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Telling three from four neutrino scenarios

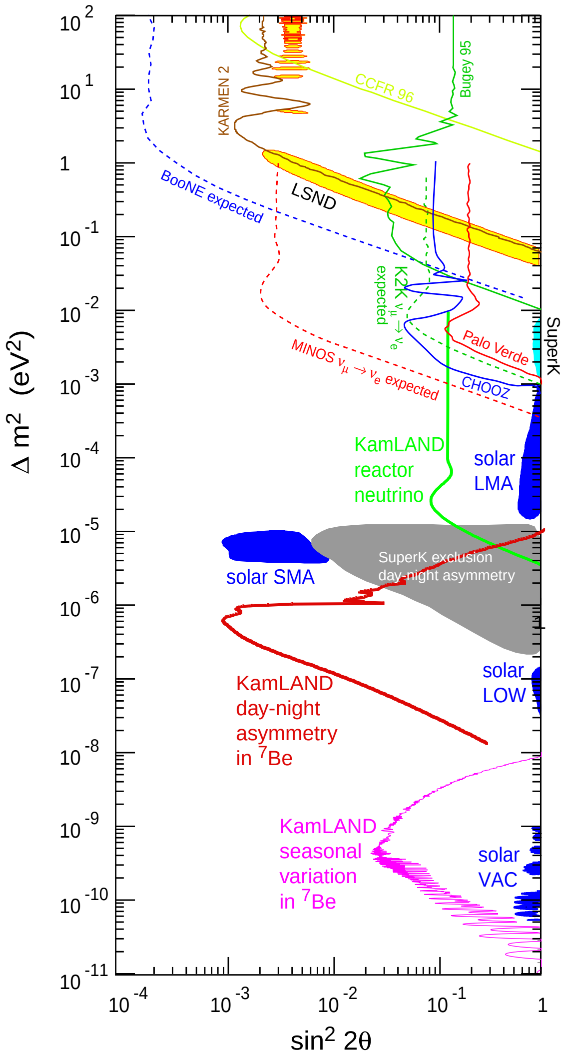
Davide Meloni

Università di Roma “La Sapienza” and INFN, Sezione di Roma

in collaboration with prof. **M.Lusignoli** and dr. **A.Donini**

Summary

1. Introduction.
2. Three or four families?
3. CP violation vs. more neutrinos.
4. Conclusions.



C. Albright et al.,FERMILAB-FN-692, April 2000

From experimental results:

- **Atmospheric neutrino data**
  $\Delta m^2_{atm} \sim (1.6 - 4) \times 10^{-3}\ eV^2$;
- **Solar neutrino data**
  $\Delta m^2_{sun} \sim 10^{-7} - 10^{-4}\ eV^2$ (MSW's);
  $\Delta m^2_{sun} \sim 10^{-10}\ eV^2$ (VO);
- **LSND** $\Delta m^2_{LSND} \sim (0.3 - 6)\ eV^2$

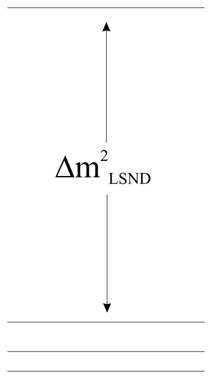
In order to explain the results, at least

Four Neutrino Families

There are two possible scenarios:

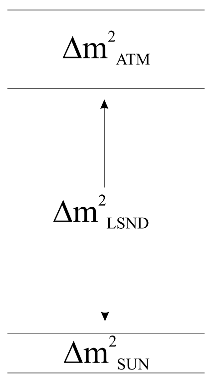
- **Three mostly degenerate neutrinos and an isolated fourth**

3+1 scheme



- **two mostly degenerate neutrino pairs**

2+2 scheme



SNO and SUPERK DATA agree with the LSND results only at the 95 % C.L. for BOTH schemes

M.C. Gonzalez-Garcia, M. Maltoni and C. Peña-Garay, hep-ph/0108073;
G.L. Fogli, E. Lisi and A. Marrone, Phys. Rev. **D 64** (2001) 093005.

