Long baseline experiments and low energy neutrino factory

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Silvia Pascoli

IPPP – Durham

1 – Outline

- **LBL ν-oscillations**
  - matter effects
  - CP-violation
  - solving degeneracies
- **LBL experiments:** **high energy neutrino factory**
  Low energy neutrino factory
- **Conclusions**

2 – LBL oscillation experiments

Long base-line neutrino oscillation experiments are sensitive to matter effects ($\Rightarrow$ type of hierarchy) and to CP violation.

Matter effects imply that

$$P(\nu_l \to \nu_{l'}) \neq P(\bar{\nu}_l \to \bar{\nu}_{l'})$$

If U is complex we have CP-violation:

$$P(\nu_l \to \nu_{l'}) \neq P(\bar{\nu}_l \to \bar{\nu}_{l'})$$

There are degenerate solutions:

$$\Delta m^2_{31} \;,\; \theta_{13} \;,\; \delta \;,\; \theta_{23}$$
$$\Delta m^2_{31}\text{'},\; \theta_{13}\text{'} \;,\; \delta\text{'} \;,\; \theta_{23}\text{'}$$

$\Rightarrow$ P, $\overline{\text{P}}$

It is necessary to disentangle

true CP-V effects due to the δ phase

from the ones induced by matter:

degeneracies.

In the range of energies ($E \sim 0.5 \div 4$ GeV) and length ($L \sim 200 \div 1000$ Km), of interest, the oscillation probability for $\nu_\mu \longrightarrow \nu_e$, in 3-neutrino mixing case, is given by:

$$
\begin{aligned}
P(\bar{P}) \simeq \;& s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2} \\
& + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \sin \frac{(A \mp \Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13} L}{2}\right) \\
& + c^2_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2}
\end{aligned}
$$

with $\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$ and

$\Delta_{13} \equiv \Delta m^2_{31}/(2E)$.

$A \equiv \sqrt{2} G_F \bar{n}_e$.

In the vacuum case, for simplicity, we identify 2-, 4- and 8- fold degeneracies [Barger, Marfatia, Whisnant]:

- (θ_{13}, δ) degeneracy [Koike, Ota, Sato; Burguet-Castell et al.] :

$$\begin{aligned} \delta' &= \pi - \delta \\ \theta'_{13} &= \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E} \cot\theta_{23} \cot \frac{\Delta m^2_{13} L}{4E} \end{aligned}$$

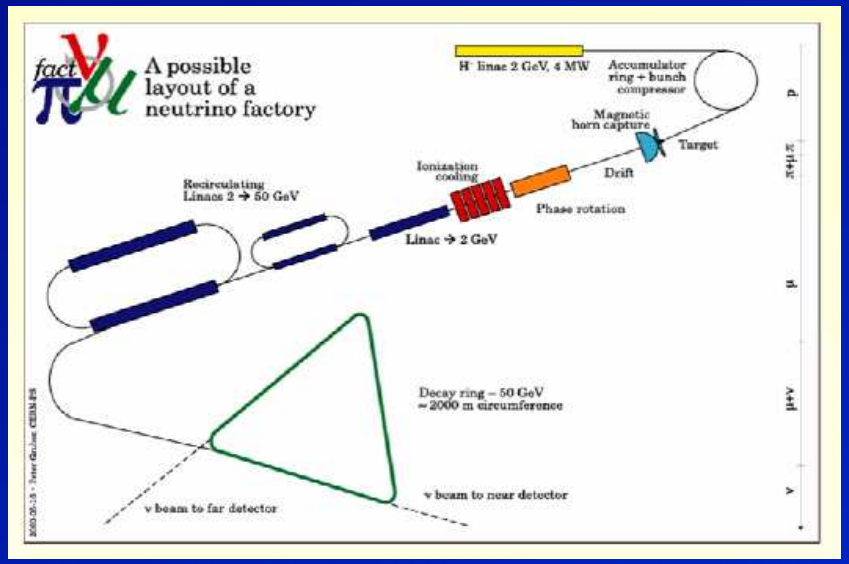
- $(\mathrm{sign}(\Delta m^2_{13}), \delta)$ degeneracy [Minakata, Nunokawa]:

$$\begin{aligned} \delta' &\qquad \pi - \delta \\ \mathrm{sign}'(\Delta m^2_{13}) &\quad -\mathrm{sign}(\Delta m^2_{13}) \end{aligned}$$

