Sensitivity of T2KK to non-standard interactions

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Sept. 10, @now2010

Ref: arXiv:1003.5554 [hep-ph]

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1. Introduction

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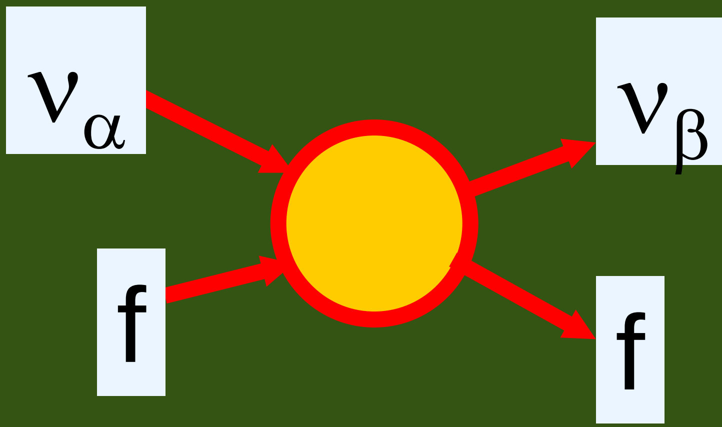
1. Motivation for research on New Physics

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.

→ 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-standard interaction

• NP in propagation (NP matter effect)

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

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

NP

• 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}

can be improved by ν_{atm}

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

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

- **Standard case with N_ν=2**

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

- **Standard case with N_ν=3**

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

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

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

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

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

● with NP

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

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

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

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

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

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

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}, $|\varepsilon_{e\tau}|$, $\arg(\varepsilon_{e\tau})$:

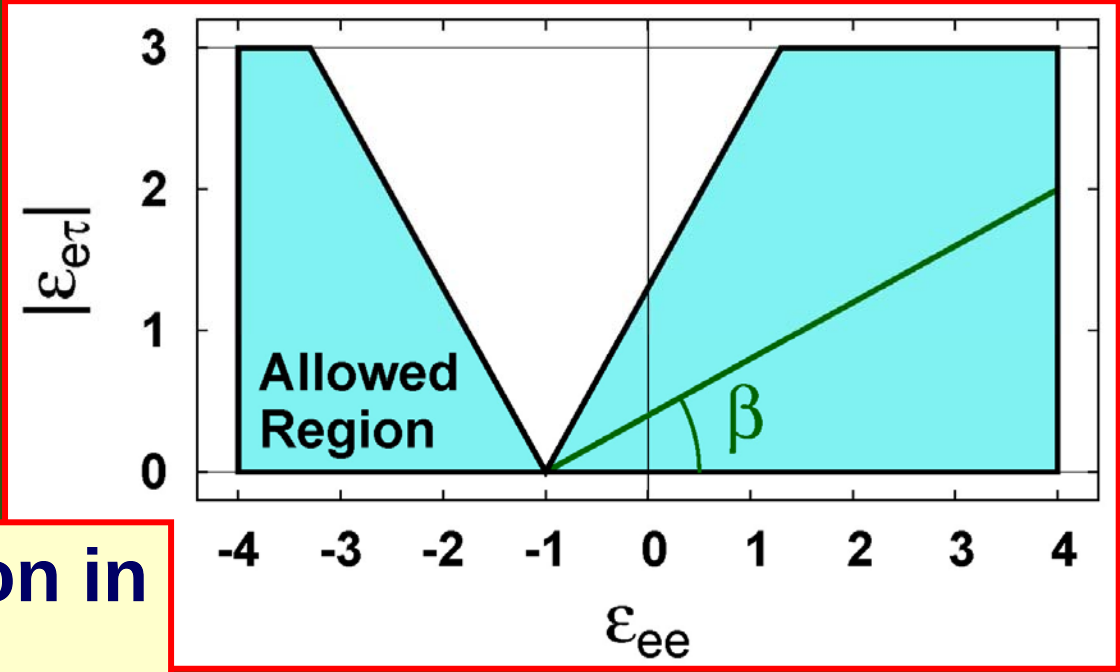
$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^{*}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

