Constraints on non-standard interaction in ν propagation from ν_{atm} & T2KK long-baseline experiment

Osamu Yasuda
Tokyo Metropolitan University

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In collaboration with Haruna OKI

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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

Information we have obtained so far:

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

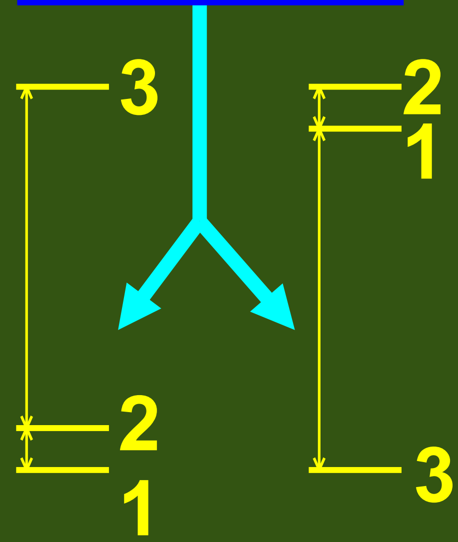
ν_{atm} + K2K, MINOS (accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5 \times 10^{-3} eV^2$

CHOOZ (reactor) → $|\theta_{13}| \leq \sqrt{0.15}/2$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \simeq \begin{pmatrix} c_{12} & s_{12} & \epsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

- θ_{13} :only upper bound is known
- δ :undetermined

- **Both mass hierarchies are allowed**



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

Next task is to measure θ_{13} , sign(Δm^2_{31}) and δ.

Future LBL exp. (on-going / under construction / proposed)

- (conventional) superbeam
  - T2K phase I (2009-, 0.75MW, E~1GeV, L=295km)
  - T2K phase II (4MW+HK, E~1GeV, L=295km)
  - T2KK (JAERI→HK&Korea, E~1GeV, L=295km&1000km)
  - NOvA (FNAL→ Ash River (MN), E~2GeV, L=810km)
  - LBNE (FNAL→Homestake(SD), E~3GeV, L=1300km)
  - SPL (CERN→Frejus, E~0.25GeV, L=130km)
- neutrino factory (E_ν~25GeV, L~3000km+7500km)
- beta beam (E_ν=0.5-1.5GeV, L~130km)

Future reactor experiments (E~4MeV, L~2km)

Double CHOOZ (France) , Daya Bay (China), Reno (Korea)

→ With these experiments, θ_{13} , sign(Δm^2_{31}) and δ are expected to be determined

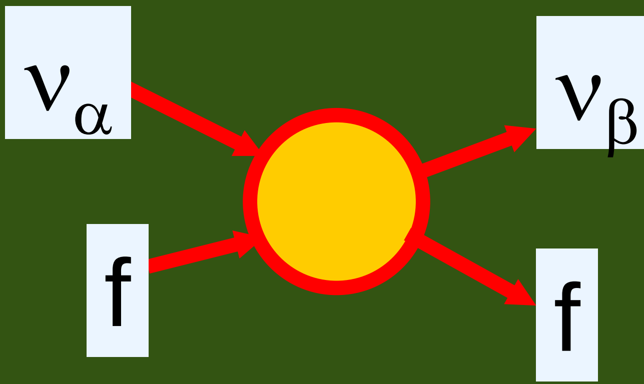
Motivation for research on New Physics

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.

Phenomenological **New Physics** considered in this talk: 4-fermi exotic interactions:

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



neutral current
Non **S**tandard
Interaction

● NSI in propagation (non-standard matter effect)

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\,\mathrm{diag}\left(\frac{m_1^2}{2E},\frac{m_2^2}{2E},\frac{m_3^2}{2E}\right)U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$A=2^{1/2}G_F N_e$ N_e= electron density

NSI

● Constraints on $\varepsilon_{\alpha\beta}$

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) w/o 1-loop arguments

related to each other by ν_{atm} ($|\epsilon_{ee}|$, $|\epsilon_{e\tau}|$, $|\epsilon_{\tau\tau}|$)

can be improved by ν_{atm} ($|\epsilon_{e\mu}|$, $|\epsilon_{\mu\tau}|$)

