Optimisation of the Low-Energy Neutrino Factory

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Outline of talk

Long-baseline (LBL) experiments and the LENF

Simulation details

Results
  CP-Violation
  Hierarchy determination

Recent hints of $\theta_{13}$

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?
Low-energy neutrino factory

- Especially if $\theta_{13}$ is large, a Low-Energy Neutrino Factory (LENF)\textsuperscript{[1]} may be able to provide a good option.

- Typical configuration\textsuperscript{[2]}: $E_\mu = 4.5$ GeV and $L = 1300$ 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.


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 it 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\[1\].

What is known about the LENF: performance

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

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

Optimization of the LENF

One of the important optimization tasks for the LENF is to understand how the physics reach depends upon the baseline distance $L$ and the stored-muon energy $E_\mu$.

As the previous talk has shown, there is now an understanding\[1\] of how the performance of a NF with the MIND performs over a large $L - E_\mu$ parameter space including values traditionally associated with the LENF.

However, if we want to extract the best performance at low-energies, this parameter space also needs to be understood for the T ASD and LAr detectors which are expected to have lower threshold energies and better energy resolutions in the low-energy region.

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- Using GLoBES\cite{Huber}, we studied the performance of the LENF over the range $1000 \leq L \leq 4000$ km and $4 \leq E_\mu \leq 25$ 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\cite{IDS-NF} 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.


\[2\] IDS-NF: \textit{Interim Design Report} (IDS-NF-020)
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Discovery: when all parameter sets with $\delta \in \{0, \pi\}$ are ruled out at the $3\sigma$ CL.

CP-Violation discovery fraction

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

\[ \sin^2 2\theta_{13} = 10^{-2} \]

\[ \sin^2 2\theta_{13} = 10^{-3} \]

PB, Huber and Pascoli: *in preparation.*
Some terminology

- For the determination of hierarchy, the discovery contours are relatively narrow in $\theta_{13}$. Discovery fraction alone isn’t very informative and instead we report discovery limits.

- The **100% discovery limit** is the smallest value of $\sin^2 2\theta_{13}$ for which all higher values have discovery fractions of 100%.

- The **0% discovery limit** provides the complementary information, it is the smallest value of $\sin^2 2\theta_{13}$ for which there is any non-zero discovery fraction.
Hierarchy determination

**Discovery:** when all parameter sets with the wrong hierarchy are ruled out at $3\sigma$ CL.

(h) 100% discovery limit

(i) 0% discovery limit

PB, Huber and Pascoli: *in preparation.*
Hierarchy determination

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Hierarchy determination with a *bimagic* baseline?

- It has been claimed that there is particular sensitivity to the hierarchy for $L = 2540 \text{ km}$ and $E_{\mu} = 5 \text{ GeV}$.

- At two distinct points in the spectrum, the oscillation probability is large for one hierarchy and small for the other. This produces a significant contrast in expected distributions.

- Can this be exploited at the NF?

Dighe *et al.* Phys. Rev. Lett 105 (2010);
See also: Raut *et al.* Phys. Lett. B 696 (2011) and Joglekar *et al.* 1011.1146
Performance of the *bimagic* baseline

- Low-energy peak in 0% discovery fraction at $L \approx 2600$ km.
- 100% discovery reach shows little variation.
- Higher energies and baselines offer further improvements as the low-energy information isn’t lost as the stored muon energy increases.

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After T2K and MINOS’s recent results are included, the global analysis of oscillation data\cite{1} excludes a zero value of $\theta_{13}$ at $3\sigma$ significance. The $1\sigma$ range is given by:

$$0.071 < \sin^2 2\theta_{13} < 0.124.$$ 

The best-fit value is very close to $\sin^2 2\theta_{13} = 10^{-1}$. Around these values, the CP-violation discovery fraction is expected to be $70 - 80\%$ for almost all of the parameter space.

Furthermore, in the $1\sigma$ interval, the hierarchy can be determined for the entirety of the parameter space for all of the detectors in our simulation.

\cite{1} Fogli et al. hep-ph/1106.6028
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- The Low-Energy Neutrino Factory can offer competitive discovery reach for key measurements compared to traditional NF designs for large $\theta_{13}$.

- Generically, we expect CP discovery fractions of 60 to 90% for $\sin^2 2\theta_{13} \gtrsim 10^{-3}$. This holds for all configurations provided extremal regions are avoided.

- Hierarchy determination is predicted for $\sin^2 2\theta_{13} \gtrsim 10^{-2}$ and potentially for as low as $\sin^2 2\theta_{13} \gtrsim 4 \times 10^{-4}$. There is a clear bias towards longer baselines.

- For large $\theta_{13}$, optimization is relatively straightforward. Performance in this region is close to optimal and this is almost independent of the exact choice of $L$ and $E_\mu$. However, a fuller understanding of the systematics involved must be developed.
Thank you.