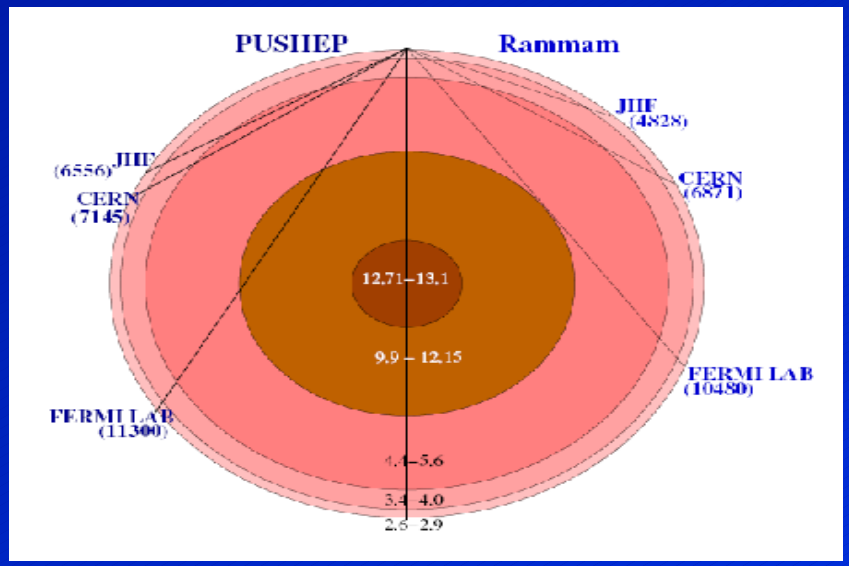
- $\theta_{23}, \pi/2 - \theta_{23}$ degeneracy [Fogli, Lisi].

Future LBL experiments:

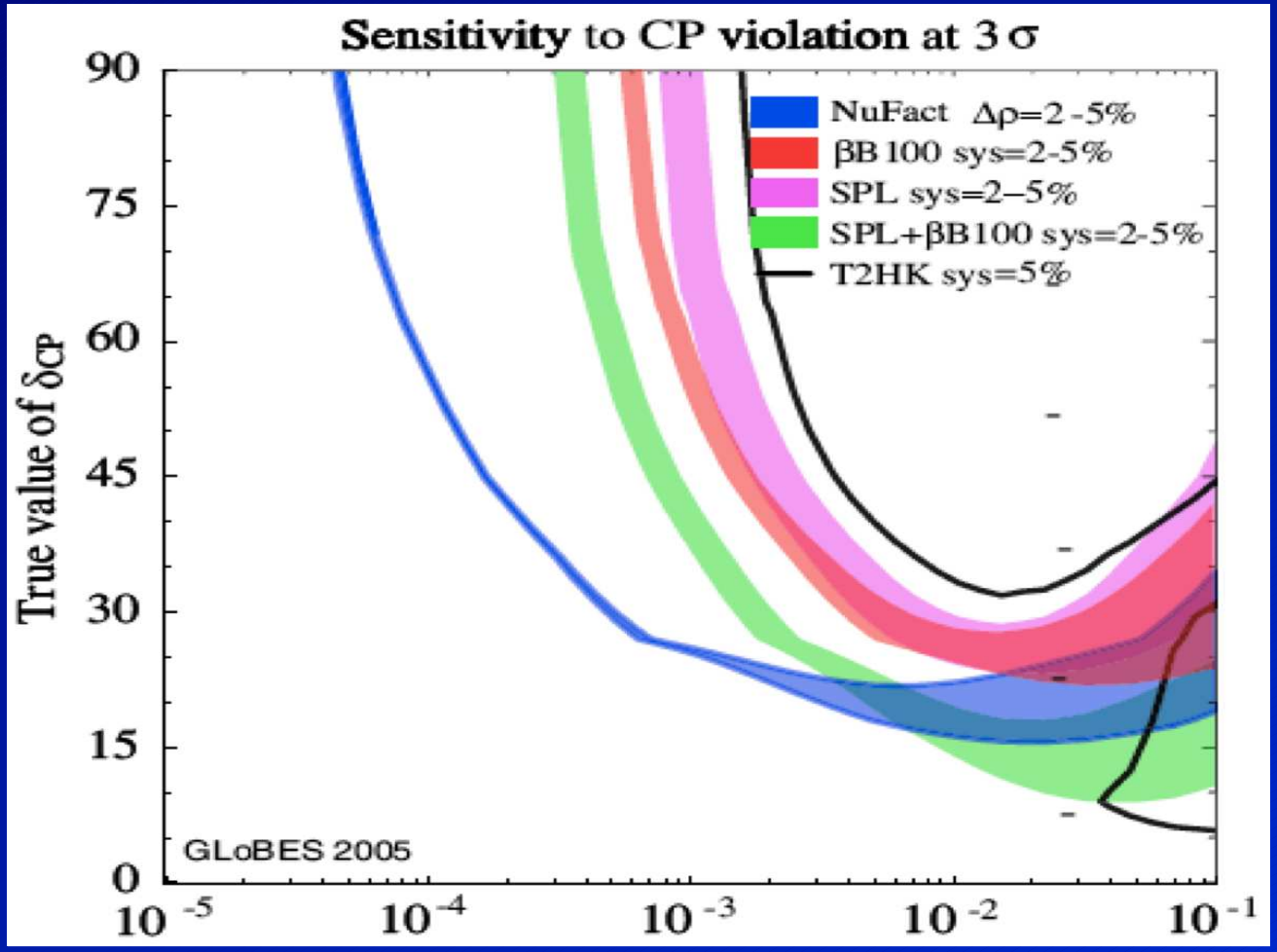
1. Superbeams: a very intense ν_μ beam produced in $\pi^\pm$, $K^\pm$ decays. Intrinsic ν_e background.
2. Beta-beams: ν_e beams given by the β-decays of high-gamma ions.
3. Neutrino factories: ν_μ-ν_e beam from high-γ muons (20 GeV - 50 GeV).



