Possibility to probe new physics in the future long baseline neutrino experiments

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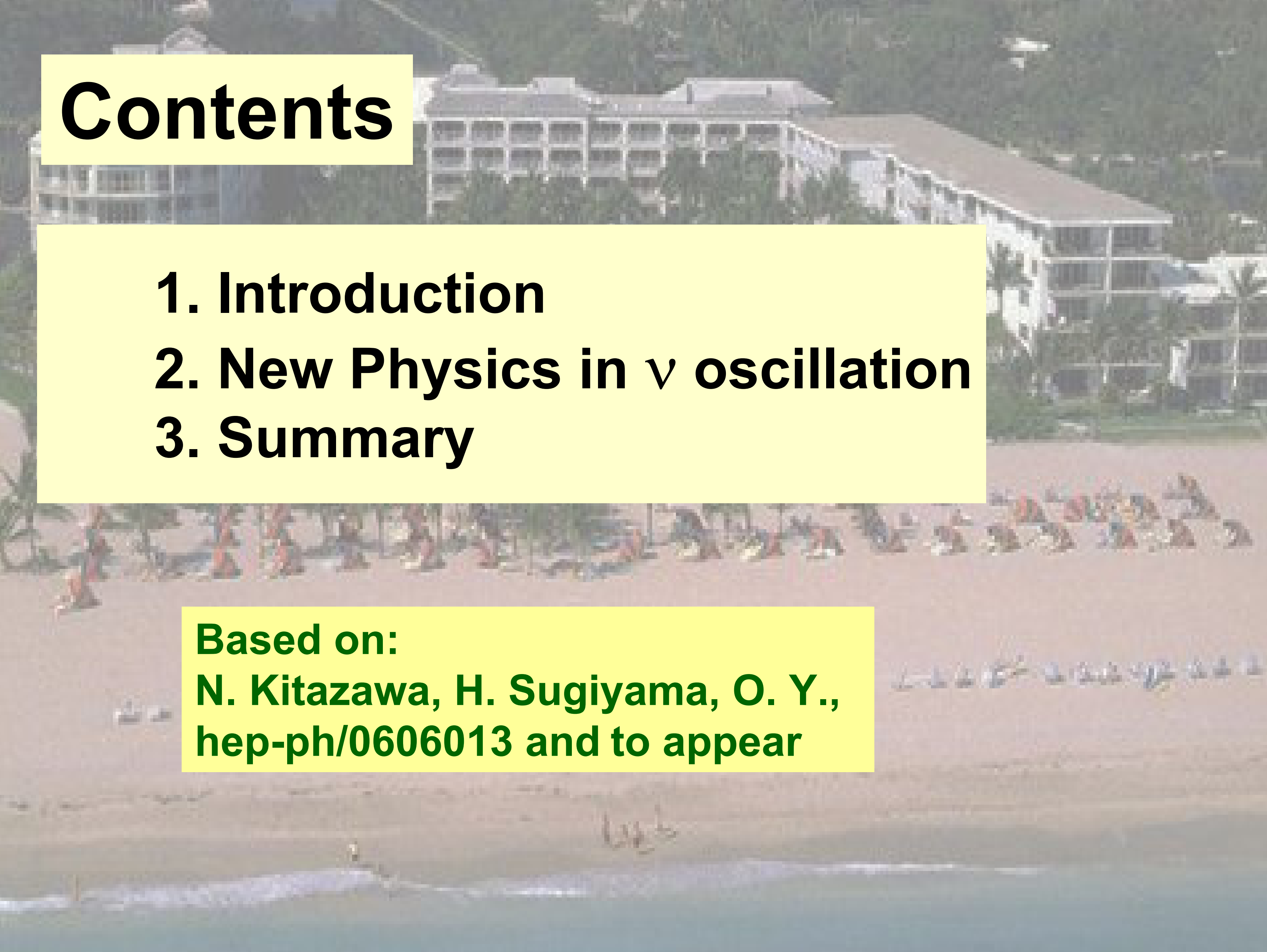
13 December 2006@Lago Mar Resort



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Based on:
N. Kitazawa, H. Sugiyama, O. Y.,
hep-ph/0606013 and to appear

1. Introduction

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

Information we have obtained so far:

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

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

CHOOZ (reactor) → $|\theta_{13}| \lesssim \sqrt{0.15}/2$

Mixing matrix has been roughly determined:

$$U=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\cong\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2}\\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2}\end{pmatrix}$$

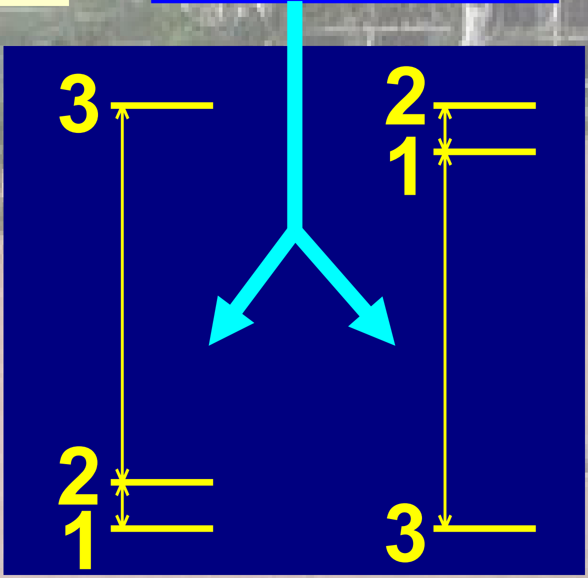
$\theta_{12}\cong\pi/6$

- Both mass hierarchies are allowed

However,

- θ_{13} :only upper bound is known
- δ :undetermined

Next task is to measure θ_{13} , sign(Δm^2_{31}) and δ



normal hierarchy

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

inverted hierarchy

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

Most realistic way to measure θ_{13} , sign(Δm^2_{31}) and δ is long baseline experiments by accelerators or reactors.

