Accelerator neutrinos for long baseline experiments and LAGUNA

General LAGUNA meeting

Aussois - 08 September 2010

Silvia Pascoli

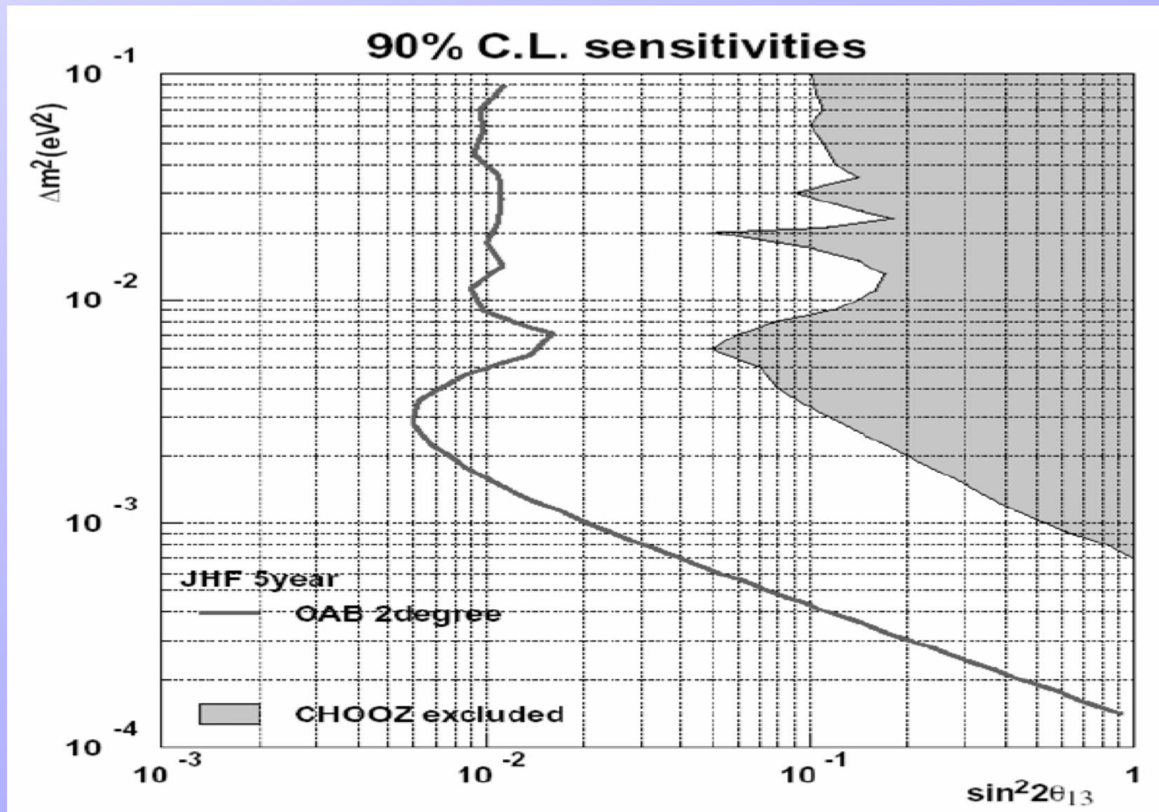
IPPP - Durham University

Based on work in collaboration with Tracey Li and Pilar Coloma.

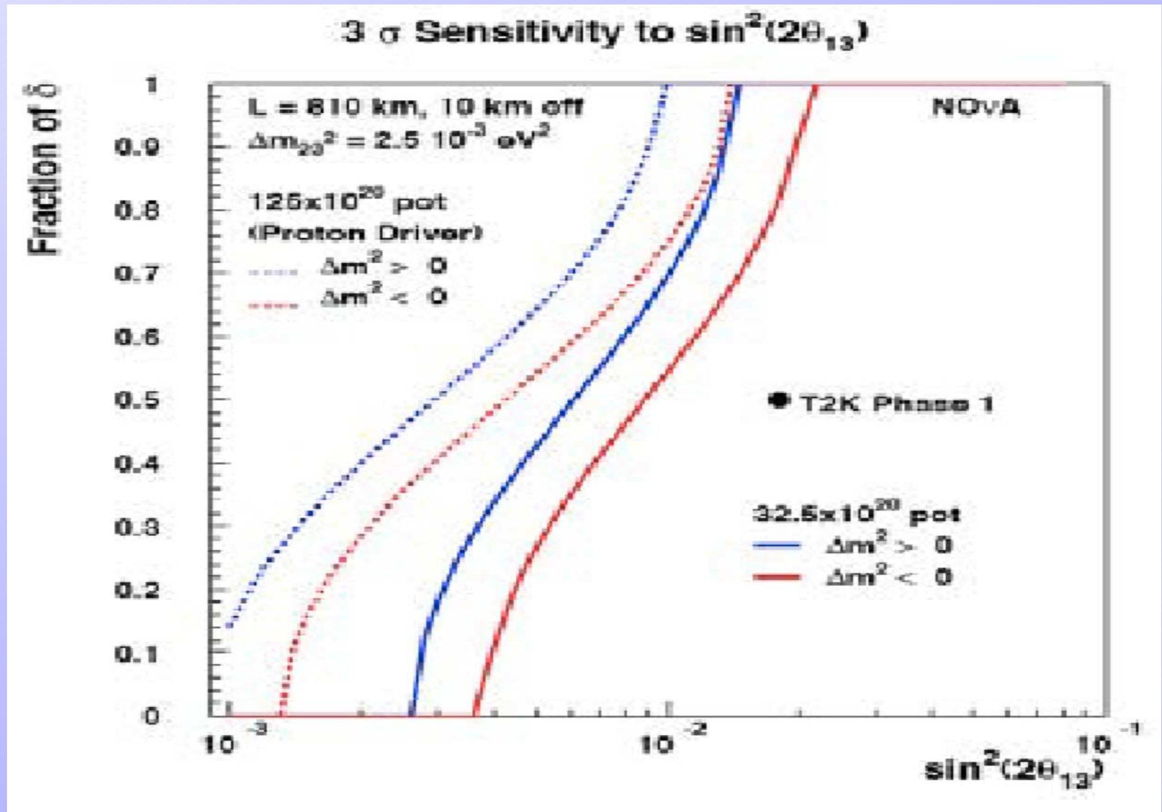
Next generation accelerator neutrino experiments search for $\nu_\mu \to \nu_e$ appearance, **hunting for** θ_{13}:

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

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

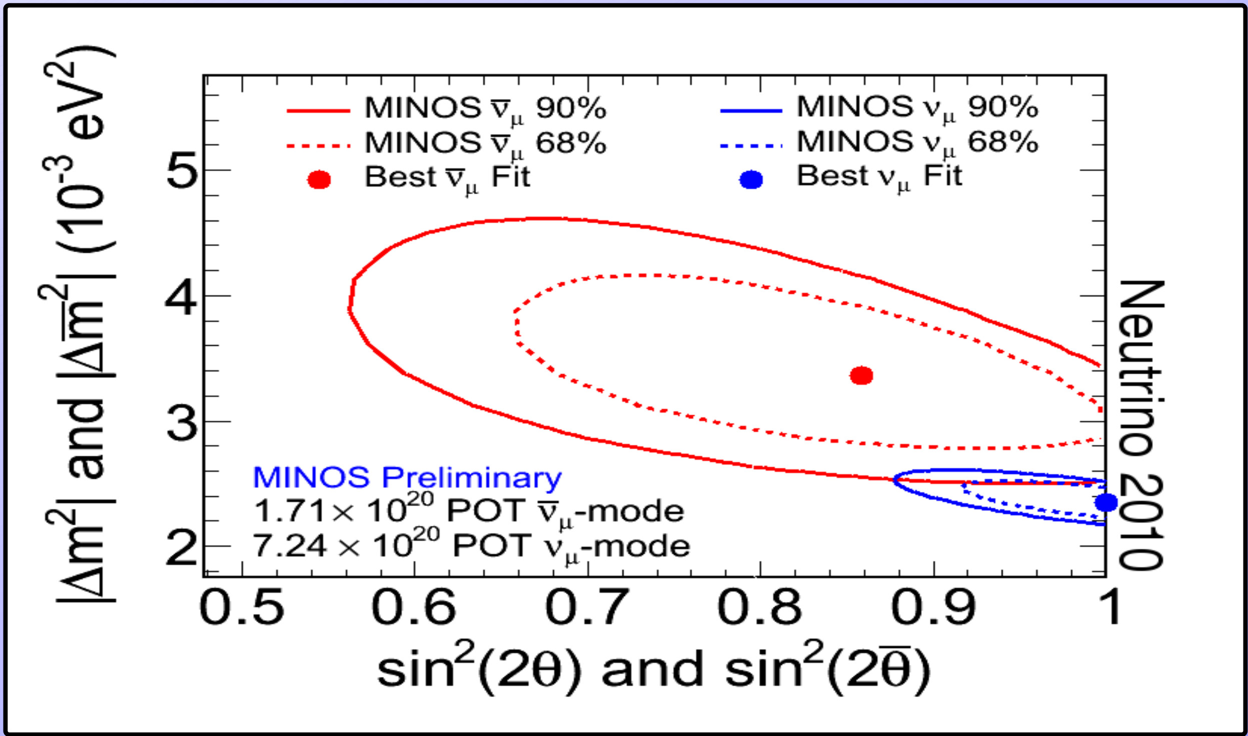


- NOνA: NUMi beam with TASD detector at 800 Km distance.

