Physics Potential of VLBL ν-oscillation expts with KEK-JAERI High Intensity Proton Accelerator

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based on the report made by

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1. Can we distinguish the neutrino mass hierarchy cases?

2. Can we distinguish the solar-neutrino oscillation scenarios? (δm^2_{SOL}, $\sin^2 2\theta_{SOL}$)

3. Can we measure the two unknown parameters $\sin^2 2\theta_{CHOOZ}$, δ_{MNS}?

4. Can we improve the measurements of δm^2_{ATM}, $\sin^2 2\theta_{ATM}$?

3 neutrino model (with Majorana masses) have

3 masses m_1, m_2, m_3

3 angles θ_{12}, θ_{23}, θ_{31}

3 phases δ_{MNS}, φ_2, φ_3

Neutrino oscillation experiments can measure

2 mass-squared differences $\delta m_{12}^2 = m_2^2 - m_1^2$, $\delta m_{13}^2 = m_3^2 - m_1^2$

3 angles θ_{12}, θ_{23}, θ_{31}

1 phase δ_{MNS}

The present experiments constrain

2 mass-squared differences $|\delta m_{13}^2| = \delta m^2_{ATM}$ 3×10^{-3} ○

$\delta m_{12}^2 = \delta m^2_{SOL}$ 1×10^{-4} / 5×10^{-6} △ LMA or SMA

3 angles $4|U_{\mu3}|^2(1-|U_{\mu3}|^2) = \sin^2 2\theta_{ATM}$ ~ 1 ○

$4|U_{e2}|^2(1-|U_{e2}|^2) \cong \sin^2 2\theta_{SOL}$ ~ 0.8 / ~ 0.002 △ LMA or SMA

$4|U_{e3}|^2(1-|U_{e3}|^2) = \sin^2 2\theta_{CHOOZ}$ $\lesssim 0.1$ ×

Goals of the future neutrino oscillation expts

	22kt 300km	100kt 2100km
Precise measurements of $|\delta m_{13}^2|$, $\sin^2 2\theta_{ATM}$	○	○
Dascrimination of SOL scenarios: δm^2_{SOL}, $\sin^2 2\theta_{SOL}$		△ LMA or not
Measurements of $\sin^2 2\theta_{CHOOZ}$	○	○
sign of δm_{13}^2		◎
(Test of MSW) sign of δm_{12}^2		△ LMA
δ_{MNS}	△ 1,000kt ◎	△ LMA

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

Parametrization of ~~the~~ MNS matrix $\qquad V_{MNS}$ vs V_{CKM}

$$V_{MNS} = \begin{pmatrix} U_{e1} & \underline{U_{e2}} & \underline{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & \underline{U_{\mu 3}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}1 & & \\ & e^{i\varphi_2} & \\ & & e^{i\varphi_3}\end{pmatrix}$$

2 Majorana phases

The matrix $U_{\alpha i}$ has 3 real angles and 1 phase just like V_{CKM}.

fixed by $U_{e2} > 0$, $U_{\mu 3} > 0$

We choose $\underline{U_{e2}} \geqslant 0$, $\underline{U_{\mu 3}} \geqslant 0$, $U_{e3} = \underline{|U_{e3}|}\, e^{i\varphi_1}$ $\qquad \boxed{\varphi_1 = -\delta_{MNS}}$

as our 4-independent parameters of $U_{\alpha i}$.

cf. L. Wolfenstein, PRL 51, 1945 (1983)
M. Kobayashi, Prog. Th. Phys. 92, 287 (1984)
★ KH + N. Okamura, NPB 548, 60 (1999)

All the other elements are then determined by the unitarity condition:

$$\begin{aligned}
U_{e1} &= \sqrt{1-|U_{e3}|^2-|U_{e2}|^2} && >0 \text{ by convention}\\
U_{\tau 3} &= \sqrt{1-|U_{e3}|^2-|U_{\mu 3}|^2} && >0 \quad \text{"}\\
U_{\mu 1} &= -(U_{e2}U_{\tau 3}+U_{\mu 3}U_{e1}U_{e3}^*)/(1-|U_{e3}|^2)\\
U_{\mu 2} &= (U_{e1}U_{\tau 3}-U_{\mu 3}U_{e2}U_{e3}^*)/(1-|U_{e3}|^2)\\
U_{\tau 1} &= (U_{e2}U_{\mu 3}-U_{\tau 3}U_{e1}U_{e3}^*)/(1-|U_{e3}|^2)\\
U_{\tau 2} &= -(U_{\mu 3}U_{e1}+U_{e2}U_{\tau 3}U_{e3}^*)/(1-|U_{e3}|^2)
\end{aligned}$$

Neutrino oscillation experiments measure only $U_{\alpha i}$, not $\underbrace{\varphi_2 \,\&\, \varphi_3}_{0\nu\beta\beta \text{ decays}}$.

$$\begin{aligned}
P_{\nu_\alpha\to\nu_\beta} &= \left|\sum_{j=1}^{3}(V_{MNS})_{\beta j}\, e^{-i\frac{m_j^2}{2E}L}\,(V_{MNS}^\dagger)_{j\alpha}\right|^2\\
&= \left|\sum_{j=1}^{3} U_{\beta j}\, e^{-i\frac{m_j^2}{2E}L}\, U_{\alpha j}^*\right|^2
\end{aligned}$$

$\cancel{CP} + \cancel{L}$

$\Rightarrow$ Leptogenesis

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$$P_{\nu_\alpha\to\nu_\alpha} = \left| U_{\alpha 1} U_{\alpha 1}^* + U_{\alpha 2} e^{-i\frac{\delta m_{12}^2}{2E}L} U_{\alpha 2}^* + U_{\alpha 3} e^{-i\frac{\delta m_{13}^2}{2E}L} U_{\alpha 3}^* \right|^2$$

$$\delta m_{12}^2 \ll \delta m_{13}^2 \sim 3\cdot 10^{-3}\,eV^2$$

$\sim 10^{-5}\,eV^2$ MSW

or $\sim 10^{-10}\,eV^2$ VO

$$P(\nu_\mu\to\nu_\mu) \longrightarrow 1 - \underbrace{\boxed{4\,|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)}}_{\sin^2 2\theta_{ATM}} \sin^2\left(\frac{\overbrace{\delta m_{13}^2}^{\delta m^2_{ATM}}}{4E}L\right)$$

for Atmospheric ν

$\alpha = \mu$

$$\frac{\delta m_{12}^2}{2E}L \ll \frac{\delta m_{13}^2}{2E}L \sim 1 \quad \begin{pmatrix} L \sim 10^4\,km \\ E \sim 1\,GeV \end{pmatrix}$$

$$P(\bar\nu_e\to\bar\nu_e) \longrightarrow 1 - \underbrace{\boxed{4\,|U_{e3}|^2(1-|U_{e3}|^2)}}_{\sin^2 2\theta_{CHOOZ}} \sin^2\left(\frac{\overbrace{\delta m_{13}^2}^{\delta m^2_{ATM}}}{4E}L\right)$$

for CHOOZ ($\alpha = e$)

$$\frac{\delta m_{12}^2}{2E}L \ll \frac{\delta m_{13}^2}{2E}L \sim 1 \quad \begin{pmatrix} L \sim 1\,km \\ E \sim 10^{-3}\,GeV \end{pmatrix}$$

$$P(\nu_e\to\nu_e) \longrightarrow 1 - \underbrace{\boxed{2\,|U_{e3}|^2(1-|U_{e3}|^2)}}_{\frac{1}{2}\sin^2 2\theta_{CHOOZ}} - \underbrace{\boxed{4\,|U_{e1}|^2|U_{e2}|^2}}_{\sin^2 2\theta_{SOL}} \sin^2\left(\frac{\overbrace{\delta m_{12}^2}^{\delta m^2_{SOL}}}{4E}L\right)$$

$$|U_{e1}|^2 \to 1-|U_{e2}|^2-|U_{e3}|^2$$

for Solar ν ($\alpha = e$)

$$\begin{matrix} \text{VO} & 1 \sim \\ \text{MSW} & 1 \ll \end{matrix} \; \frac{\delta m_{12}^2}{2E}L \ll \frac{\delta m_{13}^2}{2E}L \quad \begin{pmatrix} L \sim 10^8\,km \\ E \sim 10^{-3}\text{-}10^{-2}\,GeV \end{pmatrix}$$

$$V_{MNS} = \begin{pmatrix} \cdot & U_{e2} & U_{e3} \\ \cdot & \cdot & U_{\mu 3} \\ \cdot & \cdot & \cdot \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\varphi_2} & \\ & & e^{i\varphi_3} \end{pmatrix}$$

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Brief summary of the present neutrino oscillation expts.

Moriond'01

- Atmospheric-neutrino anomaly

$$\begin{cases} \sin^2 2\theta_{ATM} = (0.7 \sim 1.0) \\ \delta m^2_{ATM} = (2 \sim 5) \times 10^{-3}\, eV^2 \end{cases}$$

SK: 1250~1290 days
$(0.88 \sim 1)$
$(1.6 \sim 4) \times 10^{-3}$
90%CL

- Solar-neutrino deficit

LMA : $\begin{cases} \sin^2 2\theta_{SOL} = (0.42 \sim 0.74) \\ \delta m^2_{SOL} = (3 \sim 15) \times 10^{-5}\, eV^2 \end{cases}$

SMA : $\begin{cases} \sin^2 2\theta_{SOL} = (3 \sim 11) \times 10^{-3} \\ \delta m^2_{SOL} = (4 \sim 12) \times 10^{-6}\, eV^2 \end{cases}$

VO : $\begin{cases} \sin^2 2\theta_{SOL} = (0.7 \sim 1.0) \\ \delta m^2_{SOL} = (6 \sim 11) \times 10^{-11}\, eV^2 \end{cases}$

SK: 1258 days
LMA: $(0.7 \sim 1)$, $(4 \sim 16) \times 10^{-5}$
SMA: $(2 \sim 2.5) \times 10^{-3}$, $(4 \sim 6) \times 10^{-6}$
VO: ~ 1, $\sim 65 \times 10^{-11}$

- CHOOZ experiment

$$\sin^2 2\theta_{CHOOZ} < 0.18 \quad \text{for} \quad \delta m^2_{CHOOZ} = 2.0 \times 10^{-3}\, eV^2$$
$$\text{〃} < 0.10 \quad \text{for} \quad \delta m^2_{CHOOZ} = 3.5 \times 10^{-3}\, eV^2$$
$$\text{〃} < 0.06 \quad \text{for} \quad \delta m^2_{CHOOZ} = 5.0 \times 10^{-3}\, eV^2$$

- LSND experiment

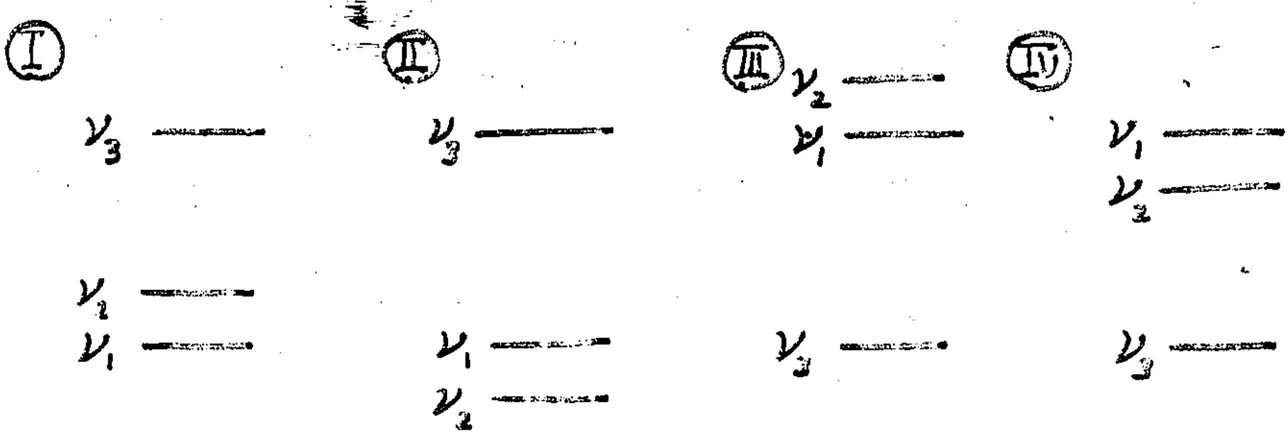
Note on the mass-hierarchy and $0\nu\beta\beta$ experiment.

