Exploring the Physics Reach of a Low Energy Neutrino Factory

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Introduction

My work is part of the EUROnu Design Study entitled ‘A High Intensity Neutrino Oscillation Facility in Europe.’

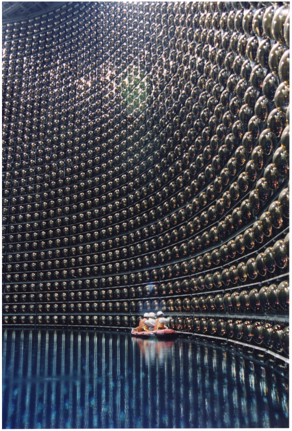
The primary aims are to study three possible future neutrino oscillation facilities (superbeam, neutrino factory, β-beam) for Europe and do a cost and performance comparison.

I look at the physics performance of a low-energy neutrino factory.

Current status of ν oscillation experiments

The current generation of ν oscillation experiments have made the following measurements of the ν mixing parameters:

- $\theta_{12} \approx 33.5^o$
- $\theta_{23} \approx 45^o$
- $\theta_{13} \leq 12.7^o$
- $\Delta m^2_{21} \approx 7.65 \times 10^{-5}\mathrm{eV}^2$
- $|\Delta m^2_{31}| \sim |\Delta m^2_{32}| \approx 2.40 \times 10^{-3}\mathrm{eV}^2$
- No information about δ.



Super-Kamiokande experiment, Japan
From Fermilab website www.fnal.gov

Aims of future oscillation experiments

- At present there are no favoured theories explaining the values of several SM parameters in the quark and lepton sectors $\longrightarrow$ the flavour problem.
- It is important to measure these parameters so that we can progress with theoretical model-building and try to solve the problem.
- The next generation of ν experiments have been designed to measure θ_{13}, δ and $\text{sign}(\Delta m^2_{31})$.
- Why are these parameters so important?

Unknown ν parameters: θ_{13}, δ, sign(Δm^2_{31})

- We know that θ_{13} is small. If $\theta_{13} = 0$ this indicates that a $\mu - \tau$ symmetry is present.
- δ is the CP violating phase. We know there's CP violation in the quark sector. If there is CP violation in the lepton sector, this could explain the matter/ anti-matter asymmetry of the universe.
- The sign of Δm^2_{31} tells us which ν is the heaviest. Is the mass ordering the same as for the quark sector, or is it inverted?

Beyond the Standard ν Model

- ν oscillations have been known about for over a decade and are part of what's now called the 'Standard ν model'
- But we haven't made much theoretical progress regarding mixing and flavour...
  $\Rightarrow$ Look for physics beyond the Standard ν Model to help us understand what's going on: CPT-violation, sterile ν's, non-standard interactions (NSI's)...

NSI's: a brief introduction

- An NSI is any interaction involving ν other than SM interactions and ν oscillations$\Rightarrow$ flavour-changing ν interactions $\nu_\alpha \to \nu_\beta$.
- Theories which predict these also predict flavour-changing charged-lepton interactions $\ell_\alpha^- \to \ell_\beta^- \sim \epsilon_{\alpha\beta}$.

Detecting NSI's with ν oscillation experiments

- People try to detect FC lepton interactions in B-physics experiments
  e.g. BaBar looks for $\tau^- \to \mu^- \gamma$.
  Square the rate to get the probability $\sim \epsilon^2$
- In ν oscillation experiments, this flavour change can occur either through an oscillation, or through a NSI:
  $\nu_\tau \to \nu_\mu \sim P_{osc}$ OR $\nu_\tau \to \nu_\mu \sim |\epsilon_{\tau\mu}|$
  Add, then square to get the probability
  $\Rightarrow$ There is an interference term $\sim \epsilon$.

