GOLDEN MEASUREMENTS
at ν-Factory

hep-ph/0002108

by

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in collaboration with

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NuFact00, Monterey, May 22-26, 2000

In 10 years from now NO SIGNIFICANT improvement is expected in :

- ϑ_{13} → Solar - Atmospheric LINK

$$\sin^2 2\theta_{13} \lesssim 5 \times 10^{-2} \quad (\text{CHOOZ})$$
$$\lesssim 1 \times 10^{-2} \quad (\text{MINOS})$$

- sign (Δm^2_{ATM}) → determine if the spectrum is

hierarchical — degenerate

- δ → $\not{CP}$ phase in the Leptonic sector

(only 1 Dirac phase)

Most sensitive transition (appearance channel)
[De Rujula, Gavela, Hernandez]

$$\overset{(-)}{\nu}_e \longrightarrow \overset{(-)}{\nu}_\mu \; (\overset{(-)}{\nu}_\tau)$$

$$\boxed{\text{Golden measurement at } \nu\text{-Fact}}$$

$$\mu^{\ominus} \longrightarrow e^- \, \nu_\mu \, \bar{\nu}_e$$

$$\bar{\nu}_e \longrightarrow \bar{\nu}_\mu \longrightarrow \mu^{\oplus}$$

$$\nu_e \longrightarrow \nu_\mu \longrightarrow \mu^{\ominus}$$

(WRONG SIGN MUONS)

$$\mu^{\oplus} \longrightarrow e^+ \, \bar{\nu}_\mu \, \nu_e$$

$$\boxed{\text{Very clear signal}}$$

⊛ Backgronds and Efficiencies are well understood [See Cervera, Dydak, Gomez-Cadenas, for LARGE MAGNETIZED IRON CALORIMETER – 40 kT]

From NUFACT 99 we received

→ One ANSWER:

OPTIMAL ENERGY

||

<u>MAXIMAL</u> → $E_\mu = 50$ GeV

→ One QUESTION:

OPTIMAL BASELINE(S)

||

?

SMA-MSW or VO solution

If
$$\begin{cases} \Delta m_{12}^2 \leq 10^{-6}\ eV^2 \ — \ \sin^2 2\theta_{12} \simeq 10^{-3} & (SMA) \\ \Delta m_{12}^2 \sim 10^{-10}\ eV^2 \ — \ \sin^2 2\theta_{12} \sim 1 & (VO) \end{cases}$$

solar parameters do not play any role at atmospheric distances.

$$\Delta_{12} \ll \Delta_{13},\, A,\, L^{-1} \propto E^{-1} \quad \left(\begin{array}{l} \Delta_{ij} = \dfrac{\Delta m_{ij}^2}{2E_\nu} \\ A = \sqrt{2}\, G_F \langle n_e \rangle \end{array} \right)$$

$$\rightarrow (\Delta_{12} \sim 0 \rightarrow \text{NO } \cancel{CP})$$

- Vacuum probability (Notice $\Delta_{13} \simeq \Delta_{23}$ for $\Delta_{12} \simeq 0$)

$$P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) = s_{23}^2 \underbrace{\sin^2 2\vartheta_{13}}_{\text{! very sensitive to } \vartheta_{13} \text{ !}} \sin^2\left(\frac{\Delta_{13} L}{2}\right) + \cdots$$

- Matter probability

$$P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) = s_{23}^2 \underbrace{\sin^2 2\vartheta_{13} \left(\frac{\Delta_{13}}{B_\mp}\right)^2}_{\sin^2 2\vartheta_{13}^M} \sin^2\left(\frac{B_\mp L}{2}\right) + \cdots$$

$$\Delta_{13}^M \equiv B_\mp = \left[\left(\Delta_{13} \cos 2\vartheta_{13} \mp A\right)^2 + \left(\Delta_{13} \sin 2\vartheta_{13}\right)^2 \right]^{1/2}$$

$\boxed{\text{SMA-MSW or VO solution}}$

If $\begin{cases} \Delta m_{12}^2 \lesssim 10^{-6}\ eV^2 \ — \ \sin^2 2\theta_{12} \simeq 10^{-3} & (\text{SMA}) \\ \Delta m_{12}^2 \sim 10^{-10}\ eV^2 \ — \ \sin^2 2\theta_{12} \sim 1 & (\text{VO}) \end{cases}$

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$$\Delta_{12} \ll \Delta_{13},\ A,\ L^{-1} \propto E^{-1} \quad \left(\begin{array}{l} \Delta_{ij} = \dfrac{\Delta m_{ij}^2}{2E_\nu} \\ A = \sqrt{2}\, G_F \langle n_e \rangle \end{array} \right)$$

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- <u>Vacuum probability</u> (Notice $\Delta_{13} \simeq \Delta_{23}$ for $\Delta_{12} \simeq 0$)

$$P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) = s_{23}^2 \,\underline{\sin^2 2\vartheta_{13}}\, \sin^2\left(\frac{\Delta_{13} L}{2}\right) + \cdots$$

! very sensitive to ϑ_{13} !

- <u>Matter probability</u>

$$P(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu) = s_{23}^2 \underbrace{\sin^2 2\vartheta_{13} \left(\frac{\Delta_{13}}{B_\mp}\right)^2}_{\sin^2 2\vartheta_{13}^M} \sin^2\left(\frac{B_\mp L}{2}\right) + \cdots$$

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Sensitivity to SIGN(Δm^2_{ATM}) and Matter Effect

[see also Barger et al., Bueno et al., Freund et al. ...]

- Sensitivity to SIGN(Δm^2_{ATM}) $\equiv$ Sensitivity to A_{CP}

$$\Delta m^2_{ATM} \longleftrightarrow -\Delta m^2_{ATM}$$
$$P(\nu_e \to \nu_\mu) \longleftrightarrow P(\bar{\nu}_e \to \bar{\nu}_\mu)$$
$$B_- \longleftrightarrow B_+$$

i) $B_{\mp} L \sim 1$ • if $BL \ll 1$ then VACUUM OSCILLATION

ii) $\Delta_{13} \cos 2\theta_{13} \sim A$ • if $A \ll \Delta_{13}$ then VACUUM OSC.

$\Delta_{13} = \dfrac{\Delta m^2_{13}}{2E}$ • if $A \gg \Delta_{13}$ then MATTER DOMIN..

