Neutrino oscillation phenomenology

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INO-KEK meeting
27 November 2007@KEK

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1. Introduction

Framework of 3 flavor ν oscillation

Mixing matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \boxed{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

Information we have obtained so far:

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8\times10^{-5}\,\text{eV}^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5\times10^{-3}\,\text{eV}^2$

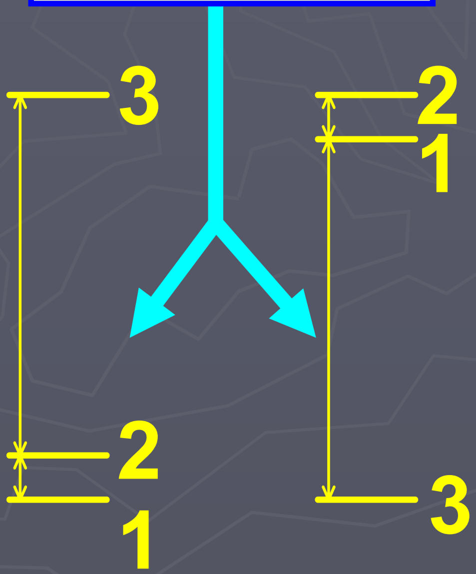
CHOOZ (reactor) → $|\theta_{13}| \leq \sqrt{0.15}/2$

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

- Both mass hierarchies are allowed

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

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



normal hierarchy

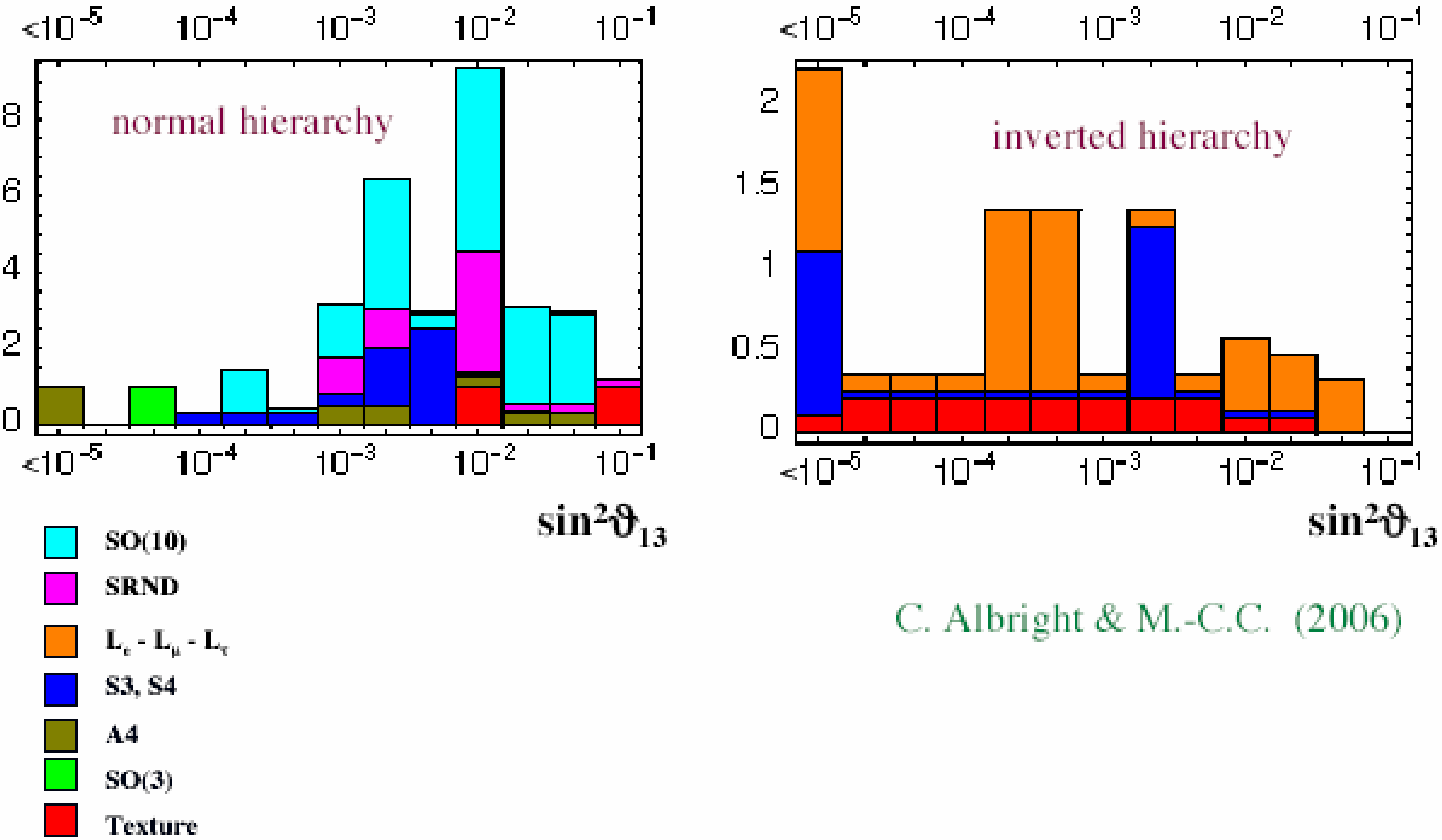
$\Delta m^2_{32} > 0$

inverted hierarchy

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

Theoretical prediction for θ_{13}

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



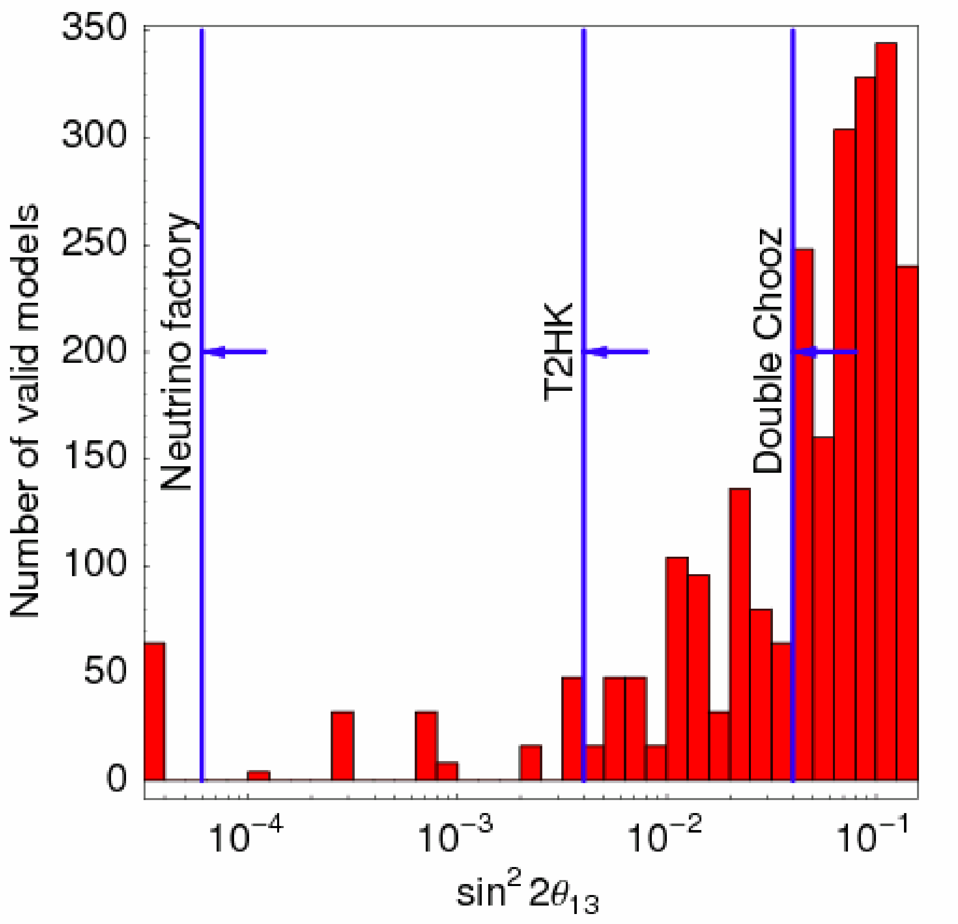
C. Albright & M.-C.C. (2006)

