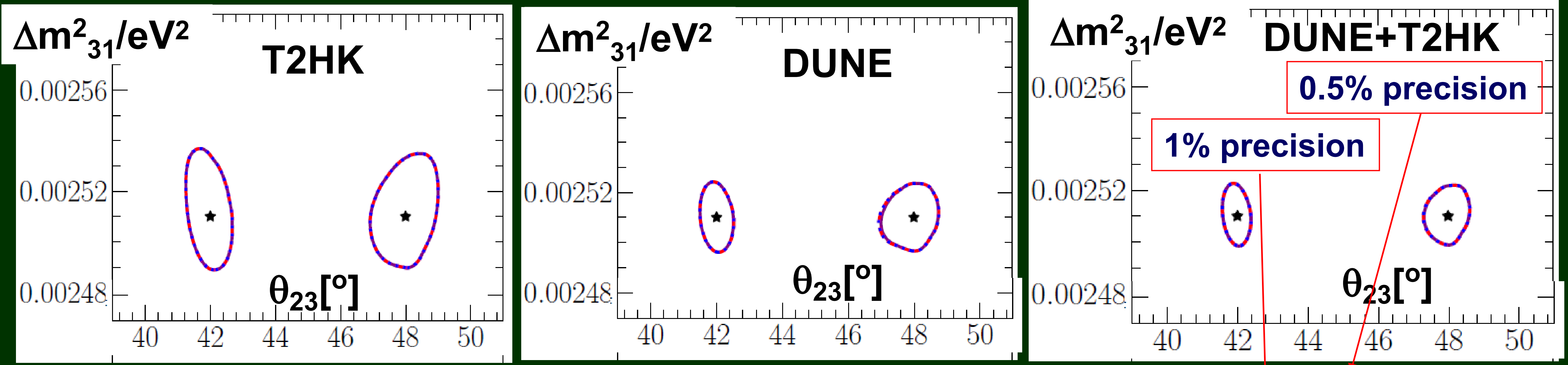
Ghosh-OY (to appear soon)

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.



T2HK	DUNE	DUNE+T2HK
$\Delta m^2_{31}/10^{-3}eV^2 = (2.51+0.02-0.03)$	(2.51 ± 0.014)	$(2.51+0.012-0.011)$
$\theta_{23} = (42\pm0.7)^\circ$	$(42\pm0.5)^\circ$	$(42\pm0.4)^\circ$

DUNE&T2HK vs Present status of global fit

	Ref	$\Delta m^2_{31}/10^{-3}eV^2$	$\theta_{23}[^\circ]$
Global fit	Nufit [2111.03086 [hep-ph]]	2.51 ± 0.03	42.1+1.1-0.9
	Bari [2107.00532 [hep-ph]]	2.49+0.02-0.03	42.4+1.0-0.9
	Valencia [2006.11237 [hep-ph]]	2.55+0.02-0.03	49.3 ± 0.8
Future exp	T2HK	2.51+0.02-0.03	42.0 ± 0.7
	DUNE	2.51 ± 0.014	42.0 ± 0.5
	DUNE+T2HK	2.51+0.012-0.011	42.0 ± 0.4

2.2 Sensitivity to Mass Ordering

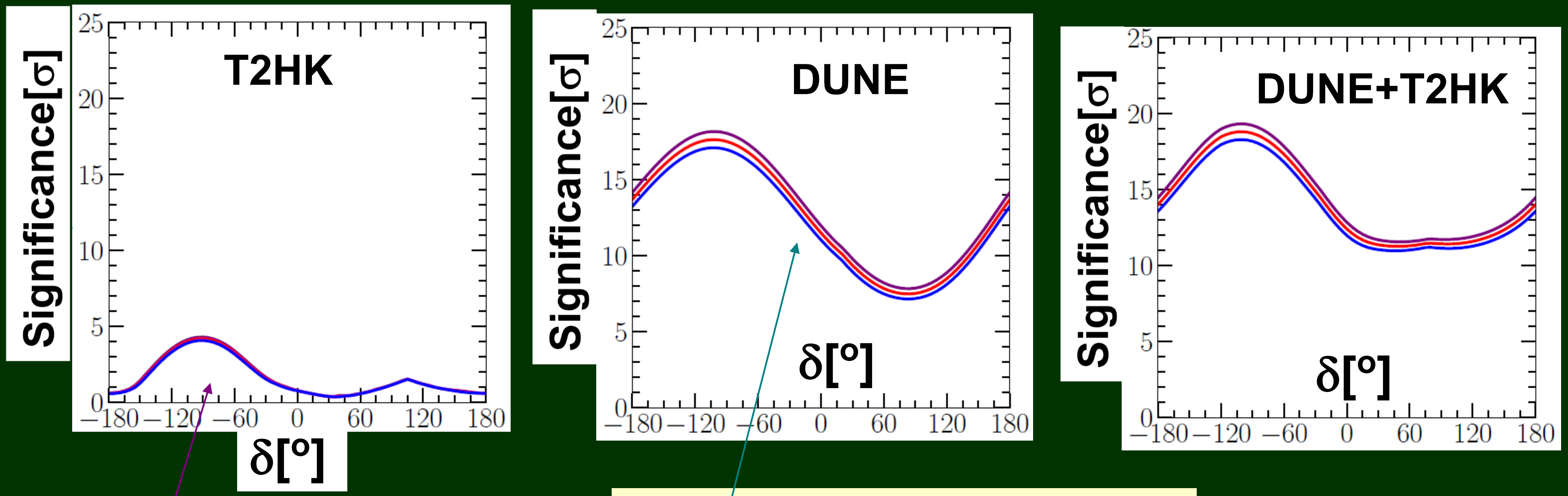
Ghosh-OY (to appear soon)

