Model independent analysis of **New Physics** interactions and implications for long baseline experiments

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Based on a work with
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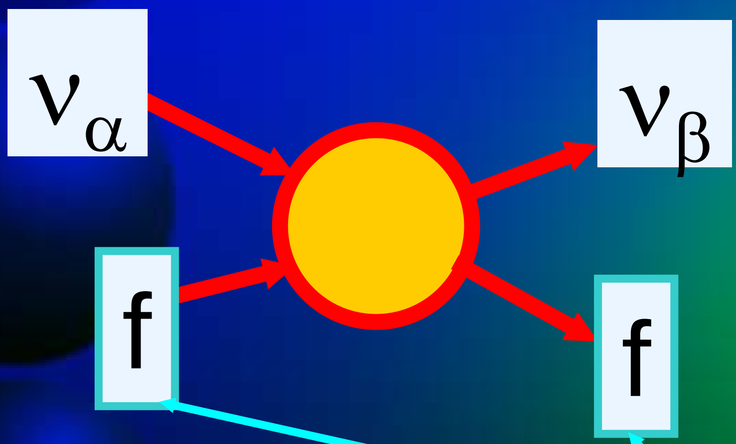
Without referring to specific models, **assuming the maximum values** of the **New Physics** parameters which are currently allowed by all the experimental data, the values of oscillation probabilities are estimated for future long baseline experiments.

NP effects in propagation (NP matter effect)

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



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

$N_e \equiv$ electron density

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

potential due to CC int

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

SM

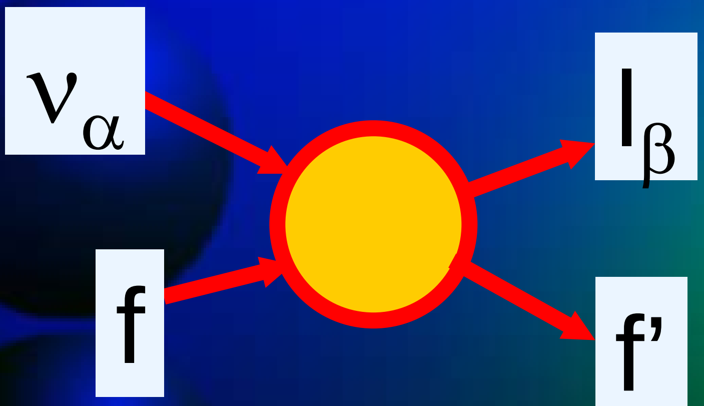
$$\mathcal{A}_0 \equiv A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow$$

NP

$$\mathcal{A} \equiv A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

NP effects at source and detector (Charged Current)

$$\mathcal{L}_{NP} = \sum_{\alpha,\beta} G_N^{\alpha\beta} \bar{\nu}_\alpha \gamma^\mu \ell_\beta \bar{f} \gamma_\mu f' + h.c.$$



SM

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

NP (source)

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

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

NP (detector)

SM+m_ν

$$\mathcal{A}_0 \equiv A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

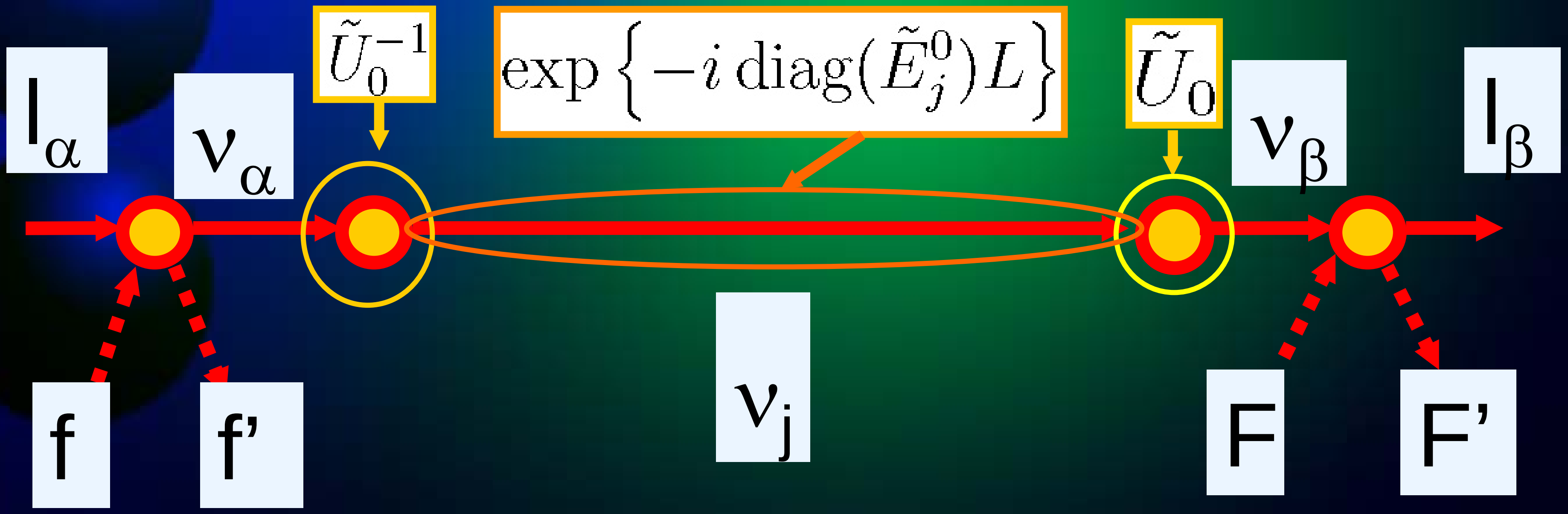
$$U_{MNS}\,\mathrm{diag}(E_j)\,U_{MNS}^{-1} + \mathcal{A}_0 \equiv \tilde{U}_0\,\mathrm{diag}(\tilde{E}_j^0)\,\tilde{U}_0^{-1}$$

$$P(\nu_\alpha \to \nu_\beta) = \left| \left[\tilde{U}_0 \exp\left\{ -i\,\mathrm{diag}(\tilde{E}_j^0) L \right\} \tilde{U}_0^{-1} \right]_{\beta\alpha} \right|^2$$

flavor eigenstate to energy eigenstate

propagation in energy eigenstate

energy eigenstate to flavor eigenstate

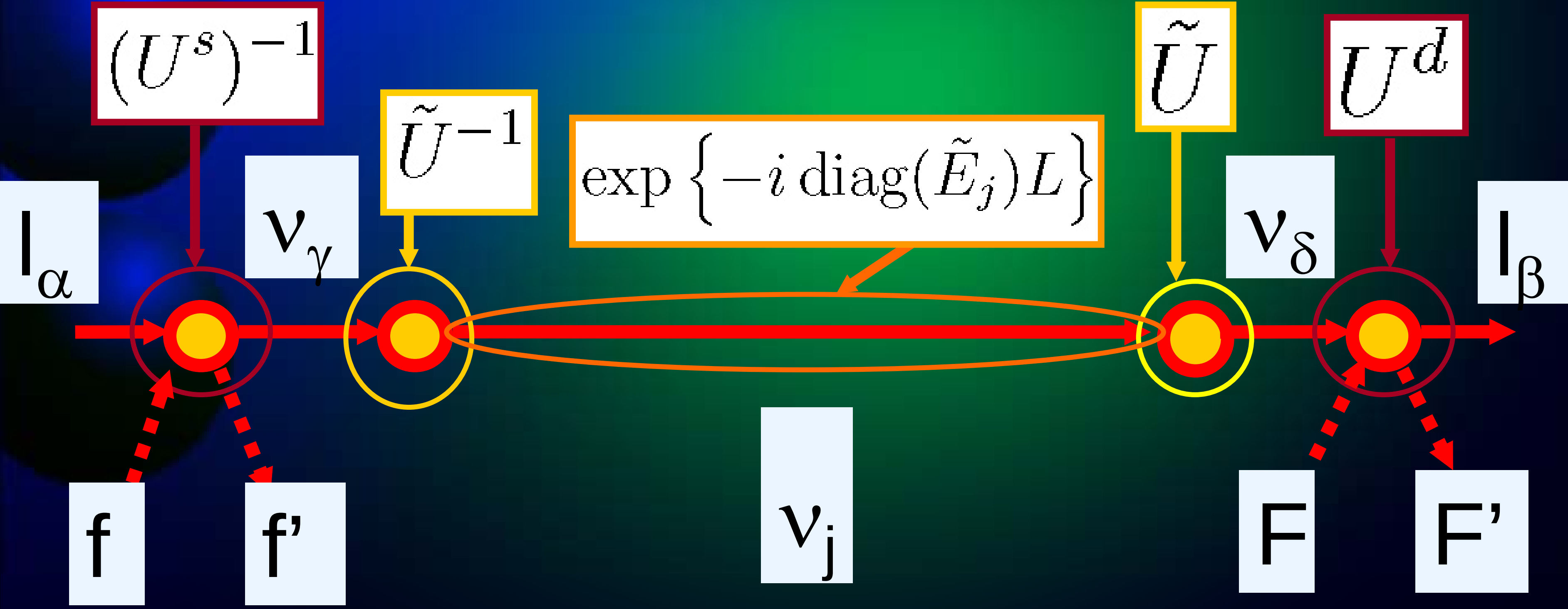


NP

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

$$U_{MNS}\,\mathrm{diag}(E_j)\,U_{MNS}^{-1} + \mathcal{A} \equiv \tilde{U}\,\mathrm{diag}(\tilde{E}_j)\,\tilde{U}^{-1}$$

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



Present talk

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

$$U_{MNS}\,\mathrm{diag}(E_j)\,U_{MNS}^{-1} + \mathcal{A} \equiv \tilde{U}\,\mathrm{diag}(\tilde{E}_j)\,\tilde{U}^{-1}$$

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

1

1

For simplicity, here we discuss the case where $U^s=U^d=1$, i.e., NP exists only in **propagation**.