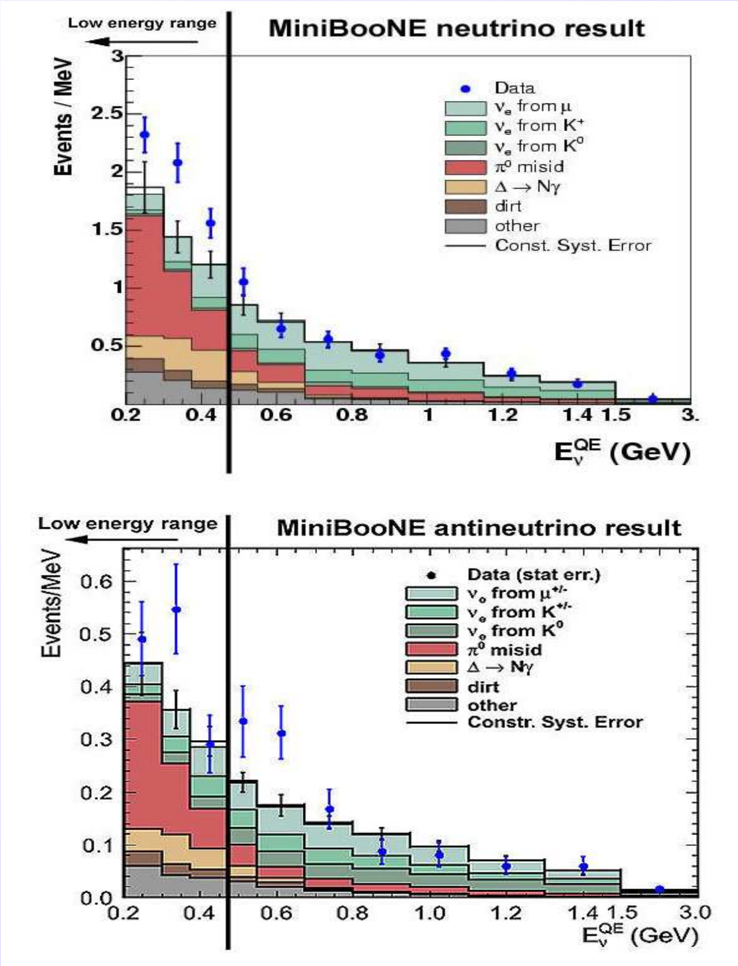


Is the 3-neutrino mixing picture correct?

MINOS reported different oscillation probabilities in the neutrino and antineutrino muon disappearance channels. This can be translated into different Δm^2.



A possible explanation, if confirmed, requires new types of matter effects which would indicate new physics beyond the SM.



http://www-boone.fnal.gov/

MiniBooNE has recently reported also the results on the antineutrino run.

- The neutrino run shows an excess at low energy. Background?
- The antineutrino data has low statistics but might indicate an excess compatible with LSND. Needs future confirmation.

These results might indicate the existence of sterile neutrinos, NSI, low energy physics BSM.... Experimentally it is important to have multiple channels and/or experiments, one or more near detectors...

1 – What next?

A- In the next future a **positive signal** for θ_{13} will open the possibility to search for CP-violation and matter effects in LBL experiments.

B- If **no positive signal**, hunt for smaller θ_{13}.

In either case, more sensitive experiments are needed.

1. **Medium term: Superbeams**: a very intense ν_μ beam. Intrinsic ν_e background.
2. **Long term:**

   i) Beta-beams: ν_e beams given by the β-decays of high-gamma ions.

   ii) Neutrino factories: ν_μ-ν_e beam from high-γ muons (few GeV - 50 GeV).

Matter effects

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):

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

The mixing angle changes with respect to the vacuum case:

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

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

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

CP-violation

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

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

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

The determination of δ and of the type of hierarchy is made more difficult by the presence of degeneracies, i.e. different sets of parameters which provide an equally good fit to the data.

It is necessary to disentangle

true CP-V effects due to the δ phase

from the ones induced by matter.

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:

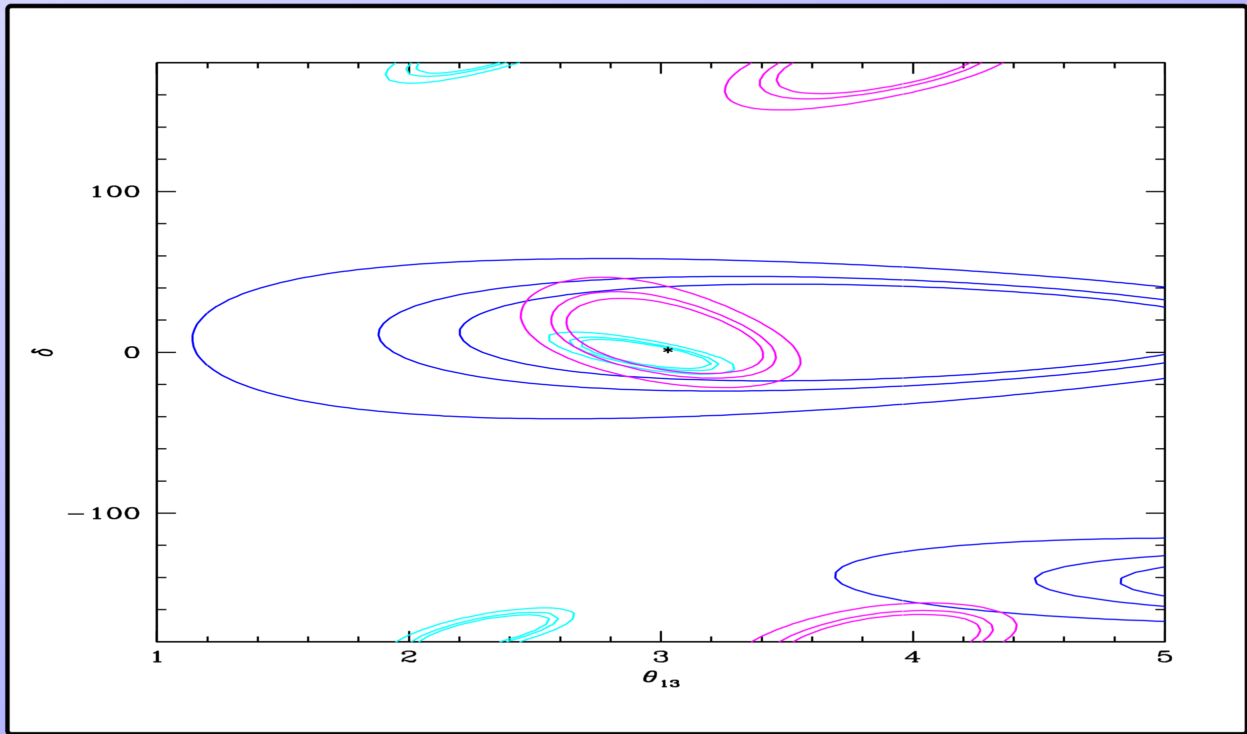
$$
\begin{aligned}
P(\bar{P}) \simeq \quad & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2} \\
& + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \sin \frac{(A \mp \Delta_{13})L}{2} \cos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

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

For large θ_{13} the intrinsic degeneracy is located at [Koike et al.; Burguet-Castell et al.]:

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

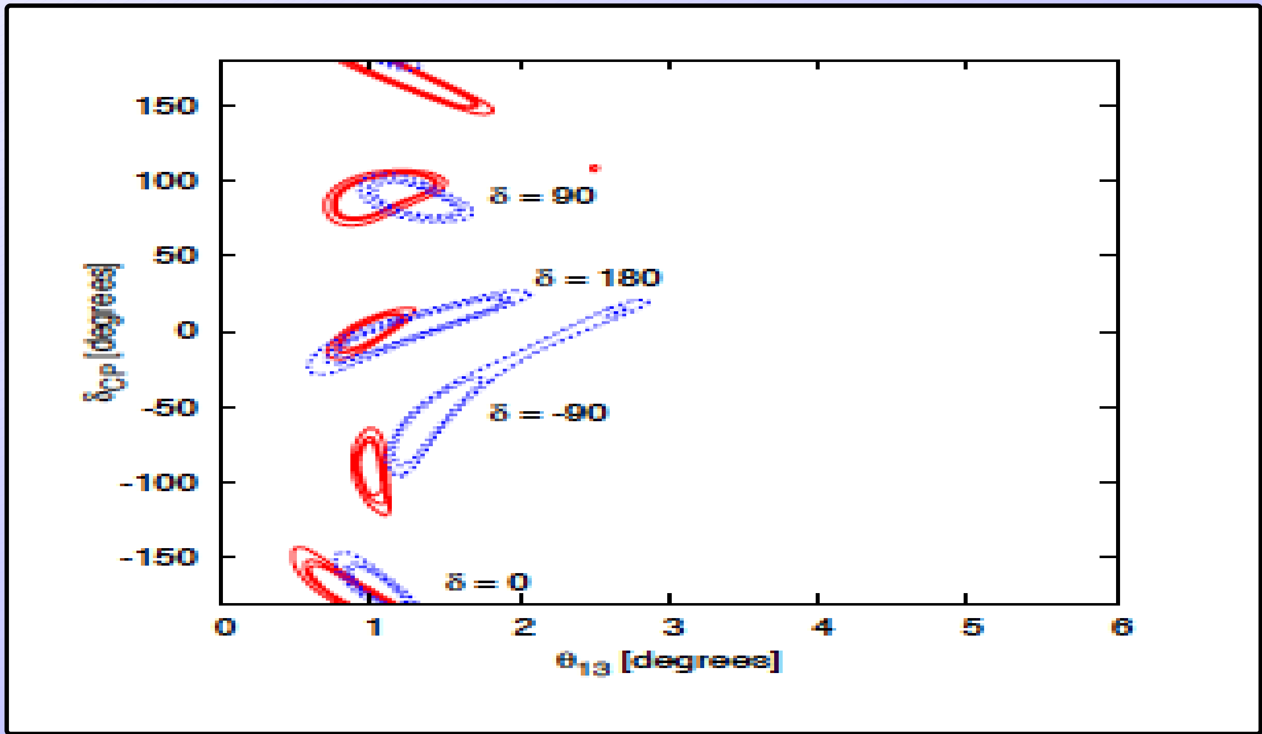
It is energy dependent.



