FOUR-FAMILY NEUTRINO OSCILLATIONS AT NUFACT

A. Donini
(UNIVERSIDAD AUTONOMA MADRID)
mainly in collaboration with
M.B. Gavela, P. Hernandez and S. Rigolin

NEAR FUTURE

- LSND will be
  CONFIRMED / NOT CONFIRMED
  by MiniBooNe

- SNO will say something on:

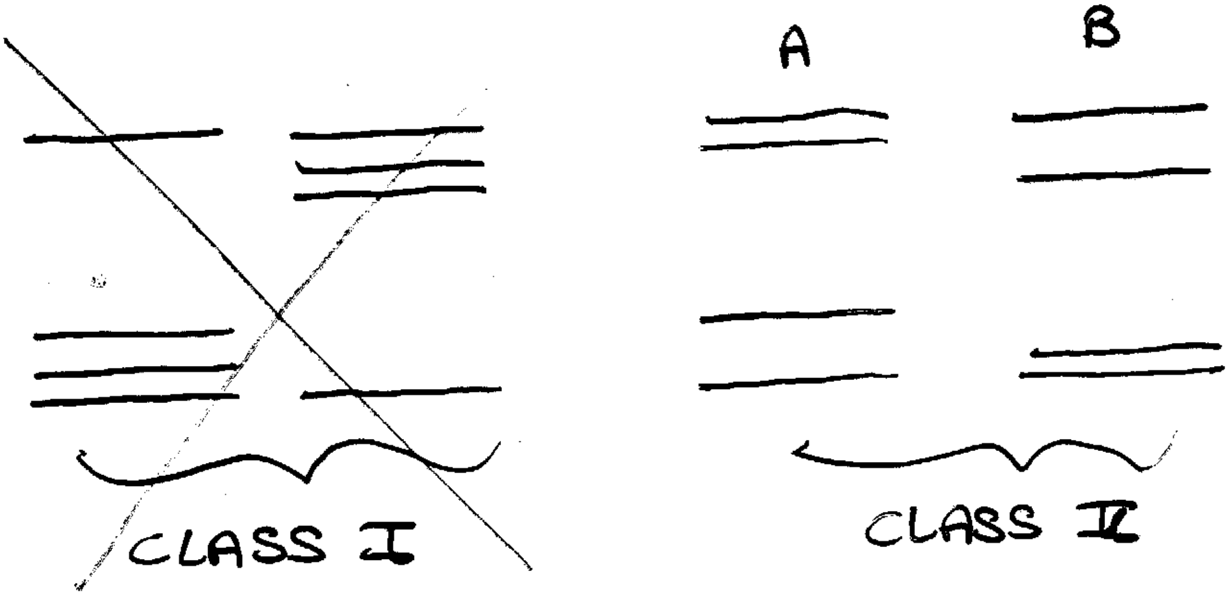
$$\boxed{\text{SOLAR NEUTRINO PROBLEM is } \nu_e \to \nu_s \text{ OR NOT}}$$

IF SNP is NOT $\nu_e \to \nu_s$ $\Rightarrow$
the REST OF THE TALK is
PROBABLY USELESS

OUTLINE

- PARAMETRIZATION ISSUE
- BOUNDS ON MIXING ANGLES
- SENSITIVITY AT THE NUFACT
- CP-VIOLATION AT THE NUFACT
- COMMENTS AND CONCLUSIONS

WHICH SCENARIO?



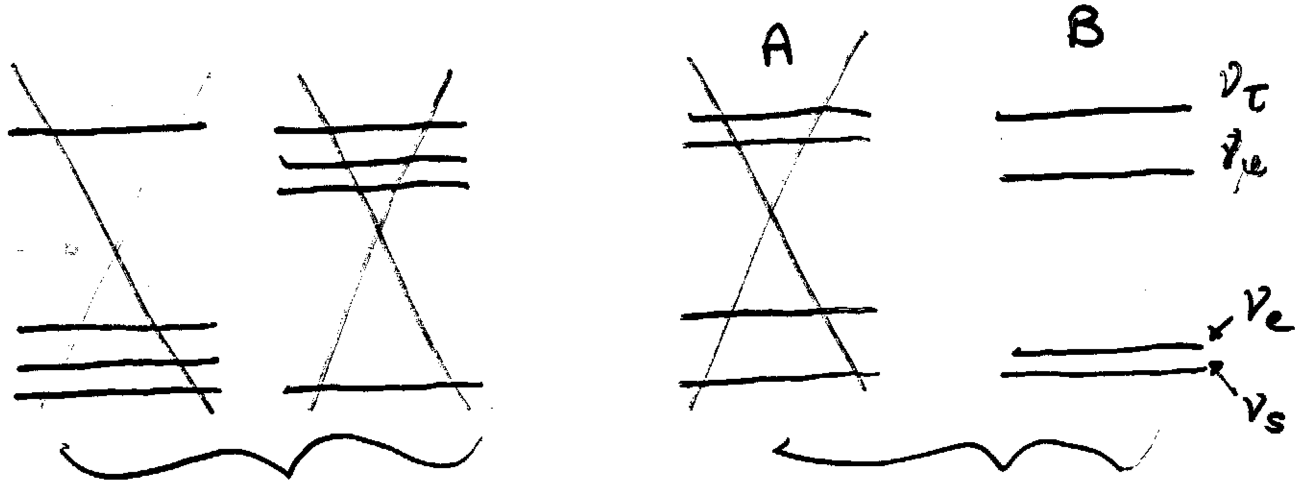
EXCLUDED BY DATA

(Bilenky, Giunti, Grimus in many papers ....)

$$\left(|U_{\mu 4} U^*_{e4}|^2 \leqslant |U_{\mu 4}|^2 |U_{e4}|^2 \leqslant 0.008 \right.$$

is not verified in the allowed LSND region)

WHICH SCENARIO?



