Long baseline neutrino physics: present and future

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1 – Outline

- Theoretical aspects of long baseline experiments:
    - Appearance probability
    - Matter effects
    - CP-violation
- Present long baseline experiments: OPERA and MINOS and T2K
- Future facilities:
    - Superbeams
    - Beta-beams
    - Neutrino factory
- Conclusions

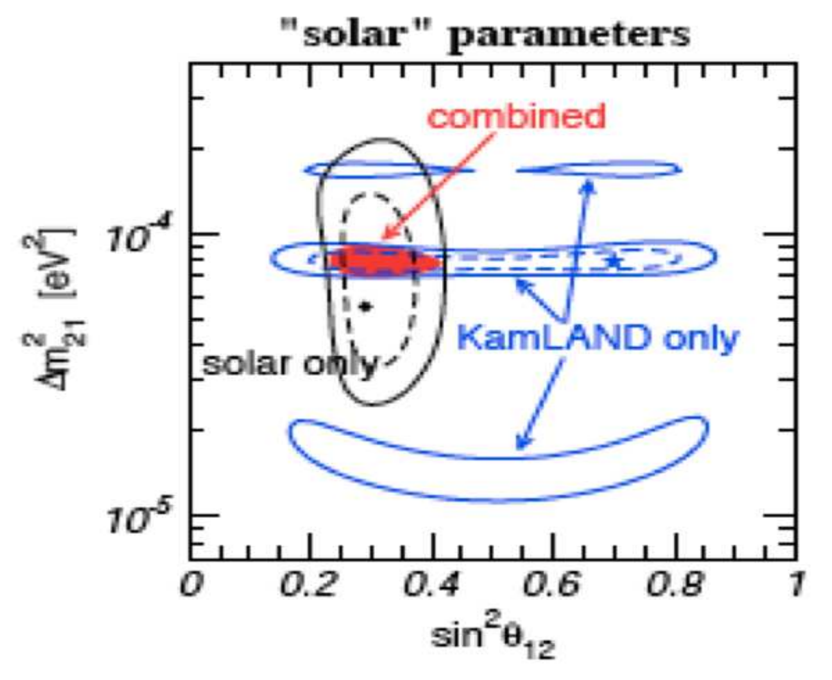
2 – ν-oscillations: present status and questions for the future

The probability of

ν_a oscillating into ν_b is:

$$P(\nu_a \to \nu_b) = |\langle \nu_b | \nu, t \rangle|^2$$

$$\simeq \sin^2 2\theta \ \sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$



[T. Schwetz, hep-ph/0606060]

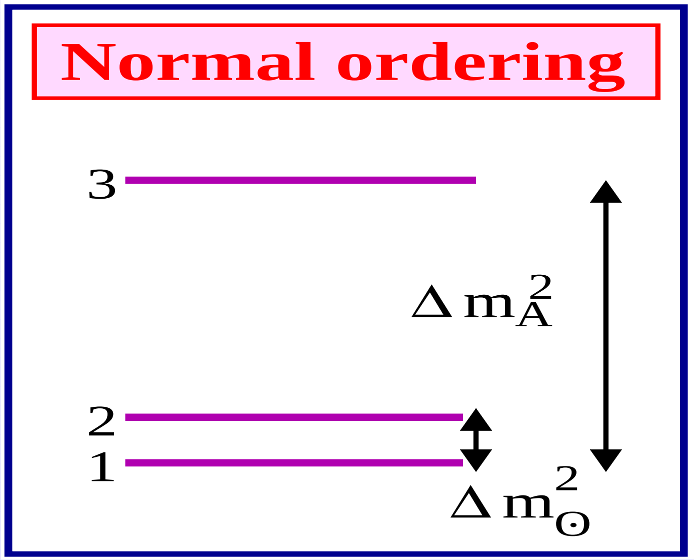
- Solar neutrino and KamLAND experiments: $\Delta m^2_\odot$, θ_{12}
- Atmospheric neutrino, K2K, MINOS experiments: $\Delta m^2_{\rm atm}$, θ_{23}