For simplicity, we'll also neglect all **complex phases**.

- Our starting point: two constraints on $\varepsilon_{\alpha\beta}$

①**Davidson et al ('03)**: Constraints from various ν experiments

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

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

②Friedland-Lunardini ('05): Constraints from atmospheric neutrinos

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

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

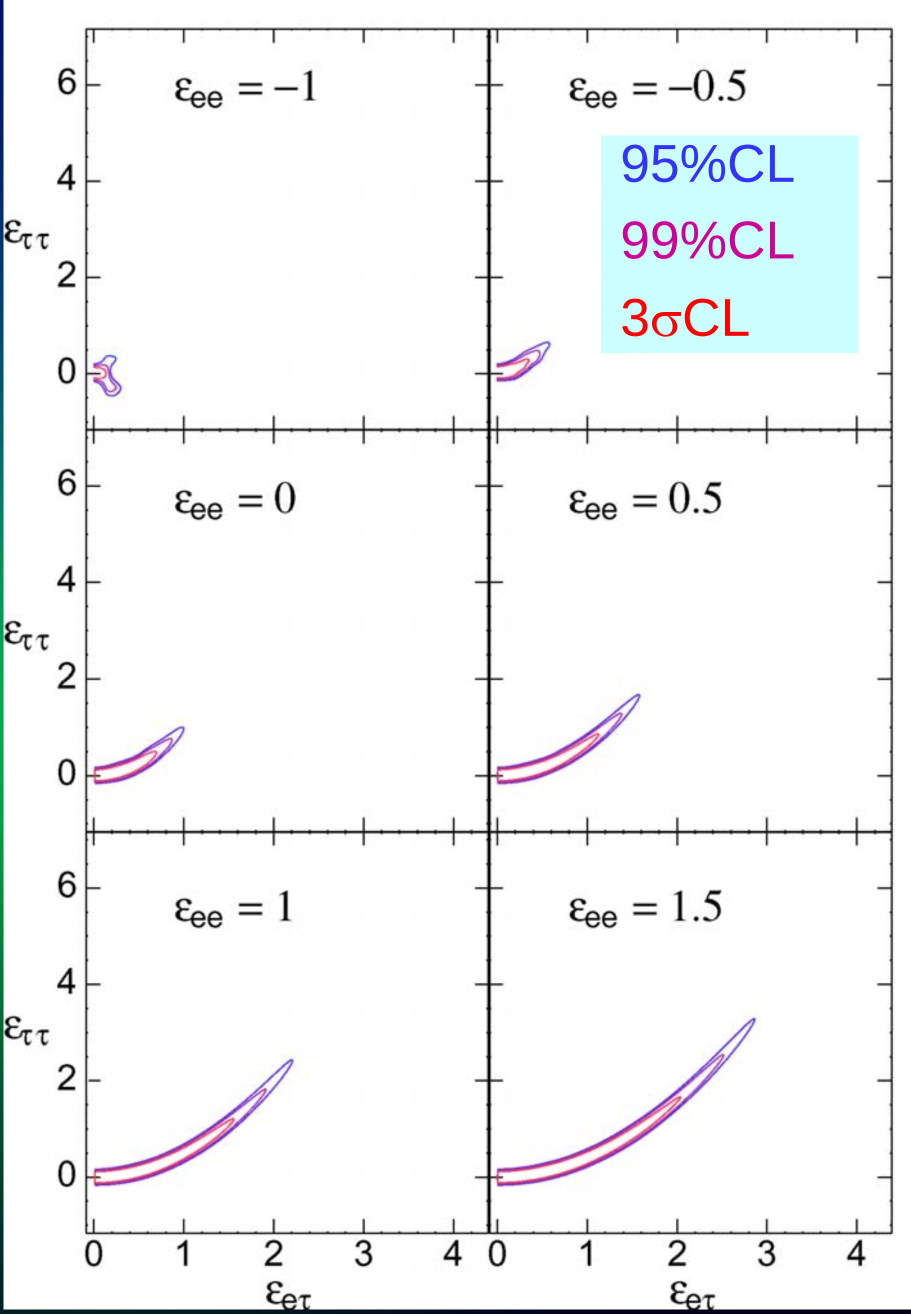
$$-1 \lesssim \epsilon_{ee} \lesssim 1.5$$

With some modifications:

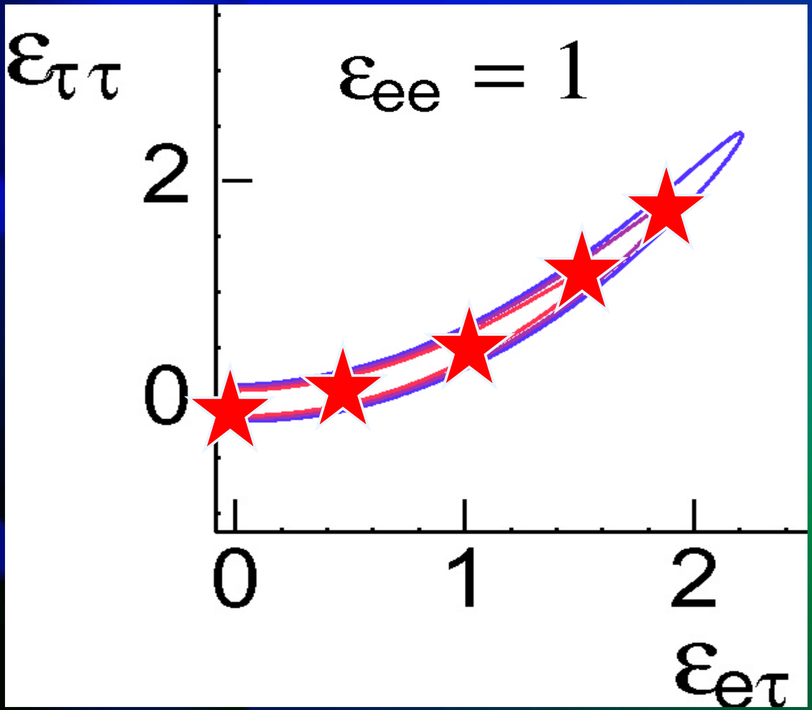
$$\cos 2\theta_{23} \sim \frac{1-\cos^2\beta}{1+\cos^2\beta}$$

$$\Delta m^2_{32} \sim 2.5 \times 10^{-3}\mathrm{eV}^2 \frac{1+\cos^{-2}\beta}{2}$$

$$\tan 2\beta \equiv \frac{2|\epsilon_{e\tau}|}{1+\epsilon_{ee}-\epsilon_{\tau\tau}}$$



Large values, if any, come from, ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$:



$$\varepsilon_{\alpha\beta} \sim \begin{pmatrix} \varepsilon_{ee} & 0 & \varepsilon_{e\tau} \\ 0 & 0 & 0 \\ \varepsilon_{e\tau} & 0 & \varepsilon_{\tau\tau} \end{pmatrix}$$

★ : Points used as reference values

$$0.9 \le \sin^2 2\theta_{23} \le 1.0$$

$$2.5\times10^{-3} eV^2 \le \Delta m^2_{32} \le 4\times10^{-3} eV^2$$

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

$$U_{MNS}\,\mathrm{diag}(0, \Delta E_{21}, \Delta E_{31})\, U_{MNS}^{-1} + A \begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix}$$

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

$$\Delta E_{jk} \equiv \frac{\Delta m^2_{jk}}{2E}$$

In low energy limit ($|\Delta E_{jk}|$ >> A), reduces to vacuum oscillation
➡ analytical result

In high energy limit ($|\Delta E_{jk}|$ << A), it reduces to N_ν=2 case
➡ analytical result

E_ν

~10MeV

~a few 10GeV

In between ($|\Delta E_{jk}|$ ~ A), analytical treatment is difficult
➡ numerical result