So far the ν-oscillation experiments measure only those terms which are proportional to

$$\sin^2\left(\underbrace{\frac{m_j^2-m_i^2}{2E}}_{\equiv \Delta_{ij}} L \times \frac{1}{2}\right)$$

Therefore, we do not yet know the ordering of the masses.

There are, in principle, 4 possible mass hierarchies :



	I	II	III	IV
δm_{12}^2	δm^2_{SOL}	$-\delta m^2_{SOL}$	δm^2_{SOL}	$-\delta m^2_{SOL}$
δm_{13}^2	δm^2_{ATM}	δm^2_{ATM}	$-\delta m^2_{ATM}$	$-\delta m^2_{ATM}$

disfavored for MSW solutions

Mass-ordered mass-eigenstates $\quad m(\nu_1') < m(\nu_2') < m(\nu_3')$

Oscillation-based mass-eigenstates $\quad \nu_1, \nu_2, \nu_3$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underset{\text{'correct' MNS matrix}}{V'_{MNS}} \begin{pmatrix}\nu_1'\\ \nu_2'\\ \nu_3'\end{pmatrix} = \underset{\text{'convenient' MNS matrix}}{V_{MNS}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$V'_{MNS} \equiv U'_{MNS} \begin{pmatrix} 1 & & \\ & e^{i\varphi_2} & \\ & & e^{i\varphi_3} \end{pmatrix} \equiv U'_{MNS}\ P'$$

$$V'_{MNS} = V_{MNS}\, O \qquad \text{where} \qquad \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = O \begin{pmatrix} \nu_1' \\ \nu_2' \\ \nu_3' \end{pmatrix}$$

$$O^{I} = \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix},\ O^{II} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},\ O^{III} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}\ \ O^{IV} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\begin{aligned} V_{MNS} &= V'_{MNS}\, O^T \\ &= U'_{MNS}\ P' O^T \\ &= \underbrace{U'_{MNS} O^T}_{U_{MNS}}\ \underbrace{O P' O^T}_{P} \\ &= U_{MNS}\ \ P \end{aligned}$$

$$P^{I} = P' = \begin{pmatrix} 1 & & \\ & e^{i\varphi_2} & \\ & & e^{i\varphi_3} \end{pmatrix},\ P^{II} = \begin{pmatrix} e^{i\varphi_2} & & \\ & 1 & \\ & & e^{i\varphi_3} \end{pmatrix},\ P^{III} = \begin{pmatrix} e^{i\varphi_1} & & \\ & e^{i\varphi_3} & \\ & & 1 \end{pmatrix},\ P^{IV} = \begin{pmatrix} e^{i\varphi_3} & & \\ & e^{i\varphi_2} & \\ & & 1 \end{pmatrix}$$

Oscillation expt's don't distinguish diagonal phase matrices P :

How about $0\nu\beta\beta$?

$$\begin{aligned} \langle m \rangle &= \left| \sum_{i=1}^{3} (V'_{MNS})^2_{ei}\ m_i' \right| \\ &= \left| \sum_{i=1}^{3} (U')^2_{ei}\ P_i'^2\, m_i' \right| \\ &= \left| \sum_{i=1}^{3} (U O)^2_{ei}\ P_i'^2\, m_i' \right| \end{aligned}$$

We find :

$$\langle m\rangle_{I} = \left| U_{e1}^2 m_0 + U_{e2}^2 e^{2i\varphi_2}\sqrt{m_0^2+\delta m^2_{SOL}} + U_{e3}^2 e^{2i\varphi_3}\sqrt{m_0^2+\delta m^2_{ATM}} \right|$$

$$\langle m\rangle_{II} = \left| U_{e2}^2 m_0 + U_{e1}^2 e^{2i\varphi_2}\sqrt{m_0^2+\delta m^2_{SOL}} + U_{e3}^2 e^{2i\varphi_3}\sqrt{m_0^2+\delta m^2_{SOL}+\delta m^2_{ATM}} \right|$$

$$\langle m\rangle_{III} = \left| U_{e3}^2 m_0 + U_{e1}^2 e^{2i\varphi_2}\sqrt{m_0^2+\delta m^2_{ATM}} + U_{e2}^2 e^{2i\varphi_3}\sqrt{m_0^2+\delta m^2_{SOL}+\delta m^2_{ATM}} \right|$$

$$\langle m\rangle_{IV} = \left| U_{e3}^2 m_0 + U_{e2}^2 e^{2i\varphi_2}\sqrt{m_0^2+\delta m^2_{ATM}-\delta m^2_{SOL}} + U_{e1}^2 e^{2i\varphi_3}\sqrt{m_0^2+\delta m^2_{ATM}} \right|$$

Since in our notation $\quad [\varphi_1 \equiv -\delta_{MNS}]$

$$U_{e3}^2 = |U_{e3}|^2 e^{2i\varphi_1}, \quad U_{e2}>0,\ U_{e3}>0$$

the $0\nu\beta\beta$ expt constrains the following two phases :

$$\begin{cases} \text{I \& II} & \varphi_2 \quad \text{and} \quad \varphi_1+\varphi_3 \\ \text{III \& IV} & \varphi_2-\varphi_1 \quad \text{and} \quad \varphi_3-\varphi_1 \end{cases}$$

If we write the above two phases as α & β, all the above expressions have the generic form

$$\langle m\rangle = \left| A + Be^{2i\alpha} + Ce^{2i\beta} \right| \quad ; A, B, C > 0$$

and hence

$$\max\{A-B-C,\ 0\} < \langle m\rangle < A+B+C$$

Cases I, II and III, IV have different behaviors.

ν- oscillation in the vacuum

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \Big\{ \mathrm{Re}[U_{\alpha 1} U^*_{\beta 1} U_{\beta 2} U^*_{\alpha 2}] \sin^2 \frac{\Delta_{12}}{2}$$
$$+ \mathrm{Re}[U_{\alpha 2} U^*_{\beta 2} U_{\beta 3} U^*_{\alpha 3}] \sin^2 \frac{\Delta_{13} - \Delta_{12}}{2}$$
$$+ \mathrm{Re}[U_{\alpha 3} U^*_{\beta 3} U_{\beta 1} U^*_{\alpha 1}] \sin^2 \frac{\Delta_{13}}{2} \Big\}$$
$$+ 2\, \mathrm{Im}[U_{\alpha 1} U^*_{\beta 1} U_{\beta 2} U^*_{\alpha 2}] [\sin \Delta_{12} + \sin(\Delta_{13} - \Delta_{12}) - \sin \Delta_{13}]$$
$$\longrightarrow \delta_{\alpha\beta} + 4 \sin^2 \frac{\Delta_{13}}{2} \Big\{ |U_{\alpha 3}|^2 (|U_{\beta 3}|^2 - \delta_{\alpha\beta}) + \Delta_{12}\, \underbrace{\mathrm{Im}[U_{\alpha 1} U^*_{\beta 1} U_{\beta 2} U^*_{\alpha 2}]}_{= J \text{ if } (\alpha,\beta) = (e,\mu), (\mu,\tau), (\tau,e)} \Big\}$$
$$+ 2 \Delta_{12} \sin \Delta_{13}\, \mathrm{Re}[U_{\alpha 2} U^*_{\beta 2} U_{\beta 3} U^*_{\alpha 3}]$$
$$+ O(\Delta_{12}^2)$$

For the four mass-hierarchies we have

$$\begin{pmatrix} \Delta_{12} \\ \Delta_{13} \end{pmatrix} = \begin{pmatrix} \Delta_{SOL} \\ \Delta_{ATM} \end{pmatrix}_{\mathrm{I}} = \begin{pmatrix} -\Delta_{SOL} \\ \Delta_{ATM} \end{pmatrix}_{\mathrm{II}} = \begin{pmatrix} \Delta_{SOL} \\ -\Delta_{ATM} \end{pmatrix}_{\mathrm{III}} = \begin{pmatrix} -\Delta_{SOL} \\ -\Delta_{ATM} \end{pmatrix}_{\mathrm{IV}}$$

Hence if we have the sensitivity to terms of order Δ_{12}

$$|\Delta_{12}| = \Delta_{SOL} = \frac{\delta m^2_{SOL}}{2E} L$$

we can distinguish I, II, III, IV. However Δ_{SOL} is very very small !

$$\Downarrow$$

Matter effects inside the earth !

ν-oscillation in the matter (earth !)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \Big[\underbrace{H_0}_{\substack{\text{vacuum}\\ \text{Hamiltonian}}} + \begin{pmatrix}\overset{(\nu_e e\to\nu_e e)\text{ potential}}{a} & & \\ & 0 & \\ & & 0\end{pmatrix}\Big]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

In the mass-eigenstate basis, the vacuum Hamiltonian is

$$H_0'\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \begin{pmatrix}\sqrt{p^2+m_1^2} & & \\ & \sqrt{p^2+m_2^2} & \\ & & \sqrt{p^2+m_3^2}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$= \left[E\cdot\mathbb{1} + \frac{1}{2E}\begin{pmatrix}0 & & \\ & \delta m_{12}^2 & \\ & & \delta m_{13}^2\end{pmatrix}\right]\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Hence in the current basis,

$$H_0 = \frac{1}{2E}V\begin{pmatrix}0 & & \\ & \delta m_{12}^2 & \\ & & \delta m_{13}^2\end{pmatrix}V^\dagger$$

$$= \frac{1}{2E}U\begin{pmatrix}0 & & \\ & \delta m_{12}^2 & \\ & & \delta m_{13}^2\end{pmatrix}U^\dagger$$

$$(H_0)_{\alpha\beta} = \frac{1}{2E}\left\{\delta m_{12}^2\, U_{\alpha 2}U_{\beta 2}^* + \delta m_{13}^2\, U_{\alpha 3}U_{\beta 3}^*\right\}$$

$$= \frac{1}{2E}\delta m_{13}^2\, U_{\alpha 3}U_{\beta 3}^*\left\{1 + \underbrace{\frac{\delta m_{12}^2}{\delta m_{13}^2}\frac{U_{\alpha 2}U_{\beta 2}^*}{U_{\alpha 3}U_{\beta 3}^*}}\right\}.$$

very small for SMA, LOW, VO
significant (a few–10%) LMA

Hence

$$\begin{cases} H_{ee} = H_{ee}^0 + a \\ H_{\alpha\beta} = H_{\alpha\beta}^0 \quad \text{if } \alpha\beta \neq ee \end{cases}$$

Therefore, by introducing the diagonarijation matrix of the full H;

$$H = \frac{1}{2E} U^m \begin{pmatrix} 0 & & \\ & (\delta m^2_{12})^m & \\ & & (\delta m^2_{13})^m \end{pmatrix} U^{m\dagger}$$

all the formulae for the oscillation probabilities are valid simply by replacing all the masses and the MNS matrix elements with those in the matter, which are labeled by m on the sholder.

