

# **Non-standard interactions in propagation through atmospheric neutrinos**

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**Based on arXiv.1503.08056, Fukasawa & OY**

**1. Introduction**

**2. New Physics in propagation**

**3. Sensitivity of  $\nu_{\text{atm}}$  at SK&HK to NSI in propagation**

**4. Conclusions**

# 1. Introduction

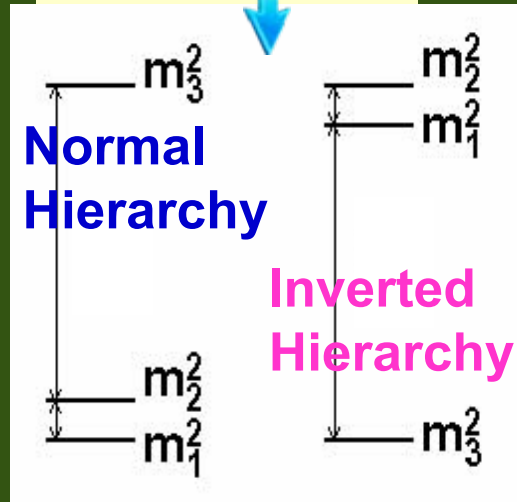
## Framework of 3 flavor $\nu$ oscillation

### Mixing matrix

Functions of  
mixing angles  
 $\theta_{12}, \theta_{23}, \theta_{13},$   
and CP phase  $\delta$

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

Both hierarchy  
patterns are  
allowed



All 3 mixing angles have been measured (2012):

$\nu_{\text{solar}}$  + KamLAND (reactor)

$$\theta_{12} \cong \frac{\pi}{6}, \Delta m_{21}^2 \cong 8 \times 10^{-5} \text{ eV}^2$$

$\nu_{\text{atm}}$  + K2K, MINOS (accelerators)

$$\theta_{23} \cong \frac{\pi}{4}, |\Delta m_{32}^2| \cong 2.5 \times 10^{-3} \text{ eV}^2$$

DCHOOZ + Daya Bay + Reno (reactors),  
T2K + MINOS, others

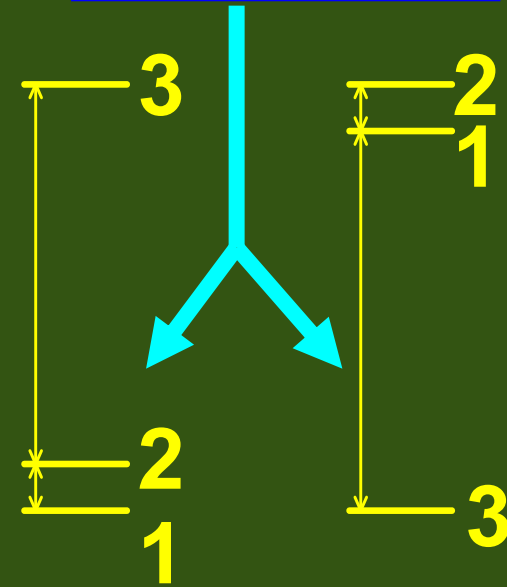
$$\theta_{13} \cong \pi / 20$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \epsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Next task is to measure  $\text{sign}(\Delta m_{31}^2)$ ,  $\pi/4 - \theta_{23}$  and  $\delta$

→ These quantities are expected to be determined in future experiments with **huge detectors**.

● Both **mass hierarchies** are allowed



normal hierarchy

inverted hierarchy

$$\Delta m_{32}^2 > 0$$

$$\Delta m_{32}^2 < 0$$

# Motivation for research on **New Physics**

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

→ Research on **New Physics** is important.

# Phenomenological scenarios of New Physics

Scenarios	Possible magnitude relative to standard value
Light sterile neutrinos	$O(10\%)$
<b>Non Standard Interactions</b> in propagation	$e-\tau: O(100\%)$ $\mu: O(1\%)$
NSI at production / detection	$O(1\%)$
Violation of unitarity due to heavy particles	$O(0.1\%)$

While no concrete model is known, scenarios with **Non Standard Interactions** in propagation could exhibit the largest effect.

## 2. New Physics in propagation

Phenomenological **New Physics** considered in this talk: 4-fermi **Non Standard Interactions**:

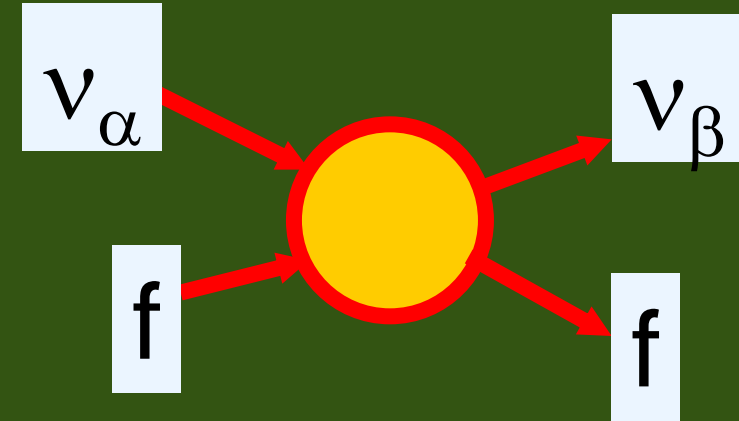
$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta} \bar{\nu}_\alpha \gamma^\mu \nu_\beta \bar{f} \gamma_\mu f'$$



**Modification of matter effect**

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

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



neutral current  
non-standard  
interaction

**NP**

## ● Constraints on $\epsilon_{\alpha\beta}$ for expts on Earth

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

**Constraints are weak**

$$\left( \begin{array}{l} |\epsilon_{ee}| \lesssim 4 \times 10^0 \\ |\epsilon_{e\mu}| \lesssim 3 \times 10^{-1} \\ |\epsilon_{\mu\mu}| \lesssim 7 \times 10^{-2} \\ |\epsilon_{e\tau}| \lesssim 3 \times 10^0 \\ |\epsilon_{\mu\tau}| \lesssim 3 \times 10^{-1} \\ |\epsilon_{\tau\tau}| \lesssim 2 \times 10^1 \end{array} \right)$$

- Summary of the constraints on  $\epsilon_{\alpha\beta}$

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

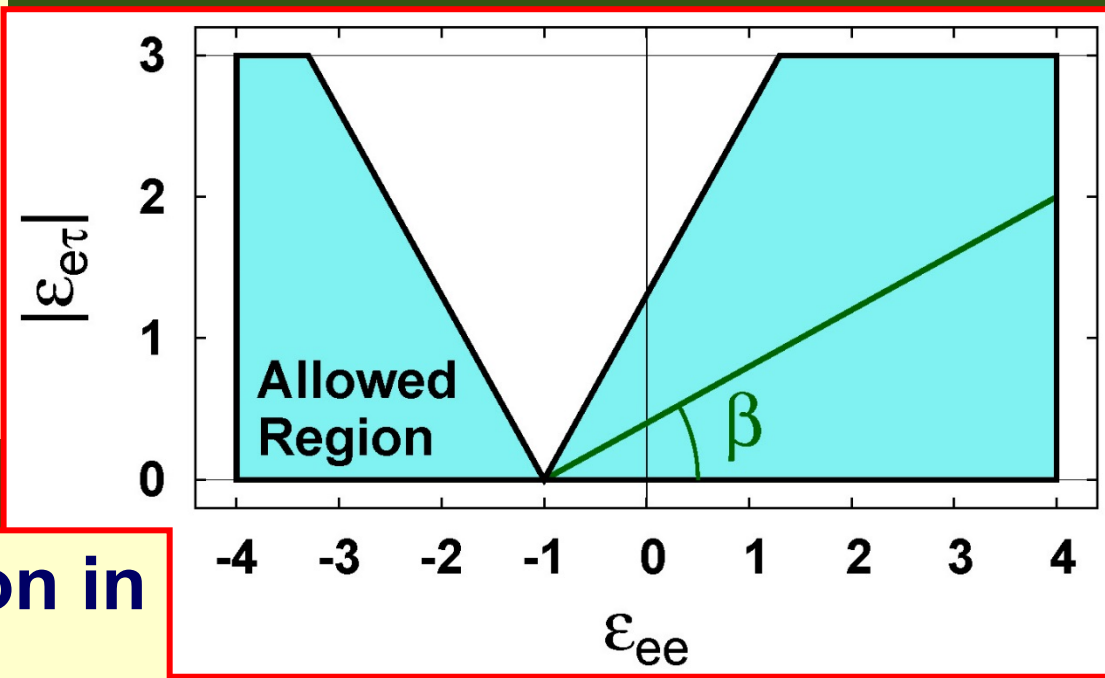
$$A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \rightarrow A \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\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