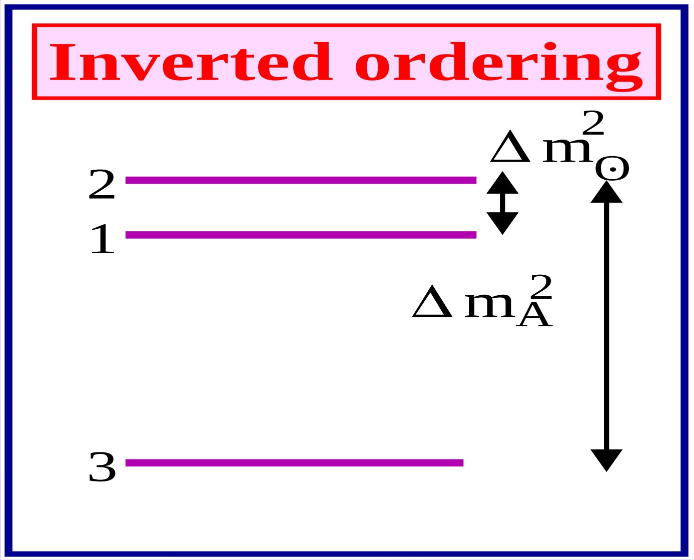
$$\Delta m^2_\odot = 8.0 \times 10^{-5}\,{\rm eV}^2 \ll \Delta m^2_{\rm atm} = 2.5 \times 10^{-3}\,{\rm eV}^2 \ \Rightarrow \mathbf{3}\ \nu.$$

Neutrino oscillations are crucial in our understanding of neutrino physics as they imply that

NEUTRINOS ARE MASSIVE AND THEY MIX.

The explanation of neutrino masses requires physics beyond the Standard Model.





$$m_1 = m_{\rm MIN}$$
$$m_2 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_\odot}$$
$$m_3 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_{\rm atm}}$$

$$m_3 = m_{\rm MIN}$$
$$m_1 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_{\rm atm} - \Delta m^2_\odot}$$
$$m_2 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_{\rm atm}}$$

Measuring neutrino masses requires to know:

- $m_{\rm MIN}$
- sign(Δm^2_{31}).

Mixing is described by a unitary matrix:

$$|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar, reactor $\theta_\odot \sim 30^o$ **Atm, Acc.** $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase **Reactor, Acc.** $\theta < 12^o$ **CPV Majorana phases**

If $U \neq U^*$, there is leptonic CP-violation.

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

- Establishing leptonic CP-V is a fundamental and challenging task.

- There are:

1 Dirac phase (measurable in long base-line experiments)

and 2 Majorana phases (one might be determined in neutrinoless double beta decay).

- Leptogenesis takes place in the context of see-saw models, which explain the origin of neutrino masses.

The observation of neutrinoless double beta decay (L violation) and of CPV in the lepton sector would be an indication, even if not a proof, of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

Questions for the future

- **What is the nature of neutrinos**?

Whether they Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$). Majorana neutrinos violate the lepton number.

- **Absolute value of neutrino masses**?

Needed the type of hierarchy and the mass scale of the lightest neutrino.

- **Leptonic CP-violation**?

$\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$.

- **Standard scenario**?