$$\begin{aligned} 2E\,a &= 2E \cdot \sqrt{2}\, G_F\, n_e \\ &= 7.56 \times 10^{-5}\ \mathrm{eV}^2 \left(\frac{\rho}{g \cdot cm^3}\right)\left(\frac{E}{GeV}\right) \end{aligned}$$

$\rho =$	1	water	
	3	crust	← VLBL from JHF
	5	mantle	← ν-factory
	13	core	← Day-Night

There is one interesting relation between $P(\nu_\alpha \to \nu_\beta)$ and $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ in the matter.

$$i\frac{\partial}{\partial t}\begin{pmatrix} \bar{\nu}_e \\ \bar{\nu}_\mu \\ \bar{\nu}_\tau \end{pmatrix} = \bar{H}\begin{pmatrix} \bar{\nu}_e \\ \bar{\nu}_\mu \\ \bar{\nu}_\tau \end{pmatrix} = \left[\overset{\text{CP}}{H_0^*} + \overset{\text{potential of } (\bar{\nu}_e \to \bar{\nu}_e)}{\begin{pmatrix} -a & & \\ & 0 & \\ & & 0 \end{pmatrix}} \right] \begin{pmatrix} \bar{\nu}_e \\ \bar{\nu}_\mu \\ \bar{\nu}_\tau \end{pmatrix}$$

Note $\quad H_0\,(\mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV}) = -H_0\,(\mathrm{IV}, \mathrm{III}, \mathrm{II}, \mathrm{I})$

Hence $\quad H\,(\mathrm{IV}, \mathrm{III}, \mathrm{II}, \mathrm{I}) = -\bar{H}^*\,(\mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV})$

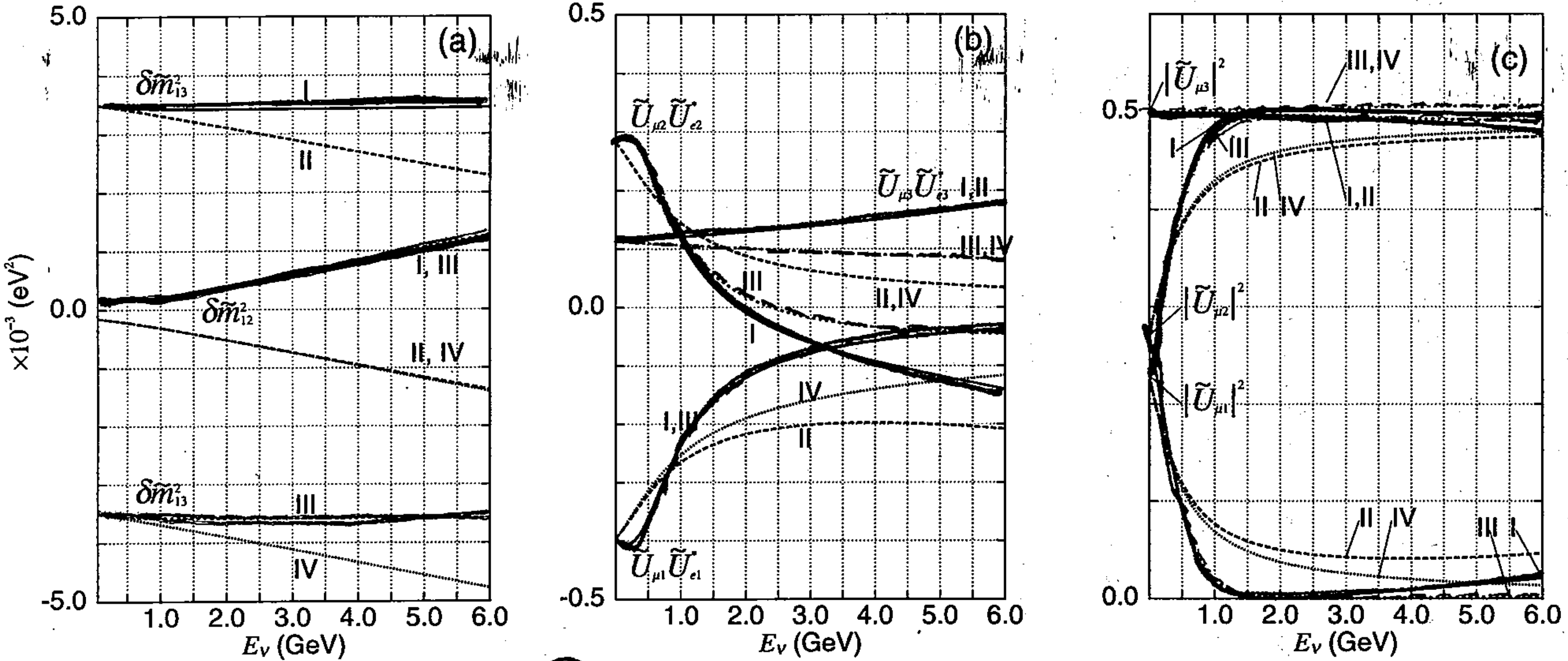
$\quad\quad \to \bar{H}\,(\mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV})$ T-reversal!

$$\underbrace{P(\nu_\alpha \to \nu_\beta)_{(\mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV})} = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)_{(\mathrm{IV}, \mathrm{III}, \mathrm{II}, \mathrm{I})}}$$

$\delta \tilde{m}^2_{ij}$ & $\tilde{U}_{\alpha j}$ inside the earth crust

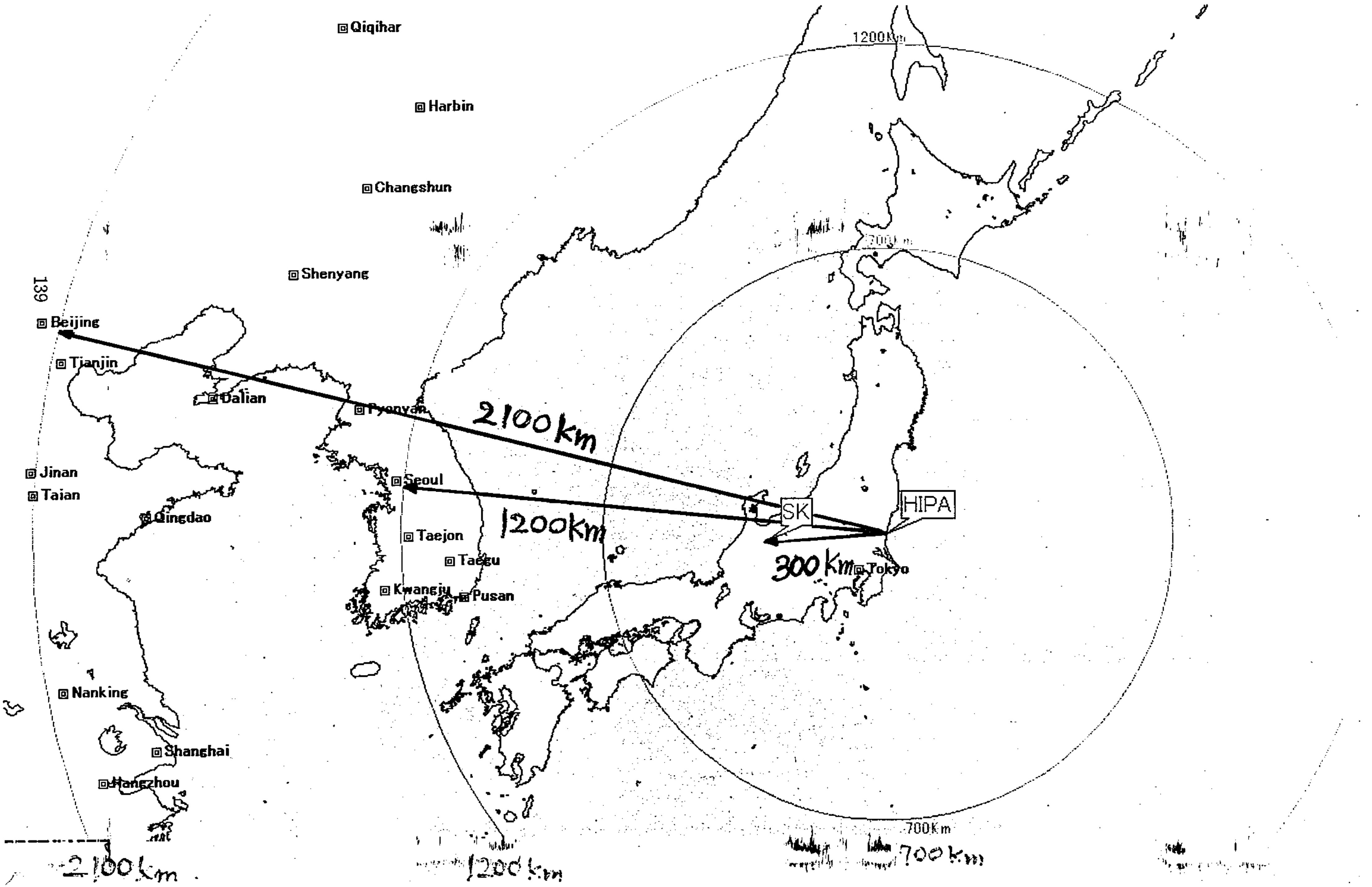
$\rho = 3g/cm^3$

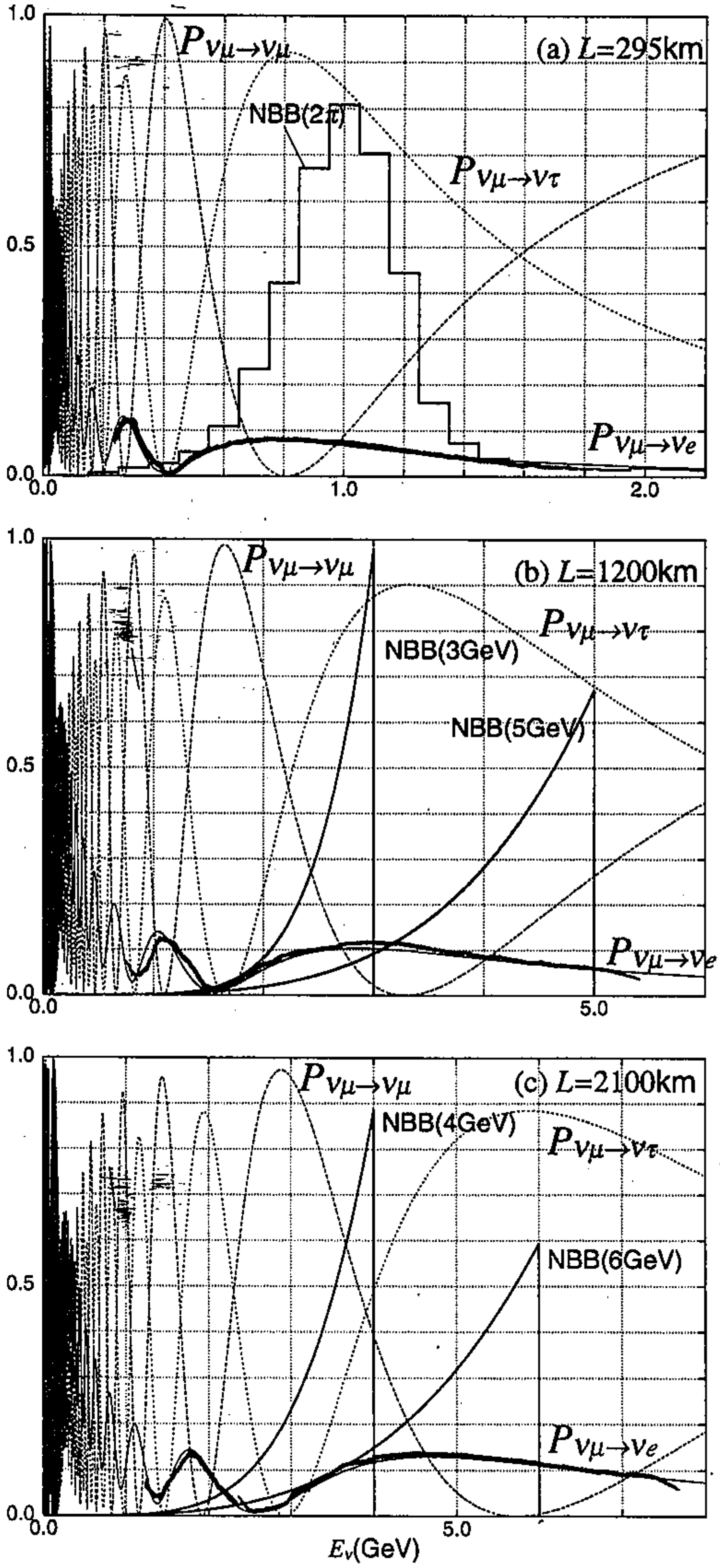
$$\left(\begin{array}{ll} \delta m^2_{ATM} = 3.5 \times 10^{-3} eV^2 & \sin^2 2\theta_{ATM} = 1 \\ \delta m^2_{SOL} = 1 \times 10^{-4} eV^2 & \sin^2 2\theta_{SOL} = 0.8 \\ \delta_{MNS} = 0^\circ & \sin^2 2\theta_{CHOOZ} = 0.1 \end{array} \right)$$



