Non-standard interactions in propagation through atmospheric neutrinos

Osamu Yasuda
Tokyo Metropolitan University

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Based on arXiv.1503.08056, Fukasawa & OY

1. Introduction

2. New Physics in propagation

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

4. Conclusions

1. Introduction

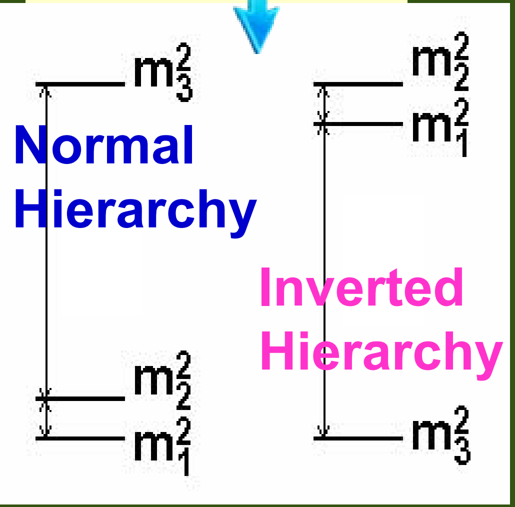
Both hierarchy patterns are allowed

Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boxed{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

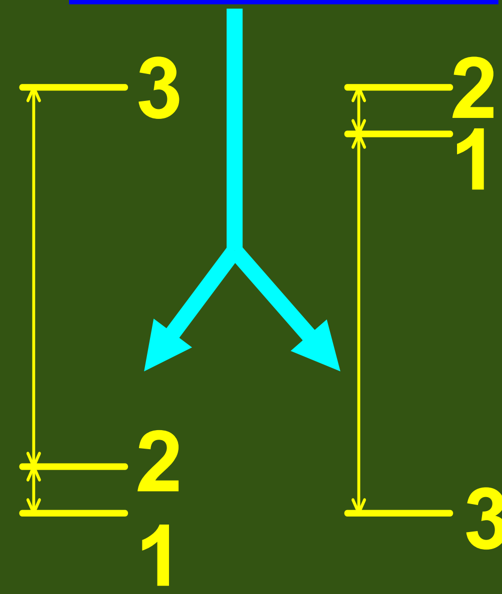
DCHOOZ+Daya Bay+Reno (reactors), T2K+MINOS, others → $\theta_{13} \cong \pi / 20$

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

● 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

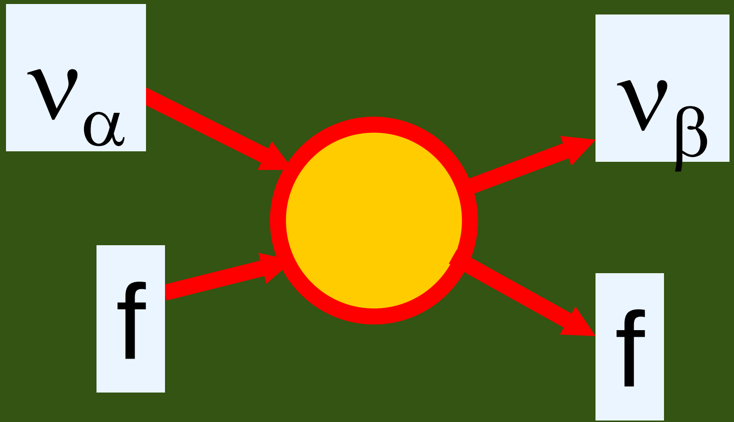
Scenarios	Possible magnitude relative to standard value
Light sterile neutrinos	O(10%)
Non Standard Interactions in propagation	e-τ: O(100%) μ: O(1%)
NSI at production / detection	O(1%)
Violation of unitarity due to heavy particles	O(0.1%)

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:

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



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

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

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

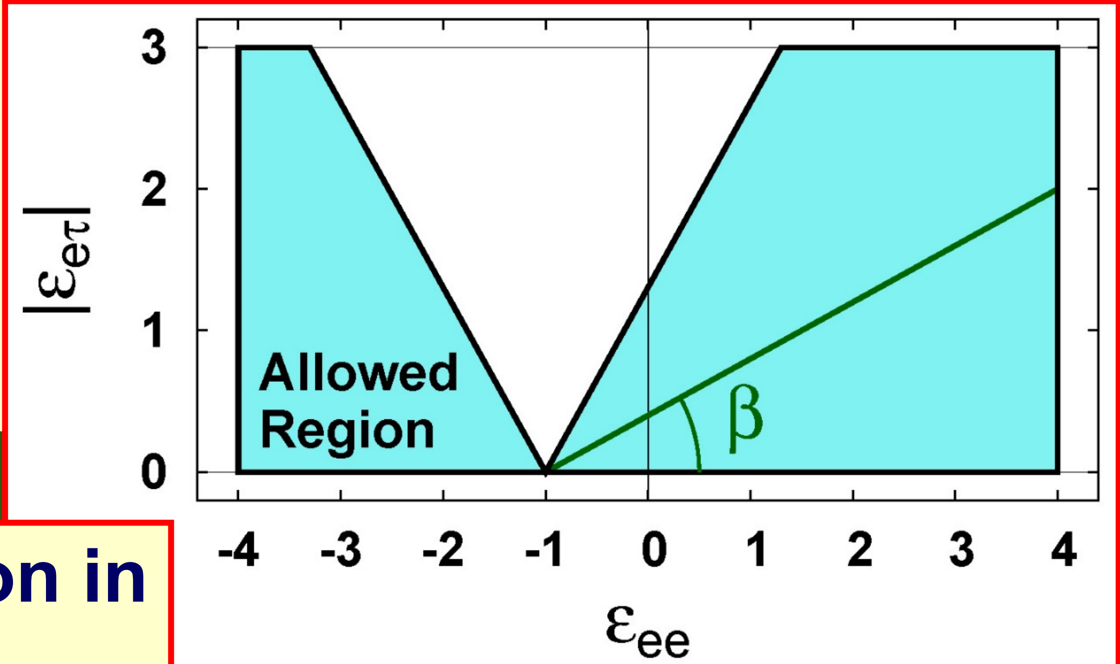
To a good approximation, we are left with 3 independent variables ε_{ee}, $|\varepsilon_{e\tau}|$, $\arg(\varepsilon_{e\tau})$:

