Will atmospheric neutrino experiment at Hyper-Kamiokande see non-standard interaction effects?

Osamu Yasuda
Tokyo Metropolitan University

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Based on arXiv:1608.05897 Fukasawa, OY

1. Introduction

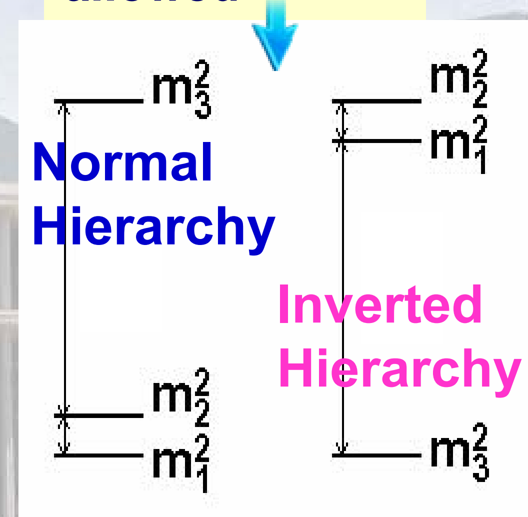
2. New Physics in propagation

3. Sensitivity of ν_{atm} at HK to NSI in propagation

4. Conclusions

1. Introduction

Both hierarchy patterns are allowed



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

All 3 mixing angles have been measured (2012):

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

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

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

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

- Both mass hierarchies are allowed

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

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

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

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.

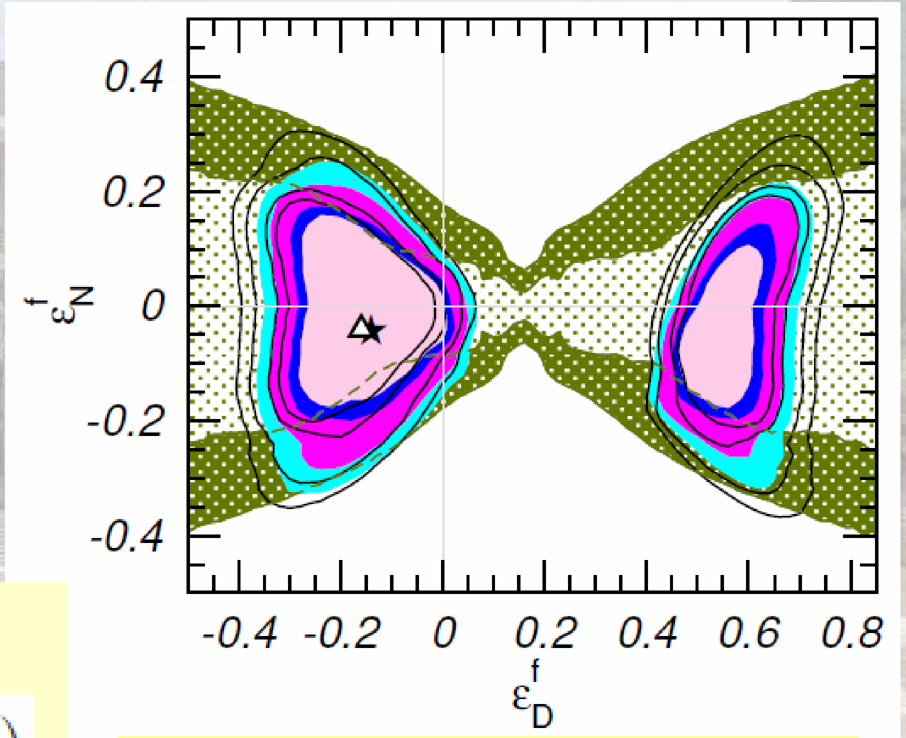
Phenomenological scenarios of New Physics

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

- Scenarios with Non Standard Interactions in propagation could exhibit the largest effect.

Motivation for Non Standard Interaction in ν propagation

- There seem to be tension between solar ν & KamLAND data.
  --> NSI may be necessary to explain data.



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

Best fit value of global fit

$$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$$

$$(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$$

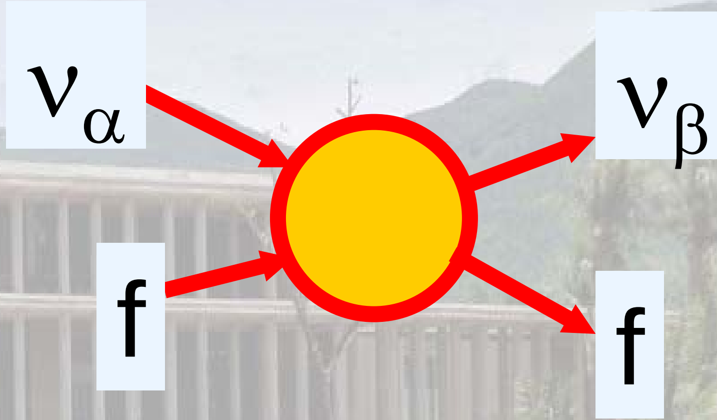
- Some model predicts large NSI.
  --> See Farzan's talk

Aim of this talk

To test the hypothesis which explains the tension between solar ν and KamLAND by NSI, we investigate whether ν_{atm} at HK has a sensitivity to NSI in propagation of taking into account of all $\epsilon_{\alpha\beta}$.

We asume:
true scenario = standard 3-flavor mixing
test scenario = best fit point w/ NSI suggested by the global analysis including solar ν and KamLAND. <-- We don't exhaust all the allowed region (say, @ 90%CL) to save CPU time.

