High energy long baseline neutrino experiments: from Superbeams to Neutrino Factory

NEU2012 Annual Meeting

CNRS - Paris

09 May 2011

Silvia Pascoli

IPPP - Durham University

Outline

1. Phenomenological aspects of long baseline neutrino oscillations

- Matter effects
- CPV
- **Degeneracies**

3. Future high energy LBL experiments

- Superbeams (LAGUNA-LBNO, LBNE)
- Betabeams and
  Neutrino Factory (HENF, LENF)

Long baseline experiments

Long baseline neutrino oscillation experiments (T2K, LBNE, EU superbeams, neutrino factories and beta beams) will aim at studying the subdominant channels

$$\nu_{\mu,e} \longrightarrow \nu_{e,\mu} \quad \bar{\nu}_{\mu,e} \longrightarrow \bar{\nu}_{e,\mu}$$

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

for negligible matter and CPV effects.

in order to establish

1. **the mass hierarchy**
2. **Leptonic CPV**
3. **non-standard effects.**

This probability depends crucially on θ_{13}

Matter effects

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

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

The mixing angle changes wrt vacuum

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

and the probability gets enhanced for neutrinos (antineutrinos) depending on the mass ordering.

CP-violation

A measure of CPV effects is given by

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

The full probability can be approximated as

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

Matter effects

CP violation

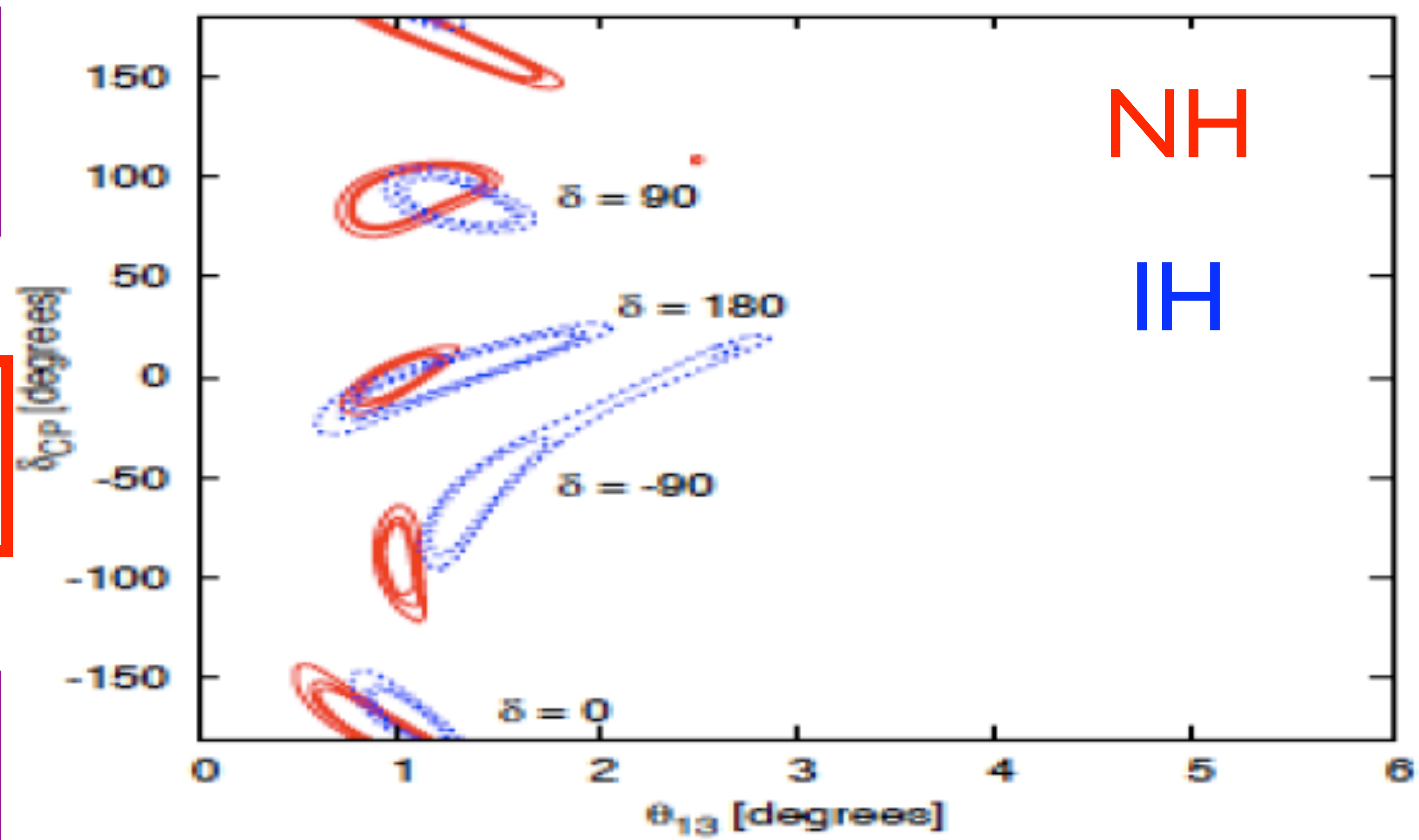
Degeneracies

The determination of CPV and the mass ordering is complicated by the issue of **degeneracies**: different sets of parameters which provide an equally good fit to the data (eight-fold degeneracies).