- Sensitivity to A_{CP} is $\boxed{\text{ENERGY DEPENDENT}}$

In some bins more INFORMATIONS on A_{CP} or SIGN(Δm^2_{ATM}) than in others:

$$\boxed{\begin{array}{c}\text{NEUTRINO ENERGY RESOLUTION} \\ \text{CAN HELP}\end{array}}$$

- Maximize the informations

→ Highest possible energy $E_\mu = 50$ GeV

→ 5 BINS of $\Delta E_\nu = 10$ GeV $\left(\frac{\Delta E_\nu}{E_\nu} \lesssim 20\% \right)$

→ For 3 REFERENCE DISTANCES $L = 732, 3500, 7332$

- $N_i^{(\pm)}(L)$ → theoretical prediction ($i=1,\dots,5$) for $\mu^\pm$

- $$n_i^{(\pm)}(L) = \frac{\mathrm{SMEAR}\left[N_i^{(\pm)}(L)\,\epsilon_i^{(\pm)}(L) + b_i^{(\pm)}(L)\right] - b_i^{(\pm)}(L)}{\epsilon_i^{(\pm)}(L)}$$

→ "SIMULATION" of REAL DATA
(ϵ_i and b_i = efficiencies and back)

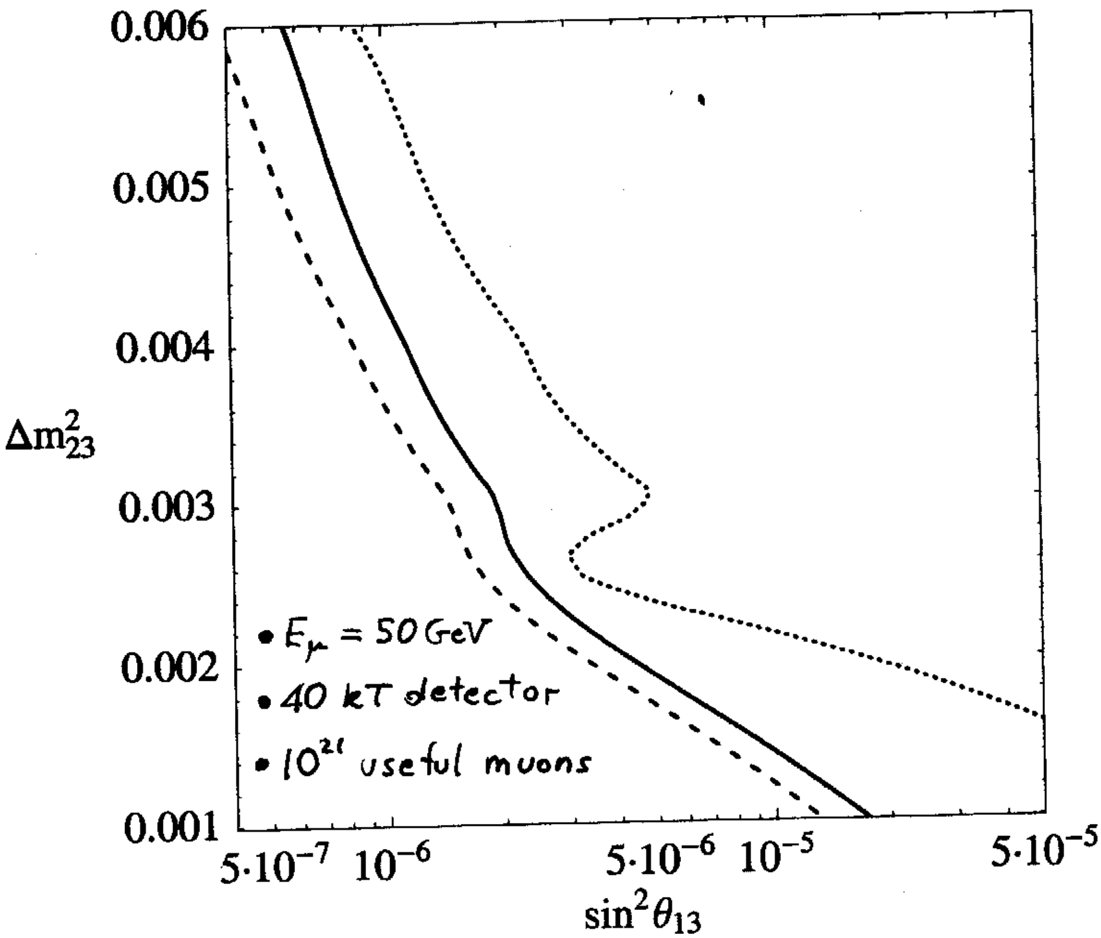
- $$\chi_L^2 = \sum_{i=1}^{5} \left[\frac{\left(n_i^+(L) - N_i^+(L)\right)}{\delta n_i^+ / \epsilon_i^+(L)} + (+ \to -) \right]$$

→ χ_L^2 MINIMIZATION
(δn_i = STATISTICAL error on n_i)

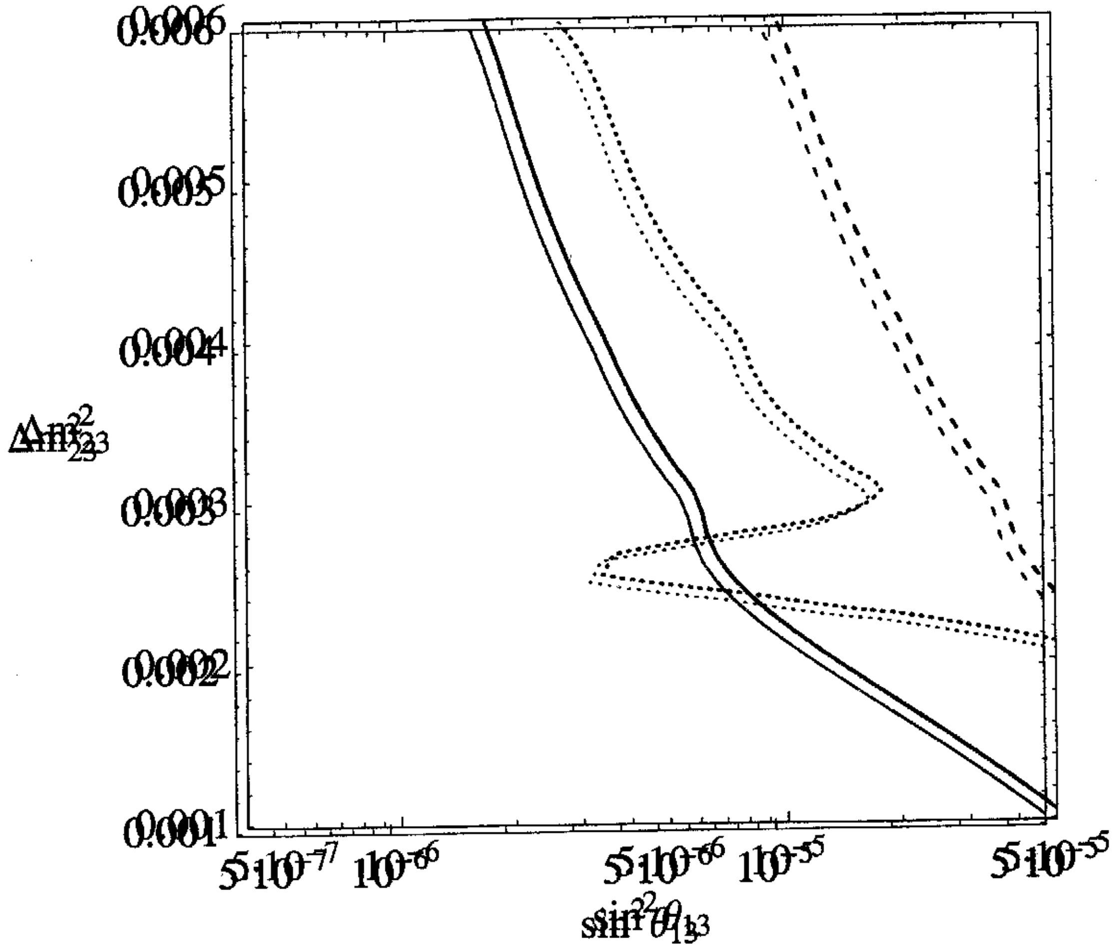
→ 6 different χ^2 $\left[3\chi_i^2,\ 2(\chi_i^2 + \chi_j^2),\ (\chi_i^2 + \chi_j^2 + \chi_k^2) \right]$