Winter: nufact07 @ Okayama

Systematic generation of ν mass matrices by extended QLC

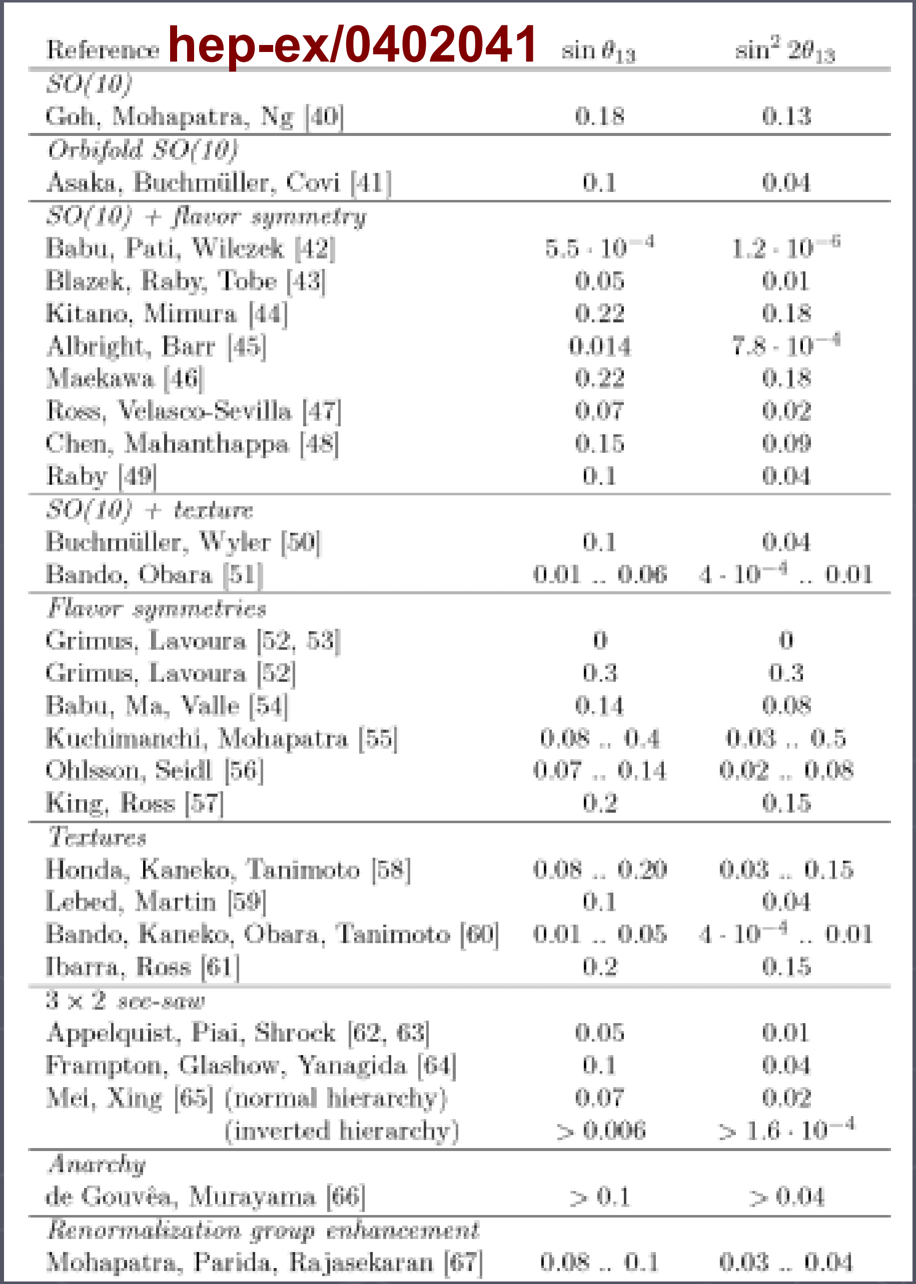
- Parameter space analysis based on realizations
- Large θ_{13} preferred
- Compared to the GUT literature:
  Some realizations with very small $\sin^2 2\theta_{13} \sim 3.3\ 10^{-5}$

(Plentinger, Seidl, Winter, hep-ph/0612169)



All kinds of values of θ_{13} are predicted by theory, and it doesn’t look like illuminating.

→ Theory is not yet developed enough to say something on mass & mixing of quarks & leptons.



hep-ex/0402041

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3 × 2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

2. Future LBL (Long BaseLine experiments)

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

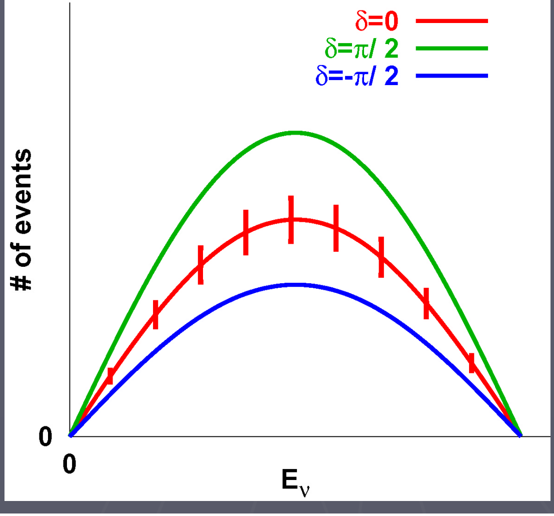
→**Matter effect** contributes in LBL in most cases

● Two points to be taken into account for precise measurements:

(1) Correlation of errors

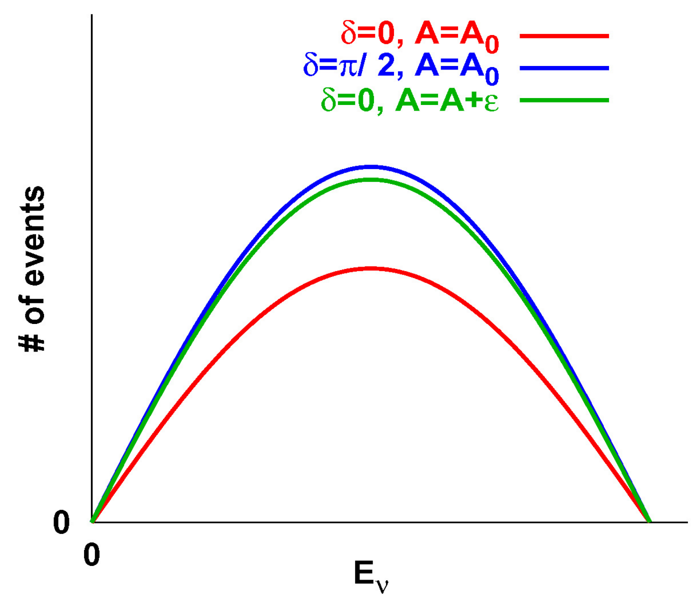
(2) Parameter degeneracy

(1) Correlation of errors



If uncertainties of other parameters (such as density of matter $\rho\propto$ A) mimic the dependence on δ, then we cannot determine δ (correlation of errors)

→We have take into account the uncertainties of other parameters to reject “δ=0”



$$\Delta\chi^2 = \sum_j \frac{[N_j(\delta) - N_j(\delta=0)]^2}{\sigma_j^2}$$

⇩

$$\Delta\chi^2 = \min_{\overline{\theta_{k\ell}}, \overline{\Delta m^2_{k\ell}}, \overline{A}} \sum_j \frac{\left[N_j(\delta; \overline{\theta_{k\ell}}, \overline{\Delta m^2_{k\ell}}, \overline{A}) - N_j(\delta=0; \theta_{k\ell}, \Delta m^2_{k\ell}, A)\right]^2}{\sigma_j^2}$$

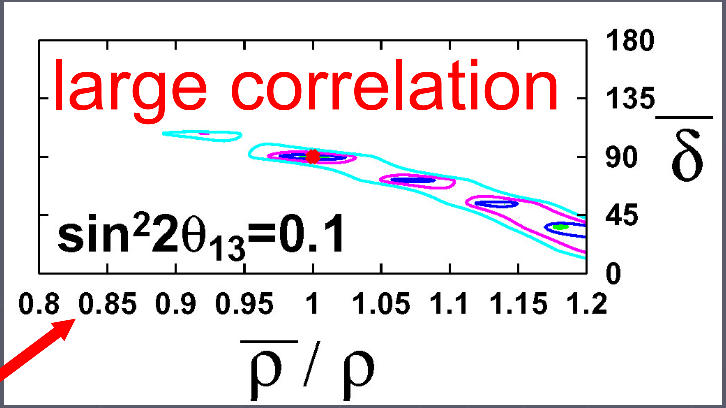
(Example) There is correlation of errors at a neutrino factory:

