Phenomenology at neutrino oscillation experiments

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Talk overview

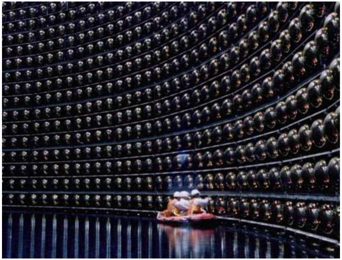
- Neutrino oscillations
- Neutrino oscillation experiments
- Future long-baseline experiments
- Phenomenology at a neutrino factory:

  - 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 ν.
- Major discovery announced in 1998 by Super-Kamiokande: neutrino oscillations.



Super-Kamiokande detector

Why do ν's oscillate?

- Oscillations occur if the interaction (flavour) states of a particle do not coincide with the mass eigenstates.
- The ν flavour states are related to the ν mass states via a mixing matrix, U_{PMNS}:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The PMNS matrix

- The PMNS matrix is a unitary 3×3 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 ν's may be Majorana particles, so we must retain the additional 2 Majorana phases:

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

[1] We assume... see later!

Majorana phases

The Majorana phases never appear in ν oscillations... why not?

- Mathematically: $\nu_\alpha \to \nu_\beta \sim U^*_{\alpha i} U_{i\beta}$ so the Majorana phases do not appear in the oscillation probabilities.
- Physically: Majorana particles appear in lepton-number violating processes. But ν oscillations only violate lepton flavour.
- So we shouldn't expect to see Majorana phases in ν oscillations.
- To measure them, we need experiments which see LNV processes, such as neutrinoless double-β decay.

Oscillation probabilities

Oscillations probabilities, in vacuum, are straightforward to calculate. The probability for $\nu_\alpha \rightarrow \nu_\beta$ takes the form:

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

- $X_{\alpha\beta}$ 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 ν - the 'baseline'.
- E is the ν energy.
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$ $(i, j = 1, 2, 3)$.

Oscillation parameters

So ν oscillations depend upon:

- 3 mixing angles - θ_{12}, θ_{23}, and θ_{13}.
- 1 CP violating phase - δ.
- 3 mass-squared differences -

  $\Delta m^2_{21} = \Delta m^2_S$,

  $\Delta m^2_{31} \simeq \Delta m^2_{32} = \Delta m^2_A$.

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

We know that all Δm^2's $\neq 0 \Rightarrow$ At least two ν masses $\neq 0$.

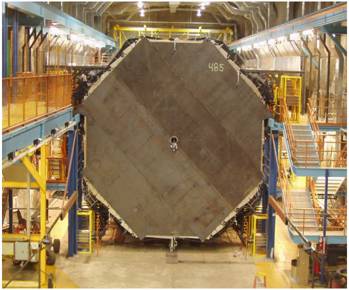
ν oscillation experiments

These parameters are measured by ν oscillation experiments.

ν oscillation experiments have three components:

ν beam $\longrightarrow$ Baseline (L) $\longrightarrow$ Detector

The NuMI beam.
lbne.fnal.gov/



The MINOS far detector.
MINOS

Designing a ν oscillation experiment

Different channels give us sensitivity to different parameters, as do different values of L and E:

- Because $\Delta m_S^2 \ll \Delta m_A^2$, there are 2 distinct oscillation frequencies.
- You can tune your experiment so that either

$$\frac{\Delta m_A^2 L}{2E} \sim 1 \qquad \text{or} \qquad \frac{\Delta m_S^2 L}{2E} \sim 1.$$

- Hence we can choose different values of L/E and have both short-baseline and long-baseline experiments.

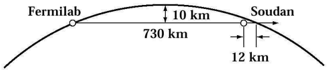
Short and long-baseline experiments

- Short-baseline experiments refer to those with a baseline of ~ 1 km.

  Example: CHOOZ.

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

  Example: MINOS.