2. New Physics in propagation



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

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

neutral current non-standard interaction

Modification of matter effect

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

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

NP

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

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

Constraints from high energy ν_{atm} data

Friedland-Lunardini, PRD72 ('05) 053009

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

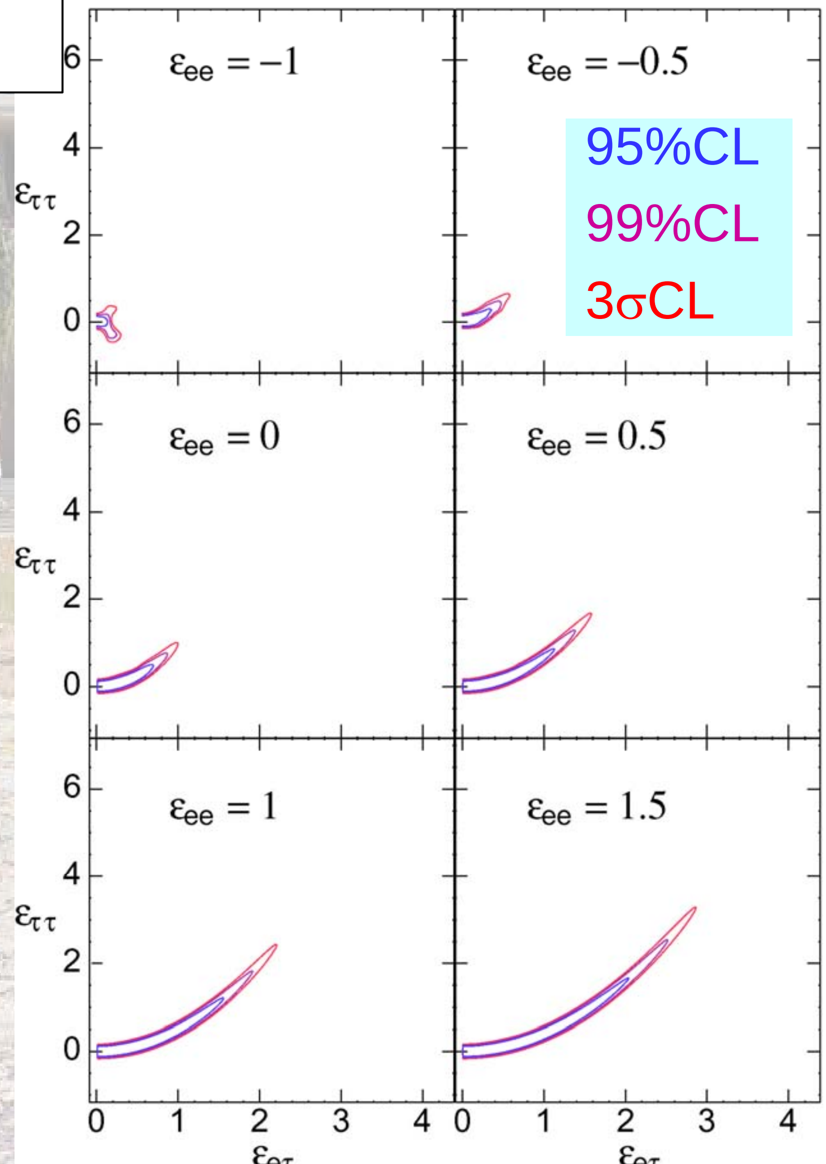
high energy ν_{atm} data implies

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

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



NuFact

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

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

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

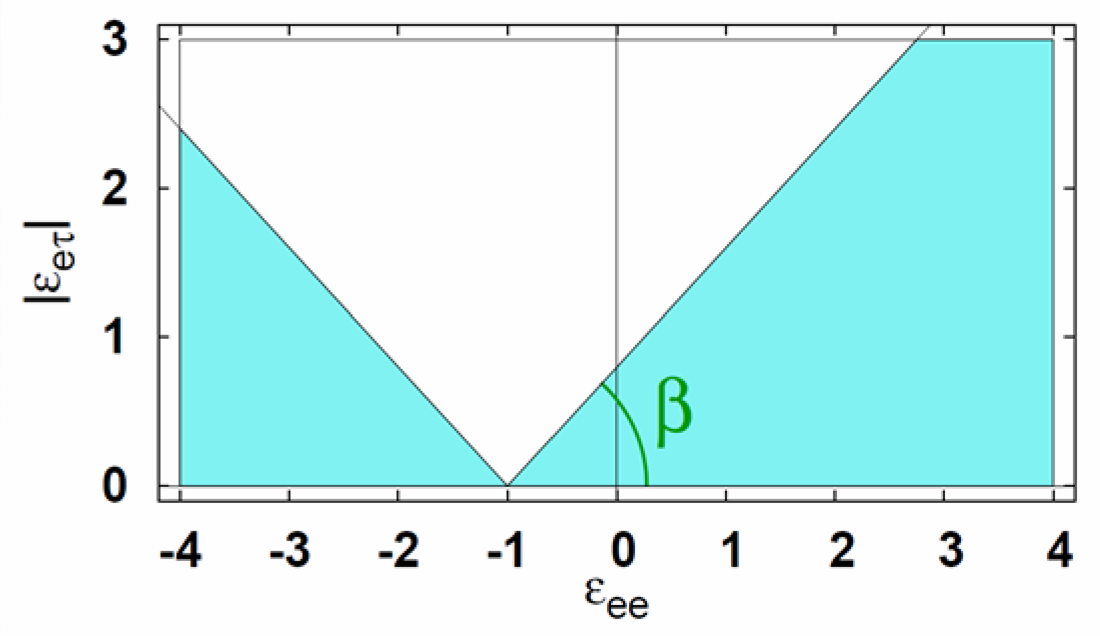
Furthermore, ν_{atm} data implies

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

Fukasawa-OY, arXiv:1607.03758

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

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



• NSI for solar ν: $\varepsilon_{\alpha\beta}$ vs (ε_D, ε_N)

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

In solar ν analysis, Δm_{31}^2 -> infinity, H -> H^{eff}

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

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

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

f = e, u or d

ε_{ee}, $|\varepsilon_{e\tau}|$, $\varepsilon_{\tau\tau}$ have to be solved from (ε_D, ε_N)

Relation between $\varepsilon_{\alpha\beta}$ & (ε_D, ε_N)

For simplicity consider

$\theta_{13} = 0$, $\theta_{23} = \pi/4$, $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$.

Then the relation is simplified.

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

$$
\begin{aligned}
3\epsilon_D &= -\frac{1}{2}\epsilon_{ee} + \frac{1}{4}\epsilon_{\tau\tau} \\
3\epsilon_N &= -\frac{1}{\sqrt{2}}\,\epsilon_{e\tau}\,.
\end{aligned}
$$

For simplicity take f=d; ε^f_D, ε^f_N

--> $\varepsilon^d_D = \varepsilon_D$, $\varepsilon^d_N = \varepsilon_N$

ν_{atm} sees only

$\varepsilon_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + 3\varepsilon^u_{\alpha\beta} + 3\varepsilon^d_{\alpha\beta}$ --> $3\varepsilon^d_{\alpha\beta}$

The allowed region in the limit $\theta_{23} = \pi/4$, $\varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$

$$\tan\beta \equiv \frac{|\epsilon_{e\tau}|}{1+\epsilon_{ee}}$$

ν_{atm} data: $|\tan\beta|<0.8$ @2.5σCL

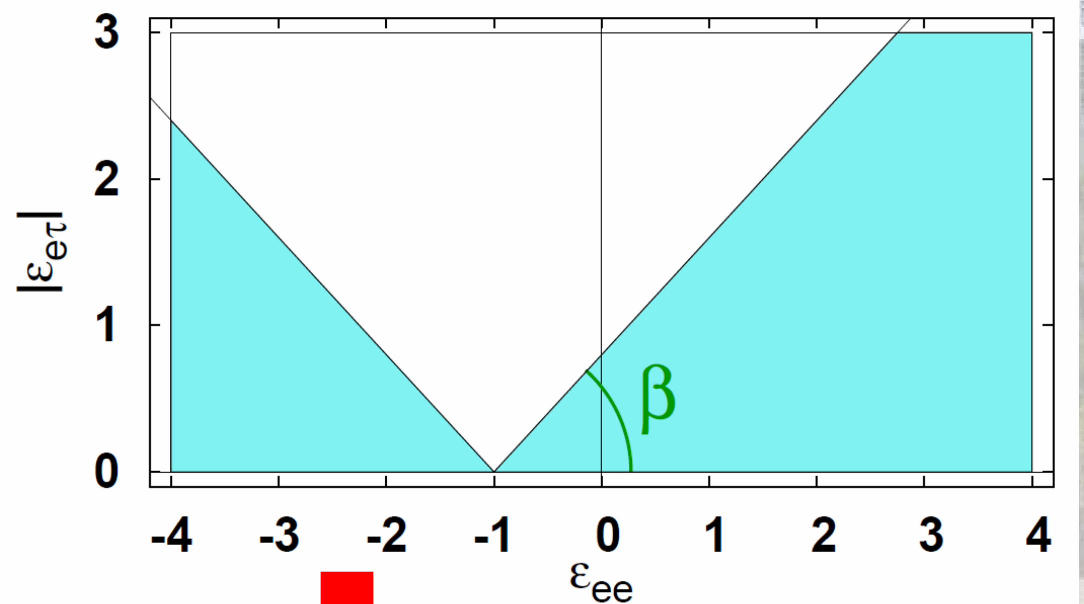
Introducing a new variable:

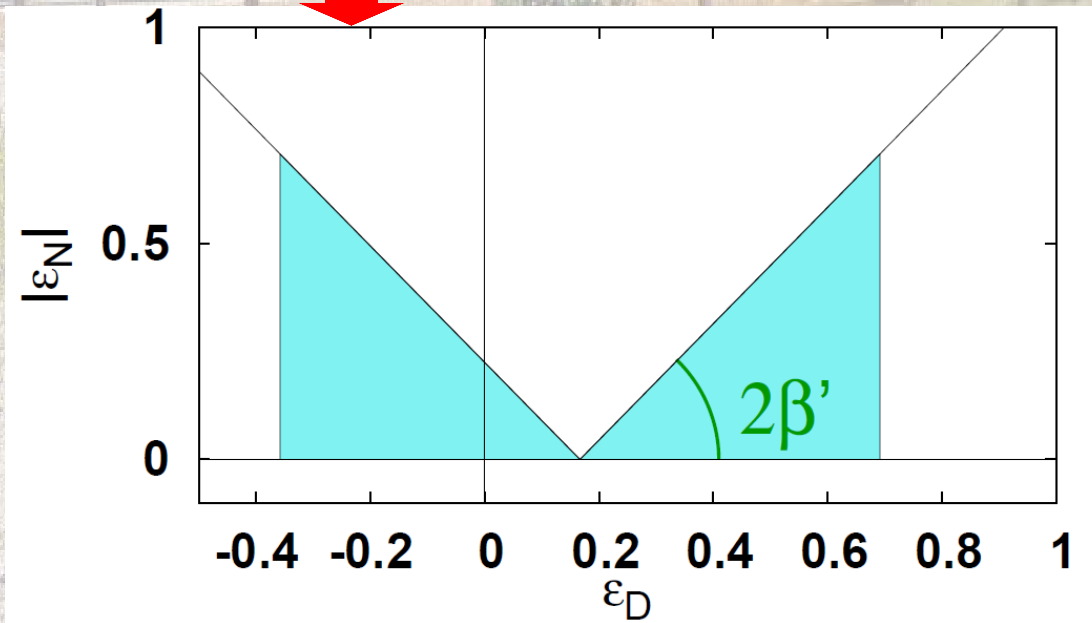
$$\tan\beta' \equiv \frac{\tan\beta}{\sqrt{2}}$$

