Study of ν oscillation
---present and future---

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1. Introduction & ν oscillation

(i) 2 flavor oscillations in vacuum

$$\left.\begin{cases} i\dfrac{d}{dx}\nu_1(x) = E_1\ \nu_1(x) \\[2ex] i\dfrac{d}{dx}\nu_2(x) = E_2\ \nu_2(x) \end{cases}\right\}$$

mass eigenstates

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

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \end{pmatrix} = U \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \end{pmatrix}$$

flavor eigenstates

$$U \equiv \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

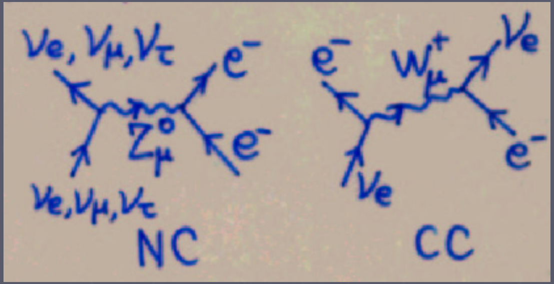
mixing matrix in vacuum

$$\boxed{P(\nu_e \to \nu_\mu; L) \quad = \quad \sin^2 2\theta\ \sin^2\left(\frac{\Delta E L}{2}\right)}$$

$$\Delta E \quad = \quad E_2 - E_1 \simeq \frac{m_2^2 - m_1^2}{2E} \equiv \frac{\Delta m^2}{2E}$$

(ii) 2 flavor oscillations in matter (MSW effect)

$$
\begin{aligned}
\mathcal{L}_{eff} &= \sqrt{2}\, G_F\, \bar{\nu}_e \gamma^\mu \nu_e\, \bar{e}\gamma_\mu e \qquad (\langle \bar{e}\gamma_\mu e\rangle \rightarrow \delta_{\mu 0} N_e(x)) \\
&= A\, \bar{\nu}_e \gamma^0 \nu_e \qquad \boxed{(A \equiv \sqrt{2}\, G_F\, N_e(x))}
\end{aligned}
$$



$$
\begin{aligned}
i\frac{d}{dx}\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \end{pmatrix} &= \left[U \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix} U^{-1} + \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \right] \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \end{pmatrix} \\
&= \tilde{U}(x) \begin{pmatrix} \tilde{E}_1 & 0 \\ 0 & \tilde{E}_2 \end{pmatrix} \tilde{U}^{-1}(x) \begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \end{pmatrix}
\end{aligned}
$$

If N_e=const.

$$
\boxed{P(\nu_e \rightarrow \nu_\mu; L) = \sin^2 2\tilde{\theta}\, \sin^2\left(\frac{\Delta\tilde{E} L}{2}\right)}
$$

$$
\begin{aligned}
\tan 2\tilde{\theta} &\equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A} \\
\Delta\tilde{E} &= \left[(\Delta E \cos 2\theta - A)^2 + (\Delta E \sin 2\theta)^2 \right]^{1/2}
\end{aligned}
$$

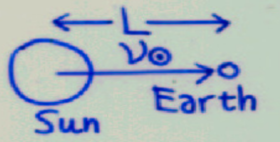
even if θ in vacuum is small $\tilde{\theta}$ in matter could be large (MSW effect)

(iii) 3 flavor ν oscillation

KamLAND(reactor) $\bar{\nu}_e \to \bar{\nu}_e$

∘ solar ν

$\nu_e \to \nu_e$



① flux of $\nu_\odot$ observed on the Earth is lower than theoretical predictions

$\underbrace{\text{GALLEX-GNO, SAGE}}_{Ga}$, $\underbrace{\text{Homestake}}_{Cl}$, $\underbrace{\text{Kamiokande, SK}}_{H_2O}$, $\underbrace{\text{SNO}}_{D_2O}$

② data/th depends on exps.

Large Mixing Angle solution

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

$\Delta m^2_{21} = 8 \times 10^{-5}\,\mathrm{eV}^2$

∘ atmospheric ν

$\nu_\mu \to \nu_\mu,\ \bar{\nu}_\mu \to \bar{\nu}_\mu$

naive expectation from

$\pi^+ \to \mu^+ + \nu_\mu$, $\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \to \mu^- + \bar{\nu}_\mu$, $\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

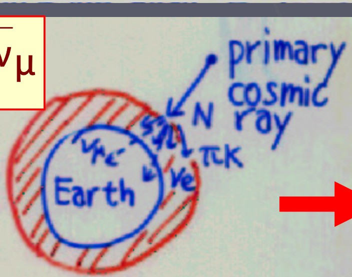
leads to

$\#(\nu_\mu + \bar{\nu}_\mu)/\#(\nu_e + \bar{\nu}_e) \simeq 2$

but observations show

① $\#(\nu_\mu + \bar{\nu}_\mu)/\#(\nu_e + \bar{\nu}_e) \simeq 1.3$

② data/th depends on zenith angle



Kamiokande
IMB
SK
Soudan2
MACRO

maximal mixing

$\theta_{23} \cong \pi/4$

$|\Delta m^2_{32}| = 2.5 \times 10^{-3}\,\mathrm{eV}^2$

K2K $\nu_\mu \to \nu_\mu$

CHOOZ **(reactor)**

$L \sim 1\,\mathrm{km}$, $E_\nu \sim 3\,\mathrm{MeV}$

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

$$\left|\frac{\Delta m^2_{21} L}{4E}\right| = \left|\frac{\Delta m^2_\odot L}{4E}\right| \ll 1$$

$N_\nu = 3$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \underbrace{4|U_{e3}|^2(1-|U_{e3}|^2)}_{\sin^2 2\theta_{13}} \sin^2\left(\frac{\boxed{\Delta m^2_{32}} L}{4E}\right)$$

$$\boxed{\Delta m^2_{32}} \equiv \Delta m^2|_{N_\nu=2}$$

small mixing

$\sin^2 2\theta_{13} < 0.15$

mixing matrix of 3 flavor ν oscillation

$N_\nu = 3$: $\nu_{atm} + \nu_{solar} + \nu_{reactor}$

Mixing matrix

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

Mixing angles & mass squared differences

$\theta_{12} \cong \pi/6, \quad \theta_{23} \cong \pi/4$

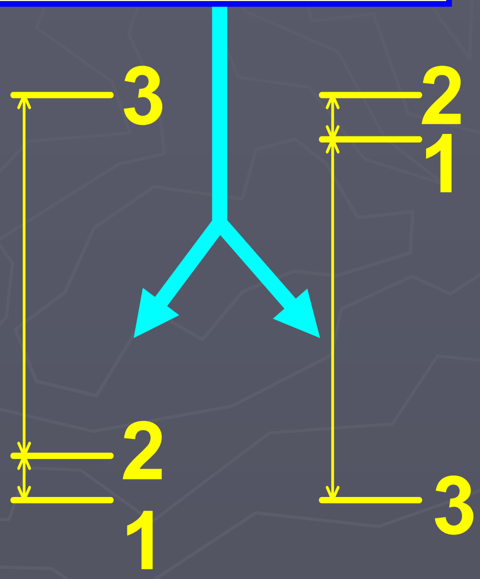
$|\theta_{13}| \cong |\varepsilon| \lesssim \sqrt{0.15}/2$

$\Delta m^2_{21} \cong 8 \times 10^{-5}\,\mathrm{eV}^2$

$|\Delta m^2_{32}| \cong 2.5 \times 10^{-3}\,\mathrm{eV}^2$

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

- Both mass hierarchies are allowed



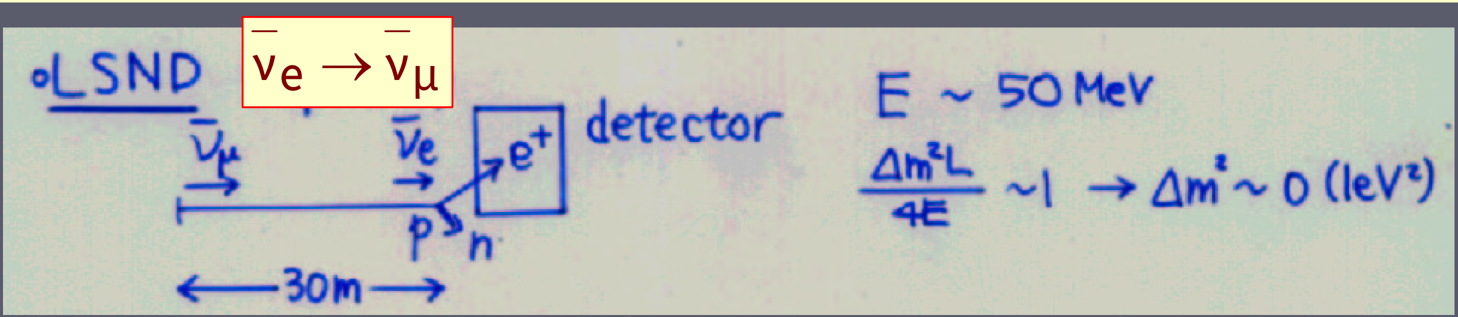
normal hierarchy

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

inverted hierarchy

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

(iv) Scenario other than 3 flavor ν oscillation



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

E ~ 50 MeV

$\frac{\Delta m^2 L}{4E} \sim 1 \to \Delta m^2 \sim O(1\text{eV}^2)$

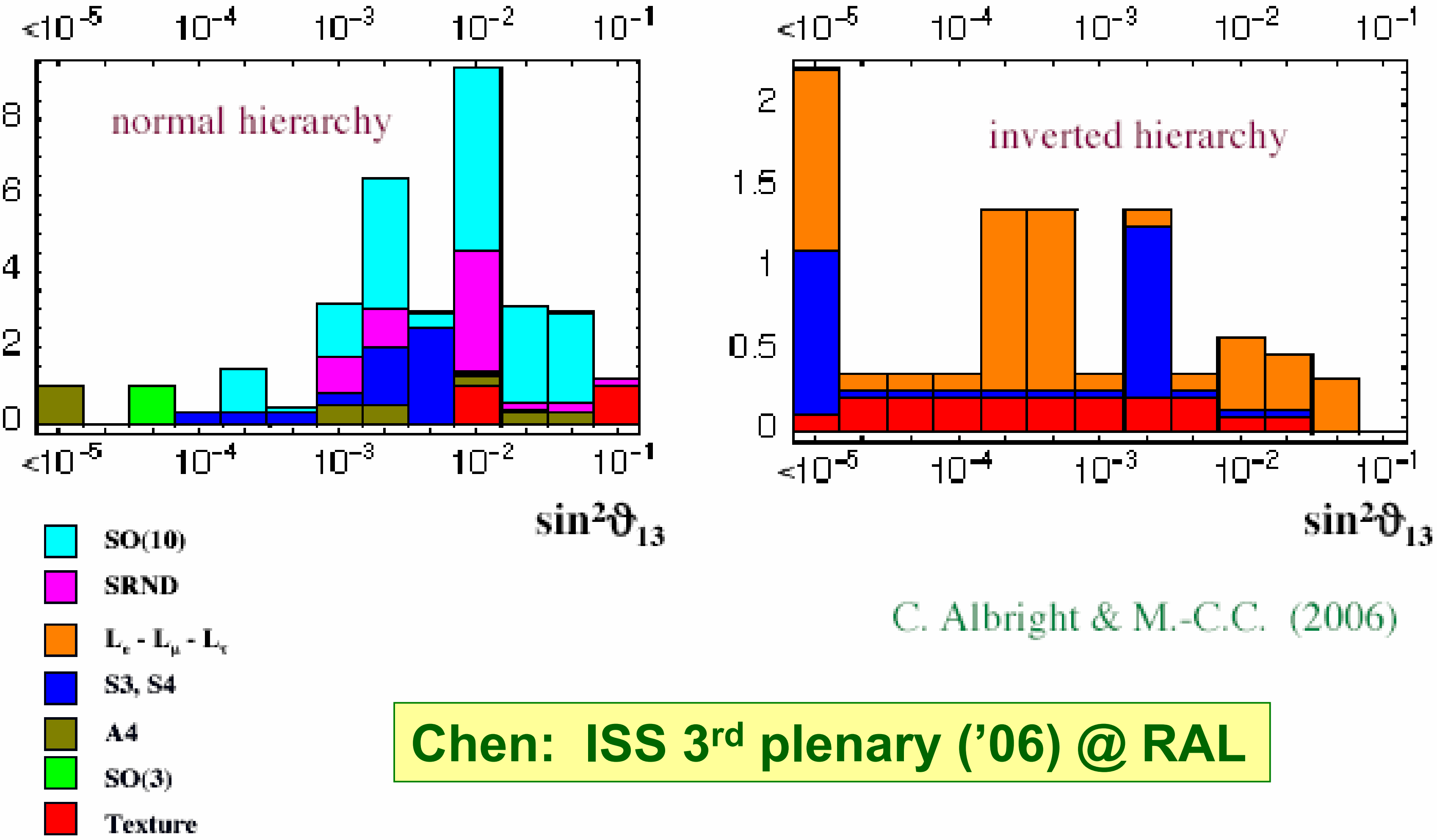
(3+2)-scenario with 2 kind of sterile neutrinos used to be the only viable scenario, but now it is under tension.

