Sensitivity to sterile ν mixings at a ν Factory
--Side business of a ν Factory --

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1. Introduction
2. Light sterile neutrinos
3. Summary

1. Introduction

1.1 Affirmative experimental results on ν oscillation

(i) ● solar ν deficit — Homestake, Kam, SK, SNO, GALLEX, SAGE, Borexino

$\nu_e \to \nu_e$

● reactor ν deficit — KamLAND

$\bar{\nu}_e \to \bar{\nu}_e$

$\Rightarrow$ $\Delta m^2 \cong 7 \times 10^{-5}\, eV^2$, $\sin^2 2\theta \cong 0.8$

(ii) ● atmospheric ν deficit — IMB, Kam, SK, Soudan2, MACRO

$\nu_\mu \to \nu_\mu$

● accelerator ν deficit — K2K, MINOS

$\nu_\mu \to \nu_\mu$

$\Rightarrow$ $\Delta m^2 \cong 2 \times 10^{-3}\, eV^2$, $\sin^2 2\theta \cong 1.0$

(iii) ● accelerator ν anomaly LSND

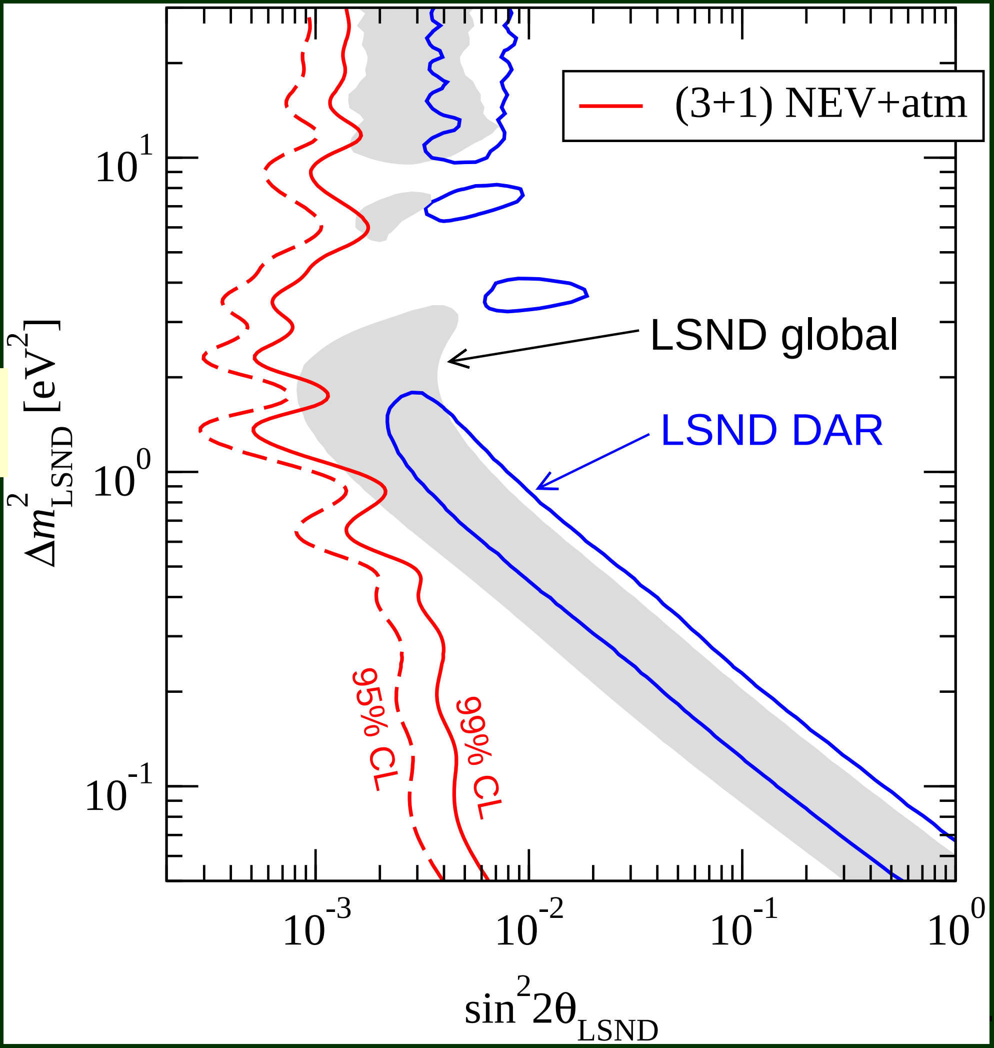
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$E_\nu \cong 50\text{MeV}$

$L \cong 30\text{m}$

$\Delta m^2 \cong O(1)\text{eV}^2$??
$\sin^2 2\theta \cong O(10^{-2})$

Maltoni et al., hep-ph/0405172



1.2 N_ν=4 schemes

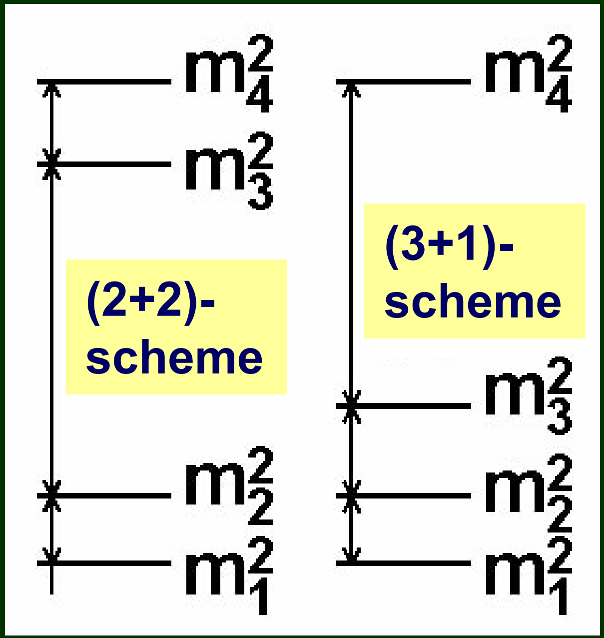
Because of the hierarchy: $\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{LSND}$

N_ν=3 schemes can't explain LSND.

