CP violation in the lepton sector and neutrino oscillations

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1. Introduction

CP violating phases in the lepton sector

Majorana mass term

$$\mathcal{L}_{Maj} = \nu_L^{T''} C^{-1} m^{(\nu)} \nu_L'' = \underbrace{\nu_L^{T''} O^T}_{\nu_L^{T'}} C^{-1} \mathrm{diag}(m_j^{(\nu)}) \underbrace{O \nu_L''}_{\nu_L'}$$

charged lepton

$$\bar{\ell}_R'' m^{(\ell)} \ell_L'' = \underbrace{\bar{\ell}_R'' V_R^{(\ell)\dagger}}_{\bar{\ell}_R'} \mathrm{diag}(m_j^{(\ell)}) \underbrace{V_L^{(\ell)} \ell_L''}_{\ell_L'} = \underbrace{\bar{\ell}_R' e^{i\alpha} e^{i\beta'\lambda_3} e^{i\gamma'\lambda_8}}_{\bar{\ell}_R} \mathrm{diag}(m_j^{(\ell)}) \ell_L$$

charged current

$$j_\mu = \bar{\ell}_L'' \gamma_\mu \nu_L'' = \bar{\ell}_L' V_L^{(\ell)} O^T \gamma_\mu \nu_L'$$

$$= \underbrace{\bar{\ell}_L' e^{i\alpha} e^{i\beta'\lambda_3} e^{i\gamma'\lambda_8}}_{\bar{\ell}_L} \gamma_\mu \underbrace{U e^{i\beta\lambda_3} e^{i\gamma\lambda_8} \nu_L'}_{\nu_L}$$

flavor eigenstete　　Majorana phases

$$\underbrace{\nu_L}_{\text{flavor eigenstete}} = U e^{i\beta\lambda_3} e^{i\gamma\lambda_8} \underbrace{\nu_L'}_{\text{mass eigenstate}}$$

mass eigenstate

$U = U(\theta_{12}, \theta_{13}, \theta_{23}; \delta)$: Maki-Nakagawa-Sakata-Pontecorvo matrix

<u>NB</u> Majorana phases do not affect ν oscillation.

$\because$ $$\nu_\beta(L) = \sum_j U_{\beta j}\, e^{-iE_jL}\,(U^{-1})_{j\alpha}\,\nu_\alpha(0)$$

$$A(\nu_\alpha\to\nu_\beta;L) = (U)_{\beta j}\,[\mathrm{diag}(e^{-iE_jL})]_{jj}\,(U^{-1})_{j\alpha}$$

Consider ν osc. with different MNSP matrix:

$$\tilde{U} \equiv \underbrace{\mathrm{diag}(e^{i\varphi_\alpha})}_{\equiv P}\, U\, \underbrace{\mathrm{diag}(e^{i\chi_j})}_{\equiv Q} = PUQ$$

$$\begin{aligned}
\tilde{A}(\nu_\alpha\to\nu_\beta;L) &= (\tilde{U})_{\beta j}\,[\mathrm{diag}(e^{-iE_jL})]_{jj}\,(\tilde{U}^{-1})_{j\alpha} \\
&= (PUQ)_{\beta j}\,[\mathrm{diag}(e^{-iE_jL})]_{jj}\,(Q^{-1}U^{-1}P^{-1})_{j\alpha} \\
&= (P)_{\beta\beta}\,(U)_{\beta j}\,[\mathrm{diag}(e^{-iE_jL})]_{jj}\,(U^{-1})_{j\alpha}\,(P^{-1})_{\alpha\alpha} \\
&= e^{i\varphi_\beta - i\varphi_\alpha}\, A(\nu_\alpha\to\nu_\beta;L)
\end{aligned}$$

$$\begin{aligned}
\therefore\ \tilde{P}(\nu_\alpha\to\nu_\beta;L) &= |\tilde{A}(\nu_\alpha\to\nu_\beta;L)|^2 \\
&= |A(\nu_\alpha\to\nu_\beta;L)|^2 \\
&= P(\nu_\alpha\to\nu_\beta;L) \quad /\!/
\end{aligned}$$

Bilenky - Hosek - Petcov PL 94B ('80) 495

Future long baseline experiments

motivation

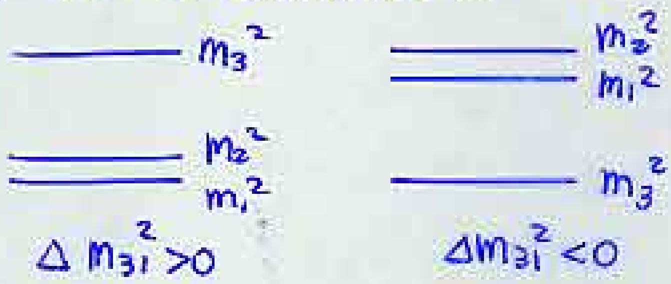
oscillation parameters in $N_\nu = 3$ framework

$$\left(\underbrace{\Delta m^2_{21}, \theta_{12}}_{\Uparrow \atop \nu_\odot} ; \underbrace{|\Delta m^2_{31}|, \theta_{23}}_{\Uparrow \atop \nu_{atm}} ; \underbrace{\boxed{\mathrm{sign}(\Delta m^2_{31}), \theta_{13}, \delta}}_{\Uparrow \atop \text{unknown}} \right)$$

next thing to do is to determine :

- $\mathrm{sign}(\Delta m^2_{31})$

  mass pattern



- θ_{13}

  known bound from CHOOZ

  $\sin^2 2\theta_{13} < 0.1$

- δ

  CP violation

$N_\nu = 3$ is assumed throughout this talk.

Near future / ongoing long baseline experiments

accel. {
- '99 – K2K KEK → SK $L = 250\,km$ $E_\nu \sim 1\,GeV$
- '04 – MINOS FNAL → Soudan $L = 730\,km$ $E_\nu \sim 10\,GeV$
- '06(?)– {ICARUS, OPERA} CERN → Grand Sasso $L = 730\,km$ $E_\nu \sim 20\,GeV$
- '07(?)– JHF (1st phase) JAERI → SK $L = 300\,km$ $E_\nu \sim 1\,GeV$ $\boxed{0.77\,MW,\ 22.5\,kt}$

reactor { '01 – KAMLAND Kashiwazaki etc. → Kam. $L \sim 170\,km$ $E_\nu \sim 4\,MeV$

→ nice check for LMA $\nu_\odot$ sol.

→ precise measurements of $(|\Delta m^2_{32}|, \theta_{23})$, θ_{13} (?)

Far future long baseline experiments

(highly speculative)

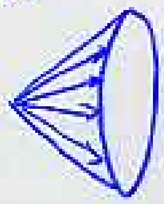
JHF (2nd phase) JAERI → HK (Hyper Kamiokande) $L = 300\,km$ $E_\nu \sim 1\,GeV$ $\boxed{4\,MW,\ 1\,Mt}$

super (conventional) beams

→ ν factory ? → ? $L = 1000\,km - 3000\,km$, $E_\nu = 20\,GeV - 50\,GeV$

→
- $\cdot$ sign(Δm^2_{31})
- $\cdot$ θ_{13}
- $\cdot$ δ ← final goal in this game

ν factories VS conventional beams

	conventional	ν factories
production process	$\pi^+ \to \mu^+ \nu_\mu$, $\mu^+ \dashrightarrow e^+ \nu_e \bar{\nu}_\mu$ $\begin{pmatrix} \nu_\mu & 99\% \\ \nu_e & 1\% \end{pmatrix}$	$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ $\begin{pmatrix} \bar{\nu}_\mu & 50\% \\ \nu_e & 50\% \end{pmatrix}$
intensity $\propto \left(\frac{E_{parent}}{m_{parent}}\right)^2$ (effect due to boost)	$\left(\frac{E_\pi}{m_\pi}\right)^2 \sim O(1)$ 	$\left(\frac{E_\mu}{m_\mu}\right)^2 \gg 1$ for $E_\mu \sim O(10\,\text{GeV})$ 
how to measure oscillations	$\nu_\mu \xrightarrow{\text{osc.}} \nu_e \xrightarrow{\text{interact w/N}} e^- X$	$\nu_e \xrightarrow{\text{osc.}} \nu_\mu \xrightarrow[\text{interact w/ N}]{} \mu^- X$ wrong sign muons cf. $\bar{\nu}_\mu \xrightarrow{\text{no osc.}} \bar{\nu}_\mu \to \mu^+ X$ right sign muons NB $\overset{\leftrightarrow}{\nu_e} N \to e^\pm X$ create showers and charge id is very difficult.
backgrounds	$O(1)\%$ · contamination of ν_e $f_B \sim O(10^{-2})$ ↑ background fraction · mis identification of π^0 with ν_e $\pi^0 \to (\gamma)$ unseen, $\gamma \to$ shower ≈ e-like event	very small in case of iron calorimeter $\nu_\mu N \to \begin{cases} \nu_\mu\ (\mu^-) & \text{unseen} \\ c \xrightarrow{\text{decay}} \mu^+ \end{cases}$ $f_B \sim O(10^{-5})$ in case of liquid Ar $f_B \sim O(10^{-5})$ in case of water Cherenkov $f_B \lesssim O(10^{-3})$

