

Future proposal for T2K exp.

Sensitivity of T2KK to NSI in propagation

In collaboration with O.Yasuda

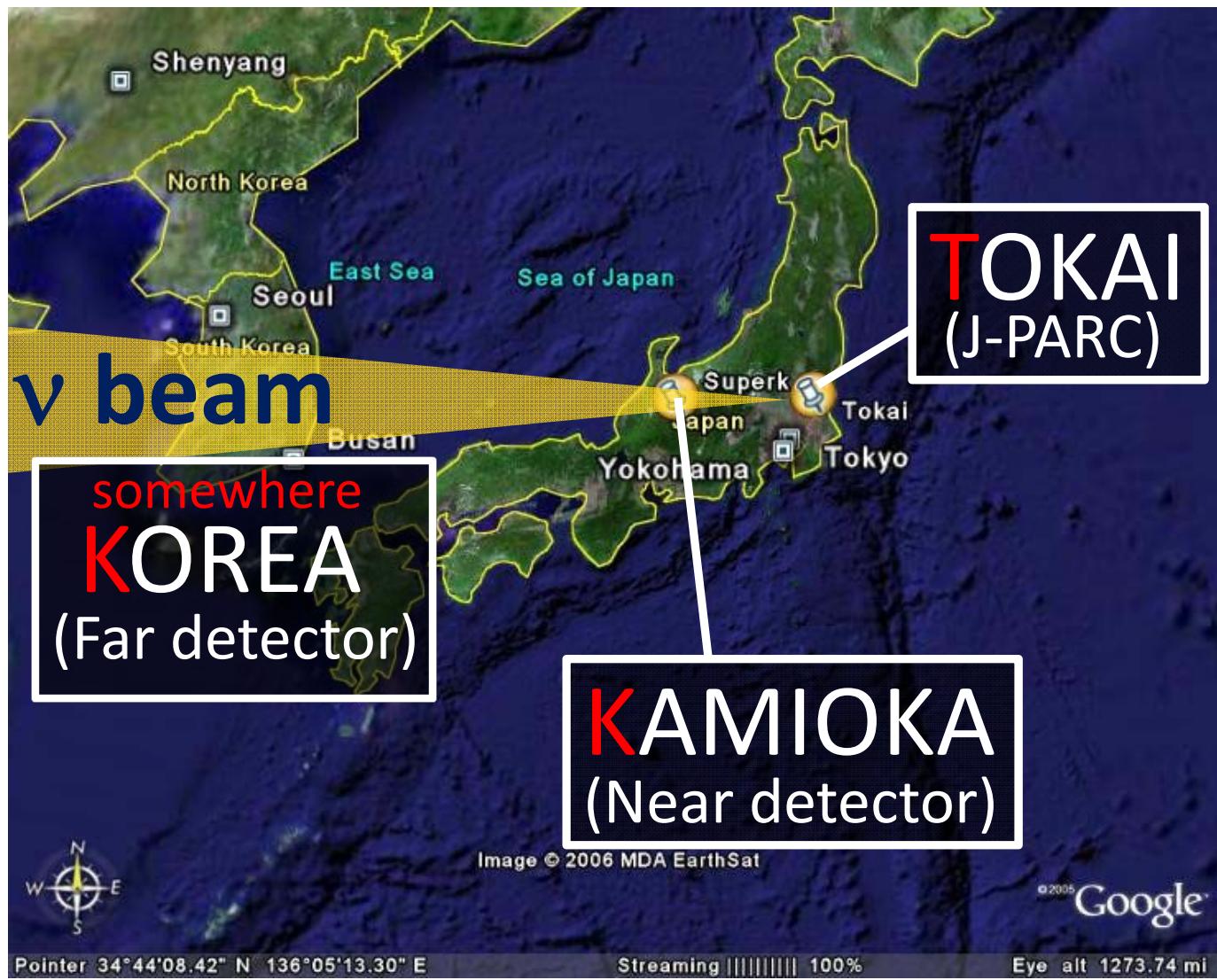
(to appear soon)

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XLVth Rencontres de Moriond
Electroweak Interaction and Unified Theories
La Thuile, March 6-13, 2010

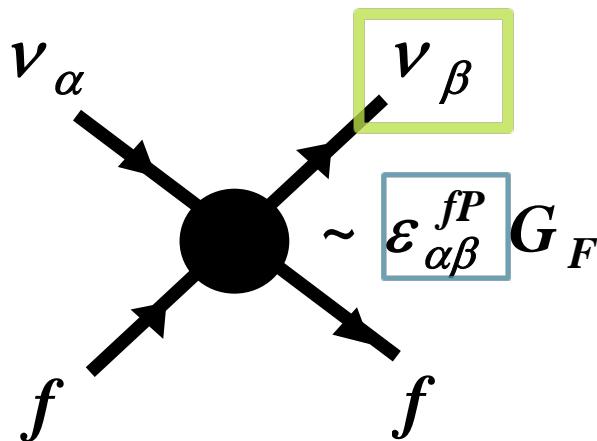
T2KK Experiment



Neutrino Oscillation with Non Standard Interaction

Non Standard Interaction

$$L_{\text{eff}}^{\text{NSI}} = - \boxed{\varepsilon_{\alpha\beta}^{\text{fP}}} 2\sqrt{2}G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta) (\bar{f} \gamma^\rho P f')$$



G_F : fermi const.

$\varepsilon_{\alpha\beta}^{\text{fP}}$: NSI coupling const.

$$P = L \text{ or } R = (1 \mp \gamma_5)/2$$

$$\nu_\alpha = \nu_e \nu_\mu \nu_\tau$$

$$f = u d e$$

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

NSI parameter

$$\varepsilon_{\alpha\beta} \equiv \varepsilon_{\alpha\beta}^e + 3\varepsilon_{\alpha\beta}^u + 3\varepsilon_{\alpha\beta}^d$$

Neutrino Oscillation w/ NSI

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

Black : standard

Red : non-standard

Restriction to NSI parameter

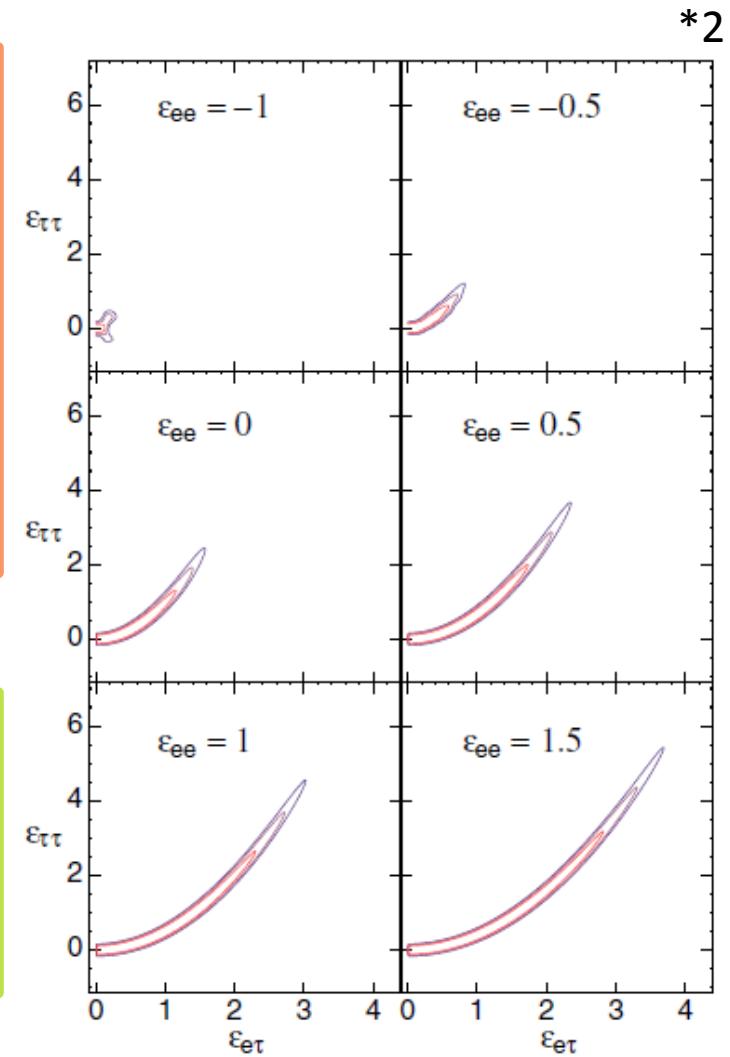
Latest Limits

$$\begin{bmatrix} |\varepsilon_{ee}| < 4.2 & |\varepsilon_{e\mu}| < 0.33 & |\varepsilon_{e\tau}| < 3.0 \\ |\varepsilon_{\mu\mu}| < 0.068 & |\varepsilon_{\mu\tau}| < 0.33 \\ |\varepsilon_{\tau\tau}| < 21 \end{bmatrix}^*_1$$

$\varepsilon_{e\mu}$ $\varepsilon_{\mu\mu}$ $\varepsilon_{\mu\tau}$ \sim small : can be neglected

Atmospheric Neutrino exp.

$$\varepsilon_{\tau\tau} \simeq \frac{|\varepsilon_{e\tau}|^2}{1 + \varepsilon_{ee}}$$



*1 Fernandez-Martinez et al. JHEP 0908:090, 2009

*2 Friedland et al. Phys. Rev. D 72 053009

Neutrino Oscillation with Non Standard Interaction

General equation for NSI in propagation

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



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

Our ansatz

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

Black : standard

Red : non-standard

Outline of our Analysis

Number of Events

$$N_i = \int_{E_i}^{E_{i+1}} dE' \int dE_\nu F(E_\nu) \sigma(E_\nu) P(E_\nu; L) R(E', E_\nu)$$

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

Backgrounds , stat. & sys. Errors
taken into account

i : energy bin

E' : reconstructed ν energy

E_ν : ν energy

F : ν flux

σ : ν cross section

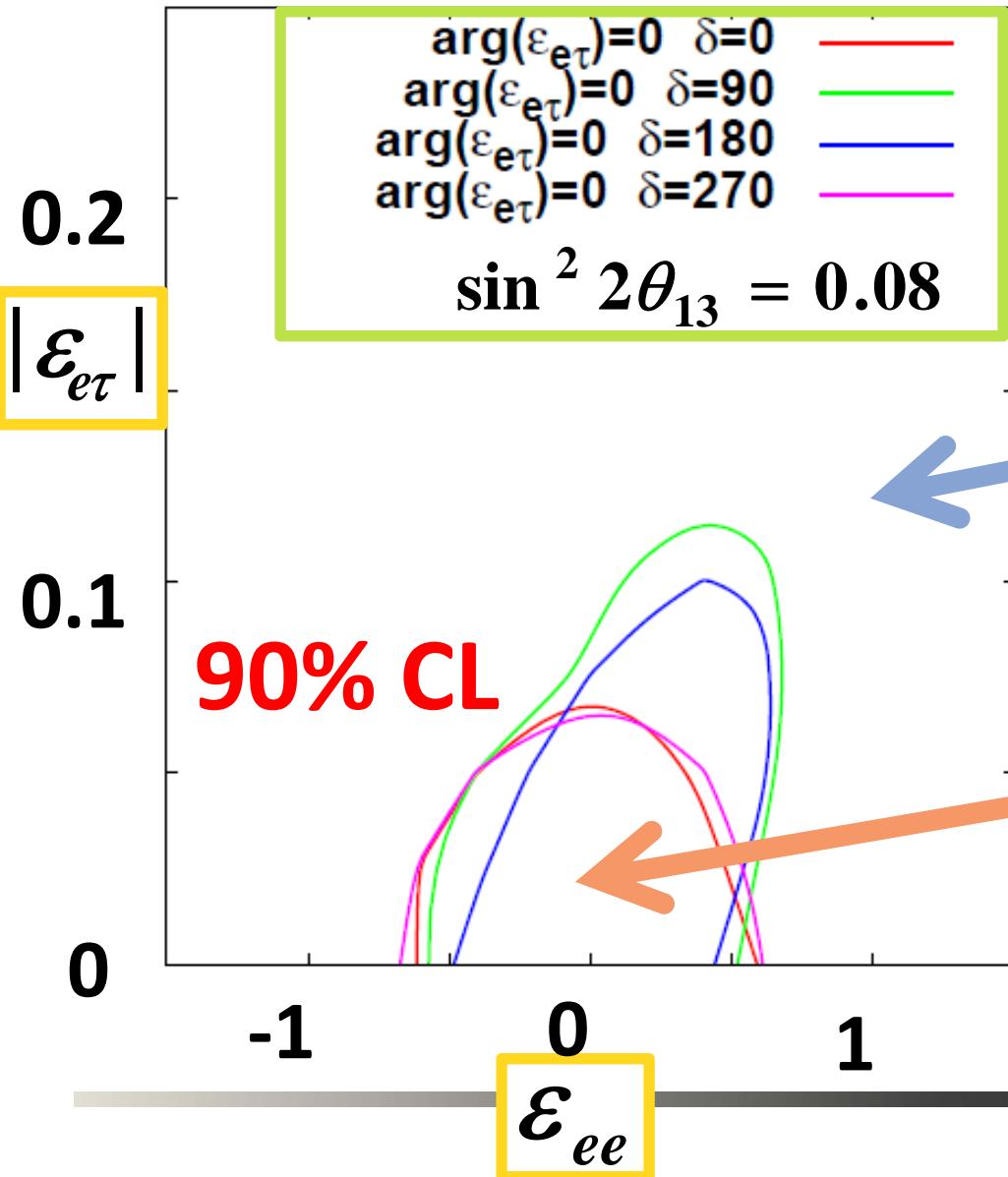
P : ν oscillation probability

R : energy resolution function

- Deviation of NSI & νSM is significant compared with errors
(at 90% CL of 2 degrees of freedom $\varepsilon_{ee}, |\varepsilon_{e\tau}|$)

