Optimisation of the Low-Energy Neutrino Factory

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NuFact 11 – *XIIIth International Workshop on Neutrino Factories, Superbeams and β-beams*

3 August 2011

Outline of talk

Long-baseline (LBL) experiments and the LENF

Simulation details

Results

- CP-Violation
- Hierarchy determination

Recent hints of θ_{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 θ_{13} is large, a Low-Energy Neutrino Factory (LENF)[1] may be able to provide a good option.
- Typical configuration[2]: $E_\mu = 4.5\,\text{GeV}$ and $L = 1300\,\text{km}$.
- 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.

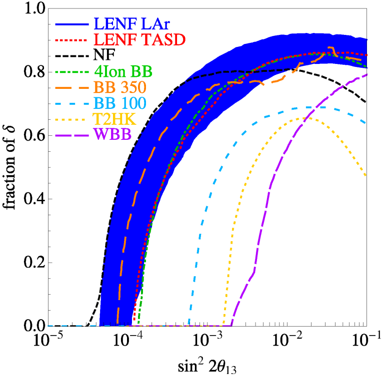
[1] Geer *et al.* Phys. Rev. D **75** (2007)
[2] Fernández Martínez *et al.* Phys. Rev. D **81** (2009)

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].

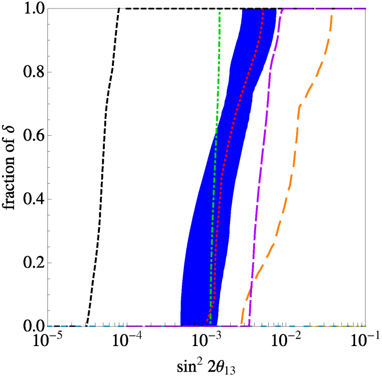
[1] Huber, Schwetz Phys.Lett. **B669** (2008)

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)

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_μ.

- 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 TASD and LAr detectors which are expected to have lower threshold energies and better energy resolutions in the low-energy region.

[1] Agarwalla *et al.* JHEP **1101** 120 (2011)

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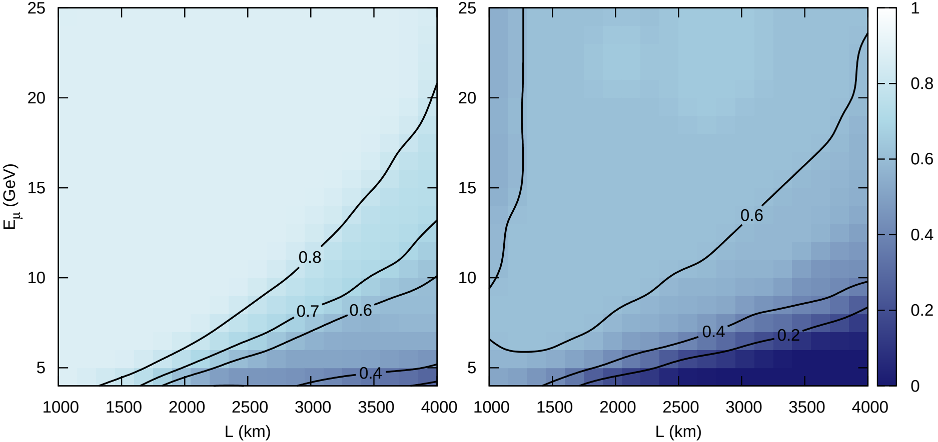
- Using GLoBES[1], we studied the performance of the LENF over the range $1000 \leq L \leq 4000\,\text{km}$ and $4 \leq E_\mu \leq 25\,\text{GeV}$.
- We assumed normal mass hierarchy and 10^{21} useful muon decays per year over a runtime of $5 + 5$ years.
- Our model of a 20 kt TASD[2] has a detection 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)

