

Neutrino Oscillations

at **NUFACT**

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Atmospheric

⊕

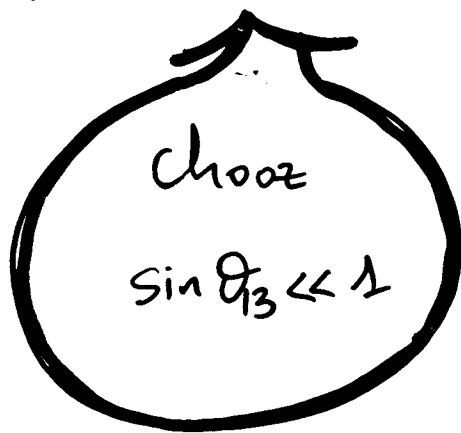
Solar anomalies

$$\Delta m_{23}^2$$

→

$$\Delta m_{12}^2$$

$$V_{CKM} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} e^{i\delta} & 0 \\ -s_{12} e^{i\delta} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

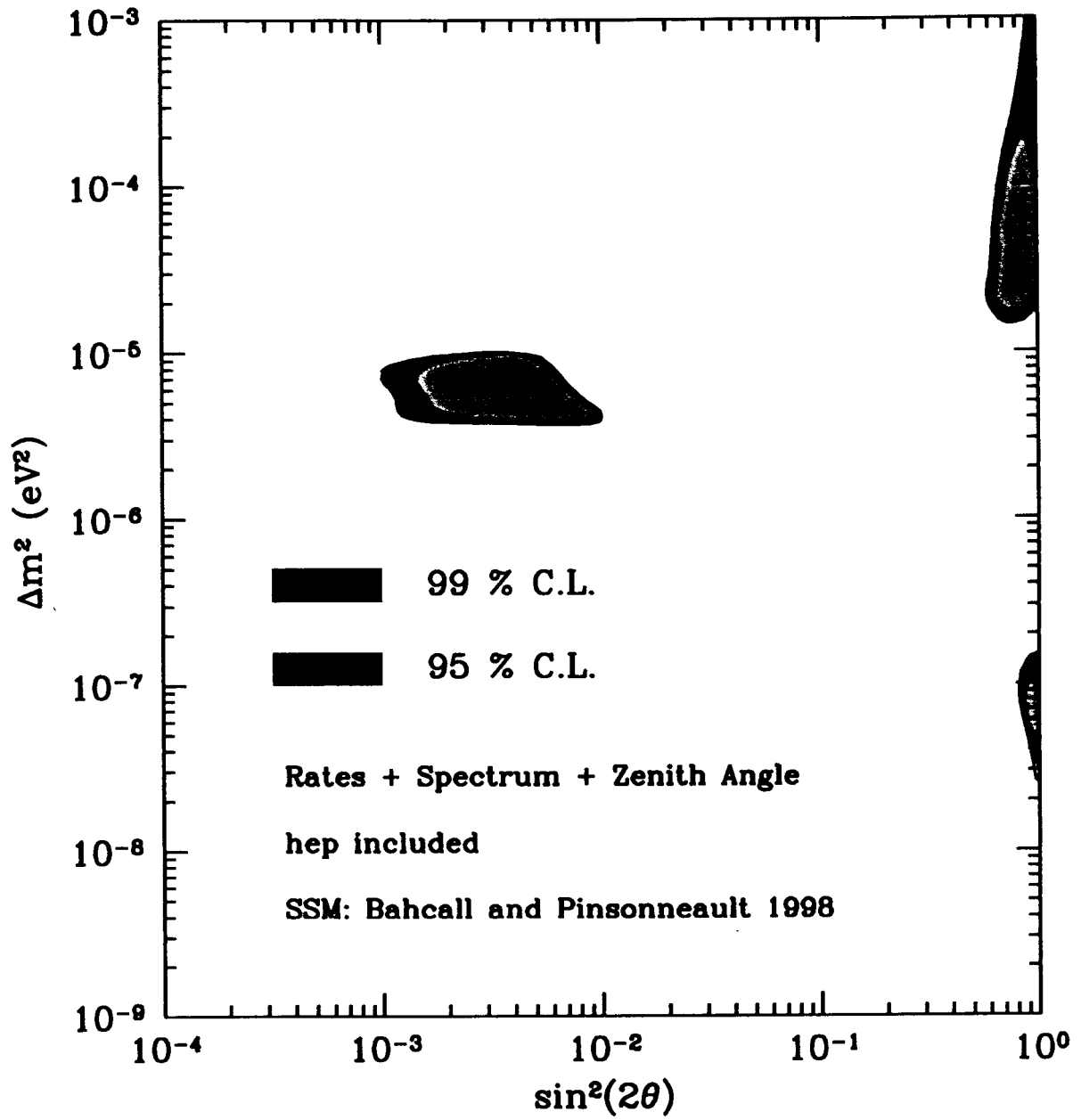


Planned LBL
accelerator experiments

Minos
Opera...

Solar and LBL
reactor experiment

Kamland
...



In 10 years from now...

θ_{13}

link between solar & atmospheric anomalies

sign(Δm_{23}^2)

ν mass spectrum \Rightarrow ν mass matrix



"hierarchical"

"degenerate"

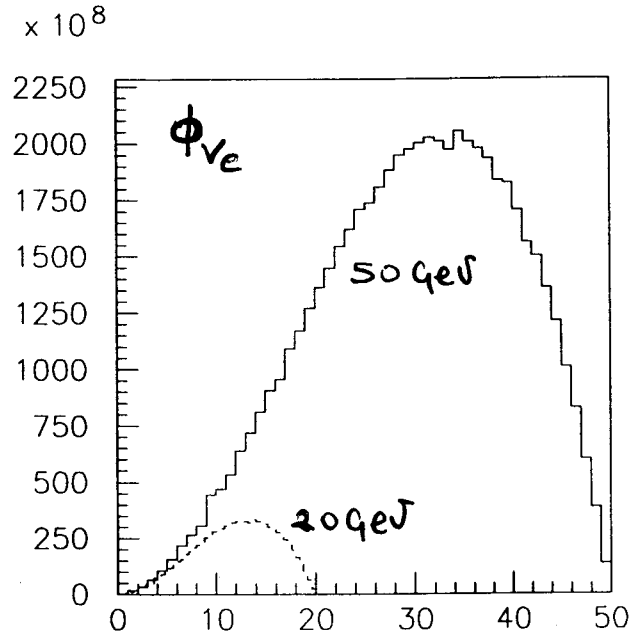
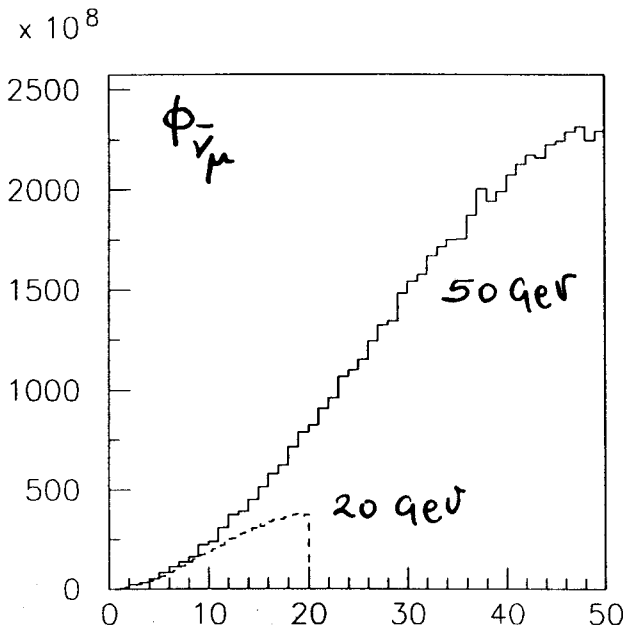
δ

\cancel{CP} in lepton sector
(only if LMA-MSW)

What is optimal E_μ ?

$$E_\mu = 50 \text{ GeV}$$

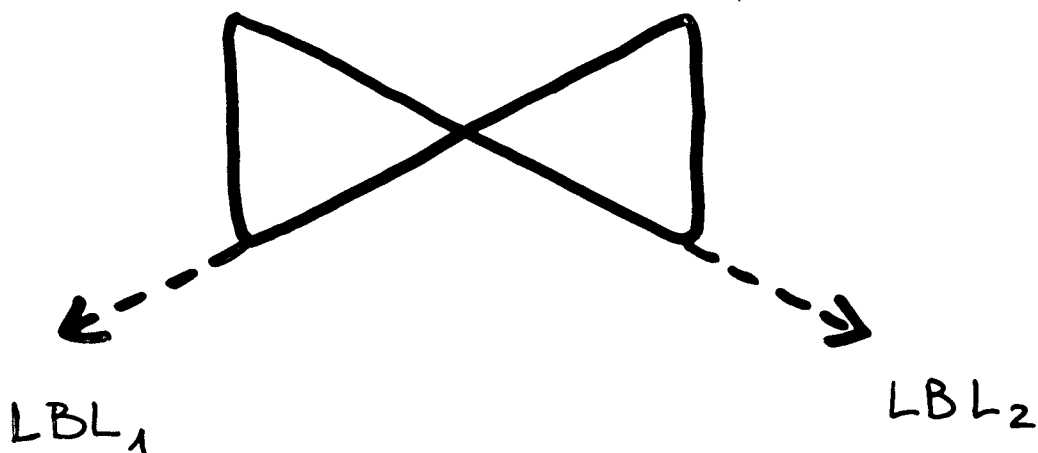
$$N_{cc} \propto \Phi_\nu \cdot \sigma \sim E_\nu^3 / L^2$$



Numu fluxes averaged at 1 km in det site

Nue fluxes averaged at 1 km in det site

What is optimal LBL?



$$\bar{E}_\mu = 50 \text{ GeV}, \quad 40 \text{ kTon}, \quad 5 \text{ years}, \quad 2 \cdot 10^{20} \mu^{\pm}$$

(or $2 \cdot 10^{21} \mu^{\pm}$, 1 year)

Data set: # of wrong sign muons in
equal bins of $\Delta E_\nu = 10 \text{ GeV}$ and

$$LBL = 732, 3500, 7332 \text{ km}$$

$$N_{i, \mu^+}^\alpha, \quad N_{i, \mu^-}^\alpha \quad \alpha = 1, 2, 3$$

$i = 1, \dots, 5$

$$\chi_\alpha^2 = \sum_i \frac{(N_{i, \mu^+}^\alpha - \text{Theo}(p_1, p_2))^2}{N_{i, \mu^+}^\alpha} + (+ \leftrightarrow -)$$

Compare six different fits:

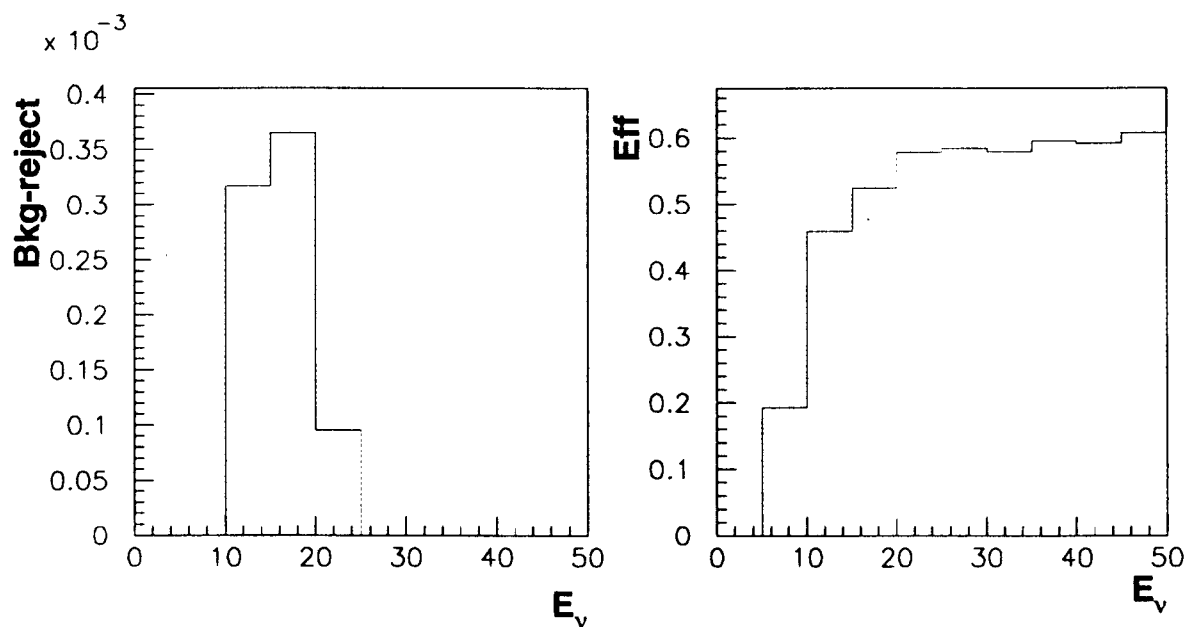
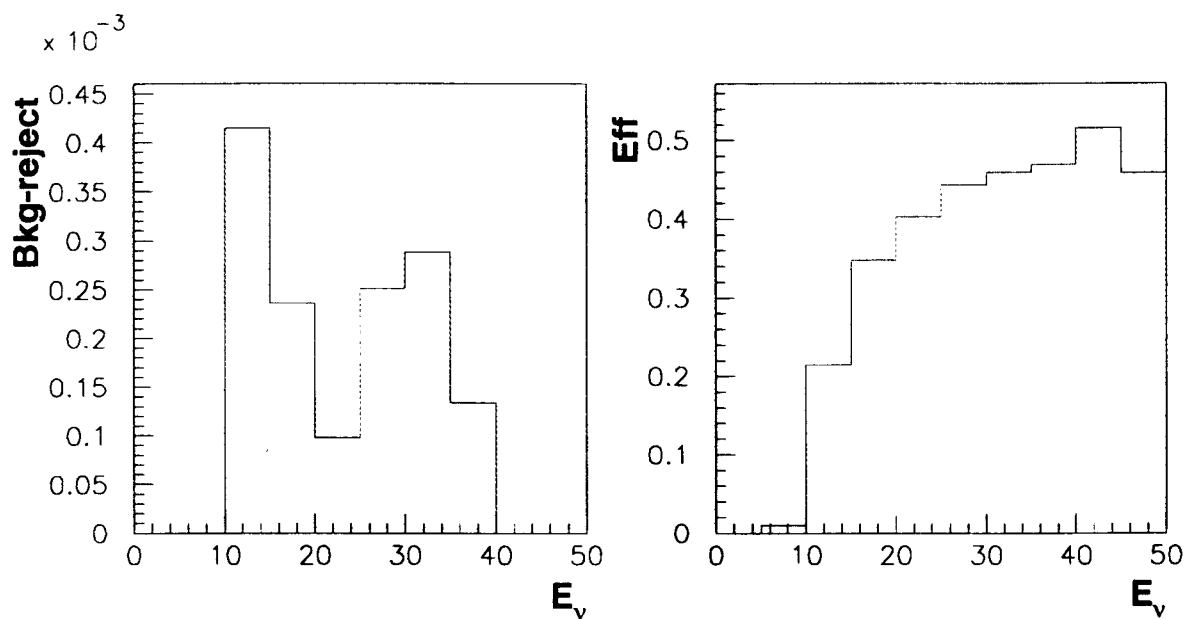
$$\textcircled{F1} \chi_1^2 (732 \text{ km}) \quad \textcircled{F2} \chi_2^2 (3500 \text{ km}) \quad \textcircled{F3} \chi_3^2 (7332 \text{ km})$$

$$\textcircled{F4} \chi_1^2 + \chi_2^2 \quad \textcircled{F5} \chi_2^2 + \chi_3^2$$

$$\textcircled{F6} \chi_1^2 + \chi_2^2 + \chi_3^2$$

Simultaneous Measurement of θ_{13}, δ III

Efficiency & Backgrounds for μ^\pm



SMA - MSW or VO

$$\Delta m_{12}^2 \lesssim 10^{-6} \text{ eV}^2 \quad \sin 2\theta_{12} \sim 10^{-3}$$