NSI, sterile neutrinos, violations of unitarity

3 – Long baseline neutrino experiments: theoretical aspects

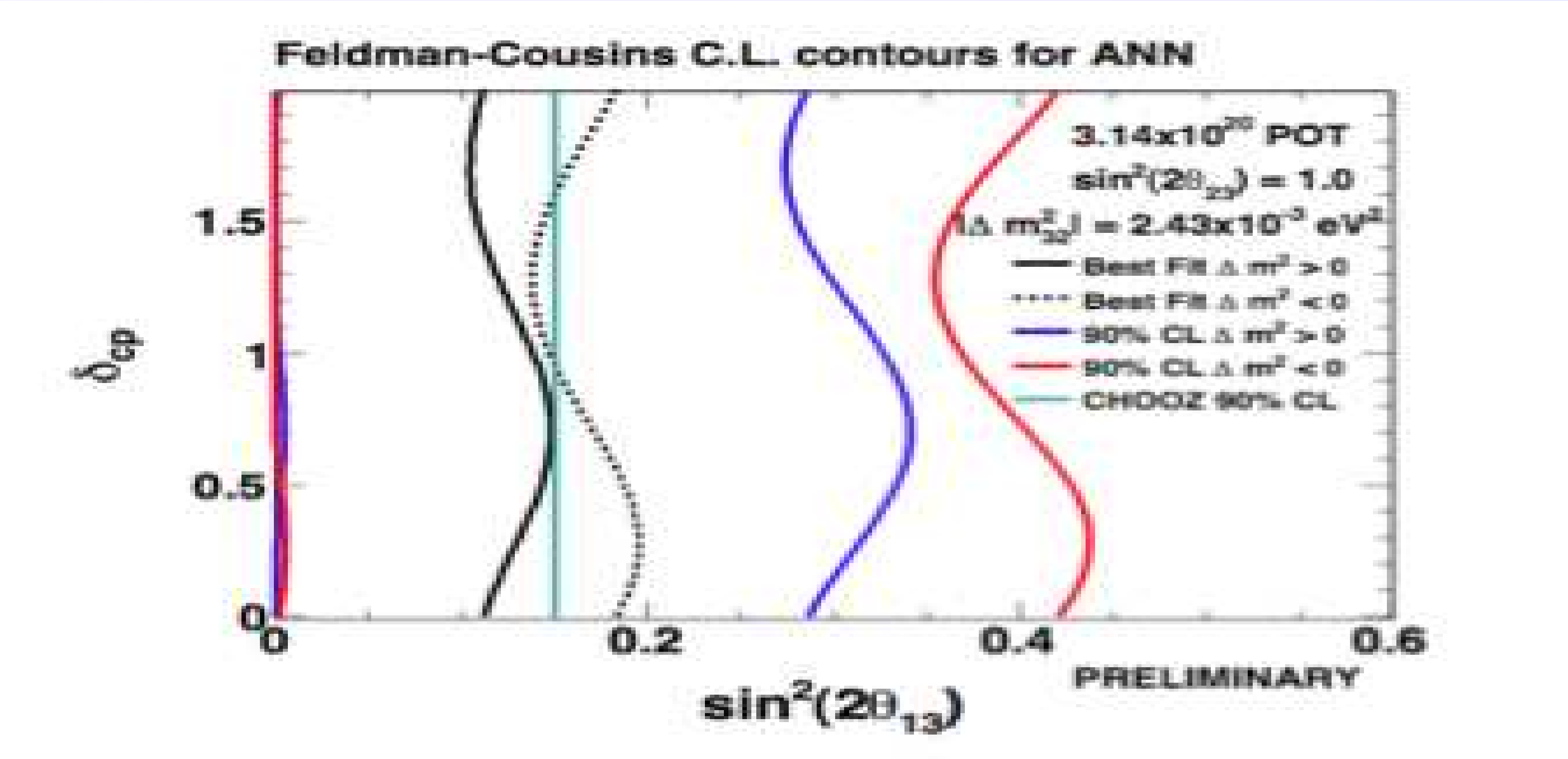
δ and the sign of Δm^2_{31} can be measured in long baseline appearance ν-oscillation experiments: they use a manmade flux of neutrinos with detectors located at 100s-1000s of km away.

These accelerator neutrino experiments search for $\nu_{\mu\ (e)} \longrightarrow \nu_{e\ (\mu)}$ appearance:

$$\boxed{P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31} L}{4E}}$$

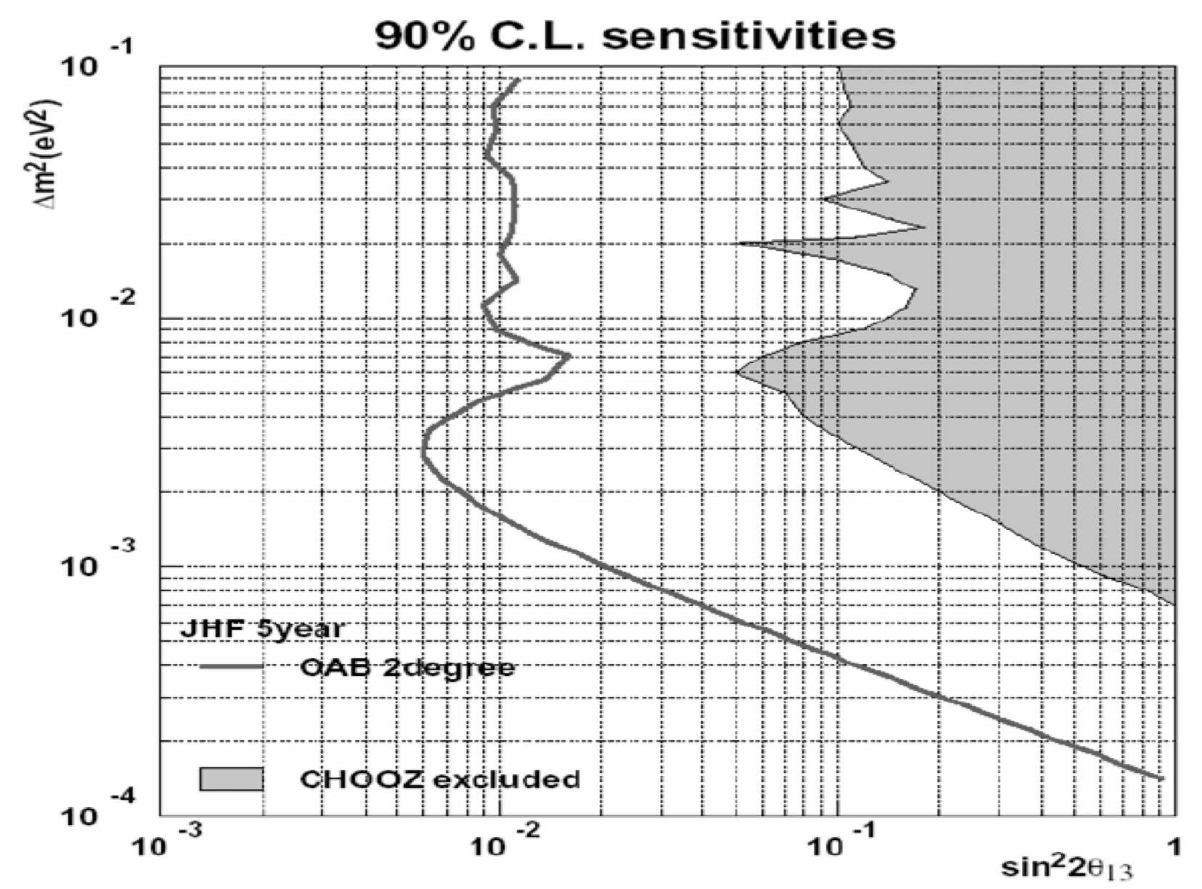
for subdominant matter effects and CPV.

- MINOS: NUMi beam sourced at Fermilab with iron magnetised detector at 735 km distance. It can improve the present sensitivity on θ_{13}.



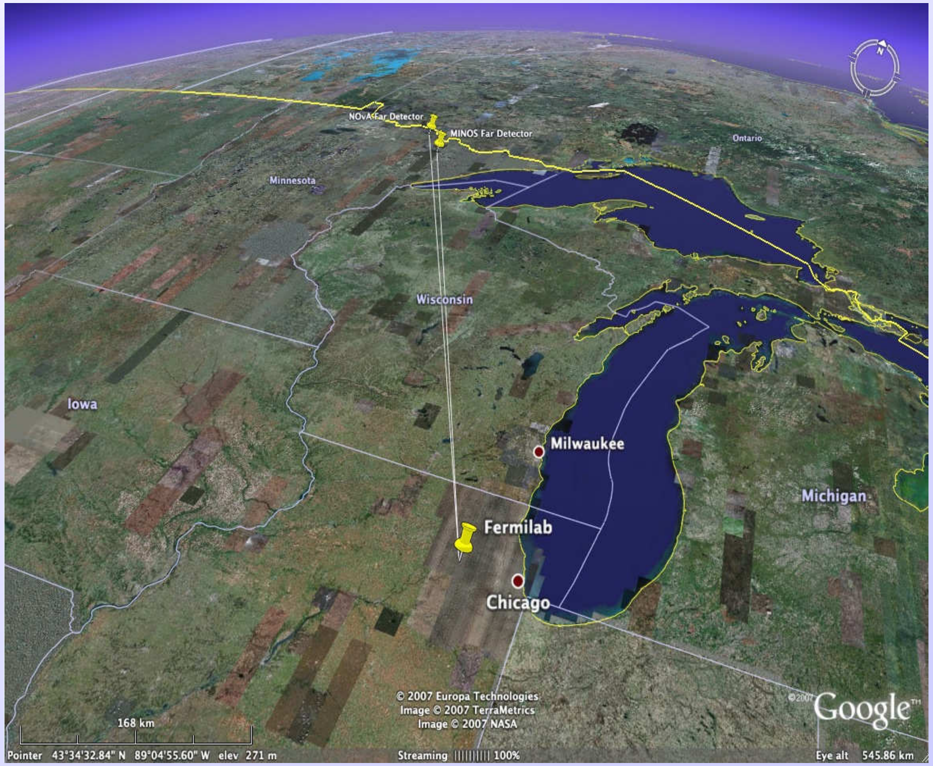
[M. Diwan, 0904.3706]

