Sensitivity of T2HKK to non-standard interactions

Osamu Yasuda
Tokyo Metropolitan University

Sep. 19, 2017@ Erice

Contents of this talk

1. Introduction

2. Nonstandard Interaction in propagation

3. Sensitivity to NSI of propagation at T2HKK

Fukasawa, Ghosh, OY, PRD95 ('17) 055005

Ghosh & OY, PRD96 ('17) 013001

Ghosh & OY, to appear soon

4. Conclusions

1. Introduction

Framework of 3 flavor ν oscillation

Mixing matrix

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

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

All 3 mixing angles have been measured

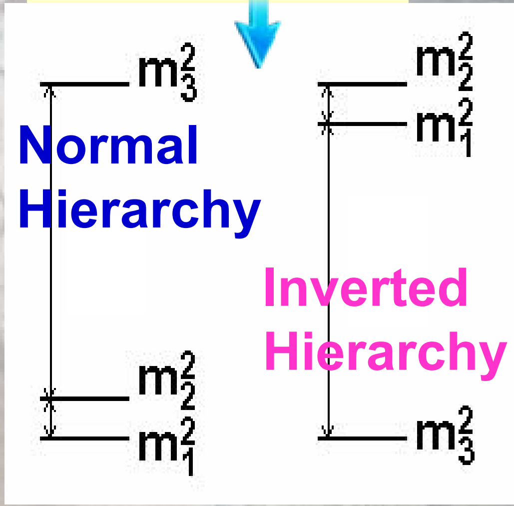
ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8 \times 10^{-5} eV^2$

ν_{atm}, K2K,T2K,MINOS,Nova (accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} eV^2$

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

Next task is to measure sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

Both hierarchy patterns are allowed



Proposed experiments

- T2HK(JP, JPARC-->HK) L=295km, E~0.6GeV
- T2HHK(JP, JPARC-->Korea) L=1100km, E~1GeV
- DUNE (US, FNAL-->Homestake, SD) , L=1300km, E~2GeV

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$$

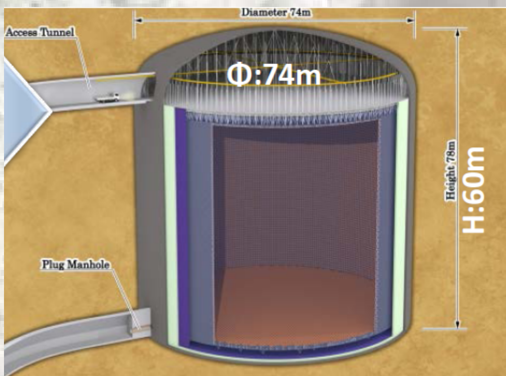
These experiments are expected to measure sign(Δm^2_{31}) , $\pi/4-\theta_{23}$ and δ

Future plan: T2HK

- **Phase 2**

0.75MW ν beam ⇒ Hyperkamiokande
(50 times K2K) (10 times SK)

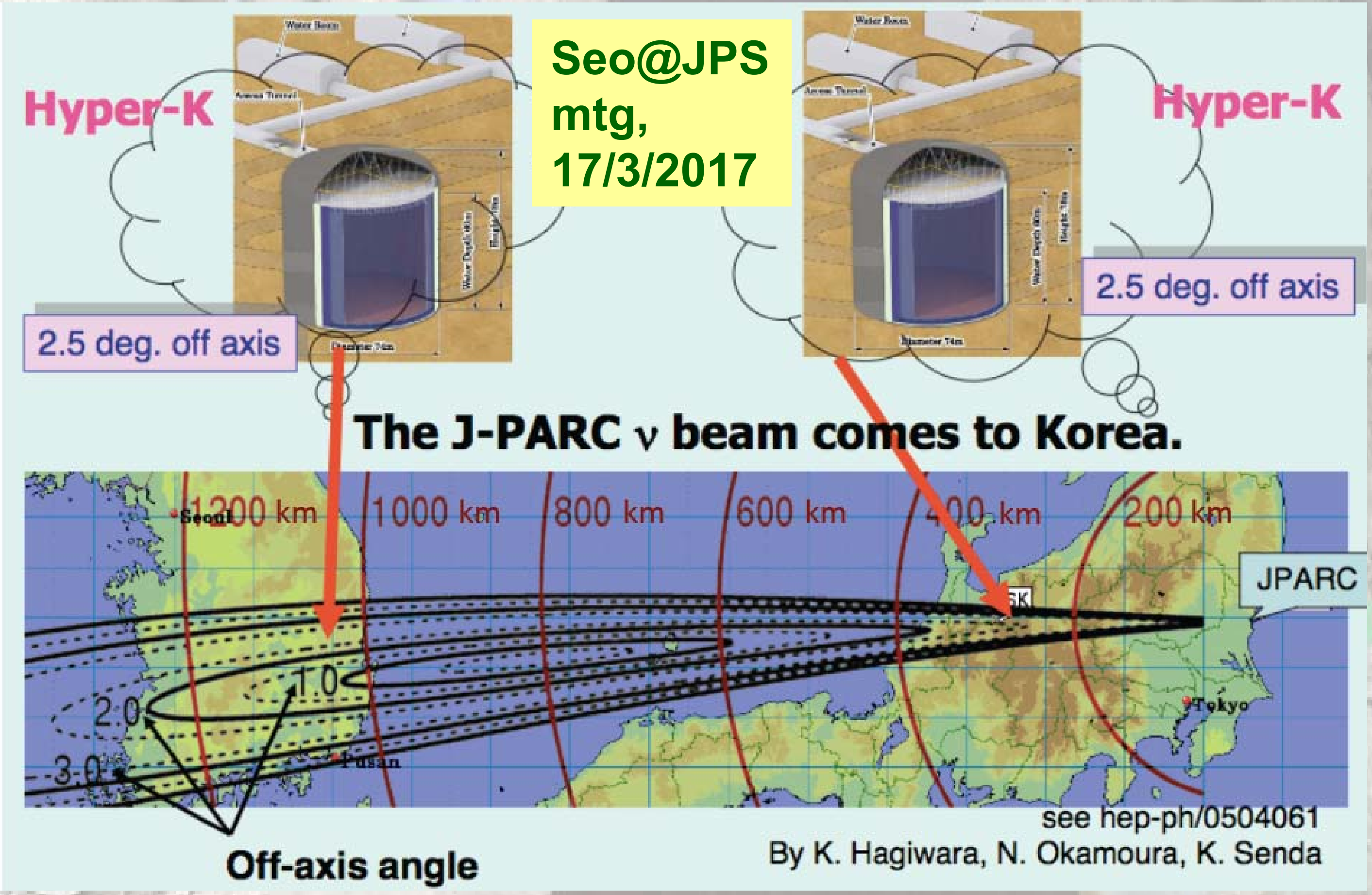
- **Extension of T2K**
- **Measurement of CP phase δ**



Hyper-kamiokande

Future plan: T2HKK

Recent revival of old T2KK idea in 2005:
T2HKK proposal w/ baselines L=295km, 1100km
→L=1100km is sensitive to the matter effect

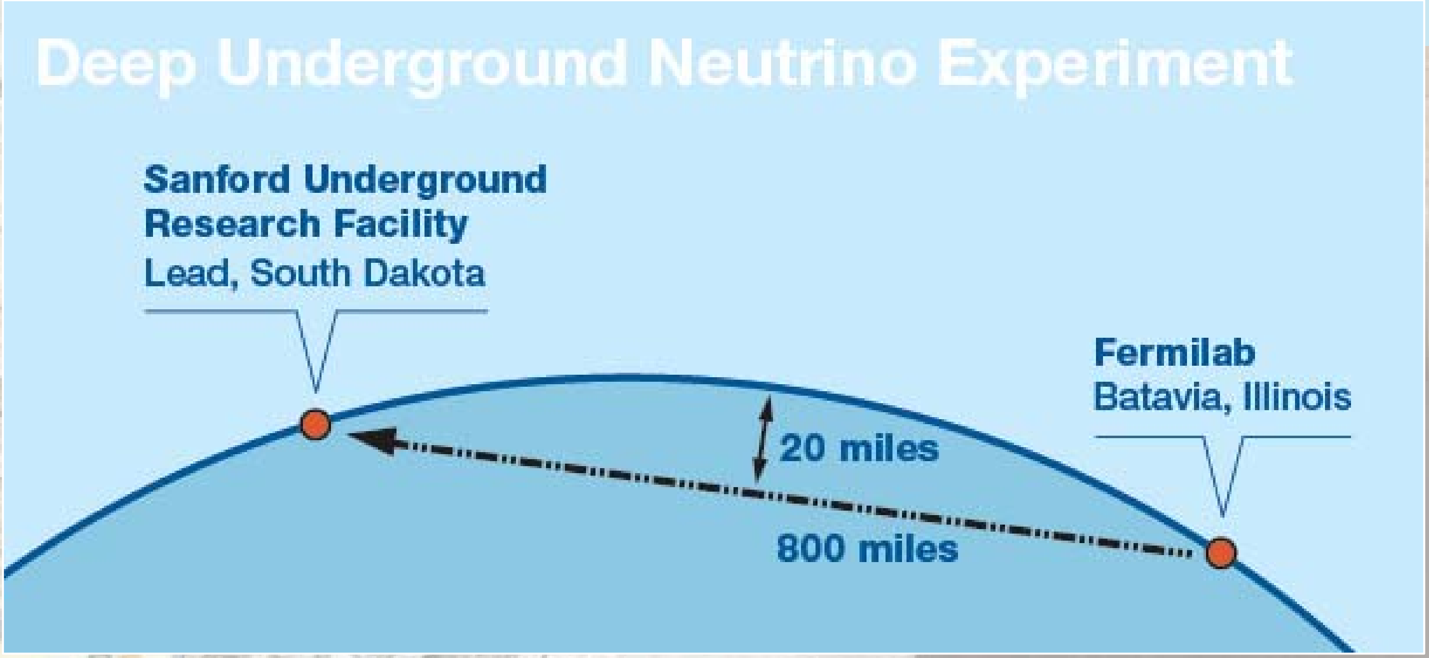


Seo@JPS mtg, 17/3/2017

Future plan: DUNE

2.3MW ν beam@Fermilab ⇒ 40-kt Liquid Argon detector @ Sanford Underground RF

E ∼ 2GeV, L ∼ 1300km



Motivation for research on New Physics

High precision measurements of ν oscillation in future experiments can be used to probe **physics beyond SM** by looking at deviation from SM+m_ν (like at B factories).

→ Research on New Physics is important.

List of New Physics discussed in ν phenomenology

Scenario beyond SM+m_ν	Experimental indication ?	Phenomenological constraints on the magnitude of the effects
Light sterile ν	Maybe	O(10%)
NSI at production / detection	×	O(1%)
NSI in propagation	Maybe	e-τ: O(100%) Others: O(1%)
Unitarity violation due to heavy particles	×	O(0.1%)

NSI: discussed in this talk

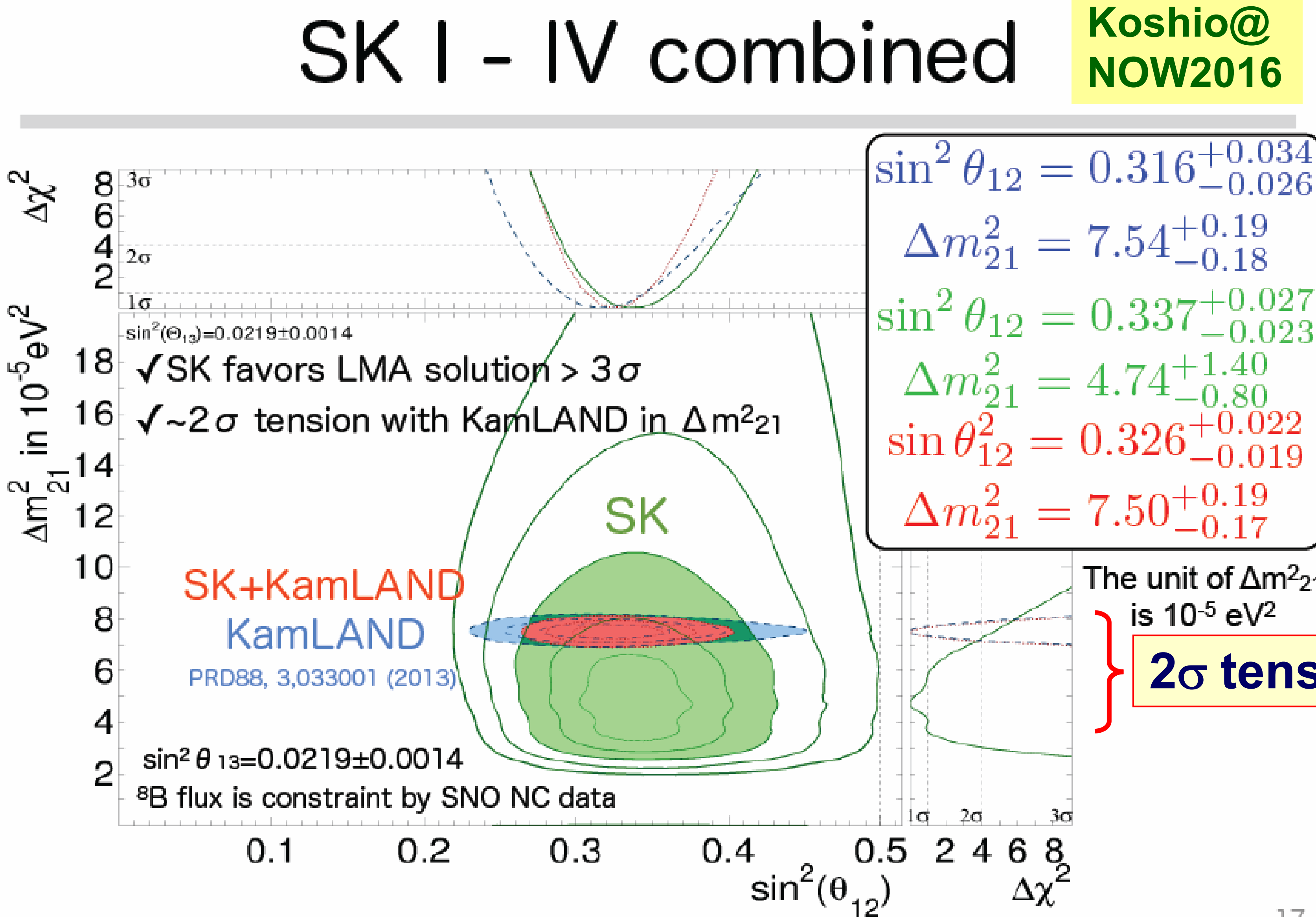
In the mean time we have had some possible tensions among the data within the standard oscillation scenario:

- ν_{solar} - KamLAND: Δm^2_{21} → NSI or sterile ν
- NOvA - T2K: θ_{23} → ??
- LSND-MiniBooNE anomaly, Reactor anomaly, Gallium anomaly → sterile ν

NSI: motivation to this talk

sterile ν : not directly related to this talk

- **Tension between Δm^2_{21}(solar) & Δm^2_{21}(KamLAND)**



Koshio@NOW2016

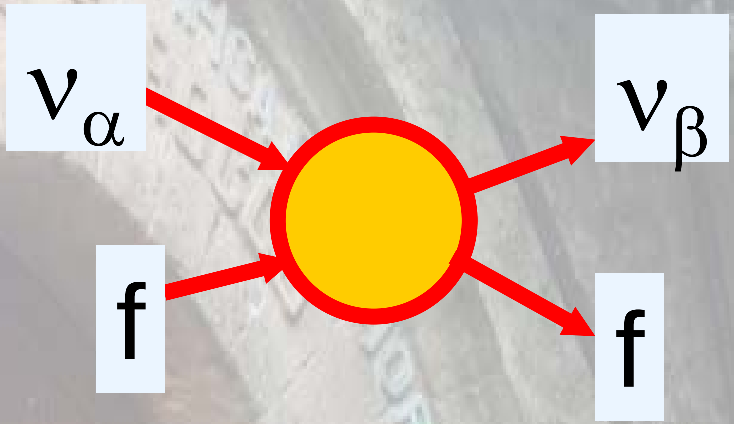
The unit of Δm^2_{21} is 10^{-5} eV^2

2σ tension

2. Nonstandard Interaction in propagation

Phenomenological New Physics considered in this talk: 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

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\left(E_1, E_2, E_3\right)U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

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

NP

Observation of matter effect needs large L

ν oscillation in matter (in two flavor toy case)

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

$$\Delta E \equiv \Delta m^2/2E$$

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

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

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

Matter effect becomes most conspicuous if $\Delta E\cos 2\theta = A$ is satisfied ($\tilde{\theta} = \pi/2$). In this case, the baseline length L has to be large:

$$\pi = \Delta \tilde{E} L = \Delta E \sin 2\theta L = A L \tan 2\theta$$

→L > π/A > O(1000km)

● Constraints on $\varepsilon_{\alpha\beta}$ from non-oscillation experiments

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

Biggio et al., JHEP 0908, 090 (2009)

Constraints are weak

$$\begin{pmatrix} |\epsilon_{ee}| \lesssim 4\times 10^{0} & |\epsilon_{e\mu}| \lesssim 3\times 10^{-1} & |\epsilon_{e\tau}| \lesssim 3\times 10^{0} \\ & |\epsilon_{\mu\mu}| \lesssim 7\times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3\times 10^{-1} \\ & & |\epsilon_{\tau\tau}| \lesssim 2\times 10^{1} \end{pmatrix}$$

● **Some model predicts large NSI** (new gauge boson mass is of O(10MeV) and SU(2) invariance is broken):
Farzan, PLB748 ('15) 311; Farzan-Shoemaker, JHEP,1607 ('16)033; Farzan-Heeck, PRD94 ('16) 053010.

●Constraints from high energy ν_{atm} oscillation

$$\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{\tau e} & 0 & \epsilon_{\tau\tau} \end{pmatrix} = V \,\mathrm{diag}\,(\lambda_{e'}, 0, \lambda_{\tau'})\; V^{-1}$$

Friedland-Lunardini, PRD72 ('05) 053009

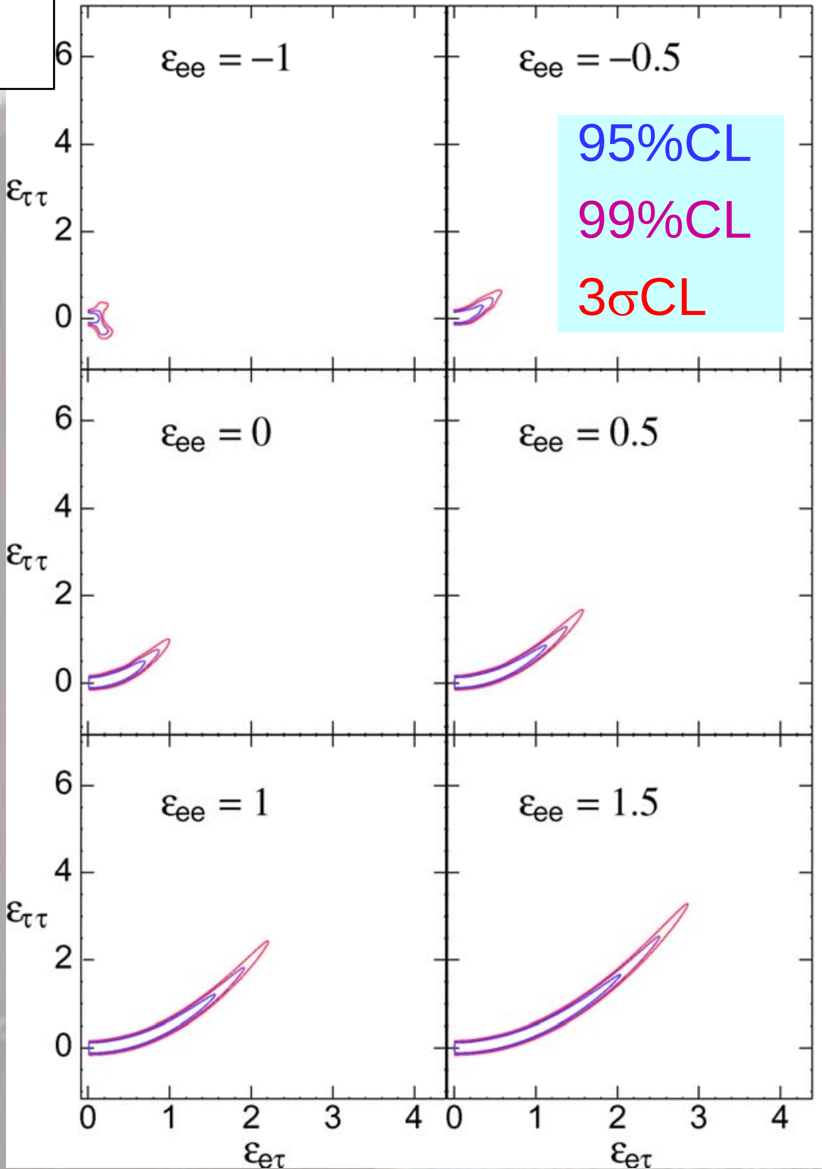
high energy ν_{atm} data implies

$$\min(\lambda_{e'}, \lambda_{\tau'}) = 0 \quad \leftrightarrow \quad \epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$$

at best fit point

$$|\min(\lambda_{e'}, \lambda_{\tau'})| \lesssim 0.2 \quad \leftrightarrow \quad \epsilon_{\tau\tau} \sim \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$$

at 99%CL



● Summary of the constraints on $\varepsilon_{\alpha\beta}$

To a good approximation, we are left with 3 independent variables ε_{ee}, $|\varepsilon_{e\tau}|$, $\arg(\varepsilon_{e\tau})$:

$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \simeq A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

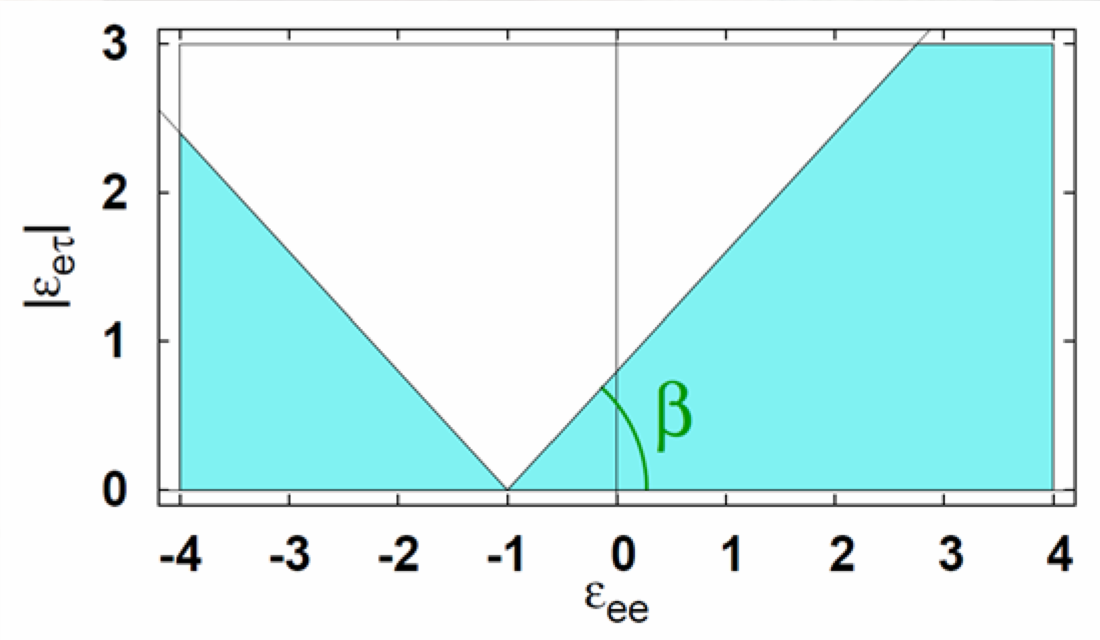
Furthermore, ν_{atm} data implies

$|\tan\beta|=|\varepsilon_{e\tau}/(1+\varepsilon_{ee})| < 0.8$ @2.5σCL

Fukasawa-OY, arXiv:1503.08056

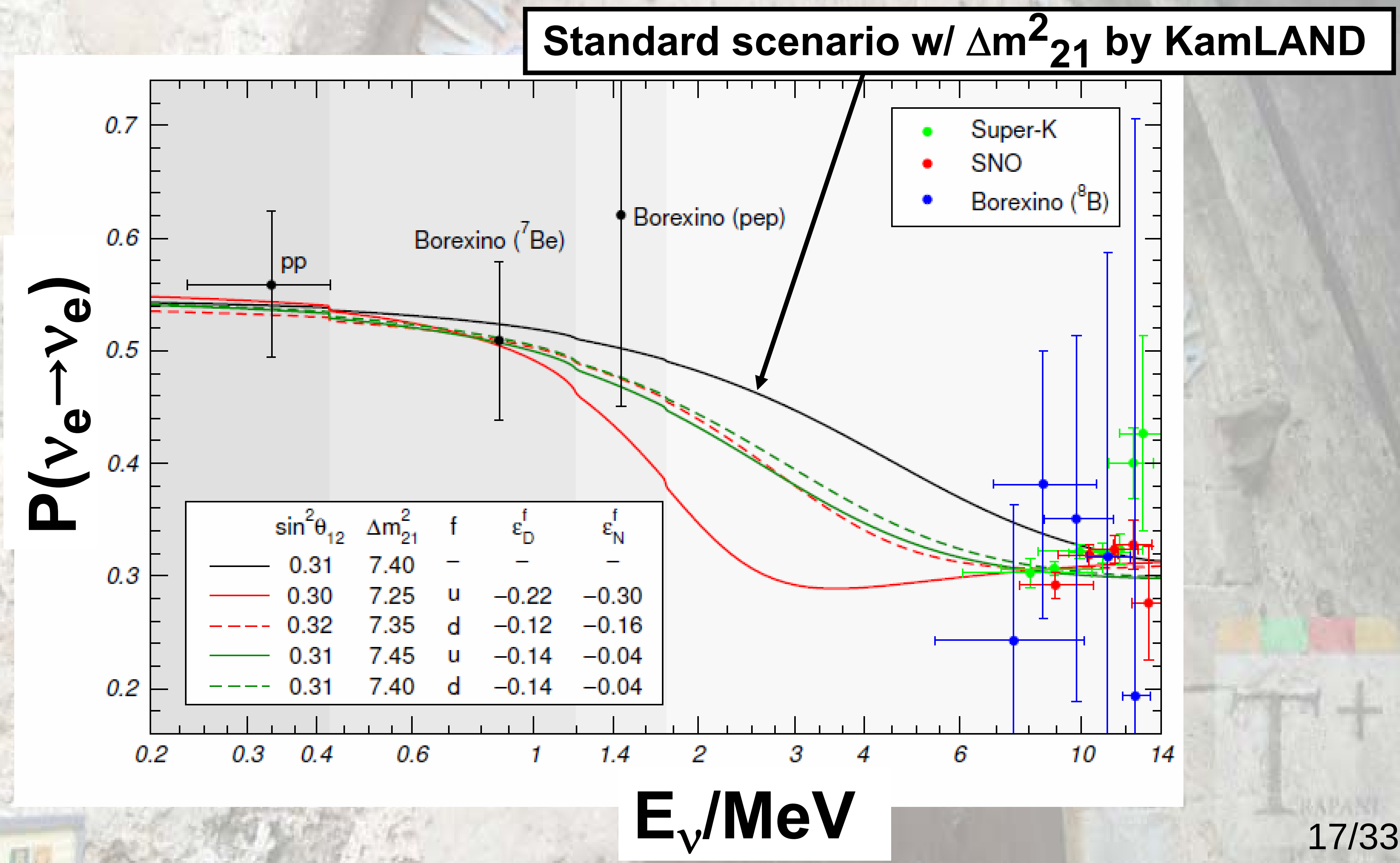
$$-4 \lesssim \epsilon_{ee} \lesssim 4,$$
$$|\epsilon_{e\tau}| \lesssim 3,$$
$$|\epsilon_{\tau\tau}| = \frac{|\epsilon_{e\tau}|^2}{|1+\epsilon_{ee}|} \lesssim 2$$

Allowed region in $(\varepsilon_{ee}, |\varepsilon_{e\tau}|)$



Tension between solar ν & KamLAND data comes from little observation of upturn by SK & SNO

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152



$\sin^2\theta_{12}$	Δm^2_{21}	f	ε^f_D	ε^f_N
0.31	7.40	–	–	–
0.30	7.25	u	−0.22	−0.30
0.32	7.35	d	−0.12	−0.16
0.31	7.45	u	−0.14	−0.04
0.31	7.40	d	−0.14	−0.04

3. Sensitivity to NSI of propagation at T2HKK

Strategy of our analysis:

- We assume $\varepsilon_{\alpha\beta}$(true) = 0 and minimize χ^2 (ε_{ee}(test), | $\varepsilon_{e\tau}$(test)|) by varying other $\varepsilon_{\alpha\beta}$(test).