Parameter space

4 ν's **6 angles + 3 CP-phases**

In our simulation: $\delta_i = 0$

$\downarrow$

CP conserving 4 ν schemes

$$\text{fixed}: \begin{cases} \theta_{12} = \theta_\odot \quad \theta_{23} = \theta_{\text{atm}} \\ \theta_{14} = \theta_{24} = 2^\circ,\ 5^\circ,\ 10^\circ \end{cases}$$

3 ν's **3 angles + 1 CP-phase**

fixed: $\theta_{12} = \theta_\odot \quad \theta_{23} = \theta_{atm}$

NUFACT vs. Conventional (Super)Beam

Conventional (Super)Beam

$$p \to \boxed{\begin{array}{c}\textbf{t}\\ \textbf{a}\\ \textbf{r}\\ \textbf{g}\\ \textbf{e}\\ \textbf{t}\end{array}} \to \begin{cases} \pi^{\pm} \to \begin{cases} \boxed{\nu_\mu\ (\bar{\nu}_\mu)} \\ \mu^{\pm} \to e^{\pm} + \ \nu_e\ (\bar{\nu}_e)\ \bar{\nu}_\mu\ (\nu_\mu) \end{cases} \\ K^{\pm},\ D^{\pm} \to \quad \nu_\mu\ (\bar{\nu}_\mu)\ \nu_e\ (\bar{\nu}_e)\ \ \ldots \end{cases}$$

One flavour (ν_μ); uncertainty on beam purity.

V. D. Barger *et al.*, arXiv:hep-ph/0103052
J. J. Gomez-Cadenas *et al.*, arXiv:hep-ph/0105297.

Neutrino Factory

$$p \to \boxed{\begin{array}{c}\textbf{t}\\ \textbf{a}\\ \textbf{r}\\ \textbf{g}\\ \textbf{e}\\ \textbf{t}\end{array}} \to \begin{cases} \pi^{\pm} \to \begin{cases} \nu_\mu\ (\bar{\nu}_\mu) \\ \mu^{\pm} \to e^{\pm} + \ \boxed{\begin{array}{c}\nu_e\ (\bar{\nu}_e)\\ \bar{\nu}_\mu\ (\nu_\mu)\end{array}} \end{cases} \\ K^{\pm},\ D^{\pm} \to \quad \nu_\mu\ (\bar{\nu}_\mu)\ \nu_e\ (\bar{\nu}_e)\ \ \ldots \end{cases}$$

Two flavours ($\nu_\mu, \bar{\nu}_e$); perfect beam purity.

S. Geer, Phys. Rev. **D 57** (1998) 6989

Experimental setup

Neutrino Factory $\rightarrow$

- 2×10^{20} UNPOLARIZED muons per year
- 5 years of DATA TAKING
- both polarities μ^+ and μ^-
- $E_\mu = 50$ GeV
- three distances : 732 Km, 3500 Km and 7332 Km

Detector capabilities $\rightarrow$

- 40 Kton of magnetized iron
- μ charge identification
- Background and efficiencies
  A. Cervera et al., Nucl. Instrum. Meth. A**451**, 123(2000)
- Neutrinos with $E_\nu \leq 5$ GeV discarded

Strategy adopted

(exploring the $\nu_e \to \nu_\mu$ channel)

$$\text{Input}: \begin{cases} \bar{\theta}_{13} \in [1^\circ, 10^\circ] \text{ and } \bar{\theta}_{34} \in [0^\circ, 50^\circ] \to N^i_{4\nu}(\bar{\theta}_{13}, \bar{\theta}_{34}) \\ \bar{\theta}_{13} \in [1^\circ, 10^\circ] \text{ and } \bar{\delta} \in [-180^\circ, 180^\circ] \to N^i_{3\nu}(\bar{\theta}_{13}, \bar{\delta}) \end{cases}$$

where

Number of Wrong-Sign Muons at fixed baseline L

$$N^i_{3,4\nu}(\dots) = \int_{E_i}^{E_i+\Delta E} \sigma(E) \times \frac{d\Phi(E)}{dE} \times P^{3,4\nu}_{e\mu}(E, \dots)\, dE$$

as a function of the energy: $i = 1, N_{bin}$

$\Downarrow$

“Experimental” Data Generation

$$n^i = \frac{\text{Smear}\left[N^i_{4\nu}\,\epsilon^i + B^i\right] - B^i}{\epsilon^i}$$

$\Downarrow$

Fit to the theoretical probability

$$\chi^2 = \sum \sum_{i=1}^{N_{bin}} \left(\frac{n^i - N^i_{3\nu}}{\delta n^i}\right)^2,$$

