4 ν oscillation analysis of atmospheric neutrino data & application to LBL experiments

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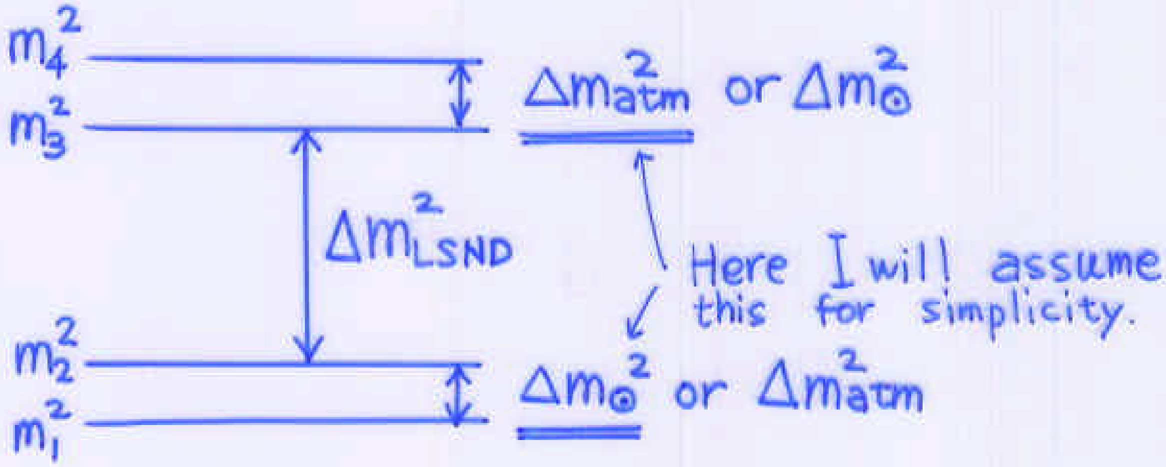
1. Introduction

(1) sterile neutrinos

* $\nu_\odot$ $\quad \Delta m_\odot^2 \sim 10^{-10}\,eV^2$ or $10^{-5}\,eV^2$
* ν_{atm} $\quad \Delta m_{atm}^2 \sim 10^{-2.5}\,eV^2$
* ν_{LSND} $\quad \Delta m_{LSND}^2 \sim 1\,eV^2$

To account for all the anomalies we need $\nu_{active} + \nu_s$.

The mass pattern has to be the following to explain three anomalies:



(2) BBN constraint on 4 ν schemes

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}\equiv U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

<u>View (A)</u> $\begin{pmatrix}\text{reactors}\\ \text{accelerators}\end{pmatrix}+\begin{pmatrix}\text{BBN}\\ N_\nu<4\end{pmatrix}$

$$\Rightarrow U\simeq\begin{pmatrix}c_\odot & s_\odot & \epsilon & \epsilon\\ \epsilon & \epsilon & c_{atm} & s_{atm}\\ \epsilon & \epsilon & -s_{atm} & c_{atm}\\ -s_\odot & c_\odot & \epsilon & \epsilon\end{pmatrix}$$

Okada - O.Y. ('97)

disfavored by SK @ ν 2000

$\nu_\odot$: $\boxed{\nu_e \leftrightarrow \nu_s \text{ w/ SMA MSW}}$

ν_{atm} : $\nu_\mu \leftrightarrow \nu_\tau$

ν_{LSND} : from small off-diagonal components

<u>View (B)</u> Forget about BBN($N_\nu<4$)

$\begin{pmatrix}\text{reactors}\\ \text{accelerators}\end{pmatrix}$ only

$$\Rightarrow U\simeq\begin{pmatrix}U_{e1} & U_{e2} & \epsilon & \epsilon\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}$$

$\nu_\odot$: analysis by Giunti - Gonzarez - Garcia - Peña - Garay ('00)

$c_s\equiv|U_{s1}|^2+|U_{s2}|^2$

SMA exists for $0\le c_s\le 1$

$\boxed{\text{LMA exists for } 0\le c_s \lesssim 0.2}$

VO exists for $0\le c_s\lesssim 0.4$

$\boxed{\nu_{atm} : \text{present work}}$

ν_{LSND} : from small off-diagonal components

2. $N_\nu = 4$ analysis of ν_{atm}

Assumptions

1) $U_{e3}, U_{e4} \to 0$ $\quad(\because |U_{e3}|, |U_{e4}| \ll 1$ from Bugey$)$

2) $\Delta m^2_{21} \equiv \Delta m^2_\odot \to 0$ $\quad(\because |\Delta m^2_\odot L_{atm}/E_{atm}| \ll 1$ for $\nu_{atm})$