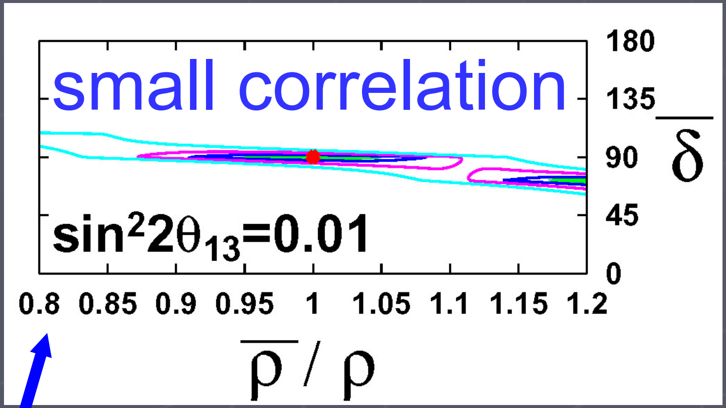
E_μ =50GeV, L=3000km

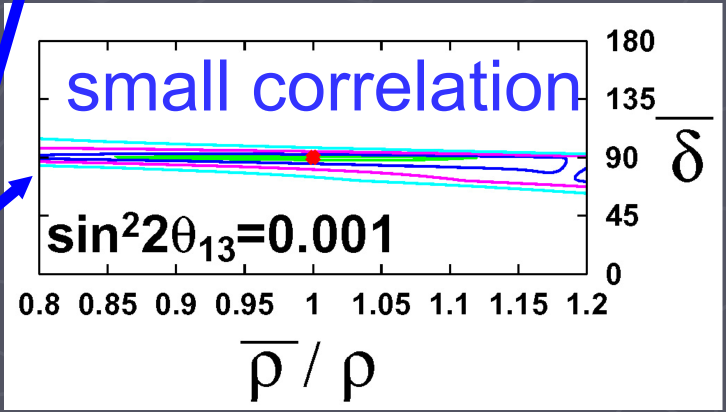
correlation of errors in ρ and δ is serious for $\sin^2 2\,\theta_{13}$ ~0.1

sensitivity to $\sin^2 2\,\theta_{13}$ of a ν factory is poor for $\sin^2 2\,\theta_{13}$ ~0.1

correlation of errors in ρ and δ is not serious for $\sin^2 2\,\theta_{13}<0.01$

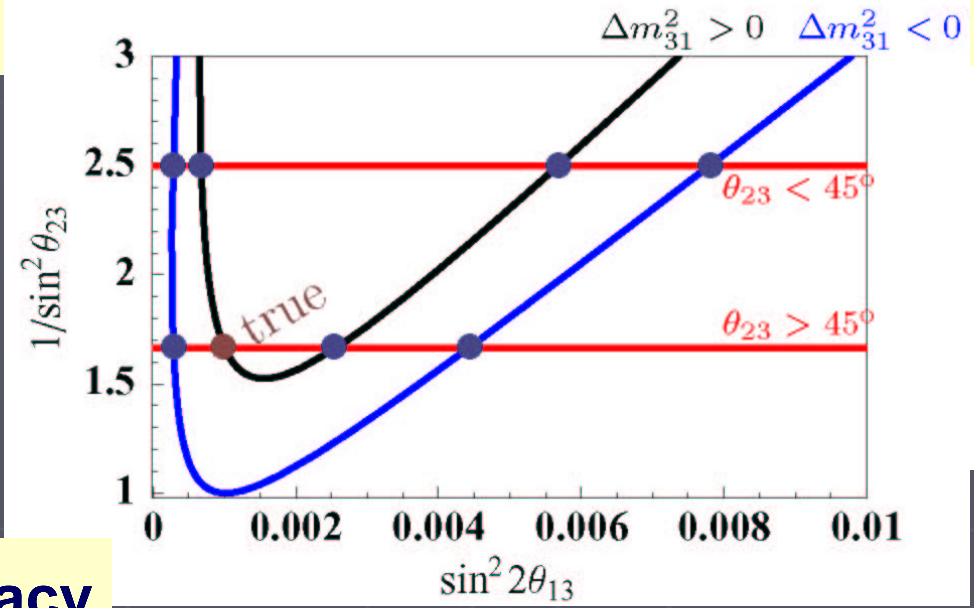






(2) Parameter degeneracy

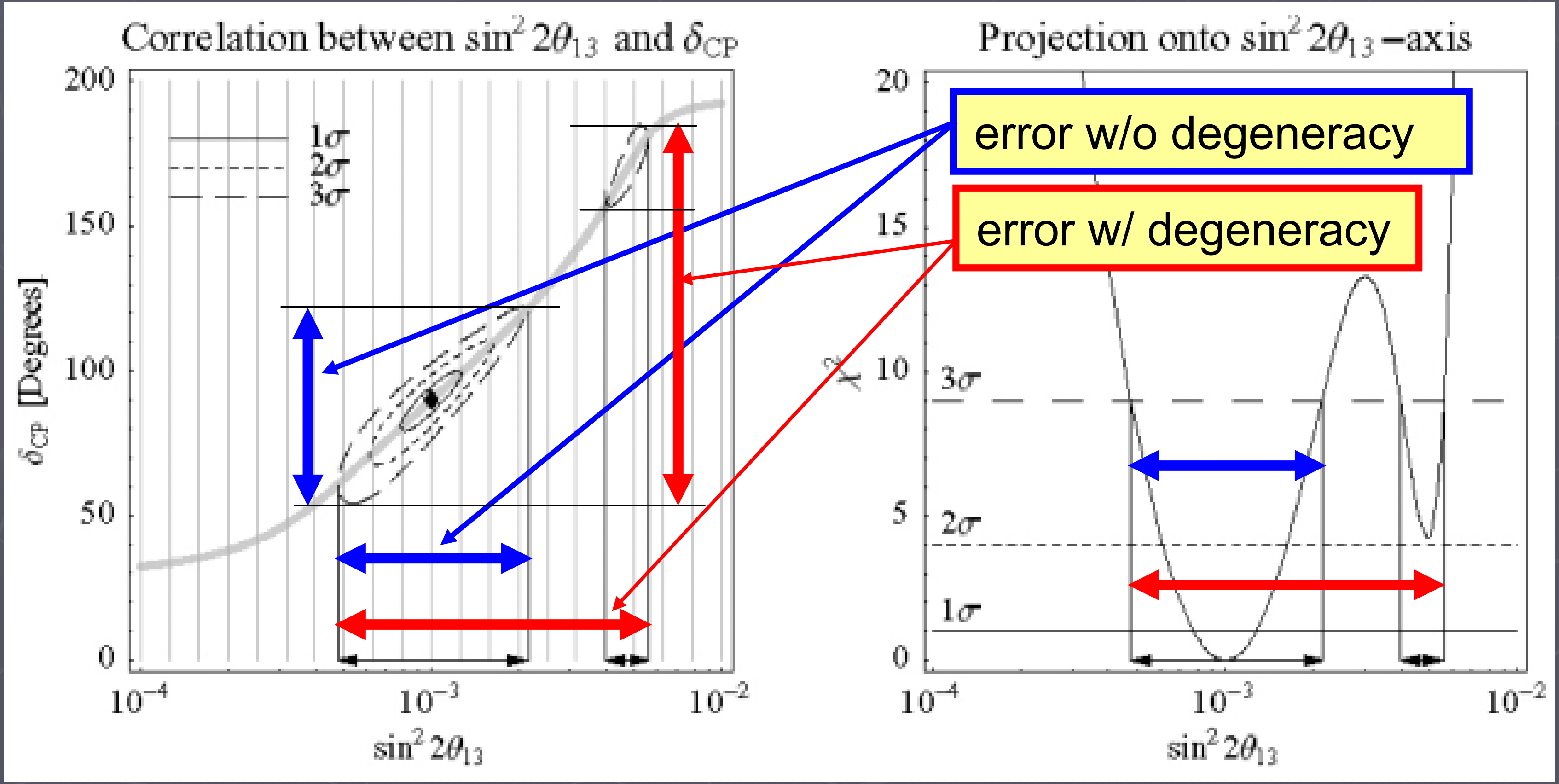
Even if we know $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu_\mu} \to \overline{\nu_e})$ in a long baseline accelerator experiments with approximately monoenergetic neutrino beam, precise determination of θ_{13} , sign(Δm^2_{31}) and δ is difficult because of the 8-fold parameter degeneracy.