Future LBL experiments

To perform precise measurements of θ_{13} and δ, one has to have a lot of numbers of events to reduce statistical errors.

→We need **high intensity** beams

Candidates for high intensity beam in the future:

- (conventional) superbeam

$$\begin{cases} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \end{cases} \qquad \begin{matrix} \boxed{\nu_\mu \rightarrow \nu_e} \\ \boxed{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} \end{matrix}$$

- neutrino factory

  μ in a storage ring

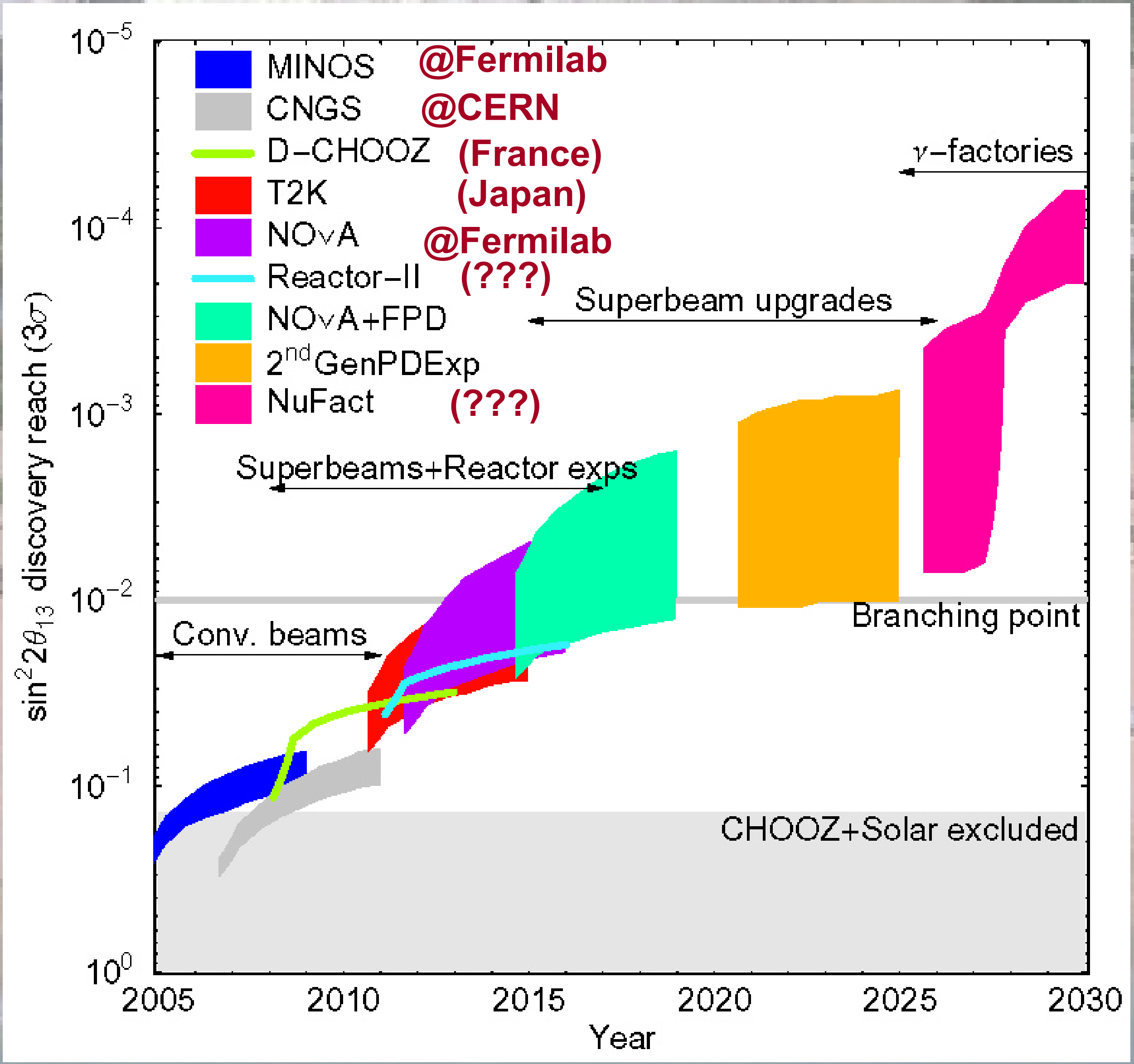
$$\begin{cases} \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{cases} \qquad \begin{matrix} \boxed{\nu_e \rightarrow \nu_\mu} \\ \boxed{\bar{\nu}_e \rightarrow \bar{\nu}_\mu} \end{matrix}$$

