Final year project presentation Neutrino oscillations and experimental sensitivity

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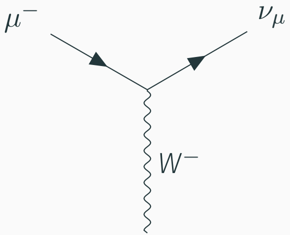
Outline

- Neutrinos
- Modelling neutrino oscillations
- Mass hierarchy and CP-violating phase
- Experimental sensitivity

What's a neutrino?



- Lightest lepton
- Spin $\frac{1}{2}$ fermion
- Interacts only via weak force
- Three flavors, produced or absorbed by corresponding charged current interaction

Neutrino oscillations: some history

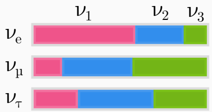
- Theorized by Bruno Pontecorvo in 1957
- Observed by SuperK (1999) and SNO (2001)
  $\hookrightarrow$ 2015 Nobel Prize
- Implications of the discovery:
  - Solar neutrino problem solved ✓
  - Beyond the Standard Model physics

Neutrino oscillations

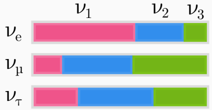
- What do we mean by oscillations?

Neutrino oscillations

- What do we mean by oscillations?
- Mass eigenstates vs Weak eigenstates



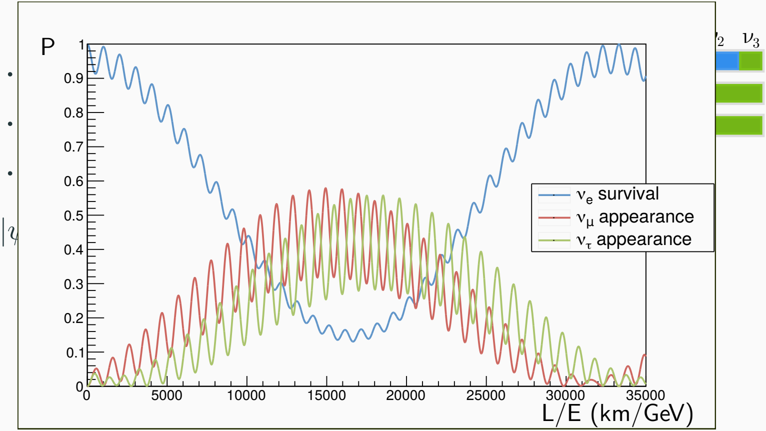
Neutrino oscillations



- What do we mean by oscillations?
- Mass eigenstates vs Weak eigenstates
- Example: oscillations through space for a ν_e

$$|\psi(x)\rangle = U_{e1}|\nu_1\rangle\, \mathrm{e}^{-\mathrm{i}p_1\cdot x} + U_{e2}|\nu_2\rangle\, \mathrm{e}^{-\mathrm{i}p_2\cdot x} + U_{e3}|\nu_3\rangle\, \mathrm{e}^{-\mathrm{i}p_3\cdot x}$$

Neutrino oscillations



$$P(\nu_\alpha \rightarrow \nu_\beta) \propto \sum_{ij} \exp\left(-i\frac{\Delta m_{ij}^2 L}{2E}\right) \qquad \Delta m_{ij}^2 = m_i^2 - m_j^2$$

Oscillations and CP-violation

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} & & \\ & U & \\ & & \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$e^{i\delta_{CP}}$$

Oscillations and CP-violation

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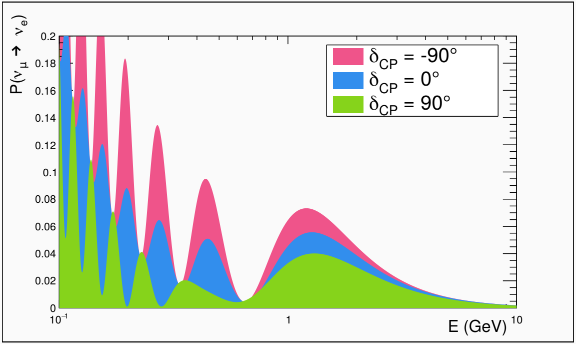
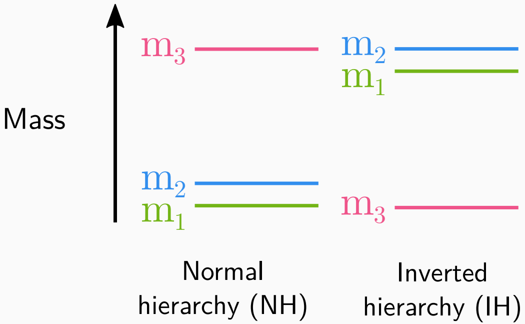
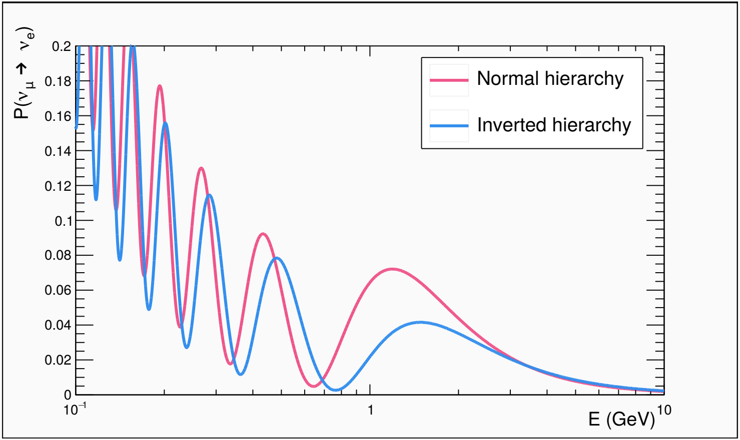