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

Furthermore, ν_{atm} data implies

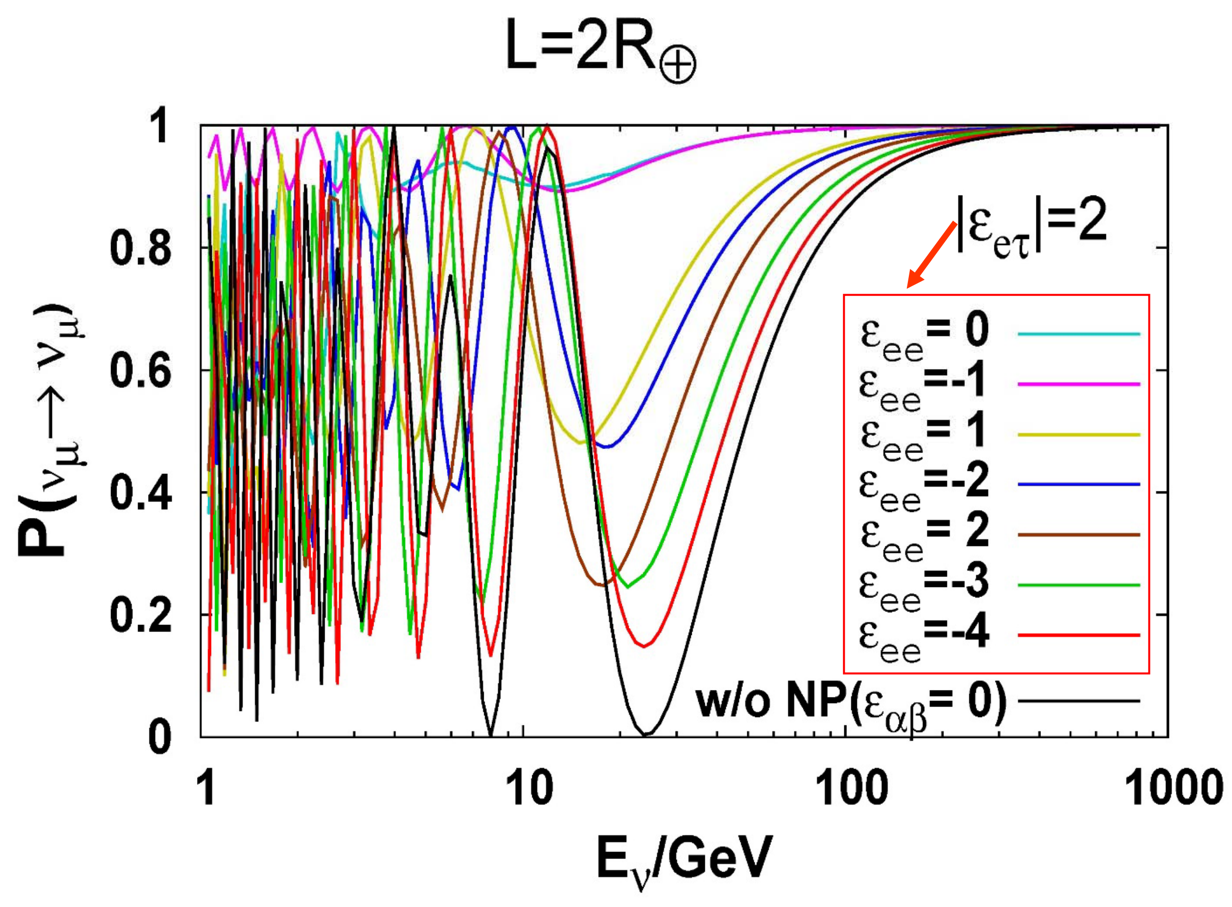
$|\tan\beta| = |\varepsilon_{e\tau}/(1+\varepsilon_{ee})| < 1.5$ @2.5σCL

Friedland-Lunardini, PRD72:053009,'05



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

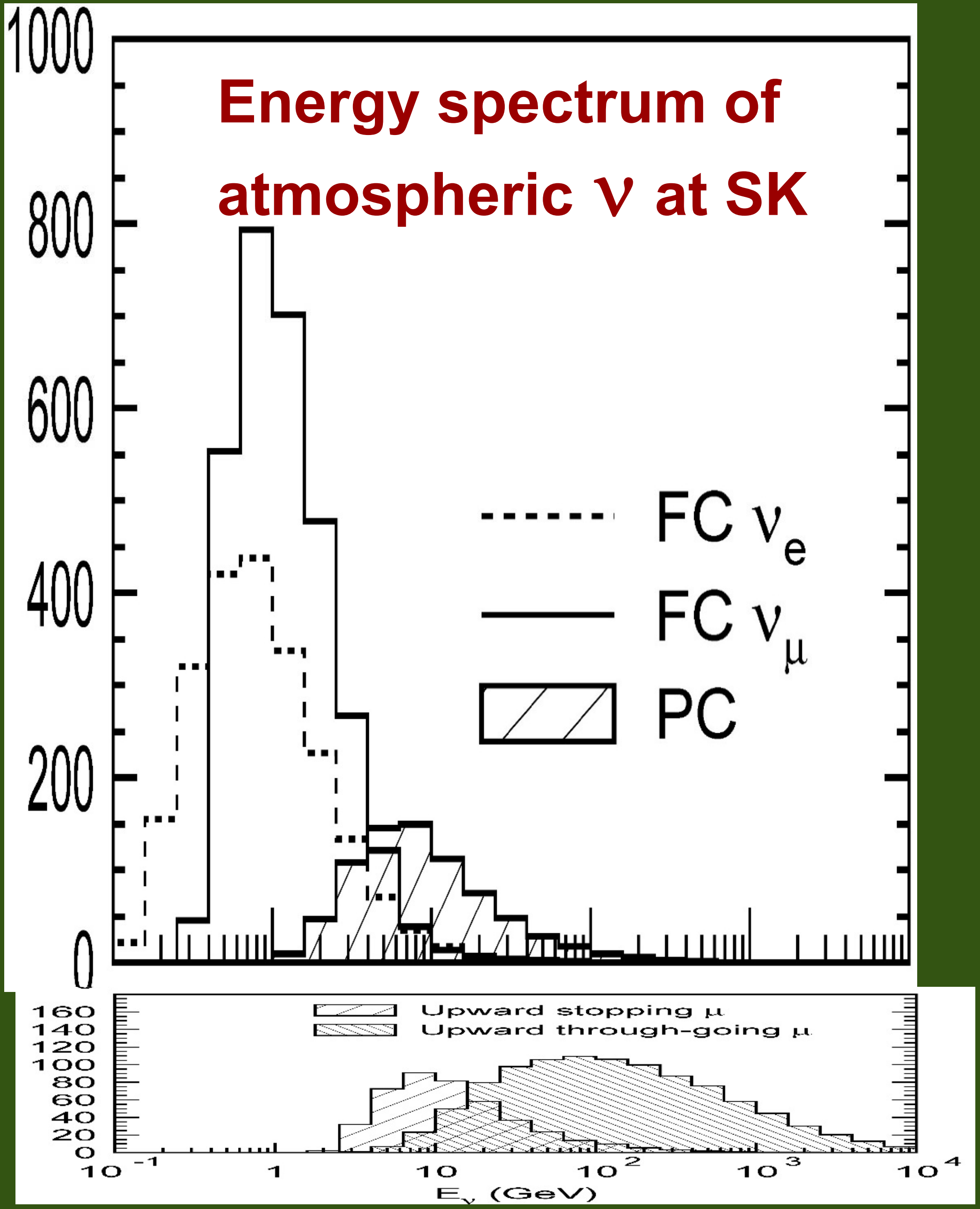
3. Sensitivity of ν_{atm} at SK&HK to NSI in propagation



