Constraints on non-standard interactions by ν_{atm}

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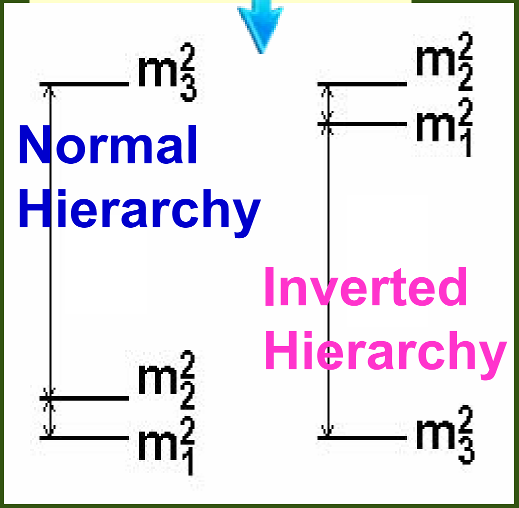
1. Introduction

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

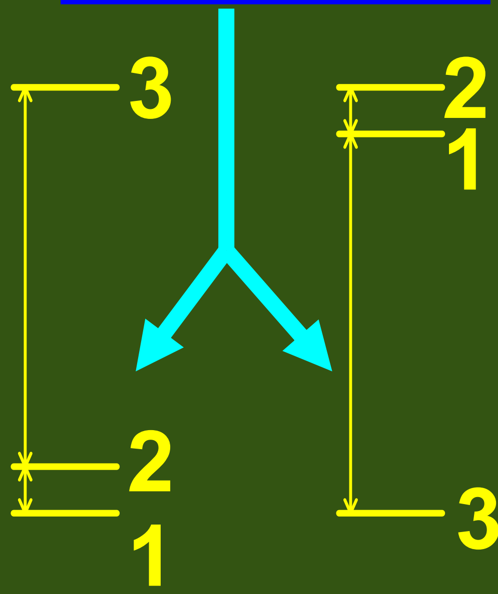
ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}$, $|\Delta m_{32}^2| \cong 2.5 \times 10^{-3}\,\mathrm{eV}^2$

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



normal hierarchy

inverted hierarchy

$\Delta m^2_{32} > 0$

$\Delta m^2_{32} < 0$

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

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).

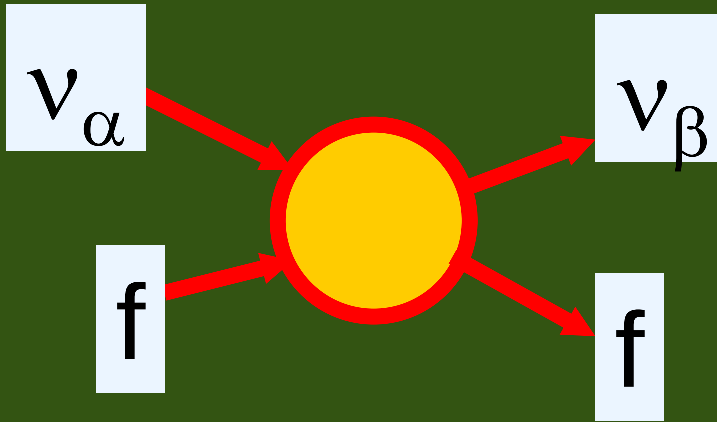
→ Research on **New Physics** is important.

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

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

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

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

Oki-Yasuda PRD82 ('10) 073009

- Standard case with $N_\nu=2$

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

- Standard case with $N_\nu=3$

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

- 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 $\longrightarrow$ constraints on NSI: $|c_0| \ll 1,\ |c_1| \ll 1$

