The Low Energy Neutrino Factory

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Based on Geer, Mena, SP, Phys.Rev.D75:093001, 2007 and Bross, Ellis, Geer, Mena, SP, Phys.Rev.D77:093012, 2008, E. Fernandez Martinez, T. Li, SP, O. Mena, Phys.Rev.D81:073010, 2010, Li et al. in preparation.

1 – Outline

- The LENF concept
- Update on detailed simulation
- LENF and LAGUNA
- LENF and NSI
- Conclusions

2 – Non too small θ_{13}: LENF

A future neutrino factory experiment will search for subdominant neutrino oscillations (possible golden, silver and platinum channels).

The oscillation probability for $\nu_e \longrightarrow \nu_\mu$, in 3-neutrino mixing case, is approximated 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 $\Delta_{13} \equiv \Delta m_{31}^2/(2E)$.
$A \equiv \sqrt{2} G_F \bar{n}_e$.

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.] :

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

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

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

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

Desirable characteristics

a) wide beam to provide information at different energies

b) detector with low energy threshold to fully exploit the oscillatory pattern of the signal (degeneracy resolution)

c) baseline > 800–1000 Km for significant matter effects

A low-energy neutrino factory satisfies all these criteria.

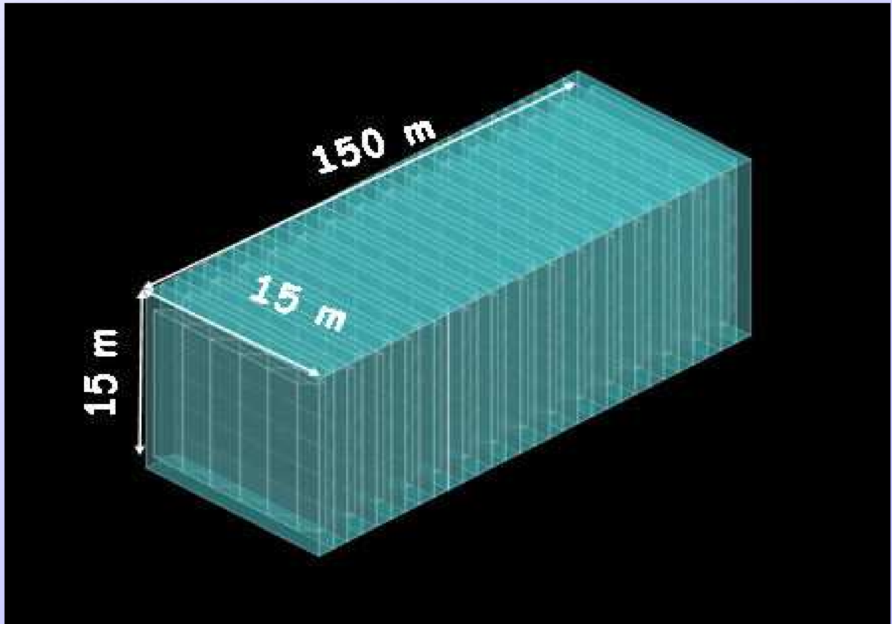
a) Muon energy ~ 4–8 GeV

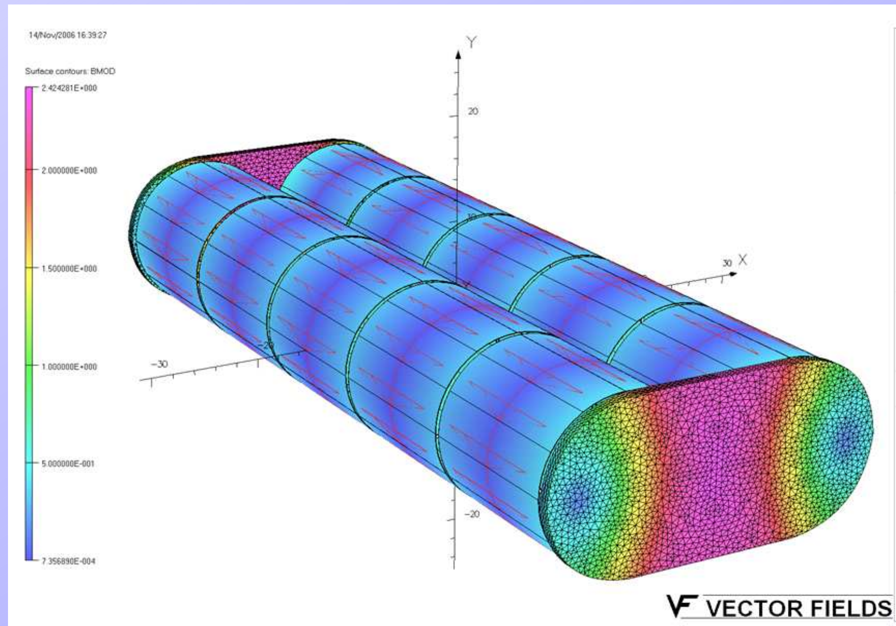
b) magnetised (!) TASD detector or Liquid Argon detector

c) distance $L \sim 1000$–2000 km

Totally active Scintillator detector extrapolating Minerνa (and NOνA) concepts.

