A Review of Works on the Neutrino Non-Standard Interaction

Hiroaki Sugiyama

(Theory group, KEK)

⋆ In this talk, no unitarity violation
no specific model

Introduction

● Theoretical view

Neutrinos have already presented

new physics beyond the standard model

neutrino mass

two large mixings

Neutrinos showed that

nature does not hate **large flavor violation**

⇒ More new physics with flavor violation for neutrinos?

ex. **N**on-**S**tandard **I**nteraction

● Experimental view

Precise measurements of oscillations

for tiny θ_{13} and leptonic CP-violation etc.

⇒ Some signatures in oscillation experiments?

Places of

Non-Standard Int.

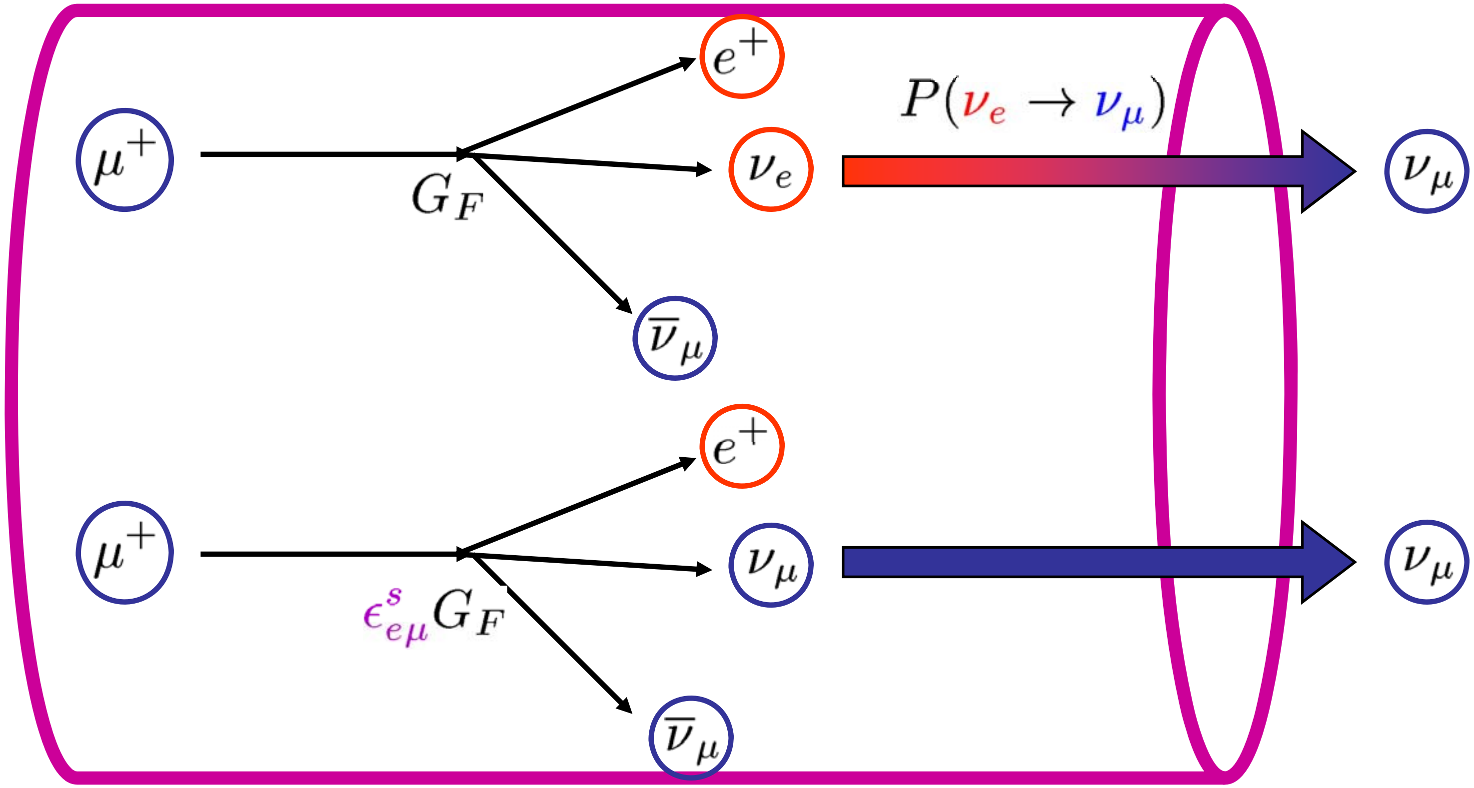
for Osci. Exp.

Source, Matter, Detector

NSI in Source and Detector

- **In source**

Y. Grossman, PLB 359, 141 (1995)



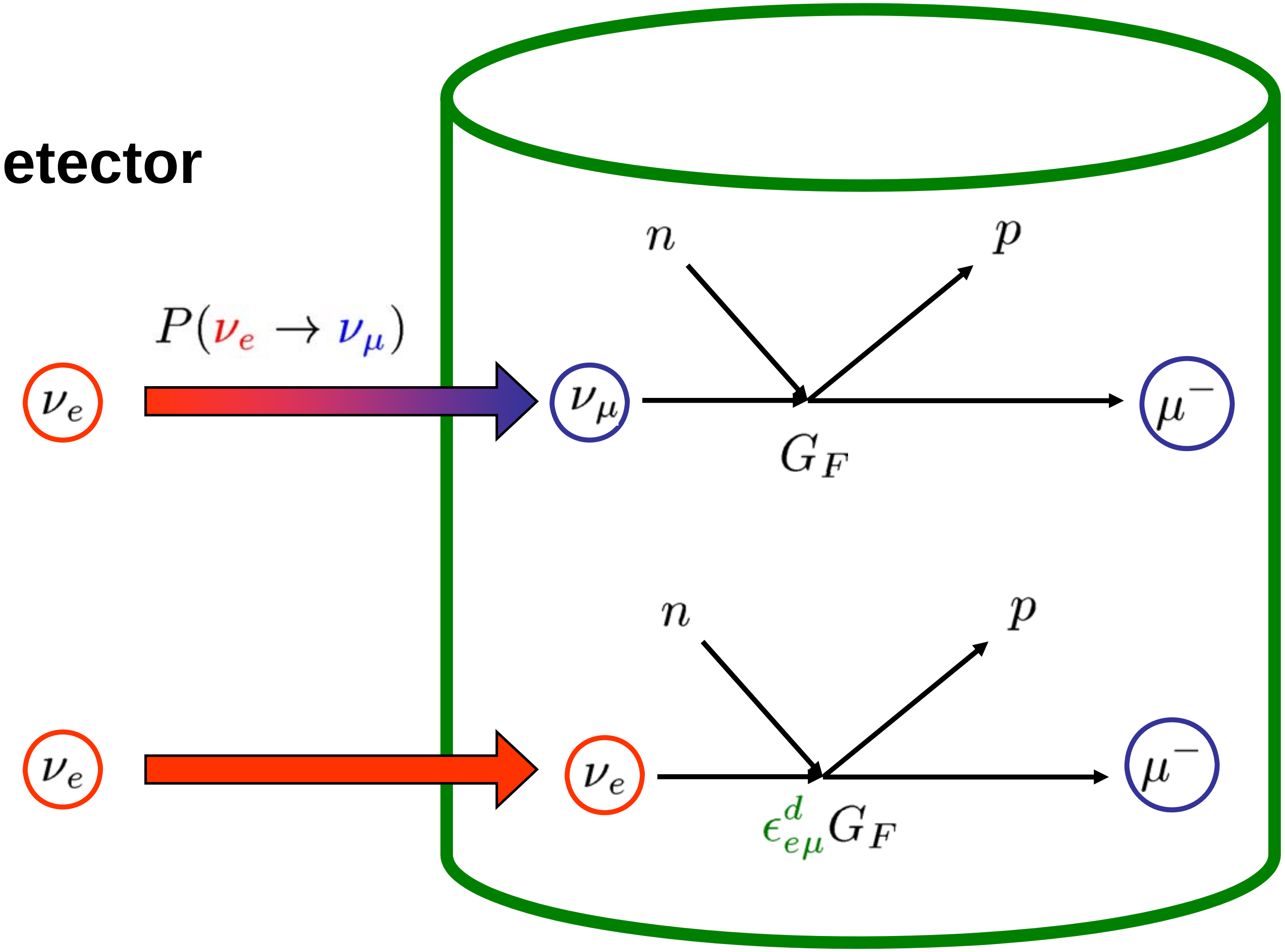
$$\mu^+ \to e^+ + \overline{\nu}_\mu + \nu^s_\mu$$

$$\nu^s_\mu = \nu_\mu - \epsilon^s_{e\mu}\nu_e$$

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

Q: large NSI ($\sin\epsilon, \ \cos\epsilon$)??