Furthermore, ν_{atm} data implies

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

Friedland-Lunardini, PRD72:053009,'05

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

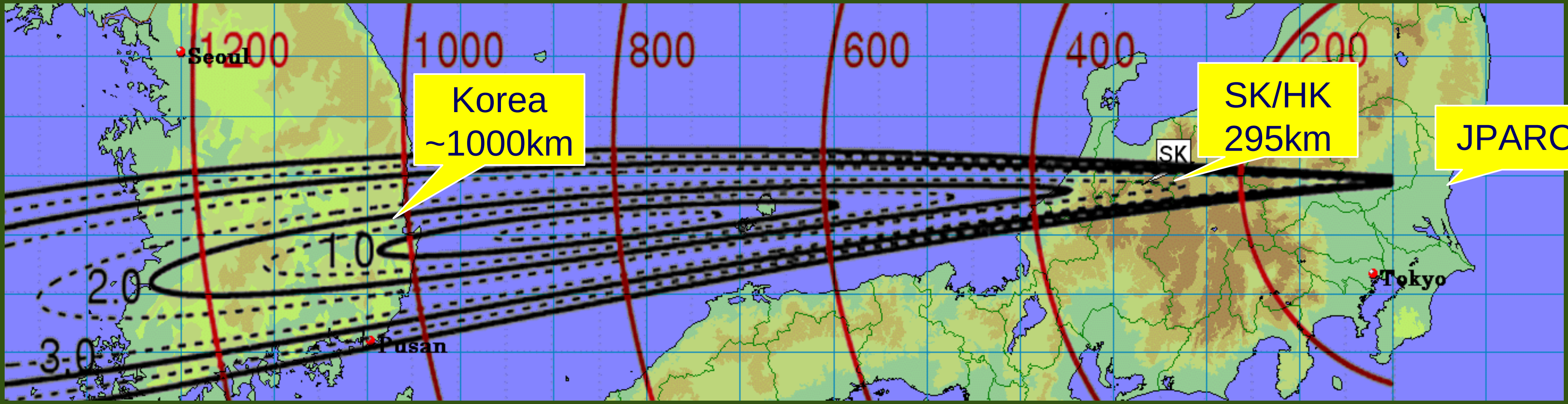


3. Sensitivity to NSI of propagation at T2KK

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/2E
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