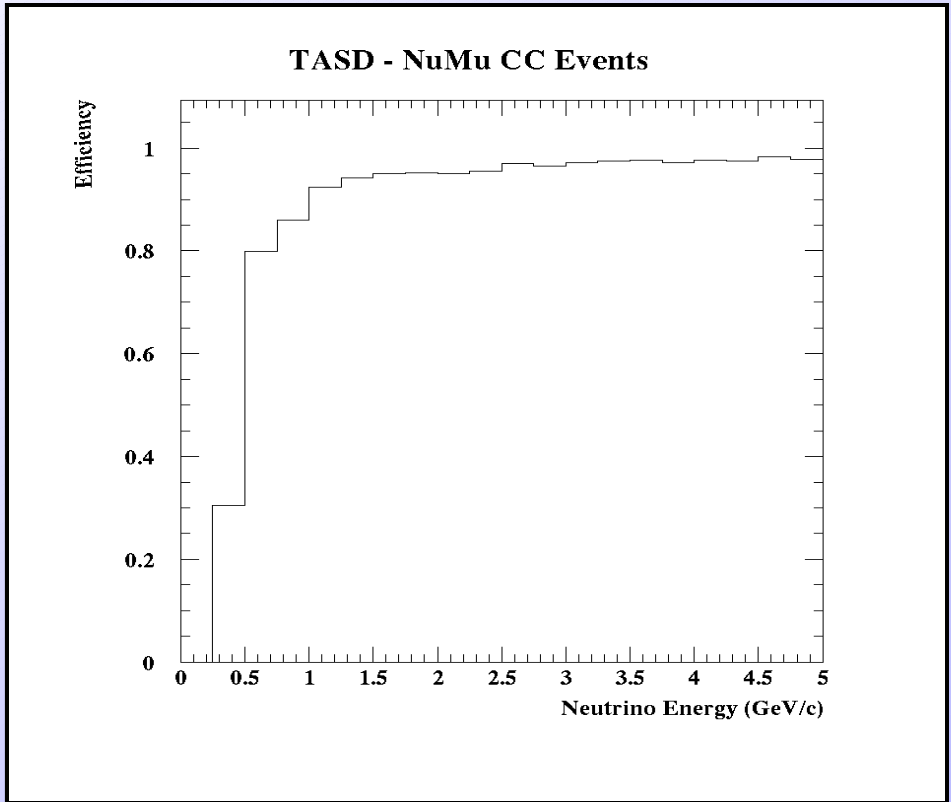
- Main challenge: magnetisation. Magnetic field required: 0.5 T.