2. Possibility of measurements of $\cancel{CP}$ in future LBL exp.

$\cancel{CP}$ in vacuum

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

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$
$$= 4\sum_{j<k} \mathrm{Im}\,(U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k}) \sin(\Delta E_{jk} L)$$
$$= 4\,\mathrm{Im}\,(U_{\beta 1} U^*_{\alpha 1} U^*_{\beta 2} U_{\alpha 2}) \Big[\underbrace{\sin(\Delta E_{12} L) + \sin(\Delta E_{23} L) - \sin(\Delta E_{13} L)}_{-4 \sin\left(\frac{\Delta E_{21} L}{2}\right) \sin\left(\frac{\Delta E_{32} L}{2}\right) \sin\left(\frac{\Delta E_{31} L}{2}\right)}\Big]$$

↑ unitarity condition

$$\left(\begin{aligned} &\mathrm{Im}\,(U_{\beta 1} U^*_{\alpha 1} U^*_{\beta 2} U_{\alpha 2}) \\ &= \mathrm{Im}\,(U_{\beta 2} U^*_{\alpha 2} U^*_{\beta 3} U_{\alpha 3}) \\ &= -\mathrm{Im}\,(U_{\beta 1} U^*_{\alpha 1} U^*_{\beta 3} U_{\alpha 3}) \\ &= \pm J \end{aligned}\right)$$

$$\boxed{J \equiv \frac{c_{13}}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\delta}$$

Jarlskog factor

$$= \pm 16 J \sin\left(\frac{\Delta E_{21} L}{2}\right) \sin\left(\frac{\Delta E_{32} L}{2}\right) \sin\left(\frac{\Delta E_{31} L}{2}\right)$$

signature of CP violation

in vacuum

compensates $\sigma_\nu : \sigma_{\bar\nu} = 2:1$

$$\mathcal{A} \equiv \frac{N(\nu_\alpha \to \nu_\beta) - 2\,N(\bar\nu_\alpha \to \bar\nu_\beta)}{N(\nu_\alpha \to \nu_\beta) + 2\,N(\bar\nu_\alpha \to \bar\nu_\beta)}$$

is a good asymmetric factor

in matter

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

$$P(\nu_\alpha \to \nu_\beta) = f(\Delta m^2_{jk},\ \theta_{jk},\ \delta,\ \boxed{A})$$

$$P(\bar\nu_\alpha \to \bar\nu_\beta) = f(\Delta m^2_{jk},\ \theta_{jk},\ -\delta,\ \boxed{-A})$$

$$P(\nu_\alpha \to \nu_\beta) - P(\bar\nu_\alpha \to \bar\nu_\beta) \not\propto \sin\delta$$

"$\mathcal{A}$" is not a good factor in matter

for ν $\quad i\dfrac{d\psi}{dt} = [U\, \mathrm{diag}(E_1, E_2, E_3)U^{-1} + \mathrm{diag}(A,0,0)]\psi$

for $\bar\nu$ $\quad i\dfrac{d\psi}{dt} = [U^*\, \mathrm{diag}(E_1, E_2, E_3)U^{*-1} - \mathrm{diag}(A,0,0)]\psi$

NB T violation

Symbolically we can diagonalize

$$U \,\mathrm{diag}(E_1, E_2, E_3) U^{-1} + \mathrm{diag}(A, 0, 0)$$

$$= U^M \,\mathrm{diag}(E_1^M, E_2^M, E_3^M)(U^M)^{-1}$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j<k} \mathrm{Re}(U_{\beta j}^M U_{\alpha j}^{M*} U_{\beta k}^{M*} U_{\alpha k}^M) \sin^2\left(\frac{\Delta E_{jk}^M L}{2}\right)$$

$$+ 2\sum_{j<k} \mathrm{Im}(U_{\beta j}^M U_{\alpha j}^{M*} U_{\beta k}^{M*} U_{\alpha k}^M) \sin(\Delta E_{jk}^M L)$$

$$\Delta E_{jk}^M \equiv E_j^M - E_k^M$$

$$P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha)$$

$$= 4\sum_{j<k} \mathrm{Im}(U_{\beta j}^M U_{\alpha j}^{M*} U_{\beta k}^{M*} U_{\alpha k}^M) \sin(\Delta E_{jk}^M L)$$

$$= \pm 16 J^M \sin\left(\frac{\Delta E_{21}^M L}{2}\right) \sin\left(\frac{\Delta E_{32}^M L}{2}\right) \sin\left(\frac{\Delta E_{31}^M L}{2}\right)$$

$$\boxed{J^M = \mathrm{Im}(U_{e1}^M U_{\mu 1}^{M*} U_{e2}^{M*} U_{\mu 2}^M)}$$

modified Jarlskog factor in matter

(identity(*): Naumov, Sov.Phys.JETP 74 ('92) 1

$$J^M \prod_{j<k} \Delta E_{jk}^M = J \prod_{j<k} \Delta E_{jk}$$)

$$= \boxed{\pm 16 J \frac{\Delta E_{21} \Delta E_{32} \Delta E_{31}}{\Delta E_{21}^M \Delta E_{32}^M \Delta E_{31}^M} \sin\left(\frac{\Delta E_{21}^M L}{2}\right) \sin\left(\frac{\Delta E_{32}^M L}{2}\right) \sin\left(\frac{\Delta E_{31}^M L}{2}\right)}$$

$\propto \sin\delta$

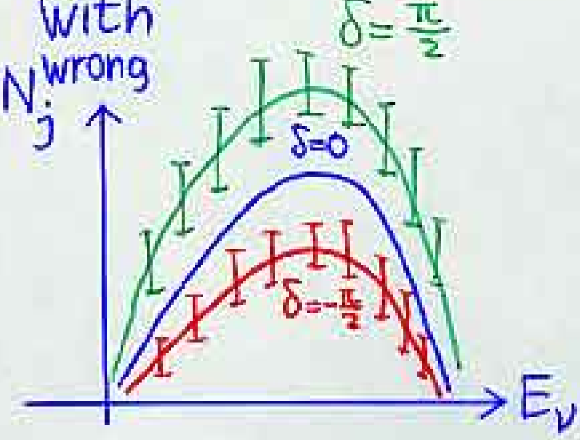
$$\cancel{T} \neq 0 \iff \sin\delta \neq 0$$

Thus T violation is clean signal of $\sin\delta \neq 0$ but it is very hard to measure experimentally.

(*) An earlier attempt : Krastev - Petcov, PL B205 ('88) 84.
Rediscovery : Harrison - Scott, PL B476 ('00) 349.

So we consider indirect measurements of CP violation

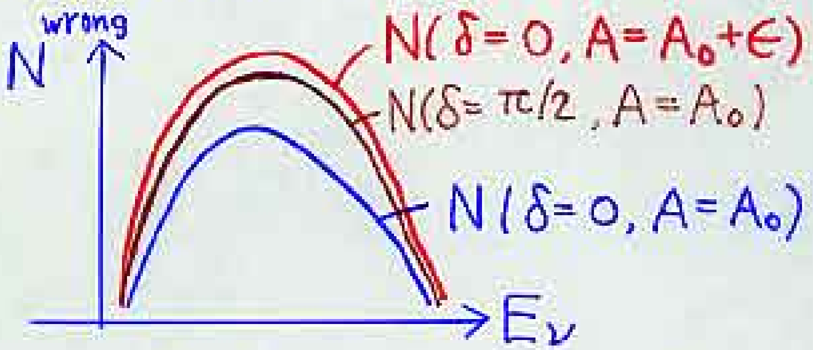
* Assume three flavor mixing and compare the data with prediction for $\delta = 0$:



* Correlation of errors

To measure δ, we have to know all other variables with certain precision.

If we had situation like:



then there would be no way to determine δ.

$$\boxed{\Delta\chi^2 \equiv \min_{\bar{\theta}_{jk}, \overline{\Delta m}^2_{jk}, \bar{A}} \sum_i \frac{\left[N_i(\Delta m^2_{jk}, \theta_{jk}; \delta; A) - N_i(\overline{\Delta m}^2_{jk}, \bar{\theta}_{jk}; \bar{\delta}=0; \bar{A})\right]^2}{\sigma_i^2}}$$

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

$$\Delta\chi^2 \gtrsim \Delta\chi^2(3\sigma\mathrm{CL})$$

→ We can estimate detector size to reject "$\delta = 0$" at 3σCL.