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**



Outline of our Analysis

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

Our ansatz

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

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

SK

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

Rate analysis only

HK

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

Rate & spectrum analysis

Parameters

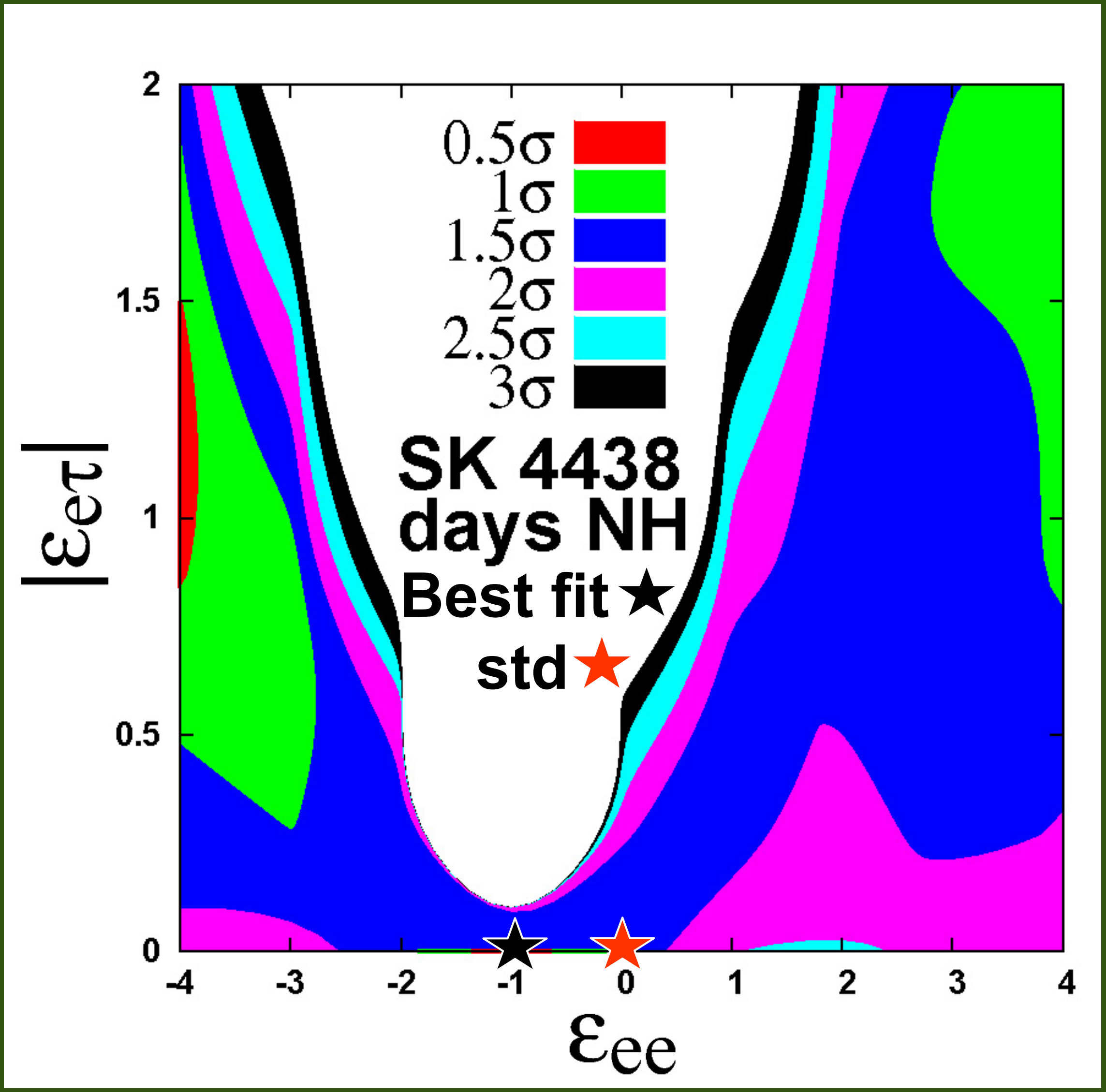
Fixed: θ_{12}, θ_{13} , Δm^2_{21}

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

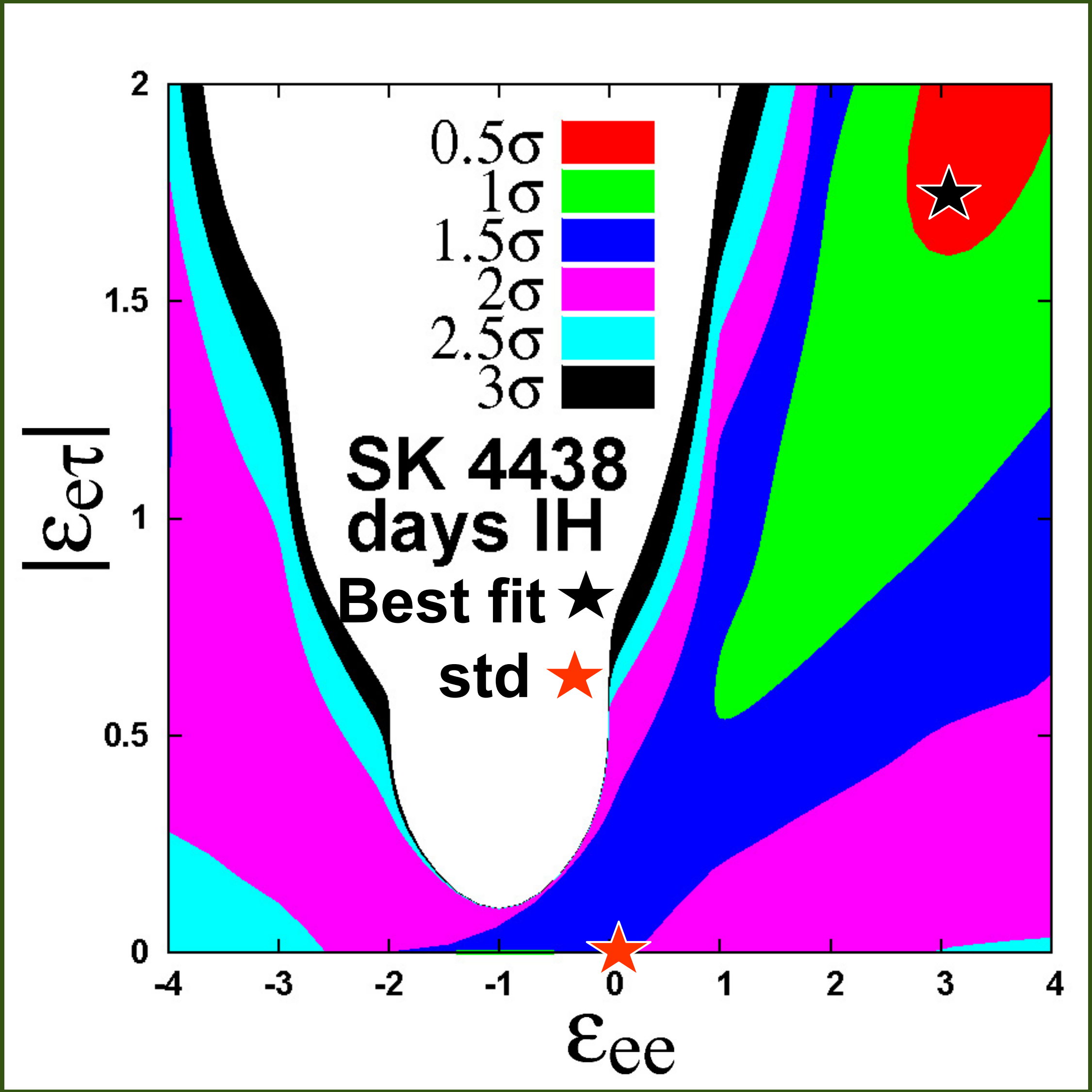
#(events)$_{HK}$ = 20 x #(events)$_{SK}$

