The Low Energy Neutrino Factory

Tracey Li
IPPP, Durham University

NuFact09
Illinois Institute of Technology, Chicago
21st July 2009

In collaboration with: Alan Bross, Malcolm Ellis, Enrique Fernandez-Martinez, Steve Geer, Olga Mena and Silvia Pascoli

Introduction

Future long-baseline experiments are primarily designed to measure:

- δ (CP violating phase)
- θ_{13} (third mixing angle)
- Sign of Δm^2_{31} (mass hierarchy)

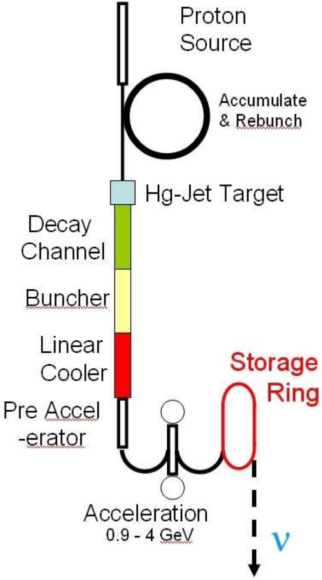
We are optimizing the low energy neutrino factory to measure these parameters.

This talk will cover:

- The experiment set-up
- Physics of neutrino oscillations
- Results for a TASD and preliminary results for a LAr detector
- Summary

Overview of the low energy neutrino factory

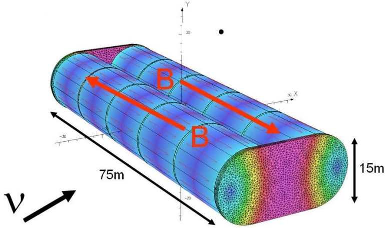
- Create an intense source of $\mu^{\pm}$.
- Cool the $\mu^{\pm} \Rightarrow$ 70% increase in flux.
- Accelerate them to energies of $E_{\mu} \sim 5$ GeV.
- Inject into a storage ring where the muons decay: $\mu^{\pm} \rightarrow e^{\pm}\nu_e(\bar{\nu}_e)\bar{\nu}_{\mu}(\nu_{\mu})$
- Detect the neutrinos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

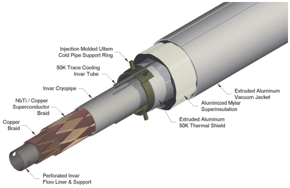


[A. Bross]

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 $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$.





The set-up

For the LENF beam set-up we assume:

- 1.4×10^{21} μ^+ and μ^- decays per year

  [C. Ankenbrandt et al. FERMILAB-PUB-09-0010APC (2009)]

- 10 years running

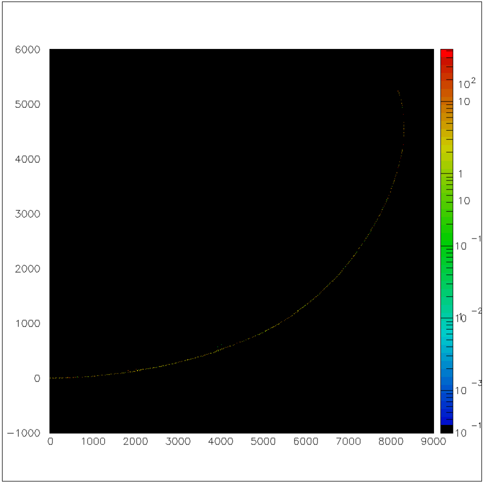
For the TASD we assume:

- $\mu^{\pm}$ 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%

TASD simulations

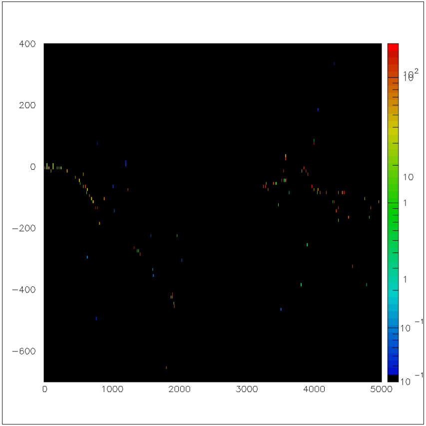
The TASD can distinguish $\mu^{\pm}$, $e^{\pm}$ and pions (work in progress).