Optimization of sensitivity to δ w.r.t. (E_μ, L)

	$\Delta\theta_{ij}, \Delta m^2_{ij}$	$\Delta A/A$	f_B	$\Delta m^2_{21}/10^{-5}eV^2$	E_{th}/GeV	E_μ/GeV	L/km	
KOS	included	$\pm 10\%$	0	5	1	$\lesssim 6$	600 - 800	$\Delta\chi^2_3$
				10	1	$\lesssim 50$	500 - 2000	
FHL	included	0	0	10	4	30 ~ 50	2800 - 4500	
PY	included	$\pm 5\%$	10^{-5}	3.2	0.1	~ 50	~ 3000	
			10^{-3}			~ 20	~ 1000	
		$\pm 10\%$	10^{-5}			~ 15	~ 1000	
			10^{-3}			~ 10	~ 800	
Huber	included	$\pm 10\%$	0	10	0.1	$\gtrsim 20$	$\gtrsim 2000$	
				3.5		25	1500	

Ref: KOS Koike - Ota - Sato, hep-ph/0011387 (revised, to be published in PRD)
FHL Freund - Huber - Lindner, NP B651 ('01) 331
PY Pinney - O.Y., PR D64 ('01) 093008
Huber private communication

※ $\Delta\chi^2$ used in the analyses of indirect CP measurements

KOS

$$\Delta\chi_3^2 \equiv \min_{\overline{\theta_{jk}},\overline{\Delta m_{jk}^2},\overline{A}} \sum_i \frac{1}{\sigma_i^2}\Big[N_i(\theta_{jk},\Delta m_{jk}^2,A,\delta)_{\nu_e\to\nu_\mu} / N_i(\theta_{jk},\Delta m_{jk}^2,A,\delta)_{\bar\nu_e\to\bar\nu_\mu} - N_i(\overline{\theta_{jk}},\overline{\Delta m_{jk}^2},\overline{A},0)_{\nu_e\to\nu_\mu} / N_i(\overline{\theta_{jk}},\overline{\Delta m_{jk}^2},\overline{A},0)_{\bar\nu_e\to\bar\nu_\mu}\Big]^2$$

indirect

(FHL, Huber
PY)

$$\Delta\chi^2_{\text{indirect}} \equiv \min_{\overline{\theta_{jk}},\overline{\Delta m_{jk}^2},\overline{A}} \sum_i \left\{ \left.\frac{[N_i(\theta_{jk},\Delta m_{jk}^2,A,\delta) - N_i(\theta_{jk},\Delta m_{jk}^2,A,0)]^2}{\sigma_i^2}\right|_{\nu_e\to\nu_\mu} + \left.\frac{[\quad // \quad]^2}{\sigma_i^2}\right|_{\bar\nu_e\to\bar\nu_\mu} + \left.\frac{[\quad // \quad]^2}{\sigma_i^2}\right|_{\nu_\mu\to\nu_\mu} + \left.\frac{[\quad // \quad]^2}{\sigma_i^2}\right|_{\bar\nu_\mu\to\bar\nu_\mu} \right\}$$

koike- Ota- Sato hep-ph/0011387 (revised)

optimization with $\Delta\chi_3^2$

$\Delta m_{21}^2 = 1 \times 10^{-4}\,eV^2$

$\sin^2 2\theta_{13} = 0.04$ $\sin^2 2\theta_{13} = 0.01$

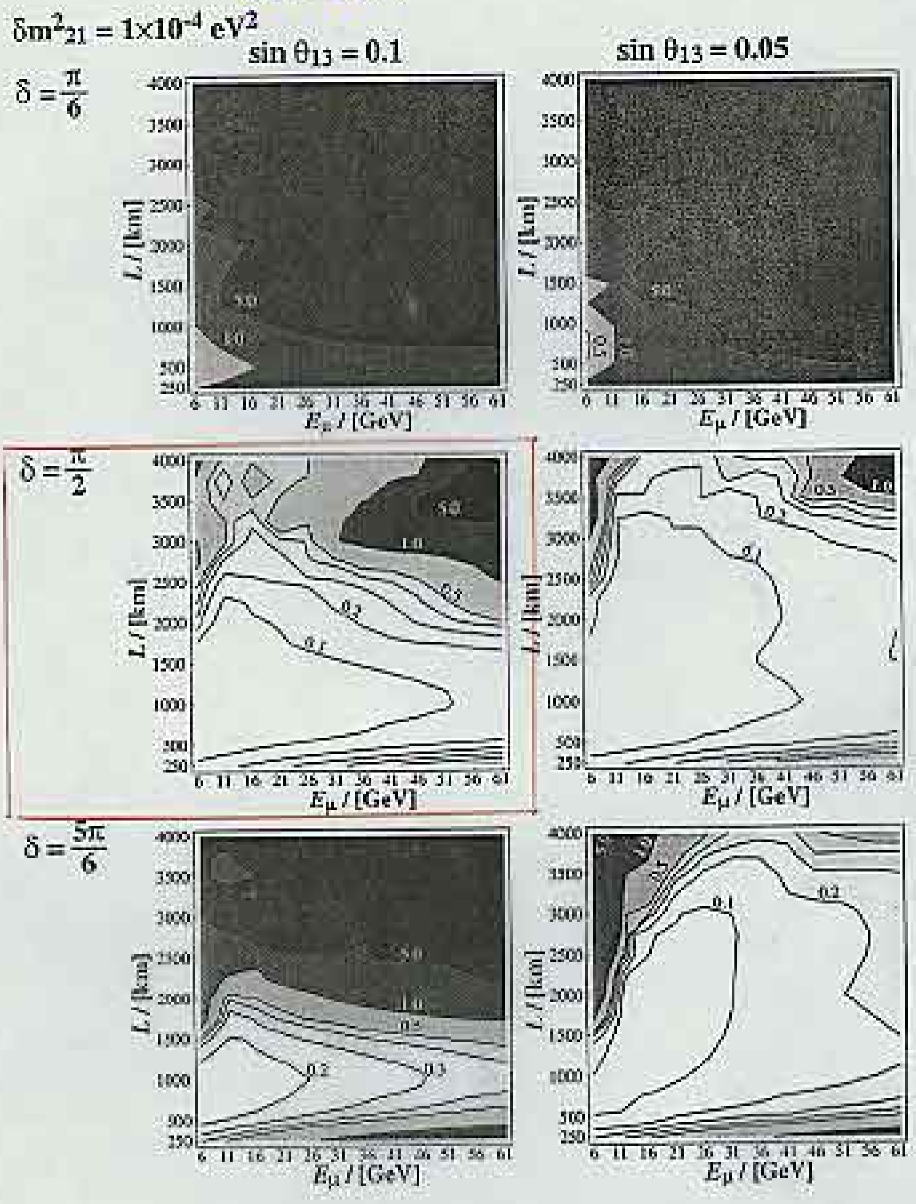


Figure 9: Same as Fig.8, but for different parameters. All the graphs presented here are for $\delta m_{21}^2 = 1 \times 10^{-4}\mathrm{eV}^2$. The graphs in left column are for $\sin\theta_{13} = 0.1$ while the ones in right column are for $\sin\theta_{13} = 0.05$. The top two graphs are for $\delta = \pi/6$, the second two graphs are for $\delta = \pi/2$, and the bottom two graphs are for $\delta = 5\pi/2$. Parameters not presented here are taken to be same as Fig.2. The difference of the sensitivity for $\delta = \pi/6$ and for $\delta = 5\pi/6$ is due to the difference of matter effect.

Koike-Ota-Sato hep-ph/0011387 (revised)

optimization with $\Delta\chi_3^2$

$\Delta m_{21}^2 = 5\times10^{-5}\,eV^2$

$\sin^2 2\theta_{13} = 0.04$ $\sin^2 2\theta_{13} = 0.01$

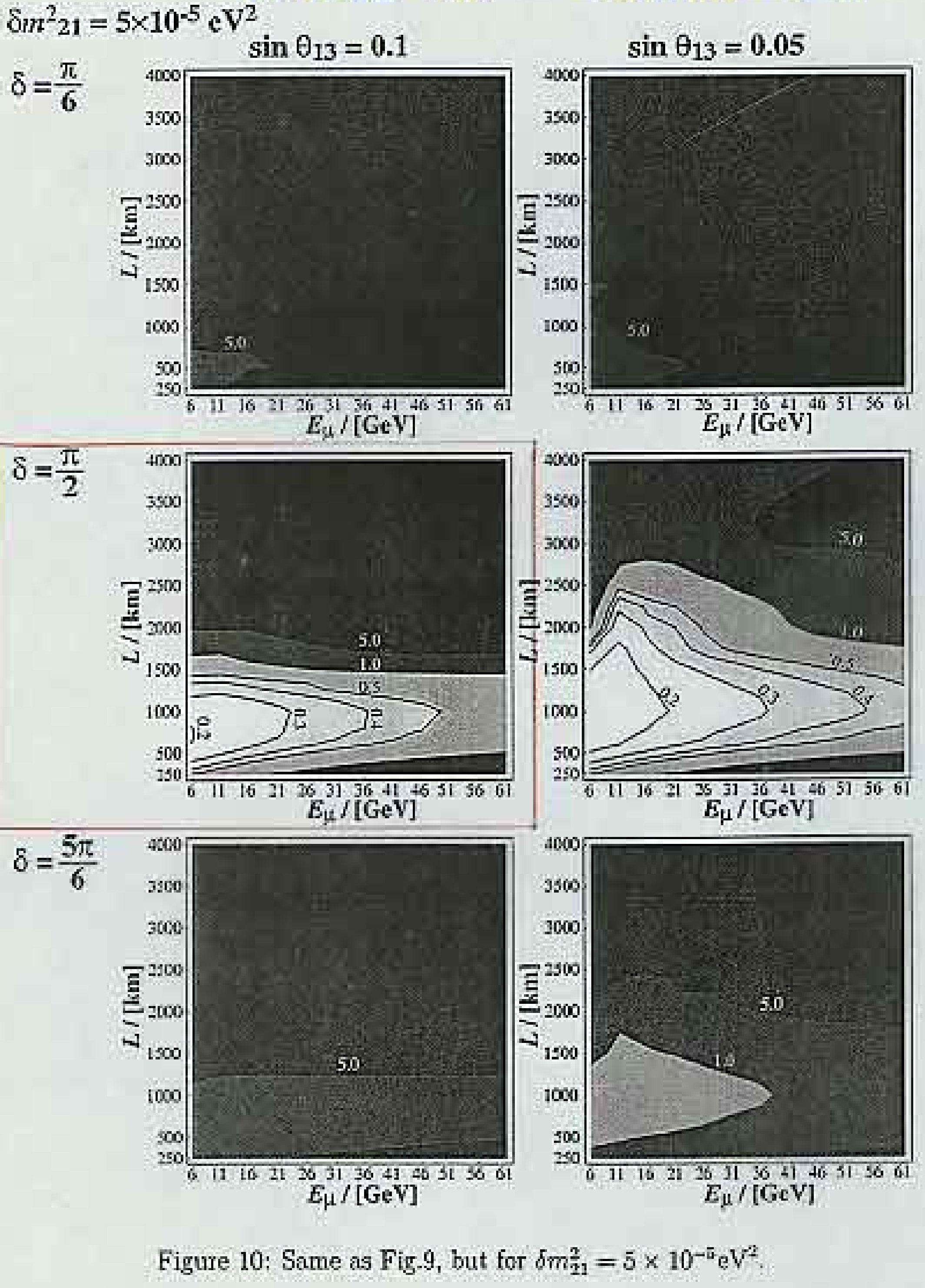


Figure 10: Same as Fig.9, but for $\delta m_{21}^2 = 5\times10^{-5}\mathrm{eV}^2$.