The 735 km MINOS baseline.

www.hep.ucl.ac.uk/minos/

An example of a SBL experiment: CHOOZ

http://phototheque.in2p3.fr

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

$$\Rightarrow \qquad \frac{\Delta m_A^2 L}{4E} \sim 1 \qquad \frac{\Delta m_S^2 L}{2E} \sim 0.03.$$

$$\Rightarrow P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_A^2 L}{4E}\right).$$

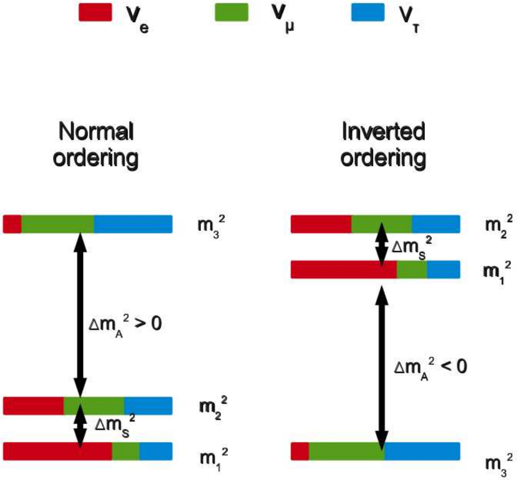
Current knowledge of mixing parameters

The most recent limits obtained by both short and long-baseline experiments can be found in
M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, arXiv:1001.4524.

Basically, this is what we know:

- $\theta_{13} \approx 0$ $\quad\quad$ $\theta_{12} \approx 35^\circ$ $\quad\quad$ $\theta_{23} \approx 45^\circ$
- $|\Delta m^2_{31}| \sim |\Delta m^2_{32}| = |\Delta m^2_A| \approx 2.4 \times 10^{-3}$ eV^2
- $\Delta m^2_{21} = \Delta m^2_S \approx 7.6 \times 10^{-5}$ eV^2 $\Rightarrow$ $\Delta m^2_S \ll |\Delta m^2_A|$.
- δ unknown.

Current knowledge summarised



Matter effects

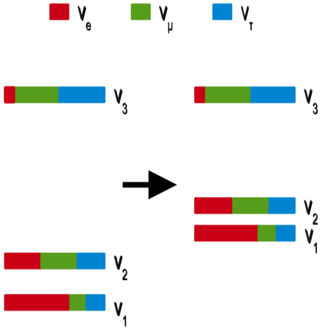
The MSW (Mikheyev-Smirnov-Wolfenstein) effect is also known as the matter effect.

L. Wolfenstein, 'Neutrino oscillations in matter', Phys. Rev. D **17**, 2369-2374 (1978).

- ν's interact with matter via neutral-current scattering.
- But ν_e's also interact via charged-current scattering

  $\Rightarrow \nu_e$'s get 'heavier' in matter.
- There isn't much ν_e in ν_3 so ν_3 isn't affected.
- But ν_1 and ν_2 get heavier.
- See picture on next slide...

ν mixing in matter



- For normal ordering (pictured): Δm^2_A gets smaller $\Rightarrow$ oscillations enhanced.
- For inverted ordering: Δm^2_A gets larger $\Rightarrow$ oscillations suppressed.
- Vice versa for $\bar{\nu}$.

Thus, matter effects enable us to determine the ν mass ordering.

Lonnnng baselines

- 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 $\sim$ 100's of km. Future baselines may be $\sim$ 1000's of km, when matter effects become significant.

Aside: mass ordering vs mass hierarchy

The **mass hierarchy** refers to the **hierarchy of the ν 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 ν 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 ν masses**).

Aims of future oscillation experiments

The goals of future ν oscillation experiments are to measure the unknown oscillation parameters:

- θ_{13}
  - symmetries
  - possibility for CPV if $\theta_{13} \neq 0$
  - value dictates how to optimise experiment (see later).
- the CP violating phase, δ
  - BAU, baryogenesis via leptogenesis?
- determine the ν mass ordering (normal or inverted)
  - need long-baseline experiments.

We would also like to look for non-standard physics.

Future long-baseline ν 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, β-beams and neutrino factories.