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

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

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

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

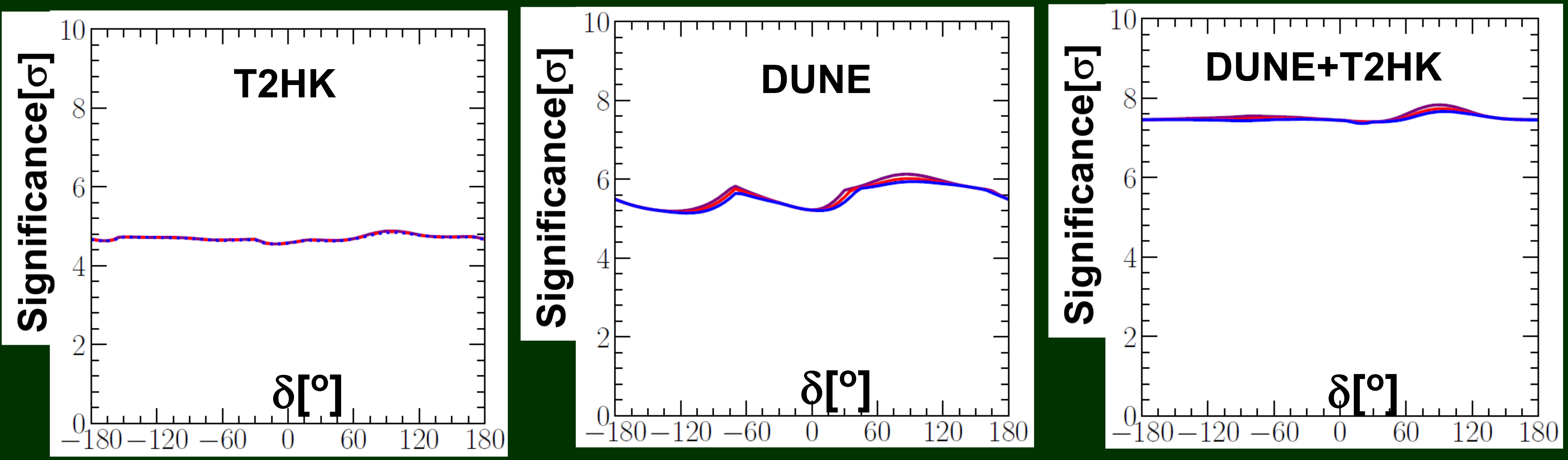
2.3 Sensitivity to Octant degeneracy

Ghosh-OY (to appear soon)