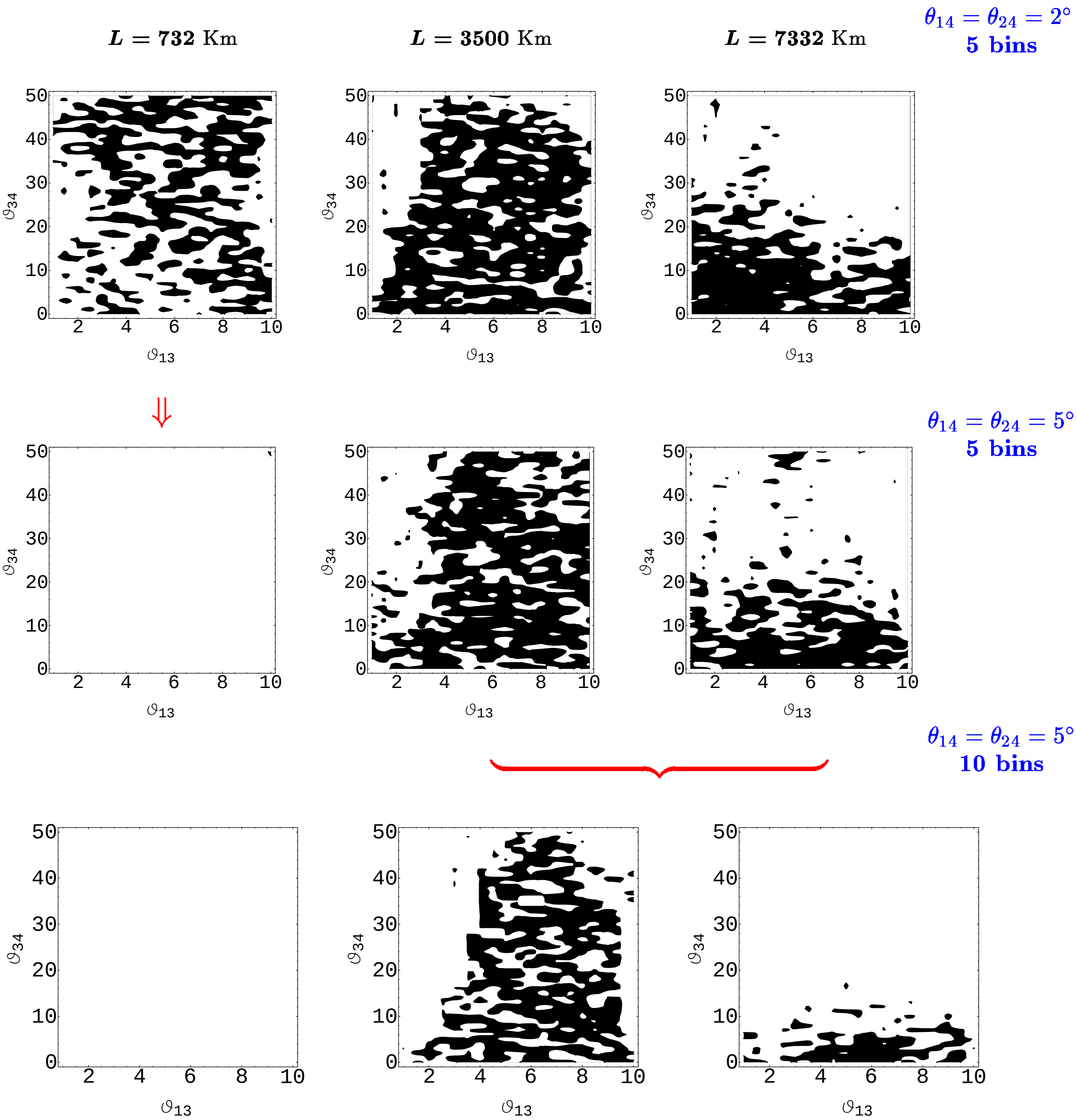
$\Downarrow$

Output: $\chi^2 < \chi^2_{68\%, n\,dof}$

The Dalmatian Plots*

(How close is the 3+1 Scheme to the Three-Family Model ?)

* W. Disney, "One hundred and one dalmatians", 1961.