	I	II	III	IV
$\delta m^2_{12} = m_2^2 - m_1^2$	+	−	+	+
$\delta m^2_{13} = m_3^2 - m_1^2$	+	+	−	−

V.L.B.L. from HIPA (JHF)

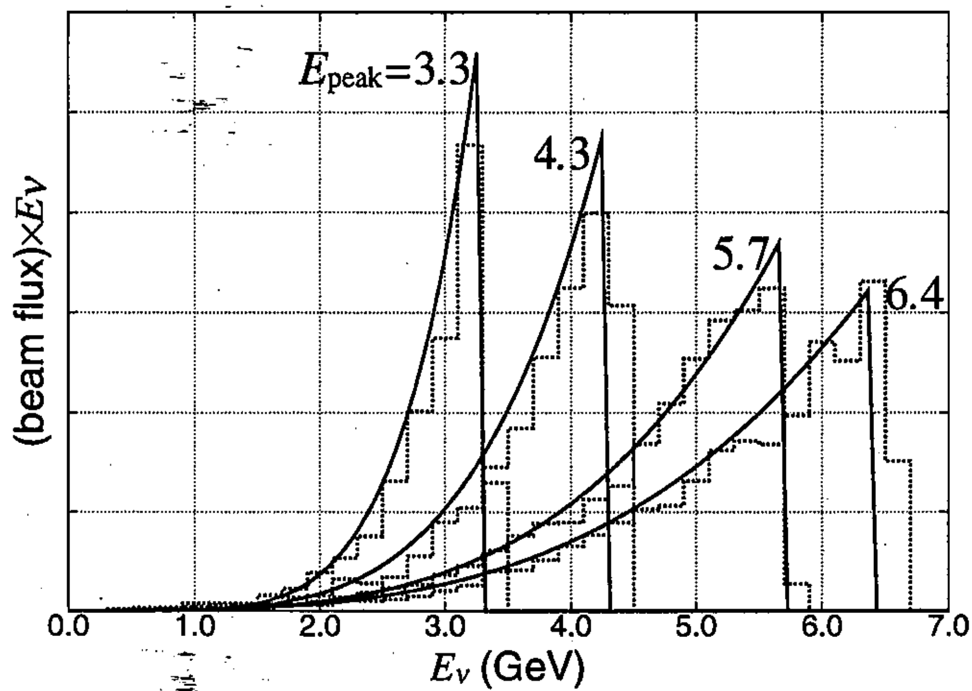




295 km

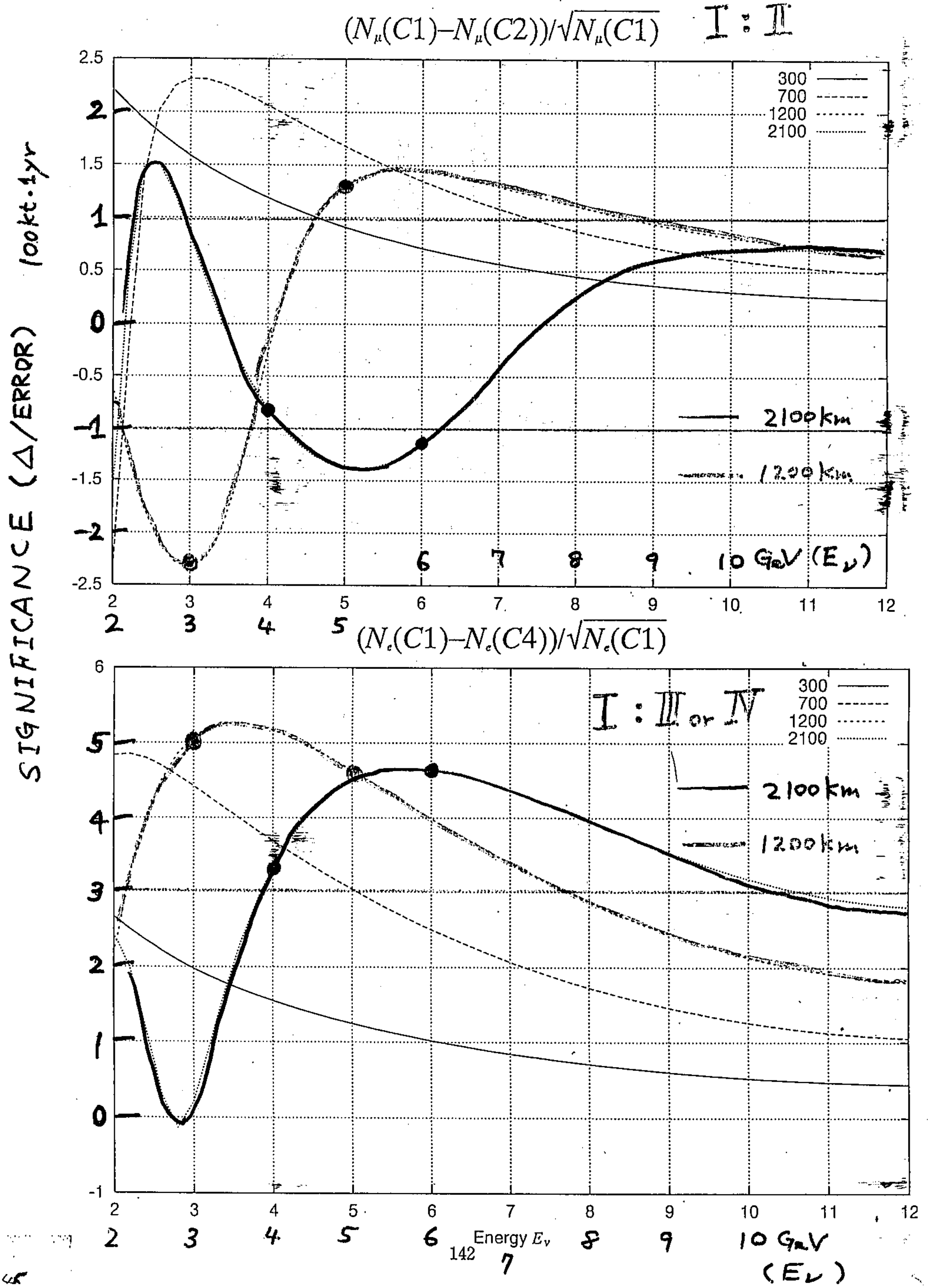
1,200 km

2,100 km

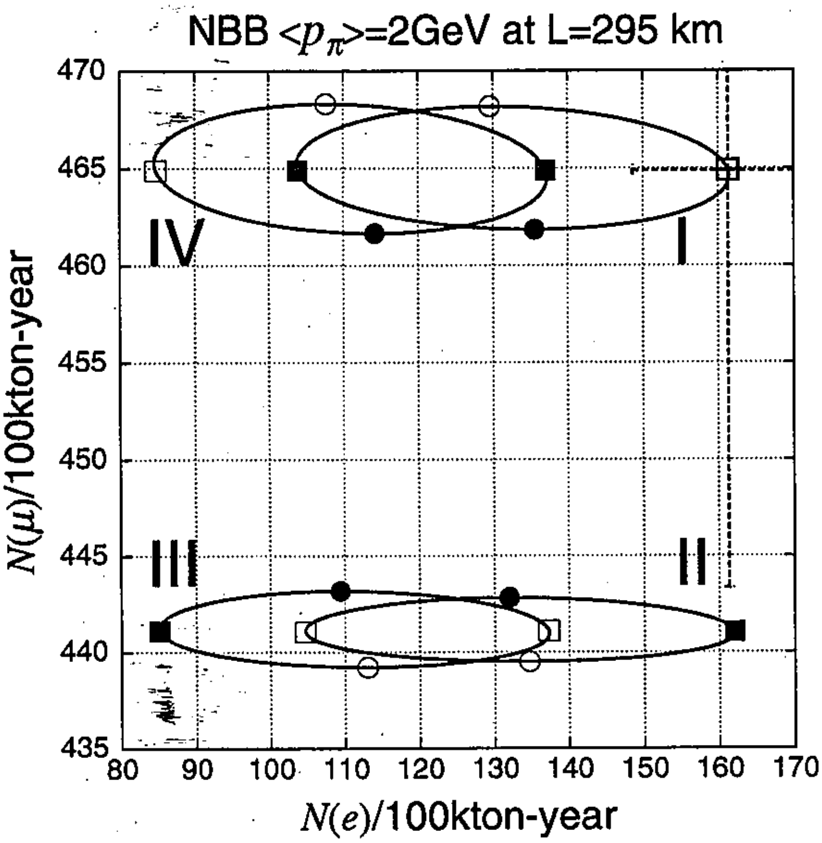


Parametrization of the HE-NBB's

VERY OLD STUDY (May 2000)



		ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	N_{NC}
300km	3GeV	7495.	43.0	55.0	0.90	2540.9
		5903.	22.0	105.0	1.20	2540.9
	6GeV	13321.	44.0	82.0	1.90	4457.4
		12400.	21.0	110.0	1.70	4457.4
700km	3GeV	1376.	7.9	10.1	0.17	466.7
		382.	3.8	43.9	0.28	466.7
	6GeV	2446.	8.1	15.0	0.35	818.7
		1699.	3.5	40.6	0.36	818.7
1200km	3GeV	468.	2.7	3.4	0.05	158.8
		85.	0.8	18.1	0.13	158.8
	6GeV	833.	2.7	5.1	0.12	278.6
		297.	1.1	25.3	0.13	278.6
2100km	3GeV	153.	0.9	1.1	0.02	51.9
		119.	0.5	2.4	0.05	51.9
	6GeV	272.	0.9	1.6	0.04	91.0
		47.	0.4	13.2	0.06	91.0



295 km

Inputs : $\delta m^2_{ATM} = 3.5 \times 10^{-3} eV^2$ $\sin^2 2\theta_{ATM} = 1$

$\delta m^2_{SOL} = 1 \times 10^{-4} eV^2$ $\sin^2 2\theta_{SOL} = 0.8$

$\delta_{MNS} = 0^\circ - 90^\circ - 180^\circ - 270^\circ - 360^\circ$ $\sin^2 2\theta_{CHOOZ} = 0.1$

