Studying neutrino oscillations at the DUNE experiment

Abbey Barnard and Dr Andy Blake
Department of Physics, Lancaster University

What is a neutrino?

Neutrinos are one of the fundamental particles of nature. They are neutral, low-mass fermions which interact principally via the weak force. There are three flavours of neutrino: electron, muon and tau. Each flavour of neutrino is partnered with its corresponding charged lepton.

Neutrino mass states

Neutrinos are the lightest fundamental particle. There are three neutrino mass states, υ_1, υ_2 and υ_3 which are made up of a combination of the flavour states υ_e, υ_μ and υ_τ. Conversely, the flavour states can be represented as a combination of mass states. Neutrinos interact via their flavour states but propagate via their mass states.

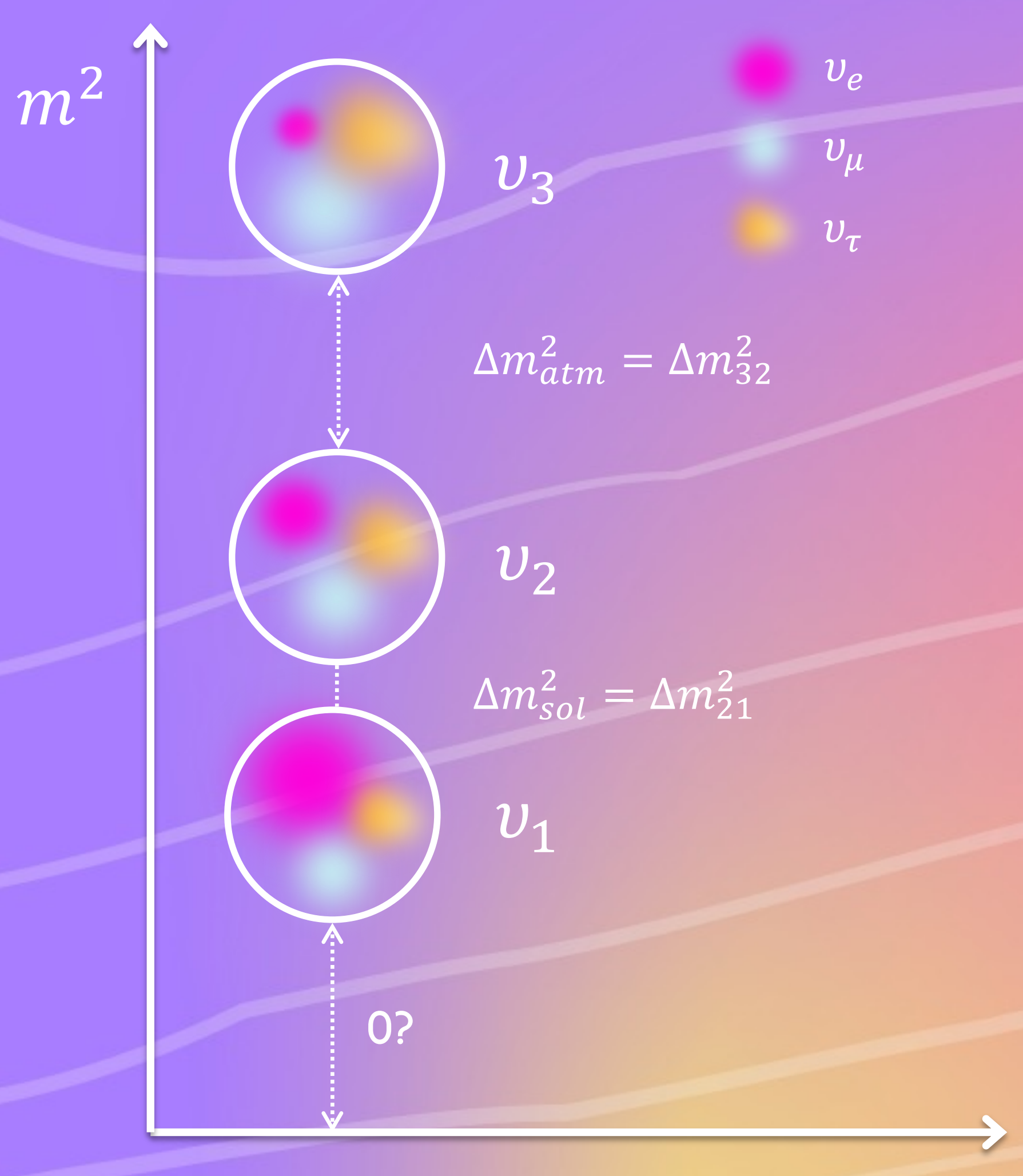


Figure 1: The normal mass ordering for neutrinos. The pink, blue and yellow regions represent the amount of electron, muon and tau flavour comprising the mass states, respectively.

Unanswered questions

We already know a lot about neutrinos! They have mass, are one of the most abundant forms of matter in our universe and exhibit a remarkable quantum mechanical behaviour known as neutrino oscillation.

