Phenomenology at neutrino oscillation experiments

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Talk overview

- Neutrino oscillations
- Neutrino oscillation experiments
- Future long-baseline experiments
- Phenomenology at a neutrino factory:
  - standard oscillations
  - non-standard interactions
- Near detectors - MINSIS
- Summary.
Neutrino basics

- A neutrino is an electrically neutral, weakly-interacting fermion.
- They are the $SU(2)$ partners of the charged leptons.
- Experimental evidence (LEP $Z^0$ decays) shows that there are 3 species of light $\nu$.
Why do $\nu$’s oscillate?

- Oscillations occur if the interaction (flavour) states of a particle do not coincide with the mass eigenstates.

- The $\nu$ flavour states are related to the $\nu$ mass states via a mixing matrix, $U_{PMNS}$:

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$
The PMNS matrix

- The **PMNS matrix** is a unitary $3 \times 3$ matrix $^1$. 

  $\Rightarrow$ Parameterised by 3 angles and 3 phases.

- For Dirac particles, $\psi \neq \bar{\psi}$, we can absorb 2 phases by making field redefinitions:

  $\Rightarrow U_{PMNS} = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$.

- But $\nu$’s may be **Majorana particles**, so we must retain the additional 2 Majorana phases:

  $U_{PMNS} = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \times \text{Diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$.

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$^1$We assume... see later!
The Majorana phases never appear in $\nu$ oscillations... why not?

- Mathematically: $\nu_\alpha \rightarrow \nu_\beta \sim U^*_{\alpha i} U_{i\beta}$ so the Majorana phases do not appear in the oscillation probabilities.

- Physically: Majorana particles appear in lepton-number violating processes. But $\nu$ oscillations only violate lepton flavour.

- So we shouldn’t expect to see Majorana phases in $\nu$ oscillations.

- To measure them, we need experiments which see LNV processes, such as neutrinoless double-$\beta$ decay.
Oscillations probabilities, in vacuum, are straightforward to calculate. The probability for $\nu_\alpha \rightarrow \nu_\beta$ takes the form:

$$P_{\alpha\beta} \sim X_{\alpha\beta}(\theta_{12}, \theta_{23}, \theta_{13}, \delta) \sin^2 \left( \frac{\Delta m^2_{ij} L}{2E} \right).$$

- $X_{\alpha\beta}$ is a function of the elements of $U_{PMNS}$. For example, $X_{\mu\tau} = \sin^2 2\theta_{23}$.
- $L$ is the distance travelled by the $\nu$ - the ‘baseline’.
- $E$ is the $\nu$ energy.
- $\Delta m^2_{ij} = m_i^2 - m_j^2$ ($i, j = 1, 2, 3$).
So $\nu$ oscillations depend upon:

- 3 mixing angles - $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$.
- 1 CP violating phase - $\delta$.
- 3 mass-squared differences -

\[ \Delta m_{21}^2 = \Delta m_S^2, \]
\[ \Delta m_{31}^2 \simeq \Delta m_{32}^2 = \Delta m_A^2. \]

There can be CP violation in the leptonic sector if all 3 mixing angles are non-zero.

We know that all $\Delta m^2$'s $\neq 0 \Rightarrow$ At least two $\nu$ masses $\neq 0$. 
These parameters are measured by $\nu$ oscillation experiments.

$\nu$ oscillation experiments have three components:

$$\nu \text{ beam} \rightarrow \text{Baseline (L)} \rightarrow \text{Detector}$$
Different channels give us sensitivity to different parameters, as do different values of $L$ and $E$:

- Because $\Delta m^2_S \ll \Delta m^2_A$, there are 2 distinct oscillation frequencies.
- You can tune your experiment so that either
  \[
  \frac{\Delta m^2_A L}{2E} \sim 1 \quad \text{or} \quad \frac{\Delta m^2_S L}{2E} \sim 1.
  \]
- Hence we can choose different values of $L/E$ and have both short-baseline and long-baseline experiments.
Short-baseline experiments refer to those with a baseline of $\sim 1$ km.

Example: CHOOZ.

Long-baseline experiments are those with baselines $\gtrsim 100$ km.