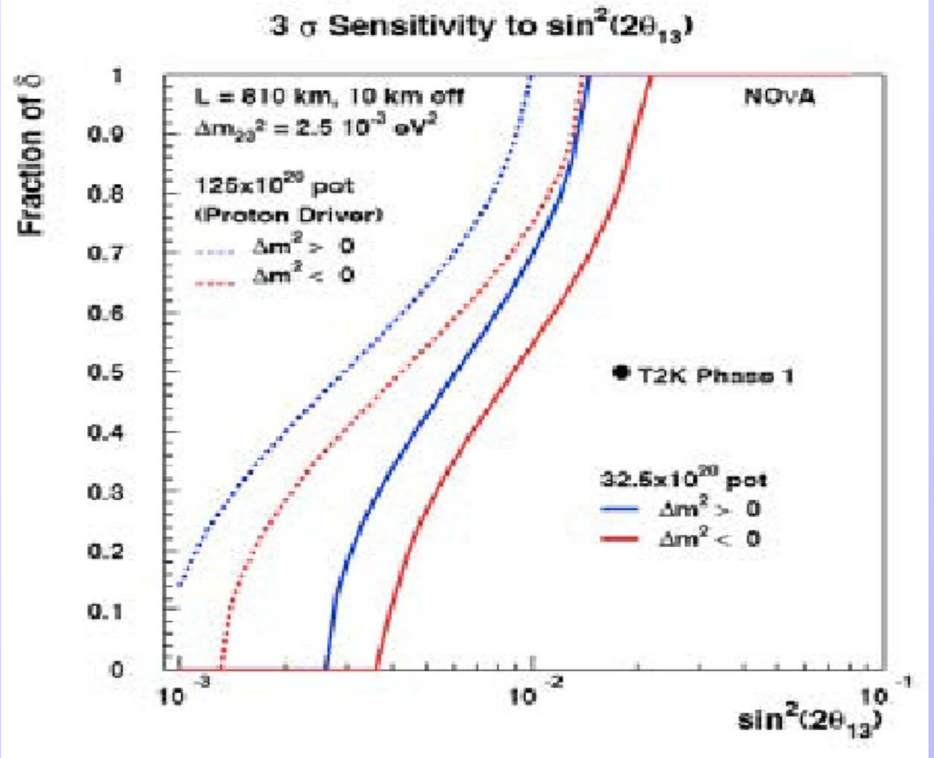
- T2K: ν_μ beam sourced at JPARC with Super-K detector at 300 km distance. Aimed at ν_e appearance.



[T2K LOI]

- NOνA: NUMi beam with scintillator detector at 800 Km distance (0.85^o OA). Aimed at ν_e appearance.





[http://www-nova.fnal.gov/]

[NOvA proposal]

These oscillations take place in matter (Earth), (e^-, p and n), $\Rightarrow$ **Matter effects violate CP**. A potential V in the Hamiltonian ($V = \sqrt{2}G_F(N_e - N_n/2)$) describes matter effects.

The probability can be approximated as (for no CPV):

$$\boxed{P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta_{13}^m L}{2}}$$

The mixing angle changes with respect to the vacuum case:

$$\boxed{\sin 2\theta_m = \frac{(\Delta m^2/2E)\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - V\right)^2}}}$$

and $\Delta_{13}^m = \sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - V\right)^2}$.

For $\Delta m^2 > 0$, the probability gets enhanced for neutrinos and suppressed for antineutrinos. Viceversa, for $\Delta m^2 < 0$. Matter effects imply that

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

If U is complex ($\delta \neq 0, \pi$), we have CP-violation:

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

A measure of CP- violating effects is provided by:

$$\boxed{A_{CP} = \frac{P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})}{P(\nu_l \to \nu_{l'}) + P(\bar{\nu}_l \to \bar{\nu}_{l'})} \propto J_{CP} \propto \sin\theta_{13} \sin\delta}$$

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 ($L \sim 200 \div 1500$ Km), of interest, the oscillation probability for $\nu_\mu \to \nu_e$, in 3-neutrino mixing case, is given by:

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

with $\tilde{J} \equiv c_{13} \sin 2\theta_{13} \, \sin 2\theta_{23} \, \sin 2\theta_{12}$ and $\Delta_{13} \equiv \Delta m_{31}^2/(2E)$.
$A \equiv \sqrt{2} G_F \bar{n}_e$.

