Low or High Energy NF?

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What we want to learn

In neutrino (oscillation) physics the open questions are

- Size of $\theta_{13}$
- $\theta_{23} = \pi/4$?
- Mass hierarchy aka sign of $\Delta m^2$
- CP violation
- New physics

Theory can provide no ordering of these, it depends on the model which one is the most important one.
Oscillations 101

- Size of $\theta_{13} - \nu_e \rightarrow \nu_e$ (reactors) or $\nu_e \rightarrow \nu_\mu$ or $\nu_\mu \rightarrow \nu_e$

- $\theta_{23} = \pi/4? - \nu_\mu \rightarrow \nu_\mu$, maybe $\nu_\mu \rightarrow \nu_\tau$

- Mass hierarchy aka sign of $\Delta m^2$ – matter effect, $\nu_e \rightarrow \nu_\mu$ or $\nu_\mu \rightarrow \nu_e$

- CP violation $\nu_e \rightarrow \nu_\mu$ or $\nu_\mu \rightarrow \nu_e$

- New physics $\nu_e \rightarrow \nu_\mu$ or $\nu_\mu \rightarrow \nu_e$ and $\nu_\tau$ appearance at short distances

Most of these oscillation modes are accessible with a neutrino factory!
This requires a detector which can distinguish $\mu^+$ from $\mu^-$ ⇒ magnetic field of around 1T

- above 3 GeV – iron calorimeter like MINOS
- below 3 GeV – magnetized, totally active, fine grained scintillator
The Issue

![Graph showing the efficiency of neutrino detection as a function of neutrino energy. The graph includes curves for different distances, such as 1300km and 4000km, and different neutrino detectors, such as LENA, IDS 1.0, and 2006 HENF. The efficiency is plotted on the y-axis, and the neutrino energy is plotted on the x-axis.](image-url)
Magnetized iron detector

- iron core magnet
- high target density
- short muon tracks
- most of the detector mass is passive

This results in

- requires a relative long muon track
- puts a severe constraint on the lowest neutrino energy
- mediocre energy resolution
- target mass limited to $\sim 100 \text{ kt}$
- high luminosity, high energy 25 GeV neutrino source
Re-analysis of detection threshold of MIND led to a reduction in muon energy from 50GeV to 25GeV.
HENF

TASD

- Fully active
- Minerva-like design
- Magnetized

This results in

- High efficiency
- Very low neutrino threshold $\sim 0.5$ GeV
- Excellent neutrino energy resolution $\sim 10\%$
- Potential to charge ID electrons

NB A liquid Argon detector could provide the same benefits at a lot less electronics channels (=larger mass)
LENF

- 20 kt
- efficiencies from Bross et al. arXiv:0911.3776v1
- includes platinum channel
- 0.7E21 muons per year and 0.7E21 anti-muons per year
- 4.5 GeV
- 10 years @ 1E7s
- 3 sigma results
LENF – CP

Bross et al., arXiv:0911.3776v1
LENF – mass hierarchy

Bross et al., arXiv:0911.3776v1
Hints for $\theta_{13} \neq 0$


$$\sin^2 \theta_{13} = 0.016 \pm 0.010 \text{ or } \sin^2 2\theta_{13} = 0.06 \pm 0.04$$

MINOS’ first $\nu_e$ appearance results
35 events seen vs $27 \pm 5 \pm 2$ expected for $3.14 \cdot 10^{20}$ pot
From hints to the hunt for $\theta_{13}$

Timeline

- **Double Chooz**: Start 09/2009, 1.5 yr with FD only, then ND+FD, 5 years total *Talk by S. Peeters, NOW 2008*
- **RENO**: Start 06/2010, ND+FD, 5 years *Talk by Y. Oh, NOW 2008*
- **Daya Bay**: 7/2011 all modules, *Talk by R. McKeown, CIPANP 09*
- **T2K**: 09/2009 - 12/2012: 0 MW - 0.75 MW linear, neutrinos only *Talk by H. Kakuno, NOW 2008*
- **NOvA**: 08/2012 - 01/2014: 2.5 kt - 15 kt linear, 1/2 neutrinos & 1/2 antineutrino *Talk by M. Messier, ICHEP08*
$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)

Current bound (3σ)

- Double Chooz
- T2K
- RENO
- Daya Bay
- NO$\nu$A: $\nu + \bar{\nu}$
- NO$\nu$A: $\nu$ only

HENF or LENF?

![Graphs showing the relationship between baseline, muon energy, and sin^2 2θ_{13} for different values of sin^2 2θ_{13}.]
The Issue
Matter density

\[ \sin^2 2\theta_{13} = 0.04 \]

Platinum

\[
sin^2 2\theta_{13} = 0.04
\]

- LENF
- LENF + platunium

HENF and LENF!


- LENF
- Upgrade to 25GeV and addition of 4000km baseline
- Addition of 7500km baseline
New Physics

Kopp, Ota, Winter, PRD78:053007, 2008
High energies are crucial!
New Physics

Antusch et al., PRD80:033002,2009
Large (!) near detector is crucial!
Summary

HENF vs LENF discussion is driven by

- boundary conditions (e.g. FNAL-DUSEL distance)
- detector technology
- Oscillation physics over a large range of the parameter space does not prefer one or the other – a very good detector helps at any energy
- New physics searches require energies significantly above \( \tau \)-production threshold

It seems that a LENF can be upgraded to higher energies in a straightforward and effective manner