- intrinsic (δ, θ_{13}) degeneracy
- $\Delta m^2_{31} \Leftrightarrow -\Delta m^2_{31}$ degeneracy
- $\theta_{23} \Leftrightarrow \pi/2 - \theta_{23}$ degeneracy

If parameter degeneracy exists, then the errors of the parameters become unnecessarily large.

Resolution of parameter degeneracy is important.



error w/o degeneracy

error w/ degeneracy

Future LBL experiments

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

→We need **high intensity beam**

Candidates for high intensity beam in the future:

- (conventional) superbeam

$$\left\{\begin{array}{l} \pi^+ \to \mu^+ + \nu_\mu \\ \pi^- \to \mu^- + \bar{\nu}_\mu \end{array}\right. \qquad \begin{array}{l} \boxed{\nu_\mu \to \nu_e} \\ \boxed{\bar{\nu}_\mu \to \bar{\nu}_e} \end{array}$$

- neutrino factory

  μ in a storage ring

$$\left\{\begin{array}{l} \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu \end{array}\right. \qquad \begin{array}{l} \boxed{\nu_e \to \nu_\mu} \\ \boxed{\bar{\nu}_e \to \bar{\nu}_\mu} \end{array}$$

- beta beam

  RI in a storage ring

$$\left\{\begin{array}{l} {}^{6}_{2}\mathrm{He} \to {}^{6}_{3}\mathrm{Li} + e^- + \bar{\nu}_e \\ {}^{18}_{10}\mathrm{Ne} \to {}^{18}_{9}\mathrm{F} + e^+ + \nu_e \end{array}\right. \qquad \begin{array}{l} \boxed{\bar{\nu}_e \to \bar{\nu}_\mu} \\ \boxed{\nu_e \to \nu_\mu} \end{array}$$

Future LBL exp. (under construction / proposed)

- ● **superbeam**

T2K phase I (2009-, 0.75MW, E~1GeV, L=295km)

T2K phase II (4MW+HK, E~1GeV, L=295km)

T2KK (JAERI→HK&Korea, E~1GeV, L=295km&1000km)

NOvA (FNAL→ Ash River (MN), E~2GeV, L=810km)

VBLNO (BNL→DUSEL*, E~2GeV, L>2500km)

(*Deep Underground Science and Engineering Laboratory: Homestake(SD), Icicle Creek(WA), San Jacinto(CA), Soudan(MN), Kimballton(VA), Henderson(CO))

SPL (CERN→Frejus, E~0.25GeV, L=130km)

- ● **neutrino factory** (E_ν<50GeV, L~3000km)
- ● **beta beam** (E_ν=0.5-1.5GeV, L~130km)

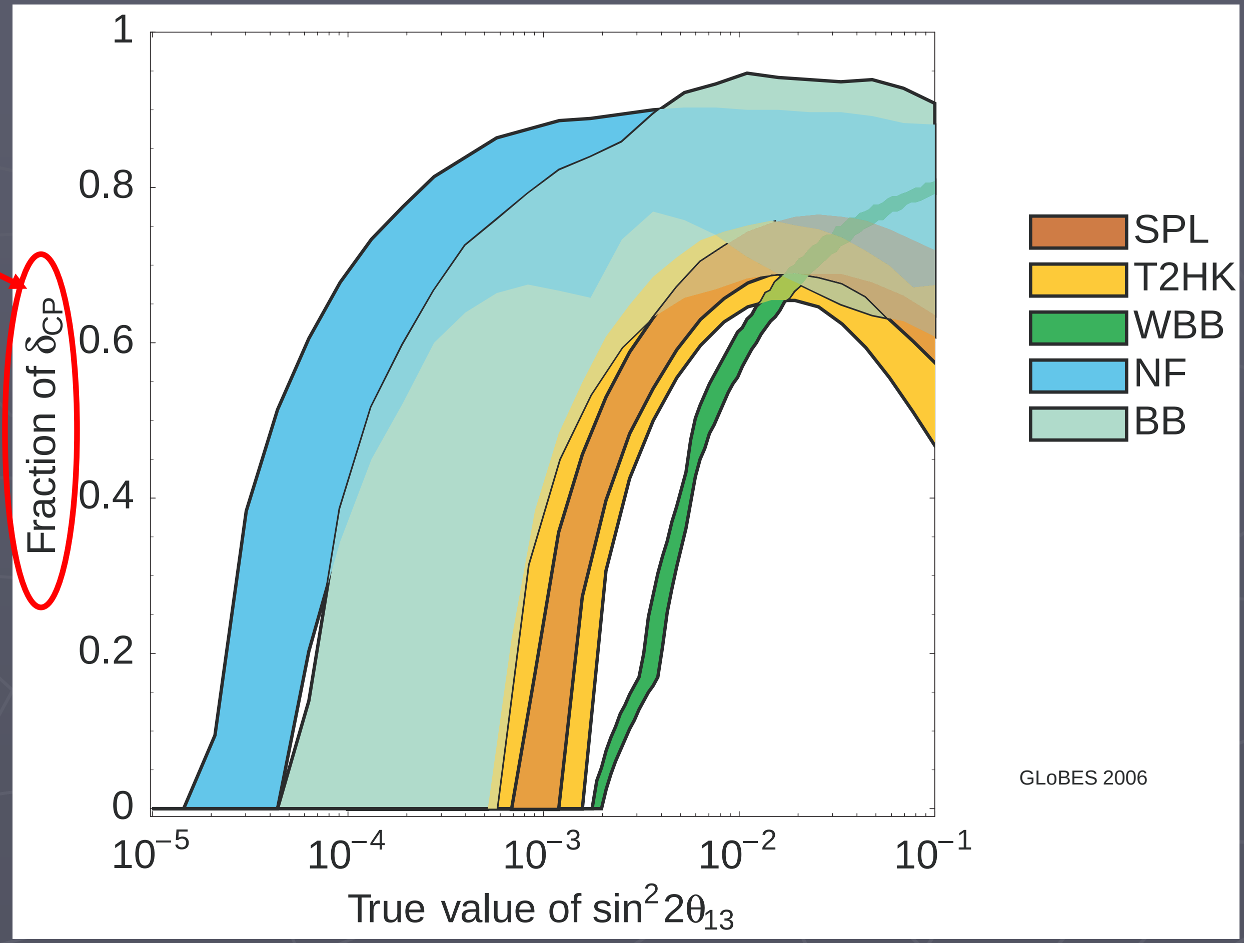
Proposed reactor experiments (E~4MeV, L~2km)

Double CHOOZ (France) , **Daya Bay** (China), **Reno** (Korea), Angra (Brazil)