Example: MINOS.
An example of a SBL experiment: CHOOZ

- The CHOOZ experiment looked for $\bar{\nu}_e \rightarrow \bar{\nu}_e$.
- Nuclear reactors provided $\bar{\nu}_e$ with $E \sim 3$ MeV.
- A detector was built at $L \sim 1$ km.

\[ \Rightarrow \quad \frac{\Delta m^2_A L}{4E} \sim 1 \quad \text{and} \quad \frac{\Delta m^2_S L}{2E} \sim 0.03. \]

\[ \Rightarrow P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \sim 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{\Delta m^2_A L}{4E} \right). \]
Current knowledge of mixing parameters

The most recent limits obtained by both short and long-baseline experiments can be found in

Basically, this is what we know:

- $\theta_{13} \approx 0 \quad \theta_{12} \approx 35^\circ \quad \theta_{23} \approx 45^\circ$

- $|\Delta m_{31}^2| \sim |\Delta m_{32}^2| = |\Delta m_A^2| \approx 2.4 \times 10^{-3}$ eV$^2$

- $\Delta m_{21}^2 = \Delta m_S^2 \approx 7.6 \times 10^{-5}$ eV$^2 \quad \Rightarrow \quad \Delta m_S^2 \ll |\Delta m_A^2|$.

- $\delta$ unknown.
Current knowledge summarised

- $v_e$
- $v_\mu$
- $v_\tau$

**Normal ordering**
- $m_3^2$
- $\Delta m_A^2 > 0$
- $\Delta m_S^2$

**Inverted ordering**
- $m_2^2$
- $\Delta m_A^2 < 0$
- $\Delta m_S^2$
- $m_3^2$
- $m_1^2$
- $m_2^2$
The MSW (Mikheyev-Smirnov-Wolfenstein) effect is also known as the matter effect.


- $\nu$’s interact with matter via neutral-current scattering.
- But $\nu_e$’s also interact via charged-current scattering
  $\Rightarrow$ $\nu_e$’s get ‘heavier’ in matter.
- There isn’t much $\nu_e$ in $\nu_3$ so $\nu_3$ isn’t affected.
- But $\nu_1$ and $\nu_2$ get heavier.
- See picture on next slide...
For normal ordering (pictured):

\[ \Delta m^2_A \text{ gets smaller } \Rightarrow \text{ oscillations enhanced.} \]

For inverted ordering:

\[ \Delta m^2_A \text{ gets larger } \Rightarrow \text{ oscillations suppressed.} \]

Thus, matter effects enable us to determine the \( \nu \) mass ordering.
The matter effect is a cumulative effect.

So the more matter there is, the larger the effect.

Future long-baseline experiment will exploit this:

Current baselines are ∼ 100’s of km. Future baselines may be ∼ 1000’s of km, when matter effects become significant.
Aside: mass ordering vs mass hierarchy

The **mass hierarchy** refers to the **hierarchy of the** $\nu$ **masses**:

- **Normal hierarchy NH** - $m_1 \simeq m_2 \ll m_3$
- **Inverted hierarchy IH** - $m_3 \ll m_1 \simeq m_2$
- **Quasi-degenerate QD** - $m_1 \simeq m_2 \simeq m_3$.

The **mass ordering** refers to the **ordering of the** $\nu$ **masses**:

- **Normal ordering NO** - $m_1 < m_2 < m_3$
- **Inverted ordering IO** - $m_3 < m_1 < m_2$.

**Oscillation experiments** can tell us about the **mass ordering** but not about the mass hierarchy (no information about the **absolute scale of** $\nu$ **masses**).
The goals of future $\nu$ oscillation experiments are to measure the unknown oscillation parameters:

- $\theta_{13}$
  - symmetries
  - possibility for CPV if $\theta_{13} \neq 0$
  - value dictates how to optimise experiment (see later).

- the CP violating phase, $\delta$
  - BAU, baryogenesis via leptogenesis?

- determine the $\nu$ mass ordering (normal or inverted)
  - need long-baseline experiments.

We would also like to look for non-standard physics.
Future long-baseline $\nu$ experiments

Future experiments will have to study appearance channels ($\nu_\alpha \rightarrow \nu_{\alpha \neq \beta}$).