$$\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}$$

$$P(L/E) \quad \text{and} \quad \bar{P}(L/E)$$

$$\theta'_{13}, \delta', \mathrm{sgn}'(\Delta m^2_{31}), \theta'_{23}$$



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

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

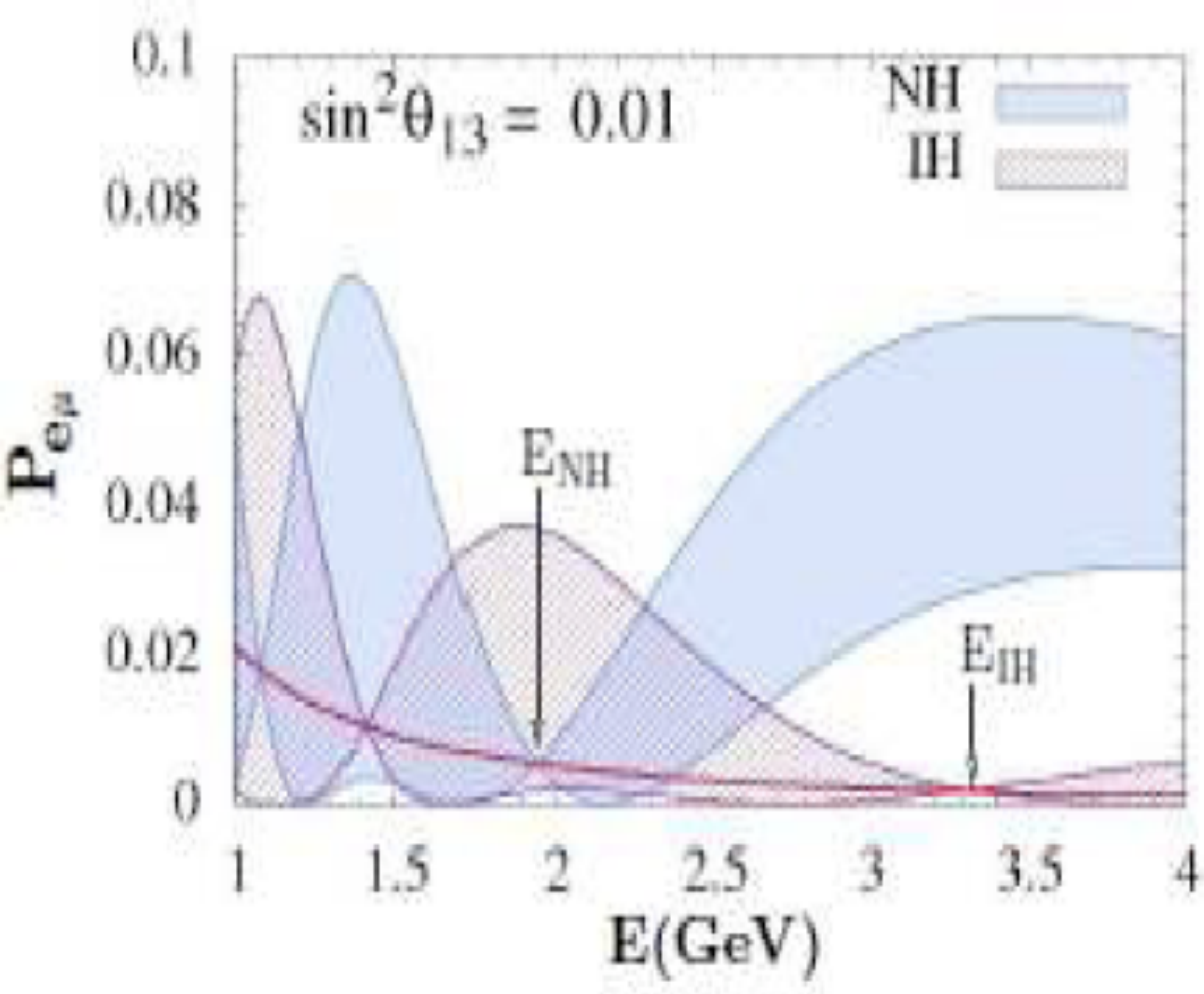
Having information at different L/E
(- more baselines,
- combine experiments, e.g. T2K+NOvA,
- use wide band beam)
can resolve this degeneracy.

- the octant of θ_{23} (low E data).

- sign(Δm^2_{31}) vs CPV (matter effects). In vacuum:

$$\delta' \to \pi - \delta \qquad \text{sign}'(\Delta m^2_{13}) \to -\text{sign}(\Delta m^2_{13})$$

This degeneracy is broken by matter effects.



Bimagic baseline at L=2540 km

Excellent sensitivity to the hierarchy

A. Dighe et al., 1009.1093; Raut et al. 0908.3741; Joglekar et al. 1011.1146

Future long baseline experiments

The baseline determines the energy of the beam: exploit first oscillation maximum for best sensitivity.

- Longer baseline > smaller flux

- Longer baseline > stronger matter effects

- The cross section scales with energy ($\sigma \propto E^2$ below GeV and $\propto E$ above)

- The energy impacts on the type of detector used.

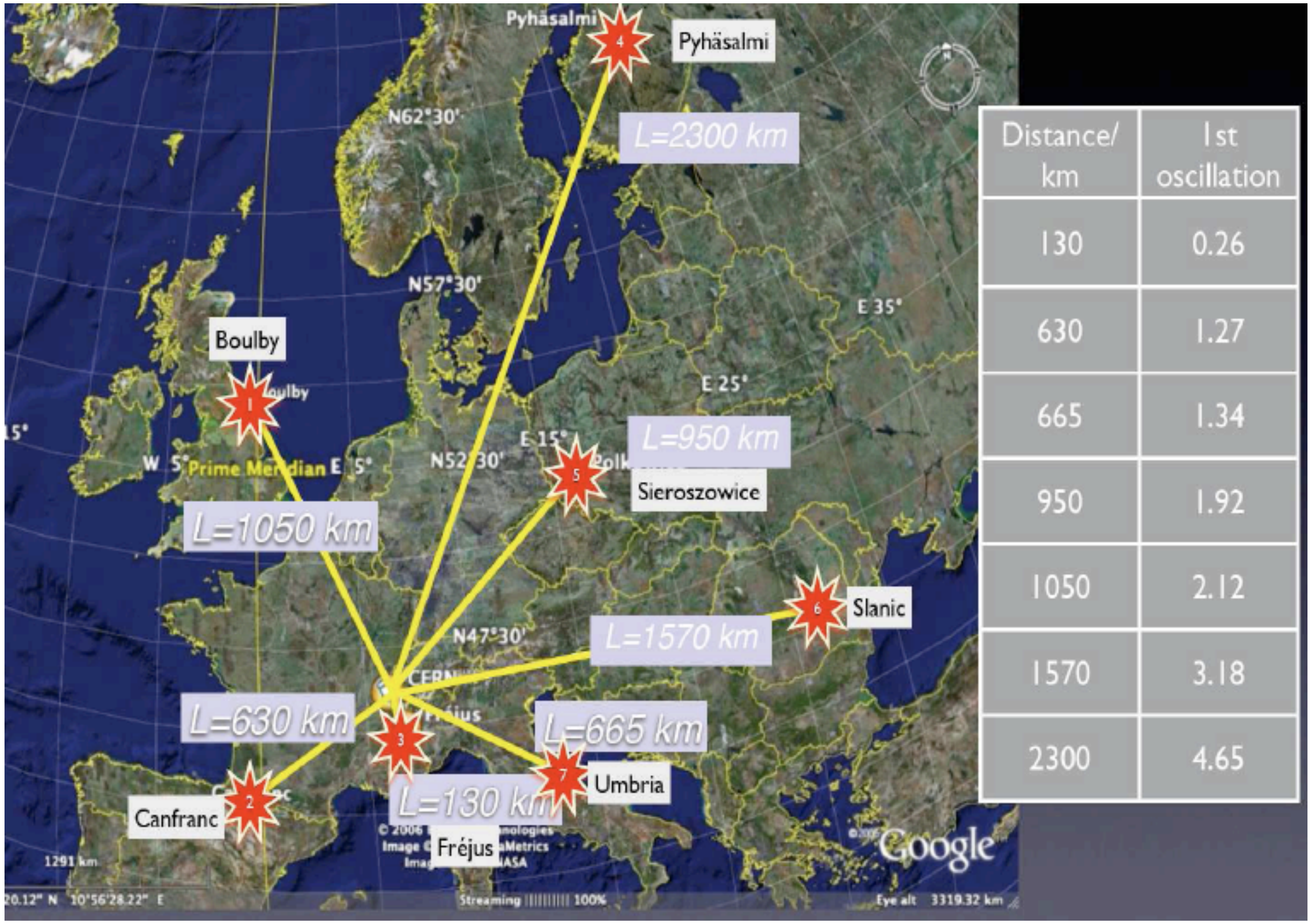
Each detector has different fiducial volume, threshold, energy resolutions, background reduction.