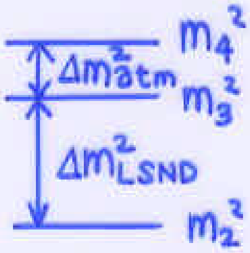
3) $\Delta m^2_{32} \equiv \Delta m^2_{LSND} = 0.3\,\mathrm{eV}^2$ as a reference value

$$\left(\because\ 1 - P(\nu_\mu \to \nu_\mu)\Big|_{CDHSW} = \underbrace{4|U_{\mu 2}|^2(1-|U_{\mu 2}|^2)}_{\lesssim 0.6 \text{ in the allowed region of } \nu_{atm}} \sin^2\!\left(\frac{\Delta m^2_{LSND} L}{4E}\right)\right)$$

$\to$ ν_e decouples from ν_μ, ν_τ, ν_s

$$U \to \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ 0 & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ 0 & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

: reduces to $N_\nu = 3$ analysis



standard parametr. in PDG $\begin{cases} \theta_{12} \leftrightarrow \theta_{23} - \frac{\pi}{2} \\ \theta_{13} \leftrightarrow \theta_{24} \\ \theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{34} \\ \delta \leftrightarrow \delta_1 \end{cases}$ present parametr.

originally we started with:

<u>6 mixing angles</u>

θ_{12}, θ_{13}, θ_{14}, θ_{23}, θ_{24}, θ_{34}

- $\theta_{12} \to \theta_\odot$ decouples as $\Delta m^2_{21} \to 0$
- θ_{13}, θ_{14} almost $\to 0$ $(\because$ Bugey$)$
- $\theta_{23} \to$ mixing of $\sin^2(\Delta m^2_{atm} L/4E)$ & $\sin^2(\Delta m^2_{LSND} L/4E)$ in ν_{atm}
- $\theta_{24} \to \theta_{atm}$
- $\theta_{34} \to$ (mixing of $(\nu_\mu \leftrightarrow \nu_\tau$ & $\nu_\mu \leftrightarrow \nu_s)$ in ν_{atm})

<u>3 CP phases</u>

δ_1, δ_2, δ_3

- $\delta_1 \to$ physical
- $\delta_2, \delta_3 \to$ decouples as $\theta_{13}, \theta_{14} \to 0$

results of the analysis

$$\chi^2 \equiv \chi^2(\text{SK contained}) + \chi^2(\text{SK upward through going } \mu)$$

* best fit : $\chi^2_{min} = 44$ (d.o.f. = 45)
  at $\Delta m^2_{43} = 1.0 \times 10^{-3}\,\text{eV}^2$
  $\delta_1 = 0$, $\theta_{24} = 40^\circ$, $\theta_{34} = 15^\circ$, $\theta_{23} = 20^\circ$

* 90% CL allowed region $\chi^2 \leq \chi^2_{min} + \underbrace{\Delta\chi^2_{90\%CL}}_{9.2\ (\text{d.o.f.}=5)}$
  wide range of $\theta_{24}, \theta_{23}, \theta_{34}, \delta_1$
  → Figs.

* pure $\nu_\mu \leftrightarrow \nu_s$ ($\theta_{23} = 0$, $\theta_{34} = \pm\frac{\pi}{2}$)
  is excluded at 99.6% CL (2.9σ CL)
  : consistent with SK result.

* To have LMA or LOW solar solution,
  $0 \leq |U_{s1}|^2 + |U_{s2}|^2 \leq 0.2$ has to be satisfied.
  → restrict the allowed region of ν_{atm}
  in Figs. : large θ_{23}, $|\theta_{34}|$

<u>NB</u> in vacuum

$$1 - P(\nu_\mu \to \nu_\mu) = \underbrace{A \sin^2\left(\frac{\Delta m^2_{LSND} L}{4E}\right)}_{\downarrow\ A/2 = \text{const.}} + B \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