[Geer et al., 2006]

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

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



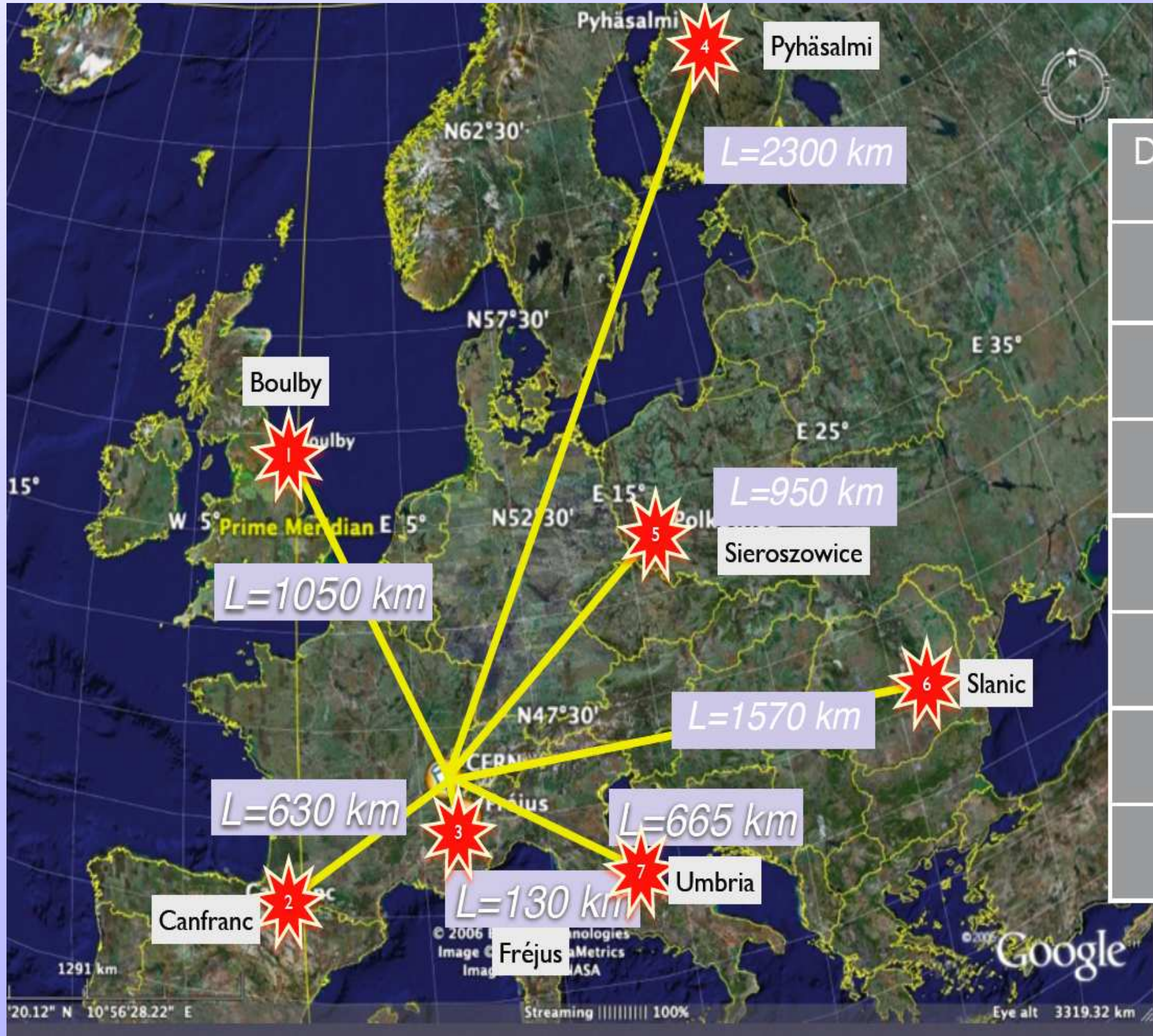
[Bernabeu et al., 2009]

It is broken by matter effects.

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

The octant degeneracy is usually very hard to resolve. **The information at low energy is very important.**

2 – Synergy between Megaton detectors and long baseline oscillations

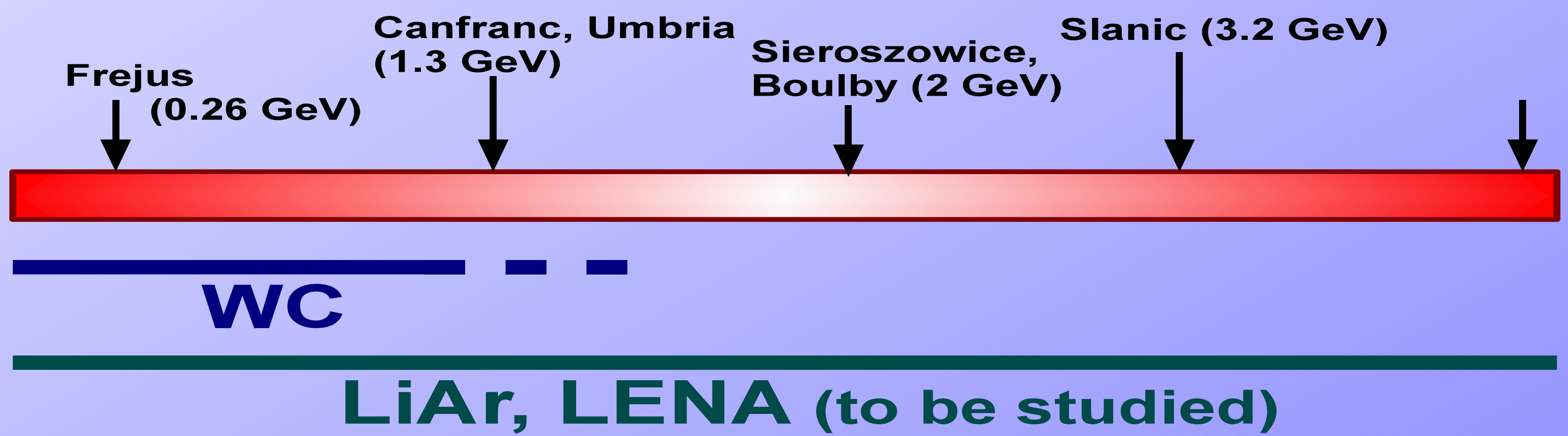


Distance/ km	1st oscillation
130	0.26
630	1.27
665	1.34
950	1.92
1050	2.12
1570	3.18
2300	4.65

Thanks to A. Rubbia

The baseline (from CERN, RAL or Germany) determines the energy of the beam: need to be on first oscillation maximum to achieve large statistics.

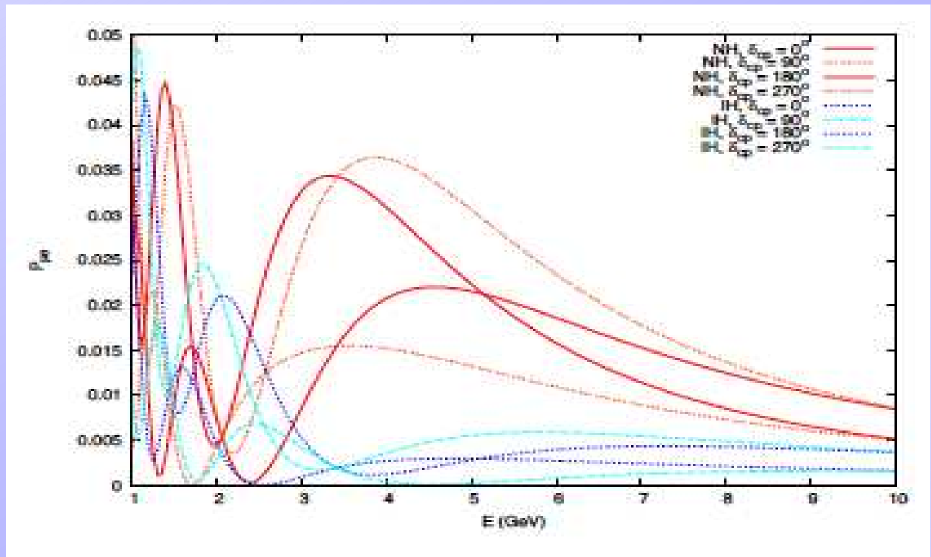
- Longer baseline $\longrightarrow$ smaller flux. Need for large detectors and high power.
- **The cross section scales with the energy** ($\sigma \propto E^2$ at low energy and $\propto E$ above GeV): higher energy $\Rightarrow$ higher σ $\Rightarrow$ larger number of events.
- **The energy impacts also on the type of detector used**



Each detector has different fiducial volume, efficiency, energy resolution, background reduction. This plays an important role on the performance.