- **In detector**



$$\nu^d_\mu + n \to \mu^- + p$$

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

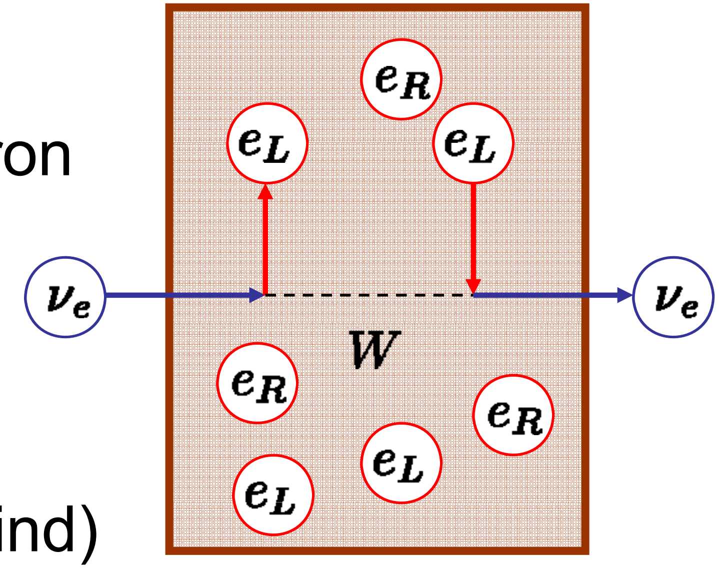
$$\begin{pmatrix} \nu^d_e \\ \nu^d_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^d_{e\mu} \\ -\epsilon^d_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

NSI in Matter

- **Standard matter effect**

Charged lepton in matter is only electron

extra potential (charged-current)
for e-flavor neutrinos only



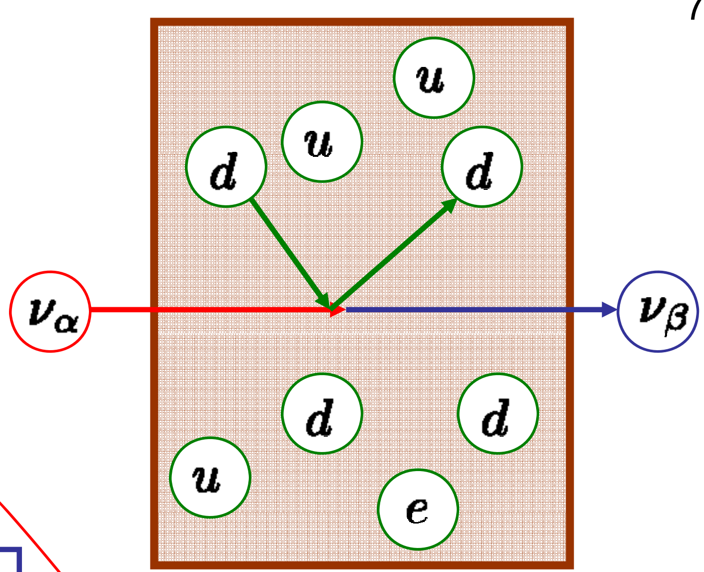
Neutral-current gives overall (flavor-blind)
phase for propagation … irrelevant

$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{2E}\left[\begin{pmatrix} & U & \end{pmatrix}\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}\begin{pmatrix} & U^\dagger & \end{pmatrix} + \begin{pmatrix}A & 0\\ 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$\rightarrow \frac{1}{2E}\begin{pmatrix} & U_M & \end{pmatrix}\begin{pmatrix}m^2_{M-} & 0\\ 0 & m^2_{M+}\end{pmatrix}\begin{pmatrix} & U_M^\dagger & \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$A \equiv 2\sqrt{2}EG_F N_e$ $\quad$ N_e : electron number density (left+right)

● Non-standard matter effect



$$\mathcal{L}_{\rm eff}^{\rm NSI} = -2\sqrt{2}G_F\, \epsilon^P_{\alpha\beta f f}\, (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\, (\overline{f}\gamma^\rho P f)$$

$$f = e, u, d \qquad P = P_L, P_R$$

Schrödinger eq. in flavor basis

$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \mathcal{H}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$\mathcal{H} = \frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f,P}\frac{n_f}{n_e}\epsilon^P_{\alpha\beta f f} \simeq \sum_P\left(\epsilon^P_{\alpha\beta ee} + 3\epsilon^P_{\alpha\beta uu} + 3\epsilon^P_{\alpha\beta dd}\right)$$

Some Examples of Effects of NSI

Confusion between Oscillation and NSI

- **Naive expectation**

oscillation

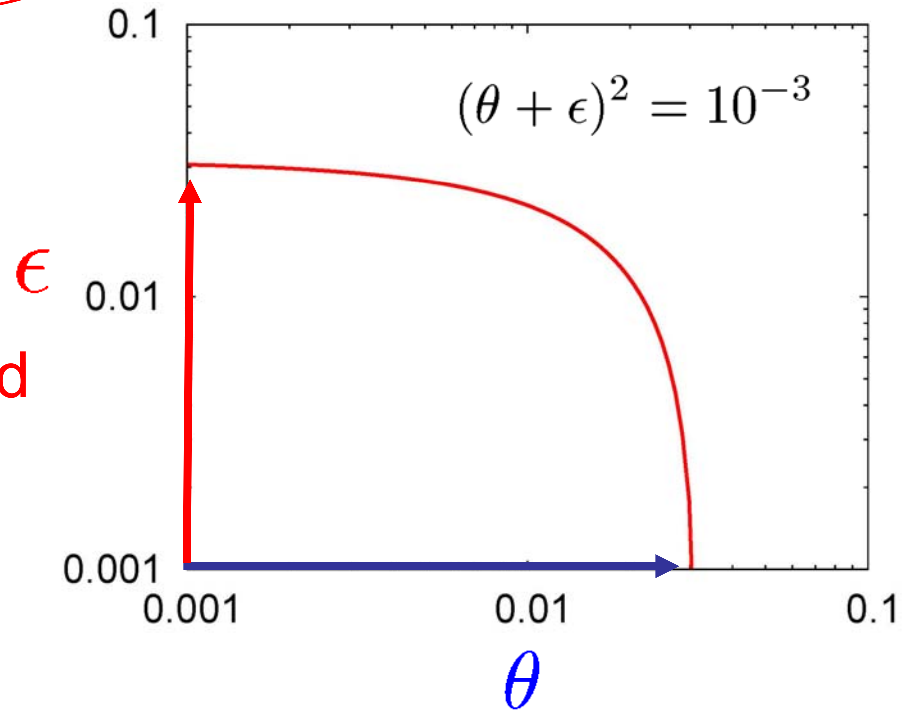
non-standard effect

Roughly, $P_{\text{transition}} \sim (\theta + \epsilon)^2$

sensitivity at ν factory

$$P \sim 10^{-4}$$

We have only upper bound on θ and ϵ even if experiments observes non-zero P



needs combined analysis

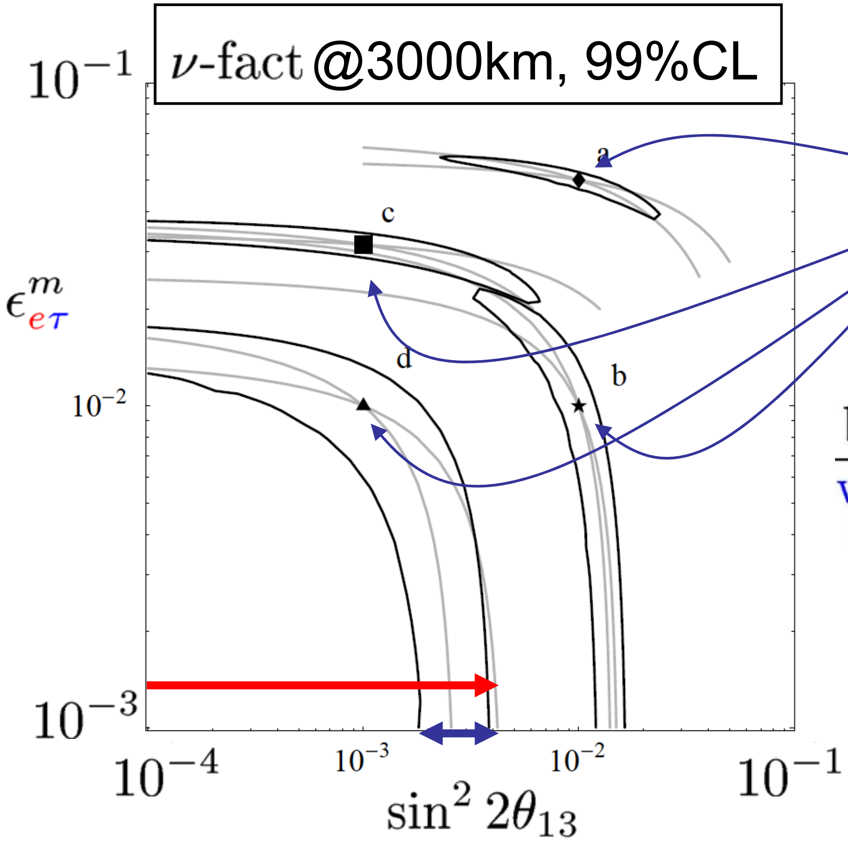
Confusion with NSI in Matter

P. Huber et.al, PRL **88,** 101804 (2002)

setup: $\nu_e \to \nu_\mu$ and $\overline{\nu}_e \to \overline{\nu}_\mu,\ \Delta m^2_{12} = 0,\ \epsilon^m_{e\tau},\ \epsilon^m_{\tau\tau},$ no phases

$$P \simeq C_1 s_{13}^2 + C_2 s_{13} \epsilon^m_{e\tau} + C_3 \left(\epsilon^m_{e\tau}\right)^2$$