- Superbeams e.g. T2K are more powerful versions of conventional ν beams:

  Beam produced from $\pi^{\pm}$ decay $\Rightarrow$ contains ν_μ with some ν_e contamination.

- β-beams:

  Beam produced from decay of radioactive ions $\Rightarrow$ a pure ν_e or $\bar{\nu}_e$ beam.

A neutrino factory

A neutrino factory is considered to be the ultimate ν experiment!

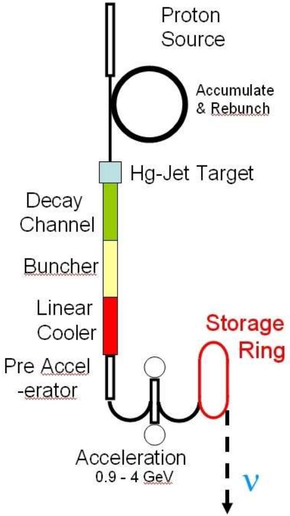
- 7500 km baseline $\Rightarrow$ guaranteed sensitivity to the mass ordering.
- The magic baseline has 'magic' properties (more later...).
- Access to multiple oscillation channels.

Brief overview of a neutrino factory

A neutrino factory produces a very pure beam of ν_μ 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.



ν oscillations at a ν factory

- A ν factory will see the 'golden channel' ($\nu_e \to \nu_\mu$):

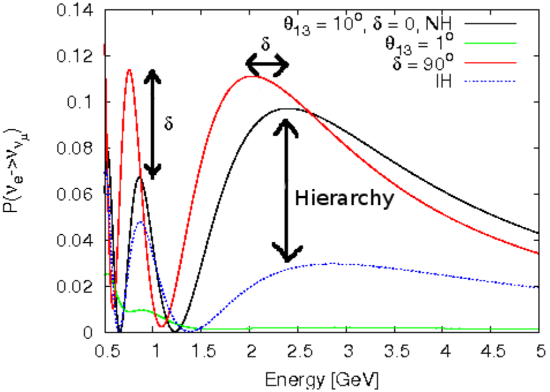
A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. Mena and S. Rigolin, Nucl. Phys. B **579**, 17 (2000).

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

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



- 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.

The degeneracy problem

The spectrum is very complicated!

$\Rightarrow$ We have a problem with degeneracies:

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

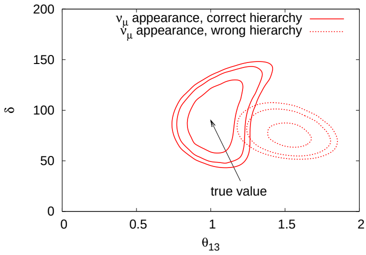
. $\Rightarrow$ This severely weakens the precision of measurements.

Possible solutions:

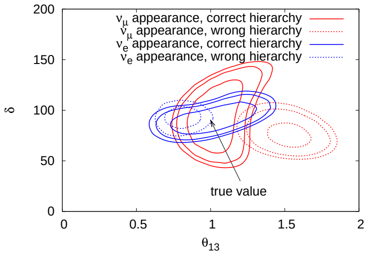
- Combine information from complementary channels.
- Use a magic baseline.

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.

Using the magic baseline to resolve degeneracies

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

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

then our probability reduces simply to

$$P_{\nu_e \to \nu_\mu} = s^2_{213} s^2_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E} - \pi\right).$$

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

- We then use a second detector at $\sim$ 4000 km to measure the full oscillation probability, including CPV effects.

Neutrino factory: one size fits all...?

- A high energy ($\sim$ 25 GeV) and a long baseline ($\sim$ 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 θ_{13}.