one can show

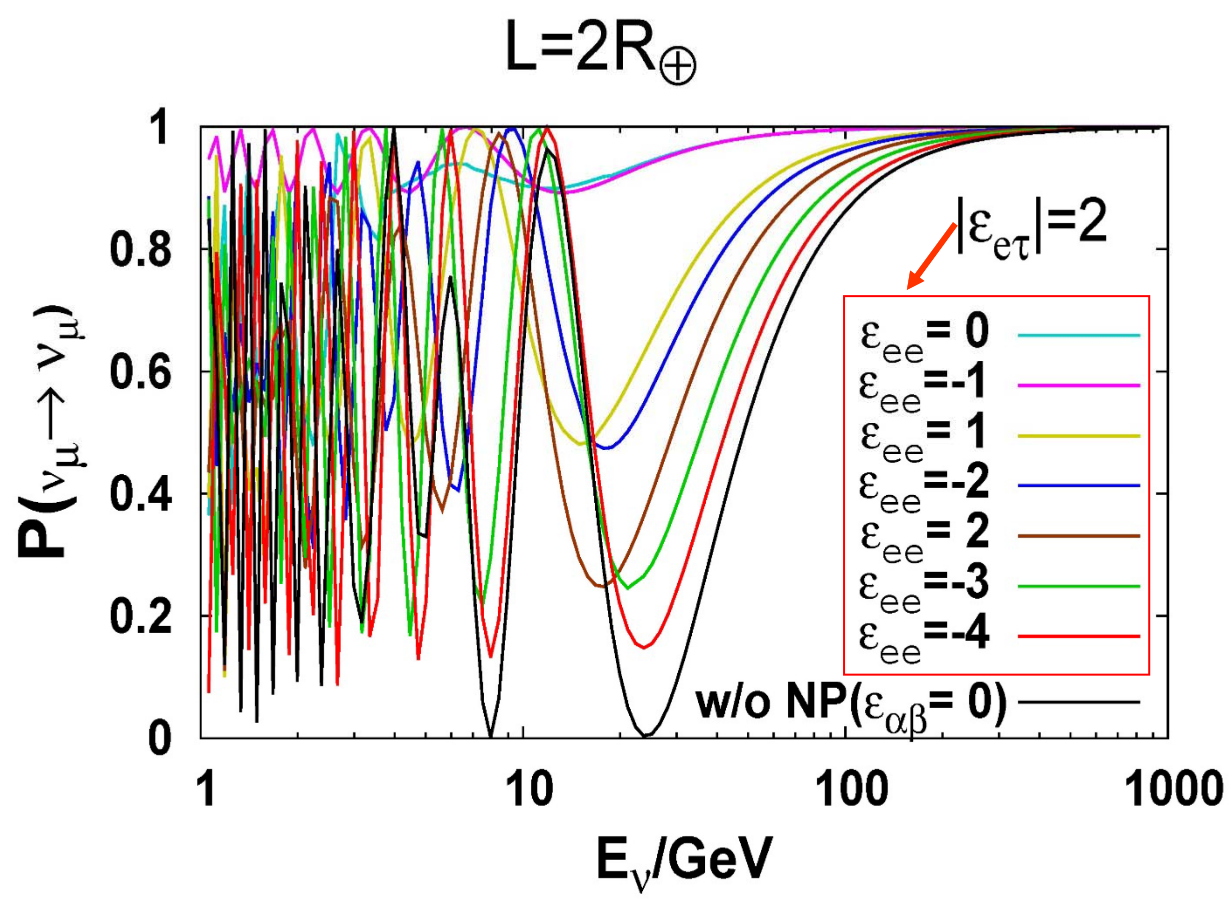
$$\tan 2\beta' = \frac{|3\epsilon_N|}{1/2 - 3\epsilon_D}$$

ν_{atm} data: $|\tan 2\beta'|<1.3$ @2.5σCL





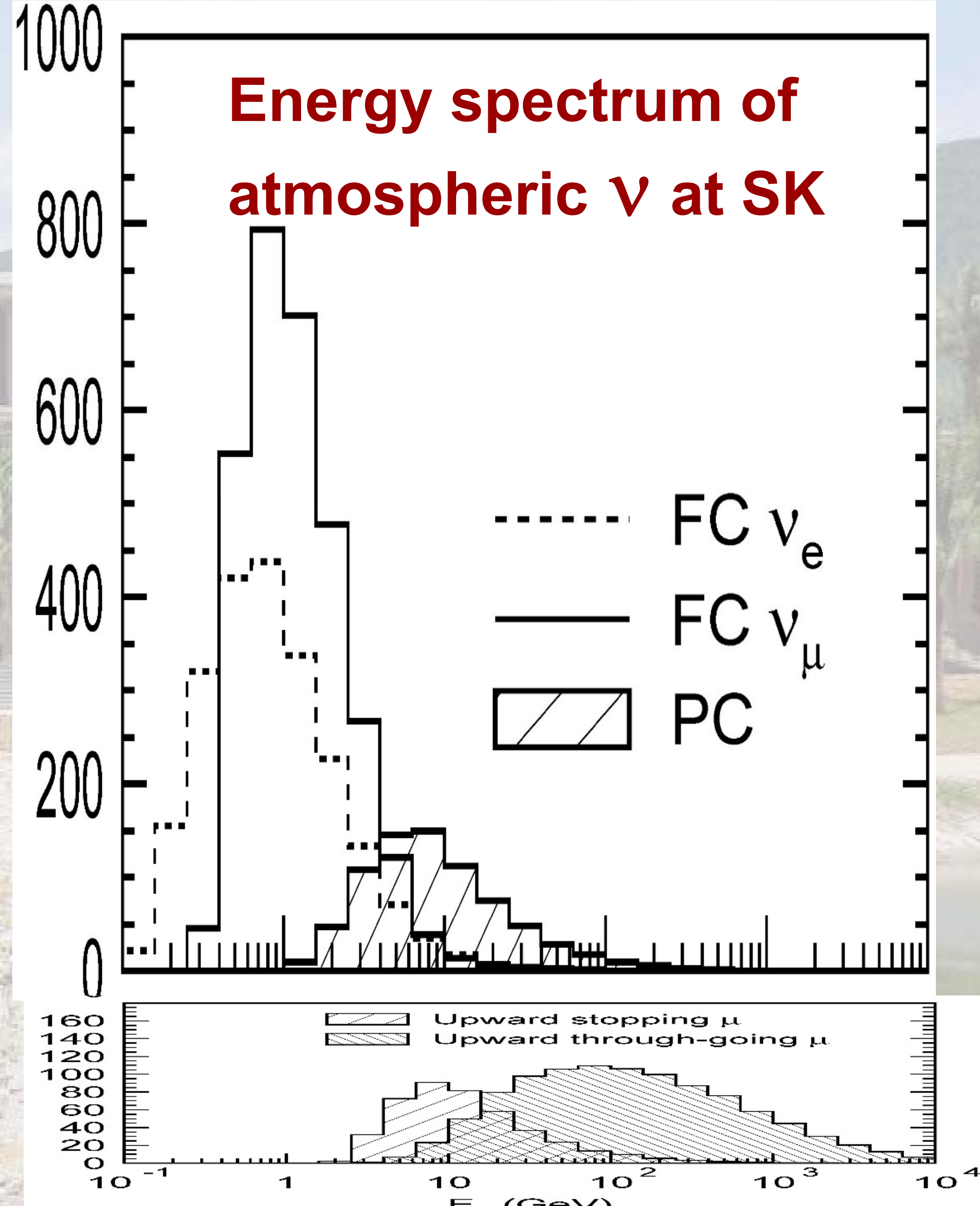
3. Sensitivity of ν_{atm} at HK to NSI in propagation



Deviation from the standard case is significant mainly for 10GeV < E < 100 GeV

Here we will discuss SK & HK because

- SK & (particularly) HK has considerable #(events) for 10GeV < E < 100 GeV
- One of the authors (OY) worked on SK before