$\theta_{23} = 0 \Leftrightarrow A \Leftrightarrow N_\nu = 2$ analysis

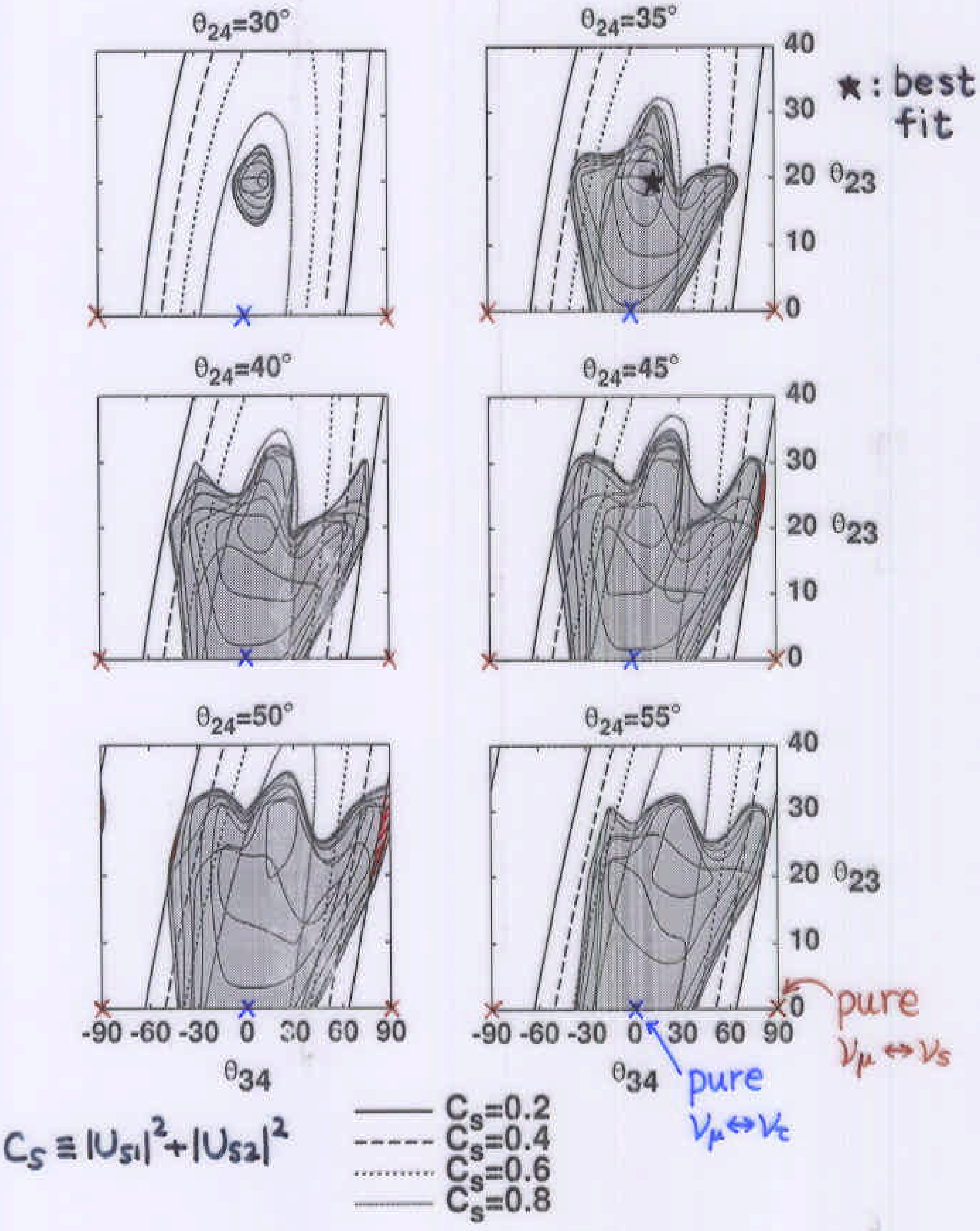
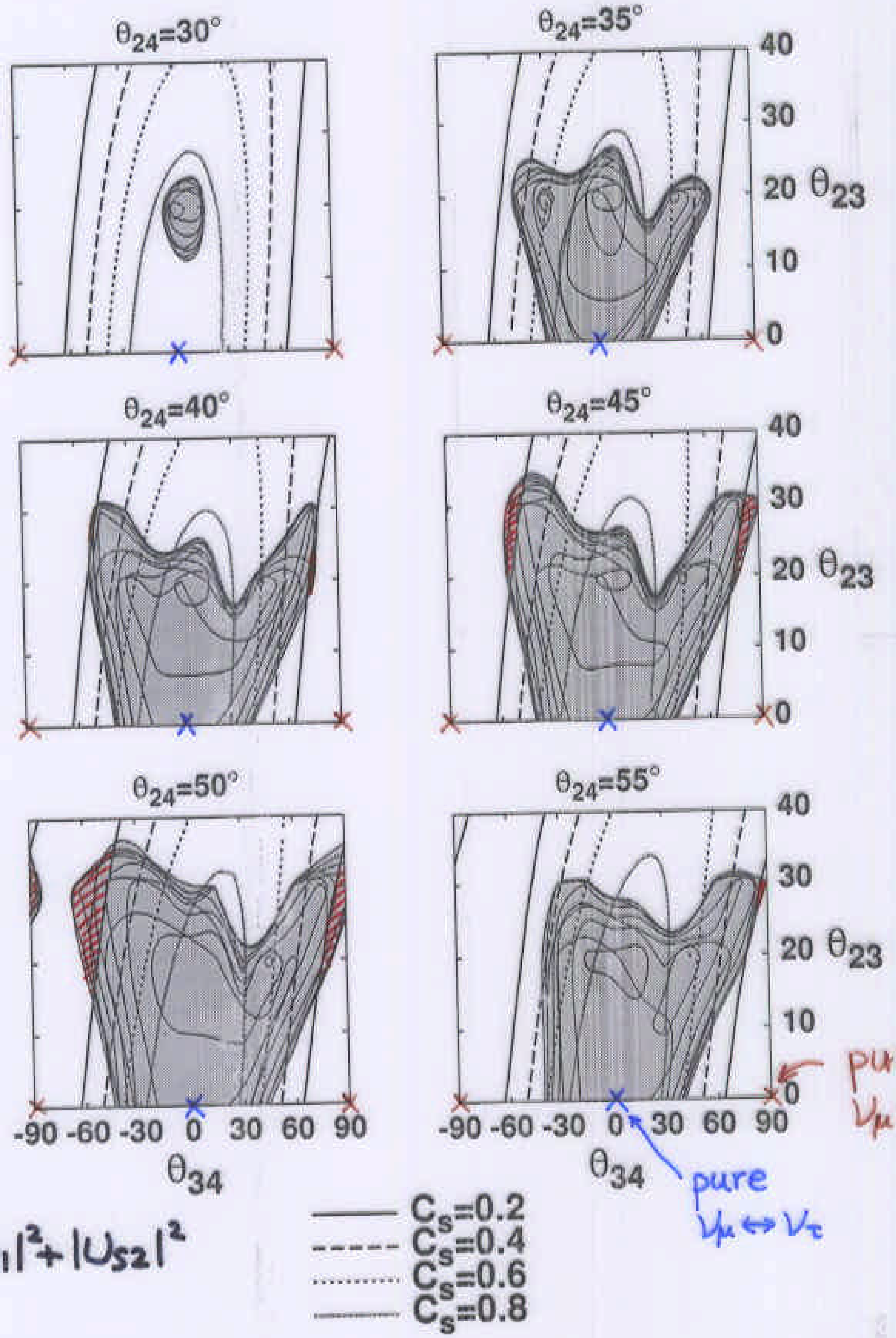