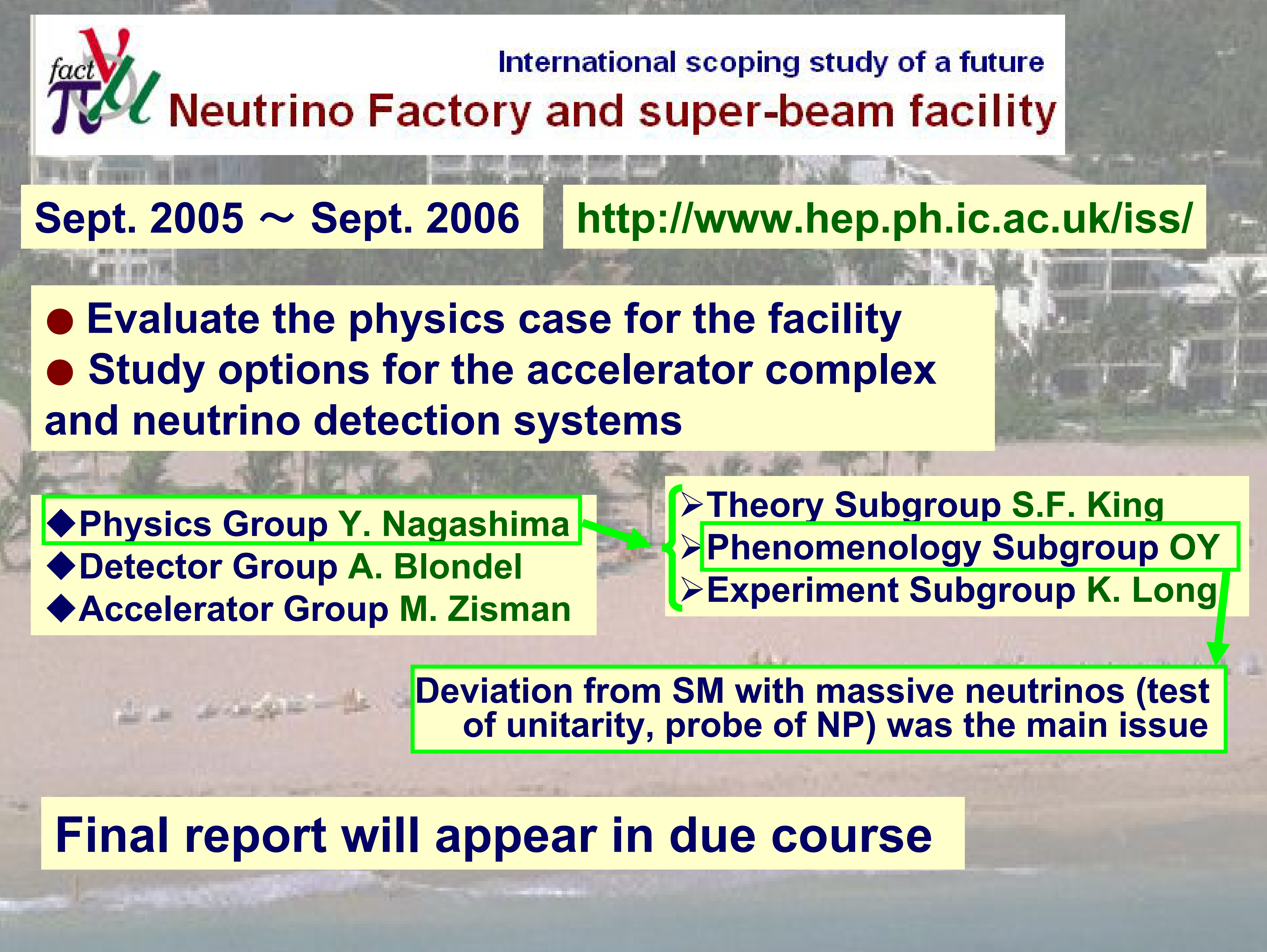
- beta beam

  RI in a storage ring

$$\begin{cases} {}^{6}_{2}\mathrm{He} \rightarrow {}^{6}_{3}\mathrm{Li} + e^- + \bar{\nu}_e \\ {}^{18}_{10}\mathrm{Ne} \rightarrow {}^{18}_{9}\mathrm{F} + e^+ + \nu_e \end{cases} \qquad \begin{matrix} \boxed{\bar{\nu}_e \rightarrow \bar{\nu}_\mu} \\ \boxed{\nu_e \rightarrow \nu_\mu} \end{matrix}$$

Example of expected sensitivity and time scale (FERMILAB-FN-0778-AD-E (=hep-ex/0509019))





International scoping study of a future Neutrino Factory and super-beam facility

Sept. 2005 ～ Sept. 2006

http://www.hep.ph.ic.ac.uk/iss/

- **Evaluate the physics case for the facility**
- **Study options for the accelerator complex and neutrino detection systems**

- **Physics Group Y. Nagashima**
- **Detector Group A. Blondel**
- **Accelerator Group M. Zisman**

- **Theory Subgroup S.F. King**
- **Phenomenology Subgroup OY**
- **Experiment Subgroup K. Long**

Deviation from SM with massive neutrinos (test of unitarity, probe of NP) was the main issue

Final report will appear in due course

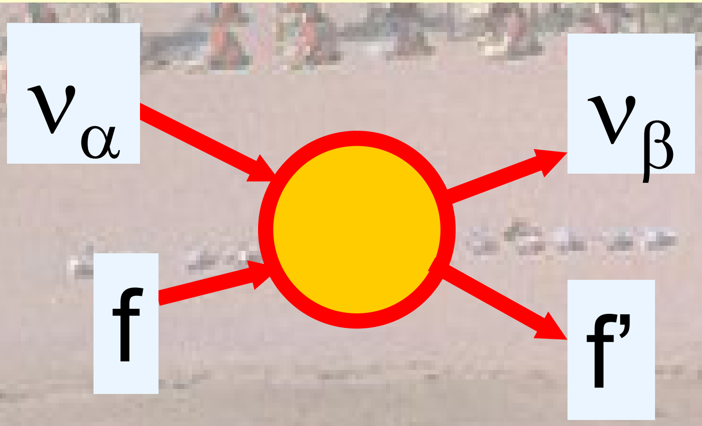
2. New Physics in ν oscillation

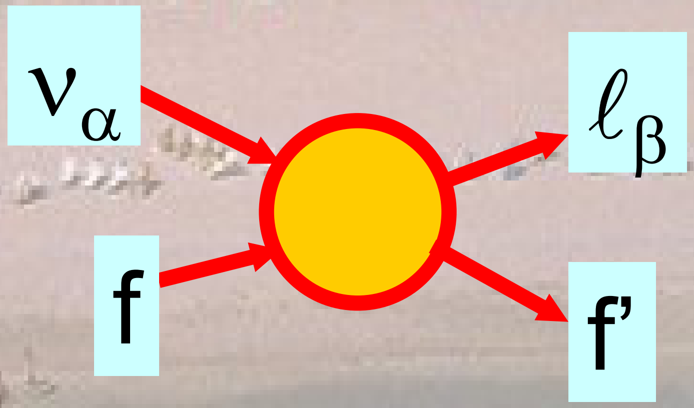
Just like at B factories, high precision measurements of ν oscillation can be used also to probe physics beyond SM by looking at from deviation from SM+masssive ν

