Neutrino Physics @

P. Hernández
CERN

Lepton flavour sector of the SM

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \quad V_{MNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The NMS matrix has four physical parameters:

Angles	Phases
3	1

$V_{NMS} \equiv$

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

Generically there is leptonic CP-violation in the SM in complete analogy with the quark sector !

(If ν are Majorana there are 2 additional phases)

Neutrino Oscillations

Neutrinos produced in a weak eigenstate can change flavour as they propagate a distance L from the production point:

Vaccuum oscillations ($W_{\alpha\beta}^{jk} \equiv [V_{\alpha j} V_{\beta j}^{*} V_{\alpha k}^{*} V_{\beta k}]$)

$$P(\nu_\alpha \to \nu_\beta) = -4 \sum_{k>j} \mathrm{Re}[\mathrm{W}_{\alpha\beta}^{\mathrm{jk}}] \sin^2\left(\frac{\Delta \mathrm{m}_{\mathrm{jk}}^2 \mathrm{L}}{4\mathrm{E}_\nu}\right) \pm 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}_{\alpha\beta}^{\mathrm{jk}}] \sin\left(\frac{\Delta \mathrm{m}_{\mathrm{jk}}^2 \mathrm{L}}{2\mathrm{E}_\nu}\right)$$

Neutrino oscillations are in principle sensitive to all the mixing angles, phase δ and mass square differences.

Evidence for neutrino oscillations

There is a strong experimental evidence in favour of neutrino oscillations:

- **Solar ν deficit**
- **Atmospheric anomaly**
- **LSND**

$$|\Delta m^2_{solar}| \quad \lll \quad |\Delta m^2_{atmos}| \quad \lll \quad |\Delta m^2_{LSND}|$$

- The mixing of the three standard neutrinos ν_e, ν_μ, ν_τ can only explain two of the anomalies:

$$\Delta m^2_{solar} = \Delta m^2_{12} \quad , \quad \Delta m^2_{atmos} = \Delta m^2_{23}$$

What we know about m_ν and V_{MNS}

Solar and atmospheric anomalies approximately decouple as independent 2-by-2 mixing phenomena because

- Mass hierarchy from solar and atmospheric data:

$$|\Delta m^2_{atmos}| = |\Delta m^2_{23}| \quad \gg \quad |\Delta m^2_{solar}| = |\Delta m^2_{12}|$$

- Small θ_{13} from Chooz reactor data

$$\boxed{\sin^2\theta_{13} \le 0.05}$$

In the approximation $\theta_{13} = 0, \;\; |\Delta m^2_{12}| \ll |\Delta m^2_{23}|$:

Atmospheric: $(\theta_{23}, \Delta m^2_{23})$

$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta_{23} \; \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu}$$

Solar: $(\theta_{12}, \Delta m^2_{12})$

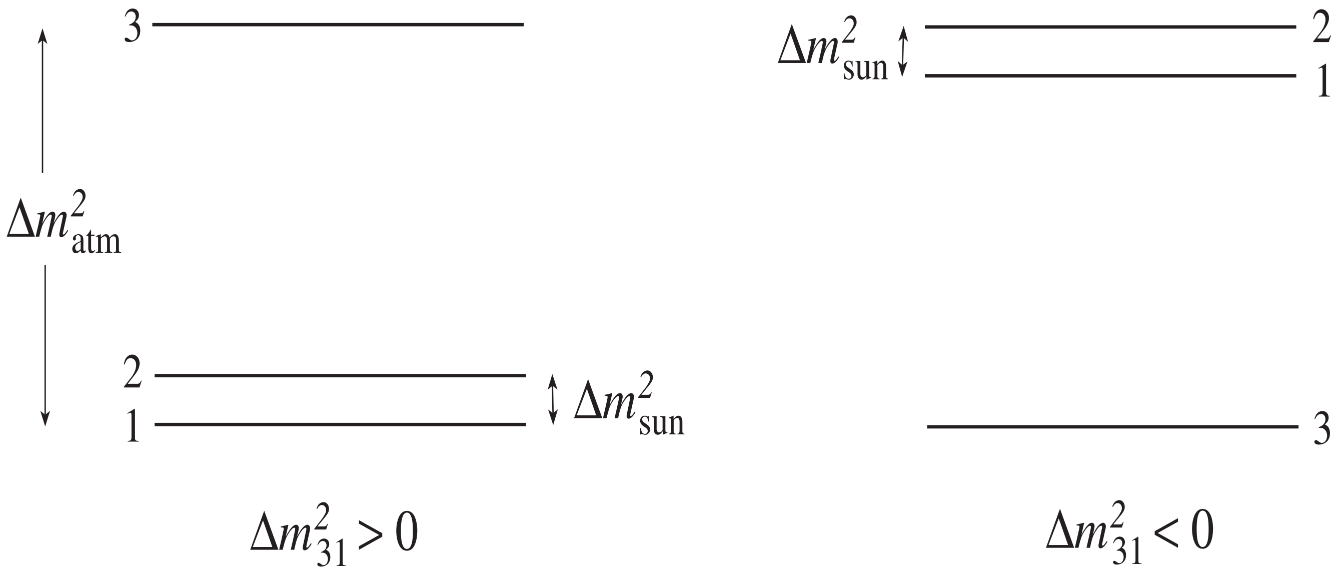
$$P_{\nu_e \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E_\nu}$$

What we don't know

- V_{NMS} : the link between solar and atmospheric anomalies:

$$\theta_{13},\ \delta$$

- The neutrino spectrum: $\mathrm{sign}(\Delta m^2_{23})$



"hierarchic" "degenerate"

Most sensitive transitions: $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$

θ_{13} and δ

I. $\theta_{13} = 0 \quad \Delta_{12} = 0$

$$P_{\nu_e \nu_\mu} = 0$$

II. $\theta_{13} > 0 \quad \Delta_{12} = 0$

$$P_{\nu_e \nu_\mu} = s_{23}^2 \ \sin^2 2\theta_{13} \ \sin^2 \left(\frac{\Delta_{23}\, L}{2} \right)$$