Experiments which will be able to do this are superbeams, $\beta$-beams and neutrino factories.

- **Superbeams** e.g. T2K are more powerful versions of conventional $\nu$ beams:
  
  Beam produced from $\pi^\pm$ decay $\Rightarrow$ contains $\nu_\mu$ with some $\nu_e$ contamination.

- **$\beta$-beams**:
  
  Beam produced from decay of radioactive ions $\Rightarrow$ a pure $\nu_e$ or $\bar{\nu}_e$ beam.
A neutrino factory is considered to be the ultimate $\nu$ experiment!

- 7500 km baseline $\Rightarrow$ guaranteed sensitivity to the mass ordering.
- The magic baseline has ‘magic’ properties (more later...).
- Access to multiple oscillation channels.
A neutrino factory produces a very pure beam of $\nu_\mu$ and $\bar{\nu}_e$ with a precisely known flux.

- Create an intense source of muons.
- Accelerate the muons.
- Inject into a storage ring where they decay:
  \[ \mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu \]
- Place a detector far away.
- Look at the disappearance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$) and appearance ($\nu_e \rightarrow \nu_\mu$) channels.
A ν factory will see the ‘golden channel’ (ν_e → ν_μ):


\[
P_{\nu_e \rightarrow \nu_\mu} = s_{213}^2 s_{23}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \\
+ s_{213} \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \times \\
\cos \left( \delta - \frac{\Delta m_{31}^2 L}{4E} \right) \\
+ \alpha^2 c_{23}^2 s_{212}^2 \left( \frac{\Delta m_{31}^2 L}{2EA} \right)^2 \sin^2 \left( \frac{AL}{2} \right).
\]

where A is the matter potential.

Information on all the parameters we want to measure.

Extract parameters by looking at the oscillation spectrum.
Optimising an experiment for standard oscillations

- $\theta_{13}$ 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.
The degeneracy problem

The spectrum is very complicated!

⇒ We have a problem with degeneracies:

- Data can be fitted to different combinations of \((\theta_{13}, \delta, \text{sign}(\Delta m^2_A))\).
- From a single measurement, we cannot tell which is the true solution (see next slide)

⇒ This severely weakens the precision of measurements.

Possible solutions:

- Combine information from complementary channels.
- Use a magic baseline.
Using complementary channels to resolve degeneracies

Only $\nu_\mu$ appearance channel:

$\nu_\mu$ and $\nu_e$ appearance channels:

GLoBES

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

Thus we can eliminate the fake solutions by combining appropriate channels.
Using the magic baseline to resolve degeneracies

- Recalling our oscillation probability, we find that if we set:

$$\sin \left( \frac{AL}{2} \right) = 0 \Rightarrow \frac{AL}{2} = \pi \Rightarrow L \sim 7500 \text{km}$$

then our probability reduces simply to

$$P_{\nu_e \rightarrow \nu_\mu} = s_{213}^2 s_{23}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} - \pi \right).$$

- Hence we get rid of the CP and solar terms, and only have to deal with $\theta_{13}$ and sign$(\Delta m_{31}^2)$.

- We then use a second detector at $\sim 4000$ km to measure the full oscillation probability, including CPV effects.
A high energy (∼ 25 GeV) and a long baseline (∼ 7500 km) guarantees sensitivity to the mass ordering.

But is a high energy and long-baseline appropriate for all scenarios?

We know that the phenomenology at these experiments will depend strongly on the value of $\theta_{13}$.

But so far we have only a weak bound: $\theta_{13} < 13^\circ$ (3σ).

Why is this a problem?
Let's go back to our oscillation probability:

\[ P_{\nu_e \nu_\mu} = s_{213}^2 s_{23}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \]

\[ + s_{213} \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \times \cos(\delta - \frac{\Delta m_{31}^2 L}{4E}) \]

\[ + \alpha^2 c_{23}^2 s_{212}^2 \left( \frac{\Delta m_{31}^2 L}{2EA} \right)^2 \sin^2 \left( \frac{AL}{2} \right). \]

- The atmospheric term contains information on \( \theta_{13} \) and the mass ordering.
- The CP term contains information on \( \theta_{13} \), \( \delta \) and the mass ordering.
- The solar term doesn't tell us anything interesting.
This is how each of the terms vary with the value of $\theta_{13}$:

$\theta_{13} = 0.1^\circ$ and $\theta_{13} = 10^\circ$
For $\theta_{13} \lesssim 1^\circ$ - **solar regime** - the solar term is dominant.