Freund - Huber - Lindner NP B651 ('01) 331

sensitivity to δ

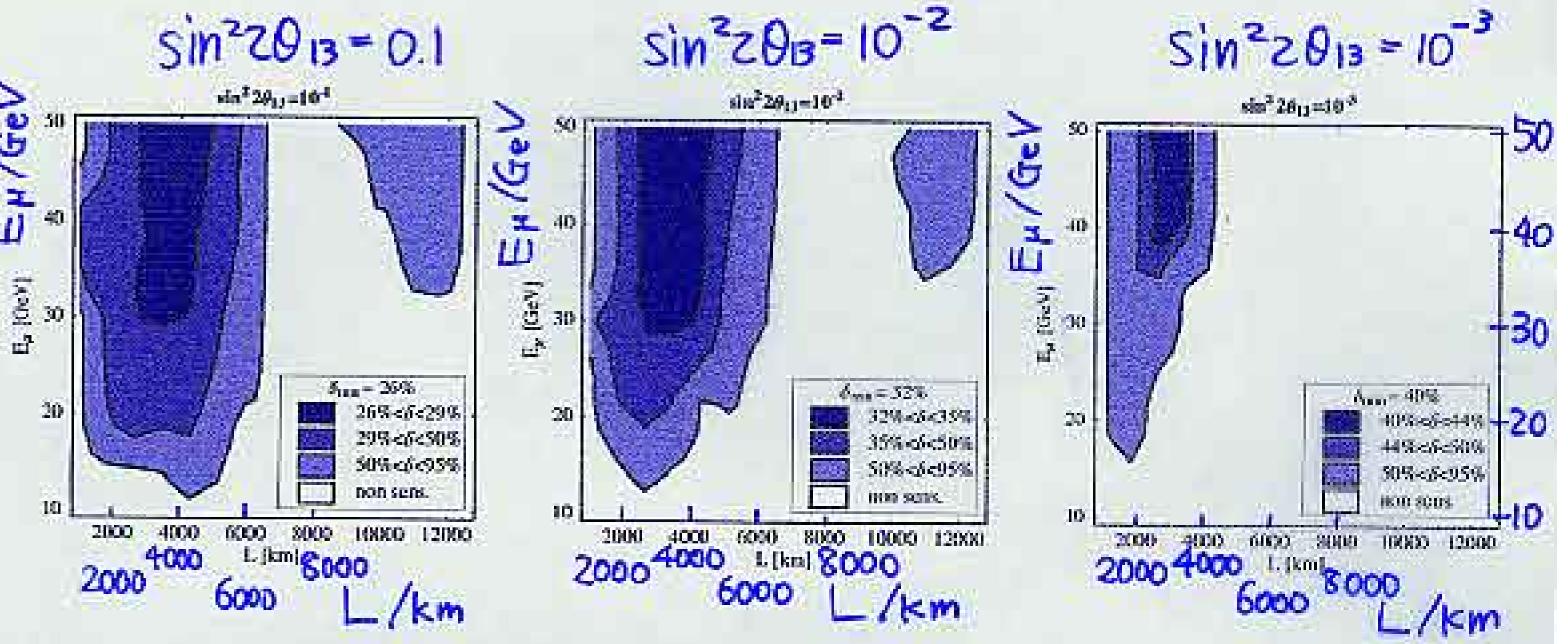
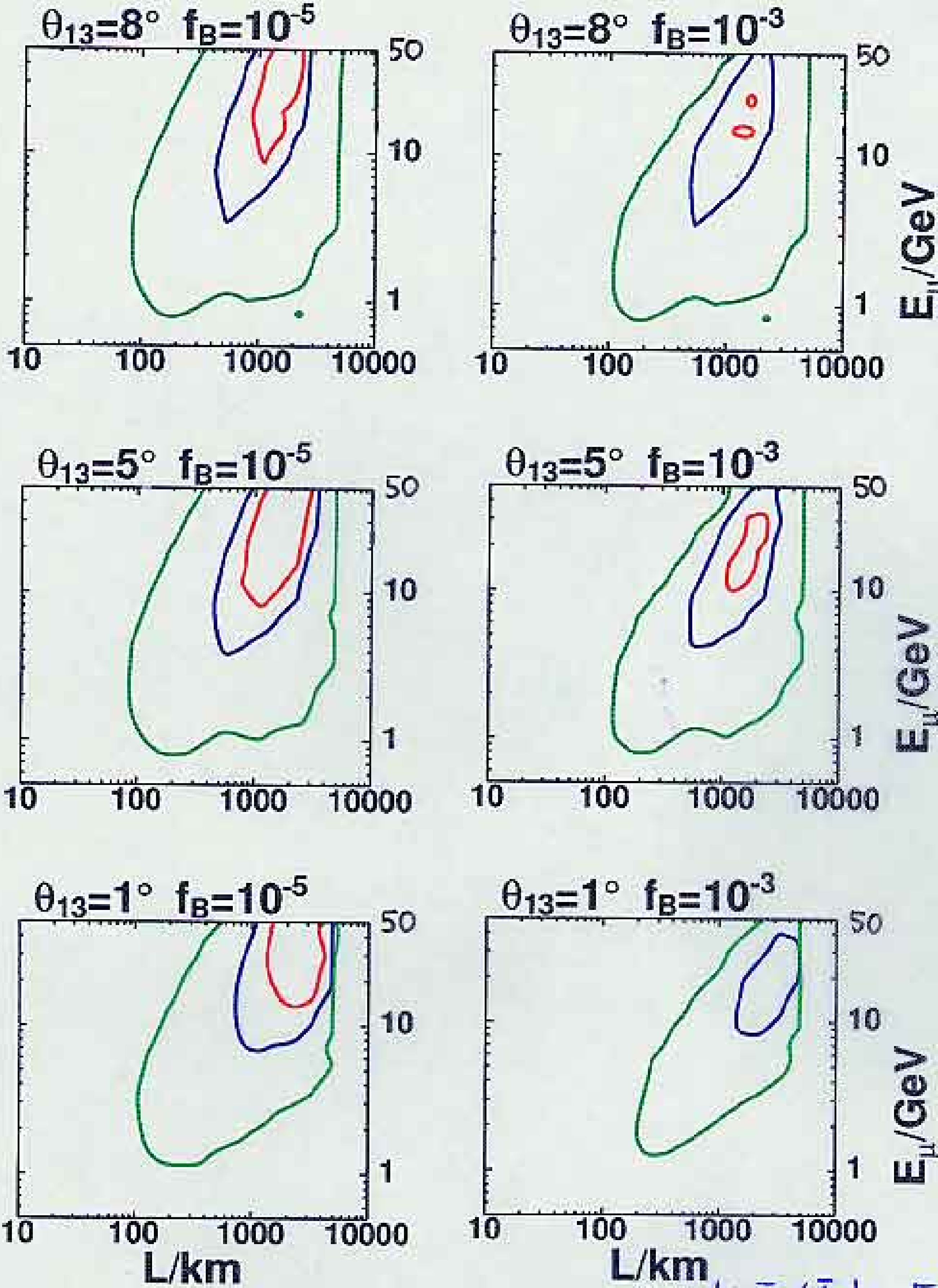


Figure 13: Results of fits of the CP phase δ_{CP} as function of the baseline L and the muon energy E_μ for $\Delta m^2_{31} = 3.5 \cdot 10^{-3}\,\mathrm{eV}^2$, $\Delta m^2_{21} = 10^{-4}\,\mathrm{eV}^2$, $\theta_{23} = \pi/4$, $\theta_{12} = \pi/4$, $N_\mu m_{kt} = 2 \cdot 10^{21}$ kt year and three values of $\sin^2 2\theta_{13}$ (10^{-1}, 10^{-2}, 10^{-3}). Dark shading indicates the preferred regions. The quantity δ plotted here is the percentage of the δ_{CP} parameter space $[-\pi/2, \pi/2]$ which is compatible with the simulated experimental data at the 3σ confidence level. The contour lines correspond to $\delta = 50\%$ and $\delta = 95\%$. In the white shaded region no information on the CP phase can be obtained.

