The Low Energy Neutrino Factory: Physics Performance

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Introduction

The low energy neutrino factory was proposed as a next-generation long-baseline experiment in the scenario that θ_{13} is large.

S. Geer, O. Mena, S. Pascoli, 'A Low energy neutrino factory for large θ_{13}'

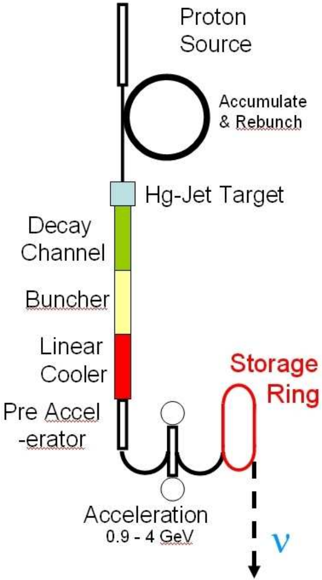
Motivation: The oscillation spectrum for energies $\lesssim 5$ GeV is very rich at ~ 1300 km, providing sensitivity to θ_{13}, δ, the mass hierarchy and θ_{23}.

Talk outline:

- The experiment
- Physics of neutrino oscillations
- Optimisation of the setup
- Comparison with other experiments
- Sensitivity to non-standard interactions
- Conclusions.

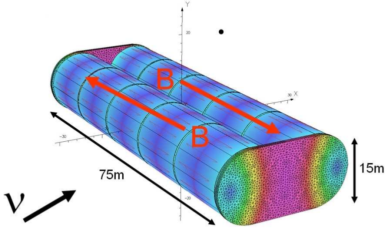
Overview of the low energy neutrino factory

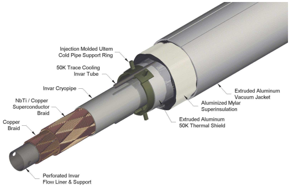
- Create an intense source of $\mu^{\pm}$.
- Cool the $\mu^{\pm} \Rightarrow$ 70% increase in flux.
- Accelerate them to energies of $E_{\mu} \sim 5$ GeV.
- Inject into a storage ring where the muons decay:
  $\mu^{\pm} \rightarrow e^{\pm}\nu_e(\bar{\nu}_e)\bar{\nu}_{\mu}(\nu_{\mu})$
- Detect the neutrinos at a baseline of 1300 km (FNAL to DUSEL).



Overview of the low energy neutrino factory

- Use a magnetized totally active scintillating detector (TASD) or liquid argon (LAr) detector.
- Magnetization is achieved through a magnetic cavern (superconducting transmission lines).
- These detectors can detect $e^{\pm}$ and $\mu^{\pm}$
  $\Rightarrow$ access to the $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channel as well as $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$.





Detectors: 20 kton TASD

For the detector we consider a magnetized totally active scintillating detector (TASD):

- $\mu^{\pm}$ detection efficiency of 73% < 1 GeV and 94% $\geqslant 1$ GeV
- $e^{\pm}$ detection efficiency of 37% < 1 GeV and 47% $\geqslant 1$ GeV
- Background of 10^{-3} on the $\overset{(-)}{\nu}_{\mu}$ appearance and disappearance channels
- Background of 10^{-2} on the $\overset{(-)}{\nu}_{e}$ appearance channel
- Detector fiducial mass of 20 kton
- Energy resolution, dE/E, of 10%.

Detectors: 100 kton LAr

Alternatively, a 100 kton liquid argon (LAr) detector could be used. To allow for uncertainties in its performance consider a range of experimental parameters:

	Conservative	**Optimistic**
Efficiency - all channels	80%	80%
Systematics	5%	2%
Energy resolution - QE events	5%	5%
Energy resolution - non-QE events	20%	10%
Background on ν_μ (dis)appearance channels	5×10^{-3}	1×10^{-3}
Background on ν_e appearance channels	0.8	1×10^{-2}

Physics of LBL ν oscillations

- The 'golden channel' is the $\nu_e \to \nu_\mu$ channel:

A. Cervera et al., 'Golden measurements at a neutrino factory'

$$
\begin{aligned}
P_{\nu_e \to \nu_\mu} &= s_{213}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\
&+ s_{213} \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \times \\
&\cos\left(\delta - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ \alpha^2 c_{23}^2 s_{212}^2 \left(\frac{\Delta m_{31}^2 L}{2EA}\right)^2 \sin^2\left(\frac{AL}{2}\right)
\end{aligned}
$$

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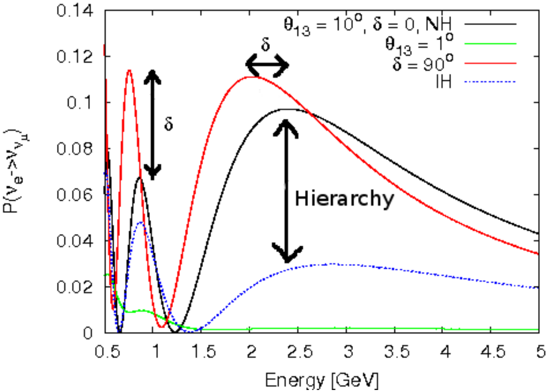
- This channel contains information on all the parameters we want to measure.
- Information is extracted by looking at the shape of the oscillation spectrum.