μ^{-} (2700 MeV/c):

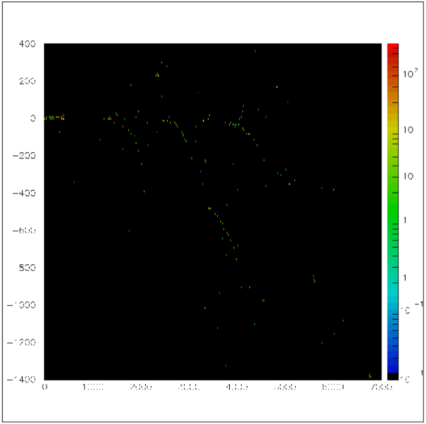


TASD simulations

e^{+} (1200 MeV/c):



π^{-} (2600 MeV/c):



Physics of LBL ν oscillations

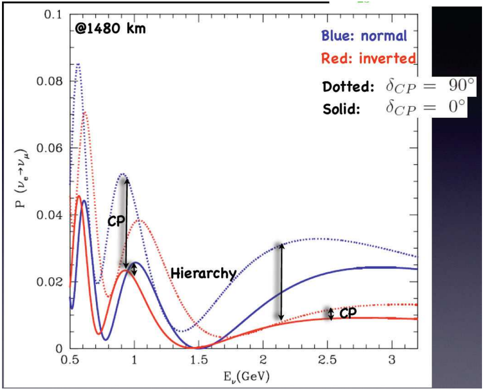
- The 'golden channel' is the $\nu_e \rightarrow \nu_\mu$ channel:
  [A. Cervera et al, 'Golden measurements at a neutrino factory']

$$
\begin{aligned}
P(\nu_e \rightarrow \nu_\mu) &= s_{213}^2 s_{23}^2 \left(\left(1 + \frac{4EA}{\Delta m_{31}^2}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - AL \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \cos\left(\frac{\Delta m_{31}^2 L}{4E}\right)\right) \\
&+ \alpha s_{213} s_{212} s_{223} \frac{\Delta m_{31}^2 L}{4E} \left(\left(1 + \frac{2EA}{\Delta m_{31}^2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{AL}{2} \cos\left(\frac{\Delta m_{31}^2 L}{4E}\right)\right) \cos\left(\frac{\Delta m_{31}^2 L}{4E} - \delta\right) \\
&+ \alpha^2 c_{23}^2 s_{212}^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right)^2
\end{aligned}
$$

.

- 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

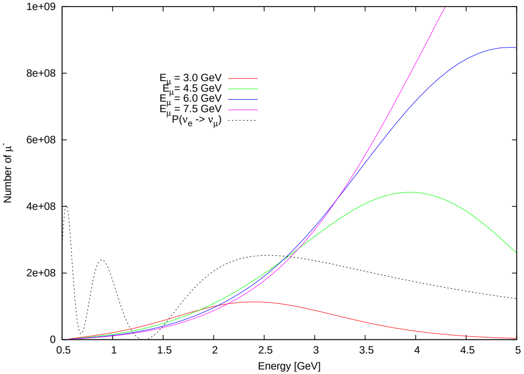


[O. Mena]

- 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.

Optimization: muon energy

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



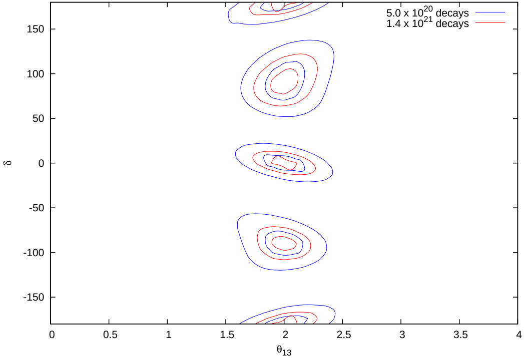
GLoBES 3.0

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

Optimization: statistics

- One advantage of the LENF is its high statistics.
- Compare the results using 5.0×10^{20} $\mu^{\pm}$ decays per year (blue) and 1.4×10^{21} decays (red):