- For simplicity we assume $\varepsilon_{\mu\alpha}$ =0.

3.1 For simplicity we assume $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2 /(1+\varepsilon_{ee})$ (It comes from ν_{atm}).

Fukasawa, Ghosh, OY, PRD95 ('17) 055005

$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

3.2 We treat $\varepsilon_{\tau\tau}$ as an independent variable:

Ghosh, OY, to appear

$$\Rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & \epsilon_{\tau\tau} \end{pmatrix}$$

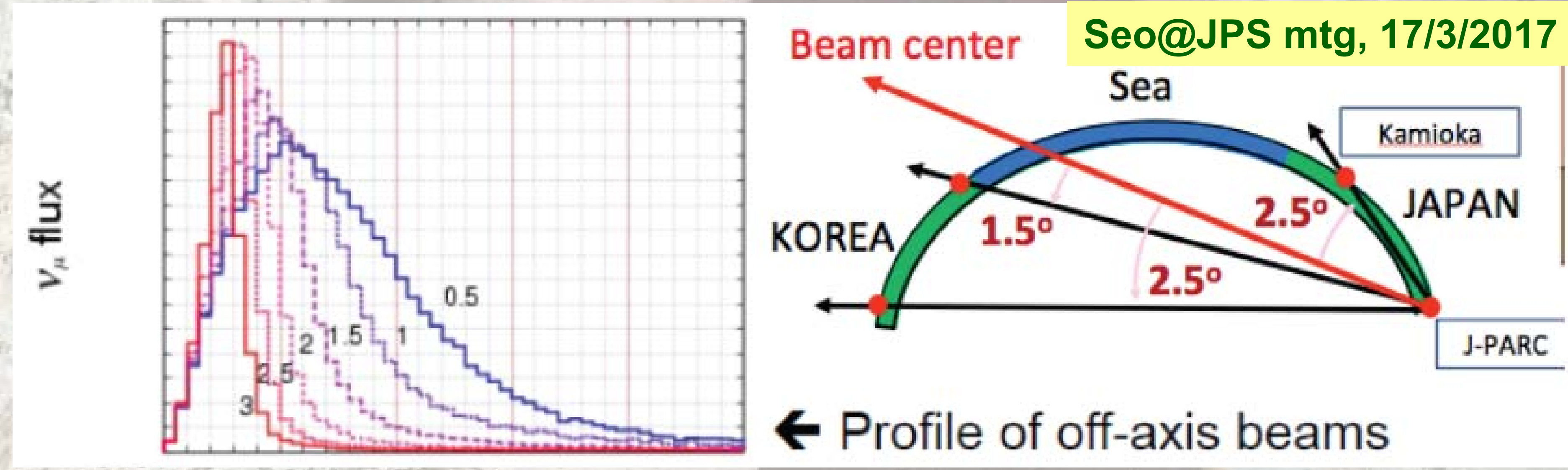
3.1 Comparison of sensitivity to NSI among different off-axis angles

Fukasawa, Ghosh, OY, PRD95 ('17) 055005

In the early stage of the T2HKK project, several options for off-axis angle were considered.

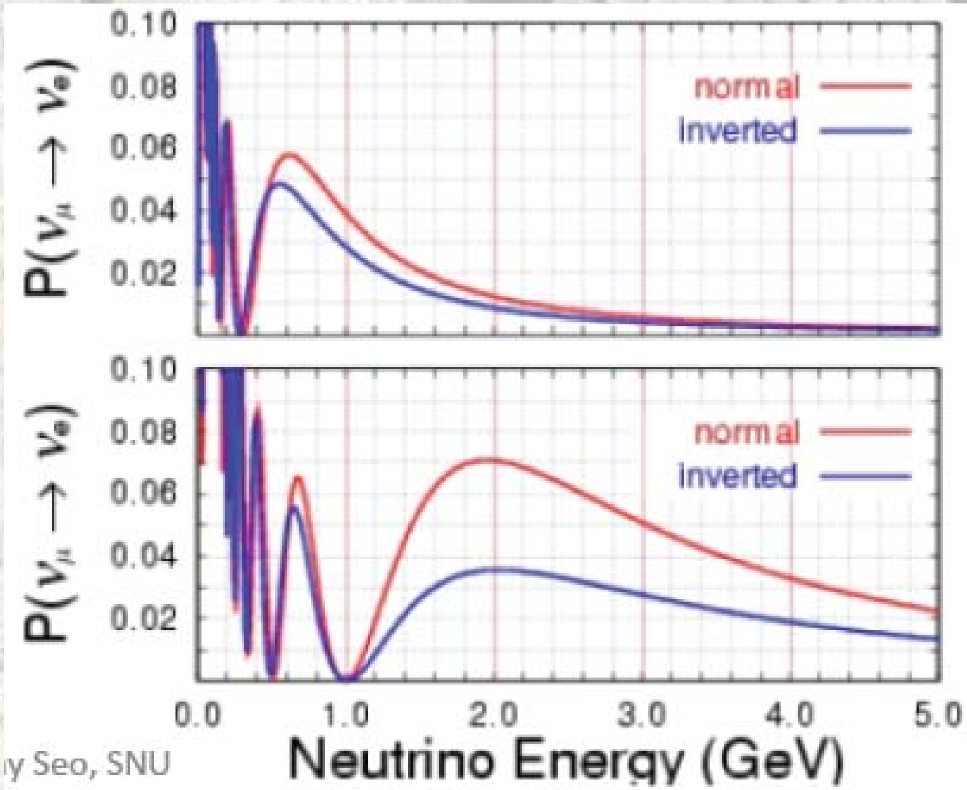
- **For different off-axis angle the energy peak is different**

Seo@JPS mtg, 17/3/2017



● **Oscillation maximum at L=1100km is different from that at L=295km**

Seo@JPS mtg,17/3/2017



← $P(\nu_\mu \rightarrow \nu_e)$ at SK/HK (L = 295 km)

← $P(\nu_\mu \rightarrow \nu_e)$ at Korea (L=1000km)

As a first step, for simplicity we assume $\varepsilon_{\mu\alpha} = 0$ and $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2 / (1+\varepsilon_{ee})$ (latter comes from ν_{atm})

$$A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \Rightarrow A \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

We marginalize χ^2 with respect to arg $(\varepsilon_{e\tau}) = \phi_{31}$

We compare the sensitivities of T2HK, T2HKK, DUNE, HK(ν_{atm})

L=295km (T2HK)

L=1100km (T2HKK)

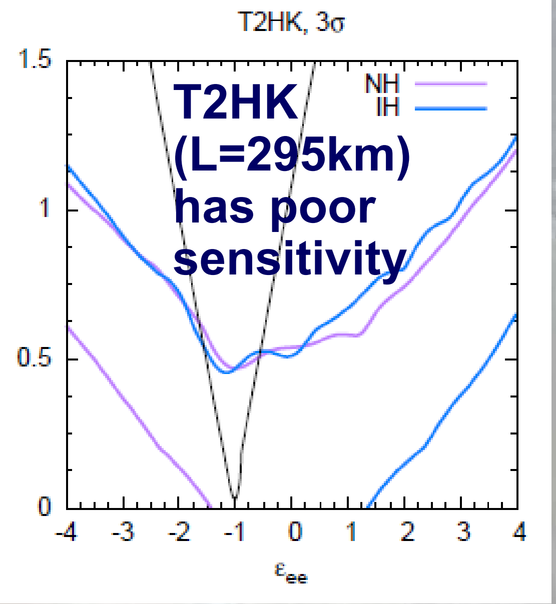
L=1300km (DUNE)

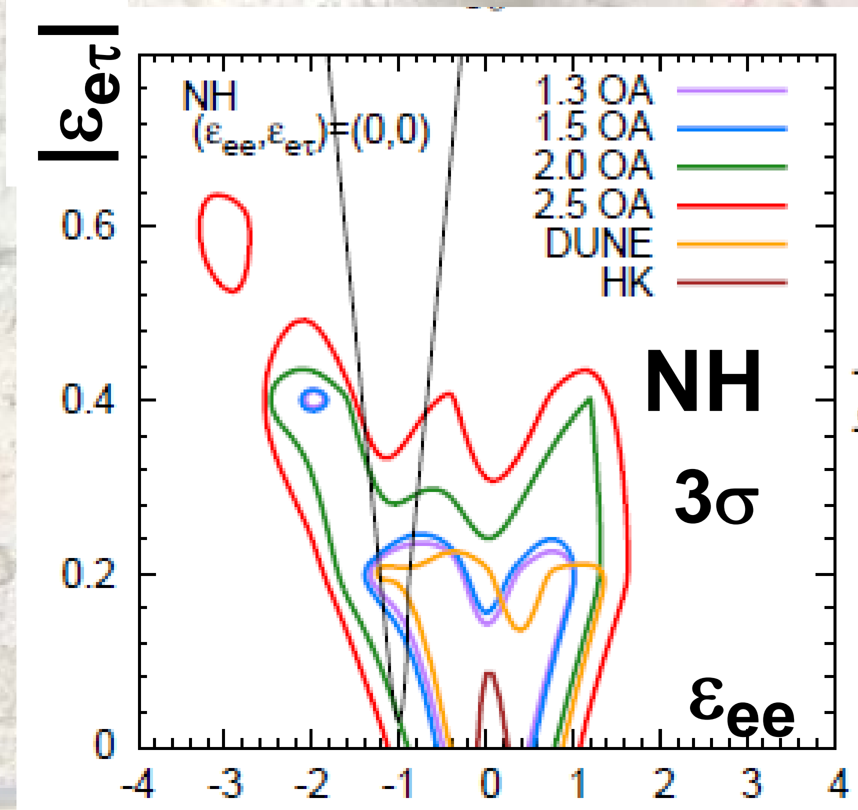
10km<L<13000km (HK(ν_{atm}))

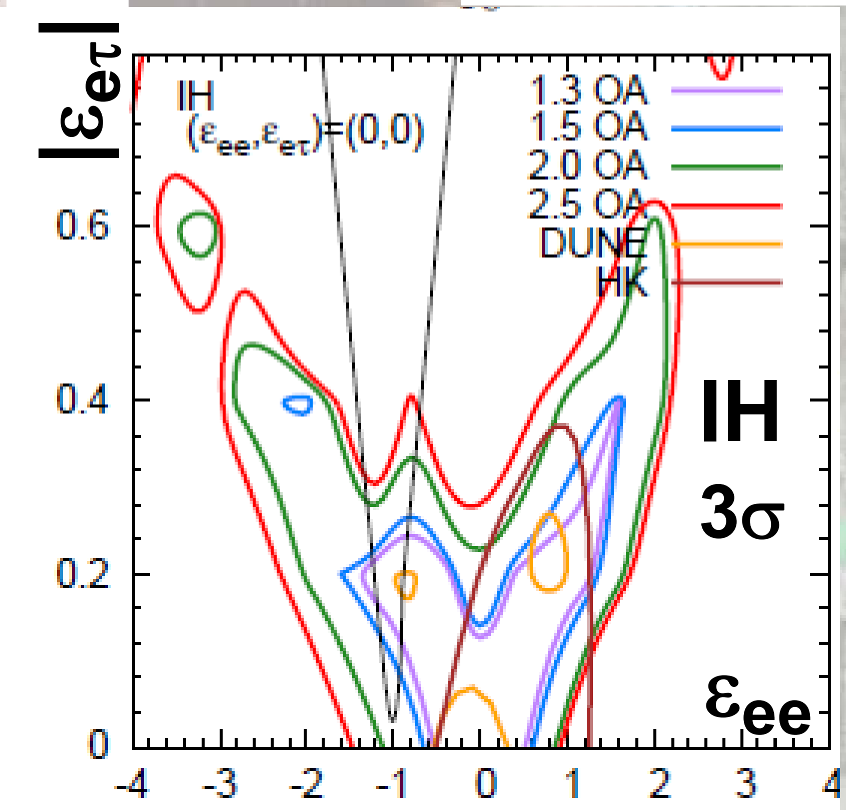
Sensitivity to (ε_{ee}, $|\varepsilon_{e\tau}|$) at 3σ

Among the Off Axis angle options of T2HKK, 1.3°is the best

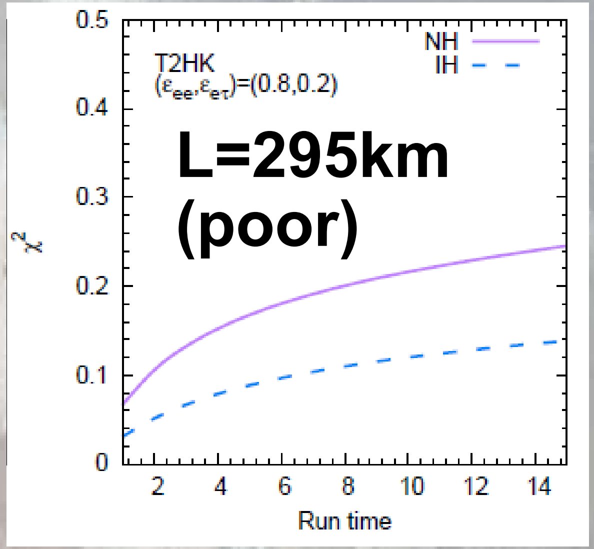
T2HKK (OA1.3°) < DUNE < HK(ν_{atm})