Here we study phenomenologically new physics which is described by exotic interactions:

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

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



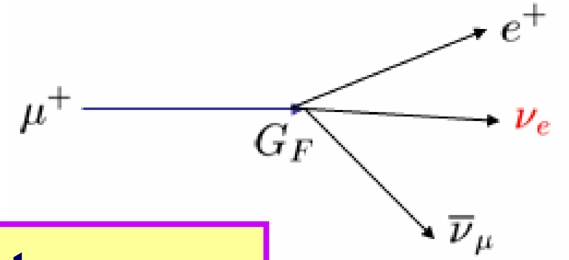


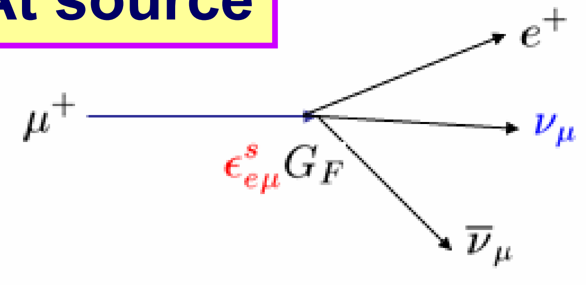
Effects of New Physics at source and detector

$$\mathcal{L}_{NP} = G_N^{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\ell_\beta\bar{f}\gamma_\mu f'$$

Grossman (PLB359:141,1995)

At source





$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_\mu^s$$

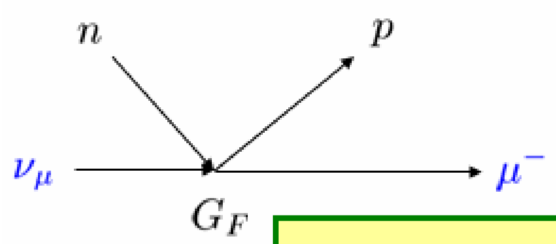
$$\nu_e^s = \nu_e + \epsilon^s_{e\mu}\nu_\mu$$

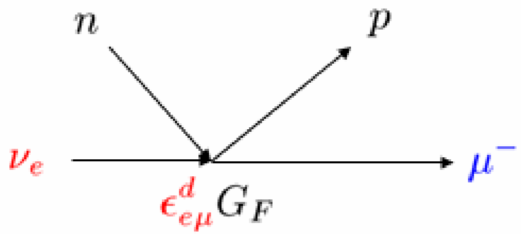
$$\begin{pmatrix} \nu_e^s \\ \nu_\mu^s \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^s_{e\mu} \\ -\epsilon^s_{e\mu} & 1 \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

Flavor basis is modified, but deviation is small:

all $|\varepsilon| < O(10^{-2})$

At detector





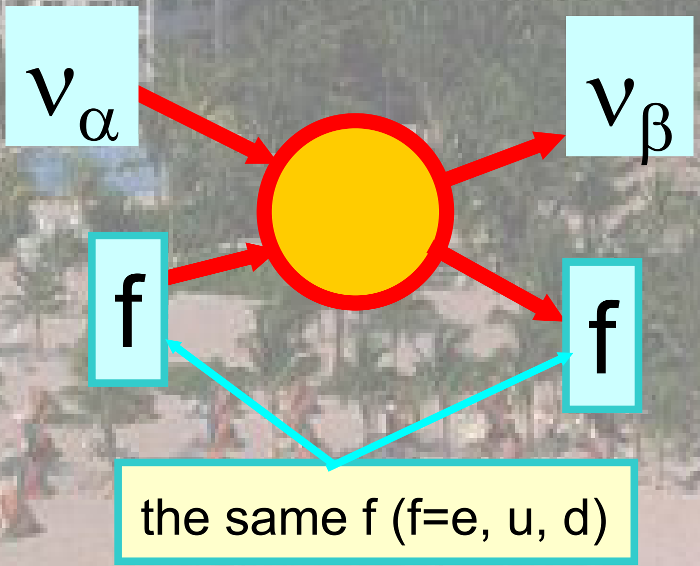
$$\nu_\mu^d + n \to \mu^- + p$$

$$\nu_\mu^d = \nu_\mu - \epsilon^d_{e\mu}\nu_e$$

$$\begin{pmatrix} \nu_e^d \\ \nu_\mu^d \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^d_{e\mu} \\ -\epsilon^d_{e\mu} & 1 \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

New Physics effects in propagation

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



the same f (f=e, u, d)

So-called MSW matter effect is modified and some of $\varepsilon_{\alpha\beta}$ can be O(1)

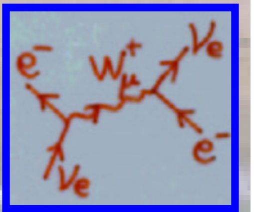
Potentially large effect may be expected