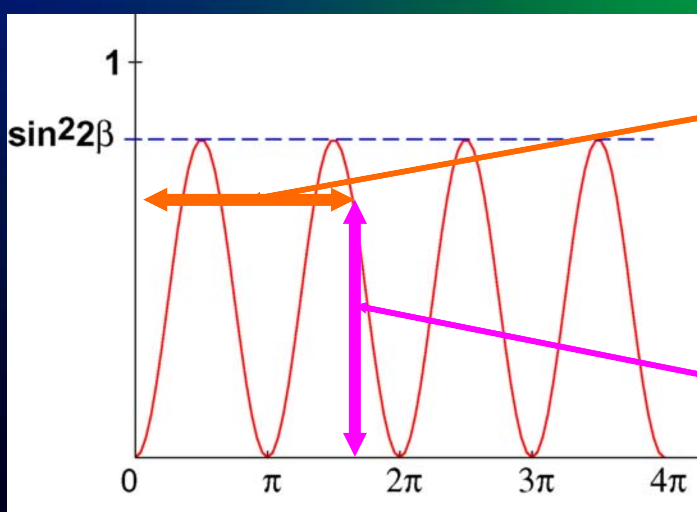
◆ In high energy limit $|\Delta E_{jk}| \ll A$ (E>a few 10 GeV), it reduces to $N_\nu=2$ case:

$$A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix} \begin{pmatrix} \lambda_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix} \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\beta \sin^2\left[\left\{(1+\epsilon_{ee}-\epsilon_{\tau\tau})^2 + 4\epsilon_{\mu\tau}^2\right\}^{1/2} AL/2\right]$$

$$\tan 2\beta \equiv \frac{2|\epsilon_{e\tau}|}{1+\epsilon_{ee}-\epsilon_{\tau\tau}}$$

if this factor~1, **$P_{e\tau}$~ O(1) !!**

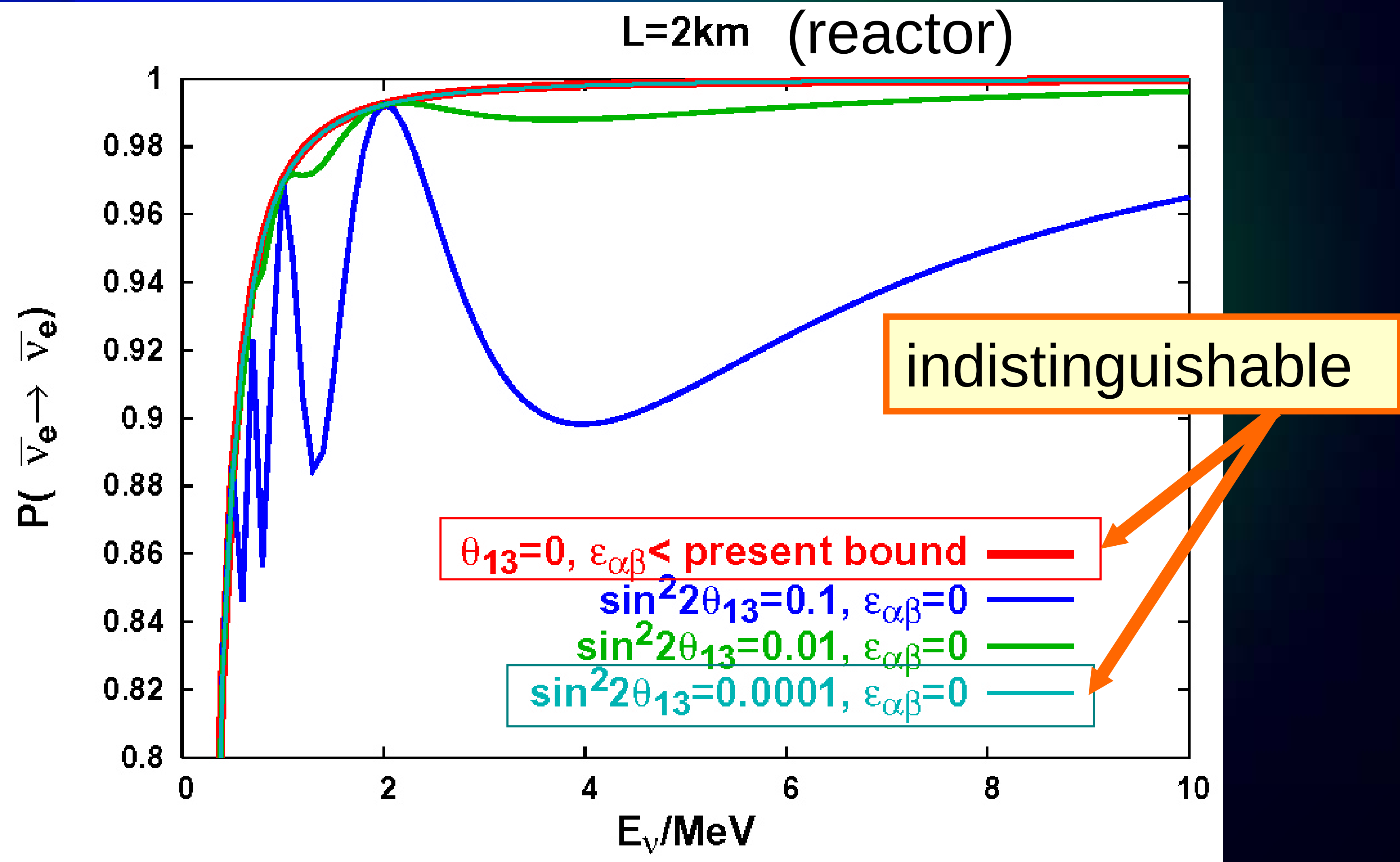


$$\left\{(1+\epsilon_{ee}-\epsilon_{\tau\tau})^2 + 4\epsilon_{\mu\tau}^2\right\}^{1/2} AL/2$$

AL/2~ L/4000km

$P(\nu_e \to \nu_\tau)|_{E\to\infty}$

◆ In low energy limit $|\Delta E_{jk}| >> A$ (E< 10 MeV), it reduces to **vacuum oscillations** ➡ **reactors** have no sensitivity to **NP** (because AL<<1)



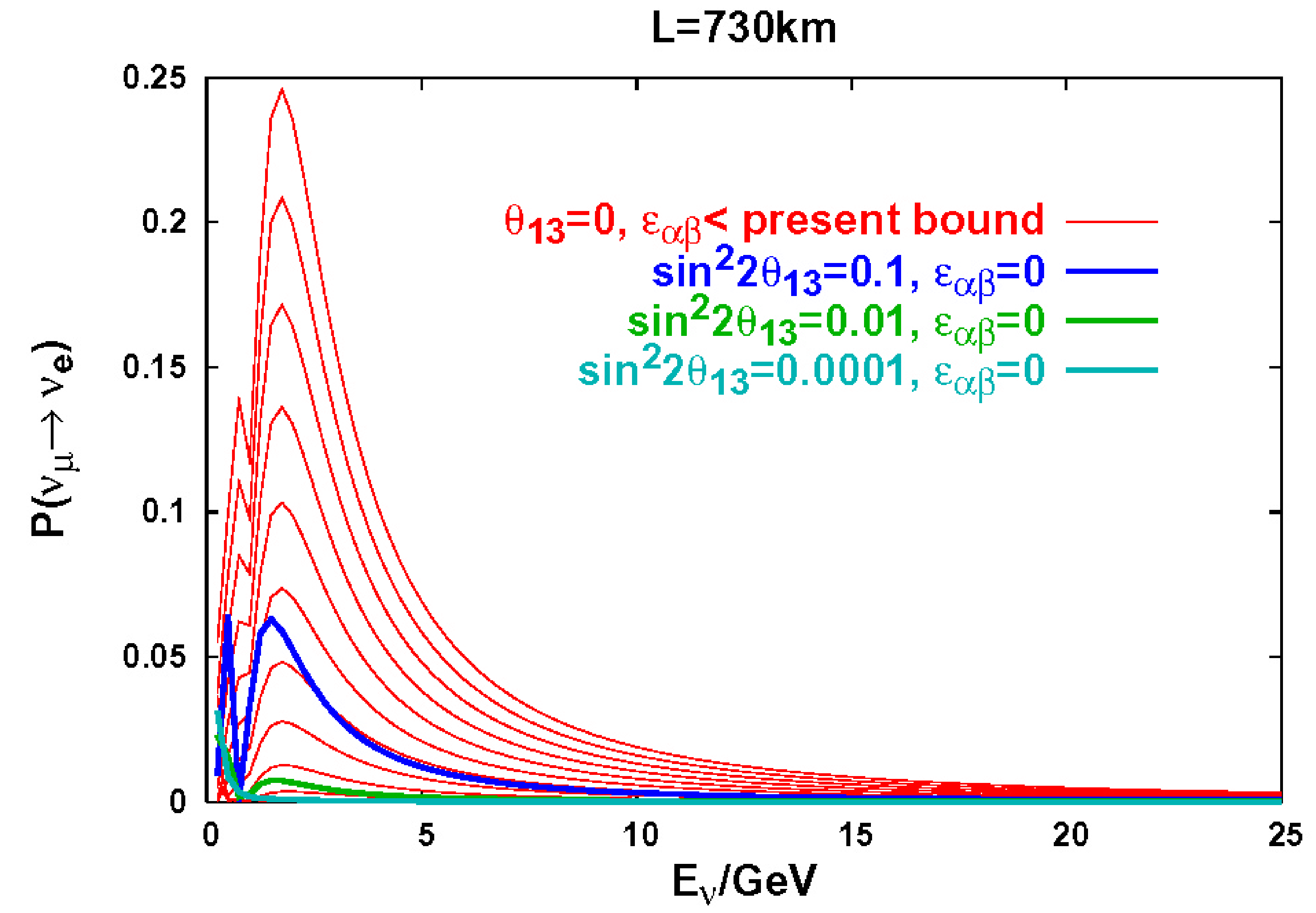
- In between 10 MeV <E< a few 10 GeV ($|\Delta E_{jk}|\sim A$), analytical treatment is difficult.
  → numerically calculated