$\Rightarrow$ A long baseline is the only way to determine the mass ordering.

For $\theta_{13} \gtrsim 1^\circ$ - **atmospheric regime** - the atmospheric and CP terms are dominant, so measurements are easier.

But we can still use a $\nu$ factory, can’t we?
Long-baseline $\Rightarrow$ strong matter effects.

**What’s the problem?**

- The earth is not CP symmetric i.e. there’s only matter and no anti-matter.
- So our beam $\nu$’s only interact with matter.
- Then how do we know if CP violation occurs because $\delta \neq 0$, $\pi$, or just because the earth is CP-asymmetric?

For large $\theta_{13}$, matter effects and CPV at a $\nu$ factory become difficult to distinguish.
But if $\theta_{13}$ is large, we can determine the mass ordering using a shorter baseline to minimise matter effects.

⇒ Consider a low energy neutrino factory (LENF).


If appropriately optimised, the low energy neutrino factory outperforms the other options...


... and lower energy = lower cost ;-)
LENF sensitivity to CPV

CP violation discovery potential:

- The high energy neutrino factory (NF) was designed for the scenario that $\theta_{13}$ is very small.

- But the low energy neutrino factory (LENF) performs better if $\theta_{13}$ is large.
LENF sensitivity to the mass ordering

Sensitivity to the mass ordering:

However, the low energy neutrino factory (LENF) is only sensitive to the mass ordering for large $\theta_{13}$. 

arXiv: 0911.3776  
GLoBES 3.0
We would also like to search for new physics with a $\nu$ factory, for example non-standard interactions (NSI’s).

- NSI’s are effective 4-point flavour-changing interactions.

- NSI’s can be parameterized as $\epsilon_{\alpha\beta}$ (model-independent) which describe the rate of the transition $\nu_\alpha \rightarrow \nu_\beta$.

\begin{itemize}
\item $\nu$ oscillation experiments are particularly powerful tools for detecting NSI's because a $\nu$ transition can occur via oscillation, or NSI:

\[
\text{Rate} = |\nu_\alpha \xrightarrow{\text{OSC}} \nu_\beta + \nu_\alpha \xrightarrow{\text{NSI}} \epsilon_{\alpha\beta} \nu_\beta|^2.
\]

\item Hence there is an interference term which is linear, rather than quadratic, in $\epsilon_{\alpha\beta}$.
\end{itemize}

Here’s an example of a specific model which predicts NSI’s:

There is a class of phenomenologically interesting models which explain light $\nu$ masses and predict the existence of low energy observables -

‘Minimal flavour seesaw models’.

In order that the model does not prevent the existence of observable FC interactions, there are 2 scales built in:

- A lepton-number violating scale, $\Lambda_{LN}$, which sets the mass scale for the SM neutrinos (seesaw scale).

- A lepton-flavour violating scale, $\Lambda_{FL}$, which sets the mass scale for the additional heavy neutrinos.

with $\Lambda_{FL} \ll \Lambda_{LN}$.

This model makes predictions for flavour changing interactions $\ell_\alpha \rightarrow \ell_\beta$ and $\nu_\alpha \rightarrow \nu_\beta$. 
Basic mechanism of the model

\[ L = L_{SM} + i \bar{N} \gamma_\mu \partial^\mu N + i \bar{N}' \gamma_\mu \partial^\mu N' \]

\[ - \left[ Y_N^b \bar{N} \tilde{\Phi}^\dagger \ell_L^b + \frac{\Lambda}{2} (\bar{N}' N^c + \bar{N} N'^c) + h.c. \right] \]

- Start with a pair of Weyl fields, \( N \) (lepton no. = +1) and \( N' \) (lepton no. = −1).

- Species with opposite LN pair up ⇒ Dirac field.

- LFV interactions ⇒ Dirac masses for heavy \( \nu' \)'s.

- LNV interactions ⇒ Masses for SM \( \nu \)'s.
The inclusion of NSI’s means that we should consider a non-unitary mixing matrix.