almost indep. of $\epsilon_{\tau\tau}$



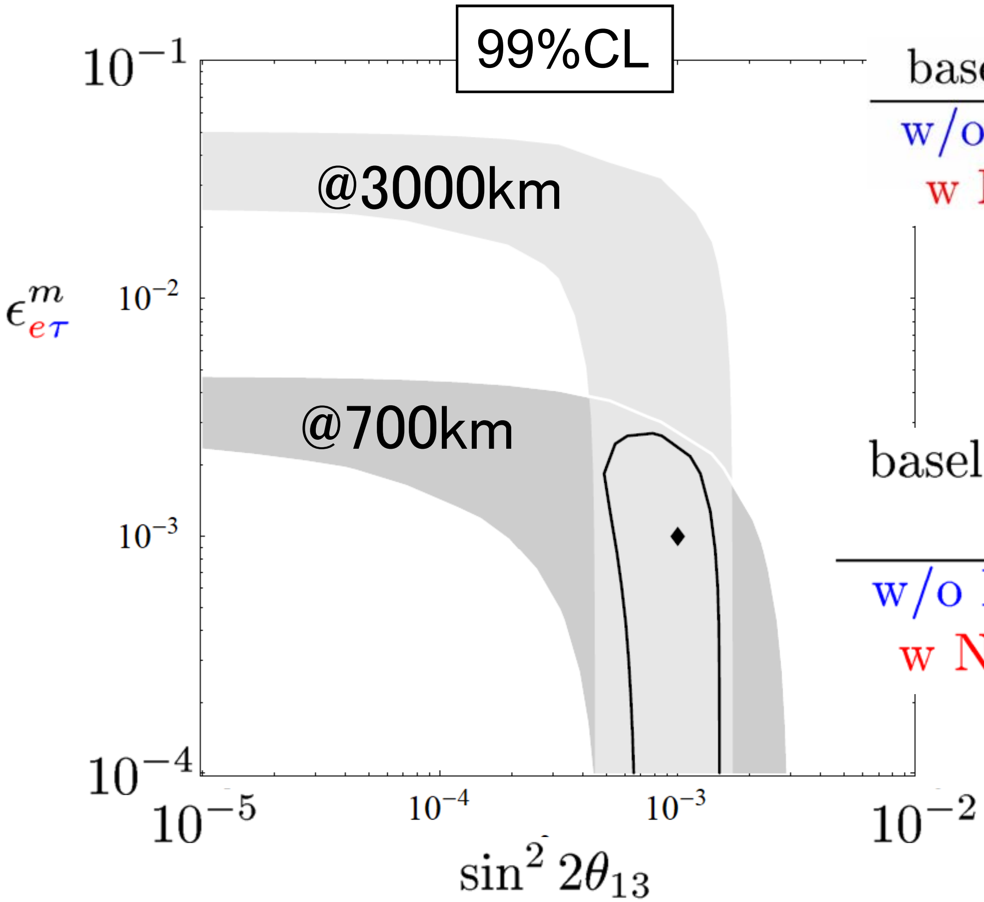
four samples

sensitivity to $\sin^2 2\theta_{13}$

baseline	700	3000	7000
w/o NSI	2×10^{-4}	3×10^{-4}	5×10^{-4}
w NSI	1×10^{-1}	7×10^{-2}	5×10^{-3}

large loss of sensitivity

How to improve?



baseline	700	3000	7000
w/o NSI	2×10^{-4}	3×10^{-4}	5×10^{-4}
w NSI	1×10^{-1}	7×10^{-2}	5×10^{-3}

baselines	700 & 3000	7000 & 7000	3000 & 7000
w/o NSI	2×10^{-4}	3×10^{-4}	3×10^{-4}
w NSI	2×10^{-3}	2×10^{-3}	2×10^{-3}

not so bad

combining two baselines is useful

spectral information

Confusion with Non-Standard Interaction in Source and Matter

P. Huber, et.al, PRD **66,** 013006 (2002)

setup: $\nu_e \to \nu_\mu,\ \Delta m^2_{12} = 0,\ \epsilon^s_{e\tau},\ \epsilon^m_{e\tau},$ no phases

$$P_{e\mu}(s_{13}, \epsilon^s_{e\tau}, \epsilon^m_{e\tau}; E) \simeq C_1(E) s^2_{13} + C_2(E) s_{13} \epsilon^m_{e\tau} + C_3(E)(\epsilon^m_{e\tau})^2 + C_4(E)\epsilon^m_{e\tau}\epsilon^s_{e\tau} + C_5(E)(\epsilon^s_{e\tau})^2 + C_6(E) s_{13}\epsilon^s_{e\tau}$$

$$s_{13} = 0,\ \epsilon^s_{e\tau} = \epsilon^m_{e\tau} \quad \Longrightarrow \quad P_{e\mu} = \underline{C_1(E)} c^2_{23}\,(\epsilon^m_{e\tau})^2$$

★ situation is the same for $\overline{P}_{e\mu}$ also

If $\epsilon^s_{e\tau}$ and $\epsilon^m_{e\tau}$ can be larger than $s^{\text{true}}_{13}/c^2_{23}$,

we can not reject $s_{13} = 0$ even with spectral information

loss of sensitivity on s_{13}

How to improve?

ϵ^s appears for any experiments in principle

ϵ^m can be negligible for experiments with short baseline or low energy

It will be better to constrain ϵ^s first

$\longrightarrow$ escape from the condition $\epsilon^s_{e\tau} = \epsilon^m_{e\tau} = s_{13}^{\rm true}/c_{23}$

▲ short baseline (near detector) $P_{\alpha\beta} = \left| \left[U^s (U^d)^\dagger \right]_{\alpha\beta} \right|^2$

$U^s = U^d \Rightarrow$ no effect

same int. $\epsilon_{\alpha\beta ud} \left(\bar{l}_\alpha \gamma_\rho P_L \nu_\beta \right) \left(\bar{u} \gamma^\rho P d \right)$

ex. super-beam $u\bar{d} \to \mu^+ \nu,\ \nu d \to u l^-$

reactor $d \to u e^- \bar{\nu},\ \bar{\nu} u \to d l^+$

$U^s \neq U^d \Leftarrow$ nu-factory $\mu^+ \to e^+ \nu \bar{\nu},\ \nu d \to u l^-$

$P \simeq \left(\epsilon^s - \epsilon^d \right)^2$

Q: How to distinguish ϵ^s and ϵ^d ??

LSND? … next slide

▲ low energy

$U^s = U^d$ is simple

ex. reactor (far detector)

$$\Rightarrow \quad P_{\alpha\beta} = \left| \sum_j \left[U^s U_{\mathrm{MNS}} \right]_{\alpha j} \exp\left(i \frac{(\Delta m^2)_{j1} L}{4E} \right) \left[U^s U_{\mathrm{MNS}} \right]^\dagger_{j\beta} \right|^2$$

Q: How to distinguish $U^s U_{\mathrm{MNS}}$ and U_{MNS} ??

LSND Result with Non-Standard Interaction

S. Bergman et.al, PRD **59**,093005 (1999)

LSND: $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \xrightarrow{30\mathrm{m}} \overline{\nu}_e \, p \to e^+ n$

result: $\overline{P}_{\mu e} = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$

$$\left.\begin{array}{ll} \mu^+ \to e^+ \nu_\alpha \overline{\nu}_e & \epsilon^s_{\mu e \omega e} \, (\overline{\mu}\gamma_\rho P_L \nu_e)\,(\overline{\nu}_\omega \gamma^\rho P e) \\ \overline{\nu}_\mu \, p \to e^+ n & \epsilon^d_{\mu e d u} \, (\overline{\nu}_\mu \gamma_\rho P_L e)\,(\overline{d}\gamma^\rho P u) \end{array}\right\}$$

$$\Rightarrow \sqrt{\sum_\omega (\epsilon^s_{\mu e \omega e} - \epsilon^d_{\mu e d u})^2} \simeq 5 \times 10^{-2}$$

disfavored

KARMEN: $\overline{P}_{\mu e} < 1.7 \times 10^{-3}$ (90% CL, @17m) $\Rightarrow \sqrt{\sum_\omega (\epsilon^s_{\mu e \omega e} - \epsilon^d_{\mu e d u})^2} < 4 \times 10^{-2}$

MiniBooNE: if no signal $\Rightarrow \sqrt{\sum_\omega (\epsilon^s_{\mu e \omega e} - \epsilon^d_{\mu e d u})^2} < 2 \times 10^{-2}$??

other constraints? …next

Constraint on NSI from Non-Osci. Exp.

Decay, Scattering

Constraints on NSI with $SU(2)$

PDG2006
table in A. Ibarra, NPB **715**, 523 (2005)

$\boxed{\text{assumption: no cancellation}}$ $(\epsilon_1 - \epsilon_2)^2 < 10^{-2} \Rightarrow \epsilon_1, \ \epsilon_2 < 10^{-1}$

- $\mu^+ \to e^+ \bar{\nu}_\beta \nu_\omega \qquad \epsilon_{\mu\beta\omega e} \, (\overline{\mu}\gamma_\rho P_L \nu_\beta)\,(\overline{\nu}_\omega \gamma^\rho P_L e)$

$\mu^- \to e^- e^+ e^-$ $\quad (\mu^+ e^-) \leftrightarrow (\mu^- e^+)$ $\quad \tau^- \to e^- \mu^+ e^-$

for LSND

$$\begin{pmatrix} \boxed{\epsilon_{\mu eee} \quad \epsilon_{\mu e\mu e} \quad \epsilon_{\mu e\tau e}} \\ \epsilon_{\mu\mu ee} \quad \epsilon_{\mu\mu\mu e} \quad \epsilon_{\mu\mu\tau e} \\ \epsilon_{\mu\tau ee} \quad \epsilon_{\mu\tau\mu e} \quad \epsilon_{\mu\tau\tau e} \end{pmatrix} < \begin{pmatrix} 1\times 10^{-6} & 3\times 10^{-3} & 7.9\times 10^{-4} \\ 0?? & 3.2\times 10^{-5} & 1\times 10^{-3} \\ 1\times 10^{-3} & 8.5\times 10^{-4} & 3.2\times 10^{-6} \end{pmatrix}$$

$\mu^- \to e^- \gamma$ $\quad \tau^- \to e^- \mu^+ \mu^-$

$\tau^- \to \mu^- e^+ e^-$ $\quad \tau^- \to e^- \mu^+ \mu^-$

standard model like (def. of G_F ??)