N_ν=4 schemes may be able to explain all.

$$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}, \Delta m^2_{43} = \Delta m^2_{LSND}$$

LEP ➔ 4^{th} ν has to be sterile



(2+2)-scheme is excluded by solar + atmospheric ν

➔ **(3+1)-scheme will be discussed**

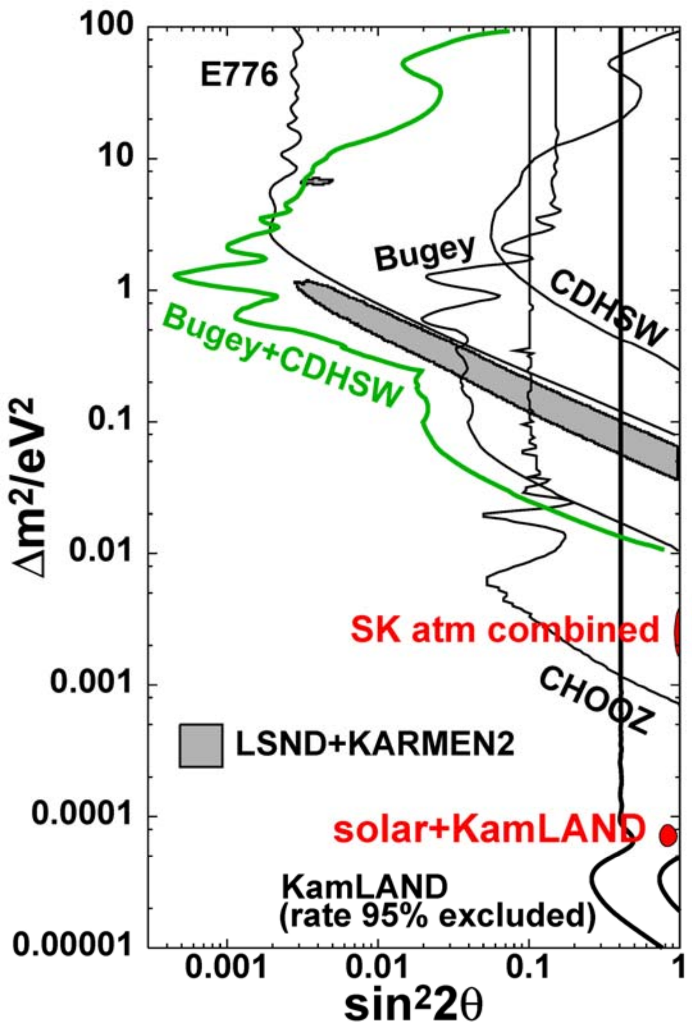
(3+1)-scheme

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2(\Delta m_{41}^2 L/4E)$$
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2(\Delta m_{41}^2 L/4E)$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu 4}|^2\sin^2(\Delta m_{41}^2 L/4E)$$

$$\sin^2 2\theta_{Bugey} > 4|U_{e4}|^2(1-|U_{e4}|^2) \cong 4|U_{e4}|^2$$

$$\sin^2 2\theta_{CDHSW} > 4|U_{\mu 4}|^2(1-|U_{\mu 4}|^2) \cong 4|U_{\mu 4}|^2$$

$$\sin^2 2\theta_{LSND} = 4|U_{e4}|^2|U_{\mu 4}|^2$$



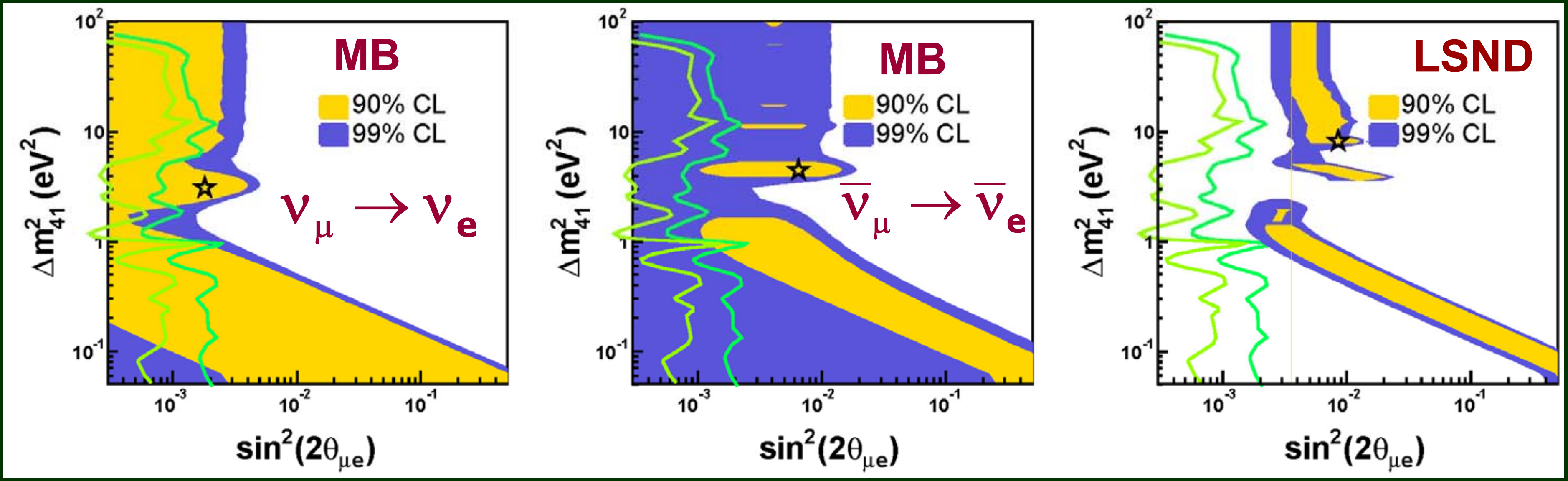
$$\Rightarrow \quad \sin^2 2\theta_{\rm LSND}(\Delta m^2) < \frac{1}{4}\sin^2 2\theta_{\rm Bugey}(\Delta m^2)\sin^2 2\theta_{\rm CDHSW}(\Delta m^2)$$

must be satisfied (Okada-OY Int.J.Mod.Phys.A12:3669,1997)

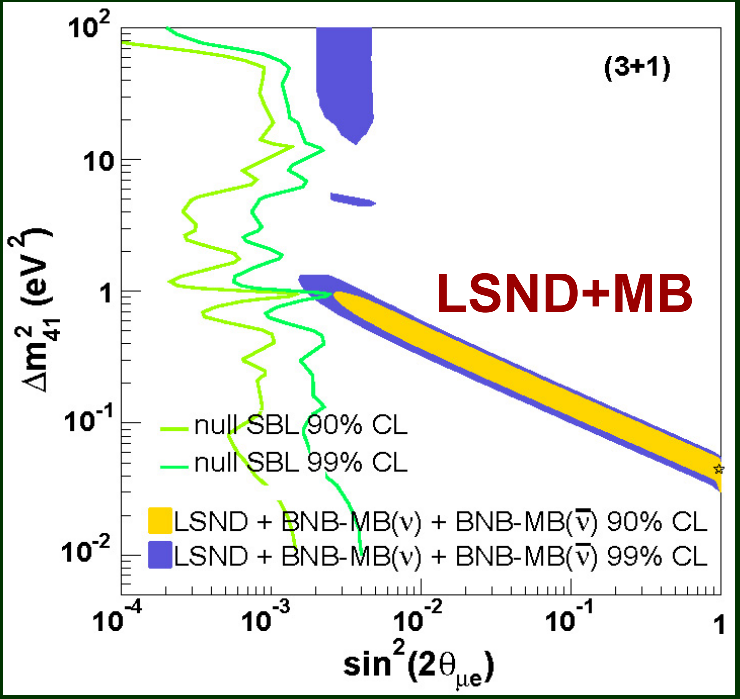
But there is no overlap between LSND and left side of Bugey+CDHSW

Recent status of LSND: Check by MiniBooNE

Karagiorgi et al, Phys.Rev.D80:073001,2009



- Neither MiniBooNE (ν or $\bar{\nu}$) nor disappearance results (CDHSW+Bugey+atm) excludes LSND at 4σ.