Sorel: ISS 2nd plenary ('06) @ KEK

http://www-kuno.phys.sci.osaka-u.ac.jp/~yoshida/ISS/presentations/23Phys_IssThreePlusTwo_sorel.pdf

Until LSND is confirmed by MiniBOONE, sterile neutrino scenarios don't seem to have strong motivations. →In most of the talk, $N_\nu = 3$ is assumed.

(v) Theoretical prediction for θ_{13}

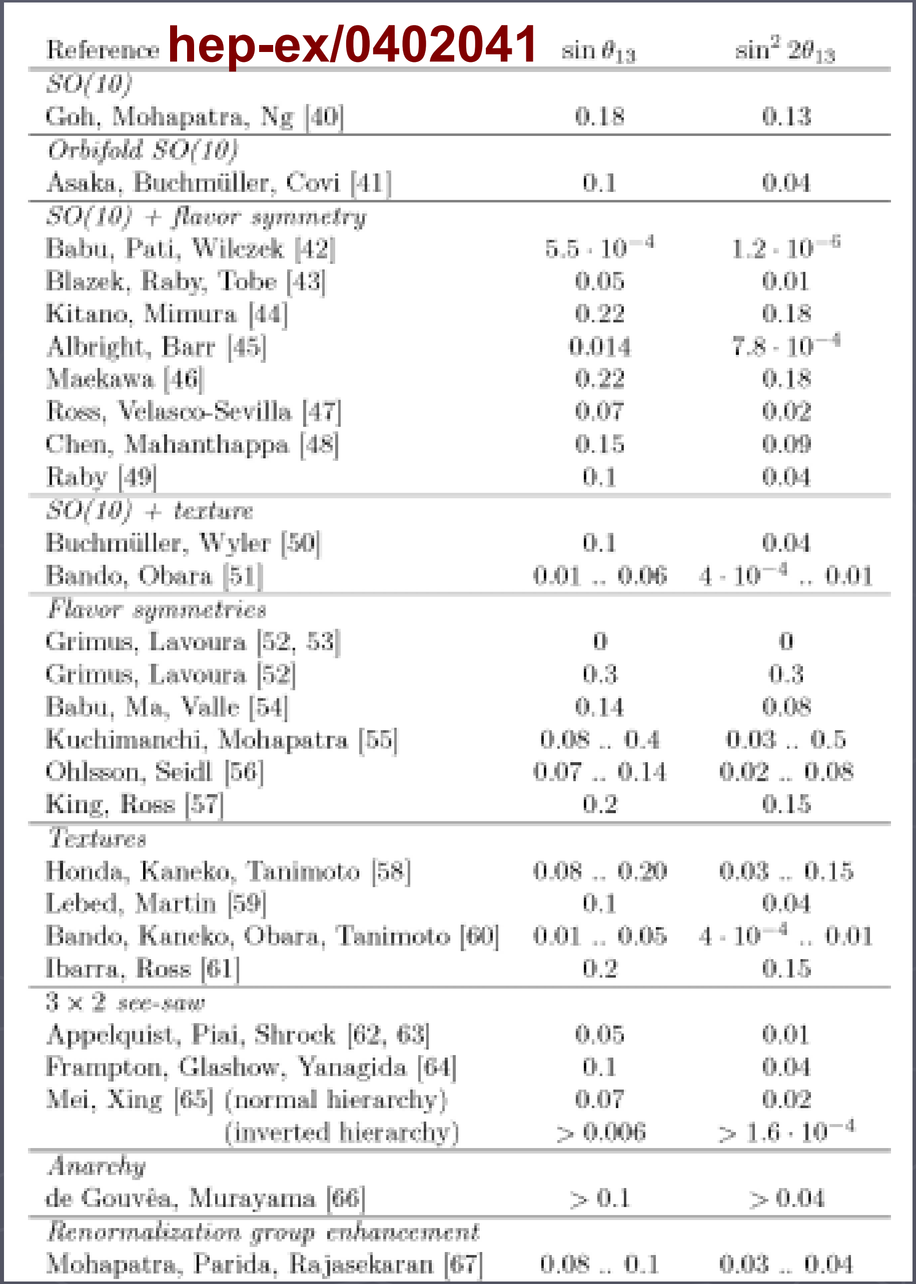


C. Albright & M.-C.C. (2006)

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

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 from 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

(vi) oscillation vs non-oscillation experiments

- **neutrino oscillation**

$$\Delta m^2_{jk}=m^2_j - m^2_k$$

- **neutrinoless double beta decay**

$$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$$

Majorana phases

- **direct measurement**

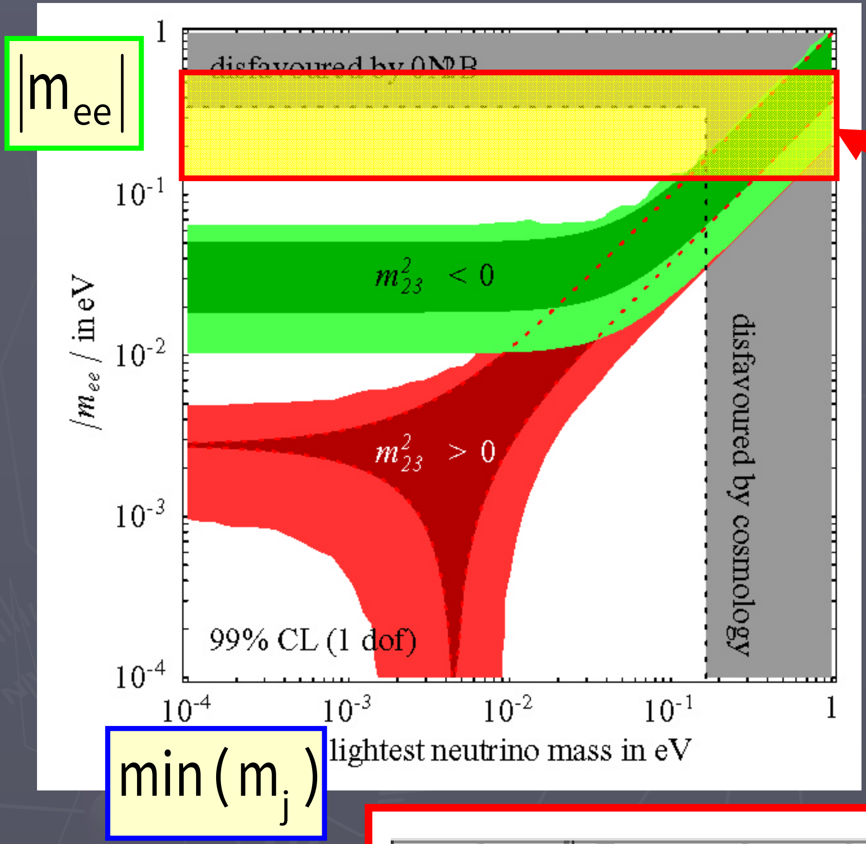
$$m_\beta=(\Sigma|U_{ej}|^2 m^2_j)^{1/2}$$

- **cosmology**

$$\Sigma m_j$$

neutrinoless double beta decay

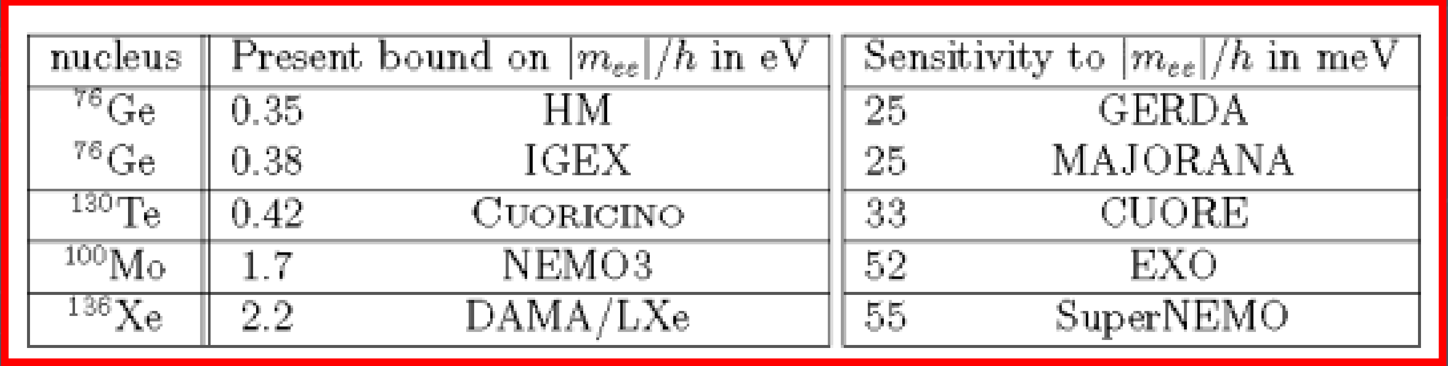
$$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$$



Affirmative result claimed by Klapdor-Kleingrothaus et al: Mod. Phys. Lett. A16, 2409 ('01)

"ββ community: very careful reaction. In any case new experiments are needed (and first of all with ^{76}Ge)." BARABASH@neutrino2006

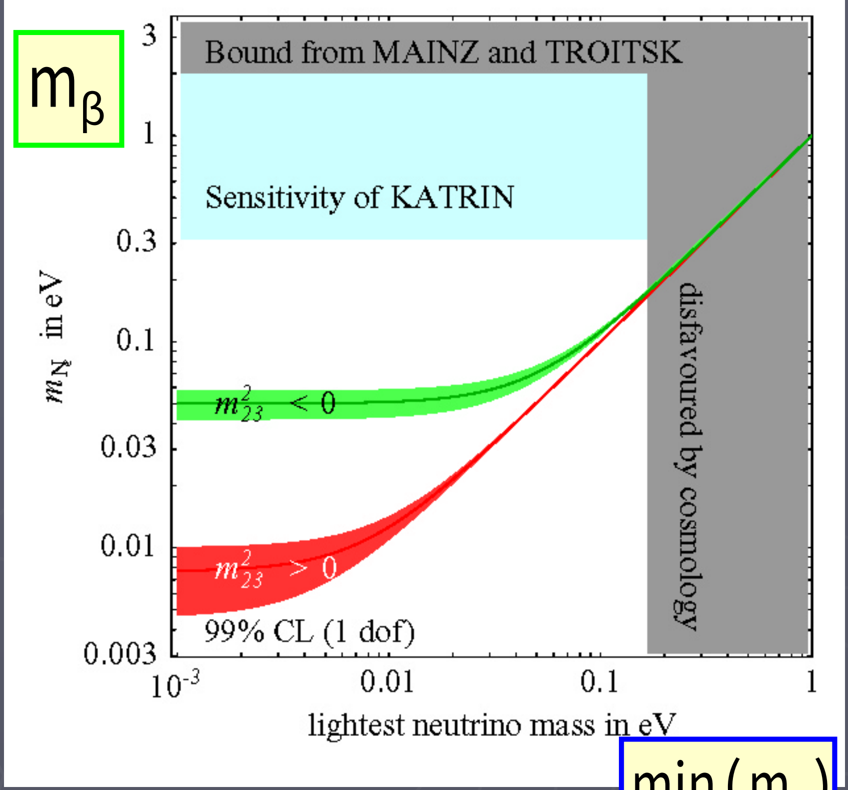
Strumia-Vissani: hep-ph/0606054



nucleus	Present bound on $\lvert m_{ee}\rvert/h$ in eV		Sensitivity to $\lvert m_{ee}\rvert/h$ in meV	
^{76}Ge	0.35	HM	25	GERDA
^{76}Ge	0.38	IGEX	25	MAJORANA
^{130}Te	0.42	CUORICINO	33	CUORE
^{100}Mo	1.7	NEMO3	52	EXO
^{136}Xe	2.2	DAMA/LXe	55	SuperNEMO