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

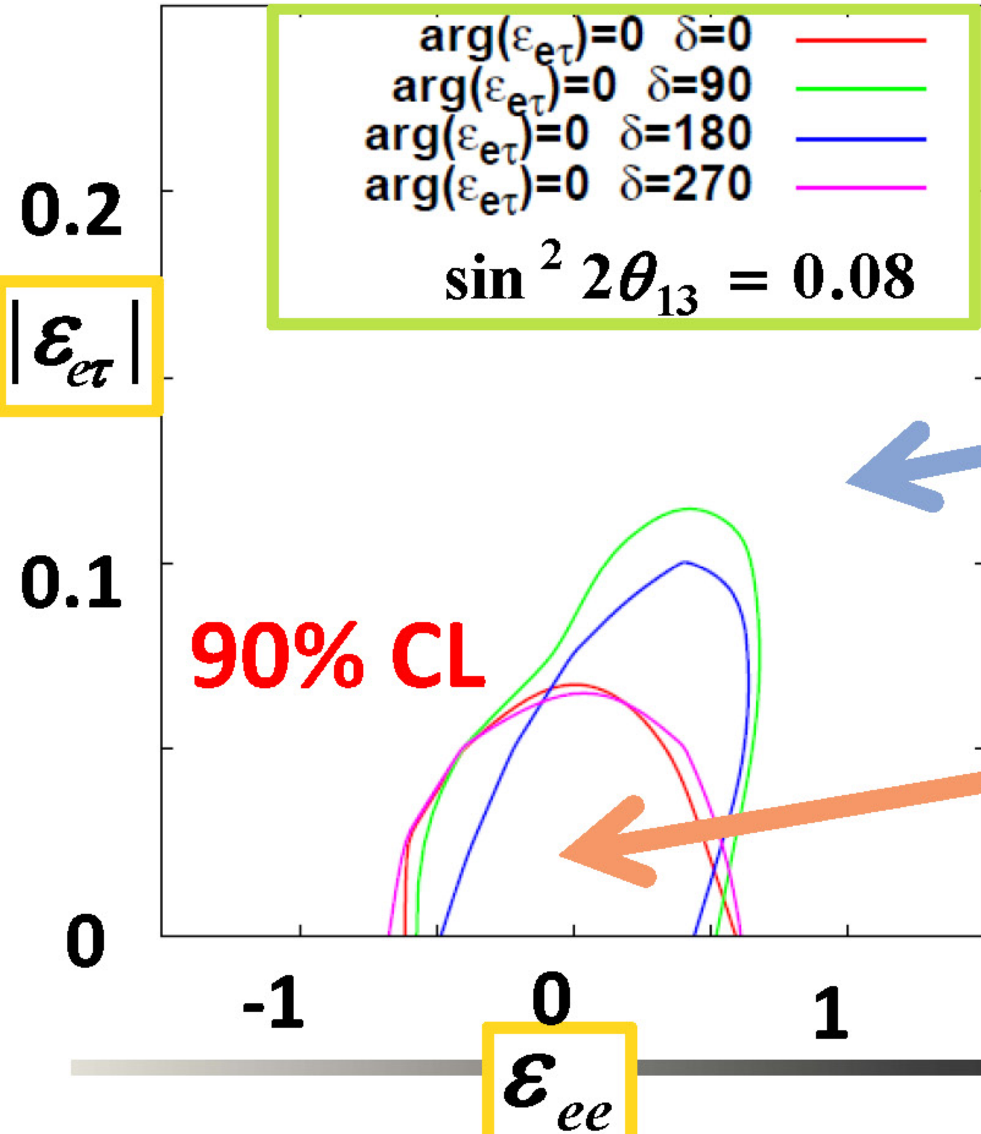
Black : standard **Red : non-standard**

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

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

$\Delta\chi^2>4.6$: 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.

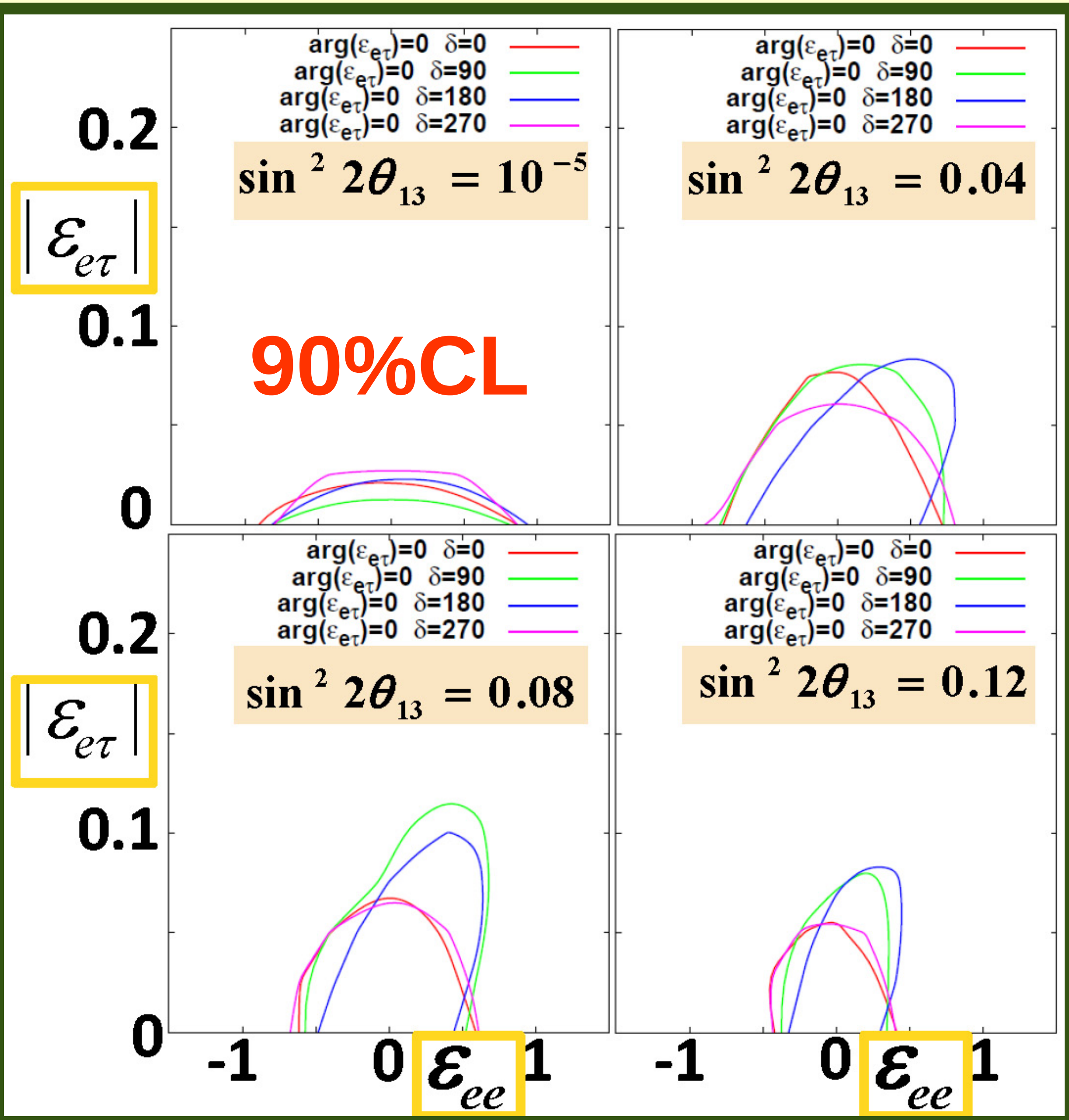
Dependence on phases δ and $\arg(\varepsilon_{e\tau})$