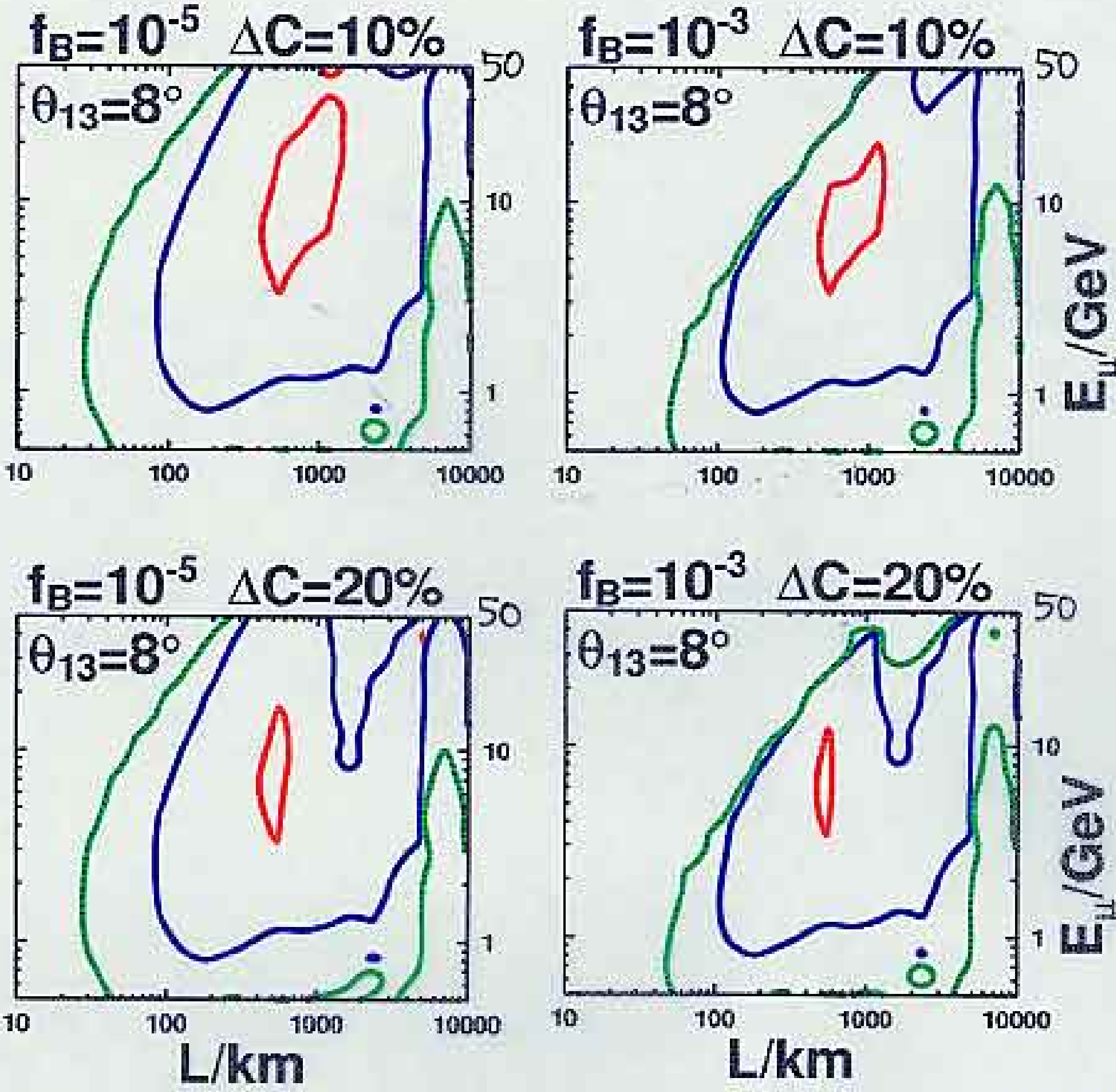


$|\Delta\bar{A}/\bar{A}| = 5\%$

60kt
100kt
1000kt

detector size
as a function of $\left\{ \begin{array}{l} \text{baseline } L \\ \text{muon energy } E_\mu \end{array} \right\}$
to reject a hypothesis $\delta=0$
at 3σ CL

Pinney-O.Y. PRD64('01)093008



$$\Delta C \equiv \left|\frac{\Delta \bar{A}}{\bar{A}}\right|$$

100kt
1000kt
10000kt

Fig.8

detector size
as a function of $\left\{\begin{array}{l}\text{baseline } L\\ \text{muon energy } E_\mu\end{array}\right\}$
to reject a hypothesis $\delta=0$
at 3σ CL Pinney-O.Y. PRD64('01)093008

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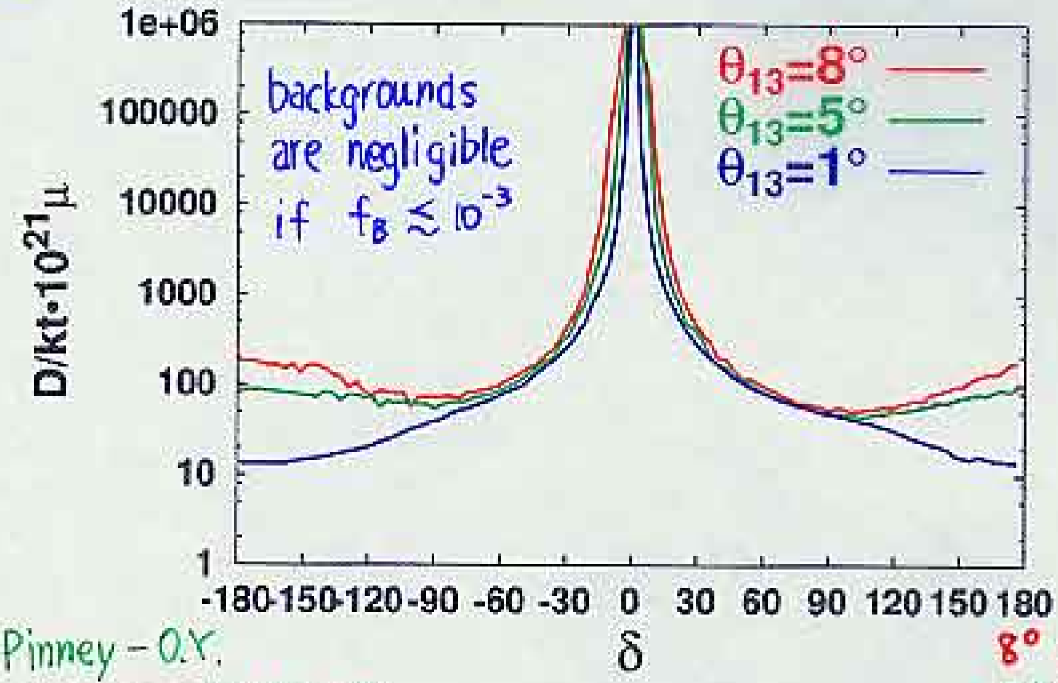
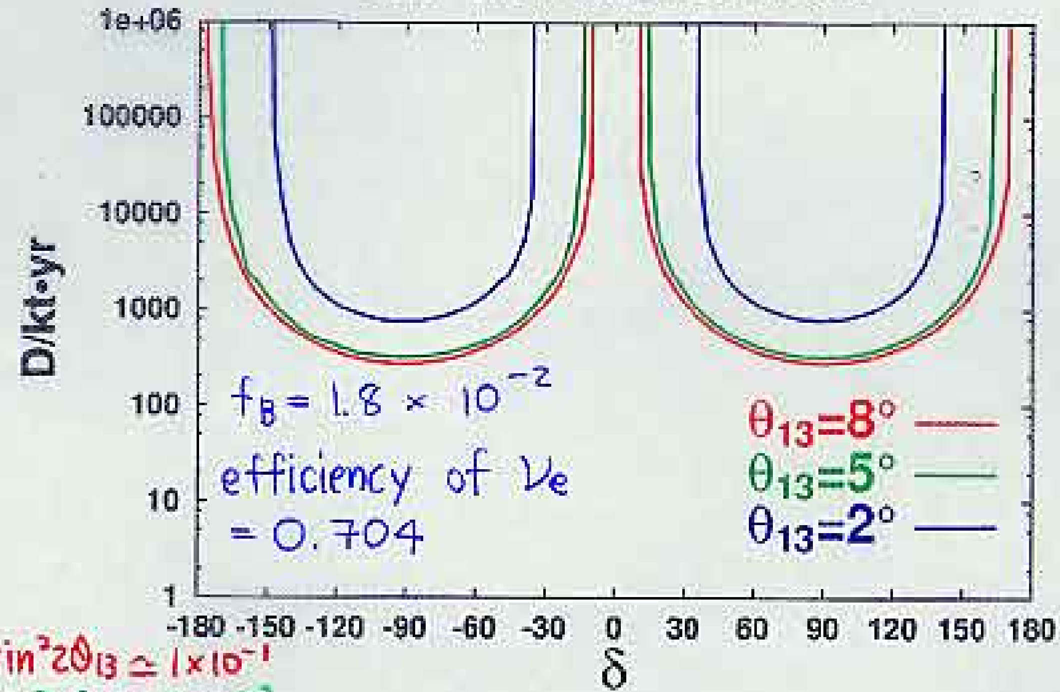
nufact (E=20GeV, L=1000km)