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

Results(1) Sensitivity to $\epsilon_{ee}, |\epsilon_{e\tau}|$



Marginalized over θ_{13} ,
 $\theta_{23}, |\Delta m_{31}^2|, \text{sign}(\Delta m_{31}^2)$

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

Results(2)⁸

Sensitivity to

ϵ_{ee} , $|\epsilon_{e\tau}|$

for various θ_{13}

90% CL

regions depend on
 $\theta_{13}, \delta, \arg(\epsilon_{e\tau})$

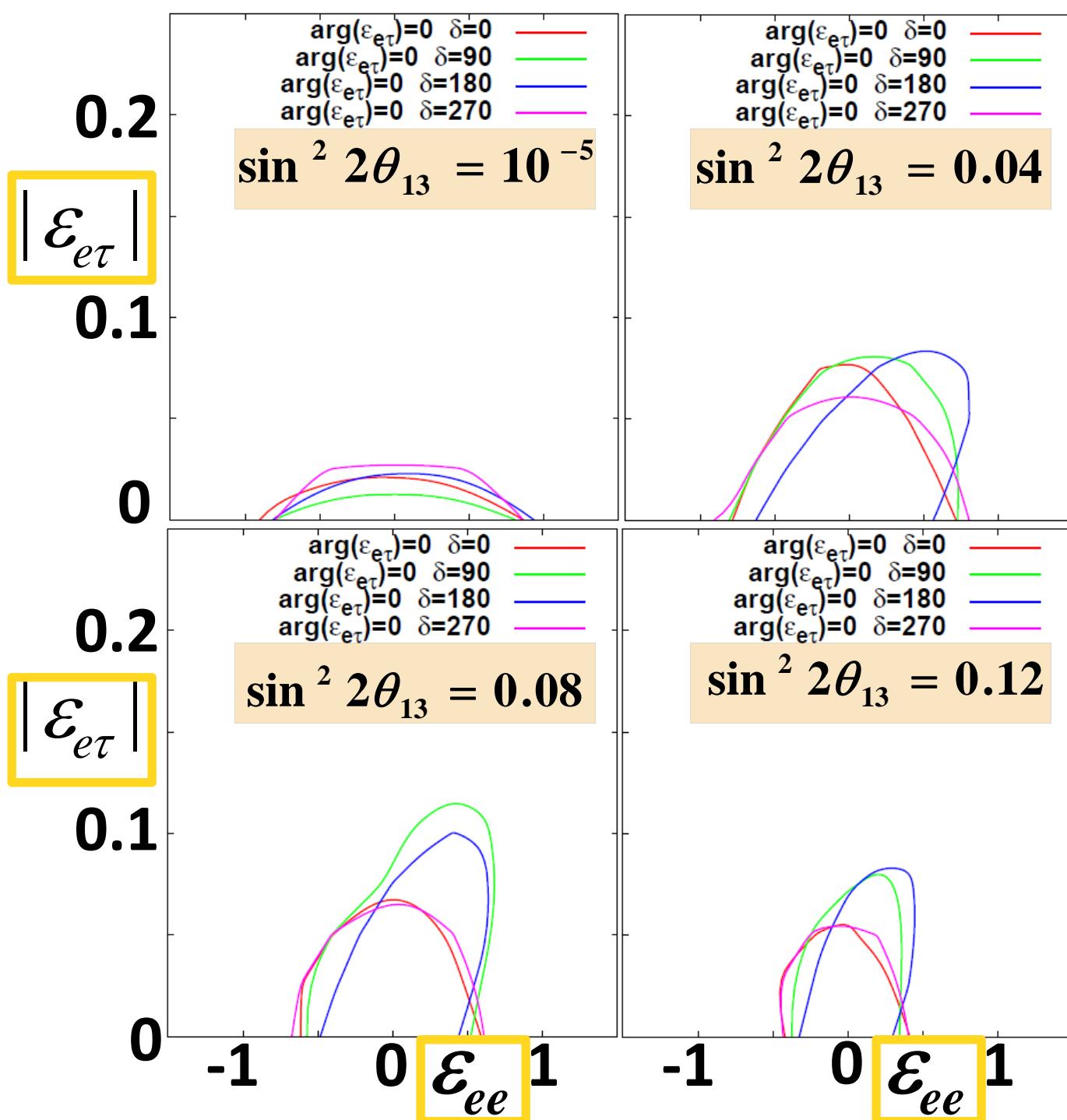
$$|\epsilon_{ee}| < 4.6$$

$$|\epsilon_{e\tau}| < 3.0$$

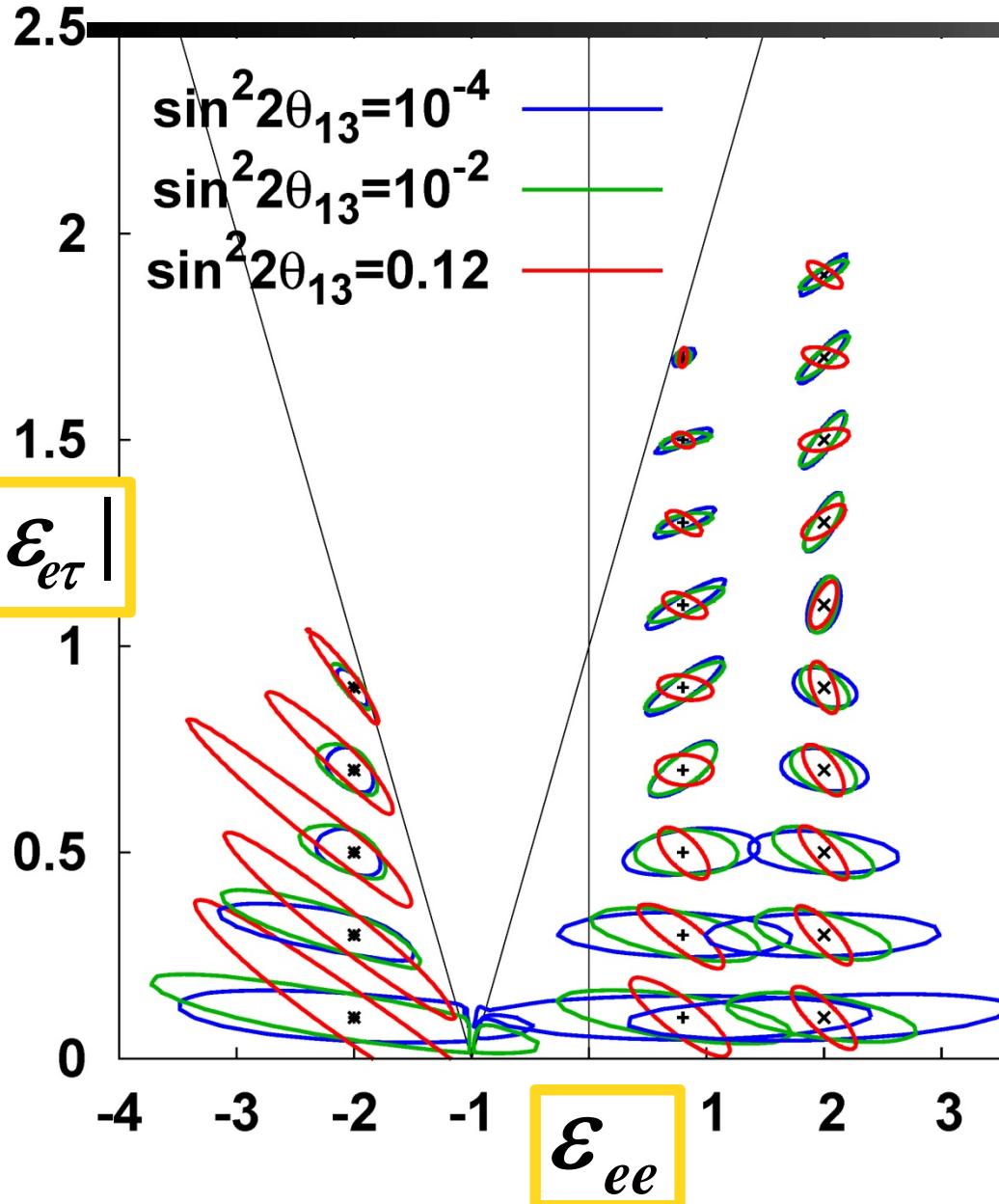


$$|\epsilon_{ee}| \leq 1.0$$

$$|\epsilon_{e\tau}| \leq 0.15$$

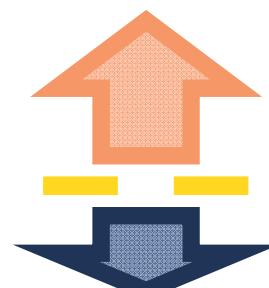


Results(3) Precision of $\varepsilon_{ee}, |\varepsilon_{e\tau}|$



$|\varepsilon_{e\tau}| \geq 0.5$
 $\varepsilon_{ee}, |\varepsilon_{e\tau}|$
determined separately

ε_{ee} not determined
 $|\varepsilon_{e\tau}|$ determined (if > 0.1)