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

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}



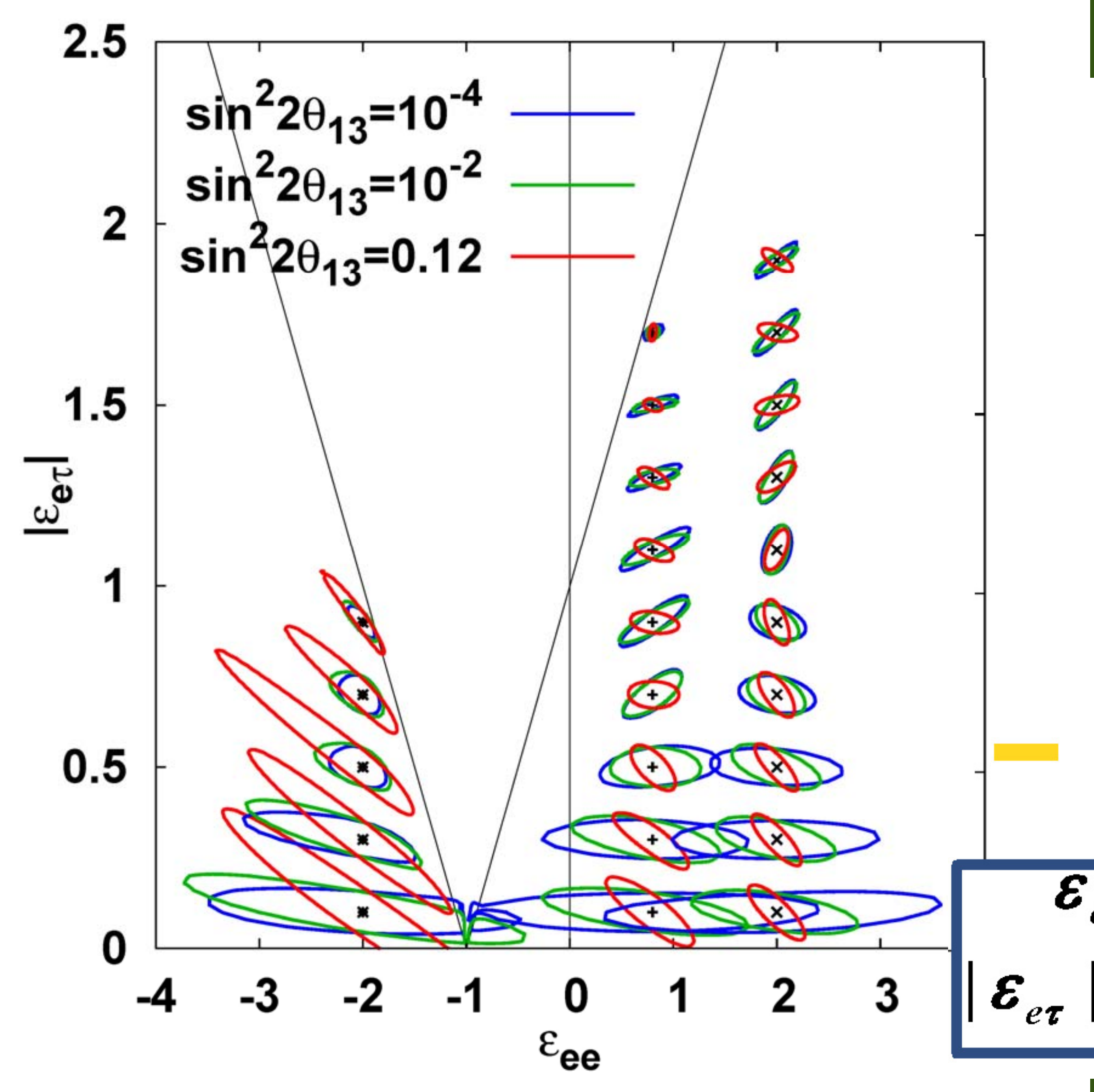
regions depend on

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

$|\varepsilon_{ee}| < 4$