with NSI

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

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

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

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

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

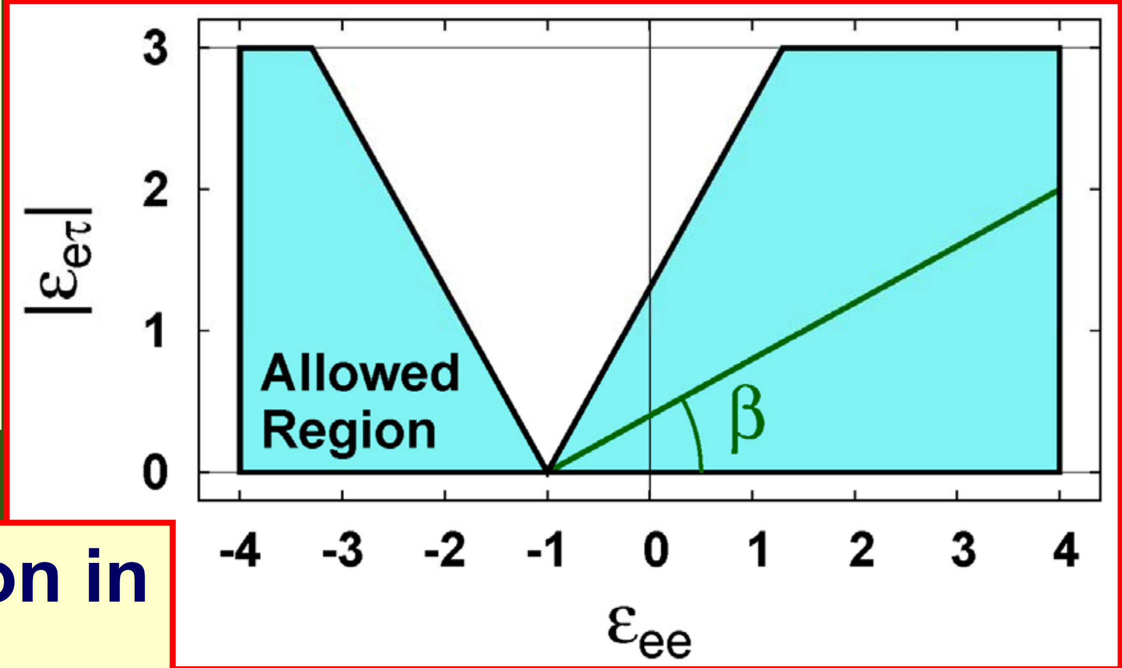
$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^{*}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

