Search for Non-Standard Interactions by ν atm

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1. Introduction

The status of standard 3 flavor ν oscillation

All 3 mixing angles have been measured in 2012.

GOAL for framework of standard 3 flavor ν

⇨ To measure Dirac CP phase and sign(Δm^2_{31}).

Future high-intensity long-baseline experiments (T2HK,LBNO,LBNE etc.) may be able to measure these quantities.

Motivation for research on New Physics

Neutrinos are the least tested particles of the Standard Model (SM). It may be possible to obtain a clue of physics beyond the Standard Model (BSM).

High precision measurements of ν oscillation in the future experiments can bring us to a new stage in which physics beyond the Standard Model is searched by looking at deviation form SM+massive ν.

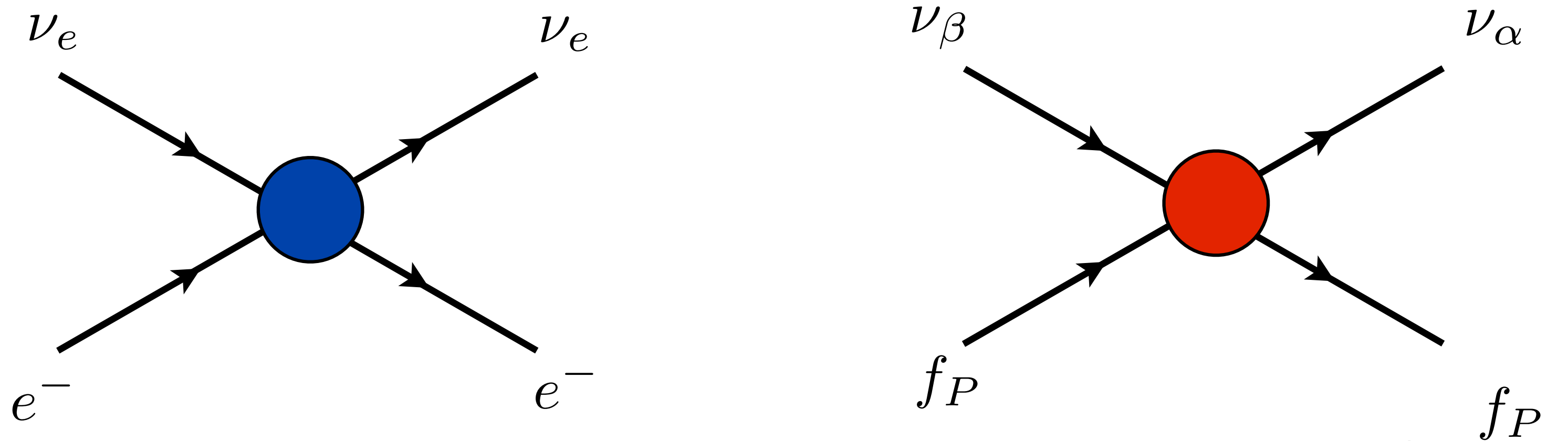
⇨We consider **flavor-dependent exotic couplings of neutrinos with matter**.

This phenomenological New Physics for the neutrino sector is less constrained by experiments than that for the charged lepton sector.

2. New Physics

Neutral current Non-Standard Interactions (NSI), which cause additional matter effects, are expressed by effective 4-fermi interactions:

$$\mathcal{L}_{NP} = -2\sqrt{2}G_F[\bar{\nu}_\alpha\gamma^\mu\nu_\beta][\epsilon^{f_L}_{\alpha\beta}\bar{f}_L\gamma_\mu f_L + \epsilon^{f_R}_{\alpha\beta}\bar{f}_R\gamma_\mu f_R].$$



standard interactions

neutral current NSI

MSW effects

additional matter effects

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = [U\mathcal{E}U^{-1} + \boxed{\mathcal{A}} + \boxed{\mathcal{A}_{\mathcal{NP}}}]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\mathcal{E} = \mathrm{diag}(0, \frac{\Delta m^2_{21}}{2E}, \frac{\Delta m^2_{31}}{2E})$$

$$\mathcal{A} = \mathrm{diag}(A_{cc}, 0, 0)$$

$$A_{\mathrm{CC}} = \sqrt{2}G_F n_e$$

$$\mathcal{A}_{NP} = A_{\mathrm{CC}}\begin{pmatrix}\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}$$

$$\epsilon_{\alpha\beta} = \sum_{P=L,R}\sum_{f=e,u,d}\epsilon^{f_P}_{\alpha\beta}n_f/n_e$$

n_f : number density of f

Matter effects affect the oscillation probability when the baseline is longer and the neutrino energy is for 10 GeV < E < 100 GeV.