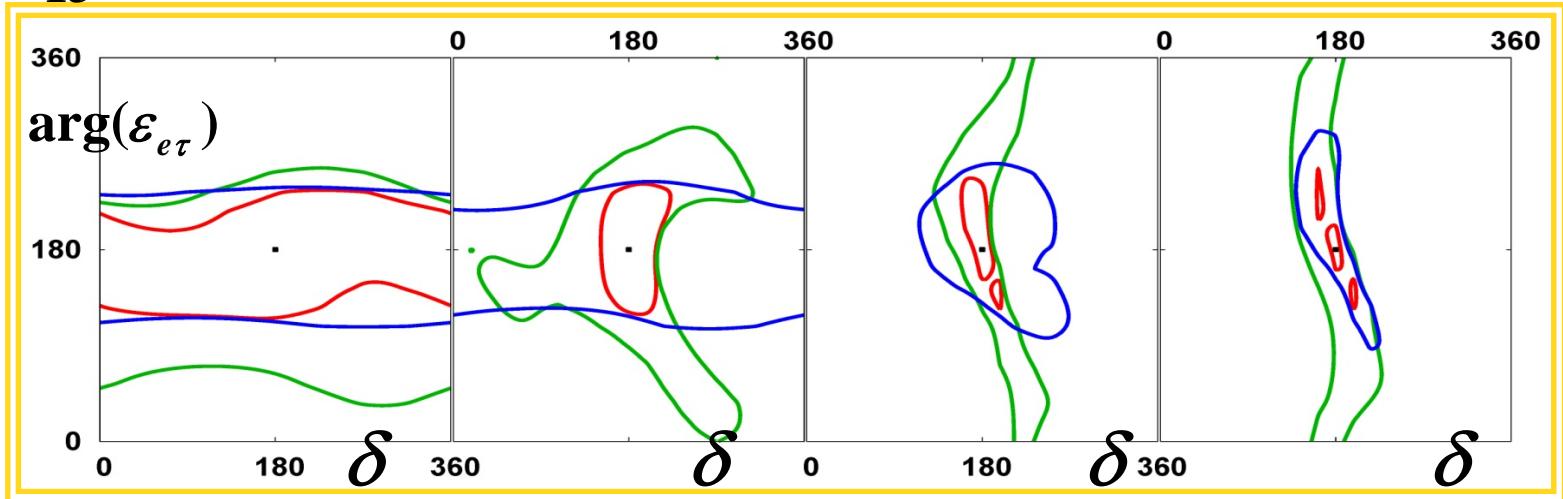


Results(4) Sensitivity to $\arg(\varepsilon_{e\tau})$, δ

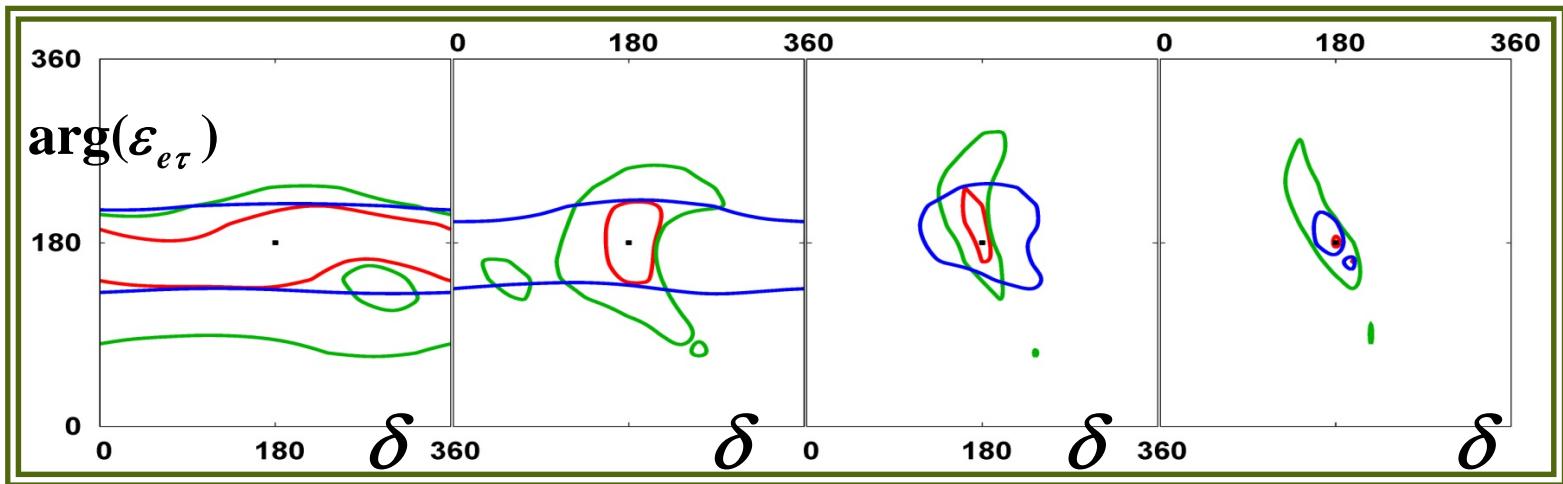
- Correlation of measured $\arg(\varepsilon_{e\tau})$ and δ

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

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



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



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

Kamioka+Korea —
Kamioka —
Korea —

Conclusions

- We studied phenomenologically sensitivity to the non-standard interactions in neutrino propagation of the T2KK neutrino long baseline experiment.
- We found that T2KK can restrict the NSI parameters

$$|\varepsilon_{ee}| \leq 1.0, |\varepsilon_{e\tau}| \leq 0.15$$

under the assumptions

$$\left\{ \begin{array}{l} \varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0 \\ \varepsilon_{\tau\tau} = \frac{|\varepsilon_{e\tau}|^2}{1 + \varepsilon_{ee}} \end{array} \right.$$

- If these parameters are large ,then T2KK can determine $\varepsilon_{ee}, |\varepsilon_{e\tau}|, \arg(\varepsilon_{e\tau}), \delta$ separately.

BACK UP



Model dependent bounds: 1-Loop arguments

Davidson et al., JHEP 0303:011,2003.

$$\left(\begin{array}{lll} -4 < \epsilon_{ee} < 2.6 & |\epsilon_{e\mu}| < 3.8 \times 10^{-4} & |\epsilon_{e\tau}| < 1.9 \\ & -0.05 < \epsilon_{\mu\mu} < 0.08 & |\epsilon_{\mu\tau}| < 0.25 \\ & & |\epsilon_{\tau\tau}| < 18.6 \end{array} \right)$$



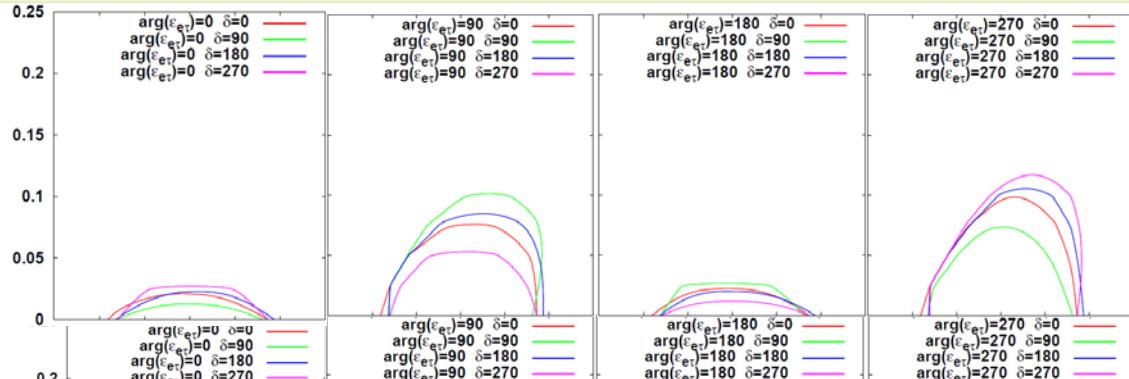
Updated result (courtesy of S. Davidson)

$$\left(\begin{array}{lll} -4 < \varepsilon_{ee}^m < 2.6 & |\varepsilon_{e\mu}^m| < 1.4 \times 10^{-4} & |\varepsilon_{e\tau}^m| < 1.2 \\ & -0.05 < \varepsilon_{\mu\mu}^m < 0.08 & |\varepsilon_{\mu\tau}^m| < 0.25 \\ & & |\varepsilon_{\tau\tau}^m| < 19 \end{array} \right)$$

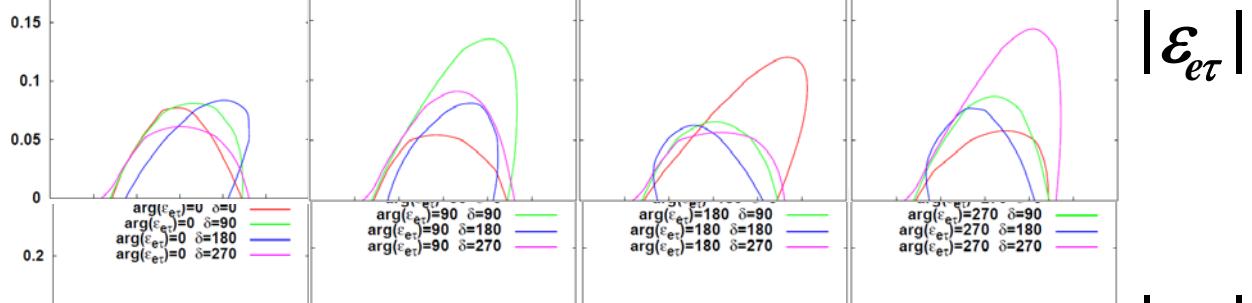
O. Yasuda, PoS NUFAC08:016,2008.