Sensitivity to ϑ_{13} : SMA solution

90% CL



- - - - - -	$\boxed{732}$ km	ONLY STATISTICS
————	3500 km	
··········	7332 km	



$\times$

$\oplus$

- - - - - - 732 km

——— $\boxed{3500}$ km

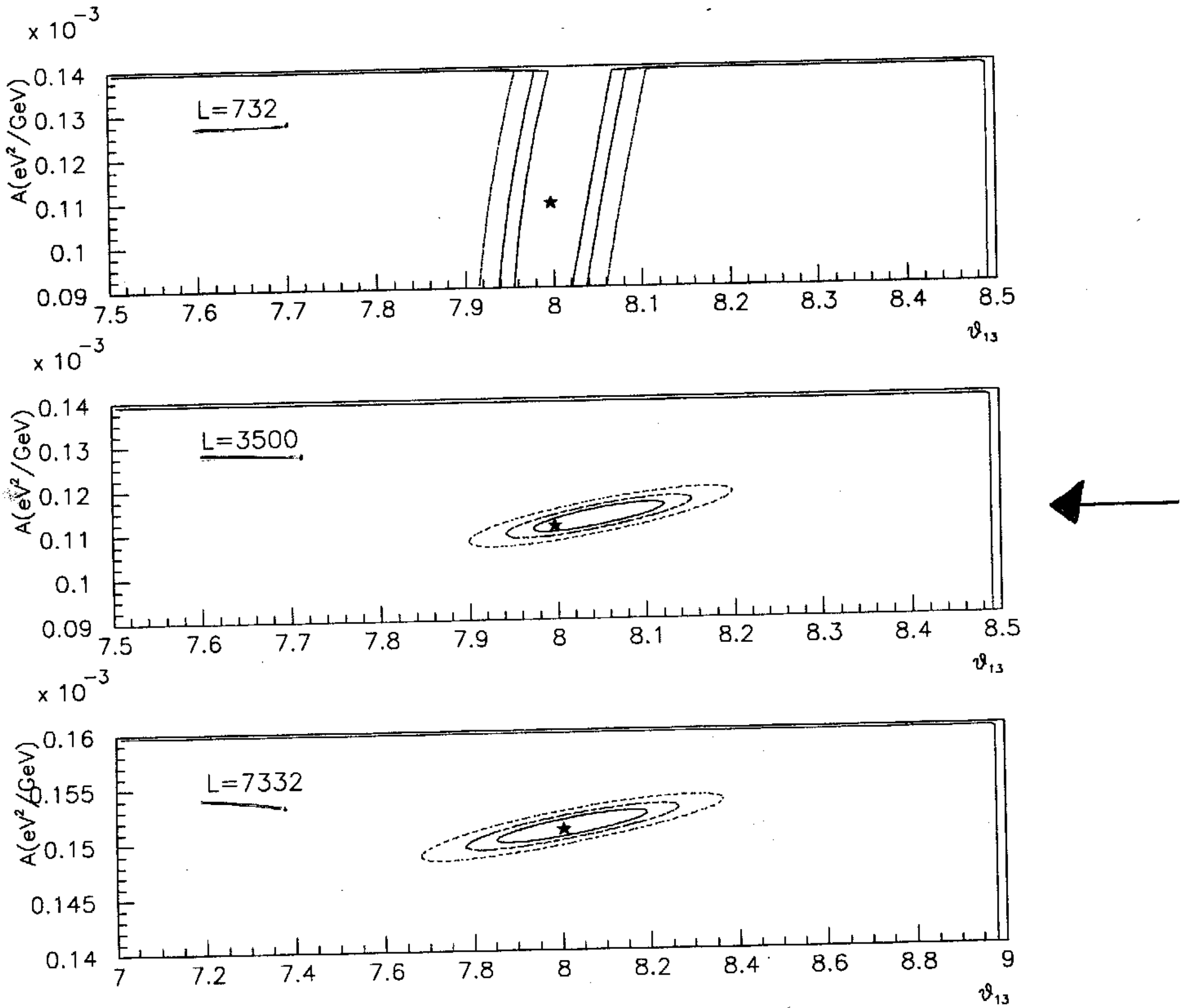
··········· 7332 km

BACKGROUNDS + EFFICIENCIES

L ~ 3000 km FAVOURED: 732 → <u>MORE BACK</u>; 7332 → <u>LESS STAT</u>

Simultaneous determination of A and ϑ_{13}

$\Delta m^2_{23} = 2.8 \times 10^{-3}\,eV^2$, $\vartheta_{23} = 45°$ $\boxed{\text{SMA solution}}$



$A = \sqrt{2}\, G_F \langle n_e \rangle$ = average matter density

[R. Gandhi et al. Astropart. Phys. 5 (1996) 81]

⊛ ONLY STATISTICS included

Simultaneous determination of A and ϑ_{13}

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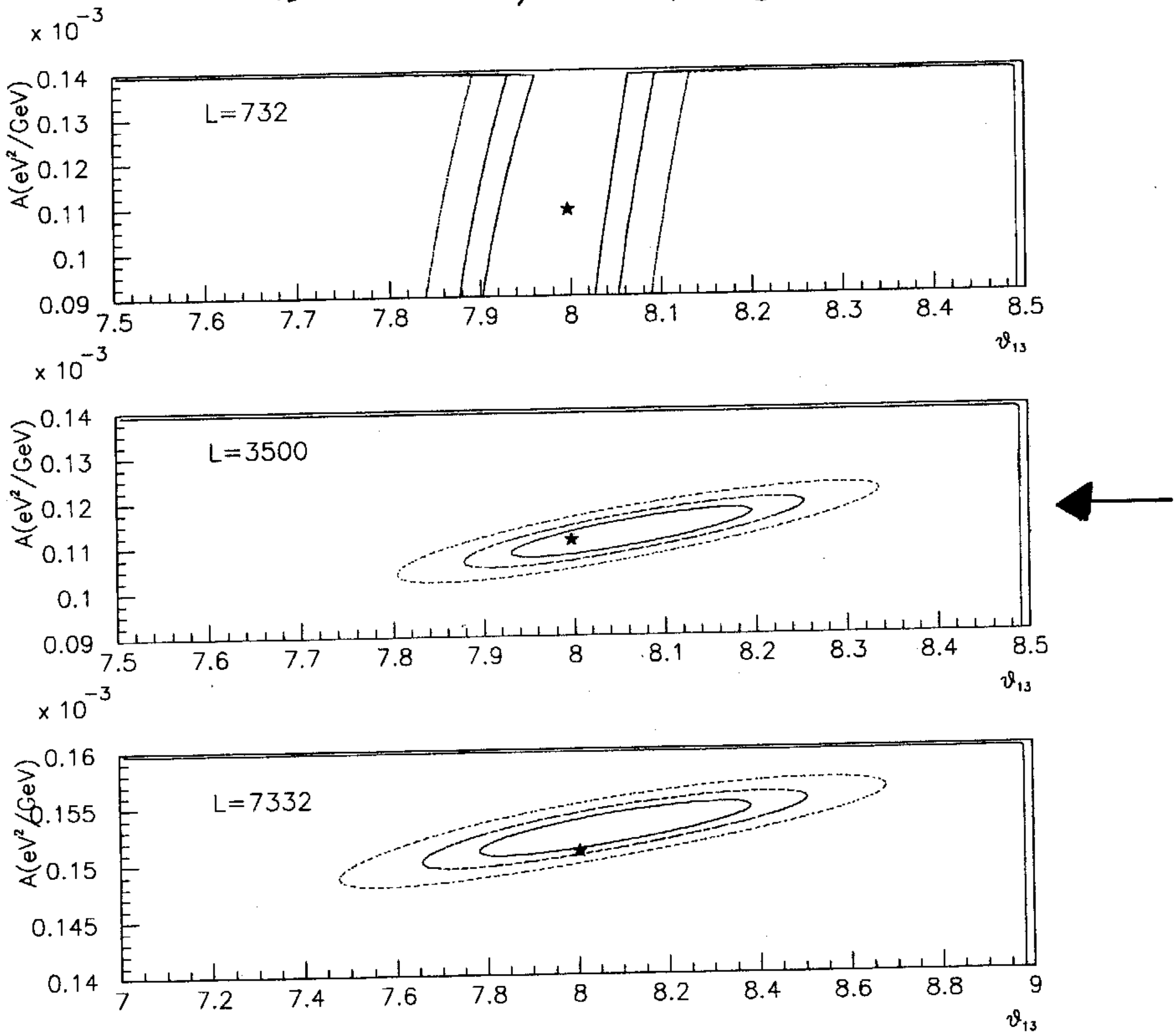