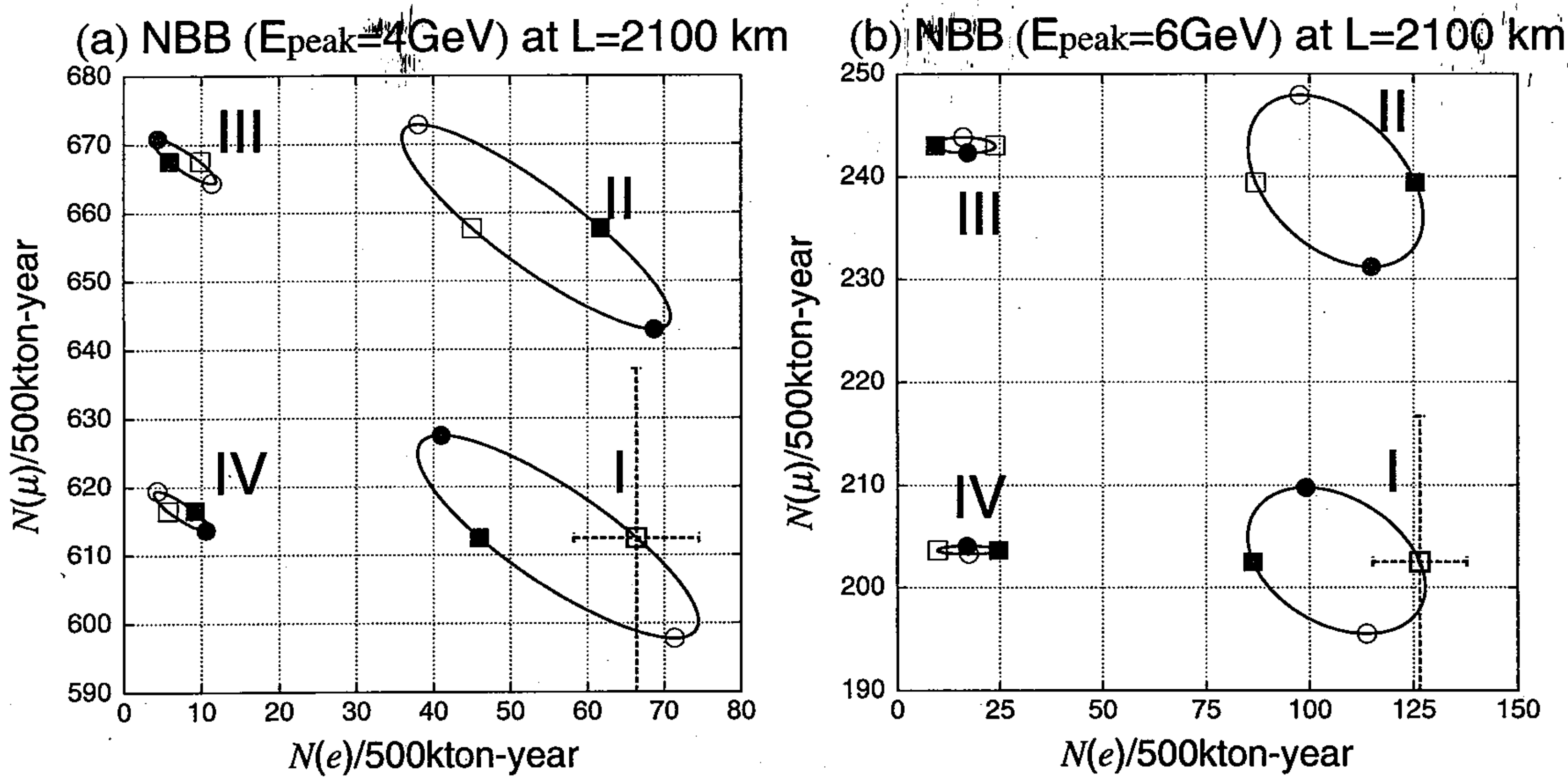
$\rho = 3\ g/cm^3$

Inputs : $\delta m^2_{ATM} = 3.5 \times 10^{-3} eV^2$ $\sin^2 2\theta_{ATM} = 1$

$\delta m^2_{SOL} = 1 \times 10^{-4} eV^2$ $\sin^2 2\theta_{SOL} = 0.8$

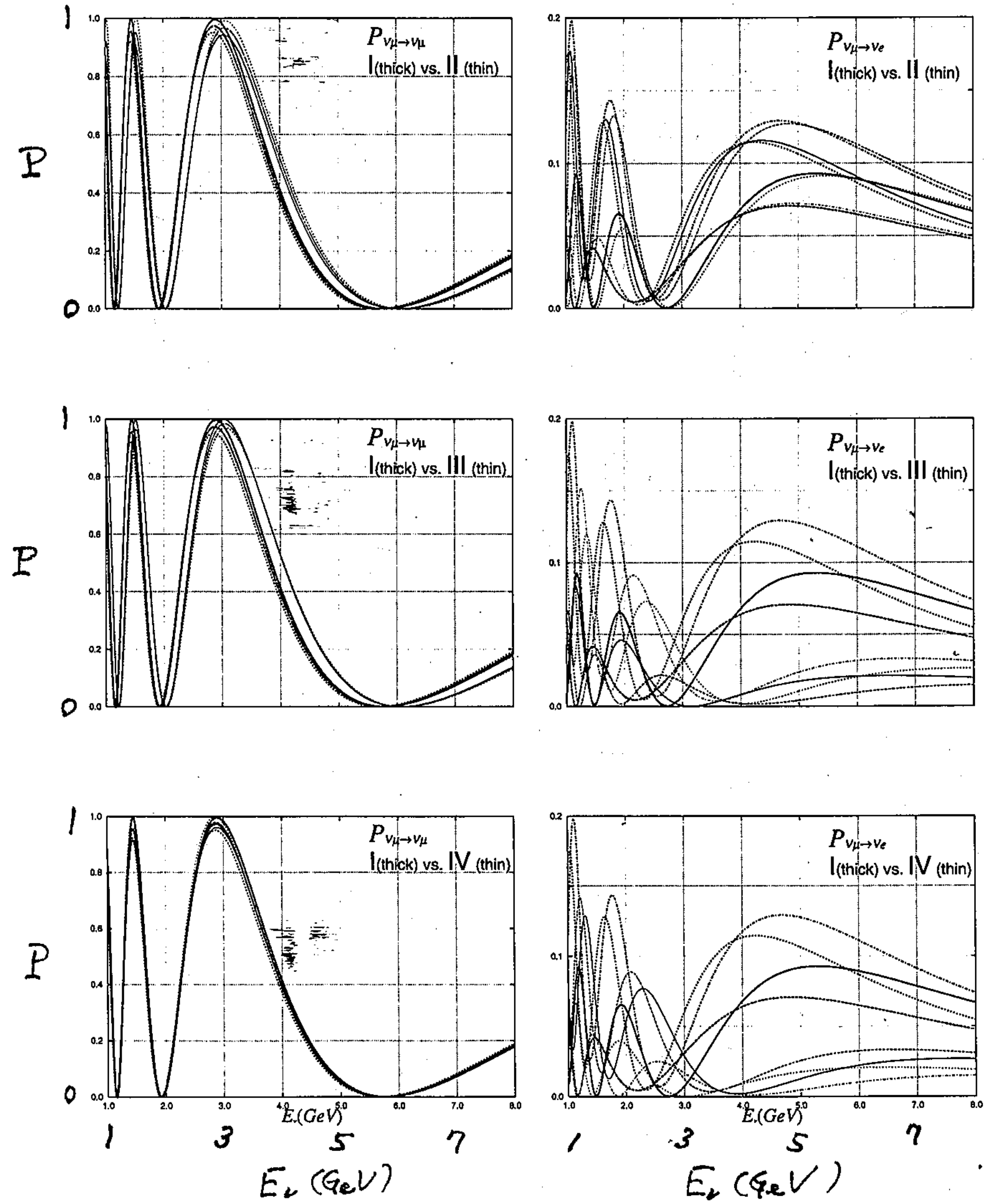
$\delta_{MNS} = 0° - 90° - 180° - 270° - 360°$ $\sin^2 2\theta_{CHOOZ} = 0.1$