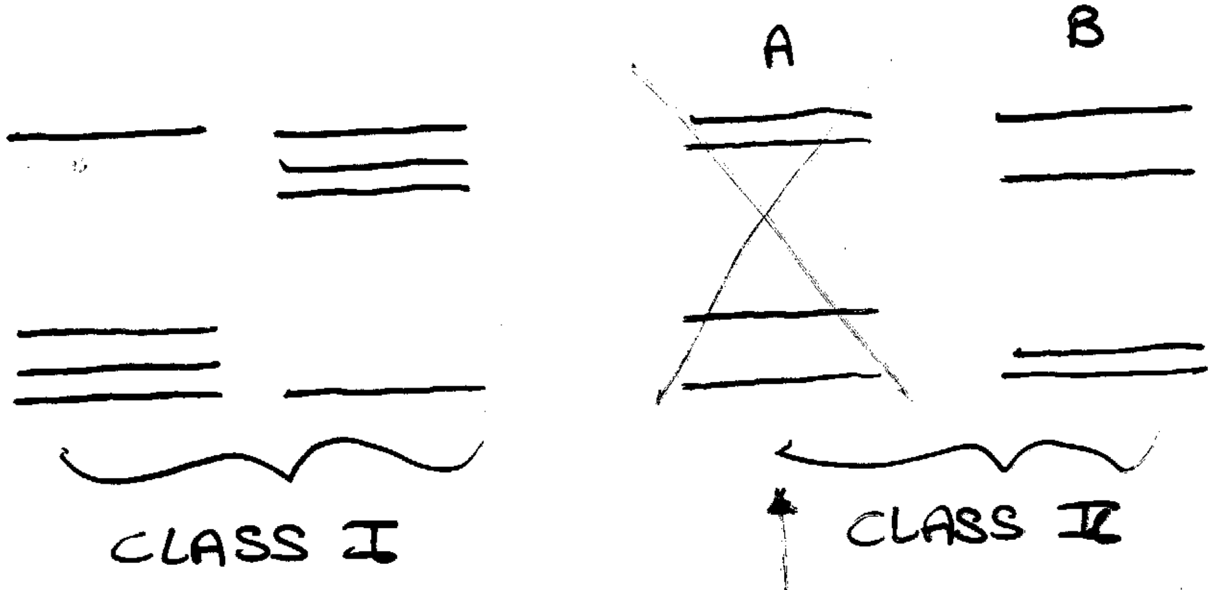
CLASS I CLASS II

$$\Downarrow$$

$$m_1 < m_2 \leq m_3 < m_4$$

$$\underbrace{\Delta m^2_{12} \sim \Delta m^2_{SUN} \sim 10^{-4}\ eV^2 \qquad \Delta m^2_{34} \sim \Delta m^2_{ATM} \sim 10^{-3}\ eV^2}_{\Delta m^2_{LSND} \sim 1\ eV^2}$$

WHICH SCENARIO?



ALMOST RULED OUT BY
HEIDELBERG-MOSCOW $\beta\beta_{0\nu}$

PARAMETRIZATION

U_{MNS} is a 4×4 UNITARY MATRIX

$\Downarrow$

6 ANGLES

3 PHASES (DIRAC)

+

3 PHASES (MAJORANA)

(not observable in oscillations)

SINCE

$$U = \prod_{1}^{6}{}_i\, U_i$$

MANY POSSIBLE PARAMETRIZATIONS

(.... DOES NOT EXIST THE "MOST GENERAL PARAMETRIZATION" ....)

EXAMPLE: 3 FAMILIES

TAKE

$$U_{MNS} = U(\theta_{23})\, U(\theta_{13}, \delta)\, U(\theta_{12})$$

$$\Downarrow$$

$$P(\nu_e \to \nu_e) = 1 - 4\, c_{12}^2 s_{12}^2 c_{13}^4 \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

$$- 4\, c_{12}^2 c_{13}^2 s_{13}^2 \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)$$

$$- 4\, s_{12}^2 c_{13}^2 s_{13}^2 \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

IF $\Delta m_{12}^2 = 0 \Rightarrow P(\nu_e \to \nu_e) = f(\cancel{\theta_{12}}, \theta_{13})$

IF $\Delta m_{23}^2 = 0 \Rightarrow \boxed{P(\nu_e \to \nu_e) = f(\theta_{12}, \theta_{13})}$

A CLEVER CHOICE ....

$$\boxed{U_{MNS} = U(\theta_{14})\,U(\theta_{13})\,U(\theta_{24}) \times U(\theta_{23},\delta_3)\,U(\theta_{34},\delta_2)\,U(\theta_{12},\delta_1)}$$

- SENSITIVITY: $\Delta m^2_{12} \sim \Delta m^2_{34} \sim 0$

  $\Rightarrow$ 4 ANGLES AND 1 PHASE

  $(\theta_{13}, \theta_{14}, \theta_{23}, \theta_{24})$ (δ_3)

