New physics effects in long baseline experiments

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Based on:

- N. Kitazawa, H. Sugiyama, OY, hep-ph/0606013
- OY, arXiv:0704.1531 [hep-ph]

1. Introduction

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

Information we have obtained so far:

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

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

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

Mixing matrix has been roughly determined:

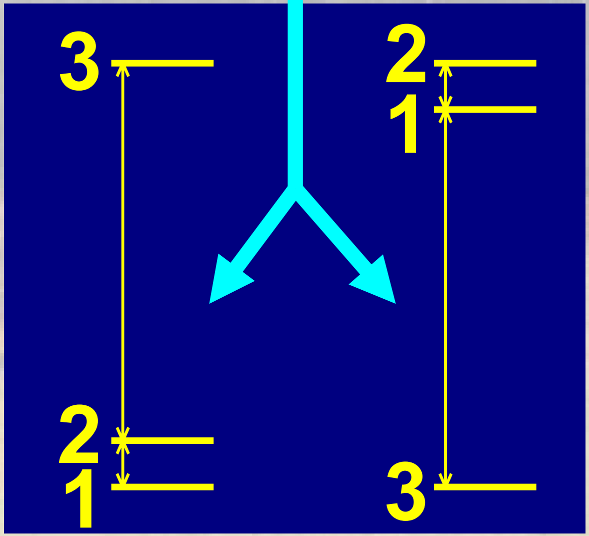
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

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

- Both **mass hierarchies** are allowed

However,

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



normal hierarchy

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

inverted hierarchy

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

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

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

$$\begin{cases} \pi^+ \to \mu^+ + \nu_\mu & \nu_\mu \to \nu_e \\ \pi^- \to \mu^- + \bar{\nu}_\mu & \bar{\nu}_\mu \to \bar{\nu}_e \end{cases}$$

- neutrino factory

  μ in a storage ring

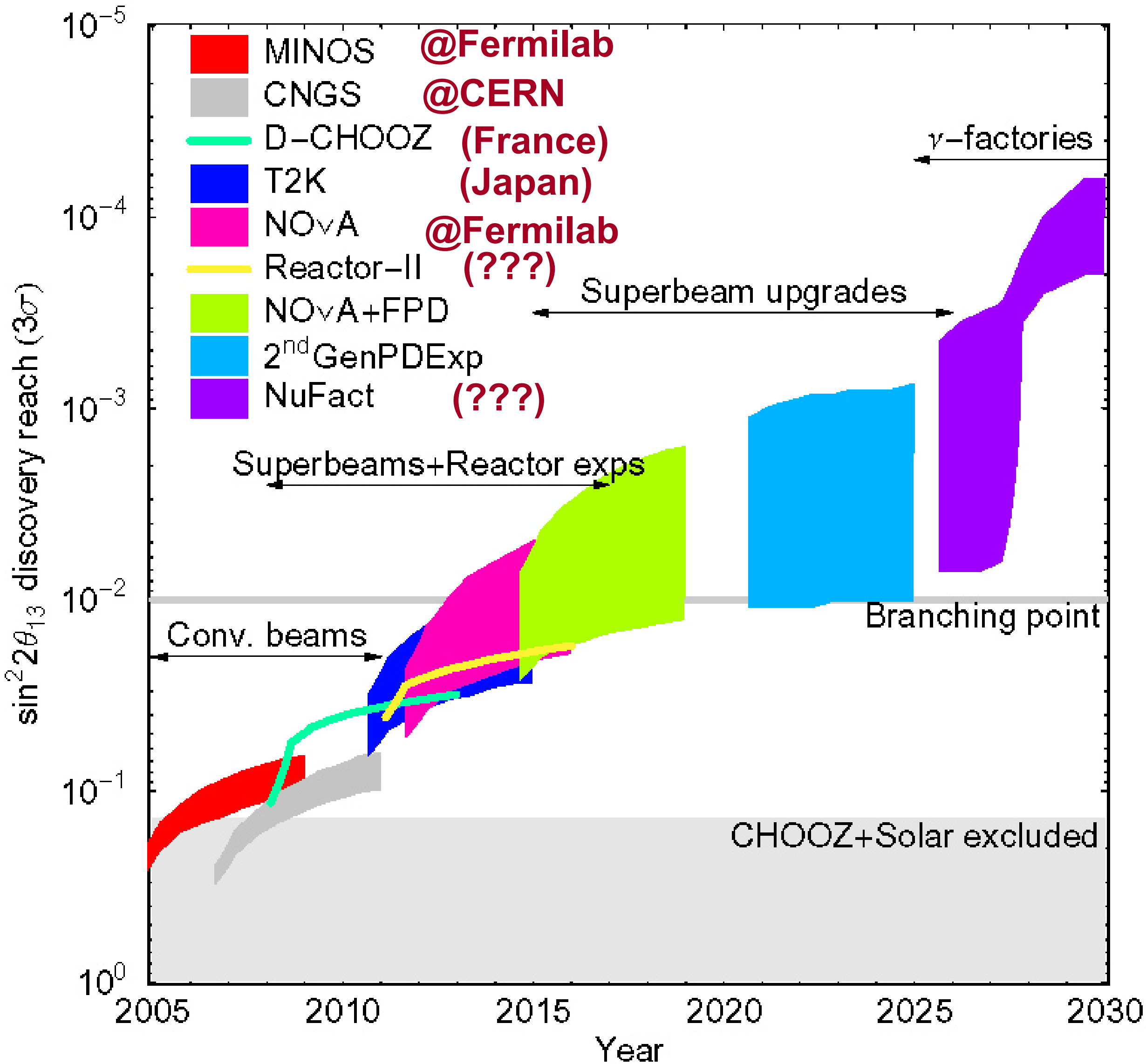
$$\begin{cases} \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu & \nu_e \to \nu_\mu \\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu & \bar{\nu}_e \to \bar{\nu}_\mu \end{cases}$$