$$\arg(\epsilon_{e\tau}) = 0 \quad \pi / 2 \quad \pi \quad 3\pi / 2$$

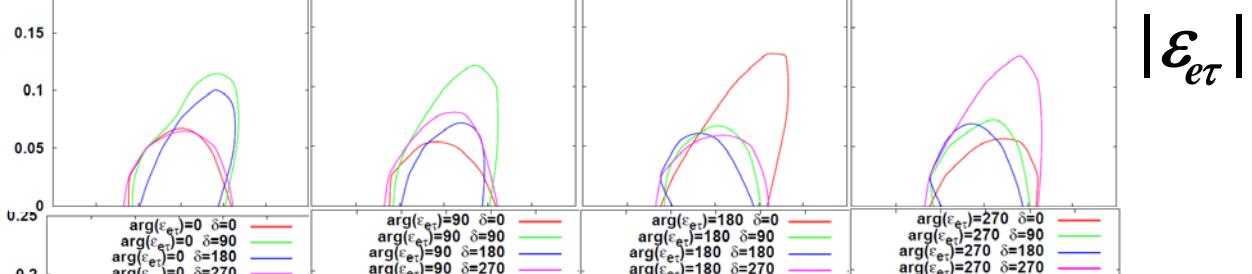
$$\sin^2 2\theta_{13} = 10^{-5}$$



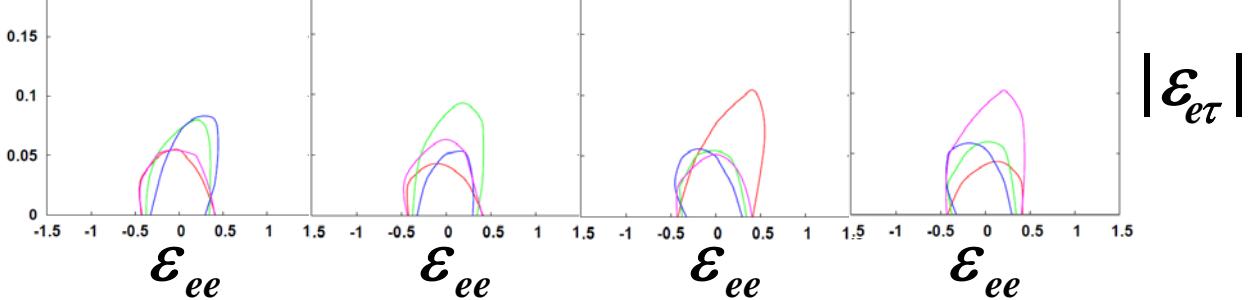
$$\sin^2 2\theta_{13} = 0.04$$



$$\sin^2 2\theta_{13} = 0.08$$



$$\sin^2 2\theta_{13} = 0.12$$



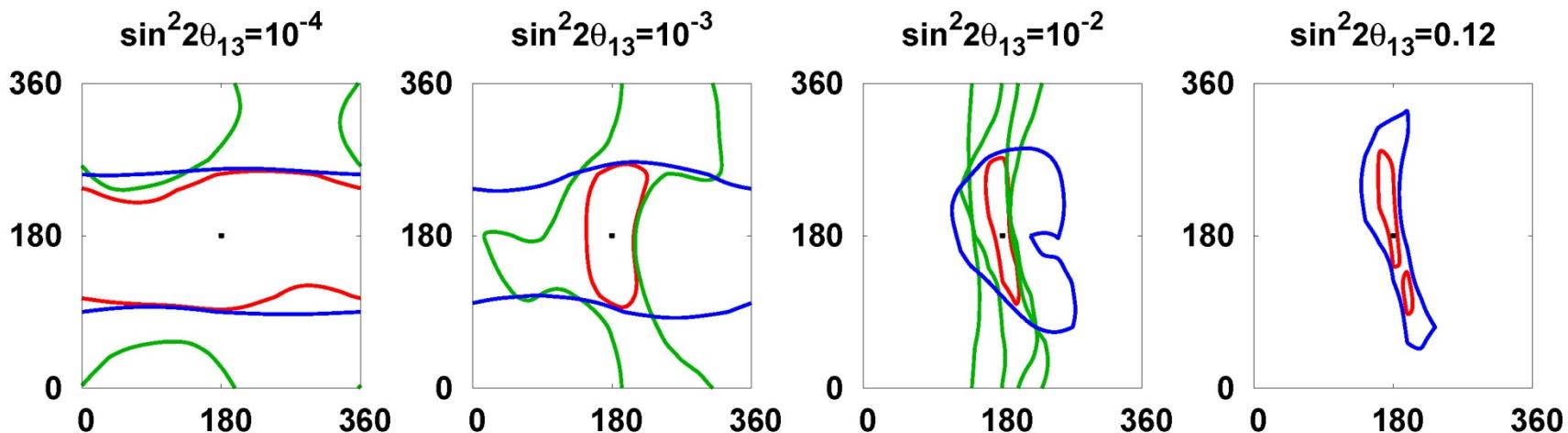


Figure 1: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.1$

$\arg(\epsilon_{e\tau})$
 δ

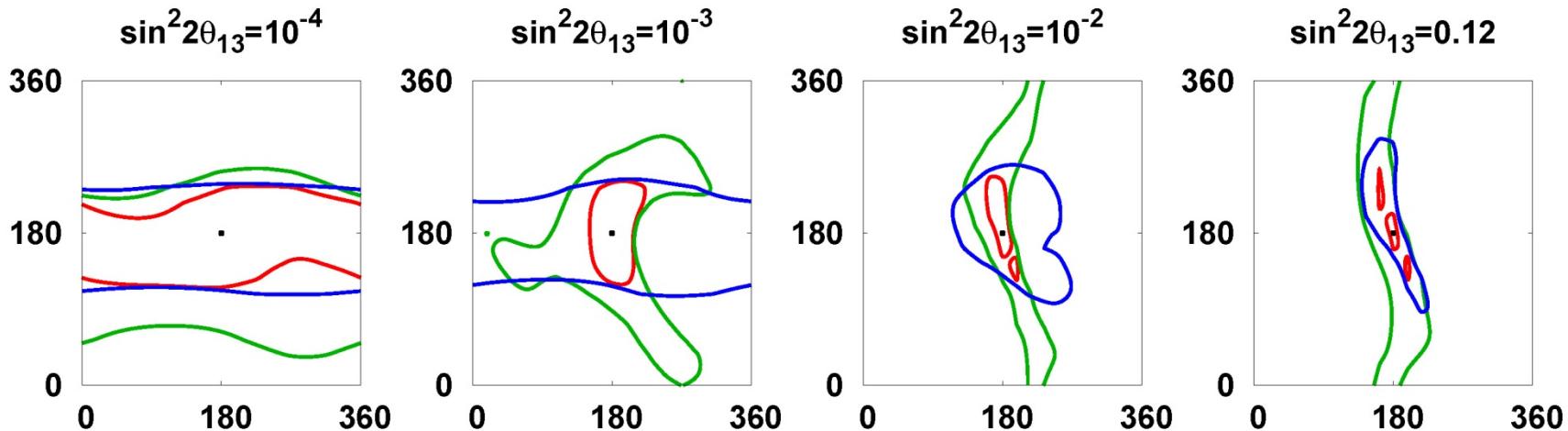


Figure 2: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.2$

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Kamioka —————

Korea —————

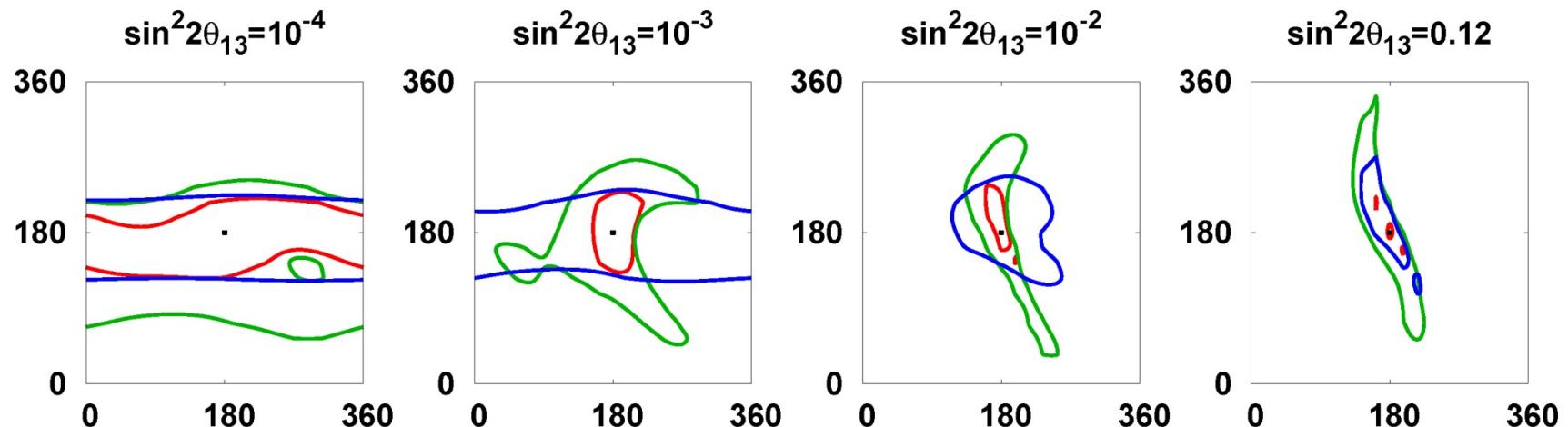


Figure 3: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.3$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

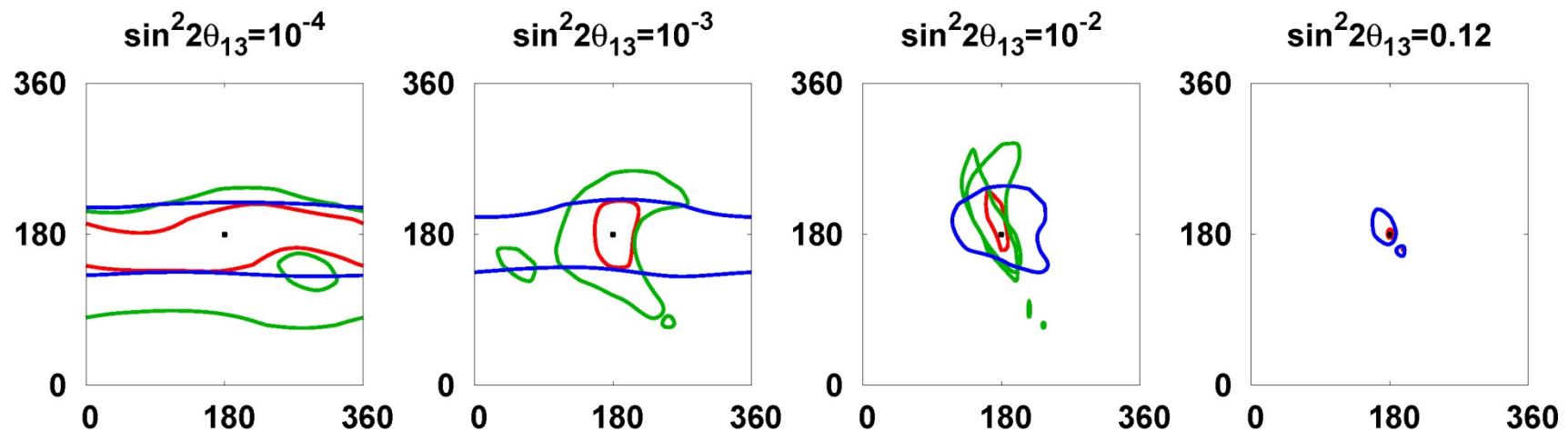


Figure 4: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.4$

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Kamioka —————

Korea —————

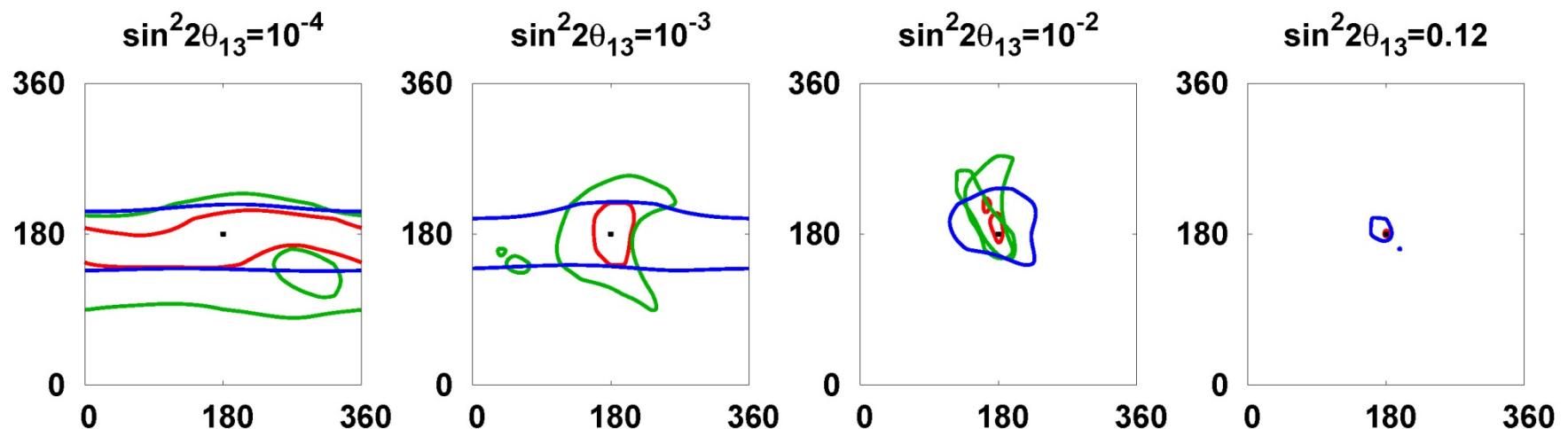


Figure 5: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.5$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

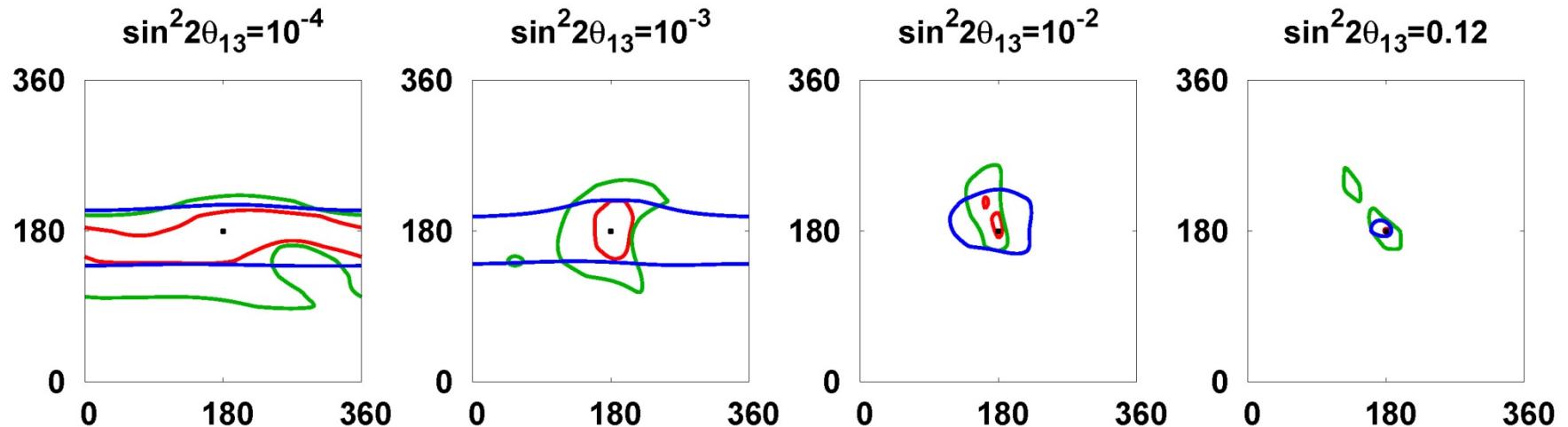


Figure 6: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.6$

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Kamioka —————

Korea —————

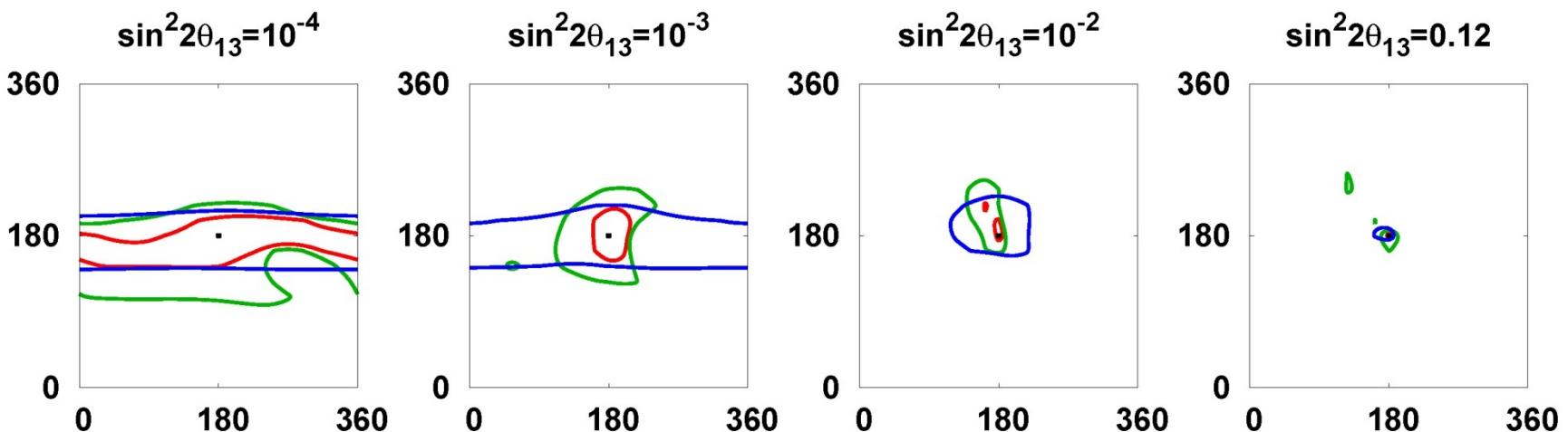


Figure 7: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.7$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