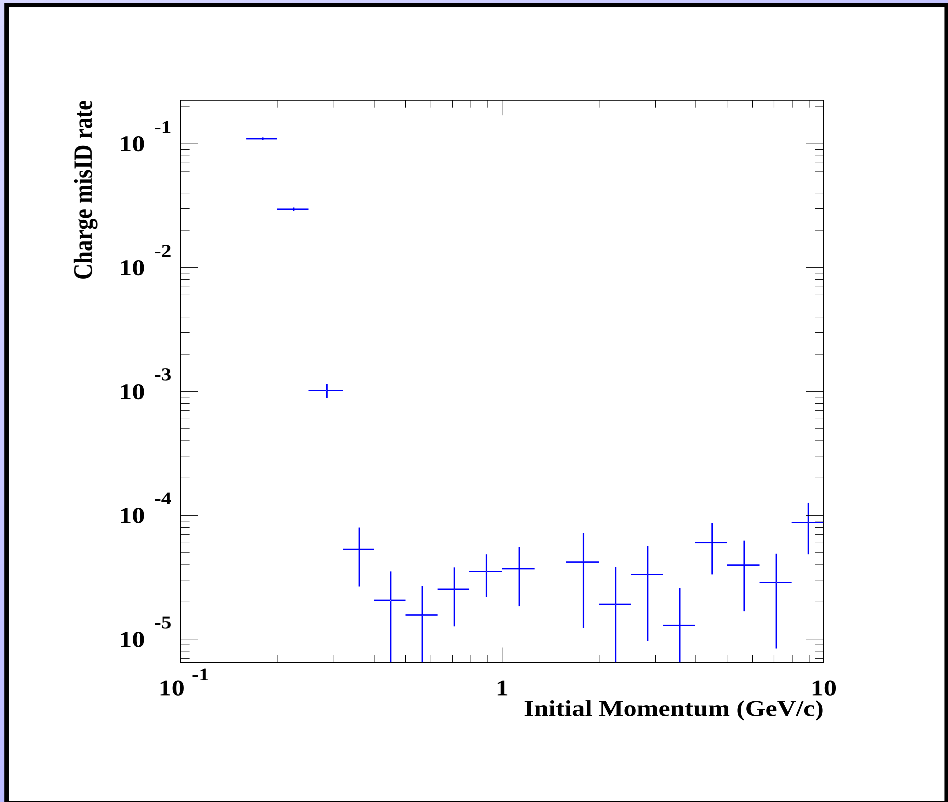


TASD performance

ν event reconstruction efficiency



muon charge mis-ID rate



LENuFact and degeneracies

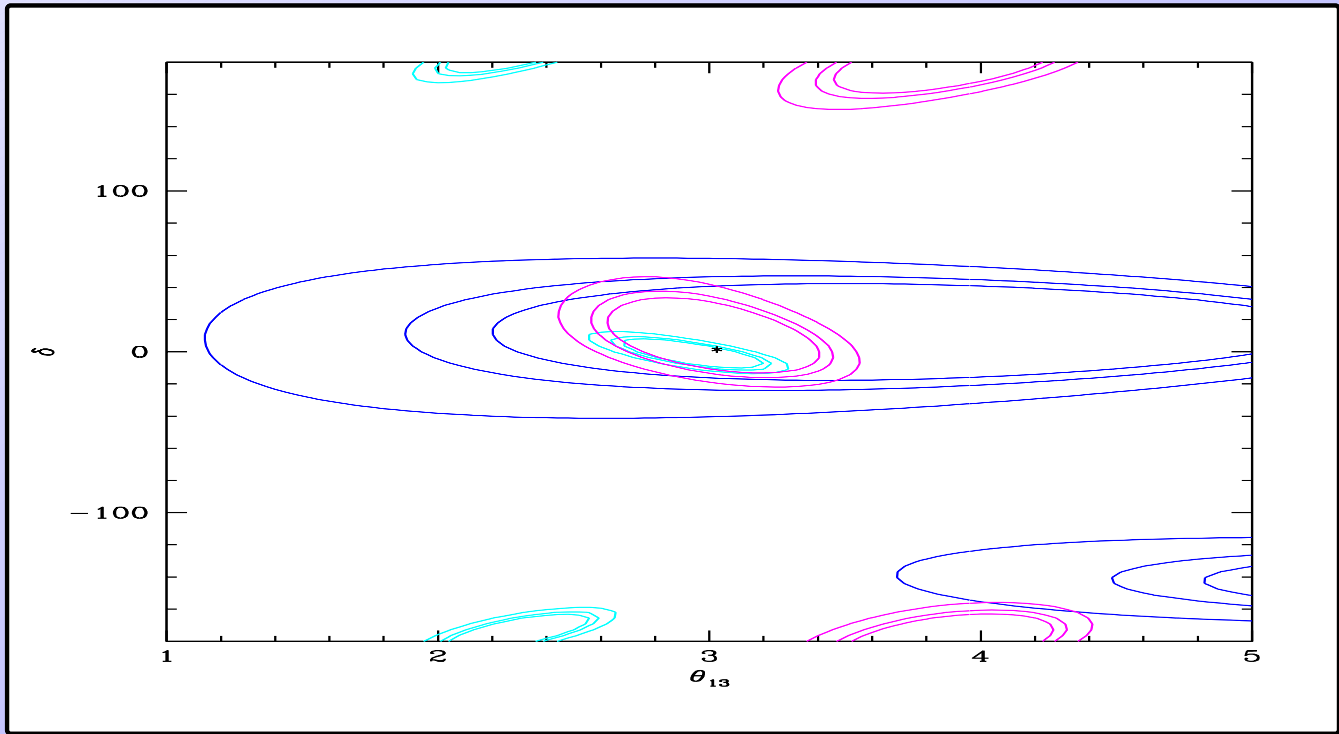
The low energy threshold allows to fully exploit the oscillatory pattern of the signal and to resolve efficiently degeneracies among the parameters for large values of θ_{13} as well as for values as small as $\theta_{13} \sim 1^o$.

- First simulation (Geer, Mena, SP, Phys.Rev.D75:093001, 2007)
- rather short baseline, $L =$1480 km (Fermilab to Henderson mine), (L= 1280 km);
- fine grained magnetized detector TASD (efficiency: 73%).
- low energy threshold: 0.5 GeV and energy resolution $dE/E = 30\%$ (very conservative!).
- Setup A: 3×10^{22} kton-decays ($\times$ 2 signs)

Setup B: 1×10^{23} kton-decays ($\times$ 2 signs)