A. Donini, M. Lusignoli and D. Meloni, Nucl. Phys. B 624, 405 (2002)

- $\nu_e \to \nu_\mu$ transition probability in the three-neutrino model:

$$P_3(\nu_e \to \nu_\mu) = C^3_{atm} \, \sin^2\left(\frac{\Delta m^2_{atm} \, L}{4\,E}\right)$$

$$C^3_{atm} = \sin^2(\theta_{23}) \; \sin^2(2\theta_{13})$$

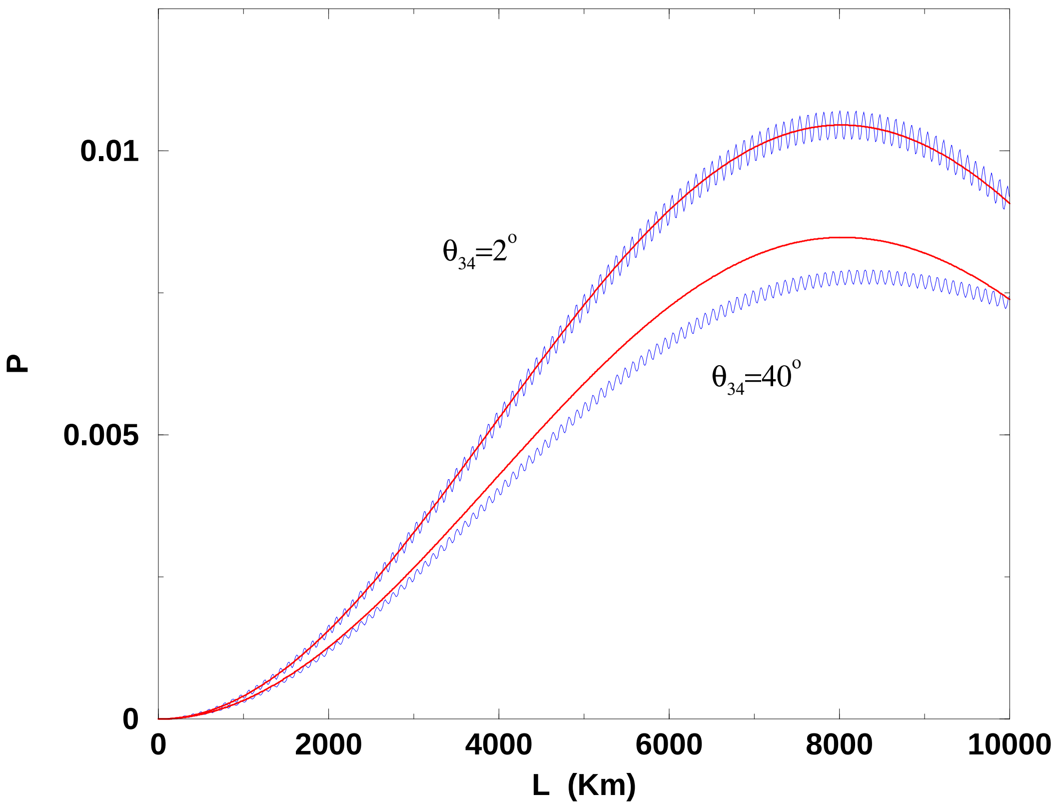
- $\nu_e \to \nu_\mu$ transition probability in the (3+1)–four-neutrino model:

$$\begin{aligned} P_{3+1}(\nu_e \to \nu_\mu) &= C^{3+1}_{LSND} \, \sin^2\left(\frac{\Delta m^2_{LSND} \, L}{4\,E}\right) \\ &+ C^{3+1}_{atm} \, \sin^2\left(\frac{\Delta m^2_{atm} \, L}{4\,E}\right) \\ &+ O(s^2_{14}, s^2_{24}, s_{14}s_{24}) \end{aligned}$$

$$\begin{cases} C^{3+1}_{LSND} = 4\, s^2_{14}\, s^2_{24}\, c^4_{34} \\ C^{3+1}_{atm} = C^3_{atm} \times \left[1 - 2\, c_{23}\, s_{34} \left(\frac{s_{24}}{s_{23}} + \frac{s_{14}c_{13}}{s_{13}}\right)\right] \end{cases}$$