III. $\theta_{13} = 0 \quad \Delta_{12} > 0$

$$P_{\nu_e \nu_\mu} = c_{23}^2 \ \sin^2 2\theta_{12} \ \sin^2 \left(\frac{\Delta_{12}\, L}{2} \right)$$

IV. $\theta_{13} > 0 \quad \Delta_{12} > 0$

$$\begin{aligned} P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} \quad &= \quad s_{23}^2 \ \sin^2 2\theta_{13} \ \sin^2 \left(\frac{\Delta_{23}\, L}{2} \right) \\ &+ \quad c_{23}^2 \ \sin^2 2\theta_{12} \ \sin^2 \left(\frac{\Delta_{12}\, L}{2} \right) \\ &+ \quad \tilde{J} \ \cos \left(\pm\delta - \frac{\Delta_{23}\, L}{2} \right) \ \frac{\Delta_{12}\, L}{2} \sin \left(\frac{\Delta_{23}\, L}{2} \right) \end{aligned}$$

$$(\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23}, \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu} \ )$$

Neutrino Factory

$$\nu_e \longrightarrow \nu_\mu, \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$$

Golden measurements at Nufact: appearance of wrong-sign muons

$$\begin{array}{ccccc}
\mu^- \longrightarrow \nu_\mu & \bar{\nu}_e & e^- & & \\
 & \downarrow & & & \\
 & \bar{\nu}_\mu & & \longrightarrow & \mu^+ \\
\mu^+ \longrightarrow \bar{\nu}_\mu & \nu_e & e^+ & & \\
 & \downarrow & & & \\
 & \nu_\mu & & \longrightarrow & \mu^-
\end{array}$$

S. Geer, hep-ph/9712290

A. De Rújula, B. Gavela, P.H., hep-ph/9811390

$N_{\mu^+,\mu^-} = 10^{21}$/y, $M_{det} = 40$ KTon y, $E_\mu = 50 GeV$

μ^- beam

Baseline	$\bar{\nu}_e$ CC	ν_μ CC	$\mu^+(10^o)$	$\mu^+(0.5^o)$
732 Km	$3 \cdot 10^7$	$6.9 \cdot 10^7$	$1.7 \cdot 10^4$	44
3500 Km	$1.3 \cdot 10^6$	$3 \cdot 10^6$	$7 \cdot 10^3$	15
7332 Km	$3 \cdot 10^5$	$6.9 \cdot 10^5$	$2.8 \cdot 10^2$	1

μ^+ beam

Baseline	ν_e CC	$\bar{\nu}_\mu$ CC	$\mu^-(10^o)$	$\mu^-(0.5^o)$
732 Km	$5.9 \cdot 10^7$	$3.5 \cdot 10^7$	$3.6 \cdot 10^4$	94
3500 Km	$2.5 \cdot 10^6$	$1.5 \cdot 10^6$	$3.1 \cdot 10^4$	85
7332 Km	$5.9 \cdot 10^5$	$3.5 \cdot 10^5$	$1.2 \cdot 10^4$	39

Atmospheric parameters:

$$\Delta m^2_{23} = 3 \cdot 10^{-3} \text{ eV}^2, \ \sin 2\theta_{23} = 1$$

Physics studies

A. De Rújula, M.B. Gavela and P. H., hep-ph/9811390

K. Dick *et al.*, hep-ph/9903308

V. Barger, S. Geer and K. Whistant, hep-ph/9906487

A. Donini *et al.*, hep-ph/9909254

A. Romanino, hep-ph/9909425

V. Barger*et al.*, hep-ph/9911524

M. Freund *et al.*, hep-ph/9912457

A. Cervera *et al.*, hep-ph/0002108

M. Freund, P. Huber, M. Lindner, hep-ph/0004085

V. Barger *et al.*, hep-ph/0004208

A. Bueno, M. Campanelli, A. Rubbia *et al.*, hep-ph/0005007

P. Lipari, *et al.*, hep-ph/0102046

In coll. with Burguet-Castell, Cervera, Donini, Gavela, Gomez-Cadenas, Mena and Rigolin

SMA-MSW or LOW scenarios: I, II

Solar parameters ($\Delta m^2_{12}, \theta_{12}, \delta$) do not affect oscillations at terrestial distances.

- Wrong–sign muon signals for decaying $\mu^{\pm}$:

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} \quad = \quad s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{23}}{B_\pm}\right)^2 \sin^2 \left(\frac{B_\pm\, L}{2}\right)$$

with $B_\pm \equiv \sqrt{(\Delta_{23} \cos 2\theta_{13} \pm A)^2 + (\Delta_{23} \sin 2\theta_{13})^2}$