1.4 Future long baseline experiments

Unknown oscillation parameters in the standard 3 flavor scenario:

$\theta_{13}, \quad \mathrm{sgn}\left(\Delta m^2_{32}\right), \quad \delta$

Ongoing & Near future experiments

Accelerator $\Rightarrow \theta_{13}, \left(\mathrm{sgn}\left(\Delta m^2_{32}\right)?\right)$

'06～ **MINOS** (FNAL→Soudan) L=730km, E ～10GeV

'08 ～ **OPERA･ICARUS** (CERN→GrandSasso) L=730km, E ～20GeV

'09 ～ **T2K** (JAERI→SK) L=295km, E ～1GeV **phase1** (0.75MW,22.5kt)

Reactor $\Rightarrow \theta_{13}$

'09～ **Double CHOOZ**

'10 (?)～ **Daya Bay**

Far future experiments

Accelerator $\Rightarrow \mathrm{sgn}\left(\Delta m^2_{32}\right), \quad \delta$

'xx～ **T2K** (JAERI→HK) L=295km, E ～1GeV **phase2** (4MW,500kt)

'yy～ **ν factory** (?→?) L ～ 4000km+7500km, E ～20GeV

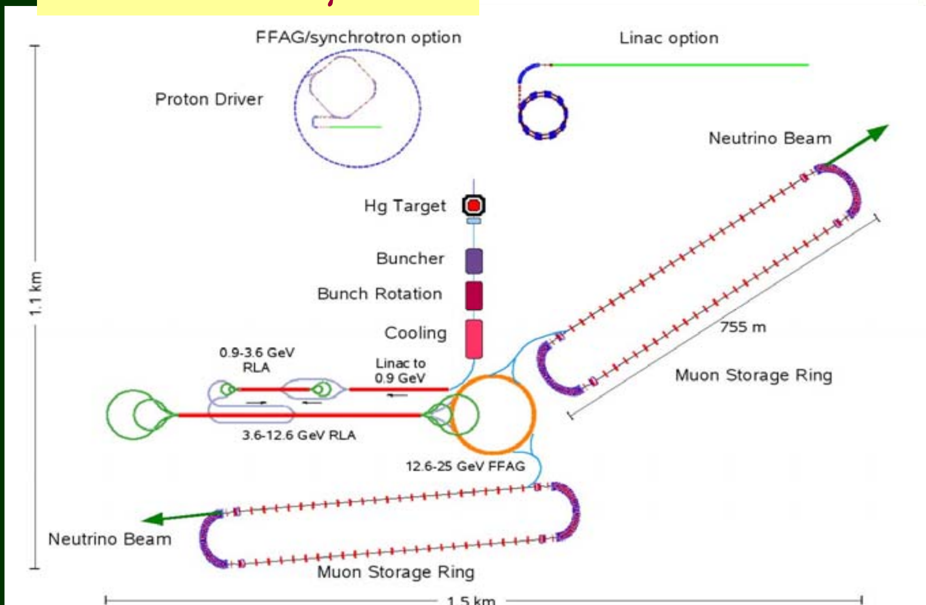
ν factory: ν from μ decays

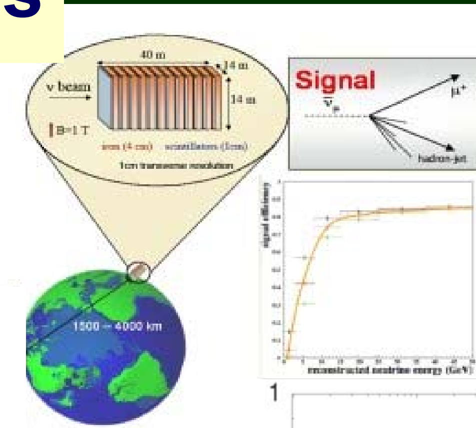
$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

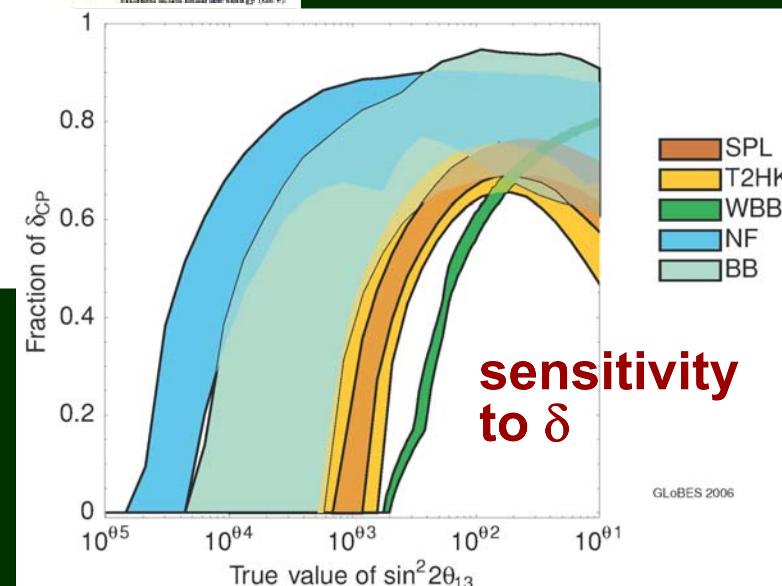
$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- Large No. of events
- Low backgrounds

