Neutrinos: tutorial

Please ask doubts, questions…

There is no crazy/stupid question!

Theory: Majorana

Show that Majorana mass terms:

$$-\mathcal{L}_m^{\text{Majorana}} = \frac{1}{2}m\overline{\psi^C}\psi + \frac{1}{2}m\bar{\psi}\psi^C \equiv \frac{1}{2}m\psi^T C\psi + \frac{1}{2}m\bar{\psi}C\bar{\psi}^T$$

- Are Lorentz invariant
- Generate massive particles
- Couple a single chirality

Theory: Majorana

Let’s do a small detour:

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A Majorana fermion is the same idea: start with a standard Dirac field and require it to be its own charged conjugate.

Theory: Majorana

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} \partial\!\!\!/ \psi - \frac{1}{2} m \bar{\psi} \psi$$

$$\psi = \psi^C \equiv C \gamma_0 \psi^*$$

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$$C \equiv i\gamma_2\gamma_0$$

$$C^\dagger = C^T = C^{-1} = -C$$

$$C^{-1}\gamma_\mu C = -\gamma_\mu^T$$

$$\gamma_0\gamma_\mu\gamma_0 = \gamma_\mu^\dagger$$

$$C\gamma_0\gamma_\mu^*\gamma_\nu^*\gamma_0 C^{-1} = \gamma_\mu\gamma_\nu$$

We know that these fermions will have mass m

Lorentz invariance?

Theory: Majorana

We will check that

$$-\mathcal{L}_m^{\text{Majorana}} = \frac{1}{2} m \overline{\psi^C} \psi + \frac{1}{2} m \bar{\psi} \psi^C \equiv \frac{1}{2} m \psi^T C \psi + \frac{1}{2} m \bar{\psi} C \bar{\psi}^T$$

- Generates Majorana fermions
- Does not couple different chiralities

$$L \equiv \frac{1+\gamma_5}{2};\ R \equiv \frac{1-\gamma_5}{2}$$

$$L^2 = L;\ R^2 = R;\ L \cdot R = 0$$

$$\gamma_\mu \gamma_5 = -\gamma_5 \gamma_\mu \Rightarrow \gamma_\mu L = R \gamma_\mu;\ \gamma_\mu R = L \gamma_\mu$$

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We can rewrite it as:

$$\psi_1 \equiv \psi_L + \psi_L^C$$

$$\psi_2 \equiv \psi_R + \psi_R^C$$

$$-\mathcal{L}_m^{\text{Majorana}} = \frac{1}{2} m \overline{\psi_1} \psi_1 + \frac{1}{2} m \overline{\psi_2} \psi_2; \;\; \psi_1^C = \psi_1; \;\; \psi_2^C = \psi_2$$

Theory: Majorana

Take-home messages:

- Majorana fermion = standard fermion + $\psi = \psi^C$

- *One* **chiral** field ψ_L + Majorana mass term $\frac{m}{2}\left(\overline{\psi_L^C}\psi_L + \psi_L\psi_L^C\right)$
  = Majorana fermion $\psi_M = \psi_L + \psi_L^C$

For more information and common misunderstandings, see e.g. arXiv:1006.1718

What about neutrinos?

In the SM, we have one chiral field ν_L

This means that we can have either

- Dirac mass, $\nu_M^{\mathrm{Dirac}} = \nu_L + \nu_R$
- Majorana mass $\nu_M^{\mathrm{Maj}} = \nu_L + \nu_L^C$

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The SM is chiral: $L\,\nu_M^{\mathrm{Dirac}} = L\,\nu_M^{\mathrm{Maj}}$

To distinguish between Dirac and Majorana, we need some chirality flip $\propto \frac{m_\nu}{E}$

Majorana phases

$$\mathcal{L}_{\mathrm{CC,lepton}} = -\frac{g}{\sqrt{2}} U_{\alpha i}\, \overline{l_\alpha} \gamma_\mu L \nu_{M,i} W_\mu^- + \mathrm{h.c.}$$

- How many phases in the unitary matrix $U_{\alpha i}$?
- What if neutrinos are Majorana?
- Are Majorana phases observable in oscillations?

$$U^{\mathrm{lep}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} e^{-i\delta_{\mathrm{CP}}} & 0 \\ -s_{12} e^{i\delta_{\mathrm{CP}}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino oscillations

Why don’t charged leptons oscillate?