• **The longer the baseline the stronger matter effects in the oscillations**. This implies an increased sensitivity to the type of neutrino mass spectrum and a better resolution of the degeneracies.

• The case of $L = 2540\ \mathrm{Km}$. Enhancement of the neutrino oscillation probability for NH and suppression of the dependence on δ for IH.



[Raut et al.]

$\Rightarrow$ Excellent sensitivity to the type of mass hierarchy.

3 – Simulation of a superbeam from CERN to Pyhäsalmi

- **The beam:** We used the fluxes provided by A. Longhin for a beam aimed at Pyhäsalmi. Intrinsic ν_e background of 0.5%. See Longhin's talk.

- **The baseline:** 2300 Km, corresponding to a first-oscillation maximum energy of 4.65 GeV. This means that most of the events are in the DIS region.

- **The detectors:**

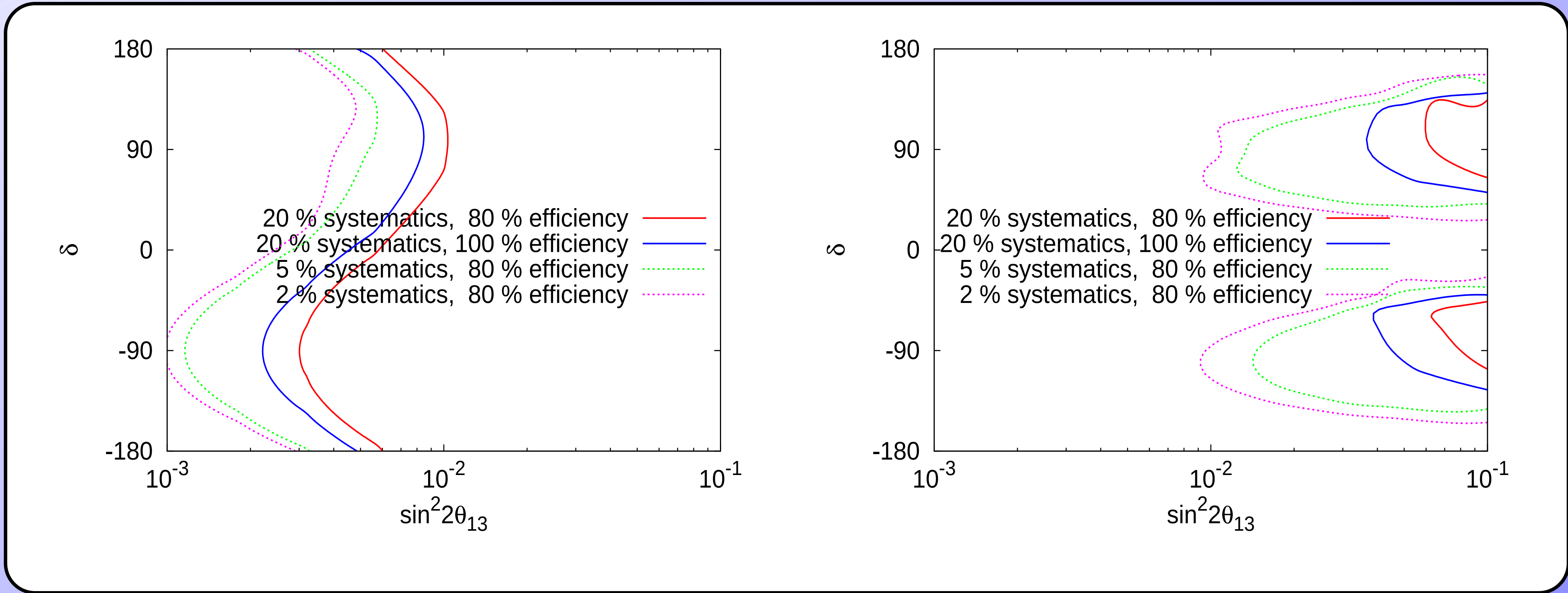
Detector	Size	Efficiency	Energy resolution	NC bckgr
MEMPHIS	440 kton WC	40% all	$(1.7 + 0.7/\sqrt{P_\mu})$% $(0.6 + 2.6/\sqrt{P_e})$%	5% and 0
GLACIER	100 kton	80% all	migration matrices*	0.5%
LENA	50 kton	90% all	5% all	5% and 0

* Thanks to L. Esposito and A. Rubbia.

- **The systematic error:** flat 5% on signal and background.

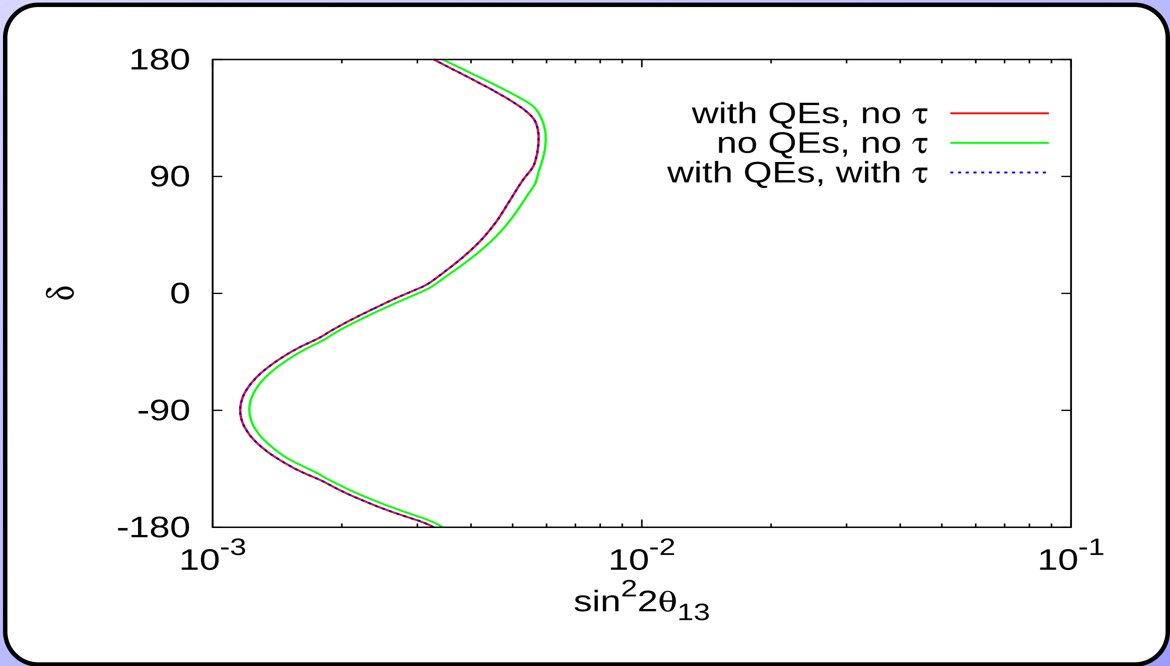
The impact of the systematic error.

The systematic error is kept at 5% on the signal and varied on the background for LiAr detector.



The ν_τ appearance channel.

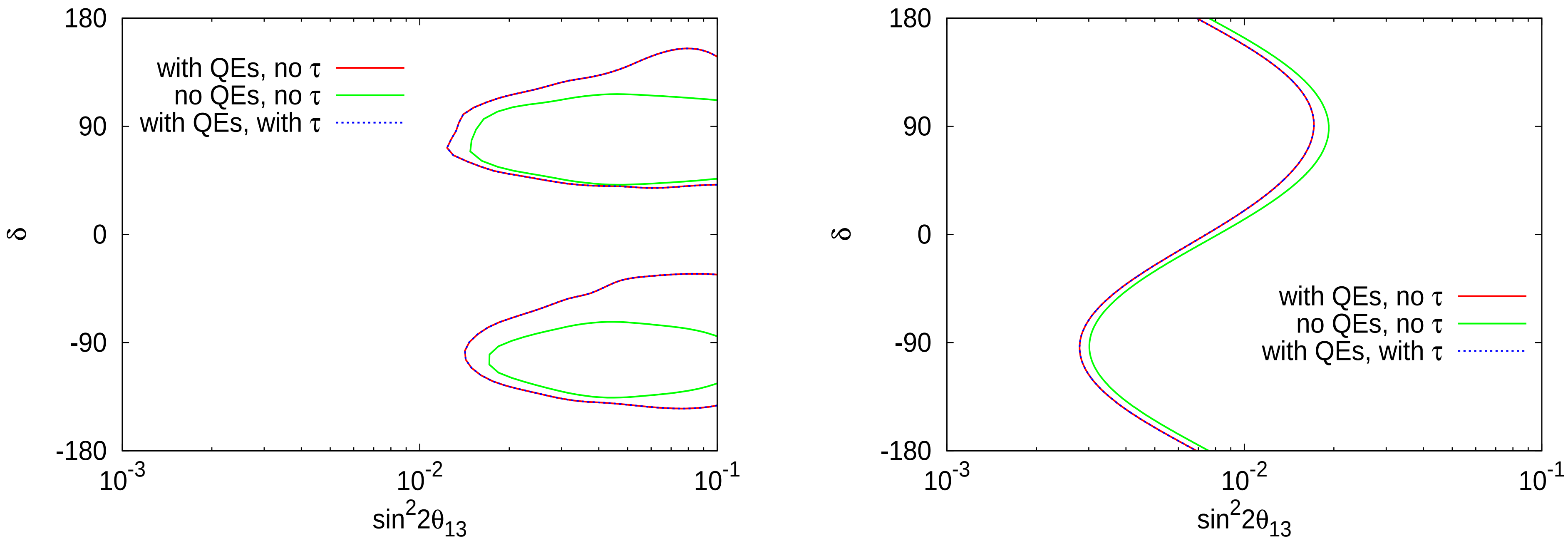
Thanks to oscillations driven by Δm^2_{31}, nearly half of the ν_μ oscillate into ν_τ. At the energy considered ν_τ appearance can become important. However for standard searches the statistics is very limited.