Fig.3 (a) $\delta_1=0$

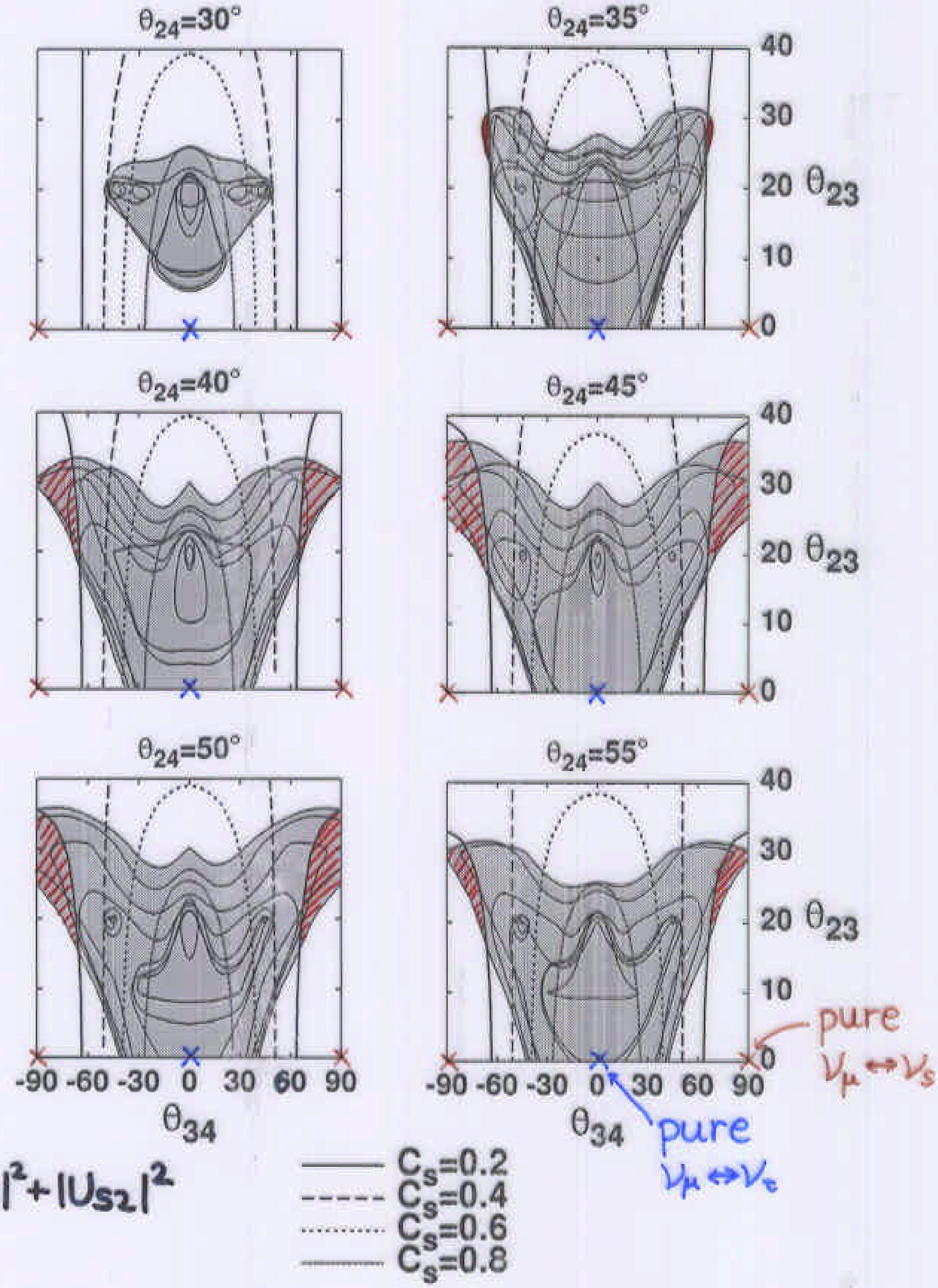


pure $\nu_\mu \leftrightarrow \nu_s$

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

$C_S \equiv |U_{S1}|^2 + |U_{S2}|^2$

Fig.3 (b) $\delta_1=\pi/4$



$C_s \equiv |U_{s1}|^2 + |U_{s2}|^2$