- **MINOS** ($\nu_\mu \rightarrow \nu_e$) (L=730km, 0<E<25GeV)
- **T2K(K)** ($\nu_\mu \rightarrow \nu_e$) (L=295km, 0<E<1GeV)
  (L=1050km, 0<E<5GeV)
- **ν factory** ($\nu_e \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_\tau$)
  (L=3000km, 0<E<50GeV)
  (L=730km, 0<E<25GeV)

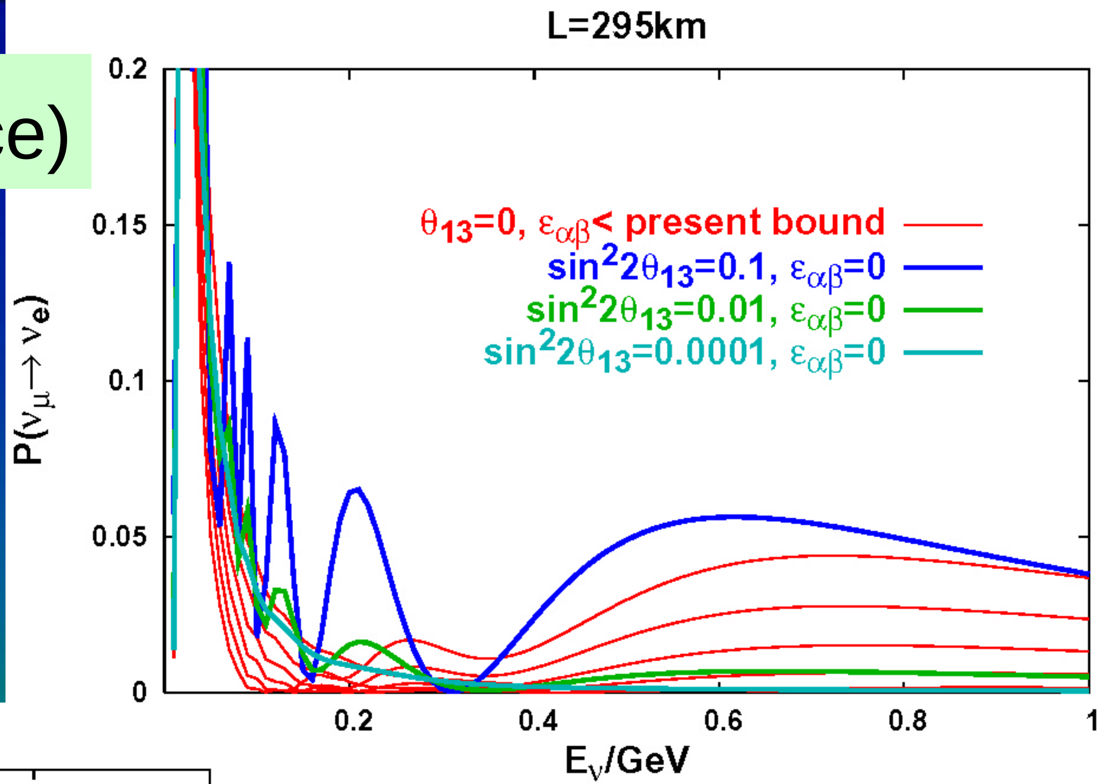
NB Plot for SM+m_ν has **&30% uncertainty** because $P_{golden} \propto s^2_{23}$, $P_{silver} \propto c^2_{23}$, $0.9<\sin^2 2\theta_{23}<1.0$. Nevertheless **NP** effects can be distinguishable even with this uncertainty, except for **T2K**.

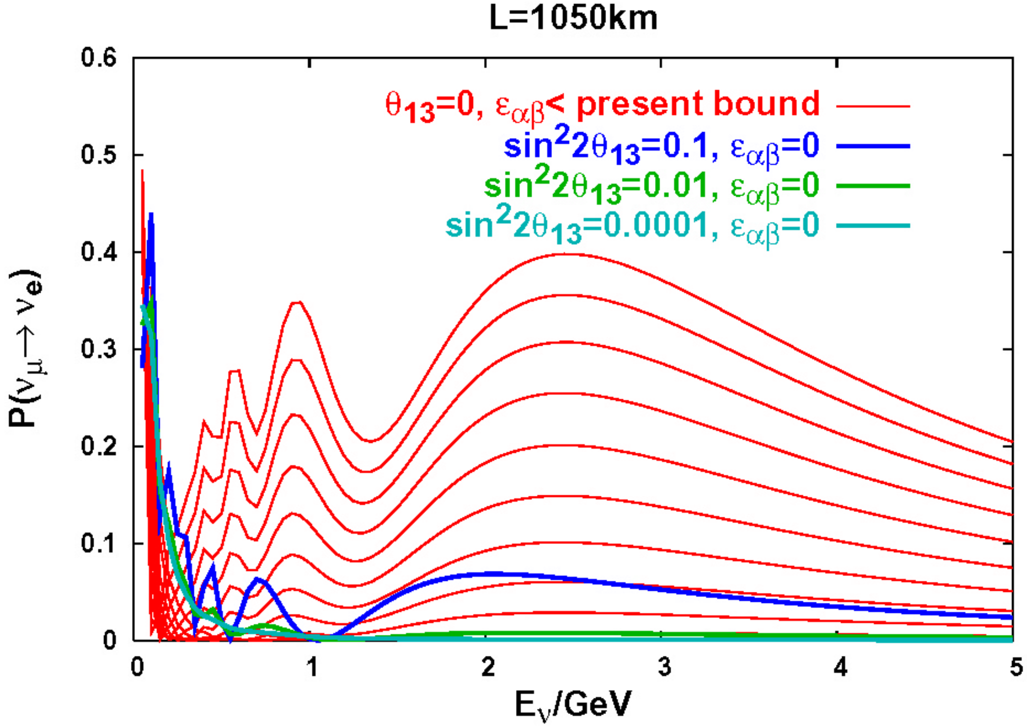
MINOS (ν_e appearance)

MINOS may see NP!