$\boxed{\text{Q: interaction with right-handed charged-lepton } (\epsilon^R)\text{??}}$

- $\begin{cases} \nu_\alpha d \to l_\beta^- u \quad \pi^- \to \overline{\nu}_\alpha l_\beta^- \\ \nu_\alpha \to (\text{matter}) \to \nu_\beta \end{cases}$

$$\epsilon^L_{\alpha\beta du}(\overline{\nu}_\alpha \gamma_\rho P_L l_\beta)(\overline{d}\gamma^\rho \underline{P_L} u)$$

$$\epsilon^L_{\alpha\beta uu}(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{u}\gamma^\rho \underline{P_L} u)$$

$$\epsilon^L_{\alpha\beta dd}(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{d}\gamma^\rho \underline{P_L} d)$$

$$\epsilon^L_{\alpha\beta qq}$$

$\pi^- \to e^- \overline{\nu}$ $\quad \mu^- \text{Ti} \to e^- \text{Ti}$ $\quad \tau^- \to e^- \pi^0$

for LSND

$$\begin{pmatrix} \epsilon^L_{eeqq} & \boxed{\epsilon^L_{e\mu qq}} & \epsilon^L_{e\tau qq} \\ & \epsilon^L_{\mu\mu qq} & \epsilon^L_{\mu\tau qq} \\ & & \epsilon^L_{\tau\tau qq} \end{pmatrix} < \begin{pmatrix} 1.6\times10^{-3}? & 2.1\times10^{-6} & 2.5\times10^{-4} \\ & 2.0\times10^{-5}? & 2.0\times10^{-4} \\ & & 3.2\times10^{-3}? \end{pmatrix}$$

standard model like

$\pi^- \to \mu^- \overline{\nu}$ $\quad \tau^- \to \nu\pi^-$ $\quad \tau^- \to \mu^- \pi^0$

$$\sqrt{\sum_\omega (\epsilon^L_{\mu e\omega e} - \epsilon^L_{\mu eqq})^2} < 3\times10^{-3} \quad \text{(LSND: } 5\times10^{-2}\text{)}$$

Non-standard interaction can **not** explain LSND result

Z. Berezhiani et al., PLB 535, 207 (2002)

- $\begin{cases} \nu_\alpha e^- \to \nu_\beta e^- \\ \nu_\alpha \to (\text{matter}) \to \nu_\beta \end{cases}$ $\quad \epsilon_{\alpha\beta ee} (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{e}\gamma^\rho \underline{P_L} e)$

$\mu^- \to e^- e^+ e^-$

$e^+ e^- \to e^+ e^-$

$\tau^- \to e^- e^+ e^-$

$$\begin{pmatrix} \epsilon_{eeee} & \epsilon_{e\mu ee} & \epsilon_{e\tau ee} \\ & \epsilon_{\mu\mu ee} & \epsilon_{\mu\tau ee} \\ & & \epsilon_{\tau\tau ee} \end{pmatrix} < \begin{pmatrix} 3 \times 10^{-2} & 1 \times 10^{-6} & 4.5 \times 10^{-4} \\ & 3 \times 10^{-3} & 1 \times 10^{-3} \\ & & 1 \times 10^{-1} \end{pmatrix}$$

standard model like

$\nu_\mu e^- \to \nu e^-$

$\tau^- \to \mu^- e^+ e^-$

$e^+ e^- \to \tau^+ \tau^-$

summary of constraints with $SU(2)$

Only ϵ_{eeee} and $\epsilon_{ee\tau\tau}$ can be rather large

Constraints on NSI without $SU(2)$

S. Davidson et al., JHEP **0303**, 011 (2003)

ex. dim-8 op. with higgs

$$(\overline{L}_\alpha P_R H^c)\,\gamma_\rho\,((H^c)^\dagger P_L L_\beta)\,(\overline{f}\gamma^\rho P f) \longrightarrow (\overline{\nu}_\alpha\gamma_\rho P_L \nu_\beta)\,(\overline{f}\gamma^\rho P f)$$

$$(\overline{L}_\alpha P_R H^c)\,\gamma_\rho\,((H^c)^\dagger P_L L_\beta)\,(\overline{f}\gamma^\rho P f) \;\not\longrightarrow\; (\overline{l}_\alpha\gamma_\rho P_L l_\beta)\,(\overline{f}\gamma^\rho P f)$$

indep.

cf. $m_t \neq m_b$

NSI for neutrinos can be constrained
by experiments with neutrinos

in principle…

Q: explicit model??

$\boxed{\text{assumption: no cancellation}}$ $(\epsilon_1 - \epsilon_2)^2 < 10^{-2} \Rightarrow \epsilon_1, \ \epsilon_2 < 10^{-1}$

- $\begin{cases} \nu_\alpha e^- \to \nu_\beta e^- \\ \nu_\alpha \to (\text{matter}) \to \nu_\beta \end{cases}$ $\epsilon^P_{\alpha\beta ee} (\overline{\nu}_\alpha \gamma_\rho P \nu_\beta)(\overline{e}\gamma^\rho P e)$

$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{e}\gamma^\rho P_L e)$

$\mu \to eee$

LEP $e^+e^- \to \nu\overline{\nu}\gamma$

$$\begin{pmatrix} -0.07 < \epsilon^L_{eeee} < 0.11 & |\epsilon^L_{e\mu ee}| < 5 \times 10^{-4} & |\epsilon^L_{e\tau ee}| < 0.4 \\ & -0.025 < \epsilon^L_{\mu\mu ee} < 0.03 & |\epsilon^L_{\mu\tau ee}| < 0.1 \\ & & -0.6 < \epsilon^L_{\tau\tau ee} < 0.4 \end{pmatrix}$$

LSND $\nu_e e \to \nu e$

CHARM II $\nu_\mu e \to \nu e$

$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\overline{e}\gamma^\rho P_R e)$

$$\begin{pmatrix} -1 < \epsilon^R_{eeee} < 0.5 & |\epsilon^R_{e\mu ee}| < 5 \times 10^{-4} & |\epsilon^R_{e\tau ee}| < 0.7 \\ & -0.027 < \epsilon^R_{\mu\mu ee} < 0.03 & |\epsilon^R_{\mu\tau ee}| < 0.1 \\ & & -0.4 < \epsilon^R_{\tau\tau ee} < 0.6 \end{pmatrix}$$

- $\nu_\alpha \to (\text{matter}) \to \nu_\beta$ $\quad\quad \epsilon^P_{\alpha\beta uu}\,(\overline{\nu}_\alpha\gamma_\rho P_L\nu_\beta)\,(\overline{u}\gamma^\rho P u)$

$$\epsilon^P_{\alpha\beta dd}\,(\overline{\nu}_\alpha\gamma_\rho P_L\nu_\beta)\,(\overline{d}\gamma^\rho P d)$$

CHARM $\nu_e q \to \nu q$

$(\overline{\nu}_\alpha\gamma_\rho P_L\nu_\beta)\,(\overline{u}\gamma^\rho P_L u)$

$$\begin{pmatrix} -1 < \epsilon^L_{eeuu} < 0.3 & |\epsilon^L_{e\mu uu}| < 7.7\times 10^{-4} & |\epsilon^L_{e\tau uu}| < 0.5 \\ & |\epsilon^L_{\mu\mu uu}| < 0.003 & |\epsilon^L_{\mu\tau uu}| < 0.05 \\ & & |\epsilon^L_{\tau\tau uu}| < 1.4 \end{pmatrix}$$

$\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}$ $\quad$ NuTeV $\nu_\mu q \to \nu q$ $\quad$ $Z \to \nu\overline{\nu}$

$(\overline{\nu}_\alpha\gamma_\rho P_L\nu_\beta)\,(\overline{u}\gamma^\rho P_R u)$

$$\begin{pmatrix} -0.4 < \epsilon^R_{eeuu} < 0.7 & |\epsilon^R_{e\mu uu}| < 7.7\times 10^{-4} & |\epsilon^R_{e\tau uu}| < 0.5 \\ & -0.008 < \epsilon^R_{\mu\mu uu} < 0.003 & |\epsilon^R_{\mu\tau uu}| < 0.05 \\ & & |\epsilon^R_{\tau\tau uu}| < 3 \end{pmatrix}$$

CHARM $\nu_e q \to \nu q$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{d}\gamma^\rho P_L d)$$

$$\begin{pmatrix} |\epsilon^L_{eedd}| < 0.3 & |\epsilon^L_{e\mu dd}| < 7.7\times 10^{-4} & |\epsilon^L_{e\tau dd}| < 0.5 \\ & |\epsilon^L_{\mu\mu dd}| < 0.003 & |\epsilon^L_{\mu\tau dd}| < 0.05 \\ & & |\epsilon^L_{\tau\tau dd}| < 1.1 \end{pmatrix}$$