Furthermore,  $\nu_{\text{atm}}$  data implies

$$|\tan\beta| = |\epsilon_{e\tau} / (1 + \epsilon_{ee})| < 1.5$$

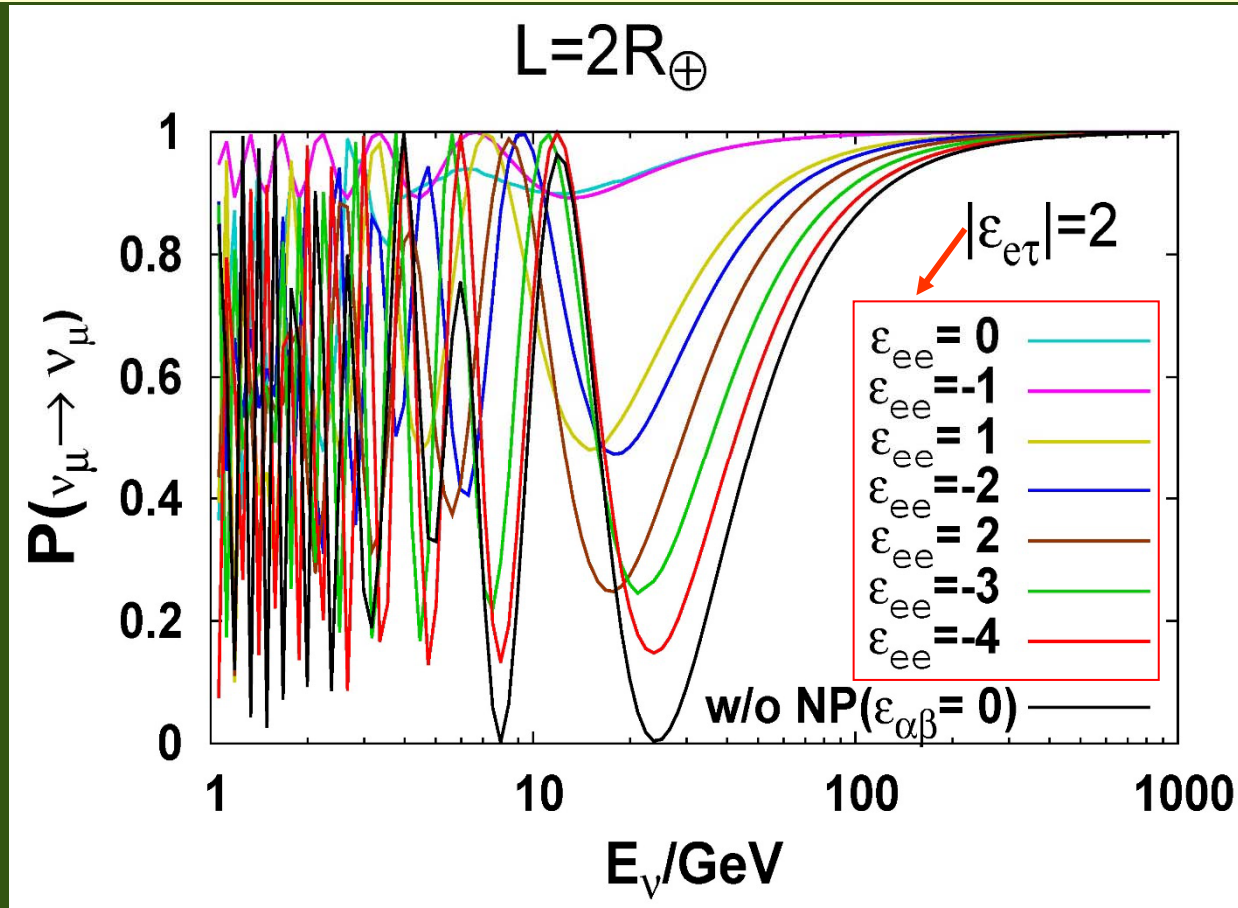
@2.5 $\sigma$ CL

Friedland-Lunardini,  
PRD72:053009,'05



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

### 3. Sensitivity of $\nu_{\text{atm}}$ at SK&HK to NSI in propagation

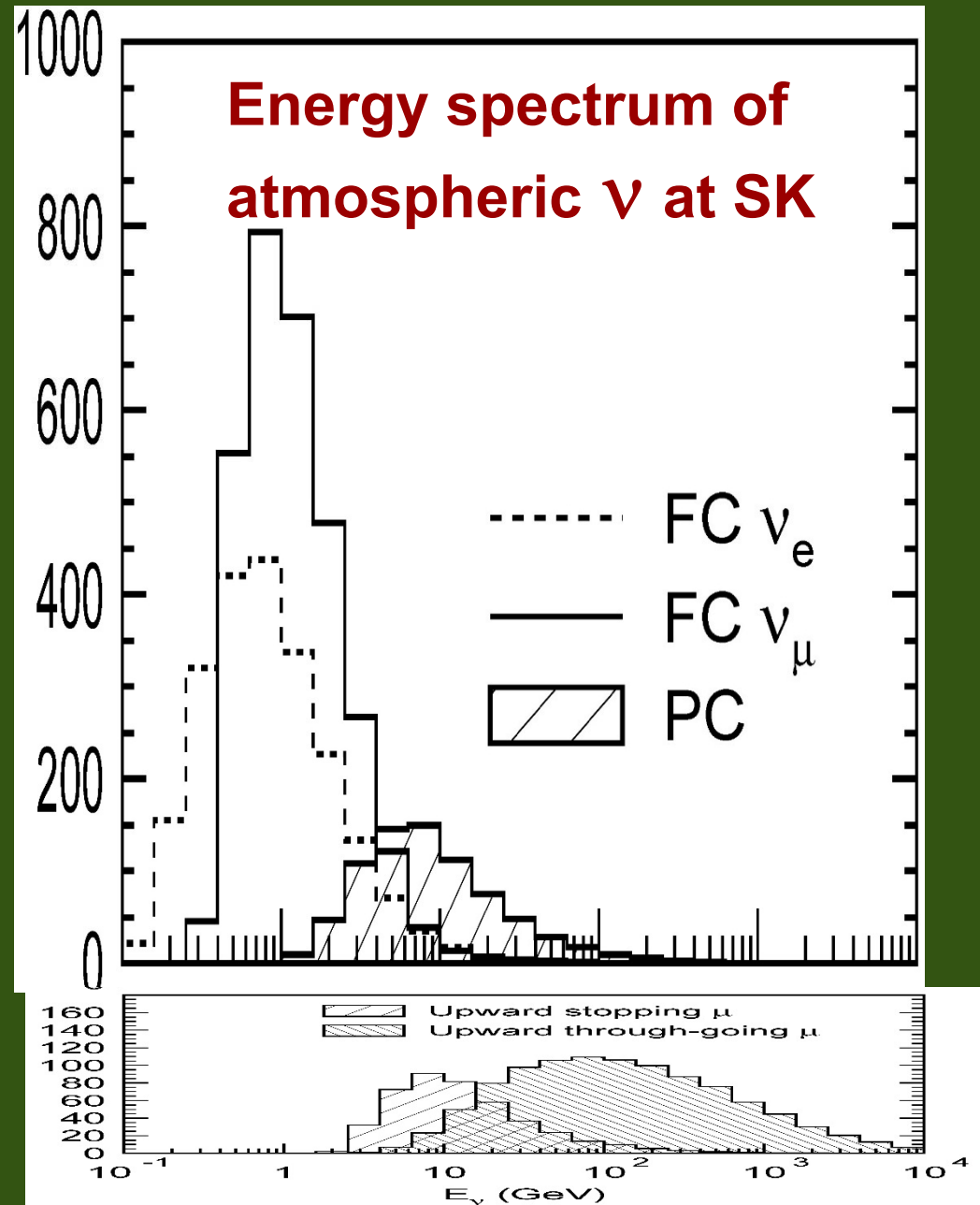


Deviation from the standard case is significant mainly for  $10\text{GeV} < E < 100\text{ GeV}$