Physics of LBL ν oscillations



- θ_{13} controls the amplitude of the oscillation $\Rightarrow$ high statistics.
- CP violation is a low energy effect $\Rightarrow$ detector with low energy threshold.
- Hierarchy determined at high energy $\Rightarrow$ long baseline.

Degeneracies

Neutrino oscillation experiments suffer from the problem of degeneracies: data can be fitted to different combinations of (θ_{13}, δ, sign[Δm^2_{31}]).

$\Rightarrow$ This severely weakens the precision of measurements.

Solutions:

- Combine experiments with different baselines
- Use a second detector and baseline.

Degeneracies

Solutions utilised by the LENF:

- Obtain and combine information from different channels:

  The degenerate solutions for each channel appear in **different** regions in the θ_{13}, δ, $\mathrm{sign}[\Delta m^2_{31}]$ plane.

  $\Rightarrow$ Degenerate solutions from one channel are eliminated by the information from a complementary channel.

- Obtain information over a range of energies:

  Complementary information can be obtained from the first and second oscillation maxima.

Optimisation of the LENF setup

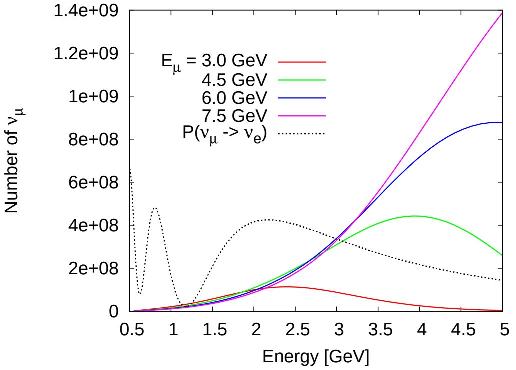
Optimisation studies have been performed, maximising sensitivities to the standard oscillation parameters θ_{13}, δ and sign$[\Delta m^2_{31}]$.

We have studied the following:

- Muon energy, E_μ
- Statistics (flux)
- Energy resolution
- Addition of the platinum channel ($\nu_\mu \rightarrow \nu_e$).

Optimising the muon energy

- Need to maximize the oscillation signal (events $\lesssim$ 3 GeV), and minimize the non-oscillating (higher energy) background.
- ν_μ energy spectrum:



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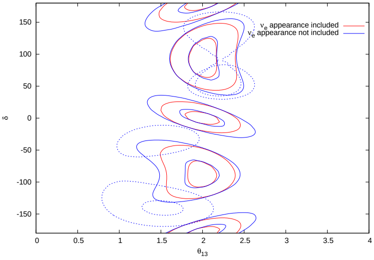
- The optimal muon energy is $E_\mu \sim 4.5$ GeV.

The platinum channel

- If the setup is not optimized, the $\overset{(-)}{\nu}_e$ appearance channel increases sensitivity to θ_{13}, δ and the mass hierarchy (left).
- With optimized E_μ, high statistics and energy resolution, the additional channel helps only with the hierarchy determination (right).

4 GeV, 5.0×10^{20} decays, $dE/E = 30\%$



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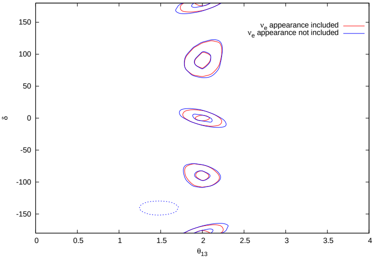
4.5 GeV, 1.4×10^{21} decays, $dE/E = 10\%$



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High statistics are vital.

Statistics

One advantage of the LENF is that it can obtain a very high flux:

- 1.4×10^{21} muon decays per year, per polarity

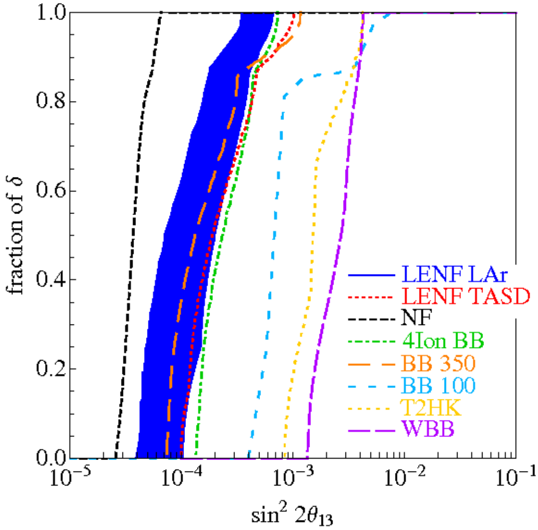
  C. Ankenbrandt et al. FERMILAB-PUB-09-0010APC (2009)
- 2×10^{7} operational seconds per year (twice that of other LBL experiments)
- Running for 10 years
- $\Rightarrow$ Total of 2.8×10^{22} decays.