⇨ **SK and HK**

3. Constraints on NSI

Constraints from terrestrial experiments

$$\begin{pmatrix}|\epsilon_{ee}| < 4\times10^0 & |\epsilon_{e\mu}| < 3\times10^{-1} & |\epsilon_{e\tau}| < 3\times10^0\\ & |\epsilon_{\mu\mu}| < 7\times10^{-2} & |\epsilon_{\mu\tau}| < 3\times10^{-1}\\ & & |\epsilon_{\tau\tau}| < 2\times10^1\end{pmatrix}$$

$$\boxed{|\epsilon_{e\mu}| \ll 1,\ |\epsilon_{\mu\mu}| \ll 1,\ |\epsilon_{\tau\mu}| \ll 1}$$

There are rooms for improvement.

Constraints from high energy behavior of ν_{atm}

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = [\underline{U\mathcal{E}U^{-1}} + \underline{\mathcal{A} + \mathcal{A}_{\mathcal{NP}}}]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

vacuum term

matter effects term

High energy ν atm data are well described by the vacuum oscillation term.

⇨ $$\boxed{\epsilon_{\tau\tau} \simeq \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}}$$

Alexander Friedland, Cecilia Lunardini, Michele Maltoni
arXiv:hep-ph/0408264

Since the vacuum term scales as 1/E, the matter effects term is dominant at high energy.

Even though the oscillation probability is changed significantly, large effects of $\varepsilon_{\tau\tau}$ can be consistent with the existing data.

We analyze with the ansatz as follows :

$$\mathcal{A}_{NP} = A_{\mathrm{CC}}\begin{pmatrix}1+\epsilon_{ee} & 0 & \epsilon_{e\tau}\\ 0 & 0 & 0\\ \epsilon^*_{e\tau} & 0 & \epsilon_{\tau\tau}\end{pmatrix} = A_{\mathrm{CC}}\begin{pmatrix}1+\epsilon_{ee} & 0 & |\epsilon_{e\tau}|e^{i\phi}\\ 0 & 0 & 0\\ |\epsilon_{e\tau}|e^{-i\phi} & 0 & \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}\end{pmatrix}.$$

4. Analysis

Super-K $$\chi^2(\epsilon_{ee}, |\epsilon_{e\tau}|) = \min[\sum_j \frac{\{N^0_j(\epsilon_{ee}, \epsilon_{e\tau}) - N_j(data)\}^2}{\sigma^2_j}$$

Hyper-K $$\chi^2(\epsilon_{ee}, |\epsilon_{e\tau}|) = \min[\sum_j \frac{\{N^0_j(\epsilon_{ee}, \epsilon_{e\tau}) - N_j(standard)\}^2}{\sigma^2_j}$$

#events@HK = 20 x #events@SK (std. case is assumed)

parameters

fixed : $\theta_{12}, \theta_{13}, \Delta m^2_{21}$
marginalized : $\theta_{23}, \Delta m^2_{31}, \delta, \arg(\varepsilon_{e\tau})$