  (ONE-MASS SCALE DOMINANCE)

- CP-VIOLATION: $\Delta m^2_{12} \sim 0$

  $\Rightarrow$ 5 ANGLES AND 2 PHASES

  $(+\,\theta_{34})$ $(+\,\delta_2)$

  (TWO-MASS SCALES DOMINANCE)

BOUNDS

- BUGEY-CHOOZ GIVE

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 2\, c_{23}^2 c_{24}^2 \left[1 - c_{23}^2 c_{24}^2\right]$$

$$\Rightarrow \boxed{\sin^2\theta_{23} \sim \sin^2\theta_{24} \lesssim 7.5 \cdot 10^{-3}}$$

(mainly Bugey for high Δm^2_{23})

- LSND GIVES $(\nu_e \to \nu_\mu)$ A BOUND FOR

$c_{13}^2 \cdot c_{24}^2 \cdot \sin^2 2\theta_{23}$ depending on Δm^2_{23}

↳ WE CHOOSE TO BE CONSERVATIVE, TAKING ALL THE GAP CROSSING ANGLES SMALL

NOTICE: BOUND ON θ_{23} SHOULD BE REDUCED TO

$$\boxed{\sin^2\theta_{23} < 3.7 \cdot 10^{-3}}$$

BY MINOS

A.D., M.B. Gavela, P. Hernandez, S. Rigolin
hep-ph/9909254, 9910516

- SHORT BASELINE

$L \cong 1$ km

$L \simeq \mathcal{O}(10$ km$)$ FOR CP-VIOLATION

- $\begin{cases} N_\mu = 2 \times 10^{20} & \text{USEFUL MUONS} \\ E_\mu = 20 \text{ GeV} & \end{cases}$

$\downarrow$

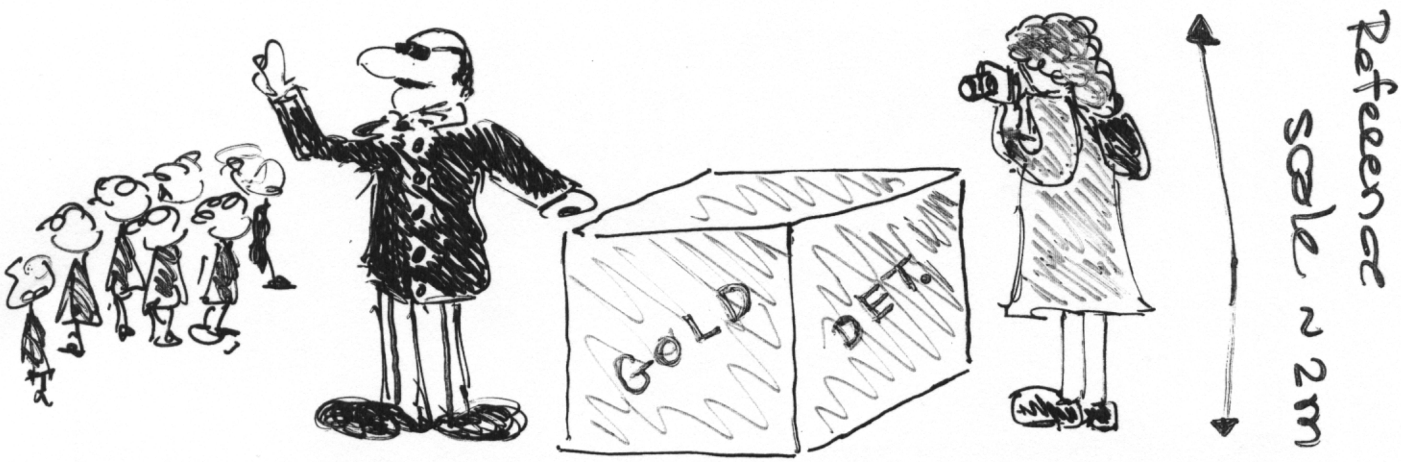
SMALL DETECTOR

$\begin{cases} M = 1 \text{ TON} & \text{AT } 1 \text{ km} \\ M = 1 \text{ KTON} & \text{AT } \mathcal{O}(10 \text{ km}) \end{cases}$