- **Superbeams**: neutrinos from pion decays with high fluxes and large detectors (T2K, LBNE, SPL in EUROnu, LAGUNA-LBNO) at L~100-2000 km. Intrinsic contamination of the beam.

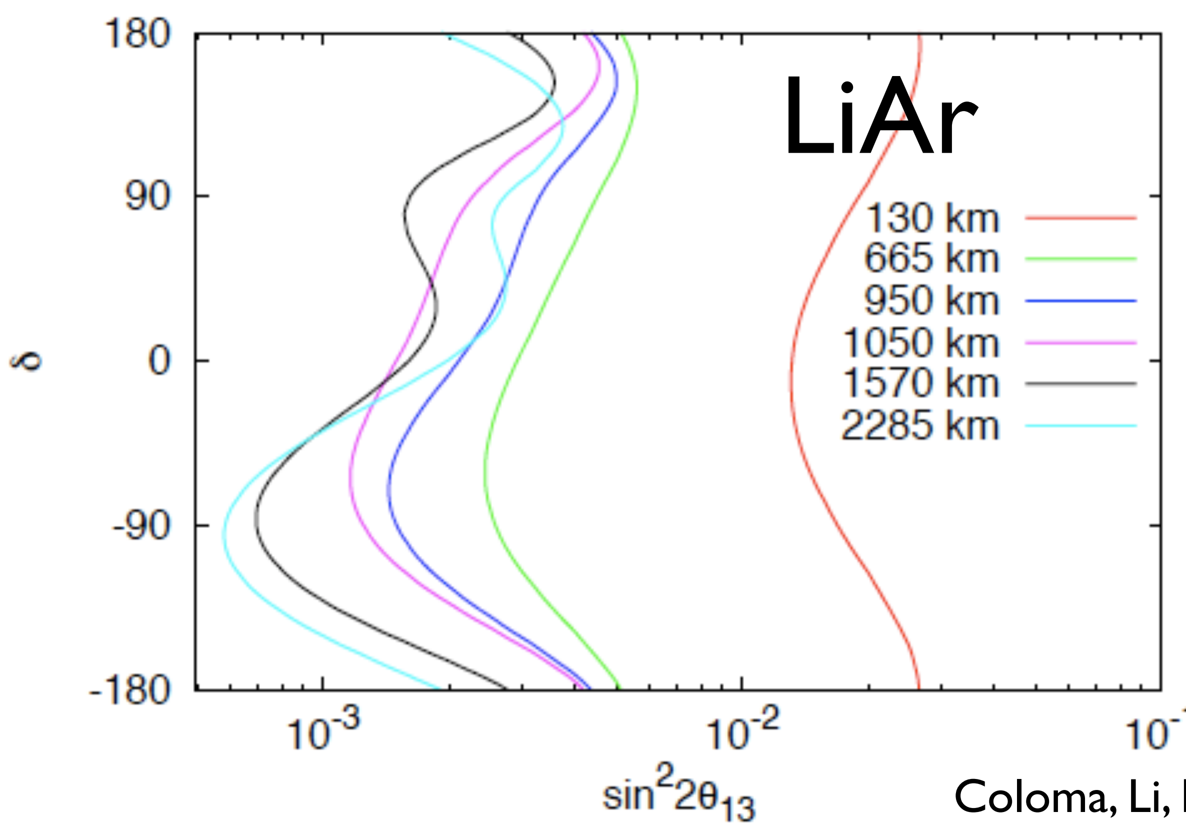
- **Betabeams**: electron neutrinos from beta decays at L~100-600 km. Pure beam but difficult to achieve high neutrino fluxes.