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

$$N_e \equiv \text{electron density}$$

potential due to CC int

additional potential $A\varepsilon_{\alpha\beta}$



SM

NP

$$\mathcal{A}_0 \equiv A\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \mathcal{A} \equiv A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Two constraints on $\varepsilon_{\alpha\beta}$ for NP effects in propagation

$$\mathcal{L}_{NP} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \bar{\nu}_\alpha \gamma^\mu \nu_\beta \left(\epsilon_{\alpha\beta}^{f\bar{f}L} \bar{f}_L \gamma_\mu f_L + \epsilon_{\alpha\beta}^{f\bar{f}R} \bar{f}_R \gamma_\mu f_R \right) + h.c.$$

①**Davidson et al (JHEP 0303:011,2003):** **Constraints from various ν experiments**

$$\epsilon_{\alpha\beta} \sim \epsilon_{\alpha\beta}^{e} + 3\epsilon_{\alpha\beta}^{u} + 3\epsilon_{\alpha\beta}^{d}$$

$$\begin{pmatrix} -3 \lesssim \epsilon_{ee} \lesssim 2 & |\epsilon_{e\mu}| \lesssim 0.5 & |\epsilon_{e\tau}| \lesssim 1.5 \\ |\epsilon_{e\mu}| \lesssim 0.5 & |\epsilon_{\mu\mu}| \lesssim 0.05 & |\epsilon_{\mu\tau}| \lesssim 0.15 \\ |\epsilon_{e\tau}| \lesssim 1.5 & |\epsilon_{\mu\tau}| \lesssim 0.15 & |\epsilon_{\tau\tau}| \lesssim 6 \end{pmatrix}$$

② Friedland-Lunardini (Phys.Rev.D72:053009,2005): Constraints from atmospheric neutrinos

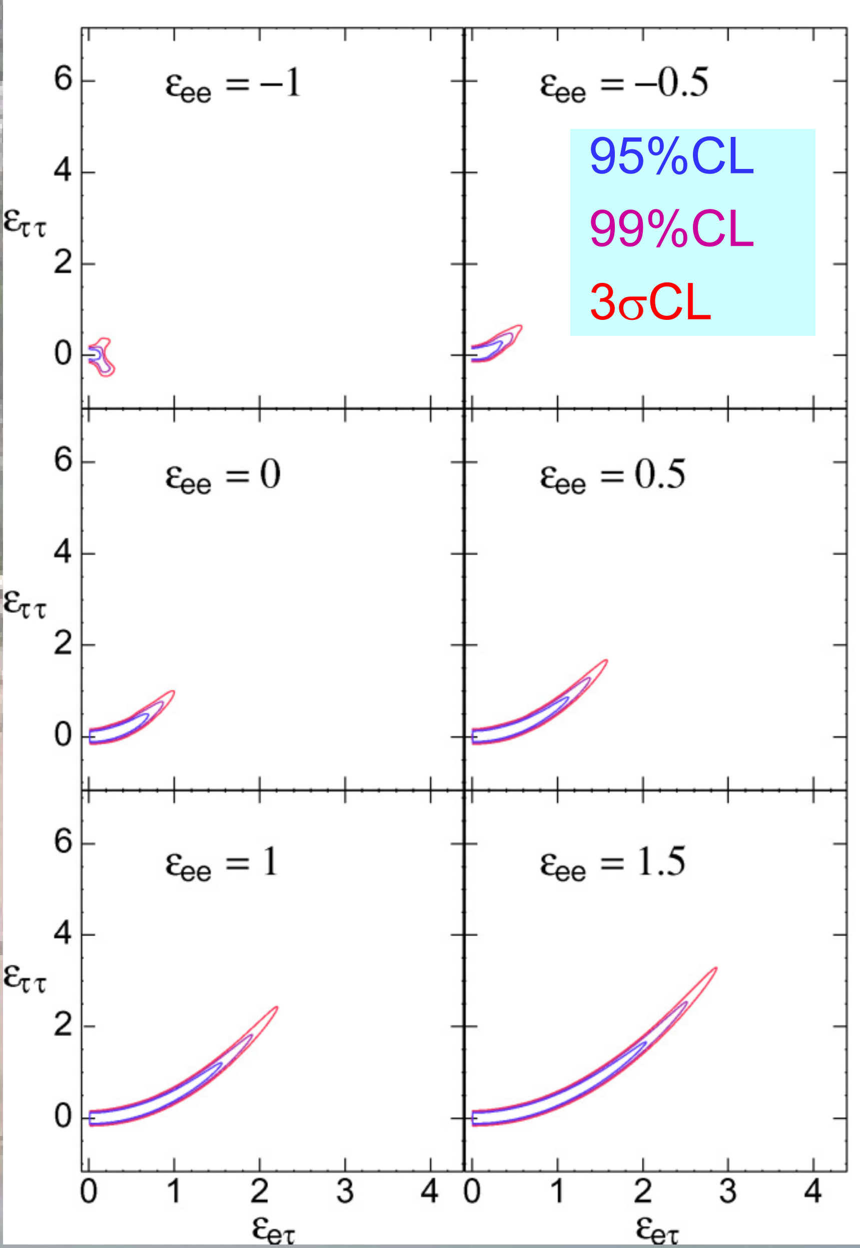
$$\epsilon_{\tau\tau} \sim \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$$

$$0 \le |\epsilon_{e\tau}| \lesssim 1 + \epsilon_{ee}$$

$$-1 \lesssim \epsilon_{ee} \lesssim 1.5$$

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ ~O(1) are consistent with atmospheric neutrino data

Basic reason that the constraints from ν_{atm} are so weak is because there are very few high energy e-like ν_{atm} data (as shown later, deviation of $\boxed{\nu_e \leftrightarrow \nu_\tau}$ oscillation with NP is significant at high energy)



Since the parameters $\varepsilon_{\alpha\beta}$ can be of O(1) only for New Physics in propagation, we will consider only NP in propagation here.