$\boldsymbol{\nu_e \to \nu_\mu}$ transition probability
in the 3- and (3+1)-neutrino models
(at the neutrino mean energy: $\boldsymbol{\bar{E}_\nu = 38}$ **GeV**)

1) Small active-sterile mixing angles: $\theta_{14} = \theta_{24} = 2^\circ$

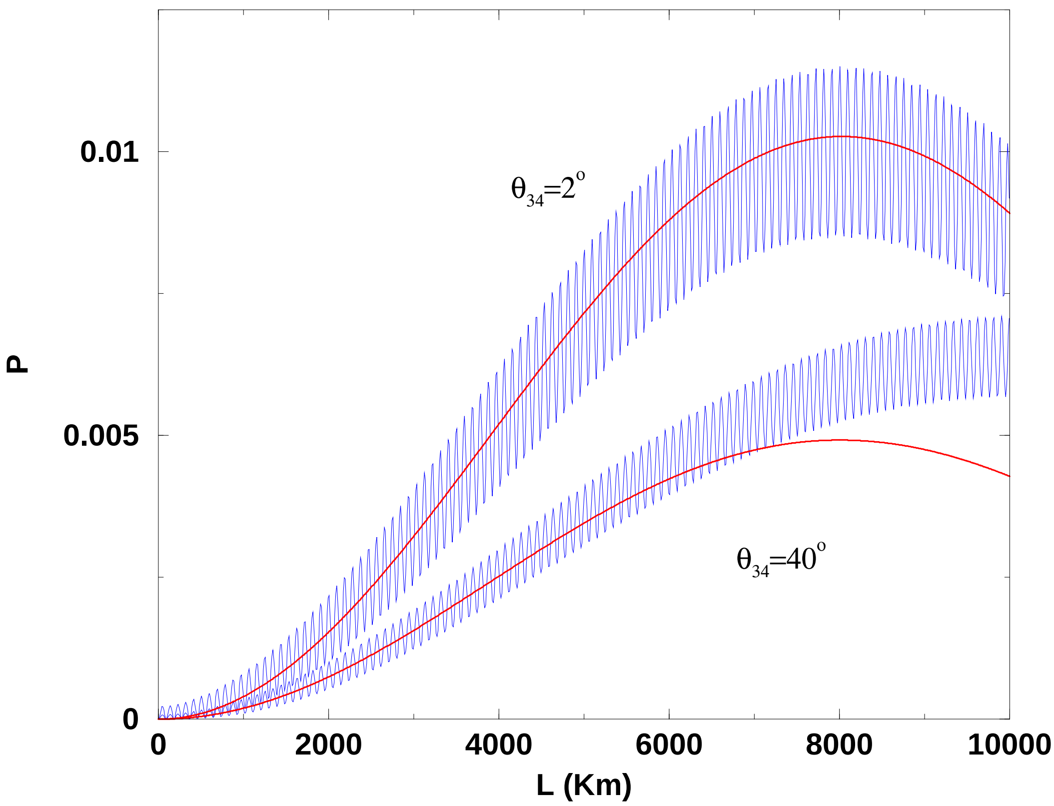


Solid lines: three-neutrino model

Wiggled lines: four-neutrino model

$\nu_e \to \nu_\mu$ transition probability
in the 3- and (3+1)-neutrino models
(at the neutrino mean energy: $\bar{E}_\nu = \mathbf{38\ GeV}$)