- beta beam

  RI in a storage ring

$$\begin{cases} {}^6_2He \to {}^6_3Li + e^- + \bar{\nu}_e & \bar{\nu}_e \to \bar{\nu}_\mu \\ {}^{18}_{10}Ne \to {}^{18}_9F + e^+ + \nu_e & \nu_e \to \nu_\mu \end{cases}$$

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**
  - Theory Subgroup S.F. King
  - Phenomenology Subgroup OY
  - Experiment Subgroup K. Long
  - Muon Subgroup L. Roberts
- **Detector Group A. Blondel**
- **Accelerator Group M. Zisman**

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

Final report:

http://www.hep.ph.ic.ac.uk/~longkr/UKNF/Scoping-study/ISS-www-site/WG1-PhysPhen/Planning-drafts/Report/Current/PhysReport.pdf

It will appear on arXiv soon.

2. New Physics in ν oscillation

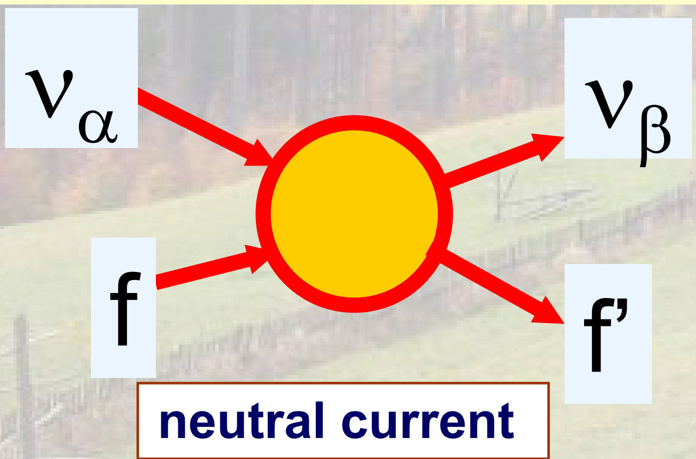
2.1 New Physics in ν oscillation

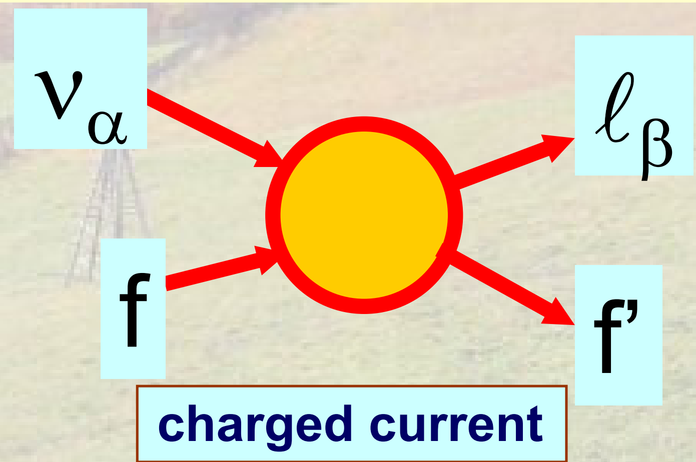
Just like at B factories, high precision measurements of ν oscillation can be used also to probe physics beyond SM by looking at from deviation from SM+masssive ν

Here we study phenomenologically new physics which is described by 4-fermi exotic interactions:

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

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





Types of New Physics

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

$$\mathcal{A}_{SM} \equiv A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \left| \left[U^d \tilde{U} \exp\left\{ -i \, \mathrm{diag}(\tilde{E}_j) L \right\} \tilde{U}^{-1} (U^s)^{-1} \right]_{\beta\alpha} \right|^2$$

with $$U \, \mathrm{diag}(E_j) \, U^{-1} + \mathcal{A}_{SM} + \mathcal{A}_{NP} \equiv \tilde{U} \, \mathrm{diag}(\tilde{E}_j) \, \tilde{U}^{-1}$$

source

$|(U^s - 1)_{\alpha\beta}| < O(10^{-2})$

$$\begin{pmatrix} \nu_e^s \\ \nu_\mu^s \\ \nu_\tau^s \end{pmatrix} = U^s U_{MNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