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

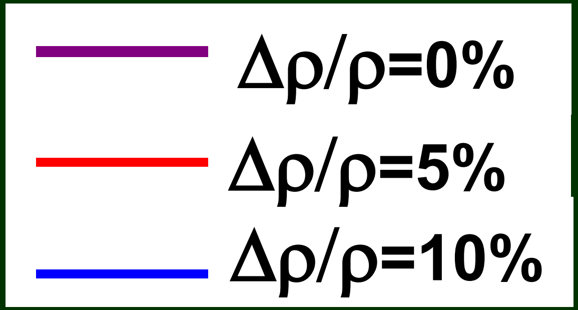
$$\theta_{23} = 42^\circ$$

Δρ/ρ=0%
Δρ/ρ=5%
Δρ/ρ=10%



2.4 Sensitivity to CP(1)

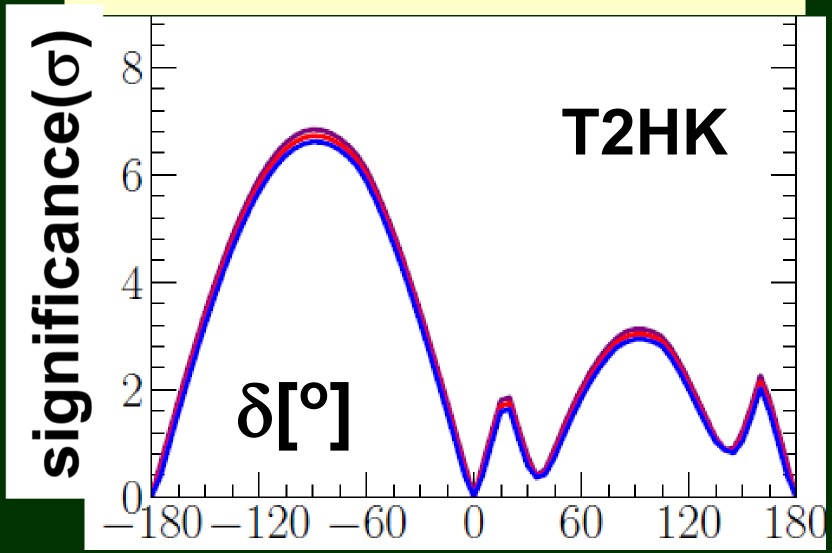
Ghosh-OY (to appear soon)

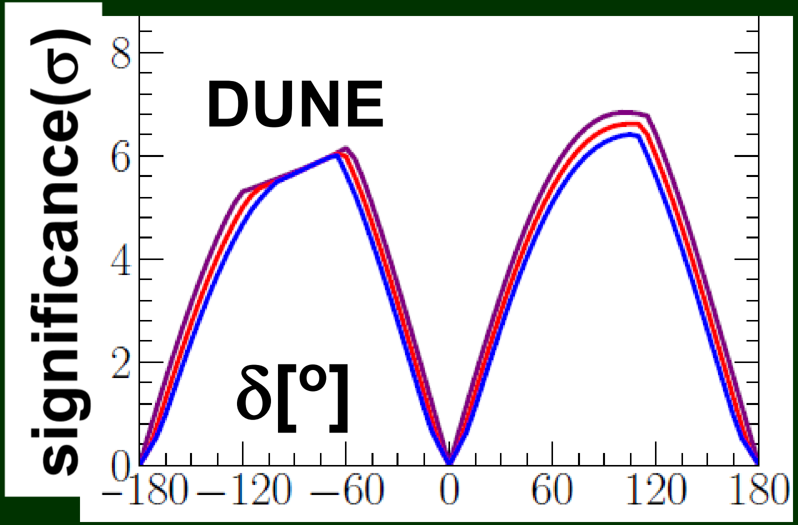


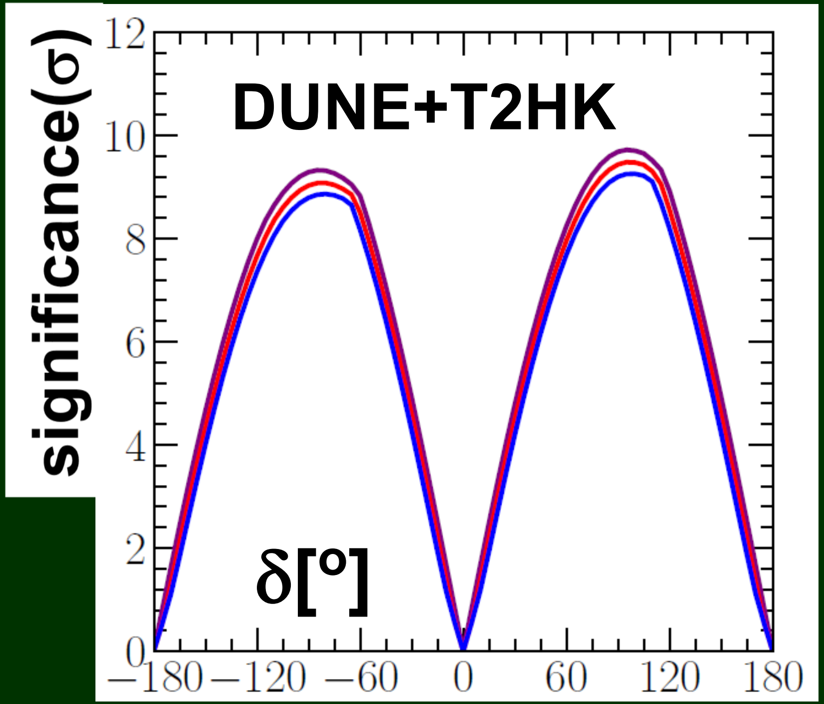
Uncertainty in matter density has some effect on DUNE.
<- DUNE has longer baseline L=1300km
However even with $\Delta\rho/\rho=10\%$, the sensitivity is excellent.