sensitivity to the CP phase δ of future experiments

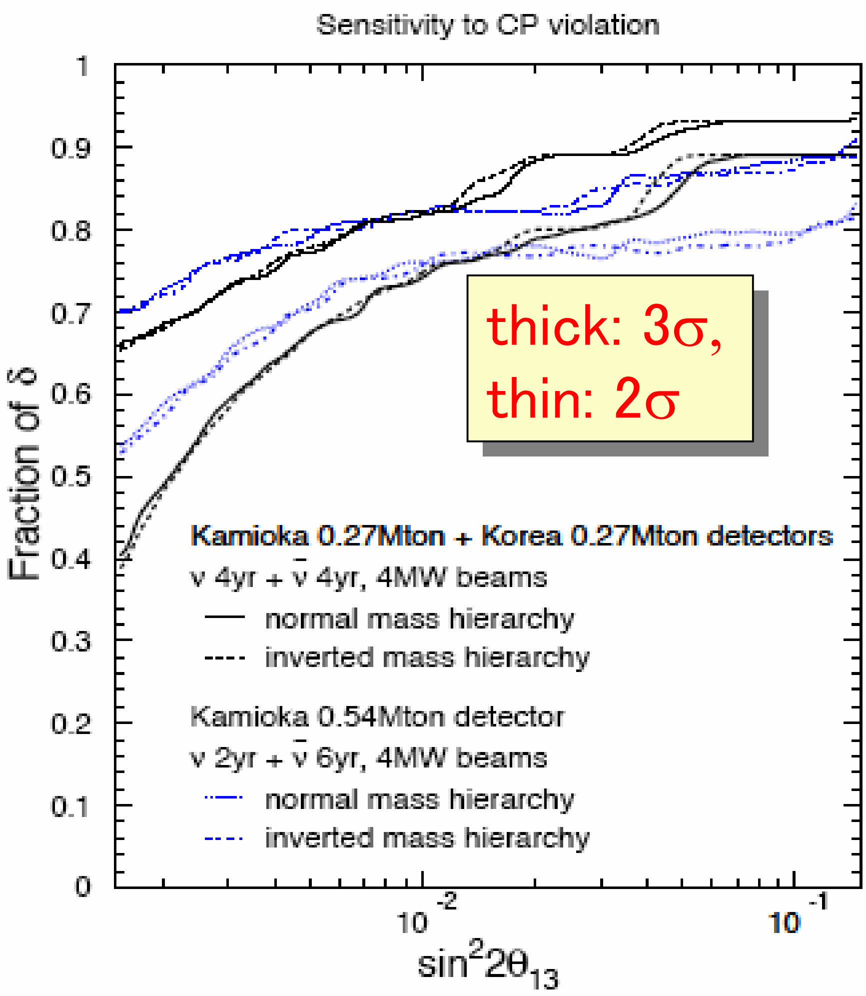
error of δ

T2HK = Tokai to HyperKamiokande

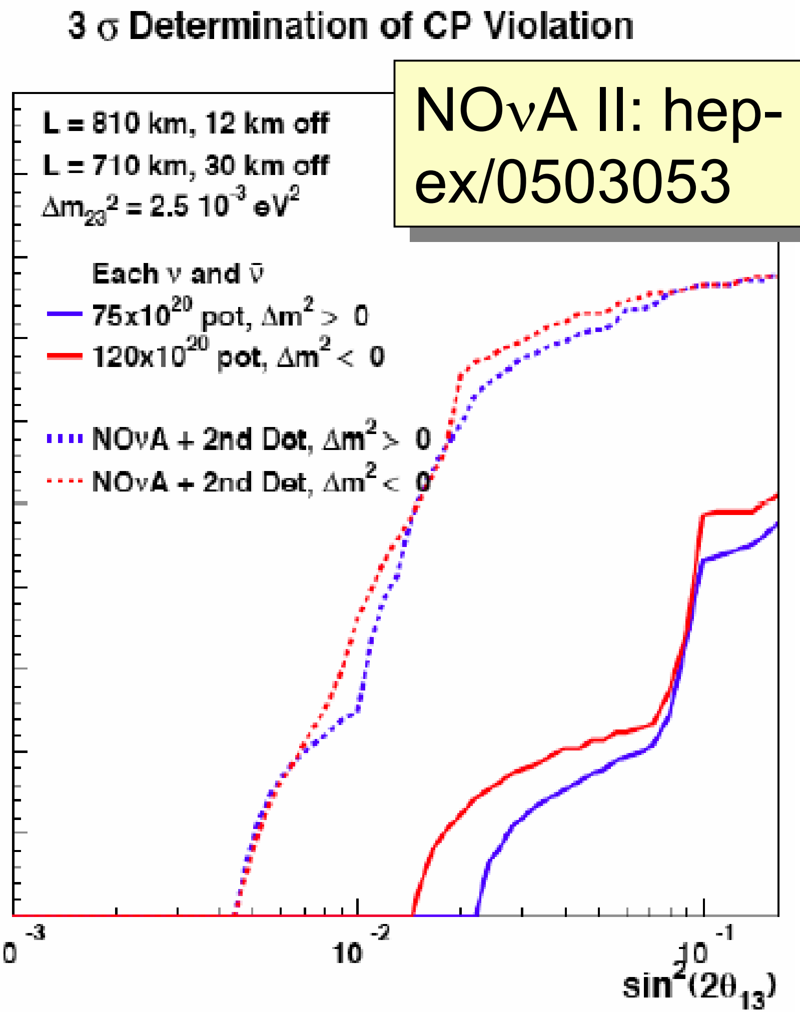


arXiv:0710.4947 [hep-ph]

T2KK vs. NOνA; CP



thick: 3σ,
thin: 2σ



NOνA II: hep-ex/0503053

Minakata@2nd T2KK workshop ('06)

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

June 2005 ～ Aug. 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**
- ➢**Muon Subgroup L. Roberts**

- **Theory Subgroup**
  Model building for neutrino mass & mixing
- **Phenomenology Subgroup**
  Deviation from SM with massive neutrinos
- **Experiment Subgroup**
  Estimation of sensitivity and resolution of degeneracy for ν factories and β beams

Final report of Physics Group :
arXiv:0710.4947 [hep-ph]

International Design Study of the Neutrino Factory

2007 ～

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

◆Accelerator Group
◆Detector Group
◆Physics and Performance Evaluation Group

Tentative plan of PPEG

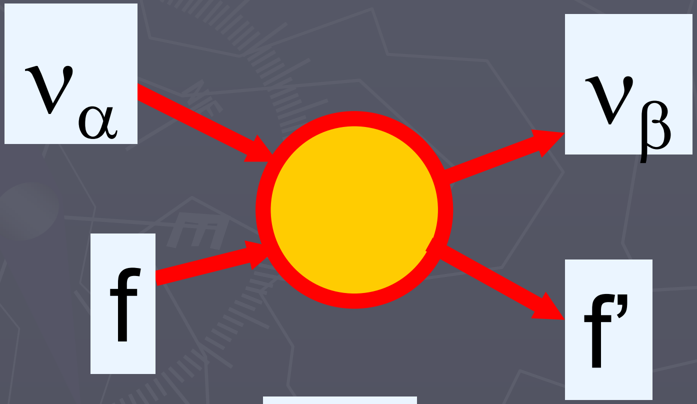
- provide sensitivity estimates as requested
- track new developments like low E NF
- understand optimization in the context of non-standard physics
- establish a physics case for all values of θ_{13}
- keep track of competitors to the NF
- near detector, both at a SB and NF
- status of cross-sections
- muon physics

3. Deviation from standard 3 flavor framework

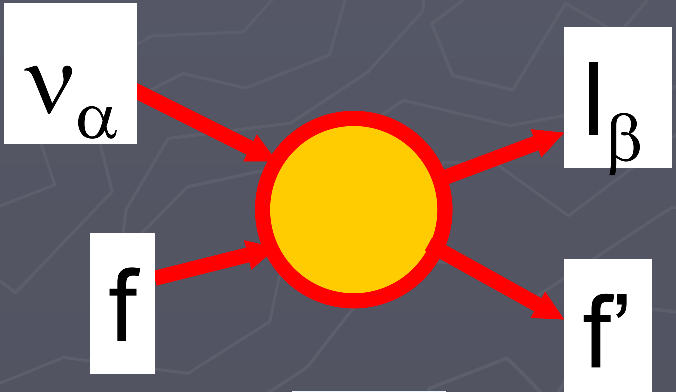
(1) New physics (NP) (exotic interactions)
(2) violation of unitarity (like at a B factory)
(3) Sterile neutrinos

(1) New physics (NP) (exotic interactions)

Flavors are not necessarily conserved:



NC



CC

Effects of New Physics on ν oscillations

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

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

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

with

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

source

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

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

propagation

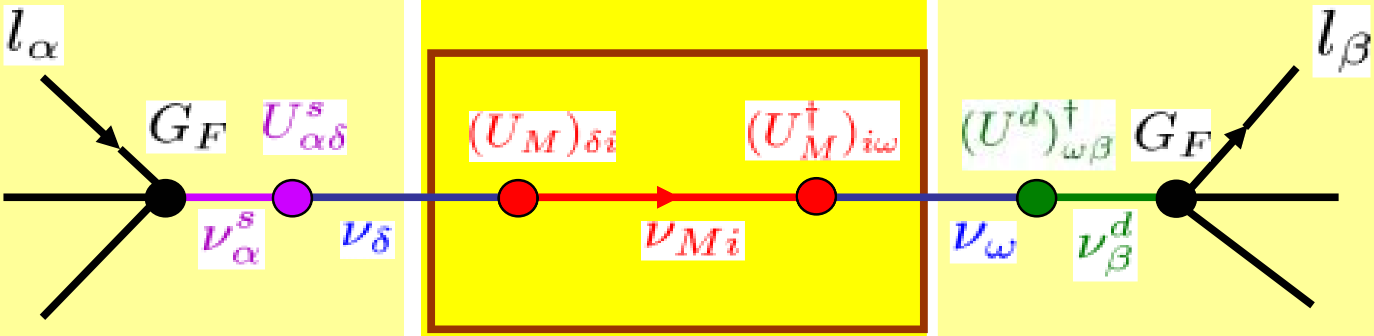
ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ ~O(1)