INO proposal



Typical sensitivity in a high energy neutrino factory:



[Blondel et al. 2005]

The sensitivity at large $\sin^2 \theta_{13}$ worsens.

3 – A low energy neutrino factory

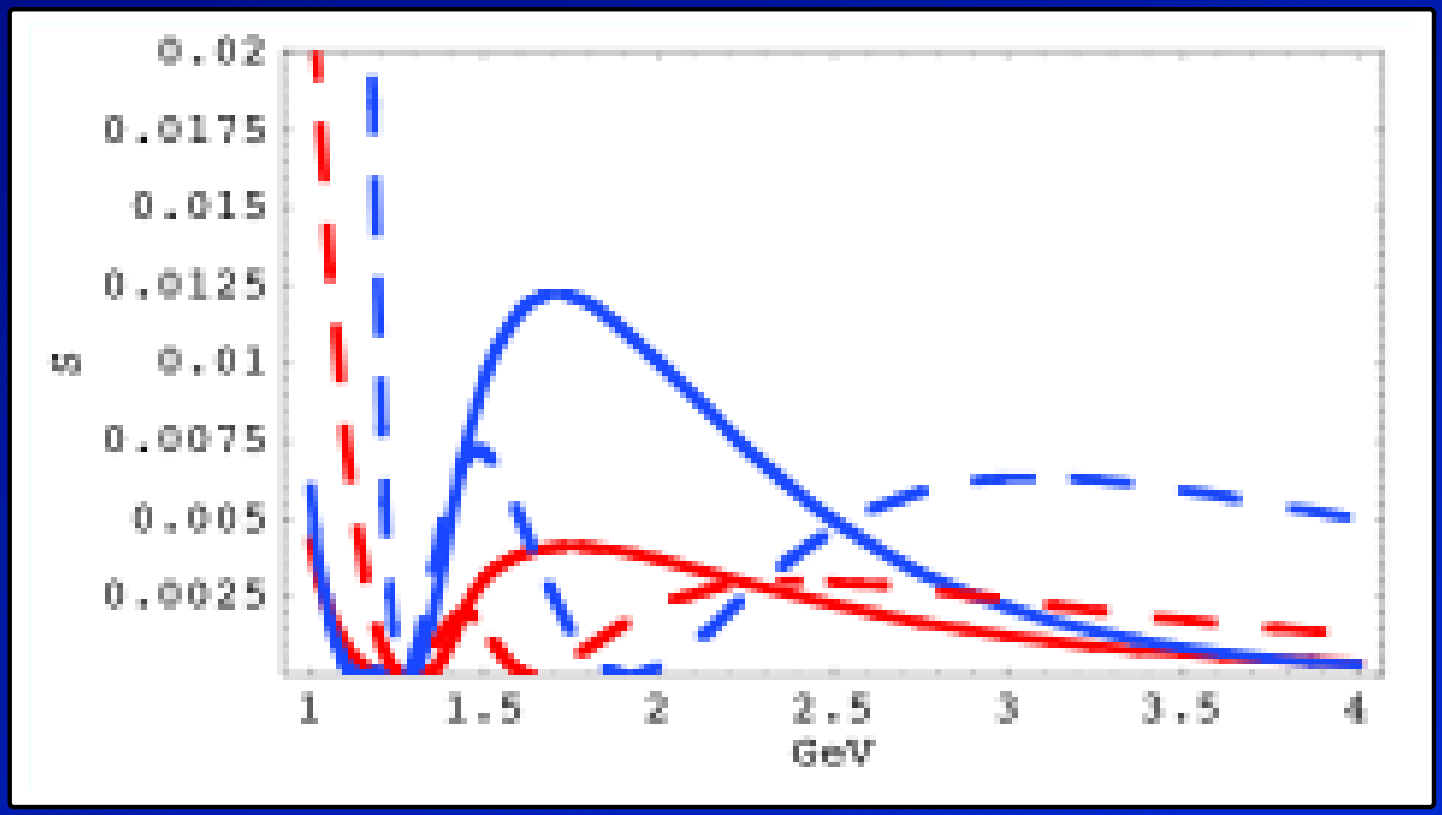
We consider the case of large θ_{13}, $\sin^2 2\theta_{13} \gtrsim 0.01$ and we study a low energy neutrino factory:

- rather short baseline, $L =$1480 km (Fermilab to Henderson mine), (L= 1280 km);
- low energy, $E \sim 1.5 - 4$ GeV;
- fine grained magnetized detector with threshold at 1 GeV.

Based on S. Geer, O. Mena, S.P., hep-ph/0701258, accepted in PRD.

We study the sensitivity to CP-violation:

$$\mathcal{S}(\delta) \equiv \frac{\Big(P(L,\delta)-P(L,0)\Big)^2}{P(L,\delta)}$$

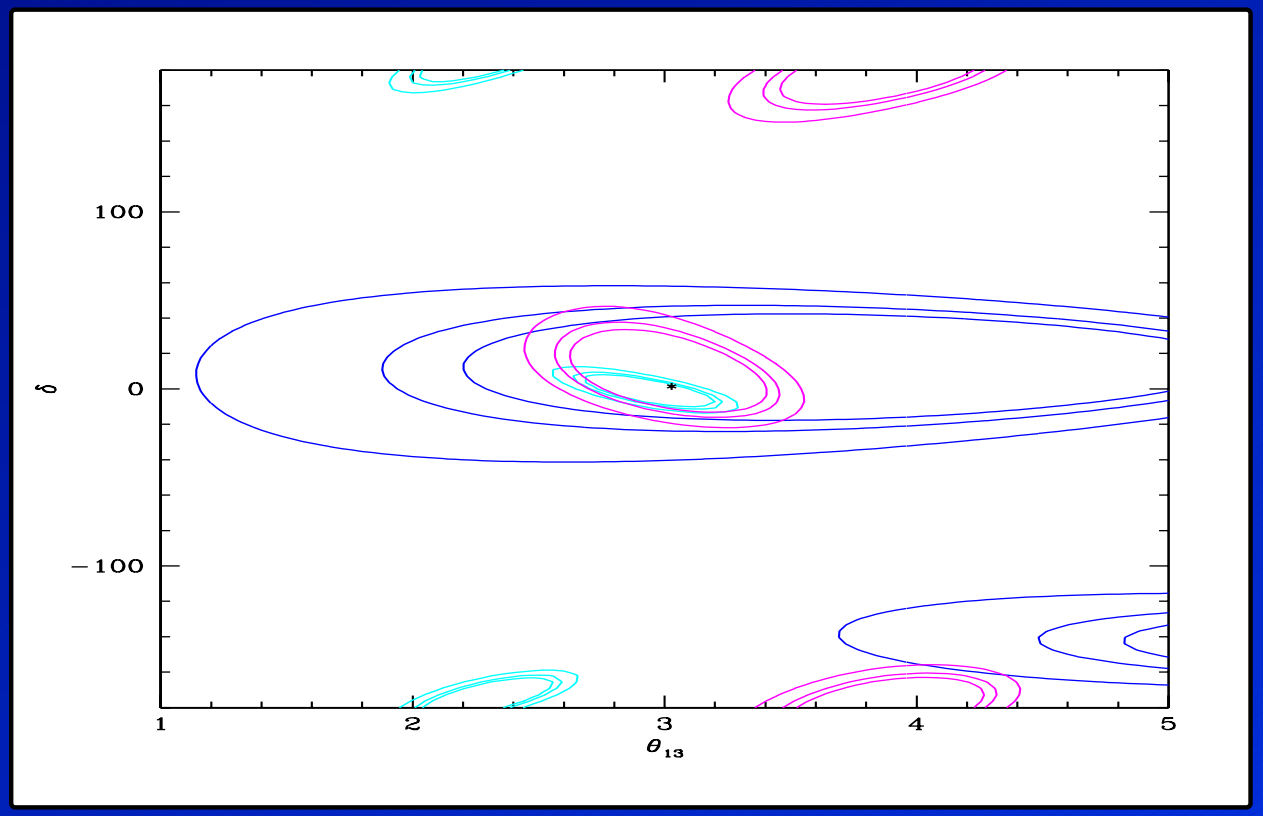


We consider $E_\mu = 4.12$ GeV and use four energy bins.

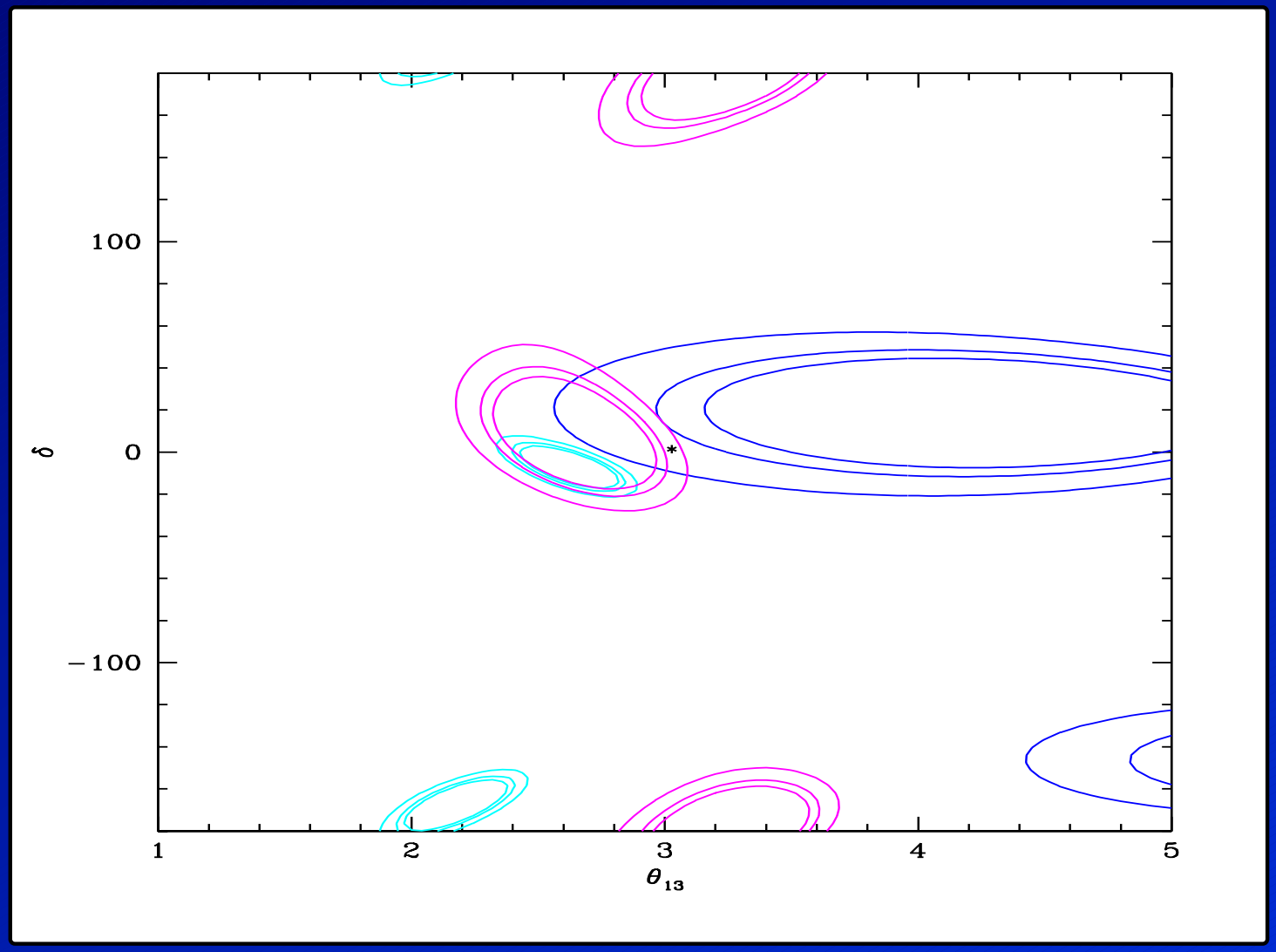
For large θ_{13} the intrinsic degeneracy is located at