⊛ STATISTICS + $\underbrace{\text{BACKGROUNDS + EFFICIENCIES}}_{\text{almost double the error !!}}$

LMA – MSW solution

If $\Delta m^2_{12} \sim 10^{-4} \div 10^{-5}$ — $\sin^2 2\vartheta_{12} \sim 1$

solar parameters can produce sizeable effects

$\longrightarrow$ **CP-VIOLATION** $\longleftarrow$

Expansion in $\frac{\Delta_{12}}{\Delta_{13}}$, $\frac{\Delta_{12}}{A}$ and ϑ_{13}

- Vacuum probability $[\Delta_{12} \sim \Delta_{13} \propto E^{-1}]$

$$P(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu) = s^2_{23} \boxed{\sin^2 2\vartheta_{13}} \sin^2\left(\frac{\Delta_{13} L}{2}\right) + \longrightarrow P_1$$

$$+ c^2_{23} \sin^2 2\vartheta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) + \longrightarrow P_4$$

$$P_2 \longleftarrow + \frac{1}{2} \boxed{\tilde{J}} \cos\delta \sin\left(\frac{\Delta_{12} L}{2}\right) \sin(\Delta_{13} L) +$$

$$P_3 \longleftarrow \mp \boxed{\tilde{J}} \sin\delta \sin\left(\frac{\Delta_{12} L}{2}\right) \cdot \sin^2\left(\frac{\Delta_{13} L}{2}\right) + \cdots$$

$(\tilde{J} = c_{12} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23})$

LARGE CORRELATION in $\vartheta_{13}, \delta, \Delta m^2_{12}$

- At small distances ($L \sim 700$ km) $\quad \Delta_{12} L \sim \Delta_{13} L \ll 1$

$$P(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu) = s_{23}^2 \boxed{\sin^2 2\vartheta_{13}} \left(\frac{\Delta_{13} L}{2}\right)^2 +$$
$$+ \, c_{23}^2 \sin^2 2\vartheta_{12} \left(\frac{\Delta_{12} L}{2}\right)^2 +$$
$$+ \, \boxed{\tilde{J}} \cos\delta \left(\frac{\Delta_{12} L}{2}\right)\left(\frac{\Delta_{13} L}{2}\right) + \cdots$$

$\left(\Delta \sim \frac{1}{E}\right)$

the $\not{CP}$ is NEGLIGIBLE (order $(\Delta_{ij} L)^3$!!)

→ All the other terms have the

SAME DEPENDENCE on E, L $\left(\frac{L^2}{E^2}\right)$

- Not possible to disantangle $\vartheta_{13}, \delta, \Delta m_{12}^2$

→ At LARGER distances ($L \gg 700$ km) MATTER effects cannot be neglected

New parameter enter → $\quad A = \sqrt{2}\, G_F\, n_e$

- Matter probability : as the vacuum with the replacements of effective ANGLES and MASSES

$$\sin^2 2\vartheta_{13} \longrightarrow \sin^2 2\vartheta_{13} \left(\frac{\Delta_{13}}{B_\mp}\right)^2 \equiv \sin 2\vartheta_{13}^M$$

$$\sin^2 2\vartheta_{12} \longrightarrow \sin^2 2\vartheta_{12} \left(\frac{\Delta_{12}}{B_\mp}\right)^2 \equiv \sin 2\vartheta_{12}^M$$

$$\Delta_{13} \longrightarrow B_\mp \equiv \Delta_{13}^M$$

$$\Delta_{12} \longrightarrow A \equiv \Delta_{12}^M$$

PROBLEM: • It is possible to DISANTANGLE $\vartheta_{13}, \delta, \Delta m_{12}^2, A$?

• Which is the BEST BASELINE ?

→ We ASSUME $\Delta m_{23}^2 = 2.8 \times 10^{-3}\, eV^2$, $\vartheta_{23} = 45°$ well MEASURED [See BARGER et al., BUENO et al.]