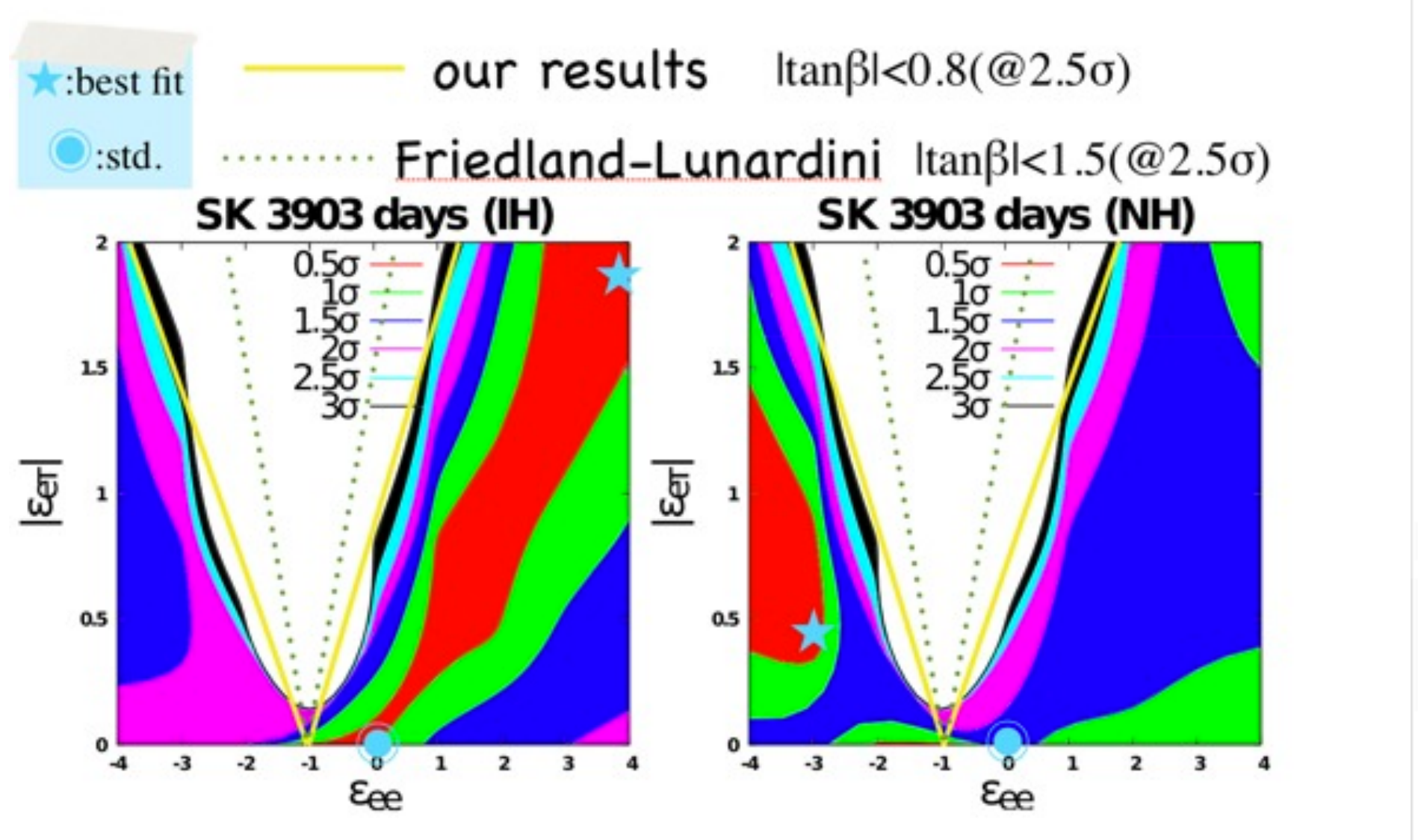
We set fixed vacuum oscillation parameters as
$\sin^2 2\theta_{12}=0.86$, $\sin^2 2\theta_{13}=0.1$, $\Delta m^2_{21}=7.6\times10^{-5}\mathrm{eV}^2$.