Furthermore, ν_{atm} data implies

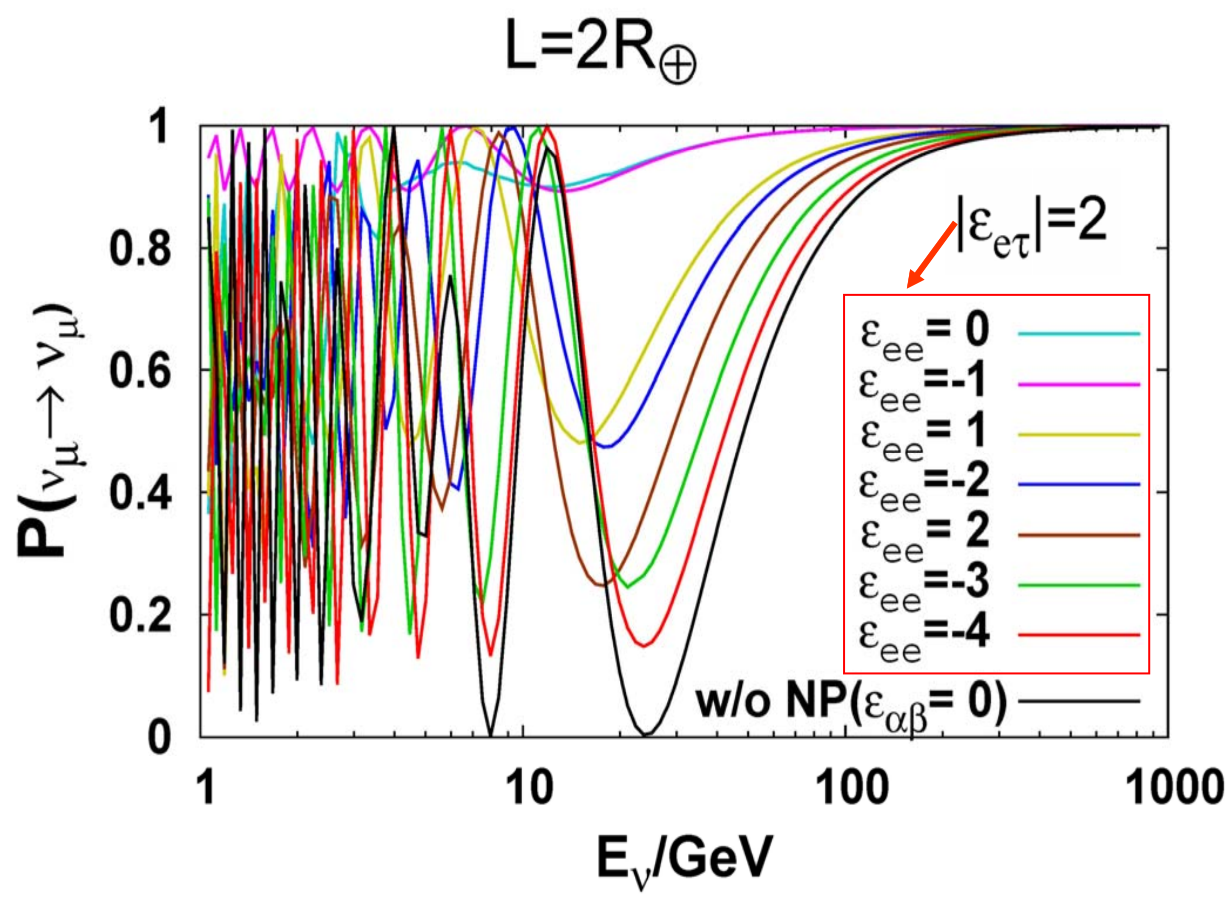
$\tan\beta = |\varepsilon_{e\tau}|/(1+\varepsilon_{ee}) < 1.5$ @2.5σCL