1σ and 3σ contours in $\theta_{13} - \delta$ plane:

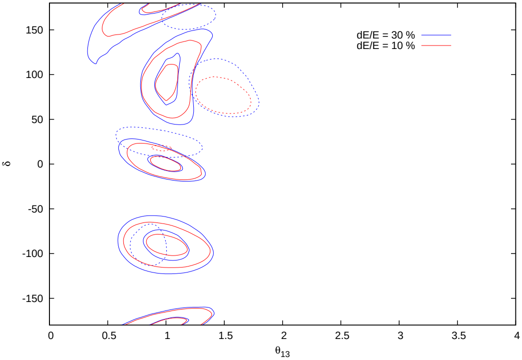


GLoBES 3.0 [A. Bross et al, in preparation]

- ⇒ Statistics are very important for the LENF.

Optimization: energy resolution

- The better the energy resolution, the more accurately the oscillation spectrum can be determined.
- For 1.4×10^{21} decays, gain significant improvement in going from $dE/E = 30\%$ to 10%:

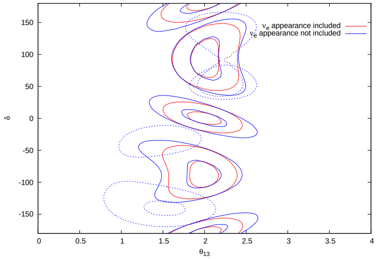


GLoBES 3.0 [A. Bross et al, in preparation]

The $\overset{(-)}{\nu}_e$ appearance channel

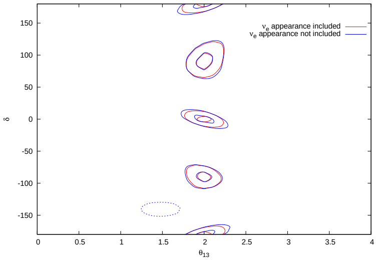
- If the set-up is not optimized, the $\overset{(-)}{\nu}_e$ appearance channel increases sensitivity to θ_{13}, δ and the mass hierarchy (left).
- With optimized E_μ, statistics and energy resolution, the additional channel helps only with the hierarchy determination (right).

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



GLoBES 3.0

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



[A. Bross et al, in preparation]

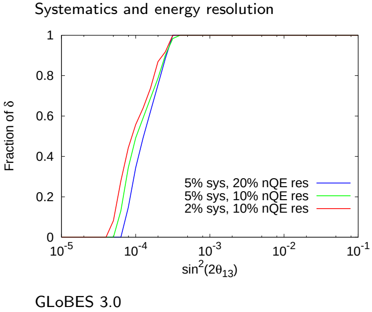
Liquid argon detector

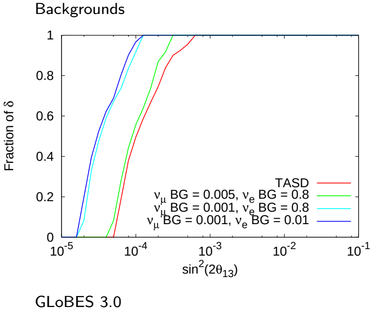
- LAr simulations are still in early stages
  $\Rightarrow$ large uncertainties in experimental parameters
- Consider two extreme scenarios for a 100 kton LAr detector:

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

[B. Fleming - private communication reported in hep-ph/0703029]

Check the effect of systematics, energy resolution and backgrounds individually, on θ_{13} discovery potential:

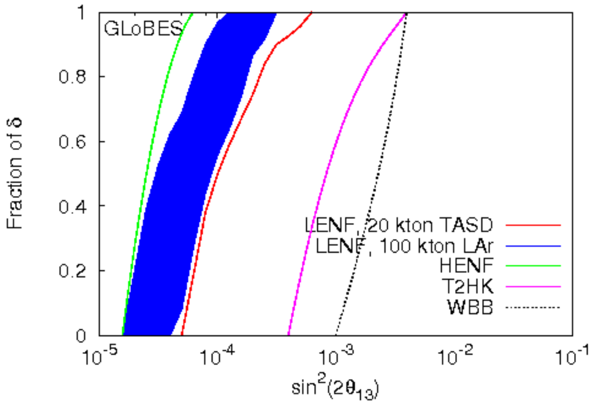




$\Rightarrow$ The background on the ν_μ (dis)appearance channels has the dominant effect.