propagation

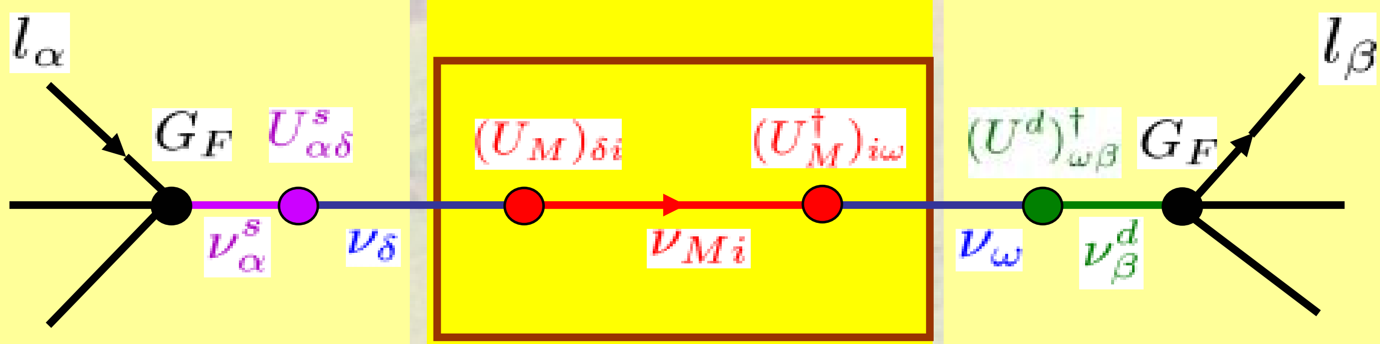
$\varepsilon_{ee}, \varepsilon_{e\tau}, \varepsilon_{\tau\tau} \sim O(1)$

$$A \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

detection

$|(U^d - 1)_{\alpha\beta}| < O(10^{-2})$

$$\begin{pmatrix} \nu_e^d \\ \nu_\mu^d \\ \nu_\tau^d \end{pmatrix} = U^d U_{MNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



(1) Effects of New Physics at source and detector

Deviation from the standard form is small:

Grossman (PLB359:141,1995)

$$|(U^s-1)_{\alpha\beta}| < O(10^{-2}),\ |(U^d-1)_{\alpha\beta}| < O(10^{-2})$$

(2) New Physics effects in propagation

1. Constraints from various ν experiments:

Davidson et al (JHEP 0303:011,2003)

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

2. Constraints from atmospheric neutrinos:

Friedland-Lunardini (Phys.Rev.D72:053009,2005)

ε_{ee}, $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ ~**O(1)** are consistent with ν_{atm} data, provided

$$\epsilon_{\tau\tau} \sim \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}} \qquad 0 \le |\epsilon_{e\tau}| \lesssim 1 + \epsilon_{ee} \qquad -1 \lesssim \epsilon_{ee} \lesssim 1.5$$

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

→ Experiments with a longer baseline are advantageous

Here we will discuss MINOS (L=730km)

2.2 Analytical formula for the oscillation probability in matter with New Physics

(1)For the standard 3 flavor case, analytical formula for the oscillation probability in matter is known:

Kimura, Takamura and Yokomakura (PLB537:86,2002)

(2) KTY formalism to more general cases (e.g., NP etc.) was discussed: OY arXiv:0704.1531 [hep-ph]

In particular, in the limit $\Delta m^2_{21} \to 0$, $P(\nu_\mu \to \nu_e)$ can be obtained analytically with

$$\mathcal{A} = A \begin{pmatrix} 1+\varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon^*_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$

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

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ ~O(1)

(1) Exact formula for oscillation probability in matter with standard 3 flavor neutrinos

Kimura, Takamura and Yokomakura (PLB537:86,2002)

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left(U\mathcal{E}U^{-1}+\mathcal{A}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\mathcal{E} \equiv \begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}$$

$$\mathcal{A} \equiv \sqrt{2}G_F N_e \begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$U\mathcal{E}U^{-1}+\mathcal{A} \equiv \tilde{U}\begin{pmatrix}\tilde{E}_1 & 0 & 0\\ 0 & \tilde{E}_2 & 0\\ 0 & 0 & \tilde{E}_3\end{pmatrix}\tilde{U}^{-1}$$

$$E_j \equiv \sqrt{m_j^2+\vec{p}^{\,2}}$$

Once the eigenvalues are known, the elements of the mixing matix can be analytically obtained.

$$\begin{aligned}P(\nu_\alpha\to\nu_\beta) \;=\; & \delta_{\alpha\beta} - 4\sum_{j<k}\mathrm{Re}\left(\tilde{X}_j^{\alpha\beta}\tilde{X}_k^{\alpha\beta *}\right)\sin^2\left(\frac{\Delta\tilde{E}_{jk}L}{2}\right)\\ & -2\sum_{j<k}\mathrm{Im}\left(\tilde{X}_j^{\alpha\beta}\tilde{X}_k^{\alpha\beta *}\right)\sin\left(\Delta\tilde{E}_{jk}L\right),\end{aligned}$$