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

2. High energy behavior of ν_{atm} data & NSI

- **Standard case with N_ν=2**

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

- **Standard case with N_ν=3**

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

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

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

→ High ν_{atm} data gives constraints on NSI:

$|c_0|\ll 1,\ |c_1|\ll 1$

● with NSI

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

$|c_0| \ll 1 \rightarrow |\varepsilon_{e\mu}| \ll 1, |\varepsilon_{\mu\mu}| \ll 1, |\varepsilon_{\mu\tau}| \ll 1$

$|\varepsilon_{\mu\tau}| \ll 1$: Already shown by Fornengo et al. PRD65, 013010, '02; Gonzalez-Garcia&Maltoni, PRD70, 033010, '04; Mitsuka@nufact08

$|\varepsilon_{\mu\mu}| \ll 1$: Already shown from other expts. by Davidson et al. JHEP 0303:011, '03

$|\varepsilon_{e\mu}| \ll 1$: New observation (analytical consideration only)

$|c_1| \ll 1 \rightarrow |\varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})| \ll 1$

Already shown by Friedland-Lunardini, PRD72:053009,'05

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

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

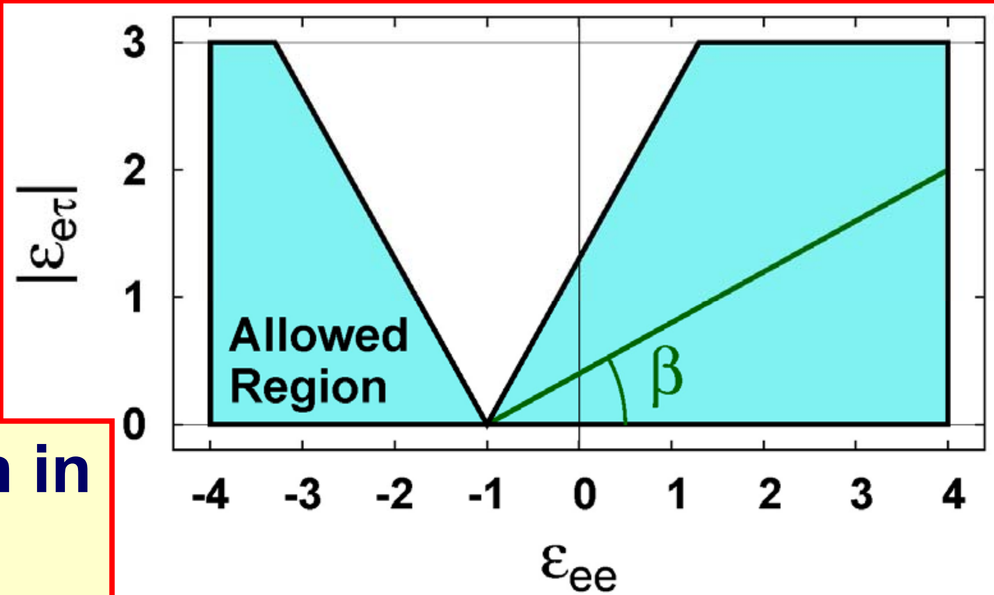
$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon^*_{e\tau}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

