Optimisation of the Low-Energy Neutrino Factory

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Invisibles ITN pre-meeting – *Universidad Autónoma de Madrid*

29 March 2012

Outline of talk

Long-baseline (LBL) experiments and the LENF

Simulation details

Discovery Potential

- CP-Violation

What next?

Conclusions

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Aims of the next generation of LBL experiments

$\theta_{13} = 0$?

Is the remaining unknown mixing angle zero (if not, by how much)?

$\delta_{CP} \in \{0, \pi\}$?

Does the leptonic sector exhibit CP-violation?

$\Delta m^2_{13} > 0$?

What is the true hierarchy of neutrino masses?

$\theta_{12},\ \theta_{23},\ \theta_{13},$
$\Delta m^2_{12},\ \Delta m^2_{13},\ \delta_{CP}$

Is that all there is? Do we need to extend the 3ν-mixing paradigm?

Aims of the next generation of LBL experiments

DONE!

T2K, MINOS, Double Chooz and Daya Bay all measure non-zero θ_{13}.

$\delta_{CP} \in \{0, \pi\}$?

Does the leptonic sector exhibit CP-violation?

$\Delta m^2_{13} > 0$?

What is the true hierarchy of neutrino masses?

$\theta_{12},\ \theta_{23},\ \theta_{13},$
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Is that all there is? Do we need to extend the 3ν-mixing paradigm?

The neutrino factory

- Neutrino Factories are long-baseline oscillation experiments which produce neutrinos from the decay of stored muons.

- The neutrino factory primarily studies wrong-sign muon events (the *golden channel*).

$$\mu^- \longrightarrow e^- + \nu_\mu + \overline{\nu_e} \rightsquigarrow \overline{\nu_\mu}$$
$$\nu_\mu \longrightarrow \nu_\mu$$

- Standard NF design[1] has a stored muon energy of $E_\mu = 25\,\text{GeV}$ and two baselines: one given by $L_1 \approx 4000\,\text{km}$ and the other by $L_2 \approx 8000\,\text{km}$.

[1] IDS-NF: *Interim Design Report* (IDS-NF-020)

Low-energy neutrino factory

- Especially for large θ_{13}, a Low-Energy Neutrino Factory (LENF)[1] may be able to provide a good alternative.
- Typical configuration[2]: $E_\mu = 4.5\,\mathrm{GeV}$ and $L = 1300\,\mathrm{km}$.
- Strong sensitivity for key measurements thanks to the rich oscillation spectrum at low energies. This reduces the effect of degeneracies in the signal and allows a clean inference of the parameters.
- Thanks to the low-energy signal, the LENF is expected to offer good sensitivities with a single baseline.

[1] Geer *et al.* Phys. Rev. D **75** (2007)

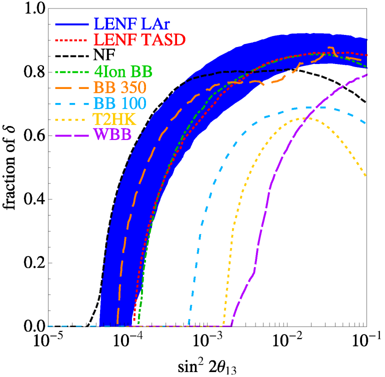
[2] Fernández Martínez *et al.* Phys. Rev. D **81** (2009)

What is known about the LENF: detectors

- The optimal detector technology for the LENF is unknown.
- As the LENF focuses on the low-energy spectrum is is vital that the detector has excellent energy resolution and a low threshold energy. Accurate measurement of the signal of wrong- and right-sign muons requires good charge identification.
- Possible magnetized candidates are the Magnetized Iron Neutrino Detector (MIND), Totally Active Scintillator Detector (TASD) and a liquid Argon detector (LAr).
- It may also be possible to have a large non-magnetized detector (*e.g* LAr or Čerenkov) which exploits statistical methods to determine particle charges[1]. However, large backgrounds ultimately reduce the sensitivity.

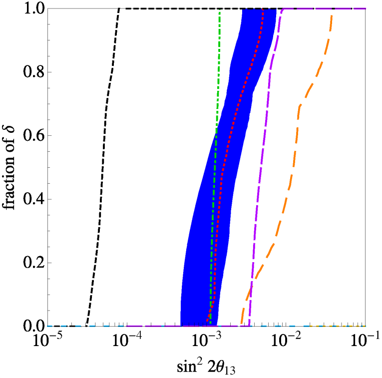
[1] Huber, Schwetz Phys.Lett. **B669** (2008)

What is known about the LENF: performance



CP Violation Discovery Comparison

- For $\sin^2 2\theta_{13} \gtrsim 10^{-2}$, LENF appears to offer equivalent or superior performance to standard NF for key measurements.