$$\tilde{X}_j^{\alpha\beta} \equiv \tilde{U}_{\alpha j}\tilde{U}_{\beta j}^*$$

$$\Delta\tilde{E}_{jk} \equiv \tilde{E}_j - \tilde{E}_k$$

$$\begin{pmatrix}\tilde{X}_1^{\alpha\beta}\\ \tilde{X}_2^{\alpha\beta}\\ \tilde{X}_3^{\alpha\beta}\end{pmatrix} = \begin{pmatrix}\frac{1}{\Delta\tilde{E}_{21}\Delta\tilde{E}_{31}}(\tilde{E}_2\tilde{E}_3,\ -(\tilde{E}_2+\tilde{E}_3),\ 1)\\ \frac{-1}{\Delta\tilde{E}_{21}\Delta\tilde{E}_{32}}(\tilde{E}_3\tilde{E}_1,\ -(\tilde{E}_3+\tilde{E}_1),\ 1)\\ \frac{1}{\Delta\tilde{E}_{31}\Delta\tilde{E}_{32}}(\tilde{E}_1\tilde{E}_2,\ -(\tilde{E}_1+\tilde{E}_2),\ 1)\end{pmatrix}\begin{pmatrix}\delta_{\alpha\beta}\\ \left[U\mathcal{E}U^{-1}+\mathcal{A}\right]_{\alpha\beta}\\ \left[\left(U\mathcal{E}U^{-1}+\mathcal{A}\right)^2\right]_{\alpha\beta}\end{pmatrix}$$

Problem: Obtain the values of $\tilde{X}_j^{\alpha\beta} \equiv \tilde{U}_{\alpha j}\tilde{U}^*_{\beta j}$ **which appear in diagonalization of**

$$\mathcal{E} \equiv \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}$$

$$U\mathcal{E}U^{-1} + \mathcal{A} \equiv \tilde{U} \begin{pmatrix} \tilde{E}_1 & 0 & 0 \\ 0 & \tilde{E}_2 & 0 \\ 0 & 0 & \tilde{E}_3 \end{pmatrix} \tilde{U}^{-1}$$

$$\mathcal{A} \equiv \sqrt{2} G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Solution: Trivial 3 identities solve it

Xing-Zhang PLB618:131,2005; OY arXiv:0704.1531 [hep-ph]

$$\delta_{\alpha\beta} = \left[\tilde{U}\tilde{U}^{-1}\right]_{\alpha\beta} = \sum_j \tilde{U}_{\alpha j}\tilde{U}^*_{\beta j} = \sum_j \tilde{X}_j^{\alpha\beta}$$

$$\left[U\mathcal{E}U^{-1} + \mathcal{A}\right]_{\alpha\beta} = \left[\tilde{U}\tilde{\mathcal{E}}\tilde{U}^{-1}\right]_{\alpha\beta} = \sum_j \tilde{U}_{\alpha j}\tilde{E}_j\tilde{U}^*_{\beta j} = \sum_j \tilde{E}_j\tilde{X}_j^{\alpha\beta}$$

$$\left[\left(U\mathcal{E}U^{-1} + \mathcal{A}\right)^2\right]_{\alpha\beta} = \left[\tilde{U}\tilde{\mathcal{E}}^2\tilde{U}^{-1}\right]_{\alpha\beta} = \sum_j \tilde{U}_{\alpha j}\tilde{E}_j^2\tilde{U}^*_{\beta j} = \sum_j \tilde{E}_j^2\tilde{X}_j^{\alpha\beta}$$

$$\begin{pmatrix} 1 & 1 & 1 \\ \tilde{E}_1 & \tilde{E}_2 & \tilde{E}_3 \\ \tilde{E}_1^2 & \tilde{E}_2^2 & \tilde{E}_3^2 \end{pmatrix} \begin{pmatrix} \tilde{X}_1^{\alpha\beta} \\ \tilde{X}_2^{\alpha\beta} \\ \tilde{X}_3^{\alpha\beta} \end{pmatrix} = \begin{pmatrix} \delta_{\alpha\beta} \\ \left[U\mathcal{E}U^{-1} + \mathcal{A}\right]_{\alpha\beta} \\ \left[\left(U\mathcal{E}U^{-1} + \mathcal{A}\right)^2\right]_{\alpha\beta} \end{pmatrix}$$

Simultaneous linear eqs.: easily solved

(2) Analytical formula for the oscillation probability in matter with New Physics in the limit $\Delta m^2_{21} \to 0$

OY arXiv:0704.1531 [hep-ph]

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & -4\mathrm{Re}\left(\tilde{X}_1^{\mu e}\tilde{X}_2^{\mu e *}\right)\sin^2\left(\frac{\Lambda_- L}{2}\right) - 4\mathrm{Re}\left(\tilde{X}_2^{\mu e}\tilde{X}_3^{\mu e *}\right)\sin^2\left(\frac{\Lambda_+ L}{2}\right) \\
& -4\mathrm{Re}\left(\tilde{X}_1^{\mu e}\tilde{X}_3^{\mu e *}\right)\sin^2\left[\frac{(\Lambda_+ - \Lambda_-)L}{2}\right] \\
& -8\mathrm{Im}\left(\tilde{X}_1^{\mu e}\tilde{X}_2^{\mu e *}\right)\sin\left(\frac{\Lambda_- L}{2}\right)\sin\left(\frac{\Lambda_+ L}{2}\right)\sin\left[\frac{(\Lambda_+ - \Lambda_-)L}{2}\right]
\end{aligned}
$$

$$
\mathcal{A} = A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & \epsilon_{\tau\tau} \end{pmatrix}
$$

