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# The Low Energy Neutrino Factory

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**Abstract.**
We show that a low energy neutrino factory with a baseline of 1300 km and muon energy of 4.5 GeV has an excellent physics reach. The results of our optimisation studies demonstrate that such a setup can have remarkable sensitivity to $\theta_{13}$ and $\delta$ for $\sin^2(2\theta_{13}) > 10^{-4}$, and to the mass hierarchy for $\sin^2(2\theta_{13}) > 10^{-3}$. We also illustrate the power of the unique combination of golden and platinum channels accessible to the low energy neutrino factory. We have considered both a 20 kton totally active scintillating detector and a 100 kton liquid argon detector as possible detector technologies, finding that a liquid argon detector with very good background rejection can produce sensitivity to $\theta_{13}$ and $\delta$ competitive with that of the International Design Study neutrino factory.

**Keywords:** Neutrino factory, neutrino oscillations, long-baseline experiments
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## INTRODUCTION

The primary aim of next-generation long-baseline neutrino oscillation experiments is to determine the values of the unknown oscillation parameters, $\theta_{13}$, $\delta$ and sign[$\Delta m^2_{31}$]. Candidates for these experiments are superbeams (e.g. T2HK [1]), $\beta$-beams [2] and neutrino factories [3]. In [4, 5] a novel low energy version of the neutrino factory was proposed, exploiting the rich oscillation spectrum at energies below $\sim 5$ GeV. Here, we review a recent detailed study of the optimisation of this setup [6], which included the platinum channel as well as the golden channel, and considered two options for a detector: a 20 kton totally active scintillating detector (TASD) [7] and a 100 kton liquid argon (LAr) detector [8].

The principle of the low energy neutrino factory is identical to that of the International Design Study neutrino factory (IDS-NF) [7]: an intense beam of muons and anti-muons is created from a proton source, the muons are then cooled and accelerated, then injected into a decay ring where they decay: $\mu^- \to \nu_\mu \bar{\nu}_e e^-$ and $\mu^+ \to \bar{\nu}_\mu \nu_e e^+$. Since we propose a setup where the parent muons need only be accelerated to 4.5 GeV rather than 25 GeV as for the IDS-NF, the acceleration stage is therefore simpler and cheaper. For detection we consider situating either a 20 kton magnetized totally active scintillating detector (TASD) or a 100 kton magnetized liquid argon (LAr) detector at a baseline of 1300 km, corresponding to the Fermilab to DUSEL baseline. The magnetization of these large-scale detectors poses severe technical challenges; one possibility is to magnetize a large cavern using superconducting transmission lines [9] into which the detector can be placed. The resultant detector would then be capable of detecting and identifying the charges of both electrons and muons. As the decaying (anti-)muons provide a source of both $\nu_e$ ($\bar{\nu}_e$) and $\nu_\mu$ ($\bar{\nu}_\mu$), this would provide access to multiple oscillation channels: the $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance channels, the $\nu_\mu$ ($\bar{\nu}_\mu$) appearance channel (the *golden* channel [10]), and also, uniquely, the $\nu_e$ ($\bar{\nu}_e$) appearance channel (the *platinum* channel).

The $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance channels, well studied by the current generation of long-baseline experiments, provide precision information on the atmospheric parameters. It is the subdominant $\nu_e$ ($\bar{\nu}_e$) appearance channel which contains information on the unknown mixing parameters. The detection of this tiny signal is what makes future experiments so challenging. The probability for this channel can be found in [10]; to leading order in the small quantities $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\sin(2\theta_{13})$ and $EA/\Delta m^2_{31}$, this becomes:

$$\begin{aligned} P_{e\mu} &= s^2_{213} s^2_{23} \sin^2\left(\frac{\Delta_{13} L}{2} - \frac{AL}{2}\right) \\ &+ \alpha s_{213} s_{212} s_{223} \frac{\Delta_{13}}{A} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta_{13} L}{2} - \frac{AL}{2}\right) \times \end{aligned}$$