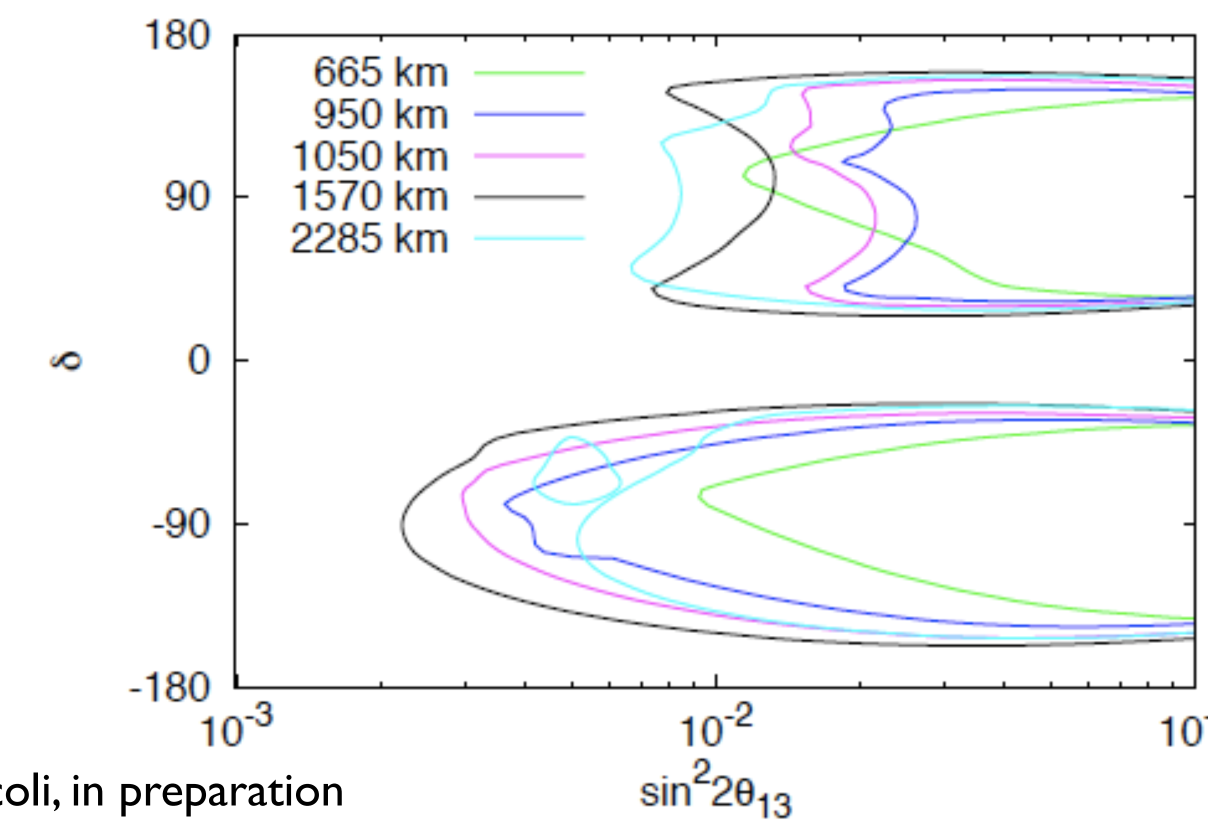
- **Neutrino factory** (HENF, LENF): neutrinos from muon decays at L~1500-7000 km. Pure beam and multiple oscillation channels but requires magnetised detector.

European options as part of LAGUNA and LAGUNA-LBNO.



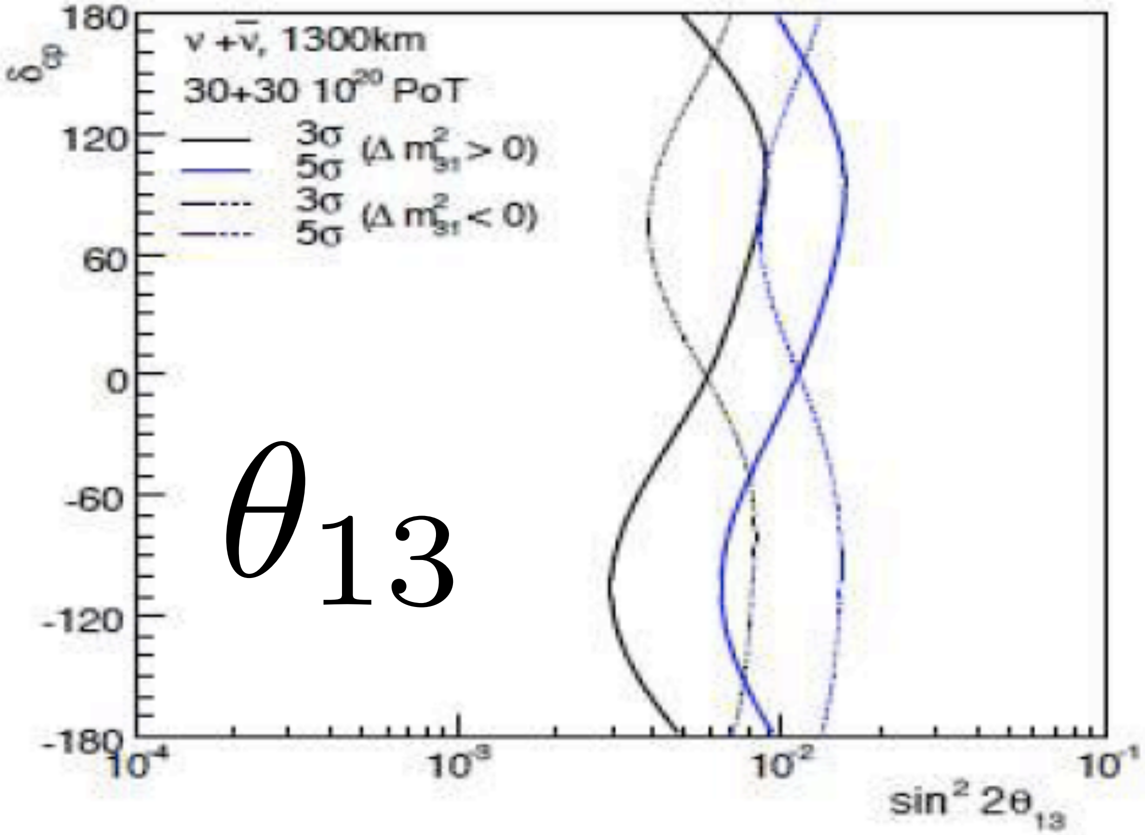
Distance/ km	1st oscillation
130	0.26
630	1.27
665	1.34
950	1.92
1050	2.12
1570	3.18
2300	4.65