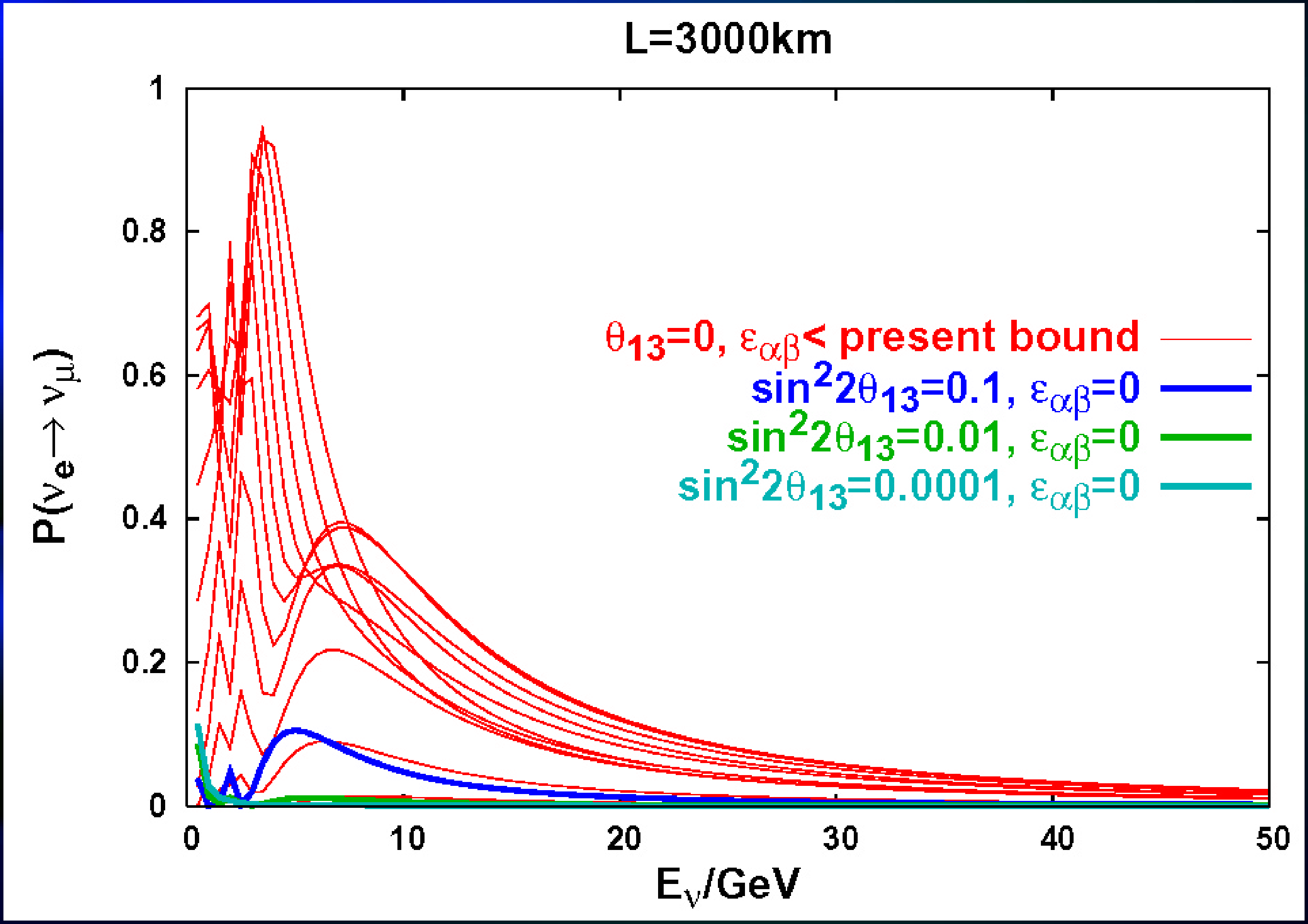


T2K(K) (ν_e appearance)



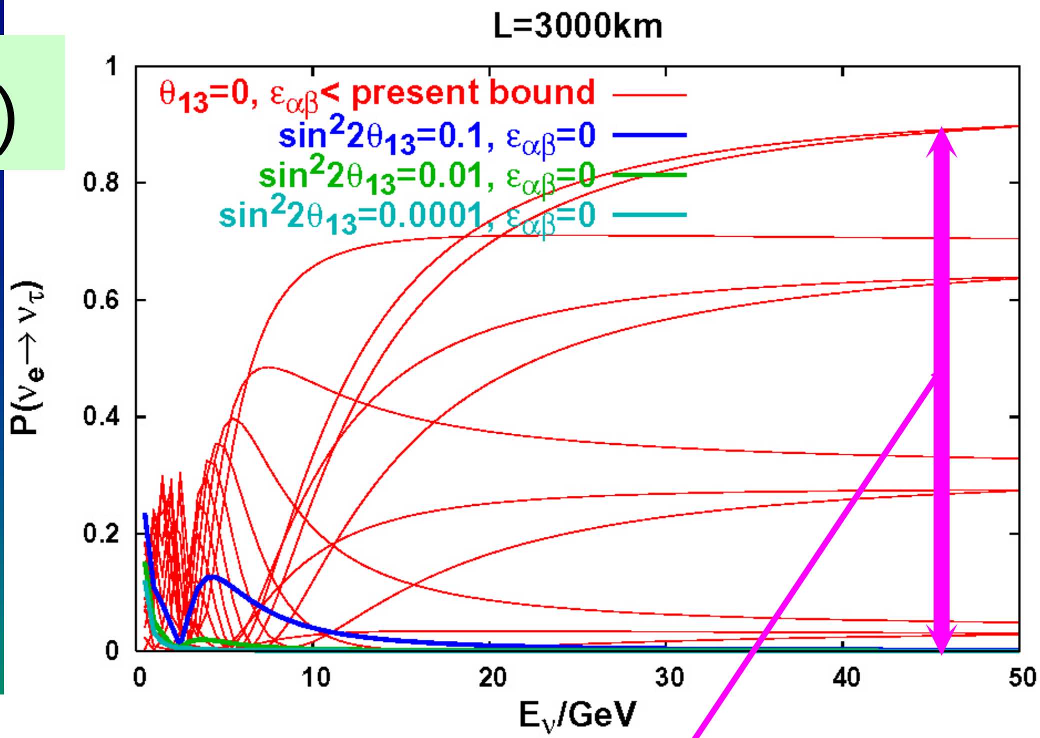


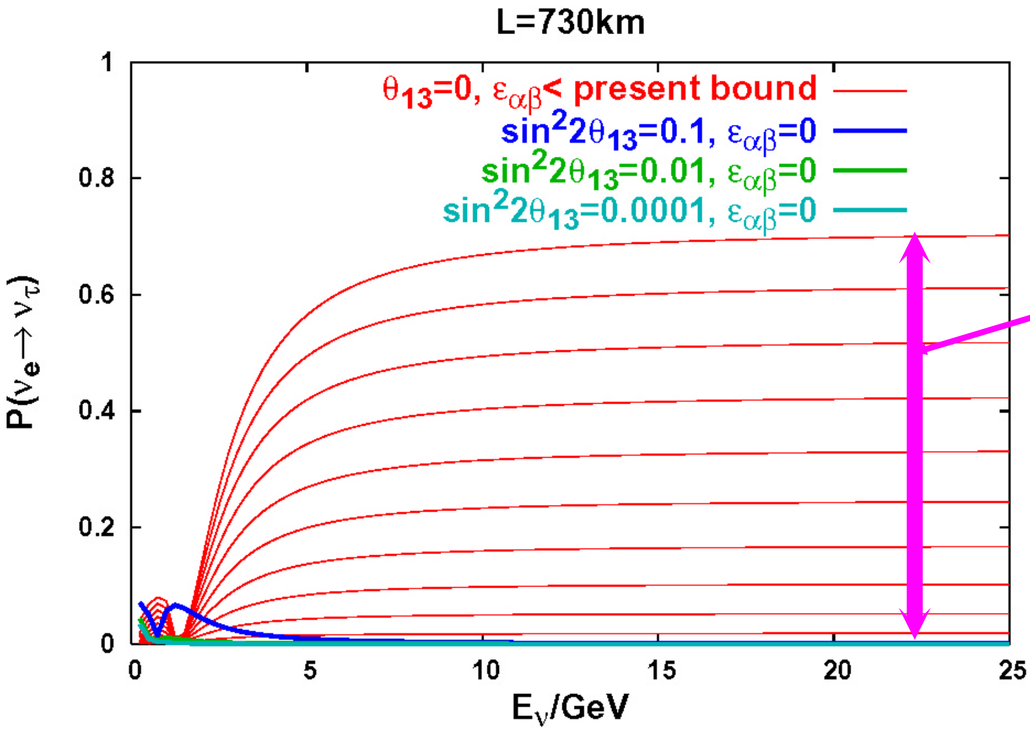
ν factory (golden channel)



ν factory (silver channel)

Amazing!!!





$$\sim \quad P(\nu_e \to \nu_\tau)\big|_{E\to\infty}$$

$$= \sin^2 2\beta \sin^2 \left[\left\{ (1+\epsilon_{ee}-\epsilon_{\tau\tau})^2 + 4\epsilon_{e\tau}^2 \right\}^{\frac{1}{2}} \frac{AL}{2} \right]$$

$$\tan 2\beta \equiv \frac{2|\epsilon_{e\tau}|}{1+\epsilon_{ee}-\epsilon_{\tau\tau}}$$

Summary

- **Assuming the maximum values** of the **NP** parameters which are currently allowed by all the experimental data, the values of oscillation probabilities are estimated (taking into account **NP in propagation only**) for future long baseline experiments.

- There is a chance that **MINOS** ($\nu_\mu \to \nu_e$), **T2K(K)** ($\nu_\mu \to \nu_e$), **ν factory** ($\nu_e \to \nu_\mu$, $\nu_e \to \nu_\tau$) see a signal of **NP** which could be larger than what is expected from the CHOOZ limit on θ_{13} in SM+m_ν.

- The silver channel ($\nu_e \rightarrow \nu_\tau$) is the most powerful to detect the effects of **New Physics** for larger value of $\varepsilon_{e\tau}$ allowed by ν_{atm} .

- The golden (for **NF**) ($\nu_e \rightarrow \nu_\mu$) and ν_e appearance (for **SB**) ($\nu_\mu \rightarrow \nu_e$) channels are also powerful to detect the effects of **New Physics** (because of large θ_{23} mixing $\nu_\mu \leftrightarrow \nu_\tau$).

- The probability to see the effects of **New Physics** depends both on the baseline and E_ν, and combination of a reactor, **T2K**, **NF** is necessary to identify the source of the oscillation.