The Neutrino Factory

Candidates for future ν experiments are: superbeams, β-beams, ν factories

The ν factory concept

- Create an intense source of $\mu^{\pm}$
- Accelerate them to energies of several GeV
- Inject into a storage ring with long straight sections where the muons decay:
  $\mu^{-} \longrightarrow \nu_{\mu} e^{-} \bar{\nu}_{e}$
- Provides a very well known flux of $\overset{(-)}{\nu}$'s with energies $< E_{\mu}$.

The 'standard' set-up involves $E_{\mu} \sim 50$ GeV and a long baseline (detectors at 4000 km and 7500 km)!

The Low-Energy Neutrino Factory (LENF)

- A high-energy ν factory would be very desirable, but is it possible to achieve similar physics results with a smaller, less ambitious experiment?
  $\Rightarrow$ Consider a low-energy ν factory.
- The basic LENF set-up that I work on is characterized by:
  L$=$ 1480 km
  E$=$ 4.12 GeV
  Can measure the ν_μ appearance and disappearance channels $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$

What happens if we can also detect $\overset{(-)}{\nu}_e$'s?

- A LENF would use a different type of detector to a HENF, because of the different energies of the ν's.
- It may be possible to detect $\overset{(-)}{\nu}_e$'s with a LENF $\Rightarrow$ will have access to the $\overset{(-)}{\nu}_e$ appearance and disappearance channels $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$.
- Will this help?

My work

I look at this experimental set-up and try to answer the following questions:

- How can we optimize the sensitivity to θ_{13} and δ?
- Can we determine the sign of Δm^2_{31}?
- Can we detect NSI's?

Collaborators: Alan Bross, Malcolm Ellis, Enrique Fernandez Martinez, Steve Geer, Silvia Pascoli

Analytic work

Derive the oscillation probabilities, in matter, for the required channels, including NSI terms. An example:

$$
\begin{aligned}
P_{e\mu} &= s_{213}^2 s_{23}^2 ((1+\frac{2A}{\Delta_{13}})\sin^2(\frac{\Delta_{13}L}{2}) - AL\sin(\frac{\Delta_{13}L}{2})\cos(\frac{\Delta_{13}L}{2})) \\
&+ \alpha s_{213} s_{212} s_{223} \frac{\Delta_{13}L}{2}((1+\frac{A}{\Delta_{13}})\sin(\frac{\Delta_{13}L}{2}) - \frac{AL}{2}\cos(\frac{\Delta_{13}L}{2})) \times \\
&\quad (\cos\delta\cos(\frac{\Delta_{13}L}{2}) - \sin\delta\sin(\frac{\Delta_{13}L}{2})) \\
&+ 4\epsilon s_{213} c_{23} s_{23}^2 (\frac{A}{\Delta_{13}}\sin^2(\frac{\Delta_{13}L}{2})\cos(\phi-\delta) \\
&\quad -\frac{AL}{2}\sin(\frac{\Delta_{13}L}{2})(\cos(\phi-\delta)\cos(\frac{\Delta_{13}L}{2}) + \sin(\phi-\delta)\sin(\frac{\Delta_{13}L}{2}))) \\
&+ 4\epsilon\alpha s_{212} s_{23} c_{23}^2 (\frac{AL}{2}\sin(\frac{\Delta_{13}L}{2})(\cos\phi\cos(\frac{\Delta_{13}L}{2}) - \sin\phi\sin(\frac{\Delta_{13}L}{2})) - \frac{AL^2\Delta_{13}}{4}\cos\phi)
\end{aligned}
$$

.

Theoretical predictions

- From these expressions, can pick out the leading order NSI terms for each channel and figure out if they're large enough to detect.
- By combining the expressions for different channels, can figure out which combinations will give us the best precision on the oscillation parameters and NSI's.
- Conclusion (in brief!): We should be able to detect $\epsilon_{e\tau}$ and the $\overset{(-)}{\nu}_e$ appearance channels will help improve sensitivity on the SO parameters.

That was the theory...

- Have performed simulations (GLoBES 3.0) of the experiment to see if the results match our theoretical predictions.
- Up to now, have focused only on the standard case (no NSI's).