NP effects in propagation becomes important when baseline L is larger

because

oscillation probability $\propto \sin^2\left(\text{something} \times \varepsilon_{\alpha\beta} AL\right)$

where AL ~ L/2000km

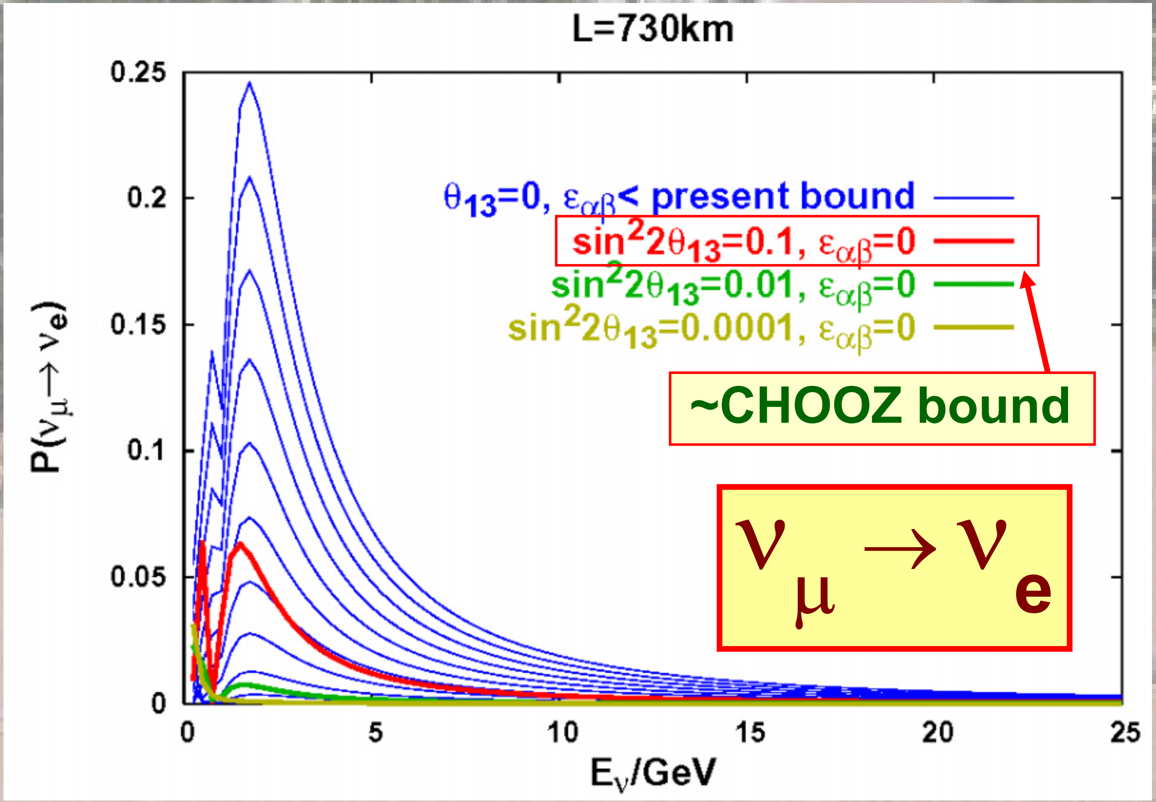
→ **Experiments with a longer baseline are advantageous**

Here we will discuss MINOS (L=730km) and ν factory (L=3000km)

Implications for ongoing experiments

MINOS (2005-)

Major channel is disappearance $(\nu_\mu \rightarrow \nu_\mu)$ but appearance $(\nu_\mu \rightarrow \nu_e)$ can be also measured



~CHOOZ bound

$\nu_\mu \rightarrow \nu_e$

Baseline L=730km is larger than K2K, so matter effect at MINOS plays a more important role than at K2K