direct measurement

$m_\beta = (\Sigma |U_{ej}|^2 m^2_j)^{1/2}$

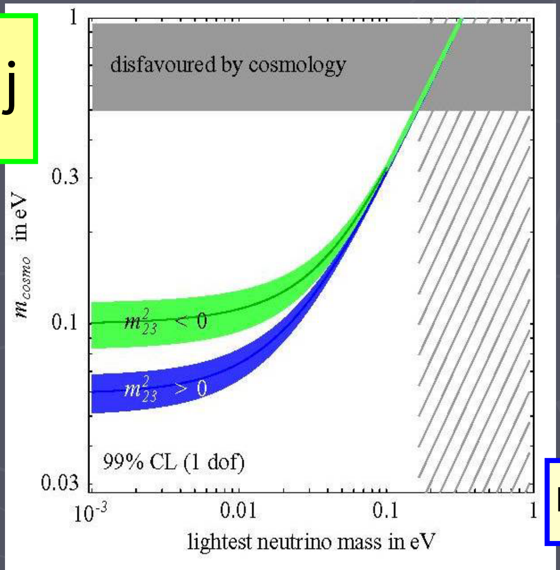


m_β

$\min(m_j)$

cosmology

Σm_j



$\sum_j m_j$

$\min(m_j)$

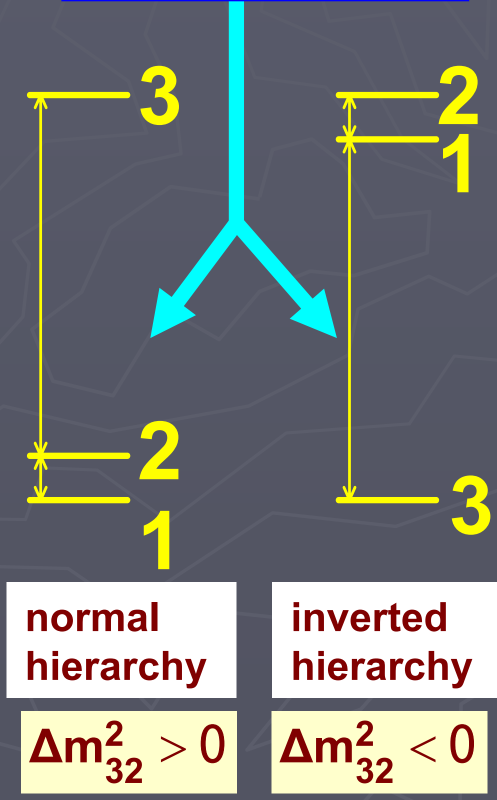
Strumia-Vissani: hep-ph/0606054

2. Future LBL (Long BaseLine experiments)

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

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

- Both mass hierarchies are allowed



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 base line experiments by accelerators or reactors.

→Matter effect contributes in LBL in most cases

Measurement of θ_{13} and sign (Δm^2_{31}) by LBL

$$\begin{aligned}
P(\nu_\mu \to \nu_e) &= s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta E_{31}}{\Delta \tilde{E}^{(-)}_{31}} \right)^2 \sin^2 \left(\frac{\Delta \tilde{E}^{(-)}_{31} L}{2} \right) \\
P(\bar{\nu}_\mu \to \bar{\nu}_e) &= s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta E_{31}}{\Delta \tilde{E}^{(+)}_{31}} \right)^2 \sin^2 \left(\frac{\Delta \tilde{E}^{(+)}_{31} L}{2} \right) \\
\Delta \tilde{E}^{(\pm)}_{31} &\equiv \sqrt{(\Delta E_{31} \cos 2\theta_{13} \pm A)^2 + (\Delta E_{31} \sin 2\theta_{13})^2}
\end{aligned}$$

to leading order in $\Delta m^2_{21} / |\Delta m^2_{32}|$

$$\text{If} \quad \Delta m^2_{31} > 0 \quad \text{then} \quad \left(\Delta E_{31} / \Delta \tilde{E}^{(-)}_{31} > 1 > \Delta E_{31} / \Delta \tilde{E}^{(+)}_{31} \right)^2$$

$$\text{If} \quad \Delta m^2_{31} < 0 \quad \text{then} \quad \left(\Delta E_{31} / \Delta \tilde{E}^{(-)}_{31} < 1 < \Delta E_{31} / \Delta \tilde{E}^{(+)}_{31} \right)^2$$

For large L, difference between $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ due to matter effect becomes significant: AL〜L/(2000km)

Measurement of θ_{13} by reactors

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta E_{31} L}{2} \right)$$

E〜4MeV,
L〜2km,
→AL<<1
(no matter effect)

Measurement of δ

$\sin^2 2\theta_{13} < 0.15$

All the contributions of δ appear with the factor of $\sin\theta_{13}$

→ It is very difficult to measure δ

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-s_{13}e^{i\delta}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Theoretical argument on measurement of δ

in vacuum

$$\left\{\begin{array}{c} P(\nu_\alpha \to \nu_\beta) \\ P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \end{array}\right\} = \delta_{\alpha\beta} - 4\sum_{j<k} \mathrm{Re}(U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k})\sin^2(\Delta E_{jk}L/2) \pm 2\sum_{j<k} \mathrm{Im}(U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k})\sin(\Delta E_{jk}L),$$

$$\begin{aligned} & P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \\ = \; & 4J[\sin(\Delta E_{12}L) + \sin(\Delta E_{23}L) + \sin(\Delta E_{31}L)] \end{aligned}$$

CP odd term

$$J \equiv \mathrm{Im}\left(U_{\alpha 1}U^*_{\beta 1}U^*_{\alpha 2}U_{\beta 2}\right) \propto \sin\delta$$

Jarlskog factor

in matter

$$\left\{\begin{array}{c} P(\nu_\alpha \to \nu_\beta) \\ P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \end{array}\right\} = \delta_{\alpha\beta} - 4\sum_{j<k} \mathrm{Re}(\tilde{U}^{(\mp)}_{\alpha j}\tilde{U}^{(\mp)*}_{\beta j}\tilde{U}^{(\mp)*}_{\alpha k}\tilde{U}^{(\mp)}_{\beta k})\sin^2(\Delta\tilde{E}^{(\mp)}_{jk}L/2) + 2\sum_{j<k} \mathrm{Im}(\tilde{U}^{(\mp)}_{\alpha j}\tilde{U}^{(\mp)*}_{\beta j}\tilde{U}^{(\mp)*}_{\alpha k}\tilde{U}^{(\mp)}_{\beta k})\sin(\Delta\tilde{E}^{(\mp)}_{jk}L),$$

$$\begin{aligned} & P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha) \\ = \; & 4\tilde{J}\left[\sin\left(\Delta\tilde{E}^{(-)}_{12}L\right) + \sin\left(\Delta\tilde{E}^{(-)}_{23}L\right) + \sin\left(\Delta\tilde{E}^{(-)}_{31}L\right)\right] \end{aligned}$$

T odd term

$$\tilde{J} \equiv \mathrm{Im}\left(\tilde{U}_{\alpha 1}\tilde{U}^*_{\beta 1}\tilde{U}^*_{\alpha 2}\tilde{U}_{\beta 2}\right) \propto \sin\delta$$

modified Jarlskog factor

Practical measurement of δ

Measure $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, and then:

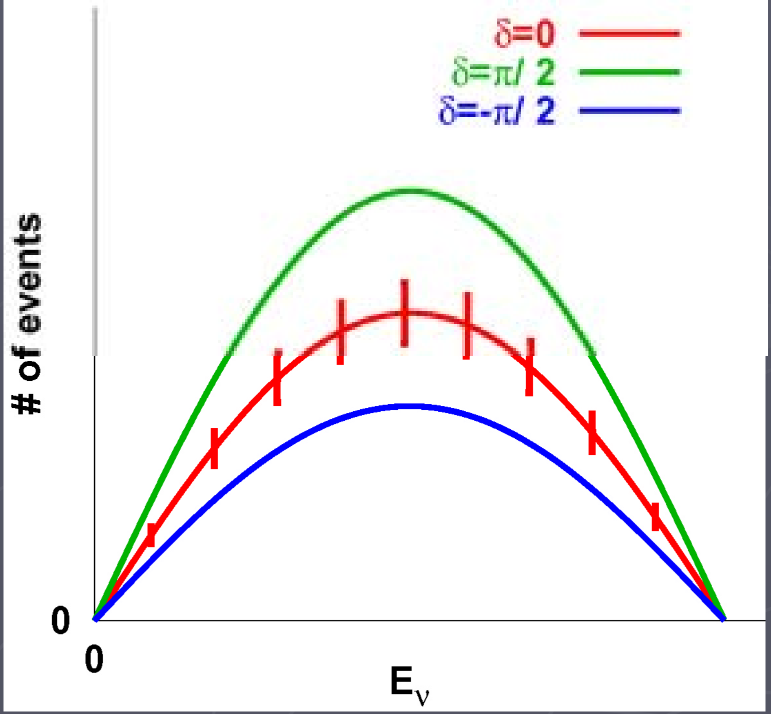
Assume three flavor mixing and compare the data with prediction for $\delta=0$:

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

To reject a hypothesis "$\delta=0$" at 3σ:

$$\Delta\chi^2 > \Delta\chi^2(3\sigma)$$

→We can estimate significance to reject "$\delta=0$" at 3σ



- **Two points to be taken into account for precise measurements:**

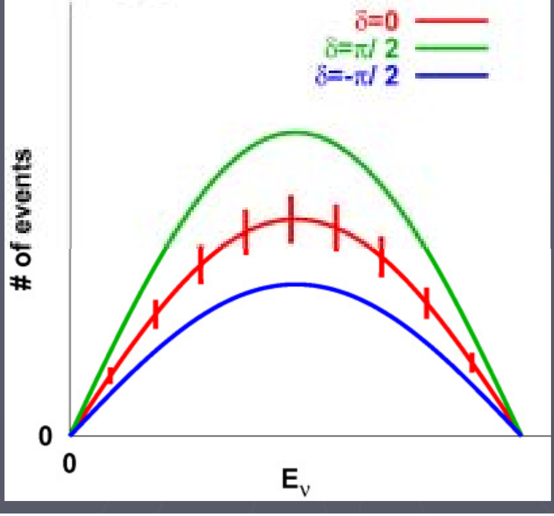
(1) Correlation of errors

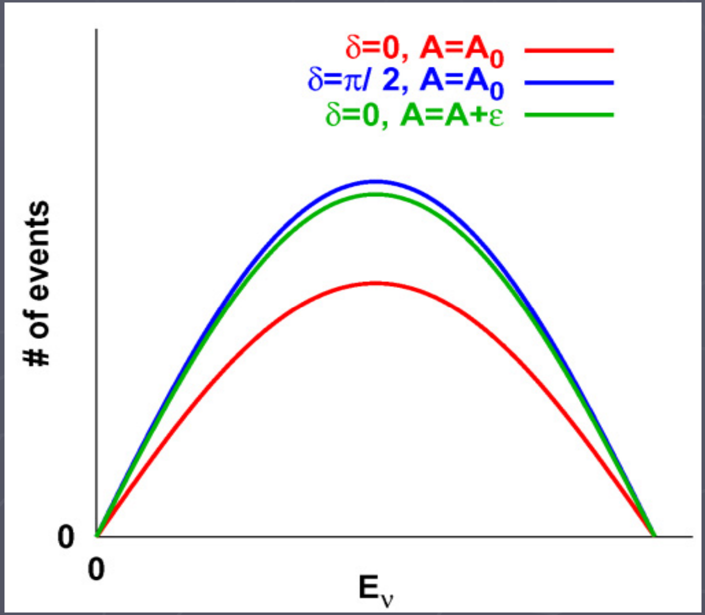
(2) Parameter degeneracy

(1) Correlation of errors

If uncertainties of other parameters (such as density of matter ρ∝ 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”





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

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

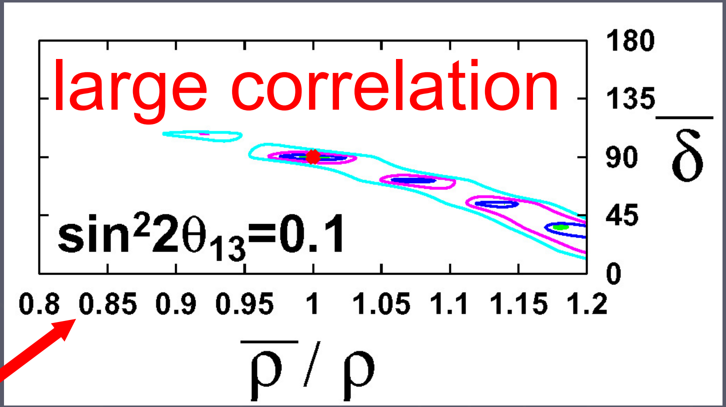
(Example) There is correlation of errors at a neutrino factory:

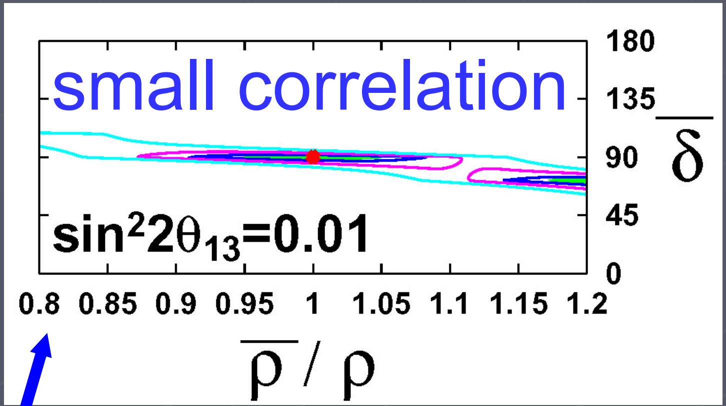
E_μ =50GeV, L=3000km

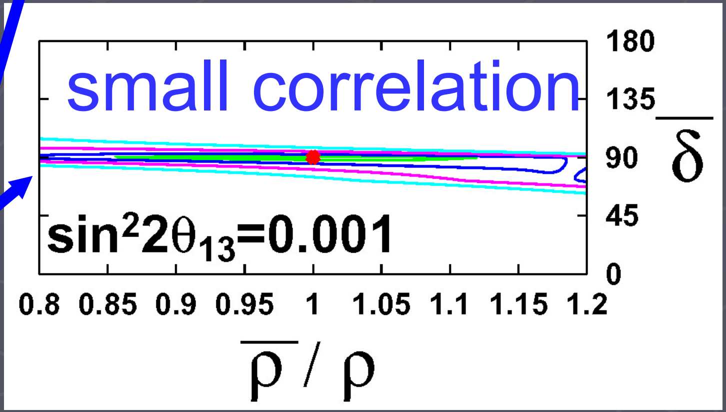
correlation of errors in ρ and δ is serious for $\sin^2 2\,\theta_{13} \sim 0.1$

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

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

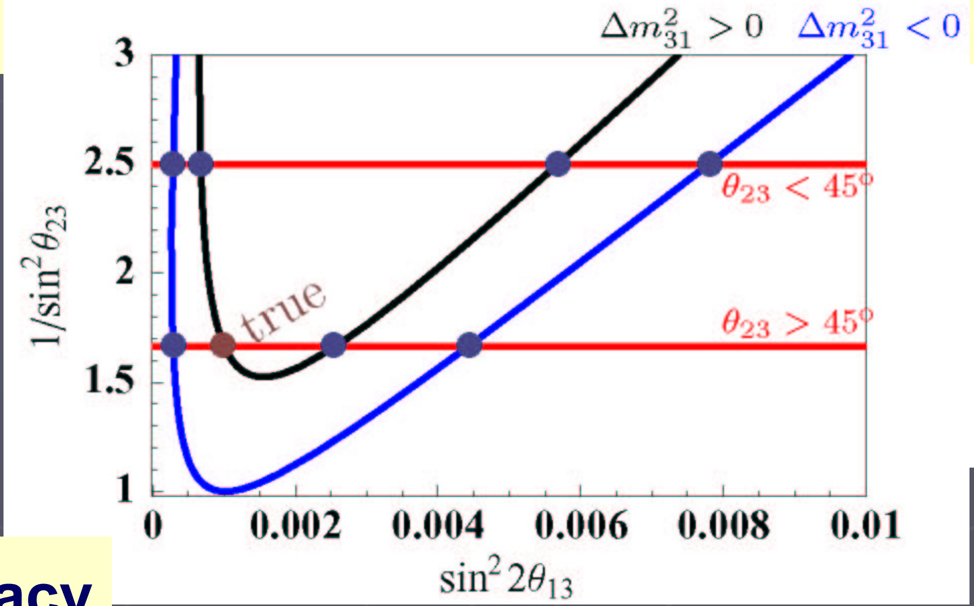






(2) Parameter degeneracy

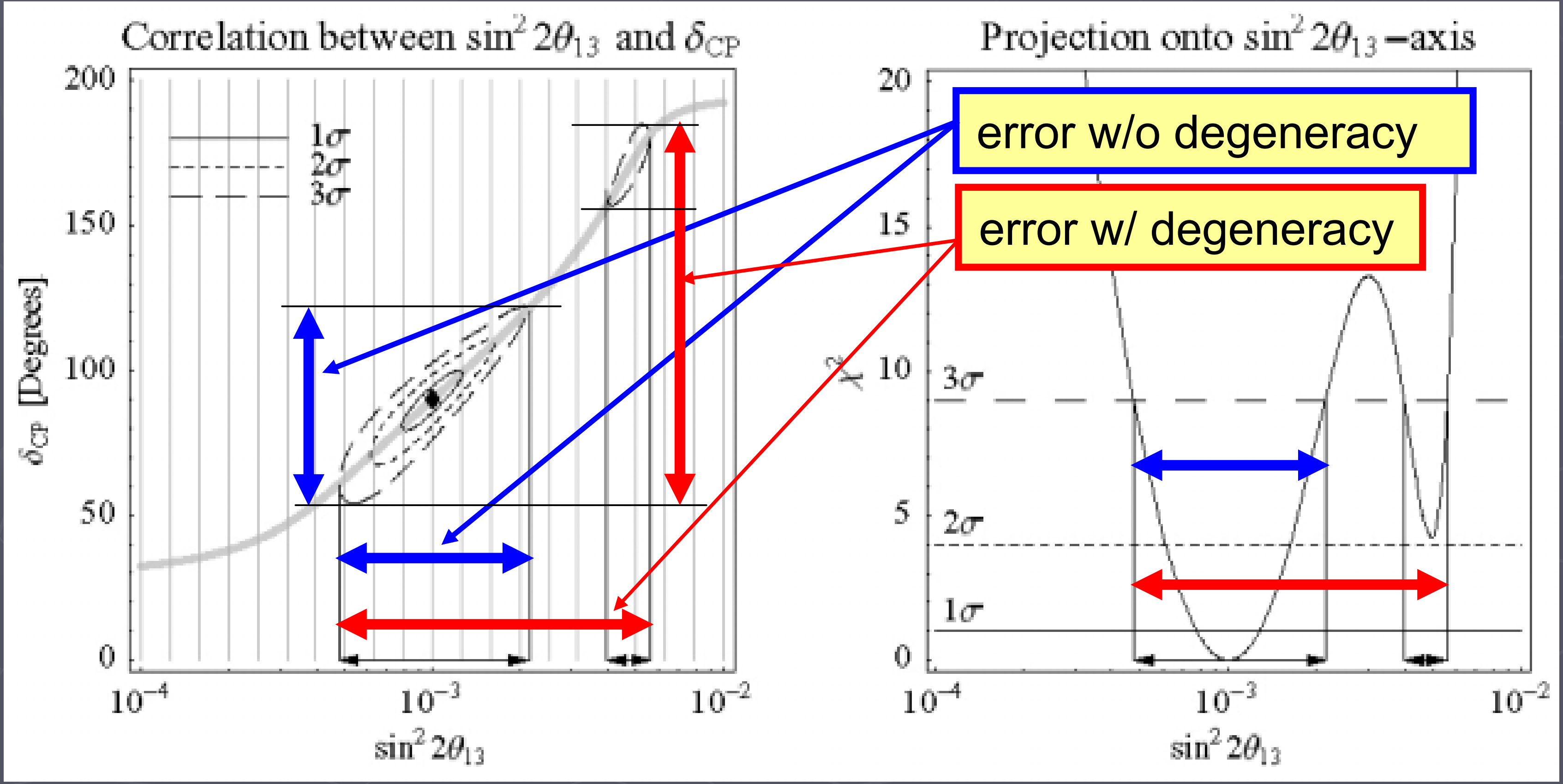
Even if we know $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu_\mu} \to \overline{\nu_e})$ in a long baseline accelerator experiments with approximately monoenergetic neutrino beam, precise determination of θ_{13} , sign(Δm^2_{31}) and δ is difficult because of the 8-fold parameter degeneracy.



- **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.**



Correlation between $\sin^2 2\theta_{13}$ and δ_{CP}

Projection onto $\sin^2 2\theta_{13}$–axis

error w/o degeneracy

error w/ degeneracy

To solve parameter degeneracy, combine the following:

(A) LBL measurement at $|\Delta m^2_{31}|L/4E=\pi/2$

→ hyperbola shrinks to a straight line

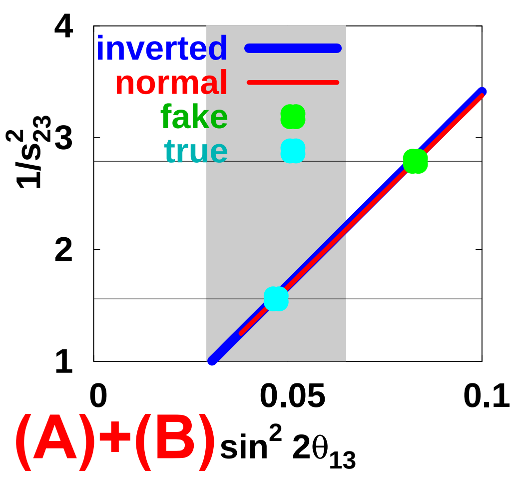
(B) reactor measurement of θ_{13} $\bar{\nu}_e \rightarrow \bar{\nu}_e$

→ depends only on θ_{13}

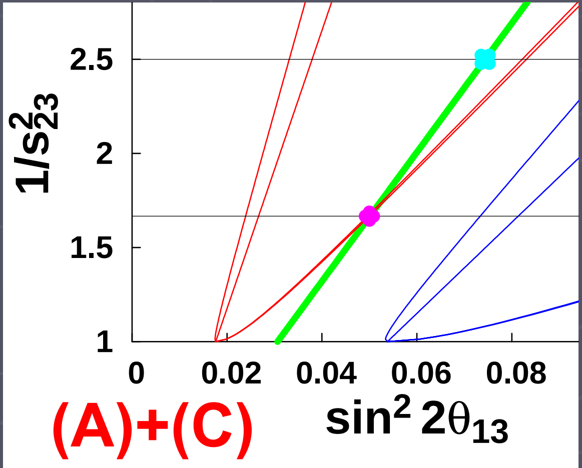
(C) LBL measurement of $\nu_\mu \rightarrow \nu_e$ **(or** $\nu_e \rightarrow \nu_\mu$ **)**

with different L/E

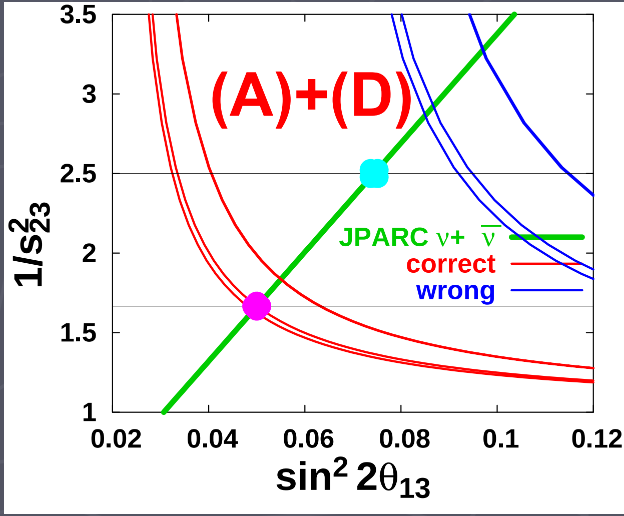
(D) measurement of $\nu_e \rightarrow \nu_\tau$



(A)+(B)



(A)+(C)



(A)+(D)

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**

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

$\nu_\mu \to \nu_e$

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

- **neutrino factory**

μ in a storage ring

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

$\nu_e \to \nu_\mu$

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

- **beta beam**

RI in a storage ring

$$\begin{cases} {}^{6}_{2}\mathrm{He} \to {}^{6}_{3}\mathrm{Li} + e^- + \bar{\nu}_e \\ {}^{18}_{10}\mathrm{Ne} \to {}^{18}_{9}\mathrm{F} + e^+ + \nu_e \end{cases}$$

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

$\nu_e \to \nu_\mu$

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)