Sensitivity of **T2HK** is poor for (NH, $\delta = +\pi/2$) & (IH, $\delta = -\pi/2$)

Sensitivity of **DUNE** is excellent for $|\sin\delta|=1$ for both mass hierarchy







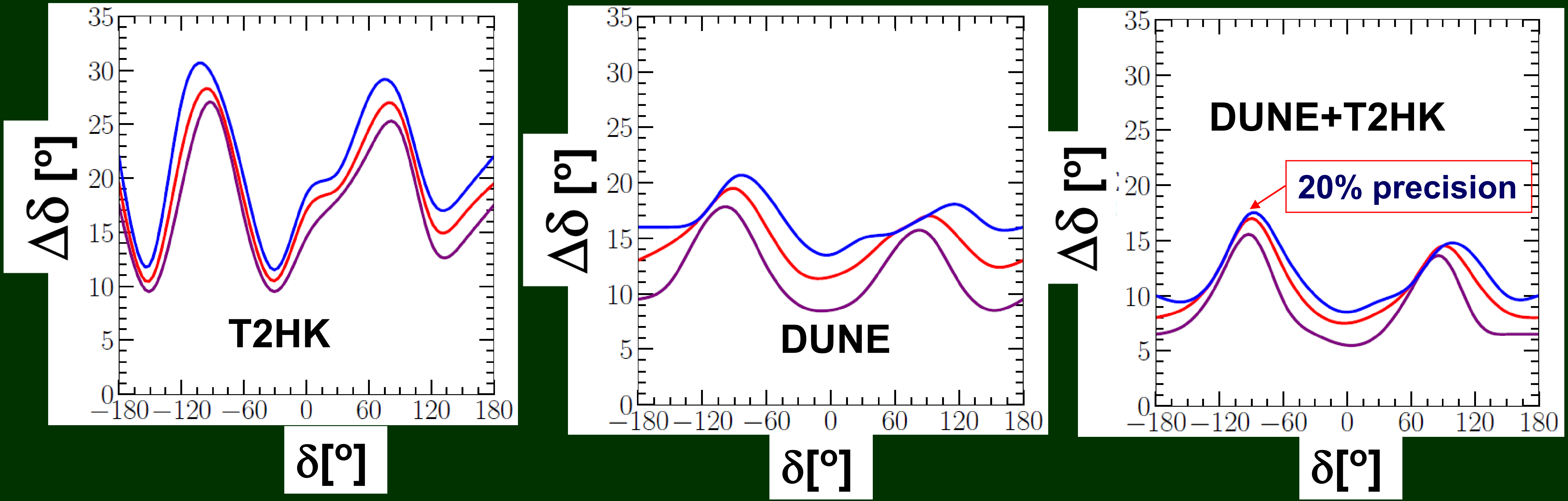
2.4 Sensitivity to CP(2)

Ghosh-OY (to appear soon)

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

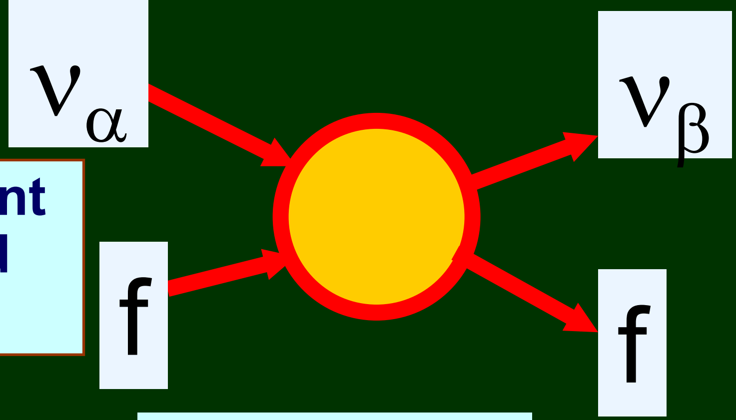
Uncertainty in matter density has some effect on the precision $\Delta\delta$ both for T2HK & DUNE.