μ, τ - CHARGE IDENTIFICATION NEEDED TO SPAN THE FULL PARAMETER SPACE

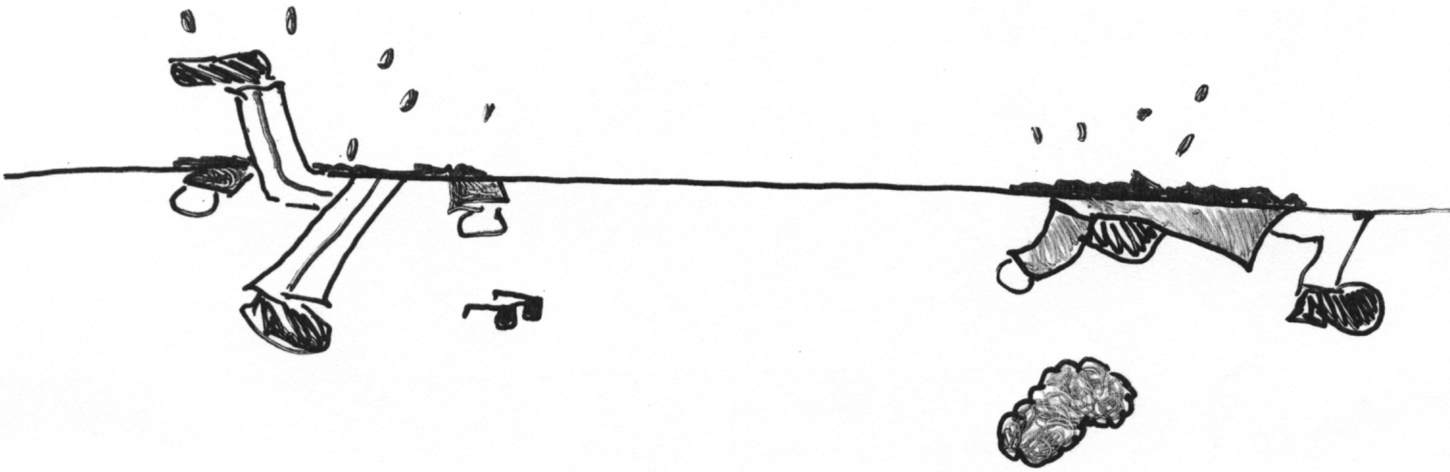
$\begin{cases} \epsilon_\mu = 0.5 \\ \epsilon_\tau = 0.35 \end{cases}$ CONSIDERED EFFICIENCIES

TYPICAL SIZE OF THE DETECTOR



The 1~~K~~TON DETECTOR
(AT 1 km)

THE 40 kTON "IRON DETECTOR"



OR "SIZE DOES MATTER ...."

μ- APPEARANCE

$$P(\nu_e \to \nu_\mu) = 4\, c_{13}^2 c_{24}^2 c_{23}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

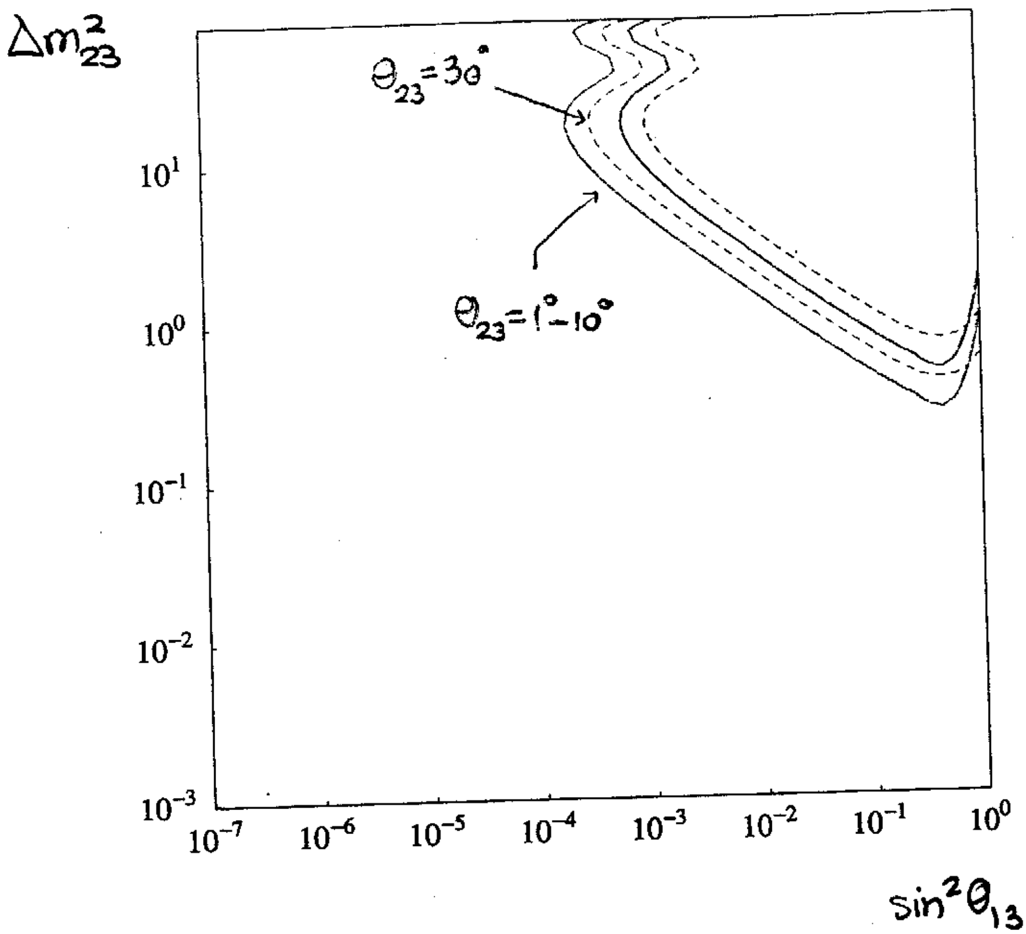
μ- DISAPPEARANCE

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\, c_{13}^2 c_{23}^2 \left(s_{23}^2 + s_{13}^2 c_{23}^2 \right) \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

τ- APPEARANCE

$$P(\nu_e \to \nu_\tau) = 4\, c_{23}^2 c_{24}^2 \Big[s_{13}^2 s_{14}^2 s_{23}^2 + c_{14}^2 c_{23}^2 s_{24}^2 - 2\, c_{14} c_{23}\, s_{14} s_{23} s_{13} s_{24} \cos\delta_3 \Big] \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