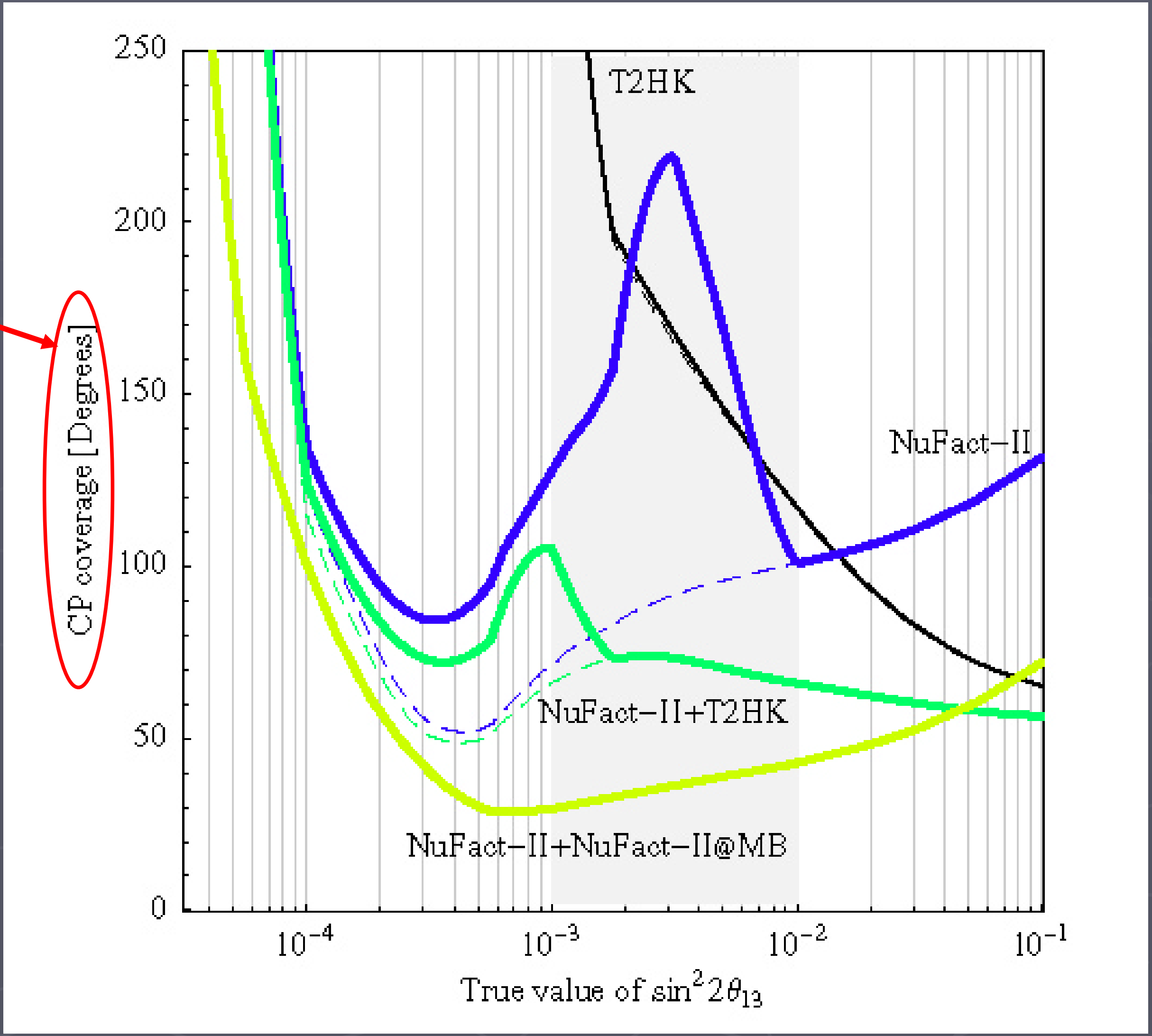
- **neutrino factory** (E_ν<50GeV, L~3000km)
- **beta beam** (E_ν=0.5-1.5GeV, L~130km)

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

Double CHOOZ (France) , Kaska (Kashiwazaki-Kariwa), Braidwood (US), Daya Bay (China), Reno (Korea), Angra (Brazil)