$\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}$

NuTeV $\nu_\mu q \to \nu q$

$Z \to \nu\overline{\nu}$

$$(\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\,(\overline{d}\gamma^\rho P_R d)$$

$$\begin{pmatrix} -0.6 < \epsilon^R_{eedd} < 0.5 & |\epsilon^R_{e\mu dd}| < 7.7\times 10^{-4} & |\epsilon^R_{e\tau dd}| < 0.5 \\ & -0.008 < \epsilon^R_{\mu\mu dd} < 0.015 & |\epsilon^R_{\mu\tau dd}| < 0.05 \\ & & |\epsilon^R_{\tau\tau dd}| < 6 \end{pmatrix}$$

- $\mu^+ \to e^+ \overline{\nu}_\beta \nu_\omega \qquad \epsilon^L_{\mu\beta\omega e} \left(\overline{\mu}\gamma_\rho P_L \nu_\beta\right)\left(\overline{\nu}_\omega \gamma^\rho P_L e\right) \quad 2\epsilon^R_{\mu\beta\omega e}\left(\overline{\mu} P_L \nu_\beta\right)\left(\overline{\nu}_\omega P_R e\right)$

$$\beta = \omega \quad \longleftarrow \quad \mu^- \to e^- \gamma ??$$

$$\beta \neq \omega \quad \longleftarrow \quad ??$$

$\boxed{\text{Q: explain LSND??}}$

- $\nu_\alpha d \to l^-_\beta u,\ \pi^- \to \overline{\nu}_\alpha l^-_\beta \qquad \epsilon^P_{\alpha\beta du}\left(\overline{\nu}_\alpha \gamma_\rho P_L l_\beta\right)\left(\overline{d}\gamma^\rho P u\right)$

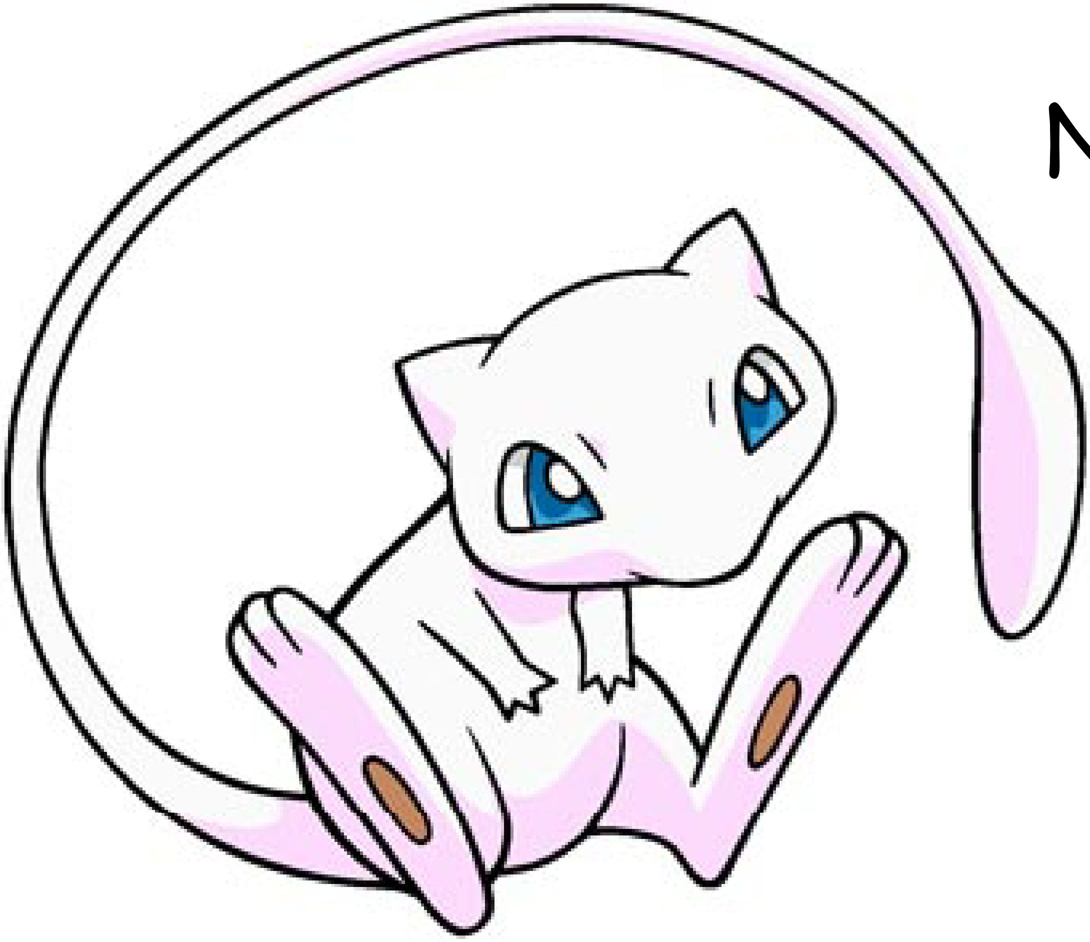
$\pi^- \to e^- \overline{\nu} \qquad \pi^- \to \mu^- \overline{\nu} \qquad \tau^- \to \nu \pi^-$

$$\begin{pmatrix} \epsilon_{eedu} & \epsilon_{e\mu du} & \epsilon_{e\tau du} \\ \epsilon_{\mu edu} & \epsilon_{\mu\mu du} & \epsilon_{\mu\tau du} \\ \epsilon_{\tau edu} & \epsilon_{\tau\mu du} & \epsilon_{\tau\tau du} \end{pmatrix} < \begin{pmatrix} 1.6\times10^{-3}? & 2.0\times10^{-5}? & 3.2\times10^{-3}? \\ 1.6\times10^{-3}? & 2.0\times10^{-5}? & 3.2\times10^{-3}? \\ 1.6\times10^{-3}? & 2.0\times10^{-5}? & 3.2\times10^{-3}? \end{pmatrix}$$

summary of constraints without $SU(2)$

ϵ^m_{ee}, $\epsilon^m_{e\tau}$, $\epsilon^m_{\tau\tau}$ can be large (especially $\epsilon^m_{\tau\tau}$)

no strong constraint for non-standard μ decay??



NSI and Osci. Exp.

Atm.ν and K2K

Solar ν and KamLAND

Long baseline

Atmospheric ν , K2K, and NSI with Matter

A. Friedland et al., PRD **72**, 053009 (2005)

2-flavor case

~~pure NSI~~

osc. + NSI $3\sigma(1\mathrm{d.o.f.})$

$$-0.02 < \epsilon_{\mu\tau} < 0.03, \ |\epsilon_{\tau\tau}| < 0.07$$

N. Fornengo et al., PRD **65**, 013010 (2002)

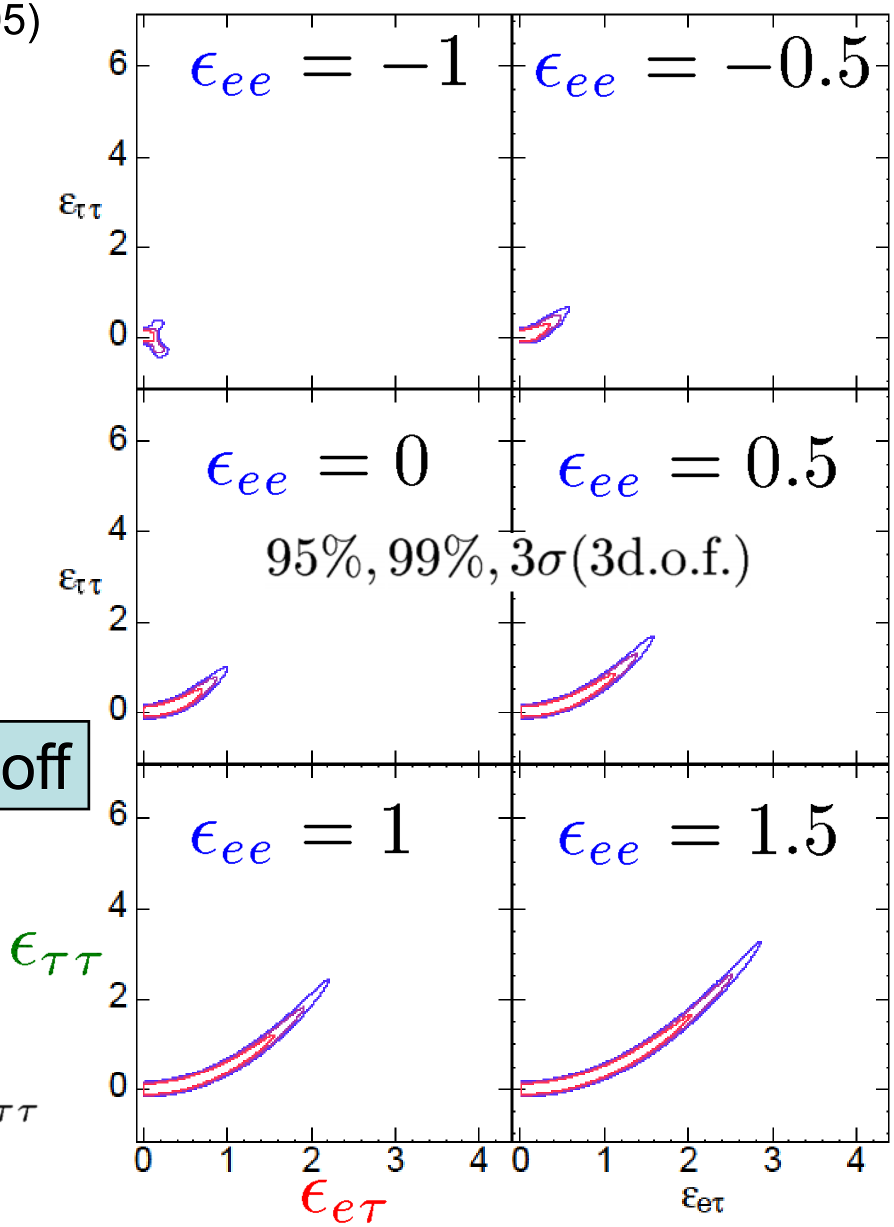
3-flavor case

large ϵ's are allowed

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

$$\epsilon_{e\tau}^2 \simeq \epsilon_{\tau\tau}(1+\epsilon_{ee})$$

read off



setup: $\Delta m_{12}^2 = 0, \ \theta_{13} = 0, \ \epsilon_{ee}, \ \epsilon_{e\tau}, \ \epsilon_{\tau\tau}$