This channel can become important to determine the octant of θ_{23} and non-standard effects.

The role of QE events.

QE events are important at energies below ~ 1.5 GeV thanks to the QE cross section. For the baseline considered this corresponds to the second oscillation maximum which is critical for the sensitivity to CPV.

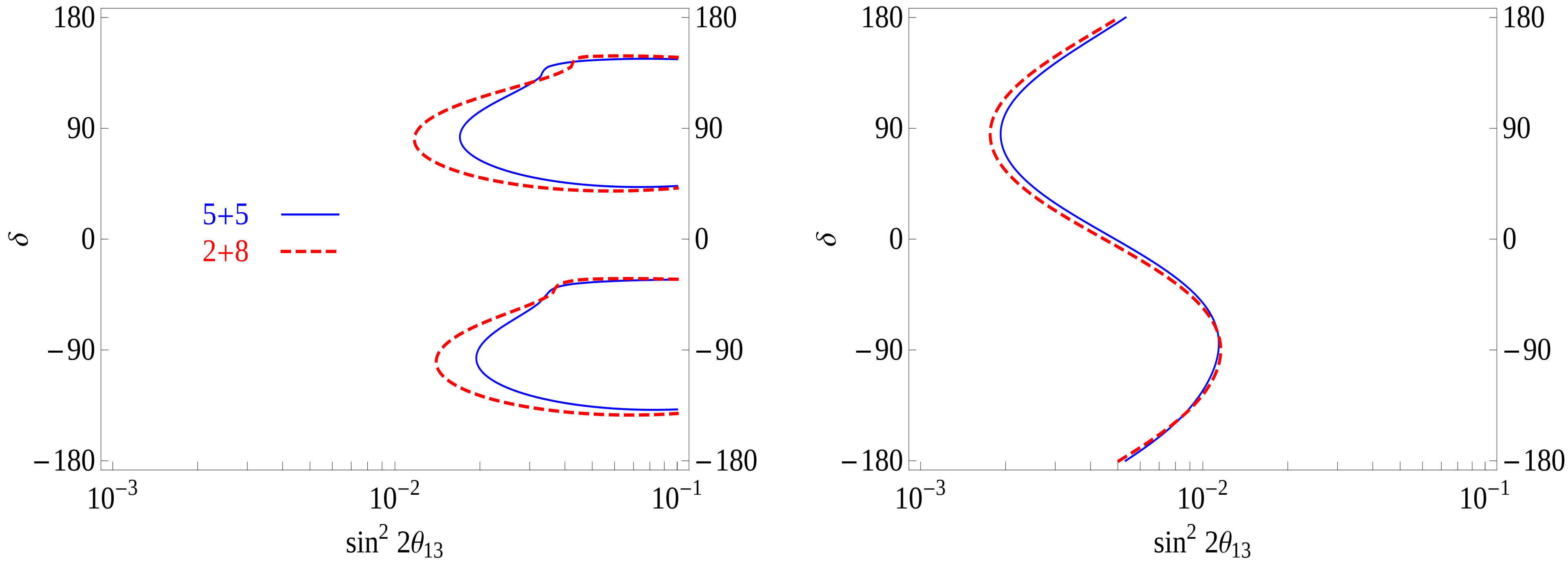


Sensitivity to CPV

Sensitivity to hierarchy

Running time

We have studied different configurations for the number of years of running: 2+2, 4+6, 5+5. Each year corresponds to 10^7 seconds.