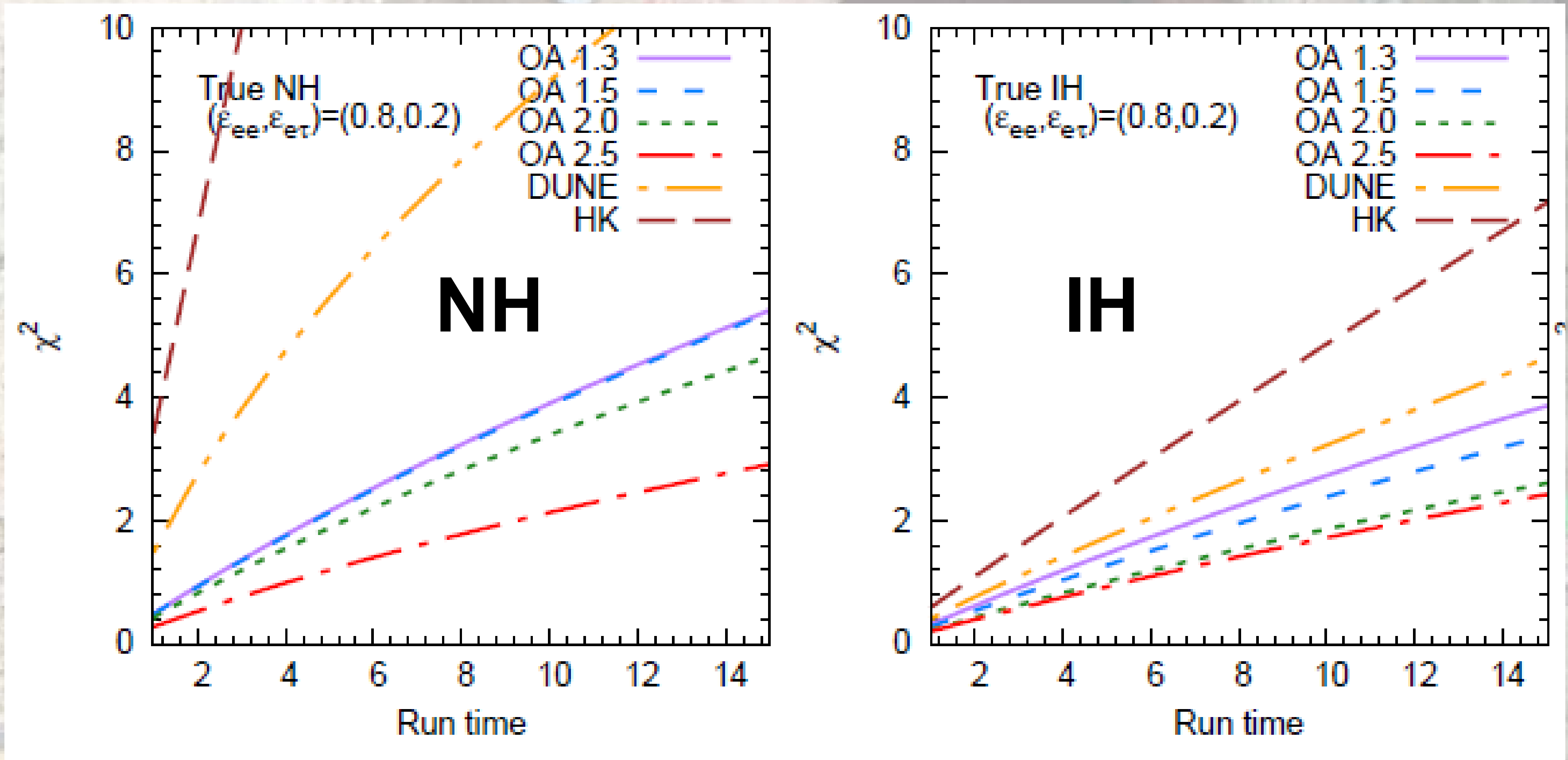




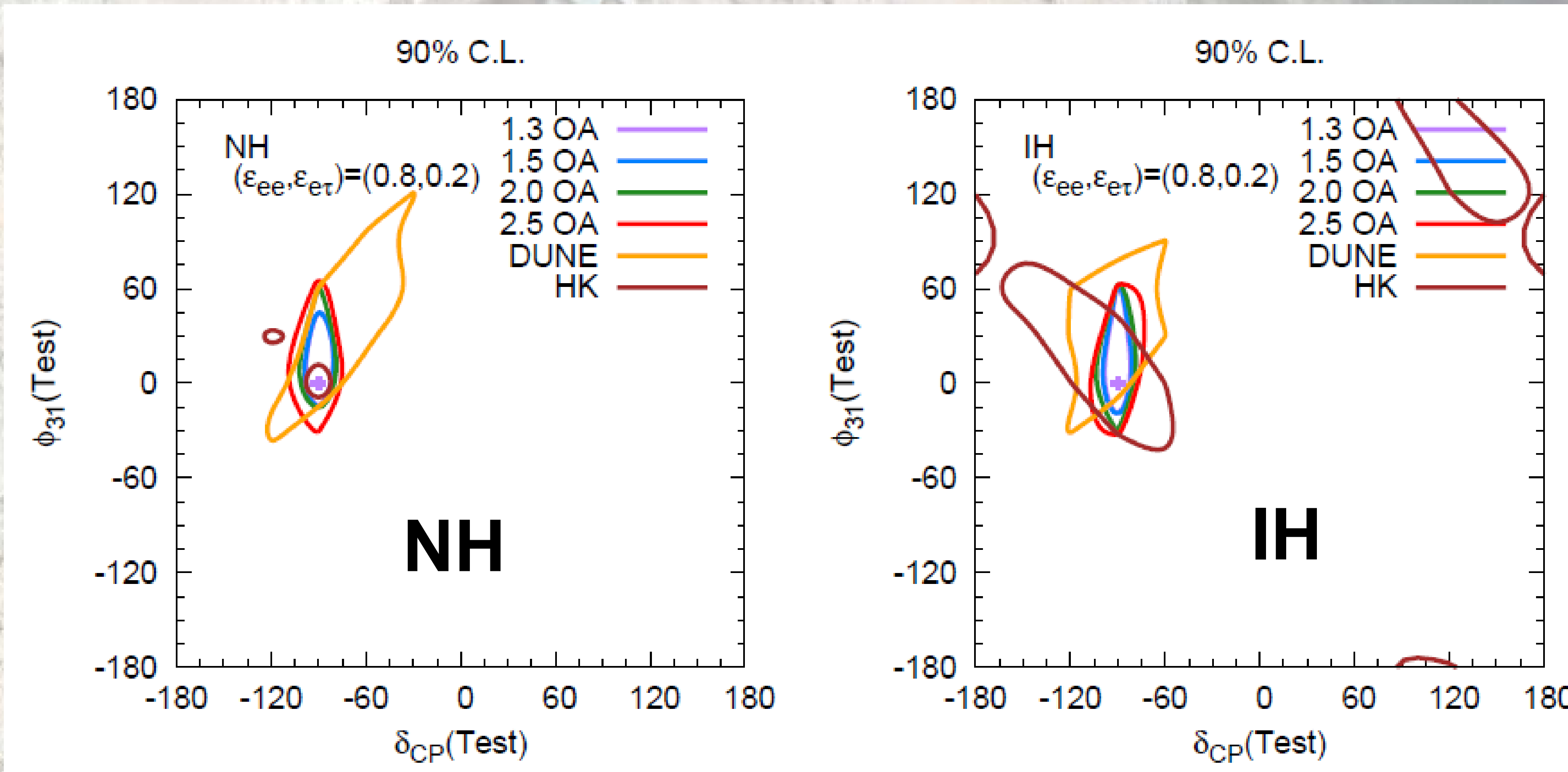
Significance to exclude NSI for the reference value ϵ_{ee} =0.8, $|\epsilon_{e\tau}|$ = 0.2



T2HKK (OA1.3°) < DUNE < HK(ν_{atm})



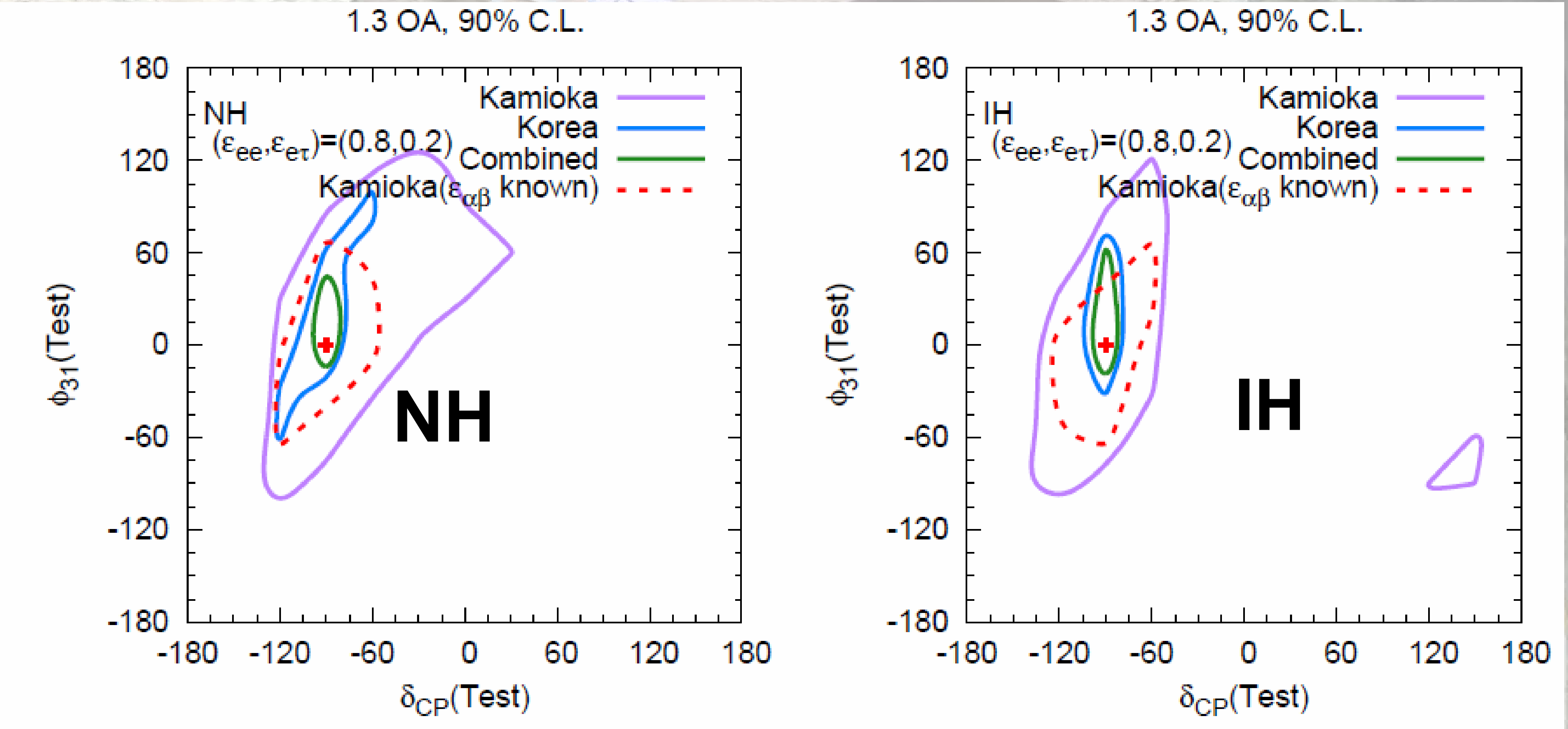
Allowed region in the presence of NSI with $\delta=-\pi/2$, $\varepsilon_{ee}=0.8$, $|\varepsilon_{e\tau}|=0.2$, $\arg(\varepsilon_{e\tau})=\phi_{31}=0$



T2HKK (OA1.3°) > DUNE, HK(ν_{atm}):degeneracy

Synergy of L=295km & L=1100km:

Allowed region in the presence of NSI with $\delta=-\pi/2$, $\varepsilon_{ee}=0.8$, $|\varepsilon_{e\tau}| = 0.2$, $\arg(\varepsilon_{e\tau}) = \phi_{31}=0$