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

$$
\Lambda_\pm = \frac{1}{2}\left[\Delta E_{31} + \frac{A(1+\epsilon_{ee})}{\cos^2\beta}\right] \pm \frac{1}{2}\sqrt{\left[\Delta E_{31}\cos 2\theta''_{13} - \frac{A(1+\epsilon_{ee})}{\cos^2\beta}\right]^2 + (\Delta E_{31}\sin 2\theta''_{13})^2}
$$

$$
\begin{aligned}
\tilde{X}_1^{\mu e} &= \frac{-1}{\Lambda_-(\Lambda_+ - \Lambda_-)}[\xi + \eta e^{-i(\arg(\epsilon_{e\mu})+\delta)} - \Lambda_+\zeta] \\
\tilde{X}_2^{\mu e} &= \frac{1}{\Lambda_+\Lambda_-}[\xi + \eta e^{-i(\arg(\epsilon_{e\mu})+\delta)} - (\Lambda_+ + \Lambda_-)\zeta] \\
\tilde{X}_3^{\mu e} &= \frac{1}{\Lambda_+(\Lambda_+ - \Lambda_-)}[\xi + \eta e^{-i(\arg(\epsilon_{e\mu})+\delta)} - \Lambda_-\zeta]
\end{aligned}
$$

$$
\begin{aligned}
\xi &\equiv [(\Delta E_{31})^2 + A(1+\epsilon_{ee})\Delta E_{31}]U_{\mu 3}|U_{e3}| \\
\eta &\equiv A\Delta E_{31}|\epsilon_{e\tau}|U_{\mu 3}U_{\tau 3} \\
\zeta &\equiv \Delta E_{31}U_{\mu 3}|U_{e3}|,
\end{aligned}
$$

depends only on $\arg(\epsilon_{e\tau})+\delta$

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

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

$$\theta''_{13} = \sin^{-1}|e^{-i\arg(\epsilon_{e\mu})}U_{e3}\cos\beta + U_{\tau 3}\sin\beta|$$

Features of the probability (in the limit $\Delta m^2_{21} \to 0$)

A) It depends only on $\arg(\varepsilon_{e\tau})+\delta$.

→ This is approximately the case also for $\Delta m^2_{21} \neq 0$.

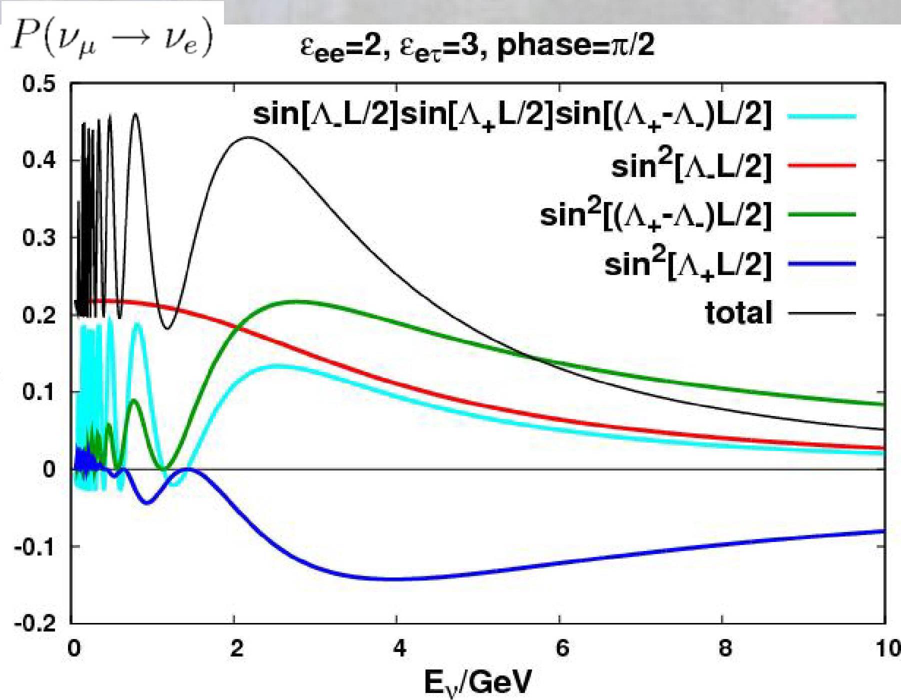
B) Each term gives a large contribution (See Fig. below).

→ Interpretation of behavior of probability is difficult.

cf In standard 3 flavor case, only one term dominates:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \left(\frac{\Delta E_{31}}{\Delta \tilde{E}_{31}} \right)^2 \sin^2 \left(\frac{\Delta \tilde{E}_{31} L}{2} \right)$$

$$\Delta \tilde{E}_{31} \equiv \left[(\Delta E_{31} \cos 2\theta_{13} - A)^2 + (\Delta E_{31} \sin 2\theta_{13})^2 \right]^{1/2}$$



$$P(\nu_\mu \to \nu_e) =$$

$$-4\mathrm{Re}\left(\tilde{X}_1^{\mu e} \tilde{X}_2^{\mu e*}\right) \sin^2\left(\frac{\Lambda_- L}{2}\right)$$

$$-4\mathrm{Re}\left(\tilde{X}_2^{\mu e} \tilde{X}_3^{\mu e*}\right) \sin^2\left(\frac{\Lambda_+ L}{2}\right)$$

$$-4\mathrm{Re}\left(\tilde{X}_1^{\mu e} \tilde{X}_3^{\mu e*}\right) \sin^2\left[\frac{(\Lambda_+ - \Lambda_-)L}{2}\right]$$