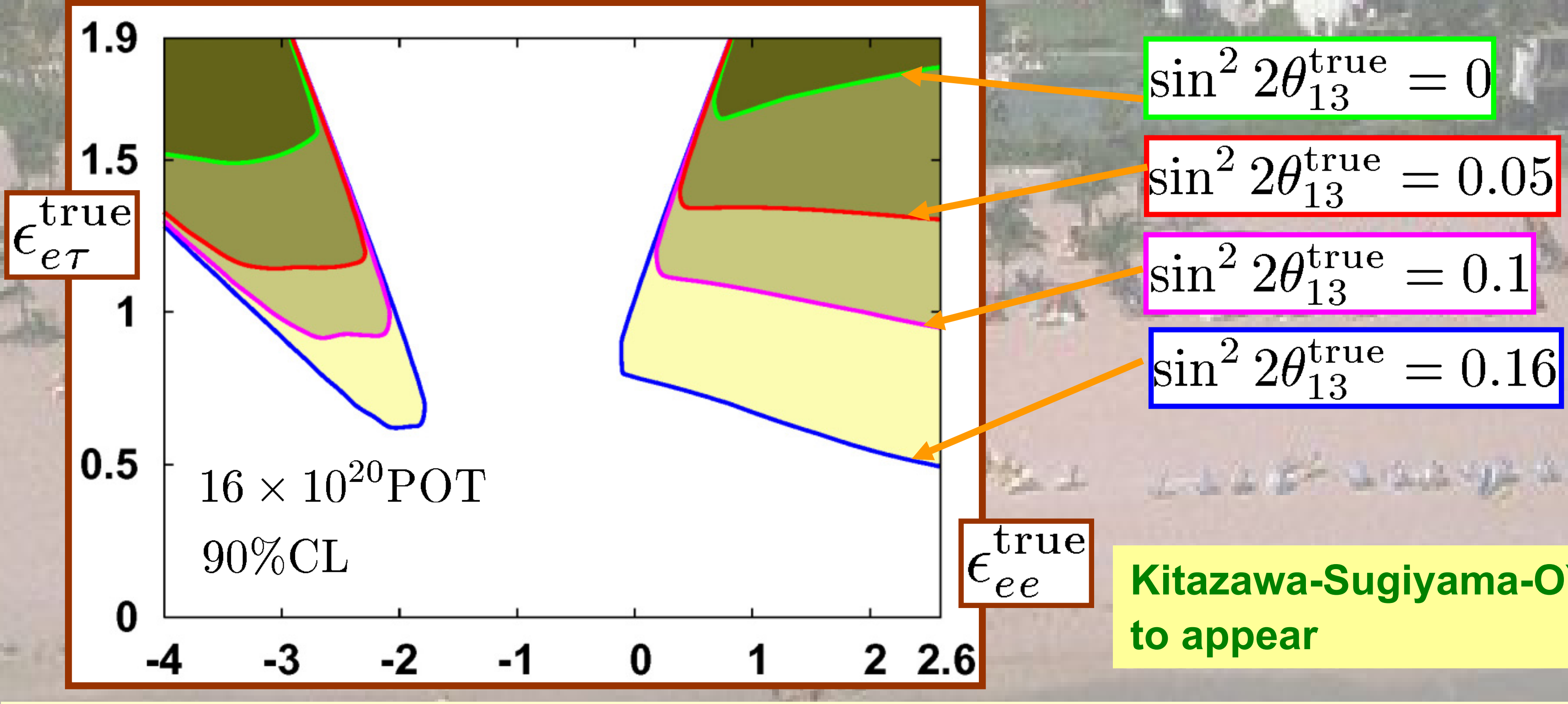
Kitazawa-Sugiyama-OY, hep-ph/0606013

For some values of ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ ~O(1) within the allowed region, there is enhancement in the channel $\nu_\mu \rightarrow \nu_e$ which cannot be explained only by the standard oscillation scenario with θ_{13}

MINOS

(1) In case MINOS observes ν_e events: If values of ε_{ee} and $\varepsilon_{e\tau}$ lie in a certain region, then MINOS can verify existence of NP

region where MINOS can prove $(\varepsilon_{ee}, \varepsilon_{e\tau}) \neq (0,0)$ for each θ_{13}

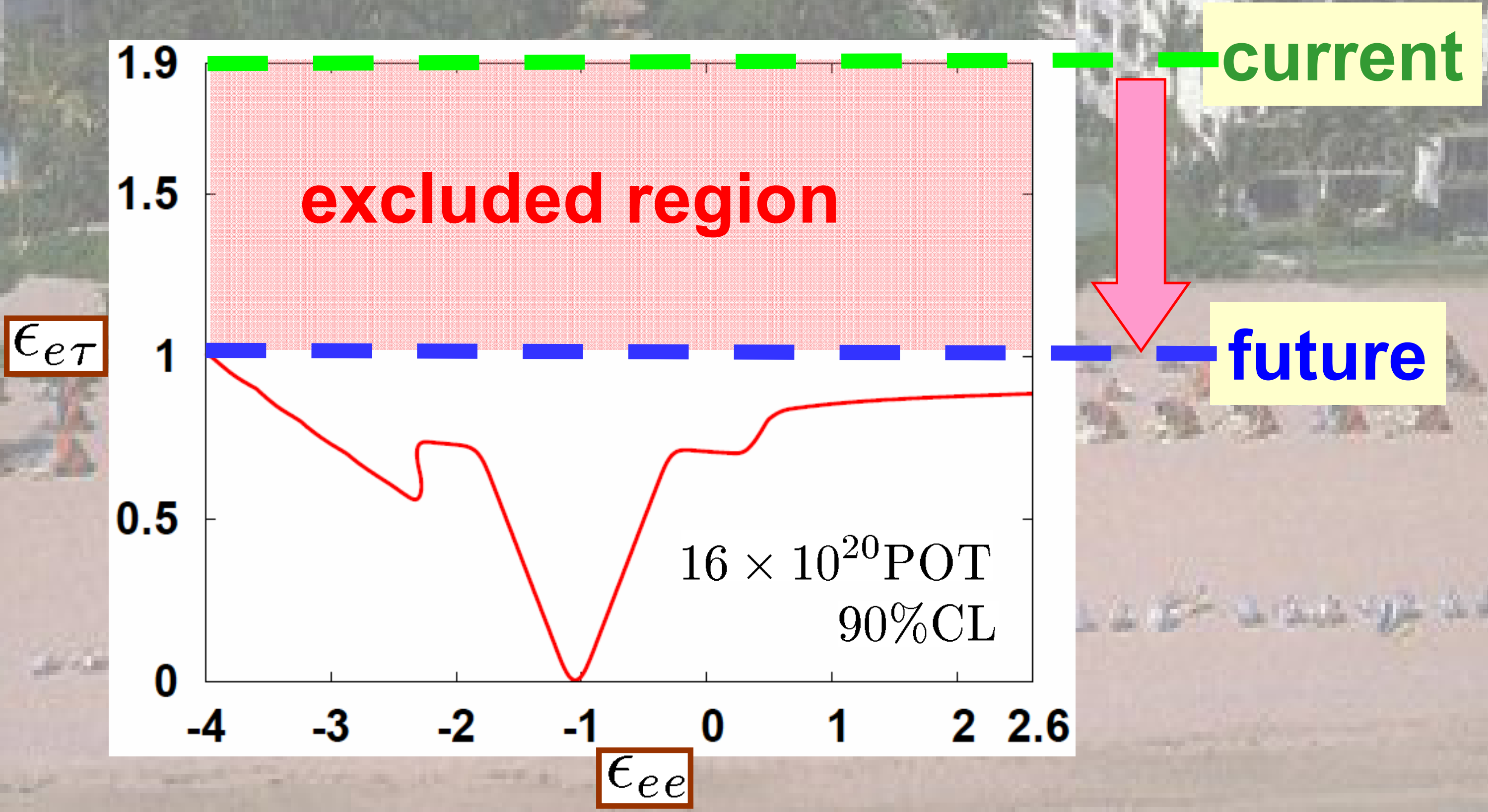


Kitazawa-Sugiyama-OY, to appear

In these cases, number of appearance events becomes so large (> 70) that it cannot be explained only by θ_{13} which would yield (<50 events)