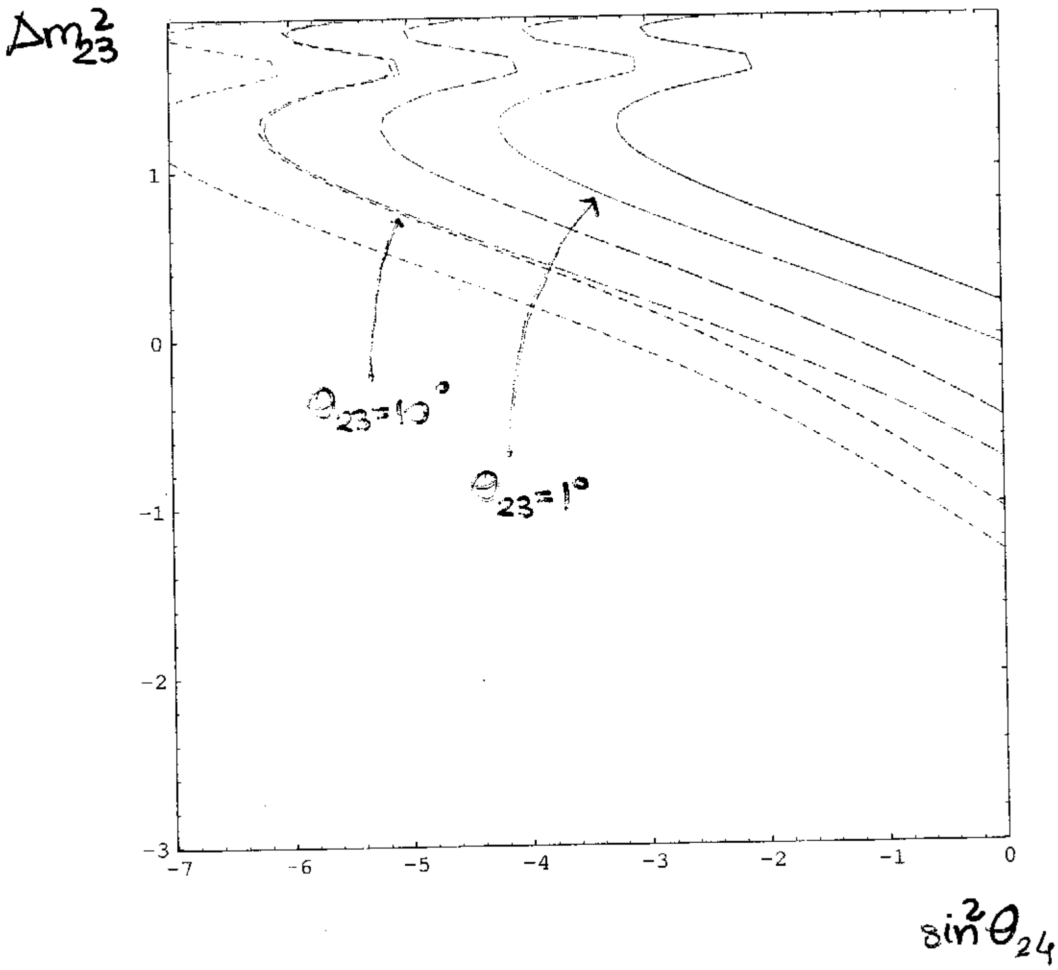
$$P(\nu_\mu \to \nu_\tau) = 4\, c_{13}^2 c_{23}^2 \Big[s_{13}^2 s_{14}^2 c_{23}^2 + c_{14}^2 s_{23}^2 s_{24}^2 + 2\, c_{14} c_{23}\, s_{14} s_{23} s_{13} s_{24} \cos\delta_3 \Big] \sin^2\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$