  But so far we have only a weak bound: $\theta_{13} < 13^\circ$ (3σ).
- **Why is this a problem?**

θ_{13} dependence of oscillation probability

Let's go back to our oscillation probability:

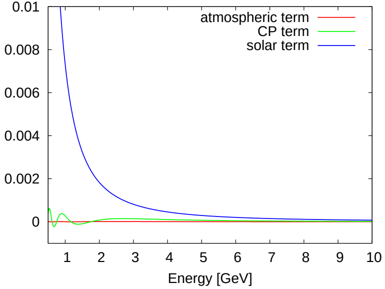
$$\begin{aligned}
P_{\nu_e\nu_\mu} &= s_{213}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\
&+ s_{213}\alpha s_{212} s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \times \cos\left(\delta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

- The atmospheric term contains information on θ_{13} and the mass ordering.
- 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}:

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



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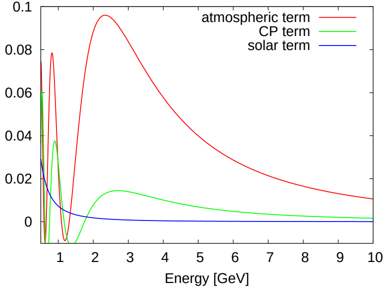
$\theta_{13} = 10^\circ$



GLoBES 3.0

Solar and atmospheric regimes

- 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 ν factory, can't we?

Matter effects fake CP violation

Long-baseline $=$ 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 ν's only interact with matter.
- Then how do we know if CP violation occurs because $\delta \neq 0$, π, or just because the earth is CP-asymmetric?

For large θ_{13}, matter effects and CPV at a ν factory become difficult to distinguish.

Neutrino factory: high energy vs low energy

- But if θ_{13} is large, we can determine the mass ordering using a shorter baseline to minimise matter effects.

  $\Rightarrow$ Consider a low energy neutrino factory (LENF).

  S. Geer, O. Mena and S. Pascoli, Phys. Rev. D **75**, 093001 (2007); A. D. Bross, M. Ellis, S. Geer, O. Mena and S. Pascoli, Phys. Rev. D **77**, 093012 (2008).

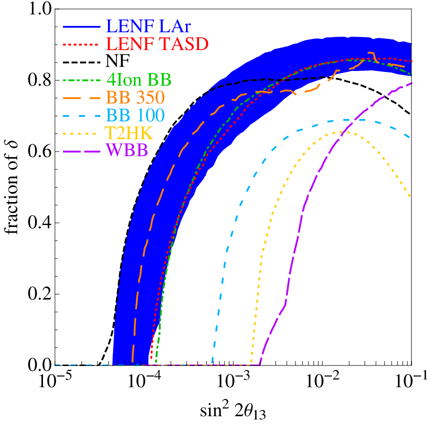
- If appropriately optimised, the low energy neutrino factory outperforms the other options...

  A. Bross, M. Ellis, E. Fernández-Martínez, S. Geer, TL, O. Mena and S. Pascoli, arXiv: 0911.3776.

  ... and lower energy = lower cost ;-)

LENF sensitivity to CPV

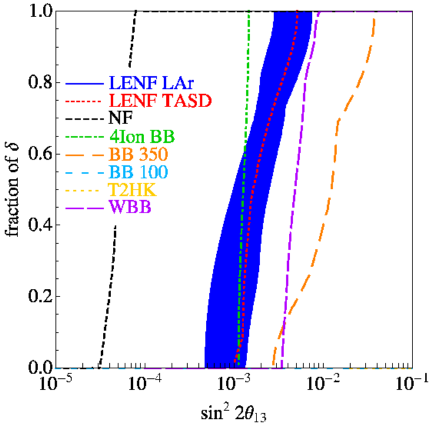
CP violation discovery potential:



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 θ_{13} is large.

Sensitivity to the mass ordering:



arXiv: 0911.3776 GLoBES 3.0

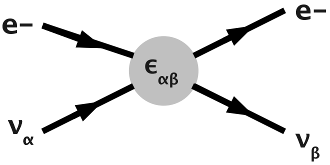
However, the low energy neutrino factory (LENF) is only sensitive to the mass ordering for large θ_{13}.

New physics at a ν factory

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 $\nu_\alpha \to \nu_\beta$.