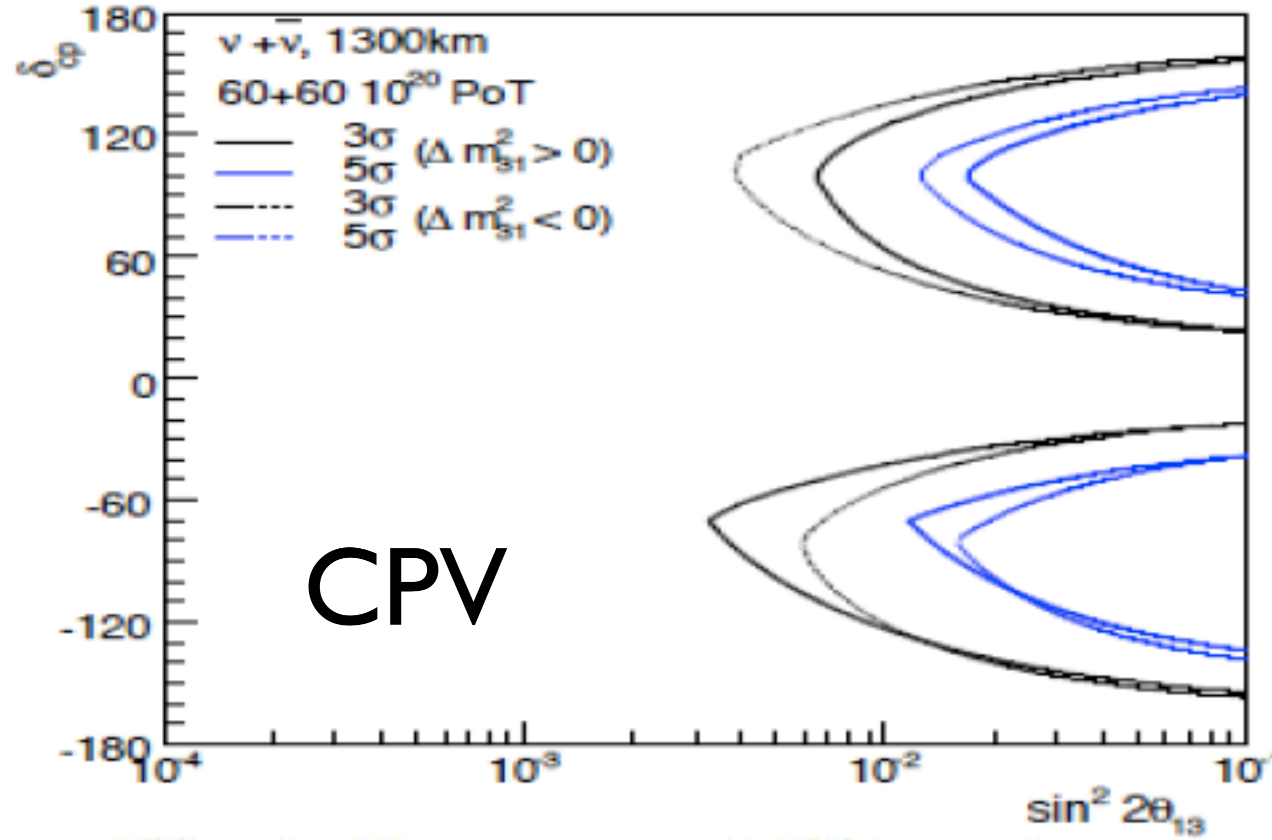




Coloma, Li, Pascoli, in preparation

LBNE with 1.2 MW; 300 kton WC or 100 kton LiAr

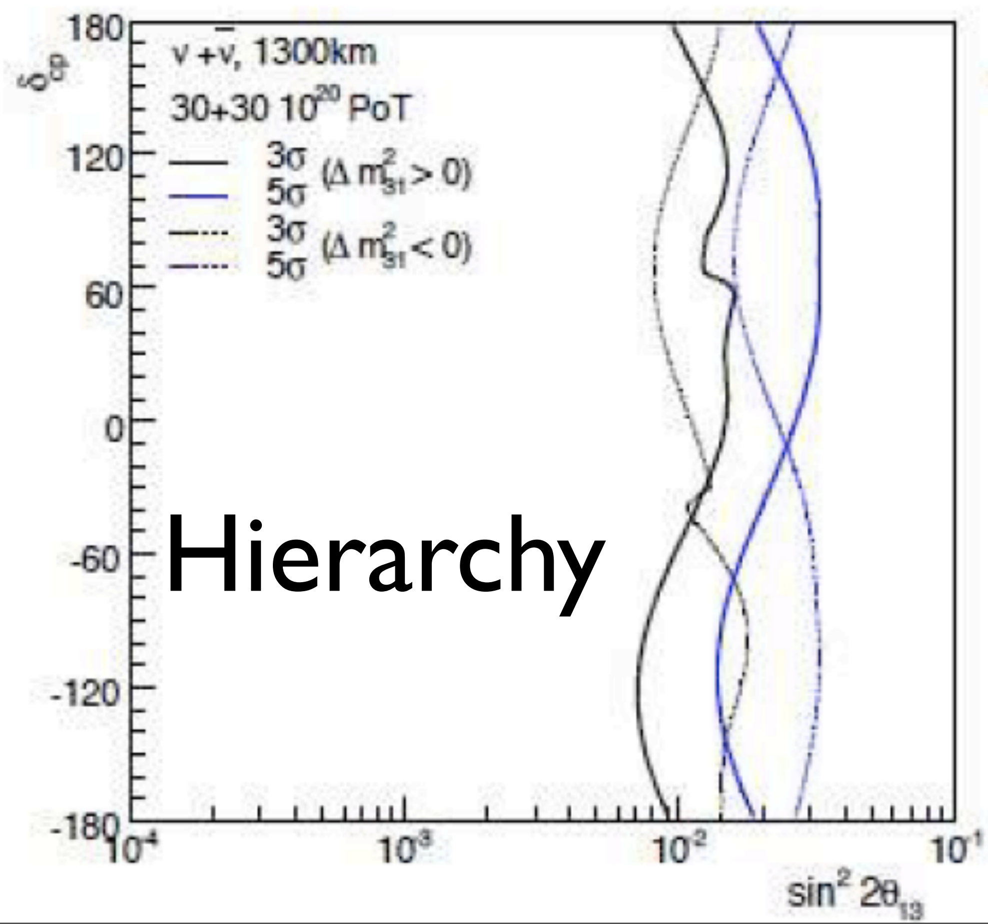




[V. Barger et al., 0705.4396]

