Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

Neutrino Phenomenology: Oscillations and Non-Standard Interactions

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What's a neutrino?

Introduction

ν oscillations

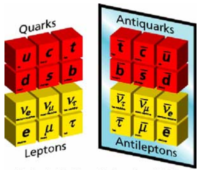
Oscillation experiments

NSI's

My work

Summary

- A ν is an electrically neutral, weakly-interacting fermion.
- It is the SU(2) partner of a charged lepton.
- Experimental evidence (LEP Z^0 decays) shows that there are three species of (light) ν, one partnering each of the charged leptons e^-, μ^-, τ^-.



The Standard Model contains 3 neutrinos of definite flavor, and a set of corresponding anti-particles.

Discovery of the ν

- The existence of the ν was predicted in 1930 by Wolfgang Pauli to explain the missing energy in nuclear β decays.
- The ν_e was first detected in the 1950's by Reines and Cowan (Hanford experiment). Reines won the Nobel Prize in 1995.
- The ν_μ was discovered in the 1960's by Danby.
- The ν_τ was discovered in 2000 by the DONUT experiment - the last SM particle to be detected (apart from the Higgs)!

“But ν’s don’t do anything!!!”

Standard Model interactions:

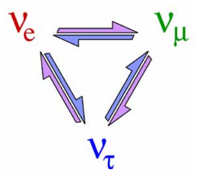
- ν’s interact via charged-current and neutral-current weak interactions.
  CC interactions: $\nu_a + \ell_b^- \rightarrow \ell_a^- + \nu_b$
  NC interaction: $\nu_a + X \rightarrow \nu_a + X$
- We use these interactions to define what we mean by a ν_e, ν_μ and ν_τ.
- These interactions are predicted by the SM (they appear in the SM Lagrangian).

"But ν's don't do anything!!!"

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

BSM properties:

- ν also **oscillate** between flavour states - experimental evidence announced by Super-Kamiokande in 1998.
- This is **not** predicted by the SM $\rightarrow$ First evidence for physics beyond the SM!



The periodic change of neutrino flavor from one type into another is referred to as neutrino oscillations.

Image from http://theta13.lbl.gov/

Why do neutrinos oscillate?

Introduction

ν **oscillations**

Oscillation experiments

NSI's

My work

Summary

- Particle oscillations are a purely quantum-mechanical phenomena (no classical analog).
- Oscillations occur if the interaction (flavour) states of a particle do not coincide with the mass eigenstates of a particle.
- The ν flavour states are related to the ν mass states via a mixing matrix (the PMNS matrix):

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

The PMNS matrix

- The PMNS matrix is a product of three 2×2 rotation matrices and two phase matrices:

$$
\begin{aligned}
U &= O_{23} V_\delta O_{13} V_\delta^\dagger O_{12} V_\zeta \\
&= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \\
&\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\zeta_1/2} & 0 & 0 \\ 0 & e^{i\zeta_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}
\end{aligned}
$$

where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$.

The PMNS matrix

Introduction

ν oscillations

Oscillation experiments

NSI's

My work

Summary

- The matrix is a 3×3 unitary matrix, and therefore contains 6 parameters:
  - 3 mixing angles - $\theta_{12}, \theta_{13}, \theta_{23}$
  - 3 phases - δ, ζ_1, ζ_2
- δ is the CP violating phase (Dirac phase) - more later...
- $\zeta_{1,2}$ are the Majorana phases. They have no effect on oscillations (won't mention them again).

Oscillation probabilities

Introduction
ν **oscillations**
Oscillation experiments
NSI's
My work
Summary

- Oscillation probabilities (in vacuum) are straightforward to calculate. The probability for the transition $\nu_a \longrightarrow \nu_b$ takes the form:

$$P_{ab} \sim X(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \sin^2(\frac{\Delta m_{ij}^2 L}{2E})$$

  where X is some function of the elements of U, L is the distance travelled by the ν, E is its energy, i and $j = 1, 2, 3$.

- Oscillations depend on mixing angles θ_{ij}, the phase δ and the mass-squared differences between mass eigenstates.

Implications for ν masses

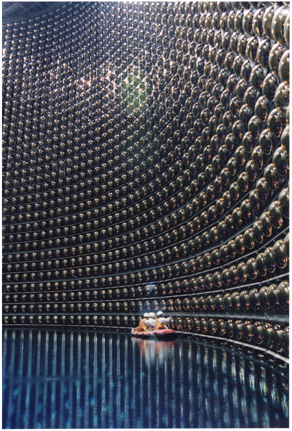
Introduction
ν **oscillations**
Oscillation experiments
NSI's
My work
Summary

- ν oscillations $\Rightarrow$ not all ν states are massless.
- This contradicts the SM where all ν are massless because there are no RH ν.
- Even if we do add RH ν to the SM to give νs Dirac masses, why is $m_\nu \ll m_{EW}$?
- ν masses must arise from some BSM mechanism (won't discuss today)

Current status of ν oscillation experiments

The current generation of ν oscillation experiments (KamLAND, SK, K2K, MINOS...) have made the following measurements of the mixing parameters:

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



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

In the near future...