- An extra ambiguity



The mass ordering



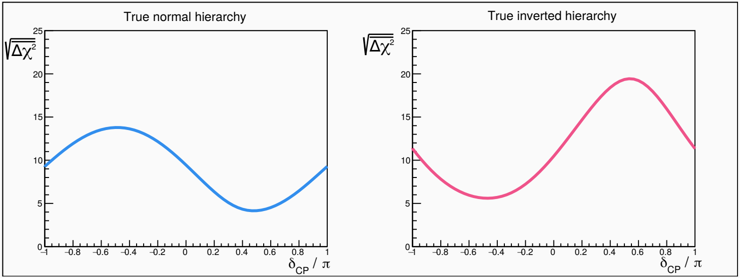
Sensitivity

- Will the experiment be able to put constraints on the parameters?
- How much data would we need?
- Define *sensitivity* statistic:

$$\overline{\Delta\chi^2} = \sum_i \frac{(y_i^A - y_i^B)^2}{\sigma_i^2}$$

Sensitivity

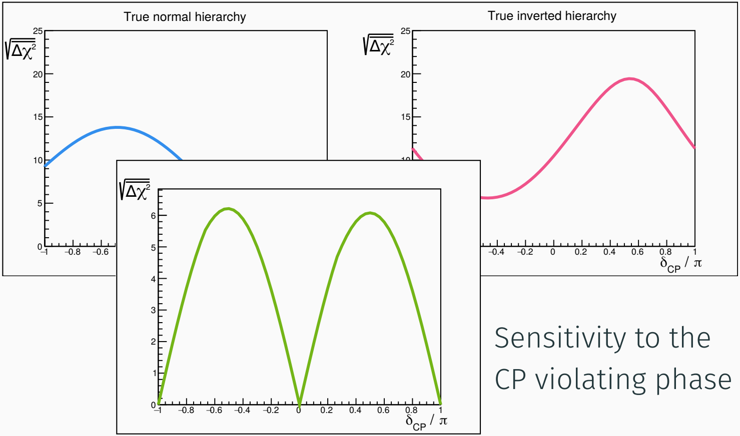
Sensitivity to the mass hierarchy



$$\overline{\Delta\chi^2} = \sum_i \frac{(y_i^A - y_i^B)^2}{\sigma_i^2}$$

Sensitivity

Sensitivity to the mass hierarchy



Sensitivity to the CP violating phase

$$\overline{\Delta\chi^2} = \sum_i \frac{(y_i^A - y_i^B)^2}{\sigma_i^2}$$

What’s next

- Improve the model by introducing statistical uncertainties
- Determine optimal running time for the experiment by estimating sensitivity as a function of exposure
- Combine model with other experiments (IceCube, T2K) to eliminate degeneracies

Summary

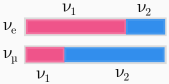
- Neutrino oscillations
- CP-violating phase and mass ordering
- Experimental sensitivity

References

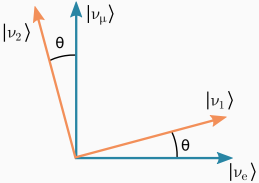
- Zuber, K. (2004). *Neutrino Physics*
- Thomson, M. (2013). *Modern Particle Physics*
- Ciuffoli, Evslin, Zhang (2013). *Sensitivity to the Neutrino Mass Hierarchy* (1305.5050)
- NOvA Collaboration (2017). *Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA* (1703.03328)
- DUNE Collaboration (2015). *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report*
- Kayser, B. (2008), *Neutrino Oscillation Phenomenology* (0804.1121)
- Qian, Tan, Wang, Ling, McKeown, Zhang (2012). *Statistical Evaluation of Experimental Determinations of Neutrino Mass Hierarchy* (1210.3651)
- Smirnov, A. (2004), *The MSW effect and Matter Effects in Neutrino Oscillations* (04122391)
- Blennow, M. (2015), *Mass hierarchy sensitivity at future oscillation facilities*