Here we will discuss SK & HK because

● SK & (particularly) HK has considerable #(events) for  $10\text{ GeV} < E < 100\text{ GeV}$

● One of the authors (OY) worked on SK before



# Outline of our Analysis

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

## Our ansatz

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

**Black : standard**

**Red : non-standard**

**SK**

$$\chi^2(\mathcal{E}_{ee}, |\mathcal{E}_{e\tau}|) = \min_{\text{parameters}} \sum_i \frac{[N_i^0(\mathcal{E}_{ee}, \mathcal{E}_{e\tau}) - N_i(\text{data})]^2}{\sigma_i^2}$$

**Rate  
analysis  
only**

**HK**

$$\Delta\chi^2(\mathcal{E}_{ee}, |\mathcal{E}_{e\tau}|) = \min_{\text{parameters}} \sum_i \frac{[N_i^0(\mathcal{E}_{ee}, \mathcal{E}_{e\tau}) - N_i(\text{std})]^2}{\sigma_i^2}$$

**Rate &  
spectrum  
analysis**

**Parameters**

**Fixed:  $\theta_{12}, \theta_{13}, \Delta m_{21}^2$**

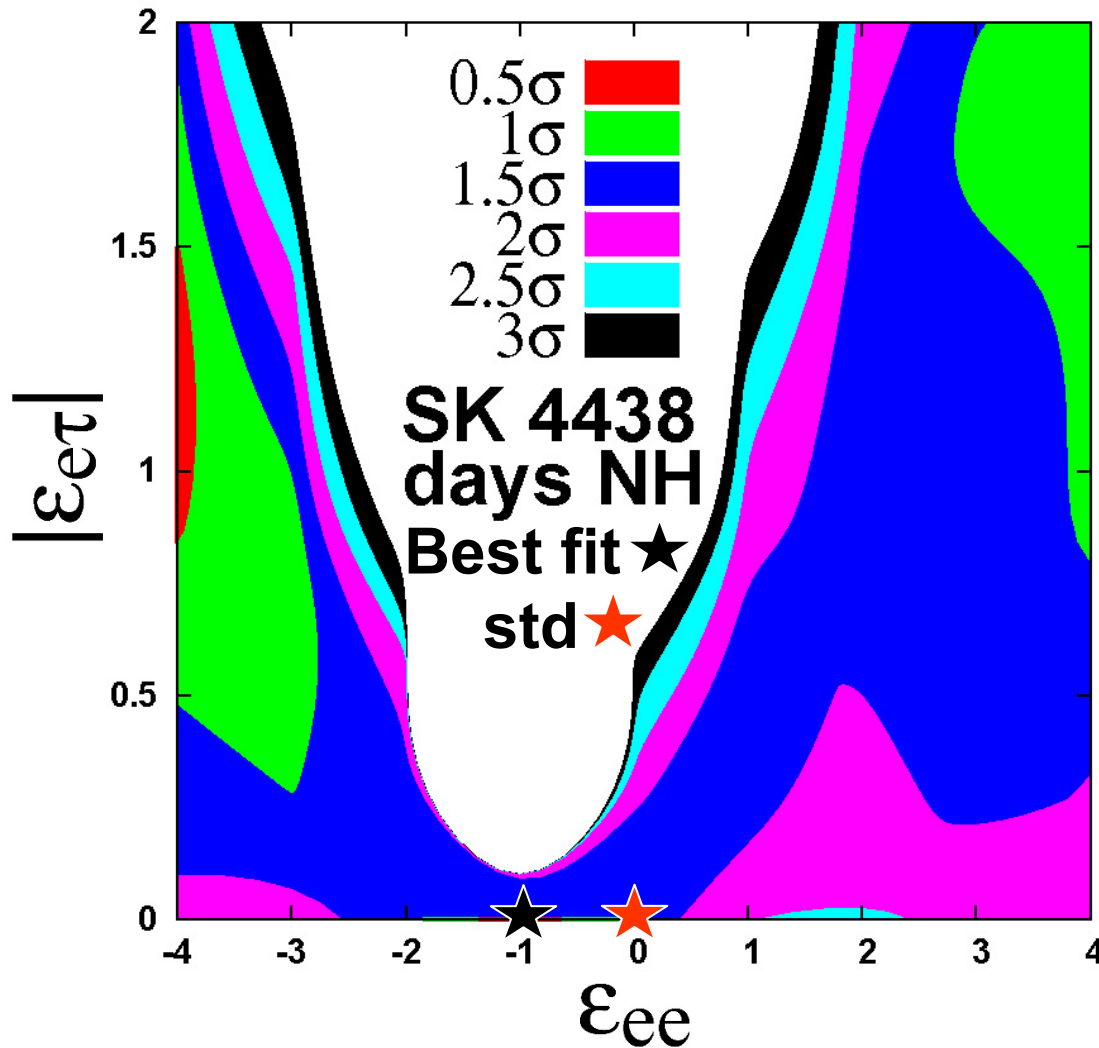
**Marginalized:  $\theta_{23}, \Delta m_{31}^2, \delta, \arg(\mathcal{E}_{e\tau})$**

**#(events)<sub>HK</sub>**

**= 20 x #(events)<sub>SK</sub>**

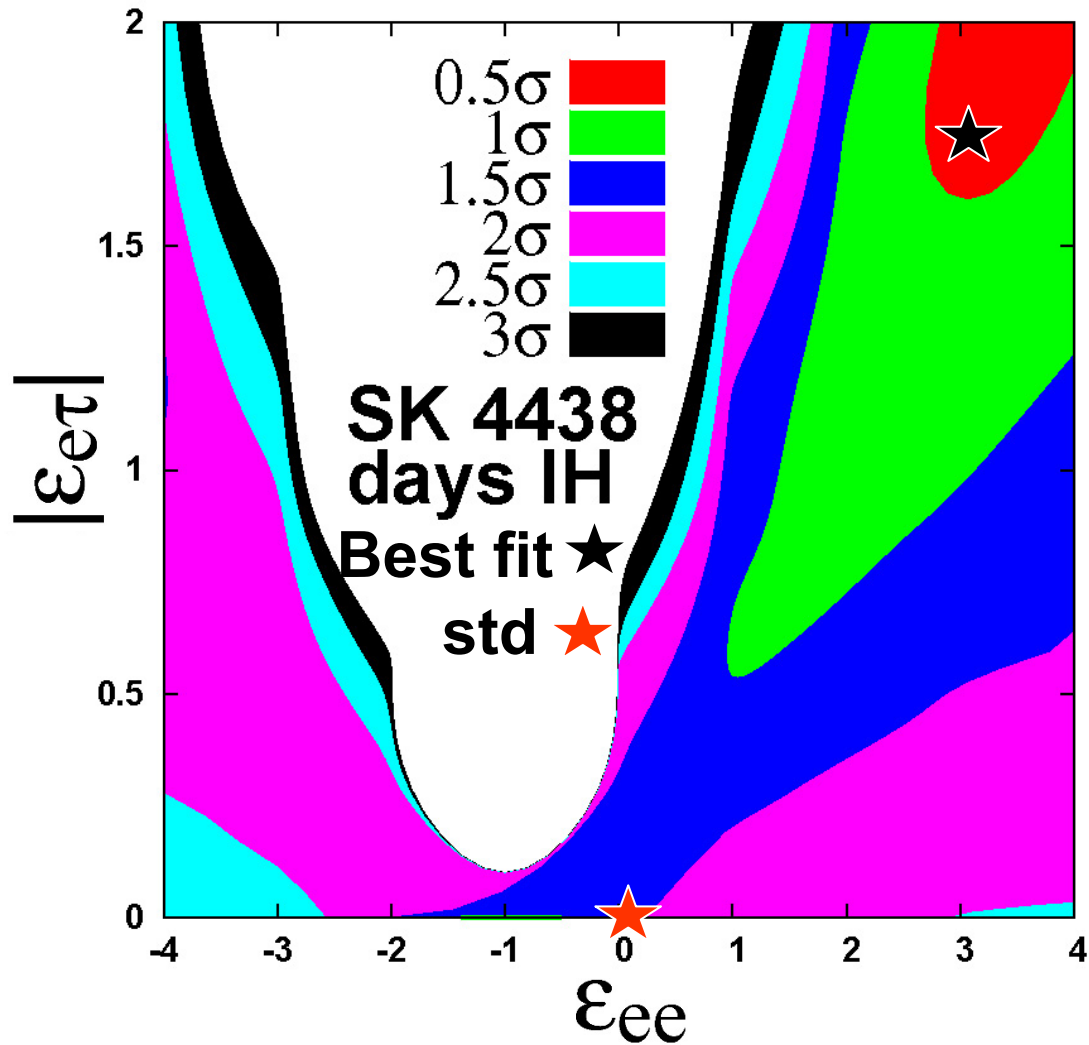
# Constraint by SK on $\varepsilon_{ee}$ , $|\varepsilon_{e\tau}|$