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

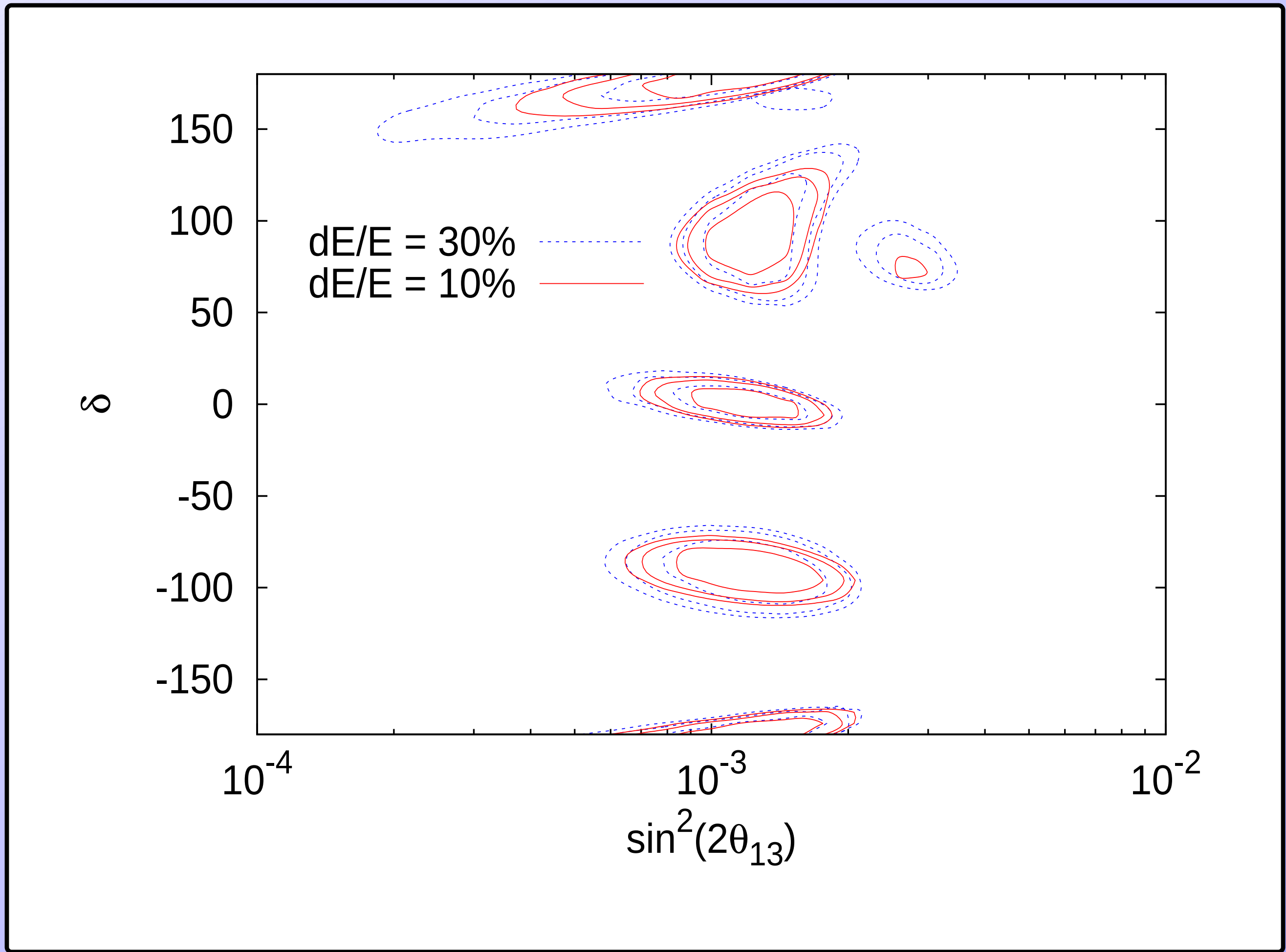
$$\delta' \simeq \pi - \delta,$$
$$\theta'_{13} \simeq \theta_{13} + \cos\delta \, \sin 2\theta_{12} \frac{\Delta m^2_{21} L}{4E} \cot\theta_{23} \cot\left(\frac{\Delta m^2_{31} L}{4E}\right) .$$



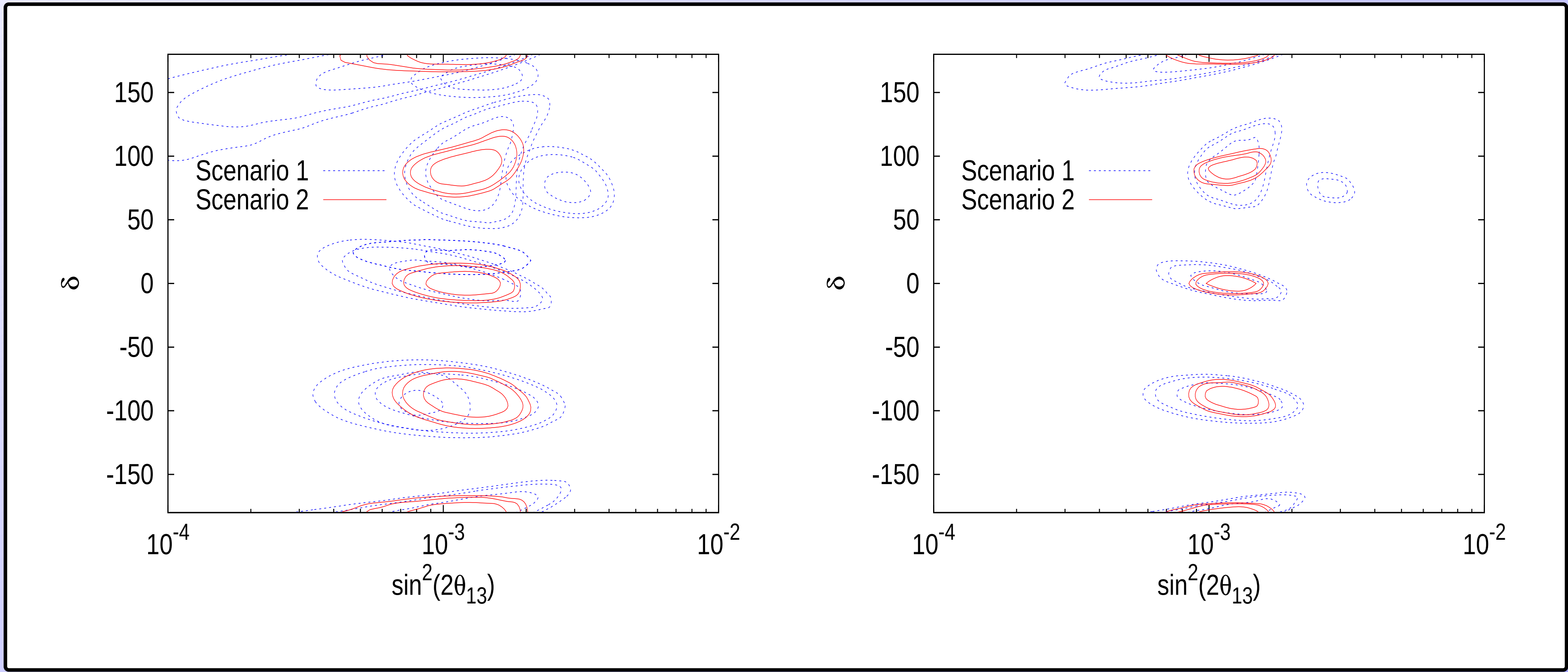
New LENF simulation

A more detailed simulation done recently (E. Fernandez Martinez, T. Li, SP O. Mena, Phys.Rev.D81:073010,2010).