NuFact

Outline of our Analysis

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

Our ansatz

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

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

$$\Delta\chi^2(\varepsilon_{ee}, |\varepsilon_{e\tau}|) = \min_{\text{parameters}} \sum_i \frac{\left[N_i^0(\varepsilon_{\alpha\beta}) - N_i\,(\textbf{std})\right]^2}{\sigma_i^2} + \chi^2_{prior}$$

spectrum analysis

$$\chi^2_{\rm prior} = \Delta\chi^2_{\rm prior}\frac{|\epsilon^f_{e\mu}|^2}{|\delta\epsilon^f_{e\mu}|^2} + \Delta\chi^2_{\rm prior}\frac{|\epsilon^f_{\mu\tau}|^2}{|\delta\epsilon^f_{\mu\tau}|^2}$$

$$0 \le |\epsilon^d_{e\mu}| \le 0.05$$
$$0 \le |\epsilon^d_{\mu\tau}| \le 0.05$$

Parameters

Fixed: θ_{12}, θ_{13}, Δm^2_{21}

Marginalized: θ_{23}, Δm^2_{31}, δ, $|\varepsilon_{e\mu}|$, $|\varepsilon_{\mu\tau}|$, $\arg(\varepsilon_{e\tau})$, $\arg(\varepsilon_{e\mu})$, $\arg(\varepsilon_{\mu\tau})$

$\#(\text{events})_{HK} = 20 \times \#(\text{events})_{SK}$

For simplicity take f=d; ε^f_D, ε^f_N -> $\varepsilon^d_D = \varepsilon_D$, $\varepsilon^d_N = \varepsilon_N$

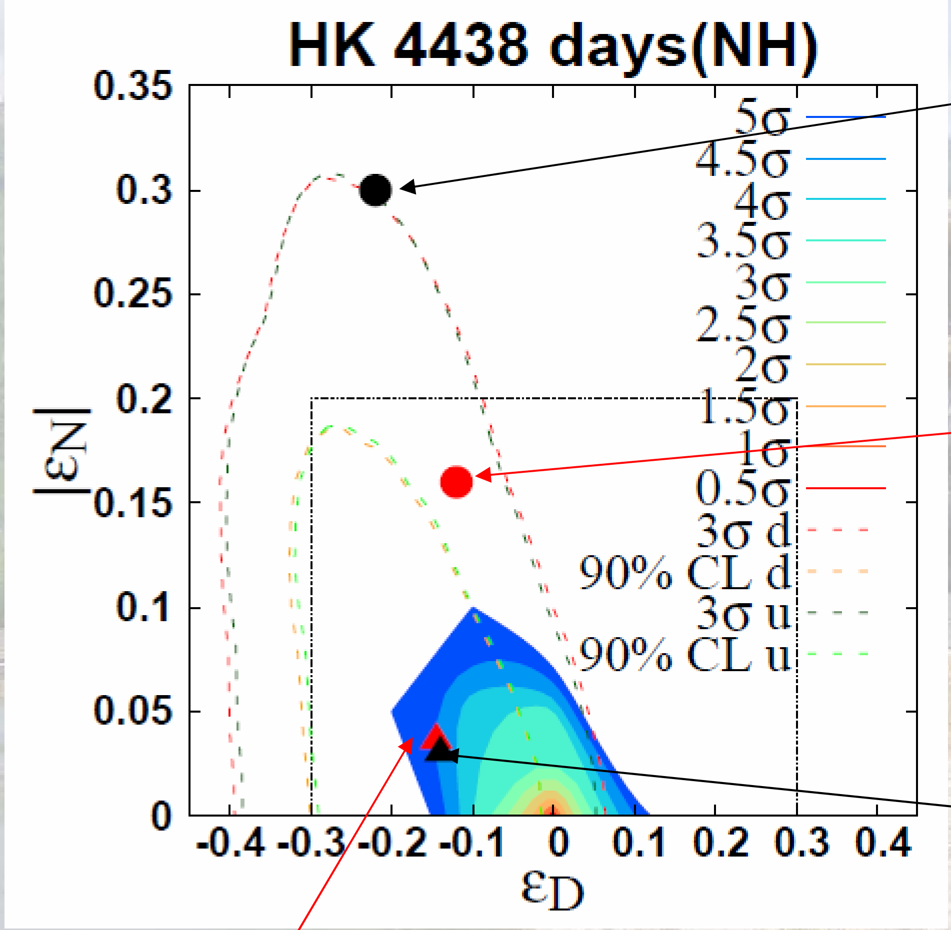
ν_{atm} sees only $\varepsilon_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + 3\varepsilon^u_{\alpha\beta} + 3\varepsilon^d_{\alpha\beta}$ --> $3\varepsilon^d_{\alpha\beta}$

1. **Set a grid on (ε_D, $|\varepsilon_N|$) plane.**
2. **Calculate a parameter set ε_{ee}, $|\varepsilon_{e\tau}|$, $\varepsilon_{\tau\tau}$ for the given point (ε_D, $|\varepsilon_N|$) on the grid varying Δm^2_{31}, θ_{23}, δ_{CP}, $|\varepsilon_{e\mu}|$, $|\varepsilon_{\mu\tau}|$, arg(ε_N), arg($\varepsilon_{e\tau}$), arg($\varepsilon_{e\mu}$), and arg($\varepsilon_{\mu\tau}$).**
3. **Dismiss the parameter set if it does not satisfy any one of the following criteria:**

$$\boxed{|\epsilon_{e\tau}| \leq 1.5} \quad \boxed{|\epsilon_{ee} - \epsilon_{\mu\mu}| \leq 2.0} \quad \boxed{|\min(\lambda_{e'}, \lambda_{\tau'})| \leq 0.2}$$

4. **Calculate χ^2 for each parameter set which passed the criteria mentioned above and then obtain the minimum value of χ^2 for the given (ε_D, $|\varepsilon_N|$)**

Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for NH



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

Best fit point of solar & KamLAND for f=u: significance:38σ

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

Best fit point of solar & KamLAND for f=d: significance:11σ

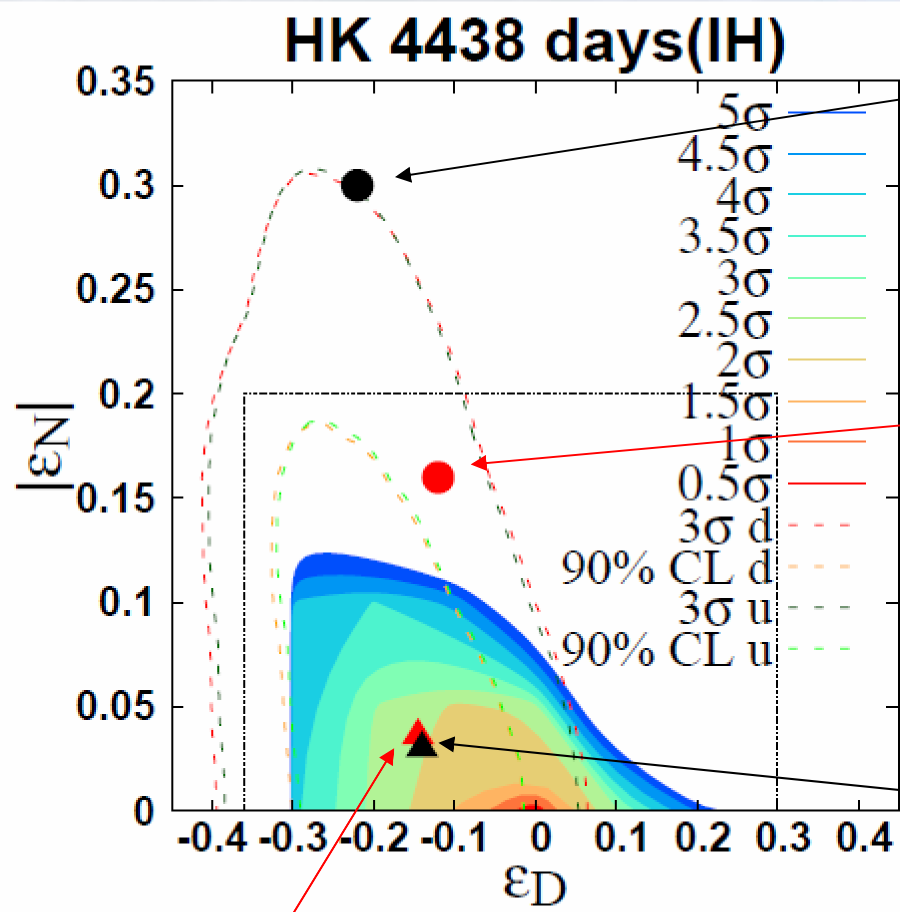
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=u: significance:5σ