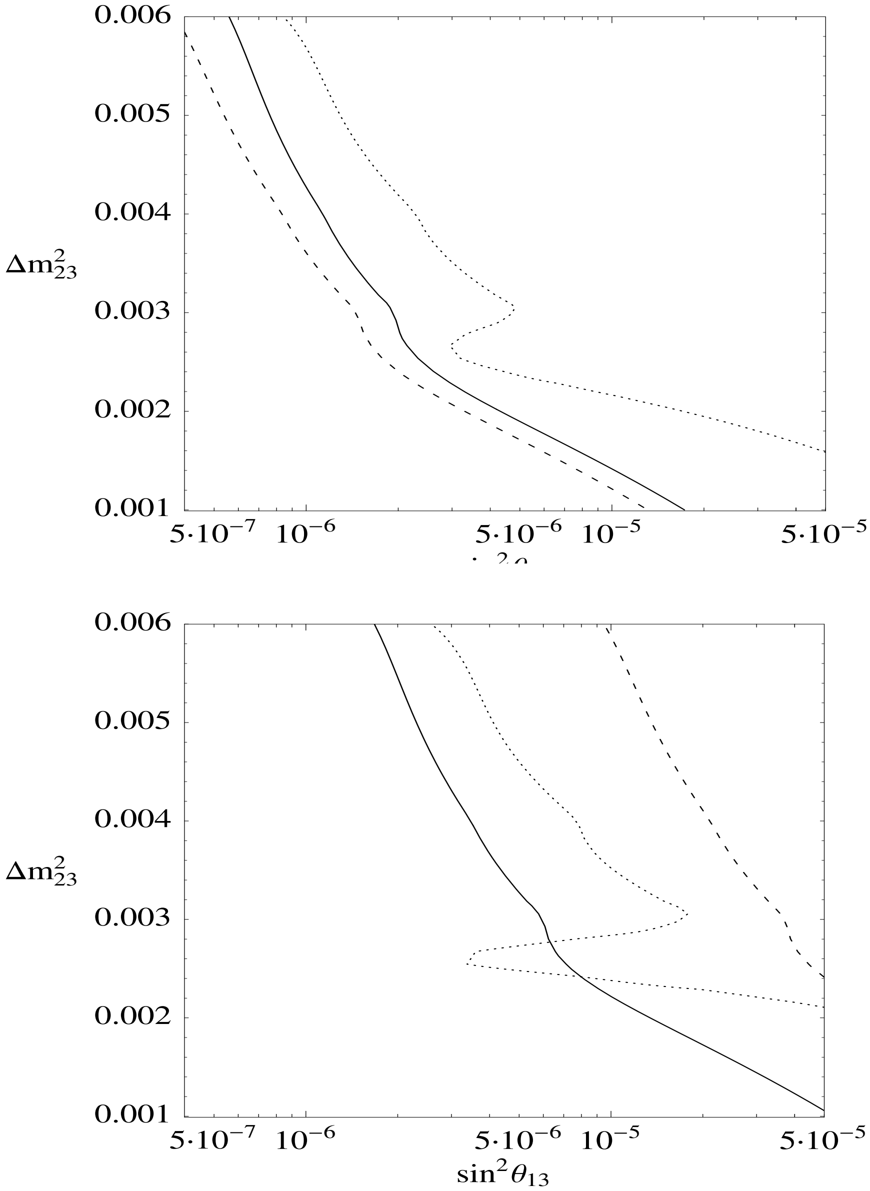
$\longrightarrow$ Measurement of θ_{13} and $\mathrm{sign}(\Delta m^2_{23})$

- ν_μ disappearance: $P_{\nu_\mu \nu_\tau}$

$\longrightarrow$ Precise measurement of $|\Delta m^2_{23}|$,$\sin^2 2\theta_{23}$

Measurement of θ_{13}

Best sensitivity obtained from wrong-sign muon search



$$N_{\mu^+,\mu^-} = 10^{21}/\text{year},\ M_{det} = 40\ \text{KTon year}$$

Present limits can be improved by more than 3-4 orders of magnitude: $\Delta m^2_{23} = 3 \cdot 10^{-3}$ eV^2 $\rightarrow \theta_{13} > 0.15°$

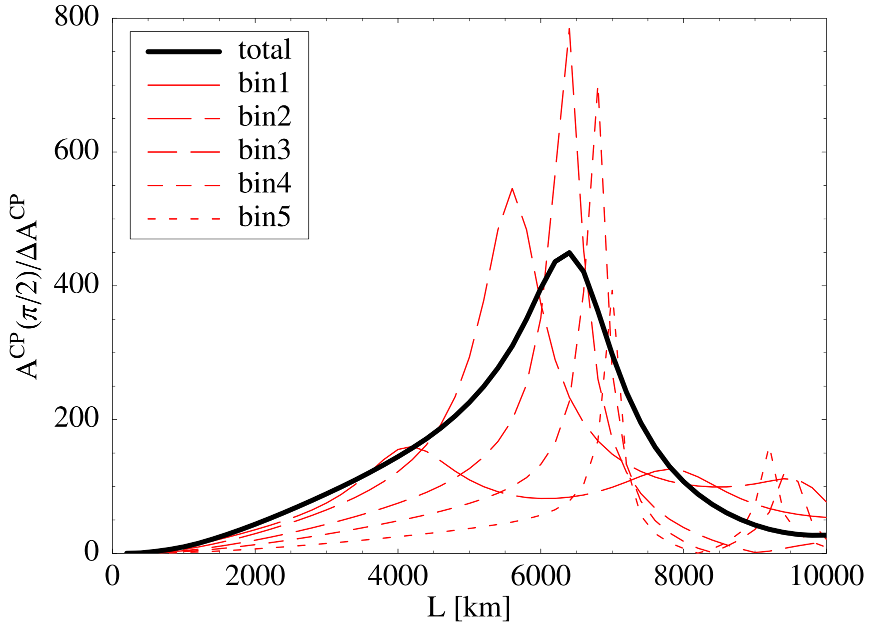
Measurement of sign(Δm^2_{23})

The sensitivity to the sign is equivalent to the sensitivity to the CP-odd asymmetry in wrong–sign muon signals for $\mu^{\pm}$:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} \quad = \quad s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2_{23}}{B_\pm}\right)^2 \quad \sin^2\left(\frac{B_\pm L}{2}\right)$$