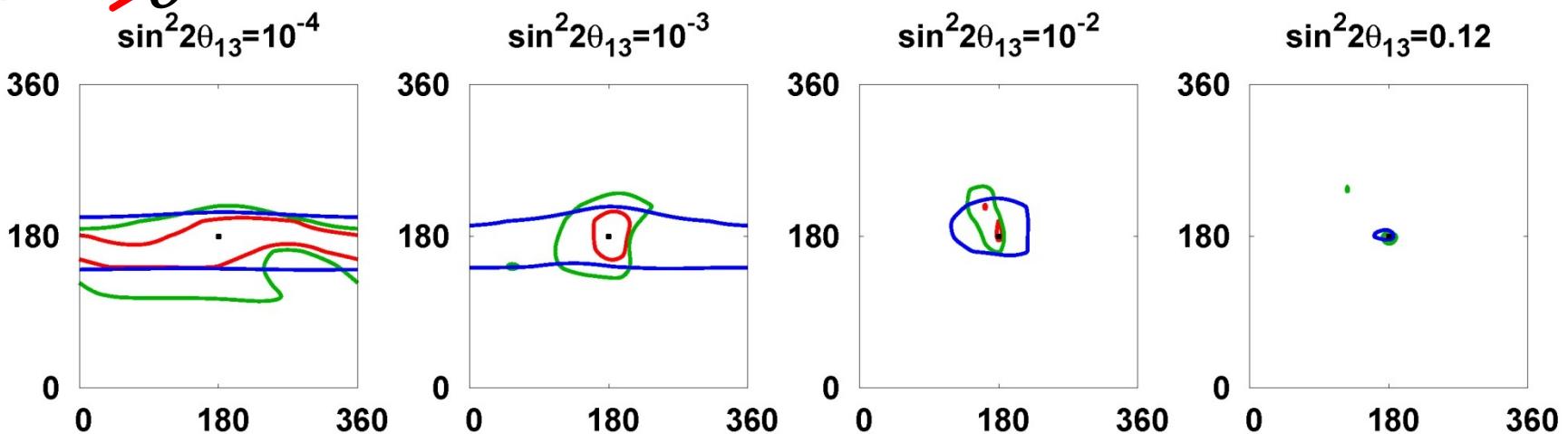
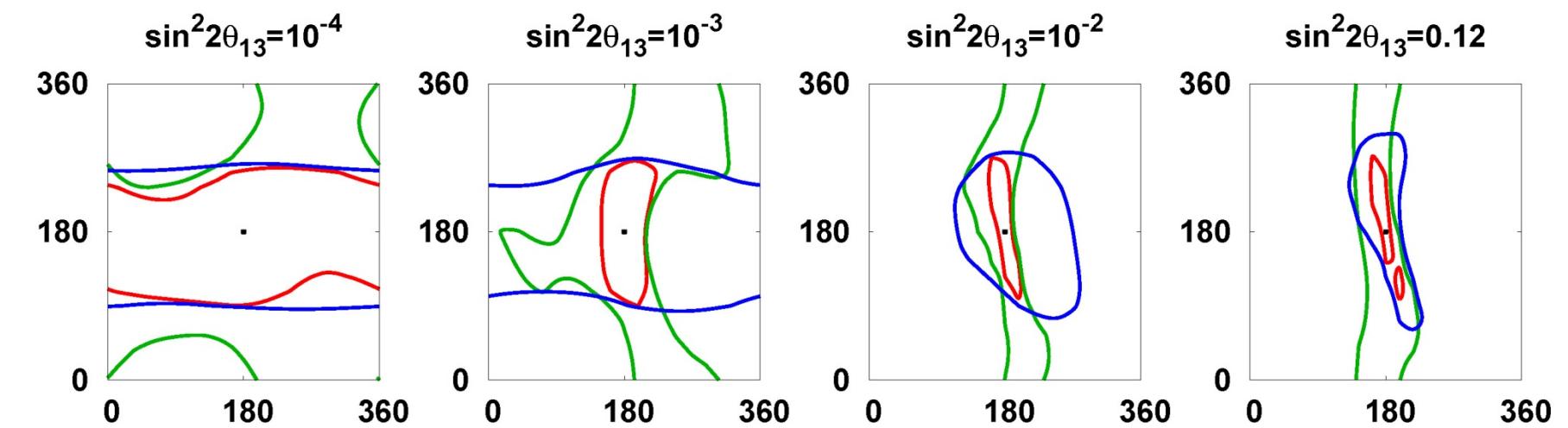


Figure 8: $\epsilon_{ee} = 0.8, |\epsilon_{e\tau}| = 0.8$

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Kamioka —————

Korea —————



$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

Figure 1: $\epsilon_{ee} = 2.0$, $|\epsilon_{e\tau}| = 0.1$

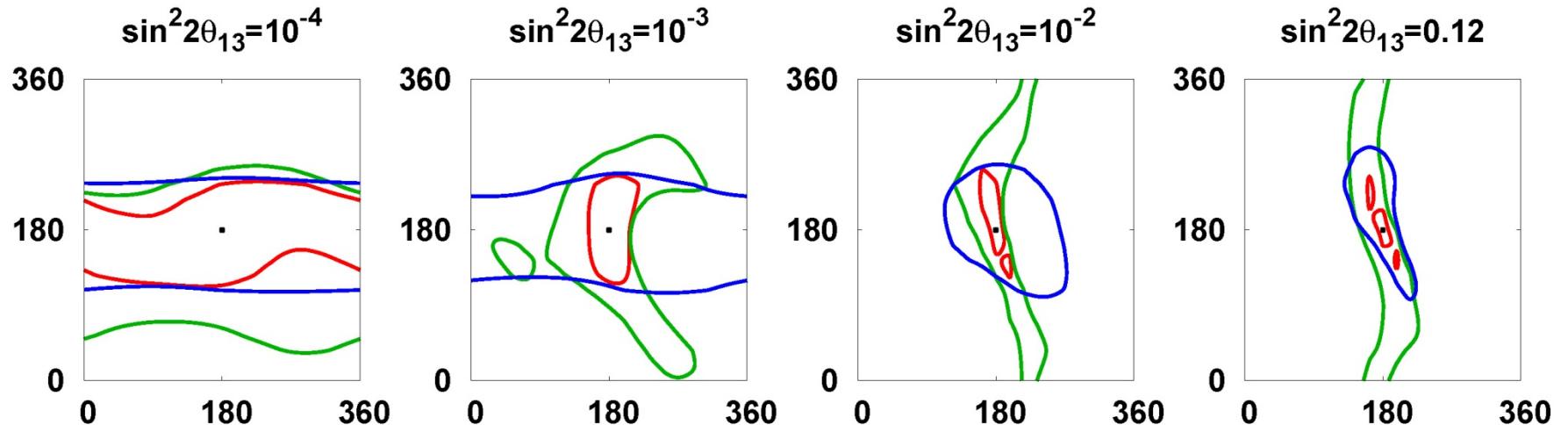


Figure 2: $\epsilon_{ee} = 2.0$, $|\epsilon_{e\tau}| = 0.2$

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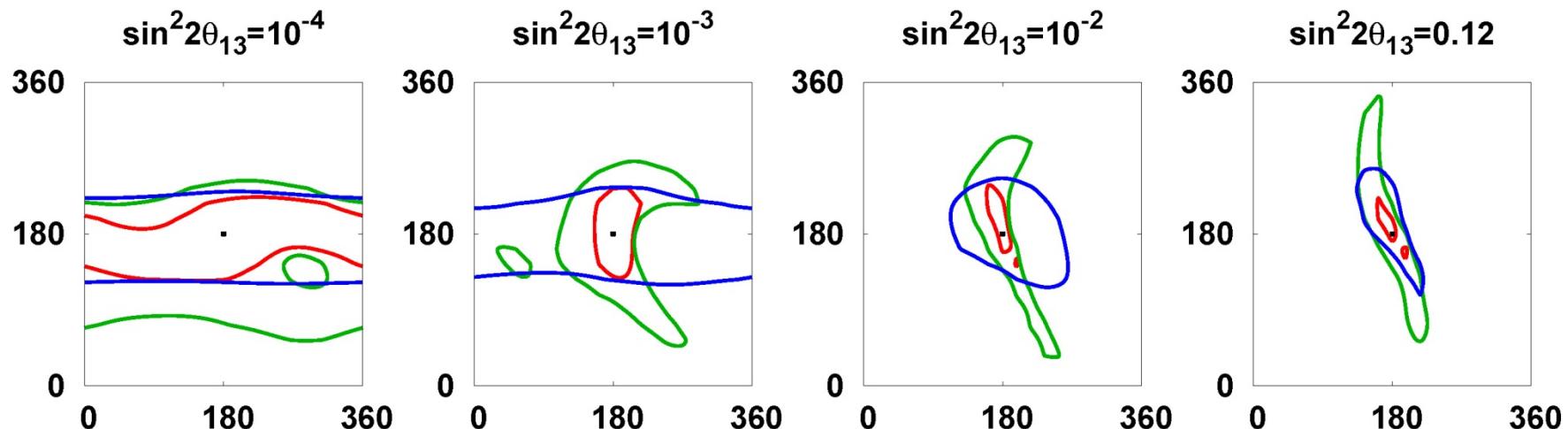


Figure 3: $\epsilon_{ee} = 2.0$, $|\epsilon_{e\tau}| = 0.3$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

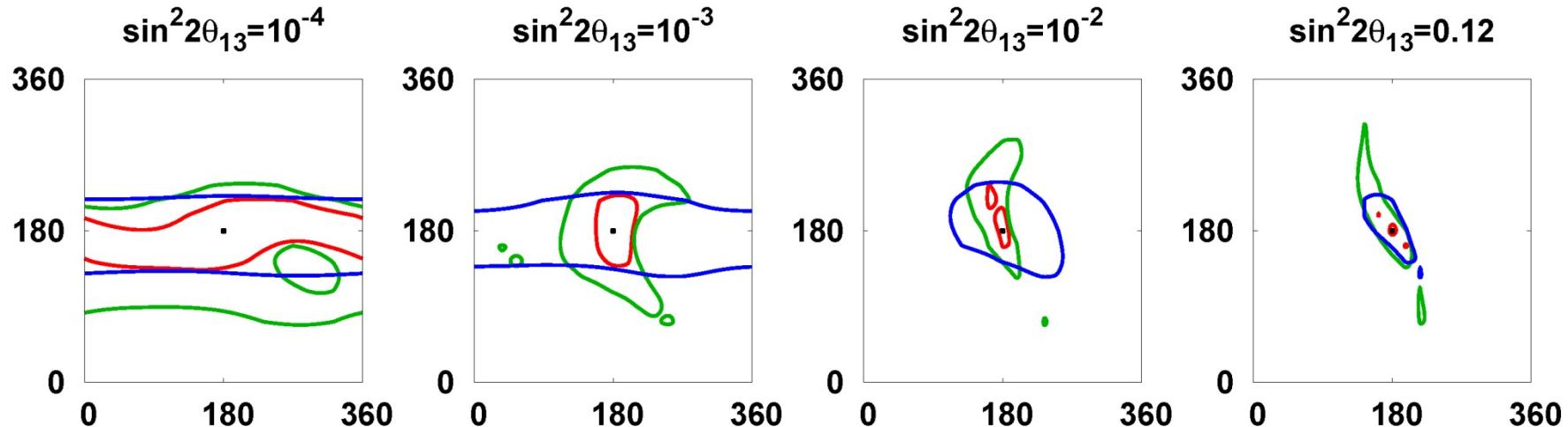


Figure 4: $\epsilon_{ee} = 2.0$, $|\epsilon_{e\tau}| = 0.4$

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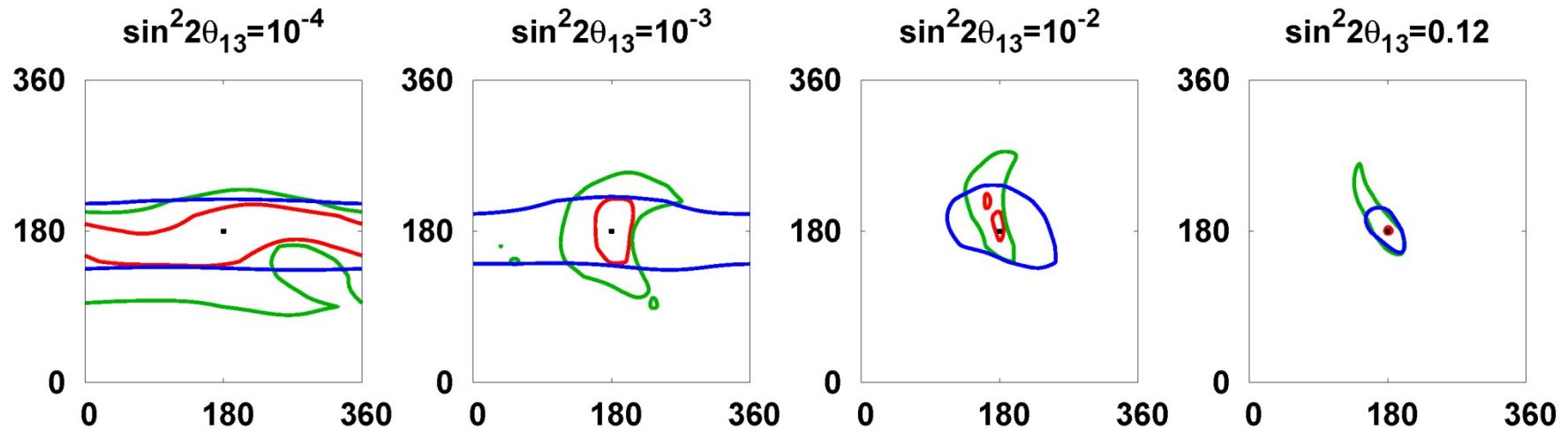