Fukasawa-OY  
arXiv.1503.08056



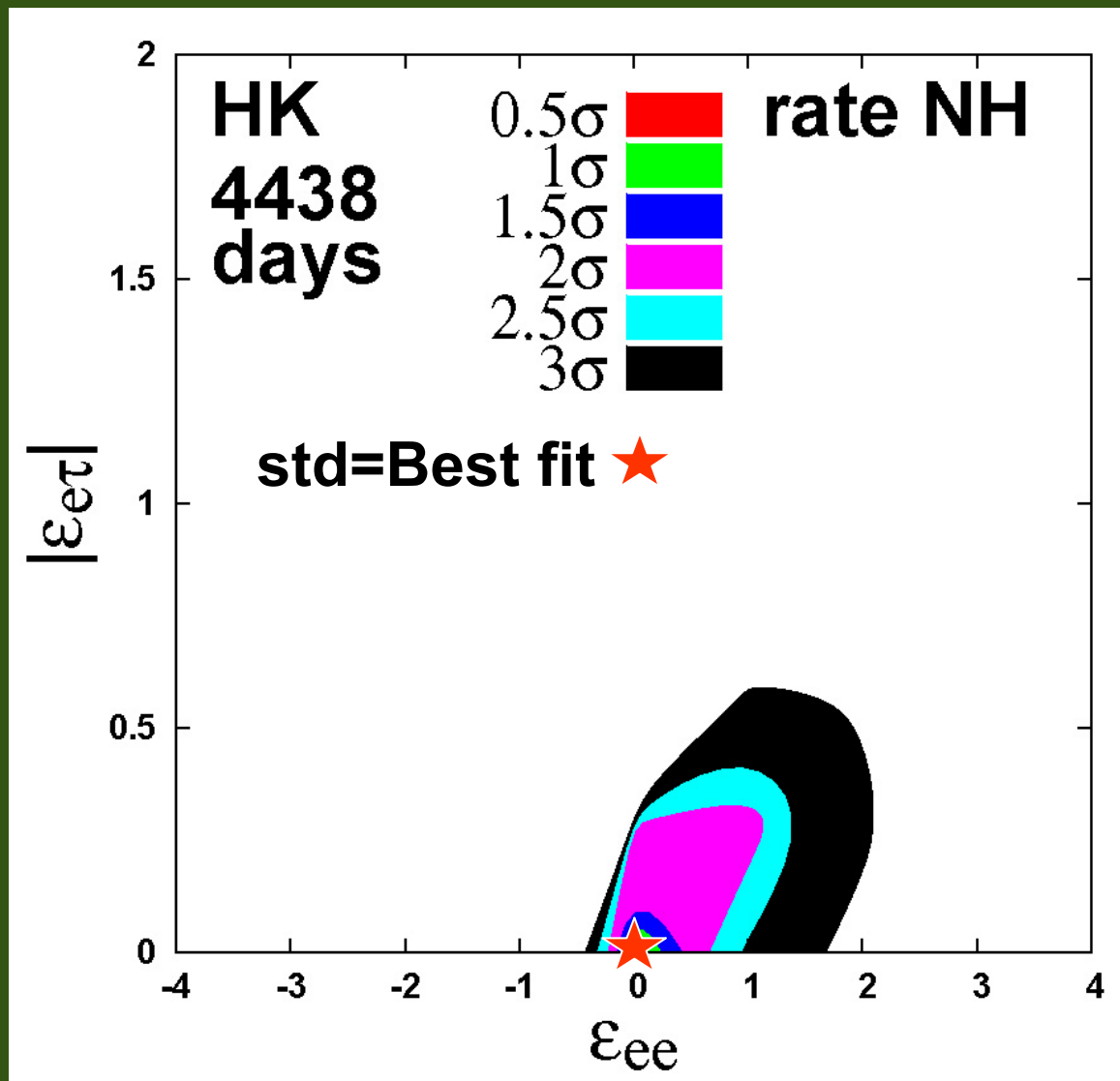
● The standard case ( $\varepsilon_{\alpha\beta}=0$ ) is **not** best fit point: This may be because we perform only the rate analysis (See discussions for HK below).

● The 2.5 $\sigma$  excluded region ( $|\tan\beta|<0.7$ ) improves the old one ( $|\tan\beta|<1.5$ ) by Friedland-Lunardini in 2005.