Hierarchy Discovery Comparison

- Potential of the LENF is evident: how can we make the most of it?

Plots: Fernández Martínez *et al.* Phys. Rev. D **81** (2009)

Outline of talk

Simulation details

- Using GLoBES[1], we studied the performance of the LENF over the range $1000 \leq L \leq 4000\,\text{km}$ and $4 \leq E_\mu \leq 25\,\text{GeV}$.
- We assumed normal mass hierarchy and 10^{21} useful muon decays per year over a runtime of $5 + 5$ years.
- Our model of a 20 kt TASD[2] has a detection efficiency of 72% below 1 GeV and 94% above with an energy resolution of 10%. Backgrounds are 0.1% of charge misidentification and neutral current events.
- Our model of an optimistic 100 kt LAr detector has a flat detection efficiency of 80%, 10% energy resolution and backgrounds of 0.1% of charge misidentification and neutral current events.

[1] Huber *et al.* Comp. Phys. Comm. **167** (2005)

[2] IDS-NF: *Interim Design Report* (IDS-NF-020)

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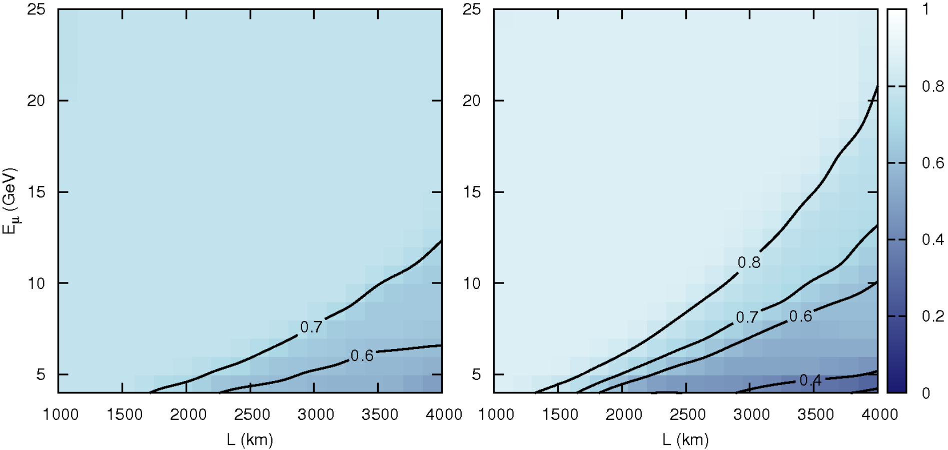
CP-Violation discovery fraction TASD

Discovery: when all parameter sets with $\delta \in \{0, \pi\}$ are ruled out at the 3σ CL.



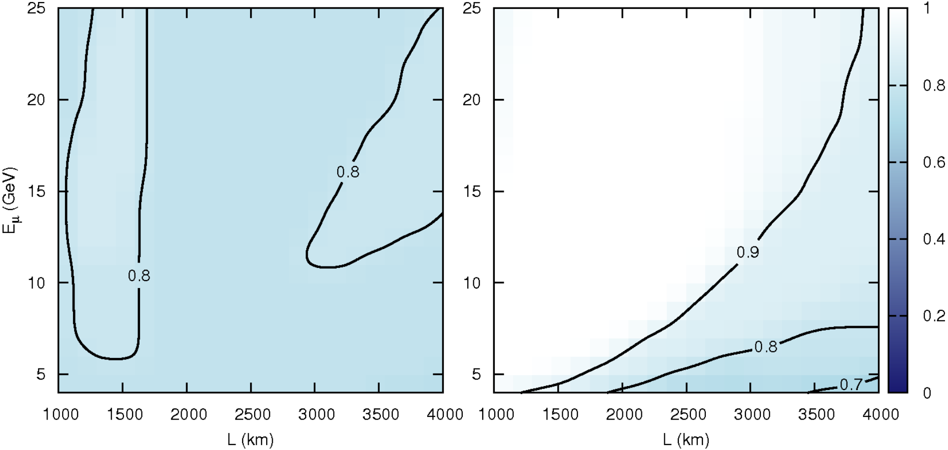
(d) $\sin^2 2\theta_{13} = 10^{-1}$

(e) $\sin^2 2\theta_{13} = 10^{-2}$

PB, Pascoli: hep-ph/1201.6299

CP-Violation discovery fraction LAr (opt)

Discovery: when all parameter sets with $\delta \in \{0, \pi\}$ are ruled out at the 3σ CL.