Furthermore, ν_{atm} data implies

$\tan\beta = |\varepsilon_{e\tau}|/(1+\varepsilon_{ee}) < 1.3$

Friedland-Lunardini, PRD72:053009,'05

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

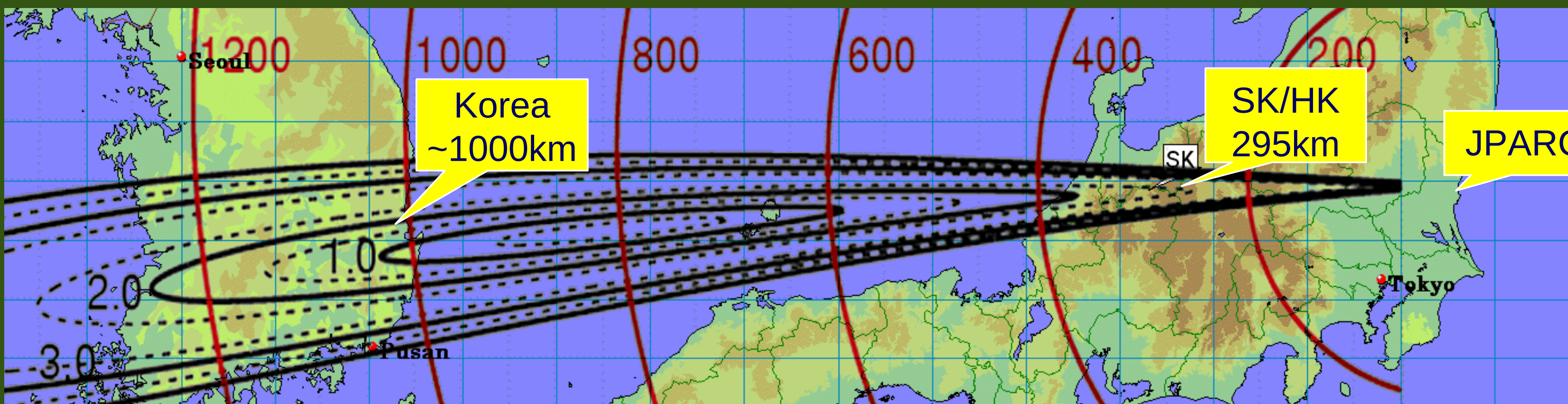


3. Sensitivity to NSI of propagation at T2KK

T2KK proposal with baselines L=295km, 1050km
→L=1050km is sensitive to the matter effect

	$\|\Delta m^2_{31}\|L/4E$	$\|\Delta m^2_{21}\|L/4E$	AL/2
L=295km	～1	～0.04	～0.06
L=1050km	～5	～0.1	～0.3

→ dependence on A & Δm^2_{21} at L=1050km is non-negligible



Outline of our Analysis

$$A \equiv \sqrt{2} G_F n_e$$

Our ansatz

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left\{U^{-1} diag\left(\frac{m_1^2}{2E}, \frac{m_2^2}{2E}, \frac{m_3^2}{2E}\right)U + A\begin{pmatrix}1+\varepsilon_{ee} & 0 & \varepsilon_{e\tau}\\ 0 & 0 & 0\\ \varepsilon_{e\tau}^* & 0 & \frac{|\varepsilon_{e\tau}|^2}{1+\varepsilon_{ee}}\end{pmatrix}\right\}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