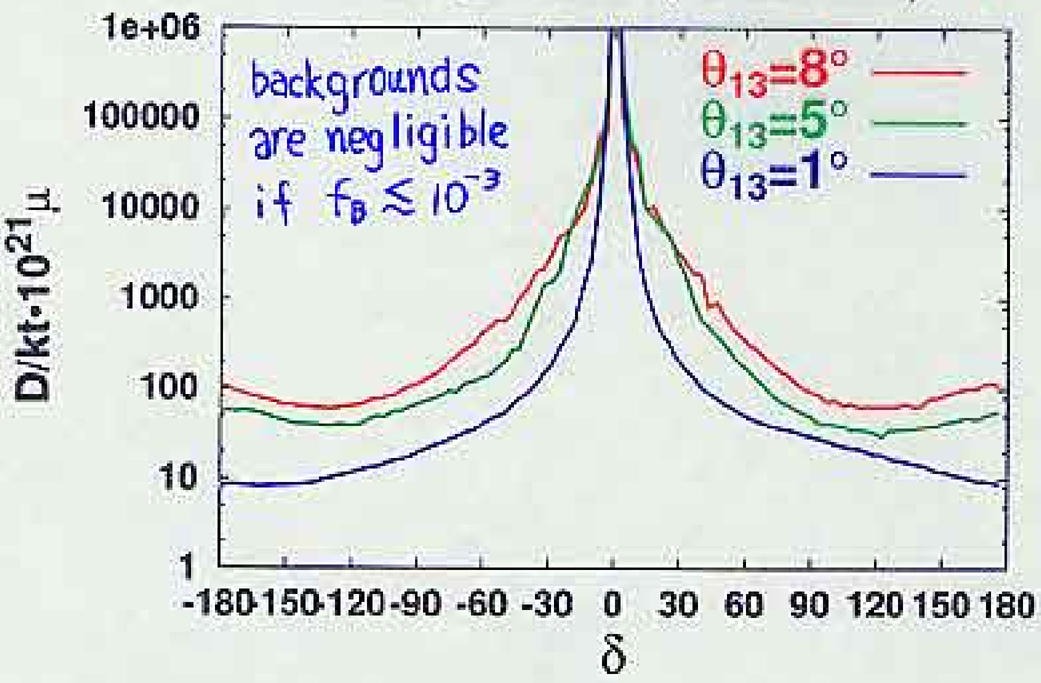
JHF 4MW NBB 1R e-like



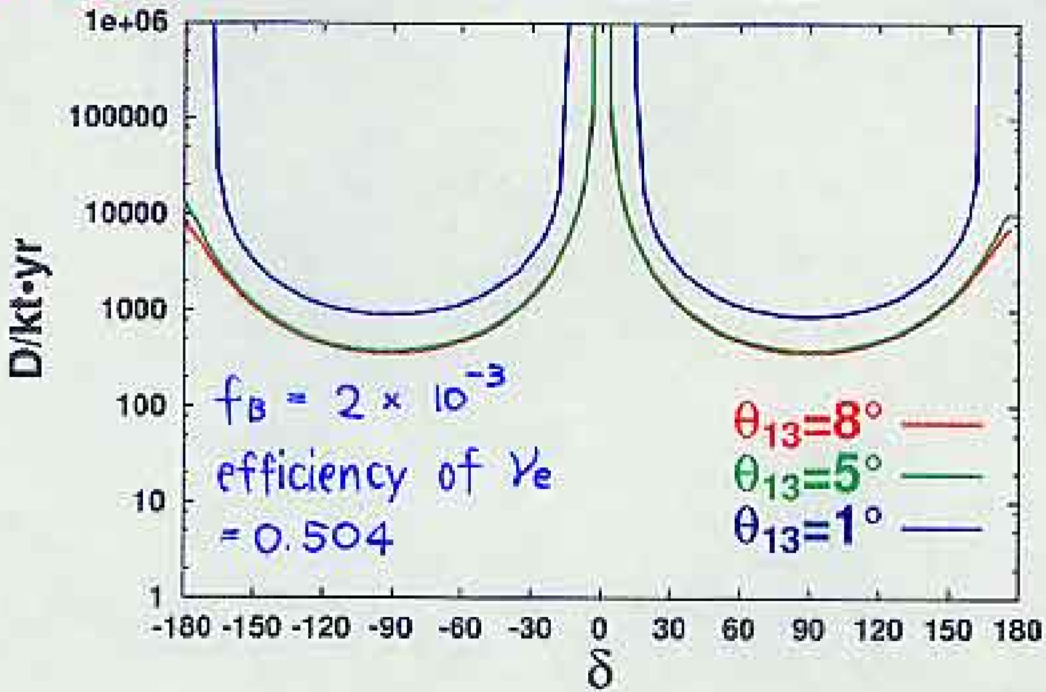
Pinney - O.Y.
PRD64('01)093008

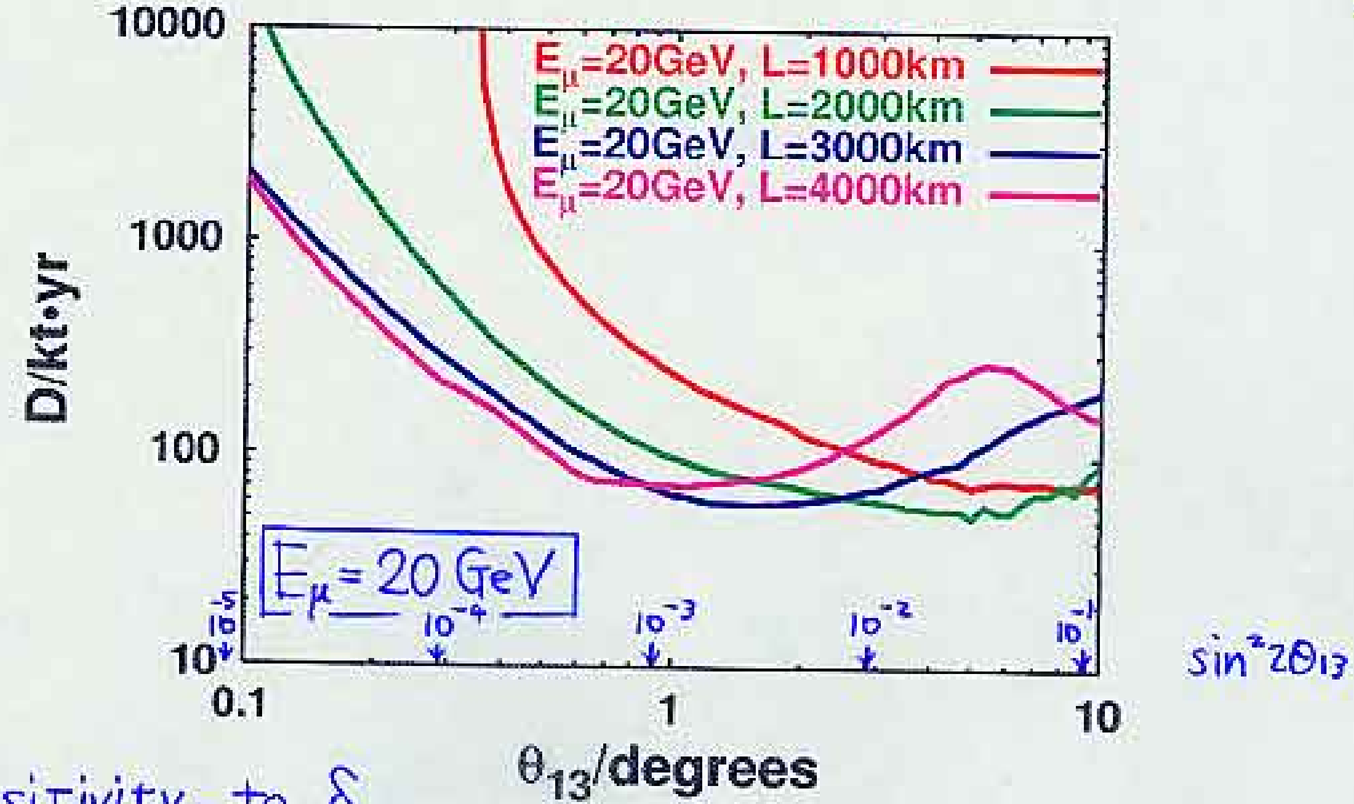
8° $\sin^2 2\theta_{13} \simeq 1\times10^{-1}$
5° $\sin^2 2\theta_{13} \simeq 3\times10^{-2}$
1° $\sin^2 2\theta_{13} \simeq 1\times10^{-3}$

nufact (E=50GeV, L=3000km)