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.] :

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

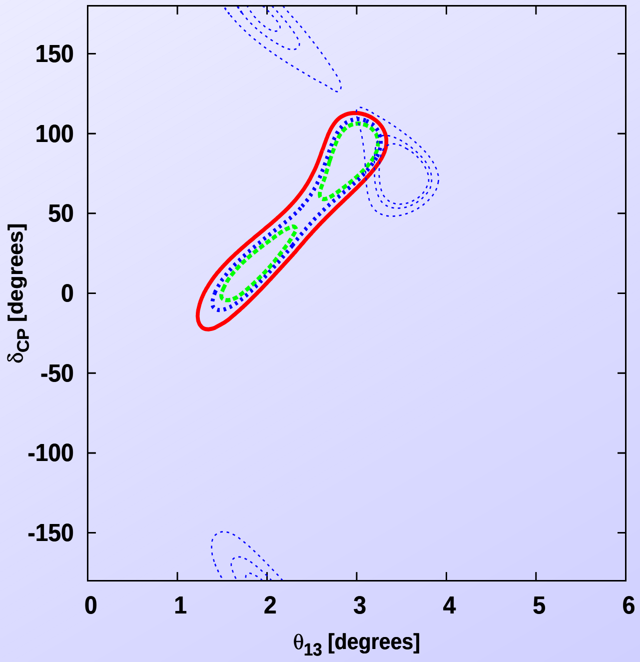
- $(\text{sign}(\Delta m^2_{13}), \delta)$ degeneracy [Minakata, Nunokawa]:

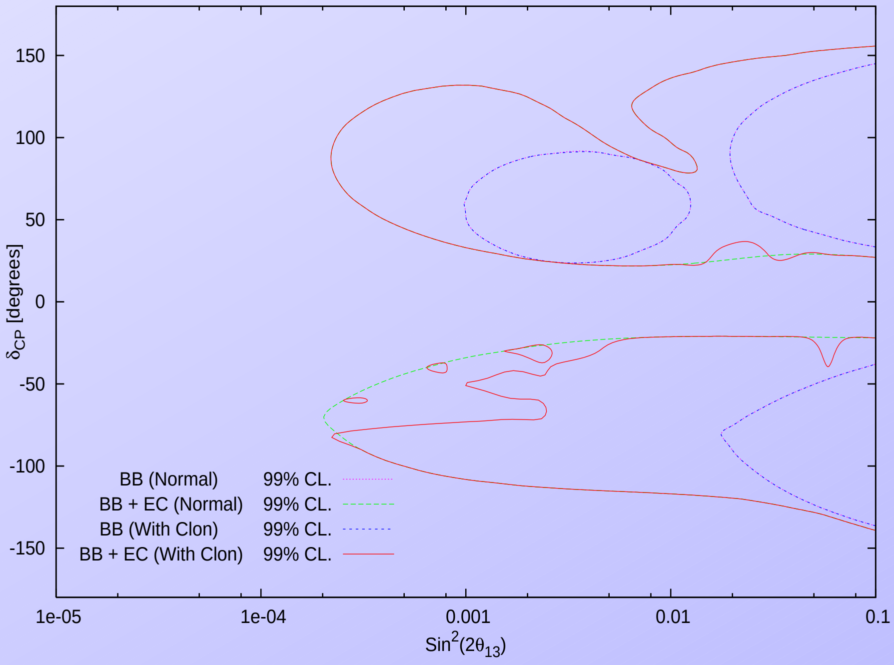
$$\begin{aligned} \delta' \quad & \quad \pi - \delta \\ \text{sign}'(\Delta m^2_{13}) \quad & \quad -\text{sign}(\Delta m^2_{13}) \end{aligned}$$

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

3 – Long baseline neutrino experiments: theoretical aspects

- degeneracies strongly affect the ability to determine the type of hierarchy and CP-violation