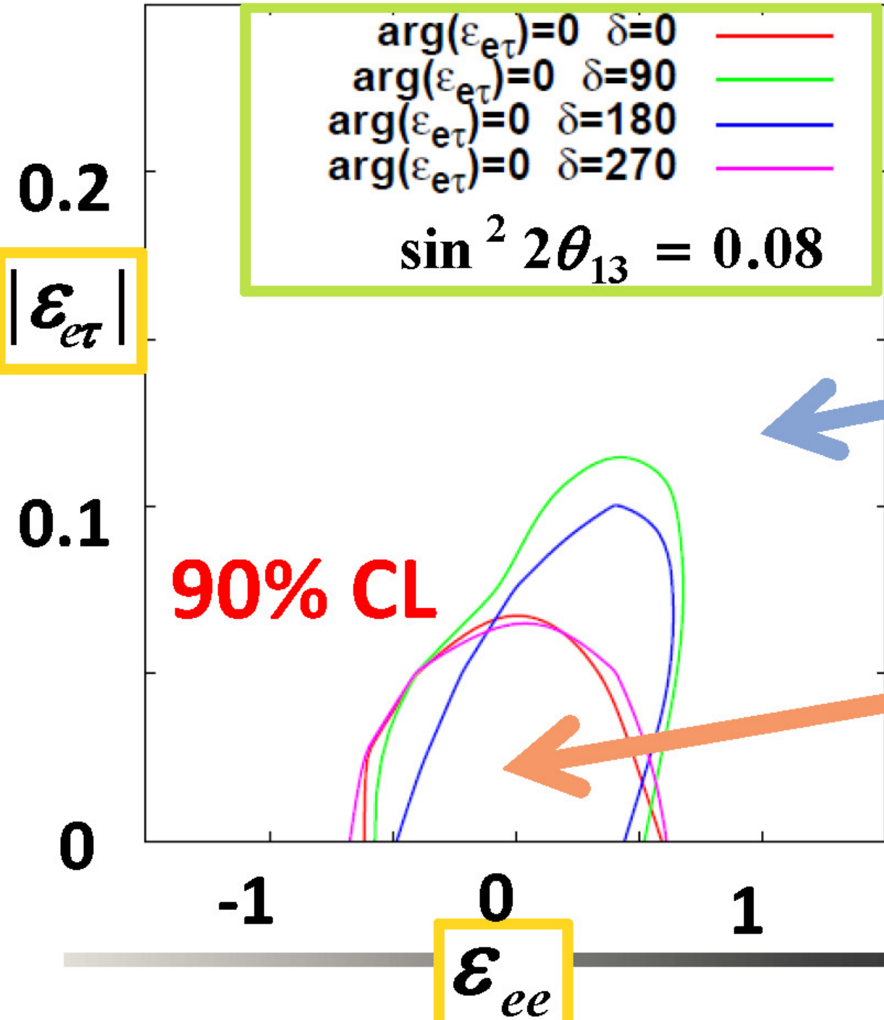
Black : standard **Red : non-standard**

$$\Delta\chi^2(\text{NSI}) = \min_{\substack{\text{std}\\ \text{parameters}}} \sum_i \frac{\left(N_i^0(\text{NSI}) - N_i\,(\text{std})\right)^2}{\sigma_i^2} + \Delta\chi^2_{\text{prior}}$$

$$\Delta\chi^2_{\text{prior}} \equiv \frac{(\sin^2 2\theta_{23} - \sin^2 2\theta_{23}^{\text{best}})^2}{(\delta \sin^2 2\theta_{23})^2} + \frac{(\Delta m_{31}^2 - \Delta m_{31}^{2\,\text{best}})^2}{(\delta \Delta m_{31}^2)^2} + \frac{(\sin^2 2\theta_{13} - \sin^2 2\theta_{13}^{\text{best}})^2}{(\delta \sin^2 2\theta_{13})^2}$$

$\Delta\chi^2$>4.6: Deviation of NSI from νSM is significant compared with errors (at 90% CL of 2 degrees of freedom ε_{ee}, | $\varepsilon_{e\tau}$ |)

Sensitivity to ε_{ee}, $|\varepsilon_{e\tau}|$



Marginalized over θ_{13}, θ_{23}, $|\Delta m^2_{31}|$, $sign(\Delta m^2_{31})$

- **Outside of the curves :** Effects of NSI can be distinguished from the standard case.
- **Inside of the curves :** Effects of NSI are not significant.