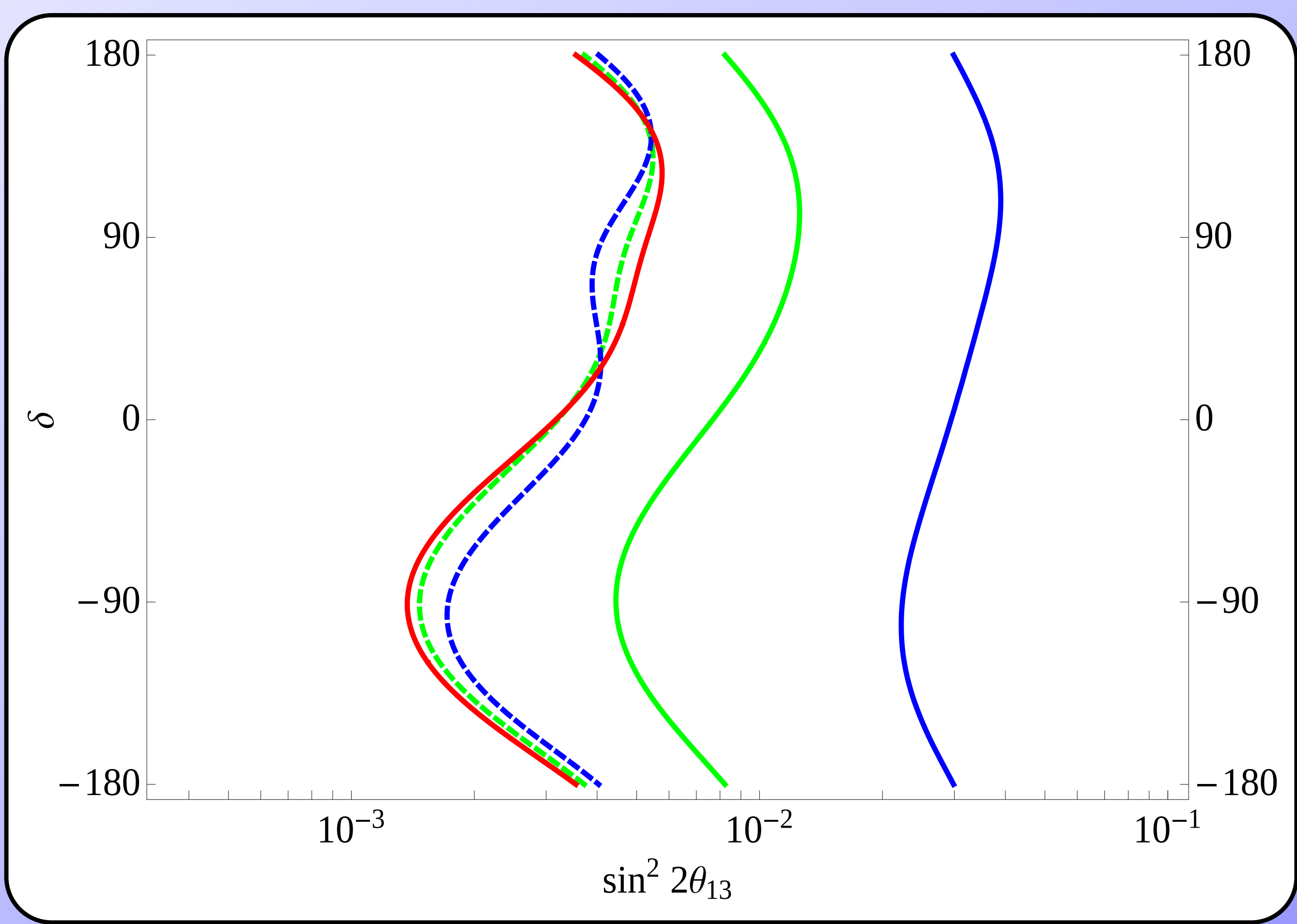


Sensitivity to CPV

Sensitivity to hierarchy

Backgrounds

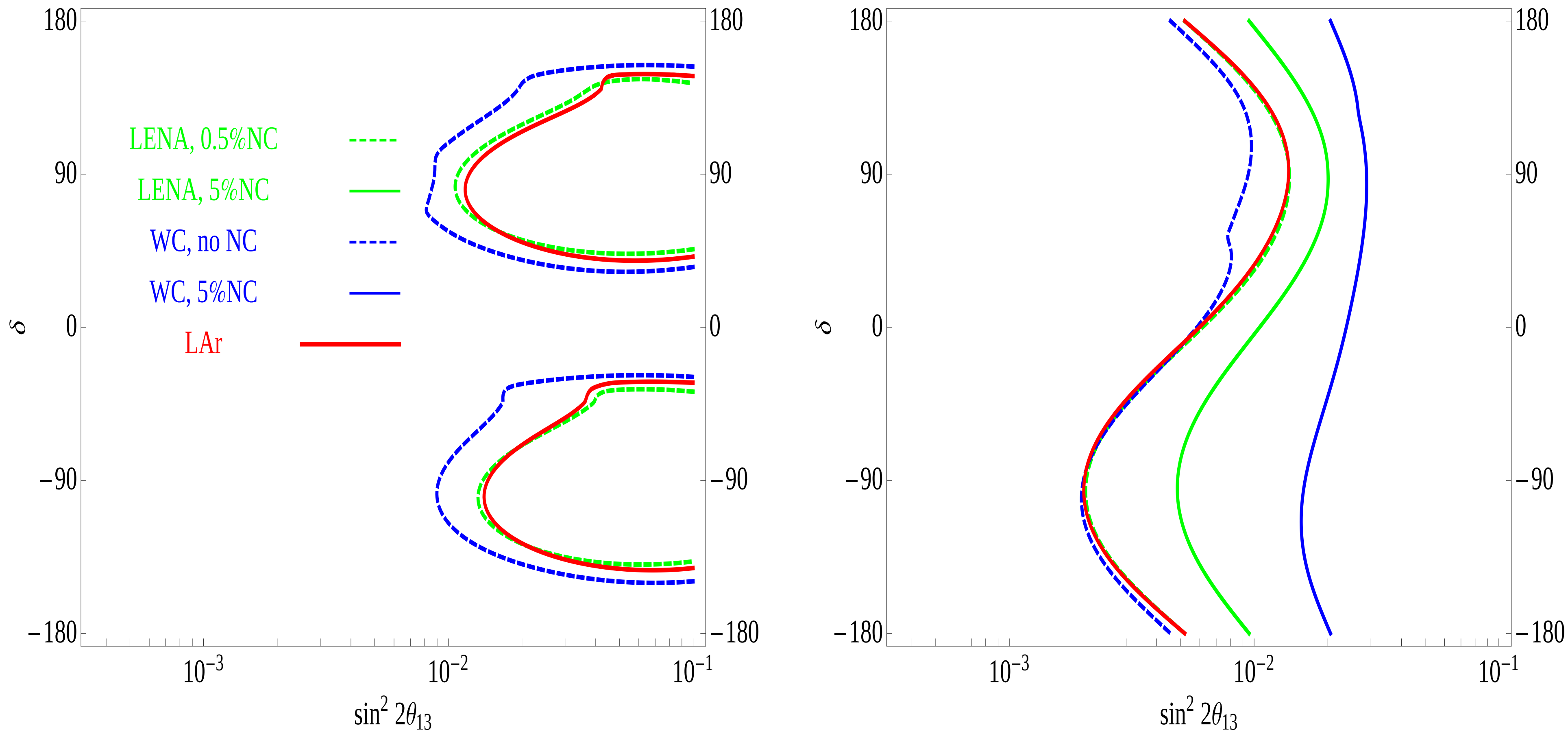
The NC backgrounds play a critical role in the sensitivity.



LENA with 5% and 0.5% NC bkgrd, WC with 5% and 0% NC bkgrd, LiAr with 0.5% NC bkgrd.

Comparison between different detectors.

The sensitivities depend significantly on the assumptions made on the detector performance.



Sensitivity to CPV

Sensitivity to hierarchy

This is work in progress:

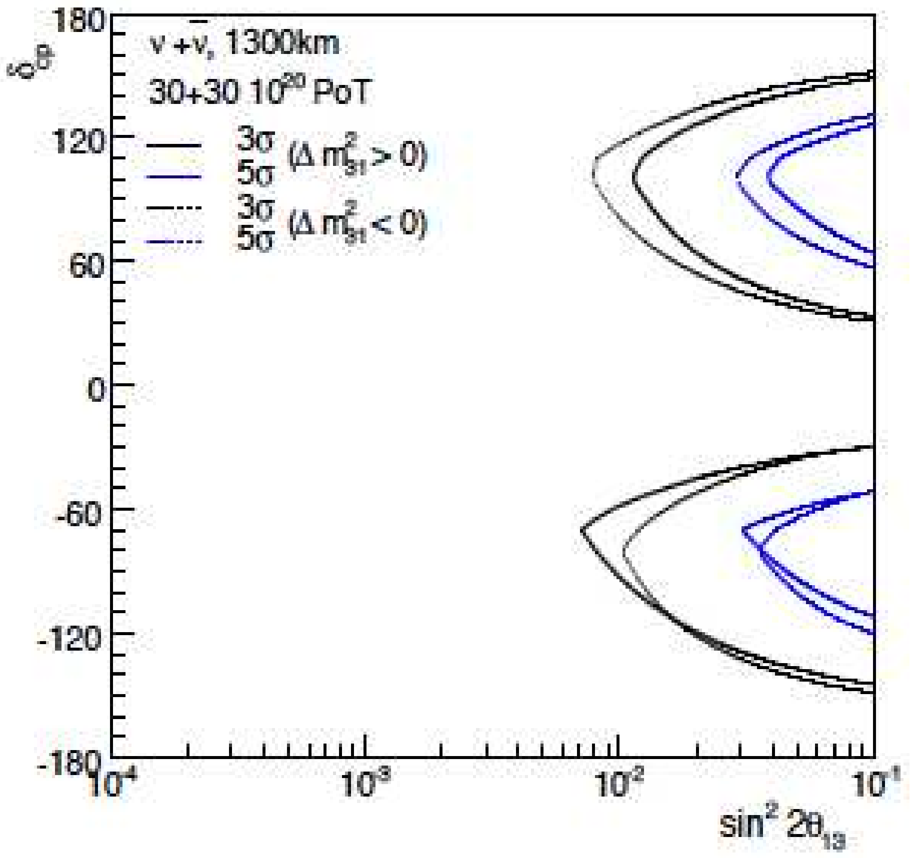
- further study of the sensitivity with optimisation of the flux and updates on the detector performance.
- study of θ_{23} deviation from maximality and non-standard effects.

The sensitivity of these experiments depends very much on the properties of the detector. Detailed simulations are needed. The **energy resolution** and the threshold determine the ability to exploit the rich oscillatory pattern, the **size and efficiency** the statistics which can be reached, **backgrounds** need to be taken into account, **systematics errors** might be the future limiting factors.

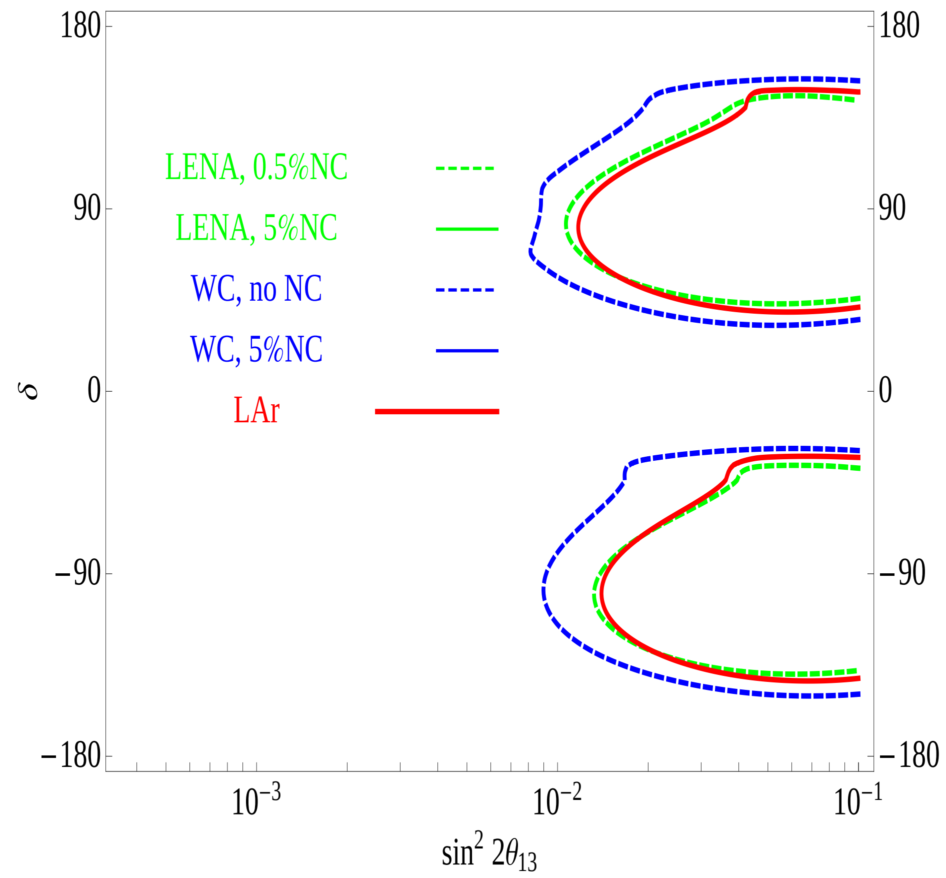
4 – Comparison with other superbeam options

It is possible to compare this setup with other options:

- LBNE with 1.2 MW; 300 kton WC or 100 kton LiAr at 1300 km.