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

Best fit point of glolal analysis for f=d: significance:5σ

Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for IH



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

Best fit point of solar & KamLAND for f=u: significance:35σ

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

Best fit point of solar & KamLAND for f=d: significance:8σ

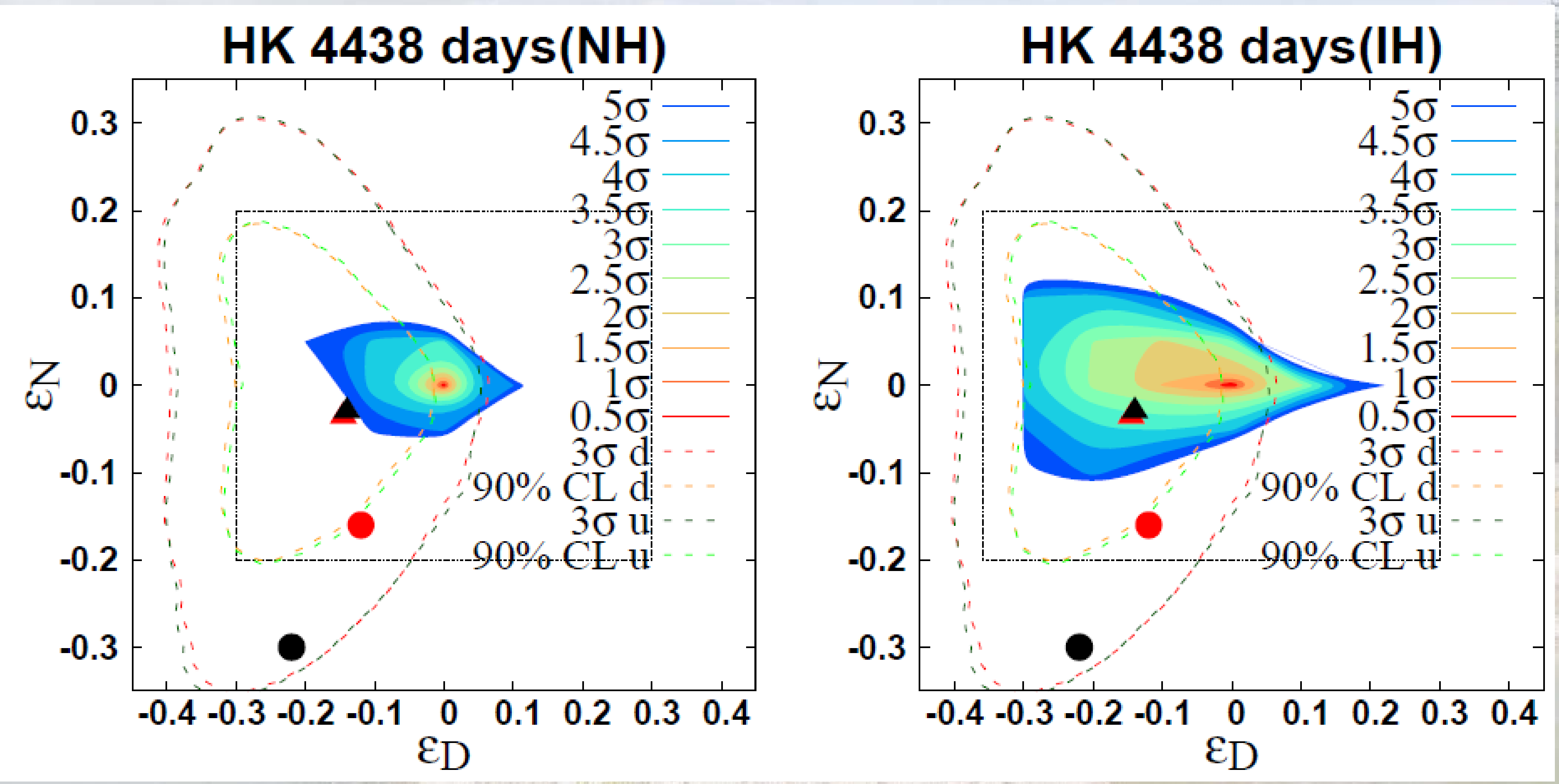
$$(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)$$

Best fit point of glolal analysis for f=u: significance:1.4σ

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

Best fit point of glolal analysis for f=d: significance:1.5σ

Sensitivity of HK: (2) Real $|\varepsilon_N|$



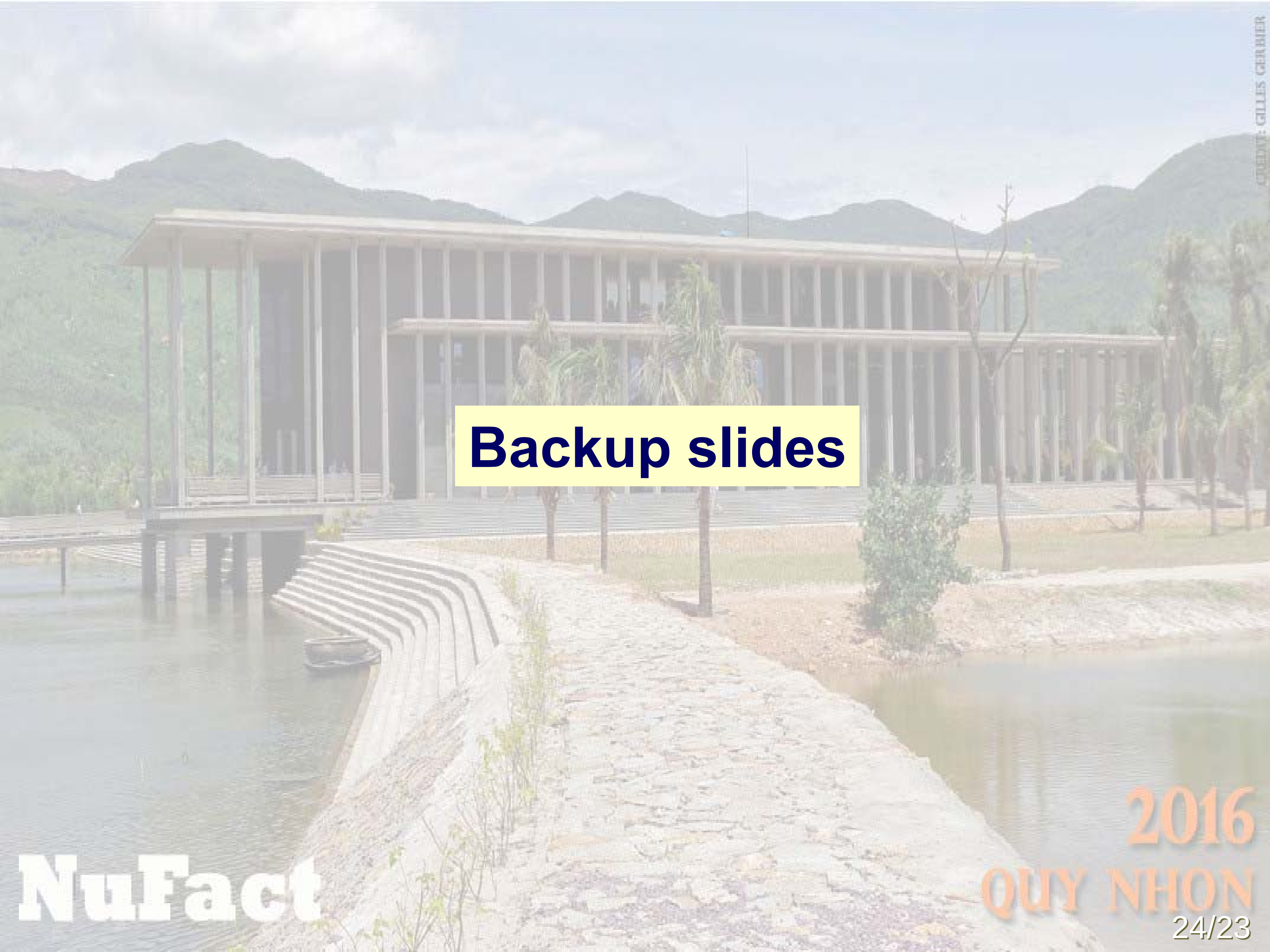
Allowed regions and significance are similar to the case for complex ε_N

4. Conclusions

- We studied sensitivity to NSI in propagation of ν_{atm} at HK taking into account of all $\varepsilon_{\alpha\beta}$, and discussed the possibility to test a hypothesis which explains the tension between solar ν and KamLAND.