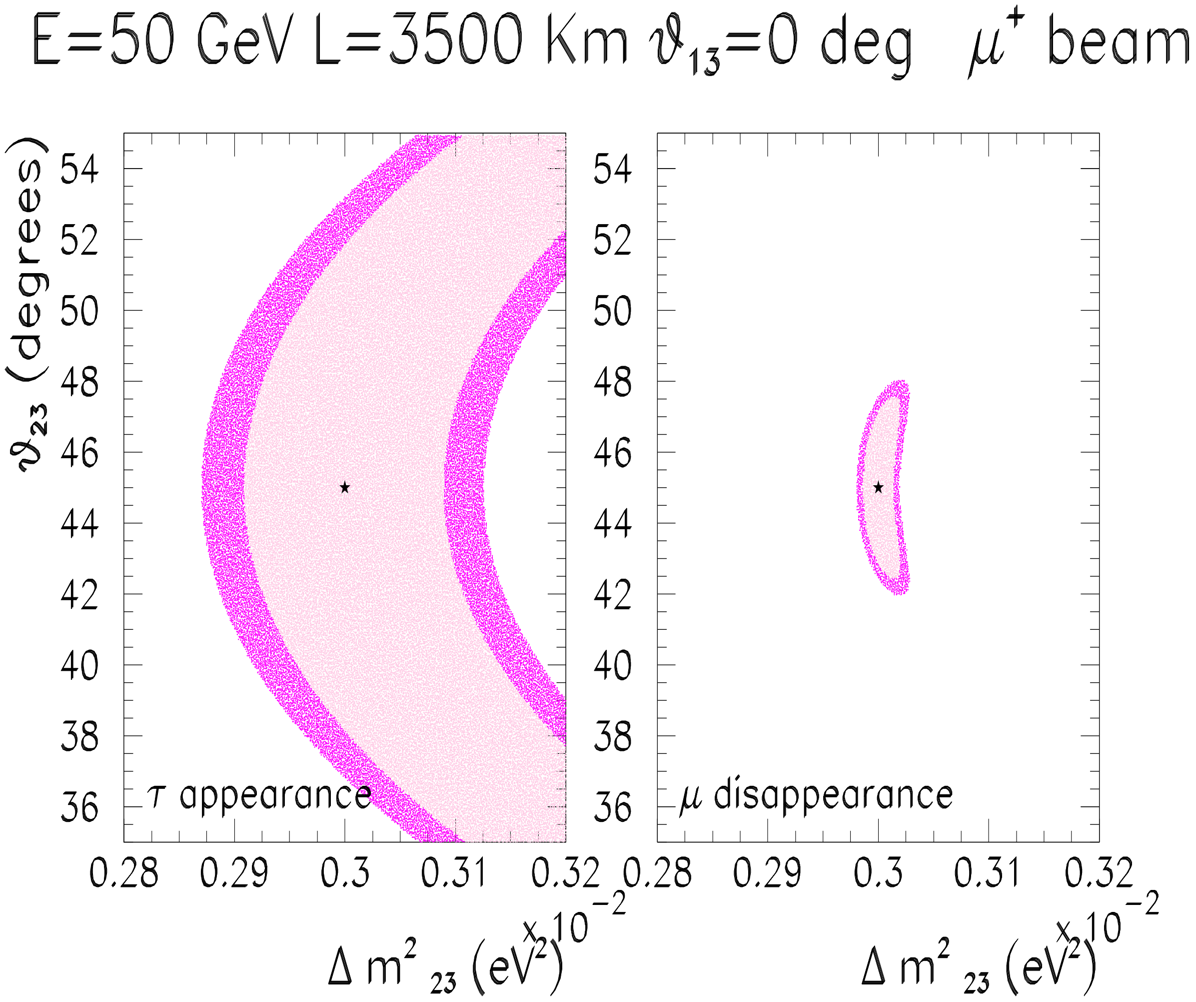
$$\Delta m^2_{23} \leftrightarrow -\Delta m^2_{23} \leftrightarrow P_{\nu_e\nu_\mu} \leftrightarrow P_{\bar{\nu}_e\bar{\nu}_\mu}$$

$$\bar{A}^{CP}_{e\mu} = \frac{\{N[\mu^-]\}_+ - \{N[\mu^+]\}_- \sigma_\nu/\sigma_{\bar{\nu}}}{\{N[\mu^-]\}_+ + \{N[\mu^+]\}_- \sigma_\nu/\sigma_{\bar{\nu}}}$$



Measurement of $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$

Best from ν_μ disappearance:



M.C. González-García

LMA-MSW scenario: III, IV

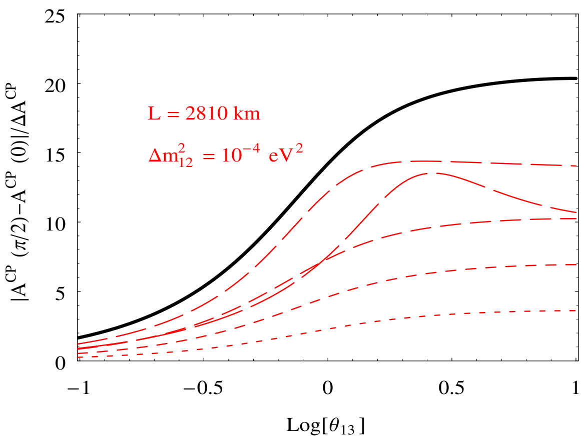
- The phase δ induces in vaccuum a CP asymmetry only in appearance measurements: $\alpha \neq \beta$

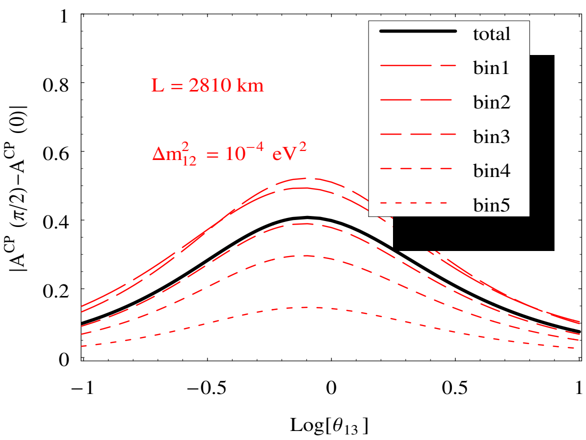
- δ is unobservable if any θ_{ij} or $\Delta m^2_{ij} = 0$:

$$P_{\nu_\alpha \nu_\beta} - P_{\bar{\nu}_\alpha \bar{\nu}_\beta} \sim \sin\delta \prod_{i \neq j} \sin 2\theta_{ij} \prod_{i \neq j} \frac{\Delta m^2_{ij}\, L}{4E_\nu}$$