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

Fukasawa-OY
arXiv.1503.08056

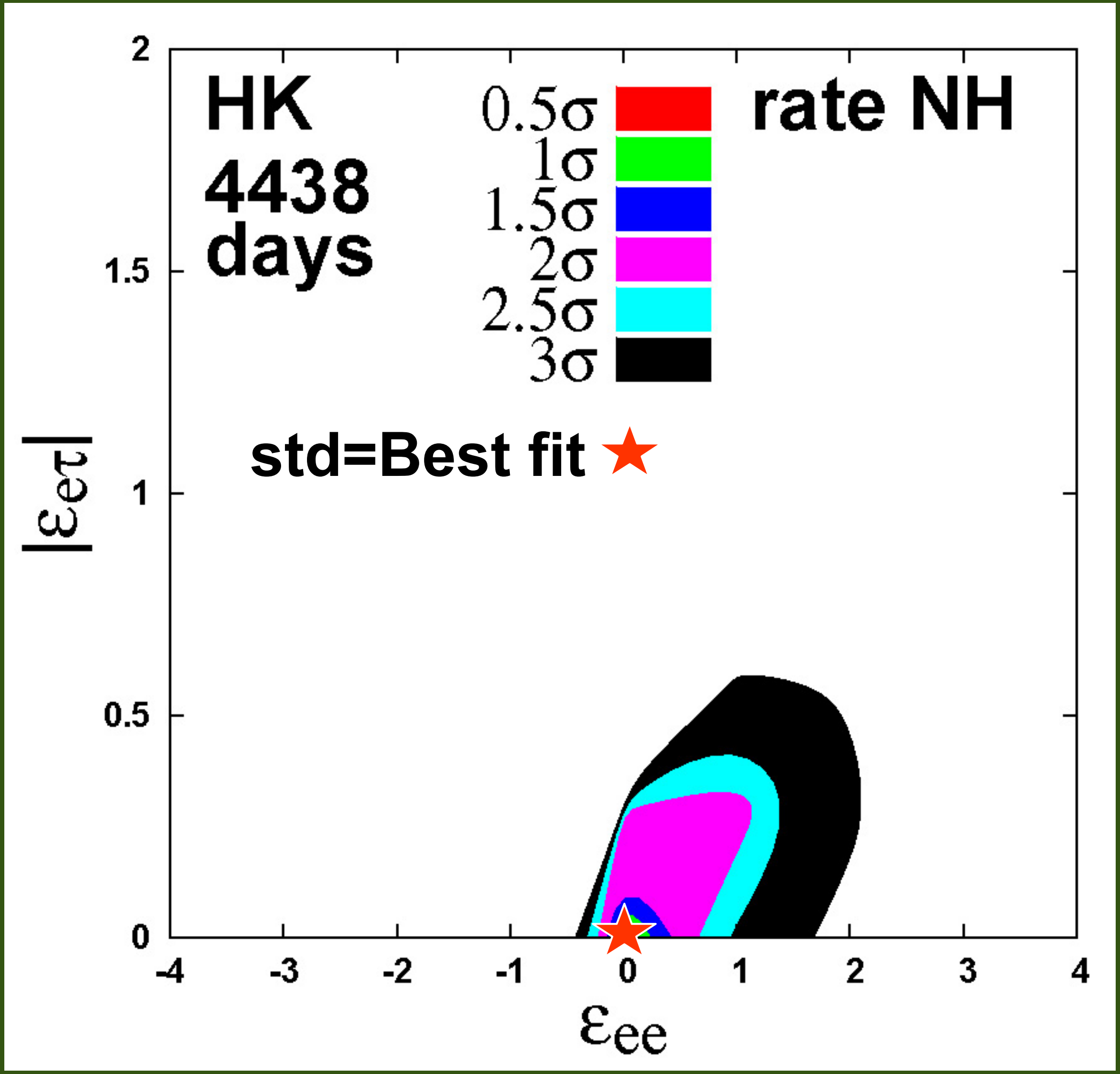


- The standard case ($\varepsilon_{\alpha\beta}$=0) is **not** best fit point: This may be because we perform only the rate analysis (See discussions for HK below).
- The 2.5σ excluded region (|tanβ|<0.7) improves the old one (|tanβ|<1.5) by Friedland-Lunardini in 2005.



0.5σ
1σ
1.5σ
2σ
2.5σ
3σ
SK 4438 days IH
Best fit ★
std ★
|εeτ|
εee
2
1.5
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4