Fig.3 (c) $\delta_1=\pi/2$

3. Implications to long baseline experiments

(1) K2K experiment (disappearance $\nu_\mu \to \nu_\mu$)

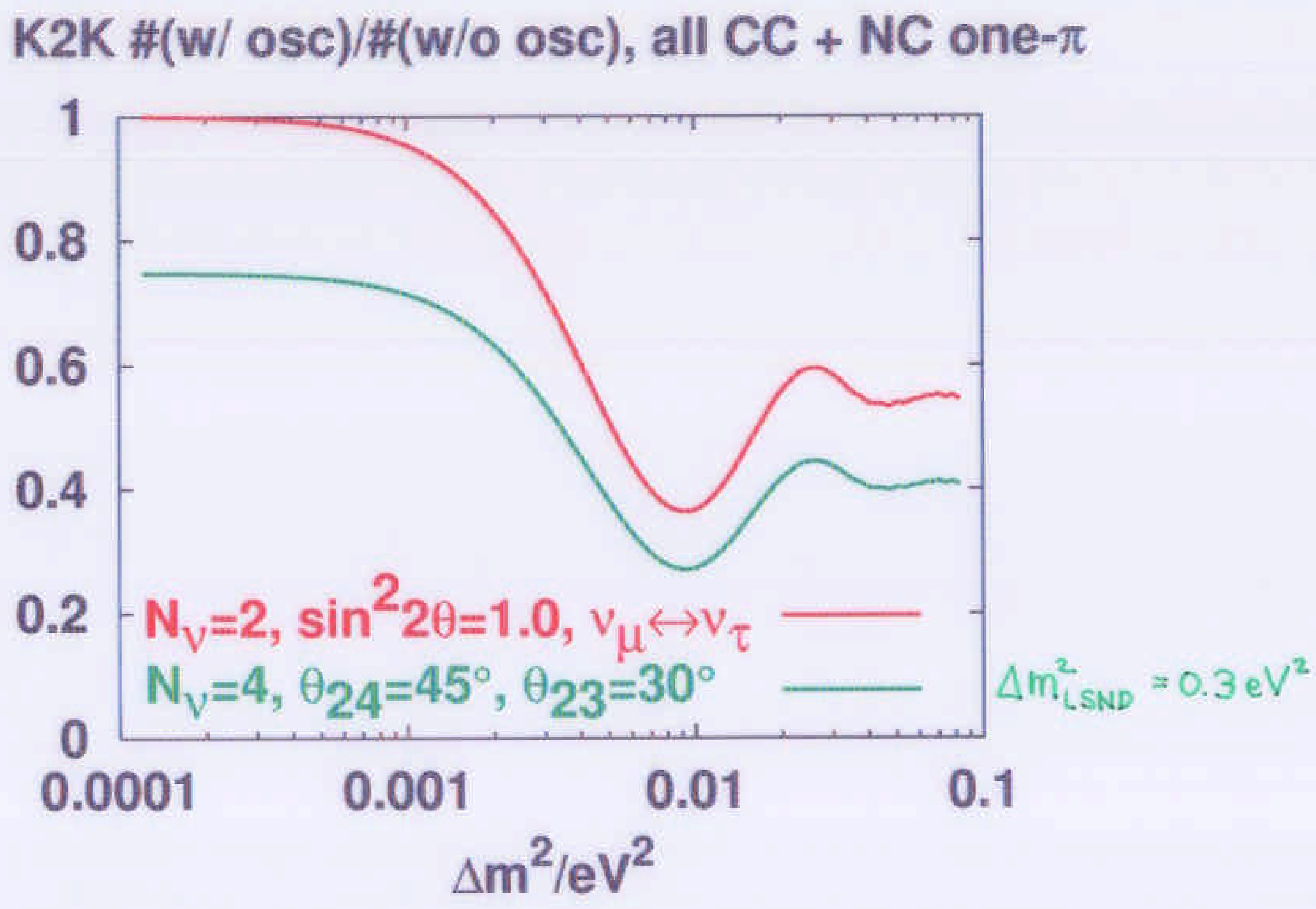
$L = 250\,\text{km}$, $\langle E_\nu \rangle = 1.4\ \text{GeV}$