3.2 More discussions on precision of the parameters

Ghosh, OY, to appear

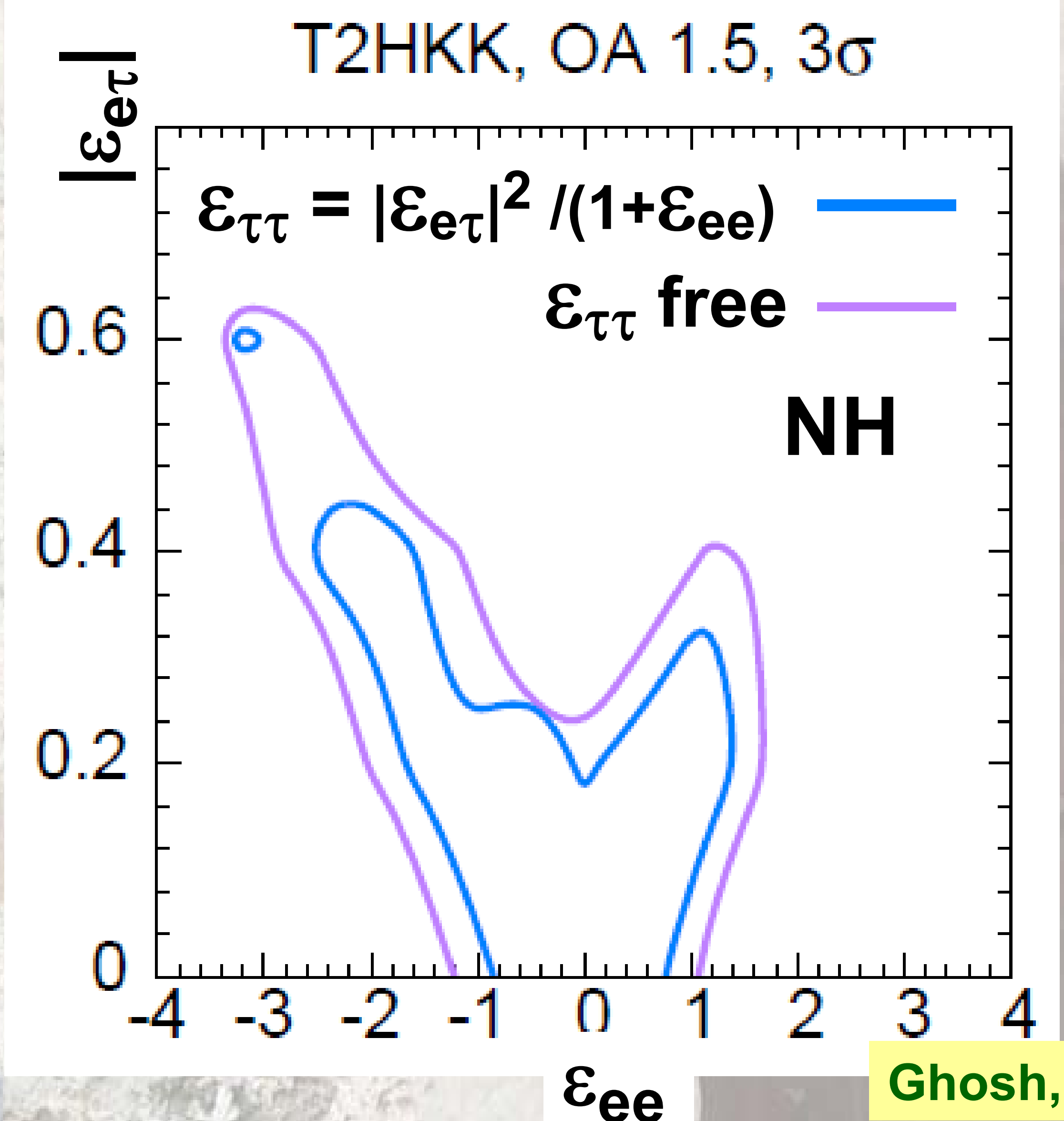
- **We extend our analysis from the conditions $[\varepsilon_{\mu\alpha} = 0$ & $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})]$ to $[\varepsilon_{\mu\alpha} = 0$ & $\varepsilon_{\tau\tau} \neq |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})]$, i.e., treat $\varepsilon_{\tau\tau}$ as an independent variable.**

$$A \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^{*} & 0 & \boxed{\epsilon_{\tau\tau}} \end{pmatrix}$$

- **We skip marginalization over Δm^2_{31} & Δm^2_{21} as a good approximation.**

- **We fix the Off-Axis angle to 1.5^o (T2HKK collaboration reached the conclusion with OA 1.5^o.**

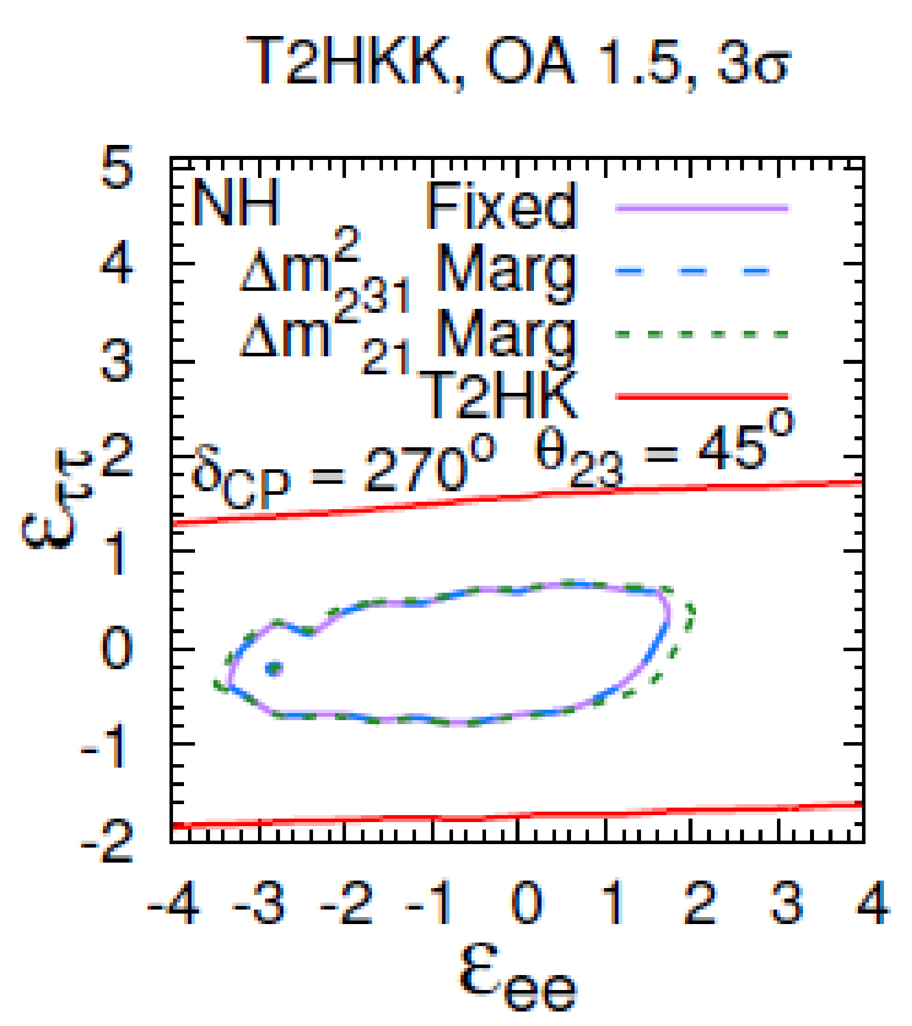
Sensitivity to (ε_{ee}, $|\varepsilon_{e\tau}|$) at 3σ is enlarged by varying $\varepsilon_{\tau\tau}$ to some extent

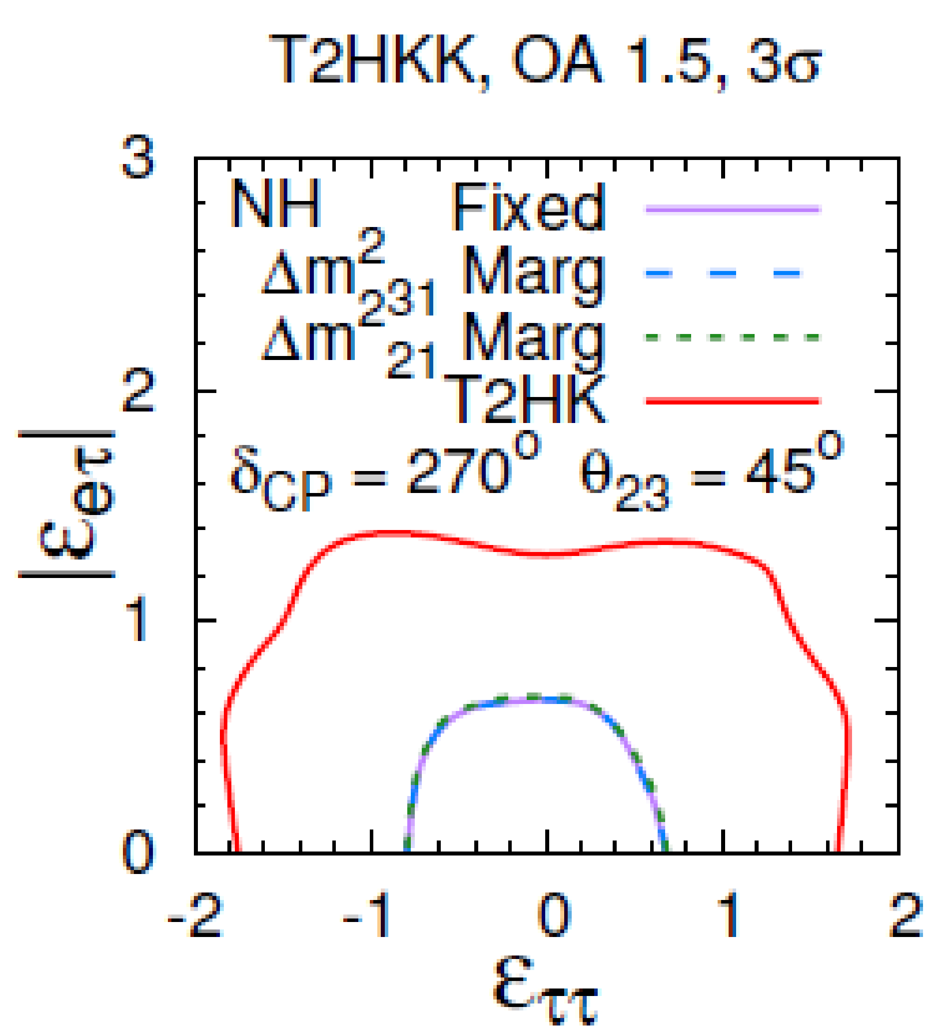


Ghosh, OY, to appear

Some correlation of $\varepsilon_{\tau\tau}$ with ε_{ee} & $|\varepsilon_{e\tau}|$ at 3σ is found

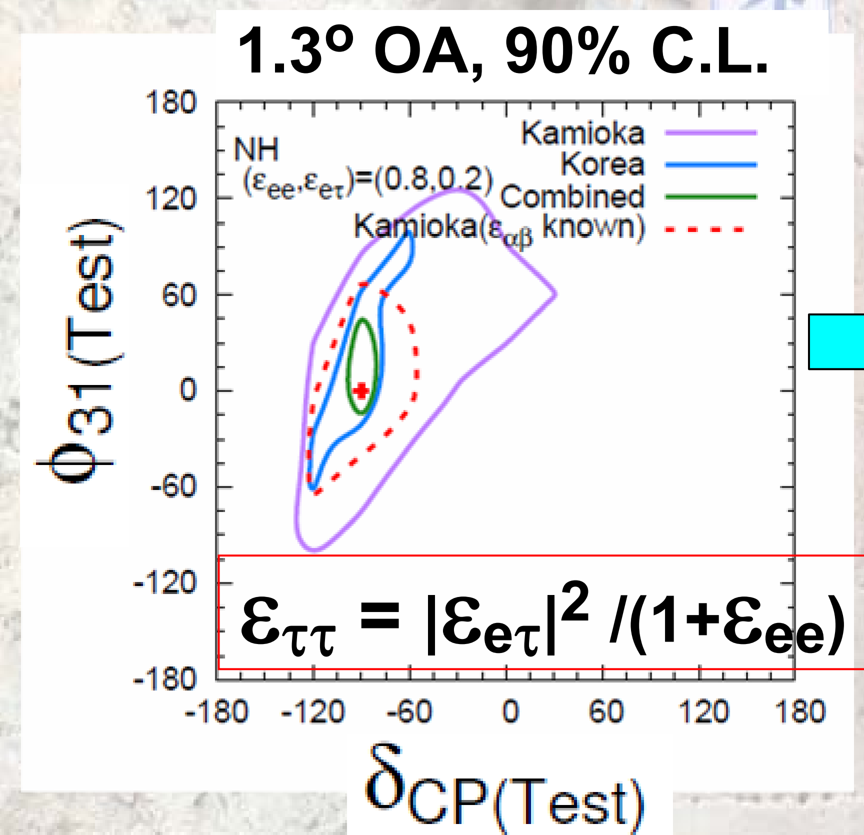
Ghosh, OY, to appear

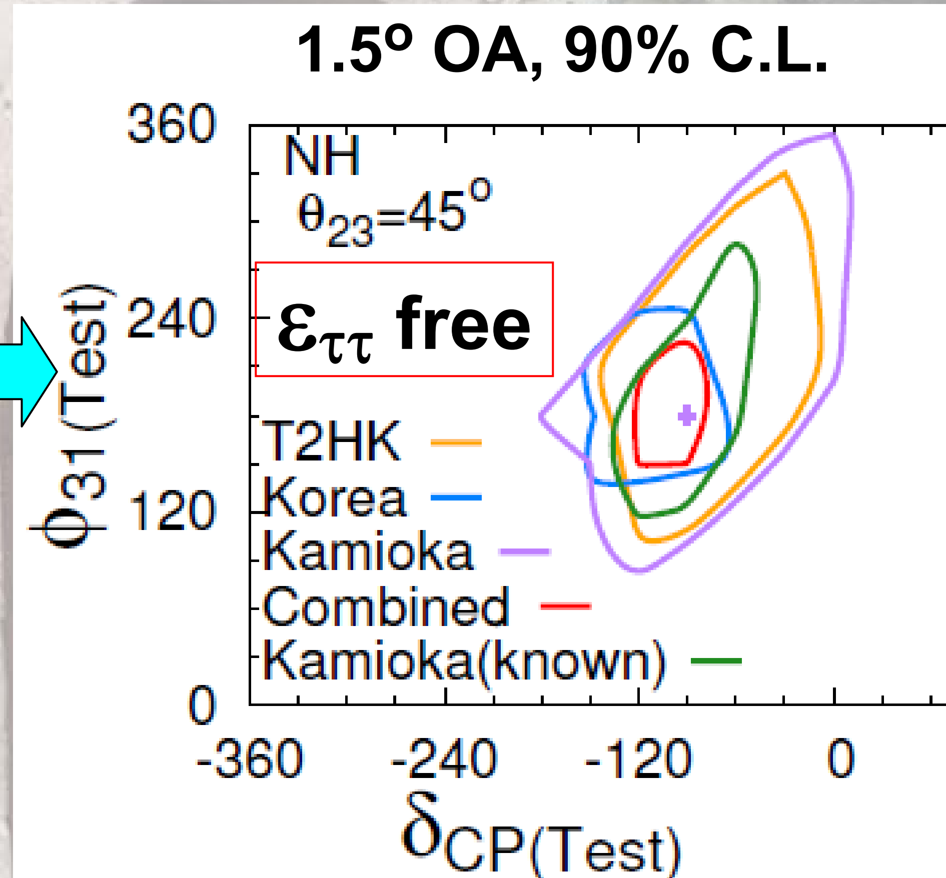




Allowed region in the presence of NSI with $\delta=-\pi/2$, $\varepsilon_{ee}=0.8$, $|\varepsilon_{e\tau}| = 0.2$, $\arg(\varepsilon_{e\tau}) = \phi_{31}=0$