300 kton WC, 5+5, 10% bckg syst, 1% sig syst,

$$\Delta m^2 = 2.7 \times 10^{-3}\ \text{eV}^2$$

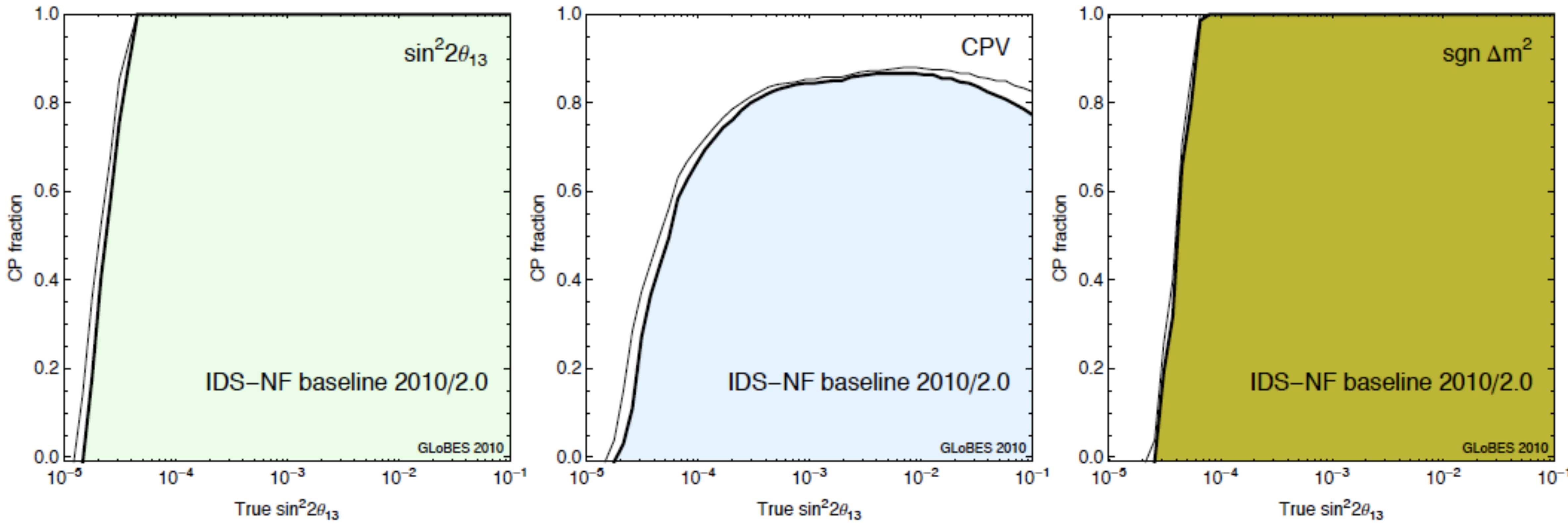


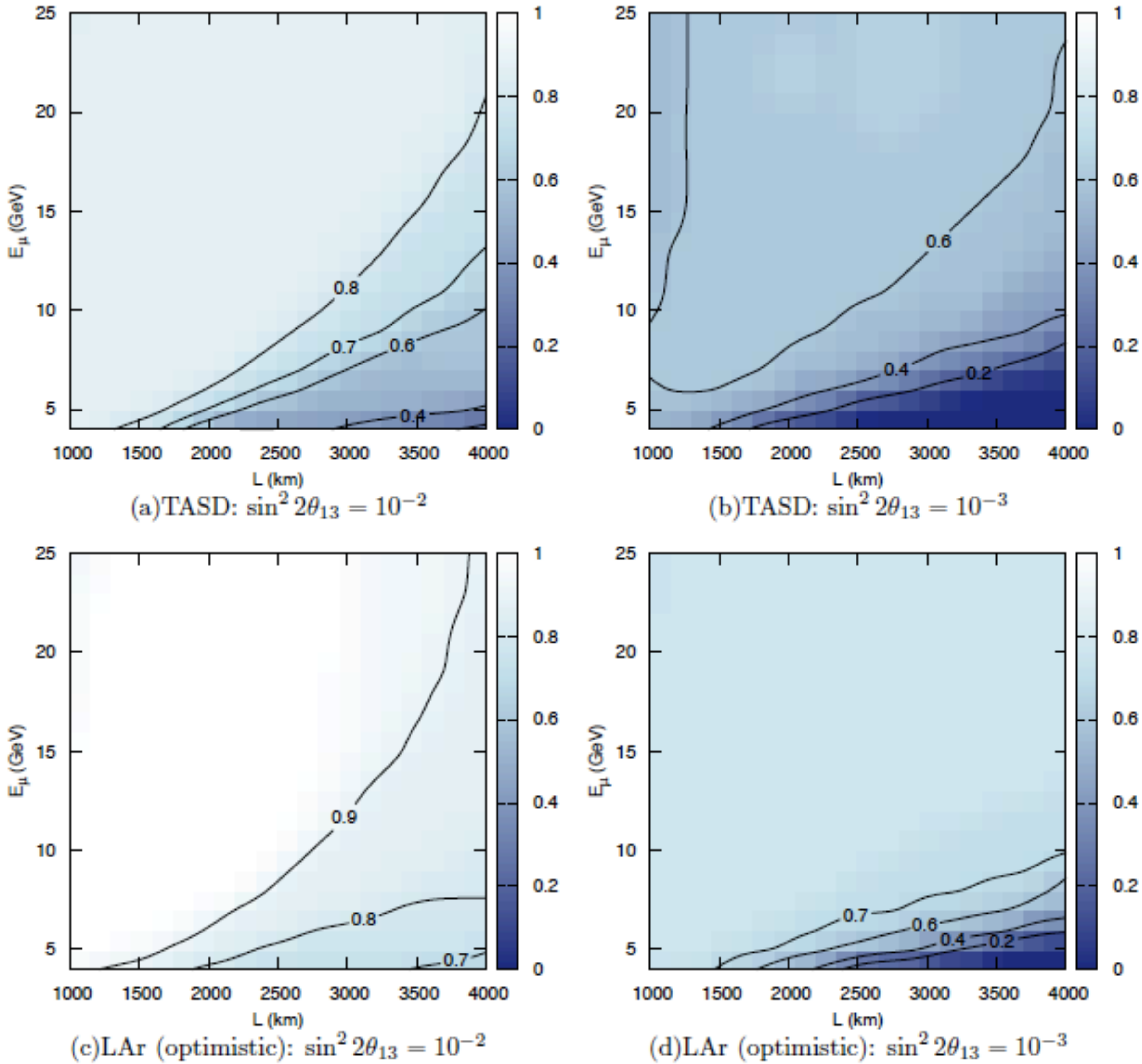
High energy betabeams

Various options have been considered for high gamma beta beams. They require an upgraded SPS or the LHC.

Neutrino factory

Neutrino factories (HENF, LENF) have an excellent reach thanks to very intense fluxes, very small backgrounds and wide beams (IDS study).