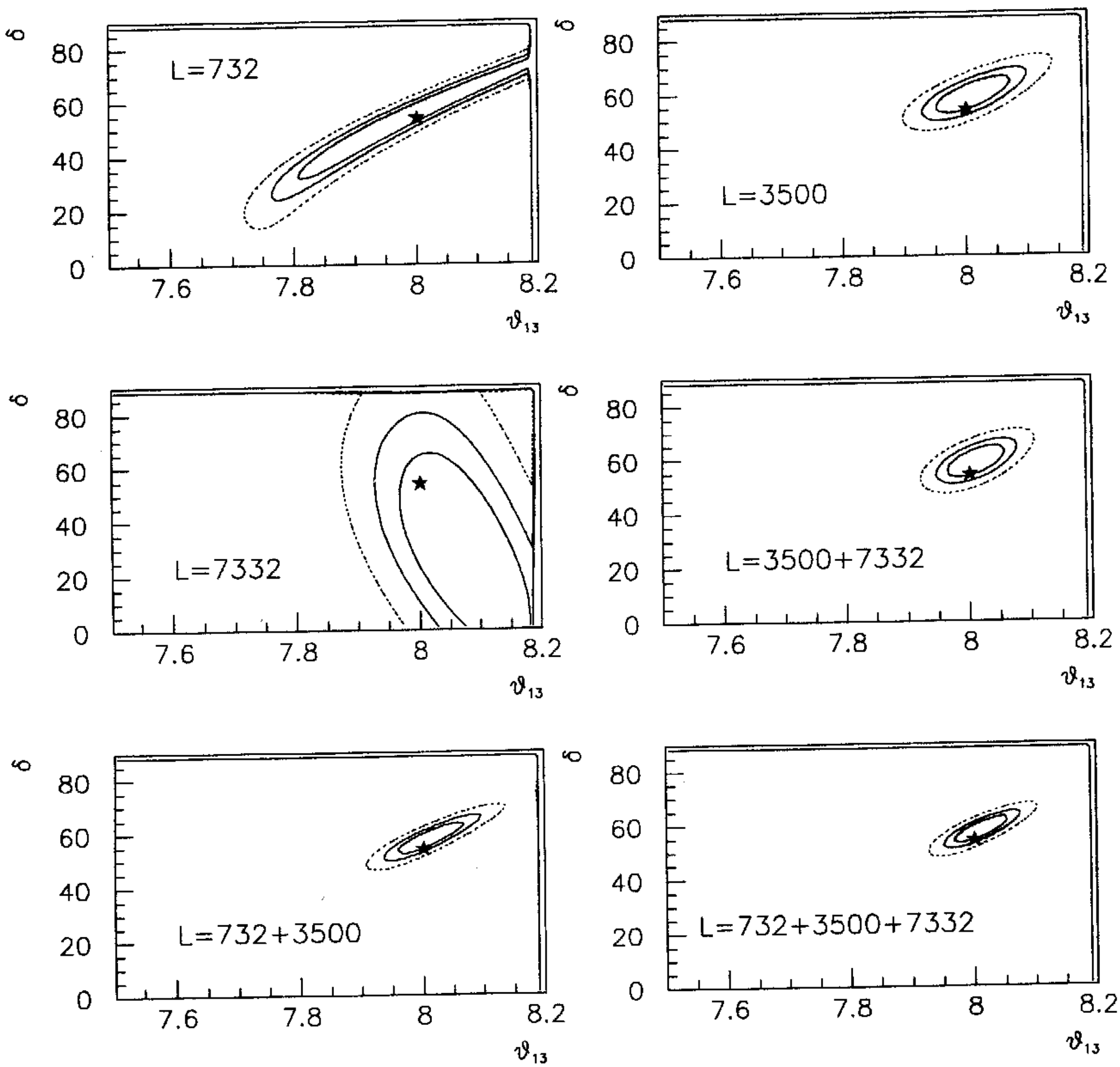
① Disantangle (A, ϑ_{13}) → as SMA case

② Disantangle (ϑ_{13}, δ)

③ Disantangle $(\Delta m_{12}^2, \vartheta_{13})$

② Simultaneous determination of δ and ϑ_{13}

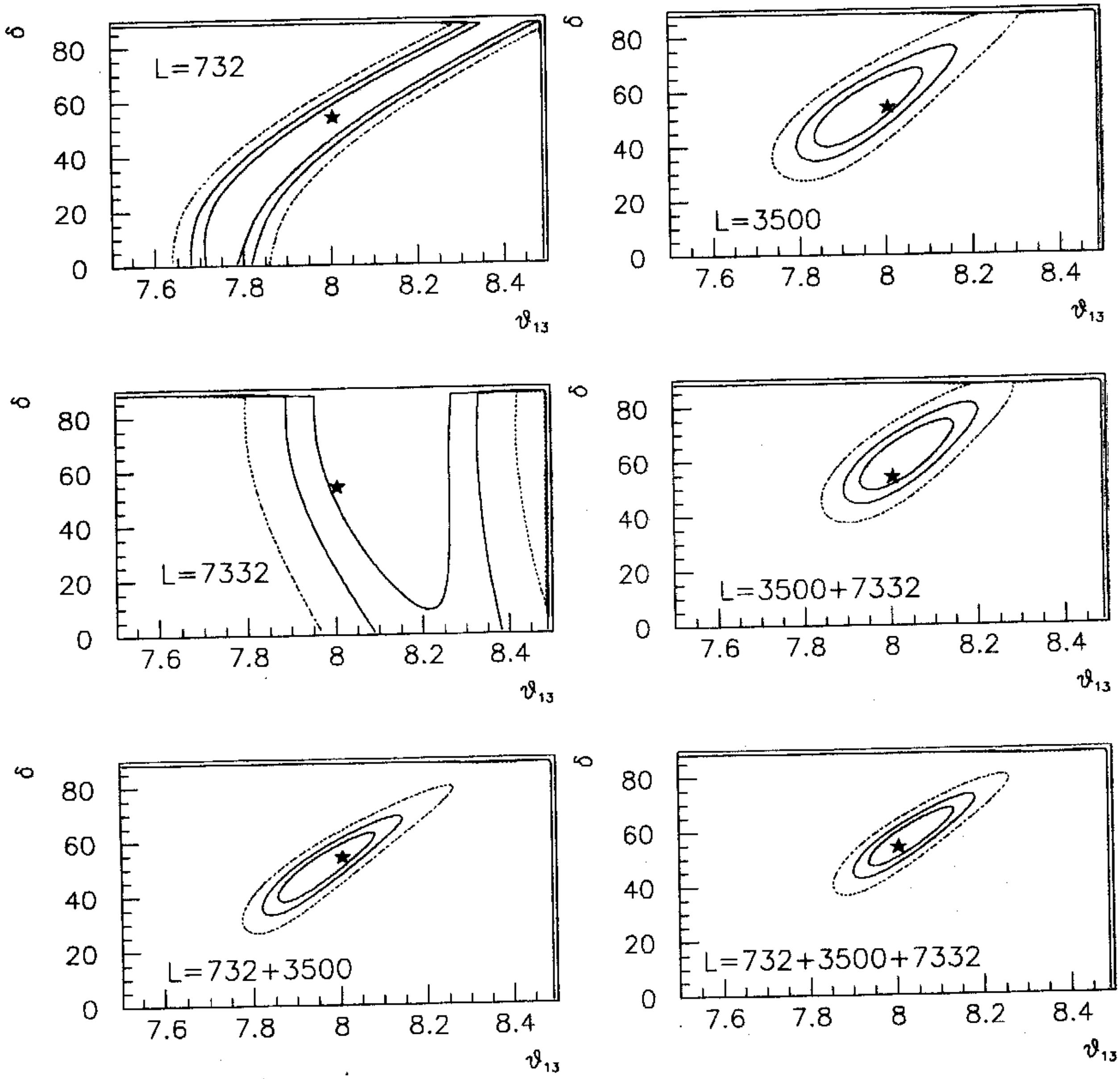
$\Delta m^2_{12} = 1 \times 10^{-4}\, eV \longrightarrow \boxed{\text{LMA solution}}$