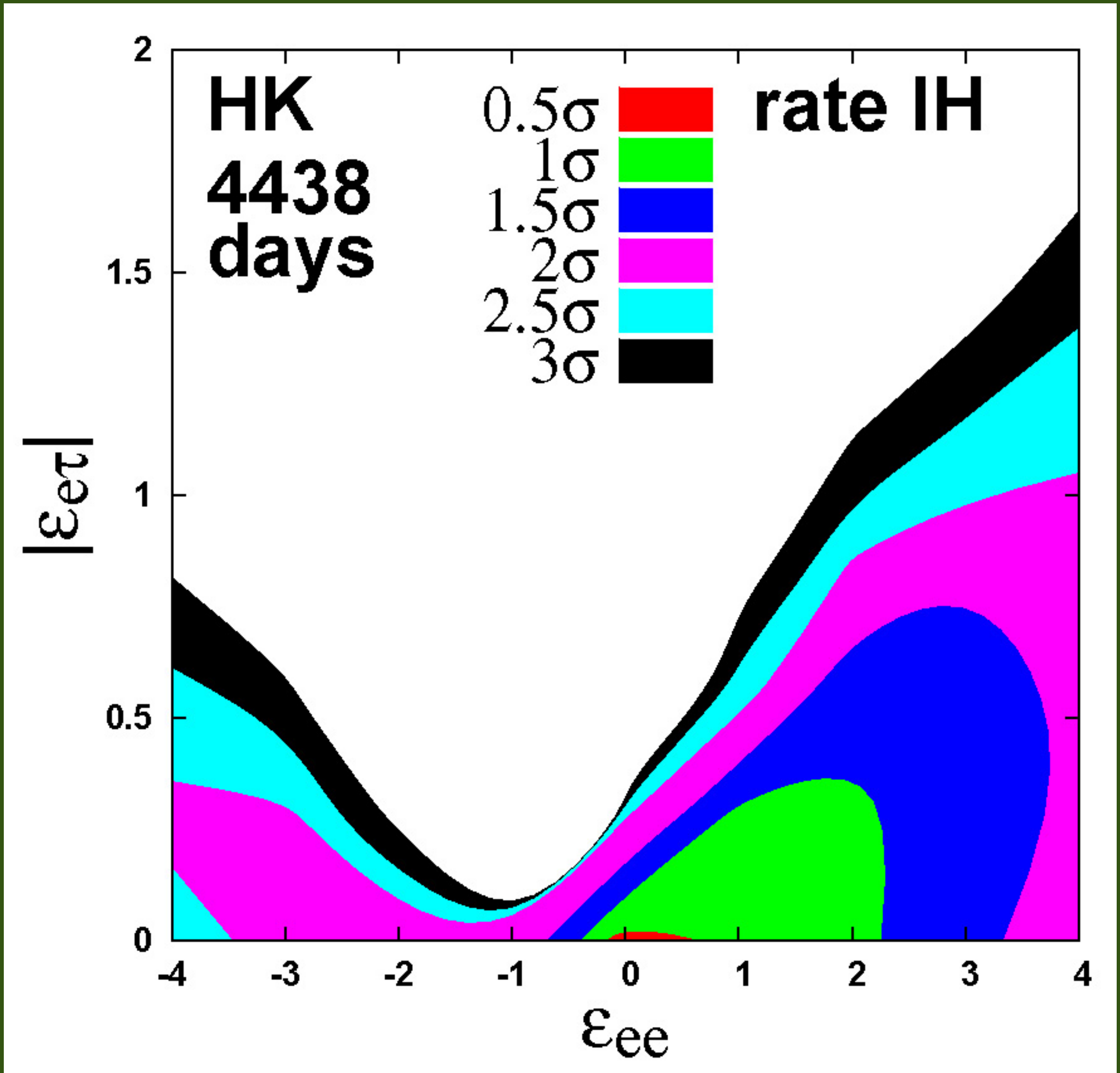
Sensitivity of HK: (1) Rate analysis



Fukasawa-OY
arXiv.1503.08056

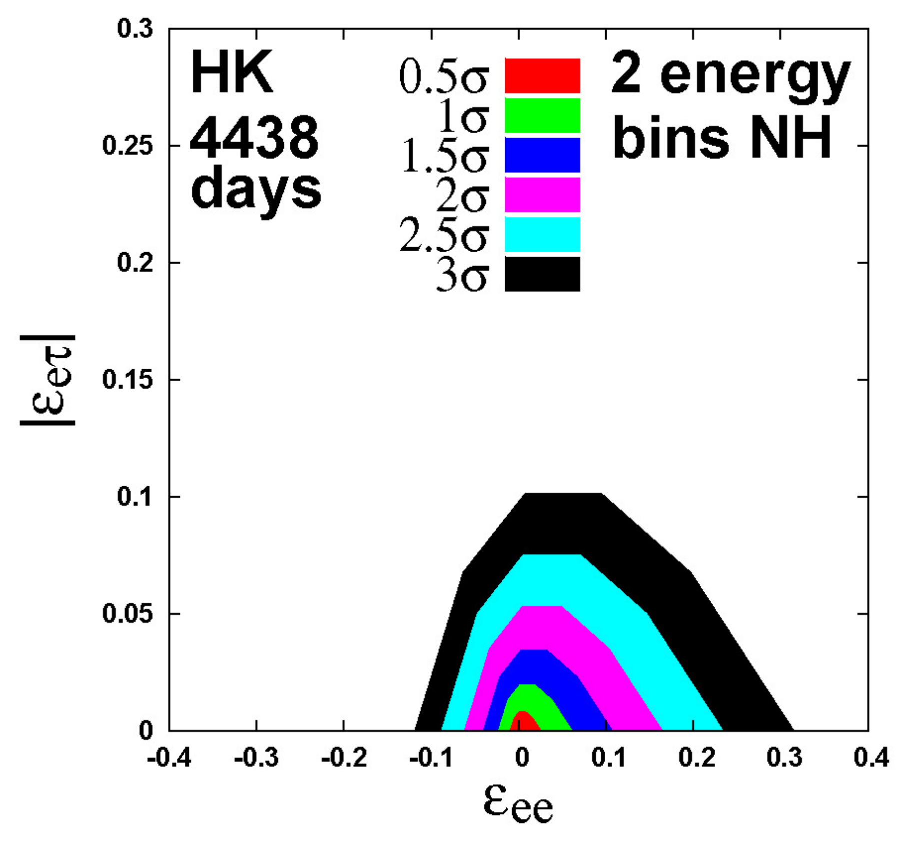
$\#(\text{events})_{HK} = 20 \times \#(\text{events})_{SK}$

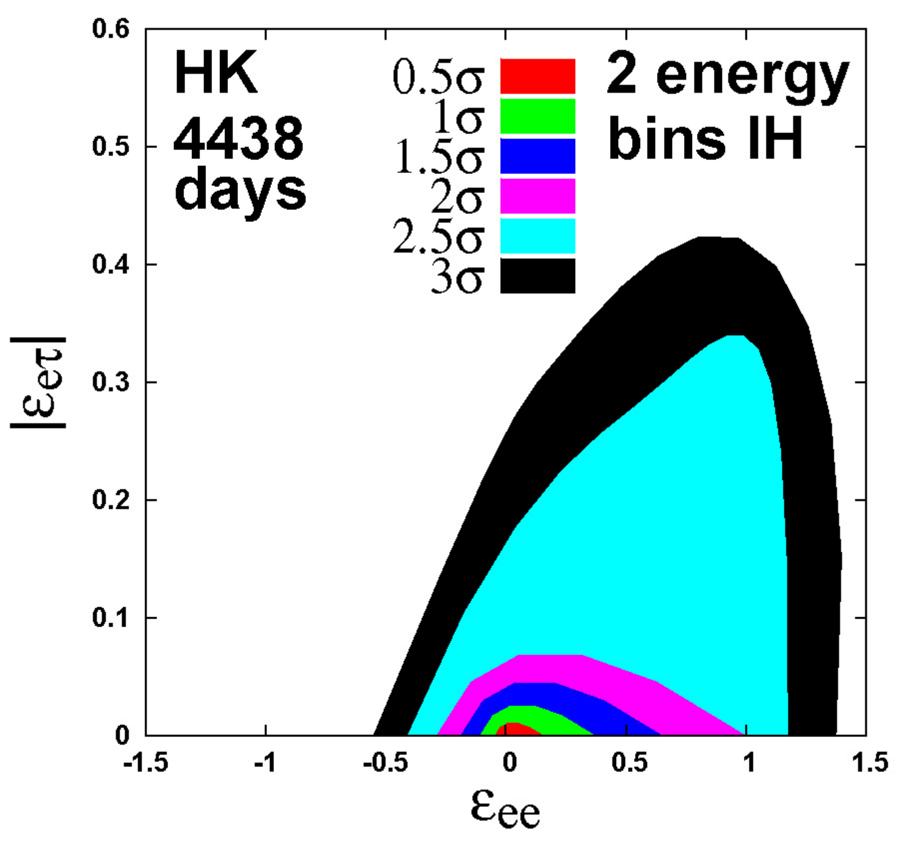
- The region $|\varepsilon_{e\tau}| > 1.5$ is excluded. The 2.5σ excluded region is $|\tan\beta| < 0.4$.



- 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 ν.