Solar parameters do not play any role at atmospheric distances \Rightarrow No $\cancel{G_F}$, θ_{13} , $\text{sig}(\Delta m_{23}^2)$

In vacuum:

$$P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) = S_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{23}^2 L}{4E_\nu}\right)$$

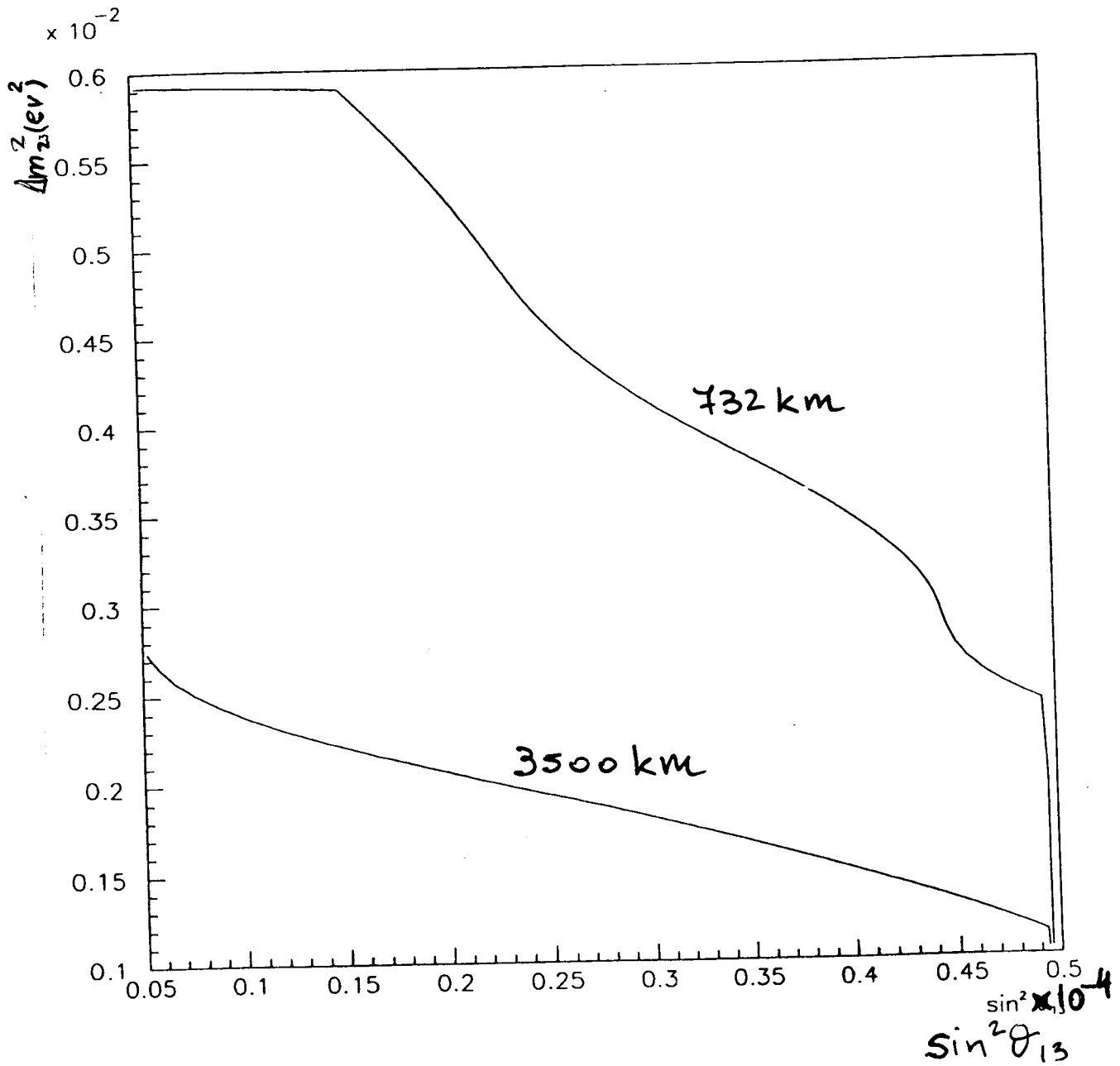
$$A \equiv 2\sqrt{2} G_F N_e E_\nu \approx 0 \text{ (} 10^{-3} \text{ eV}^2 \text{)}$$

In matter:

$$P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) = S_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta m_{23}^2}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{4E_\nu}\right)$$

$$B_\pm \equiv \sqrt{\Delta m_{23}^2 + A^2 \mp 2A \Delta m_{23}^2 \cos 2\theta_{13}}$$

Sensitivity to θ_{13} SMSW



sign (Δm_{23}^2)

see also Barger et al.
hep-ph/9911524

→ need L large $B_{\pm} L \gtrsim \pi$

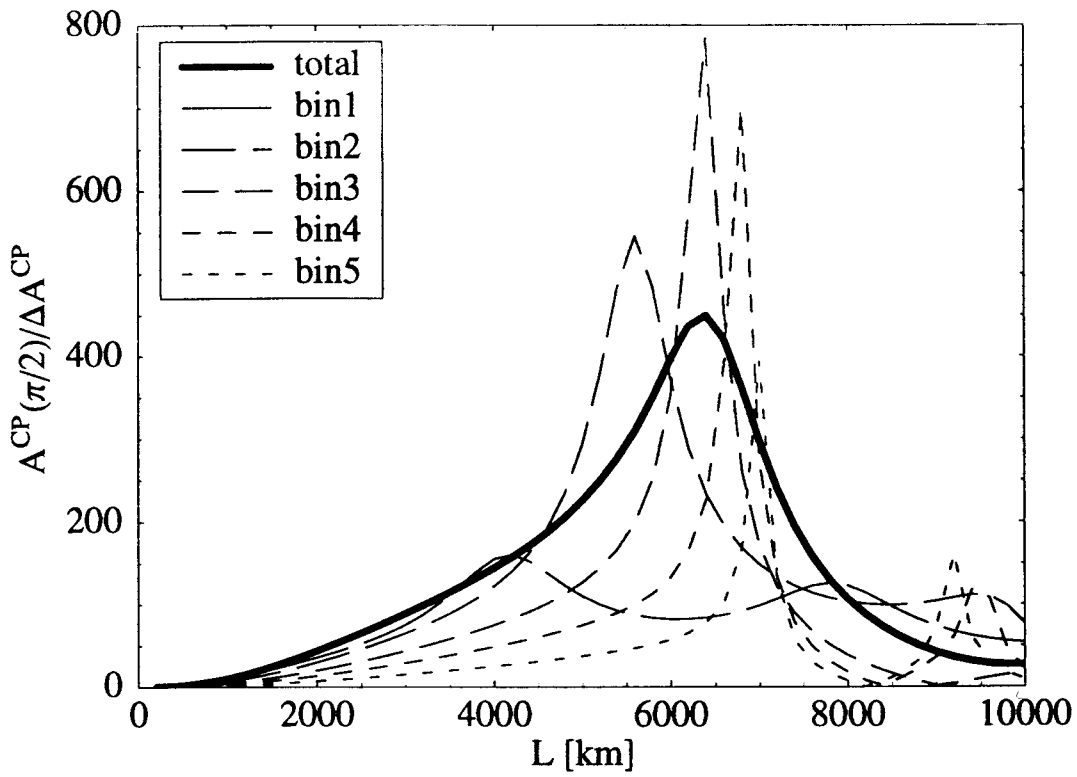
→ $\Delta m_{23}^2 \rightarrow -\Delta m_{23}^2 \Leftrightarrow CP$

Sensitivity to sign \approx sensitivity to P_{CP}

$$P_{CP} \equiv P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$$

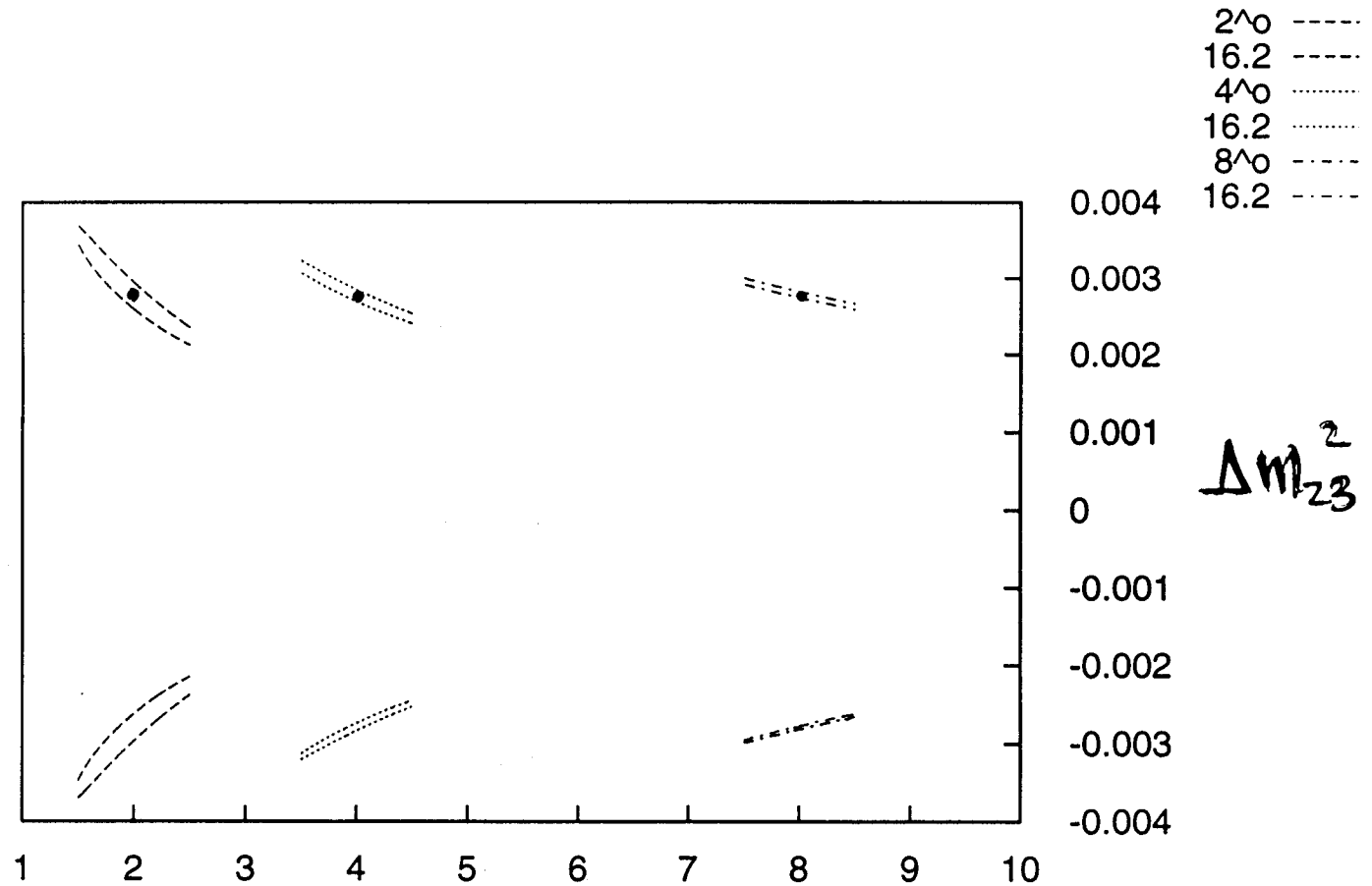
$$\mu = \sqrt{2} G_F \langle N_e \rangle$$

see also A. Bruno et al.
CERN-EP-99-074
Freund et al.
hep-ph/9912457



$$A^{CP} \equiv \frac{N_{\mu^+} - N_{\mu^-} \cdot R}{N_{\mu^+} + N_{\mu^-} \cdot R} \sim P_{CP}$$