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

detection

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

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



(i) Effects of New Physics at source and detector

Deviation from the standard form is small:

Grossman (PLB359:141,1995)

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

(ii) 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

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

In general:

NP effects at production and at detection becomes important when L is smaller

$|\varepsilon_{\alpha\beta}| < O(10^{-2})$

$$P(\nu_\alpha \to \nu_\beta) \to \left| \left[U^d (U^s)^{-1} \right]_{\beta\,\alpha} \right|^2$$

i.e., no BG from osc. in the limit of $L \to 0$

⇒ Experiments with a shorter baseline are advantageous

NP effects in propagation becomes important when L is larger

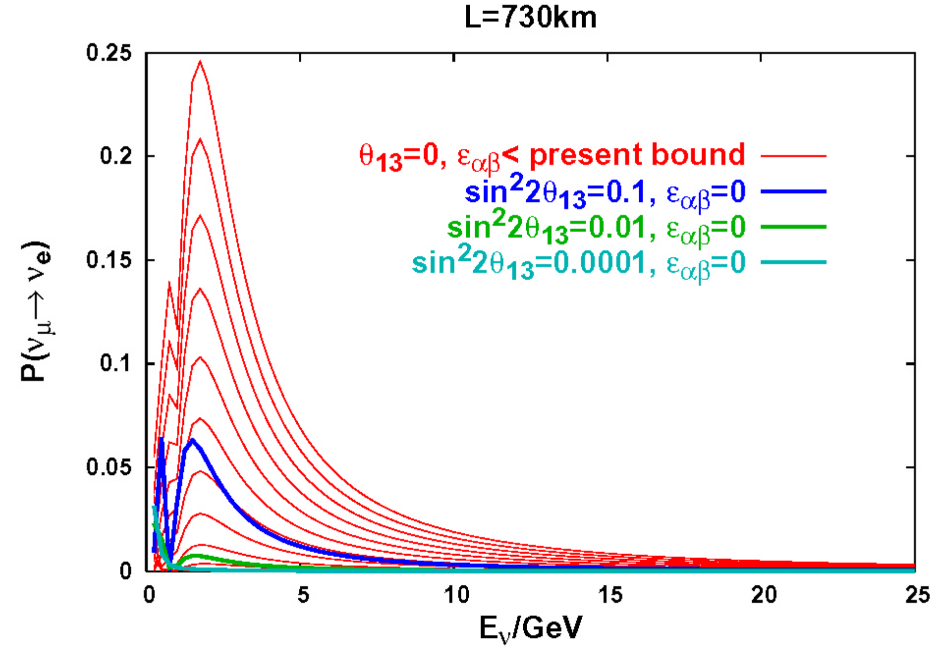
$\varepsilon_{\alpha\beta}$ can be of O(1)

because AL $\varepsilon_{\alpha\beta} \sim \varepsilon_{\alpha\beta}$ (L/2000km)

⇒ Experiments with a longer baseline (e.g., INO) are advantageous

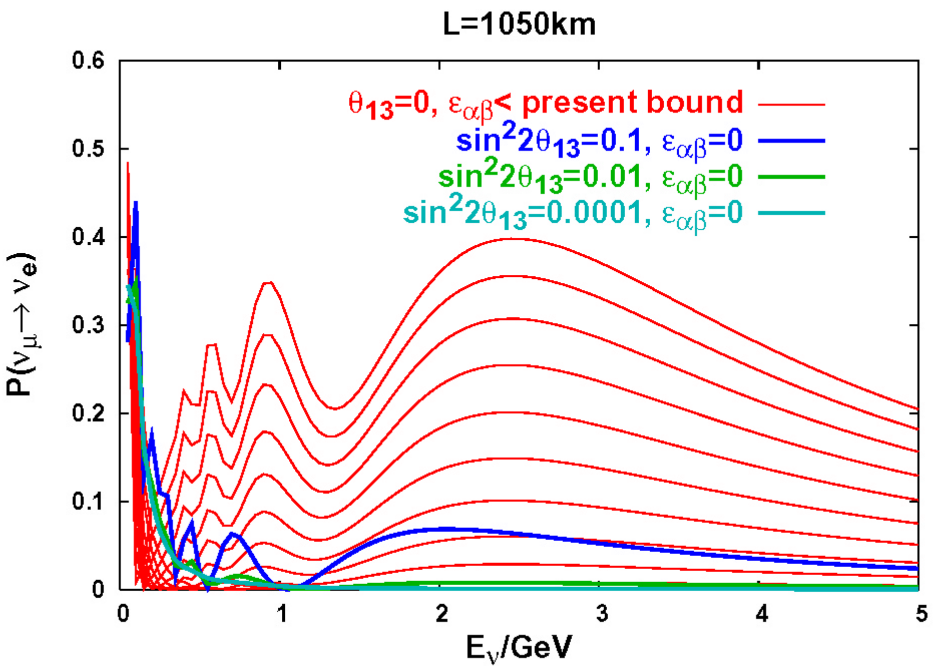
MINOS (ν_e appearance)

$\nu_\mu \to \nu_e$



T2KK (ν_e appearance)