⊛ ONLY STATISTICS included

Simultaneous determination of δ and ϑ_{13}

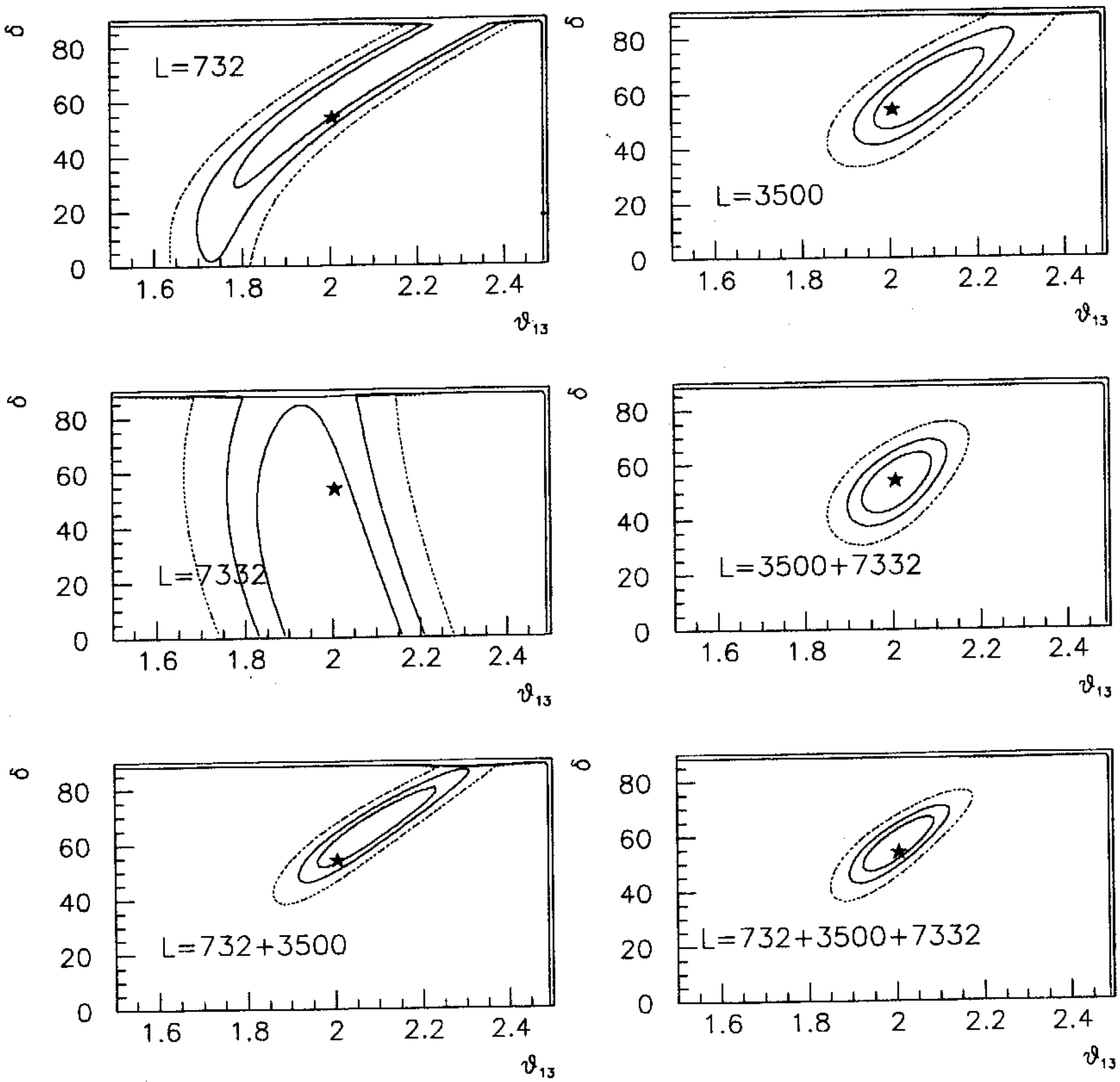
$\Delta m^2_{12} = 1 \times 10^{-4} eV^2 \longrightarrow$ $\boxed{\text{LMA solution}}$



★ STATISTICS + BACKGROUNDS + EFFICIENCIES

Simultaneous determination of δ and ϑ_{13}

$\Delta m^2_{12} = 1 \times 10^{-4}\, eV^2 \longrightarrow$ $\boxed{\text{LMA solution}}$

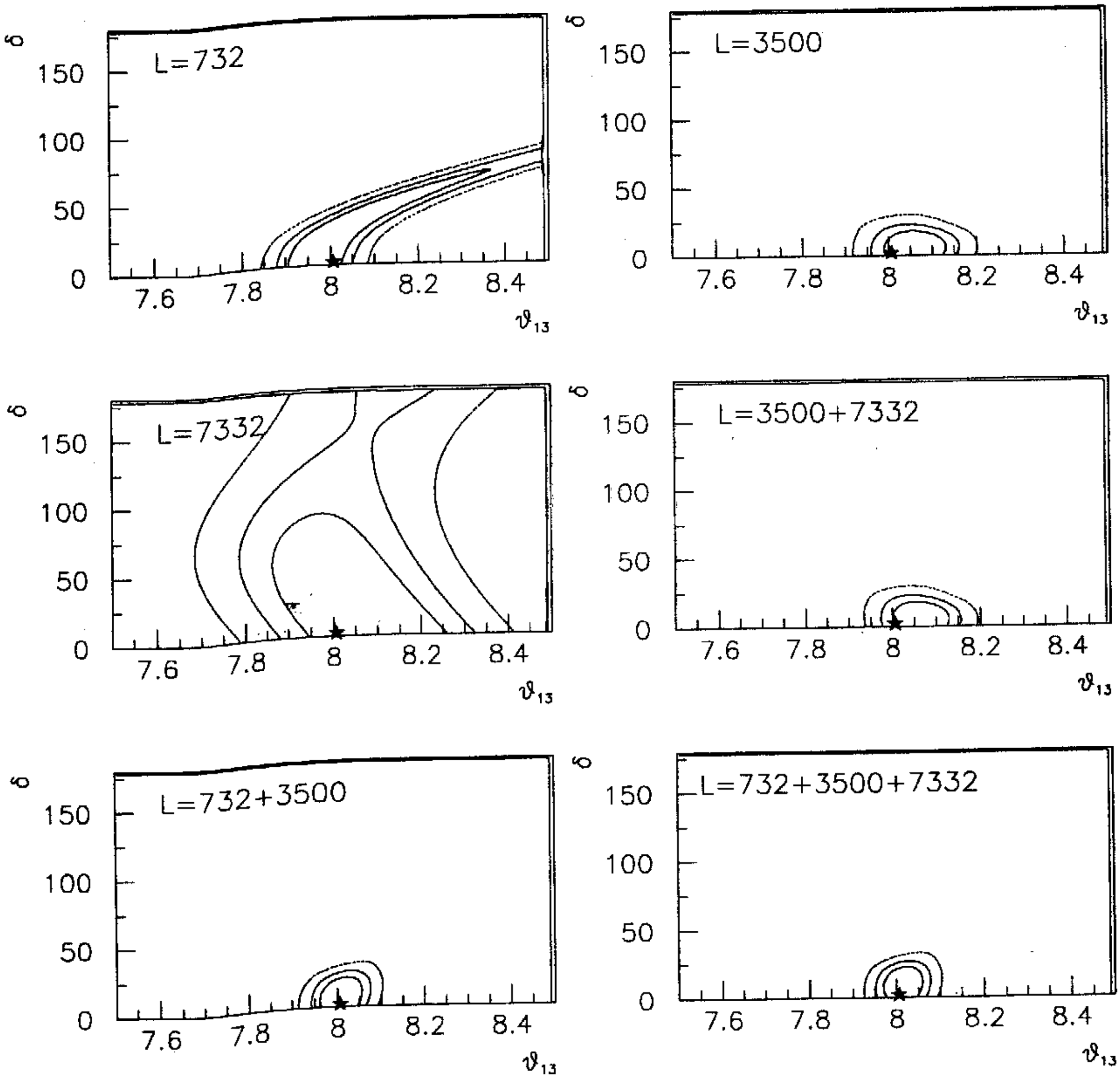


- Same conclusion also for $\vartheta_{13} = 2°$

⊗ STATISTICS + BACKGROUNDS + EFFICIENCIES

Simultaneous determination of δ and ϑ_{13}

$N_\mu^{TOT} = 10^{21}$ — $\Delta m^2_{12} = 1 \times 10^{-4}\, eV^2 \longrightarrow$ $\boxed{\text{LMA solution}}$