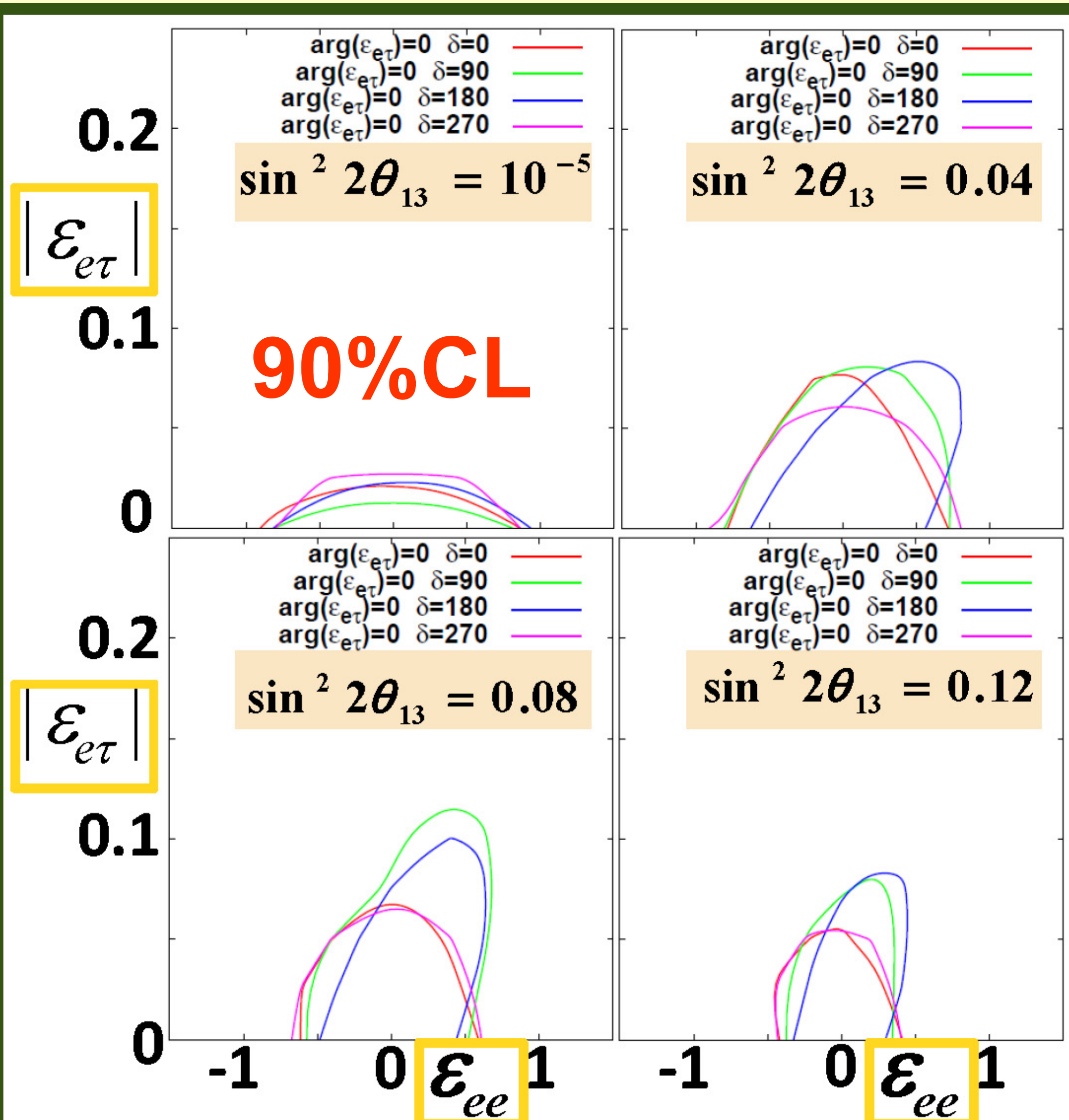
Dependence on phases δ and $\arg(\varepsilon_{e\tau})$

$$P(\nu_\mu \to \nu_e) \cong P_0(\nu_\mu \to \nu_e)\Big|_{\Delta m^2_{21}=0} + \Delta m^2_{21} P_1(\nu_\mu \to \nu_e)$$