Figure 5: $\epsilon_{ee} = 2.0, |\epsilon_{e\tau}| = 0.5$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

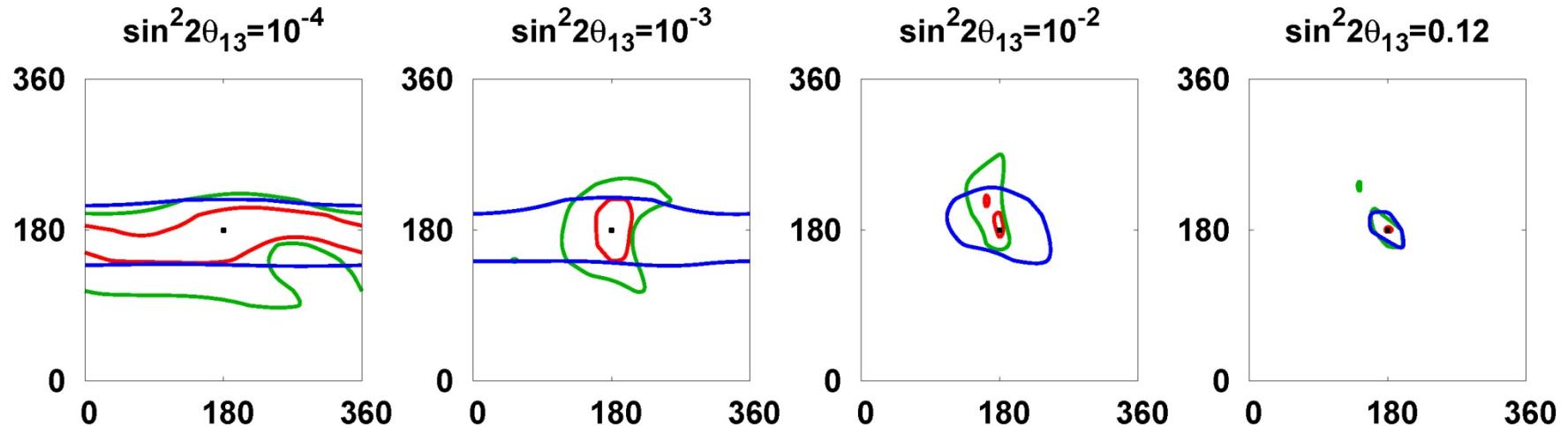


Figure 6: $\epsilon_{ee} = 2.0, |\epsilon_{e\tau}| = 0.6$

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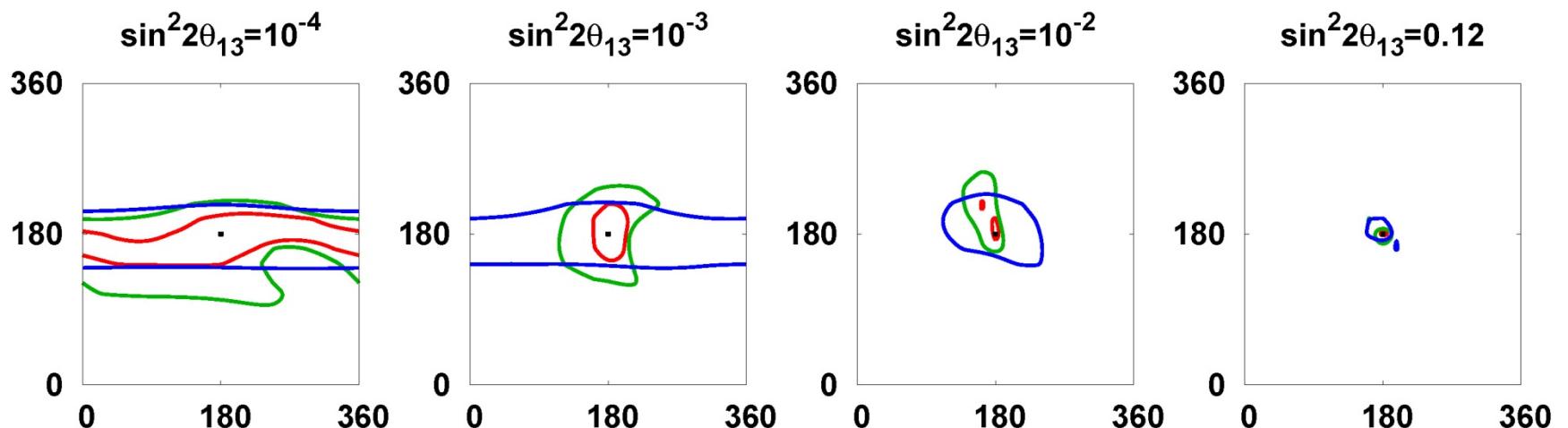


Figure 7: $\epsilon_{ee} = 2.0, |\epsilon_{e\tau}| = 0.7$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

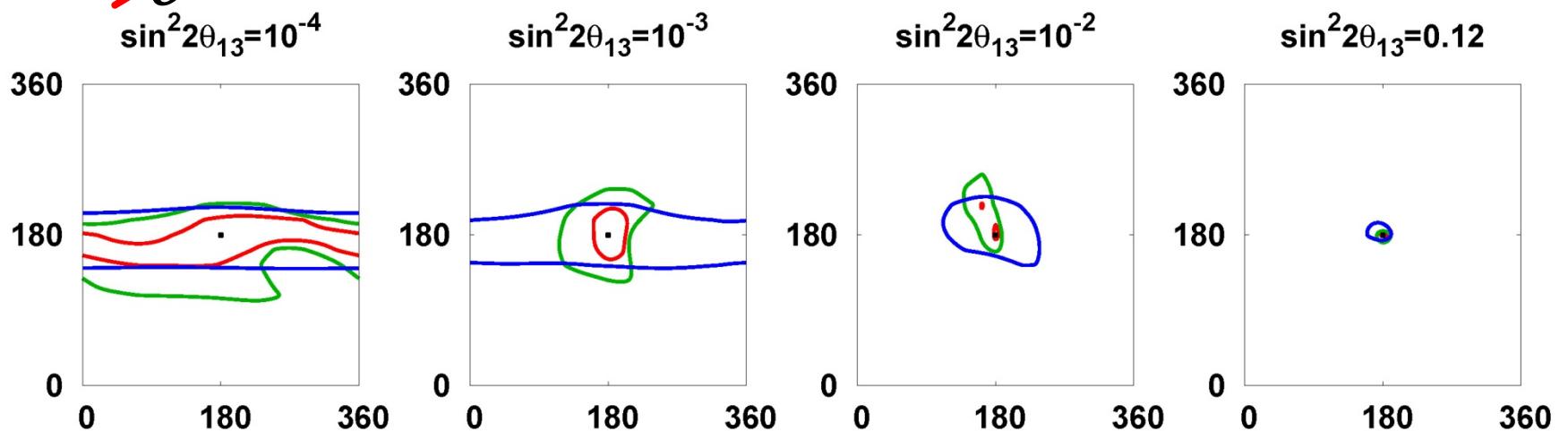


Figure 8: $\epsilon_{ee} = 2.0, |\epsilon_{e\tau}| = 0.8$

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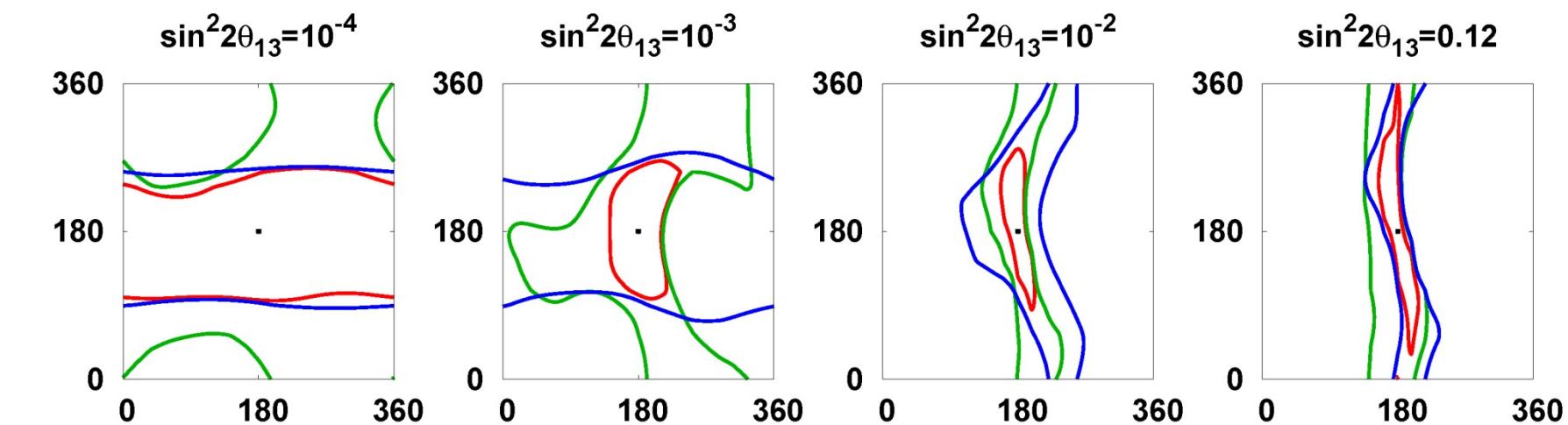


Figure 1: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.1$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