$$\text{ratio} = \frac{\#\ \text{events (CC+NC with oscillation)}}{\#\ \text{events (CC+NC without oscillation)}}$$

as a function of Δm^2 for $\left\{\begin{array}{l}\text{standard } N_\nu = 2 \text{ case} \\ \text{the present case} \\ \text{of } N_\nu = 4\end{array}\right\}$

The ratio is lower for $N_\nu = 4$.

ratio of $\frac{\text{\# events with oscillation}}{\text{\# events without oscillation}}$



(2) possibility of measurement of $\not{CP}$ at JHF experiment (2006? ~)

$L = 295$ km, $\langle E_\nu \rangle = 1.4$ GeV   disappearance $\nu_\mu \to \nu_\mu$

matter effect is negligible ($\because$ L is not so long)

$$P(\nu_\mu \to \nu_s) - P(\bar{\nu}_\mu \to \bar{\nu}_s) = 2J \sin\left(\frac{\Delta m^2_{atm} L}{2E}\right)$$

$$J \equiv \frac{C_{24}}{4} \sin 2\theta_{24} \sin 2\theta_{23} \sin 2\theta_{34} \sin\delta_1$$

In our scenario w/ LMA $\nu_\odot$ solution

J is expected be large $\Longrightarrow$ large $\not{CP}$ is expected

<u>Advantage of NC events</u>   T. Nakaya

difference of # (events) $\left\{\begin{array}{l} \nu_\mu N \to \nu_\mu N \pi^0 \\ \bar{\nu}_\mu N \to \bar{\nu}_\mu N \pi^0 \end{array}\right.$

$$N_\nu = \int dE\, \sigma_\nu(E) f_\nu(E) [1 - P(\nu_\mu \to \nu_s)]$$

$$N_{\bar{\nu}} = \int dE\, \sigma_{\bar{\nu}}(E) f_{\bar{\nu}}(E) [1 - P(\bar{\nu}_\mu \to \bar{\nu}_s)]$$

(for simplicity I have assumed $f_\nu = f_{\bar{\nu}}$)

$$\boxed{R \equiv \frac{\left.\frac{N_\nu(\delta_1)}{N_{\bar{\nu}}(\delta_1)}\right|_{data} - \left.\frac{N_\nu(\delta_1=0)}{N_{\bar{\nu}}(\delta_1=0)}\right|_{MC}}{\left.\frac{N_\nu(\delta_1)}{N_{\bar{\nu}}(\delta_1)}\right|_{data} + \left.\frac{N_\nu(\delta_1=0)}{N_{\bar{\nu}}(\delta_1=0)}\right|_{MC}}}$$

if $\delta_1 = 0$

$$|R| < |\delta R| \sim \frac{1}{2\sqrt{N_{\bar{\nu}}(\delta_1=0)}} \sim 0.05$$

for 10^{21} POT

The most optimistic set of parameters

$\Delta m^2_{43} = 1.3 \times 10^{-3}\ \mathrm{eV}^2$, $\theta_{24} = 35°$, $\theta_{23} = 30°$, $\theta_{34} = 65°$, $\delta_1 = 90°$