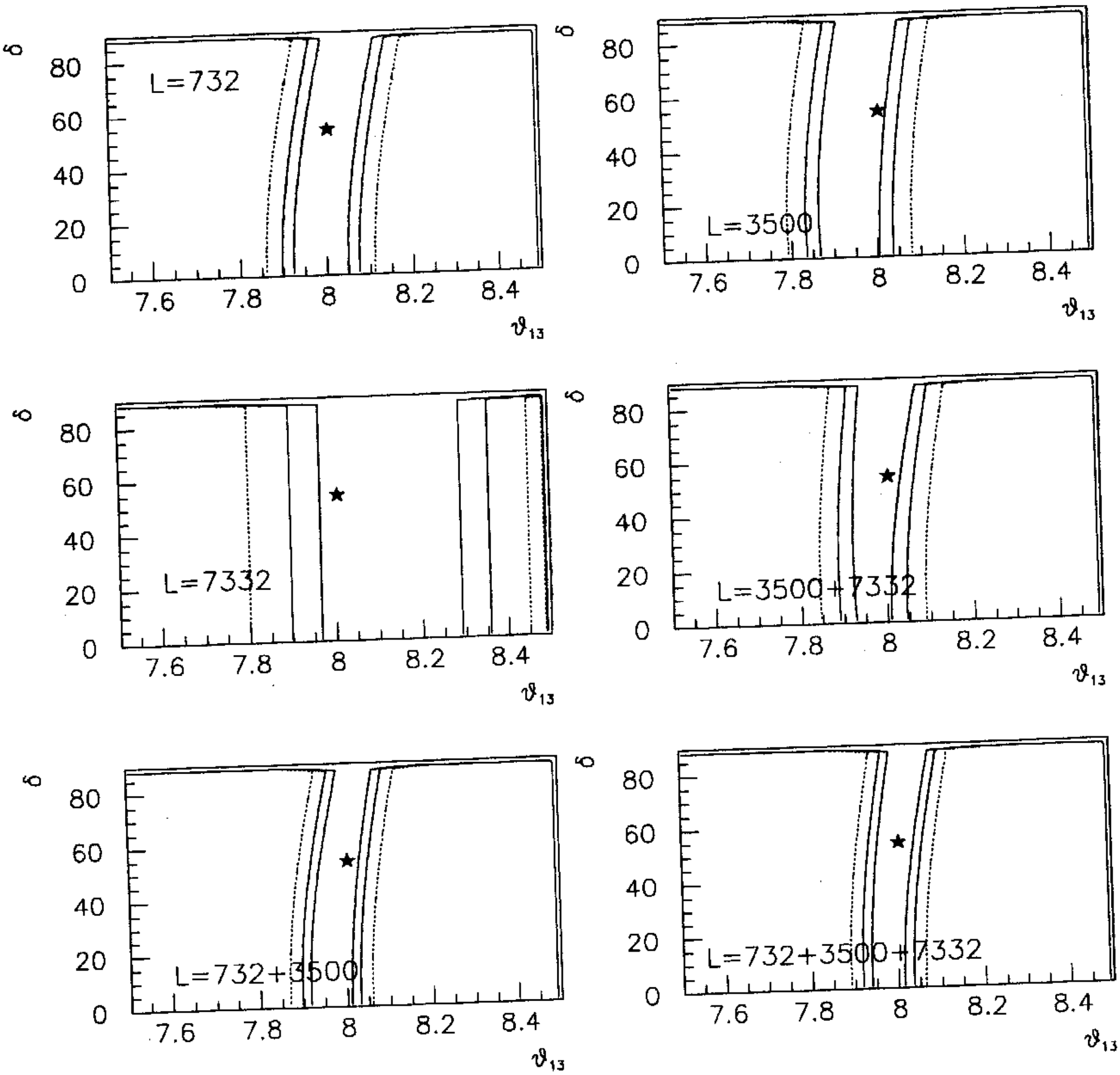
- Same conclusion also for $\delta = 0$ (π)

⊛ STATISTICS + BACKGROUNDS + EFFICIENCIES

At 732 km $\delta = 0 \neq \delta = \pi$? $(\Delta_{12} \to -\Delta_{12})$!!

Simultaneous determination of δ and θ_{13}

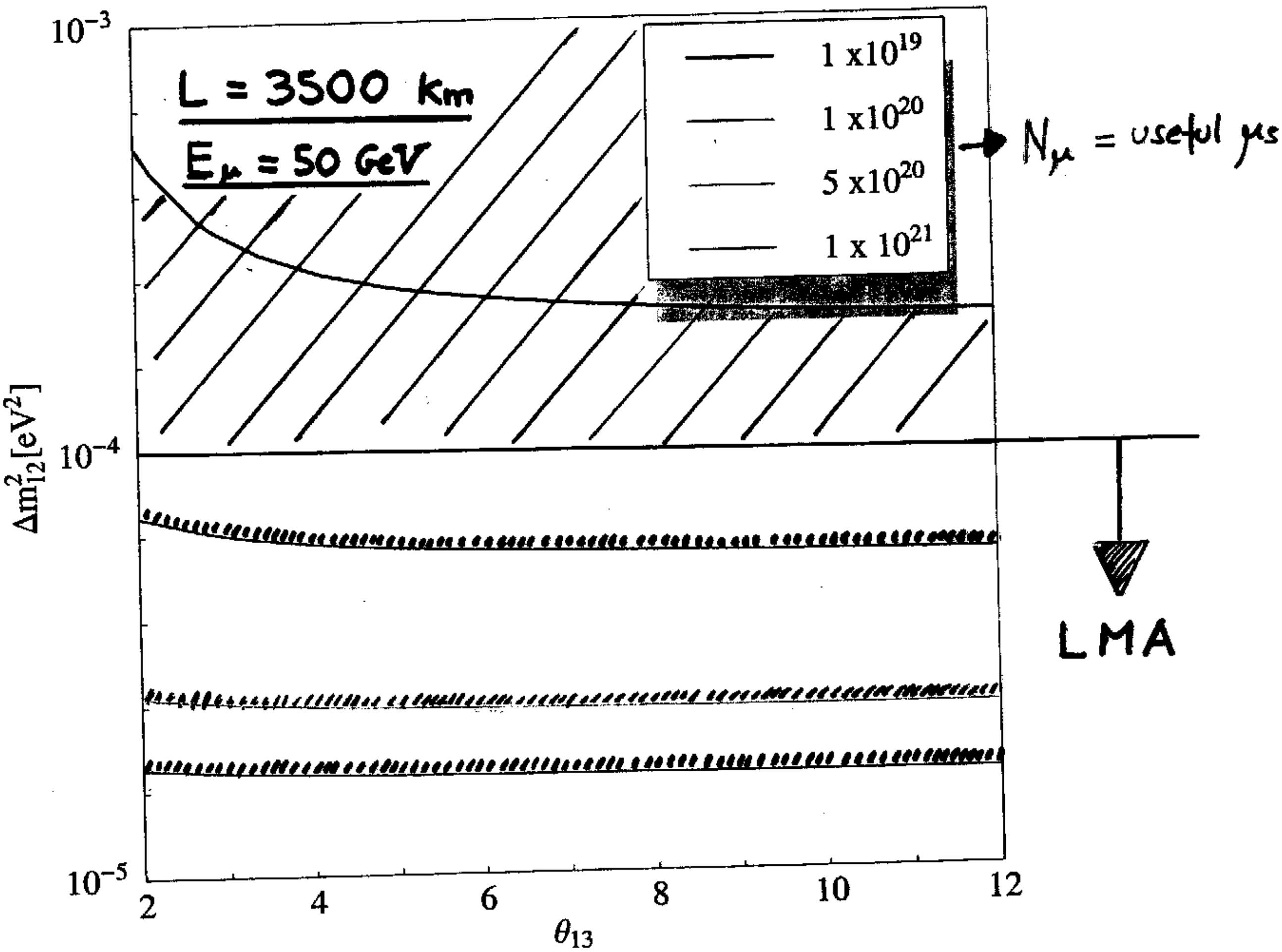
$\Delta m^2_{12} = 1 \times 10^{-5}\, eV^2 \longrightarrow$ $\boxed{\text{LMA solution}}$