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



NSI's at long-baseline experiments

- ν oscillation experiments are particularly powerful tools for detecting NSI's because a ν transition can occur via oscillation, or NSI:

$$\mathrm{Rate} = \left| \;\; \nu_\alpha \xrightarrow{\mathrm{OSC}} \nu_\beta \quad + \quad \nu_\alpha \xrightarrow[\varepsilon_{\alpha\beta}]{\mathrm{NSI}} \nu_\beta \;\; \right|^2 .$$

- Hence there is an interference term which is linear, rather than quadratic, in $\varepsilon_{\alpha\beta}$.

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

NSI's from a specific model

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

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

'Minimal flavour seesaw models'.

B. Gavela, T. Hambye, D. Hernández and P. Hernández, JHEP **0909**, 038 (2009).

Minimal flavour seesaw models: brief overview

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, Λ_{LN}, which sets the mass scale for the SM neutrinos (seesaw scale).
- A lepton-flavour violating scale, Λ_{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 $\ell_\alpha \to \ell_\beta$ and $\nu_\alpha \to \nu_\beta$.

Basic mechanism of the model

$$
\begin{aligned}
L &= L_{SM} + i\bar{N}\gamma_\mu \partial^\mu N + i\bar{N}'\gamma_\mu \partial^\mu N' \\
&- [Y_N^b \bar{N}\tilde{\phi}^\dagger \ell_L^b + \frac{\Lambda}{2}(\bar{N}' N^c + \bar{N} N'^c) + h.c.]
\end{aligned}
$$

- Start with a pair of Weyl fields, N (lepton no. $= +1$) and N' (lepton no. $= -1$).
- Species with opposite LN pair up $\Rightarrow$ Dirac field.
- LFV interactions $\Rightarrow$ Dirac masses for heavy ν's.
- LNV interactions $\Rightarrow$ Masses for SM ν's.

The PMNS matrix revisited

- 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:

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

S. Antusch, C. Biggio, E. Fernández-Martínez, M. B. Gavela and J. López-Pavón, JHEP **10**, 084 (2006).

- In our model:

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

  where y and Λ_{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 $\varepsilon_{e\tau} e^{i\phi_{e\tau}}$:

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

Degeneracies with NSI's

The spectrum just got even more complicated...

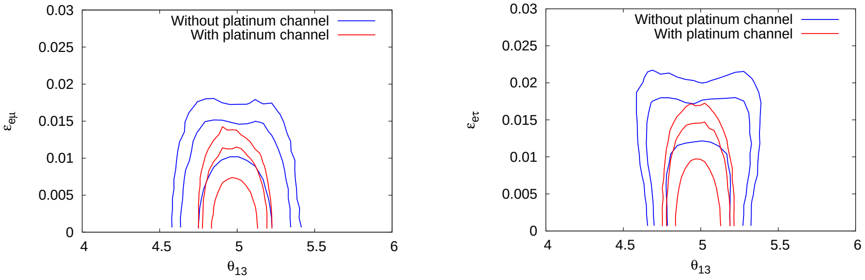
- When we include NSI's, the parameter space is vastly increased and so the degeneracy problem is magnified.
- Crucially, we must ensure that NSI's do not degrade our sensitivity to the oscillation parameters.
- The high-energy ν factory is already immune to this problem because of the 'magic baseline'.
- But for the LENF, we have to find a solution: the addition of the 'platinum channel' ($\nu_\mu \to \nu_e$) 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:

$\varepsilon_{e\mu}$ $\varepsilon_{e\tau}$



E. Fernández-Martínez, TL, O. Mena and S. Pascoli MonteCUBES

- The sensitivity to both oscillation parameters and NSI's is increased by including the $\nu_\mu \to \nu_e$ channel.
- We can obtain an upper bound of $\sim 10^{-2}$... Can we do better?

Near detectors

- 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 ν factory? We already have existing ν beams, so let's build a detector now for one of these beams...

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The idea: place a ν_τ detector very close (1 km) to the ν_μ beam source at Fermilab and look for $\nu_\mu \to \nu_\tau$ transitions.