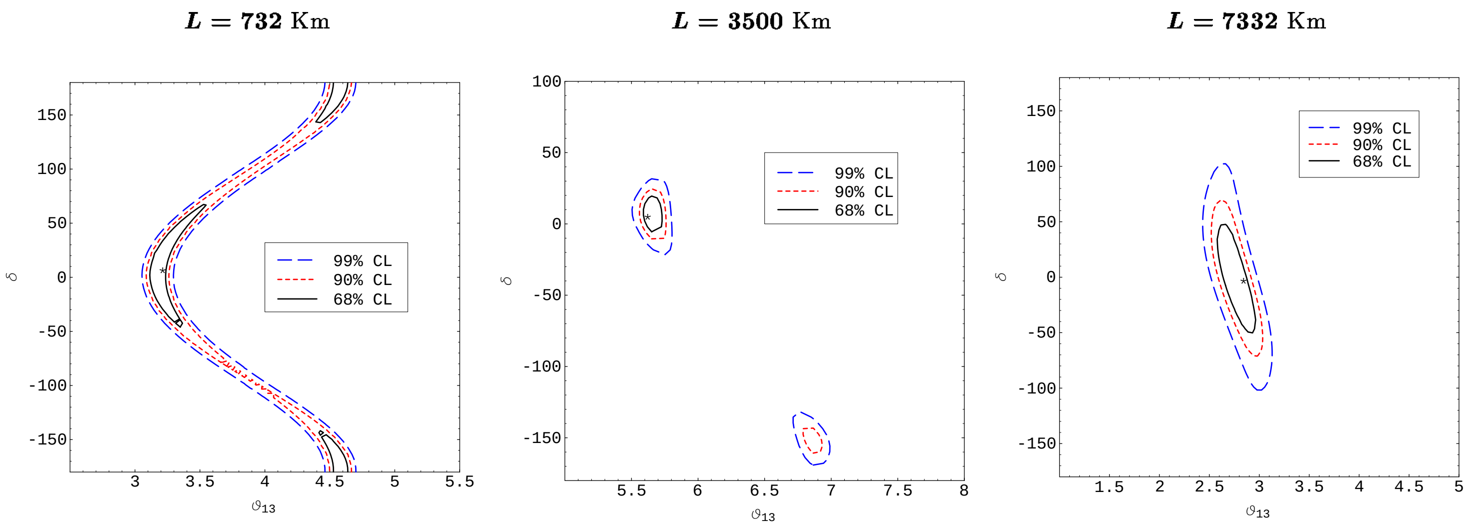
1) "Not-so-small" active-sterile mixing angles:
$\theta_{14} = \theta_{24} = 5°$



Solid lines: three-neutrino model

Wiggled lines: four-neutrino model

If a **MISIDENTIFICATION** occurs
(i.e. for the dark spots of the Dalmatian Plots)
do we fit a
NON-VANISHING CP-VIOLATING PHASE?



The answer is NO !
(with ∼ 6000 fits performed, we get:

$\delta \in [-15°, 15°]$

in the 31%, 50%, 37% of the cases)

Can we MISS a

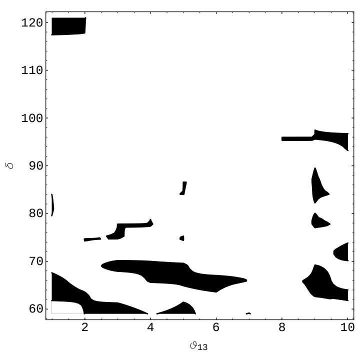
MAXIMAL ($\delta = 90°$) CP-VIOLATING PHASE

in the three-family model

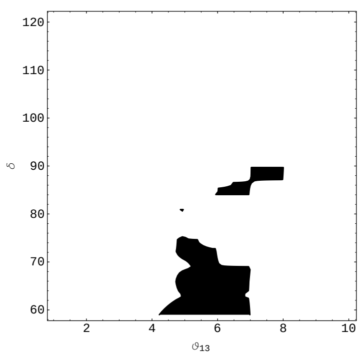
by fitting in a

CP-CONSERVING four-family model?

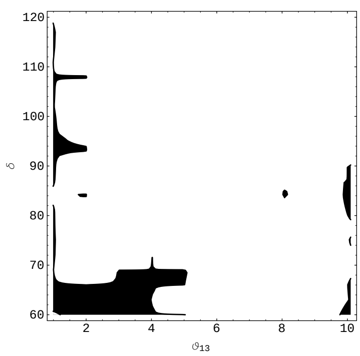
$L = 732$ Km



$L = 3500$ Km



$L = 7332$ Km



The answer is: it depends !

At short and large distance, sometimes;

at intermediate distance, rarely.

Problem solved by

COMBINING TWO BASELINES

Conclusions

- data described in the CP conserving four–family **may also be fitted** with the three–family formulae

- the confusion zones **are reduced in size** for increasing gap–crossing angles and energy resolution of the detector

- in the confusion regions **δ is generally not large**

- data that can be fitted with a CP phase close to 90° in the three–neutrino theory **cannot be described** in a CP conserving 3+1 theory

- in the 2+2 scheme the ambiguity with a three–neutrino theory is essentially absent:
  the dalmatians are affected by albinism