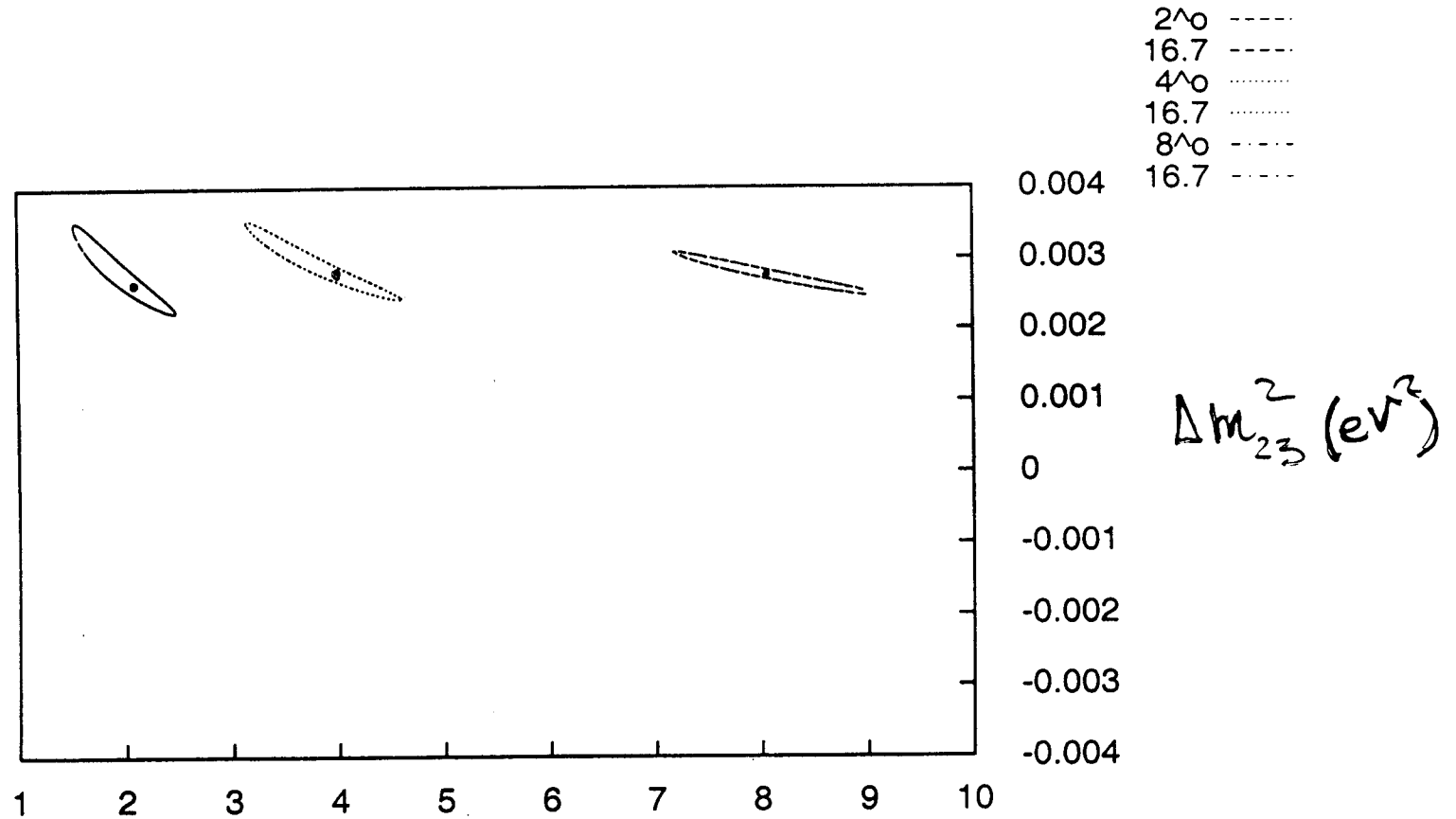
732 km



Sign cannot be distinguished!

$L = 3500 \text{ km}$

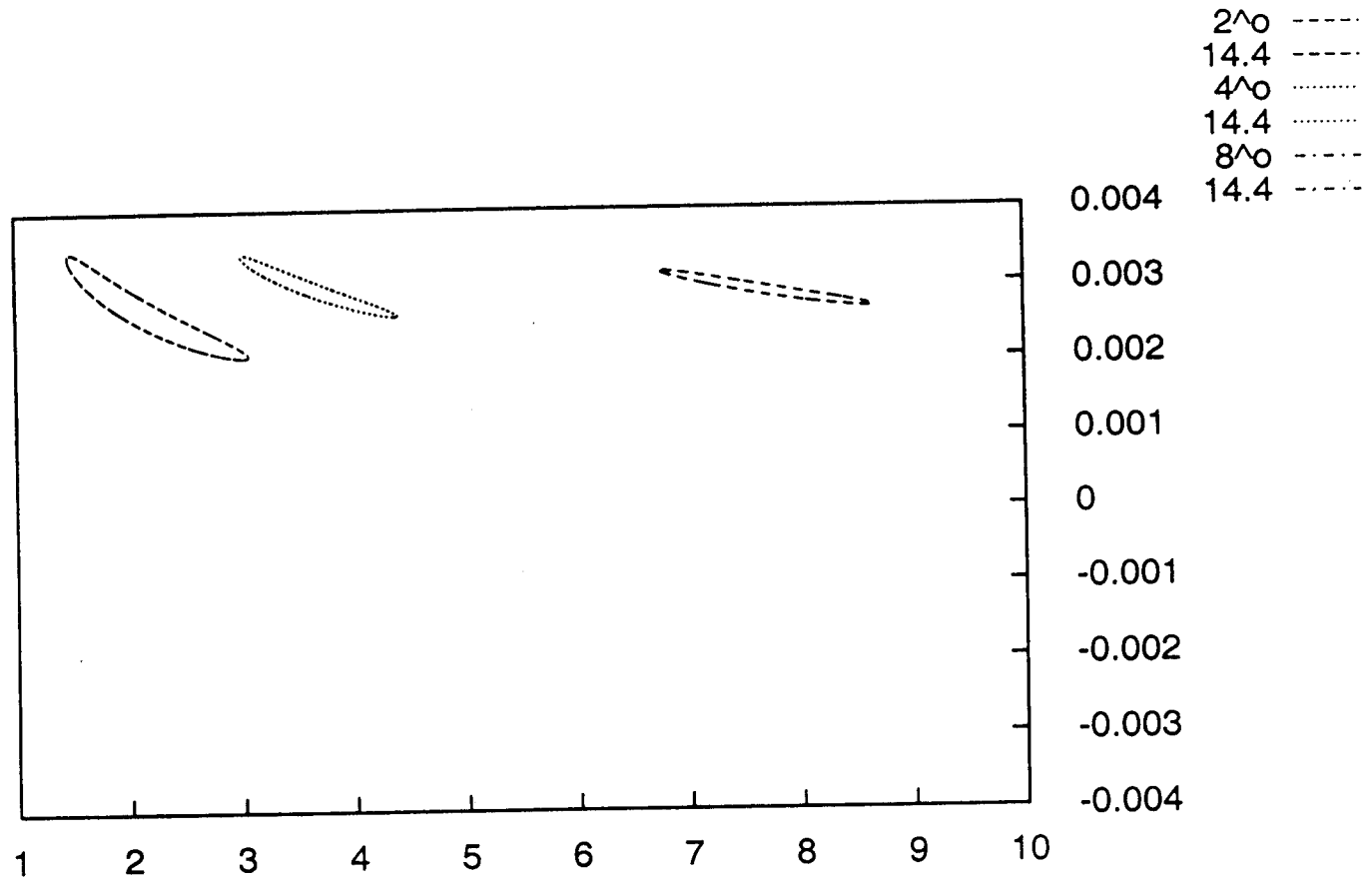
$L=3500$



$\text{Sign}(\Delta m_{23}^2)$ can be distinguished at 99% CL

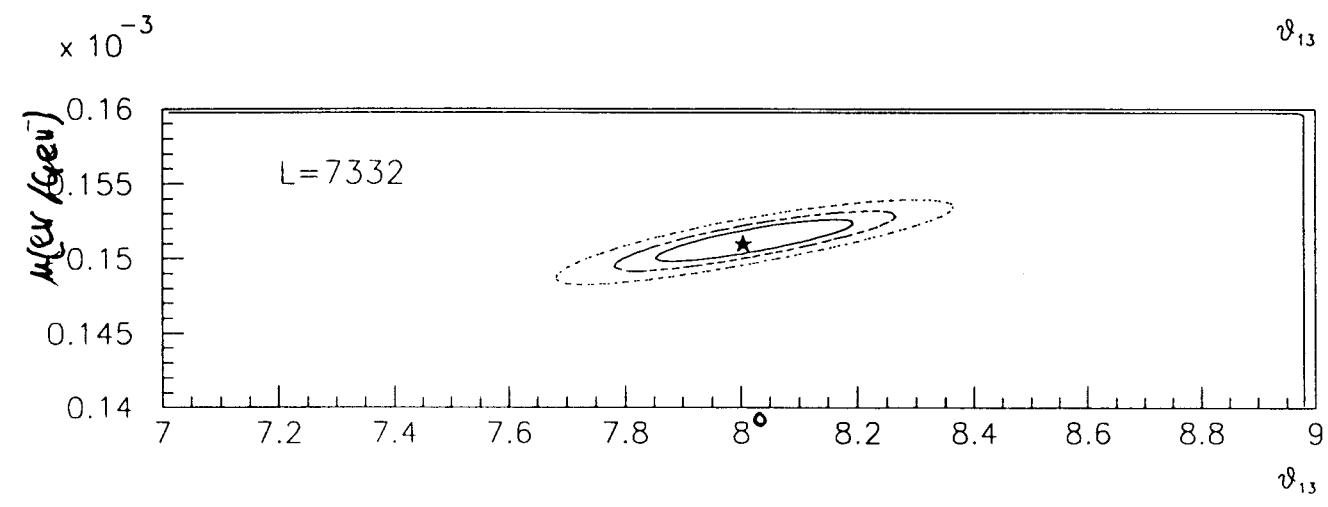
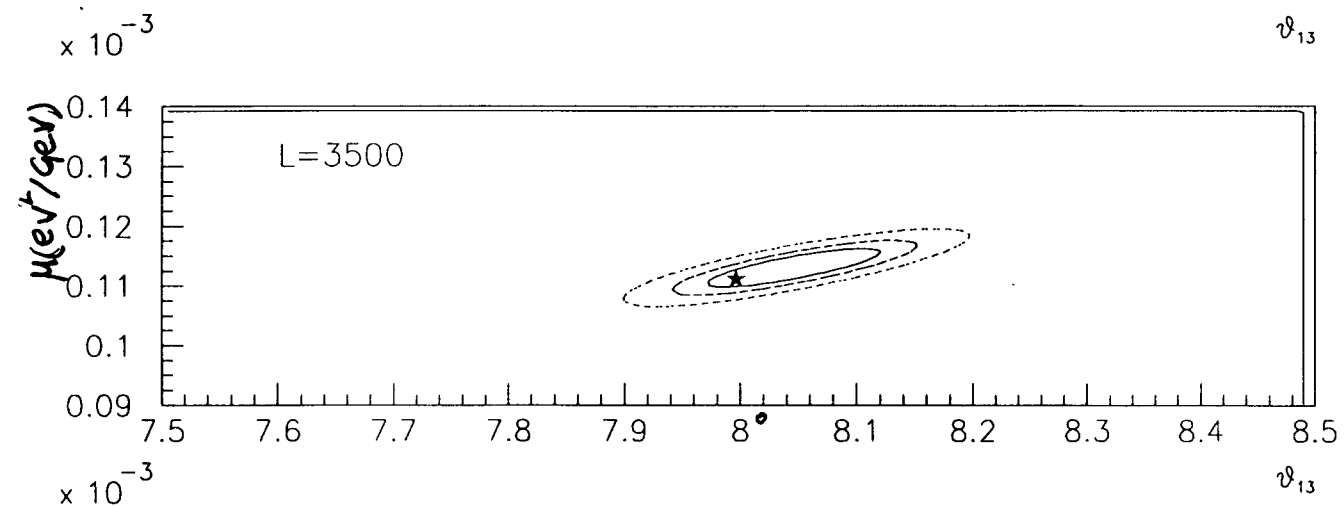
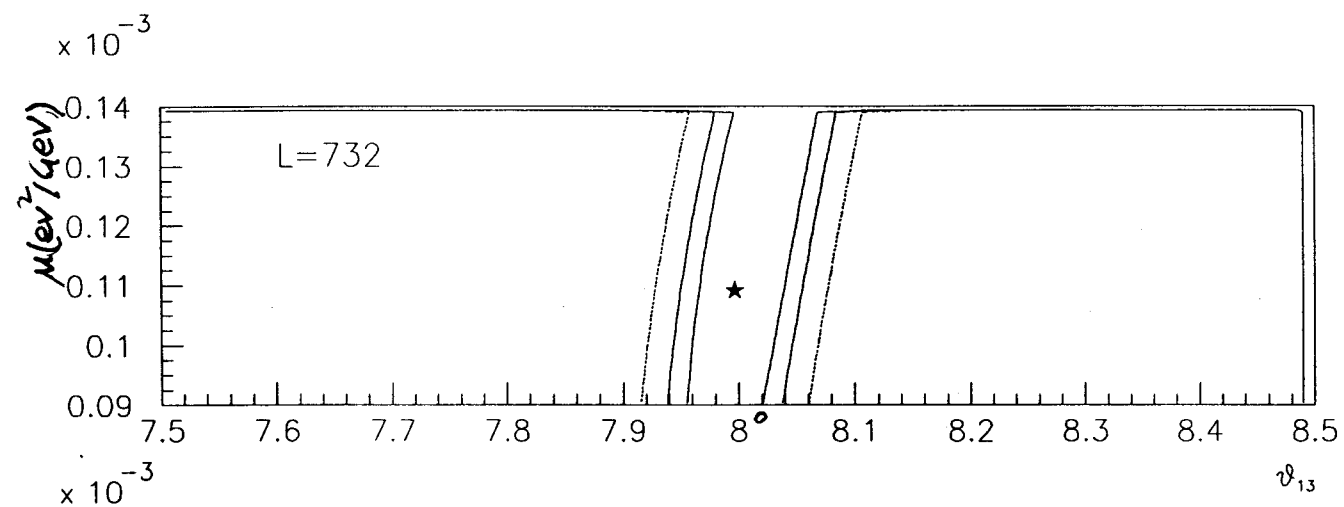
$$L = 7332 \text{ km}$$

$$L = 7332$$



sign(Δm_{23}^2) can be distinguished at 99% CL

Simultaneous determination of $\mu \equiv \sqrt{2} G_F \langle N_e \rangle$ and ϑ_{13} if SMA-MSW