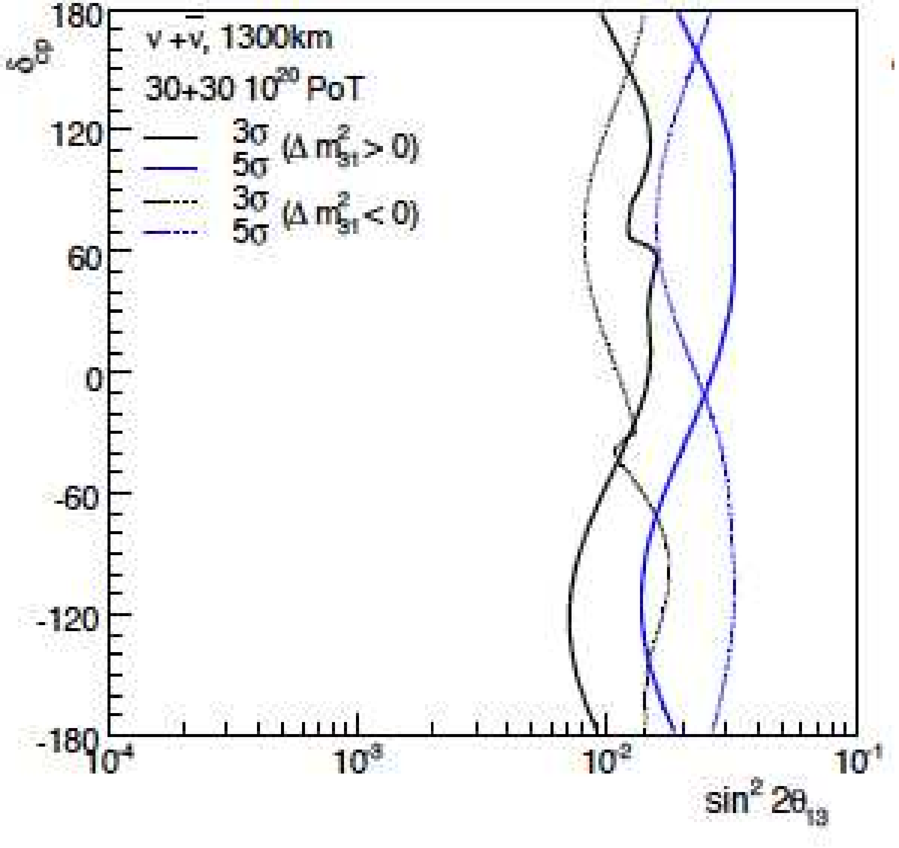


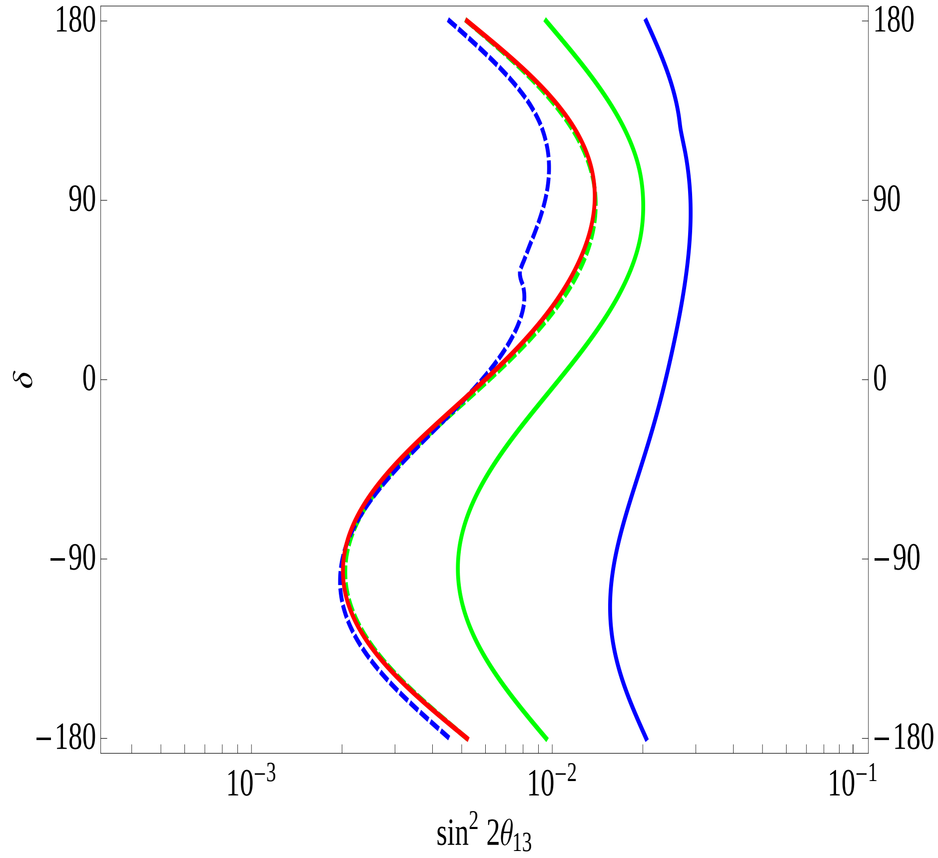
[V. Barger et al., 0705.4396]



Sensitivity to CPV.

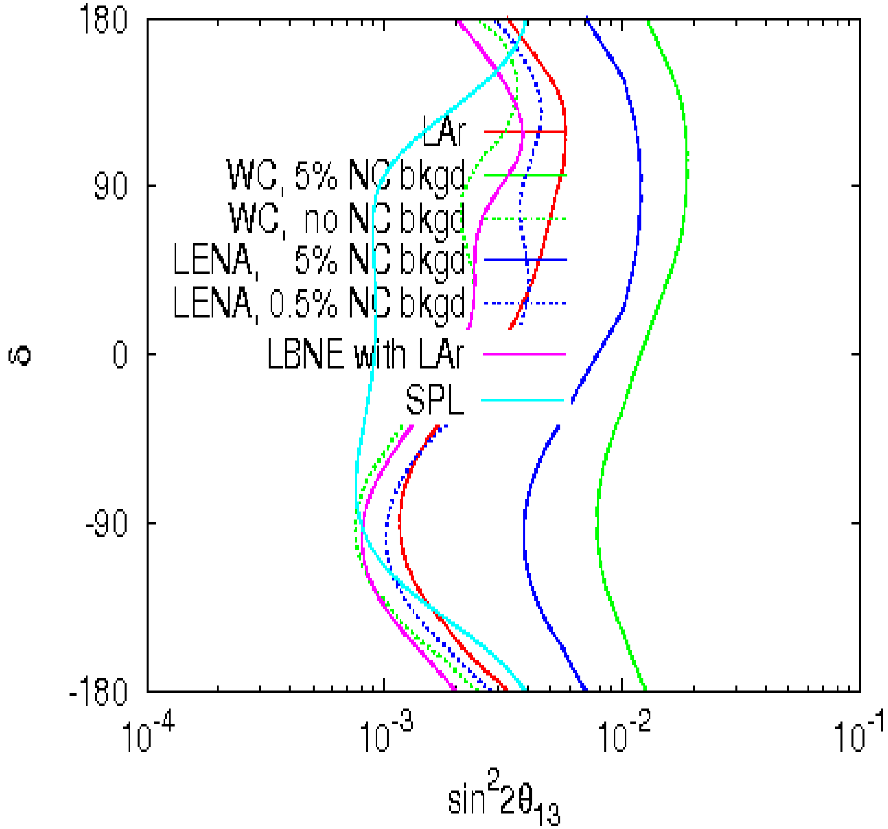
4 – Comparison with other superbeam options

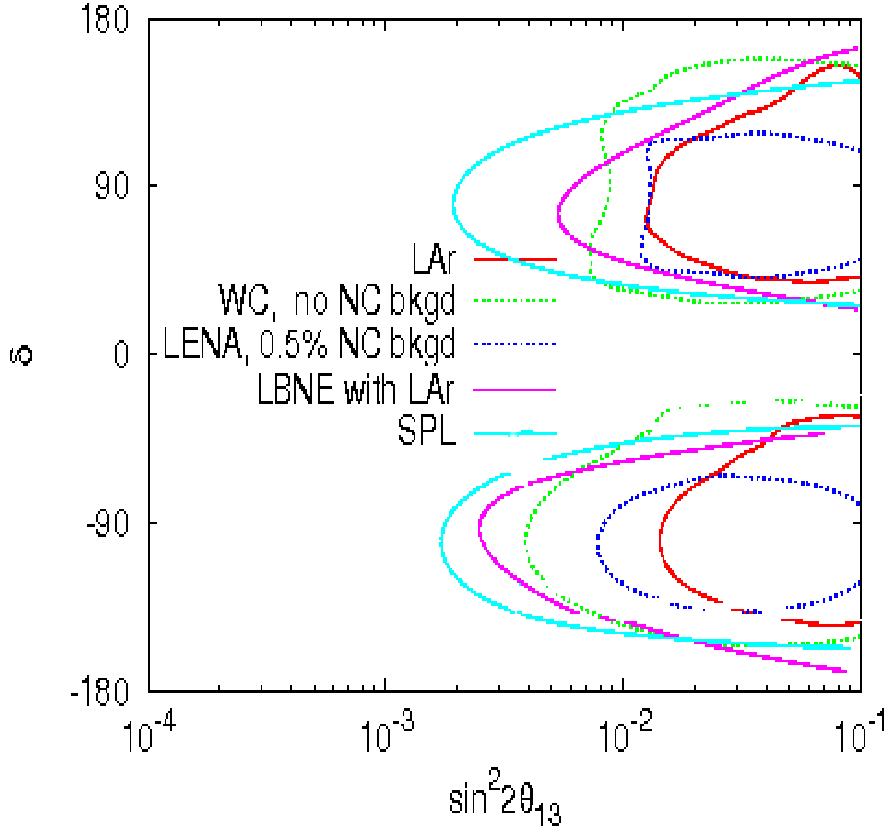




[V. Barger et al., 0705.4396]

Sensitivity to the type of mass hierarchy.