- Effects of δ are more significant in subleading transitions: $\nu_e \to \nu_\mu$:

$$\begin{aligned} A^{CP}_{\nu_\mu \nu_\tau} &\sim \sin 2\,\theta_{13} \;\; (\Delta_{12} L/2) \\ A^{CP}_{\nu_e \nu_\mu} &\sim \frac{\Delta_{12} L/2}{\sin 2\theta_{13}} \quad \text{or} \quad \frac{\sin 2\theta_{13}}{\Delta_{12} L/2} \end{aligned}$$





Measurement of CP violation

Observable CP asymmetries are not clean signatures of CP violation:

- $\sigma_\nu \neq \sigma_{\bar{\nu}}$
- matter effects induce a CP-odd asymmetry even for $\sin\delta = 0$

Approximate formula up to $O(\theta_{13})^3$, $O(\Delta_{12})^3$:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{23}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A\,L}{2}\right)$$

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin\left(\frac{AL}{2}\right)\frac{\Delta_{23}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\,\cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right)$$

$$B_\pm = |A \pm \Delta_{23}| \qquad \Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu}$$

A. Cervera *et al*, hep-ph/0002108

Correlation between θ_{13} and δ

Assume the true parameters are $\bar{\theta}_{13}, \bar{\delta}$:

- Consider fixed E_ν and L and charge ν:

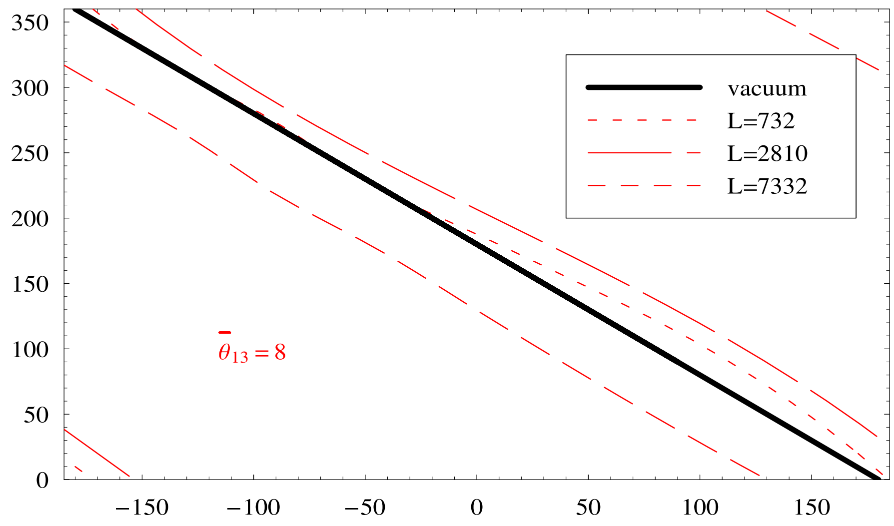
$$P_{\nu_e \nu_\mu}(\theta_{13}, \delta) = P_{\nu_e \nu_\mu}(\bar{\theta}_{13}, \bar{\delta}) \rightarrow \quad \theta_{13} = A + B \cos\delta$$

- Consider fixed E_ν and L and two polarities ν and $\bar{\nu}$:

$$\begin{aligned} P_{\nu_e \nu_\mu}(\theta_{13}, \delta) &= P_{\nu_e \nu_\mu}(\bar{\theta}_{13}, \bar{\delta}) \\ P_{\bar{\nu}_e \bar{\nu}_\mu}(\theta_{13}, \delta) &= P_{\bar{\nu}_e \bar{\nu}_\mu}(\bar{\theta}_{13}, \bar{\delta}) \end{aligned}$$

Generically two solutions!

1

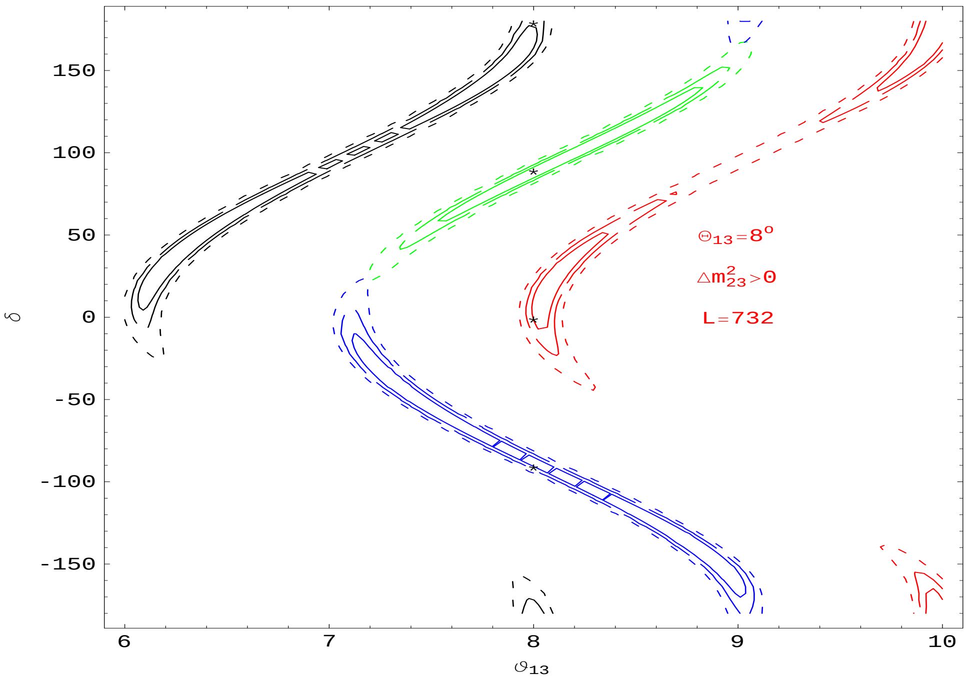


A significant E_ν and L dependence solves this double degeneracy.