-> enlarged to some extent by varying $\varepsilon_{\tau\tau}$





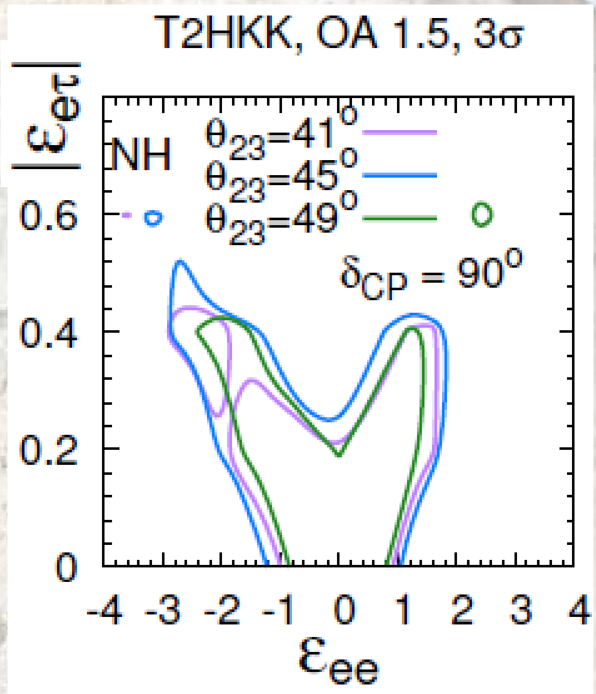
Ghosh, OY, to appear

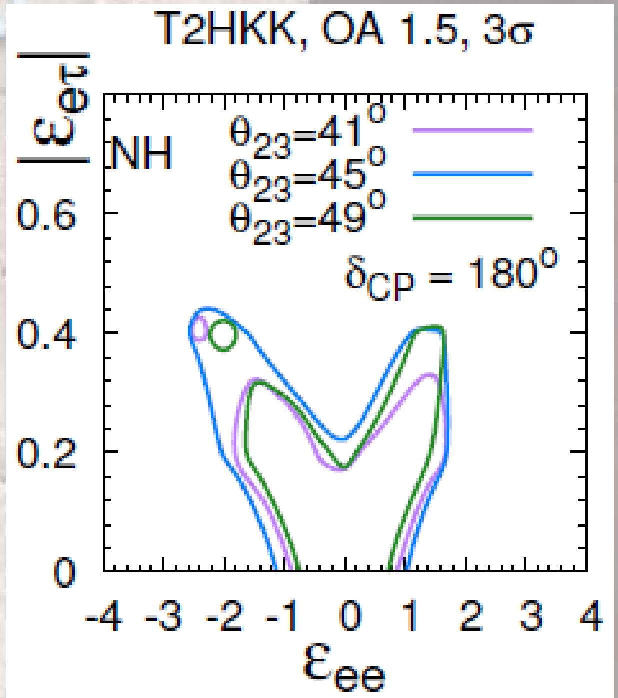
Ghosh, OY, to appear

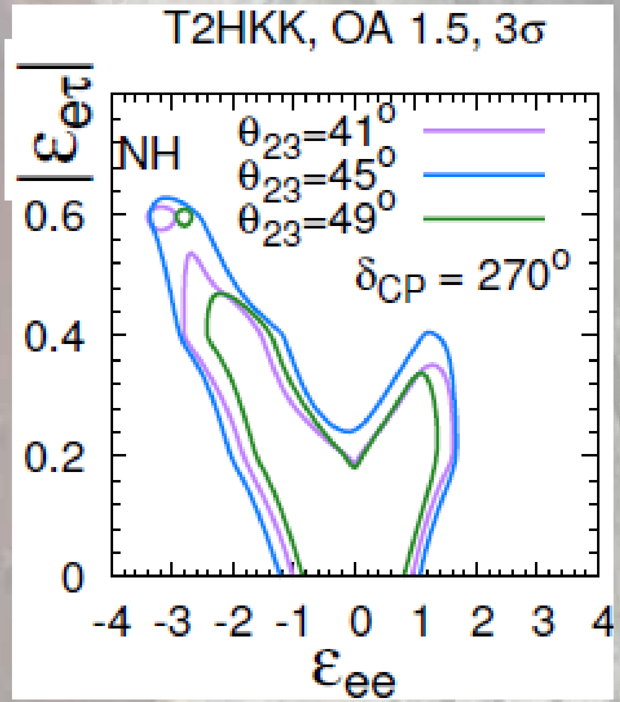
Dependence of sensitivity to (ε_{ee}, $|\varepsilon_{e\tau}|$) on θ_{23} and δ

-> not so large

$\varepsilon_{\tau\tau}$ free







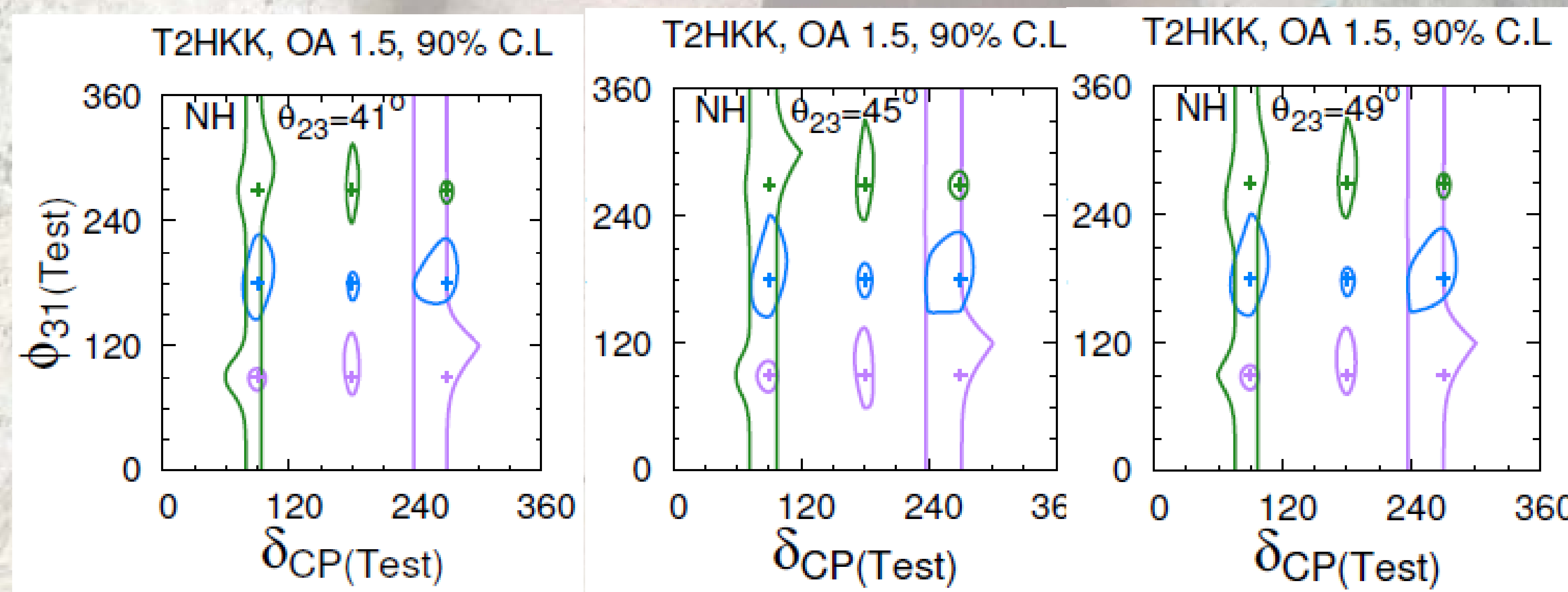
Dependence of allowed region in (δ, ϕ_{31}) on θ_{23} and δ

Ghosh, OY, to appear

ϕ_{31}= arg ($\varepsilon_{e\tau}$)

-> not so large except for (δ, ϕ_{31}) = (π/2, 3π/2), (3π/2, π/2)
(Explanation of the phenomena is under investigation)

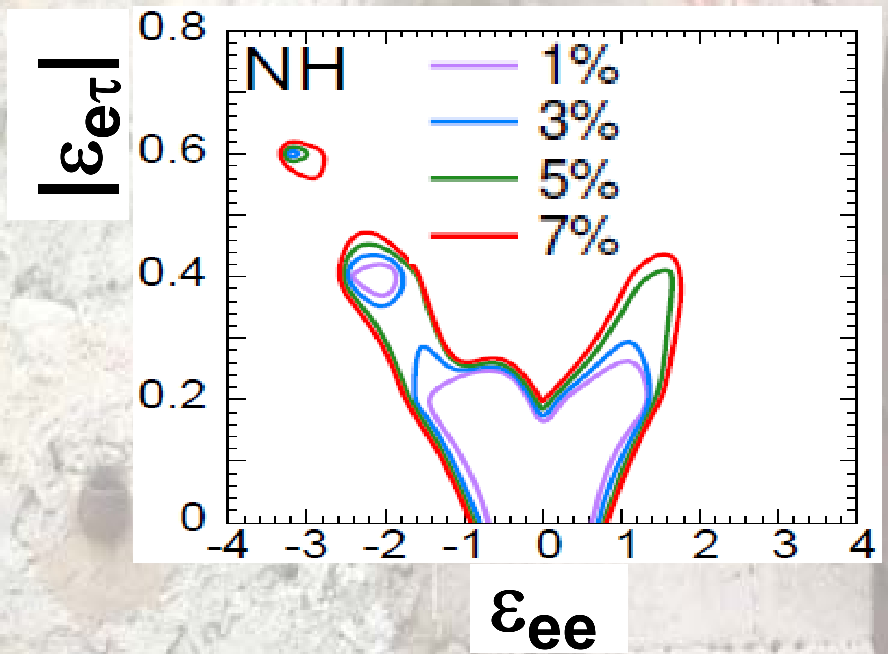
$\varepsilon_{\tau\tau}$ free

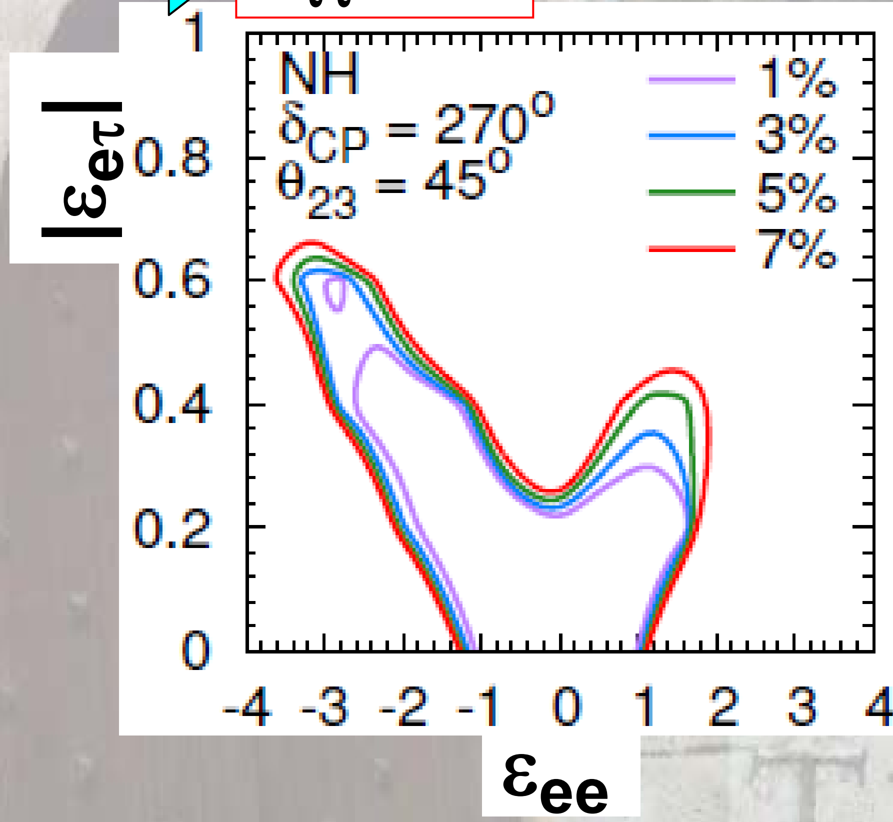


Dependence of allowed region in (ϵ_{ee}, $|\epsilon_{e\tau}|$) at 3σ on the systematic error (T2HKK OA 1.5^o)

5% -> 3% improves the sensitivity to some extent

$\epsilon_{\tau\tau} = |\epsilon_{e\tau}|^2 /(1+\epsilon_{ee})$ → $\epsilon_{\tau\tau}$ free





Ghosh & OY, PRD96 ('17) 013001

Ghosh, OY, to appear

4. Conclusions

- T2HKK has sensitivity to NSI and its sensitivity is comparable to that of DUNE.
- As far as NSI is concerned, the option with OA1.3^{o} has the best sensitivity among all OA angle options of T2HKK.
- Combination of T2HK and T2HKK will allow us to determine δ and arg($\varepsilon_{e\tau}$) separately, if (ε_{ee}, | $\varepsilon_{e\tau}$|) lies within the sensitivity region.