→ very good sensitivity







$\nu_e \rightarrow \nu_\mu$

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

golden channel

$\nu_\mu \rightarrow \nu_\mu$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

disappearance channel

$\nu_e \rightarrow \nu_\tau$

$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$

silver channel

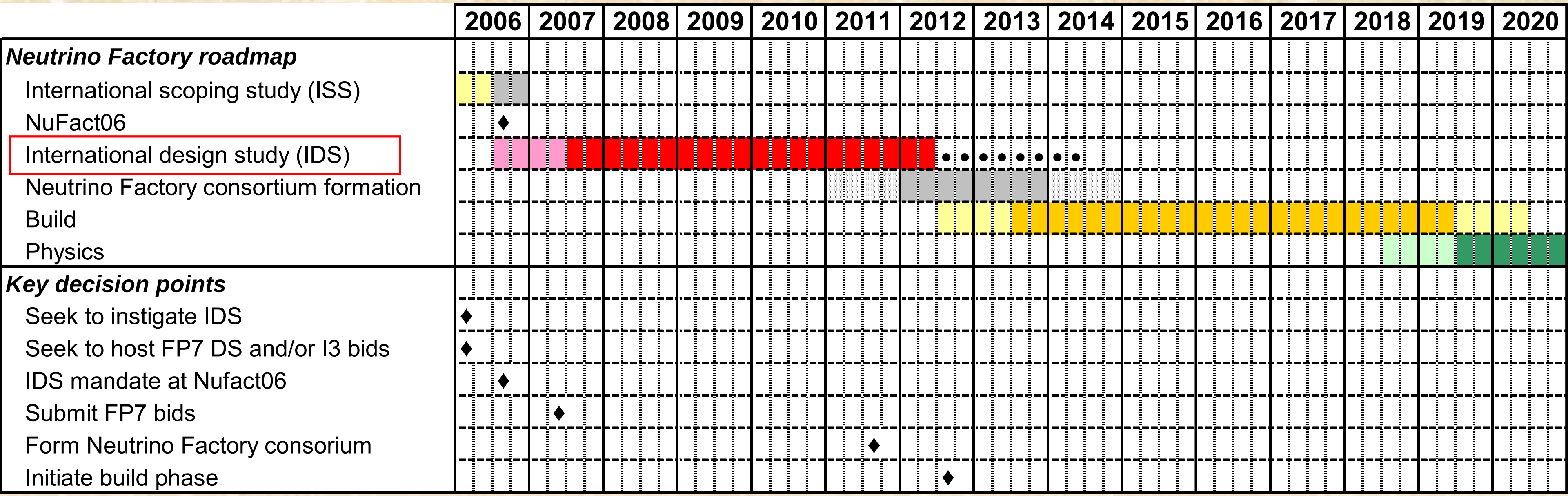
$\nu_\mu \rightarrow \nu_\tau$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$

discovery channel

K.Long

NF roadmap: key decision points



- Ambitious, science-driven schedule
- Issue now is to establish vibrant R&D programme
- Vision for International Design Study phase:
  - International collaboration; coordinated effort:
    - *Concept development – full system*
    - *Accelerator R&D*
    - *Detector R&D*

Nagashima: ISS 3rd plenary ('06) @ RAL

1.5 Motivation for research on New Physics and τ detection at ν factory

- Just like at B factories, high precision measurements of ν oscillation at ν factory will allow us to probe physics beyond SM by looking at deviation from SM+massive ν.
- If θ_{13} turns out to be large, search for new physics and test of unitarity will be even more important subjects at ν factory. (cf. $\sin^2\theta_{13}=0.02\pm0.01$@$1\sigma$, Fogli et al, arXiv:0905.3549 [hep-ph])

● If 3 flavor unitarity is guaranteed, then roughly speaking, we could guess (discovery) from (golden) + (disappearance) at ν factory from 3 flavor unitarity:

$$P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau) = 1$$

disappearance channel

discovery channel

Probability of the time reversal process could be obtained if we can guess the CP phase.

$\nu_e \to \nu_\mu$

golden channel

● Intuitively, therefore, τ detection is supposed to be important to test New Physics which violates unitarity.
→ Quantitative estimate is necessary to draw conclusions.

New physics which can be probed at a neutrino factory includes:

- **Non standard interactions in propagation**
- **Non standard interactions at production / detection**
- **Violation of unitarity due to heavy particles**
- **Schemes with light sterile neutrinos**

$$\sum_{\beta=e,\mu,\tau} P(\nu_\alpha \to \nu_\beta) = 1$$

Scenarios	3 flavor unitarity
NSI in propagation	✓
NSI at production / detection	×
Violation of unitarity due to heavy particles	×
Light sterile neutrinos	×

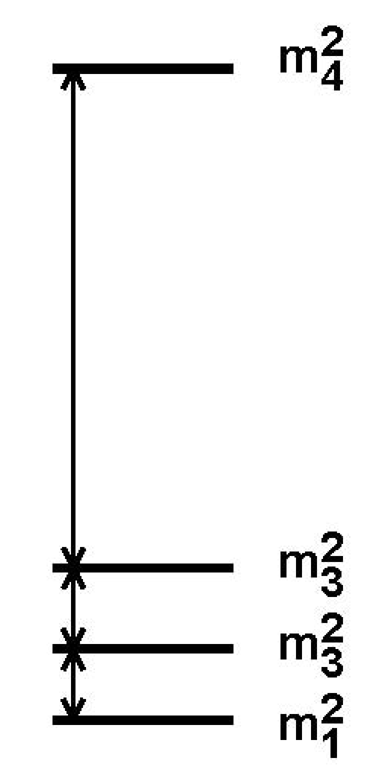
Scenarios	Phenomenological bound on deviation of unitarity
NSI at production / detection	O(0.1%)
Violation of unitarity due to heavy particles	O(1%)
Light sterile neutrinos	O(10%)

Light sterile neutrinos could be phenomenologically more promising than others!

2. Light sterile neutrinos

(3+1)-scheme w/ LSND: the situation is unclear, but it's worth checking it

(3+1)-scheme w/o LSND: still a possible scenario, provided that the mixing angles satisfy all the constraints of the negative results



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$U = R_{34}(\theta_{34},\, 0)\; R_{24}(\theta_{24},\, 0)\; R_{23}(\theta_{23},\, \delta_3)\; R_{14}(\theta_{14},\, 0)\; R_{13}(\theta_{13},\, \delta_2)\; R_{12}(\theta_{12},\, \delta_1)$$

θ_{34} : ratio of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ in ν_{atm}

θ_{24} : ratio of $\sin^2(\frac{\Delta m^2_{\rm atm} L}{4E})$ and $\sin^2(\frac{\Delta m^2_{\rm SBL} L}{4E})$ in ν_{atm}

θ_{14} : mixing angle in $\nu_{reactor}$ at L=O(10m)