sensitivity to the CP phase δ of future experiments

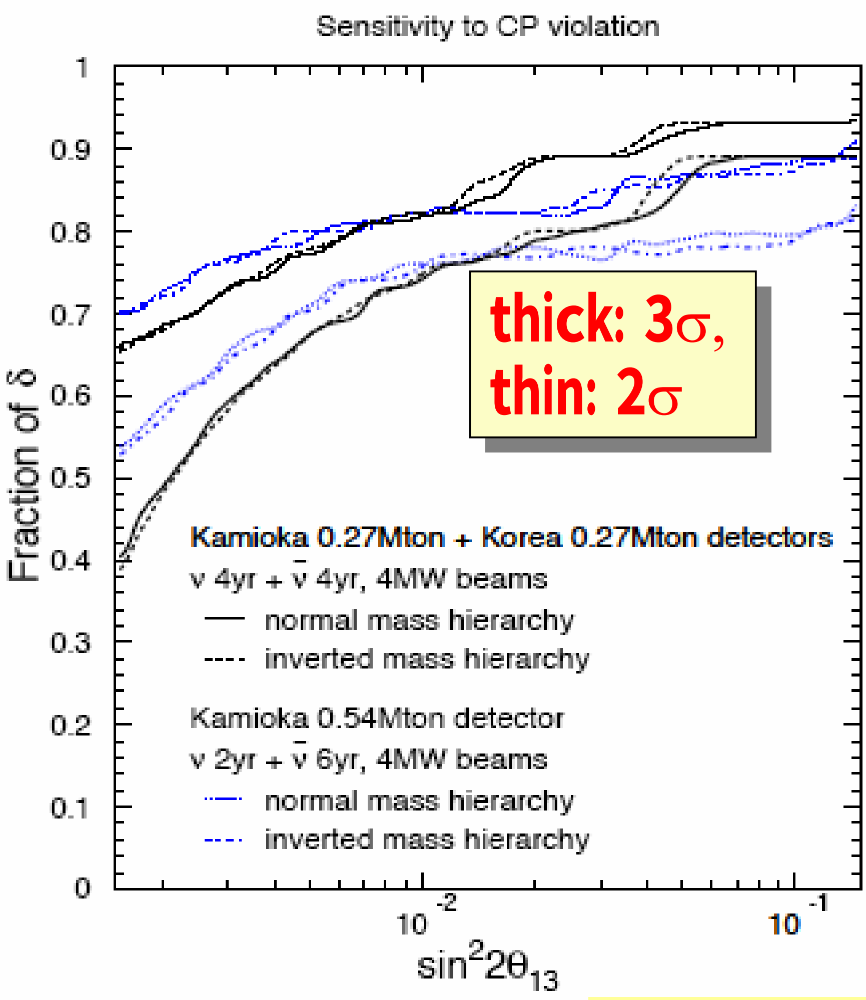
error of δ



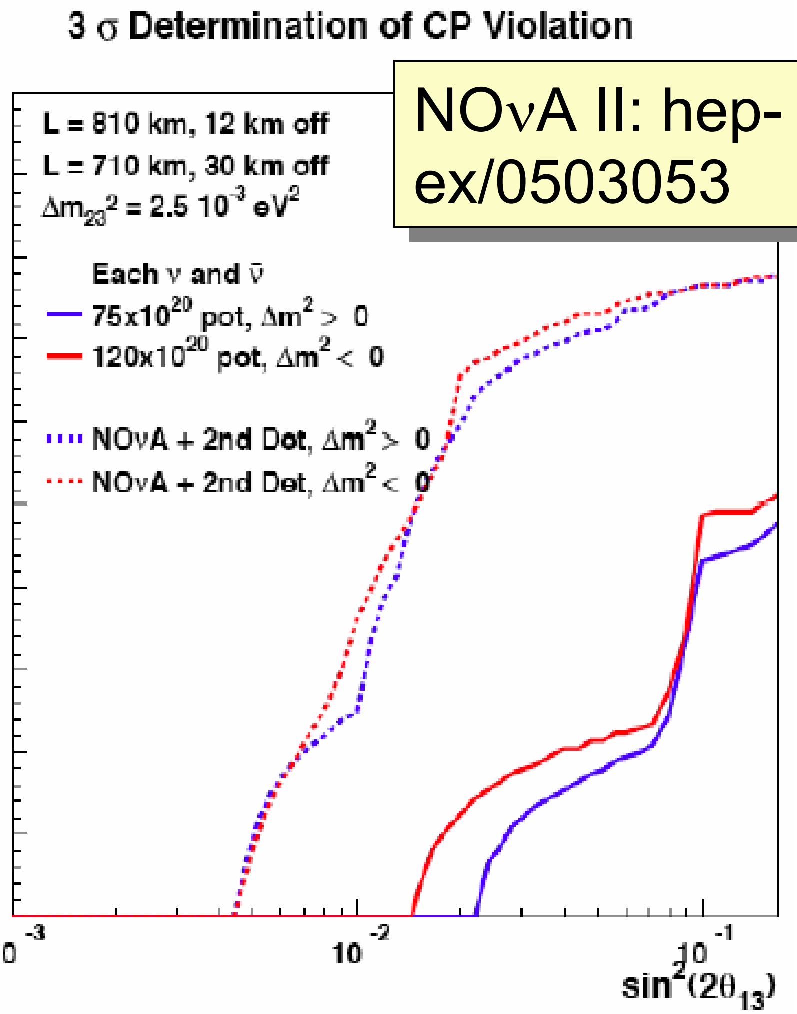
T2HK = Tokai to HyperKamiokande

Huber-Lindner-Winter JHEP 0505:020,2005

T2KK vs. NOνA; CP

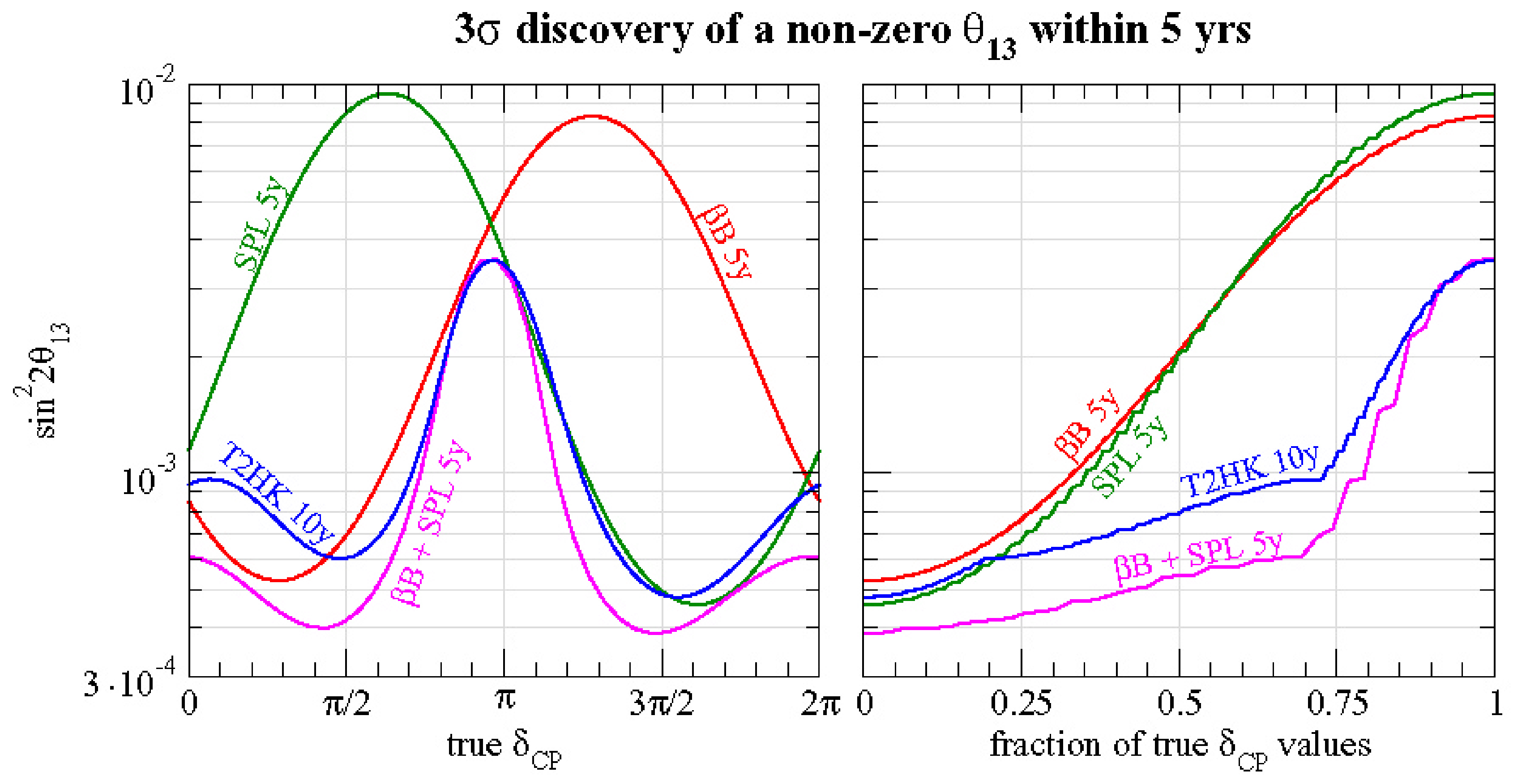


thick: 3σ, thin: 2σ



NOνA II: hep-ex/0503053

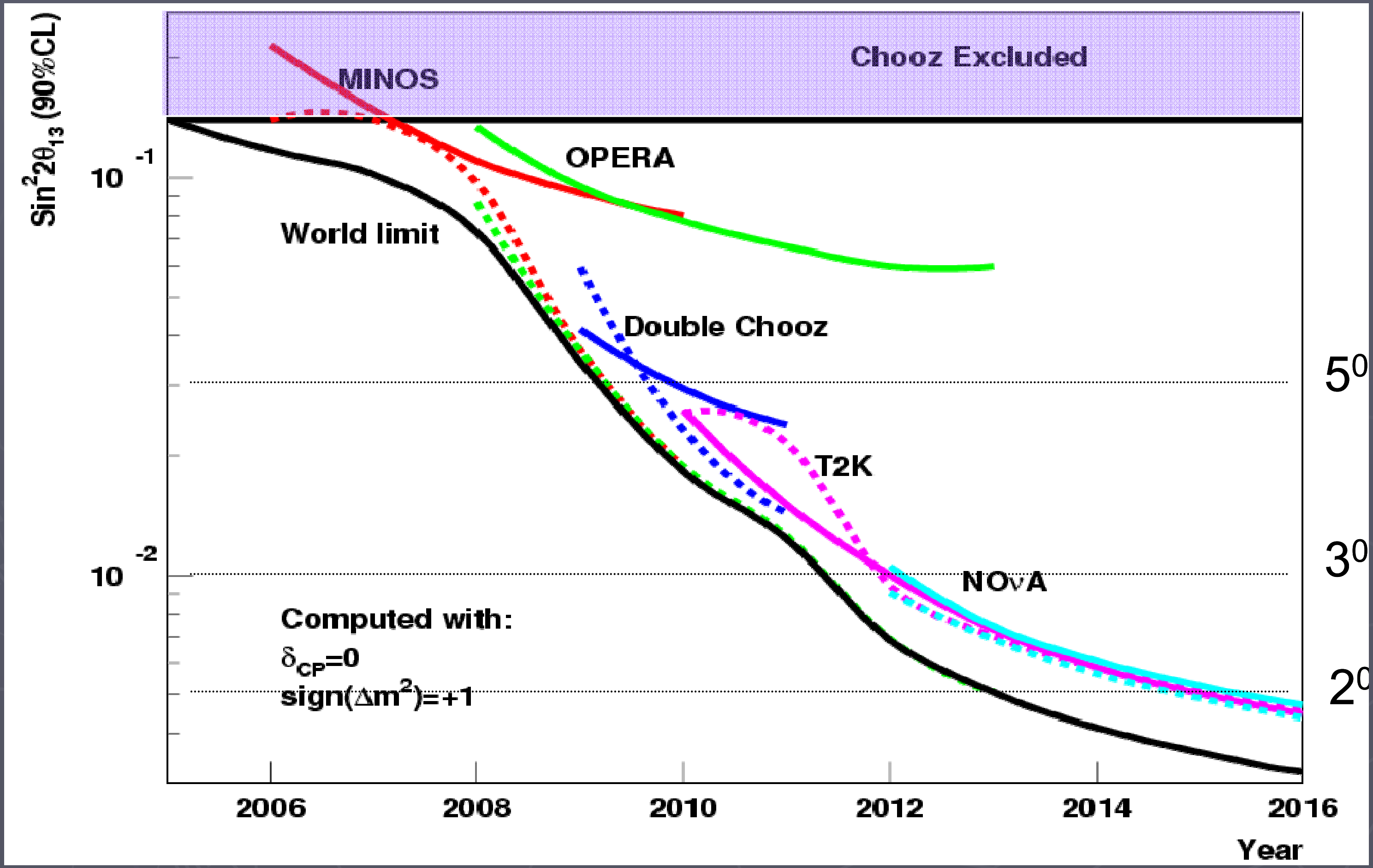
Minakata@2nd T2KK workshop ('06)



J.E. Campagne, M. Maltoni, M. Mezzetto, T. Schwetz, hep-ph/0603172

Expected sensitivity to $\sin^2 2\,\theta_{13}$ of ongoing and near future experiments

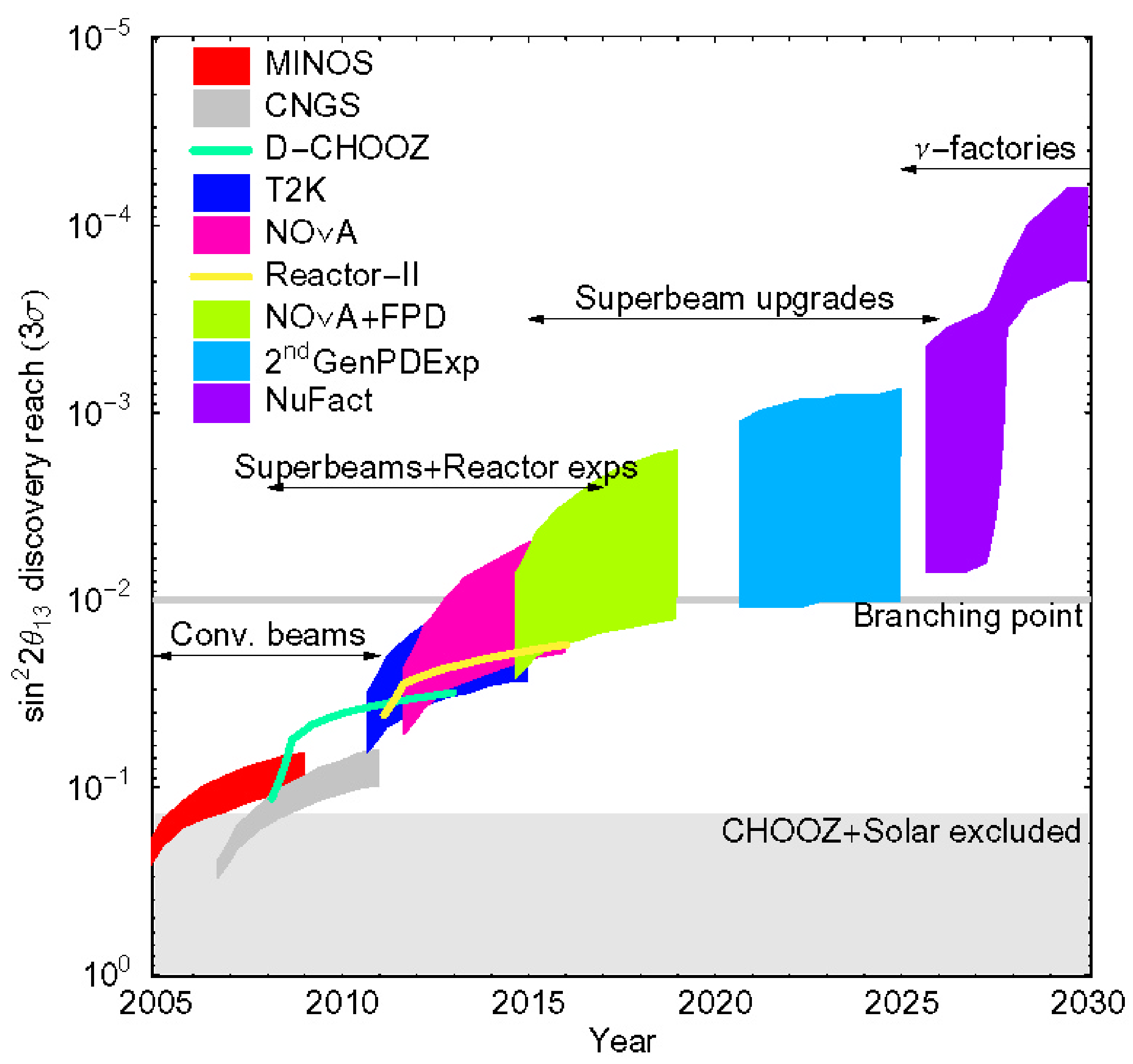
Mezzetto



MINOS(2005-): FNAL → Soudan, E_ν~4GeV, L=735km

OPERA(CNGS)(2006-): CERN → Gran Sasso, E_ν~17GeV, L=732km

“Physics at a Fermilab proton driver”, hep-ex/0509019



ν Roadmap (A. Cervera, Geneva Univ.)

1^{st} step: transition era

Ongoing: 2005-2010

- Improve the precision on the atm. parameters looking at ν_μ disappearance
- Confirm (atm. osc) = ($\nu_\mu \rightarrow \nu_\tau$) and first look at $\nu_\mu \rightarrow \nu_e$

Approved/Proposed: 2008-2015

2^{nd} step: θ_{13} era

- Demonstrate visibility of sub-leading transitions: $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_e$
- Explore θ_{13} down to 2^0 (today $<10^0$)

3^{rd} step: precision era

To be prepared: 2015-2025

$\sin^2 2\theta_{13} > 0.01$

$\sin^2 2\theta_{13} < 0.01$

$\theta_{13} > 3^0$ — Known by 2011 — $\theta_{13} < 3^0$

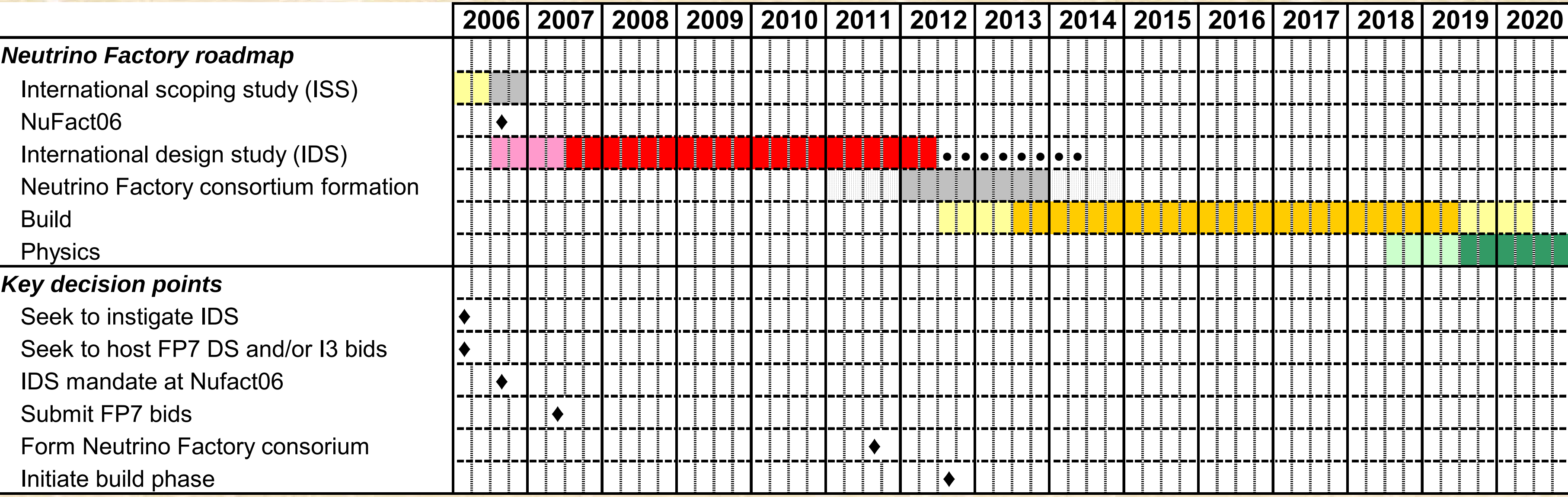
- Existing facilities could reach it
- … but with very small sensitivity to δ_{CP} and mass hierarchy

- No access for ongoing experiments at that time

Cleaner and more intense beams + larger detectors

K.Long

NF roadmap: key decision points



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Neutrino Factory roadmap															
International scoping study (ISS)	🟨🟨▨▨														
NuFact06	◆														
International design study (IDS)	🟪🟪	🟪🟪🟥🟥	🟥🟥🟥🟥	🟥🟥🟥🟥	🟥🟥🟥🟥	🟥🟥🟥🟥	🟥🟥••	••••	••						
Neutrino Factory consortium formation						░░░░	▨▨▨▨	▨▨▨▨	░░░░						
Build							🟨🟨	🟨🟨🟧🟧	🟧🟧🟧🟧	🟧🟧🟧🟧	🟧🟧🟧🟧	🟧🟧🟧🟧	🟧🟧🟧🟧	🟧🟧🟨🟨	🟨🟨
Physics													🟩🟩	🟩🟩■■	■■■■
Key decision points															
Seek to instigate IDS	◆														
Seek to host FP7 DS and/or I3 bids	◆														
IDS mandate at Nufact06	◆														
Submit FP7 bids		◆													
Form Neutrino Factory consorium						◆									
Initiate build phase							◆								

- **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

International scoping study of a future

Neutrino Factory and super-beam facility

Mandate

The international scoping study of a future accelerator neutrino complex will be carried by the international community between NuFact05, Frascati, 21-26 June 2005, and NuFact06. The plan for the scoping study is summarised below. The physics case for the facility will be evaluated and options for the accelerator complex and neutrino detection systems will be studied. The principal objective of the study will be to lay the foundations for a full conceptual-design study of the facility. The plan for the scoping study has been prepared in collaboration by the international community that wishes to carry it out; the ECFA/BENE network in Europe, the Japanese NuFact-J collaboration, the US Muon Collider and Neutrino Factory Collaboration and the UK Neutrino Factory collaboration. CCLRC's Rutherford Appleton Laboratory will be the 'host laboratory' for the study.