Friedland-Lunardini, PRD72:053009,'05

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



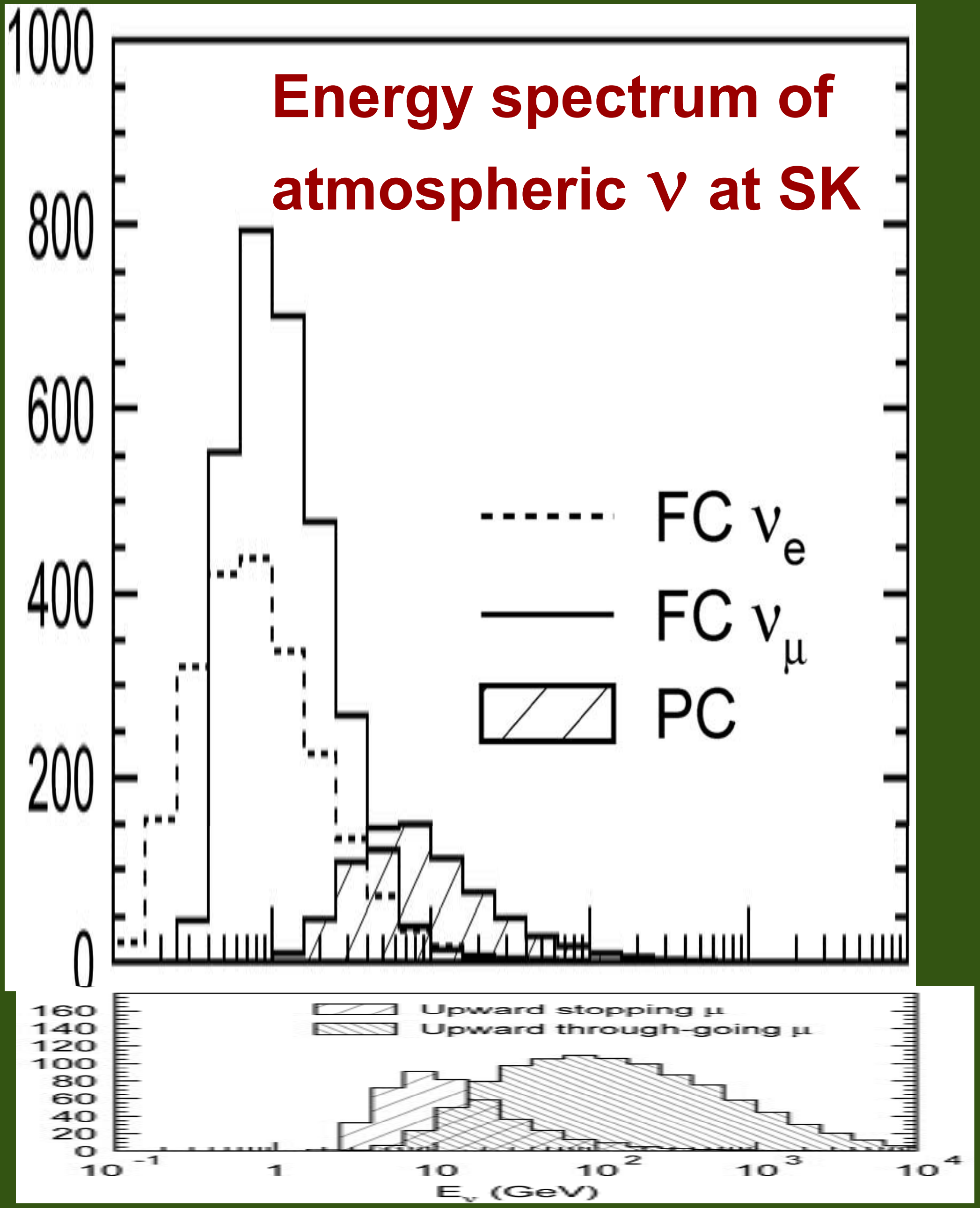
3. Sensitivity of ν_{atm} at SK&HK to NSI in propagation



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 us (OY) worked on SK before.**



Outline of our Analysis

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

Our ansatz

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

SK

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

HK

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

- **Hypothetical #(events) with standard 3-flavor scheme: $\theta_{23}=\pi/4$, Δm^2_{31} =2.5x10^{-3}eV^2**
- **#(events)$_{HK}$= 20 x #(events)$_{SK}$**