Sensitivity of HK: (2) Spectrum analysis

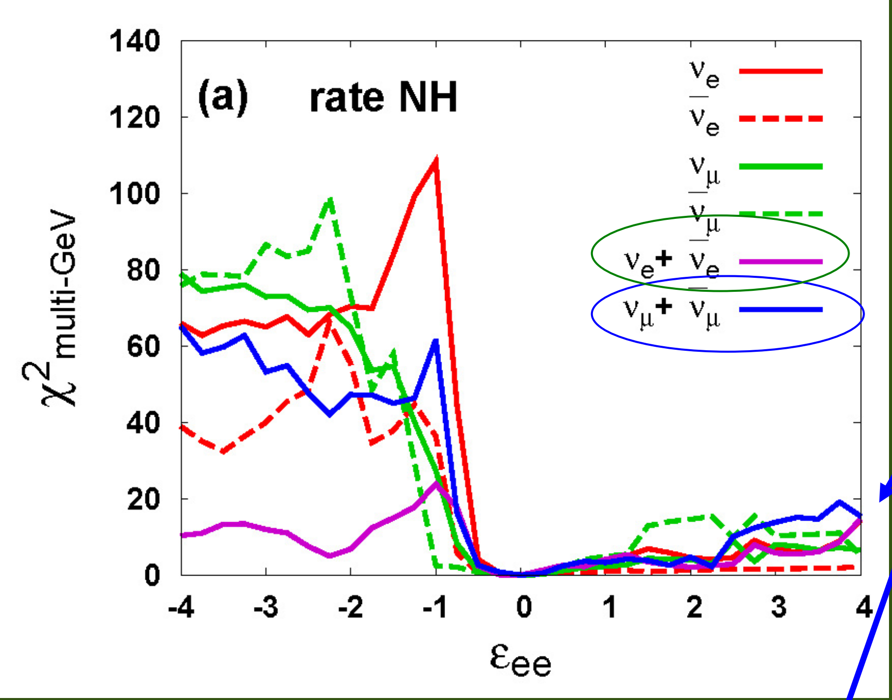


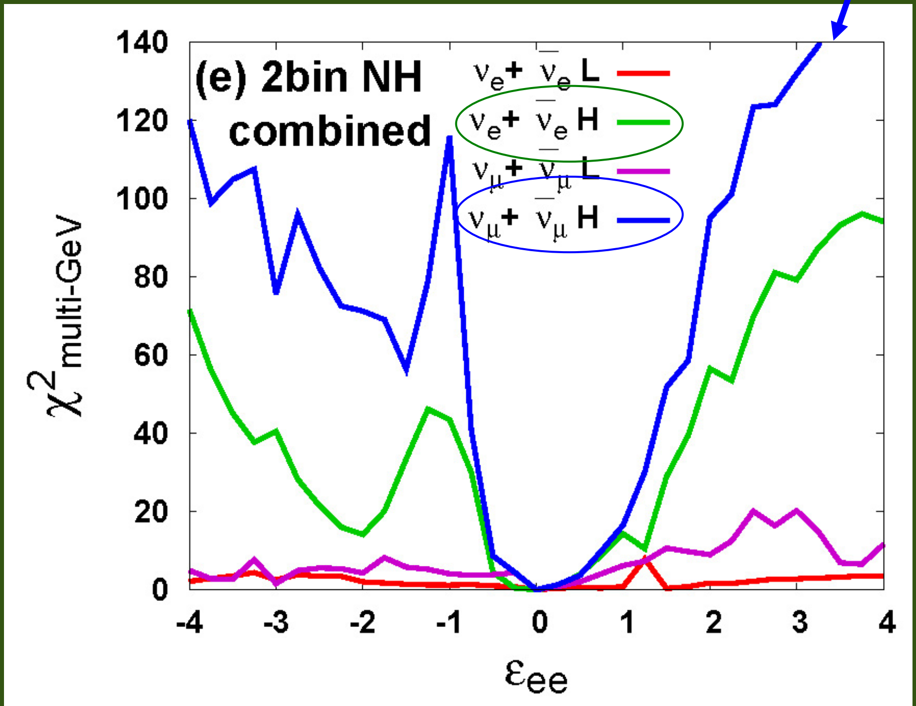


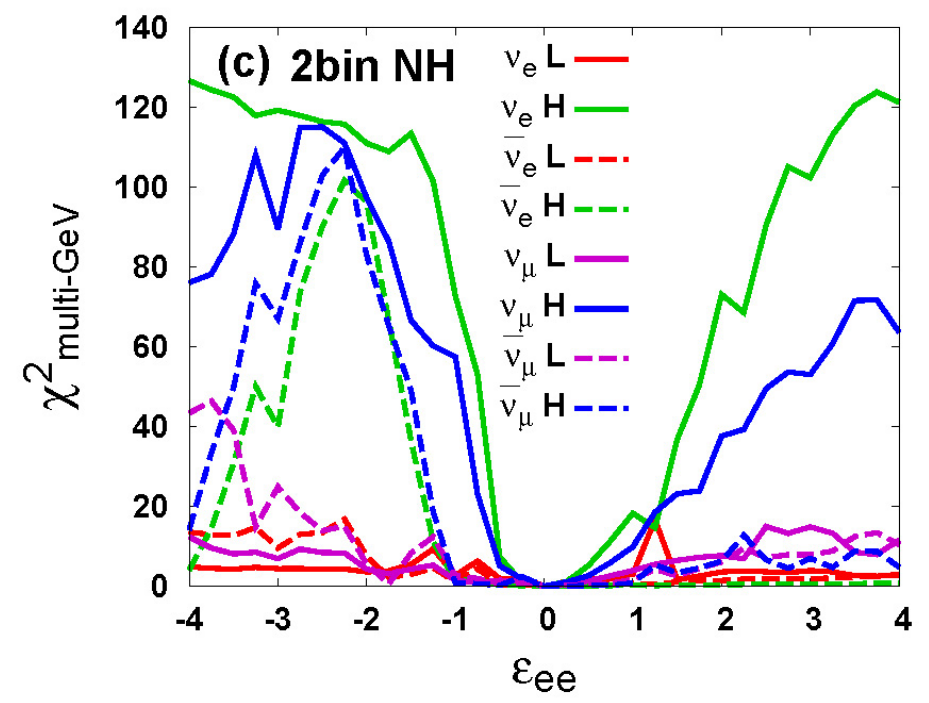
- With the information of the energy spectrum, the allowed region becomes much smaller (Note the difference in scale). The 2.5σ excluded region is $|\tan\beta|<0.1$.

Behaviors of χ^2 (NH) for multi-GeV: Rate VS Spectrum

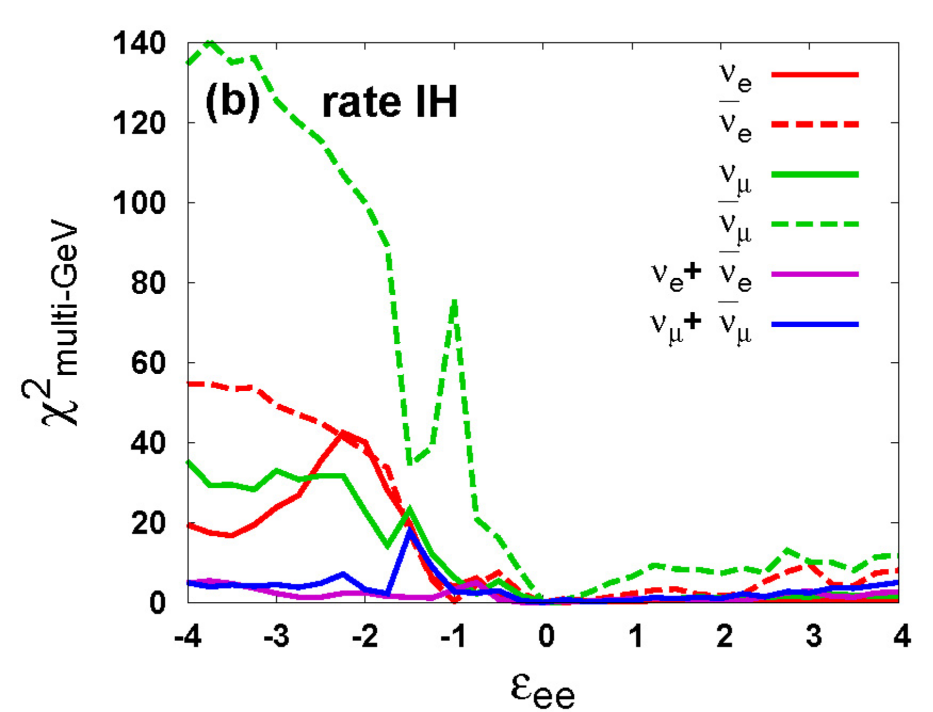
Destructive phenomenon between Low & High energy bins → Information on energy spectrum is important