Backup slides

● Constraints from high energy ν_{atm} data

Friedland-Lunardini, PRD72 ('05) 053009

➢ Standard case with N_ν=3

$$1 - P(\nu_\mu \to \nu_\mu) \sim \left(\frac{\Delta m^2_{31}}{2AE}\right)^2 \left[\sin^2 2\theta_{23}\left(\frac{c^2_{13}AL}{2}\right)^2 + s^2_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{AL}{2}\right)\right] \propto \frac{1}{E^2}$$

Consistent with data

➢ Deviation of 1-P($\nu_\mu \to \nu_\mu$) due to NP contradicts with data

$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21}\sin^2(c_{22}L)}{E^2}$$

Oki-OY, PRD82 ('10) 073009

$|c_0| \ll 1 \to |\epsilon_{e\mu}| << 1, |\epsilon_{\mu\mu}| << 1, |\epsilon_{\mu\tau}| << 1$

$|c_1| \ll 1 \to \left|\epsilon_{\tau\tau} - |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})\right| << 1$

● NSI for solar ν: $\varepsilon_{\alpha\beta}$ vs $(\varepsilon_D, \varepsilon_N)$

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152

In solar ν analysis, $\Delta m_{31}^2 \rightarrow \infty$, $H \rightarrow H^{eff}$

To a good approximation, the oscillation probability is described by 2 mass eigenstates:

$$H^{\rm eff} = \frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix}$$

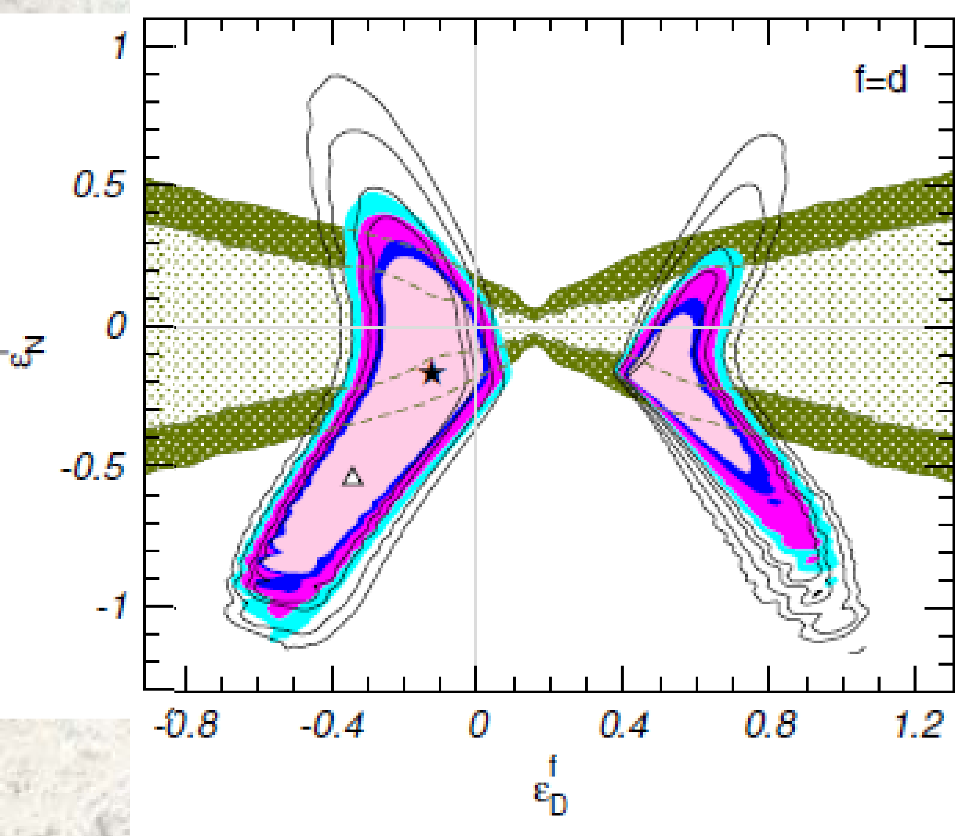
$$+ \begin{pmatrix} c_{13}^2 A & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\epsilon_D^f & \epsilon_N^f \\ \epsilon_N^{f*} & \epsilon_D^f \end{pmatrix}$$

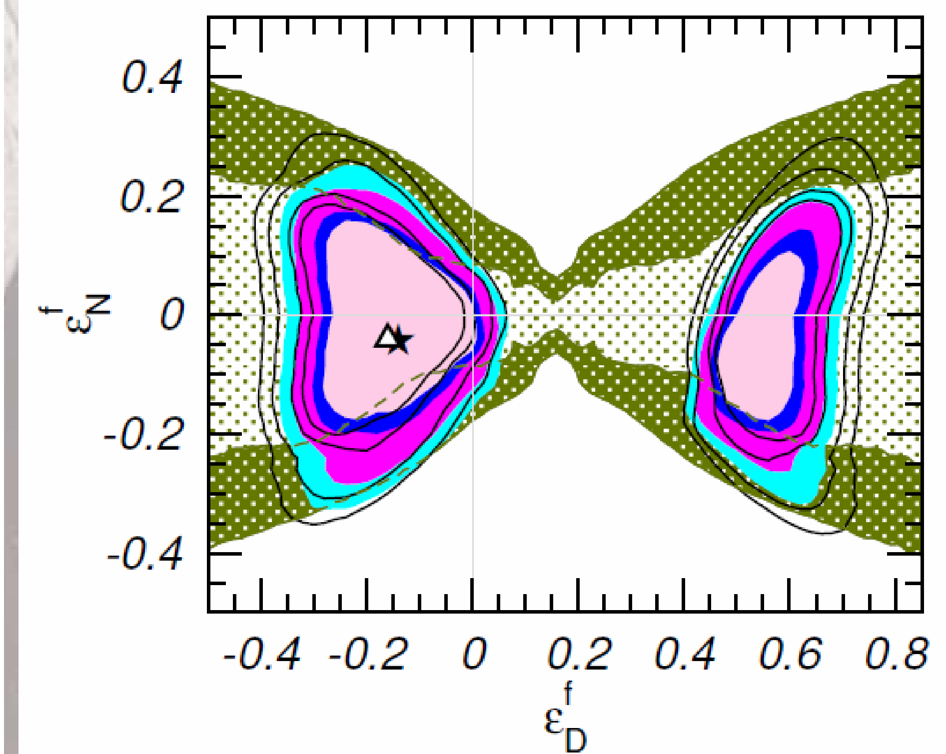
$$\begin{aligned} \epsilon_D^f &= c_{13} s_{13} \mathrm{Re}\left[e^{i\delta_{\rm CP}} \left(s_{23}\epsilon_{e\mu}^f + c_{23}\epsilon_{e\tau}^f\right)\right] - \left(1 + s_{13}^2\right) c_{23} s_{23} \mathrm{Re}\left[\epsilon_{\mu\tau}^f\right] \\ &\quad - \frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \\ \epsilon_N^f &= c_{13}\left(c_{23}\epsilon_{e\mu}^f - s_{23}\epsilon_{e\tau}^f\right) + s_{13} e^{-i\delta_{\rm CP}} \left[s_{23}^2 \epsilon_{\mu\tau}^f - c_{23}^2 \epsilon_{\mu\tau}^{f*} + c_{23} s_{23}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right)\right] \end{aligned}$$

f = e, u or d

Tension between solar ν & KamLAND can be solved by NSI

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152





Best fit value of solar-KL

$$(\epsilon_D^u, \epsilon_N^u) = (-0.22, -0.30)$$

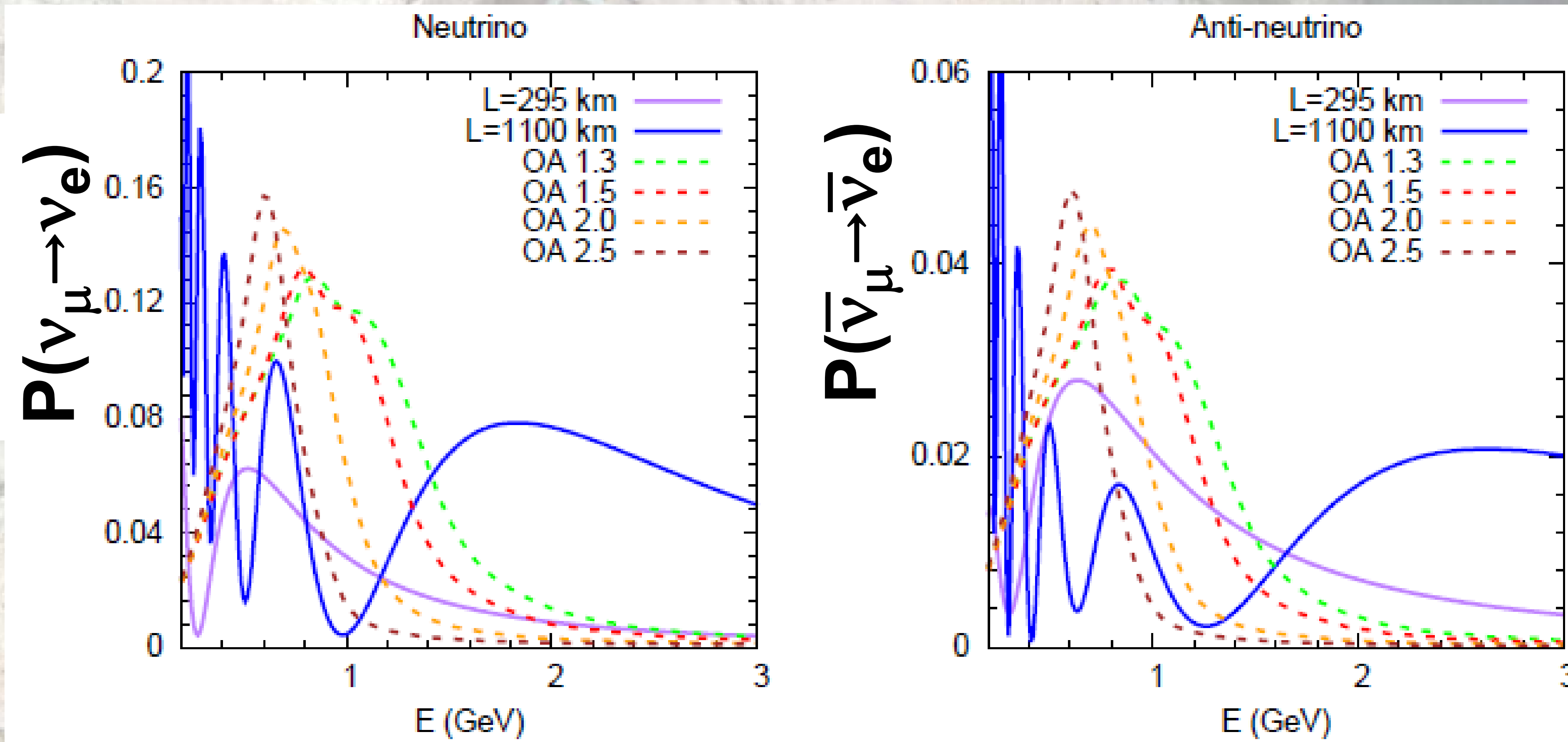
$$(\epsilon_D^d, \epsilon_N^d) = (-0.12, -0.16)$$