(a)TASD: $\sin^2 2\theta_{13} = 10^{-2}$

(b)TASD: $\sin^2 2\theta_{13} = 10^{-3}$

(c)LAr (optimistic): $\sin^2 2\theta_{13} = 10^{-2}$

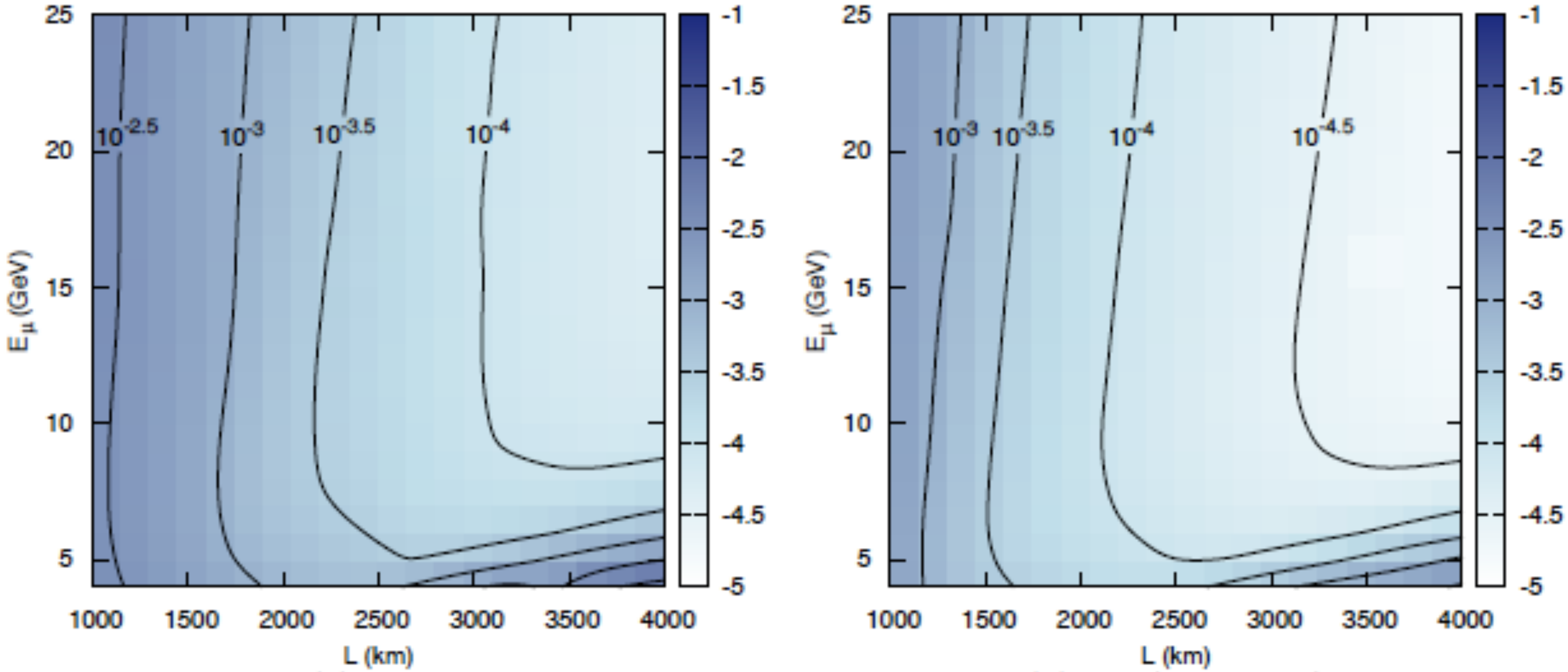
(d)LAr (optimistic): $\sin^2 2\theta_{13} = 10^{-3}$

Sensitivity to CP-violation.

Lines show the fraction of delta for which CPV can be determined.

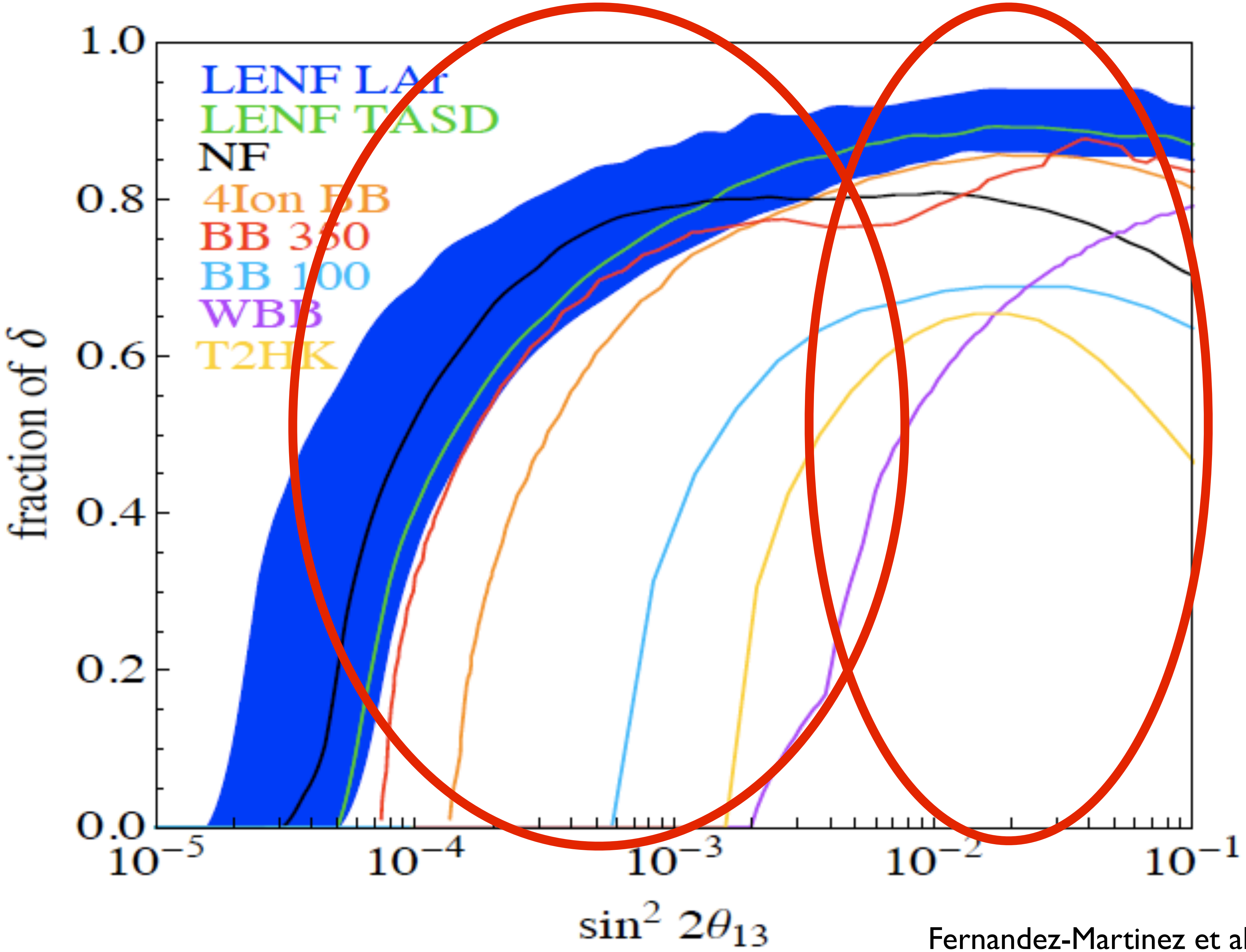
Excellent sensitivity for large θ_{13} rather independent from L and E and increase in sensitivity with energy for small θ_{13}.