$|\varepsilon_{e\tau}| < 3$

$|\epsilon_{ee}| \lesssim 1$
$|\epsilon_{e\tau}| \lesssim 0.2$

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($\varepsilon_{e\tau}$)

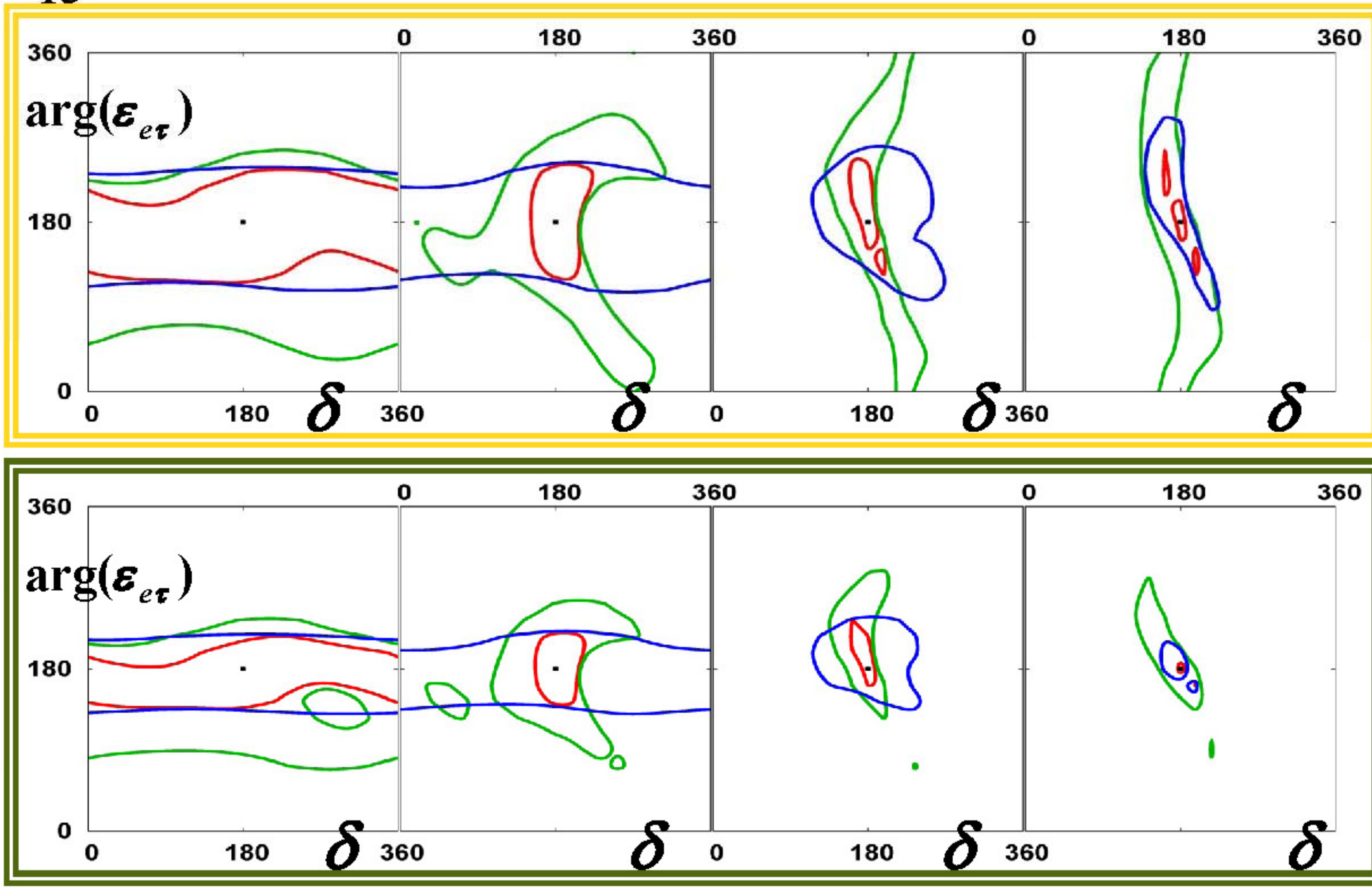
- Correlation of measured $\arg(\varepsilon_{e\tau})$ and δ