Function of $\delta+\arg(\varepsilon_{e\tau})$

Approximately function of $\arg(\varepsilon_{e\tau})$ only

Sensitivity to ε_{ee}, $|\varepsilon_{e\tau}|$ for various θ_{13}



regions depend on

$\theta_{13}, \delta, \arg(\varepsilon_{e\tau})$

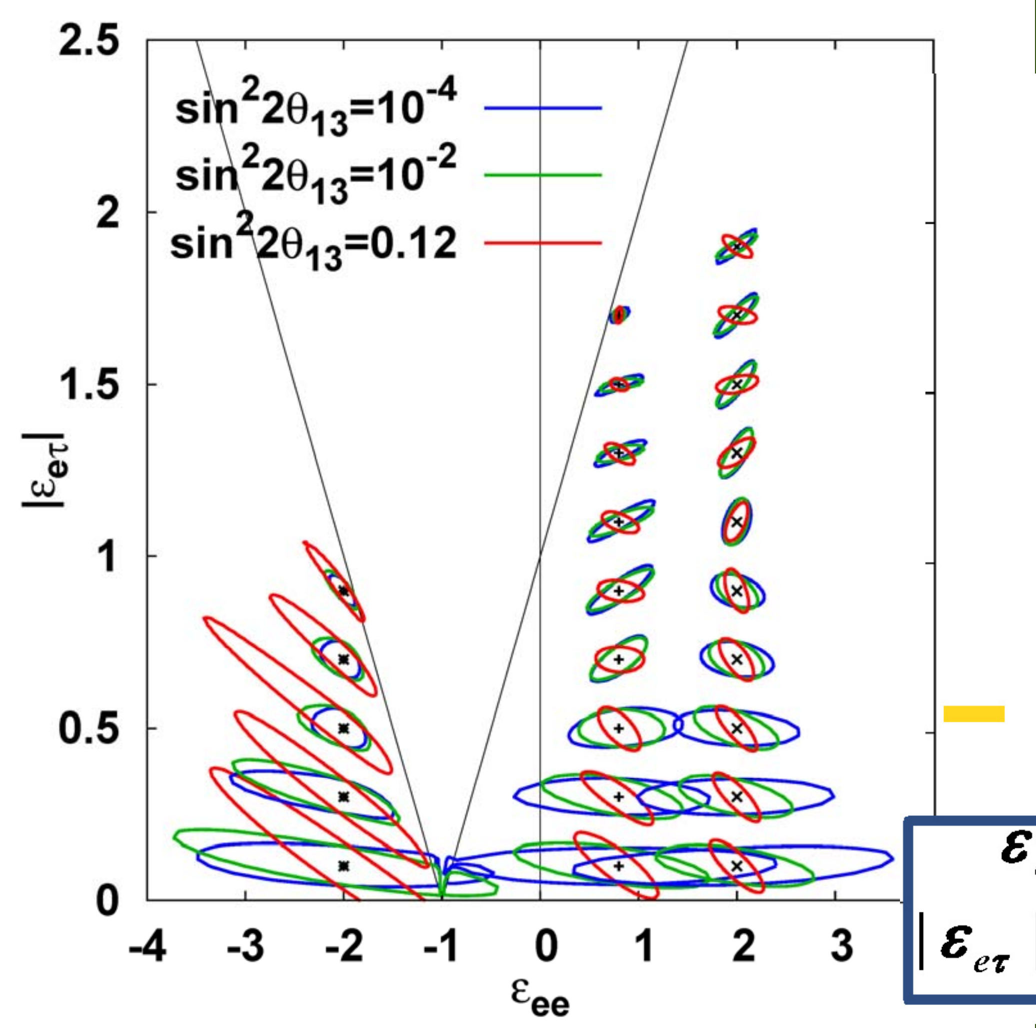
$|\varepsilon_{ee}| < 4$

$|\varepsilon_{e\tau}| < 3$

$|\epsilon_{ee}| \lesssim 1$

$|\epsilon_{e\tau}| \lesssim 0.2$

Precision of ε_{ee}, $|\varepsilon_{e\tau}|$



$|\varepsilon_{e\tau}| \geq 0.5$

$\varepsilon_{ee}, |\varepsilon_{e\tau}|$
determined separately

ε_{ee} **not determined**

$|\varepsilon_{e\tau}|$ **determined (if > 0.1)**

Sensitivity to δ and $\arg(\varepsilon_{e\tau})$

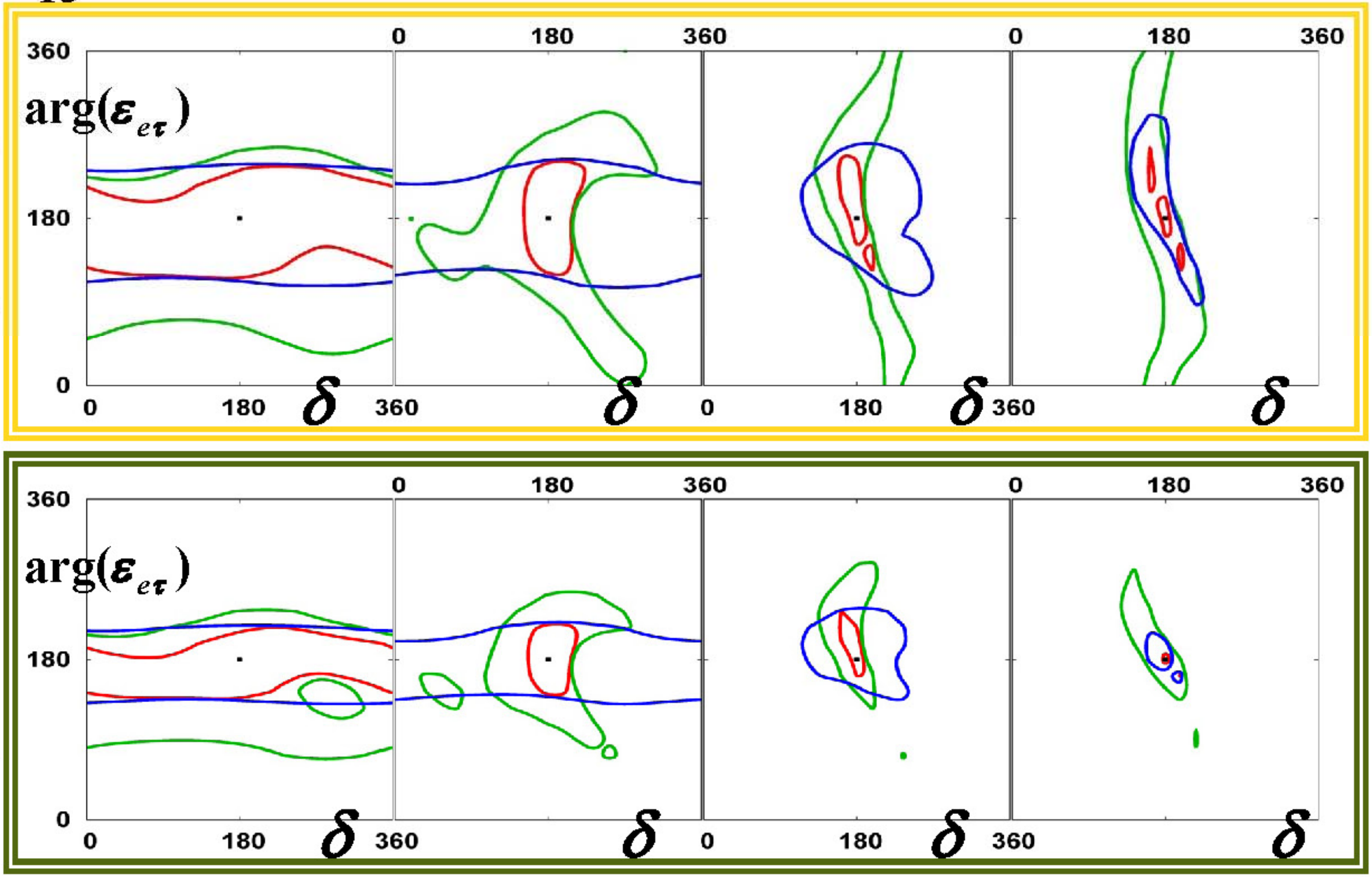
Kamioka+Korea
Kamioka
Korea

- Correlation of measured $\arg(\varepsilon_{e\tau})$ and δ