The golden and platinum channels are statistics limited, so a high flux is essential.

To make a fair comparison with other experiments, halve the LENF flux so that the operational time is the same.

Results: 3σ θ_{13} discovery potential

Compare with **HENF**, WBB, T2HK and different β-beams.



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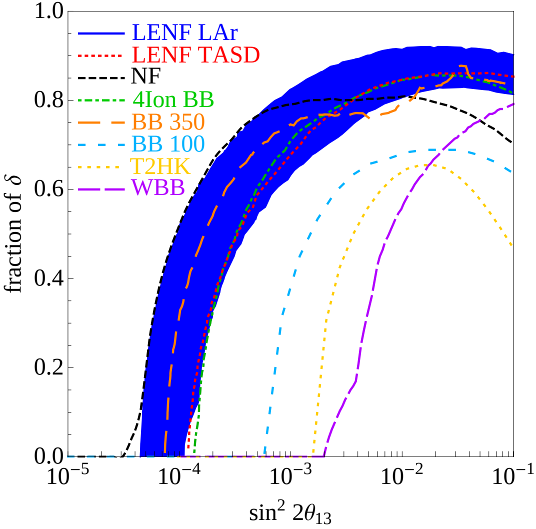
Results: 3σ CP discovery potential

Compare with **HENF**, WBB, T2HK and different β-beams.



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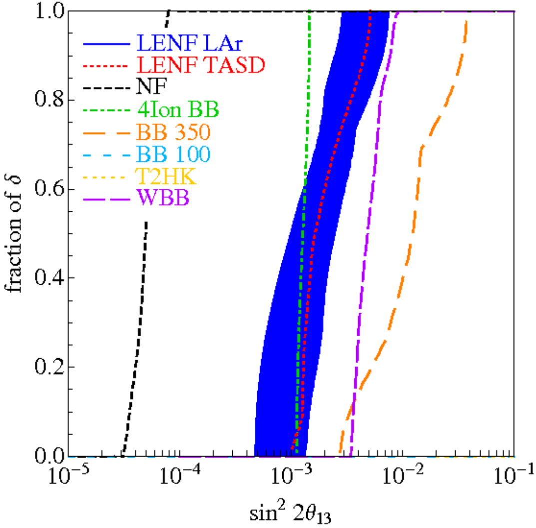
Results: 3σ hierarchy sensitivity

Compare with **HENF**, WBB, T2HK and different β-beams.



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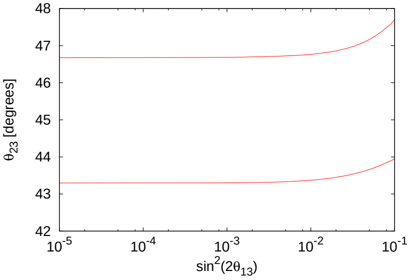
Sensitivity to θ_{23}

We are also interested in being able to measure the deviation of θ_{23} from $\pi/4$ (left), and in determining the octant ($>$ or $< \pi/4$) (right).

Deviation from $\pi/4$



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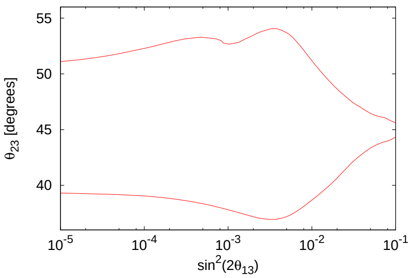
Identifying the octant



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Can exclude maximal mixing at 3σ for $\theta_{23} \lesssim 43°$ and $\gtrsim 47°$.

Can identify the octant for $\theta_{23} \lesssim 37°$ and $\gtrsim 53°$.

Variation of sensitivities with exposure

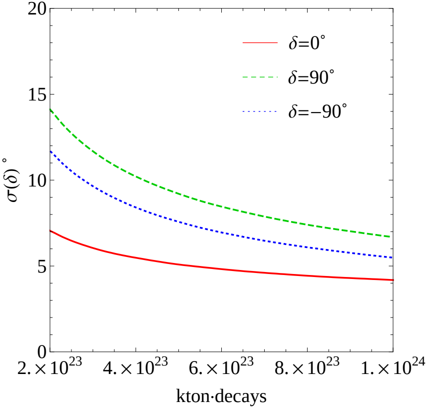
Using a 20 kton TASD, the LENF has a total exposure of
1.4×10^{21} decays $\times$ 2 polarities $\times$ 10 years $\times$ 20 kton
$= 5.6 \times 10^{23}$ kton decays.