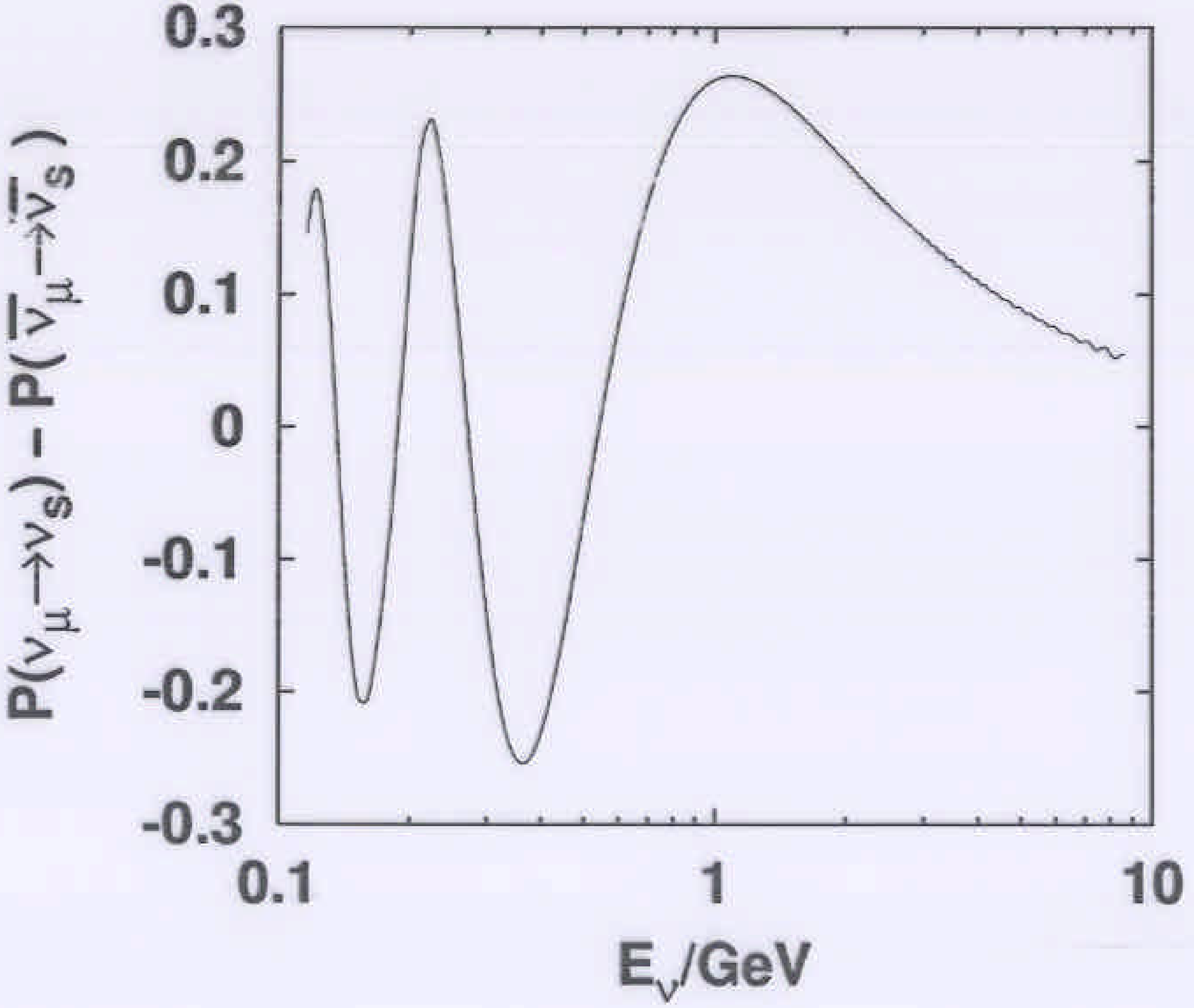
yields for 10^{21} POT at SK

(Wide Band Beam)

	no osc	$\delta_1 = \frac{\pi}{2}$	$\delta_1 = 0$	$\delta_1 = -\frac{\pi}{2}$
N_ν	392	363	318	302
$N_{\bar{\nu}}$	199	156	162	186

$-0.1 \lesssim R \lesssim 0.1$

If we are lucky, we may find $\not{CP}$ as (3-4)σ CL effect after 5 year run with 10^{21} POT/yr.