However, there are many things which we don't yet know, such as their mass ordering (normal, inverted or degenerate), whether or not there is a fourth mass state, and their absolute masses. Neutrinos are believed to violate CP symmetry; however, this has not yet been observed.

Figure 1 shows the normal mass ordering for neutrinos. Each mass state consists of different proportions of flavour states.

What is DUNE?

DUNE (Deep Underground Neutrino Experiment) is a next-generation neutrino experiment that will revolutionize our understanding of neutrino physics. DUNE will operate from the Fermi Laboratory in the USA and will consist of an intense accelerator neutrino beam and two detectors: near and far. Figure 3 shows the relative locations of these detector components.

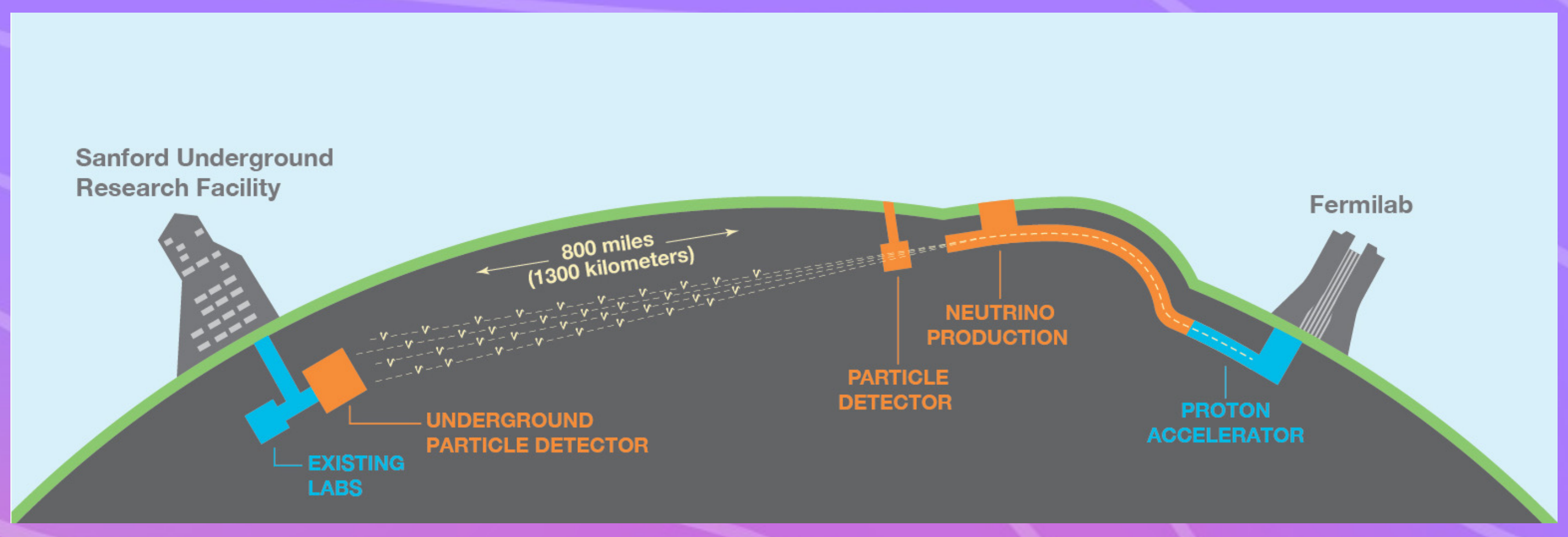


Figure 3: Schematic of the DUNE experiment at Fermilab [2].

The main physics goals of DUNE are to perform precise measurements of neutrino oscillations, search for proton decays and observe neutrinos from supernovae bursts should one happen during the experiment's operational lifetime.

DUNE will utilise liquid argon time projection chambers to detect charged particles from neutrino interactions. Argon is used as the detection medium because it is inert, and it must be cryogenically cooled to remain liquid. Charged particles moving through the detector ionise the argon atoms and the resulting free electrons drift in an applied electric field until they are detected by an anode assembly. It is here that the collected electrons are amplified into an electrical signal and high-resolution images are obtained. Figure 4 shows an example of one of these images. The time in ticks is plotted against wire number, where different wire numbers correspond to different areas of the detector.