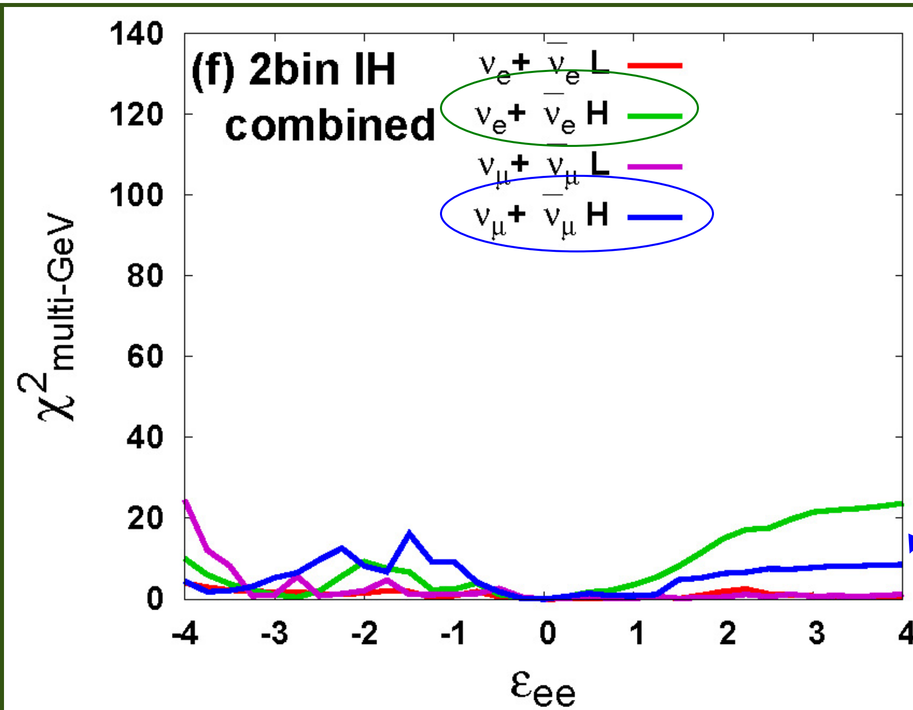


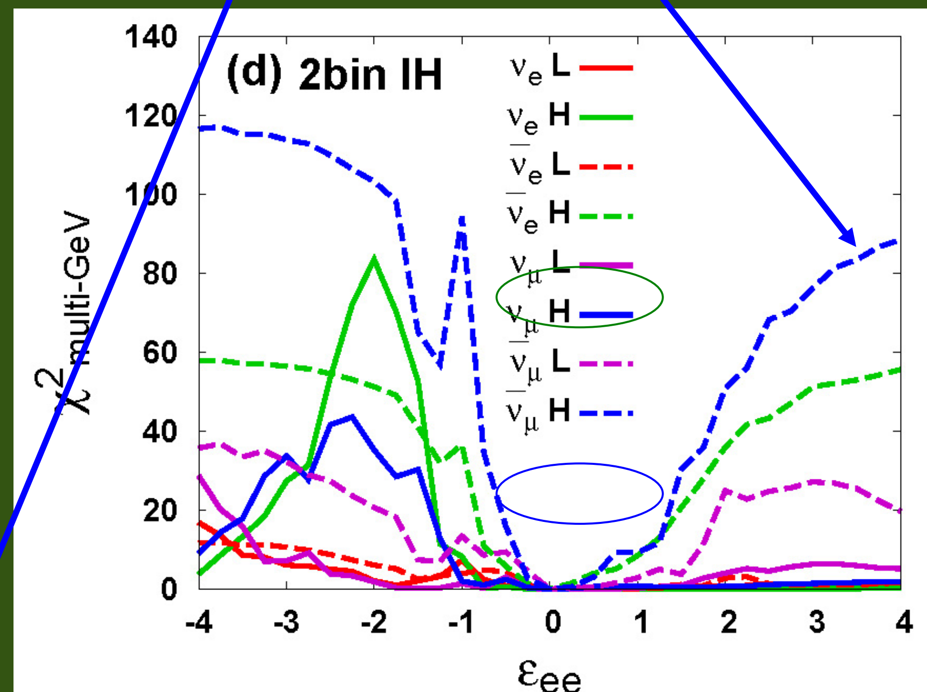


Behaviors of χ^2 (IH) for multi-GeV: $\nu+\overline{\nu}$ vs individual ν&$\overline{\nu}$



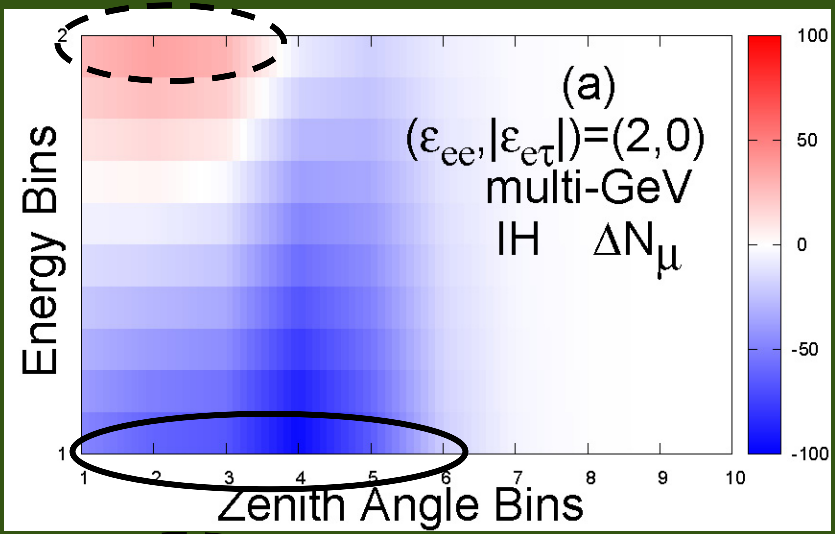
Destructive phenomenon between ν & $\overline{\nu}$ → Distinction between ν & $\overline{\nu}$ gives important information on ε_{ee}