Obviously the full, high-energy matrix, $U_{PMNS}$, is unitary, but at our low-energy experiments we see an approximation, $N$:

$$(NN^\dagger)_{\alpha\beta} = \delta_{\alpha\beta} - \varepsilon_{\alpha\beta}.$$ 


In our model:

$$\varepsilon_{\alpha\beta} = \frac{v^2 y^2}{\Lambda_{FL}^2} Y_\alpha^* Y_\beta$$

where $y$ and $\Lambda_{FL}$ are the parameters we want to constrain.

Which $\varepsilon_{\alpha\beta}$’s can we measure?
Well, for example, the LENF has leading order sensitivity to the NSI parameters $\varepsilon_{e\mu} e^{i\Phi_{e\mu}}$ and $\varepsilon_{e\tau} e^{i\Phi_{e\tau}}$:

\[
P_{\nu_e \to \nu_\mu} = s_{213}^2 s_{23}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right)
+ s_{213} \alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \cos \left( \delta - \frac{\Delta m_{31}^2 L}{4E} \right)
+ \alpha^2 c_{23}^2 s_{212}^2 \left( \frac{\Delta m_{31}^2 L}{2EA} \right)^2 \sin^2 \left( \frac{AL}{2} \right)
- 4\varepsilon_{e\tau} s_{213} c_{23} s_{23} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \cos \left( \delta + \Phi_{e\tau} - \frac{\Delta m_{31}^2 L}{4E} \right)
+ 4\varepsilon_{e\tau} s_{212} c_{23} s_{23} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \cos \left( \Phi_{e\tau} + \frac{\Delta m_{31}^2 L}{4E} \right)
+ 4\varepsilon_{e\tau}^2 c_{23}^2 s_{23}^2 \sin^2 \left( \frac{AL}{2} \right)
- 4\varepsilon_{e\mu} s_{213} c_{23}^2 s_{23} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \cos \left( \delta + \Phi_{e\mu} - \frac{\Delta m_{31}^2 L}{4E} \right)
- 4\varepsilon_{e\mu} s_{212} c_{23}^2 s_{23} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2} \right) \cos \left( \Phi_{e\mu} + \frac{\Delta m_{31}^2 L}{4E} \right)
+ 4\varepsilon_{e\mu}^2 c_{23}^2 s_{23}^2 \sin^2 \left( \frac{AL}{2} \right).
\]
Degeneracies with NSI’s

The spectrum just got even more complicated...

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

- Crucially, we must ensure that NSI’s do not degrade our sensitivity to the oscillation parameters.

- The high-energy $\nu$ factory is already immune to this problem because of the ‘magic baseline’.

- But for the LENF, we have to find a solution: the addition of the ‘platinum channel’ ($\nu_\mu \rightarrow \nu_e$) is essential in maximising the experimental sensitivity to all parameters.

E. Fernández-Martínez, TL, O. Mena and S. Pascoli.
Maximising the LENF sensitivity to NSI's

- Simulate $\varepsilon_{e\mu} = \varepsilon_{e\tau} = 0$ and look at the 68%, 90% and 95% confidence level contours in the $\theta_{13} - \varepsilon$ plane:

![Graphs of $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$](graphs)

- The sensitivity to both oscillation parameters and NSI's is increased by including the $\nu_\mu \rightarrow \nu_e$ channel.

- We can obtain an upper bound of $\sim 10^{-2}$. Can we do better?
So far I’ve talked about the physics at the far detector of a neutrino factory.

But we can also use a near detector ($L \sim 1$ km)

$\Rightarrow$ no oscillations, only ‘zero-distance’ effects.

But why wait for a $\nu$ factory? We already have existing $\nu$ beams, so let’s build a detector now for one of these beams...
The idea: place a $\nu_\tau$ detector very close (1 km) to the $\nu_\mu$ beam source at Fermilab and look for $\nu_\mu \rightarrow \nu_\tau$ transitions.
Discovery potential of near detectors

- A near detector at a $\nu$ experiment has the advantage of having a very high event rate $\Rightarrow$ high statistics.