PS: quarks do oscillate too. The problem is that quarks come in hadrons, which are typically heavy and unstable. Thus, we have to look for these oscillations at particle colliders.
And we have seen them! They have been very relevant to observe CP violation in the quark sector. Google “meson oscillations”.

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- What are neutrino oscillations?
- What induces neutrino oscillations?
- What is a charged lepton? How do we distinguish them?

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Neutrino oscillations

- Reactors: isotropic flux of ~10^{20} neutrinos/s
- How far do we have to place a detector to be sensitive to $\Delta m^2_{32} \sim 10^{-3}\,\mathrm{eV}^2$?
- How large must it be to have ~few events/day?

Tip: gnu units. It can handle natural units! [Load as units -u natural] [GF=fermicoupling]

Daya Bay


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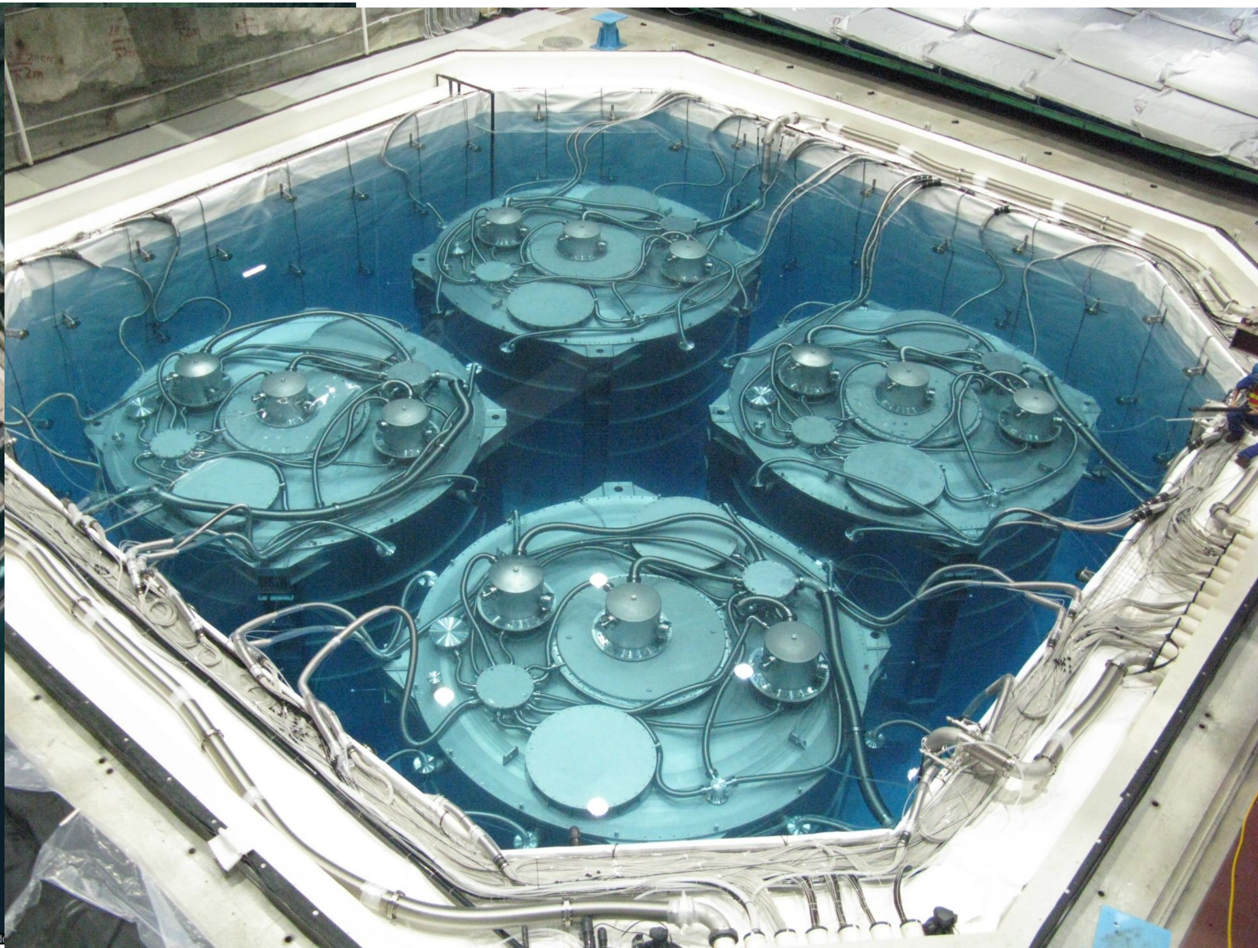
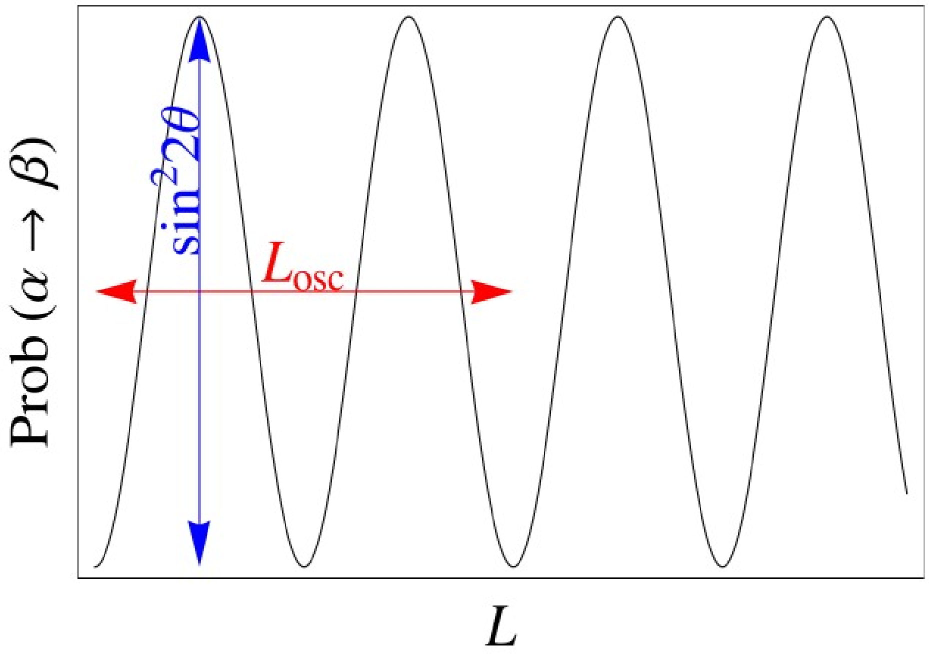
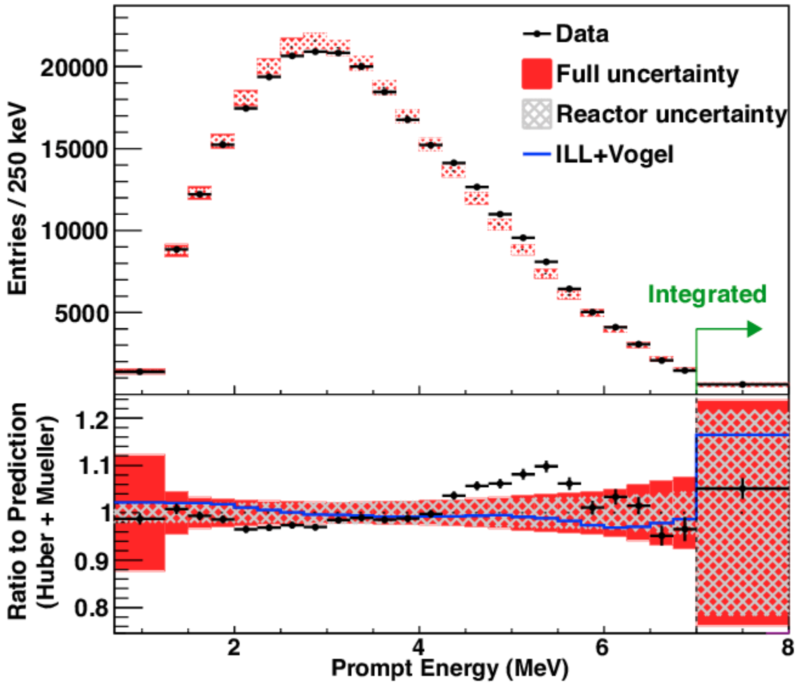


Neutrino oscillations

- Compute the number of events, and the relevance of systematic uncertainties





Neutrino oscillations

Experimental effects are very important:

- Energy resolution and calibration: Δm^2
- Flux normalization, cross section and background: θ

Neutrino oscillations

- Can 4-neutrino oscillations be resonantly enhanced?
- Where can we search for it?