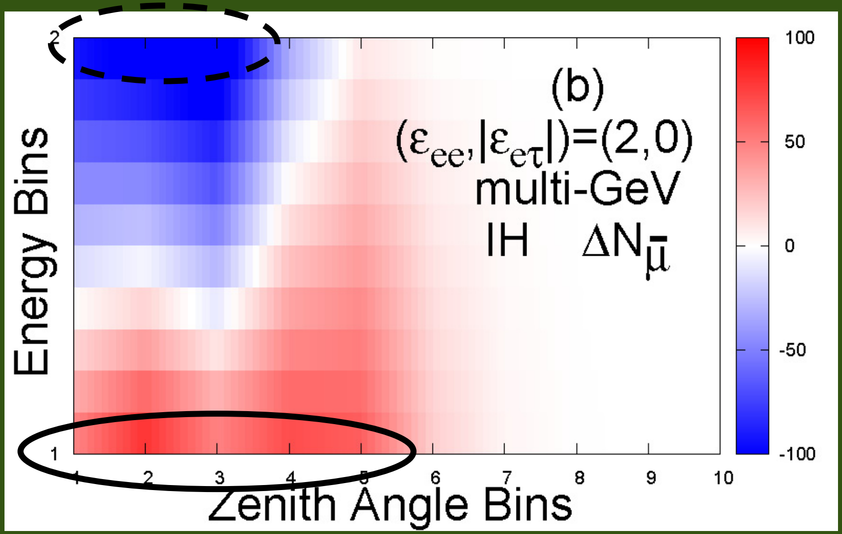


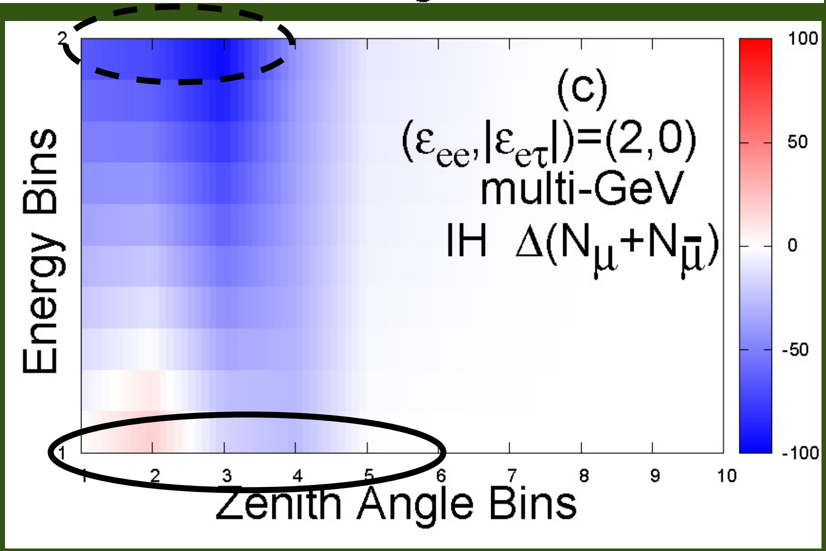


Behaviors of #(events) for multi-GeV: $\nu+\bar{\nu}$ vs individual ν&$\bar{\nu}$

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



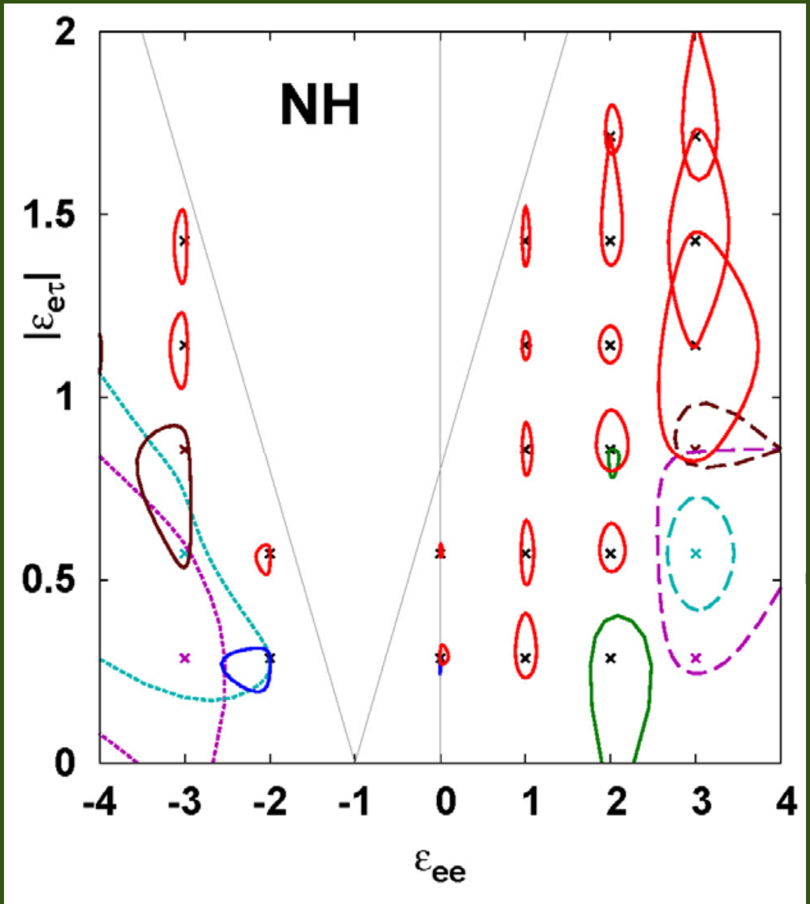


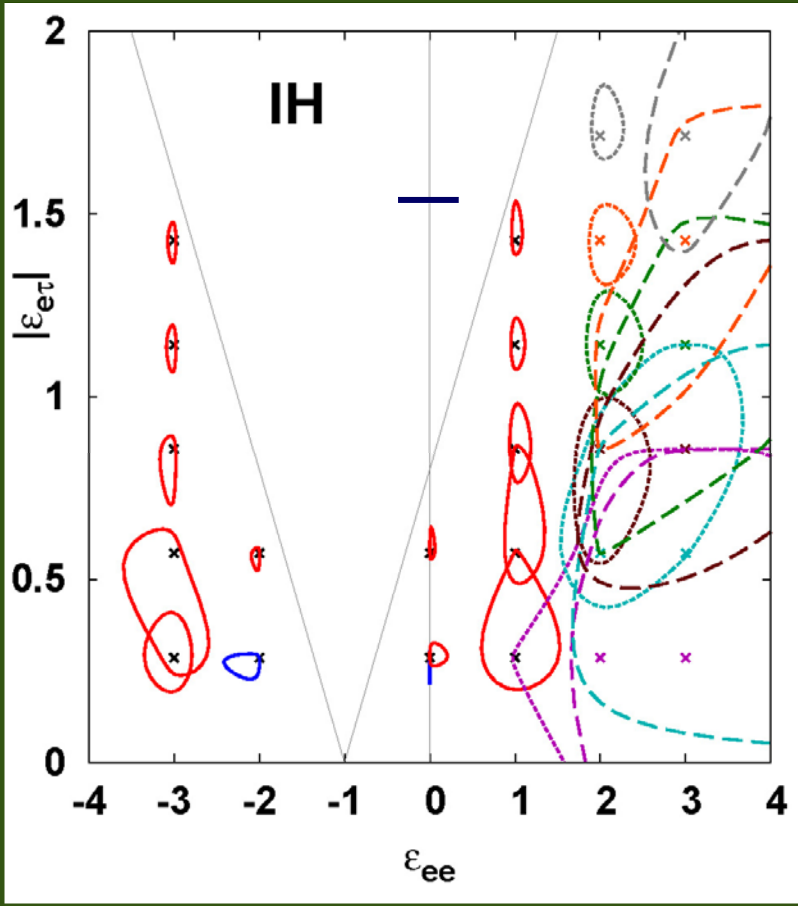


Theoretical understanding in terms of oscillation probabilities is under study.

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

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





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 ν_{atm} at SK & HK

- The constraint $|\tan\beta| := |\varepsilon_{e\tau}/(1+\varepsilon_{ee})| < 0.7$ from SK ν_{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 ν_{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 ν & $\bar{\nu}$ is important to reduce the allowed region of ε_{ee} (but not $\varepsilon_{e\tau}$).→Further efforts to separate ν & $\bar{\nu}$ should be made.

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

Backup slides

Constraints on NSI from high energy behavior of ν_{atm} data

Oki-Yasuda PRD82 ('10) 073009

- **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 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 energy ν_{atm} data is well described by standard scheme → constraints on NSI: $\boxed{|c_0| \ll 1,\ |c_1| \ll 1}$

● with NSI

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

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

$|\varepsilon_{\mu\tau}| << 1$: 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)

$|c_1| \ll 1 \to \quad \left| \varepsilon_{\tau\tau} - \frac{|\varepsilon_{e\tau}|^2}{1+\varepsilon_{ee}} \right| << 1$

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