- **Improved energy resolution**

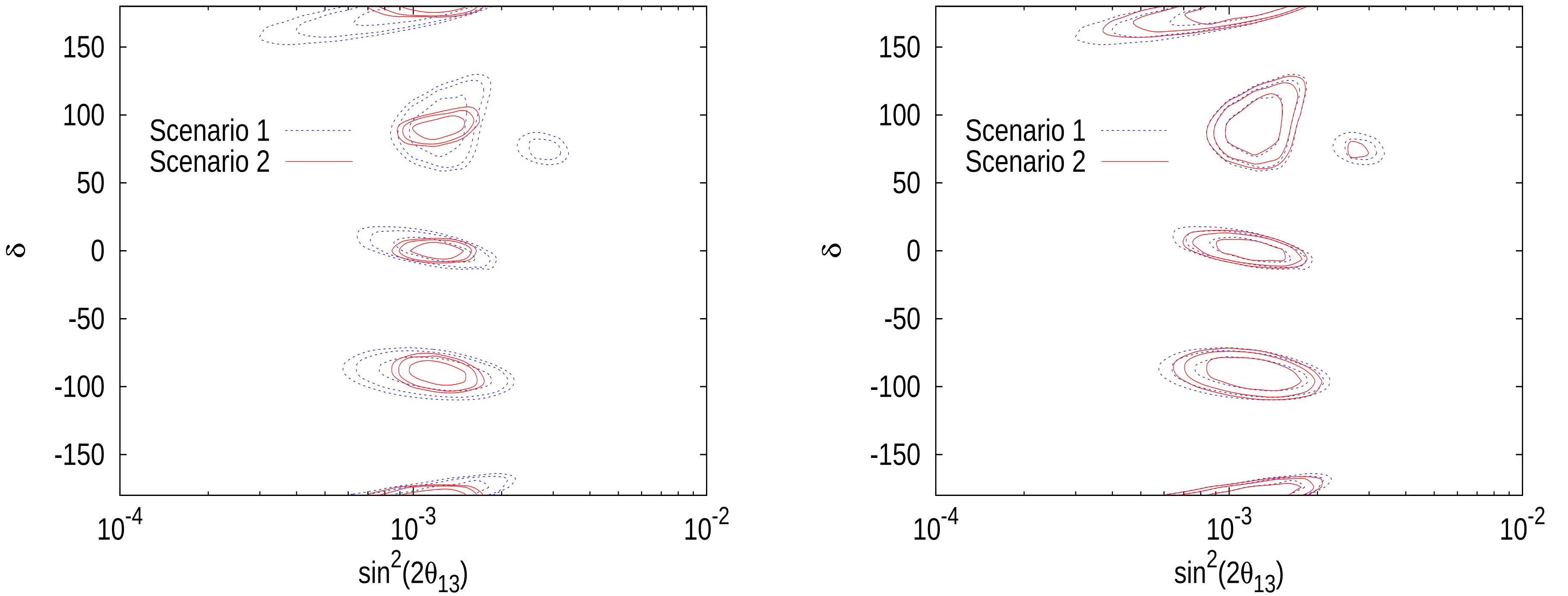


- **Larger neutrino flux**: 5×10^{20} and 1.4×10^{21} muon decay per year



The higher number of neutrino events is critical in achieving strong sensitivity.