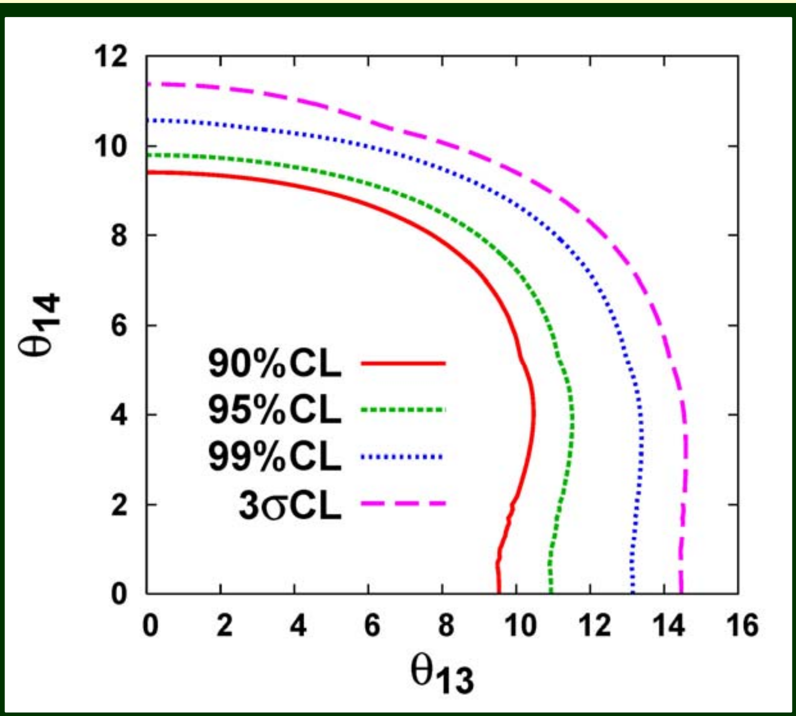
2.2 Constraints on (3+1)-scheme from ν_{atm} and SBL

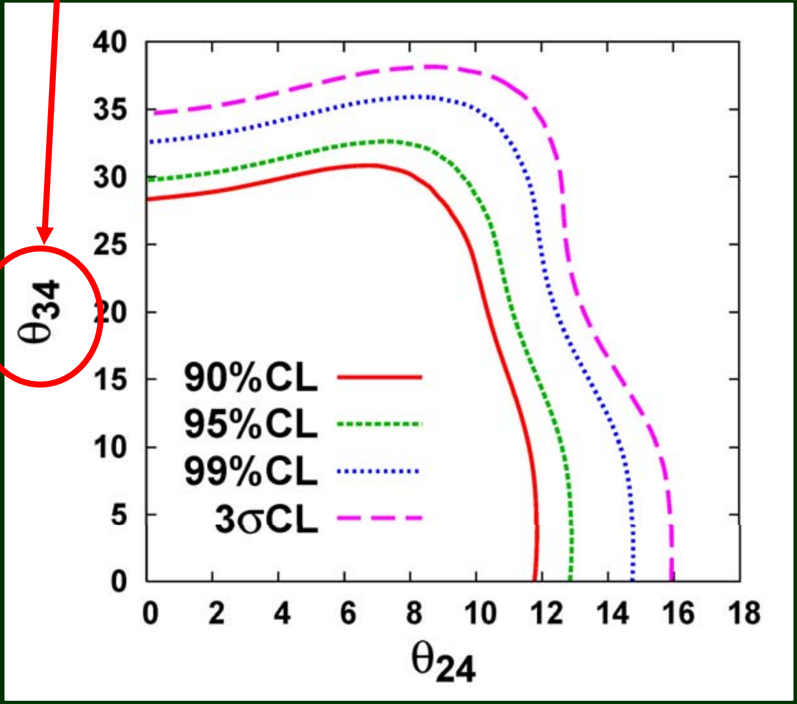
Donini-Maltoni-Meloni-Migliozzi-Terranova, JHEP 0712:013,'07

$$U = R_{34}(\theta_{34})\ R_{24}(\theta_{24})\ R_{23}(\theta_{23},\ \delta_3)\ R_{14}(\theta_{14})\ R_{13}(\theta_{13},\ \delta_2)\ R_{12}(\theta_{12},\ \delta_1)$$

Assumption on rapid oscillations in ν_{atm}: $\Delta m^2_{41} > 0.1\ eV^2$

θ_{34} : could be relatively large





2.3 Sensitivity to θ_{14}, θ_{24}, θ_{34} at ν factory with far detectors

Donini, Fuki, Lopez-Pavon, Meloni, OY,
JHEP 0908:041,2009

5×10^{20} μ^{-}+μ^{+}'s/yr × 4 yrs
(E_μ/GeV, L/km)= (50,3000+7500) or (20, 4000+7500)
50kton MIND + 4kton MECC

statistical errors + systematic errors + BG

efficiency ~ 0.7 for μ, ~0.65 for τ

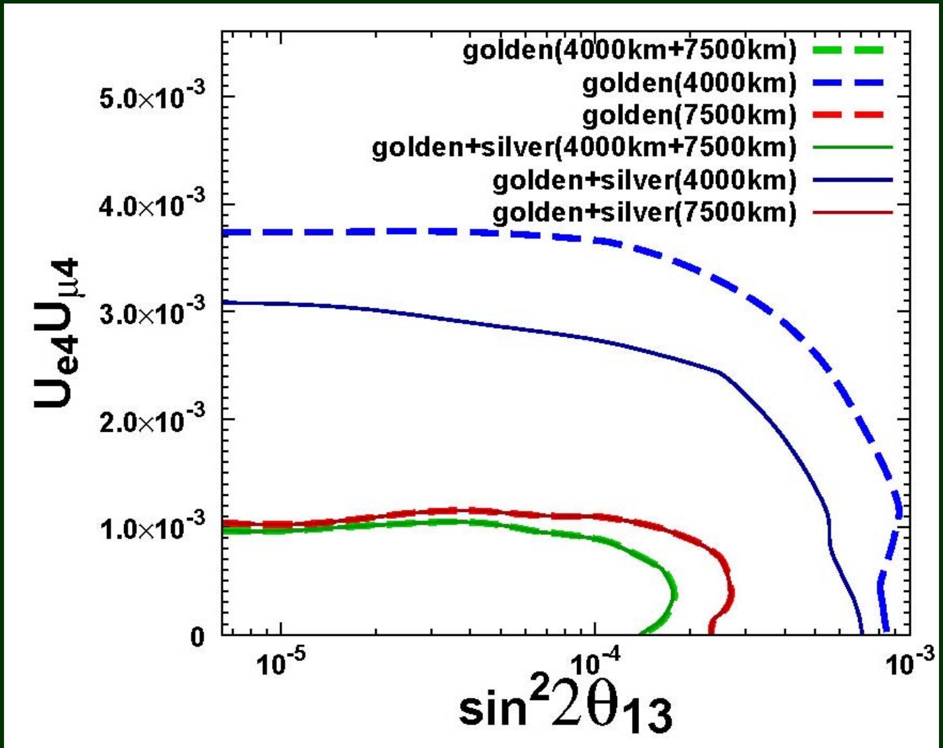
NB. Magnetized Emulsion Cloud Chamber (MECC)
active target: iron
$\tau\rightarrow\mu$ decay + $\tau\rightarrow$e decay + $\tau\rightarrow$hadron decay are used