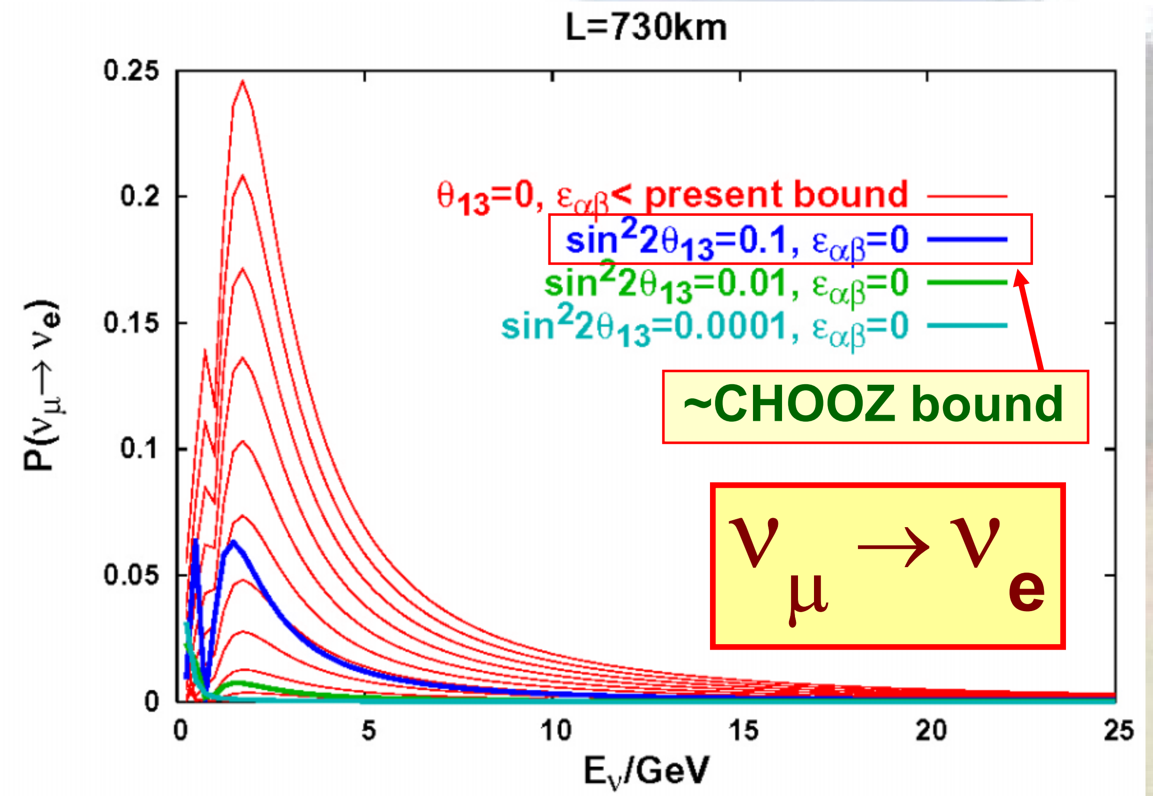
$$-8\mathrm{Im}\left(\tilde{X}_1^{\mu e} \tilde{X}_2^{\mu e*}\right) \sin\left(\frac{\Lambda_- L}{2}\right) \sin\left(\frac{\Lambda_+ L}{2}\right) \sin\left[\frac{(\Lambda_+ - \Lambda_-)L}{2}\right]$$

2.3 Implications of NP for ongoing experiments

MINOS (2005-)

