The Low Energy Neutrino Factory: Physics Performance

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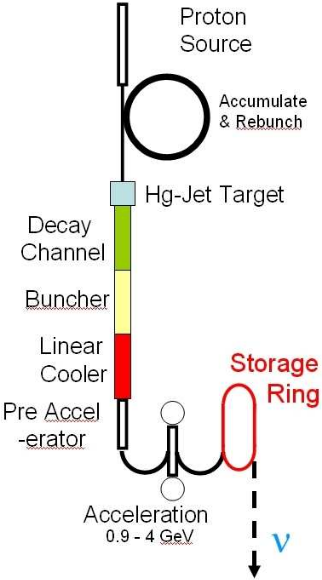
Talk outline

- Review of LENF setup and motivation
- Standard oscillations
- Non-standard interactions
- Conclusions.

LENF review: beam and baseline

- $E_{\mu} \sim 4.5$ GeV
- $L = 1300$ km
- 1.4×10^{21} muon decays per year per polarity
- Running time: $5 + 5$ years
- 1.4×10^{22} muon decays in total.



Detector options: 20 kton totally active scintillating detector (TASD) or 100 kton Liquid Argon (LAr).

	TASD	**LAr**
Fiducial mass	20 kton	100 kton
Threshold	0.5 GeV	0.5 GeV
Efficiency ($\mu^{\pm}$)	94%	80%
Efficiency ($e^{\pm}$)	47%	80%
Systematics	2%	$2-5\%$
Energy resolution	10%	5%
Background ($\mu^{\pm}$)	1×10^{-3}	$1-5\times10^{-3}$
Background ($e^{\pm}$)	10^{-2}	$10^{-2}-0.8$

Channels:

$\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$ - **disappearance**

$\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ - **golden**

$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ - **platinum**.

LENF motivation

The low energy neutrino factory was proposed as a next-generation long-baseline experiment in the scenario that θ_{13} is large.

S. Geer, O. Mena, S. Pascoli, Phys. Rev. D **75**, 093001 (2007).

Motivation: The oscillation spectrum for energies $\lesssim 5$ GeV is very rich at ~ 1300 km, providing sensitivity to θ_{13}, δ, the mass hierarchy and θ_{23}.

But why is the LENF suitable for large θ_{13}?

θ_{13} dependence of oscillation probability

This is the oscillation probability for the golden channel, $\nu_e \rightarrow \nu_\mu$:

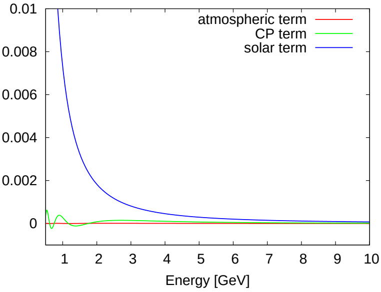
$$
\begin{aligned}
P_{\nu_e \nu_\mu} &= s^2_{213} s^2_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - \frac{AL}{2}\right) \\
&+ s_{213} \alpha s_{212} s_{223} \frac{\Delta m^2_{31} L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m^2_{31} L}{4E} - \frac{AL}{2}\right) \\
&\quad \times \cos\left(\delta - \frac{\Delta m^2_{31} L}{4E}\right) \\
&+ \alpha^2 c^2_{23} s^2_{212} \left(\frac{\Delta m^2_{31} L}{2EA}\right)^2 \sin^2\left(\frac{AL}{2}\right).
\end{aligned}
$$

- The atmospheric term contains information on θ_{13} and the mass hierarchy.
- The CP term contains information on θ_{13}, δ and the mass ordering.
- The solar term doesn't tell us anything interesting.

θ_{13} dependence of oscillation spectrum

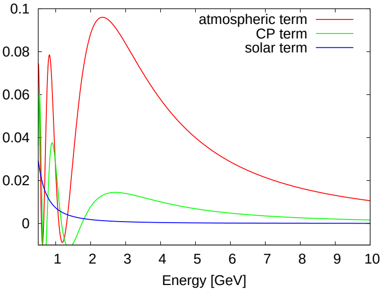
This is how each of the terms vary with the value of θ_{13}:

$\theta_{13} = 0.1^\circ$



GLoBES 3.0

$\theta_{13} = 10^\circ$



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The solar term is dominant when $\sin^2(2\theta_{13}) \lesssim 10^{-3}$.