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**

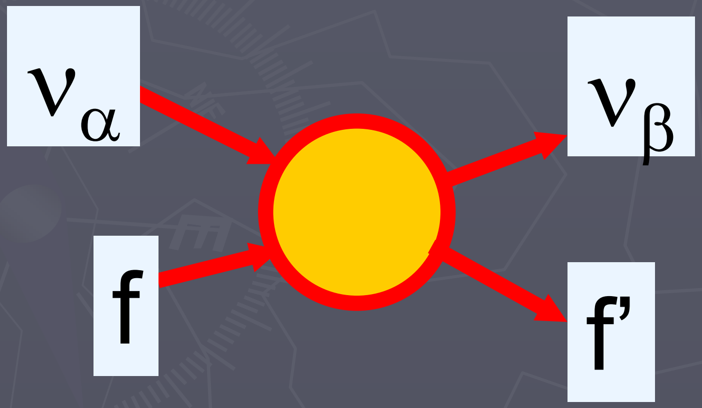
- ◆**Physics Group**
  - ➢**Theory Subgroup**
  - ➢**Phenomenology Subgroup**
  - ➢**Experiment Subgroup**
- ◆**Detector Group**
- ◆**Accelerator Group**

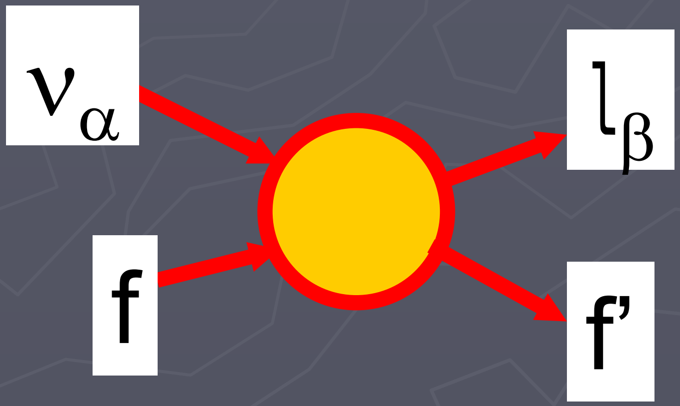
- **Theory Subgroup**
  Model building for neutrino mass & mixing
- **Phenomenology Subgroup**
  Deviation from SM with massive neutrinos
- **Experiment Subgroup**
  Estimation of sensitivity and resolution of degeneracy for ν factories and β beams

Deviation from SM which has been discussed at Phenomenology Subgroup

1. Check of unitarity (like at a B factory)
2. Study of new physics (NP) (exotic interactions)

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





(1) Check of unitarity

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, hep-ph/0607020

- Assume new physics at $\Lambda >> v$. In the flavor basis, generically

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

$$L = i\sum_{\alpha,\beta}\overline{\nu_\alpha}\,\not\partial K_{\alpha\beta}\nu_\beta - \sum_{\alpha,\beta}\overline{\nu_\alpha}\,M_{\alpha\beta}\nu_\beta$$

$$-\sum_{\alpha}\frac{g}{\sqrt{2}}\left(W^+_\mu\overline{l_a}\gamma^\mu P_L\nu_\alpha + h.c\right) - \sum_{\alpha}\frac{g}{c_W}\left(Z_\mu\overline{\nu_\alpha}\gamma^\mu P_L\nu_\alpha + h.c\right) + \dots$$

↳ $\nu_\alpha(x) = \sum_i N_{\alpha i}\nu_i(x)$

- $$\mathrm{L} = \sum_i \overline{\nu_i}(i\not\partial - m_i)\nu_i - \sum_{\alpha,i}\frac{g}{\sqrt{2}}\left(W^+_\mu\overline{l_a}\gamma^\mu P_L N_{\alpha i}\nu_i + h.c\right)$$

$$-\sum_i\frac{g}{c_W}\left(Z_\mu\overline{\nu_i}\gamma^\mu P_L\left(N^\dagger N\right)_{ij}\nu_j + h.c\right) + \dots$$

↳ $\langle \nu_i | \nu_j \rangle = \delta_{ij}$ $\quad$ $\mathrm{NN}^+ \neq 1$ $\quad$ $\langle \nu_\beta | \nu_\alpha \rangle \neq \delta_{\alpha\beta}$

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, hep-ph/0607020

Mixing Matrix from oscillations and rare decays (3σ)

$W \to l_\alpha \nu$ $\quad Z \to$ invisible $\quad$ rare lepton decays

universality tests

With unitarity

[M. C. Gonzalez Garcia hep-ph/0410030]

$$|U|^2 = \begin{pmatrix} 0.62-0.77 & 0.22-0.37 & <0.04 \\ 0.04-0.27 & 0.18-0.53 & 0.34-0.67 \\ 0.04-0.28 & 0.19-0.55 & 0.31-0.66 \end{pmatrix}$$

Without unitarity

$$|N|^2 = \begin{pmatrix} 0.57-0.79 & 0.21-0.43 & <0.04 \\ 0.04-0.30 & 0.17-0.53 & 0.33-0.67 \\ 0.01-0.40 & 0.09-0.60 & 0.26-0.68 \end{pmatrix}$$

Lopez: ISS 3rd plenary ('06) @ RAL Preliminary

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, hep-ph/0607020

The L=0 effect

$$P(\nu_\alpha \to \nu_\beta, L=0) = \left|\sum_i N_{\alpha i} N^*_{\beta i}\right|^2$$

PRESENT

KARMEN

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

$$\left|\sum_i N_{\mu i} N^*_{ei}\right| < 0.05$$

NOMAD

$$\nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_\tau$$

$$\left|\sum_i N_{ei} N^*_{\tau i}\right| < 0.09$$

$$\left|\sum_i N_{\mu i} N^*_{\tau i}\right| < 0.013$$

FROM DECAYS

$$\mu \to e\gamma$$

$$\left|\sum_i N_{\mu i} N^*_{ei}\right| < 7.2 \cdot 10^{-5}$$

$$\tau \to e\gamma \qquad \tau \to \mu\gamma$$

$$\left|\sum_i N_{ei} N^*_{\tau i}\right| < 0.016$$

$$\left|\sum_i N_{\mu i} N^*_{\tau i}\right| < 0.013$$

FUTURE@NF

40kt Iron cal

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

$$\left|\sum_i N_{\mu i} N^*_{ei}\right| < 2.3 \cdot 10^{-4}$$

4kt OPERA (100 m)

$$\nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_\tau$$

$$\left|\sum_i N_{ei} N^*_{\tau i}\right| < 2.9 \cdot 10^{-3}$$

$$\left|\sum_i N_{\mu i} N^*_{\tau i}\right| < 2.6 \cdot 10^{-3}$$

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

Models which predict non-unitarity include:

Czakon, Gluza, Zralek, Acta Phys. Polon. B32 (2001) 3735;
Bekman, Gluza, Holeczek, Syska Zralek, Phys. Rev. D66 (2002) 093004;
Langacker, London, Phys. Rev. D 38 (1988) 907;
Bilenky, Giunti, Phys. Lett. B300 (1993) 137;
Nardi, Roulet, Tommasini, Phys. Lett. B327 (1994) 319;
Bergmann, Kagan, Nucl. Phys. B538 (1999) 368;
Loinaz, Okamura, Takeuchi, Wijewardhana, Phys. Rev. D67, 073012 (2003);
Loinaz, Okamura, Rayyan, Takeuchi, Wijewardhana,
Phys. Rev. D68, 073001 (2003); Phys. Rev. D70, 113004 (2004);
Broncano, Gavela, Jenkins, Phys. Lett. B552 (2003) 177;
De Gouvea, Giudice, Strumia, Tobe, Nucl. Phys. B623 (2002) 395.

(2) Study of New Physics

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

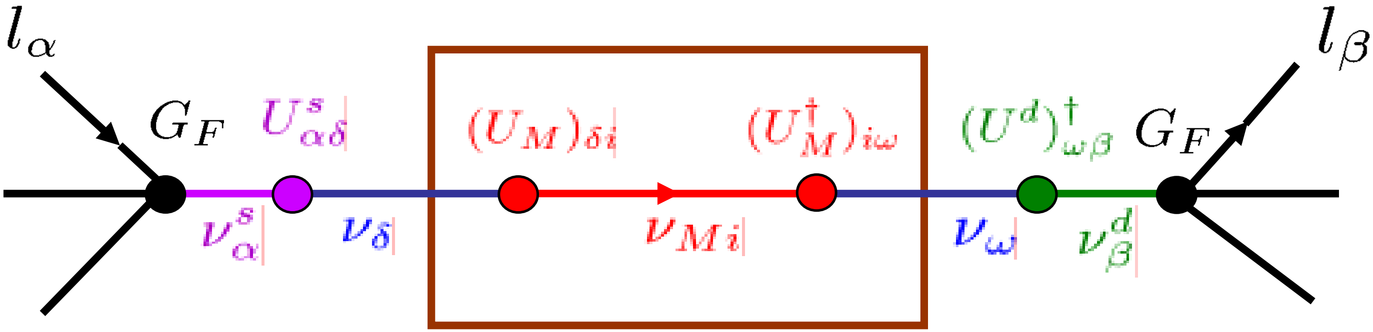
$$P(\nu_\alpha \to \nu_\beta) = \left|\left[\boxed{U^d}\,\boxed{\tilde U}\,\boxed{\exp\{-i\,\mathrm{diag}(\tilde E_j)L\}}\,\boxed{\tilde U^{-1}}\,\boxed{(U^s)^{-1}}\right]_{\beta\alpha}\right|^2$$

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

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

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

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



In general:

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

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

i.e., no BG from osc. in the limit of L → 0

⇒ Experiments with a shorter baseline are advantageous

NP effects in propagation becomes important when L is larger

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

⇒ Experiments with a longer baseline are advantageous

Works which discussed NP in ν oscillation include:

Grossman, Phys. Lett. B359, 141 (1995);
Gonzalez-Garcia, Grossman, Gusso, Nir, Phys. Rev. D64, 096006 (2001);
Gago, Guzzo, Nunokawa, Teves, Zukanovich Funchal, Phys. Rev. D64, 073003 ('01);
Ota, Sato, Yamashita, Phys. Rev. D65, 093015 (2002);
Huber, Schwetz, Valle, Phys. Rev. Lett. 88, 101804 (2002);
Campanelli, Romanino, Phys. Rev. D66, 113001 (2002);
Huber, Schwetz, Valle, Phys. Rev. D66, 013006 (2002);
Ota, Sato, Phys. Lett. B545, 367 (2002);
Ota, Sato, Phys. Rev. D71, 096004 (2005);
Blennow, Ohlsson, Winter, hep-ph/0508175;
Honda, Okamura, Takeuchi, hep-ph/0603268；
Kitazawa, Sugiyama, OY, hep-ph/0606013；
Friedland, Lunardini, hep-ph/0606101;
Ota et al, "Discovery Reach for Non-Standard Interactions in a Neutrino Factory", (to appear).