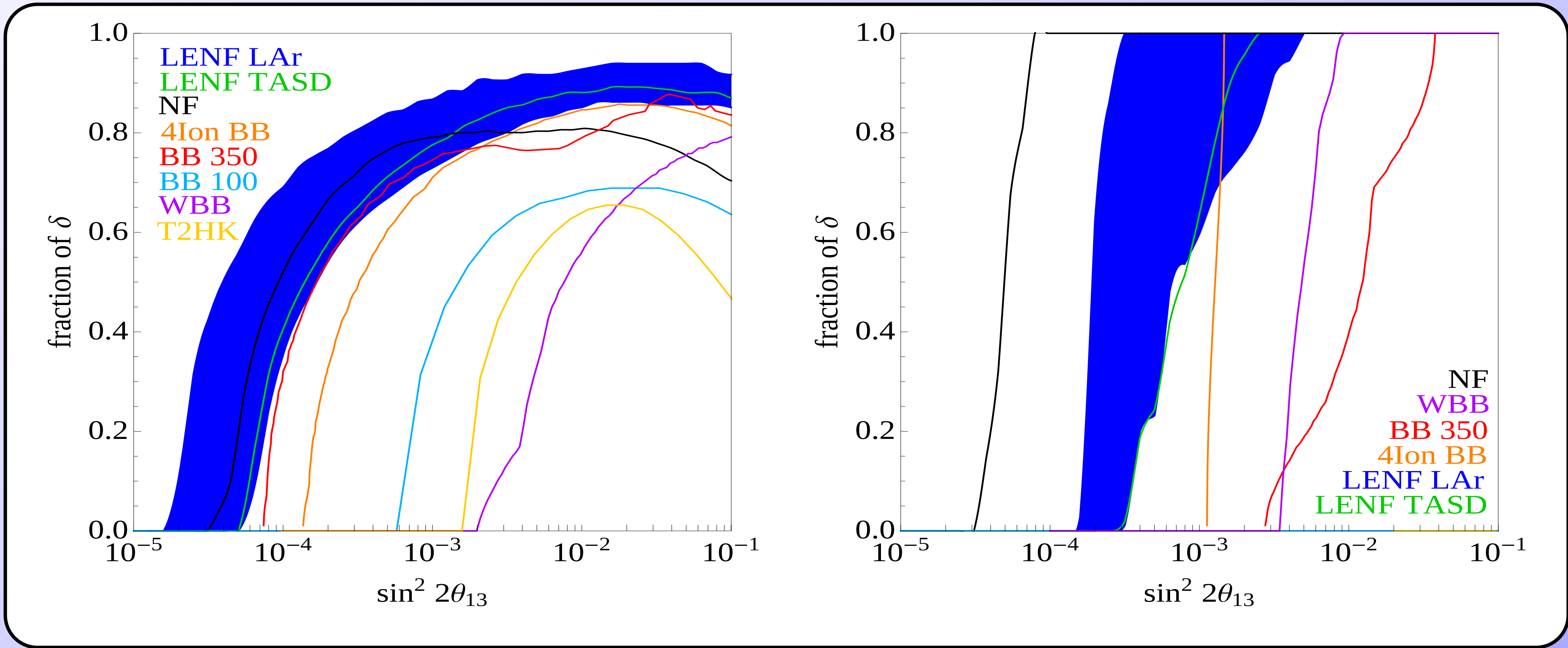
- **Inclusion of the platinum channel**: the TASD and LiAr detector would allow in principle to detect also the "wrong" ν_e. Strong magnetic field is required to determine the associated charge.



0 background $\quad$ 10^{-2} background

The background of platinum channel determines how useful its inclusion is.

Sensitivity to the CPV and type of neutrino mass hierarchy



Excellent sensitivity can be reached for CP-violation and also for the type of mass hierarchy.

3 – LENF and LAGUNA

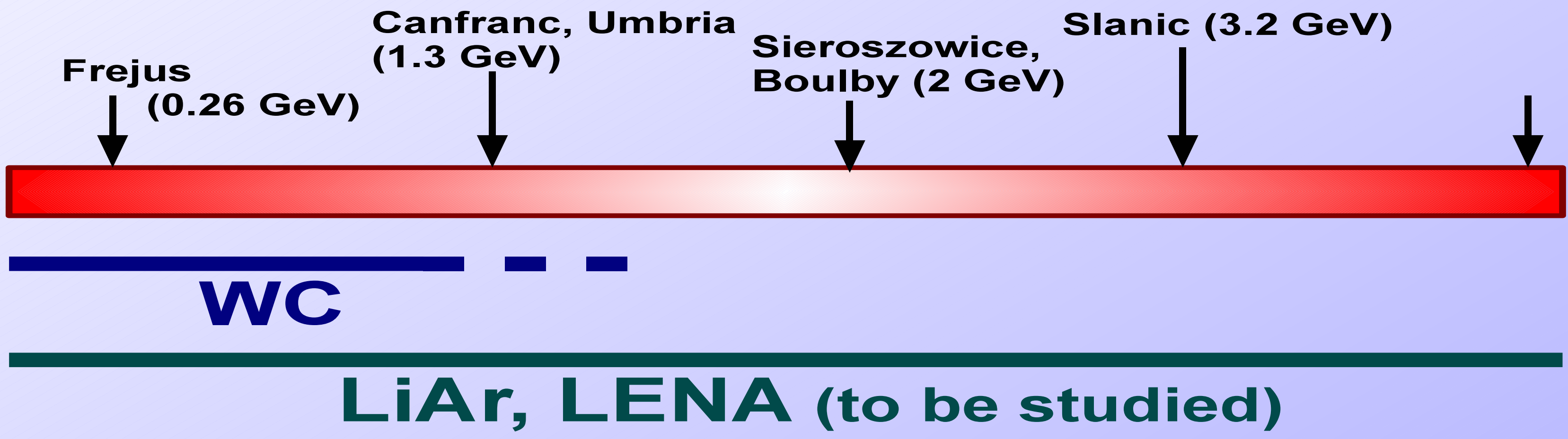
The synergy between LAGUNA and long baseline experiments is two-fold:

- detectors
- location of the underground laboratory ⇒ baseline (from CERN or RAL).