- In addition, the $\nu_\mu \rightarrow \nu_\tau$ channel turns out to have a very rich sensitivity to NSI’s, and hence is dubbed the

Let’s see how a near detector can constrain our MFV model.
Current bounds on the MFV model

The best bound on this model so far comes from the MEGA experiment, which measured


\[ Br(\mu^+ \rightarrow e^+\gamma) \leq 1.2 \times 10^{-11} \quad (90\% \text{ CL}) \]

where

\[ B(\ell_\alpha \rightarrow \ell_\beta) = \frac{\Gamma(\ell_\alpha \rightarrow \ell_\beta\gamma)}{\Gamma(\ell_\alpha \rightarrow \ell_\beta\nu_\alpha\bar{\nu}_\beta)}. \]

How do we relate this branching ratio to our predictions?
The NSI’s depend on the Yukawa couplings $Y_\alpha, Y_\beta$, which are functions of the neutrino mixing parameters.

We need to relate these couplings to the observed branching ratios.

First we can relate $NN^\dagger$ to these branching ratios:

$$\frac{|(NN^\dagger)_{\alpha\beta}|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}} = \frac{\Gamma(\ell_\alpha \rightarrow \ell_\beta \gamma)}{\Gamma(\ell_\alpha \rightarrow \ell_\alpha \nu_\beta \bar{\nu}_\beta)} \frac{96\pi}{100\alpha}$$

and thus obtain an upper bound on $|(NN^\dagger)_{\alpha\beta}|^2$. 
So we can deduce that:

$$\frac{y^2 v^2}{\Lambda_{FL}^2} < \frac{\text{Bound on } (NN^\dagger)_{\alpha\beta}}{|Y^*_\alpha Y_\beta|}$$

where $|Y^*_\alpha Y_\beta|$ is predicted theoretically by the model.

However the Yukawa couplings depend strongly upon the CP violating Dirac phase, $\delta$, and the Majorana phase, $\alpha$.

Neither of these phases is known at present!

Therefore we can only obtain predictions as a function of $\delta$ and $\alpha$. 
Weakened sensitivity

The model predicts that

\[ Y_e = e^{i\delta} s_{13} + e^{-i(\alpha - \pi/2)} s_{12} \left( \frac{|\Delta m^2_{21}|}{|\Delta m^2_{31}|} \right)^{1/4}. \]

Hence for some values of \( \delta \) and \( \alpha \), \( Y_e \ll 1 \)

\[ \Rightarrow \] The interaction rates for transitions involving electrons become very small and we lose sensitivity in this region.

**Solution:** look at a different channel without electrons e.g. \( \mu \rightarrow \tau \).
Neutrino transitions are related to NSI’s via:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = |(NN^\dagger)_{\alpha\beta}|^2 \]

Hence with a (realistic!) \(10^{-6}\) sensitivity to \(P_{\nu_\mu \rightarrow \nu_\tau}\), we obtain a bound of \((NN^\dagger)_{\mu\tau} < 1 \times 10^{-3}\).

For comparison, the current bound from a lepton experiment comes from the limit:

\[ Br(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8} \Rightarrow (NN^\dagger)_{\tau\mu} < 4.3 \times 10^{-3}. \]
So **MINSIS** could obtain better sensitivity than **MEGA** in some regions of parameter space:

\[
\frac{\sigma^2}{\Lambda^2} \quad 0, 0.005, 0.01, 0.015
\]

R. Alonso de Pablo, B. Gavela, TL

**MINSIS** can be complementary to charged lepton experiments.
Future long-baseline experiments such as neutrino factories are being optimised to measure $\theta_{13}$, $\delta$ and the mass hierarchy.

Complementary channels and/or a magic baseline can be used to resolve degeneracies and enhance experimental sensitivity.

In some scenarios, a low energy neutrino factory will out-perform a high energy neutrino factory.

Long-baseline experiments are powerful tools for detecting non-standard interactions.

Near detectors are also good probes of non-standard interactions.

Neutrino experiments can be complementary to charged lepton experiments.
Oscillation parameter update:

The MSW effect:

Overview of past, current and future neutrino facilities (and a lot of theory too!):

The low energy neutrino factory:
**NSI’s (theory):**

**MFV model:**

**MINSIS:**
- www-off-axis.fnal.gov/MINSIS/.