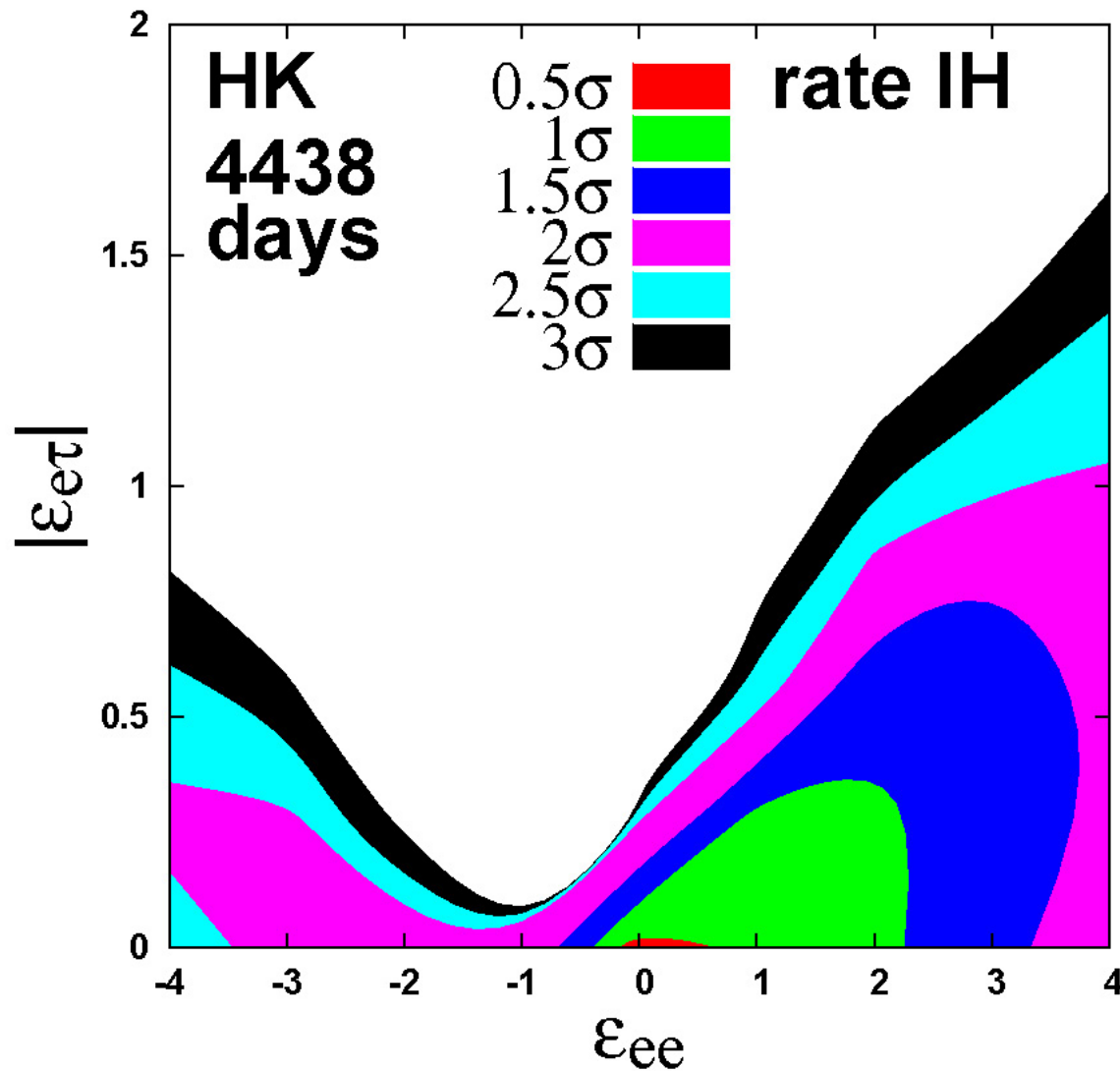
# Sensitivity of HK: (1) Rate analysis

Fukasawa-OY  
arXiv.1503.08056



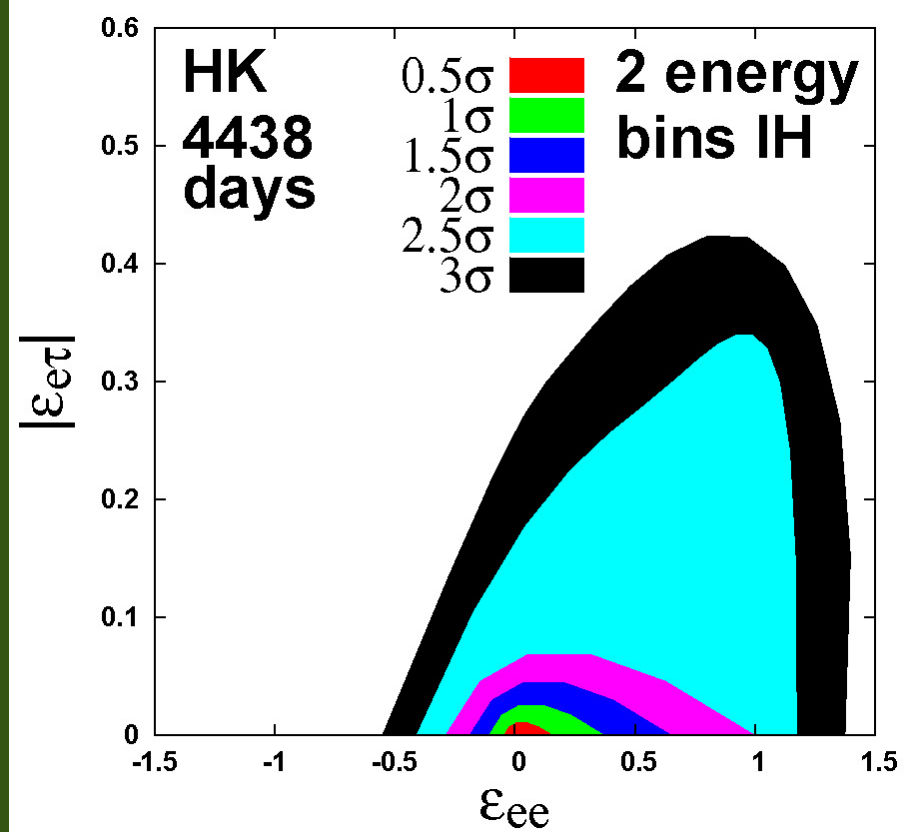
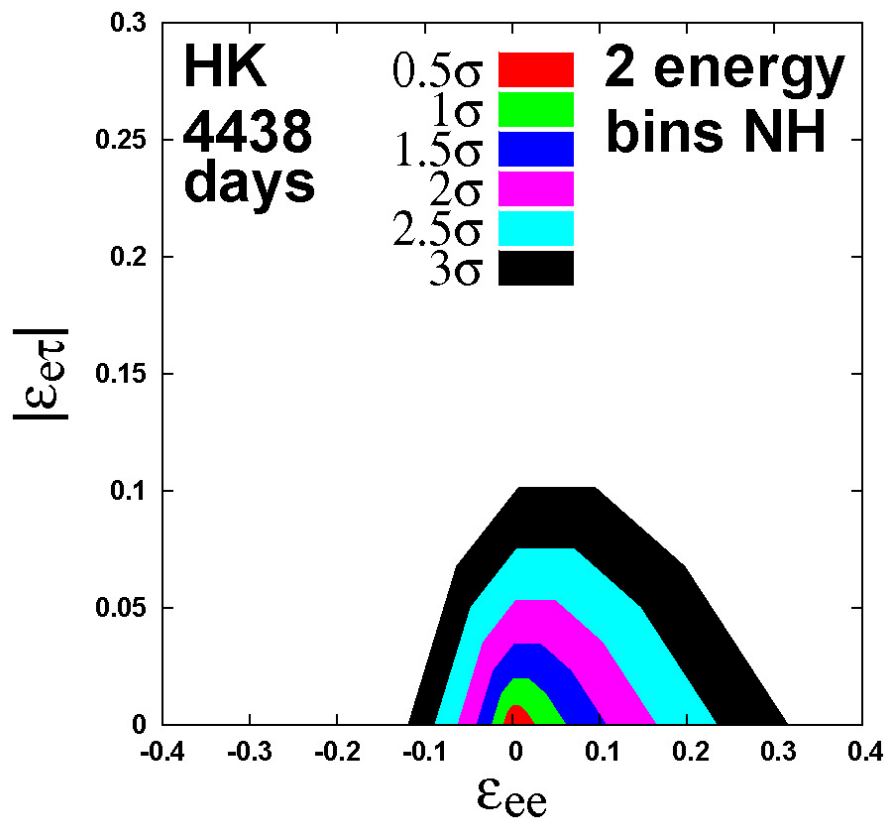
#(events)<sub>HK</sub>  
= 20 x #(events)<sub>SK</sub>

● The region  $|\epsilon_{e\tau}| > 1.5$  is excluded.  
The 2.5 $\sigma$  excluded region is  $|\tan\beta| < 0.4$ .



- The case of IH has a much larger allowed region. This may be because the resonance occurs for the  $\bar{\nu}$  channel which has less #(events) than  $\nu$ .