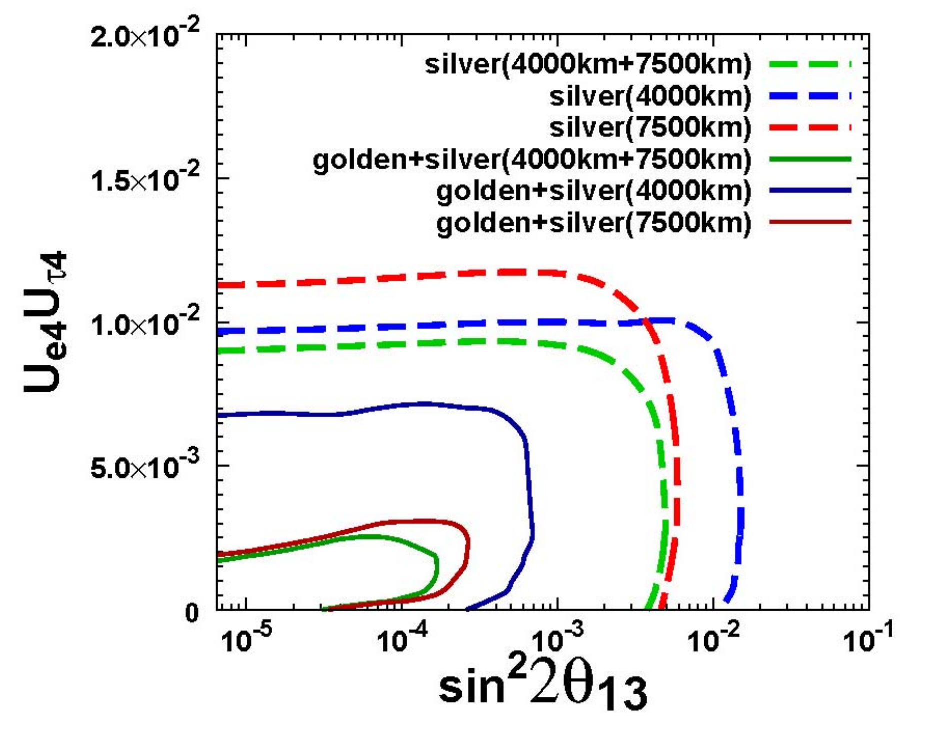
golden + silver

Donini, Fuki, Lopez-Pavon, Meloni, OY, JHEP 0908:041,2009

$$P(\nu_e \to \nu_\mu) = 4\mathrm{Re}\left[U_{e3}U^*_{\mu 3}(U^*_{e3}U_{\mu 3} + U^*_{e4}U_{\mu 4})\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$

$$P(\nu_e \to \nu_\tau) = 4\mathrm{Re}\left[U_{e3}U^*_{\tau 3}(U^*_{e3}U_{\tau 3} + U^*_{e4}U_{\tau 4})\right]\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cdots$$





$4|U_{e4}U_{\mu 4}|^2 > 5.8\mathrm{x}10^{-6}$

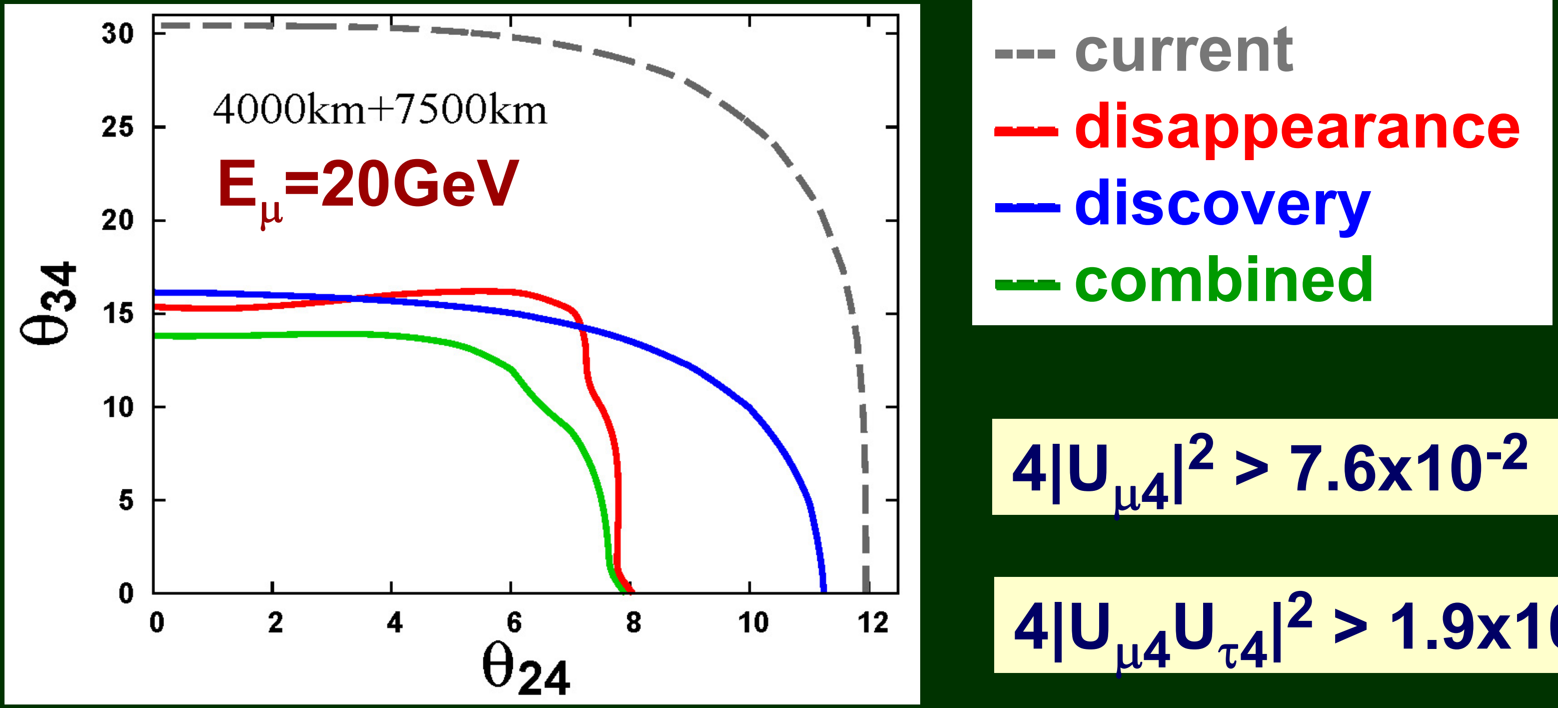
$4|U_{e4}U_{\tau 4}|^2 > 3.8\mathrm{x}10^{-5}$

disappearance + discovery

Donini, Fuki, Lopez-Pavon, Meloni, OY, JHEP 0908:041,2009

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2 - |U_{\mu 4}|^2) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \cdots$$

$$P(\nu_\mu \to \nu_\tau) = 4\mathrm{Re}\left[U_{\mu 3} U_{\tau 3}^* (U_{\mu 3}^* U_{\tau 3} + U_{\mu 4}^* U_{\tau 4})\right] \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + \cdots$$