$$
\cos(\delta - \frac{\Delta_{13}L}{2})
$$

$$
+ \quad \alpha^2 c_{23}^2 s_{212}^2 (\frac{\Delta_{13}}{A})^2 \sin^2(\frac{AL}{2})
$$

where $\Delta_{13} = \Delta m_{31}^2/2E$, $A$ is the matter potential, $s_{ij} = \sin\theta_{ij}$, $s_{2ij} = \sin(2\theta_{ij})$, $c_{ij} = \cos\theta_{ij}$, $c_{2ij} = \cos(2\theta_{ij})$, $E$ is the neutrino energy and $L$ is the baseline.

The first two terms (the *atmospheric* and *CP* terms) are oscillatory functions of $L/E$, with the amplitude of the oscillation being modulated by $\sin(2\theta_{13})$. The CP term has an inverse dependence on the neutrino energy, so that CP violation is most visible at low energies, at the second or third oscillation maxima rather than the first. Therefore a detector with a low energy threshold is desirable; an estimate for the energy threshold of the TASD and LAr detectors is 0.5 GeV which is below the energy of the second oscillation maximum. Conversely, the dominant term at high energies is the atmospheric term, which is how the mass hierarchy can be identified - hence the need for long baselines and high energies. It is these requirements which direct the optimisation of a long-baseline experiment.

## OPTIMISATION OF THE LOW ENERGY NEUTRINO FACTORY

We have studied a setup having a baseline of 1300 km, a beam capable of delivering $1.4 \times 10^{21}$ useful muon decays per year, per polarity, and a running time of 10 years (this is double the duration estimated for the IDS-NF [7]). For the detector we here assume a TASD with a fiducial mass of 20 kton (the LAr detector will be described in the following section), efficiency for $\mu^{\pm}$ detection of 73% below 1 GeV and 94% above, efficiency for $e^{\pm}$ detection of 37% below 1 GeV and 47% above, a background level of $10^{-3}$ on the $\nu_e \rightarrow \nu_\mu$ ($\bar{\nu}_e \rightarrow \bar{\nu}_\mu$) and $\nu_\mu \rightarrow \nu_\mu$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$) channels and a background of $10^{-2}$ on the $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) channels. Work is progressing on producing TASD simulations to assess the ability of the detector to distinguish between $e^-$, $e^+$, $\mu^-$, $\mu^+$ and background pion events.

Relative to previous studies [4, 5] we have increased the muon energy and revised our estimate of the number of muon decays and the energy resolution, and have considered the addition of the platinum channels. We have performed numerical simulations using the GLoBES software [11], marginalising over all parameters and using the oscillation parameters and errors in [12]: $\sin^2\theta_{12} = 0.3$, $\theta_{23} = \pi/4$, $\Delta m_{21}^2 = 8.5 \times 10^{-5}$ eV$^2$, and $|\Delta m_{31}^2| = 2.5 \times 10^{-3}$ eV$^2$ with a 10% uncertainty of the solar parameters, 4% on the atmospheric parameters and 2% on the matter density.

We have increased the muon energy to 4.5 GeV as a result of studying how the number of signal and background events alters with energy: the aim is to maximise the number of oscillating signal events whilst simultaneously keeping the non-oscillating higher energy background to a minimum. We find that an increase in energy from 4.12 GeV to 4.5 GeV produces an increase only in the number of oscillating events, whereas for energies greater than $\sim 5$ GeV, only the background events increase significantly.

A re-optimisation study of the accelerator complex [13] has led to a revised estimate of the number of muon decays, so that it is now possible to have $1.4 \times 10^{21}$ rather than $5.0 \times 10^{20}$ decays per year. This is complemented by an improved energy resolution of 10%.