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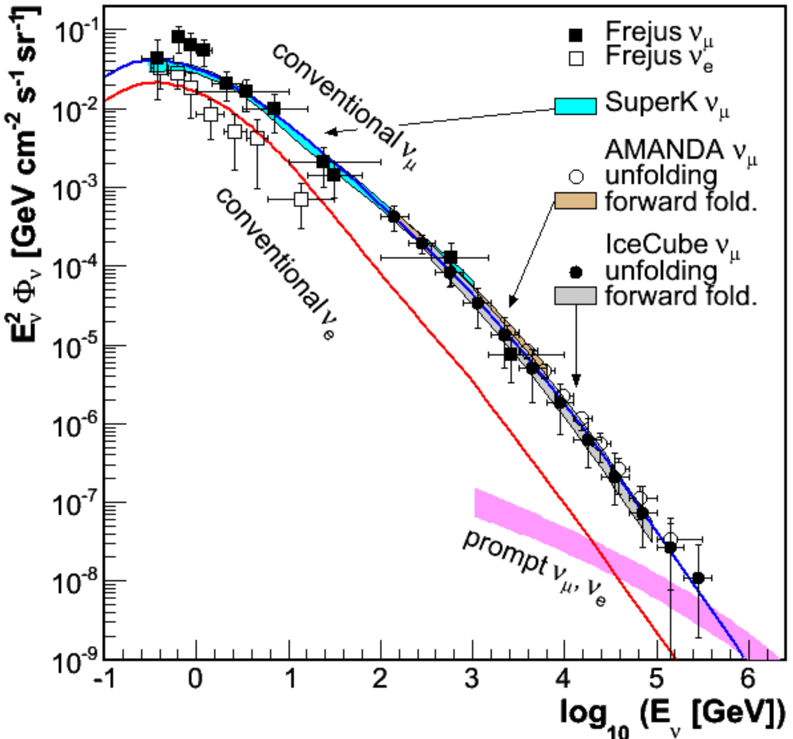

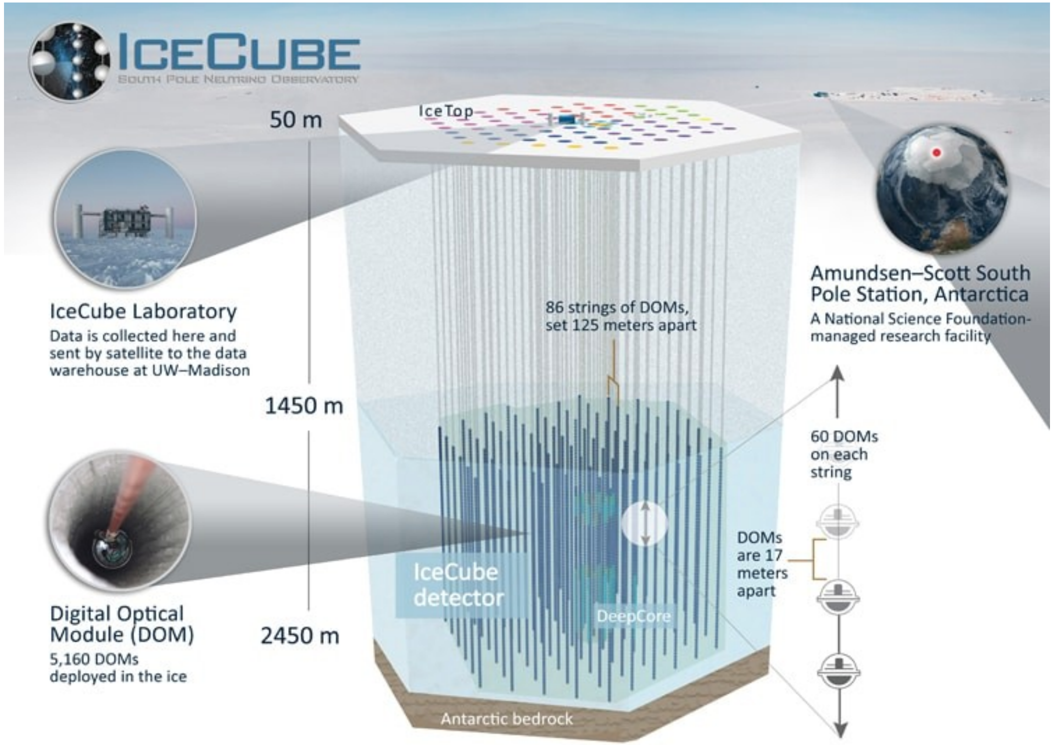

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