$\sin^2 2\theta_{13} = 10^{-4}$ $\quad 10^{-3}$ $\quad 10^{-2}$ $\quad 0.12$

$\varepsilon_{ee} = 0.8$
$|\varepsilon_{e\tau}| = 0.2$

$\varepsilon_{ee} = 0.8$
$|\varepsilon_{e\tau}| = 0.4$



- If $(\varepsilon_{ee}, |\varepsilon_{e\tau}|, s_{13})$ are large, we can determine $\arg(\varepsilon_{e\tau}), \delta$

4. Summary (1)

- **We provided an analytical argument on the oscillation probability for high energy atmospheric neutrinos that $|\varepsilon_{\mu\alpha}| \ll 1$ & $|\varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})| \ll 1$ must hold.**

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

- **Deviation of $1-P(\nu_\mu \to \nu_\mu)$ from the standard case in high energy ν_{atm} data gives strong constraints on Non Standard Interaction.**

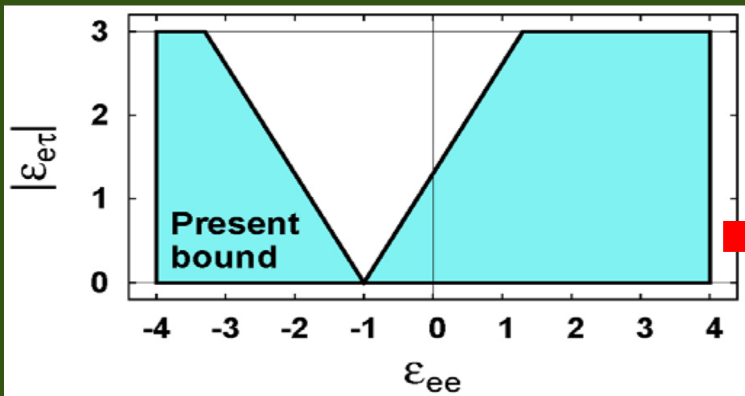