Outline of talk

CP-Violation discovery fraction TASD

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

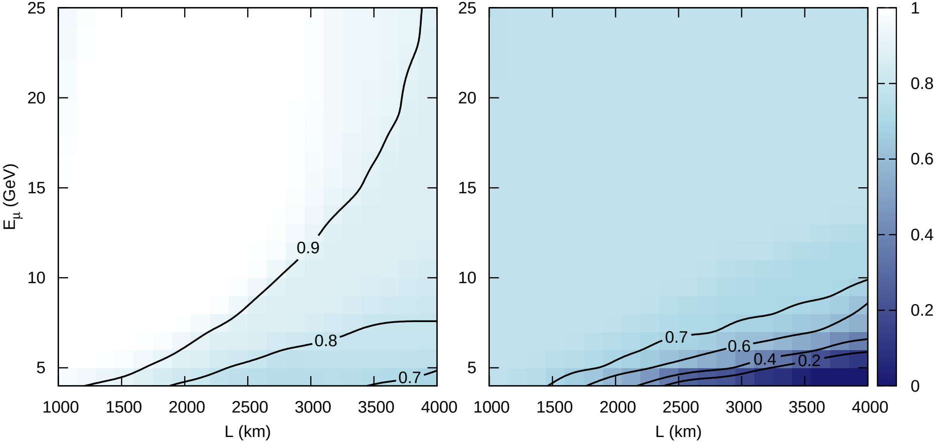


(d) $\sin^2 2\theta_{13} = 10^{-2}$ (e) $\sin^2 2\theta_{13} = 10^{-3}$

PB, Huber and Pascoli: *in preparation*.

CP-Violation discovery fraction LAr (opt)

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

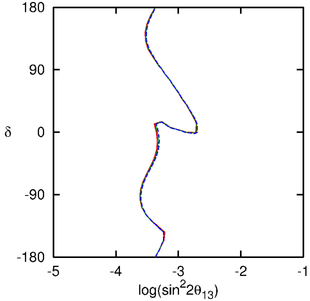


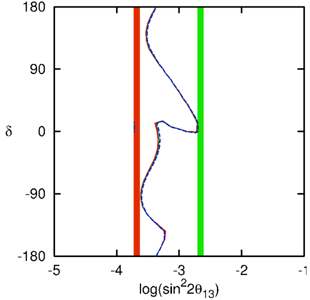
(f) $\sin^2 2\theta_{13} = 10^{-2}$ (g) $\sin^2 2\theta_{13} = 10^{-3}$

PB, Huber and Pascoli: *in preparation*.

Some terminology

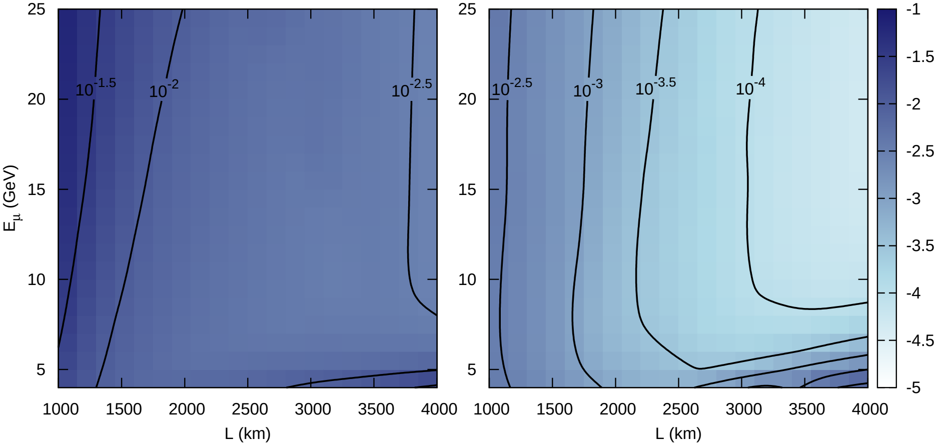
- For the determination of hierarchy, the discovery contours are relatively narrow in θ_{13}. Discovery fraction alone isn't very informative and instead we report discovery limits.
- The 100% discovery limit is the smallest value of $\sin^2 2\theta_{13}$ for which *all* higher values have discovery 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 3σ CL.