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



3. Sensitivity of T2HK & DUNE to NSI

neutral current non-standard interaction



f = e, u or d

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

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

Modification of matter effect

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

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

NP

Solar ν basis

$$\mathcal{H} = R_{23}\,\tilde{R}_{13}\,\mathcal{H}^{\rm eff}\,\tilde{R}_{13}^{-1}\,R_{23}^{-1}$$

$$\mathcal{A}^{\rm eff}\big|_{2\times 2} = \begin{pmatrix} Ac_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

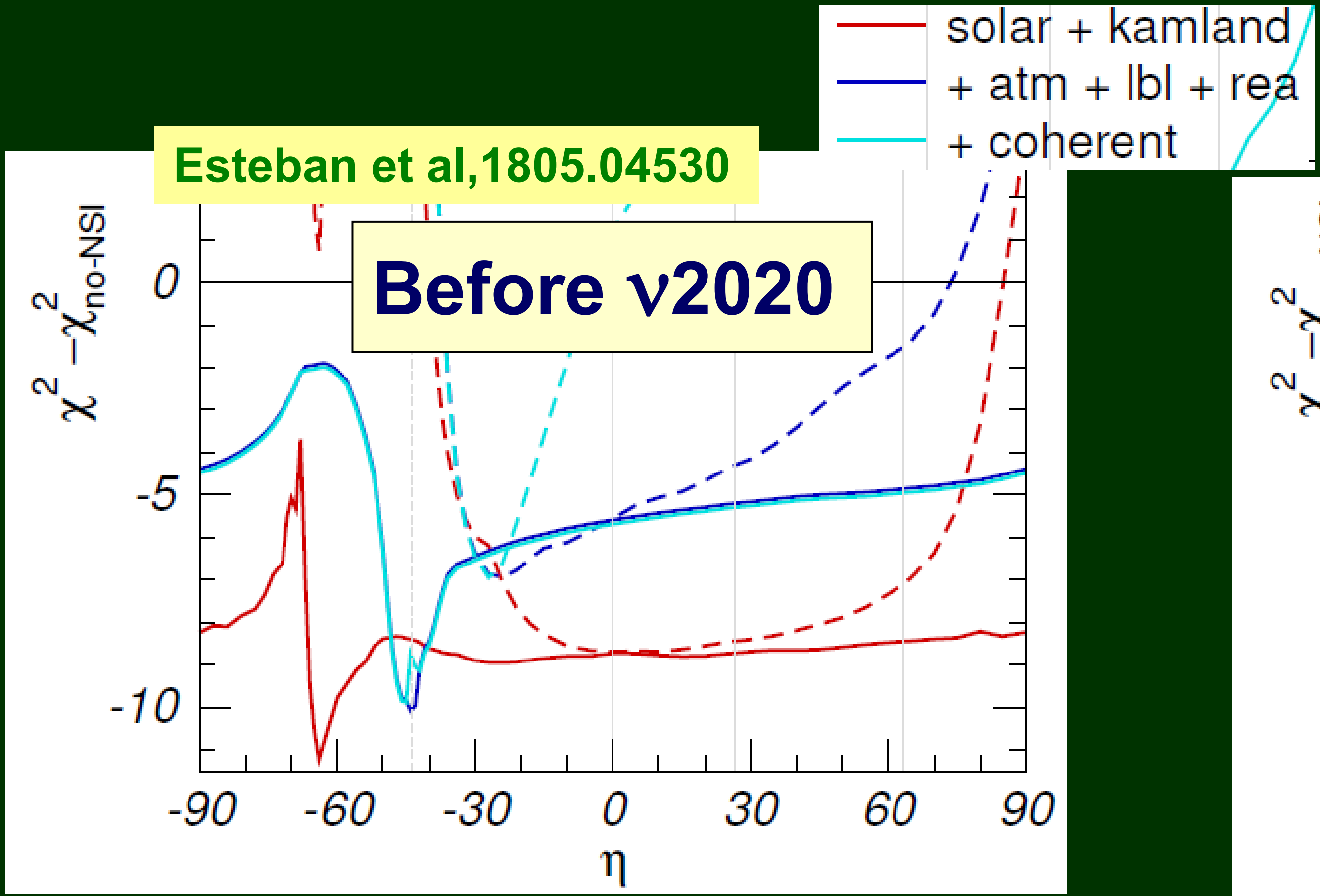
Terrestrial ν basis

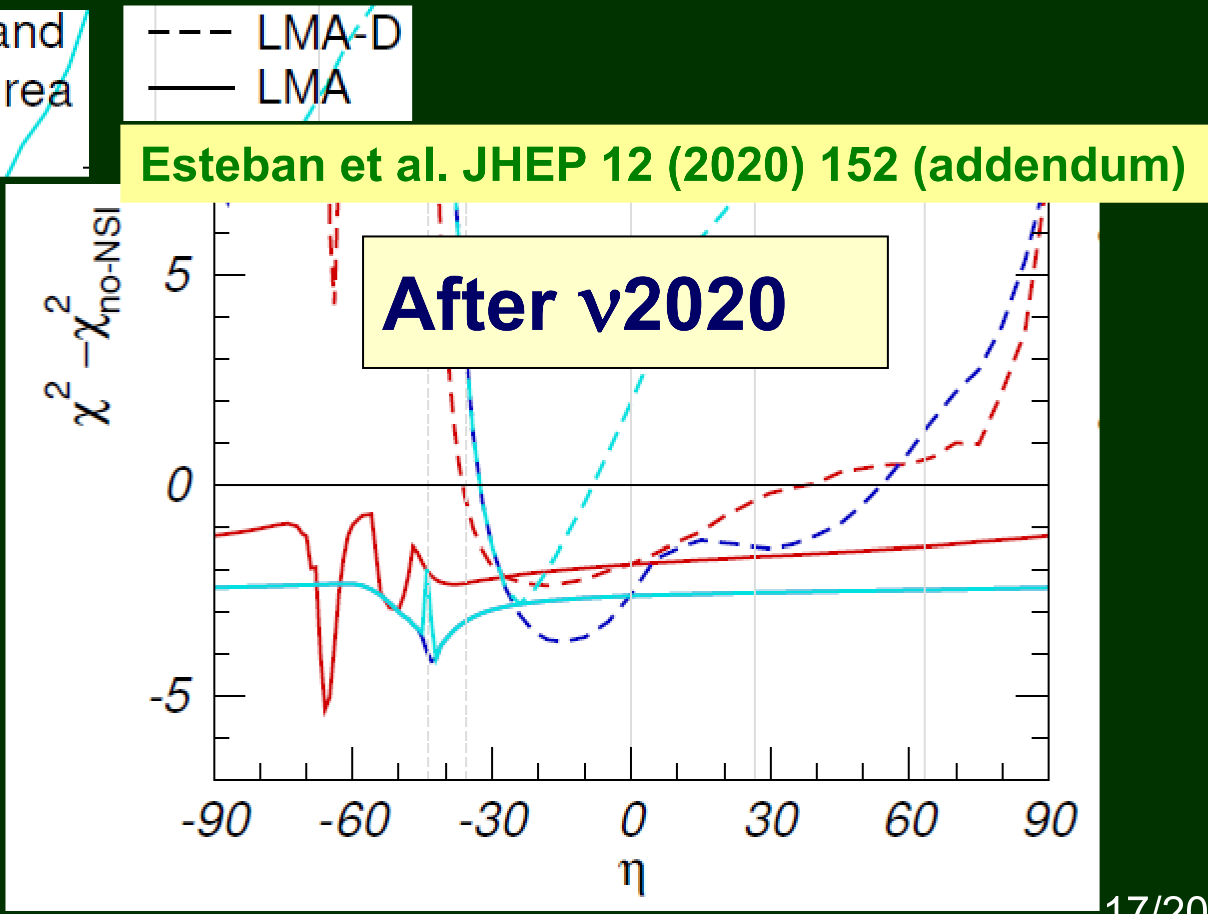
$$\varepsilon^{f}_{\alpha\beta} \equiv \varepsilon^{f,L}_{\alpha\beta} + \varepsilon^{f,R}_{\alpha\beta} = \varepsilon^{\eta}_{\alpha\beta}\,\xi^{f}$$