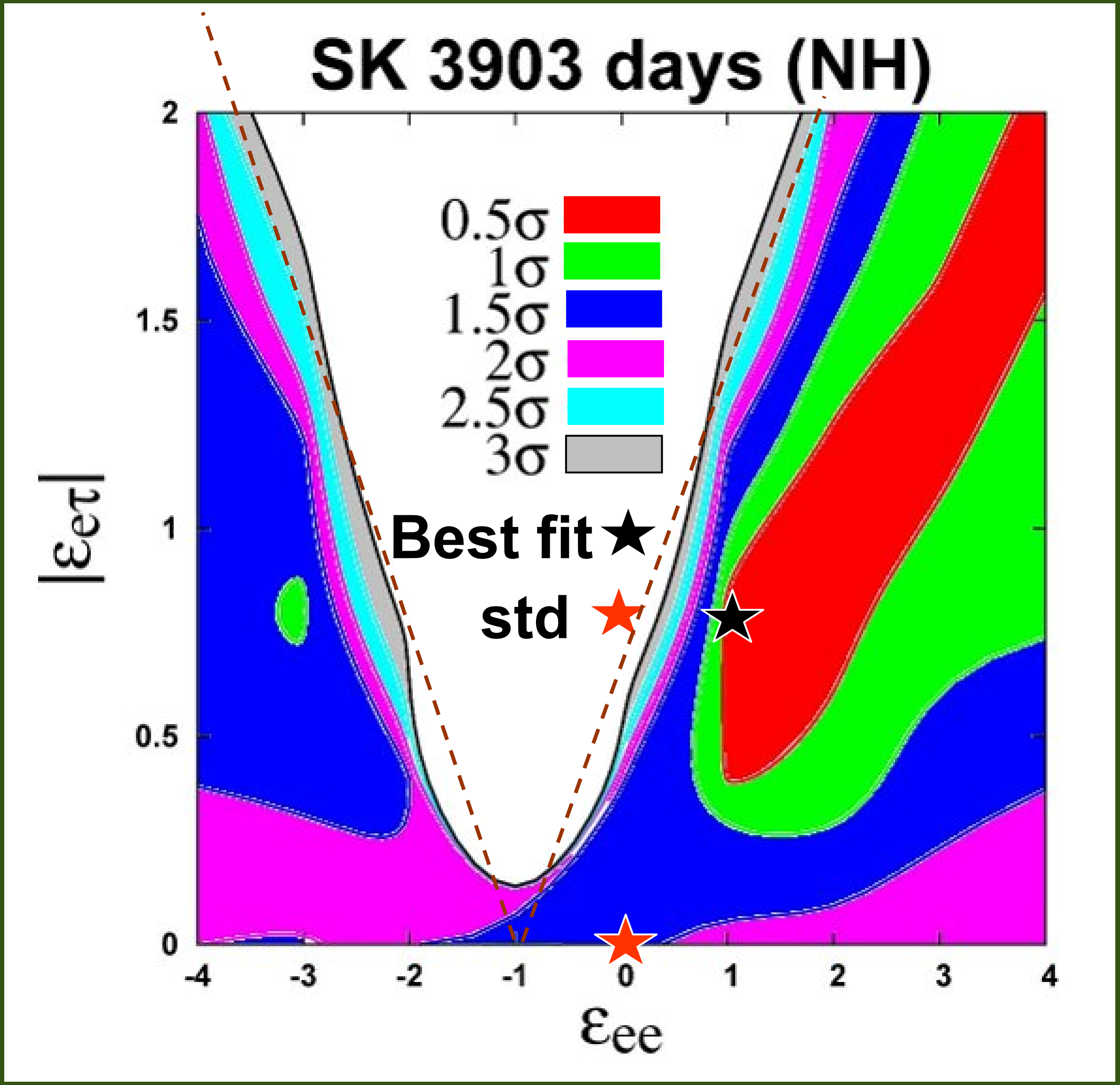
Parameters

Fixed: θ_{12}, θ_{13} , Δm^2_{21}

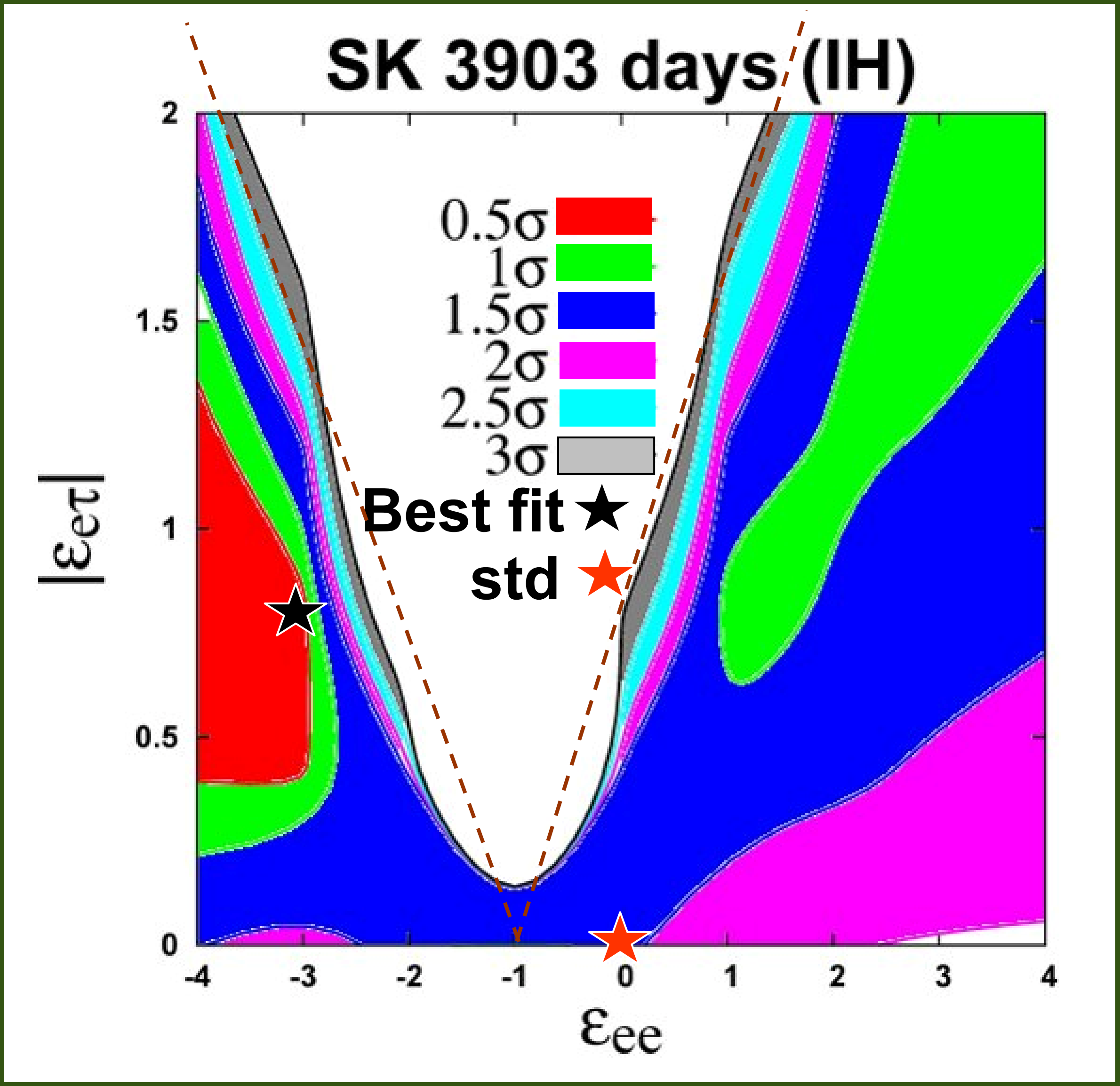
Marginalized: θ_{23}, Δm^2_{31}, δ, arg($\varepsilon_{e\tau}$)

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

Fukasawa-OY (Preliminary)