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

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



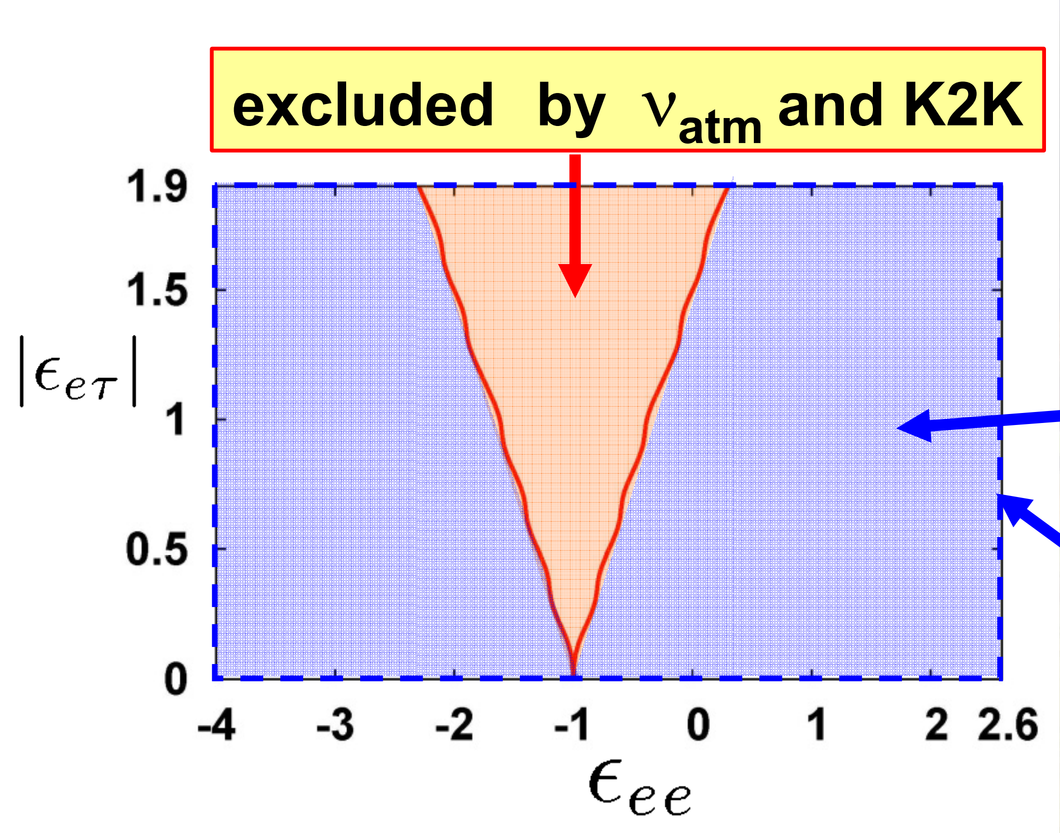
Kitazawa-Sugiyama-OY, hep-ph/0606013

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

Summary: current constraints on NP parameters ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$

various ν experiments → inside of [dashed box] is allowed
Davidson et al (JHEP 0303:011,2003)

atmospheric neutrinos+K2K → inside of [triangle] is excluded
Friedland-Lunardini (Phys.Rev.D72:053009,2005)



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

Roughly, $|\epsilon_{e\tau}| < |1+\epsilon_{ee}|$

$|\epsilon_{\tau\tau}| < 1.9$

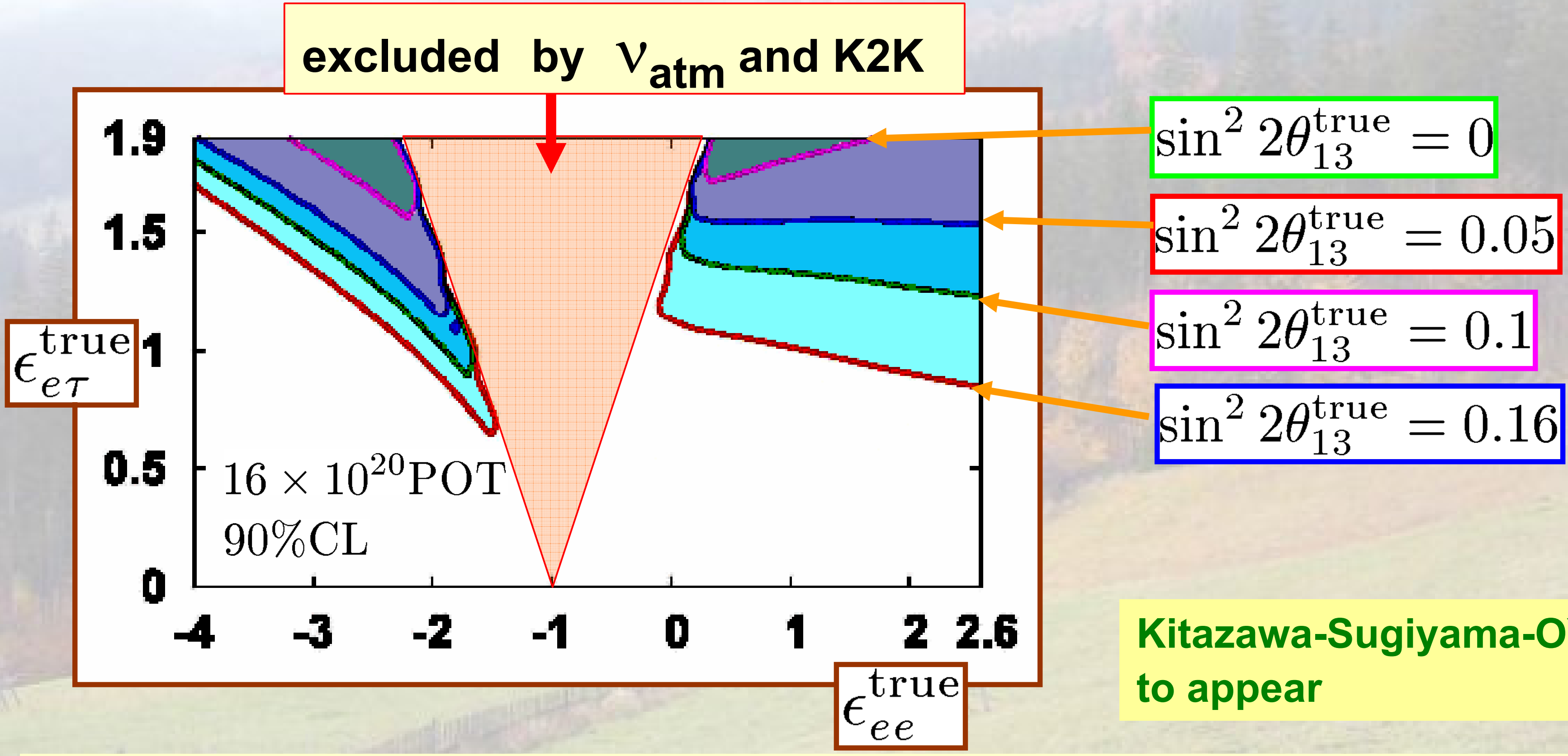
:allowed region by all data

allowed by various ν experiments

MINOS

(1) In case MINOS observes ν_e events: If values of ε_{ee} and $\varepsilon_{e\tau}$ lie in the colored 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}