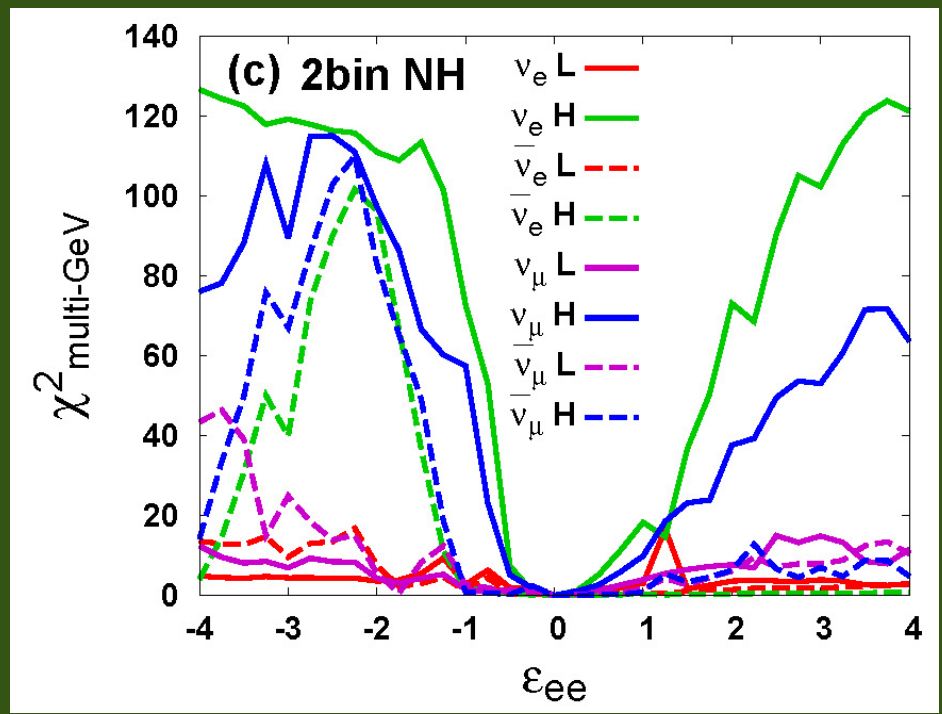
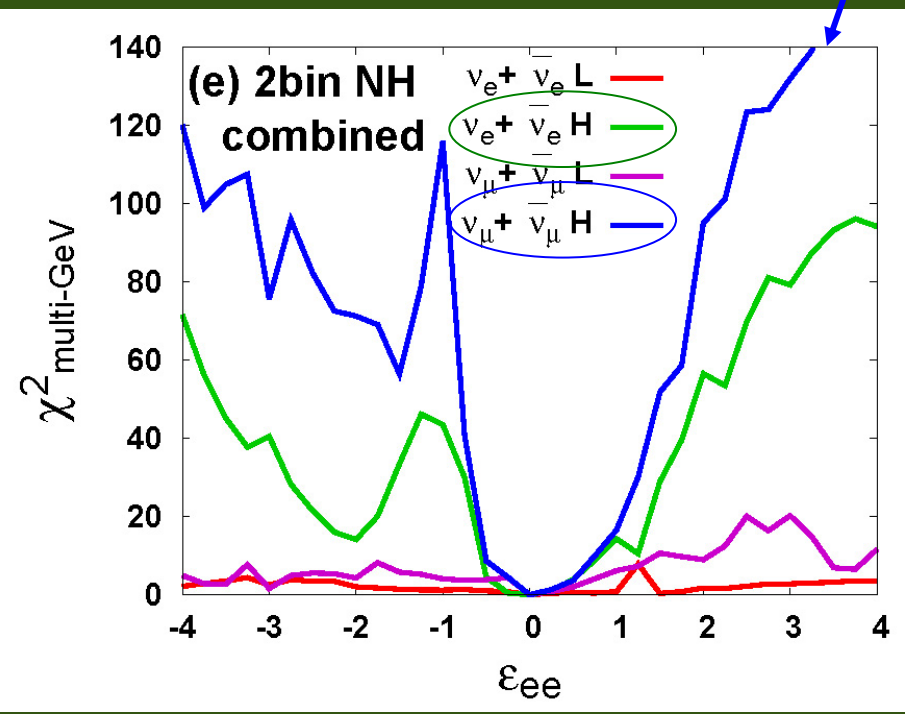
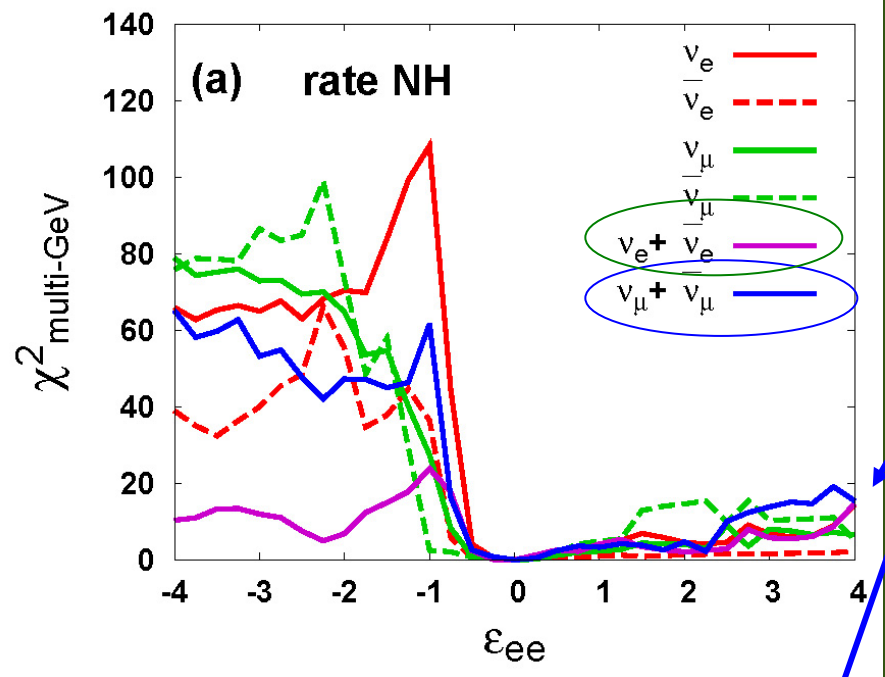
# Sensitivity of HK: (2) Spectrum analysis



- With the information of the energy spectrum, the allowed region becomes much smaller (Note the difference in scale). The 2.5 $\sigma$  excluded region is  $|\tan\beta| < 0.1$ .