LMA-MSW Solution

$$\Delta m_{12}^2 \sim 10^{-4} - 10^{-5} \text{ eV}^2 \quad \sin 2\theta_{12} \sim 1$$

- solar parameters affect sizeably the oscillation probabilities at terrestrial distances
- ~~CP~~ sizeable!
- More unknown parameters: harder to disentangle
(θ_{13}, δ)

Approximation $O\left(\frac{\Delta m_{12}^2}{\Delta m_{23}^2}, \frac{\Delta m_{12}^2}{A}, \theta_{13}\right)^2$

In vacuum:

$$\begin{aligned}
 P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) &= s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{23}^2 L}{4E\nu} \\
 &+ c_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E\nu} \\
 &+ J \cos\left(\pm\delta - \frac{\Delta m_{23}^2 L}{4E\nu}\right) \sin \frac{\Delta m_{12}^2 L}{4E\nu} \sin \frac{\Delta m_{23}^2 L}{4E\nu}
 \end{aligned}$$

$$J \equiv \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$P_{CP} \equiv P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) \propto \sin \delta$$

$$A_{CP} = \frac{N_{\mu^+} - N_{\mu^-R}}{N_{\mu^+} + N_{\mu^-R}}, \quad \frac{A_{CP}}{\delta A_{CP}} \propto E_\nu^{1/2} \left| \sin \frac{\Delta m_{23}^2 L}{4E\nu} \right|$$

In matter,

$$\sin 2\theta_{13} \longrightarrow \frac{\Delta m_{23}^2}{B_{\pm}} \sin 2\theta_{13}$$

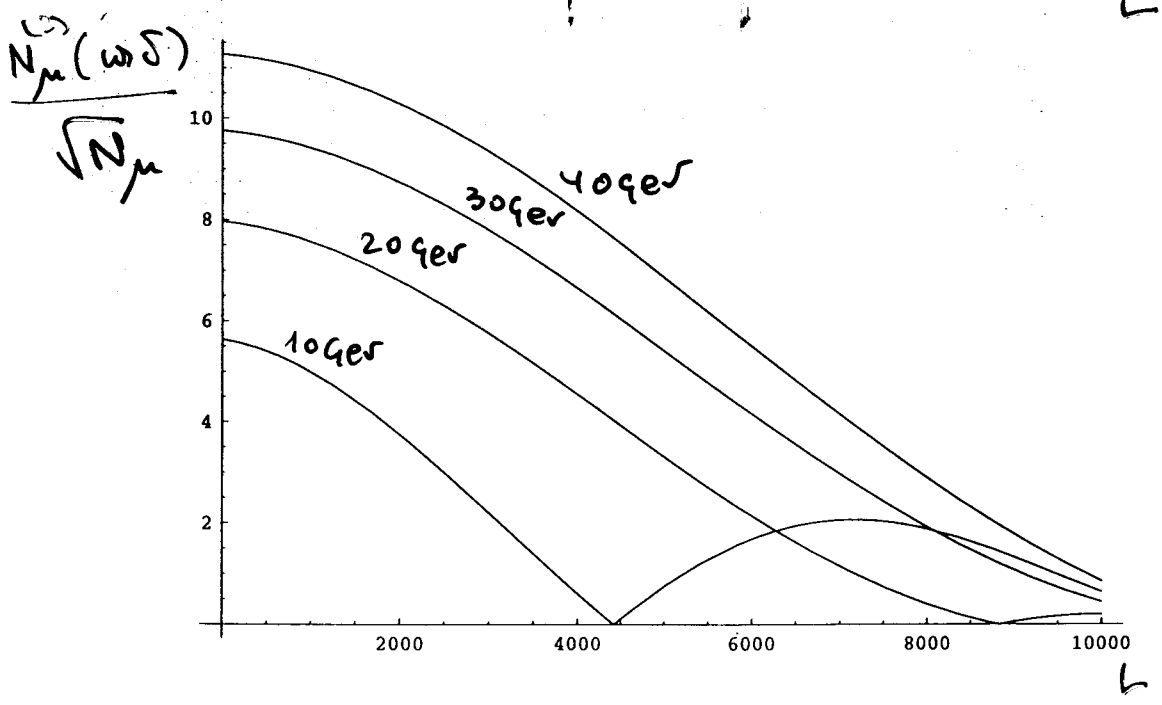
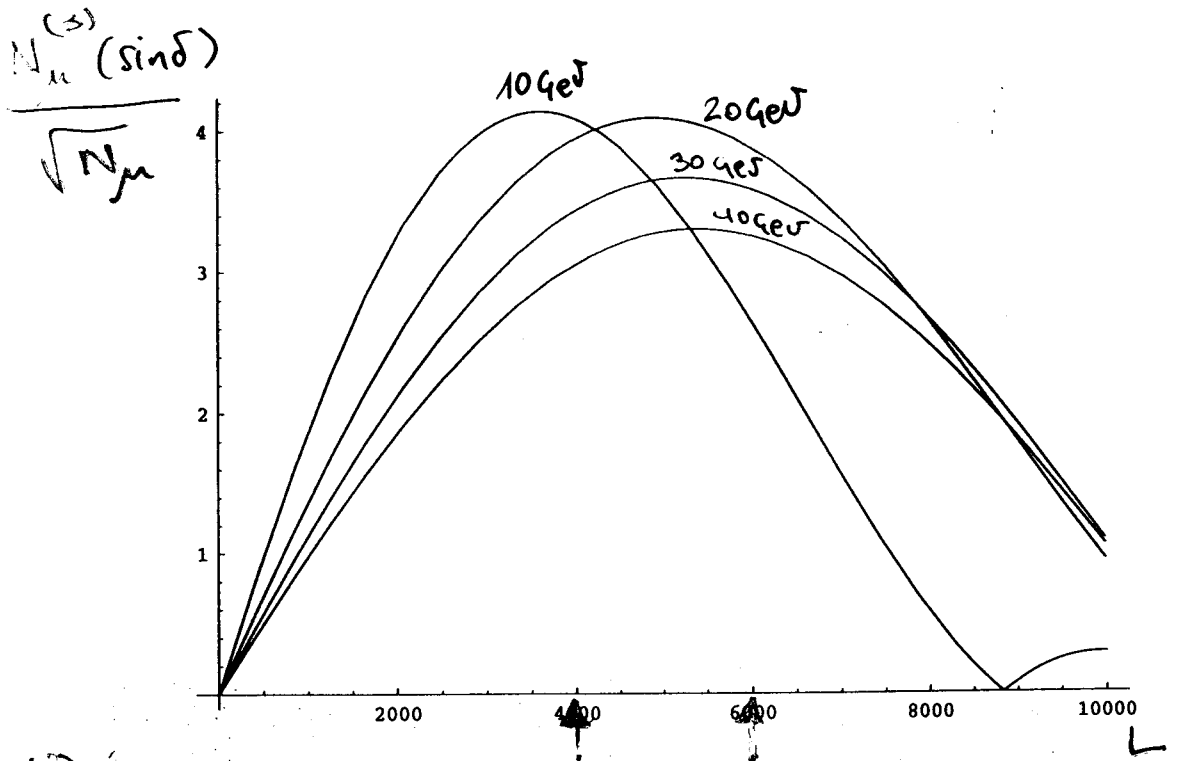
$$\sin 2\theta_{12} \longrightarrow \frac{\Delta m_{12}^2}{A} \sin 2\theta_{12}$$

$$\Delta m_{23}^2 \longrightarrow B_{\pm}$$

$$\Delta m_{12}^2 \longrightarrow A$$

$P_{\mu\mu} \neq 0$ for $\delta = 0$!

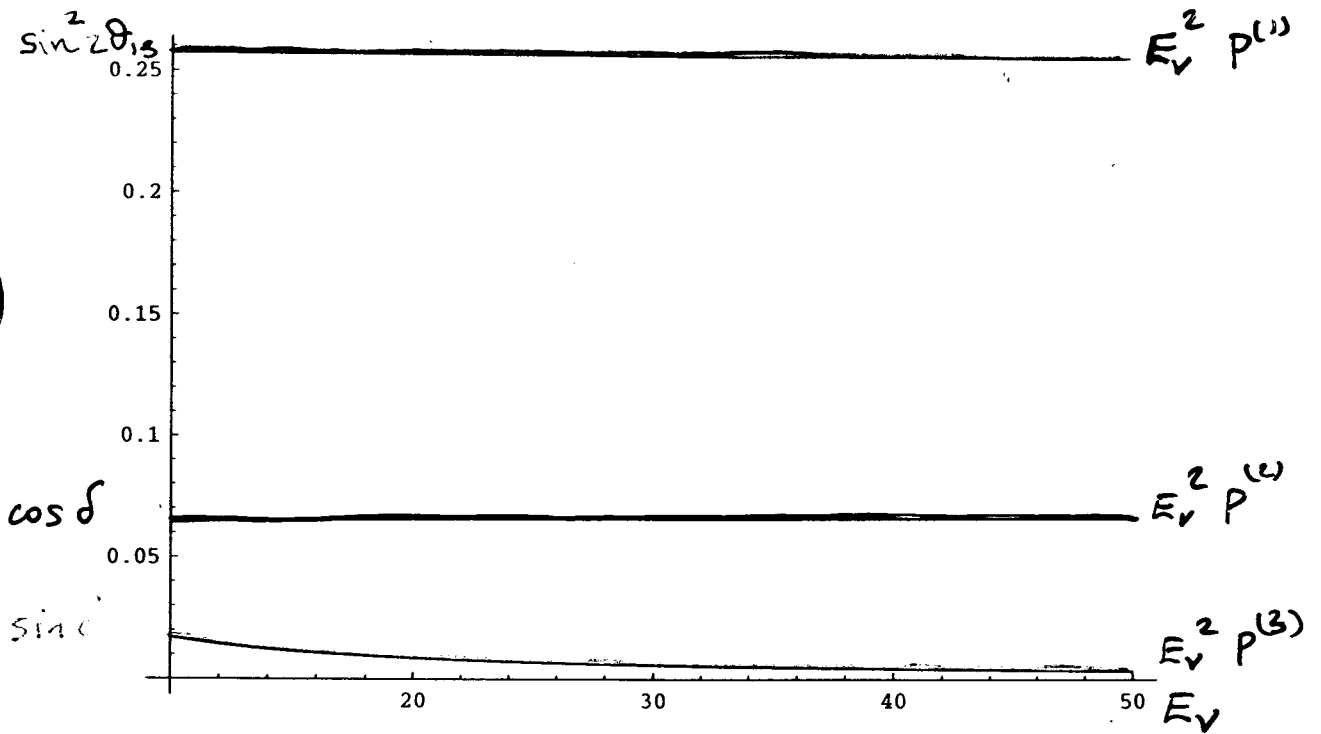
Instead: what is the relative size of the terms which depend on δ



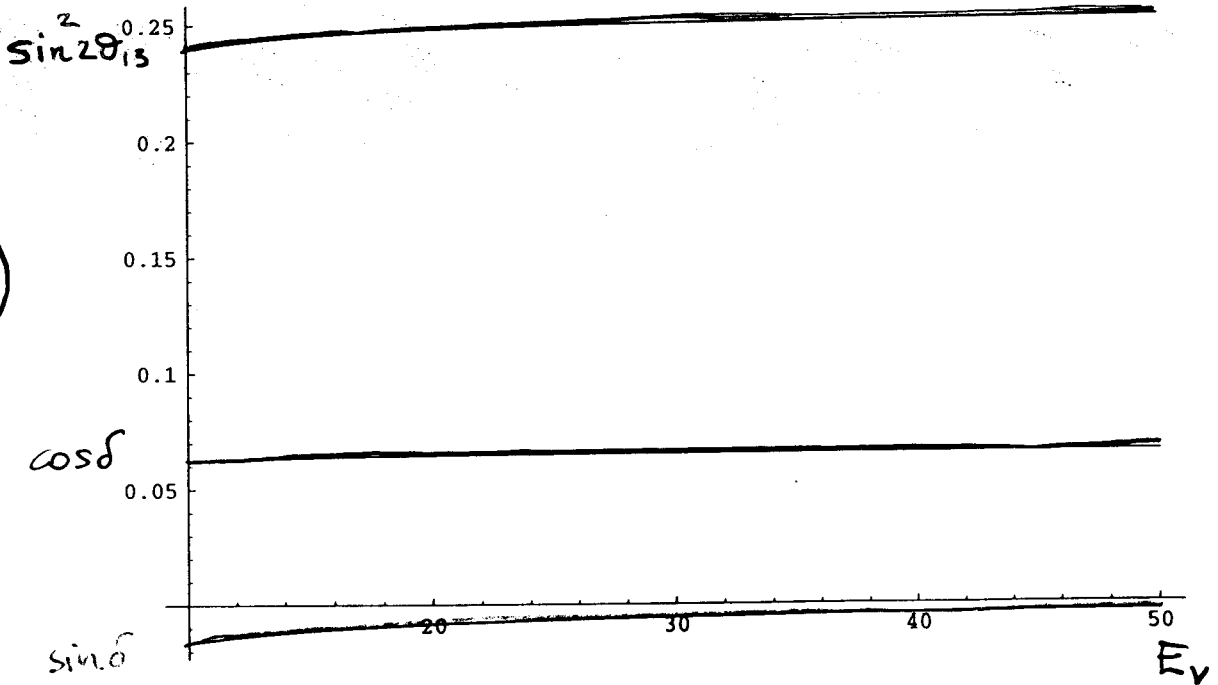
$\nu_e \rightarrow \nu_{\mu}$

732 km

(✓)