2×10^{19} USEFUL MOONS

2×10^{20} USEFUL MOONS

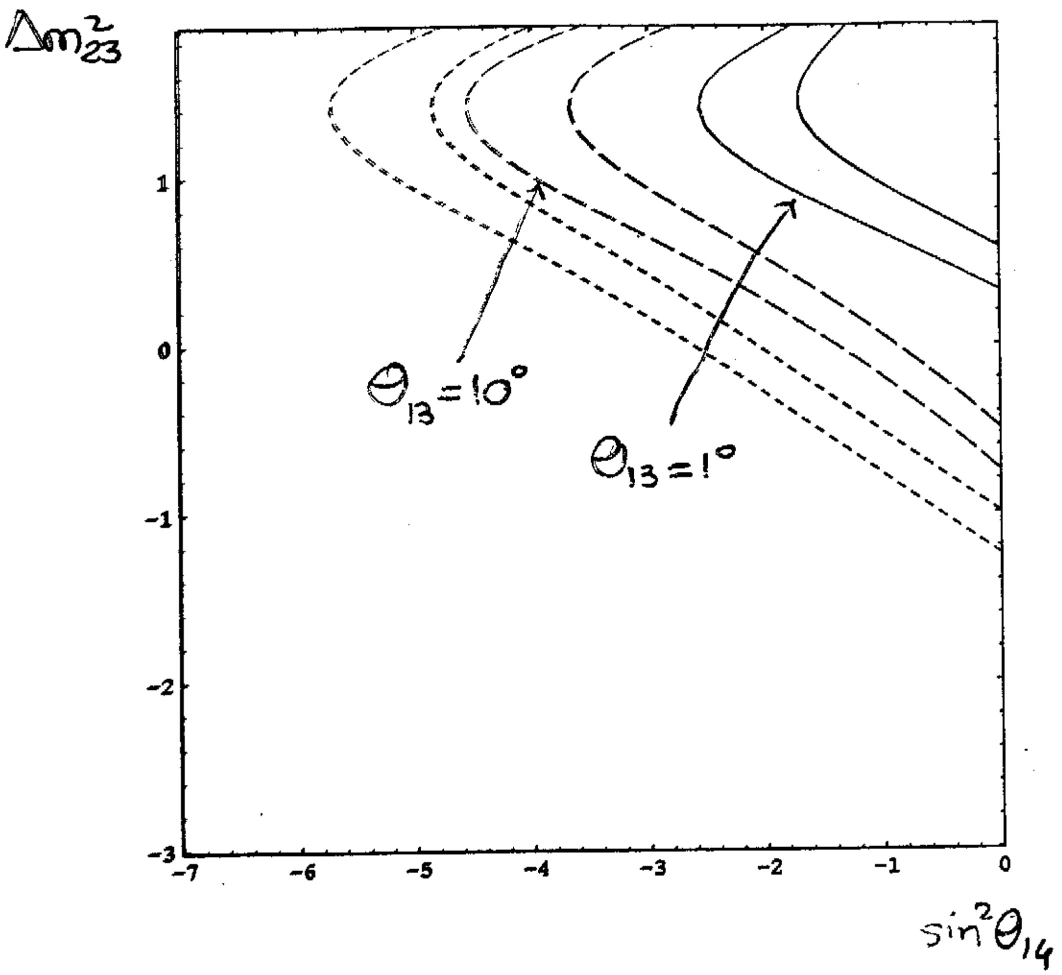
$\theta_{24} = \theta_{14} = 1^\circ$



2×10^{19} USEFUL MUONS

2×10^{20} USEFUL MUONS