Kamioka+Korea (red)
Kamioka (green)
Korea (blue)

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

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

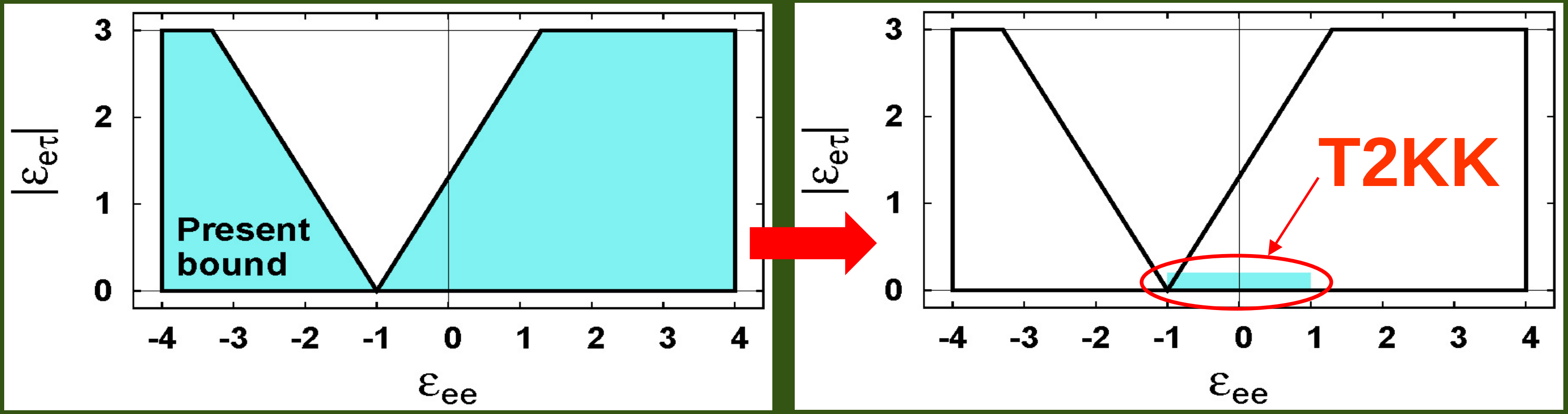
$\varepsilon_{ee} = 0.8$
$|\varepsilon_{e\tau}| = 0.4$



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

4. Conclusions (1)

- 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.

4. Conclusions (2)

- 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.

- Deviation of $1-P(\nu_\mu \rightarrow \nu_\mu)$ from the standard case in high energy ν_{atm} data gives strong constraints on New Physics.

→ 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?

Backup slides

● O(1)

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

$$c_0 \simeq 4\tilde{X}_1^{\mu\mu}\tilde{X}_2^{\mu\mu} \sin^2\left(\frac{\Delta\tilde{E}_{21} L}{2}\right) + 4\tilde{X}_3^{\mu\mu} \sin^2\left(\frac{(1+\epsilon_{ee}+\epsilon_{\tau\tau})AL}{2}\right)$$