Simultaneous fits to θ_{13} and δ

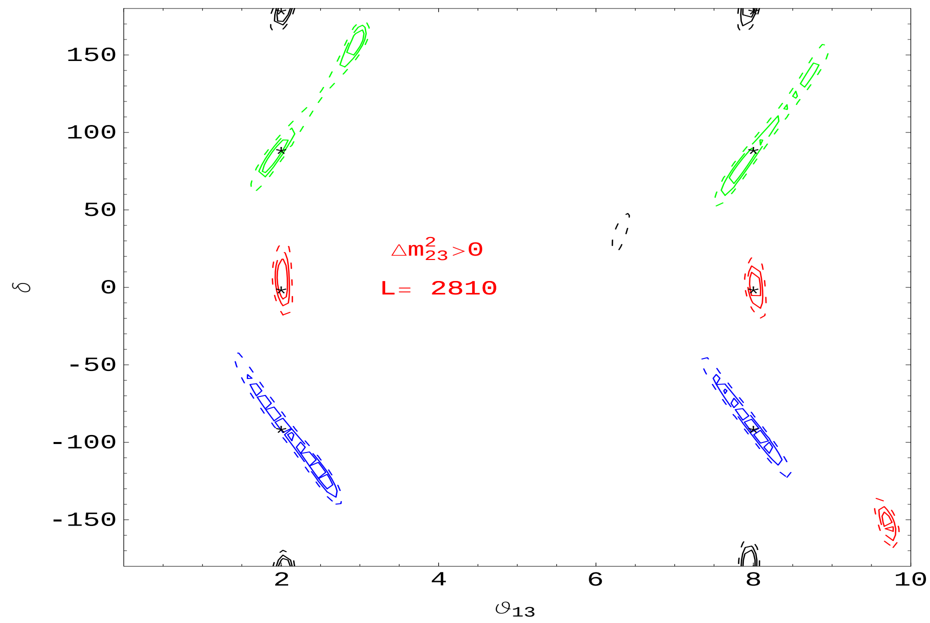
Two polarities are essential to reduce the degeneracy in the solutions $\longrightarrow$ L must be large enough so that the functions $P_{\nu_e\nu_\mu}$ and $P_{\bar{\nu}_e\bar{\nu}_\mu}$ are significantly different !

$L = 732$ Km (CERN-Gran Sasso) :



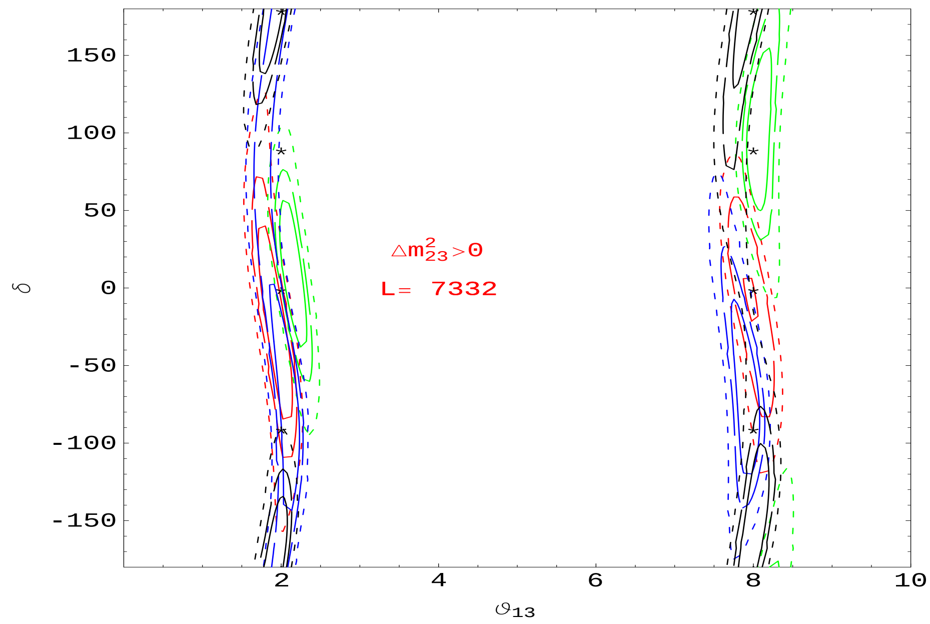
$$P_{\nu_e\nu_\mu} \simeq P_{\bar{\nu}_e\bar{\nu}_\mu} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{23}L}{2}\right)^2 + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}L}{2}\right)^2 + \tilde{J}\, \frac{\Delta_{12}L}{2}\, \frac{\Delta_{13}L}{2}\, \cos\delta$$

$L = 2810$ Km (CERN-La Palma) :



Optimal L is in the intermediate range !

$L = 7332$ Km (CERN-?) :