$\rho = 3g/cm^3$



$L = 2{,}100\text{km}$

$P(\nu_\mu \to \nu_\mu)$ vs E_ν $\qquad$ $P(\nu_\mu \to \nu_e)$ vs E_ν

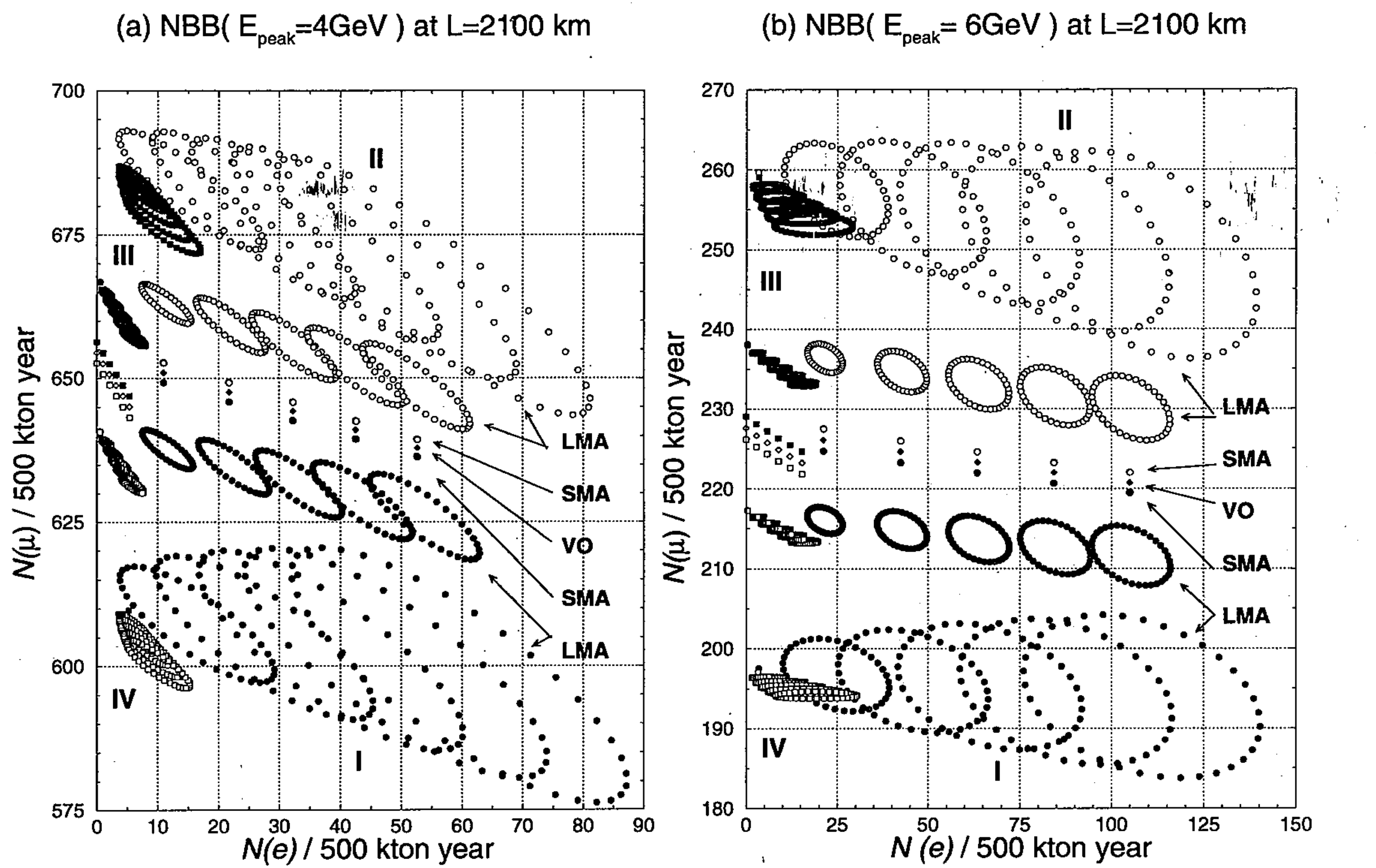


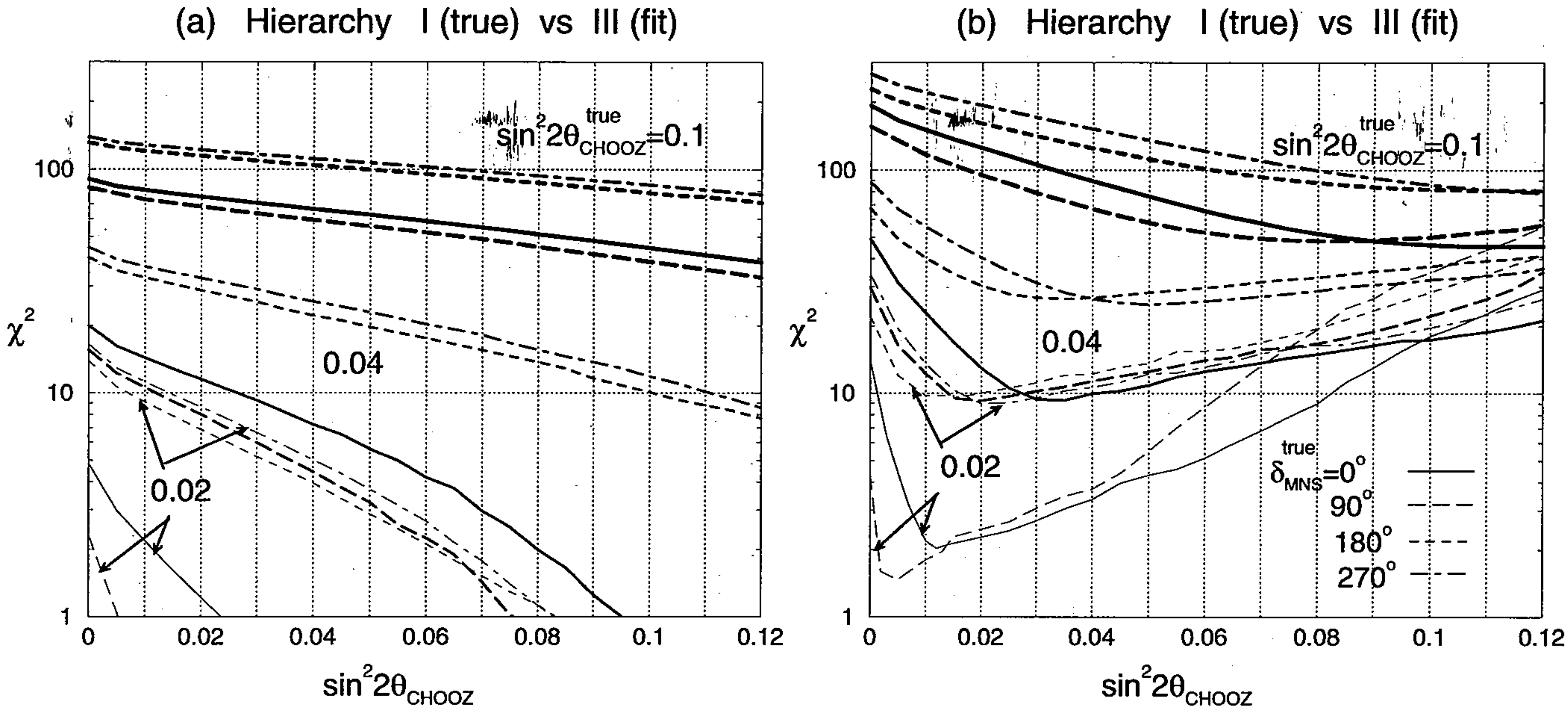
Inputs: $\delta m^2_{ATM} = 3.5 \times 10^{-3} eV^2$ $\qquad$ $\sin^2 2\theta_{ATM} = 1$

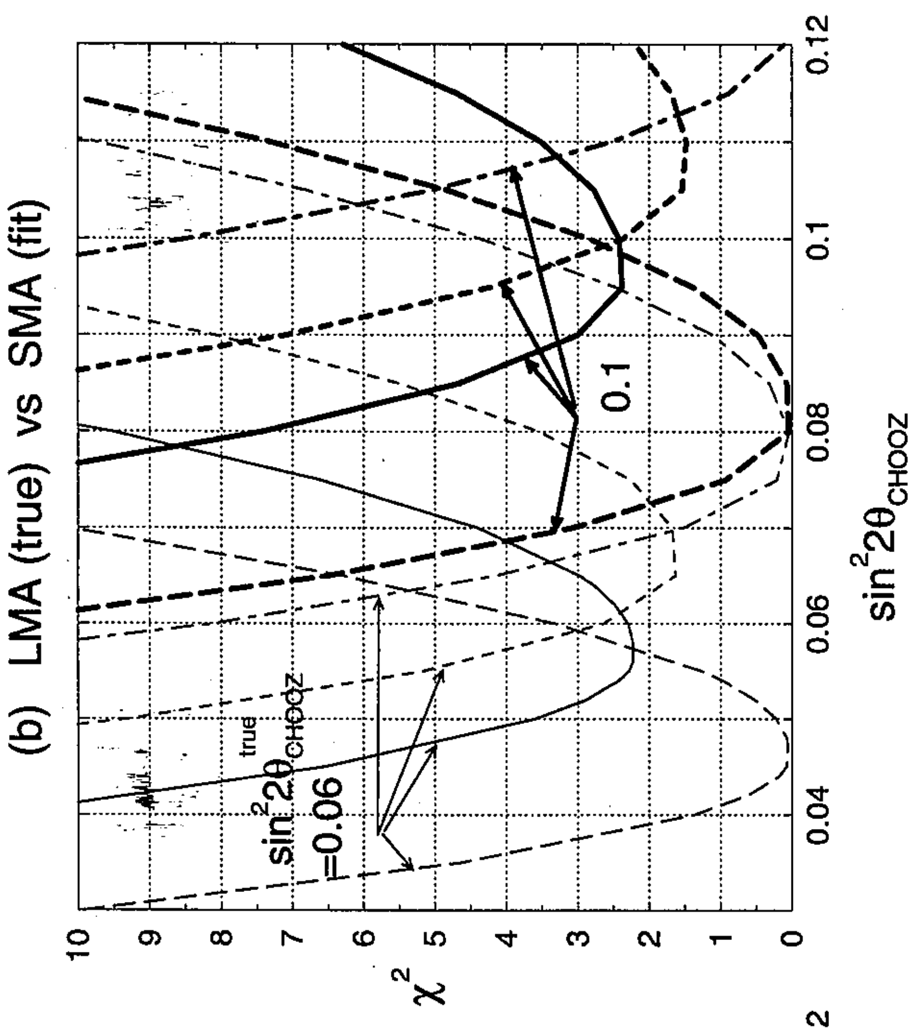
$\delta m^2_{SOL} = 1 \times 10^{-4} eV^2$ $\qquad$ $\sin^2 2\theta_{SOL} = 0.8$

$\delta_{MNS} = \begin{cases} 0^\circ & \text{———} \\ 90^\circ & \text{— — —} \\ 180^\circ & \text{- - - - - -} \\ 270^\circ & \text{—·—·—} \end{cases}$ $\qquad$ $\sin^2 2\theta_{CHOOZ} = 0.1$

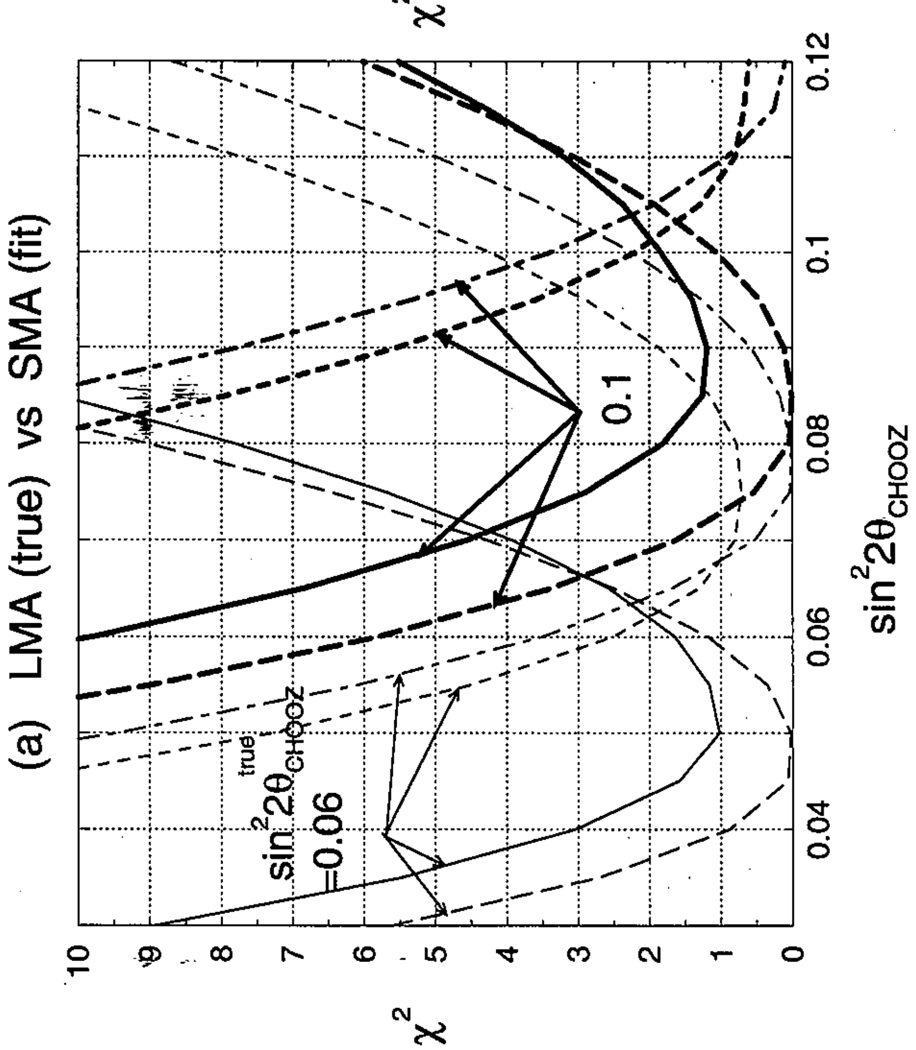
$\rho = 3g/cm^3$


(a) NBB(E_{peak}=4GeV) at L=2100 km
(b) NBB(E_{peak}= 6GeV) at L=2100 km
$N(\mu)$ / 500 kton year
$N(e)$ / 500 kton year
700
675
650
625
600
575
0
10
20
30
40
50
60
70
80
90
I
II
III
IV
LMA
SMA
VO
SMA
LMA
$N(\mu)$ / 500 kton year
N (e) / 500 kton year
270
260
250
240
230
220
210
200
190
180
0
25
50
75
100
125
150
I
II
III
IV
LMA
SMA
VO
SMA
LMA