→ It would be great if we can constrain/determine c_0, c_1, c_{2j} ($j=0,1,2$) in high energy ν_{atm} data:

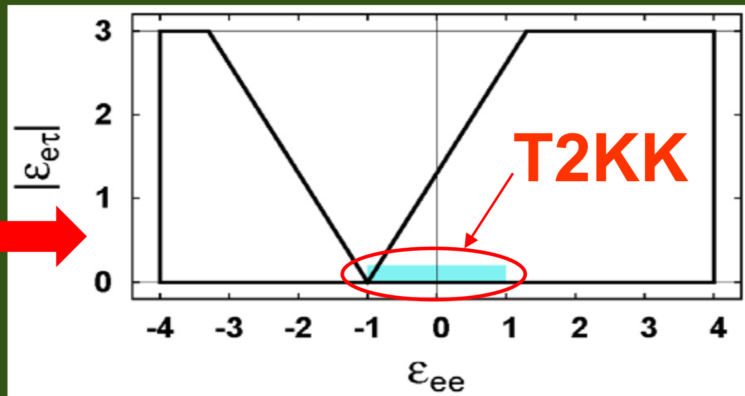
$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21}\sin^2(c_{22}L)}{E^2}$$

Is it possible at SK, IceCube, HK?

4. Summary (2)

- We studied phenomenologically sensitivity to NSI in propagation of the T2KK proposal.
- Under the assumptions $\varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0$ & $\varepsilon_{\tau\tau}=|\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$, we found that T2KK can restrict the NSI parameters: $|\epsilon_{ee}| \lesssim 1,\ |\epsilon_{e\tau}| \lesssim 0.2$





- If ε_{ee}, $|\varepsilon_{e\tau}|$ and s_{13} are large, then T2KK can determine ε_{ee}, $|\varepsilon_{e\tau}|$, δ and $\arg(\varepsilon_{e\tau})$ separately.