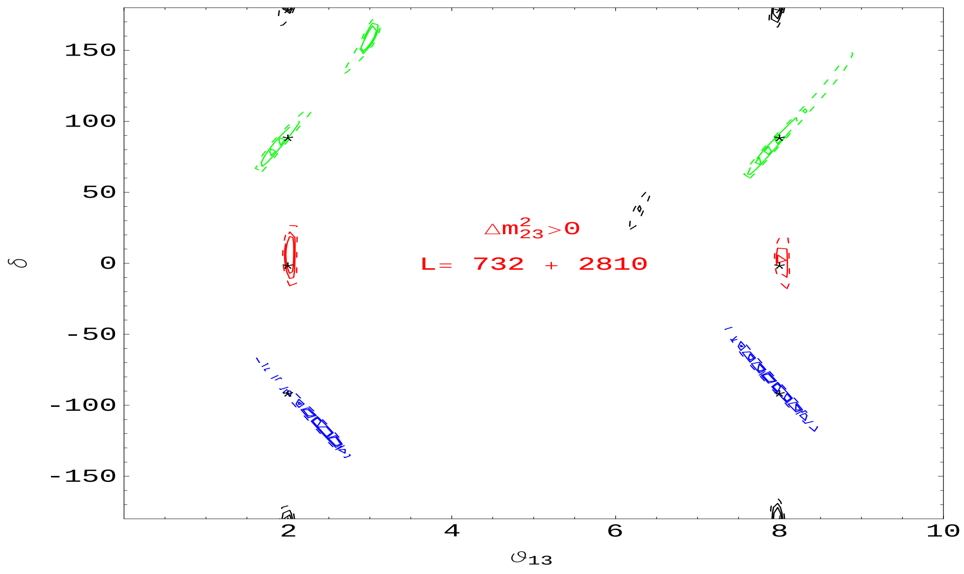


At very long baselines, the sensitivity to δ is again lost

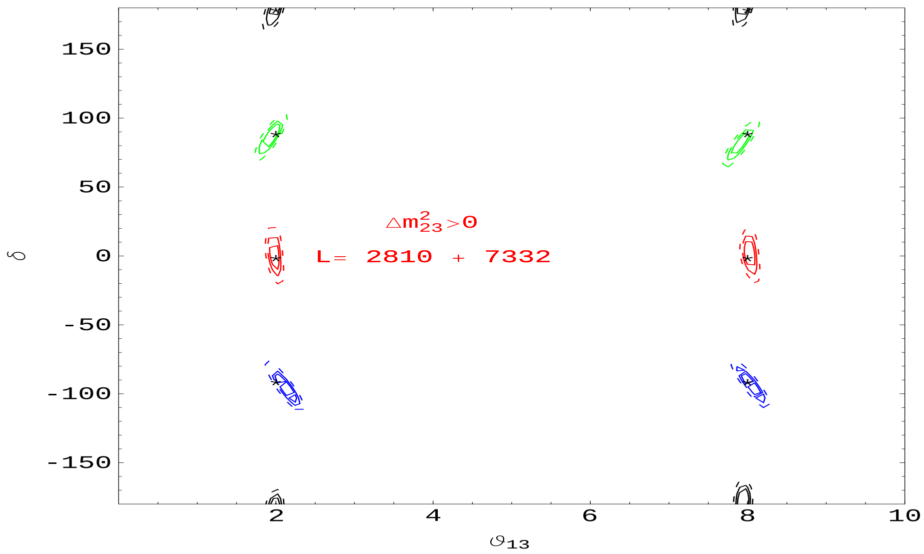
Simultaneous fits to θ_{13} and δ

The remaining double degeneracy can be resolved by increasing statistics or combining two baselines:

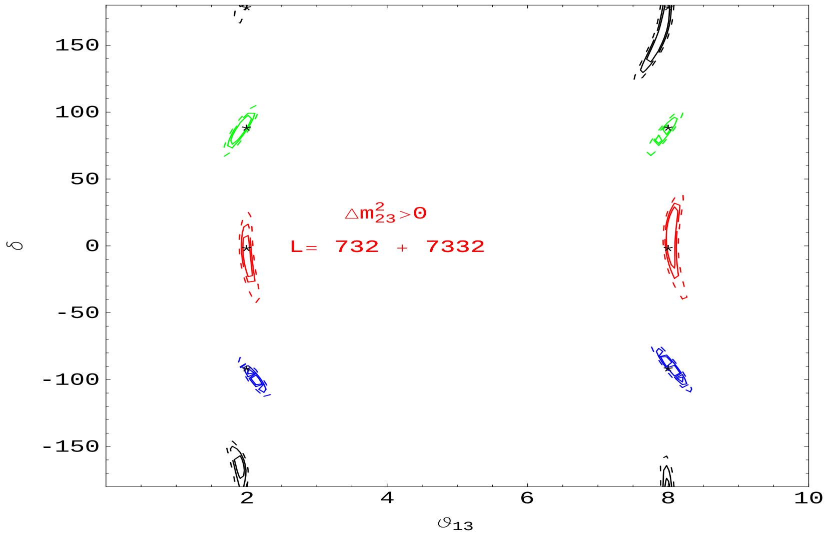
$L = 732$ Km + $L = 2810$ Km



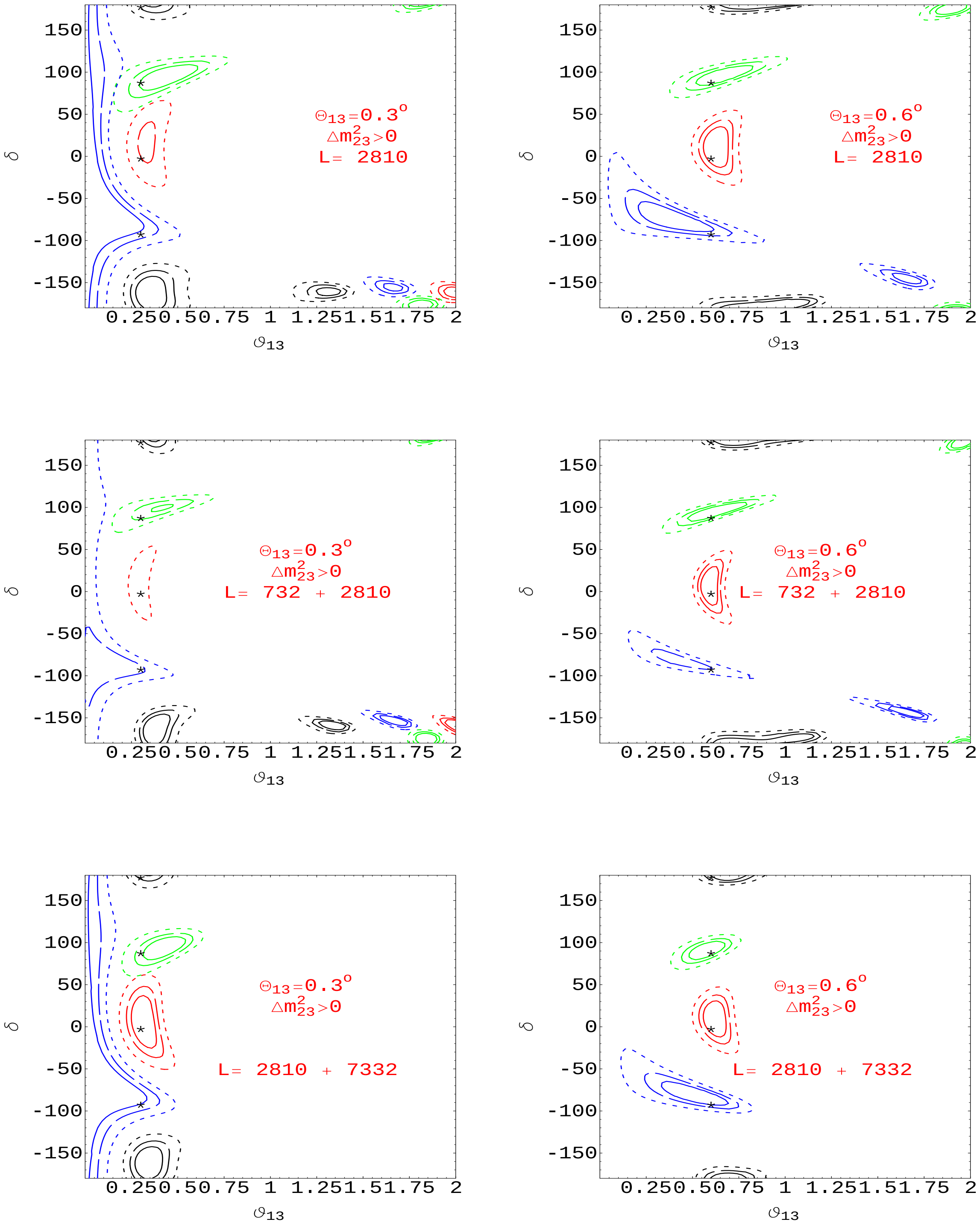
$L = 2810$ Km + $L = 7332$ Km :