The atmospheric term is dominant when $\sin^2(2\theta_{13}) \gtrsim 10^{-3}$.

Long-baseline matter effects vs CP violation

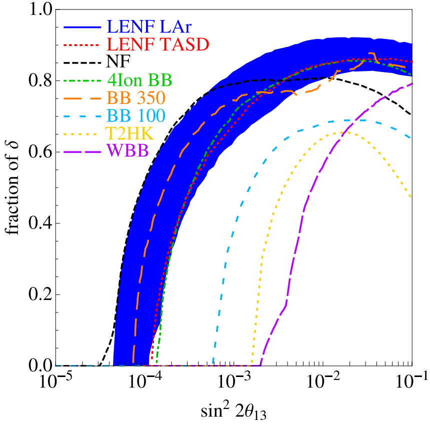
When the solar term is dominant, a long baseline and high energy is the only way to determine the mass hierarchy $\Rightarrow$ HENF.

But if the atmospheric term is dominant:

- Measurements can be extracted more easily as the oscillations are easier to see.
- **Matter effects and CPV at a HENF become difficult to distinguish.**

$\Rightarrow$ **A shorter baseline with less matter effect is preferable for large θ_{13}.**

LENF sensitivity: CP discovery

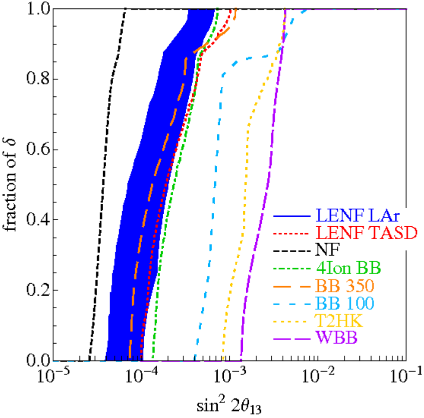


arXiv: 0911.3776 GLoBES 3.0

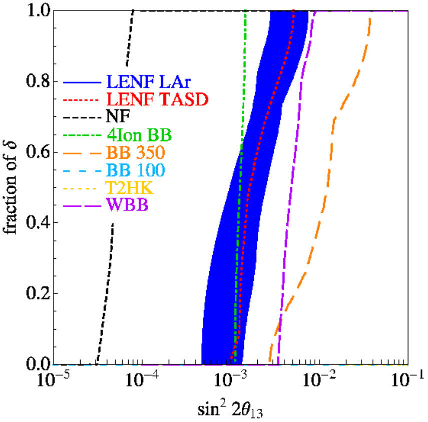
- The **high energy neutrino factory (NF)** was designed for the scenario that θ_{13} **is very small**.
- But the low energy neutrino factory (LENF) performs better if $\sin^2(2\theta_{13}) \gtrsim 10^{-3}$.

LENF sensitivity: θ_{13} and hierarchy

θ_{13} discovery:



Hierarchy sensitivity:



arXiv: 0911.3776

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For $\sin^2(2\theta_{13}) > 1 \times 10^{-3}$ - 100% coverage for θ_{13} discovery.

For $\sin^2(2\theta_{13}) > 4 \times 10^{-3}$ - 100% coverage for hierarchy sensitivity.

The platinum channels

A full standard oscillation analysis can be found in arXiv:0911.3776.

This includes a study of the effect of adding the platinum channels ($\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$).

These channels are experimentally very challenging to observe.

So **precisely how important are the platinum channels?**

Platinum channels vs statistics

Compare the effect of the **platinum channels** with the effect of **increasing statistics**. Consider 3 scenarios:

- 2.8×10^{22} total muon decays, no platinum channel
  Most optimistic statistics - re-optimized accelerator front-end $\Rightarrow$ 40% increase, and double the running time.
- 1.0×10^{22} total muon decays, no platinum channel
  Same statistics as HENF, with all muons to a single baseline
- 1.0×10^{22} total muon decays, with platinum channel.