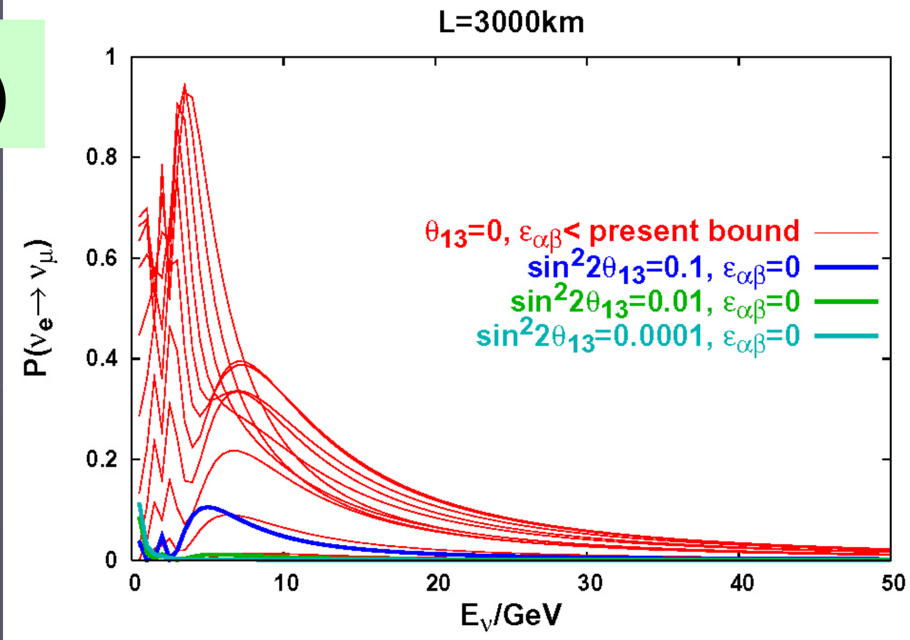
$\nu_\mu \to \nu_e$



NK,HS,OY, hep-ph/0606013

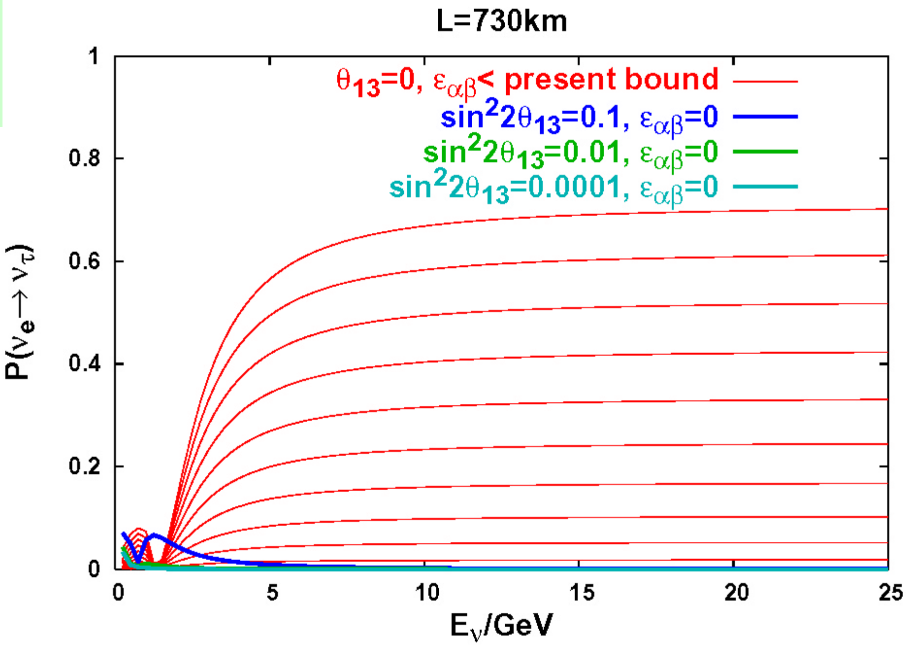
ν factory (golden channel)

$\nu_e \to \nu_\mu$



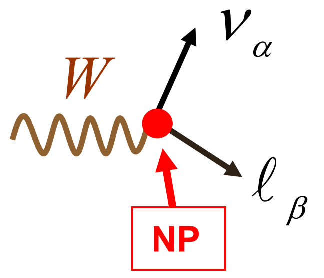
ν factory (silver channel)

$\nu_e \to \nu_\tau$



NK,HS,OY, hep-ph/0606013

(2) Unitarity violation due to heavy ν



minimal non-unitary model

***$U \rightarrow N$* (non-unitary)**

$NN^\dagger - 1$: deviation from unitarity

mostly from rare decays

$$|NN^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.1\cdot 10^{-5} & < 1.6\cdot 10^{-2} \\ < 7.1\cdot 10^{-5} & 0.995 \pm 0.005 & < 1.0\cdot 10^{-2} \\ < 1.6\cdot 10^{-2} & < 1.0\cdot 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

90% C.L.

Constraints on unitary violation are strong:

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

Minimal case: Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP 0610:084,2006.

Non-minimal case: Abada, Biggio, Bonnet, Gavela, Hambye, arXiv:0707.4058 [hep-ph]

Even stronger constraints → more difficult to detect

Unitarity violation is similar to NP effects at production and at detection → becomes important when L is smaller

$$P(\nu_\alpha \to \nu_\beta) \to \left| \left[(1+\eta)\, U \exp\left[-i\, \mathrm{diag}\,(E_j)\right] U^{-1} (1+\eta)^{-1} \right]_{\beta\alpha} \right|^2$$

$$\eta \equiv (NN^\dagger - 1)/2$$

$$|\eta_{\alpha\beta}| < O(10^{-2})$$

$$U^s \to 1+\eta/2,\ U^d \to 1+\eta/2$$

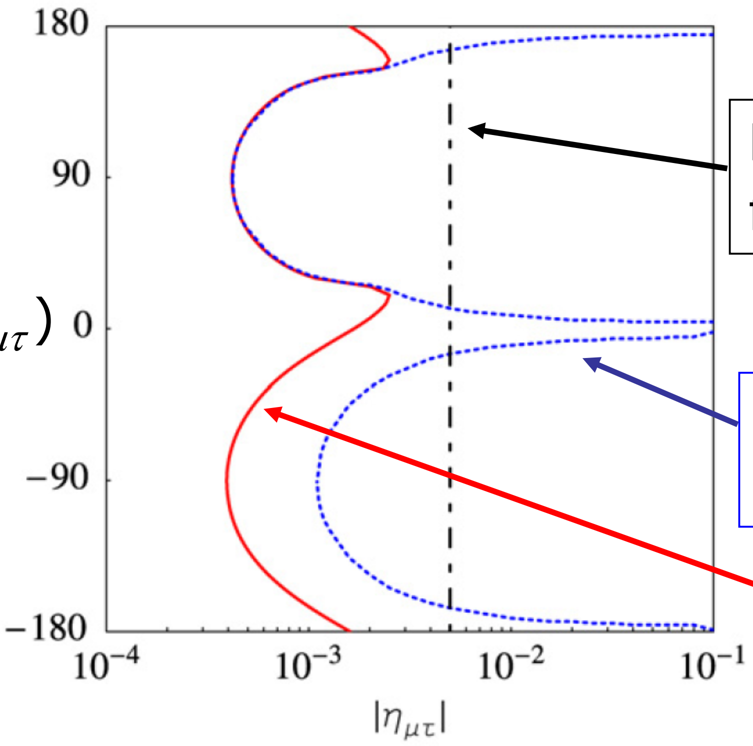
→ Experiments with a shorter baseline are advantageous

Neutrino factory with a baseline L=130km

Fernandez-Martinez, Gavela, Lopez-Pavon, OY, Phys.Lett.B649:427-435,2007

Phase of N

$\nu_\mu \leftrightarrow \nu_\tau$



Present bound from $\tau \rightarrow \mu\,\gamma$

Sensitivity to arg($\eta_{\mu\tau}$)

Sensitivity to $|\eta_{\mu\tau}|$

For non-trivial arg($\eta_{\mu\tau}$), one order of magnitude improvement for $\eta_{\mu\tau}$

(3A) Sterile neutrinos assuming LSND

$\Delta m^2_{\text{sol}} \sim 10^{-4}\,\text{eV}^2$ $\Delta m^2_{\text{atm}} \sim 10^{-3}\,\text{eV}^2$ $\Delta m^2_{\text{LSND}} \sim O(1)\,\text{eV}^2$

→ **at least one ν_s is required**

$\text{LSND}(\bar{\nu}_\mu \to \bar{\nu}_e)$: affirmative

$\text{MiniBOONE}(\nu_\mu \to \nu_e)$: negative

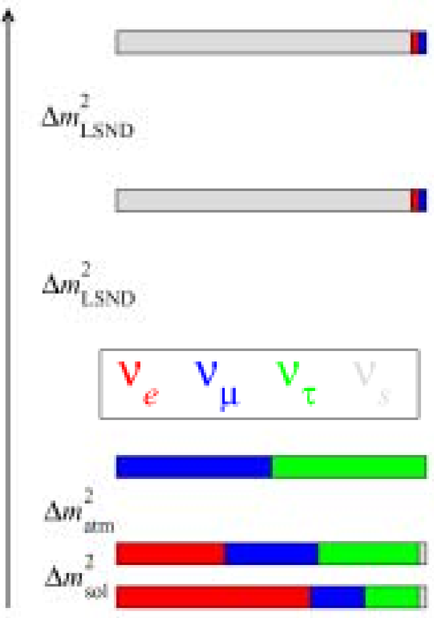
→ **difference between ν & anti-ν may offer a promising fit**

(3+2)-scheme w/ CP phase δ

$$
\begin{aligned}
P_{\nu_\mu\to\nu_e} &= 4\,|U_{e4}|^2|U_{\mu4}|^2\sin^2\phi_{41} \\
&+ 4\,|U_{e5}|^2|U_{\mu5}|^2\sin^2\phi_{51} \\
&+ 8\,|U_{e4}U_{\mu4}U_{e5}U_{\mu5}|\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54}-\delta)
\end{aligned}
$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E}, \qquad \boxed{\delta \equiv \arg\left(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5}\right)}\,.$$