(✓)



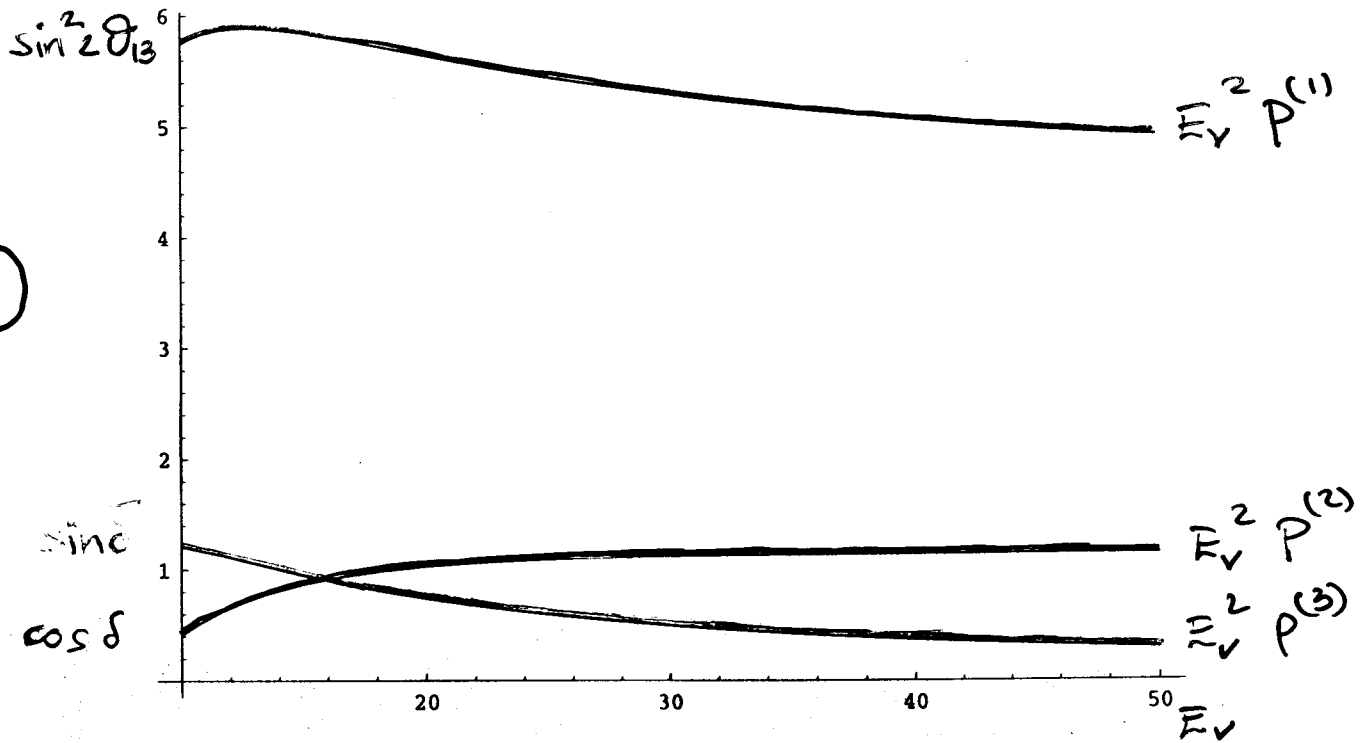
(1) $P \propto \sin^2 2\theta_{13}$

(2) $P \propto \cos \delta$

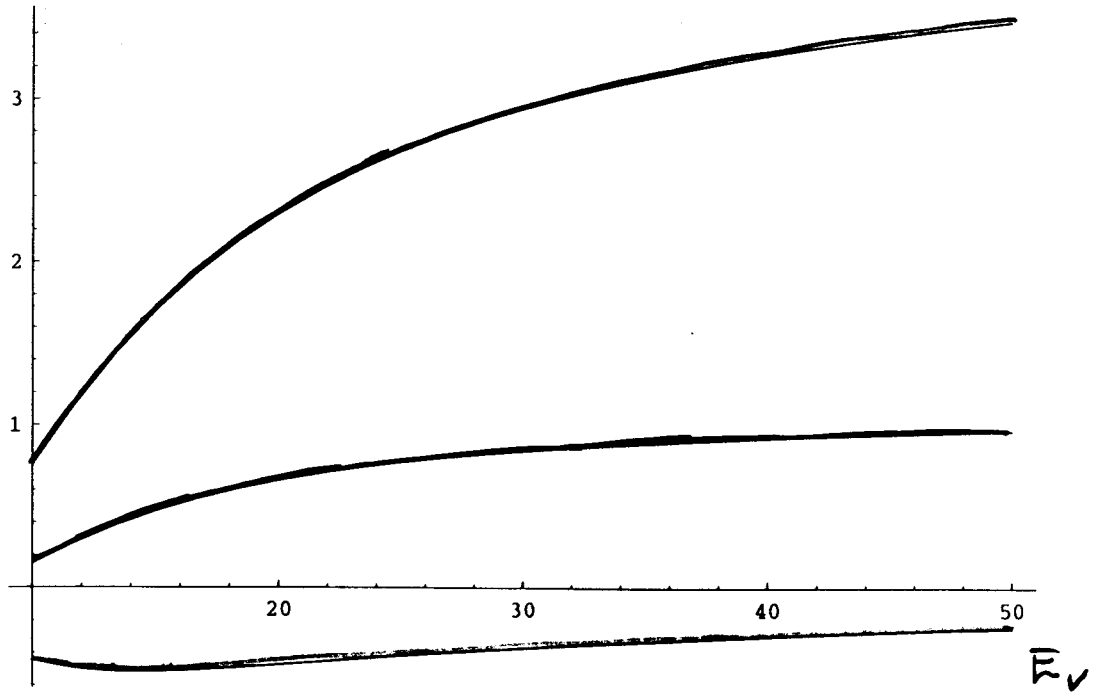
(3) $P \propto \sin \delta$

3500 km

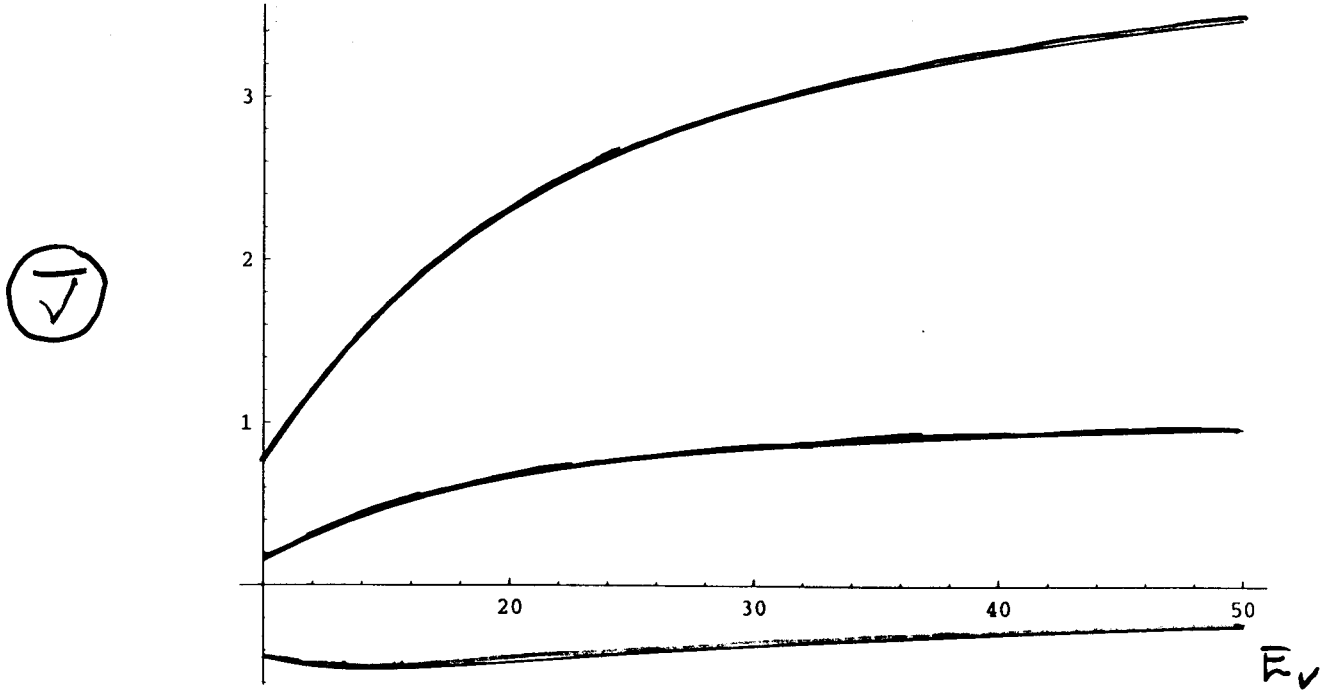
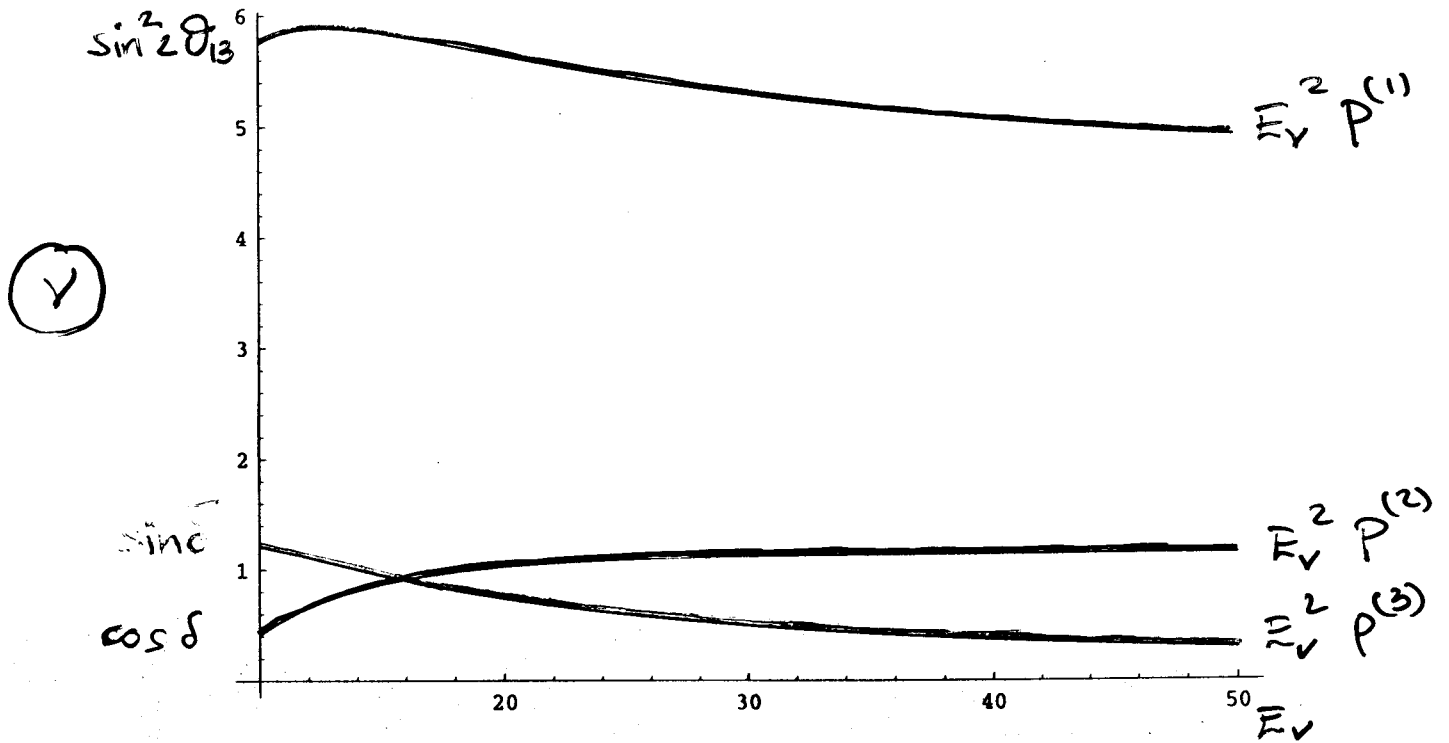
(Y)



(Z)