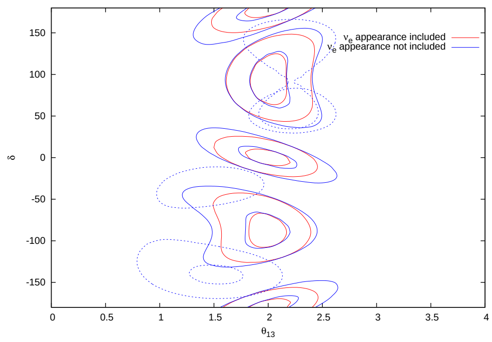


**FIGURE 1.** $5.0 \times 10^{20}$ decays per year, 30% energy resolution

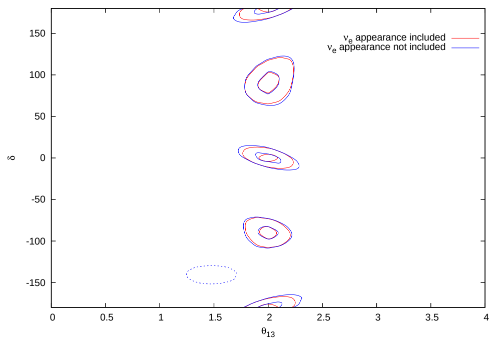


**FIGURE 2.** $1.4 \times 10^{21}$ decays per year, 10% energy resolution

The power of the platinum channels comes from the fact that the degeneracies in the $\theta_{13}$, $\delta$, sign[$\Delta m_{31}^2$] parameter space occur in *different* regions for the golden and platinum channels. Hence the degenerate solutions appearing from one channel can be eliminated by the information from another channel. In particular, in [14] it was shown that the combination of CPT conjugate channels (e.g. $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$) with the *same* baseline is particularly powerful in resolving the hierarchy degeneracy, a technique that the low energy neutrino factory is able to exploit.

The results of these optimisation studies are summarised in Figs. 1 and 2 where we show the $3\sigma$ and $5\sigma$ allowed contours in the $\theta_{13}$-$\delta$ plane when including the platinum channel (red lines) and without this channel (blue lines). The dotted lines correspond to the wrong hierarchy solutions. In Fig. 1 we show the results as obtained from the setup prior to our optimisation, and in Fig. 2 we show the results from our optimised setup. Clearly there is a dramatic improvement in sensitivity to $\theta_{13}$, $\delta$ and sign$[\Delta m^2_{31}]$, which can mainly be attributed to the increase in statistics. Also we observe that the platinum channels significantly improve the performance of the non-optimal setup, whereas for the optimised setup, we observe a much smaller difference, although there is still a little to be gained in terms of hierarchy sensitivity. We conclude that the addition of the platinum channels will be crucial in enabling the low energy neutrino factory to reach its full potential if statistics are limited.

## SIMULATIONS OF A 100 KTON LIQUID ARGON DETECTOR

Recently, there has been growing interest in the idea of a large-scale liquid argon detector. We have thus considered a 100 kton LAr detector as an alternative to the 20 kton TASD. To accommodate the fact that work on this detector technology is still in the preliminary stages, we consider a range of detector parameters, as shown in Table 1. The conservative values are taken from [15] and the optimistic values are the same as those we estimate for the TASD. Studying which of these variables has the dominant effect, we find that the uncertainty in the systematics and energy resolution has a negligible effect in comparison to the effect of altering the $\nu_\mu$ background by a factor of five. The background on the platinum channels does not play any significant effect because we are considering the high-statistics optimised setup described in the previous section, where the addition of the platinum channel does not have much of an impact. Therefore we conclude that it is vital to minimise the $\nu_\mu$ background for this detector to be effective, and to obtain an accurate estimate of its value to enable realistic simulations to be performed.