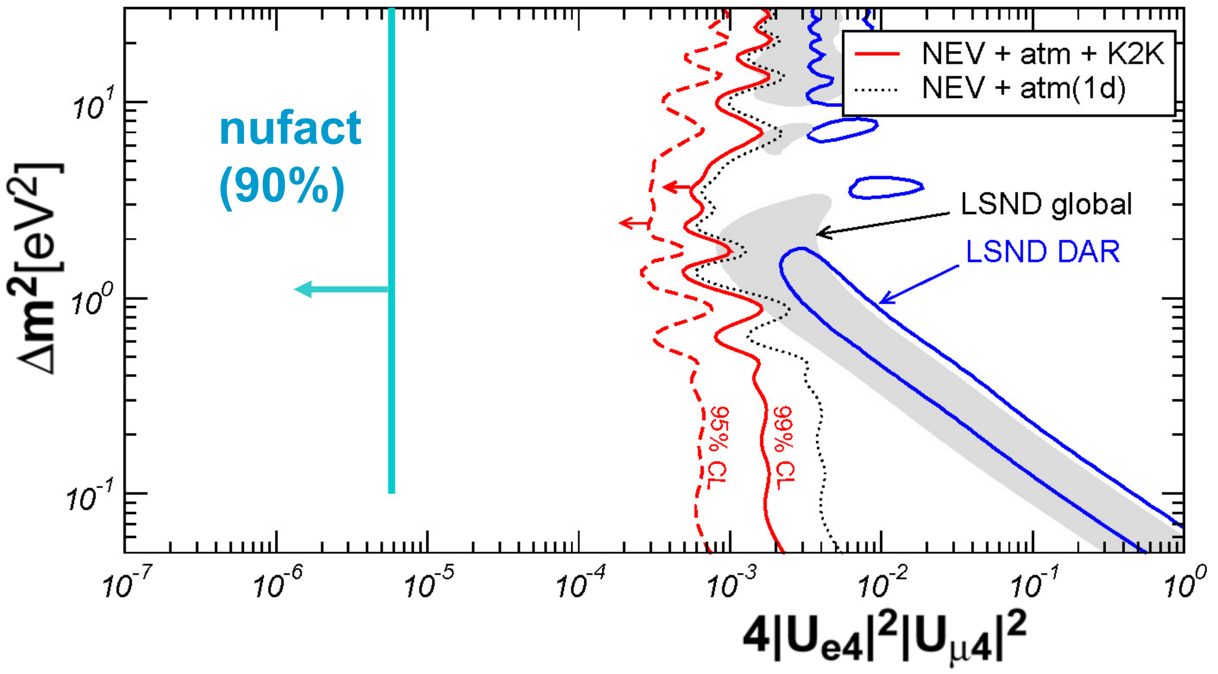


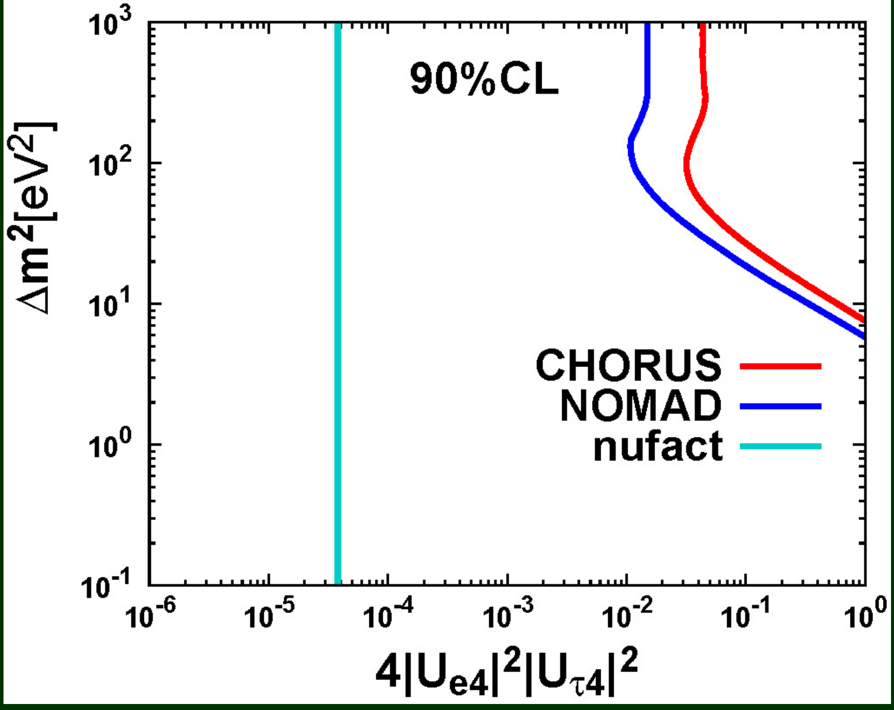
$4|U_{\mu 4}|^2 > 7.6\text{x}10^{-2}$

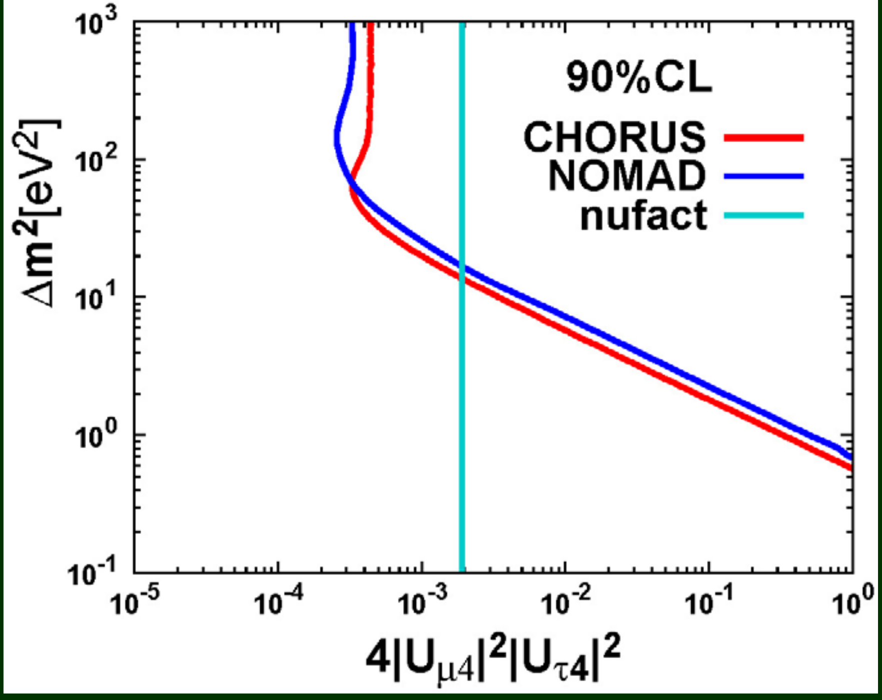
$4|U_{\mu 4}U_{\tau 4}|^2 > 1.9\text{x}10^{-3}$

Comparison with the present bound

Sensitivity to the 4ν mixings with ν_e is very good compared to the present bound.
→ It could serve as a severe test of LSND/MiniBooNE.