Future work (in progress)

- Analytical treatment of probabilities
- Inclusion of **NP** at source (U^s) & detector (U^d)

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

NP

$$= \sum_{j,k} (U^d \tilde{U})_{\beta j} (U^s \tilde{U})^*_{\alpha j} (U^d \tilde{U})^*_{\beta k} (U^s \tilde{U})_{\alpha k} e^{-i\Delta \tilde{E}_{jk} L}$$

- U^s and U^d only change the magnitudes of P (the oscillation lengths are not modified).
- The best way to measure U^s and U^d is to take the limit L→0.
- For **SB**/**BB**, processes of production and detection are both hadronic, so $U^d = U^s$ ➡ **SB**/**BB** with L→0 is useless.
- For **NF**, production process is **leptonic** while detection process is **hadronic**, so U^d ❍ U^s ➡ **NF** with L→0 is **useful!**

In case of N_ν=2 using Grossman's notation

- At source

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

NF

(leptonic)

$$\varepsilon_{e\mu}^{s} = \varepsilon_{e\mu}^{\text{lepton}}$$

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

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

SB/BB

(hadronic)

$$\varepsilon_{e\mu}^{s} = \varepsilon_{e\mu}^{\text{hadron}}$$

$$\pi^+ \to \mu^+ + \nu_\mu^s$$

$$\nu_\mu^s = \nu_\mu - \varepsilon_{e\mu}^s \nu_e$$

$$n \to p + e^- + \overline{\nu_e^s}$$

$$\overline{\nu_e^s} = \overline{\nu_e} + \varepsilon_{e\mu}^s \overline{\nu_\mu}$$

- At detector (hadronic)

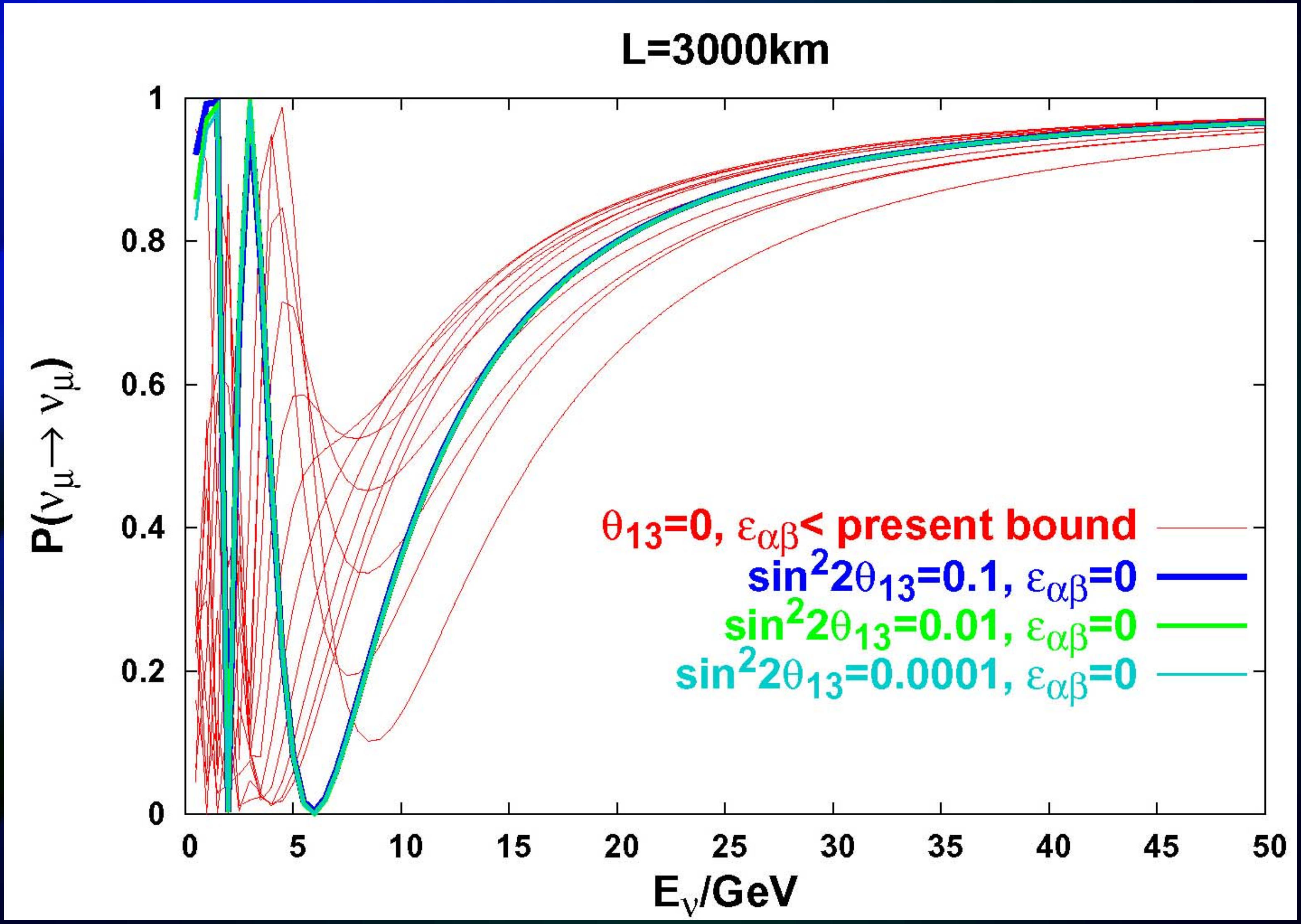
$$\begin{pmatrix} \nu_e^d \\ \nu_\mu^d \end{pmatrix} = \begin{pmatrix} 1 & \epsilon_{e\mu}^d \\ -\epsilon_{e\mu}^d & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

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

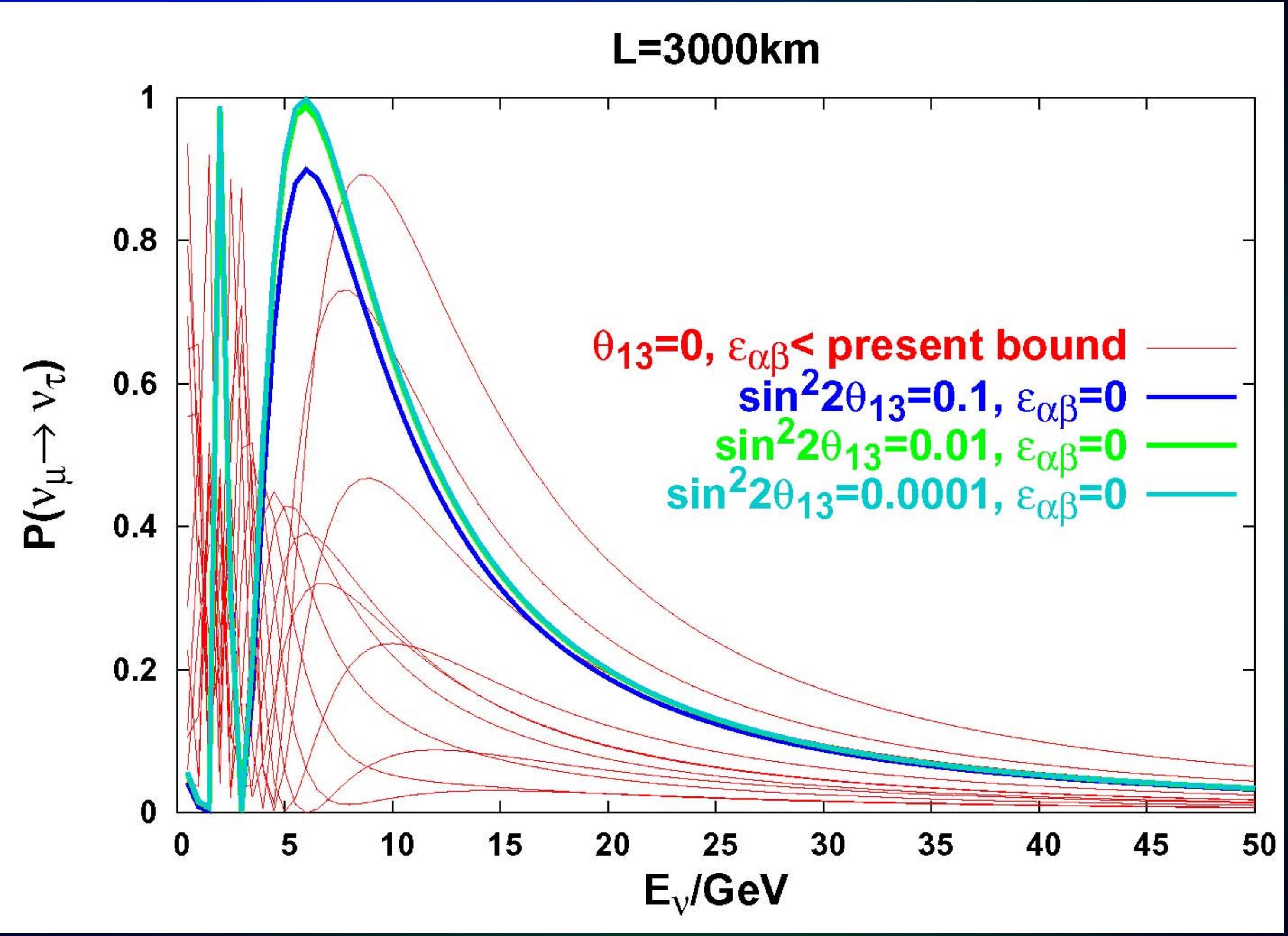
$$\nu_\mu^d = \nu_\mu - \epsilon_{e\mu}^d \nu_e$$