Discovery potential of near detectors

- A near detector at a ν experiment has the advantage of having a very high event rate $\Rightarrow$ high statistics.
- In addition, the $\nu_\mu \to \nu_\tau$ channel turns out to have a very rich sensitivity to NSI's, and hence is dubbed the

Discovery
CHANNEL™

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

The MEGA Collaboration, Phys. Rev. Lett. **83**, 1521 (1999).

$$Br(\mu^+ \to e^+\gamma) \leqslant 1.2 \times 10^{-11} \qquad \text{(90\% CL)}$$

where

$$B(\ell_\alpha \to \ell_\beta) = \frac{\Gamma(\ell_\alpha \to \ell_\beta\gamma)}{\Gamma(\ell_\alpha \to \ell_\beta\nu_\alpha\bar{\nu}_\beta)}.$$

How do we relate this branching ratio to our predictions?

Bounds from charged lepton experiments

- The NSI's depend on the Yukawa couplings Y_α, Y_β, 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:

S. Antusch, C. Biggio, E. Fernández-Martínez, M. B. Gavela and J. López-Pavón, JHEP **10**, 084.

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

and thus obtain an upper bound on $|(NN^\dagger)_{\alpha\beta}|^2$.

Any holes anywhere?

- 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, δ, and the Majorana phase, α.
- Neither of these phases is known at present!
- Therefore we can only obtain predictions as a function of δ and α.

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 δ and α, $Y_e \ll 1$

$\Rightarrow$ 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. $\mu \rightarrow \tau$.

Bounds from MINSIS

- Neutrino transitions are related to NSI's via:

S. Antusch, C. Biggio, E. Fernández-Martínez, M. B. Gavela and J. López-Pavón, JHEP **10**, 084.

$$P(\nu_\alpha \to \nu_\beta) = |(NN^\dagger)_{\alpha\beta}|^2$$

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

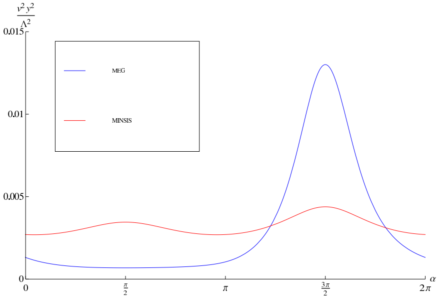
- For comparison, the current bound from a lepton experiment comes from the limit:

$$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \quad \Rightarrow (NN^\dagger)_{\tau\mu} < 4.3 \times 10^{-3}.$$

The BABAR collaboration, Phys. Rev. Lett. **104** 021802 (2010).

MINSIS vs MEGA

So MINSIS could obtain better sensitivity than MEGA in some regions of parameter space:



R. Alonso de Pablo, B. Gavela, TL

MINSIS can be complementary to charged lepton experiments.

Summary

- Future long-baseline experiments such as neutrino factories are being optimised to measure θ_{13}, δ 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.

Suggested references (1/2)

- **Oscillation parameter update**:

  - M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, arXiv:1001.4524.

- **The MSW effect**:

  - L. Wolfenstein, Phys. Rev. D **17**, 2369-2374 (1978).

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

  - [The ISS Physics Working Group], Rept. Prog. Phys. **72**, 106201 (2009), arXiv: 0710.4947 (hep-ph).

- **The low energy neutrino factory**:

  - A. Bross, M. Ellis, E. Fernández-Martínez, S. Geer, T. Li, O. Mena and S. Pascoli, arXiv: 0911.3776.

Suggested references (2/2)

- **NSI's** (theory):

  - T. Ota, J. Sato and N. Yamashita, Phys. Rev. D **65**, 093015 (2002), arXiv:hep-ph/0112392;

  - S. Antusch, C. Biggio, E. Fernández-Martínez, M. B. Gavela and J. López-Pavón, JHEP **10**, 084 (2006), arXiv:hep-ph/060702;

  - S. Antusch, J. P. Baumann and E. Fernández-Martínez, Nucl. Phys. B **810**, 369-388 (2009), arXiv:0807.1003 (hep-ph).

- **MFV model**:

  - B. Gavela, T. Hambye, D. Hernández and P. Hernández, JHEP **0909**, 038 (2009), arXiv:0906.1461 (hep-ph).

- **MINSIS**:

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