$$\delta' \simeq \pi - \delta,$$

$$\theta'_{13} \simeq \theta_{13} + \cos\delta \, \sin 2\theta_{12} \, \frac{\Delta m^2_{21} L}{4E} \, \cot\theta_{23} \cot\left(\frac{\Delta m^2_{31} L}{4E}\right).$$

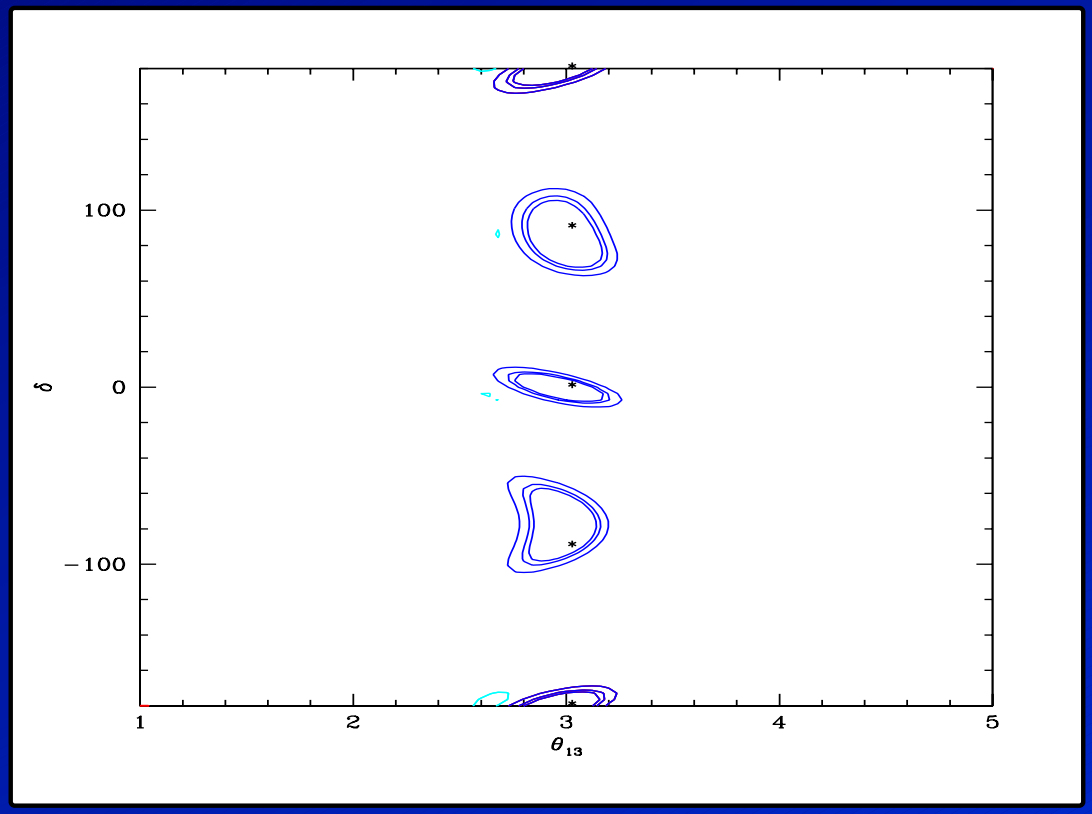


The octant degeneracy is usually very hard to resolve.