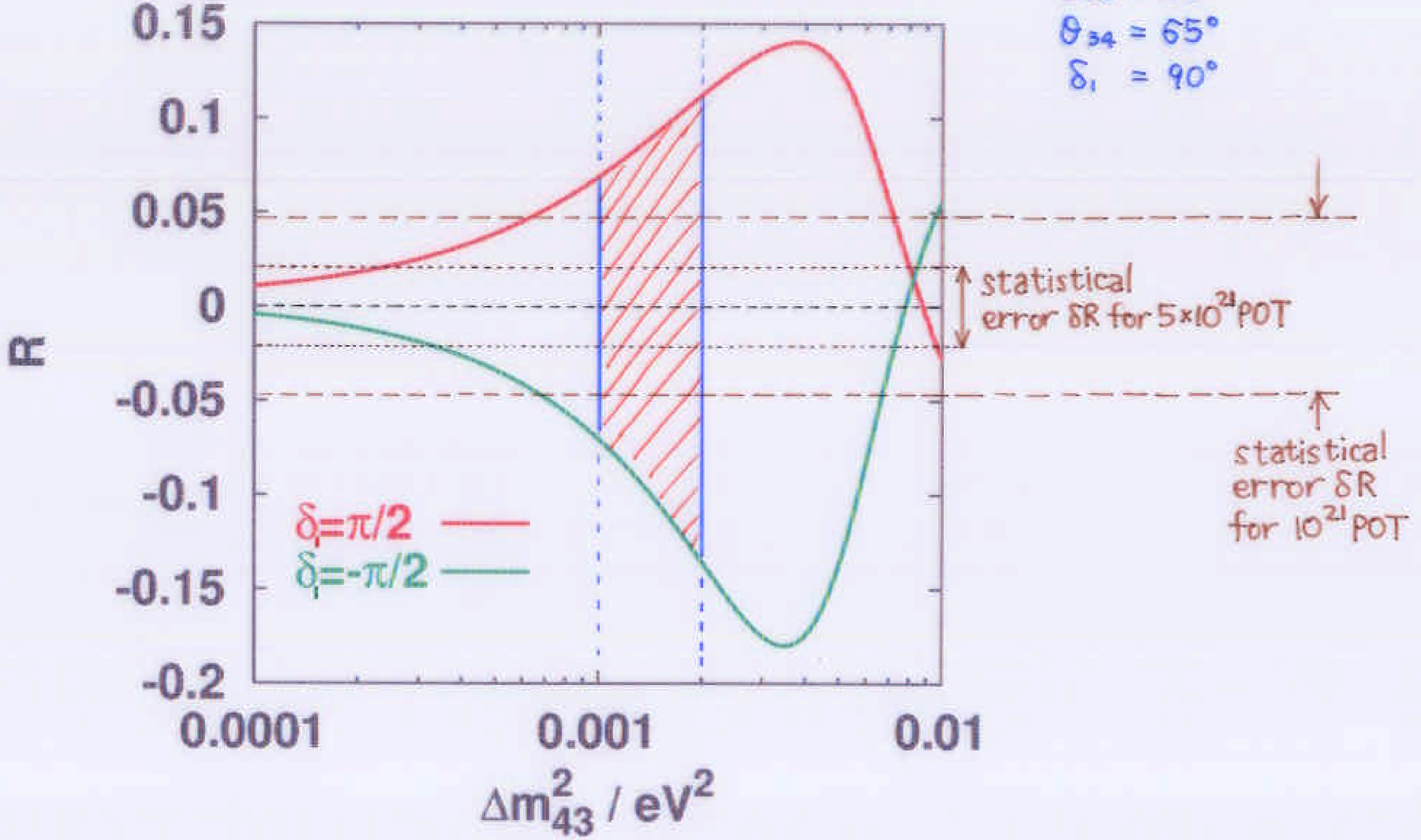


One of the most optimistic case

$\Delta m_{43}^2 = 1.3 \times 10^{-3} eV^2$
$\theta_{24} = 35^\circ$
$\theta_{23} = 30^\circ$
$\theta_{34} = 65^\circ$
$\delta_1 = 90^\circ$

$$R \equiv \frac{\left.\frac{N_\nu(\delta_1)}{N_{\bar\nu}(\delta_1)}\right|_{data} - \left.\frac{N_\nu(\delta_1=0)}{N_\nu(\delta_1=0)}\right|_{MC}}{\left.\frac{N_\nu(\delta_1)}{N_{\bar\nu}(\delta_1)}\right|_{data} + \left.\frac{N_\nu(\delta_1=0)}{N_{\bar\nu}(\delta_1=0)}\right|_{MC}}$$

$\theta_{24} = 35°$
$\theta_{23} = 30°$
$\theta_{34} = 65°$
$\delta_1 = 90°$



4. Conclusions

* 4 ν scenario w/o BBN constraint ($N_\nu < 4$) gives wide range of the oscillation parameters for ν_{atm}:

$$30° \lesssim \theta_{24} \equiv \theta_{atm} \lesssim 55°$$
$$6 \times 10^{-4} eV^2 \lesssim \Delta m^2_{43} \lesssim 7 \times 10^{-3} eV^2$$
$$0 \leq \theta_{23} \lesssim 35°$$
$$-45° \lesssim \theta_{34} \lesssim 90°$$
$$0 \leq \delta_1 \leq 360°$$

(pure $\nu_\mu \leftrightarrow \nu_s$ is excluded at 99.6% (2.9σ) CL)

* Small portion of the allowed region for ν_{atm} is consistent with LMA $\nu_\odot$ solution ($0 \leq |U_{s1}|^2 + |U_{s2}|^2 \lesssim 0.2$)

$\longrightarrow$ $15° \lesssim \theta_{23} \lesssim 35°$: large contribution of $\sin^2\left(\frac{\Delta m^2_{LSND} L}{4E}\right)$

$60° \lesssim \theta_{34} \lesssim 90°$ or $-90° \lesssim \theta_{34} \lesssim -45°$: large mixing of $\nu_\mu \leftrightarrow \nu_\tau$ & $\nu_\mu \leftrightarrow \nu_s$

* #(events) at K2K is expected to be lower than $N_\nu = 2$ case.

* $\cancel{CP}$ may be measurable at JHF by comparing NC π^0 events from ν_μ & $\bar{\nu}_\mu$.