3500 km



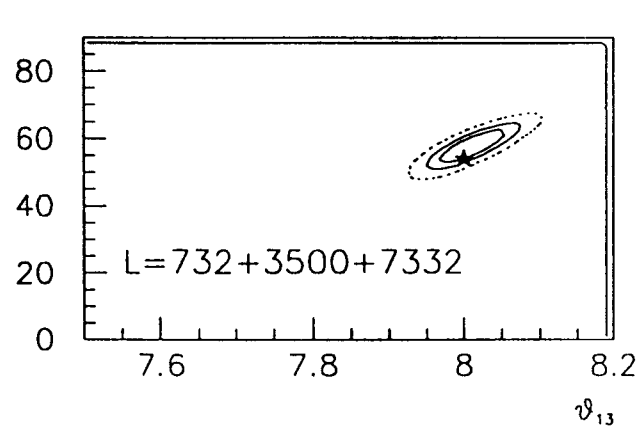
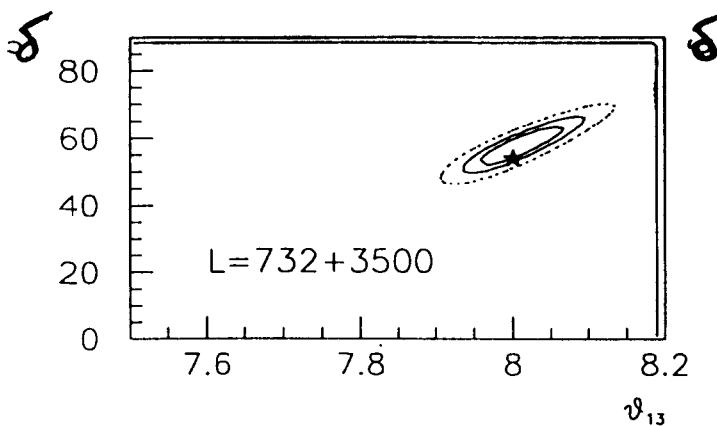
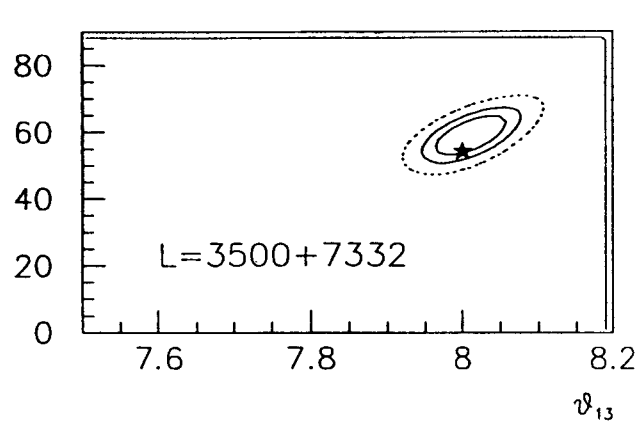
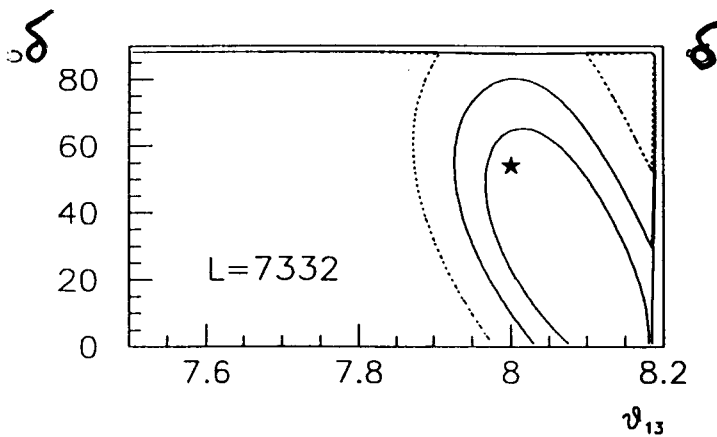
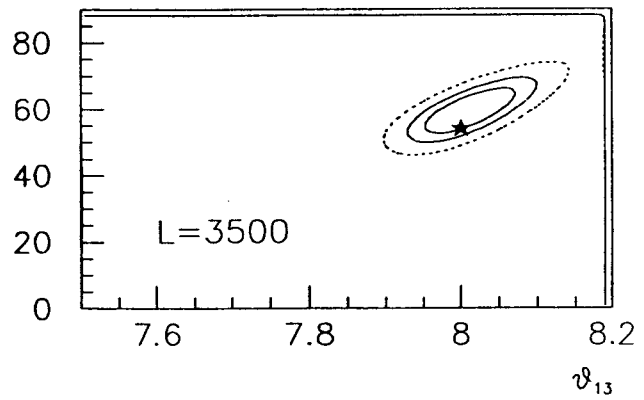
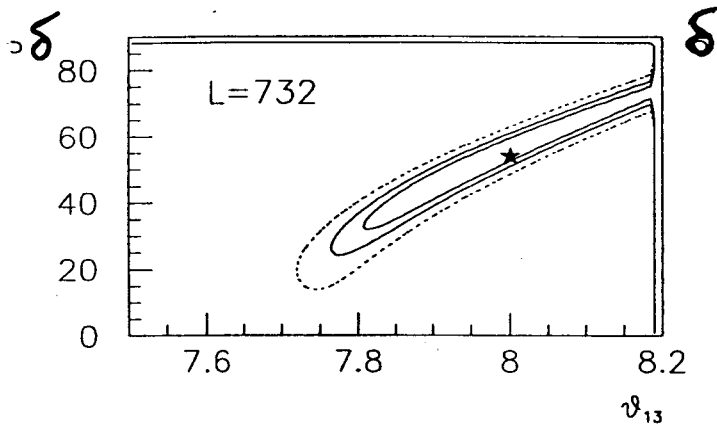
Only statistical errors

LM SW

$$\Delta m_{12}^2 = 10^{-4} \text{ eV}^2 \quad \theta_{12} = \pi/4$$

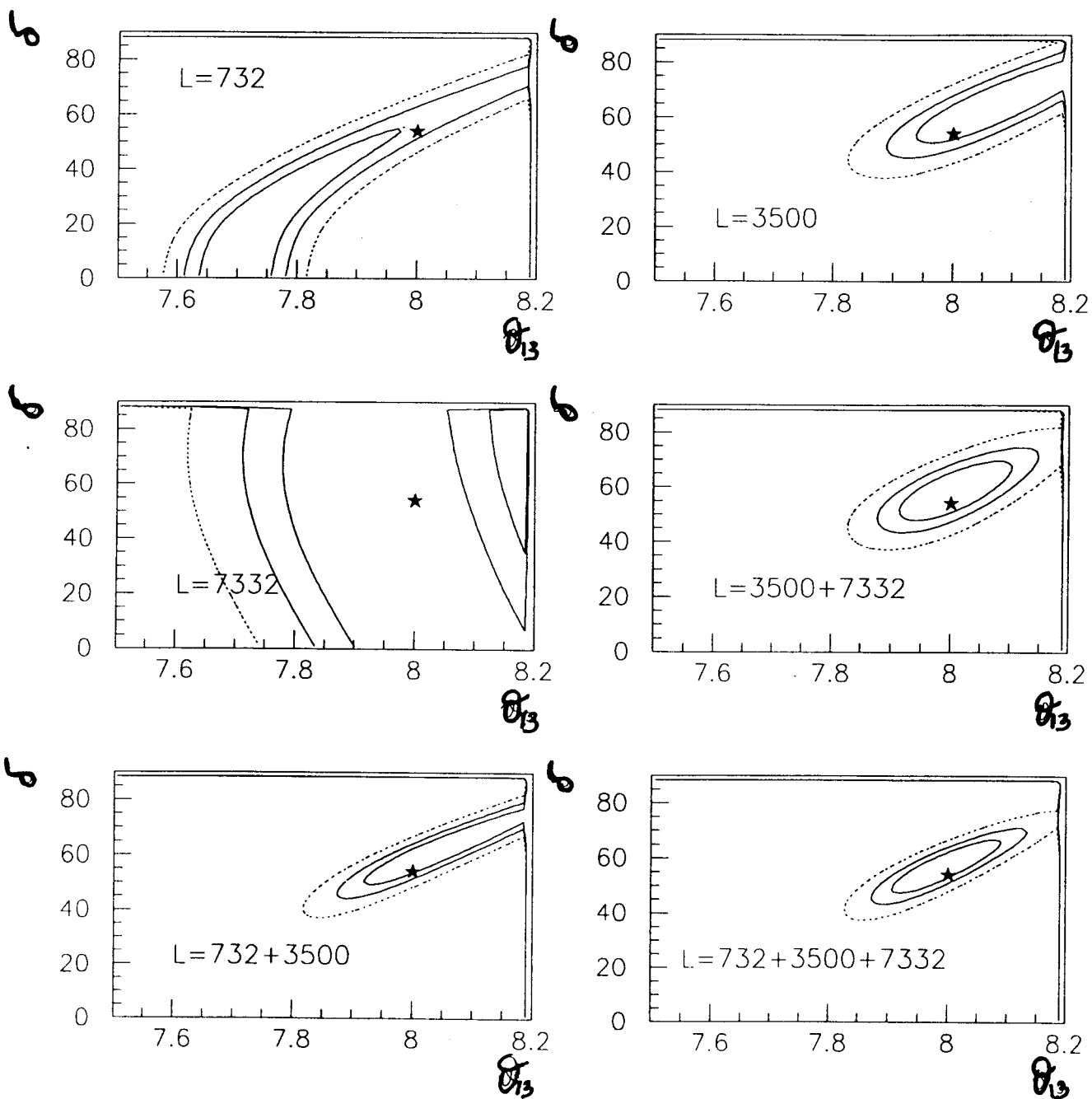
$$\Delta m_{23}^2 = 2.8 \cdot 10^{-3} \text{ eV}^2 \quad \theta_{23} = \frac{1}{4}$$

68.5% CL, 90% CL, 99% CL

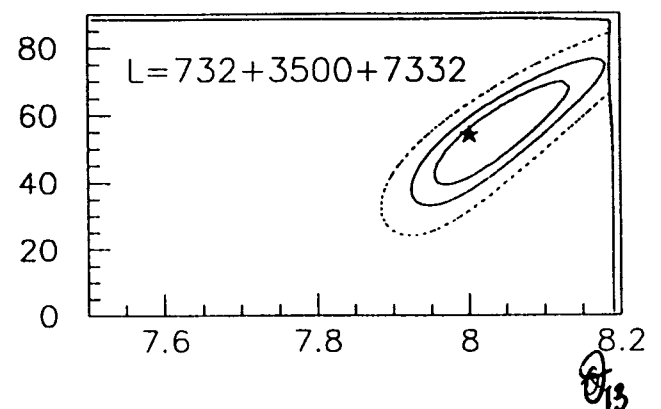
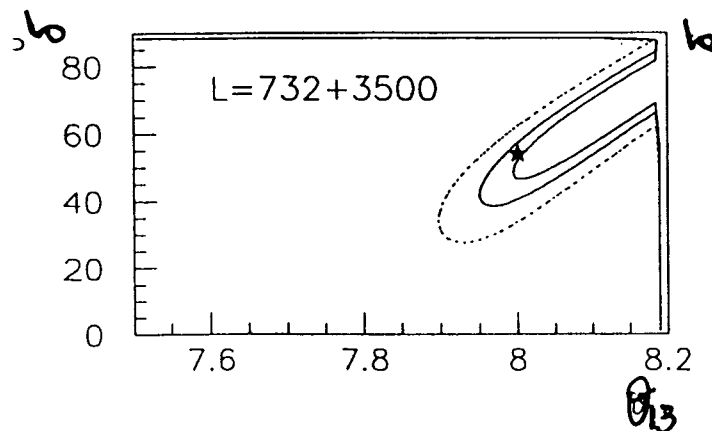
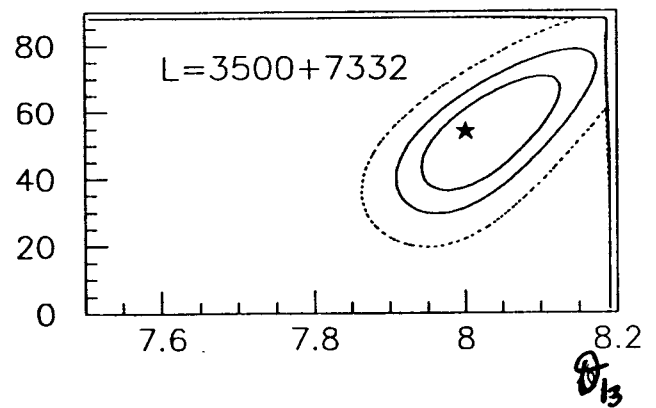
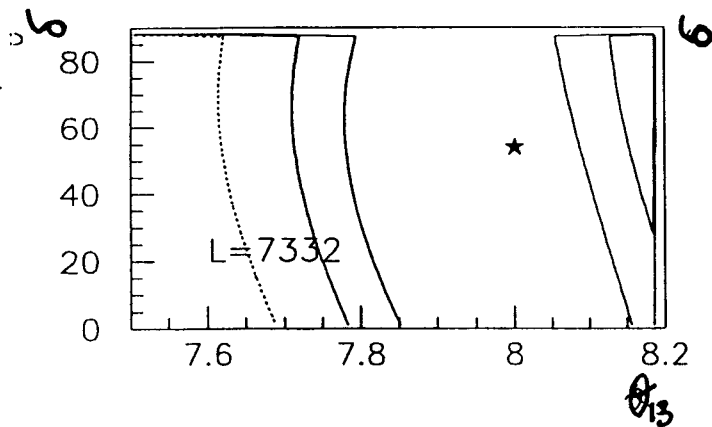
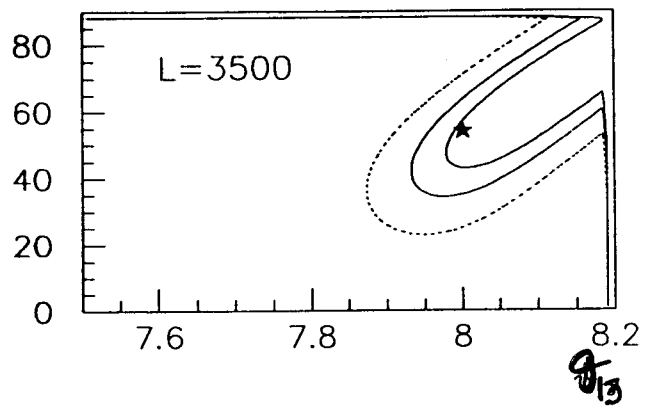
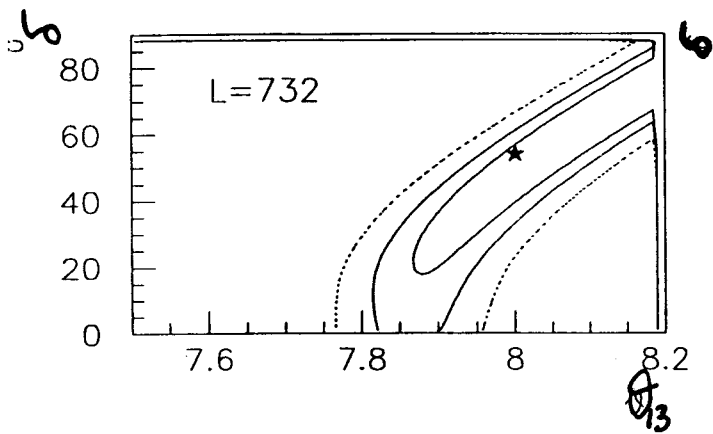