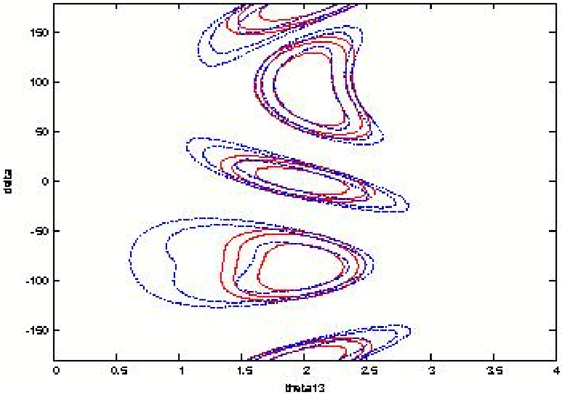
Some results:

Precision on θ_{13} and δ

$68\%, 90\%$ and 95% contours in the $\theta_{13} - \delta$ plane.

Blue: no $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ channel

Red: with $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ channel

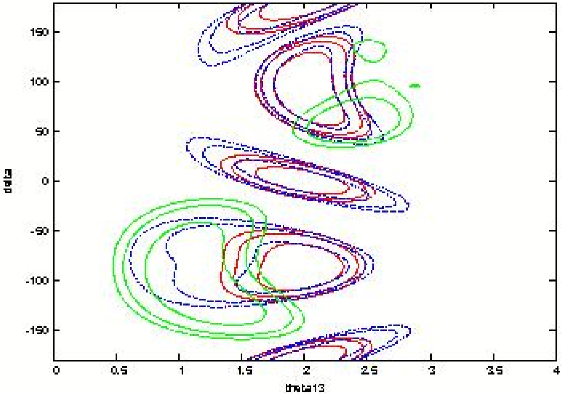


Determining the mass hierarchy

Blue: no $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channel

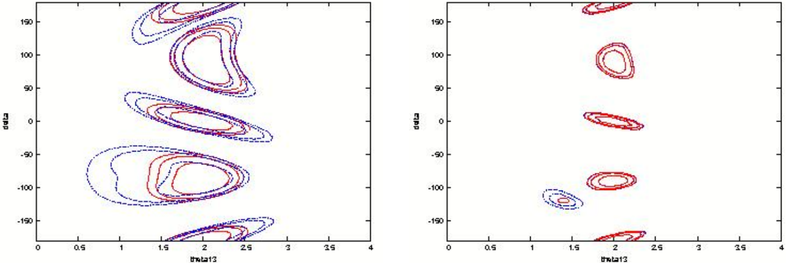
Red: with $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channel

Green: wrong solution obtained if there's no $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channel



Things we can't predict theoretically!

- Simulations also enable us to see the effect of experimental factors which we can't predict theoretically: statistics, energy resolution, efficiency, background levels etc.
- Our experimental colleagues tell us they may be able to get 3× the flux that we used in the previous simulations:



- Conclusion: A drastic improvement! Maybe it's not worth having the $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channel after all...

Further work

- Play around with more experimental parameters e.g. muon energy, detector size, to assess their effects.
- Consider the octant (deviation of θ_{23} from 45^o) degeneracy.
- Find out if the $\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_e$ channel can give us any useful information.
- Add NSI's into the simulations.

Summary

- I look at the physics reach of a low-energy neutrino factory, in particular to its sensitivity to measuring θ_{13}, δ, sign(Δm^2_{31}) and NSI's.
- Have shown that this set-up has the capability to determine the ν mass hierarchy, and is sensitive to some NSI parameters.
- Have demonstrated that a clear improvement in the sensitivity to θ_{13}, δ and the mass hierarchy is gained by including the $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ channels, for sufficiently high efficiencies/ low backgrounds. This will help us decide what specifications are required by the detector.
- Have found that the LENF appears to be limited by statistics $\Rightarrow$ most important factors may be maximizing the flux and detector size.