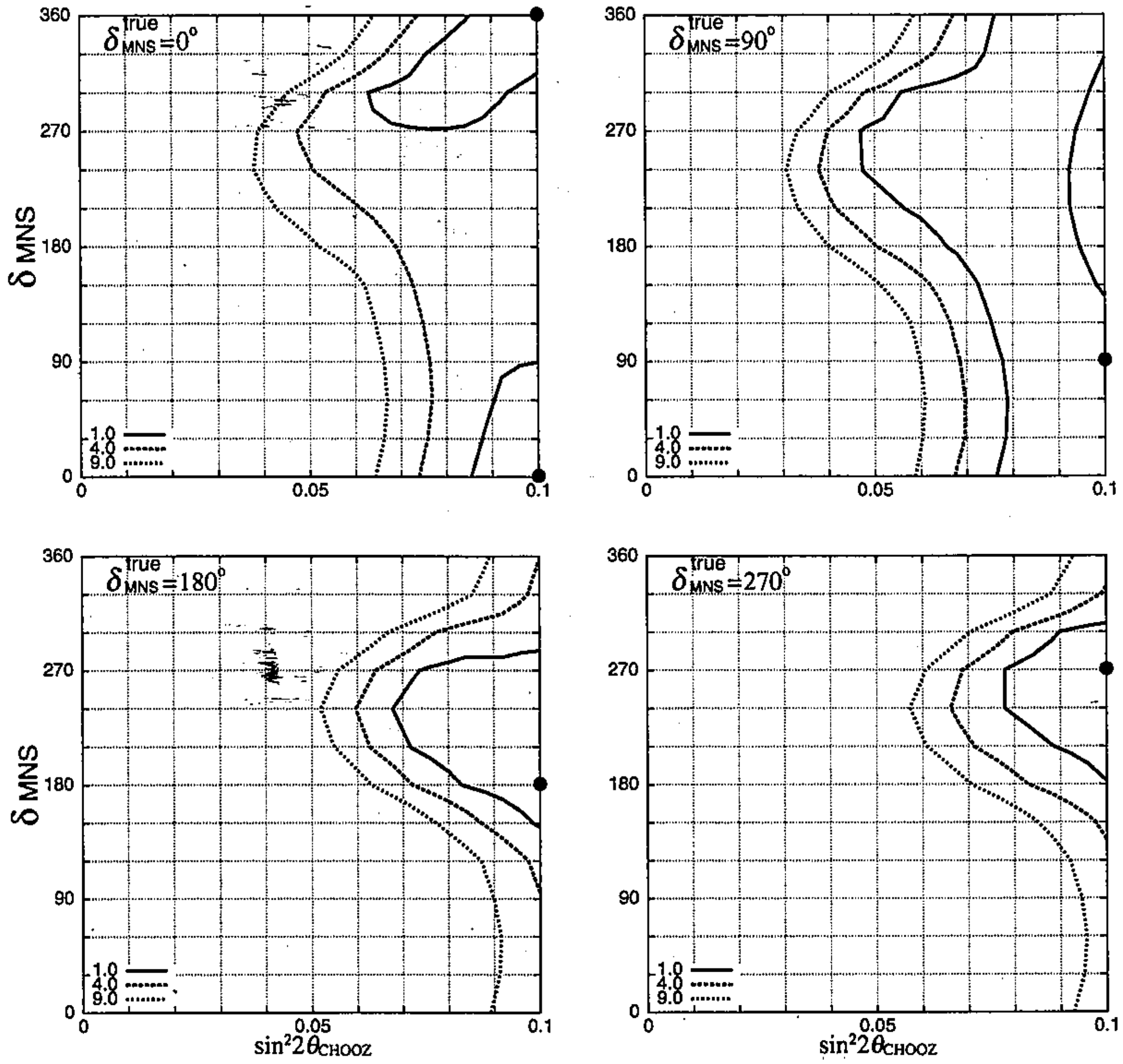

(a) Hierarchy I (true) vs III (fit)
$\sin^2 2\theta_{CHOOZ}^{true}=0.1$
0.04
0.02
χ^2
100
10
1
0
0.02
0.04
0.06
0.08
0.1
0.12
$\sin^2 2\theta_{CHOOZ}$
(b) Hierarchy I (true) vs III (fit)
$\sin^2 2\theta_{CHOOZ}^{true}=0.1$
0.04
0.02
$\delta_{MNS}^{true}=0^\circ$
90°
180°
270°
χ^2
100
10
1
0
0.02
0.04
0.06
0.08
0.1
0.12
$\sin^2 2\theta_{CHOOZ}$



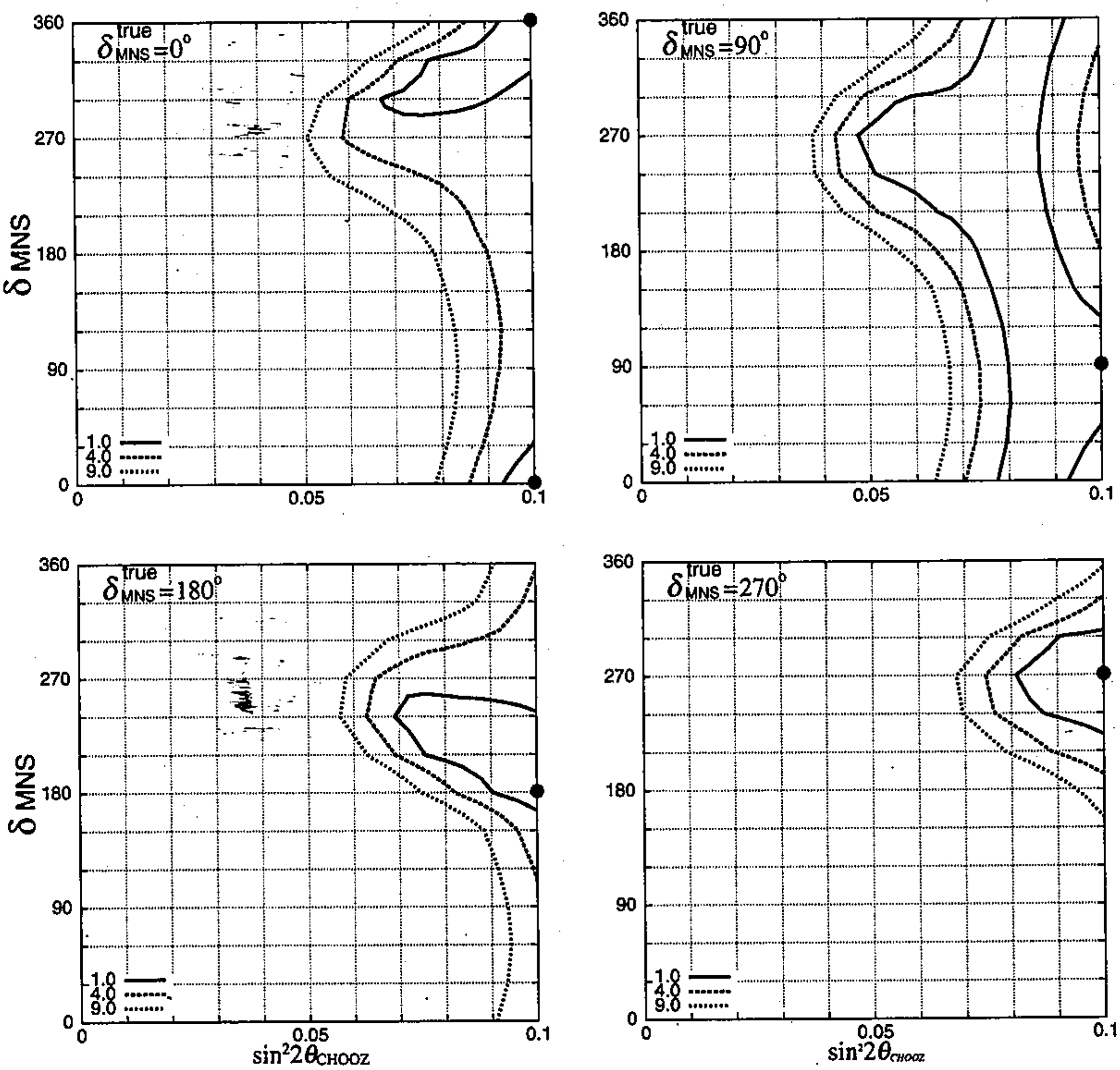
(b) LMA (true) vs SMA (fit)
$\sin^2 2\theta_{CHOOZ}^{true}$
=0.06
0.1
χ^2
$\sin^2 2\theta_{CHOOZ}$



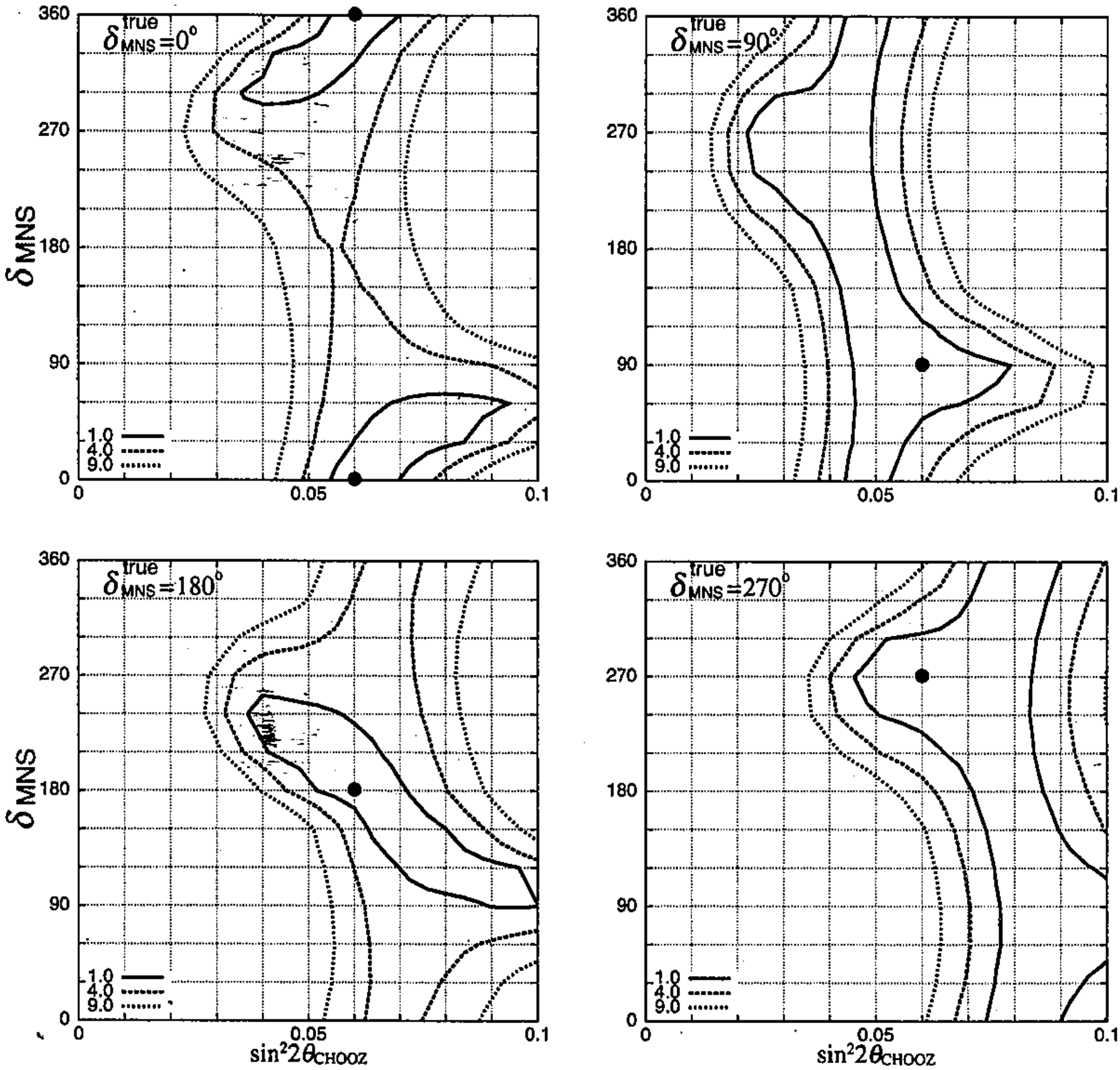
(a) LMA (true) vs SMA (fit)
$\sin^2 2\theta_{CHOOZ}^{true}$
=0.06
0.1
χ^2
$\sin^2 2\theta_{CHOOZ}$