(f) $\sin^2 2\theta_{13} = 10^{-1}$ (g) $\sin^2 2\theta_{13} = 10^{-2}$

PB, Pascoli: hep-ph/1201.6299

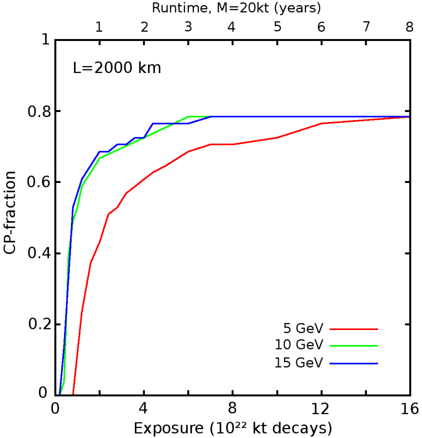
CP-fraction and *exposure*

- Defined by

$$\text{Exposure} = (\text{Detector mass}) \times \begin{pmatrix} \text{Number of useful} \\ \text{muon decays per year} \end{pmatrix} \times (\text{Runtime})\,.$$

- Setting θ_{13} to the Daya Bay best-fit value, we plot the discovery fraction as a function of exposure for the TASD detector and $L = 2000\,\text{km}$.

- The CP-fraction rises quickly until it saturates due to systematic errors. The lower-E_μ configuration still reaches the saturation point but requires $2 - 3$ times higher exposure.



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- In light of T2K, MINOS and Daya Bay, the traditional discovery searches should no longer be the sole concern when studying future LBL experiments.
- We must decide which questions we would like to ask. Fortunately, there is no shortage of effects which may influence LBL physics:

$$\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

Non-Standard Interactions?

$$L \sim \underline{\mathbf{3}} \qquad \zeta' \sim \underline{\mathbf{1}}'$$

$$\mathcal{L}_{M_\nu} \supset y(LL)''\zeta'$$

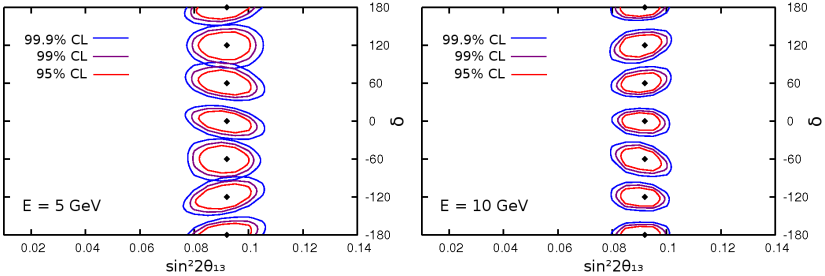
Flavour symmetries?

$$\nu_S$$

Sterile neutrinos?

Precision parameter determination

- One way to begin addressing these questions (and others) is to make precision measurements of the neutrino oscillation parameters.
- A full precision study of the LENF is currently underway (see also Coloma *et al.* 1203.5651). Here, we present some examples of the precision attainable for certain benchmark configurations.
- We plot the sensitivity of the LENF to $\sin^2 2\theta_{13}$ for different values of δ. The simulation uses the TASD detector and $L = 2000\,\text{km}$.



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Conclusions

- The Low-Energy Neutrino Factory is an attractive option for a next-generation facility capable of both discovery and precision physics.
- As L and E_μ vary, we generally see CP discovery fractions of 70 to 90% for $\sin^2 2\theta_{13} \gtrsim 10^{-2}$.
- By choosing the right beam energy, we may be able to reduce the required exposure before we reach saturation for measurements of CP-violation.
- If not measured already, hierarchy determination is predicted to always be possible for $\sin^2 2\theta_{13} \gtrsim 10^{-2}$.
- A precision study of the LENF at large θ_{13} is underway. Initial simulations suggest the ability to determine $\sin^2 2\theta_{13}$ to within $\sim 5\%$.

Thank you.