$$\Delta m_{12}^2 = 10^{-4} \text{ eV}^2$$

Backgrounds \oplus Efficiencies included

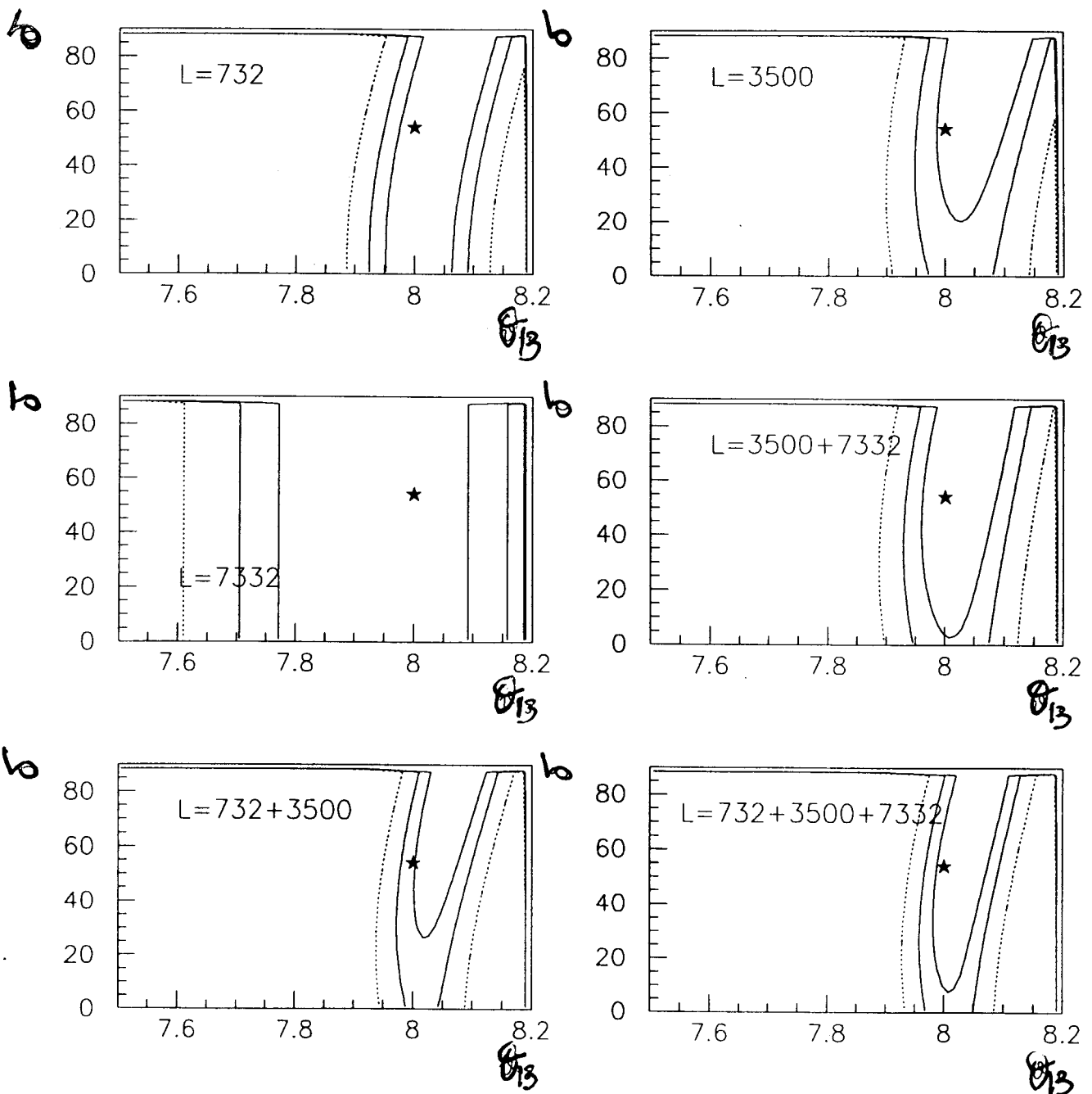


$$\Delta m_{12}^2 = 5 \cdot 10^{-5} \text{ eV}^2$$



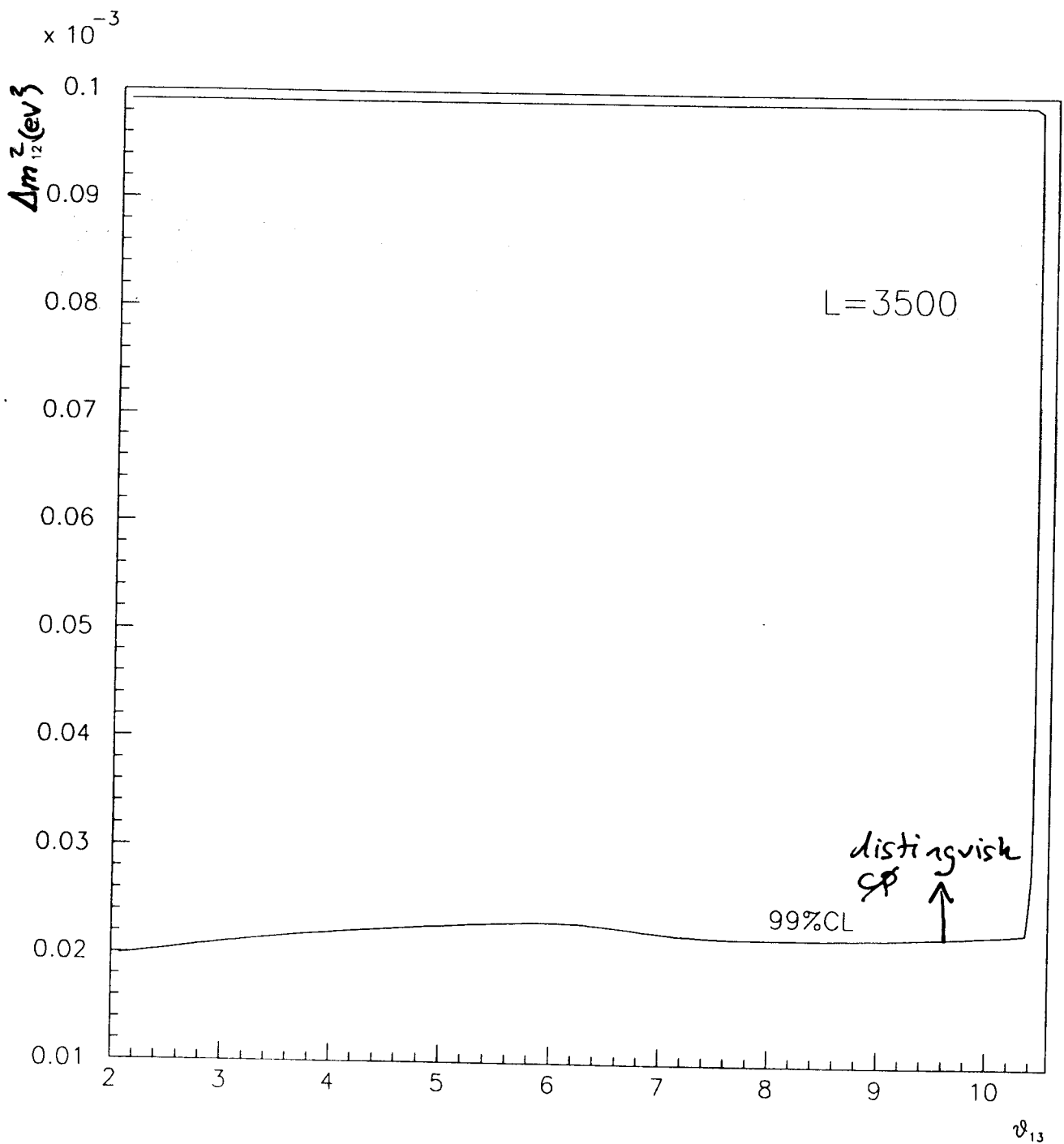
$$\Delta m_{12}^2 = 10^{-5} \text{ eV}^2$$

No sensitivity to θ_{13} !

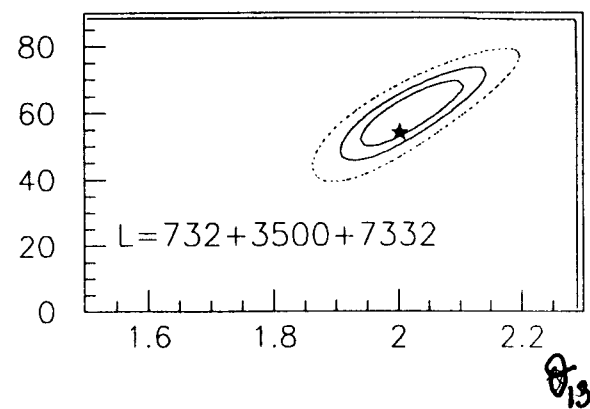
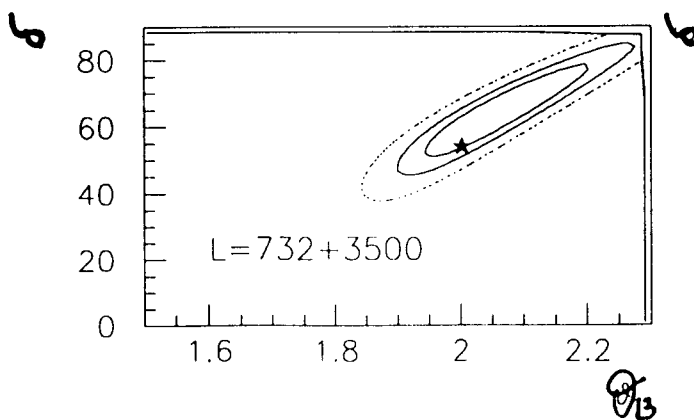
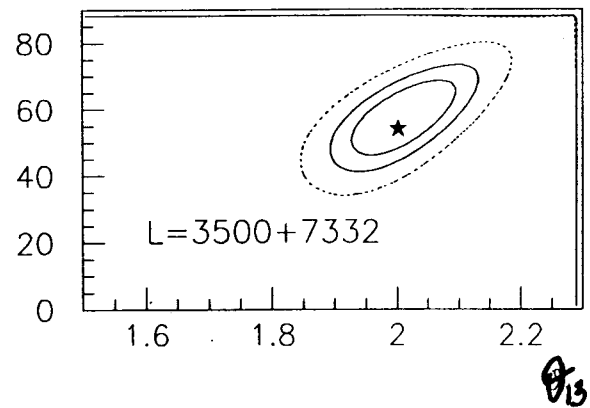
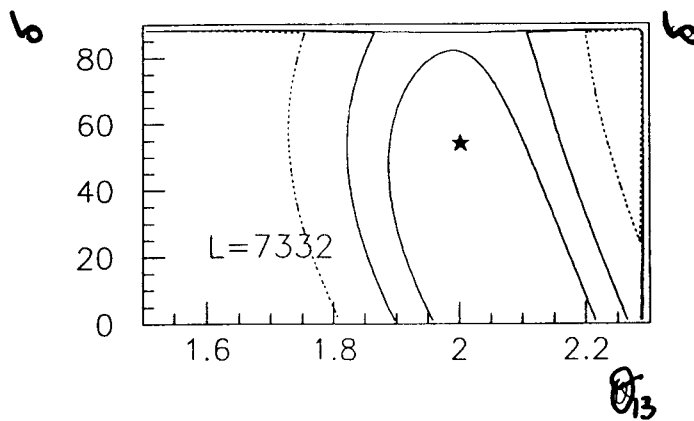
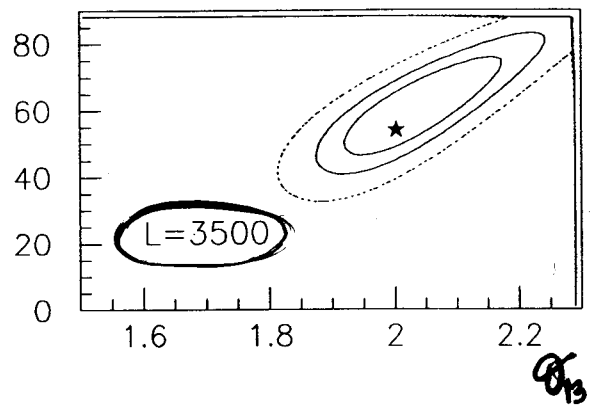
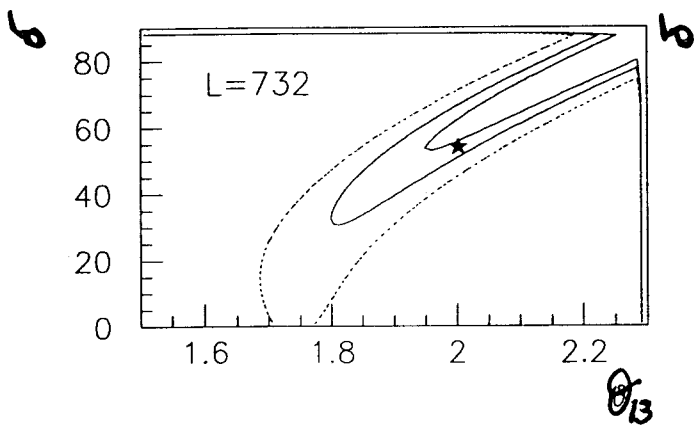