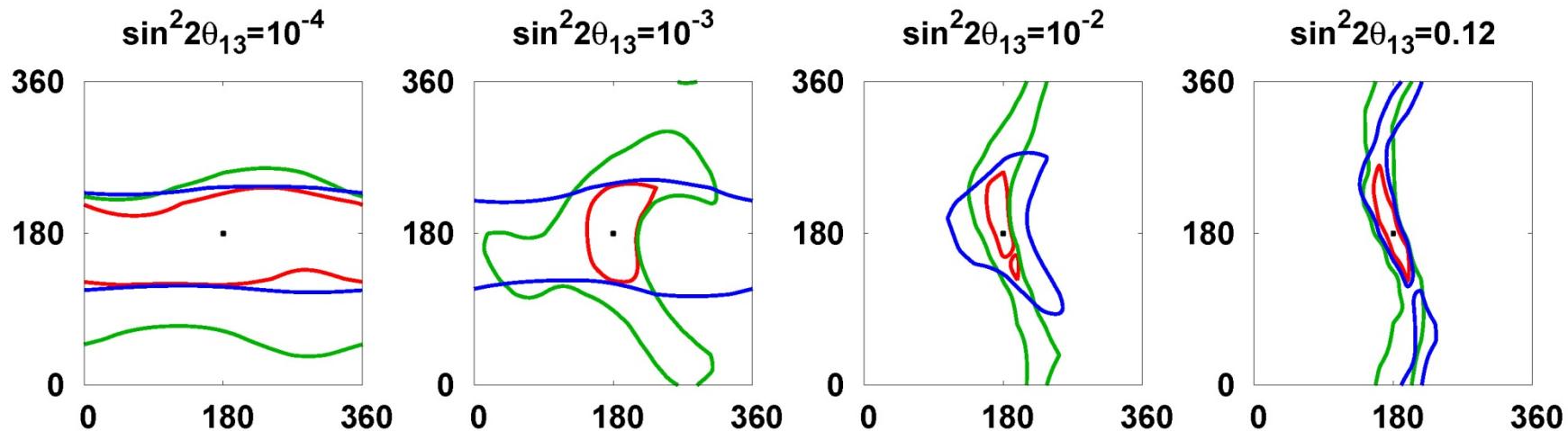


Figure 2: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.2$

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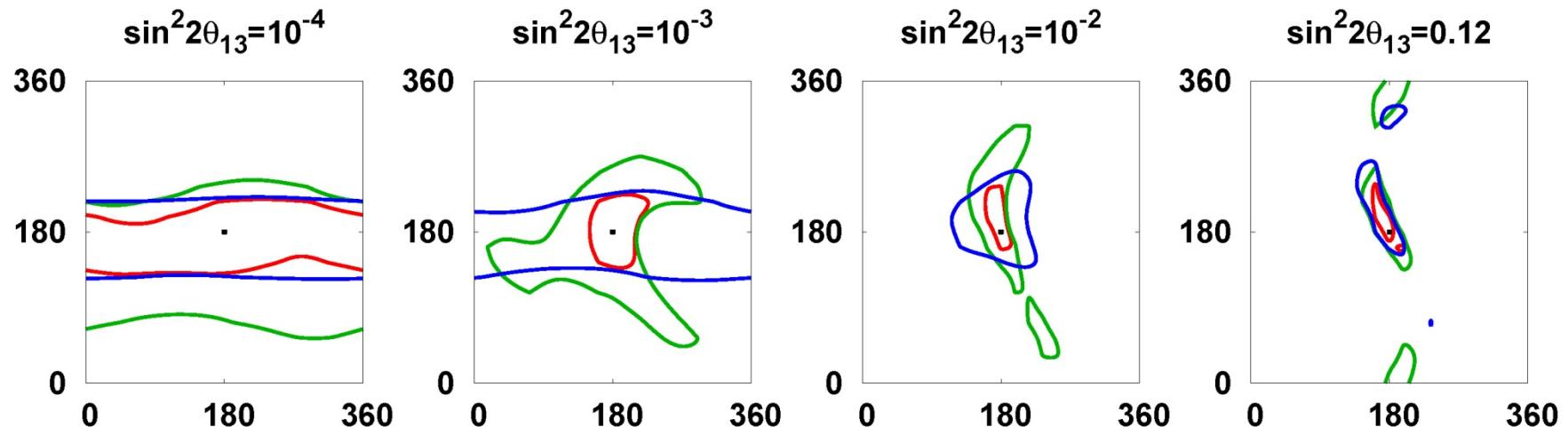


Figure 3: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.3$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

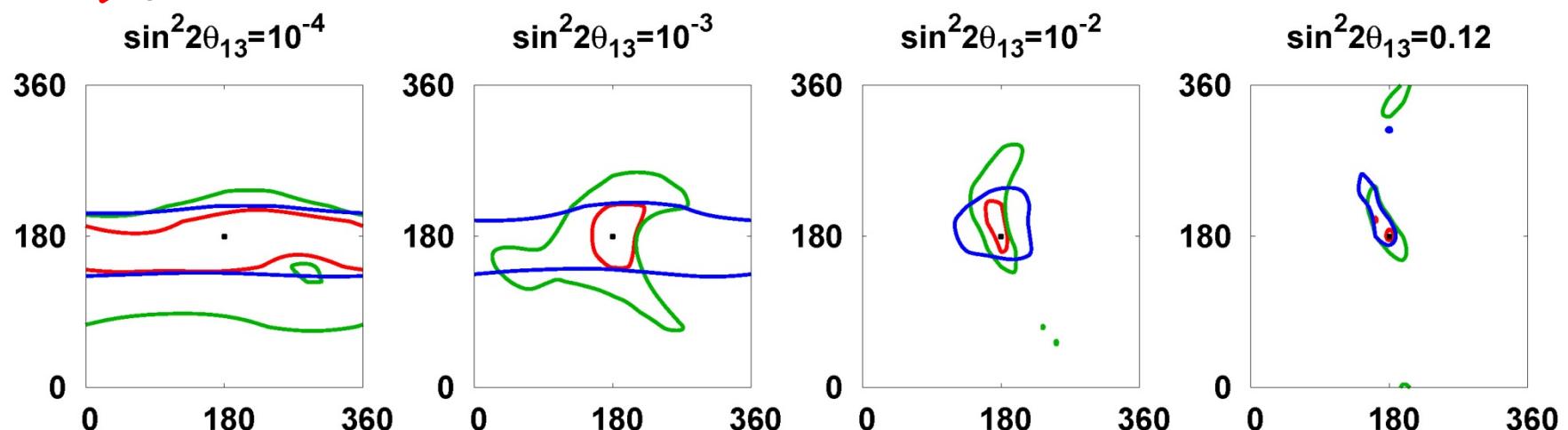


Figure 4: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.4$

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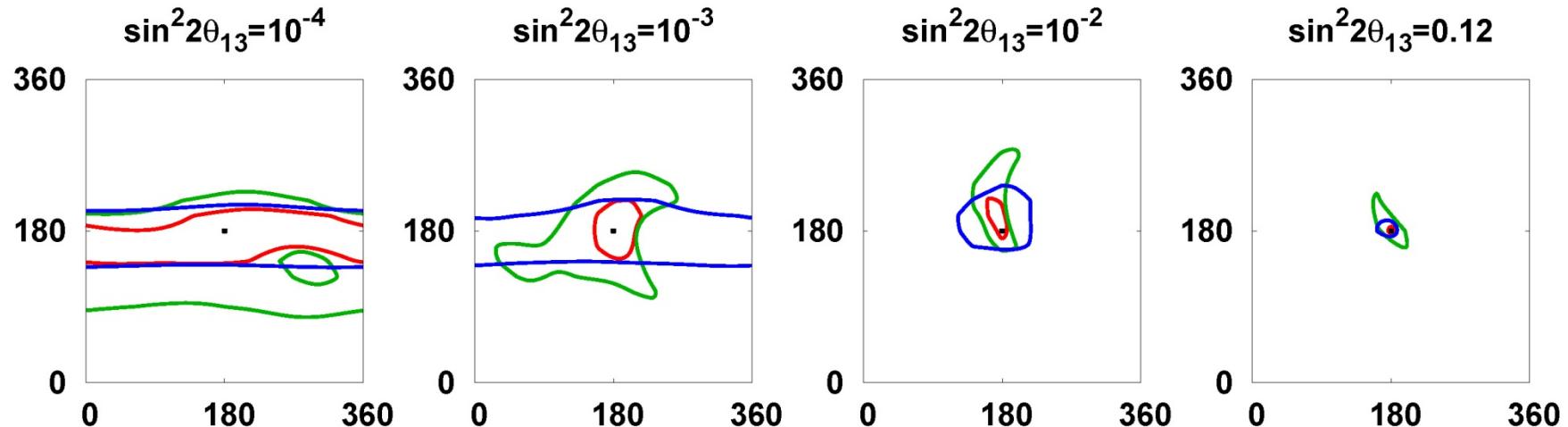


Figure 5: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.5$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

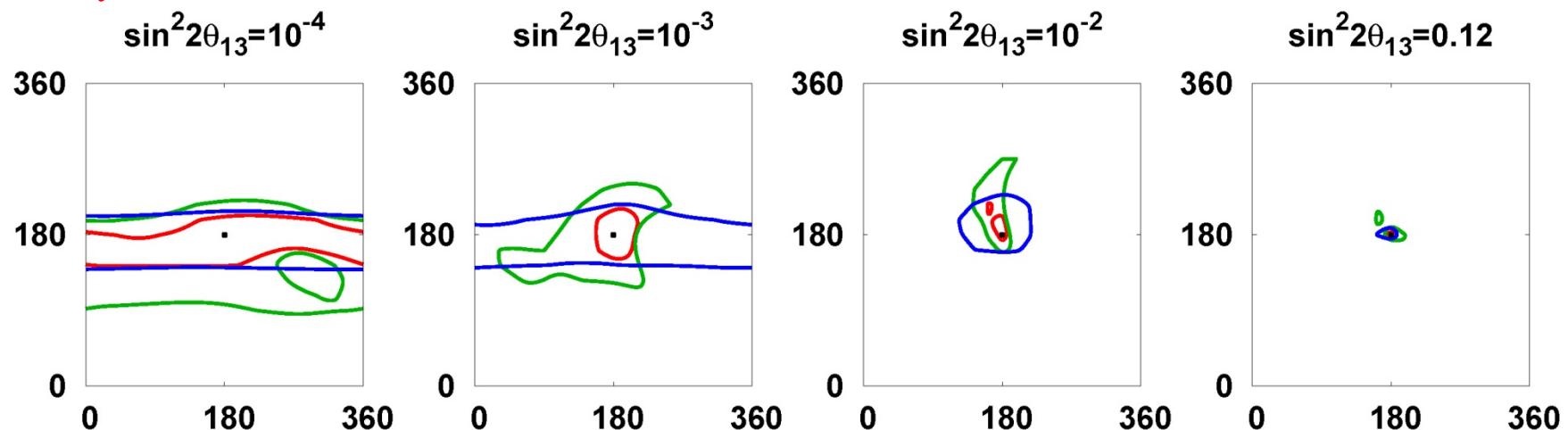


Figure 6: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.6$

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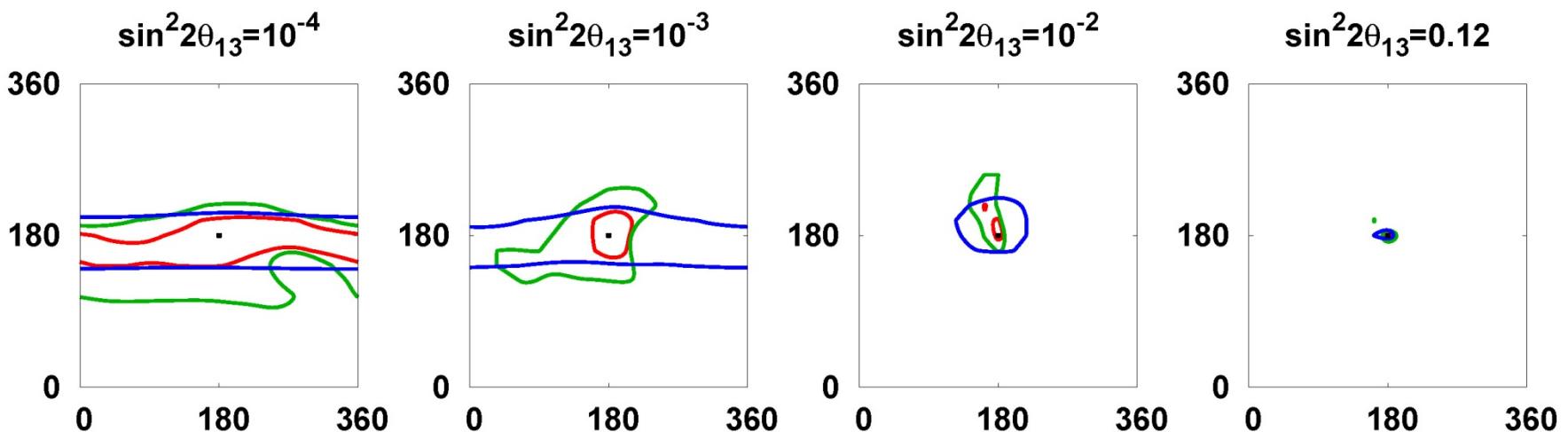