bound on $\epsilon_{\tau\tau}$

atm. ν

measured values with NSI

as pure oscillation ★

$\sin^2 2\theta_m = 1,\ \Delta m_m^2$

K2K $\Downarrow$

comparison $\longrightarrow$ bound on ϵ

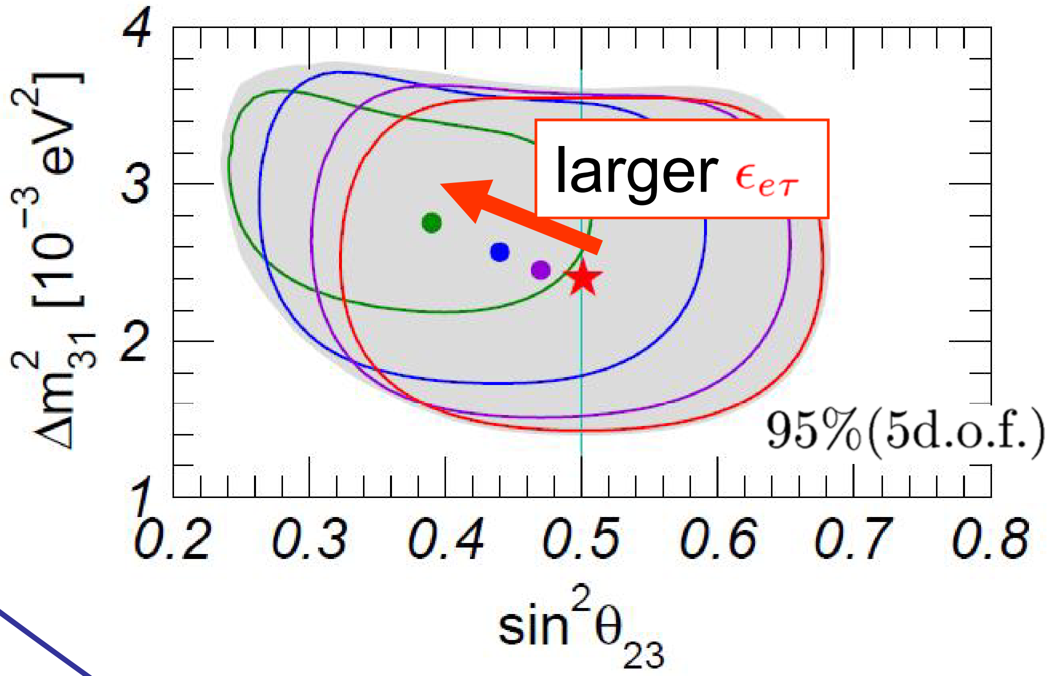
true values ● ● ●

$$\sin 2\theta_{23} \simeq \frac{2\cos^2\beta}{1+\cos^2\beta}$$

$$\Delta m_{32}^2 \simeq \frac{1}{2}\left(1+\frac{1}{\cos^2\beta}\right)\Delta m_m^2$$

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

$\epsilon_{ee} = -0.15,\ \epsilon_{e\tau} = 0$ - 0.9



MINOS $\nu_\mu \to \nu_\mu$ $\longrightarrow$ minor change

A. Friedland et al., PRD 74, 033012 (2006)

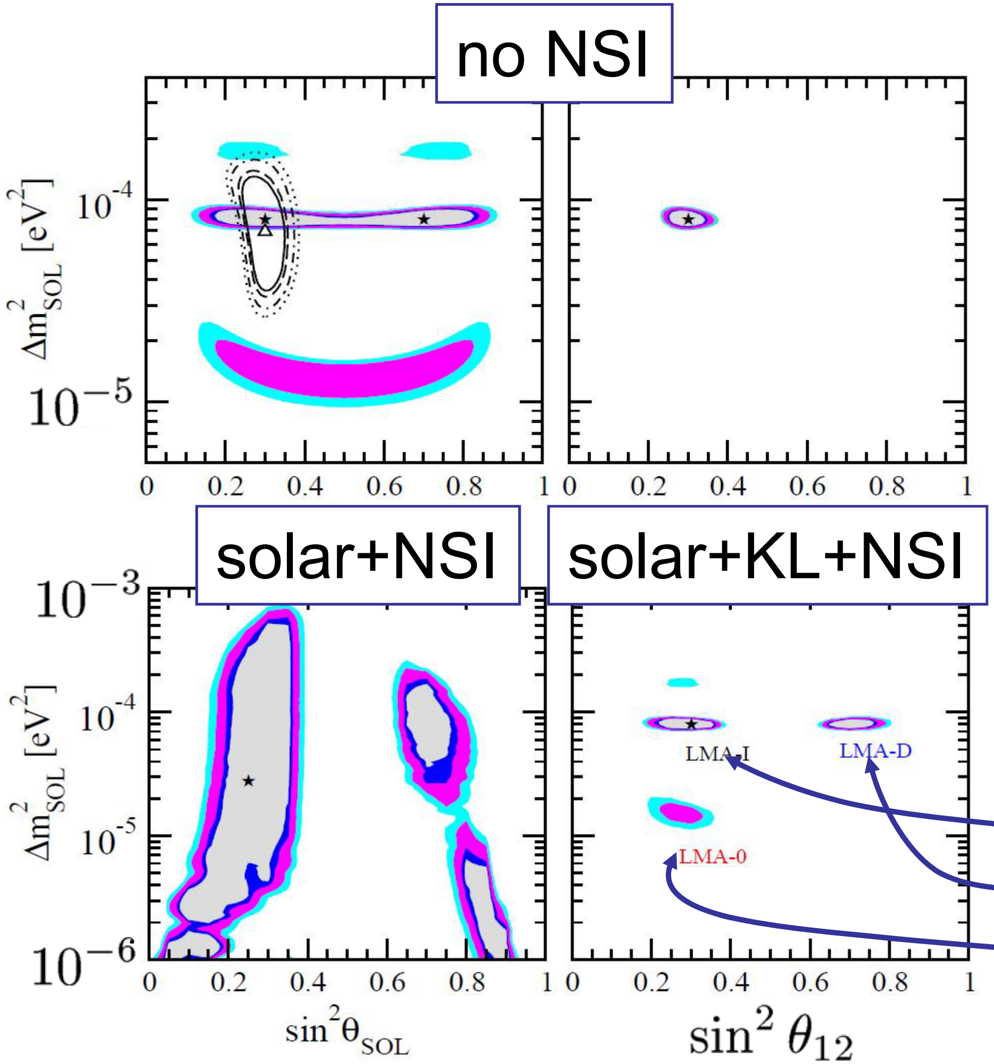
$\epsilon_{\mu\tau}$ is constrained by 2-flavor analysis(?)

$|\epsilon_{\mu\tau}| < 0.03\ (3\sigma,\ 1\text{d.o.f.})$ $\longleftarrow$ N. Fornengo et al., PRD **65**, 01301 (2002)

Solar ν , KamLAND, and NSI with Matter

O.G. Miranda et al., JHEP **0610**, 008 (2006),[hep-ph/0406280]

setup: 2-flavor, NSI with d



$$\mathcal{H}_{\rm NSI} = \sqrt{2} G_F n_d \begin{pmatrix} 0 & \epsilon_{12} \\ \epsilon_{12} & \epsilon_{22} \end{pmatrix}$$