Best fit value of global fit

$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

$$(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)$$

T2HKK:Appearance probability at L=1050km



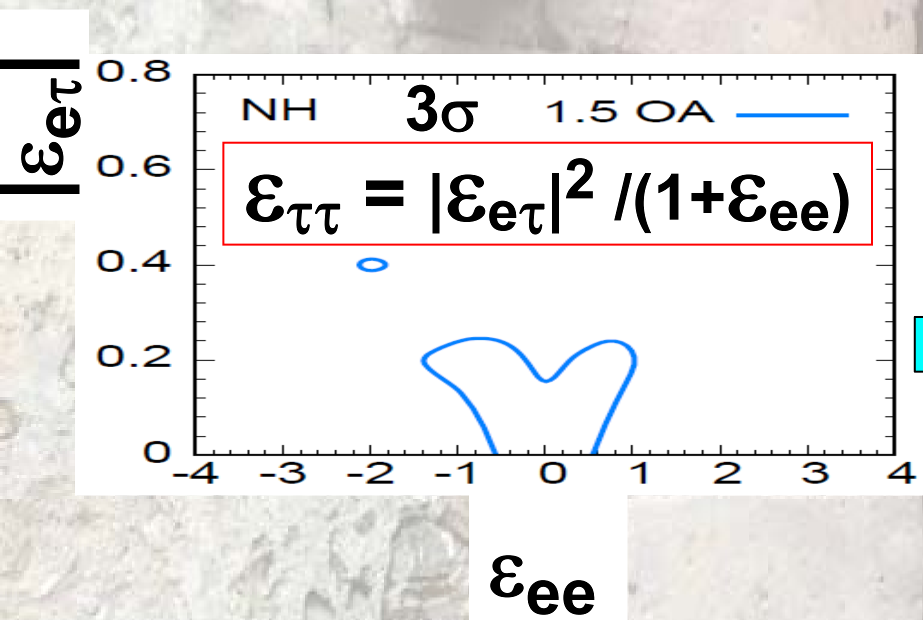
List of candidate sites in Korea

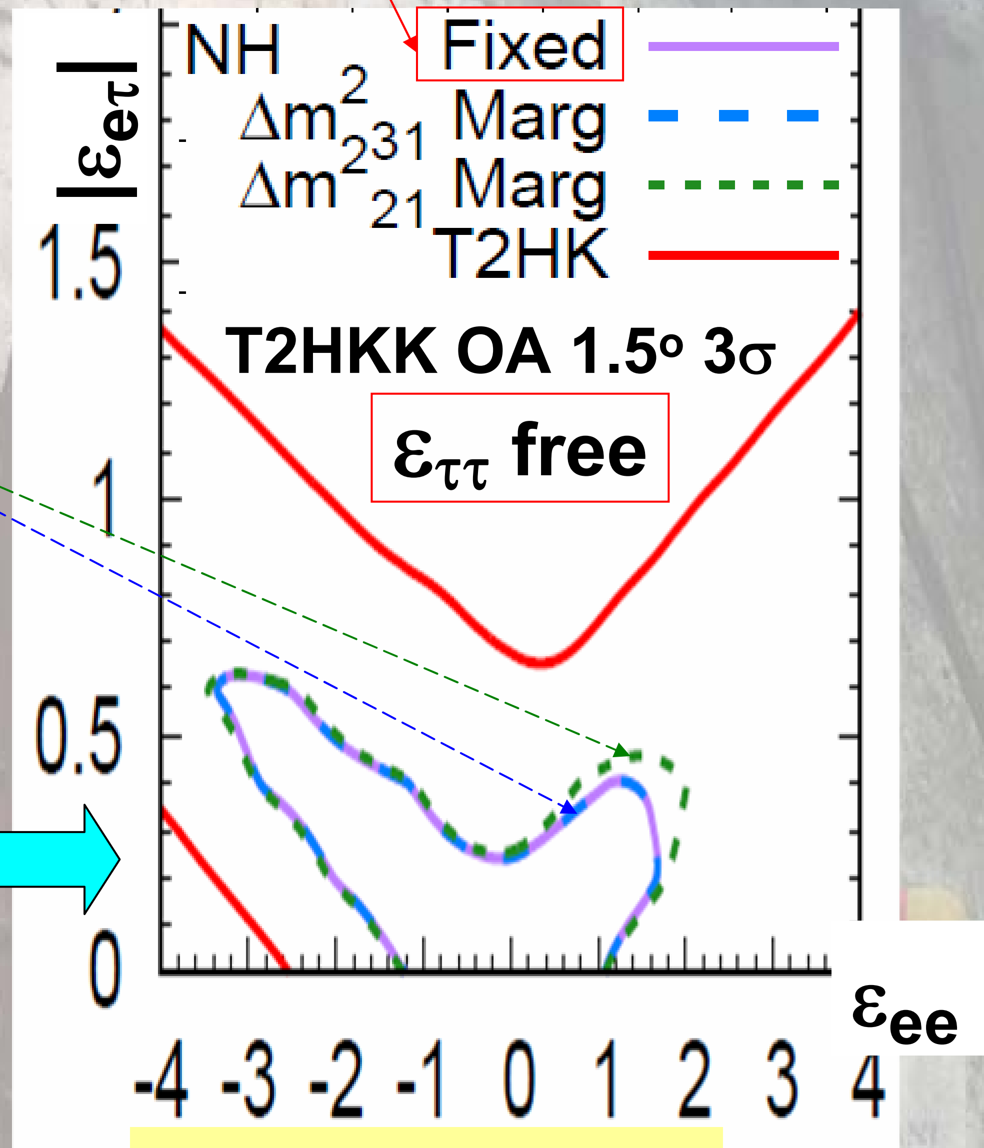
Site	Height (m)	Baseline (km)	Off-axis angle (degree)	Elements of rock
Mt. Bisul	1084	1088	1.3°	Granite porphyry, Andesitic breccia
Mt. Hwangmae	1113	1140	1.8°	Flake granite, Porphyritic gneiss
Mt. Sambong	1186	1180	1.9°	Porphyritic granite, Biotite gneiss
Mt. Bohyun	1124	1040	2.2°	Granite, Volcanic rocks, Volcanic breccia
Mt. Minjuji	1242	1140	2.2°	Granite, Biotite gneiss
Mt. Unjang	1125	1190	2.2°	Rhyolite, Granite porphyry, Quartz porphyry

Sensitivity to (ε_{ee}, $|\varepsilon_{e\tau}|$) at 3σ is enlarged by varying $\varepsilon_{\tau\tau}$ to some extent

Fixed: marginalization over Δm^2_{31} & Δm^2_{21} is skipped

Marginalization over Δm^2_{31} & Δm^2_{21} gives little contribution.





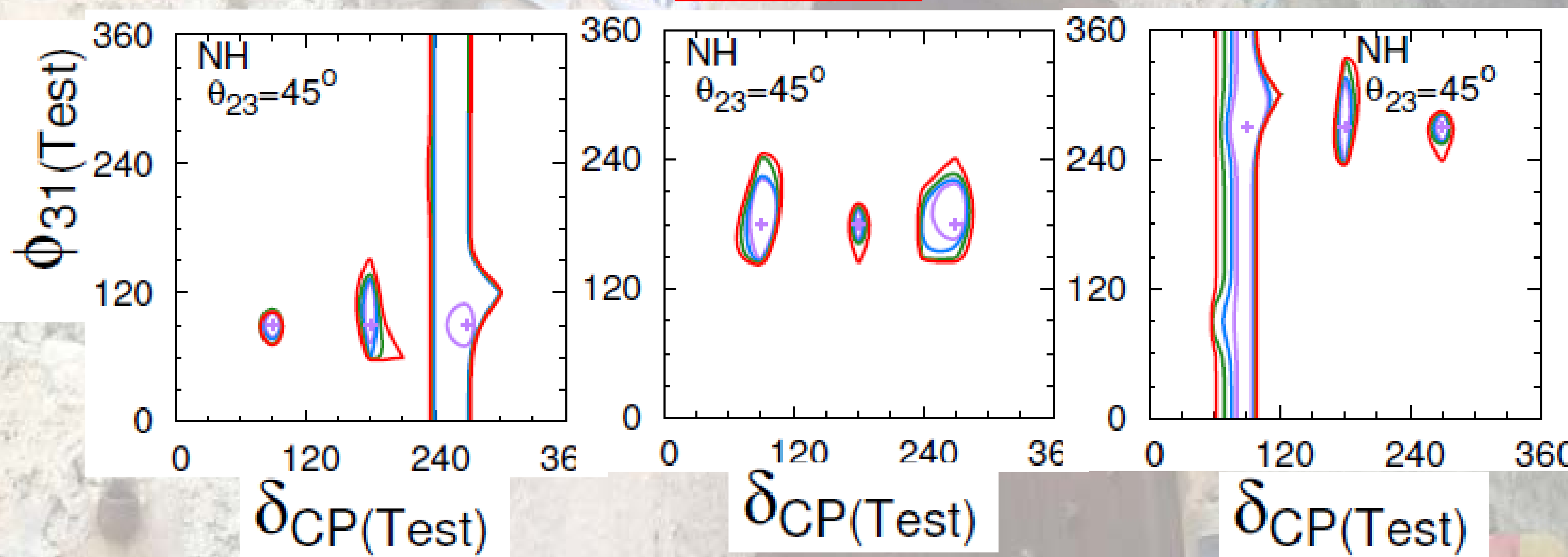
Ghosh, OY, to appear

Dependence of allowed region in (δ, ϕ_{31}) at 90%CL on the systematic error (T2HKK OA 1.5^o)

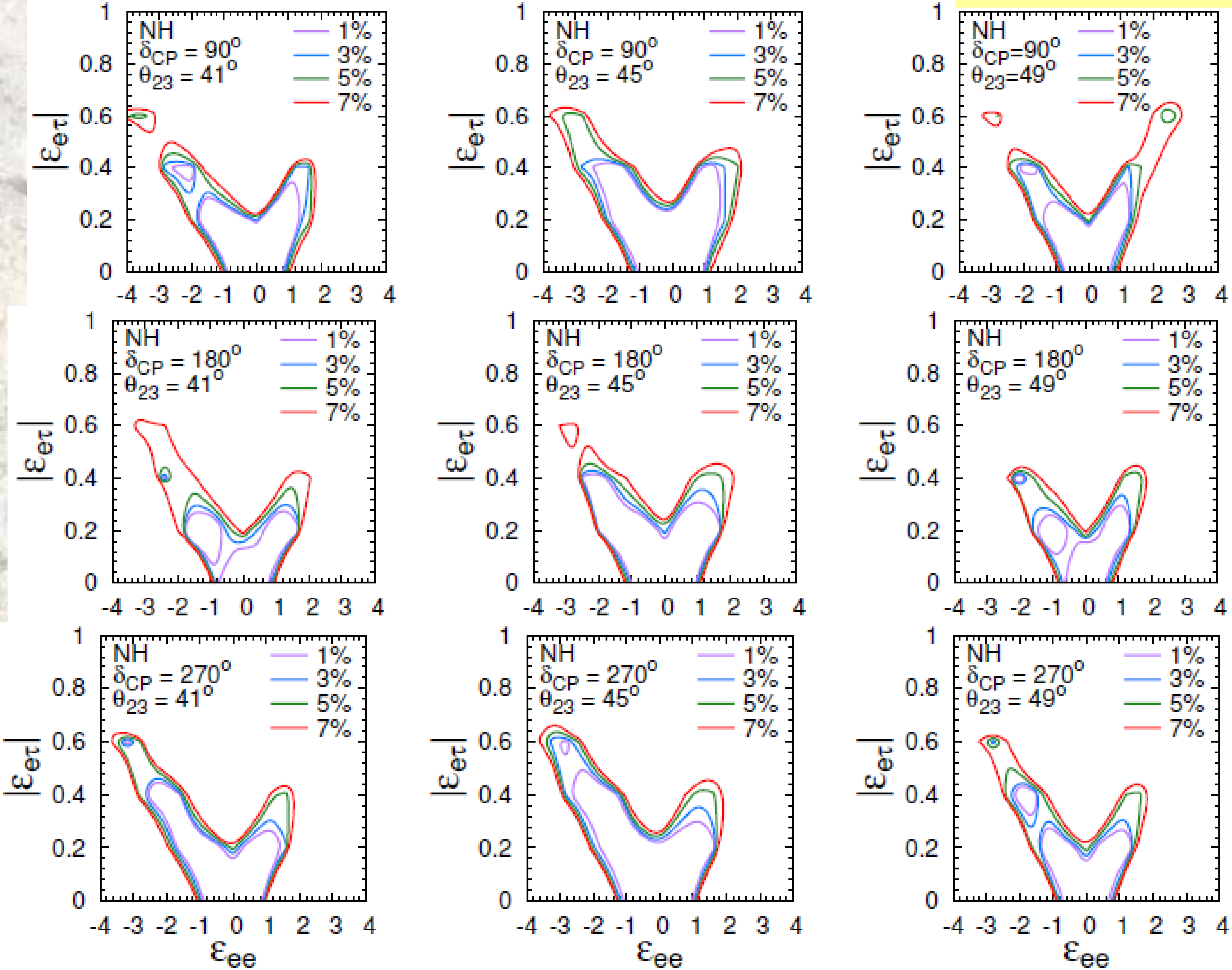
3% -> 1% improves the sensitivity in some case

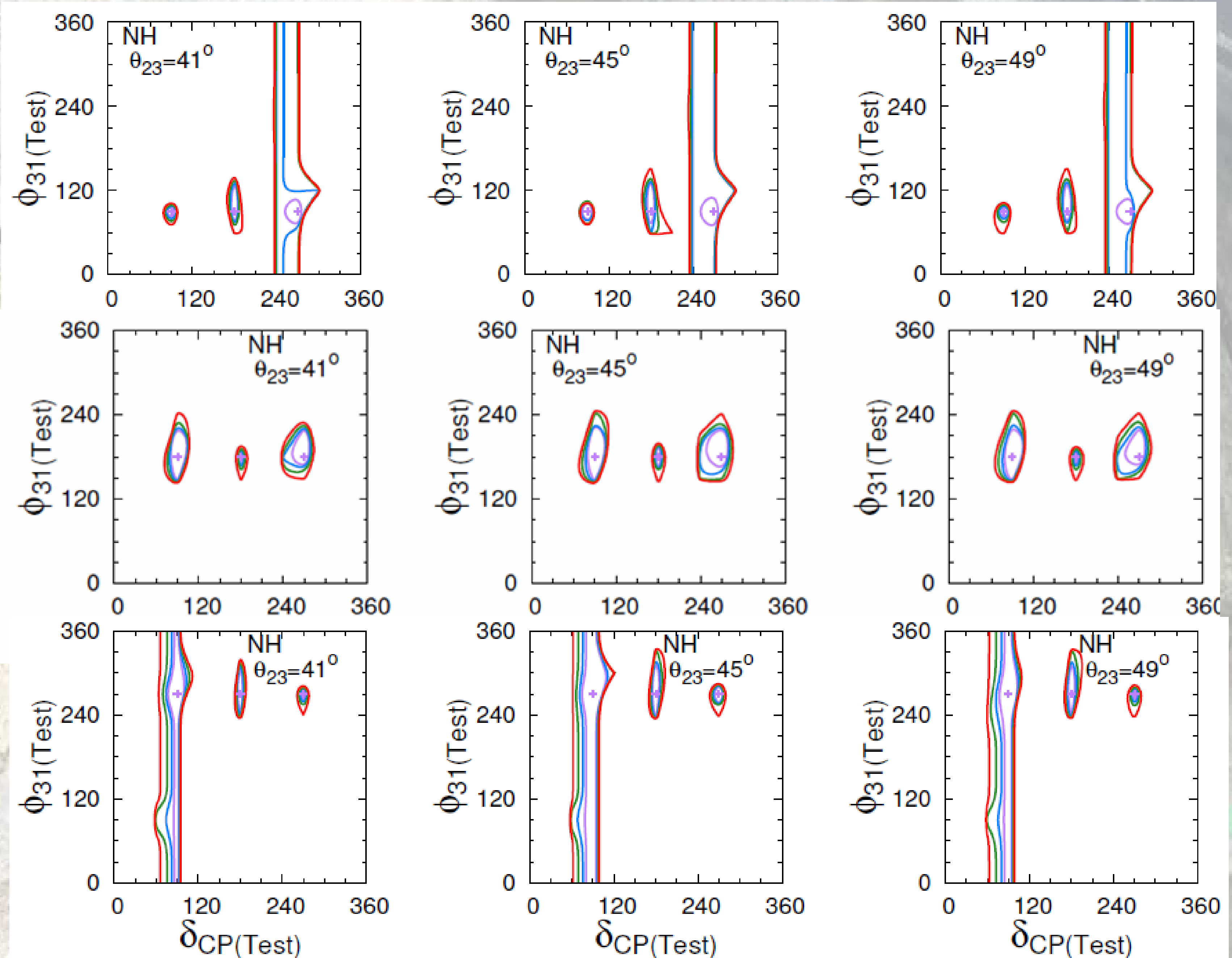
$\varepsilon_{\tau\tau}$ **free**

Ghosh, OY, to appear



Ghosh, OY, to appear





Ghosh, OY, to appear