Neutrino oscillations

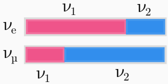
- Mass eigenstates and weak eigenstates
- Two neutrinos



$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$



- Mass eigenstates and weak eigenstates
- Two neutrinos



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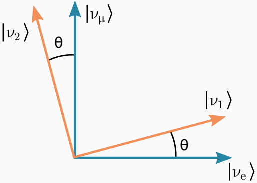


$$|\psi(0)\rangle = |\nu_e\rangle \equiv \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

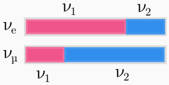
$$|\psi(x)\rangle = \cos\theta|\nu_1\rangle\, \mathrm{e}^{-\mathrm{i}p_1\cdot x} + \sin\theta|\nu_2\rangle\, \mathrm{e}^{-\mathrm{i}p_2\cdot x}$$

$$P(\nu_e, L) = |\langle\nu_e|\psi(L)\rangle|^2 \neq 1$$

Different masses $\rightarrow$ different phases $\rightarrow$ flavor oscillations

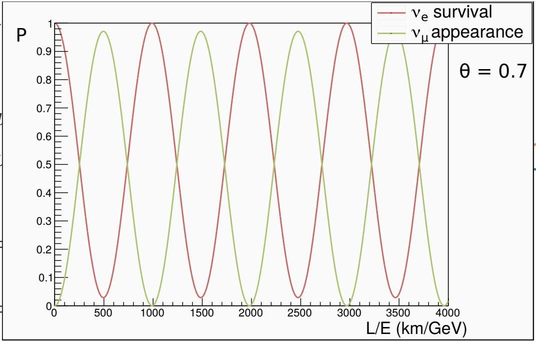
Neutrino oscillations

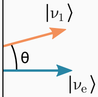
- Mass eigenstat
- Two neutrinos



$|\psi(0)\rangle =$

$|\psi(x)\rangle =$





$$P(\nu_e, L) = |\langle \nu_e | \psi(L) \rangle|^2 \neq 1$$

Different masses $\rightarrow$ different phases $\rightarrow$ flavor oscillations

$$P(\nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{\Delta m^2 L}{4E}$$

PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-\mathrm{i}\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{\mathrm{i}\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$c_{23} = \cos\theta_{23}, \quad s_{12} = \sin\theta_{12}, \quad \ldots$$

Three neutrino case

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-\mathrm{i}\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{\mathrm{i}\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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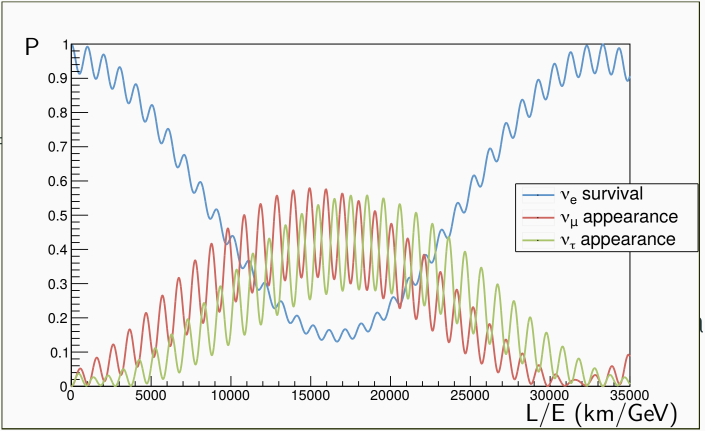
$$c_{23} = \cos\theta_{23}, \quad s_{12} = \sin\theta_{12}, \quad \dots$$

$\rightarrow$ Three mixing angles (Euler angles), one imaginary phase

$$P(\nu_\alpha \rightarrow \nu_\beta) \propto \sum_{ij} \exp\left(-i\frac{\Delta m^2_{ij} L}{2E}\right) \qquad \Delta m^2_{ij} = m^2_i - m^2_j$$

Three neutrino case

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \quad \cdots \quad \begin{matrix} 0 \\ 0 \\ 1 \end{matrix}\Bigg] \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



$\rightarrow$ ... ase

$$P(\nu_\alpha \rightarrow \nu_\beta) \propto \sum_{ij} \exp\left(-i\frac{\Delta m^2_{ij} L}{2E}\right) \qquad \Delta m^2_{ij} = m^2_i - m^2_j$$

Matter effects

- The Earth contains electrons
- Electron-neutrinos are “slowed down”