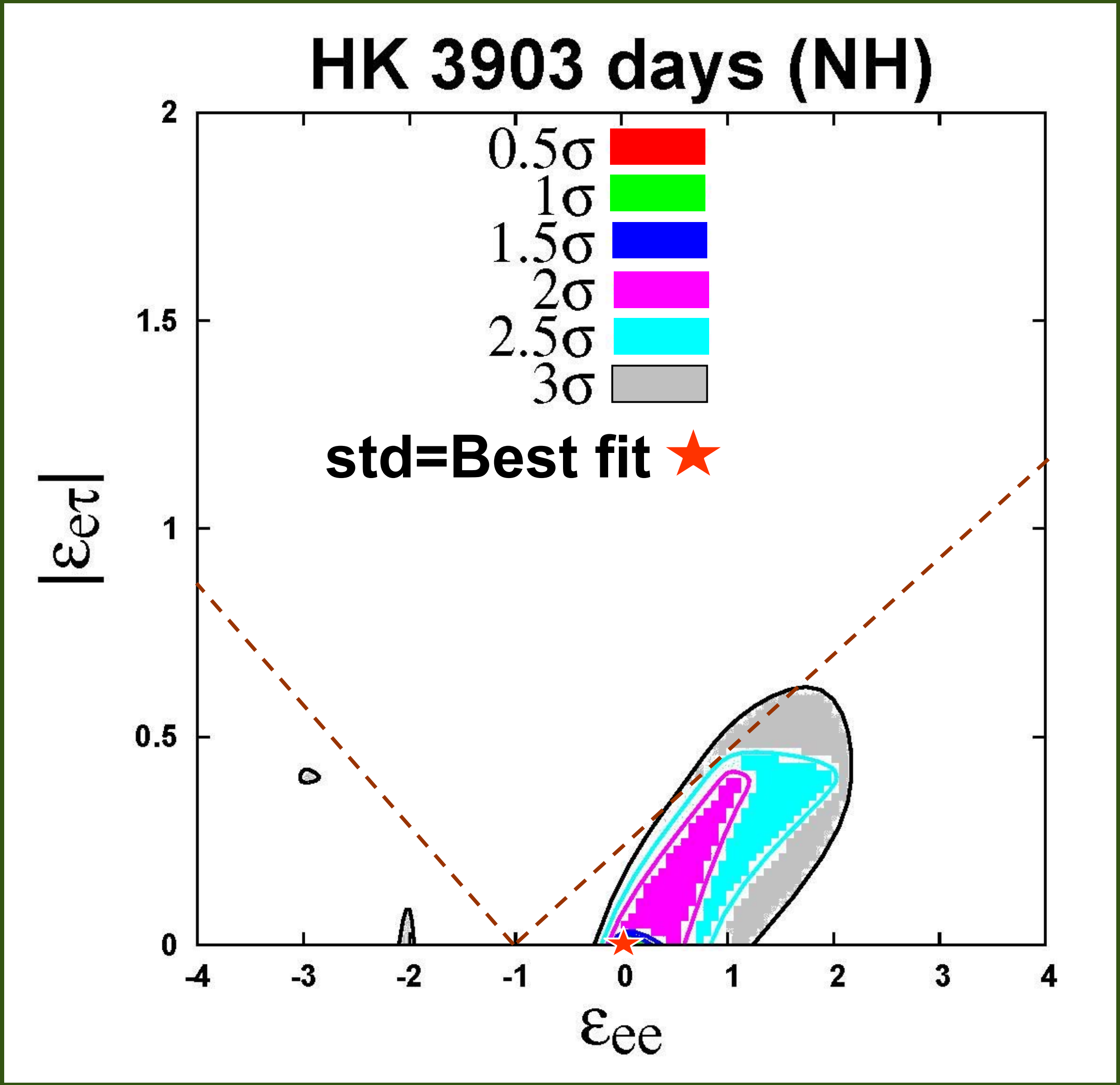


- The standard case ($\varepsilon_{\alpha\beta}=0$) is **not** best fit point (1.4σ). This may be because we have been unable to reproduce SK MC results completely.
- The 2.5σ excluded region ($\tan\beta<0.8$) improves the old one ($\tan\beta<1.5$) by Friedland-Lunardini in 2005.


SK 3903 days (IH)
0.5σ
1σ
1.5σ
2σ
2.5σ
3σ
Best fit
std
$|\varepsilon_{e\tau}|$
ε_{ee}
2
1.5
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4