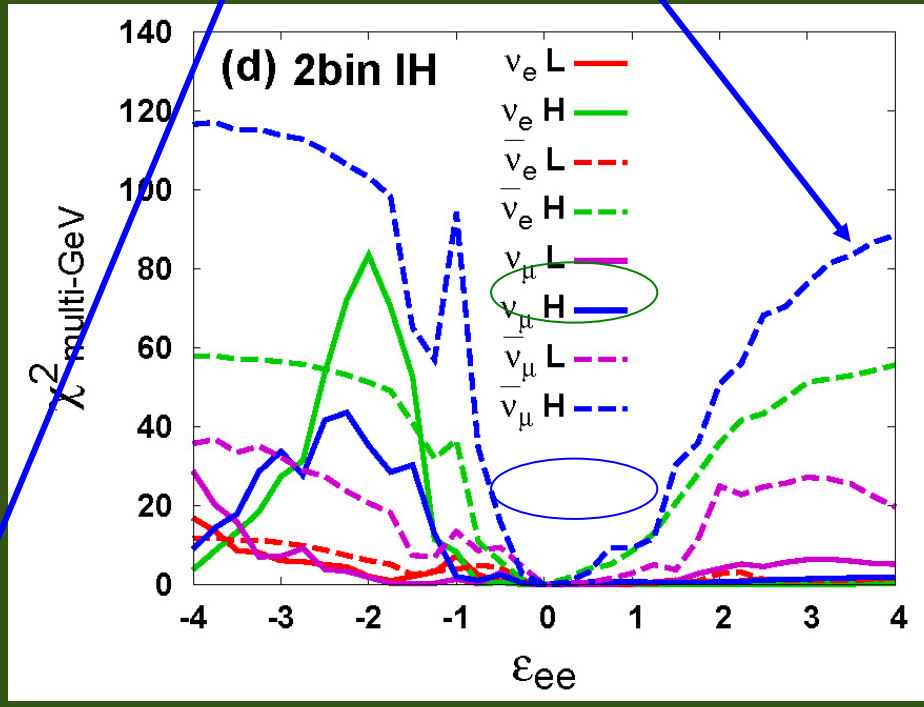
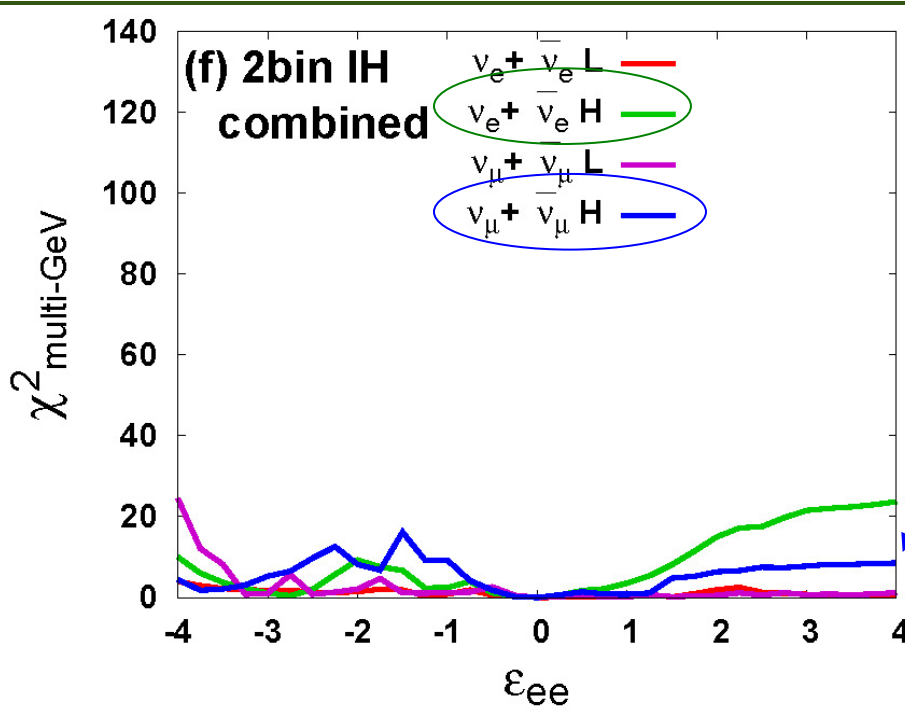
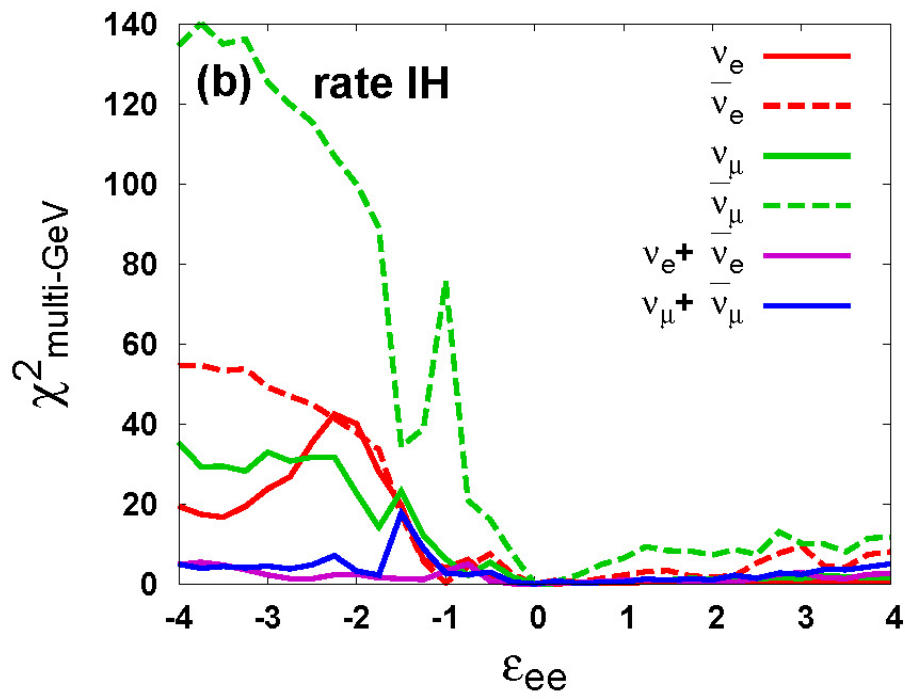
# Behaviors of $\chi^2$ (NH) for multi-GeV: Rate VS Spectrum

**Destructive phenomenon between Low & High energy bins  $\rightarrow$  Information on energy spectrum is important**



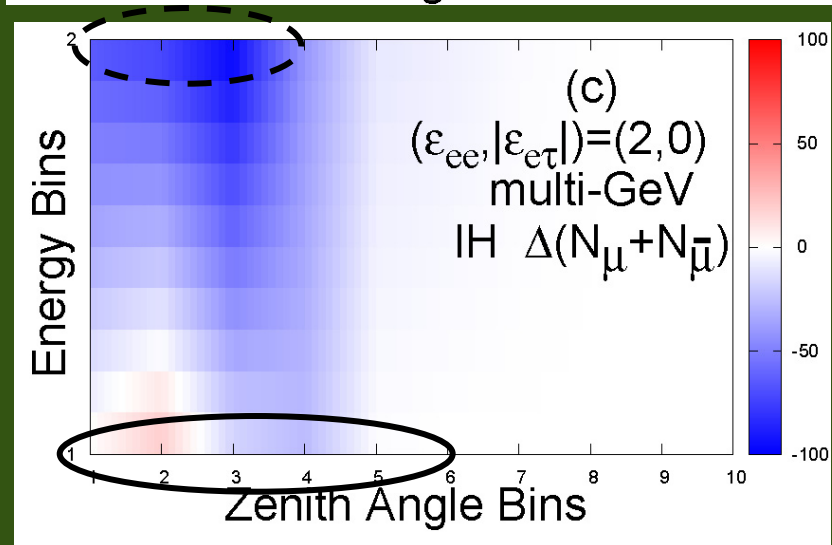
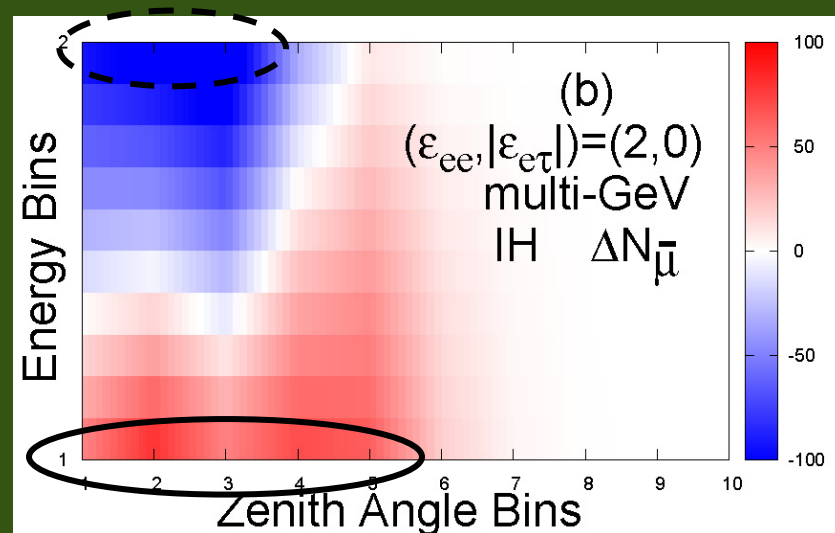
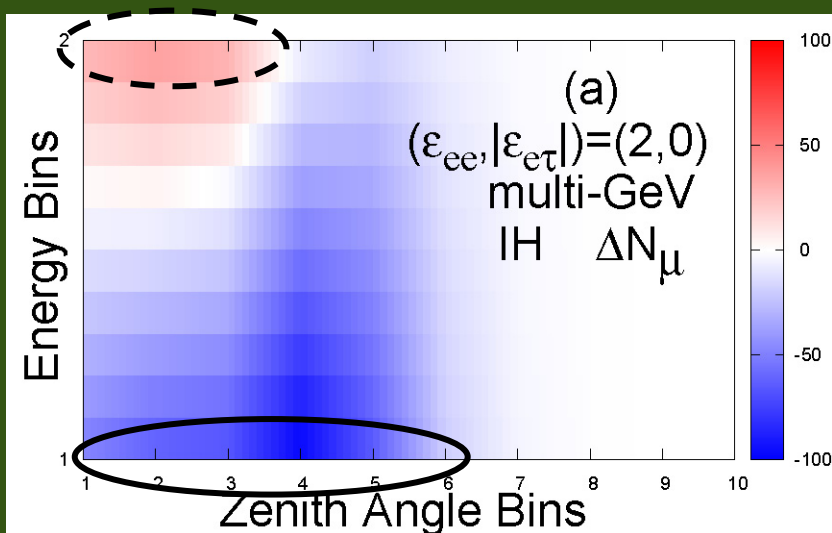
# Behaviors of $\chi^2$ (IH) for multi-GeV: $\nu+\bar{\nu}$ vs individual $\nu$ & $\bar{\nu}$