$$\begin{aligned}
4\tilde{X}_1^{\mu\mu}\tilde{X}_2^{\mu\mu} &\simeq 1 - \frac{1+\epsilon_{ee}+\epsilon_{\tau\tau}}{(1+\epsilon_{ee})|\epsilon_{\mu\tau}|^2 + \epsilon_{\tau\tau}|\epsilon_{e\mu}|^2 - 2\mathrm{Re}(\epsilon_{e\mu}\epsilon_{\mu\tau}(\epsilon_{e\tau})^*)}\left(\frac{|\epsilon_{e\mu}|^2+|\epsilon_{\mu\mu}|^2+|\epsilon_{\mu\tau}|^2}{1+\epsilon_{ee}+\epsilon_{\tau\tau}} - \epsilon_{\mu\mu}\right)^2 \\
4\tilde{X}_3^{\mu\mu} &\simeq 4\frac{|\epsilon_{e\mu}|^2+|\epsilon_{\mu\mu}|^2+|\epsilon_{\mu\tau}|^2}{(1+\epsilon_{ee}+\epsilon_{\tau\tau})^2} - 4\frac{(1+\epsilon_{ee})|\epsilon_{\mu\tau}|^2 + \epsilon_{\tau\tau}|\epsilon_{e\mu}|^2 - 2\mathrm{Re}(\epsilon_{e\mu}\epsilon_{\mu\tau}(\epsilon_{e\tau})^*)}{(1+\epsilon_{ee}+\epsilon_{\tau\tau})^3} \\
\Delta\tilde{E}_{21} &\simeq 2A\left[\frac{(1+\epsilon_{ee})|\epsilon_{\mu\tau}|^2 + \epsilon_{\tau\tau}|\epsilon_{e\mu}|^2 - 2\mathrm{Re}(\epsilon_{e\mu}\epsilon_{\mu\tau}(\epsilon_{e\tau})^*)}{1+\epsilon_{ee}+\epsilon_{\tau\tau}}\right]
\end{aligned}$$

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

$|\varepsilon_{\mu\tau}| \ll 1$: Already shown by Fornengo et al. PRD65, 013010, '02

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

$|\varepsilon_{e\mu}| \ll 1$: New observation

- **O(1/E)**

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

$$\frac{c_1}{E}\simeq -2s_{23}^2(\epsilon_{ee}+\epsilon_{\tau\tau})(1+\epsilon_{ee}+\epsilon_{\tau\tau})A\zeta\frac{\Delta m_{31}^2}{E}\sin^2\left[\frac{A\zeta}{2(1+\epsilon_{ee}+\epsilon_{\tau\tau})}\right]$$

$$\zeta\equiv\epsilon_{\tau\tau}-|\epsilon_{e\tau}|^2/(1+\epsilon_{ee})$$

$\rightarrow \left| \varepsilon_{\tau\tau} - |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee}) \right| << 1$

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

- **To summarize**

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

T violation : standard vs NP (1)

$$\mathrm{Im}(\tilde{X}_1^{\mu e}\tilde{X}_2^{\mu e*}) = \frac{-1}{(\Delta\tilde{E}_{21})^2\Delta\tilde{E}_{31}\Delta\tilde{E}_{32}}\mathrm{Im}\left[\left\{Y_3^{\mu e}-(\tilde{E}_2+\tilde{E}_3)Y_2^{\mu e}\right\}\left\{Y_3^{\mu e}-(\tilde{E}_3+\tilde{E}_1)Y_2^{\mu e}\right\}^*\right]$$
$$= \frac{-1}{\Delta\tilde{E}_{21}\Delta\tilde{E}_{31}\Delta\tilde{E}_{32}}\mathrm{Im}\left\{Y_3^{\mu e}(Y_2^{\mu e})^*\right\}.$$

$$Y_2^{\mu e} = (U\mathcal{E}U^{-1}+\mathcal{A})_{\mu e} = (U\mathcal{E}U^{-1})_{\mu e}$$
$$Y_3^{\mu e} = \left[\left(U\mathcal{E}U^{-1}+\mathcal{A}\right)^2\right]_{\mu e} = (U\mathcal{E}^2U^{-1})_{\mu e} + (U\mathcal{E}U^{-1})_{\mu e}\mathcal{A}_{ee} + (U\mathcal{E}U^{-1})_{\mu\tau}\mathcal{A}_{\tau e}\,,$$

$$\mathrm{Im}\left\{Y_3^{\mu e}(Y_2^{\mu e})^*\right\} = \mathrm{Im}\left[(U\mathcal{E}U^{-1})^*_{\mu e}\left\{(U\mathcal{E}^2U^{-1})_{\mu e}+(U\mathcal{E}U^{-1})_{\mu\tau}\mathcal{A}_{\tau e}\right\}\right]$$
$$= \mathrm{Im}\left\{Y_3^{\mu e}(Y_2^{\mu e})^*\right\}_{\mathrm{std}} + \mathrm{Im}\left\{Y_3^{\mu e}(Y_2^{\mu e})^*\right\}_{\mathrm{NP}}\,,$$