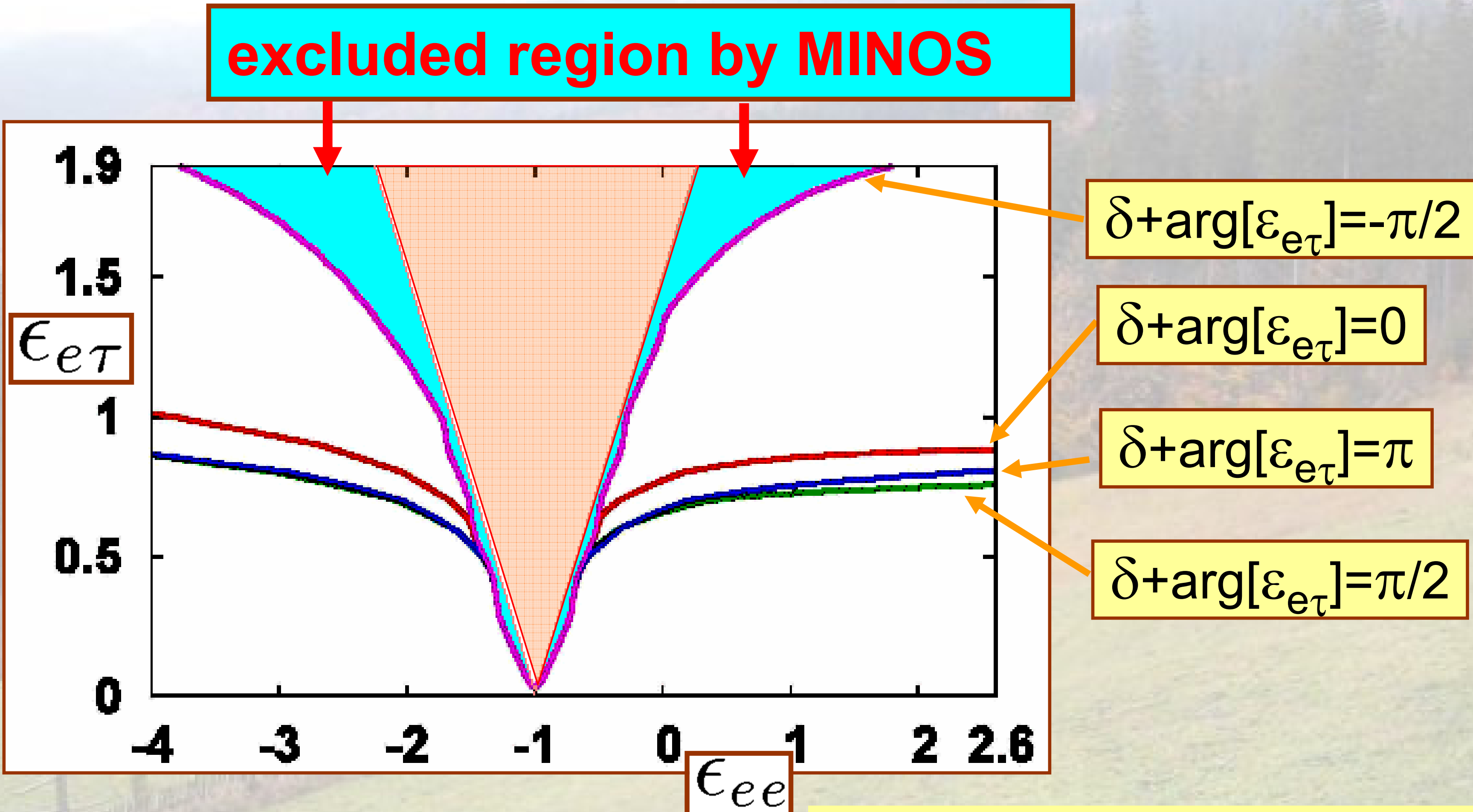


Kitazawa-Sugiyama-OY, to appear

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 slightly improved in the (ε_{ee}, | $\varepsilon_{e\tau}$ |) plane.



Kitazawa-Sugiyama-OY, to appear

3. Summary

- New Physics in ν oscillation (during propagation) was discussed in the case where the $\varepsilon_{\alpha\beta}$ parameters are of O(1). This kind of search of New Physics is complementary to those at LHC and ILC.
- The analytical formula was obtained for $P(\nu_\mu \to \nu_e)$ in the presence of NP (in propagation) in the limit $\Delta m^2_{21} \to 0$.
- At ongoing MINOS, if values of ε_{ee} and $\varepsilon_{e\tau}$ lie in a certain region, then MINOS can verify existence of NP.

  If no ν_e events are observed at MINOS, then a constraint is slightly improved in the (ε_{ee}, | $\varepsilon_{e\tau}$ |) plane.
- Many more works yet have to be done (analysis for future intense LBL; global analysis of NP in production, propagation, detection, etc.)