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

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Based on arXiv:1608.05897 Fukasawa, OY
1. Introduction

2. New Physics in propagation

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

4. Conclusions
1. Introduction

Framework of 3 flavor $\nu$ oscillation

Mixing matrix

$$

\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}

$$

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

All 3 mixing angles have been measured (2012):

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

$\theta_{12} \approx \frac{\pi}{6}, |\Delta m^2_{21}| \approx 8 \times 10^{-5} \text{eV}^2$

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

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

$\nu_{\text{DCHOOZ+Daya Bay+Reno (reactors)}, T2K+MINOS, others}$

$\theta_{13} \approx \pi / 20$
Both mass hierarchies are allowed

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

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

$\rightarrow$ Research on New Physics is important.
### Phenomenological scenarios of New Physics

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

Scenarios with **Non Standard Interactions in propagation** could exhibit the largest effect.
Motivation for Non Standard Interaction in $\nu$ propagation

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

Best fit value of global fit

\[
(\epsilon_D^u, \epsilon_N^u) = (-0.140, -0.030)
\]
\[
(\epsilon_D^d, \epsilon_N^d) = (-0.145, -0.036)
\]

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

Gonzalez-Garcia, Maltoni, JHEP 1309 (2013) 152
Aim of this talk

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

We assume:
true scenario = standard 3-flavor mixing
test scenario = best fit point w/ NSI suggested by the global analysis including solar $\nu$ 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:

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

Modification of matter effect

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

\[ A \equiv \sqrt{2} G_F N_e \quad N_e \equiv \text{electron density} \]
• 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

$$
\begin{pmatrix}
|\varepsilon_{ee}| \lesssim 4 \times 10^0 \\
|\varepsilon_{e\mu}| \lesssim 3 \times 10^{-1} \\
|\varepsilon_{\mu\mu}| \lesssim 7 \times 10^{-2} \\
|\varepsilon_{e\tau}| \lesssim 3 \times 10^0 \\
|\varepsilon_{\mu\tau}| \lesssim 3 \times 10^{-1} \\
|\varepsilon_{\tau\tau}| \lesssim 2 \times 10^1
\end{pmatrix}
$$
Constraints from high energy $\nu_{atm}$ data

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

high energy $\nu_{atm}$ 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

Friedland-Lunardini, PRD72 (‘05) 053009
Summary of the constraints on $\varepsilon_{\alpha\beta}$

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

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

Furthermore, $\nu_{atm}$ data implies

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

Fukasawa-OY, arXiv:1607.03758

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

$$-4 \lesssim \varepsilon_{ee} \lesssim 4, \quad |\varepsilon_{e\tau}| \lesssim 3, \quad |\varepsilon_{\tau\tau}| = \frac{|\varepsilon_{e\tau}|^2}{|1 + \varepsilon_{ee}|} \lesssim 2$$
NSI for solar $\nu$: $\varepsilon_{\alpha\beta}$ vs $(\varepsilon_D, \varepsilon_N)$

In solar $\nu$ analysis, $\Delta m_{31}^2 \to \infty$, $H \to H^{\text{eff}}$

$$H^{\text{eff}} = \frac{\Delta m_{21}^2}{4E} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \begin{pmatrix} c_{13}^2 A & 0 \\ 0 & 0 \end{pmatrix} + A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\varepsilon_D^f & \varepsilon_N^f \\ \varepsilon_N^f & \varepsilon_D^f \end{pmatrix}$$

\[
\varepsilon_D^f = c_{13}s_{13}\text{Re} \left[ e^{i\delta_{\text{CP}}} (s_{23}\varepsilon_{e\mu}^f + c_{23}\varepsilon_{e\tau}^f) \right] - (1 + s_{13}^2) c_{23}s_{23}\text{Re} \left[ \varepsilon_{\mu\tau}^f \right] - \frac{c_{13}^2}{2} (\varepsilon_{ee}^f - \varepsilon_{\mu\mu}^f) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} (\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f)
\]

\[
\varepsilon_N^f = c_{13} \left( c_{23}\varepsilon_{e\mu}^f - s_{23}\varepsilon_{e\tau}^f \right) + s_{13}e^{-i\delta_{\text{CP}}} \left[ s_{23}^2 \varepsilon_{\mu\tau}^f - c_{23}^2 \varepsilon_{\mu\mu}^f + c_{23}s_{23} (\varepsilon_{\tau\tau}^f - \varepsilon_{\mu\mu}^f) \right]
\]