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

A. Rubbia

- **The energy impacts on the type of detector used**

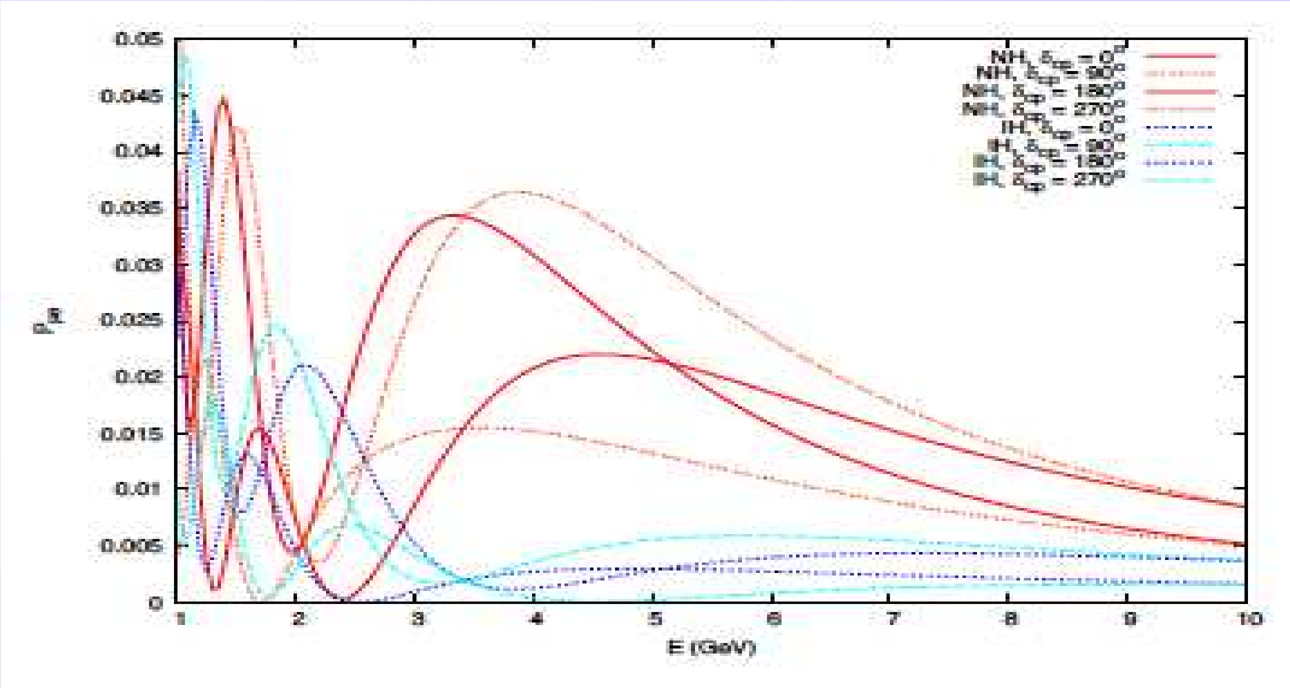


- Each detector has different fiducial volume, efficiency, energy resolution, background reduction and can/cannot be ”easily” magnetised (necessary for full exploitation of the LENF).

- **The cross section scales with the energy** ($\sigma \propto E^2$ at low energy and $\propto E$ above GeV)

• **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.