[J. Bernabeu et al., 2009]

4 – Long baseline neutrino experiments: experimental aspects

Future LBL experiments:

1. **Superbeams**: a very intense ν_μ beam. Intrinsic ν_e background. Typical energies: 100 MeV to few GeV $\longrightarrow$ WC, LiAr or scintillator detector.
2. **Beta-beams**: ν_e beams given by the β-decays of high-gamma ions. Same energy and type of detector as for superbeams.
3. **Neutrino factories**: ν_μ-ν_e beam from high-γ muons (20 GeV - 50 GeV). The detector needs to be magnetised to distinguish the signal from the background.

Flux and Baseline

- The statistics plays an important role in determining the physics reach.
- Backgrounds depend on the type of beam: superbeams have an intrinsic background which limits the reach for very small θ_{13}. Betabeams have a very “clean” beam but they might be limited in flux and energy. Neutrino factory beams could be very well controlled.
- The longer the baseline the stronger matter effects in the oscillations. This implies an increased sensitivity to the type of neutrino mass spectrum.
- The longer the baseline the higher the energy as the experiments try to increase the sensitivity by having the average energy at first oscillation maximum. Higher energy typically implies higher cross section but also impacts on the type of detector used (WC versus LiAr vs scintillator vs iron magnetised).

Detector

- The sensitivity of these experiments depends very much on the properties of the detector (backgrounds, energy resolution, size). It is critical to perform detailed simulations of these detectors.

- Superbeams and betabeams do not need magnetisation which is instead necessary for neutrino factory.
- The energy resolution and the threshold determine the ability to exploit the rich oscillatory pattern and therefore resolve degeneracies.
- The size and efficiency determine the statistics which can be reached, this is very critical for betabeams.
- Systematics errors might be the future limiting factors.

5 – Conventional and first generation superbeam experiments

- OPERA: from CERN to Gran Sasso where the OPERA detector is located. It looks for ν_τ appearance to check for the oscillation hypothesis of the atmospheric and accelerator neutrino disappearance.

- MINOS: NUMi beam sourced at Fermilab with iron magnetised detector at 735 km distance. It will determine $\Delta m^2_{\rm A}$ with ~ 10 % uncertainty. It can improve the present sensitivity on θ_{13}.

- Superbeams use a more intense ν_μ beam from $\pi(K)$ decays and search for ν_e appearance. They can be off-axis (nearly monochromatic beam and reduced backgrounds) (T2K and NOvA) or on-axis (wide-band beam).

6 – Betabeams

- In betabeams ions are accelerated to high gamma and then stored in a decay ring. From their beta decays a pure beam of ν_e is produced with a well known spectrum. [Zucchelli; Mezzetto; Huber et al.; Donini et al.; Bouchet et al.; Campagne et al.; Agarwalla et al.; Rubbia et al.; Cervera et al.]

- low energy option: $\gamma \sim 100$ with ^{6}He and ^{18}Ne and $L = 130$ km (CERN-Frejus). No sensitivity to matter effects.

- high energy: $\gamma \sim 400$ with longer distances. Improved sensitivity.

- high Q-value: use of ^{8}B and ^{8}Li for a high neutrino energy.