- At present there are no favoured theories explaining the values of the free SM parameters in the quark and lepton sectors. It is important to measure these parameters so that we can progress with theoretical model-building and come closer to understanding the physics of flavour.
- The next generation of experiments (due to start running in the next few years) have been designed to measure θ_{13} and δ. What's special about these parameters?

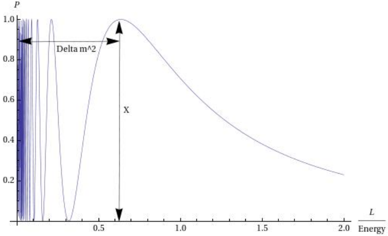
θ_{13} and δ

- θ_{13} is small. If $\theta_{13} = 0$ this indicates (together with $\theta_{23} = 45^o$) that a $\mu - \tau$symmetry is present. θ_{13} is also closely related to δ...
- δ is the CP violating phase. We know there's CP violation in the quark sector, but have not yet observed any in the lepton sector. If there is CP violation in the lepton sector, this could explain the matter/ anti-matter asymmetry of the universe (baryogenesis via leptogenesis).

How to measure θ and $|\Delta m^2|$

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- $P_{ab} \sim X(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \sin^2(\frac{\Delta m^2_{2(3)1} L}{2E})$



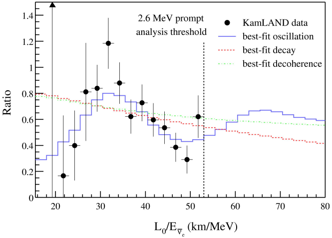
- Can only see this if $\frac{\Delta m^2_{2(3)1} L}{2E} \sim 2\pi$.
  $\rightarrow$ Each experiment can only measure either Δm^2_{21} or Δm^2_{31}.

How to measure θ and Δm^2 - KamLAND example

- The KamLAND experiment measures $\bar{\nu}_e \rightarrow \bar{\nu}_e$:

$$P_{\bar{e}\bar{e}} \approx 1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- They obtain the following data:



From www.nu.to.infn.it/

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're still not very close to understanding the structure of flavour and mixing.
- We'd like to look for physics beyond the Standard ν Model to help us understand what's going on:
  - sterile ν
  - CPT/ Lorentz invariance violation
  - ν decay
  - non-standard ν interactions (NSI's).

What's an NSI?

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- An NSI is any interaction involving ν other than SM interactions and ν oscillations$\Rightarrow$ flavour-changing ν interactions $\nu_\alpha \to \nu_\beta$.
- These appear in theories which predict the existence of some (high-energy) particle which couples to leptons (e.g. R-parity violating SUSY, RS models with RH ν in the bulk).
- So these theories also predict flavour-changing charged-lepton interactions $\ell_\alpha^- \to \ell_\beta^-$.
- At the low energies at which we perform experiments, we can approximate these interactions as effective 4-point interactions, with strength $\epsilon_{\alpha\beta}$.

How big is ϵ?

- Weak interactions are suppressed by a factor of $1/m_W^2$.
- Expect ν NSI's to be suppressed by a factor of $1/m_{NP}^2$ if mediated by new physics particles.
- $\Rightarrow$ Guess that $|\epsilon_{\alpha\beta}| \sim \frac{m_W^2}{m_{NP}^2} \sim (\frac{80\,GeV}{1\,TeV})^2 \sim 10^{-3} - 10^{-2}$ relative to G_F, the weak interaction.

Detecting NSI's

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- 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 $\sim \epsilon^2 \sim 10^{-6}$ - eek!
- In ν oscillation experiments, this flavour change can occur either through an oscillation, or through a NP process:
  $\nu_\tau \to \nu_\mu \sim P_{\tau\mu}$ or $\nu_\tau \to \nu_\mu \sim |\epsilon_{\tau\mu}|$
  Add, then square to get the probability: there is an interference term which is linear in ϵ.
- Not great, but better to measure ϵ than ϵ^2!

Matter matters

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- ν NSI's are a matter effect - they arise because ν's interact with the matter through which they propagate.
- So the more matter you have, the larger the effect of the NSI $\Rightarrow$ dense matter and/ or long baselines $\sim$ 1000's km enhance the effect.
- (Long baselines are also useful in oscillation experiments for other reasons).

The 735km MINOS baseline
http://www.hepl.harvard.edu/neutrino

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

What do I work on?

- I work on the phenomenology of long-baseline neutrino oscillation experiments.
- Specifically, I'm looking at the physics reach of a low-energy neutrino factory which has access to the $\nu_e \to \nu_\mu$ channel, with particular interest in the sensitivity to non-standard neutrino interactions.

Which means...

After we (hopefully) have better bounds on θ_{13} and δ, what do we do next?