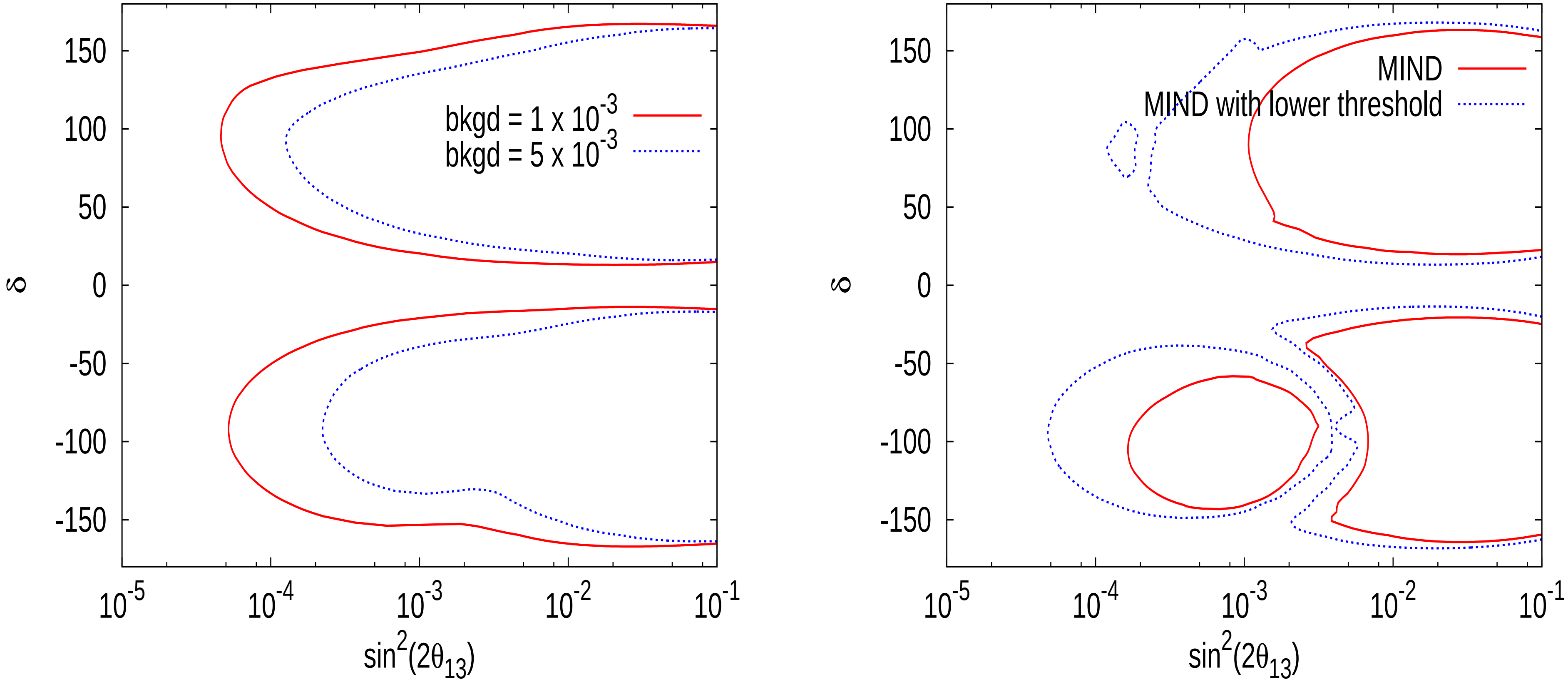


[Raut et al., arXiv:0908.3741]

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

New simulation of LENF with 8 GeV from CERN to Pyhasalmi (2300 km):

work in progress.



50 kton LiAr | 100 kton MIND

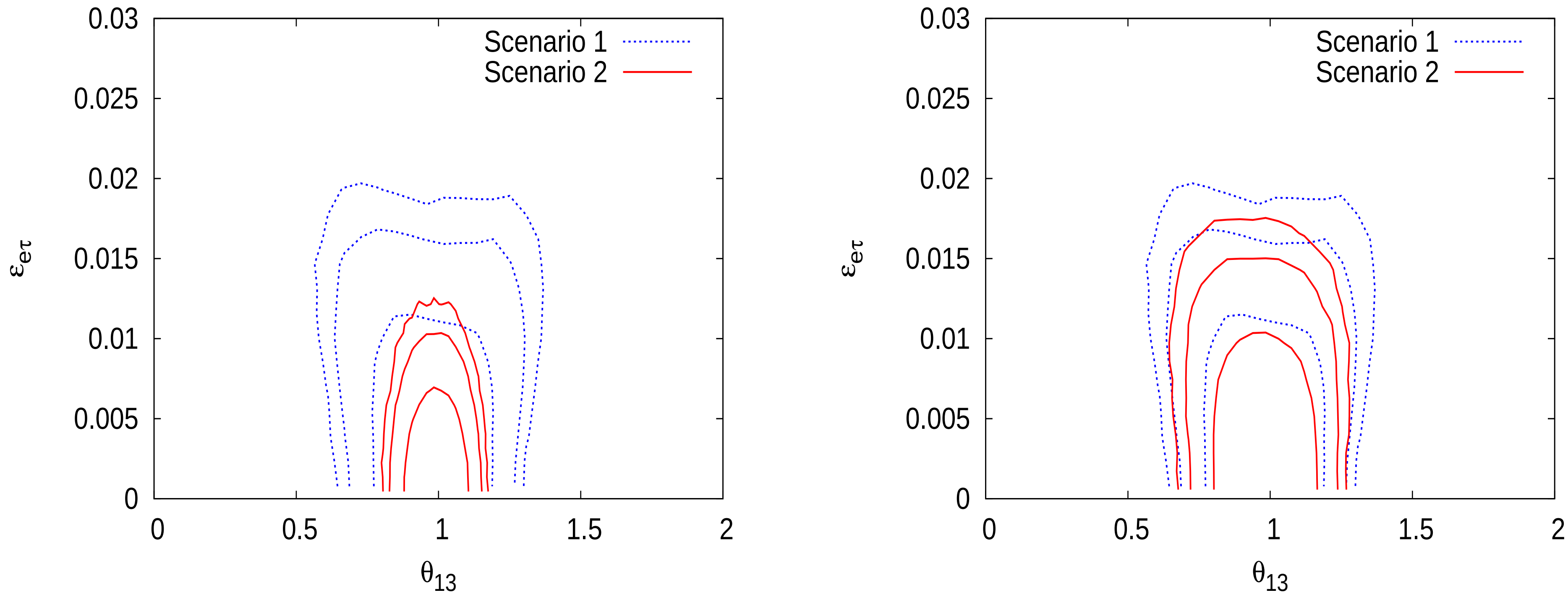
4 – NSI and LENF (work in progress)

Non-standard interactions can manifest themselves in propagation (we do not consider for the moment NSI in production and detection). The Hamiltonian is modified:

$$H = H^{\text{standard}} + A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

and the probability contains a dependence on $\epsilon_{\ell\ell'}$. (see Winter's talk)

- Degeneracy between SO and NSI parameters. The platinum channel can help in resolving this degeneracies but requires low backgrounds and high statistics.



94% efficiency, 0 background

37% efficiency, 10^{-2} background

5 – Conclusions

- The LENF has excellent sensitivity, which is competitive with other future proposed experiments. The reach in the type of mass hierarchy is limited w.r.t. the HENF due to the significantly shorter baselines.

- The sensitivity of these experiments depends very much on the properties of the detector (backgrounds, energy resolution, size...). Detailed simulations of these detectors are needed. Work in progress.

- The synergy between LAGUNA and LENF is two-fold:

a) type of detector (WC, LiAr, LENA)

b) location of the underground laboratory which defines the baseline ($\Rightarrow$E).

- The LENF has good reach in testing NSI. In this case the addition of the platinum channel is useful in resolving the degeneracies between the SO and NSI parameters.