θ_{14} FROM τ^- - APPEARANCE



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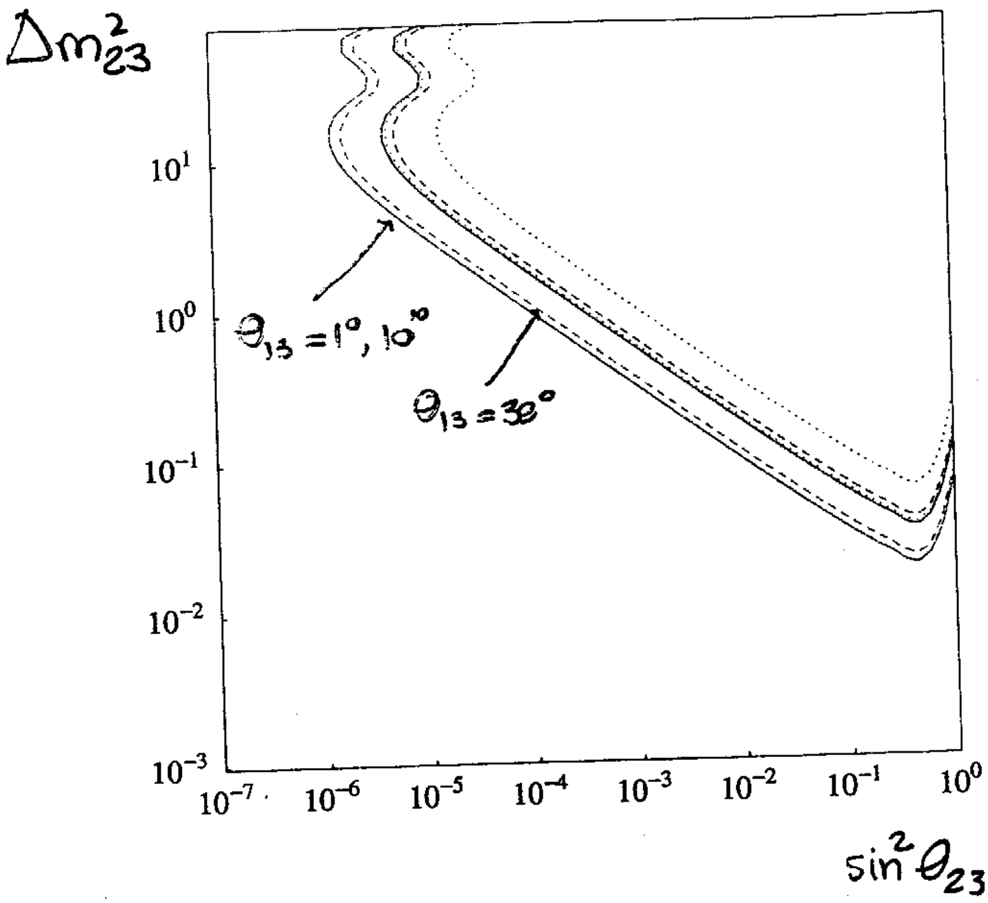
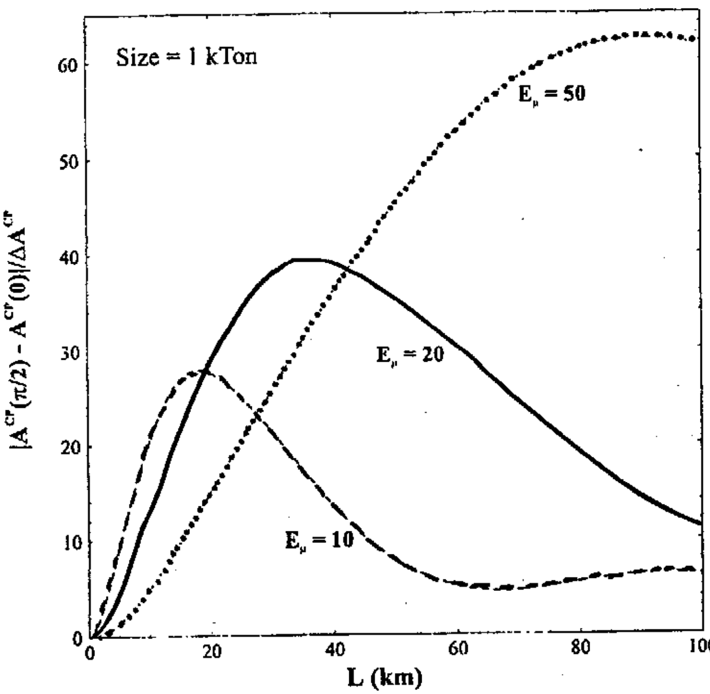
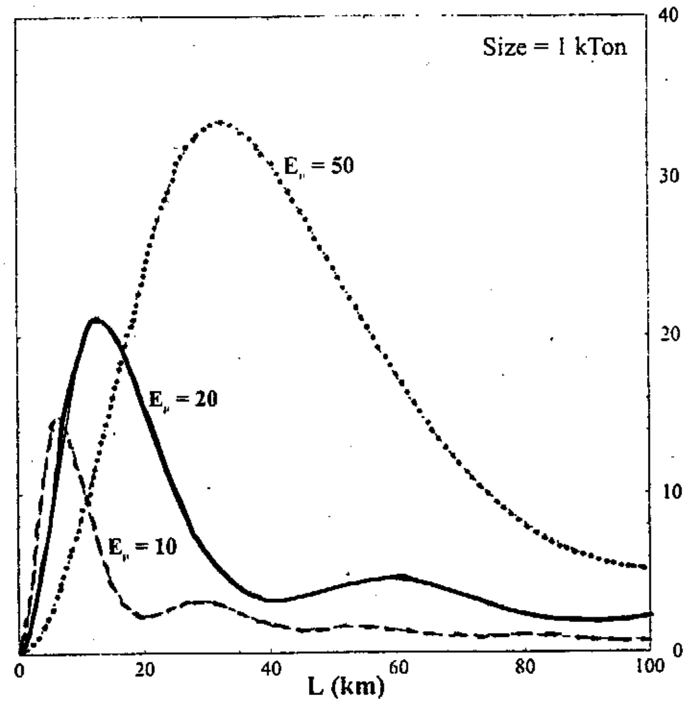