7 – A neutrino factory

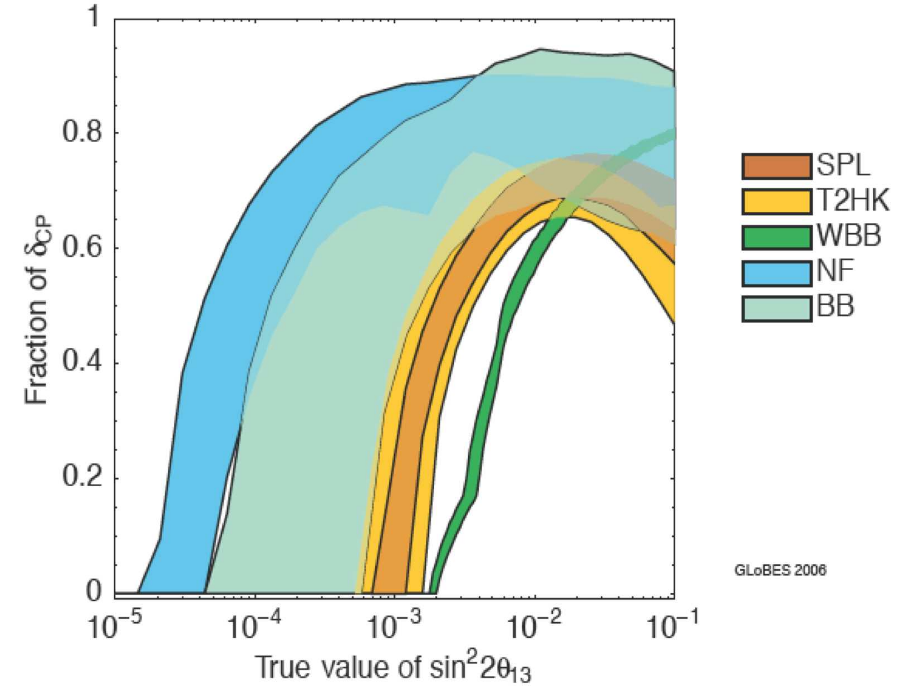
- The beam is sourced from high gamma μ decays, $\mu^- \longrightarrow e^-\bar{\nu}_e\nu_\mu$. It is necessary to detect wrong-sign muons.

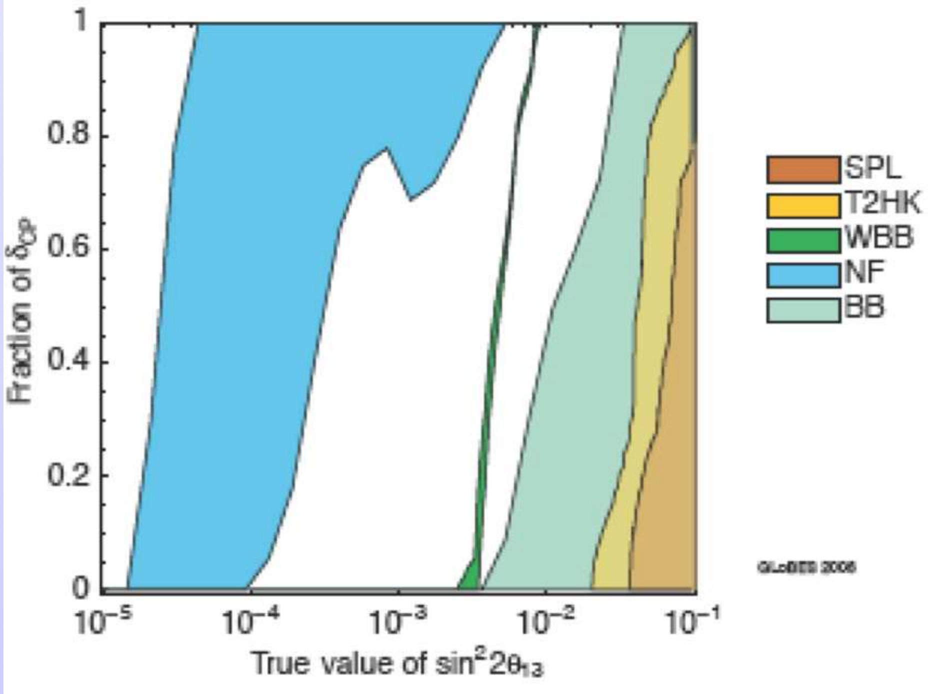
- High energy baseline scenario: Very long baselines and high energies ($E_\mu \sim 20 - 50$ GeV) .The baseline detector is a 50 kton iron magnetized detector located at 3000 km and 7000 km (magic baseline).

- LENF: For lower thresholds, it is possible to reduce the energy of the muons (streamlining the acceleration steps to $\sim 4\,\mathrm{GeV}$) and correspondingly the distance (Fermilab-Dusel, $L =$1480 km):

low-energy neutrino factory concept.

A summary of the sensitivity of some studied setups:





Sensitivity to CPV and the type of neutrino mass hierarchy [from the ISS study]

8 – Conclusions

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

- If θ_{13} is within reach of the upcoming generation of reactor and accelerator neutrino experiments, the quest for CP-violation and matter effects will soon be possible.

- The physics reach depends critically on the type of LBL experiment and on its experimental details (baseline, flux, detector). Various joint experimental-phenomenological international studies (EUROnu, LAGUNA, IDS) aim at making the analysis of these facilities more precise and reliable.