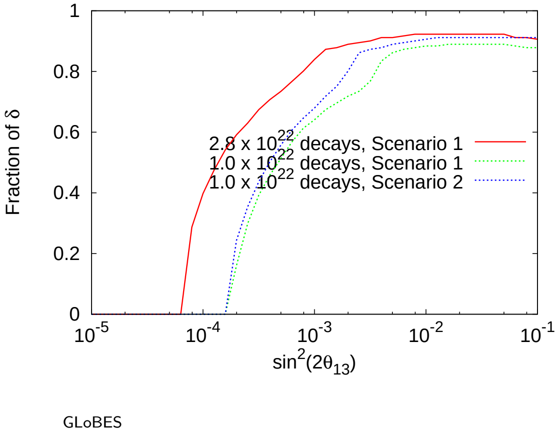
See also J. Tang and W. Winter, Phys. Rev. D **81**, 033005 (2010).

Platinum channel assumptions:

- Efficiency $= 37\%$ for $E < 1$ GeV, 47% for $E > 1$ GeV
- Background (charge mis-ID rate) $= 10^{-2}$.

Platinum channel: CP discovery

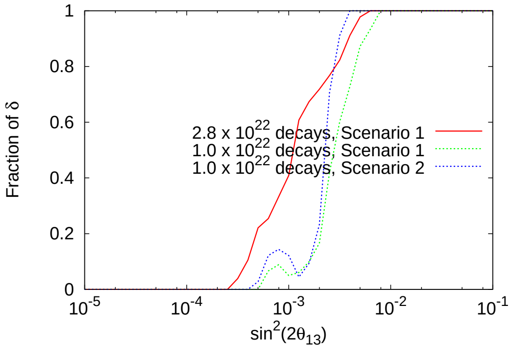
Scenario 1: no platinum channels, **Scenario 2**: with platinum channels



- For 1.0×10^{22} decays and $\sin^2(2\theta_{13}) \sim 10^{-3}$, the platinum channel increases CPV sensitivity by $\sim 10\%$.
- But higher statistics are always better.

Platinum channel: hierarchy sensitivity

Scenario 1: no platinum channels, **Scenario 2**: with platinum channels



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- $\sin^2(2\theta_{13}) \lesssim 4 \times 10^{-3}$: higher statistics are better.
- $4 \times 10^{-3} \lesssim \sin^2(2\theta_{13}) \lesssim 10^{-2}$: the platinum channel helps.
- $\sin^2(2\theta_{13}) > 10^{-2}$: the platinum channel is unnecessary.

Standard oscillation summary

- The LENF has better sensitivity to CP violation than the HENF for $\sin^2(2\theta_{13}) \gtrsim 10^{-3}$.

- The LENF has 100% coverage to θ_{13} and the mass hierarchy for $\sin^2(2\theta_{13}) \gtrsim 4 \times 10^{-3}$.

- The performance of the LENF is very sensitive to statistics.

  J. Tang and W. Winter, Phys. Rev. D **81**, 033005 (2010).

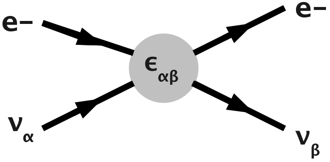
- If the LENF is only to be considered for $\sin^2(2\theta_{13}) > 10^{-2}$, the platinum channel adds only a little to the CP sensitivity.

Non-standard interactions: introduction

We would also like to search for new physics with a ν factory, for example non-standard interactions (NSI's).

- NSI's are effective 4-point flavour-changing interactions.
- NSI's can be parameterized as $\varepsilon_{\alpha\beta}$ (model-independent) which describe the rate of the transition $\nu_\alpha \rightarrow \nu_\beta$.

  T. Ota, J. Sato and N. Yamashita, Phys. Rev. D **65**, 093015 (2002).



The LENF has leading order sensitivity to the NSI parameters $\varepsilon_{e\mu} e^{i\phi_{e\mu}}$ and $\varepsilon_{e\tau} e^{i\phi_{e\tau}}$:

$$
\begin{aligned}
P_{\nu_e \to \nu_\mu} &= s_{213}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\
&+ s_{213}\, \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\delta - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ \alpha^2 c_{23}^2 s_{212}^2 \left(\frac{\Delta m_{31}^2 L}{2EA}\right)^2 \sin^2\left(\frac{AL}{2}\right) \\
&- 4\varepsilon_{e\tau} s_{213} c_{23} s_{23}^2 \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\delta + \phi_{e\tau} - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ 4\varepsilon_{e\tau}\, \alpha s_{212} c_{23}^2 s_{23} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\phi_{e\tau} + \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ 4\varepsilon_{e\tau}^2 c_{23}^2 s_{23}^2 \sin^2\left(\frac{AL}{2}\right) \\
&- 4\varepsilon_{e\mu} s_{213} c_{23}^2 s_{23} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\delta + \phi_{e\mu} - \frac{\Delta m_{31}^2 L}{4E}\right) \\
&- 4\varepsilon_{e\mu}\, \alpha s_{212} c_{23}^2 s_{23} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \cos\left(\phi_{e\mu} + \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ 4\varepsilon_{e\mu}^2 c_{23}^2 s_{23}^2 \sin^2\left(\frac{AL}{2}\right).
\end{aligned}
$$

Degeneracies and NSI's

When we include NSI's, the parameter space is vastly increased and so the degeneracy problem is magnified.

With SO parameters alone we already have a degeneracy problem:

- Data can be fitted to different combinations of (θ_{13}, δ, sign(Δm^2_{31})).
- From a single measurement, we cannot tell which is the true solution (see next slide).

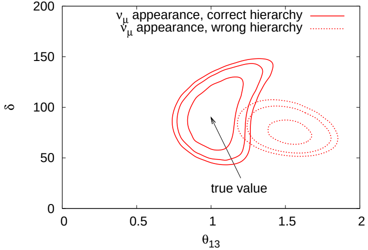
$\Rightarrow$ This severely weakens the precision of measurements.

Possible solutions:

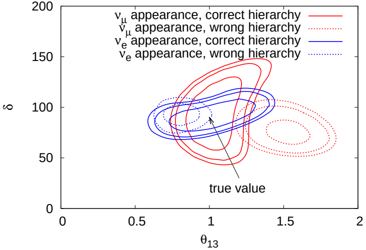
- Combine information from complementary channels (**LENF**).
- Use a magic baseline (**HENF**).

Using complementary channels to resolve degeneracies

Only ν_μ appearance channel:



ν_μ and ν_e appearance channels:



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The degenerate solutions appear in different regions of parameter space for each channel.

Thus we can eliminate the fake solutions by combining appropriate channels.

The same technique applies to resolving SO-NSI degeneracies.

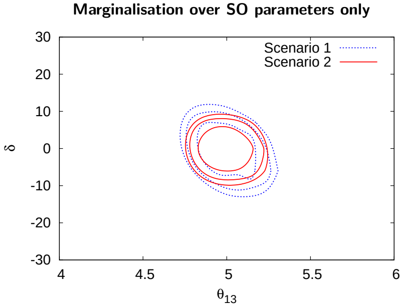
Degeneracies and NSI's

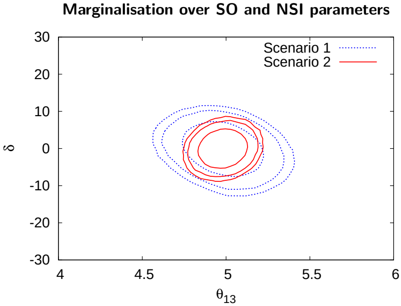
- We must ensure that NSI's do not degrade our sensitivity to the oscillation parameters.
- The high-energy ν factory is already immune to this problem because of the magic baseline (sets $\sin\left(\frac{AL}{2}\right)$ to zero $\Rightarrow$ all NSI terms vanish).
- But for the LENF, we need a solution. We find that the platinum channel ($\nu_\mu \rightarrow \nu_e$) enhances the sensitivity to all parameters.

Effect of NSI's on standard oscillation measurements

Even if all the NSI's are zero, marginalising over them weakens the precision of the oscillation measurements.

Scenario 1: no platinum channel, Scenario 2: platinum channel included (eff $= 47\%$, bkgd $= 10^{-2}$).





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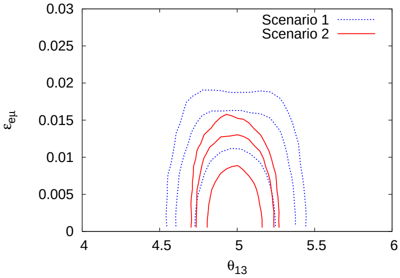
The platinum channel helps to maintain the sensitivity to the SO parameters.

Bounds on $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$: $\theta_{13} = 5^\circ$

The current upper bounds on $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ are $\sim 10^{-1}$.