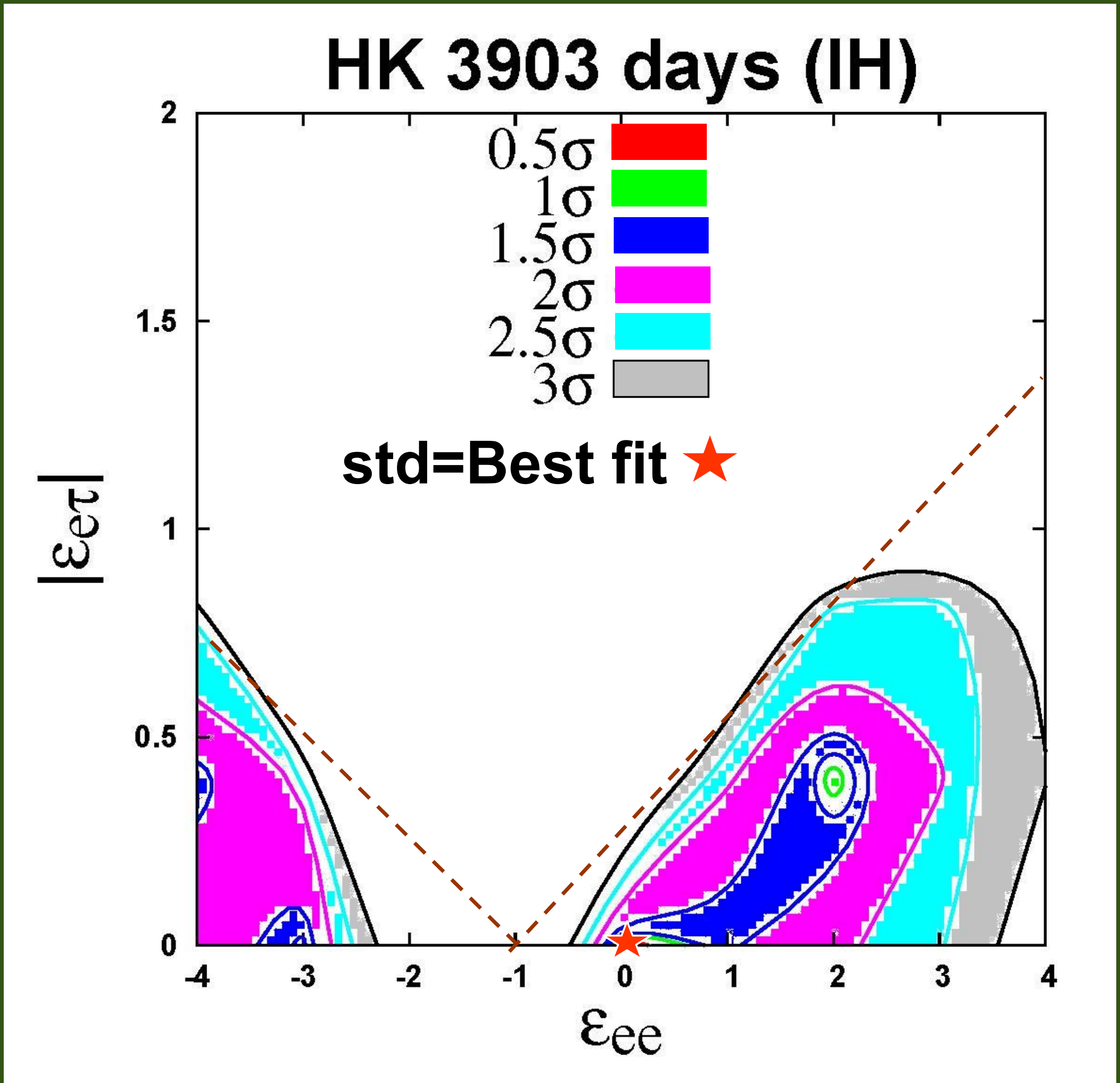
Sensitivity of HK to ε_{ee}, | $\varepsilon_{e\tau}$ |

Fukasawa-OY (Preliminary)



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

- #(events) with standard scheme are assumed
- The region | $\varepsilon_{e\tau}$ | >1 is excluded. The 2.5σ excluded region is tanβ<0.3.



HK 3903 days (IH)
0.5σ
1σ
1.5σ
2σ
2.5σ
3σ
std=Best fit ★
|εeτ|
εee
2
1.5
1
0.5
0
-4
-3
-2
-1
0
1
2
3
4

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.

- While we have been unable to reproduce SK MC results completely, updated SK ν_{atm} data ($\tan\beta<0.8$@2.5σCL) improve the constraints previously obtained by Friedland-Lunardini in 2005 ($\tan\beta<1.5$@2.5σCL).

- Future observations of ν_{atm} at HK are expected to improve the constraint further ($\tan\beta<0.3$@2.5σCL). Improvement of the constraint on ε_{ee} seems hard.