MINOS

(2) In case no ν_e events are observed at MINOS: constraint is improved from $|\epsilon_{e\tau}| \leq 1.9$ to $|\epsilon_{e\tau}| \leq 1$

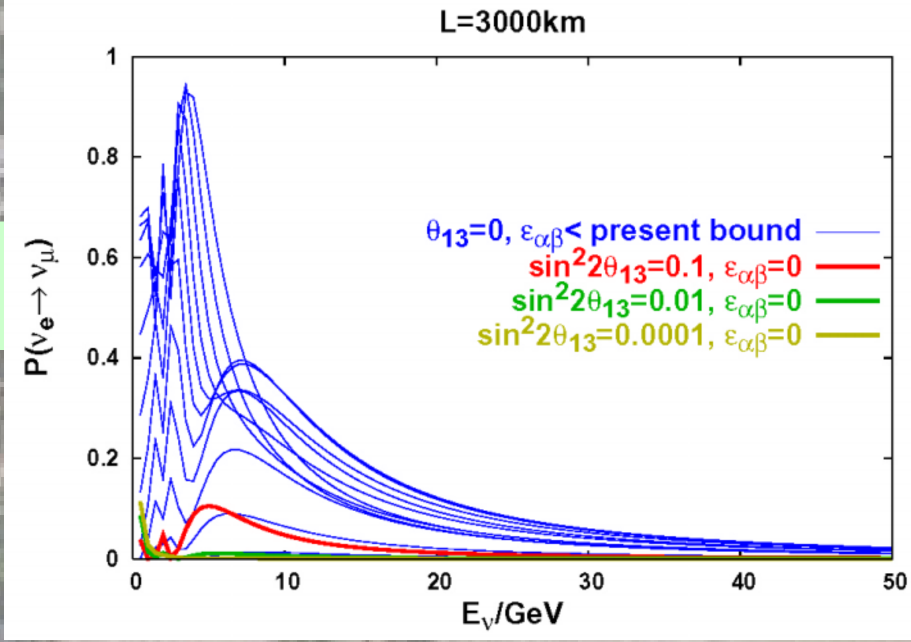


Kitazawa-Sugiyama-OY, to appear

Implications for (far) future experiments

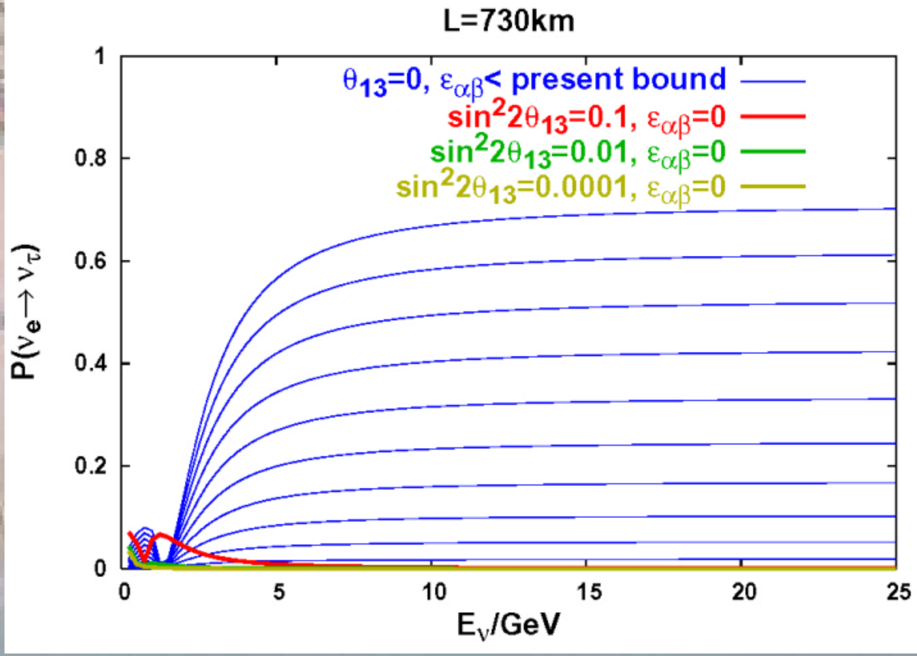
ν factory (golden channel)

$\nu_e \to \nu_\mu$



ν factory (silver channel)

$\nu_e \to \nu_\tau$



most striking channel
→Even if $\epsilon_{\alpha\beta}$ are small, effects may be observed

Kitazawa-Sugiyama-OY, hep-ph/0606013

3. Summary

- New Physics in ν oscillation (during propagation) was discussed in the case where the $\varepsilon_{\alpha\beta}$ parameters are of O(1).

- At ongoing MINOS, if values of ε_{ee} and $\varepsilon_{e\tau}$ lie in a certain region and value of θ_{13} is known from reactor experiments, then MINOS can verify existence of NP.

  If no ν_e events are observed at MINOS, then a constraint is improved from $|\varepsilon_{e\tau}|<1.9$ to $|\varepsilon_{e\tau}|<1.0$.

- At future ν factory, potentially huge NP effects in propagation are expected particularly at the silver channel $\nu_e \rightarrow \nu_\tau$ as well as at the golden channel $\nu_e \rightarrow \nu_\mu$