We have studied how the performance is affected by the exposure.

e.g. Look at the 1σ error in the measurement of δ as a function of exposure:

Variation of sensitivities with exposure

Systematics and backrounds



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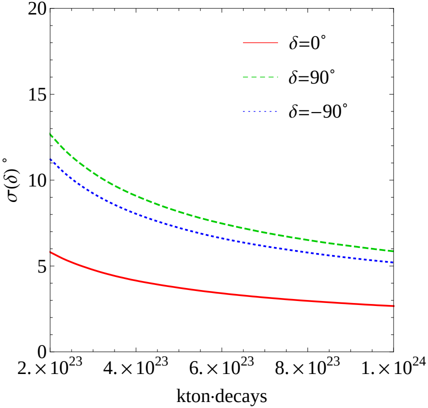
No systematics or backgrounds



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- Sharp increase in precision by having an exposure above 3×10^{23} kton decays.
- Effect of systematics and backgrounds is to effectively halve the exposure.

Sensitivity to non-standard interactions

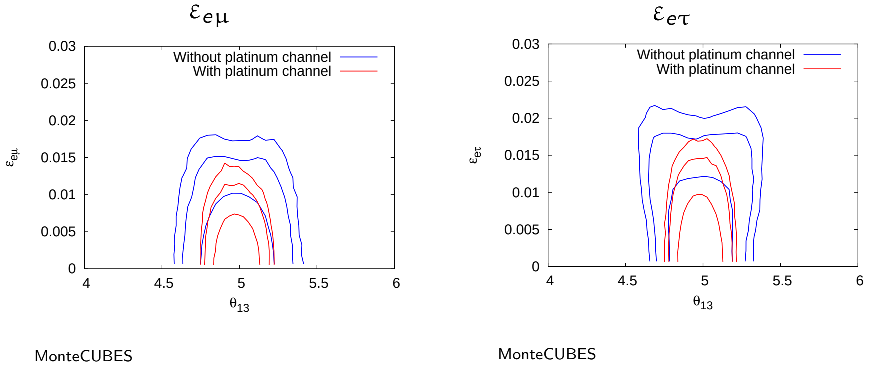
The LENF has leading order sensitivity to the NSI parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$:

$$
\begin{aligned}
P_{\nu_e \to \nu_\mu} &= s_{213}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\
&+ s_{213}\, \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\delta - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ \alpha^2 c_{23}^2 s_{212}^2 \left(\frac{\Delta m_{31}^2 L}{2EA}\right)^2 \sin^2\left(\frac{AL}{2}\right) \\
&- 4\varepsilon_{e\tau} s_{213} c_{23} s_{23}^2 \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\delta + \phi_{e\tau} - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ 4\varepsilon_{e\tau}\, \alpha s_{212} c_{23}^2 s_{23} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\phi_{e\tau} + \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ 4\varepsilon_{e\tau}^2 c_{23}^2 s_{23}^2 \sin^2\left(\frac{AL}{2}\right) \\
&- 4\varepsilon_{e\mu} s_{213} c_{23}^2 s_{23} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\delta + \phi_{e\mu} - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&- 4\varepsilon_{e\mu}\, \alpha s_{212} c_{23}^2 s_{23} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\phi_{e\mu} + \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ 4\varepsilon_{e\mu}^2 c_{23}^2 s_{23}^2 \sin^2\left(\frac{AL}{2}\right)
\end{aligned}
$$

Sensitivity to non-standard interactions

The addition of the platinum channel enhances the sensitivity to NSI's.

Simulate $\varepsilon_{e\mu} = \varepsilon_{e\tau} = 0$ and look at the 68%, 90% and 95% confidence level contours in the $\theta_{13} - \varepsilon$ plane:



Can obtain an upper bound of $\sim 10^{-2}$ on $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ at 90% CL. (IDS-NF will have sensitivity down to $\sim 10^{-3}$).

Summary

- We have simulated the following LENF setup, optimised for measuring θ_{13}, δ and the mass hierarchy:

  L $= 1300$ km, $E_\mu = 4.5$ GeV, 1.4×10^{21} $\mu^\pm$ decays per year for 10 years.

- Using either a 20 kton TASD or 100 kton LAr detector, the LENF has excellent sensitivity to θ_{13} and CP violation down to $\sin^2(2\theta_{13}) \simeq 10^{-4}$, and to the mass hierarchy for $\sin^2(2\theta_{13}) > 10^{-3}$.

- The LENF also has good sensitivity to θ_{23} and to the NSI parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$.