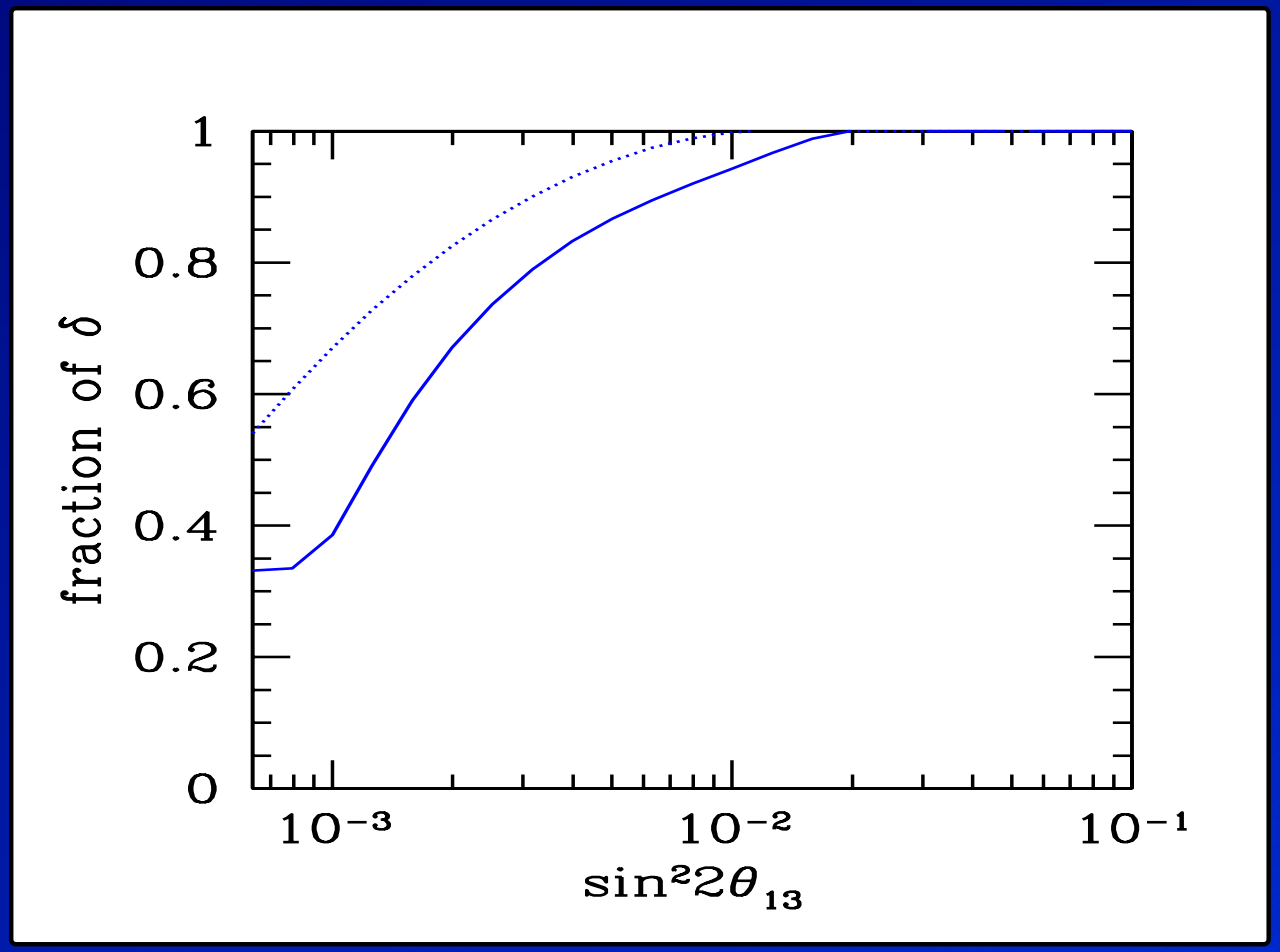
The information at low energy is very important.

We simulate the sensitivity of the low energy neutrino factory, exploiting the disappearance and the golden channels.