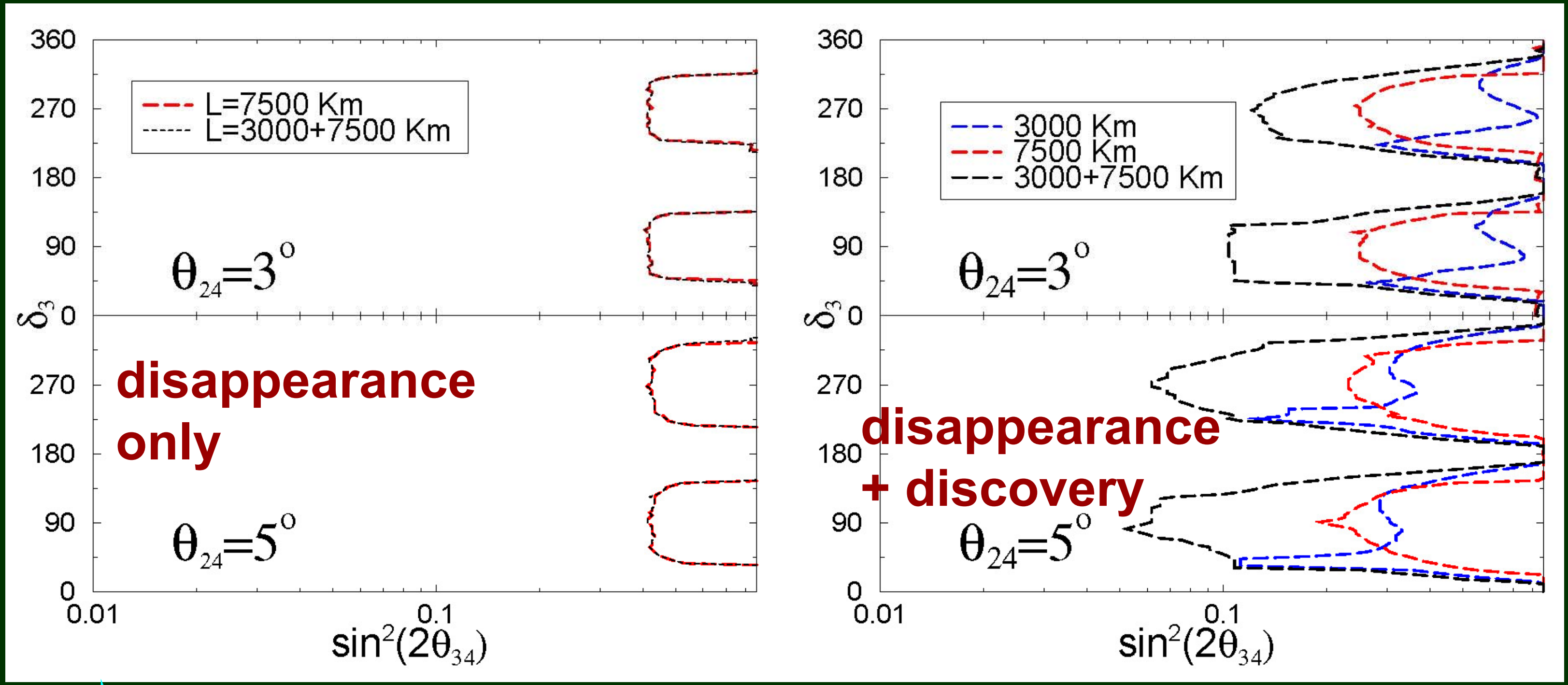


2.4 Sensitivity to the new CP phase

Donini, Fuki, Lopez-Pavon, Meloni, OY, JHEP 0908:041,2009

If sterile neutrino mixings are found, we can search for the new CP phase.

$$\begin{aligned} & P(\nu_\mu \to \nu_\tau) - P(\bar{\nu}_\mu \to \bar{\nu}_\tau) \\ = \; & 2 s_{24}\, s_{34} \boxed{\sin \delta_3} \sin(\Delta m^2_{31} L/4E) + \cdots \end{aligned}$$



→ **Discovery channel is crucial to measure the new CP phase**

3. Summary

- ν factory can search for sterile neutrino mixings.

- ν factory can offer a powerful test of LSND/MiniBooNE.

- In absence of 3 flavor unitarity, τ detectors in principle give us important information on New Physics.

- To measure the new CP phase due to sterile neutrino mixings, discovery channel is crucial.

Backup slides

Summarized bounds

- Without considering mixing bounds (90 % CL)

$$|\varepsilon_{\alpha\beta}| < \begin{pmatrix} 2.0\times10^{-3} & 0.6\times10^{-4} & 0.8\times10^{-2} \\ 0.6\times10^{-4} & 0.8\times10^{-3} & 0.5\times10^{-2} \\ 0.8\times10^{-2} & 0.5\times10^{-2} & 2.7\times10^{-3} \end{pmatrix}$$

- Including mixing bounds (90 % CL)

$$|\varepsilon_{\alpha\beta}| < \begin{pmatrix} 2.0\times10^{-3} & 0.6\times10^{-4} & 1.6\times10^{-3} \\ 0.6\times10^{-4} & 0.8\times10^{-3} & 1.1\times10^{-3} \\ 1.6\times10^{-3} & 1.1\times10^{-3} & 2.7\times10^{-3} \end{pmatrix}$$

Off-diagonals from mixing with heavy states

- If NU is due to some mixing with heavy states, then ε is negative semi-definite
- In particular this implies

Antusch, Baumann, Fernandez-Martinez, NPB810(2009)369, 0807.1003

$$|\varepsilon_{\alpha\beta}|^2 \leq |\varepsilon_{\alpha\alpha}\varepsilon_{\beta\beta}|$$

as well as

$$\varepsilon_{\alpha\alpha} < 0$$

Direct bounds on prod/det NSI

From μ, β, π decays and zero distance oscillations

$$2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R}d\right) \qquad 2\sqrt{2}G_F\varepsilon^{\mu e}_{\alpha\beta}\left(\bar{\mu}\gamma^\mu P_L\nu_\beta\right)\left(\bar{\nu}_\alpha\gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.042 & 0.025 & 0.042 \\ 2.6\cdot 10^{-5} & 0.1 & 0.013 \\ 0.087 & 0.013 & 0.13 \end{pmatrix} \qquad \left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

Bounds order $\sim 10^{-2}$

C. Biggio, M. Blennow and EFM 0907.0097