- We need to design and build an experiment which will give even better precision on these parameters, and which will answer other questions in ν physics, including the sign of Δm^2_{31} and the existence of NSI's.
- I look at a particular experiment set-up:
  L$\sim$ 1000km, E$\sim$ 1GeV, measures $\nu_e \to \nu_\mu$ and $\nu_\mu \to \nu_e$ and try to answer the following questions:

Which means...

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- Which NSI parameters is the experiment sensitive to?
- How sensitive is it, and how can we optimize the sensitivity to NSI's?
- Can we determine the sign of Δm_{31}^2?
- Is it possible to disentangle all the parameter degeneracies?

Which NSI parameters can be detected?

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

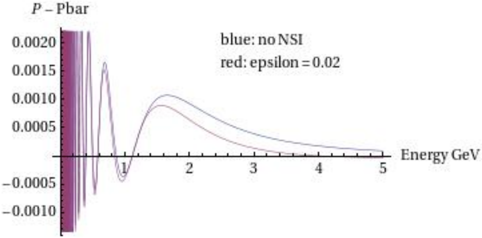
- The transition probability for $\nu_\mu \to \nu_e$ is:

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

- The leading order NSI effect $\sim \epsilon_{e\tau}$ (causes $\nu_e \to \nu_\tau$).

How sensitive is the experiment?

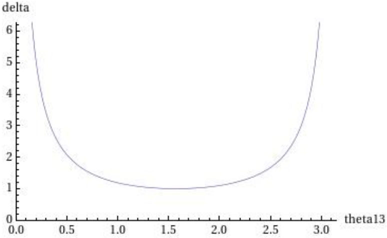
- When detecting NSI's, the 'background' is the standard oscillation (SO) contribution.
- Matter effects amplify the NSI contribution relative to the SO contribution.
- Can further amplify the effect by considering the CP-violating quantity $P_{\mu e} - P_{\bar{\mu}\bar{e}}$:



Parameter degeneracies

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- The 'degeneracy problem' is well-known in ν physics.
- The problem: oscillation formulae are a function of several mixing parameters. It is not always possible to disentangle them all.
- E.g. suppose that $X \sim \theta_{13} \cos\delta$. We measure the quantity $\theta_{13} \cos\delta$ and obtain a degenerate locus of points in the θ_{13}/δ parameter space:



Parameter degeneracies

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- Now include all the unknown parameters:
  θ_{13}, δ, signΔm^2_{31}, octant of θ_{23}, $|\epsilon|, \phi$
- It gets quite complicated...
- However, have shown that if we have access to the CPT conjugate channel $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$, and can obtain data from the first two oscillation maxima, then all degeneracies can be resolved.

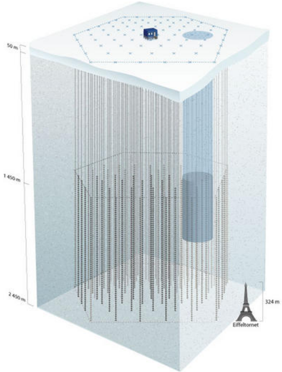
What next

Introduction
ν oscillations
Oscillation experiments
NSI's
My work
Summary

- Analytic part is pretty much finished.
- We know what the experiment is capable of, in theory!
- Next we need to simulate the experiment, to see what effect hardware/ software effects (e.g. energy resolution, smearing, efficiency) would have on the results.

Quick aside on ν experiments

- Oscillation experiments:
  - long baseline ($>$ 100's of km) or short baseline ($\sim$1km)
  - use ν from nuclear reactors, beams, atmospheric ν, solar ν
- $0\nu\beta\beta$:
  - test whether ν are Dirac or Majorana particles
  - measure Majorana phases
  - measure absolute masses of ν's (rather than Δm^2)
- ν telescopes:
  - can detect high-energy cosmic ν, $(10^{11} - 10^{21}\text{eV})$!
  - search for SUSY, dark matter...



The IceCube experiment
From http://icecube.wisc.edu/

Areas of ν physics

Introduction

ν oscillations

Oscillation experiments

NSI's

My work

Summary

- Particle physics: origin of ν mass, flavour physics, CP violation in lepton sector, GUT's, BSM theories.
- Cosmology/ astrophysics: BAU (baryongenesis via leptogenesis), inflation, early universe physics (structure formation), dark matter.
- Geophysics: use ν to probe the internal structure of the earth.
- Quantum physics: quantum-mechanical theory and concepts behind ν oscillations, relation between particle oscillations and quantum entanglement.

Summary: ν Physics = New Physics

- ν oscillations $\Rightarrow$ BSM physics.
- It's important to measure the ν mixing parameters to help us build and test models of flavour structure and BSM physics.
- When looking for physics beyond the standard ν model, long-baseline experiments are a very powerful tool for measuring NSI's.
- I look at the physics reach of a low-energy neutrino factory. We have shown that this set-up has the capability to measure $\epsilon_{e\tau}$, determine the ν mass hierarchy, and resolve parameter degeneracies.