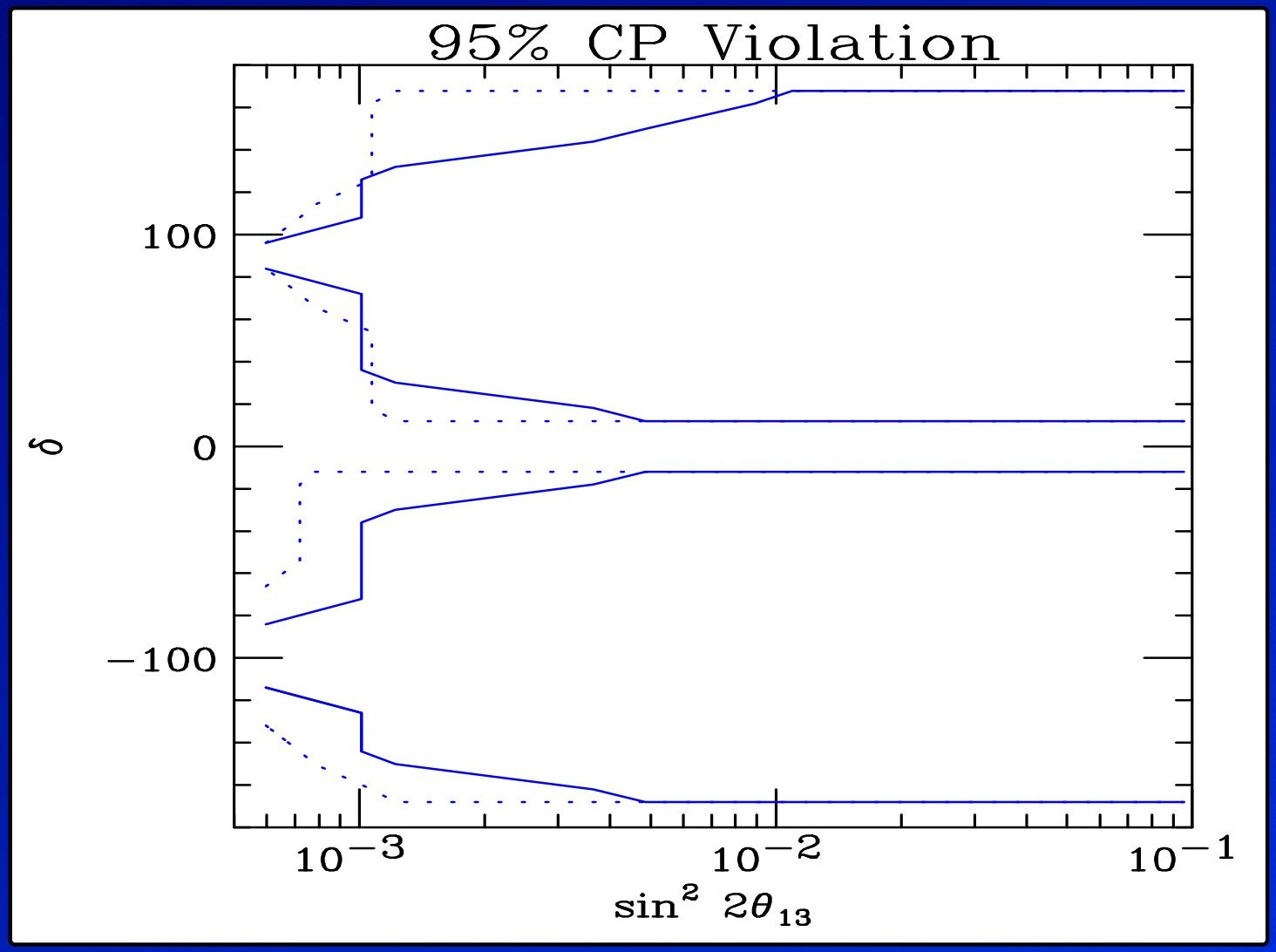
There are no sign and octant (almost) degeneracies and the determination of θ_{13} and δ are very good.

The exclusion plots for the type of hierarchy.



For values of $\sin^2\theta_{13} \sim 0.01$, it can be established independently from the δ phase.

Very good sensitivity to CP-violation:



4 – Conclusions

- Establishing the **type of hierarchy** and CP-violation are two of the crucial questions in neutrino physics.

- They can be probed in future LBL experiments.

For large θ_{13}, a low energy factory would give very good sensitivity to the type of hierarchy and CP-violation, solving (practically) all degeneracies.