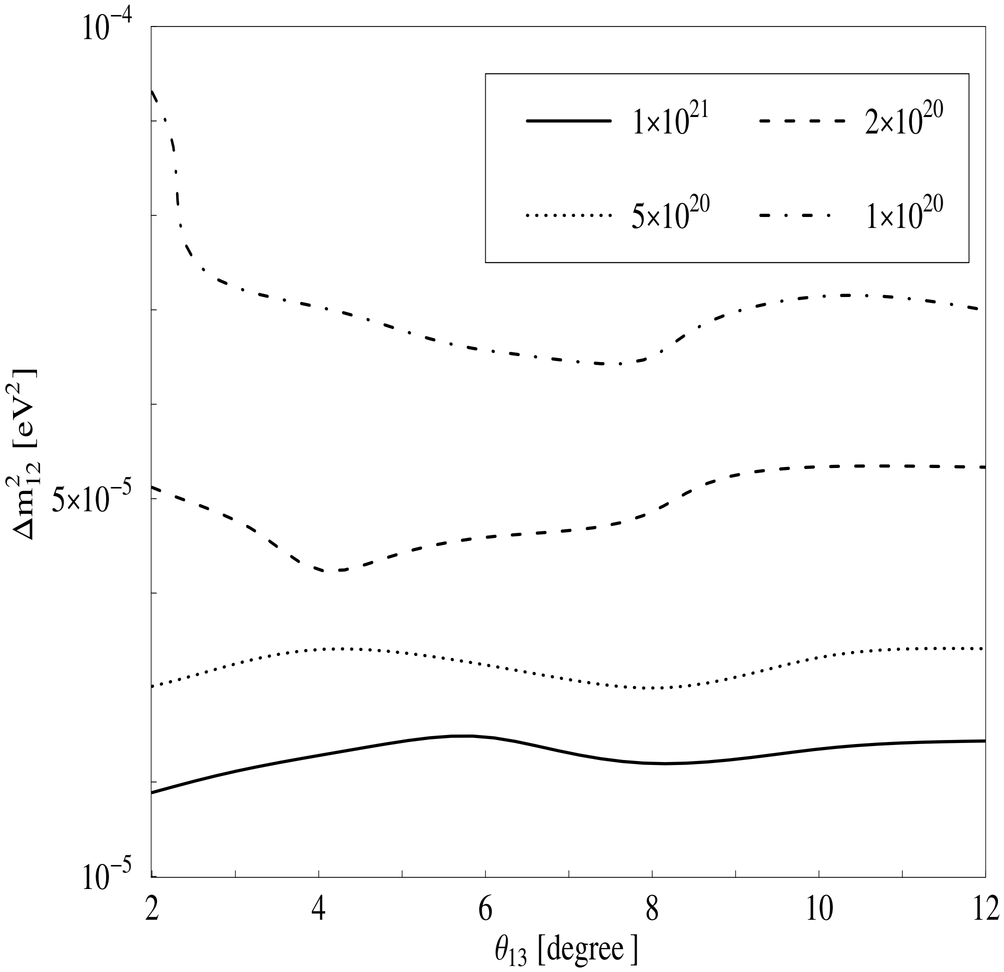
$L = 732$ Km $+$ $L = 7332$ Km :



Sensitivity to δ decreases with $\theta_{13} \leq 1^{\circ}(\Delta m^2_{12} = 10^{-4} eV^2)$



The sensitivity to CP-violation decreases linearly with $|\Delta m^2_{12}|$: how much of the LMA range can we cover ?



$|\Delta m^2_{12}| > 2 \times 10^{-5}$ eV^2 in order to distinguish a maximal CP-odd phase, $\delta = 90°$ from $\delta = 0°$ at 99% CL , with very small dependence on θ_{13} .

Conclusions

- νfact is a facility to perform precision neutrino oscillation physics

- Measurement of atmospheric parameters $(\sin^2 2\theta_{23}$, $|\Delta m^2_{23}|)$ at $\sim 1\%$ level

- Measurement of θ_{13} and sign(Δm^2_{23}) if $\theta_{13} >$ few tenths of a degree

- Discover leptonic CP-violation **iff LMA**