$\delta = \frac{\pi}{2}$ can be distinguished from
 $\delta = 0$ at 99% CL for

$$\Delta m_{12}^2 \gtrsim 2 \cdot 10^{-5} \text{ eV}^2$$

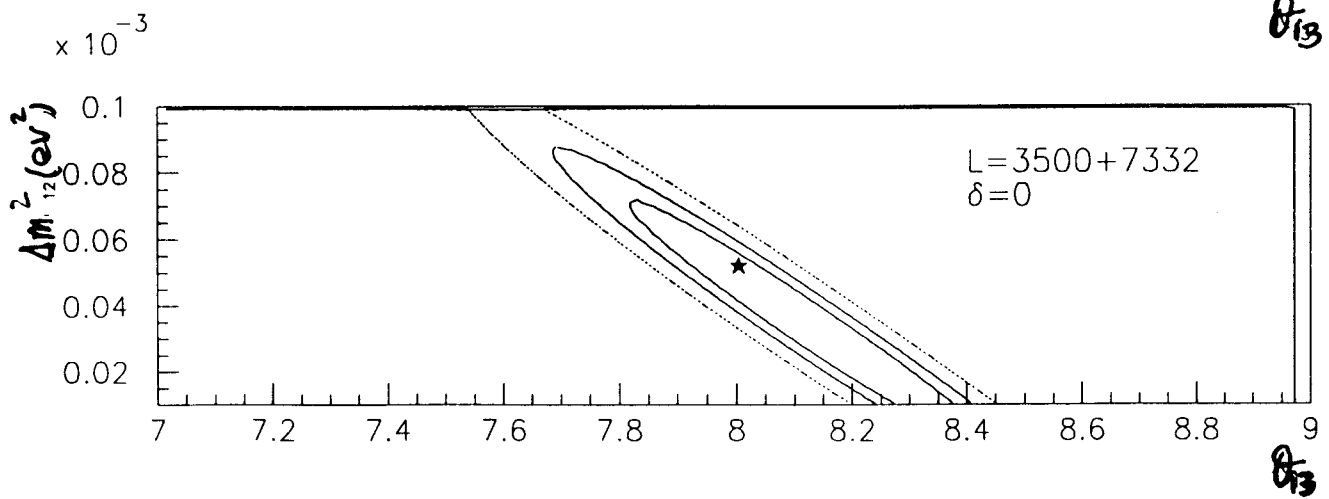
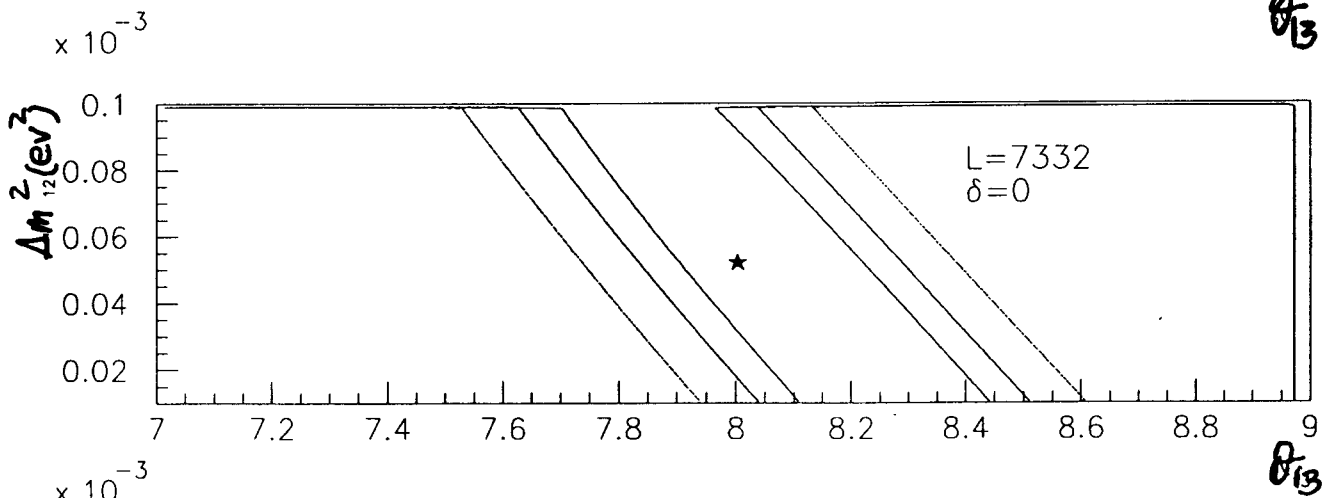
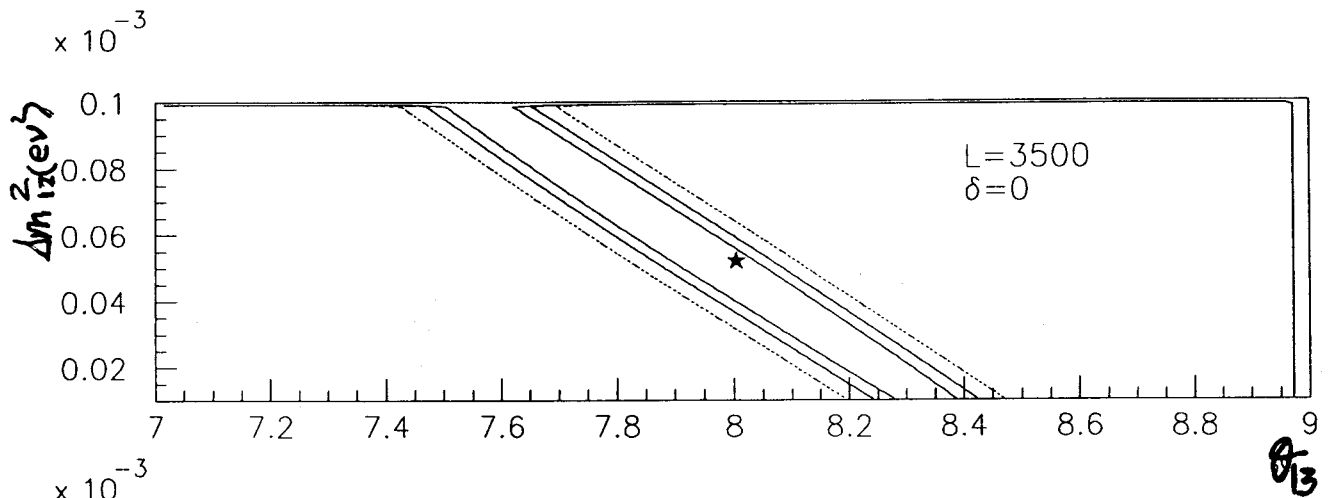


$$\Delta m_{12}^2 = 10^{-4} \text{ eV}^2$$

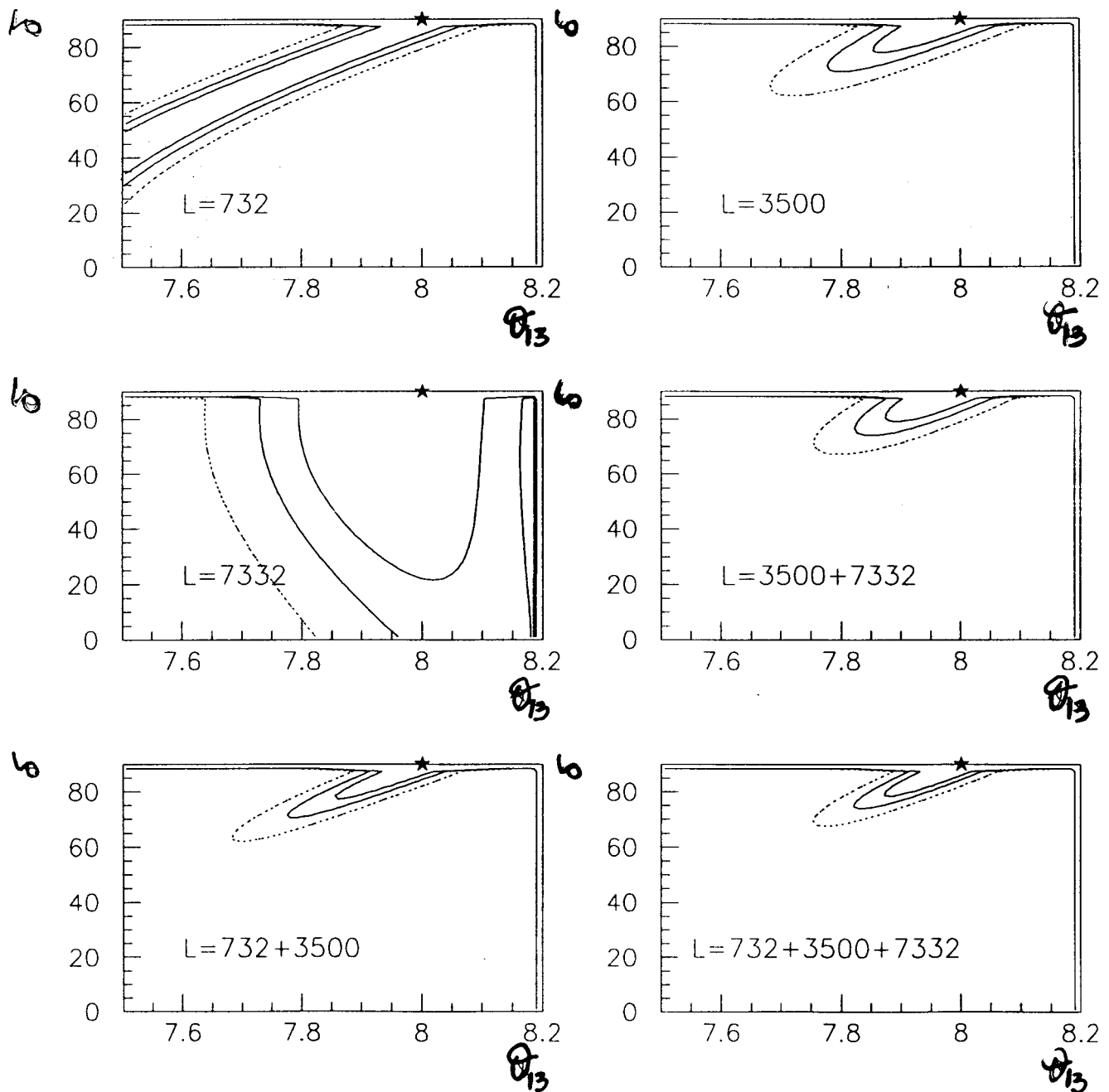


Correlation $\Delta m_{12}^2, \theta_{13}$

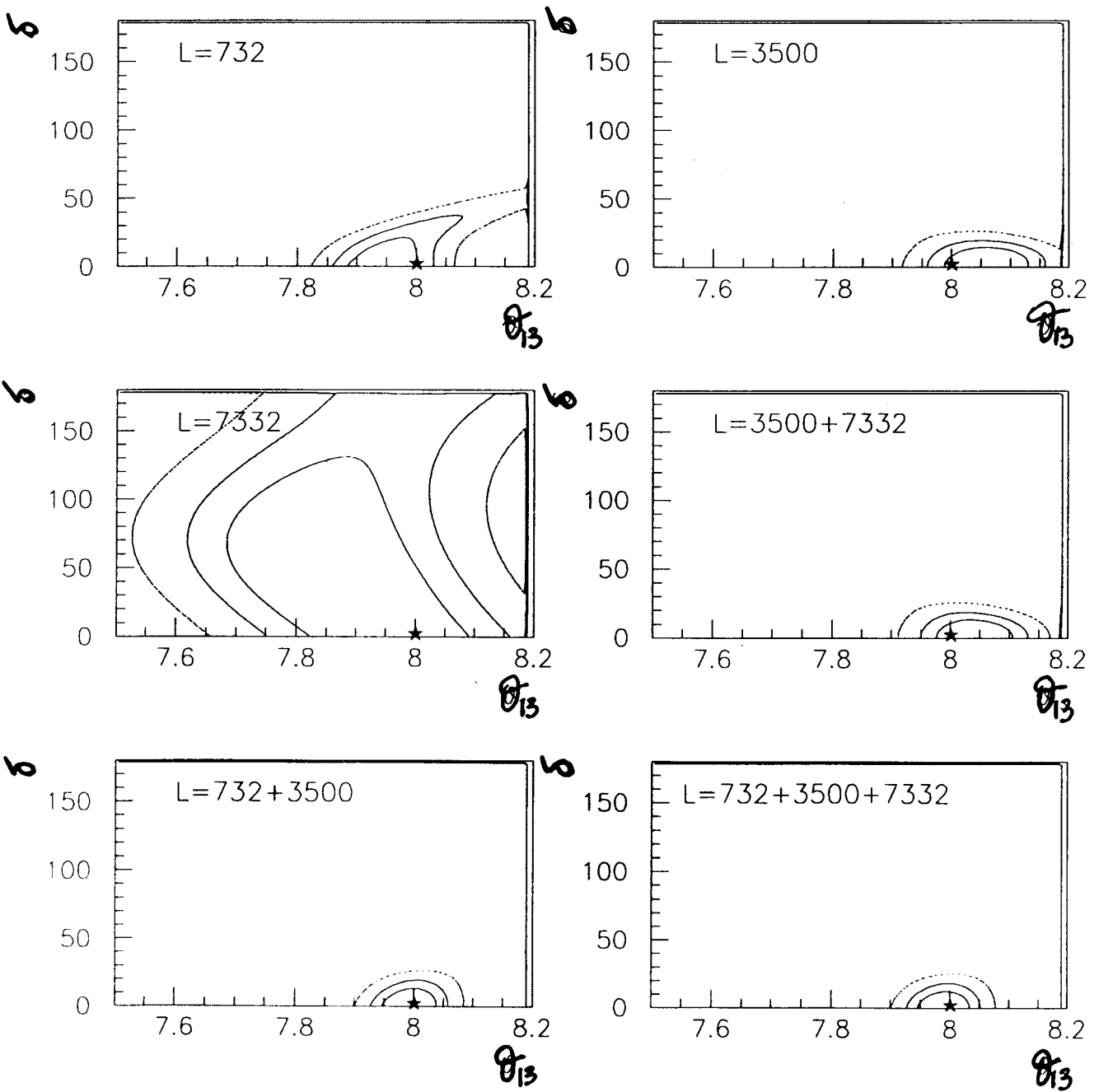
Need measurement of Δm_{12}^2 from
LBL reactor exps!



$$\Delta m_{12}^2 = 10^{-4} \text{ eV}^2$$



$$\Delta m_{12}^2 = 10^{-4} \text{ eV}^2$$



Conclusions

SMSW

sign (Δm_{23}^2)

3500 km ✓

θ_{13}

3500 km ✓

μ

≈ 3500 km ✓

LMSW

sign (Δm_{23}^2)

3500 km ✓

(θ_{13}, δ)

3500 km ✓