- ν_{atm} at HK will exclude (or see) the signal of NSI at the following CL.
NH(IH) f=u (best fit pnt of solar-KL): 38σ (35σ)
NH(IH), f=d (best fit pnt of solar-KL): 11σ(8σ)
NH(IH), f=u (best fit pnt of global): 5σ(1.4σ)
NH(IH), f=d (best fit pnt of global): 5σ(1.5σ)

- NSI which was suggested by ν_{solar} (E~10MeV) may be detected by ν_{atm} (E~10GeV) at HK through the matter effect.



Backup slides

Relation between $\varepsilon_{\alpha\beta}$ & (ε_D, ε_N)

For simplicity consider θ_{13} =0, θ_{23} = $\pi/4$.

$$
\begin{aligned}
3\epsilon_D &= -\frac{1}{2}\epsilon_{ee} + \frac{1}{4}\epsilon_{\tau\tau} \\
3\epsilon_N &= -\frac{1}{\sqrt{2}}\,\epsilon_{e\tau}\,.
\end{aligned}
$$

$$
\begin{pmatrix} \lambda_{e'} \\ \lambda_{\tau'} \end{pmatrix} = \frac{1+\epsilon_{ee}+\epsilon_{\tau\tau}}{2} \pm \sqrt{\left(\frac{1+\epsilon_{ee}-\epsilon_{\tau\tau}}{2}\right)^2 + |\epsilon_{e\tau}|^2}
$$

If 1+ε_{ee} >0 $\varepsilon_{\tau\tau}$ >0, then $\lambda_{e'}$ > $\lambda_{\tau'}$

In the case of $\lambda_{\tau'} \neq 0$

$$\lambda_{\tau'} = \frac{1+\epsilon_{ee}+\epsilon_{\tau\tau}}{2} - \sqrt{\left(\frac{1+\epsilon_{ee}-\epsilon_{\tau\tau}}{2}\right)^2 + |\epsilon_{e\tau}|^2} = \alpha\ (>0)$$

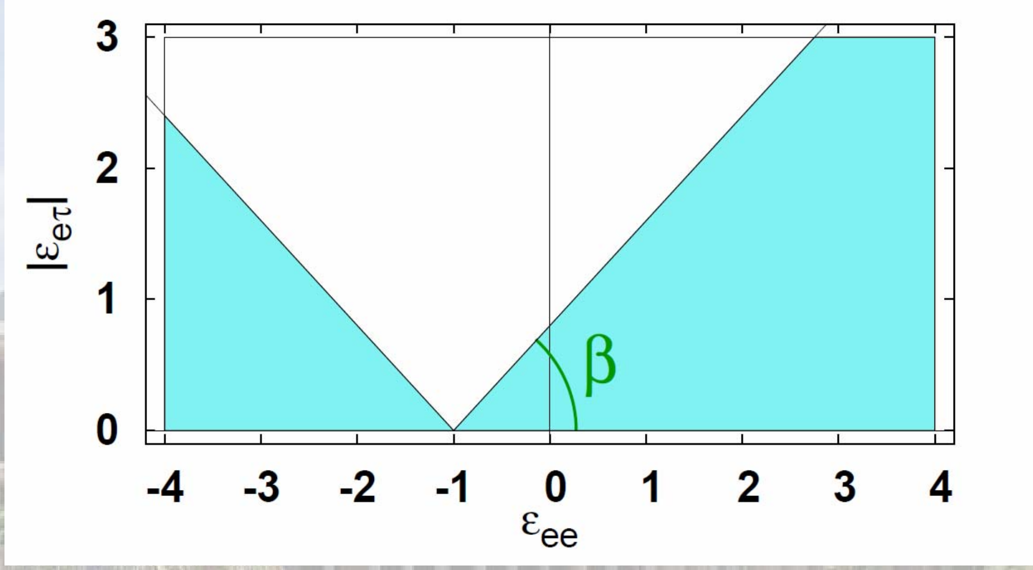
$\varepsilon_{\tau\tau}$ satisfies the following relation:

$$\epsilon_{\tau\tau} - \alpha = \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}-\alpha} = \frac{2|3\epsilon_N|^2}{1+\epsilon_{ee}-\alpha}$$

$$1+\epsilon_{ee}-\alpha = \frac{1}{2}(1-6\epsilon_D) - \frac{\alpha}{4} + \frac{1}{2}\left\{\left(1-6\epsilon_D-\frac{\alpha}{2}\right)^2 + 4|3\epsilon_N|^2\right\}^{1/2}$$

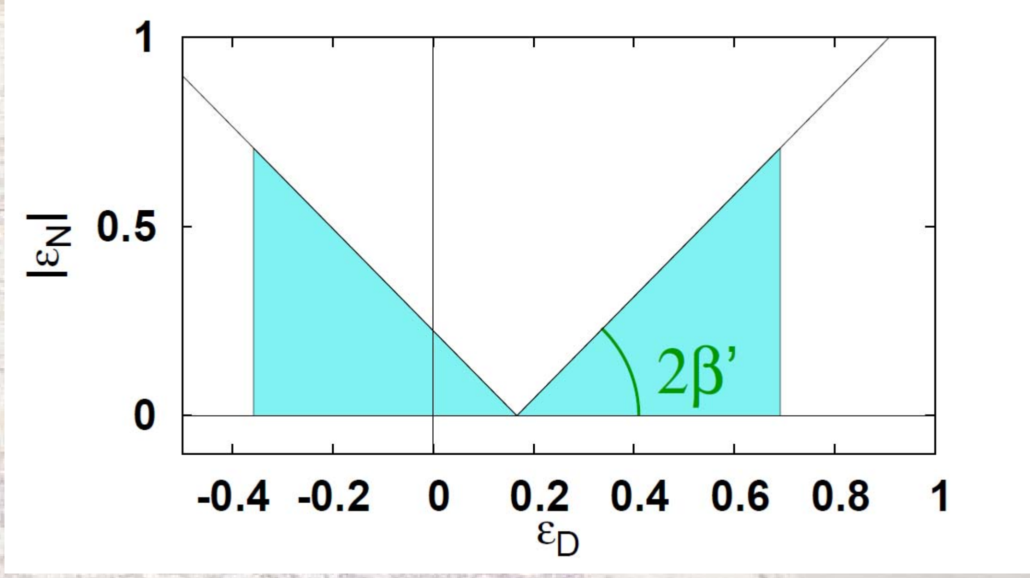
In the case of α ≠ 0, the x-intercept shifts:

$$\tan\beta = \frac{|\epsilon_{e\tau}|}{1+\epsilon_{ee}-\alpha}$$



$$\tan 2\beta' = \frac{|3\epsilon_N|}{1/2-3\epsilon_D-\alpha/4}$$

$$\tan\beta' \equiv \frac{\tan\beta}{\sqrt{2}}$$

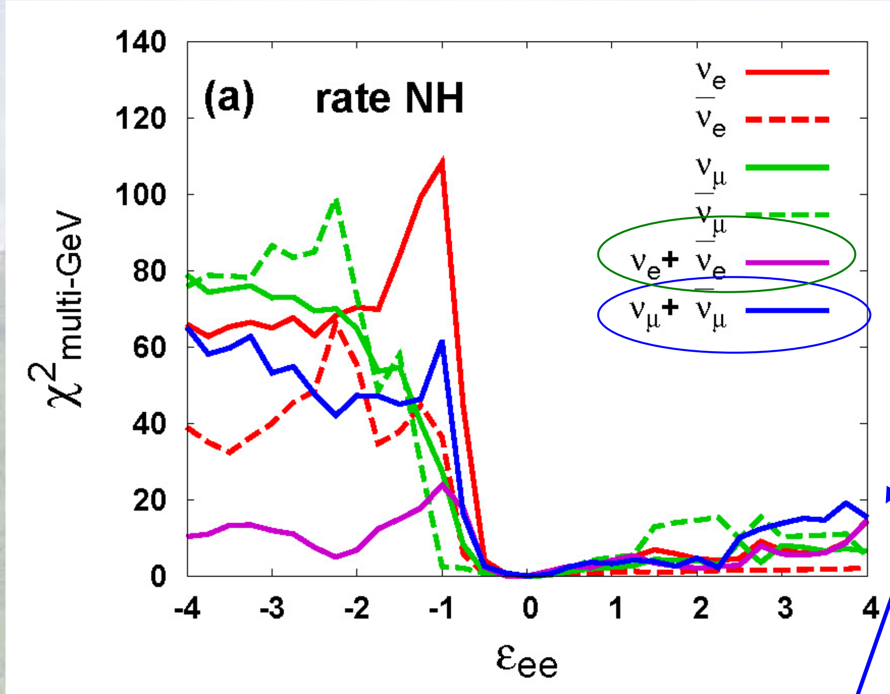


NuFact

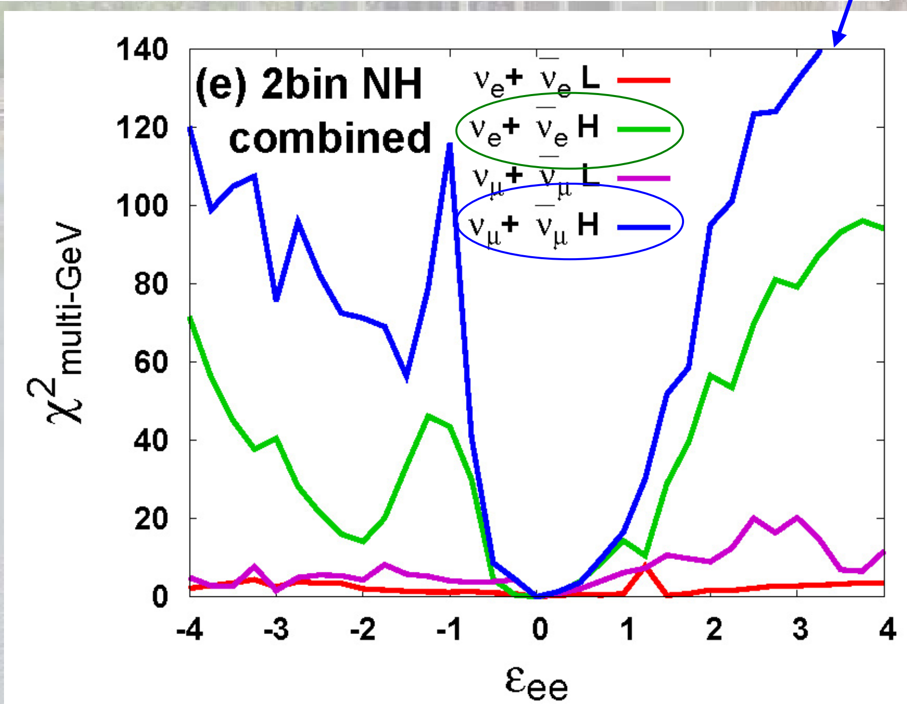
Difference with our previous work (Fukasawa-OY, arXiv:1607.03758)

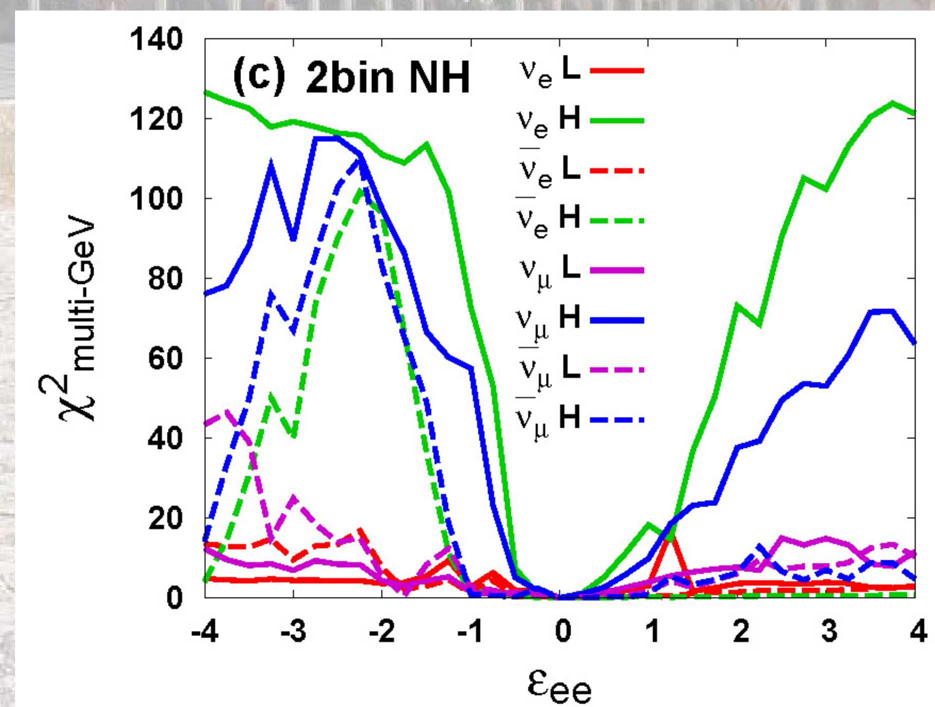
1. Previously $\varepsilon_{\alpha\mu}$ =0 was assumed.
   --> $\varepsilon_{\alpha\mu}$ is taken into account.
2. Previously $\varepsilon_{\tau\tau}=|\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$ was assumed.
   --> Deviation from $\varepsilon_{\tau\tau}-|\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})=0$ is taken into account.
3. The result is obtained in the (ε_D, $|\varepsilon_N|$)-plane.

Behaviors of χ^2 (NH) for multi-GeV: Rate VS Spectrum for $\varepsilon_{e\tau}=0$



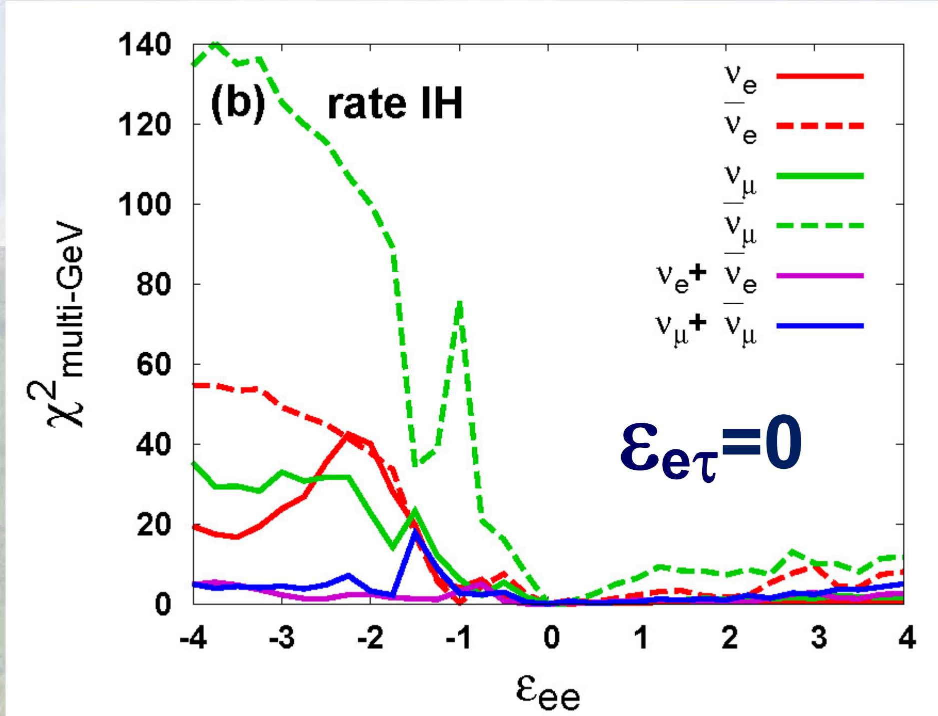
Destructive phenomenon between Low & High energy bins → Information on energy spectrum is important