$$\varepsilon_{e\mu}^{d} = \varepsilon_{e\mu}^{\text{hadron}}$$

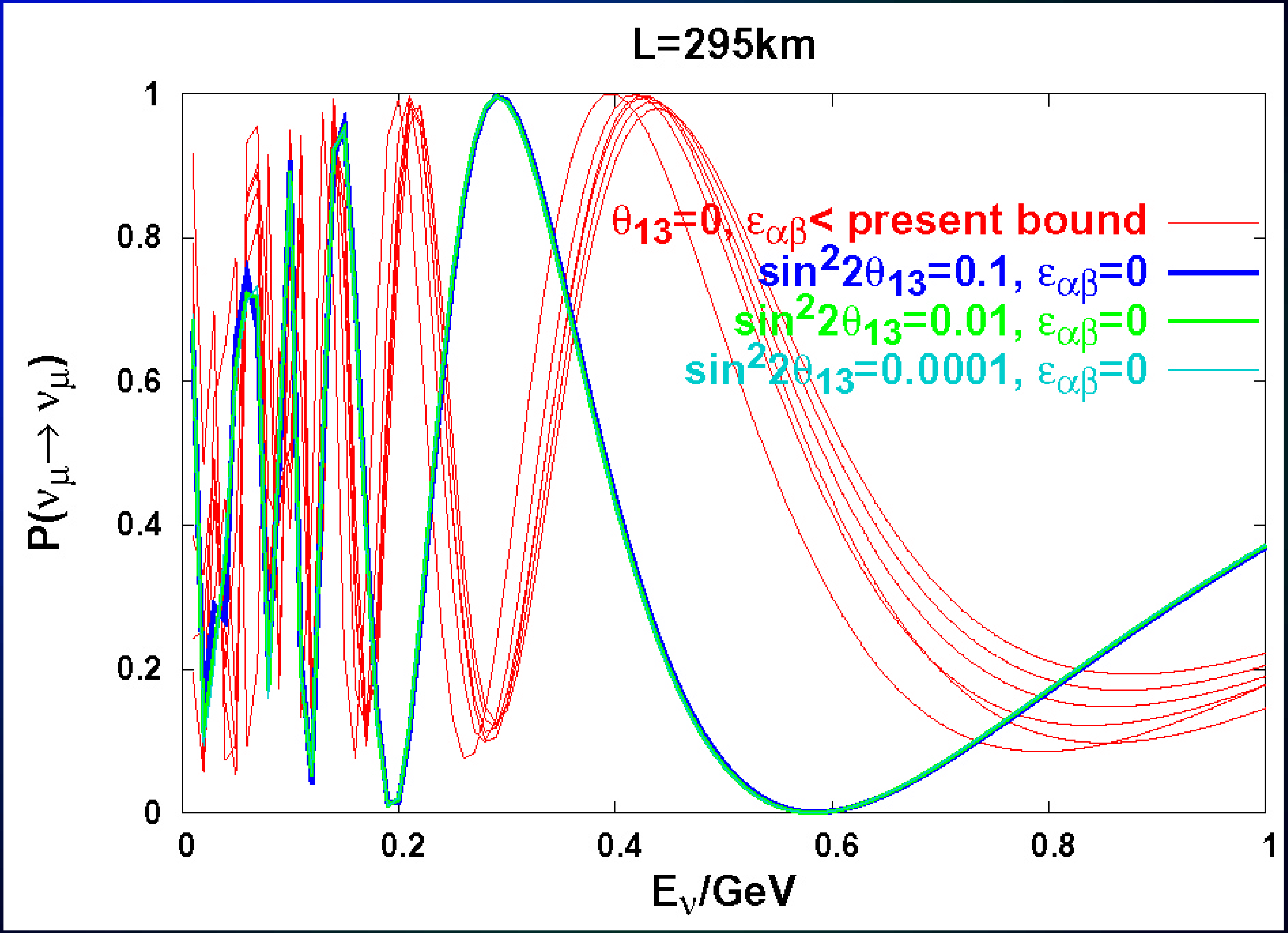
Backup slides



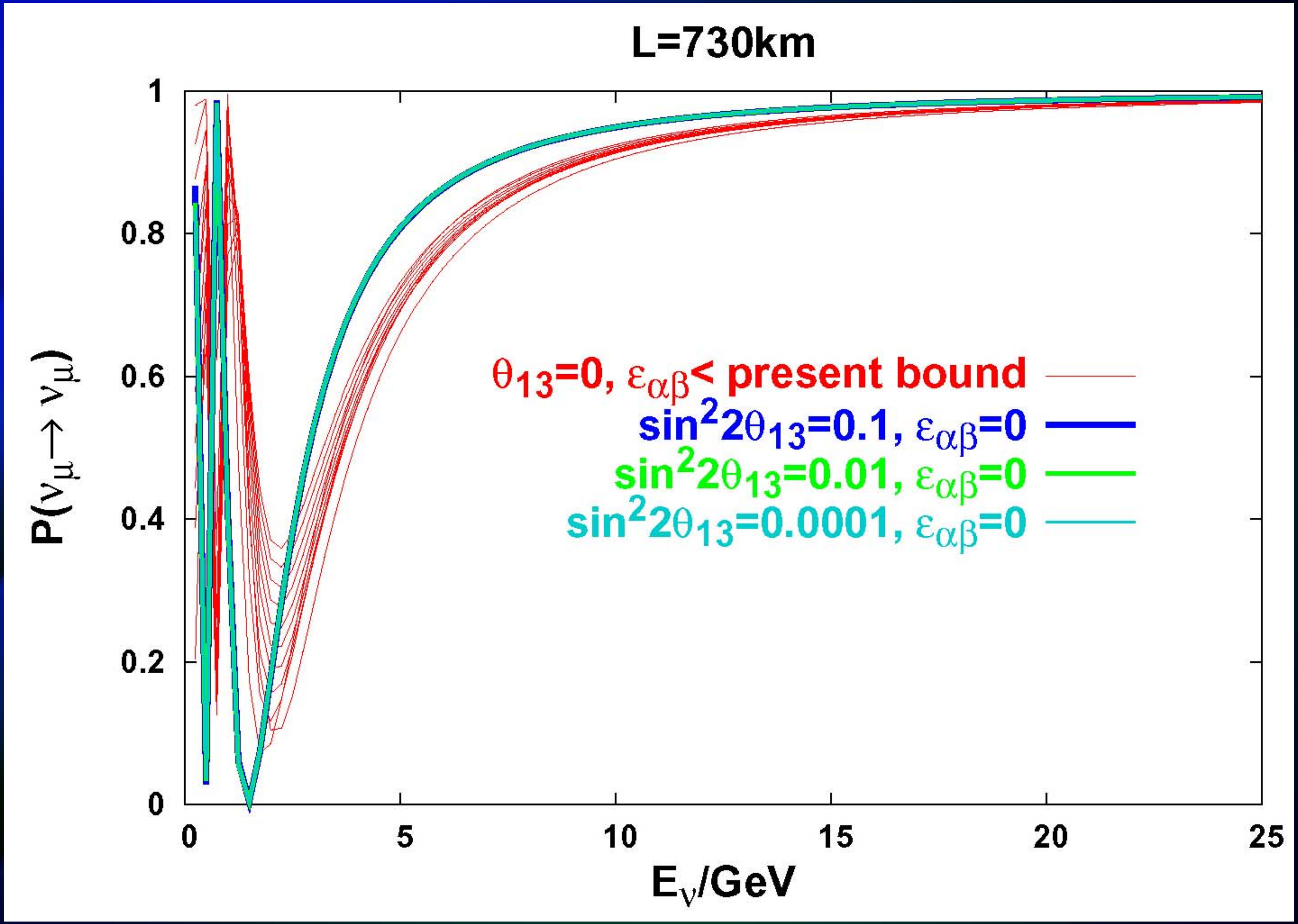
L=3000km
$P(\nu_\mu \to \nu_\mu)$
E_ν/GeV
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35
40
45
50
$\theta_{13}=0$, $\varepsilon_{\alpha\beta}<$ present bound
$\sin^2 2\theta_{13}=0.1$, $\varepsilon_{\alpha\beta}=0$
$\sin^2 2\theta_{13}=0.01$, $\varepsilon_{\alpha\beta}=0$
$\sin^2 2\theta_{13}=0.0001$, $\varepsilon_{\alpha\beta}=0$