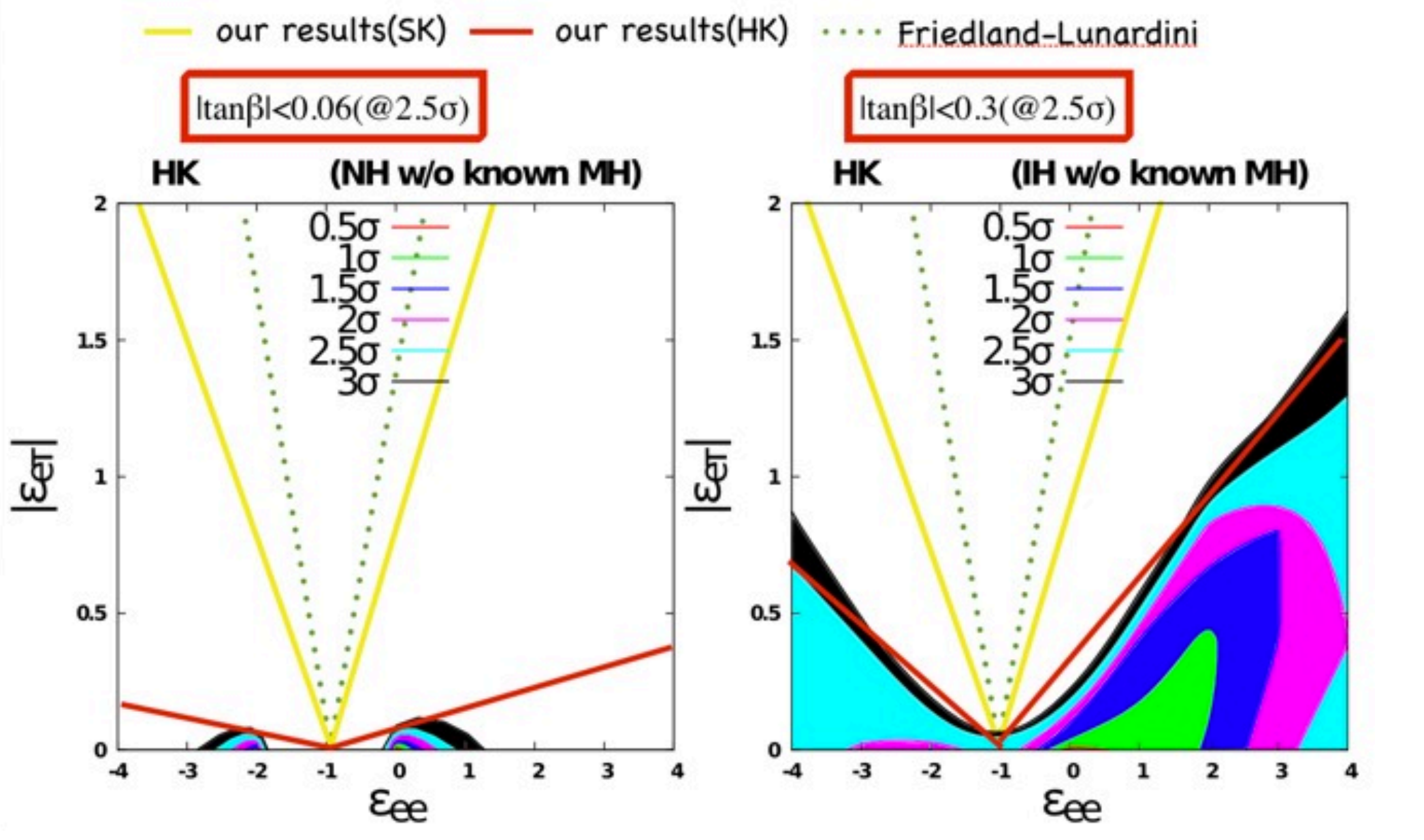
For the purpose of obtaining a 2-dimensional allowed region, χ^2 was marginalized over $\theta_{23}, \Delta m^2_{31}, \delta, \arg(\varepsilon_{e\tau})$.