P. Ballett et al. in preparation



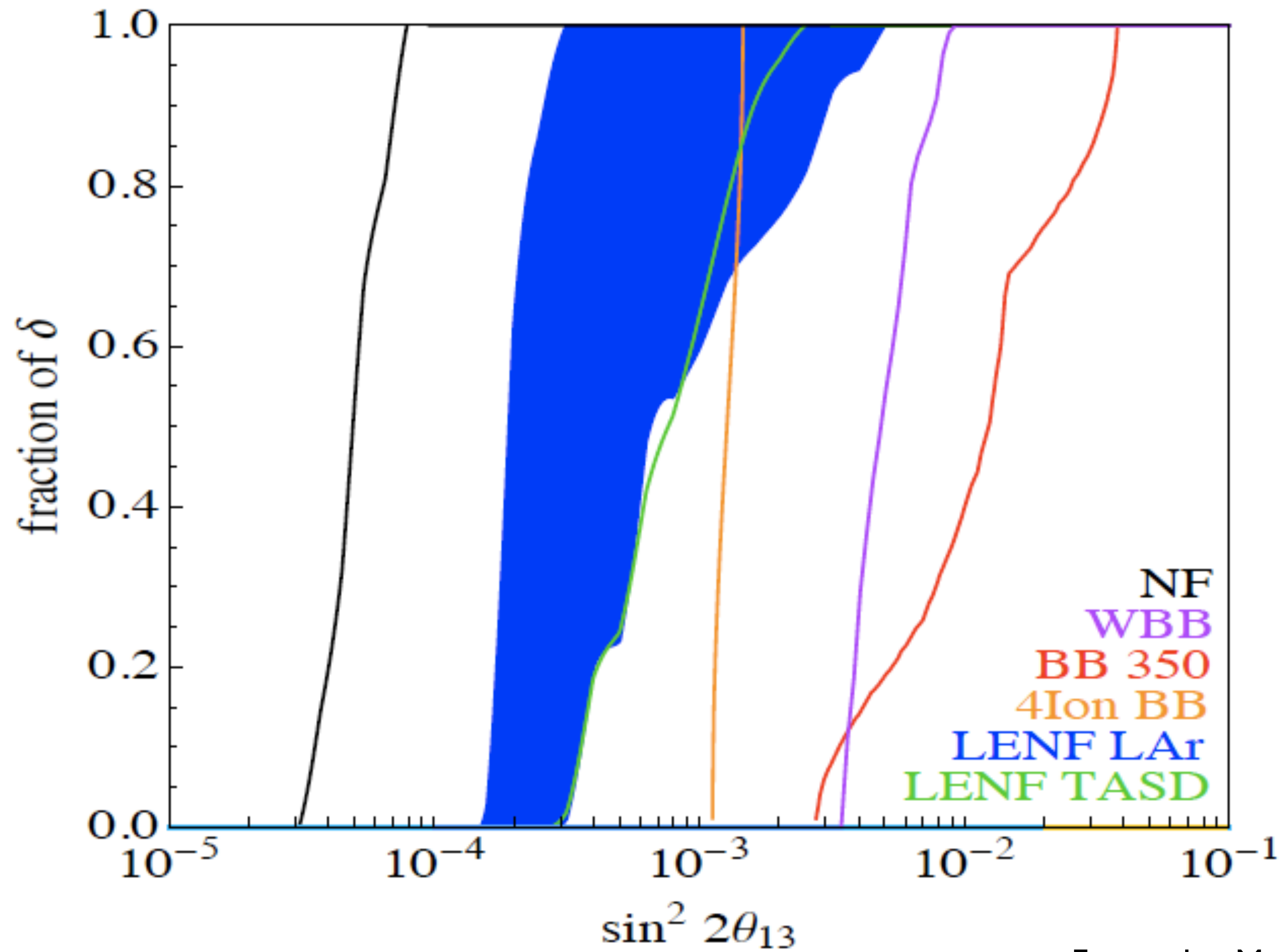
(a)TASD (b)LAr (optimistic)

The sensitivity to the mass hierarchy increases with distance and energy, due to stronger matter effects.



Fernandez-Martinez et al., 0911.3776

Depending on the values of θ_{13} and on the precision required, **different experimental setups and optimisations are required.**



Fernandez-Martinez et al., 0911.3776

Similar considerations hold also for the type of mass ordering, with long baselines (and consequently high energies) preferred for small θ_{13}.

Going beyond the standard 3 neutrino mixing scenario

A plethora of hints of physics beyond 3 neutrino mixing and SM interactions is present.

MINOS antineutrino disappearance data

LSND appearance experiment

MiniBooNE neutrino and antineutrino results

Reactor anomaly

If confirmed, it needs a radical shift in understanding of neutrino and physics BSM and requires a reanalysis of future neutrino oscillation experiments (use near detectors for SBL physics).

Conclusions

- In the past few years, the neutrino oscillation parameters have been measured with precision.

- The present and future experiments are going to greatly improve the precision and search for theta13. The value of theta13 plays a crucial role in shaping the future nu oscillation programme.

- Superbeams, Betabeams and Neutrino Factories have excellent sensitivities to CPV and the neutrino mass hierarchy. The physics reach depends critically on the parameters of the setups.