**TABLE 1.** Conservative and optimistic estimates for a 100 kton liquid argon detector

| | **Conservative** | **Optimistic** |
|---|---|---|
| Efficiency (all channels) | 80% | 80% |
| Systematics | 5% | 2% |
| Energy resolution - QE events | 5% | 5% |
| Energy resolution - non-QE events | 20% | 10% |
| Background - $\nu_\mu$ (dis)appearance | $5\times10^{-3}$ | $1\times10^{-3}$ |
| Background - $\nu_e$ appearance | 0.8 | $1\times10^{-2}$ |

## RESULTS

Here we show how the performance of the optimised low energy neutrino factory compares to that of other experiments - the IDS-NF and T2HK setups as described in [7], and the wide-band beam with a 100 kton LAr detector described in [16]. In Figs. 3, 4 and 5 we show the $\theta_{13}$ discovery potential, CP discovery potential and hierarchy sensitivity, in terms of CP fraction, for these experiments. For $\theta_{13}$ sensitivity, we see that a very aggressive LAr detector can be competitive with the IDS-NF for all values of $\theta_{13}$. For CP discovery, the LENF with either detector will provide comparable sensitivity to the IDS-NF if $\sin^2(2\theta_{13}) > 10^{-2}$, and will be competitive for all values of $\theta_{13}$ if the optimistic LAr detector is the detector of choice. For hierarchy sensitivity, the low energy neutrino factory with its shorter baseline cannot compete with the high energy setup, but it still improves upon the next best competitor (WBB) by an order of magnitude in $\sin^2(2\theta_{13})$.

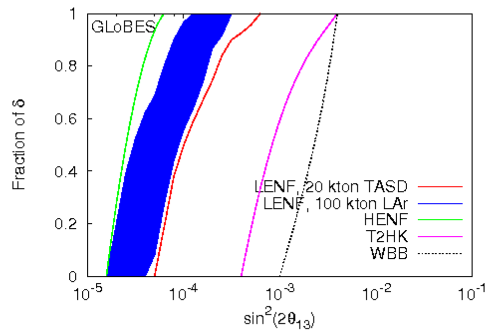


**FIGURE 3.** $\theta_{13}$ discovery potential

This remarkable performance can be attributed to a combination of high statistics, and a baseline which enables a clean measurement of the CP phase but is still sufficiently long to provide some sensitivity to the hierarchy.

## CONCLUSIONS

We have shown that an optimised low energy neutrino factory has excellent sensitivity to the standard oscilla-

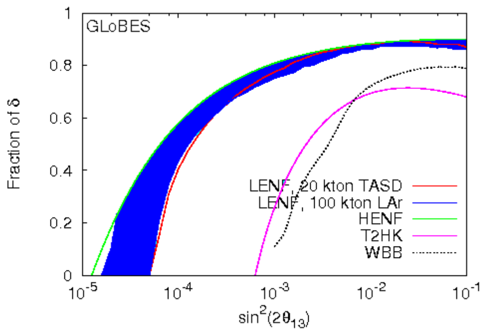


**FIGURE 4.** CP discovery potential

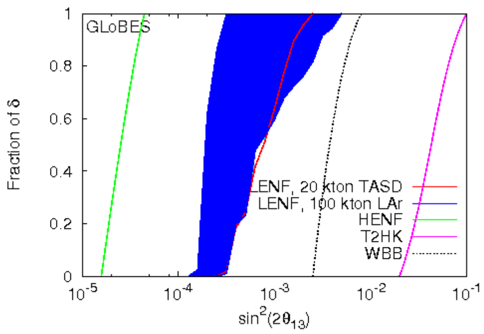


**FIGURE 5.** Hierarchy sensitivity

tion parameters $\theta_{13}$ and $\delta$, for $\sin^2(2\theta_{13}) > 10^{-4}$, and to sign$[\Delta m^2_{31}]$ for $\sin^2(2\theta_{13}) > 10^{-3}$. The sensitivity to $\theta_{13}$ and $\delta$ is comparable to that of the high-energy neutrino factory if $\sin^2(2\theta_{13}) > 10^{-2}$. The low energy neutrino factory is therefore a potential candidate for a next-generation oscillation experiment in the scenario that $\theta_{13}$ is not exceedingly small, $\sin^2(2\theta_{13}) > \text{few} \times 10^{-4}$.

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