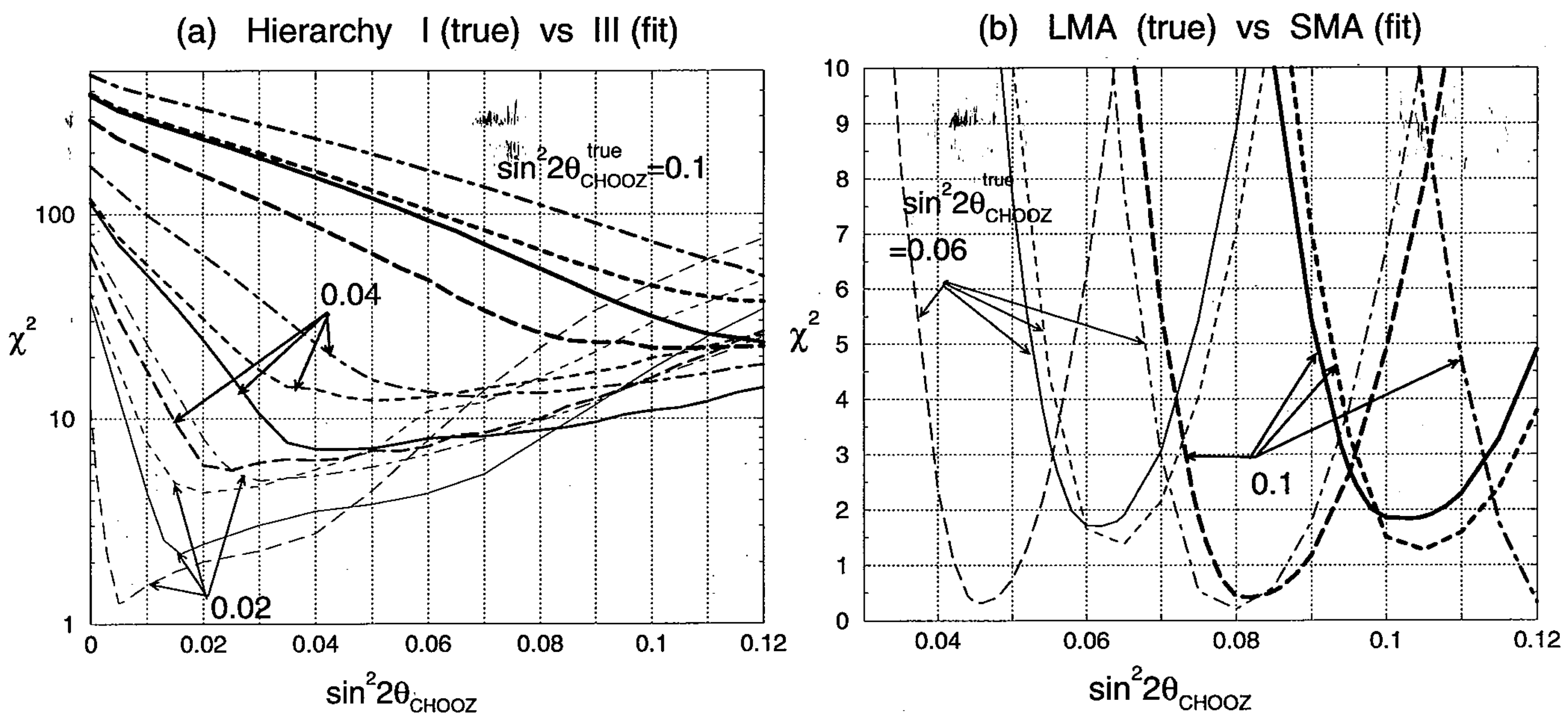
$\delta_{MNS}^{true}=0^\circ$
$\delta_{MNS}^{true}=90^\circ$
$\delta_{MNS}^{true}=180^\circ$
$\delta_{MNS}^{true}=270^\circ$
δ MNS
$\sin^2 2\theta_{CHOOZ}$
1.0
4.0
9.0
0
90
180
270
360
0.05
0.1



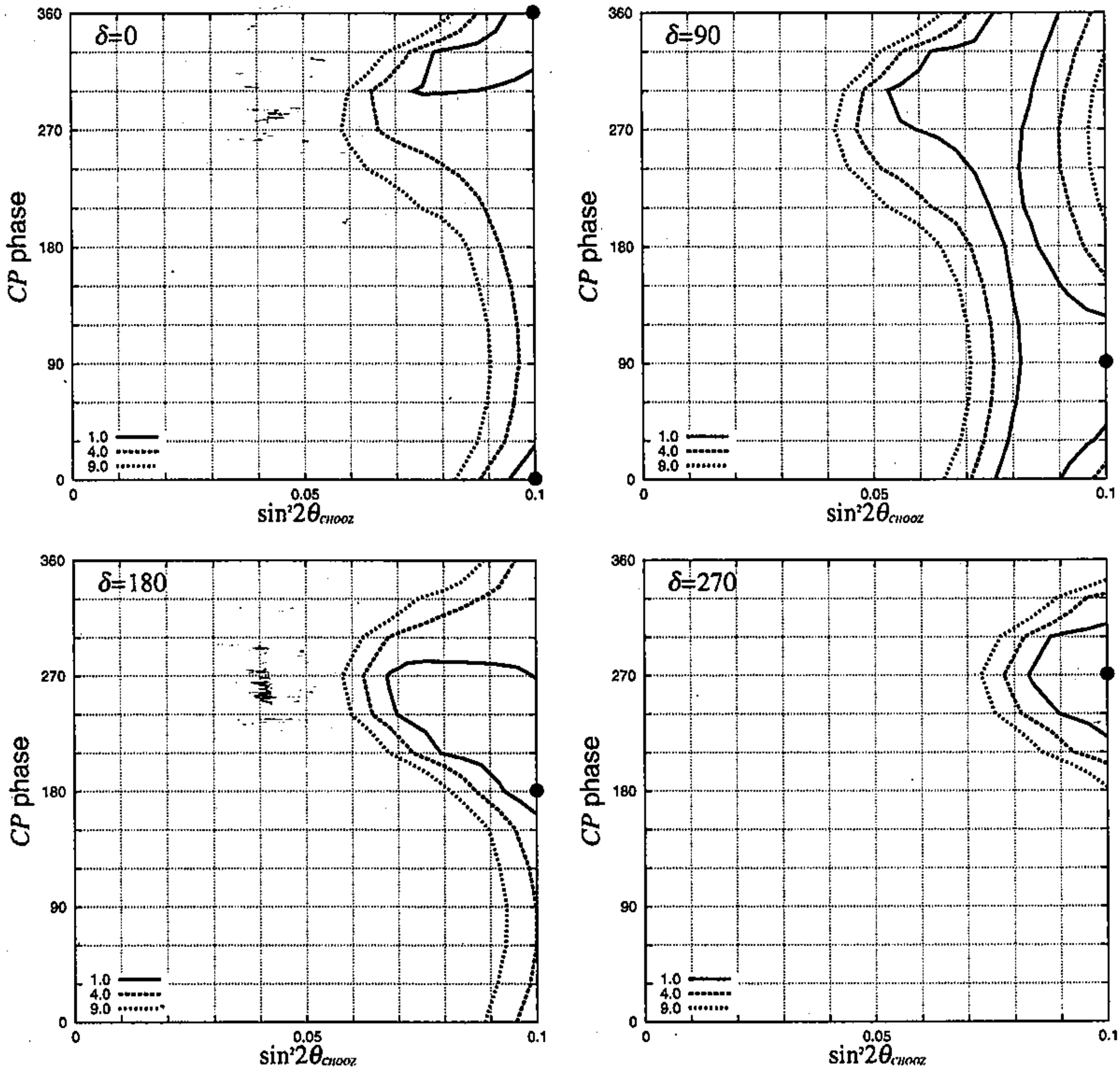
$\delta_{MNS}^{true}=0°$
$\delta_{MNS}^{true}=90°$
$\delta_{MNS}^{true}=180°$
$\delta_{MNS}^{true}=270°$
δ MNS
360
270
180
90
0
0.05
0.1
1.0
4.0
9.0
$\sin^2 2\theta_{CHOOZ}$



$\delta_{MNS}^{true}=0^{\circ}$
$\delta_{MNS}^{true}=90^{\circ}$
$\delta_{MNS}^{true}=180^{\circ}$
$\delta_{MNS}^{true}=270^{\circ}$
δ_{MNS}
$\sin^2 2\theta_{CHOOZ}$
1.0
4.0
9.0
0
90
180
270
360
0.05
0.1



(a) Hierarchy I (true) vs III (fit)
χ^2
100
10
1
0
0.02
0.04
0.06
0.08
0.1
0.12
$\sin^2 2\theta_{CHOOZ}$
$\sin^2 2\theta_{CHOOZ}^{true}$=0.1
0.04
0.02
(b) LMA (true) vs SMA (fit)
χ^2
10
9
8
7
6
5
4
3
2
1
0
0.04
0.06
0.08
0.1
0.12
$\sin^2 2\theta_{CHOOZ}$
$\sin^2 2\theta_{CHOOZ}^{true}$
=0.06
0.1



δ=0
δ=90
δ=180
δ=270
CP phase
sin²2θ_CHOOZ
1.0
4.0
9.0

Physics Potential of VLBL ν-oscillation expts with KEK-JAERI High Intensity Proton Accelerator

2001. 11. 9 @ ICRR

by K. Hagiwara (KEK)

based on the report made by M. Aoki, K.H. } KEK, Theory
Y. Hayato, T. Kobayashi } KEK, neutrino
T. Nakaya, K. Nishikawa } Kyoto
N. Okamura } Virginia Tech.

$L = 295$ km @ 100 kt·year
+
$L = 2{,}100$ km @ 500 kt·year × 2

1. Can we distinguish the neutrino mass hierarchy cases?

◎ III ($\delta m^2_{13} = -\delta m^2_{ATM}$) can be rejected at $\underline{3\text{-}\sigma}$ if $\sin^2 2\theta_{CHOOZ} \gtrsim \underline{0.4}$
$\underline{1\text{-}\sigma}$ 〃 $\gtrsim \underline{0.2}$.

2. Can we distinguish the solar-neutrino oscillation scenarios? (δm^2_{SOL}, $\sin^2 2\theta_{SOL}$)

△ SMA/VO can be rejected at $\underline{1\text{-}\sigma}$ if { LMA with $1\times10^{-4}\,eV^2$
and $\sin^2 2\theta_{CHOOZ} \gtrsim 0.6$
and $\delta_{MNS} \sim 0°$ or $\sim 180°$

3. Can we measure the two unknown parameters $\sin^2 2\theta_{CHOOZ}$, δ_{MNS}?

△ ($\sin^2 2\theta_{CHOOZ}$, δ_{MNS}) can be localized at $\underline{1\text{-}\sigma}$ if { LMA with $\delta m^2_{SOL} = 1\times10^{-4}\,eV^2$
and $\sin^2 2\theta_{CHOOZ} \gtrsim 0.6$
and $\delta_{MNS} \sim 0°$ or $\sim 180°$

4. Can we improve the measurements of δm^2_{ATM}, $\sin^2 2\theta_{ATM}$?

○ $\Delta\,\delta m^2_{ATM} \sim \pm 1\times10^{-5}\,eV^2$
$\Delta \sin^2 2\theta_{ATM} \sim \pm 0.01$
} if LMA is true and if LMA is assumed in the fit

} if LMA is true and if SMA/VO is assumed in the fit