JHF 4MW NBB π^0cut





sensitivity to δ

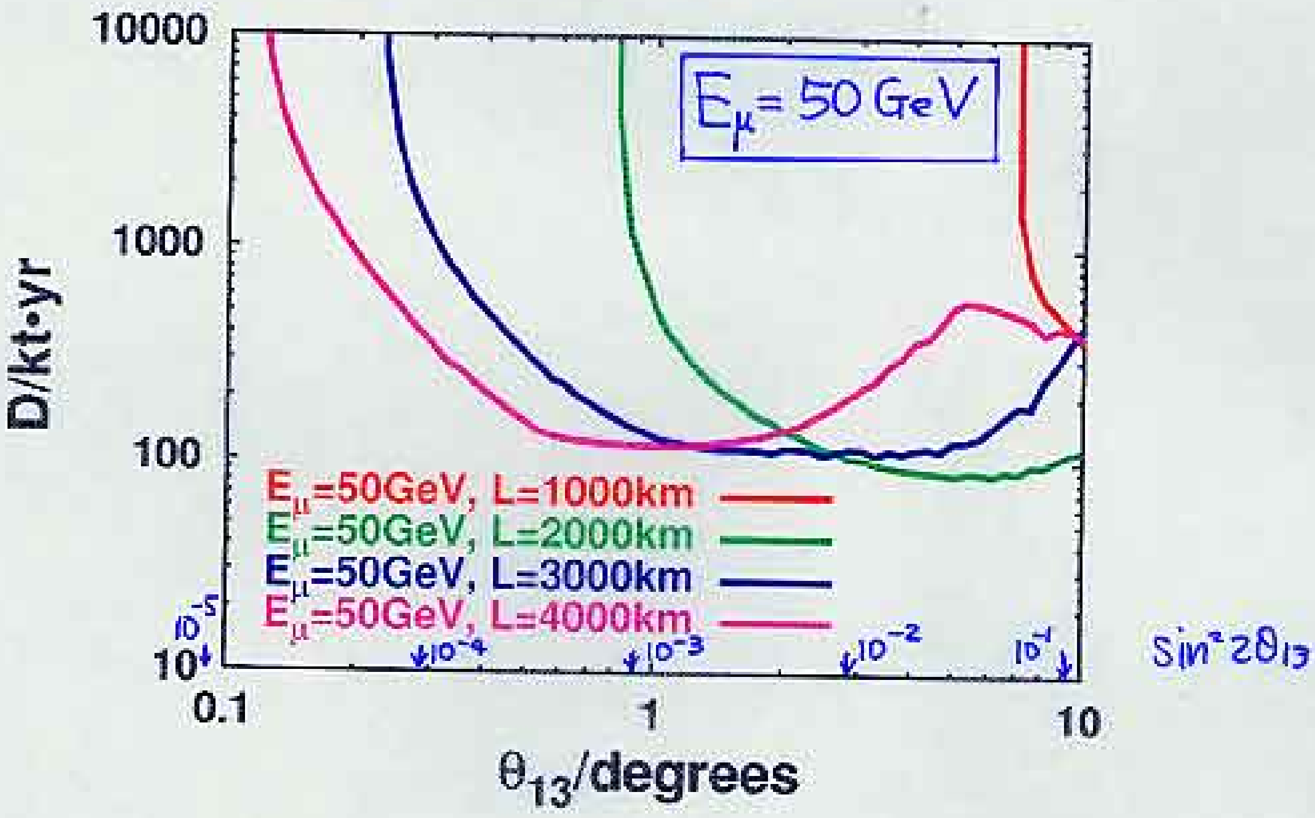


Fig. 1. Data size (kt·yr) required to reject a hypothesis of $\bar{\delta} = 0$ at 3σ when the true value is $\delta = \pi/2$, in the case of a neutrino factory with 10^{21} useful muon decays per year and a background fraction $f_B = 10^{-3}$.

$\boxed{f_B = 10^{-3}}$

J. Pinney hep-ph/0106210

General features

if $f_B = 10^{-3}$ & $\sin^2 2\theta_{13} \sim 0.1$

then lower E_μ & L preferred

PY $E_\mu \sim 20$ GeV
$L \sim 1000$ km

if $|\Delta A/A| \leq 10\%$ ← This may be too pessimistic
cf. Geller - Hara @nufact01
hep-ph/0111342
$|\Delta P/P| \lesssim 5\%$

then lower E_μ & L preferred

KOS $E_\mu \lesssim 7$ GeV, $L \sim 500-700$ km

PY $E_\mu \sim 15$ GeV, $L \sim 1000$ km

Huber $E_\mu \sim 25$ GeV, $L \sim 1500$ km

Otherwise $E_\mu \sim 50$ GeV, $L \sim 3000$ km
is the optimum.

NB The results are in qualitative agreement, but more detailed analysis seems to be needed to reach quantitative agreement.

The behavior of $\Delta\chi^2_{\text{indirect}}$ & $\Delta\chi^2_3$ at large E_μ

$$\left.\begin{array}{l} \underset{\text{KOS}}{\Delta\chi^2_3} \propto \\ \\ \underset{\text{PY}}{\Delta\chi^2_{\text{indirect}}} \propto \end{array}\right\} \frac{\tilde{J}^2}{E_\mu}\left(\sin\delta + \text{const.}\cos\delta\frac{\Delta m^2_{32}L}{E_\mu} + \cdots\right)^2$$

$\boxed{\text{as } E_\mu \to \text{large}}$

after correlations of errors are taken into account

where

$$\tilde{J} \equiv \frac{c_{13}}{8}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

→ • sensitivity is lost at large E_μ

(consistent with the claim by Lipari PR D64 ('01) 033002)

• both $\Delta\chi^2_3$ & $\Delta\chi^2_{\text{indirect}}$ are sensitive mainly to $\sin\delta$ and a little to $\cos\delta$

cf. (the case ($E_\mu = 50\,\text{GeV}$, $L = 3000\,\text{km}$)

$$\frac{\Delta m^2_{32}L}{E_\mu} \sim 1$$

is expected to be sensitive both $\sin\delta$ & $\cos\delta$)

* J. Sato claims :

main contribution is from $\sin\delta$

main contrib. is from $\cos\delta$

$$\Delta\chi^2 = F(\sin\delta) + \underbrace{\cancel{G(\cos\delta)}}_{\text{this corresponds mainly to CP-even processes}}$$

$$\Downarrow$$

$$\Delta\tilde{\chi}^2 = F(\sin\delta)$$

* Optimum set $(\tilde{E}_\mu, \tilde{L})$ obtained from $\Delta\tilde{\chi}^2$ is different from

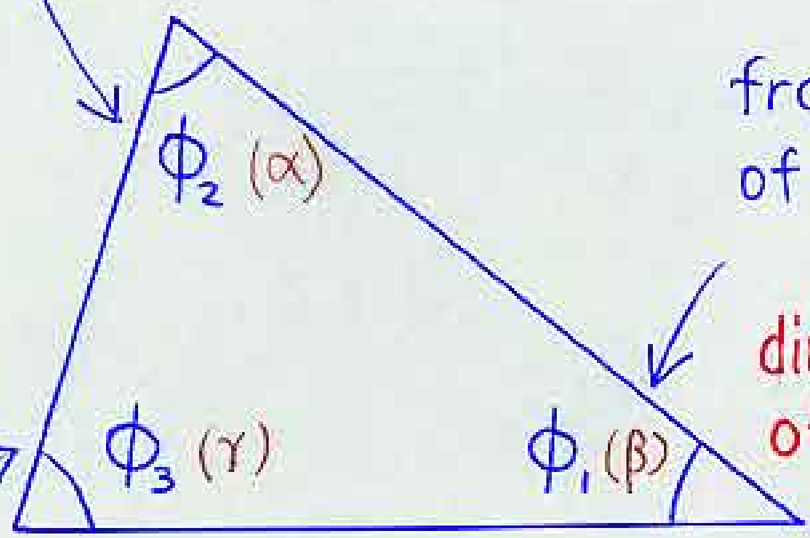
(E_μ, L) obtained from $\Delta\chi^2$.

* I claim that we are assuming the framework of $N_\nu = 3$ from the beginning and we should not lose useful information by discarding $G(\cos\delta)$.

$\longrightarrow$ The correct optimum set is (E_μ, L).

<u>NB</u> B factory (Thanks to N. Kitazawa)

from measurements
of $B \to 2\pi$: not necessarily CP-odd
indirect measurement of $\cancel{CP}$



from measurements
of $\begin{pmatrix} B^0 \to J/\psi\, K_s \\ \bar{B}^0 \to J/\psi\, K_s \end{pmatrix}$
direct measurement
of $\cancel{CP}$

from measurements
of $B^\pm \to D_1^0 K^\pm$: not necessarily CP-odd
indirect measurement of $\cancel{CP}$

$$\boxed{\begin{aligned} \tan\phi_3 &= -\frac{t_{12}\sin\delta}{t_{12}\cos\delta + t_{23}s_{13}} \\ \tan\phi_2 &= -\frac{t_{12}t_{23}\sin\delta}{t_{12}t_{23}\cos\delta - s_{13}} \\ \phi_1 &= \pi - \phi_2 - \phi_3 \end{aligned}}$$

ϕ_j $(j=1,2,3)$ do depend on $\cos\delta$ as well as $\sin\delta$.

parameter degeneracy (2^3 fold)