Schwetz-Mangold@nufact07

$\phi_{54}^{best} = 1.64\,\pi$

$$\Delta m^2_{41} = 0.89 \text{ eV}^2$$
$$\Delta m^2_{51} = 6.49 \text{ eV}^2$$

$$\chi^2_{\text{min}} = 94.5/(107-7)$$

Karagiorgi@nufact07

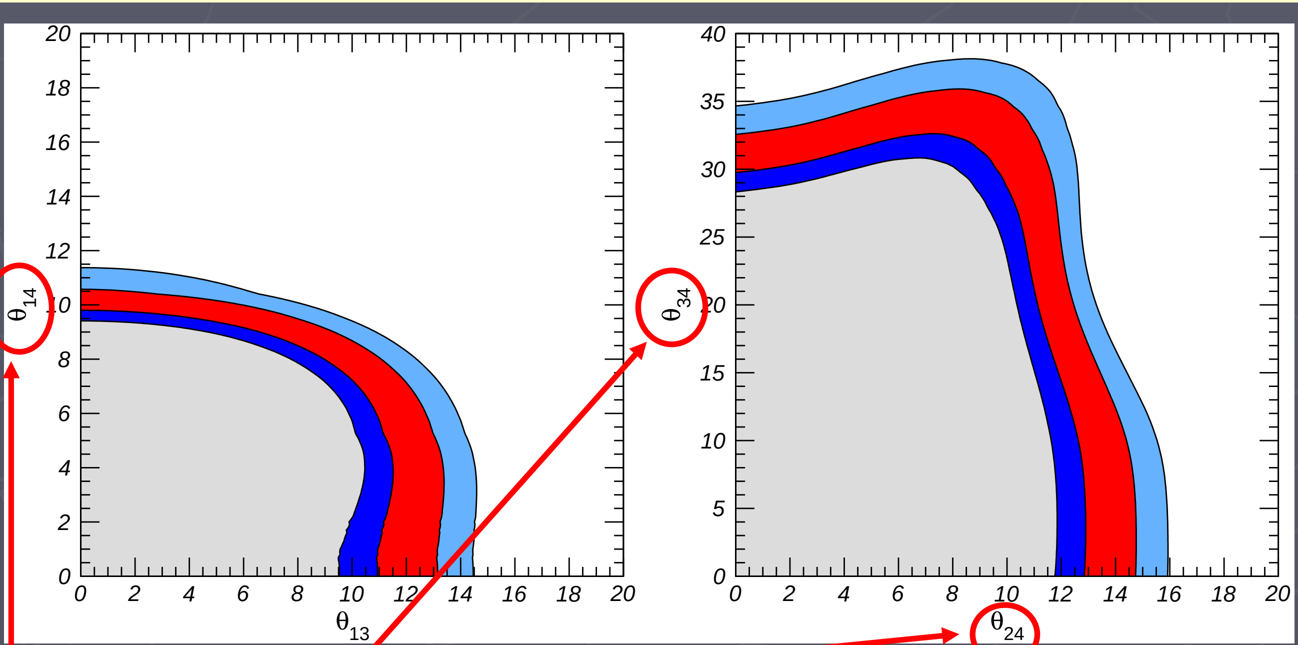
$\chi^2/ndf = 146.7/156$
gof=69%
$\phi_{54}^{best} = 1.74\,\pi$

- (3+2) schemes
  - offer the possiblity of CP violation to reconcile LSND and MiniBooNE,
  - but there is tension between appearance and disappearance data (3σ, 4σ for MB300)

(3B) Sterile neutrinos w/o assuming LSND

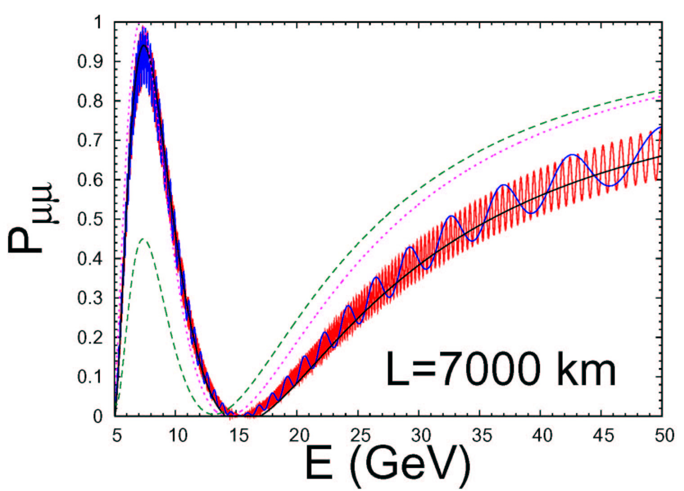
Without assuming LSND and imposing all the negative constraints one can still consider (3+1)-scheme

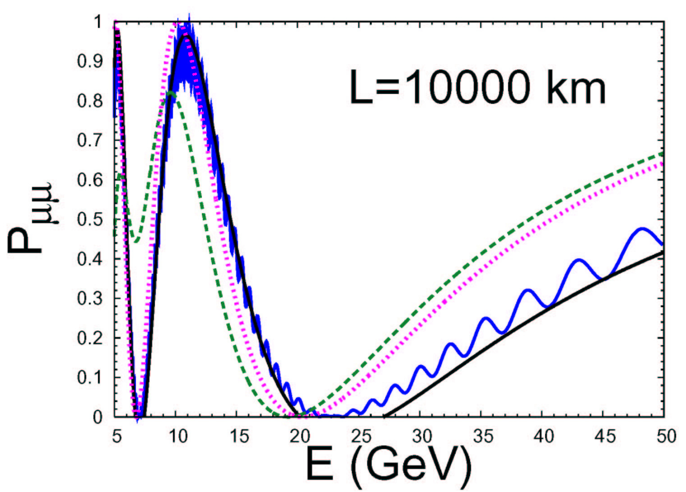
"3+1 sterile neutrinos at the CNGS" Donini, Maltoni, Meloni, Migliozzi, Terranova, arXiv:0704.0388v2 [hep-ph]

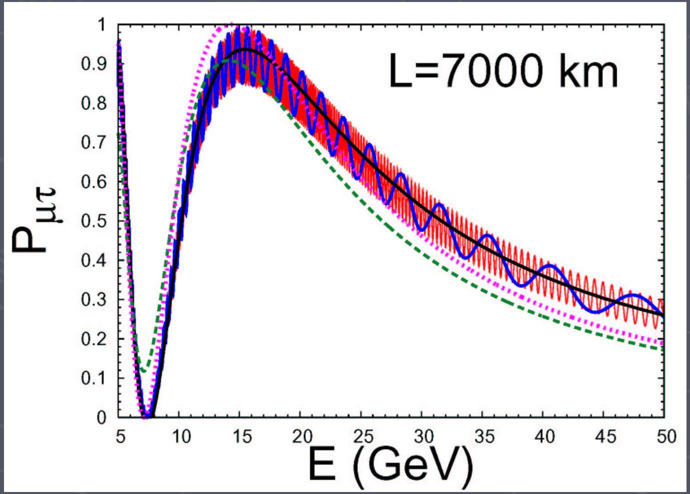


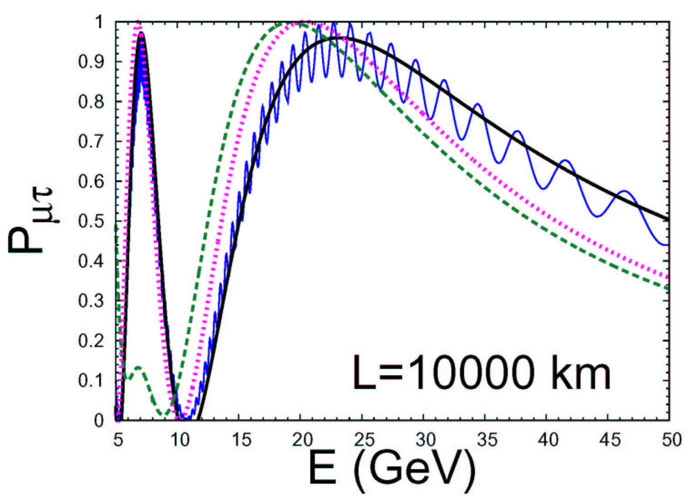
θ_{14} , θ_{24} , θ_{34} : angles which appear only in 4ν scenario

“Signatures of heavy sterile neutrinos at long baseline experiments”
Dighe, Ray, arXiv:0709.0383 [hep-ph]









In either case (3A) or (3B), sterile neutrino oscillations will exhibit enhancement/suppression for ν or anti- ν, and experiments with a longer baseline (such as INO) are expected to have good sensitivity to sterile neutrinos.

3. Summary

- A brief review was given on the known parameters in SM+massive ν. Efforts to determine the unknown parameters (θ_{13} , δ , sign(Δm^2_{31})) in the future experiments were described.
- The future neutrino experiments with high precision will be able to see deviation from SM such as non-std. interactions, unitarity violation, sterile neutrinos, etc.
- Experiments with longer baselines (such as INO) are advantageous to search for NP in propagation and sterile neutrinos.