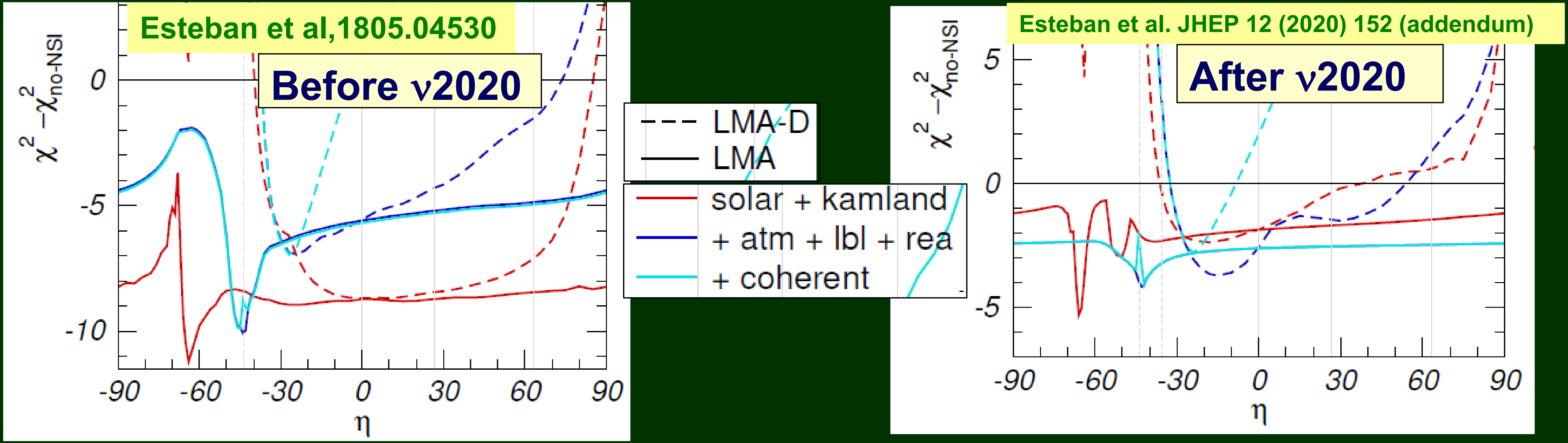
$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + \left(2 + Y_n^{\oplus}\right)\varepsilon^{u}_{\alpha\beta} + \left(1 + 2Y_n^{\oplus}\right)\varepsilon^{d}_{\alpha\beta} = \Big(\overbrace{\boxed{\varepsilon^{e}_{\alpha\beta}}}^{=0\text{ is assumed}} + \varepsilon^{p}_{\alpha\beta}\Big) + Y_n^{\oplus}\varepsilon^{n}_{\alpha\beta}$$

$$= \sqrt{5}\,\left(\cos\eta + Y_n^{\oplus}\sin\eta\right)\varepsilon^{\eta}_{\alpha\beta}$$

$$\xi^{u} = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta) \qquad \xi^{d} = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)$$







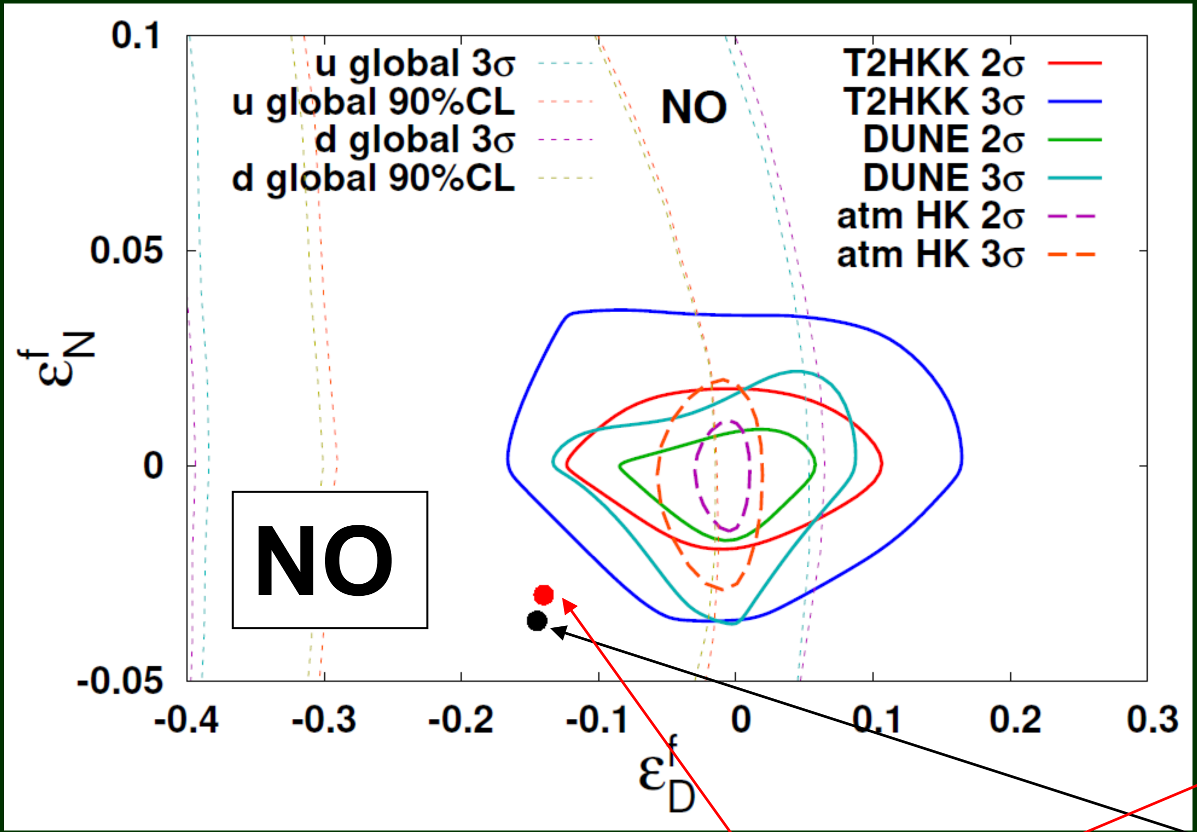
Before ν2020, η other than best-fit point of global fit: $\eta \sim \arctan(-1/Y_n) = -43.6^o$ (NSI effect vanishes for $\eta = -43.6^o$ on the Earth) gives bad fit