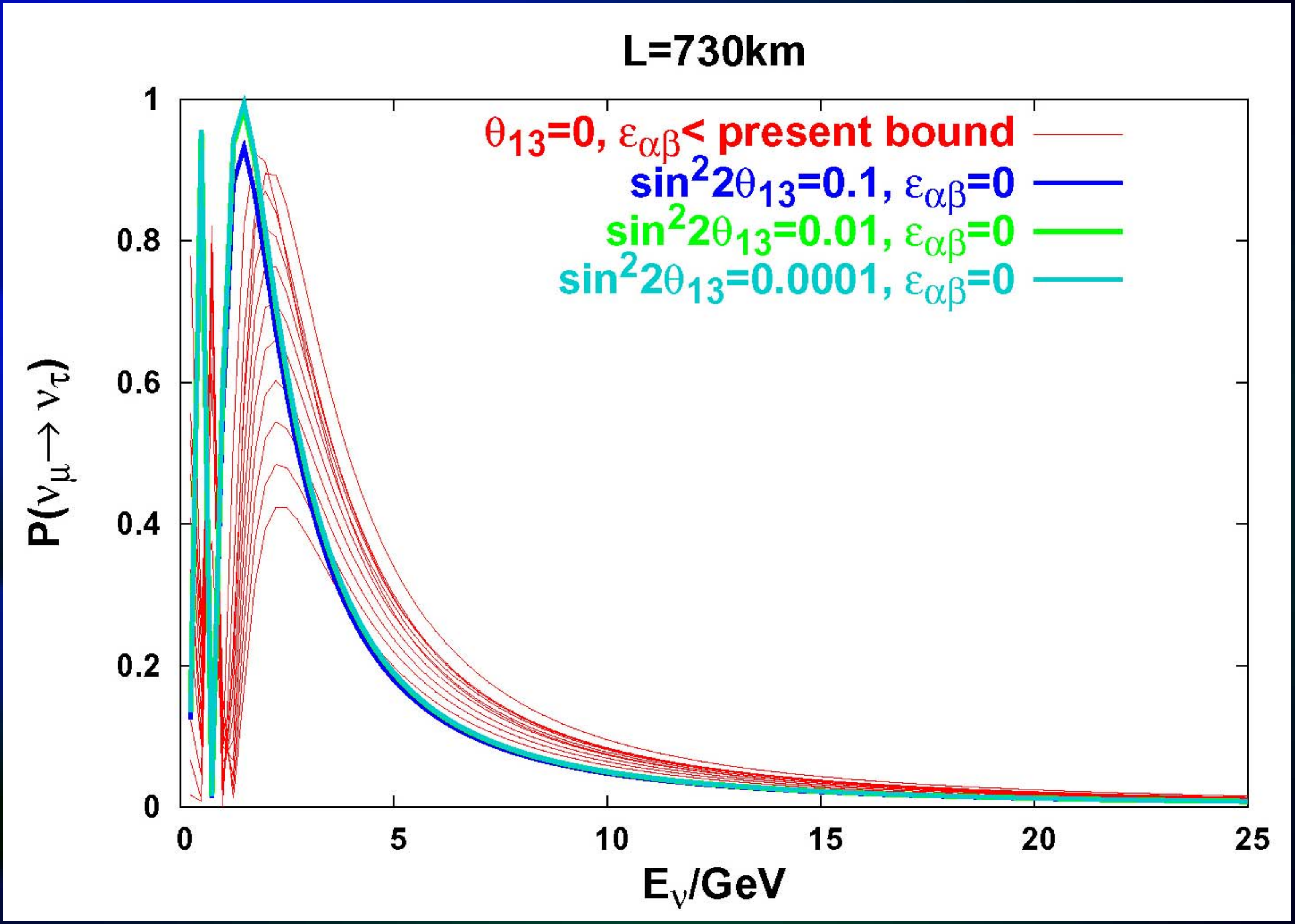


L=3000km
θ_{13}=0, $\epsilon_{\alpha\beta}$< present bound
$\sin^2 2\theta_{13}$=0.1, $\epsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.01, $\epsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.0001, $\epsilon_{\alpha\beta}$=0
$P(\nu_\mu \to \nu_\tau)$
E_ν/GeV
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35
40
45
50

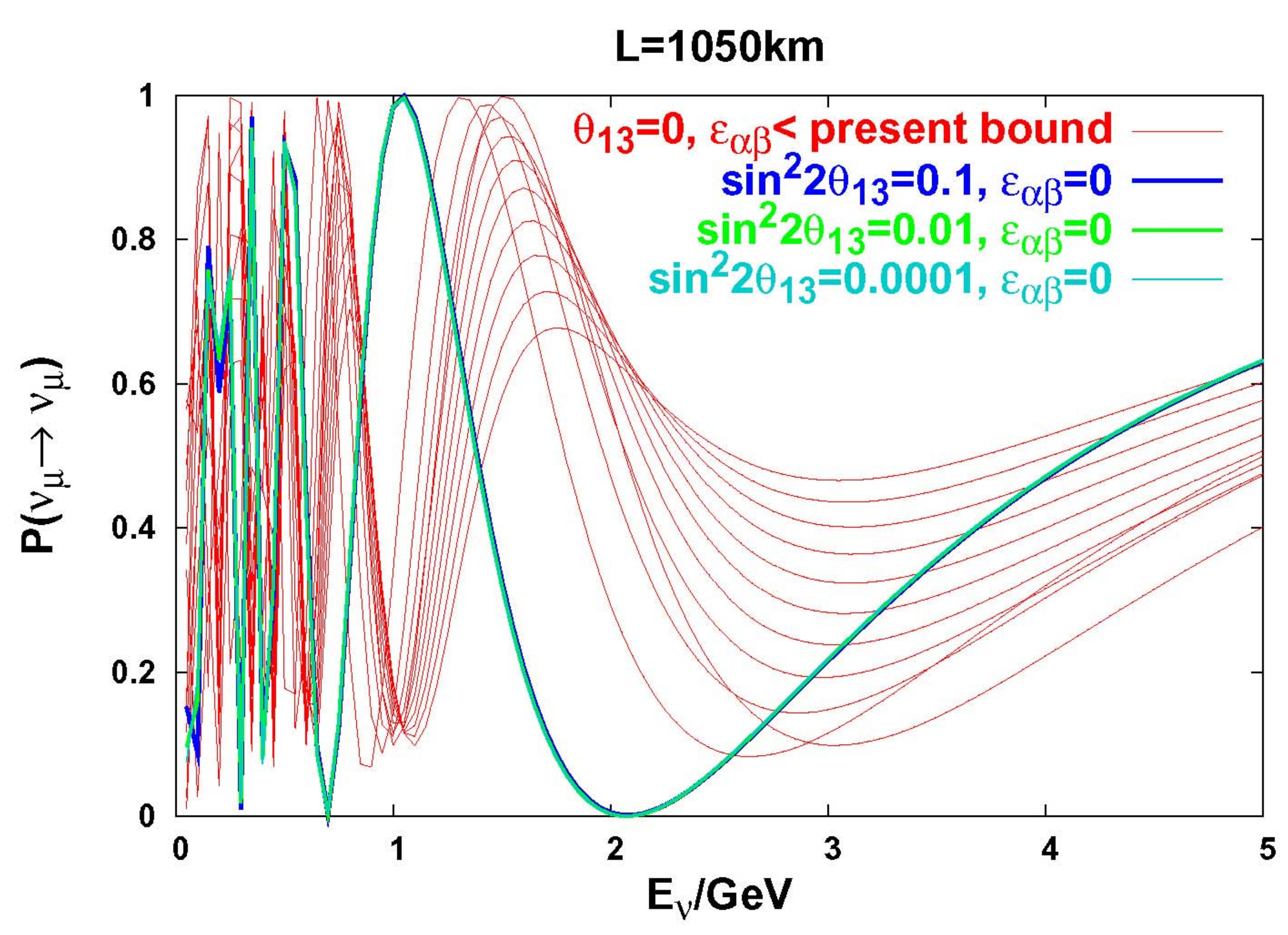


L=295km
θ_{13}=0, $\varepsilon_{\alpha\beta}$< present bound
$\sin^2 2\theta_{13}$=0.1, $\varepsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.01, $\varepsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.0001, $\varepsilon_{\alpha\beta}$=0
$P(\nu_\mu \to \nu_\mu)$
E_ν/GeV
0
0.2
0.4
0.6
0.8
1


L=730km
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
$P(\nu_\mu \to \nu_\mu)$
E_ν/GeV
$\theta_{13}=0$, $\varepsilon_{\alpha\beta}$< present bound
$\sin^2 2\theta_{13}=0.1$, $\varepsilon_{\alpha\beta}=0$
$\sin^2 2\theta_{13}=0.01$, $\varepsilon_{\alpha\beta}=0$
$\sin^2 2\theta_{13}=0.0001$, $\varepsilon_{\alpha\beta}=0$



L=730km
θ_{13}=0, $\varepsilon_{\alpha\beta}$< present bound
$\sin^2 2\theta_{13}$=0.1, $\varepsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.01, $\varepsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.0001, $\varepsilon_{\alpha\beta}$=0
$P(\nu_\mu \rightarrow \nu_\tau)$
E_ν/GeV
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25



L=1050km
θ_{13}=0, $\varepsilon_{\alpha\beta}$< present bound
$\sin^2 2\theta_{13}$=0.1, $\varepsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.01, $\varepsilon_{\alpha\beta}$=0
$\sin^2 2\theta_{13}$=0.0001, $\varepsilon_{\alpha\beta}$=0
$P(\nu_\mu \rightarrow \nu_\mu)$
E_ν/GeV
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5