* (δ, θ_{13}) ambiguity

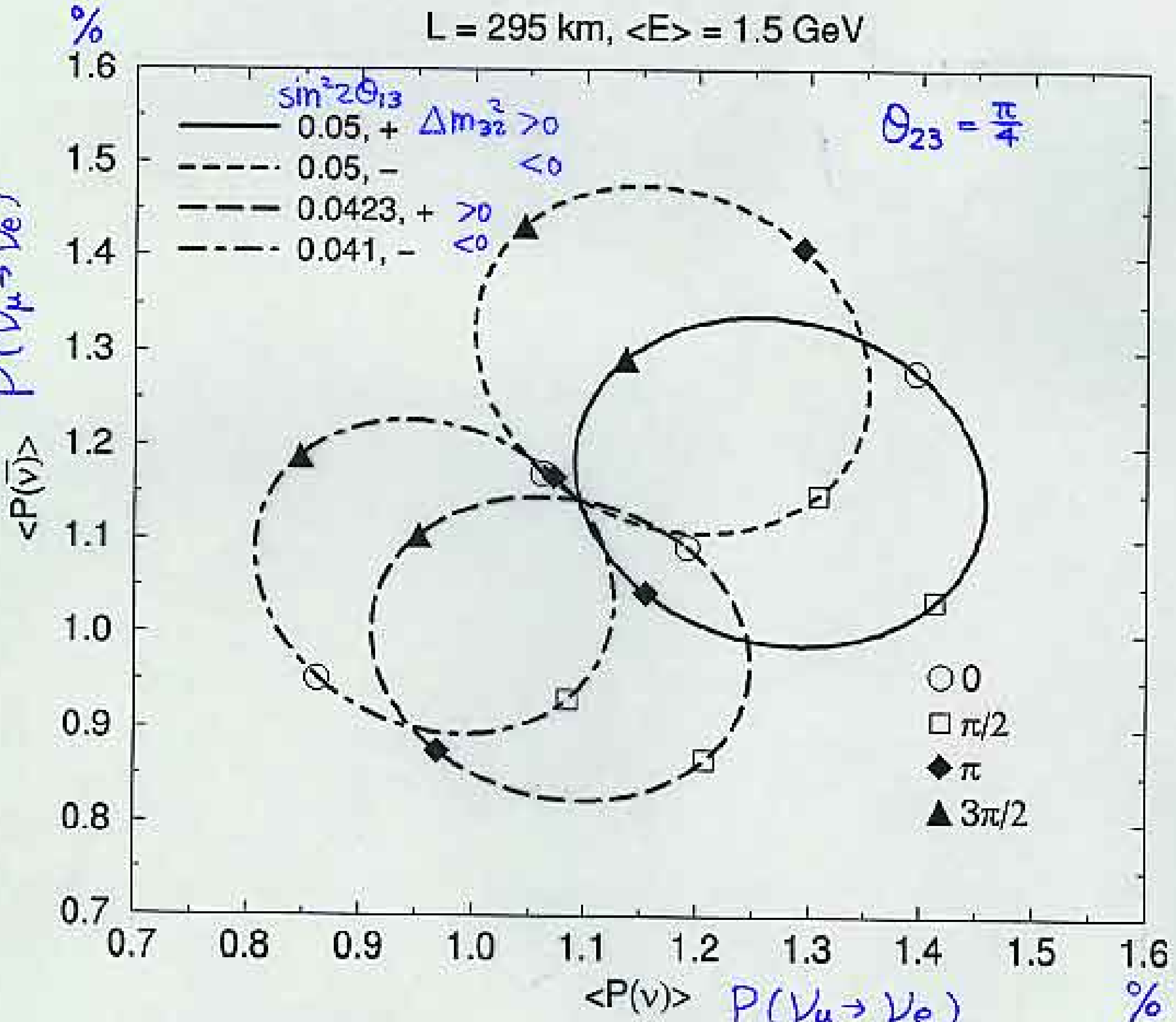
  Burguet-Castell et al. NPB608('01)301

* sign (Δm^2_{32}) ambiguity

  Minakata-Nunokawa JHEP0110('01)001

* $(\theta_{23}, \frac{\pi}{2}-\theta_{23})$ ambiguity

  Barger-Marfatia-Whisnant, hep-ph/0112119



Minakata-Nunokawa hep-ph/0111131

3. Summary

$\boxed{D \equiv \text{ detector size to reject } \delta = 0 \text{ @ } 3\sigma \text{CL}}$

JHF phase II (4MW)

$D_{JHF} \gtrsim 1 \, \text{Mt} \cdot \text{yr}$ for $\sin^2 2\theta_{13} \gtrsim 0.005$

ν factory

$D_{\nu \text{factory}} \gtrsim 100 \, \text{kt} \cdot 10^{21} \mu$

for $\sin^2 2\theta_{13} \gtrsim 10^{-4}$

optimal set

$$(E_\mu, L) \sim \begin{cases} (50\,\text{GeV}, 3000\,\text{km}) & f_B \lesssim 10^{-5} \\ (20\,\text{GeV}, 1000\,\text{km}) & f_B \sim 10^{-3} \end{cases}$$

f_B : background fraction

My personal impression

1st stage JHF phase I (2007 ~)

measurement of θ_{13}

2nd stage JHF phase II (? ~)

measurement of δ

(if θ_{13} turns out to be small

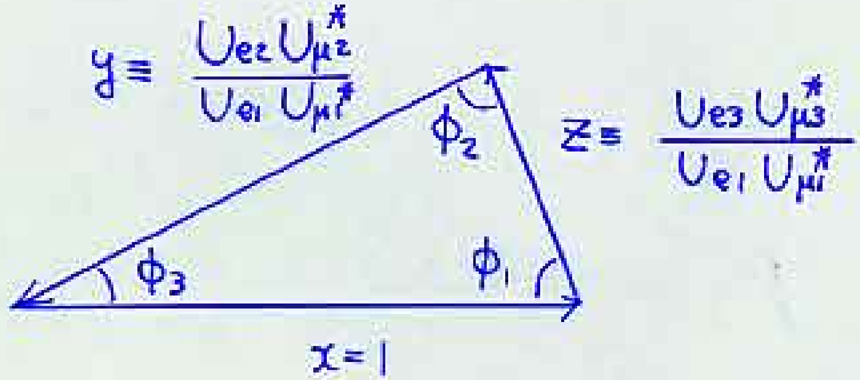
3rd stage ν factory (?? ~)

measurement of δ)

Future problems

- direct measurement of CP?
- test of unitarity

Farzan - Smirnov hep-ph/0201105



detemination of y, z and one of the angles ϕ_j $(j=1,2,3)$ gives a check of unitarity.

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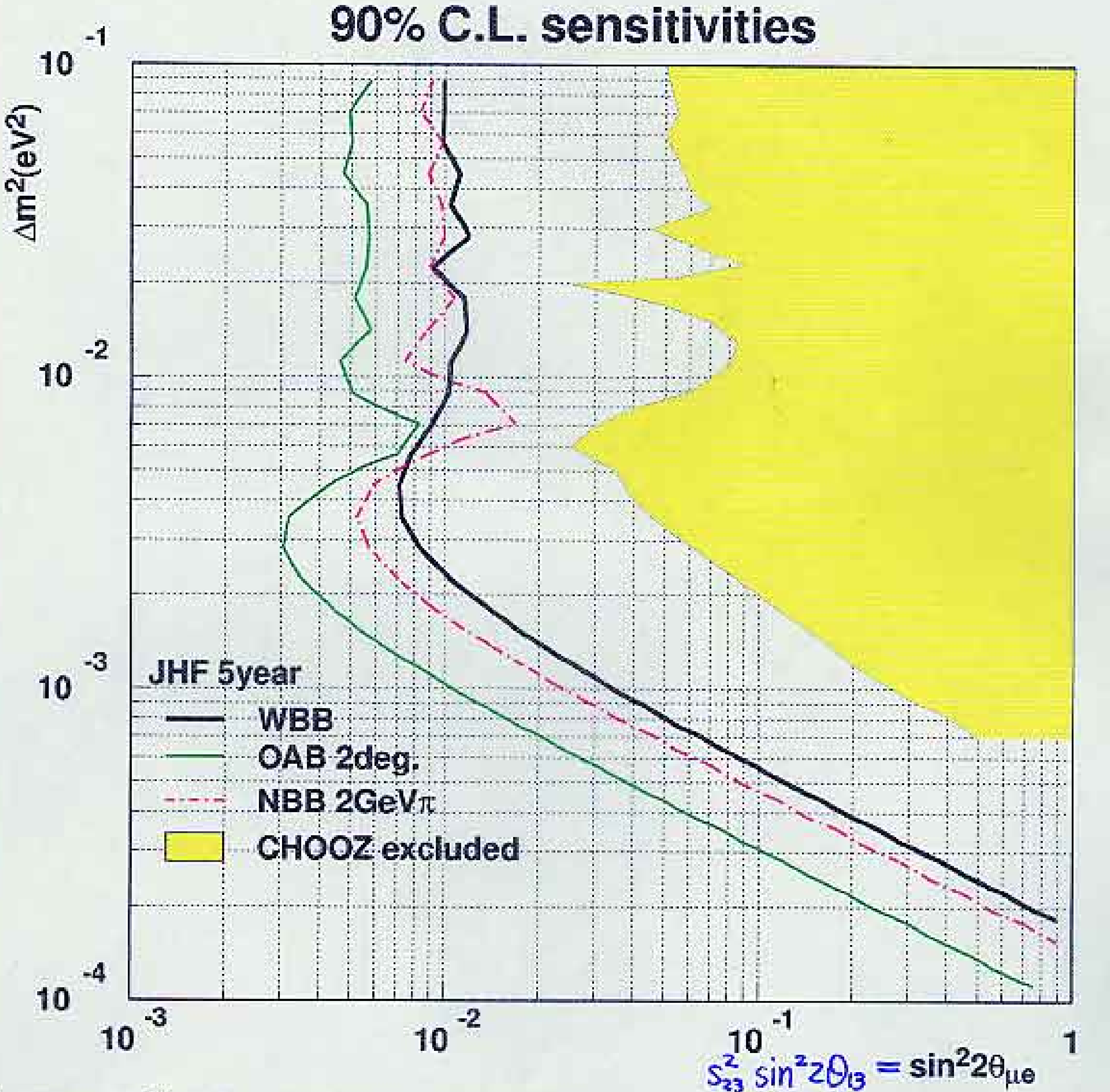
A2

sensitivity to θ_{13} of JHF

Y. Itow et al. hep-ex/0106019



4: The 90% C.L. sensitivity contours for 5 years exposure of WBB, OA
ions. The 90% C.L. excluded region of CHOOZ is plotted as a comparison
aximum mixing of $\sin^2\theta_{23} = 0.5$ is assumed to convert from $\sin^2 2\theta_{13}$ to