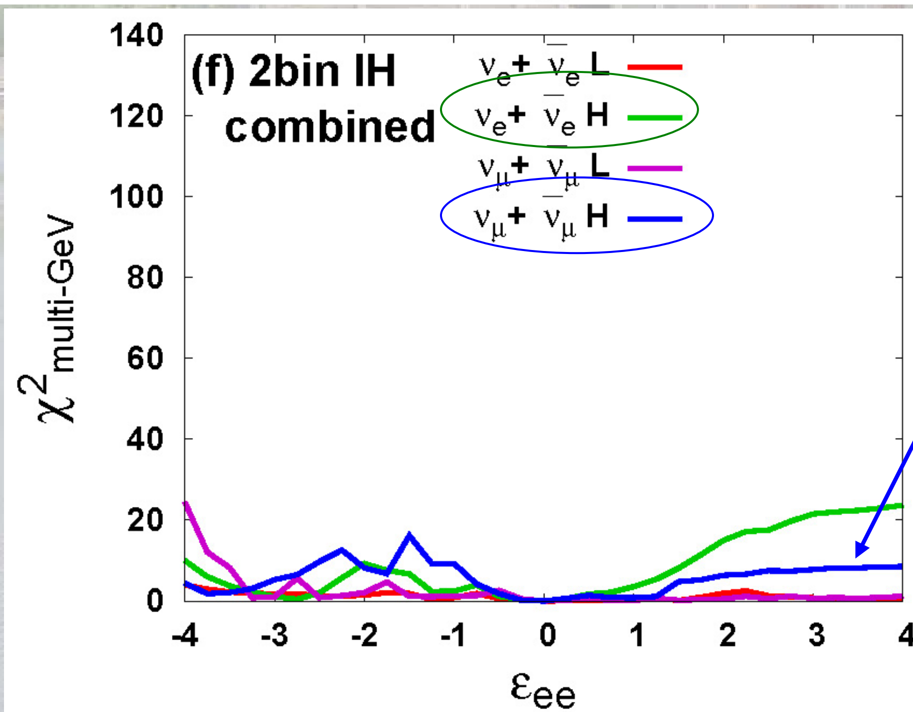


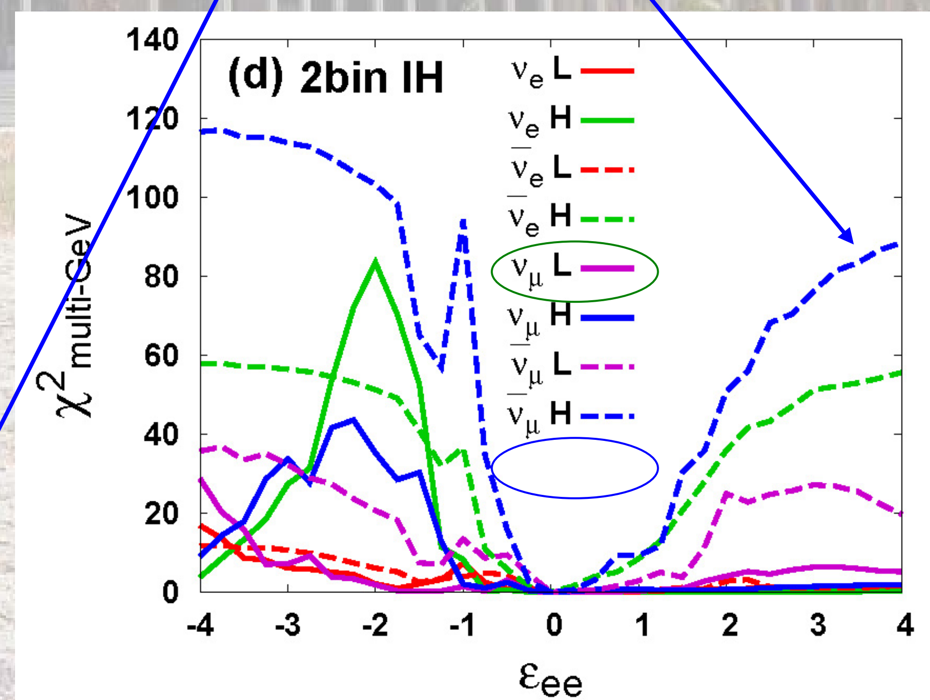


Behaviors of χ^2 (IH) for multi-GeV: $\nu+\overline{\nu}$ vs individual ν&$\overline{\nu}$ for $\varepsilon_{e\tau}=0$

Destructive phenomenon between ν & $\overline{\nu}$ → Distinction between ν & $\overline{\nu}$ gives important information on ε_{ee}

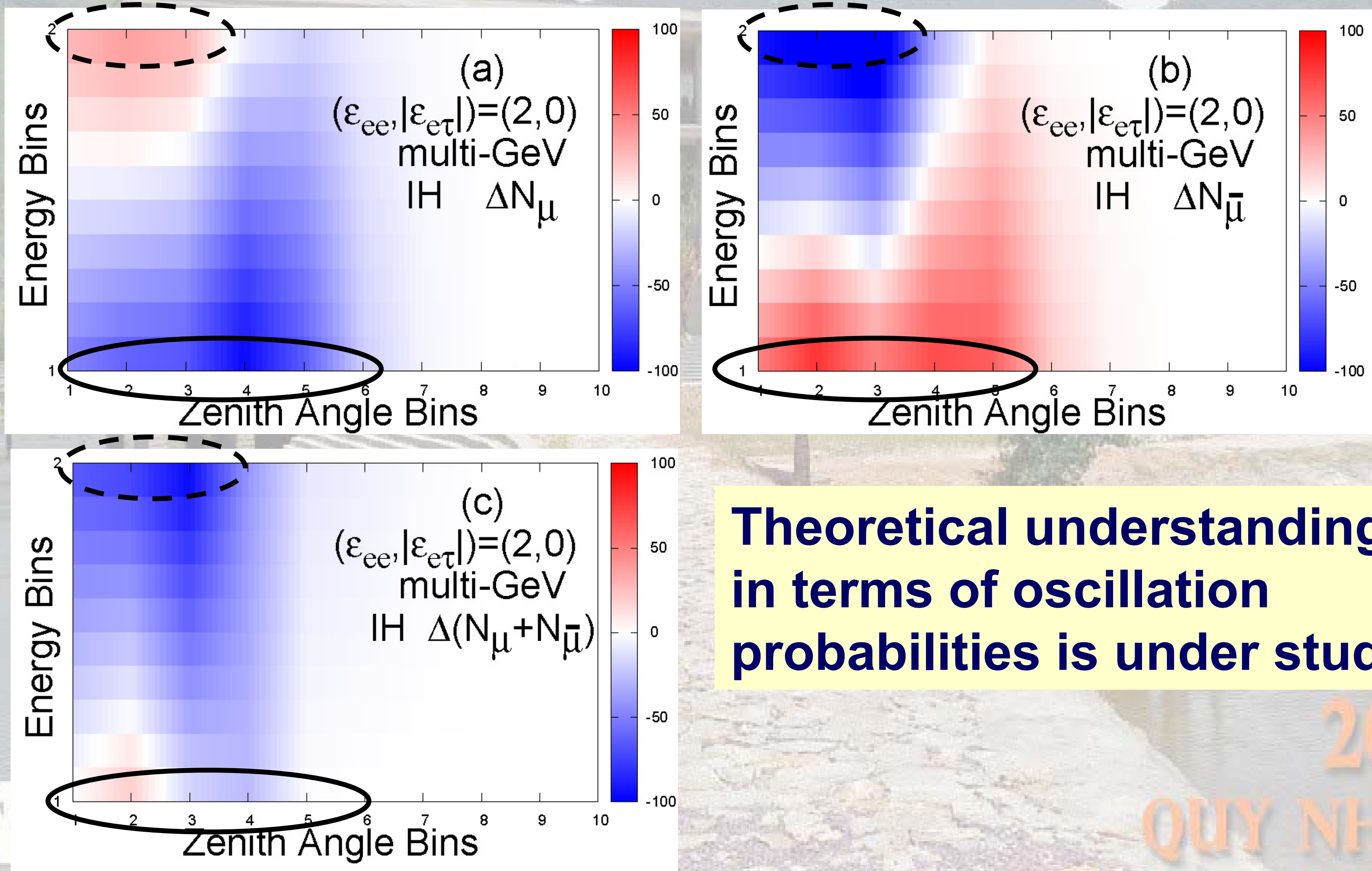






Behaviors of #(events) for multi-GeV: $\nu+\bar{\nu}$ vs individual ν&$\bar{\nu}$

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



Theoretical understanding in terms of oscillation probabilities is under study.