$$\epsilon_{12} \simeq \sum_P (-s_{23}\epsilon^P_{e\tau dd})$$

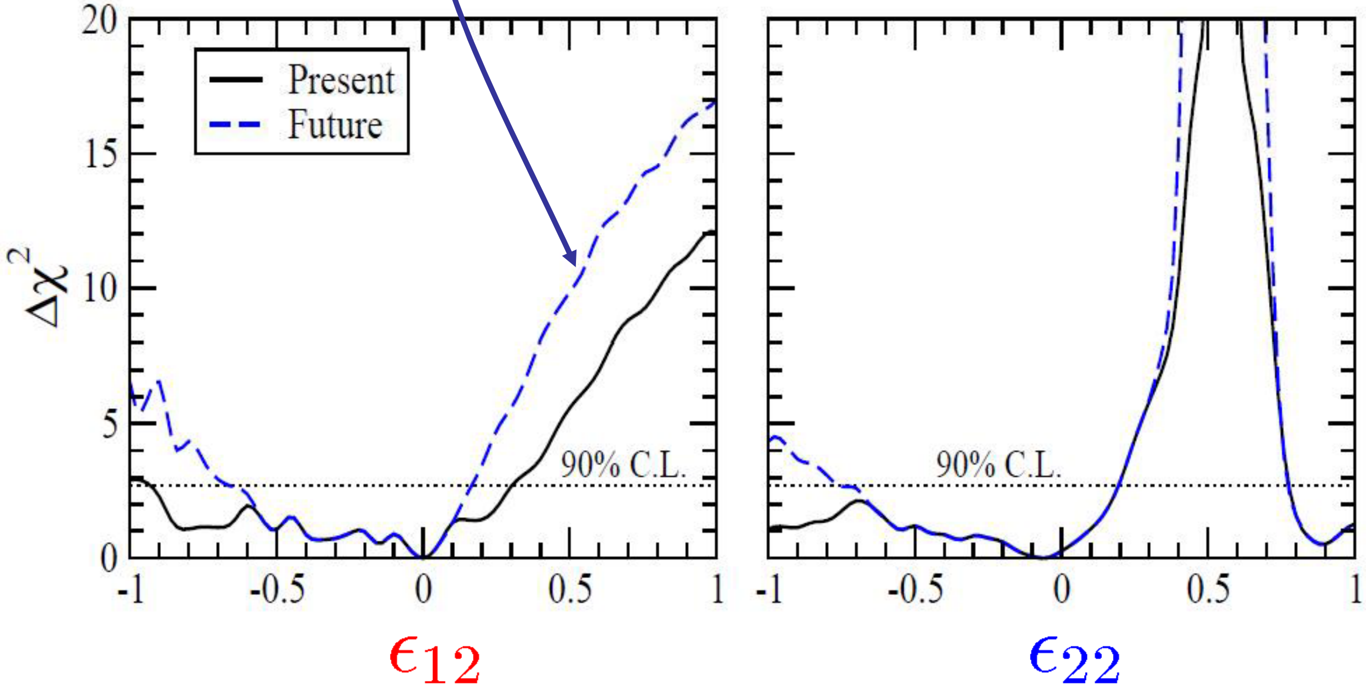
$$\epsilon_{22} \simeq \sum_P (s^2_{23}\epsilon^P_{\tau\tau dd} - \epsilon^P_{eedd})$$

$$\epsilon_{12}, \epsilon_{22} \in [-1, 1]$$

	ϵ_{12}	ϵ_{22}
LMA-I	0	-0.05
LMA-D	-0.15	0.90
LMA-0	0.10	0.30

diff. in low energy $\nu_{\rm sol}$

fixed oscillation parameters



almost no constraint from solar ν and KamLAND

Long Baseline Experiments and NSI

- ν_μ **appearance in nu-fact**

  P. Huber et.al, PRL **88,** 101804 (2002) $\longrightarrow$ previous slides

- ν_τ **appearance in nu-fact**

  A.M. Gago et al., PRD 64, 073003 (2001)

  setup: NSI with matter (u or d)

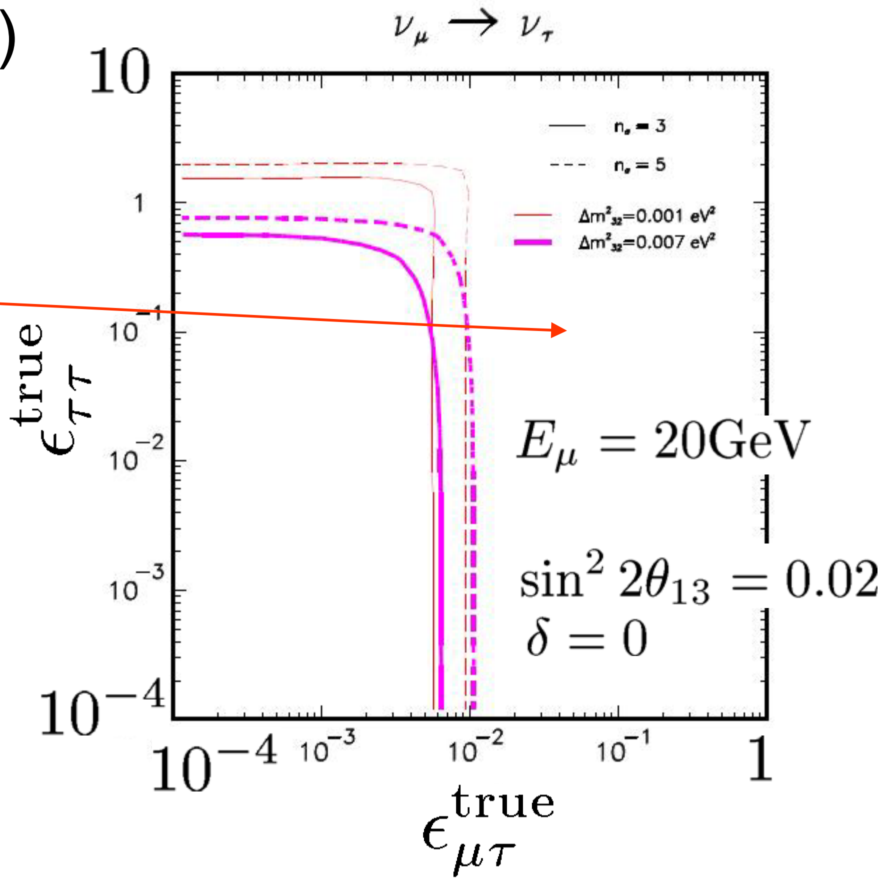
▲ $\nu_\mu \rightarrow \nu_\tau \; + \; \overline{\nu}_\mu \rightarrow \overline{\nu}_\tau$

setup: $\epsilon_{\mu\tau}, \; \epsilon_{\tau\tau}$

If true values exist within the region, we can reject $\epsilon_{\mu\tau} = \epsilon_{\tau\tau} = 0$

sensitivity: $\epsilon_{\mu\tau} \simeq 6 \times 10^{-3}$

$\epsilon_{\tau\tau} \simeq 1.7$



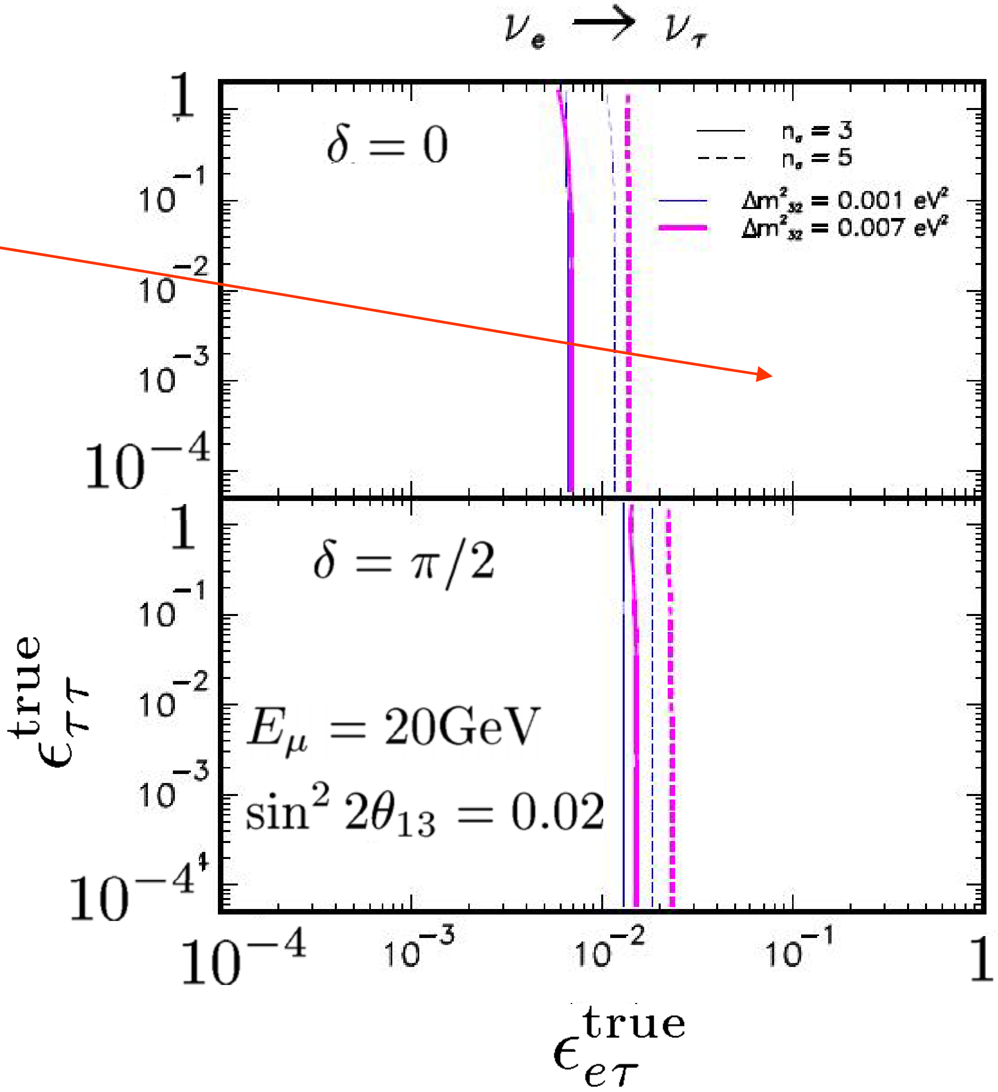
$\nu_e \to \nu_\tau \;+\; \overline{\nu}_e \to \overline{\nu}_\tau$