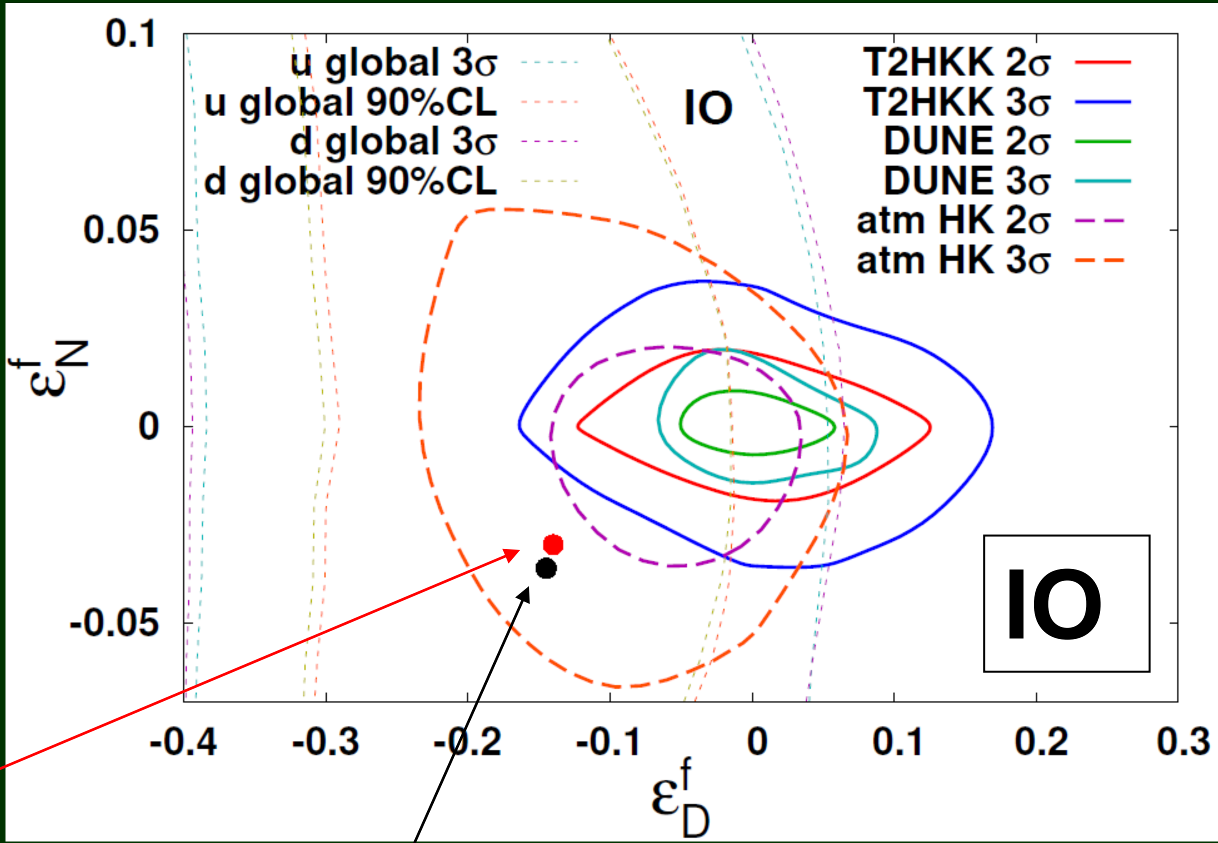
➔ After ν2020, fit for other η is not particularly bad compared with $\eta = -43.6^o$

➔ Here significance of NSI at DUNE, ν_{atm}@HK, T2HKK (possible extension of T2HK) is compared only the case for $\tan\eta = 1/2$ ($\epsilon^d = 0$; $\eta = 26.6^o$) and $\tan\eta = 2$ ($\epsilon^u = 0$; $\eta = 64.4^o$), assuming old design of HK (0.56 Mton fiducial volume x 12 yrs).

●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

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%).
- ν_{atm}@HK, DUNE and T2HKK have some sensitivity to NSI and they cover some of the allowed region in the (ϵ^f_D, ϵ^f_N)-plane suggested by the solar ν tension (although there is less tension now).