T violation : standard vs NP (2)

$$\begin{aligned}\mathrm{Im}\,\{Y_3^{\mu e}(Y_2^{\mu e})^*\}_{\mathrm{std}} &\equiv \mathrm{Im}\left[(U\mathcal{E}U^{-1})^*_{\mu e}(U\mathcal{E}^2U^{-1})_{\mu e}\right]\\ &= \mathrm{Im}\left[\{(\Delta E_{31})^2X_3^{\mu e} + (\Delta E_{21})^2X_2^{\mu e}\}\{\Delta E_{31}(X_3^{\mu e})^* + \Delta E_{21}(X_2^{\mu e})^*\}\right]\\ &= \Delta E_{21}\Delta E_{31}\Delta E_{32}\,\mathrm{Im}\,(X_3^{\mu e}(X_2^{\mu e})^*)\\ &= \Delta E_{21}\Delta E_{31}\Delta E_{32}\,\frac{1}{8}c_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta\end{aligned}$$

$$\begin{aligned}\mathrm{Im}\,\{Y_3^{\mu e}(Y_2^{\mu e})^*\}_{\mathrm{NP}} &\equiv \mathrm{Im}\left\{(U\mathcal{E}U^{-1})^*_{\mu e}(U\mathcal{E}U^{-1})_{\mu\tau}\mathcal{A}_{\tau e}\right\}\\ &= \mathrm{Im}\left[A(\epsilon_{e\tau})^*\{\Delta E_{31}(X_3^{\mu e})^* + \Delta E_{21}(X_2^{\mu e})^*\}(\Delta E_{31}X_3^{\mu\tau} + \Delta E_{21}X_2^{\mu\tau}\}\right]\\ &= A|\epsilon_{e\tau}|\left[(\Delta E_{31})^2\,\mathrm{Im}\{(X_3^{\mu e})^*X_3^{\mu\tau}\,e^{2i\gamma}\}\right.\\ &\qquad +\Delta E_{31}\Delta E_{21}\,\mathrm{Im}\{(X_3^{\mu e})^*X_2^{\mu\tau}\,e^{2i\gamma} + (X_2^{\mu e})^*X_3^{\mu\tau}\,e^{2i\gamma}\}\\ &\qquad \left.+(\Delta E_{21})^2\,\mathrm{Im}\{(X_2^{\mu e})^*X_2^{\mu\tau}\,e^{2i\gamma}\}\right]\\ &\simeq A\Delta E_{31}\Delta E_{21}|X_2^{\mu e}||X_3^{\mu\tau}|\mathrm{Im}(\epsilon_{e\tau})\end{aligned}$$

$$\frac{\mathrm{Im}\,\{Y_3^{\mu e}(Y_2^{\mu e})^*\}_{\mathrm{NP}}}{\mathrm{Im}\,\{Y_3^{\mu e}(Y_2^{\mu e})^*\}_{\mathrm{std}}} \simeq \frac{A|\epsilon_{e\tau}|\sin(\arg(\epsilon_{e\tau}))}{\Delta E_{32}s_{13}\sin\delta} \sim \frac{A}{\Delta E_{32}}\frac{|\epsilon_{e\tau}|}{s_{13}} \sim \frac{10|\epsilon_{e\tau}|}{s_{13}}$$

T violating part : standard vs NP

$$\frac{(\text{T violation})_{\text{NP}}}{(\text{T violation})_{\text{std}}} \cong \frac{AE\,|\varepsilon_{e\tau}|\sin(\arg(\varepsilon_{e\tau}))}{|\Delta m^2_{31}|\,s_{13}\sin\delta} \cong \frac{10\,|\varepsilon_{e\tau}|}{s_{13}} \bullet \frac{\sin(\arg(\varepsilon_{e\tau}))}{\sin\delta}$$