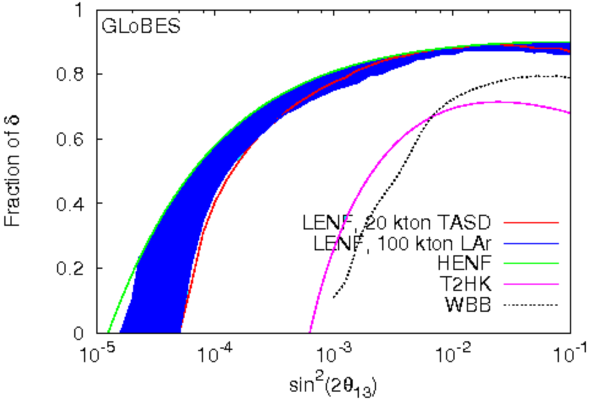
Comparison with other experiments

Compare LENF results (TASD and LAr) with those for the HENF, T2HK (ISS report [0710.4947]) and **WBB** ([hep-ph/0703029]) for θ_{13} **discovery potential** (3σ):



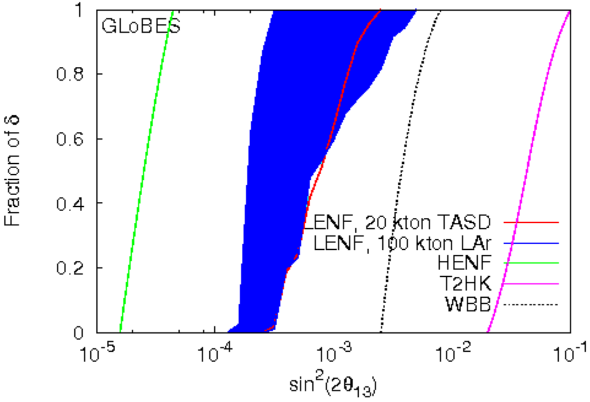
Comparison with other experiments

Compare LENF results (TASD and LAr) with those for the HENF, T2HK (ISS report [0710.4947]) and **WBB** ([hep-ph/0703029]) for **CP discovery potential** (3σ):



Comparison with other experiments

Compare LENF results (TASD and LAr) with those for the HENF, T2HK (ISS report [0710.4947]) and **WBB** ([hep-ph/0703029]) for **hierarchy sensitivity** (3σ):



Summary

- We have simulated the following LENF set-up, optimized 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} down to $\sin^2(2\theta_{13}) \simeq 10^{-4}$, to CP violation for $\sin^2(2\theta_{13}) \gtrsim 10^{-4}$, and to the mass hierarchy for $\sin^2(2\theta_{13}) \gtrsim 10^{-3}$.

- Future detailed studies of TASD and LAr detector performance will allow a full assessment of the capabilities of the set-up.

Appendix: Experiment details

- **HENF**: $E_\mu = 20$ GeV, 10^{21} decays/ year, 2% systematics, 5 years in μ^- mode + 5 years in μ^+ mode.
  Detectors: 50 kton MIND @ 4000 km and 7500 km, threshold = 1 GeV, efficiency = 50%.

- **T2HK**: 4 MW, 50 GeV protons, 2 years ν + 8 years $\bar{\nu}$.
  Detector: 440 kton WC @ 295 km, 2^0 off-axis.

- **WBB**: 120 GeV protons, 10^{21} PoT/ year, 5% systematics, 5 years @ 1 MW (ν) + 5 years @ 2 MW ($\bar{\nu}$).
  Detector: 100 kton LAr.