Models which predict relatively large NP effect include:

Grossman (Randall-Sundrum model), ISS 1st Physics Workshop @Imperial Coll.: http://www.hep.ph.ic.ac.uk/~longkr/UKNF/Scoping-study/ISS-www-site/WG1-PhysPhen/Workshops/2005-11/Programme/Talks/iss-london-yuvalg.pdf

A recent work which discussed NP effects in propagation

Kitazawa, Sugiyama, OY, hep-ph/0606013

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

Two constraints on $\varepsilon_{\alpha\beta}$

① **Davidson et al (JHEP 0303:011,2003):** Constraints from various ν experiments

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

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

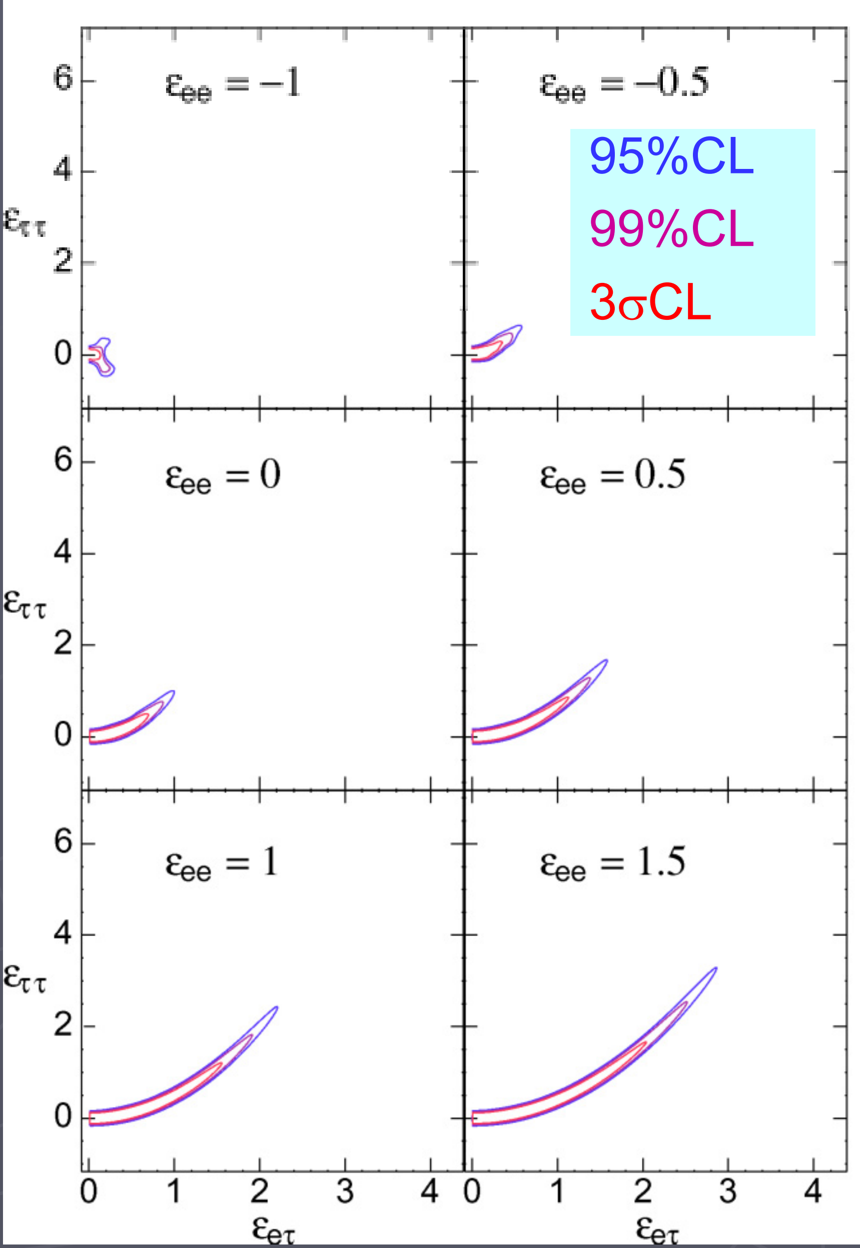
②**Friedland-Lunardini** (Phys.Rev.D72:053009,2005): Constraints from atmospheric neutrinos

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

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

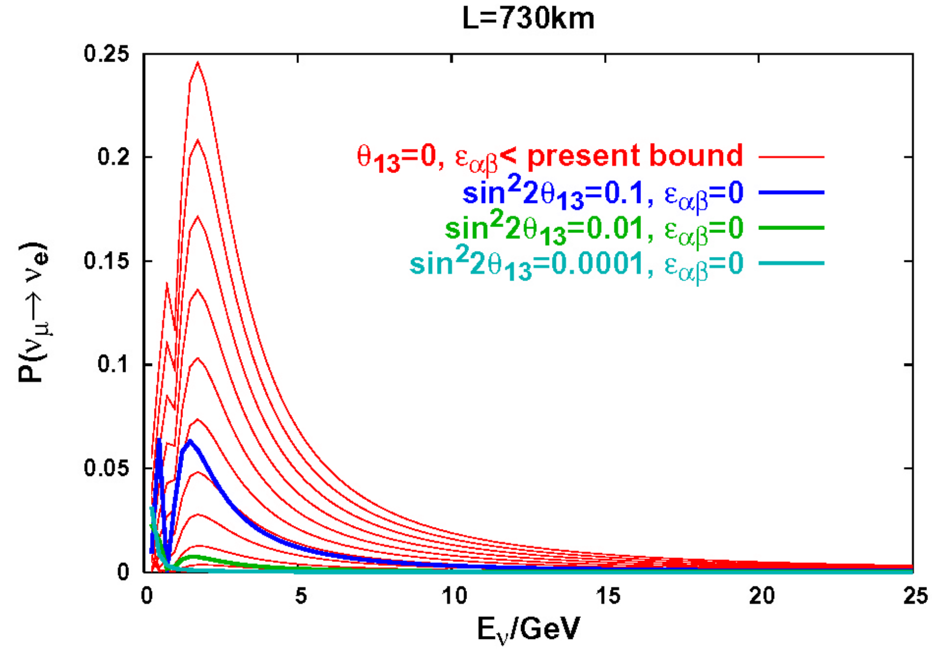
$$-1 \lesssim \epsilon_{ee} \lesssim 1.5$$

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ ~O(1) are consistent with atmospheric neutrino data



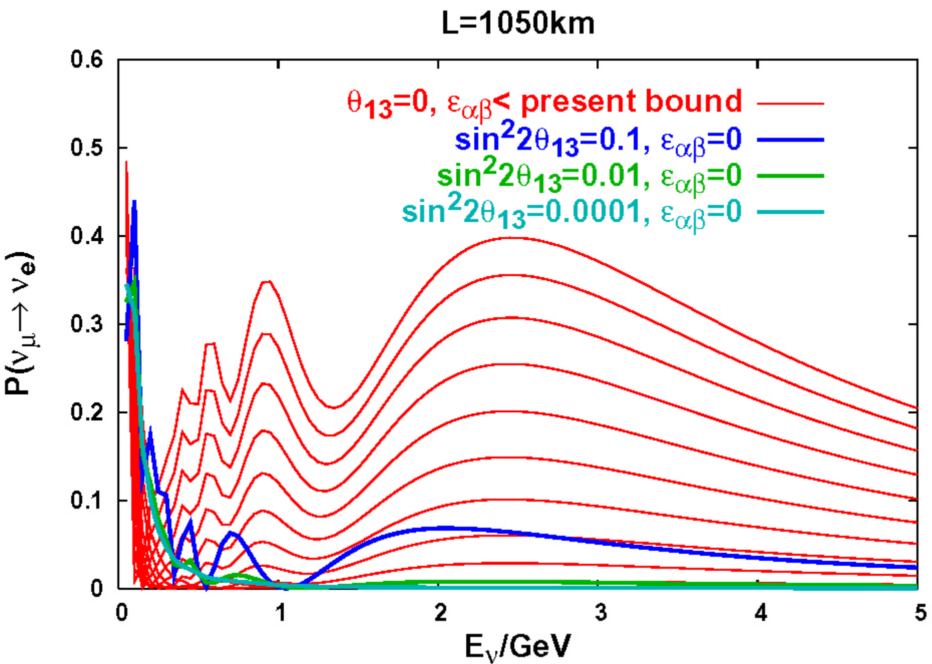
MINOS (ν_e appearance)

$\nu_\mu \to \nu_e$



T2KK (ν_e appearance)

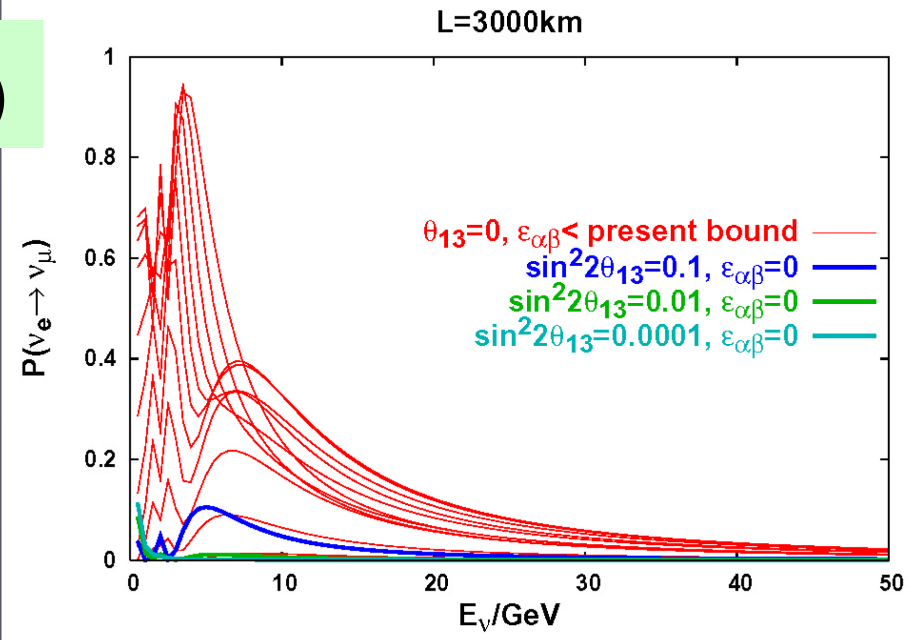
$\nu_\mu \to \nu_e$



NK,HS,OY, hep-ph/0606013

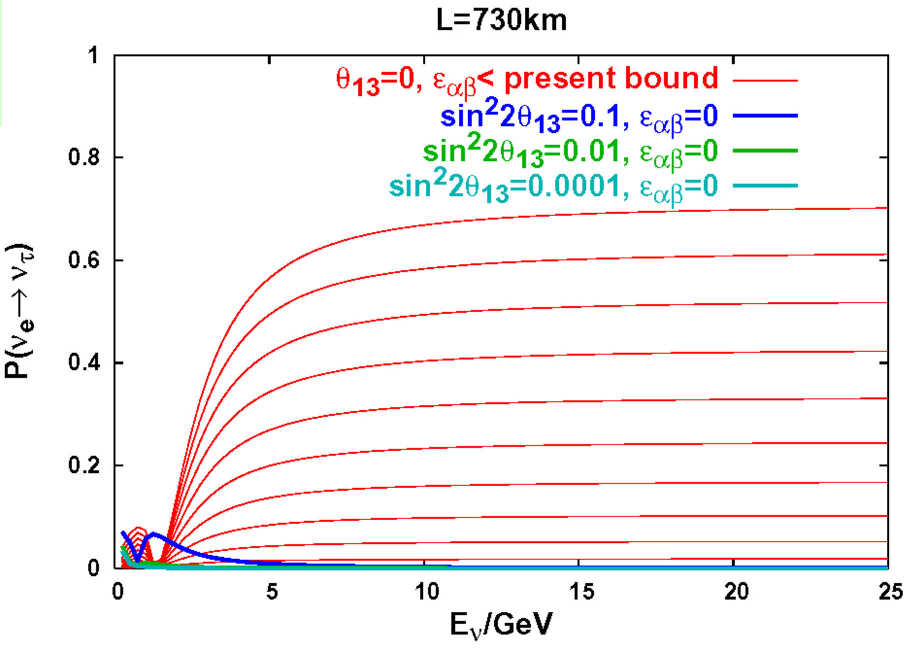
ν factory (golden channel)

$\nu_e \rightarrow \nu_\mu$



ν factory (silver channel)

$\nu_e \rightarrow \nu_\tau$



NK,HS,OY, hep-ph/0606013

In the final ISS report, due to time constraint, only qualitative discussions on deviation from SM+massive ν will be given.

There are a lot of problems to be worked out:

- **Quantitative discussions on non-unitarity and the NP effects**
- **Predictions of various models on deviation from SM+massive ν**

→ Predictions by theorists could change plans of ν experiments in the far future dramatically.

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.
- Like B factories, the future neutrino experiments with high precision will be able to see deviation from SM, and it is emphasized that theorists should make efforts to predict possible deviations of various models from SM.