C. Biggio, M. Blennow, E. Fernández-Martínez, JHEP **0908**, 090 (2009).

Simulate $\varepsilon_{e\mu} = \varepsilon_{e\tau} = 0$ and $\theta_{13} = 5^\circ$:



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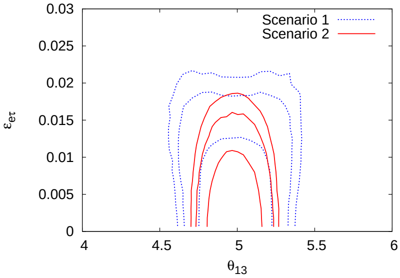

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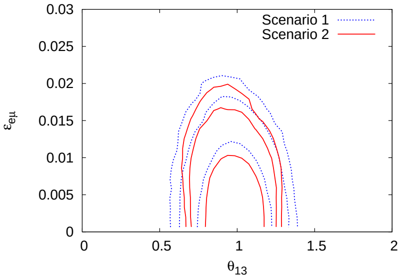
- For $\theta_{13} = 5^\circ$, the platinum channel enhances sensitivities.
- We can obtain a 95% upper bound of $\sim 10^{-2}$ on $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ (HENF can reach $\sim 10^{-3}$).

Bounds on $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$: $\theta_{13} = 1^\circ$

Do the same for $\theta_{13} = 1^\circ$:



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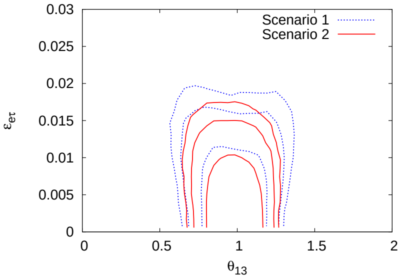

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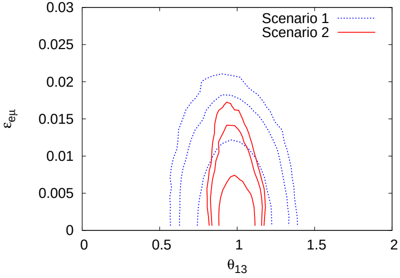
The platinum channels are not as effective when θ_{13} is small.

We find that the **results are not improved by increasing statistics** (unlike for oscillation measurements).

Effect of a perfect platinum channel

But if the platinum channels have (hypothetically!) perfect efficiency and no background:



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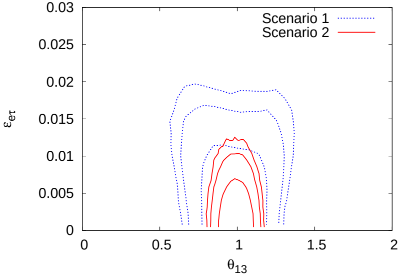

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A perfect platinum channel would enhance sensitivities for all values of θ_{13}.

$\Rightarrow$ **There is a critical number of platinum events needed for these channels to be useful.**

NSI summary

- The LENF sensitivity to NSI's is limited by the oscillation-NSI degeneracy.
- To resolve the degeneracy, complementary information from an additional channel or an additional baseline is required.
- Statistics are not important for NSI measurements as they do not help to resolve the degeneracies.
- For the assumed efficiency (47%) and background (10^{-2}), the platinum channel is only helpful if $\theta_{13} \sim 5^\circ$.
- If the performance can be sufficiently improved (difficult...) the platinum channel will also be useful for small θ_{13}.

See also D. Meloni, T. Ohlsson, W. Winter and H. Zhang, arXiv:0912.2735.

Conclusions

- For $\sin^2(2\theta_{13}) > 10^{-2}$ and 1.4×10^{22} decays, the LENF has
  - 100% θ_{13} discovery potential and hierarchy sensitivity
  - $\sim 80\%$ CP discovery potential.
- The platinum channel will increase the CP sensitivity by a few % but adds nothing else to the oscillation sensitivity.
- The LENF has sensitivity to matter NSI's down to $\sim 10^{-2}$.
- The sensitivity to NSI's is limited by degeneracies.
- To resolve the degeneracies we need to include the platinum channels, or a second detector.
- The current estimates of the platinum channel performance indicate that it will only be useful for very large θ_{13}.