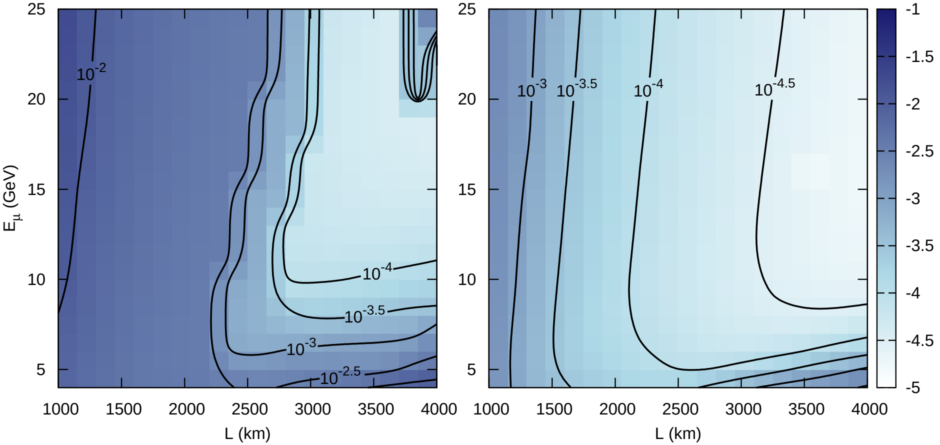
(h) 100% discovery limit

(i) 0% discovery limit

PB, Huber and Pascoli: *in preparation*.

Hierarchy determination LAr (opt)

Discovery: when all parameter sets with wrong hierarchy are ruled out at the 3σ CL.



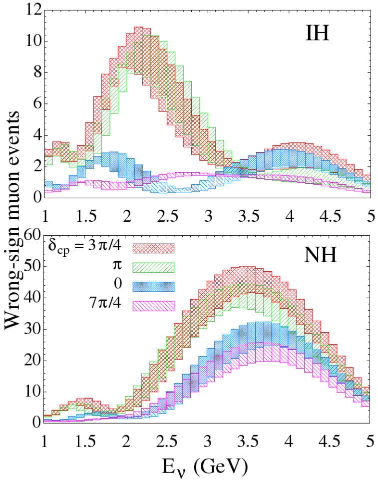
(j) 100% discovery limit

(k) 0% discovery limit

PB, Huber and Pascoli: *in preparation*.

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?

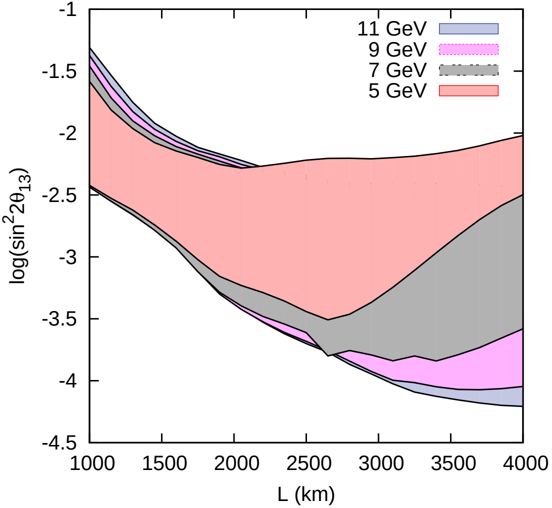


Dighe *et al.* (2010)

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 $L \approx 2600\,\text{km}$.
- 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.

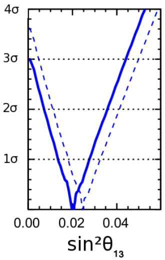
PB, Huber and Pascoli: *in preparation*.

Outline of talk

Recent hints of θ_{13}

- After T2K and MINOS's recent results are included, the global analysis of oscillation data[1] excludes a zero value of θ_{13} at 3σ significance. The 1σ 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 1σ interval, the hierarchy can be determined for the entirety of the parameter space for all of the detectors in our simulation.

[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 θ_{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 θ_{13}, optimization is relatively straightforward. Performance in this region is close to optimal and this is almost indpendent of the exact choice of L and E_μ. However, a fuller understanding of the systematics involved must be developed.

Thank you.