$\varepsilon_{ee}$, $|\varepsilon_{e\tau}|$, $\varepsilon_{\tau\tau}$ have to be solved from $(\varepsilon_D, \varepsilon_N)$
Relation between $\varepsilon_{\alpha\beta}$ & $(\varepsilon_D, \varepsilon_N)$

For simplicity consider

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

Then the relation is simplified.

\[
\begin{align*}
\varepsilon^f_D &= c_{13} s_{13} \text{Re} \left[ e^{i\delta_{CP}} \left( s_{23} \varepsilon^f_{e\mu} + c_{23} \varepsilon^f_{e\tau} \right) \right] - \left( 1 + s_{13}^2 \right) c_{23} s_{23} \text{Re} \left[ \varepsilon^f_{\mu\tau} \right] \\
&\quad - \frac{c_{13}^2}{2} \left( \varepsilon^f_{ee} - \varepsilon^f_{\mu\mu} \right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} \left( \varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu} \right) \\
\varepsilon^f_N &= c_{13} \left( c_{23} \varepsilon^f_{e\mu} - s_{23} \varepsilon^f_{e\tau} \right) + s_{13} e^{-i\delta_{CP}} \left[ s_{23}^2 \varepsilon^f_{\mu\tau} - c_{23}^2 \varepsilon^{f*}_{\mu\tau} + c_{23} s_{23} \left( \varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu} \right) \right]
\end{align*}
\]

For simplicity take $f=d$; $\varepsilon^f_D$, $\varepsilon^f_N$

$\rightarrow \varepsilon^d_D = \varepsilon_D$, $\varepsilon^d_N = \varepsilon_N$

$\nu_{\text{atm}}$ sees only

$\varepsilon_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + 3 \varepsilon^{u}_{\alpha\beta} + 3 \varepsilon^{d}_{\alpha\beta} \rightarrow 3 \varepsilon^{d}_{\alpha\beta}$
The allowed region in the limit $\theta_{23} = \pi/4$, $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|^2/(1+\epsilon_{ee})$

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

$\nu_{\text{atm}}$ data: $|\tan \beta| < 0.8$ @2.5$\sigma$CL

Introducing a new variable:

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

one can show

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

$\nu_{\text{atm}}$ data: $|\tan 2\beta'| < 1.3$ @2.5$\sigma$CL
3. Sensitivity of $\nu_{\text{atm}}$ at 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

Our ansatz

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

Black : standard  Red : non-standard

\begin{align*}
\Delta \chi^2_{ee, e\tau} &= \min_{\text{parameters}} \sum_i \left[ N_i^0 (\mathcal{E}_{\alpha\beta}) - N_i^{(\text{std})} \right]^2 + \chi^2_{\text{prior}} \\
\chi^2_{\text{prior}} &= \Delta \chi^2_{\text{prior}} \frac{|\epsilon_{e\mu}|^2}{|\delta \epsilon_{e\mu}|^2} + \Delta \chi^2_{\text{prior}} \frac{|\epsilon_{\mu\tau}|^2}{|\delta \epsilon_{\mu\tau}|^2}
\end{align*}

Parameters

Fixed: $\theta_{12}, \theta_{13}, \Delta m^2_{21}$

Marginalized: $\theta_{23}, \Delta m^2_{31}, \delta, |\epsilon_{e\mu}|, |\epsilon_{\mu\tau}|, \arg(\epsilon_{e\tau}), \arg(\epsilon_{e\mu}), \arg(\epsilon_{\mu\tau})$