setup: $\epsilon_{e\tau},\ \epsilon_{\tau\tau}$

If true values exist within the region, we can reject $\epsilon_{e\tau} = \epsilon_{\tau\tau} = 0$

sensitivity: $\epsilon_{e\tau} \simeq 7 \times 10^{-3}$ for $\delta = 0$

$\epsilon_{e\tau} \simeq 1.3 \times 10^{-2}$ for $\delta = \pi/2$

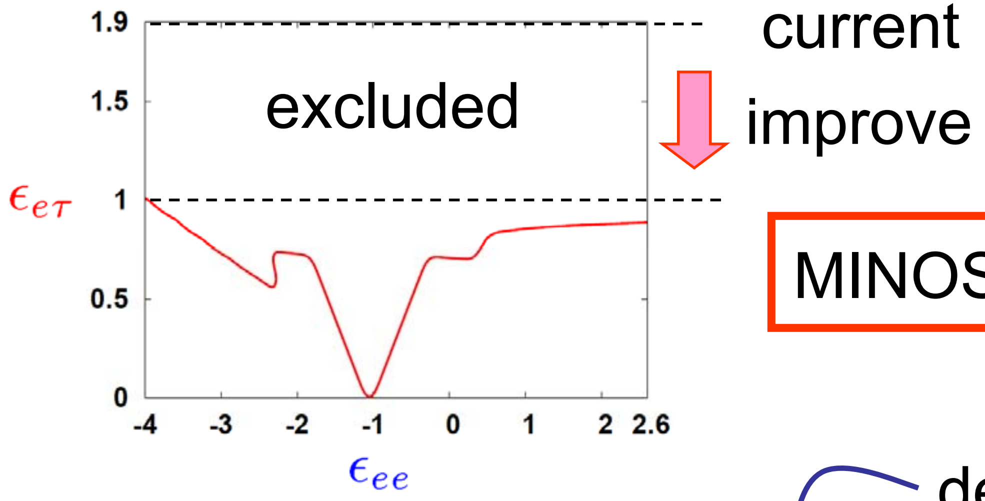


$\nu_\mu \to \nu_e$ in MINOS and NSI with matter

A $\left\{ \begin{array}{l} \text{N. Kitazawa et al,. hep-ph/0606013} \\ \text{S.H., talk in Joint Meeting (APS-DPF2006+JPS2006…), Hawaii, Oct. 2006} \end{array} \right.$

B M. Blennow et al,. hep-ph/0702059

setup for A: $\epsilon_{ee}, \epsilon_{e\tau}, (\epsilon_{\tau\tau})$



MINOS can put a bound $|\epsilon_{e\tau}| < 1$

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

setup for B: $\epsilon_{\tau\tau}$ for $\nu_\mu \to \nu_\mu$, complex $\epsilon_{e\tau}$ for $\nu_\mu \to \nu_e$

MINOS can put a bound $|\epsilon_{e\tau}| < 2.5$

need stringent bound on θ_{13}

- $\nu_\mu \to \nu_e$ **in T2KK and NOvA**

  similar baseline length to MINOS

  better sensitivity on $P_{\mu e}$ with off-axis beam than MINOS

  neutrino mode + anti-neutrino mode

  ⇩

  much better sensitivity on NSI than MINOS??

- **Others?**

  ex. Okamura-san's talk

Summary

- **Sensitivity** on θ_{13} is made much worse by introducing NSI

  $\longrightarrow$ We need more study on effects of NSI

  There are several open questions

- NSI has been constrained stringently

  by charged-leptons stringently with $SU(2)$

  $\longrightarrow$ Only $\underbrace{\nu_e e^- \to \nu_e e^-}_{\epsilon_{eeee}}$ and $\underbrace{\nu_\tau e^- \to \nu_\tau e^-}_{\epsilon_{\tau\tau ee}}$ can be rather large

- Large NSI is possible in the case without $SU(2)$

  $\longrightarrow$ $\epsilon_{eeff},\ \epsilon_{e\tau ff},\ \epsilon_{\tau\tau ff}$ can be large

  No strong constraint for $\mu^+ \to e^+ \bar{\nu}_\beta \nu_\omega$?

- **MINOS** and **nu-fact** have some sensitivity on NSI ($\cancel{SU(2)}$)

Backup

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta f f}^{P}\, (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\, (\overline{f}\gamma^\rho P f)$$

neutral-current-like

$$f = e, u, d \qquad P = P_L, P_R$$

Fierz transformation

$$(\overline{\nu}_\alpha \gamma_\rho P_L f)\, (\overline{f}\gamma^\rho P_L \nu_\beta) = -\, (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\, (\overline{f}\gamma^\rho P_L f)$$

charged-current-like

$$(\overline{\nu}_\alpha P_R f)\, (\overline{f} P_L \nu_\beta) = \frac{1}{2}\, (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\, (\overline{f}\gamma^\rho P_R f)$$

$$(\overline{\nu}_\alpha \sigma^i P_R f)\, (\overline{f}\sigma^i P_L \nu_\beta) = -\frac{1}{2}\, (\overline{\nu}_\alpha \gamma_\rho P_L \nu_\beta)\, (\overline{f}\gamma^\rho P_R f)$$

$$i = 1, 2, 3$$

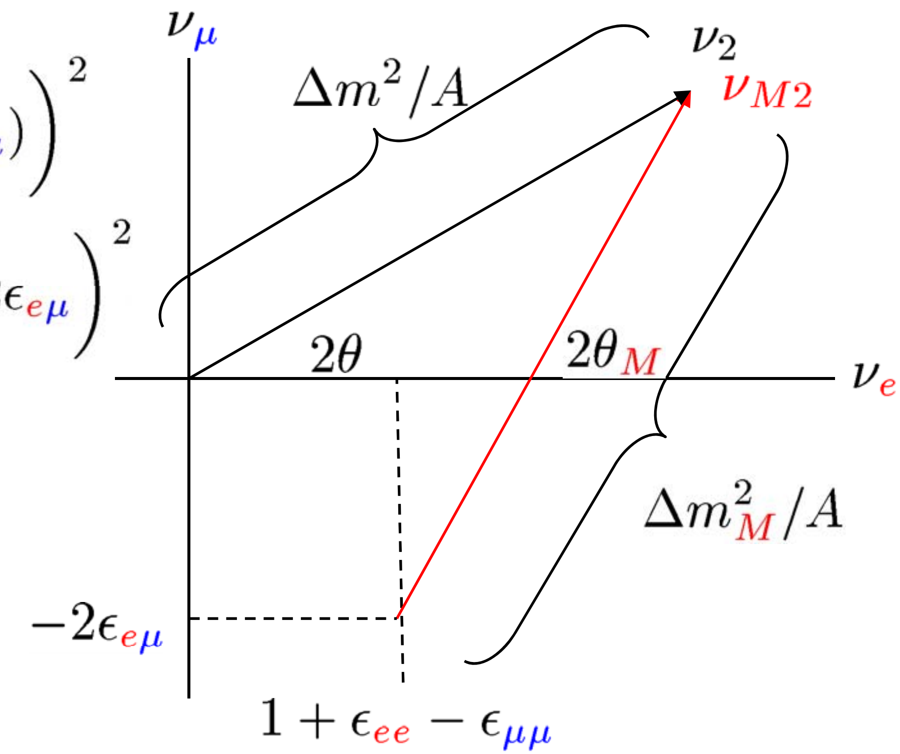
$$i\frac{d}{dL}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{2E}\left[\begin{pmatrix} & U & \end{pmatrix}\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}\begin{pmatrix} & U^\dagger & \end{pmatrix} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu}\\ \epsilon_{e\mu} & \epsilon_{\mu\mu}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$\epsilon_{\alpha\beta} \equiv \sum_{f,P}\frac{N_f}{N_e}\epsilon^P_{\alpha\beta ff}$$

N_f : number density of f (left+right)

$$\frac{(\Delta m^2_M)^2}{A^2} = \left(\frac{\Delta m^2}{A}\cos 2\theta - (1+\epsilon_{ee}-\epsilon_{\mu\mu})\right)^2 + \left(\frac{\Delta m^2}{A}\sin 2\theta + 2\epsilon_{e\mu}\right)^2$$

$$\sin 2\theta_M = \frac{\Delta m^2 \sin 2\theta + 2A\epsilon_{e\mu}}{\Delta m^2_M}$$



short baseline

$$P_{\alpha\beta} = \left| \left[U^s (U^d)^\dagger \right]_{\alpha\beta} \right|^2$$

vacuum osc.

$$P_{\alpha\beta} = \left| \sum_{j,k} [U^s U_{\mathrm{MNS}}]_{\alpha j} \exp\left(i \frac{(\Delta m^2)_{j1} L}{4E} \right) [U^s U_{\mathrm{MNS}}]^\dagger_{jk} \left[U^s (U^d)^\dagger \right]_{k\beta} \right|^2$$

osc. in matter

$$P_{\alpha\beta} = \left| \sum_{j,k} \left[U^s U^M_{\mathrm{MNS}} \right]_{\alpha j} \exp\left(i \frac{(\Delta m^2_M)_{j1} L}{4E} \right) \left[U^s U^M_{\mathrm{MNS}} \right]^\dagger_{jk} \left[U^s (U^d)^\dagger \right]_{k\beta} \right|^2$$