In comparing, one should take into account that LBNE uses 10% systematic error on the background, but 1 year corresponds to 1.7×10^7 seconds. SPL has 4 MW of power.

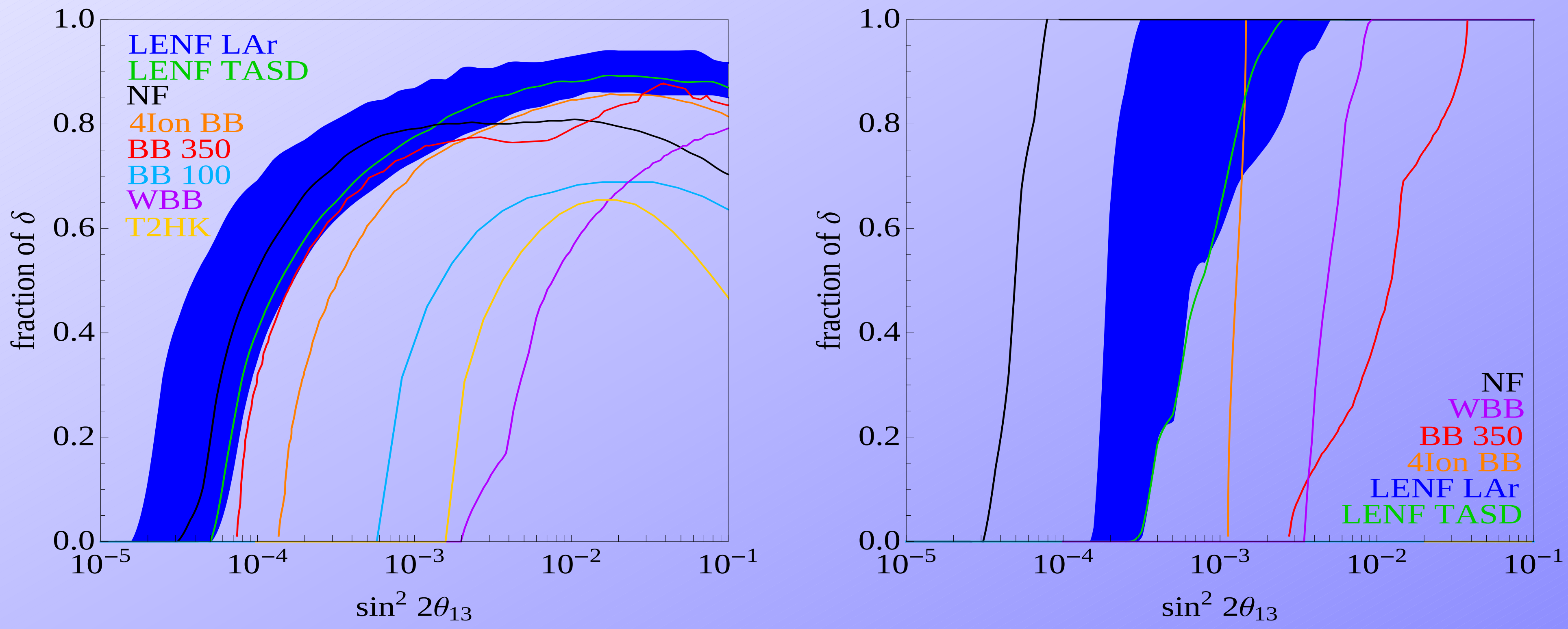
5 – Long term plan

In order to achieve better sensitivity (if θ_{13} is very small and/or precision is required), it is necessary to have higher statistics and lower backgrounds: **betabeams and neutrino factories**.

The low energy neutrino factory uses:

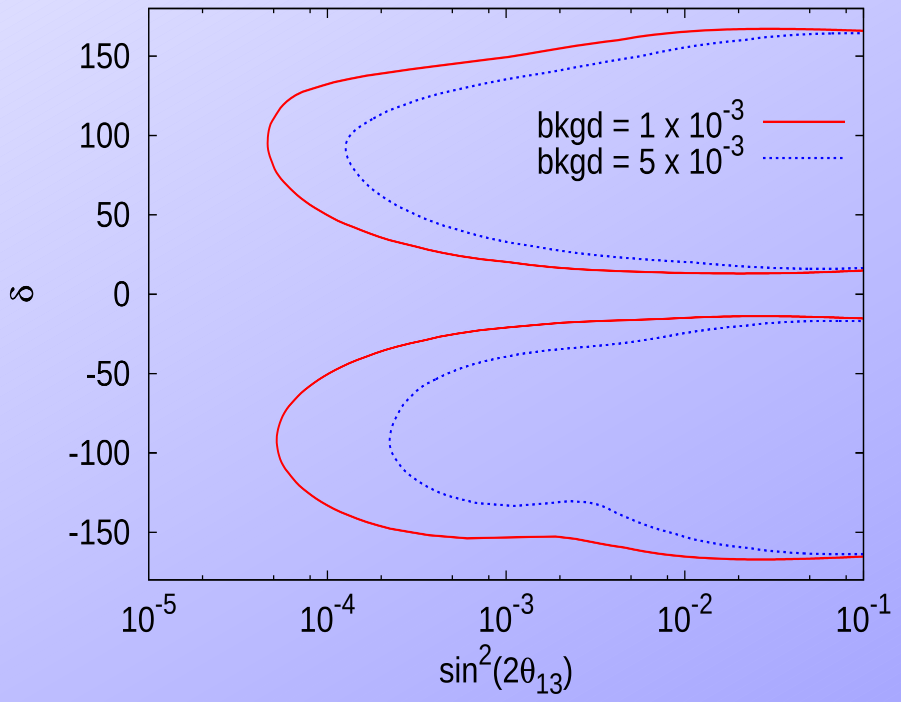
- muons at few GeV which decay into ν_e and ν_μ. The golden channel is the appearance $\nu_e \longrightarrow \nu_\mu$;
- baselines of 1000-2000 km;
- magnetised detector with low energy threshold $\sim$GeV: TASD, improved MIND, LiAr.

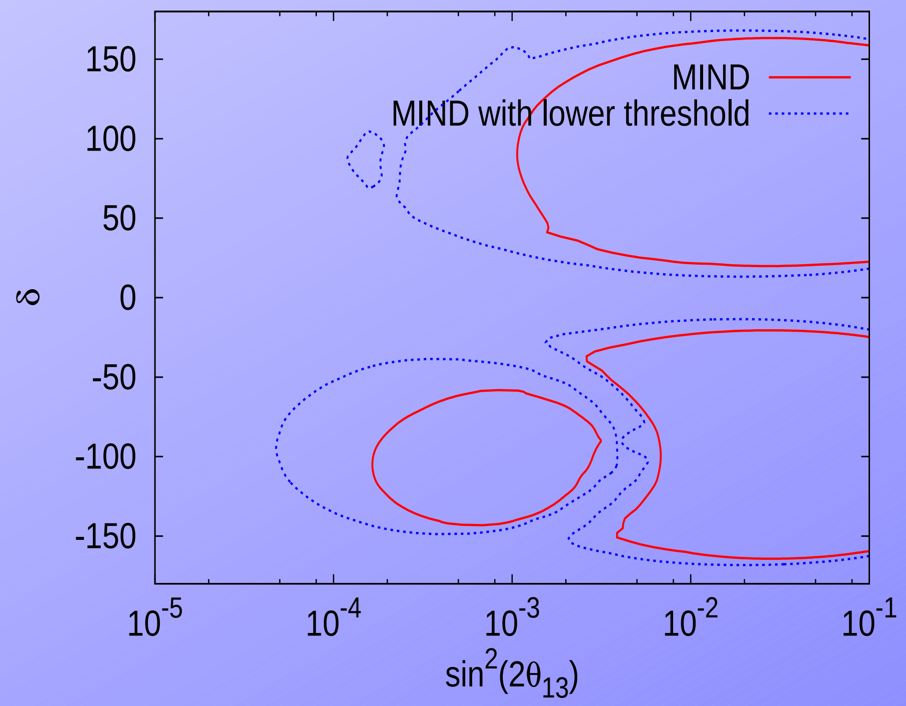
The setup Fermilab-DUSEL has been studied with a 35 kton TASD and a 50 kton LiAr magnetised detectors.



Sensitivity to the CPV and type of neutrino mass hierarchy [Bross et al.]

A similar study has been started for the CERN-Pyhäsalmi baseline with a 50 kton LiAr magnetised detector or a MIND detector with improved efficiency at low energy.





[Li and Pascoli, in prep.]

6 – Conclusions

The synergy between LAGUNA and long baseline experiments is two-fold.

• type of detector (WC, LiAr, LENA); • baseline ($\Rightarrow$E).

- We performed a detailed simulation of CERN-Pyhäsalmi setup.

- Very good sensitivity to θ_{13}, CPV and hierarchy, comparable with other superbeam options on a similar timescale.

- Work in progress (!):

  i) optimisation of the flux;

  ii) further study of the detector performance;

  iii) role of near detector;

  iv) magnetisation of the detector.