⊛ STATISTICS + BACKGROUNDS + EFFICIENCIES

CP-violation "discovery"

<Preliminary>



- "DISCOVERY" = 99% CL separation $\delta = \pi/2 \longleftrightarrow \delta = 0$
- For $N_\mu \lesssim 10^{20}$ NO possible DISCRIMINATION
- For $N_\mu = 10^{21}$ (almost independent of ϑ_{13}) if

$$\boxed{\Delta m^2_{12} \gtrsim 2 \times 10^{-5} \ eV^2}$$

Conclusions

SMA-MSW solution:

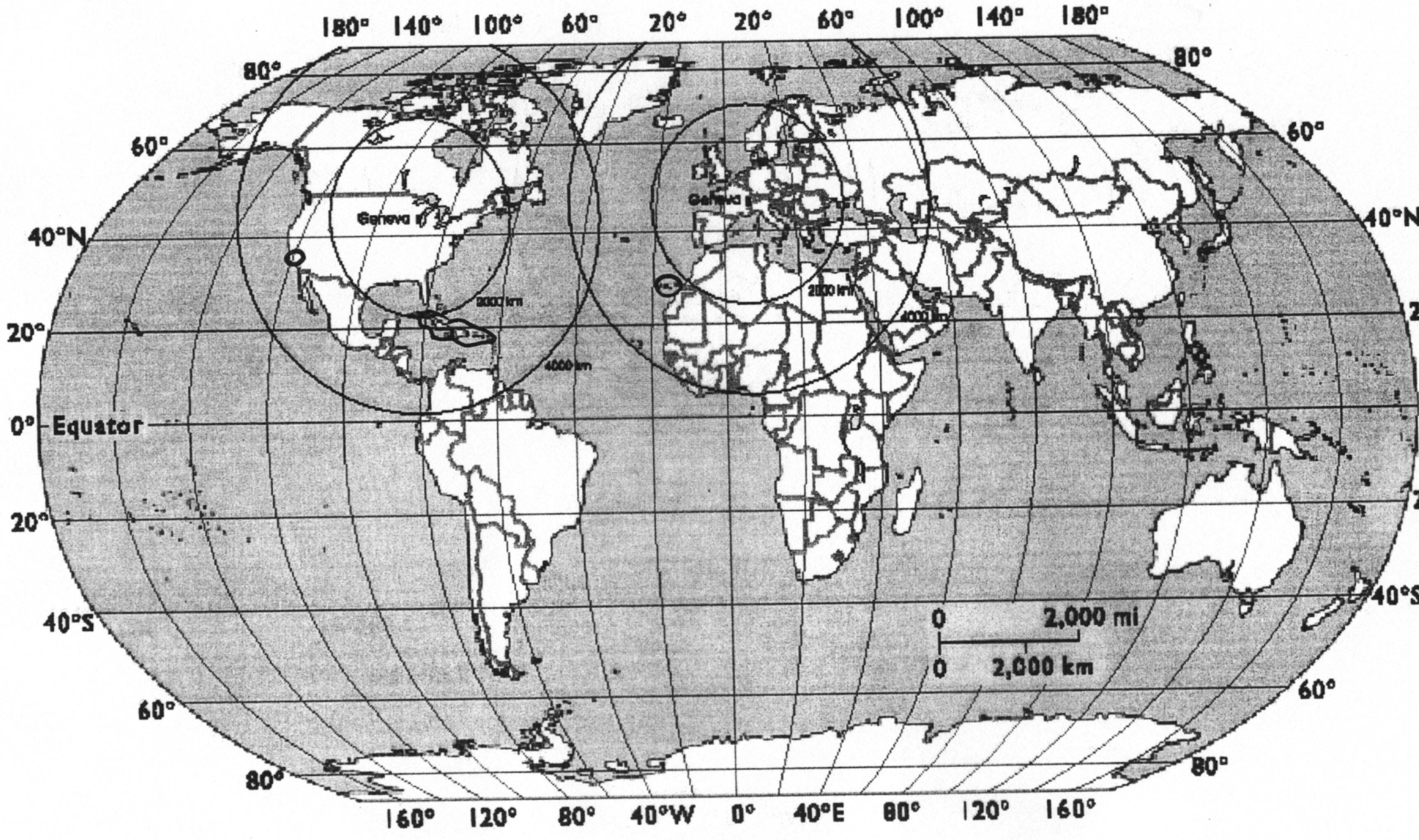
	L (km)
• sensitivity to ϑ_{13}	! = 3500 !
• sign(Δm^2_{ATM}), A	$\gtrsim 3500$
• (ϑ_{13}, A) simultaneously	$\gtrsim 3500$ (>?)

LMA-MSW solution:

	L (km)
• (ϑ_{13}, δ) simultaneously	! = 3500 !
• sign(Δm^2_{ATM}), A	$\gtrsim 3500$
• $(\vartheta_{13}, \Delta m^2_{SUN})$ simultaneously	?

we should know before ν-FACTORY

Where ?



Geneva (IL) $\xleftrightarrow{\sim 7000\text{ km}}$ Geneva (CH)

- Optimization of E

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

- Optimization of L

$$L \sim 3000 \text{ km}$$

- Optimization of "QUALITY of LIFE"

  - CANARIAS islands
  - CARIBEAN islands
  - SOUTH CALIFORNIA