**Destructive phenomenon between  $\nu$  &  $\bar{\nu} \rightarrow$  Distinction between  $\nu$  &  $\bar{\nu}$  gives important information on  $\epsilon_{ee}$**



# Behaviors of #(events) for multi-GeV: $\nu+\bar{\nu}$ vs individual $\nu$ & $\bar{\nu}$

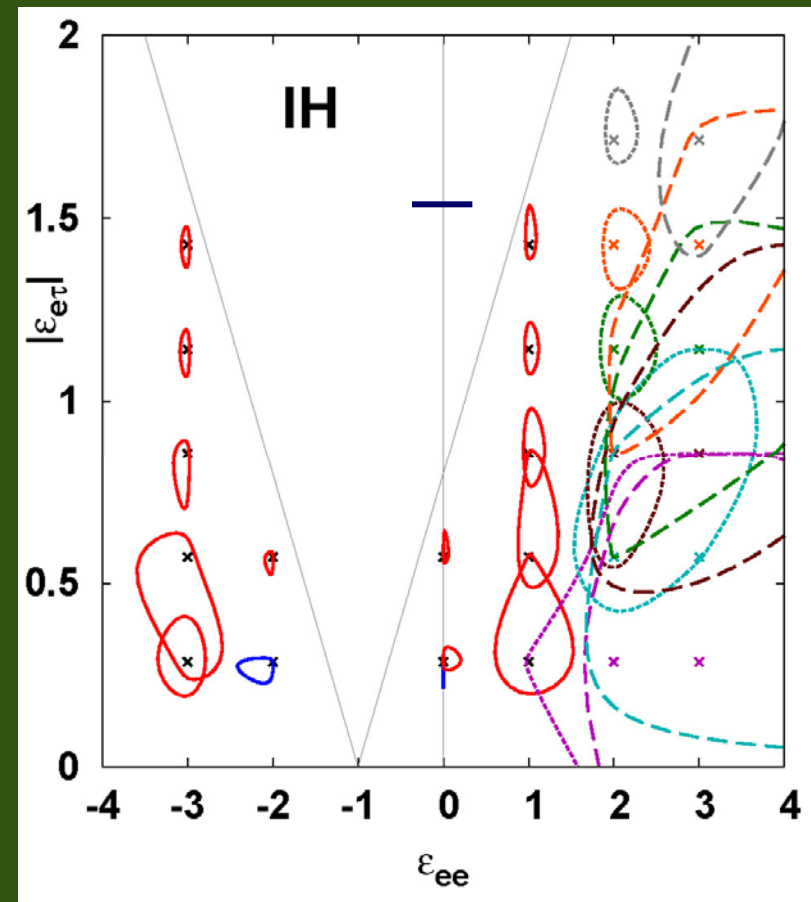
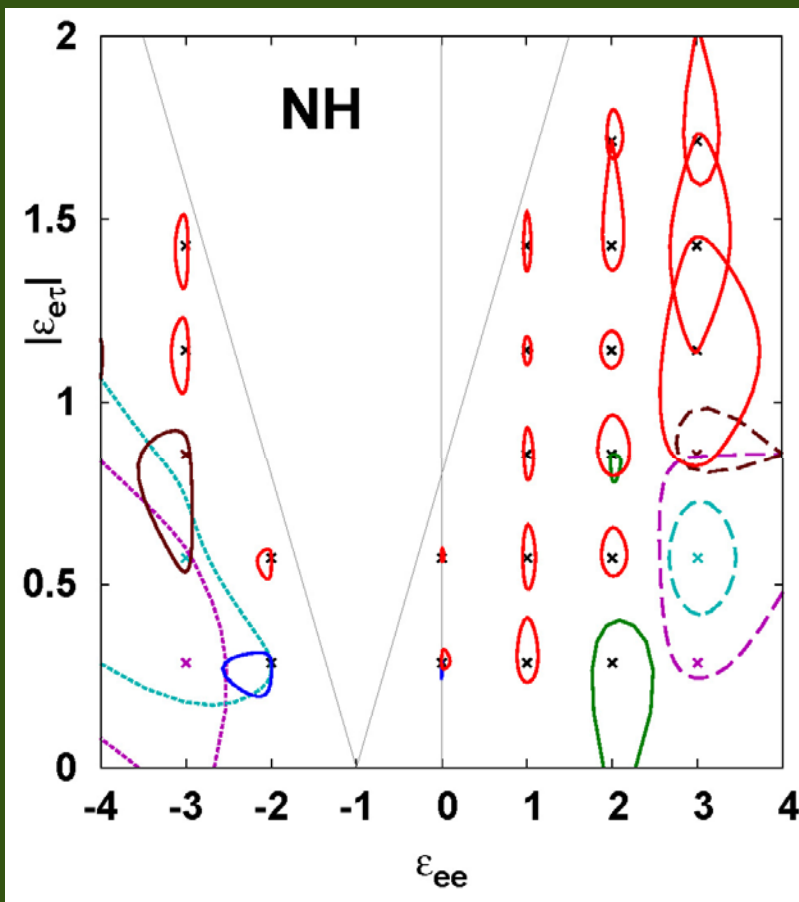
# Destructive phenomenon between $\nu$ & $\bar{\nu}$



Theoretical understanding in terms of oscillation probabilities is under study.

# Sensitivity of HK: (3) Spectrum analysis in the presence of NSI

Relatively good sensitivity to NSI for  $|\epsilon_{ee}| < 2$



## 4. Conclusions

- Under the assumptions  $\varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0$  &  $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2 / (1 + \varepsilon_{ee})$ , we studied sensitivity to NSI in propagation of  $\nu_{\text{atm}}$  at SK & HK
- The constraint  $|\tan\beta| := |\varepsilon_{e\tau} / (1 + \varepsilon_{ee})| < 0.7$  from SK  $\nu_{\text{atm}}$  for 4438 days was improved the previous result  $|\tan\beta| < 1.5$  obtained by Friedland-Lunardini in 2005.
- The analysis of SK was performed with energy rate only. This may be the reason why the allowed region is large due to the destructive phenomenon.

● Future observations of  $\nu_{\text{atm}}$  at HK are expected to improve the constraint:  $|\tan\beta| < 0.2$ .

● The information of the energy spectrum is important to reduce the allowed region.

● The individual information of  $\nu$  &  $\bar{\nu}$  is important to reduce the allowed region of  $\varepsilon_{ee}$  (but not  $\varepsilon_{e\tau}$ ). → Further efforts to separate  $\nu$  &  $\bar{\nu}$  should be made.

● In the presence of NSI, HK has Relatively good sensitivity to NSI for  $|\varepsilon_{ee}| < 2$ .