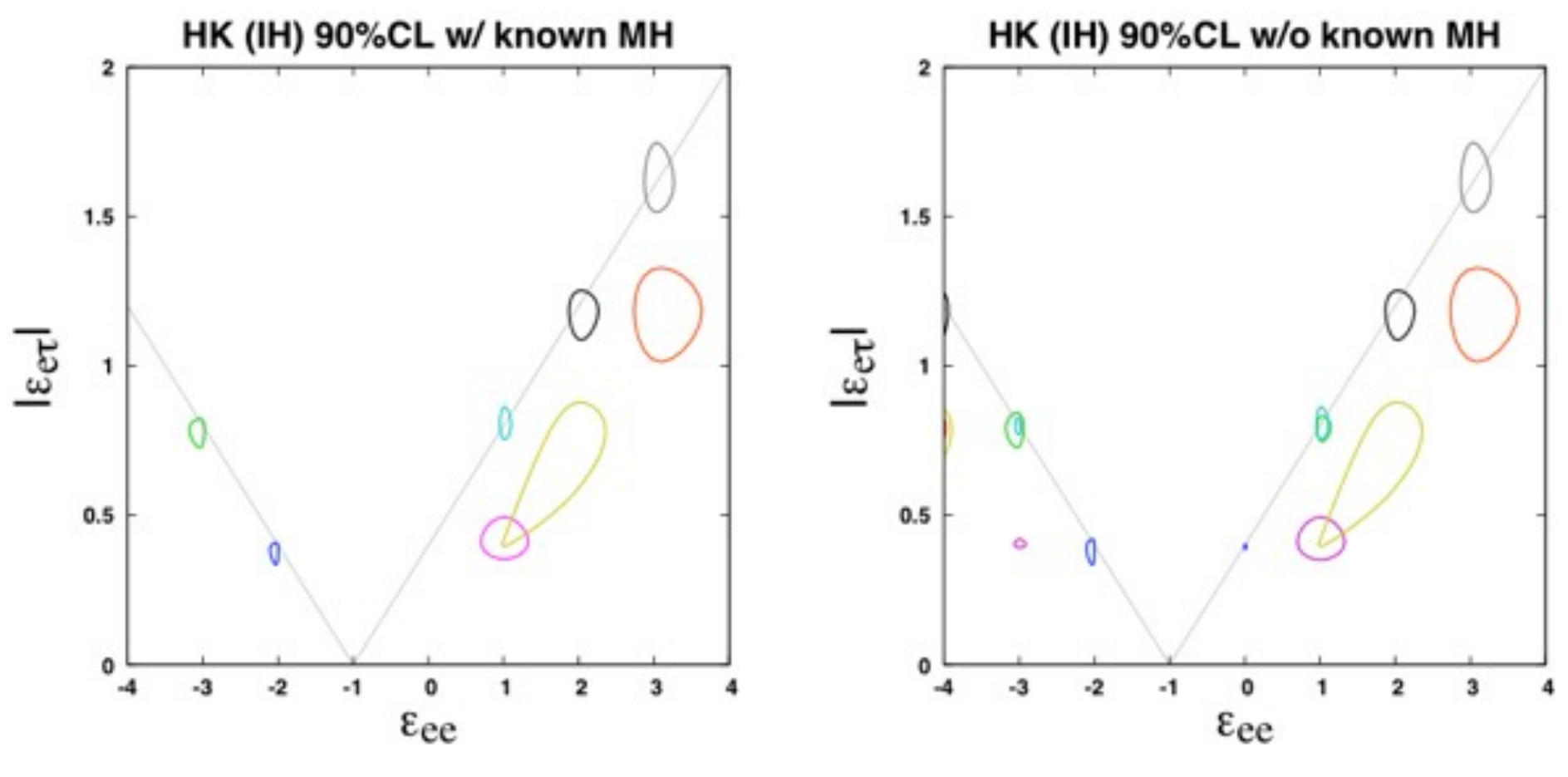
systematic errors

Uncertainties we considered are as follows :
$\sigma(\nu_{\mathrm{atm}}\ \mathrm{flux})=\infty$, σ(Sub-GeV/Multi-GeV)=10% , $\sigma(e/\mu)_{\mathrm{sub}}$=10%, $\sigma(e/\mu)_{\mathrm{multi}}$=10% , $\sigma(\bar{\nu}/\nu)_{\mathrm{sub}}=\sigma(\bar{\nu}/\nu)_{\mathrm{multi}}$=10%.

5. Results







Although updated data of SK (3903 days) were used, large NSI are not excluded. In addition standard case is not best fit. The reason that scenario with New Physics are preferred may be because we have not reproduced SK MC results completely. However, the exclude region is improved compared with old one given by Friedland-Lunardini in 2005. The region $|\varepsilon_{e\tau}|>1$ is excluded. The excluded region by HK is improved compared with SK.

6. Conclusions

・Considering constraints from terrestrial experiments and high energy behavior of ν_{atm}, we set the ansatz :

$$\varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0\ \&\ \varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee}).$$

Under the ansats we studied sensitivity to NIS of ν_e-ν_τ sector in propagation at SK and HK.

・The excluded region at SK is improved compared with old one given by Friedland-Lunardini in 2005.

・ The excluded region at HK are obtained and HK are expected to improve constraints.

・ We studied sensitivity to non-zero NSI at HK. If NSI are sufficiently large, HK can determine ε_{ee} and $|\varepsilon_{e\tau}|$ to some extent.