Figure 7: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.7$

$\uparrow \arg(\epsilon_{e\tau})$
 $\rightarrow \delta$

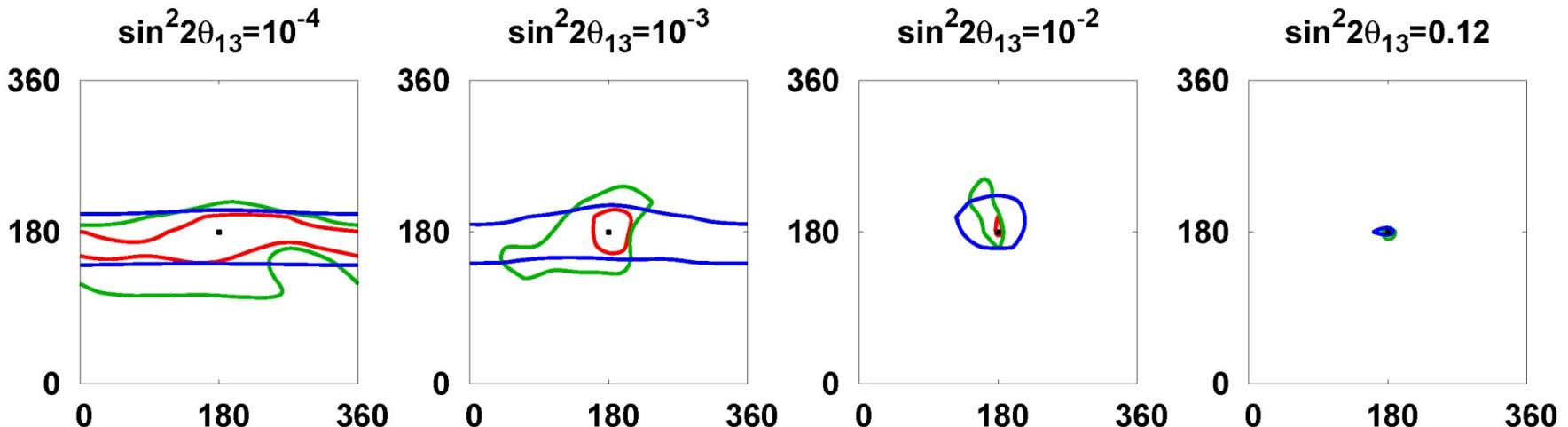


Figure 8: $\epsilon_{ee} = -2.0$, $|\epsilon_{e\tau}| = 0.8$

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Kamioka —————

Korea —————

2 flavor analysis for Atmospheric ν in vacuum

$$\left| \frac{\Delta m_{21}^2}{2E} L \right| \ll 1 \quad , \quad \left| \frac{\Delta m_{31}^2}{2E} L \right| \sim \mathcal{O}(1)$$

$$\begin{aligned}
P_{(\nu_\alpha \rightarrow \nu_\beta)}^{(1)} &\sim \delta_{\alpha\beta} - 4\{\Re(U_{\beta 1}U_{\alpha 2}^* + U_{\beta 2}U_{\alpha 2}^*)U_{\beta 3}^*U_{\alpha 3}\} \sin^2(1.27 \frac{\Delta m_{31}^2}{E} L) \\
&\quad + 2\{\Im(U_{\beta 1}U_{\alpha 2}^* + U_{\beta 2}U_{\alpha 2}^*)U_{\beta 3}^*U_{\alpha 3}\} \sin(2.54 \frac{\Delta m_{31}^2}{E} L) \\
&= \begin{cases} 4|U_{\beta 3}|^2|U_{\alpha 3}|^2 \sin^2(1.27 \frac{\Delta m_{31}^2}{E} L) & (\nu_\alpha \rightarrow \nu_\beta) \\ 1 - 4(1 - |U_{\alpha 3}|^2)|U_{\alpha 3}|^2 \sin^2(1.27 \frac{\Delta m_{31}^2}{E} L) & (\nu_\alpha \rightarrow \nu_\alpha) \end{cases}
\end{aligned}$$

$$\begin{aligned}
U_{MNS} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{13} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}
\end{aligned}$$

$$\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^e + 3\epsilon_{\alpha\beta}^u + 3\epsilon_{\alpha\beta}^d$$

$$\left[\begin{array}{lll} \left\{ \begin{array}{l} |\epsilon_{ee}^{eL}| < 0.06 \\ |\epsilon_{ee}^{eR}| < 0.14 \end{array} \right. & |\epsilon_{e\mu}^{eP}| < 0.10 & \left\{ \begin{array}{l} |\epsilon_{e\tau}^{eL}| < 0.4 \\ |\epsilon_{e\tau}^{eR}| < 0.27 \end{array} \right. \\ & |\epsilon_{\mu\mu}^{eP}| < 0.03 & \left\{ \begin{array}{l} |\epsilon_{\mu\tau}^{eP}| < 0.10 \\ |\epsilon_{\tau\tau}^{eL}| < 0.16 \\ |\epsilon_{\tau\tau}^{eR}| < 0.4 \end{array} \right. \end{array} \right]$$

$$e : p : N = 1 : 1 : 1$$

$$e : u : d = 1 : 3 : 3$$

$$\left[\begin{array}{lll} \left\{ \begin{array}{l} |\epsilon_{ee}^{uL}| < 1.0 \\ |\epsilon_{ee}^{uR}| < 0.7 \end{array} \right. & |\epsilon_{e\mu}^{uP}| < 0.05 & |\epsilon_{e\tau}^{uP}| < 0.5 \\ & \left\{ \begin{array}{l} |\epsilon_{\mu\mu}^{uL}| < 0.003 \\ |\epsilon_{\mu\mu}^{uR}| < 0.008 \end{array} \right. & |\epsilon_{\mu\tau}^{uP}| < 0.05 \\ & & \left\{ \begin{array}{l} |\epsilon_{\tau\tau}^{uL}| < 1.4 \\ |\epsilon_{\tau\tau}^{uR}| < 3 \end{array} \right. \end{array} \right]$$

$$\left[\begin{array}{lll} \left\{ \begin{array}{l} |\epsilon_{ee}^{dL}| < 0.3 \\ |\epsilon_{ee}^{dR}| < 0.6 \end{array} \right. & |\epsilon_{e\mu}^{dP}| < 0.05 & |\epsilon_{e\tau}^{dP}| < 0.5 \\ & \left\{ \begin{array}{l} |\epsilon_{\mu\mu}^{dL}| < 0.003 \\ |\epsilon_{\mu\mu}^{dR}| < 0.015 \end{array} \right. & |\epsilon_{\mu\tau}^{dP}| < 0.05 \\ & & \left\{ \begin{array}{l} |\epsilon_{\tau\tau}^{dL}| < 1.1 \\ |\epsilon_{\tau\tau}^{dR}| < 6 \end{array} \right. \end{array} \right]$$

$$\boxed{\begin{array}{lll} |\epsilon_{ee}| < 4.2 & |\epsilon_{e\mu}| < 0.33 & |\epsilon_{e\tau}| < 3.0 \\ & & \\ & |\epsilon_{\mu\mu}| < 0.068 & |\epsilon_{\mu\tau}| < 0.33 \\ & & \\ & & |\epsilon_{\tau\tau}| < 21 \end{array}}$$

Restrict from atmospheric v exp. (1)

$$H_{NSI} = U_{MNS} \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} U_{MNS}^\dagger + \sqrt{2} G_F n_e \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & \epsilon_{\tau\tau} \end{pmatrix}$$

$$O = \begin{pmatrix} \cos \beta & 0 & \sin \beta e^{-2i\psi} \\ 0 & 1 & 0 \\ -\sin \beta e^{2i\psi} & 0 & \cos \beta \end{pmatrix}$$

$$\left\{ \begin{array}{l} \tan 2\beta = \frac{2|\epsilon_{e\tau}|}{1+\epsilon_{ee}-\epsilon_{\tau\tau}} \\ 2\psi = \arg(\epsilon_{e\tau}) \end{array} \right.$$

$$\left\{ \begin{array}{l} \lambda'_e = \frac{\sqrt{2}G_F n_e}{2} \{1 + \epsilon_{ee} + \epsilon_{\tau\tau} + \sqrt{(1 + \epsilon_{ee} - \epsilon_{\tau\tau})^2 + 4|\epsilon_{e\tau}|^2}\} \\ \lambda'_\mu = 0 \\ \lambda'_\tau = \frac{\sqrt{2}G_F n_e}{2} \{1 + \epsilon_{ee} + \epsilon_{\tau\tau} - \sqrt{(1 + \epsilon_{ee} - \epsilon_{\tau\tau})^2 + 4|\epsilon_{e\tau}|^2}\} \end{array} \right.$$

Restrict from atmospheric v exp. (2)

$$\Delta \equiv \frac{\Delta m_{31}^2}{4E}, \quad \Delta_o dot \equiv \frac{\Delta m_{21}^2}{4E} \rightarrow 0, \quad \theta_{13} \rightarrow 0$$

$$\begin{aligned} H_{NSI} &= \Delta O^\dagger \{ O U_{MNS} diag(\frac{m_1^2}{2E}, \frac{m_2^2}{2E}, \frac{m_3^2}{2E}) U_{MNS}^\dagger O^\dagger + diag(\lambda'_e, \lambda'_\mu, \lambda'_\tau,) \} O \\ &= \Delta O^\dagger \begin{pmatrix} -c_\beta^2 + s_\beta^2 c_{2\theta} + \frac{\lambda'_e}{\Delta} & s_\beta s_{2\theta} e^{-2i\psi} & c_\beta s_\beta (1 + c_{2\theta}) e^{-2i\psi} \\ s_\beta s_{2\theta} e^{2i\psi} & -c_{2\theta} & s_{2\theta} c_\beta \\ c_\beta s_\beta (1 + c_{2\theta}) e^{2i\psi} & s_{2\theta} c_\beta & -s_\beta^2 + c_\beta^2 c_{2\theta} + \frac{\lambda'_\tau}{\Delta} \end{pmatrix} O \end{aligned}$$

$$\frac{\sqrt{2}G_F n_e}{2} \{ 1 + \epsilon_{ee} + \epsilon_{\tau\tau} - \sqrt{(1 + \epsilon_{ee} - \epsilon_{\tau\tau})^2 + 4|\epsilon_{e\tau}|^2} = 0$$

$$\epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1 + \epsilon_{ee}}$$

of events

$$N_i = \int_{E_i}^{E_{i+1}} dE' \int_{-\infty}^{\infty} dE_\nu \frac{1}{\sqrt{\pi}\delta E} \exp\left\{-\left(\frac{E_\nu - E'}{\delta E}\right)^2\right\} F(E_\nu) P(E_\nu) \sigma(E_\nu) vol$$

i : energy bin
 E' : reconstructed ν energy
 E_ν : ν energy
 F : ν flux
 σ : ν cross section
 P : ν oscillation probability
 δE : energy resolution
 vol : fiducial mass

$$\begin{aligned}
& \Delta\chi^2 \\
= & \min_{param} \left[\sum_{k=1}^4 \left\{ \sum_{i=1}^5 \frac{\{N^0(e)_i + B^0(e)_i - N_i^{NSI} \sum_{l=3,7} (1 + f(e)_l^i \epsilon_l) - B_i^{NSI} \sum_{l=1,2,7} (1 + f(e)_l^i \epsilon_l)\}^2}{\sigma_i^2} \right. \right. \\
+ & \sum_{i=1}^{20} \frac{\{N^0(\mu)_i + B^0(\mu)_i - N_i^{NSI} \sum_{l=4,5,7} (1 + f(\mu)_l^i \epsilon_l) - B_i^{NSI} \sum_{l=4,6,7} (1 + f(\mu)_l^i \epsilon_l)\}^2}{\sigma_i^2} \Big\} \\
+ & \sum_{l=1 \sim 7} (\frac{\epsilon_l}{\tilde{\sigma}_l})^2 \\
+ & \left. \frac{2.7 \times (\sin^2(2\theta_{23}) - 1.0)^2}{(0.06)^2} + \frac{(\sin^2(\theta_{13}) - 0.02)^2}{(0.01)^2} + \frac{(|\Delta m_{31}^2| - 2.4 \times 10^{-3} eV^2)^2}{(1.5 \times 10^{-4} eV^2)^2} \right]
\end{aligned}$$

$N, B : (\epsilon_{ee} = 0, |\epsilon_{e\tau}| = 0, arg(\epsilon_{e\tau}) = 0, \theta_{12}, \theta_{23}, \theta_{13}, \Delta m_{21}^2, \Delta m_{31}^2, \delta)$

$N^0, B^0 : (\epsilon_{ee}, |\epsilon_{e\tau}|, arg(\epsilon_{e\tau}), \bar{\theta}_{12}, \bar{\theta}_{23}, \bar{\theta}_{13}, \Delta \bar{m}_{21}^2, \Delta \bar{m}_{31}^2, \bar{\delta})$

- 1 overall background normalization for electron events
- 2 energy dependent uncertainty for electron events
- 3 uncertainties in the signal detection efficiency for electron events
- 4 uncertainty in the spectrum shape for muon events
- 5 uncertainties in the signal detection efficiency for muon events
- 6 uncertainty in the separation of QE and non-QE interactions in the muon events
- 7 possible flux difference between Kamioka and Korea