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

$\#(\text{events})_{\text{HK}} = 20 \times \#(\text{events})_{\text{SK}}$
1. Set a grid on \((\varepsilon_D, |\varepsilon_N|)\) plane.
2. Calculate a parameter set \(\varepsilon_{ee}, |\varepsilon_{e\tau}|, \varepsilon_{\tau\tau}\) for the given point \((\varepsilon_D, |\varepsilon_N|)\) on the grid varying \(\Delta m^2_{31}, \theta_{23}, \delta_{CP}, |\varepsilon_{e\mu}|, |\varepsilon_{\mu\tau}|, \arg(\varepsilon_N), \arg(\varepsilon_{e\tau}), \arg(\varepsilon_{e\mu}),\) and \(\arg(\varepsilon_{\mu\tau})\).
3. Dismiss the parameter set if it does not satisfy any one of the following criteria:
   \[
   |\varepsilon_{e\tau}| \leq 1.5 \quad |\varepsilon_{ee} - \varepsilon_{\mu\mu}| \leq 2.0 \quad |\min (\lambda_{e'}, \lambda_{\tau'})| \leq 0.2
   \]
4. Calculate \(\chi^2\) for each parameter set which passed the criteria mentioned above and then obtain the minimum value of \(\chi^2\) for the given \((\varepsilon_D, |\varepsilon_N|)\).

\(\nu_{atm}\) sees only \(\varepsilon_{\alpha\beta} = \varepsilon_{e\alpha\beta} + 3\varepsilon_{u\alpha\beta} + 3\varepsilon_{d\alpha\beta} \rightarrow 3\varepsilon_{d\alpha\beta}\)
Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for NH

Best fit point of solar & KamLAND for $f=u$: significance: $38\sigma$

Best fit point of solar & KamLAND for $f=d$: significance: $11\sigma$

Best fit point of global analysis for $f=u$: significance: $5\sigma$

Best fit point of global analysis for $f=d$: significance: $5\sigma$
Sensitivity of HK: (1) Complex $|\varepsilon_N|$ for IH

Best fit point of solar & KamLAND for $f=u$:
significance: $35\sigma$

Best fit point of solar & KamLAND for $f=d$:
significance: $8\sigma$

Best fit point of global analysis for $f=u$:
significance: $1.4\sigma$

Best fit point of global analysis for $f=d$:
significance: $1.5\sigma$

$(\varepsilon^u_D, \varepsilon^u_N) = (-0.22, -0.30)$

$(\varepsilon^d_D, \varepsilon^d_N) = (-0.12, -0.16)$

$(\varepsilon^u_D, \varepsilon^u_N) = (-0.140, -0.030)$
Sensitivity of HK: (2) Real $|\varepsilon_N|$ 

Allowed regions and significance are similar to the case for complex $\varepsilon_N$
4. Conclusions

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

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

- NSI which was suggested by $\nu_{solar}$ ($E\sim10\text{MeV}$) may be detected by $\nu_{atm}$ ($E\sim10\text{GeV}$) at HK through the matter effect.
Backup slides
Relation between $\varepsilon_{\alpha\beta}$ & ($\varepsilon_D$, $\varepsilon_N$)

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

$$\begin{align*}
3\varepsilon_D &= -\frac{1}{2}\varepsilon_{ee} + \frac{1}{4}\varepsilon_{\tau\tau} \\
3\varepsilon_N &= -\frac{1}{\sqrt{2}}\varepsilon_{e\tau}.
\end{align*}$$

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

If $1 + \varepsilon_{ee} > 0$ $\varepsilon_{\tau\tau} > 0$, then $\lambda_{e'} > \lambda_{\tau'}$
In the case of $\lambda_{\tau'} \neq 0$

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

$\epsilon_{\tau\tau}$ 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 $\alpha \neq 0$, the x-intercept shifts:

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

$$\tan 2\beta' = \frac{|3\varepsilon N|}{1/2 - 3\varepsilon D - \alpha/4}$$

$$\tan \beta' \equiv \frac{\tan \beta}{\sqrt{2}}$$
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 $(\varepsilon_D, |\varepsilon_N|)$-plane.

Difference with our previous work  
(Fukasawa-OY, arXiv:1607.03758)
Behaviors of $\chi^2 (NH)$ for multi-GeV: Rate VS Spectrum for $\epsilon_{ee} = 0$

Destructive phenomenon between Low & High energy bins $\rightarrow$ Information on energy spectrum is important
Behaviors of $\chi^2$ (IH) for multi-GeV: $\nu + \overline{\nu}$ vs individual $\nu$ & $\overline{\nu}$ for $\varepsilon_{e\tau} = 0$

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