2×10^{19} USEFUL MUONS

2×10^{20} USEFUL MUONS

Energy Dependence – $\mu\tau$ channel





Set # 1

$\Delta m^2_{23} = 0.3\ eV^2$

$\Delta m^2_{34} = 2.8 \times 10^{-3}\ eV^2$

$\vartheta_{cj} = 5^\circ$ $\vartheta_{34} = 45^\circ$

Set # 2

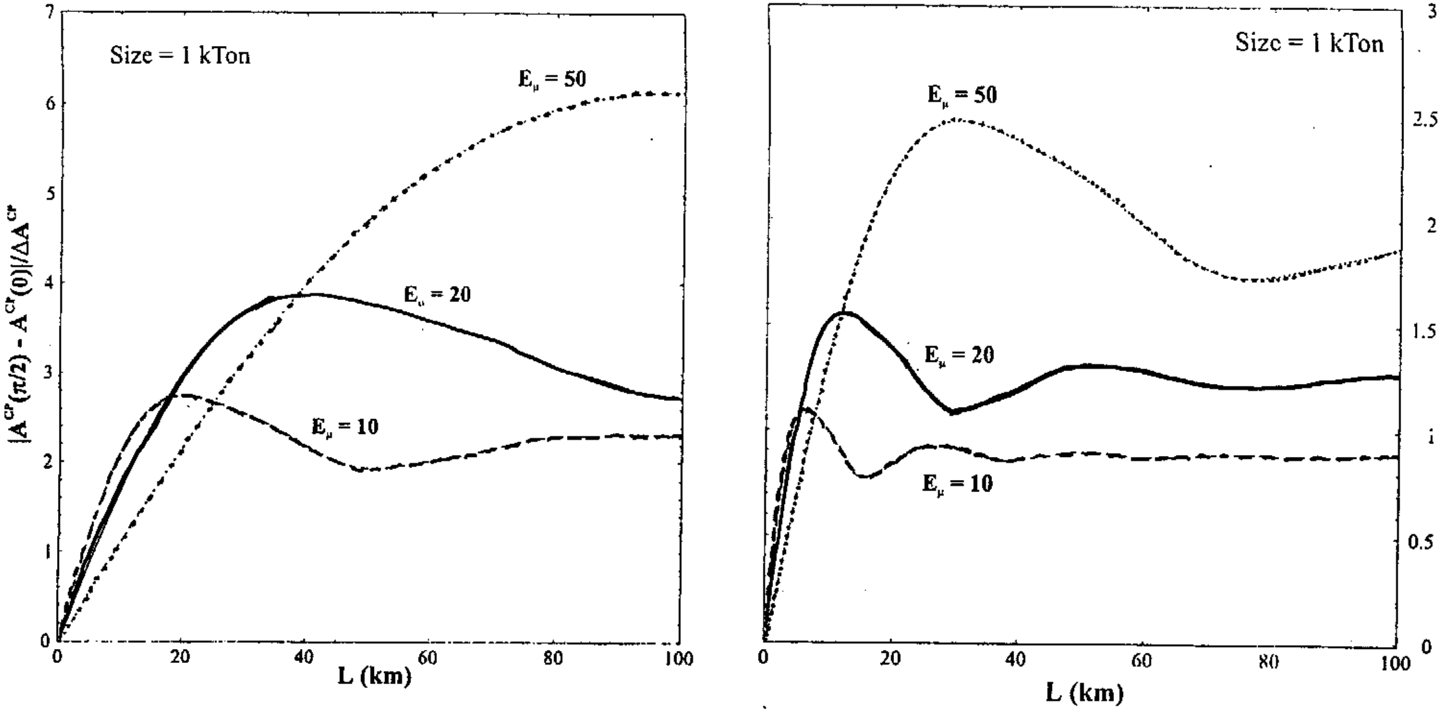
$\Delta m^2_{23} = 1\ eV^2$

$\Delta m^2_{34} = 2.8 \times 10^{-3}\ eV^2$

$\vartheta_{cj} = 2^\circ$ $\vartheta_{34} = 45^\circ$

2×10^{20} useful μ 1 kTon detector

Energy Dependence – eμ channel



Set # 1:

$\Delta m^2_{23} = 0.3\ eV^2$

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▲ 2×10^{20} useful μ — 1 kTon detector

CP-VIOLATION

TWO MASS DIFFERENCES NEEDED:

$$\begin{cases} J^{ij}_{\alpha\beta} = \mathrm{Im}\left[U_{\alpha i} U^{*}_{\alpha j} U^{*}_{\beta i} U_{\beta j} \right] \\ \Delta_{ij} = \dfrac{\Delta m^2_{ij} L}{4E} \end{cases}$$

$$\Downarrow$$

$$\Delta P_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) =$$

$$= -4 J^{34}_{\alpha\beta} \left[\sin 2\Delta_{23} + \sin 2\Delta_{34} + \sin 2\Delta_{42} \right]$$

$$+ 4 J^{12}_{\alpha\beta} \sin 2\Delta_{21}$$

$$+ 4 J^{13}_{\alpha\beta} \left[\sin 2\Delta_{31} - \sin 2\Delta_{32} \right]$$

$$+ 4 J^{14}_{\alpha\beta} \left[\sin 2\Delta_{41} - \sin 2\Delta_{42} \right]$$

Kalliomäki, Maalampi, Tanimoto

hep-ph/9909301

SINCE CP-VIOLATION

IN FOUR-~~F~~FAMILY SCENARIO

GOES WITH

$$\left(\frac{\Delta m^2_{ATM} L}{4E}\right) \sin^2\left(\frac{\Delta m^2_{LSND} L}{4E}\right)$$

MUCH BIGGER

MAXIMUM

MUCH NEARER

THAN FOR

THREE-FAMILY

(DOMINATED BY Δm^2_{SUN})

WE MEASURE THE STATISTICAL SIGNIFICANCE OF THE ASYMMETRIES

$$\frac{A_{\alpha\beta}}{\Delta A_{\alpha\beta}} \propto \frac{P_{\alpha\beta}^{\not{CP}}}{\sqrt{P_{\alpha\beta}^{CP}}}$$

DUE TO THIS FACTOR

CP-VIOLATION IS BETTER MEASURED IN

$P(\nu_\mu \to \nu_\tau)$

THAN

$P(\nu_e \to \nu_\mu)$

(OPPOSITE TO THREE-FAMILY)

MATTER EFFECTS
(... a comment....)

IN THE LAST MONTHS,

Kolliomäki, Maalampi, Tanimoto
hep-ph/9909301

Hattori, Hasuike, Wakaizumi
hep-ph/0002096

CONSIDERED MATTER EFFECTS
IN FOUR-FAMILY NEUTRINO MODEL

$$\ldots + \begin{pmatrix} 0 & & & \\ & A+B & & \\ & & B & \\ & & & B \end{pmatrix}$$

AND FOUND IT NEGLIGIBLE.
HOWEVER, $L < 100$ km

$\Rightarrow$ ..... YOU CAN DRAW
YOUR OWN CONCLUSION
....

CONCLUSIONS

- NUFACT IS SENSITIVE TO THE WHOLE PARAMETER SPACE IN THE ONE-MASS DOMINANCE SCENARIO

  θ_{13}, θ_{14}, θ_{23}, θ_{24}

  (PROBABLY NOT TO δ_3)

- μ AND τ-CHARGE IDENTIFICATION NEEDED

- $L \sim 1$ km, $M \gtrsim 1$ TON, 2×10^{20} MUONS

  (PERHAPS, BETTER INCREASING M A BIT...)

- CP-VIOLATION SEEMS TO BE "EASY" TO STUDY WITH 1 KTON, $L = 10$-100 km IN THE $\nu_\mu \to \nu_\tau$ CHANNEL

- HOWEVER: NO SERIOUS STUDY OF BACKGROUND, EFFICIENCY, CORRELATIONS

  HAVE BEEN DONE