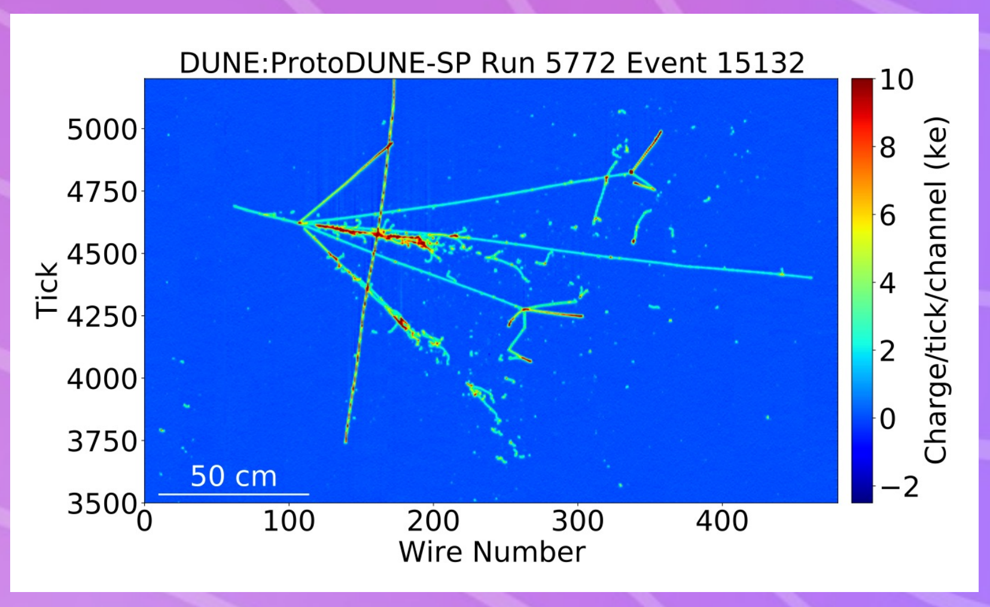


Figure 4: Particle tracks seen in the protoDUNE detector at CERN [3]. This candidate is a 6 GeV/c kaon.

What are neutrino oscillations?

As neutrinos propagate through space, they can oscillate between their different flavor states. Oscillations occur as a result of the mass states changing phase over time. Just as quark sector mixing can be described by the Cabibbo–Kobayashi–Maskawa matrix (CKM matrix), neutrino mixing can be described by the **Pontecorvo–Maki–Nakagawa–Sakata matrix** (PMNS matrix). Neutrino flavour states can be expressed using the following equation

$$\begin{bmatrix} \upsilon_e \\ \upsilon_\mu \\ \upsilon_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \upsilon_1 \\ \upsilon_2 \\ \upsilon_3 \end{bmatrix} \qquad (1)$$

where the left-hand matrix represents the flavour state neutrinos, the centre matrix is the PMNS matrix with components representing the mass states in terms of flavour and the right-hand matrix represents the mass state neutrinos.

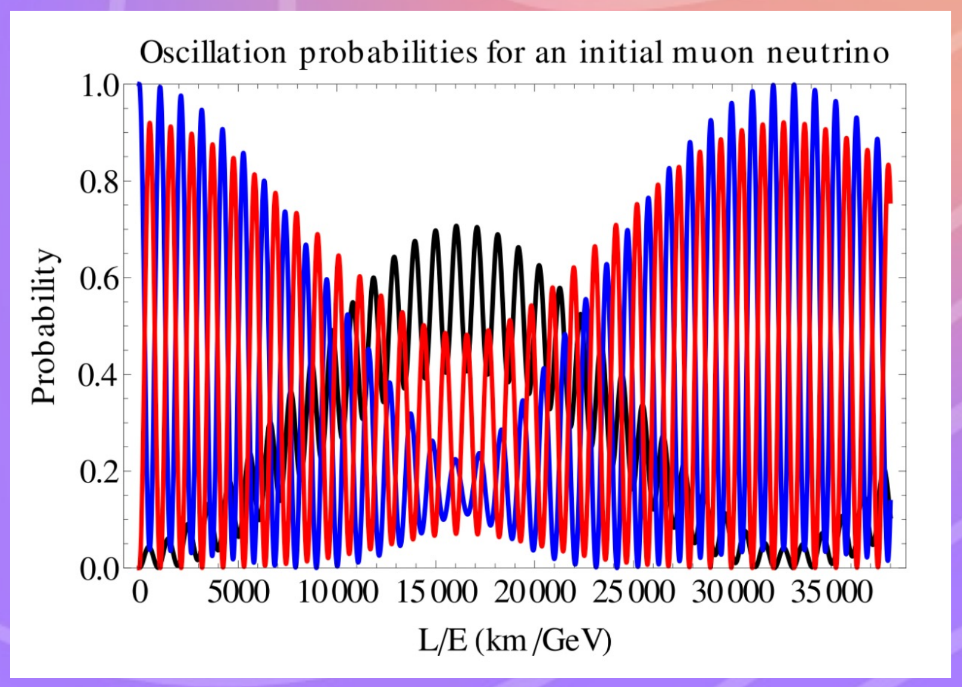


Figure 2: Oscillation probability as a function of $\frac{L}{E}$ for muon neutrinos over a long range [1]. The blue line represents muon flavour, whilst the red and black lines represent tau and electron flavours, respectively.

Neutrino oscillation probability

Using quantum mechanics, we can derive the oscillation probability P between two flavour states to be

$$P = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right) \qquad (2)$$

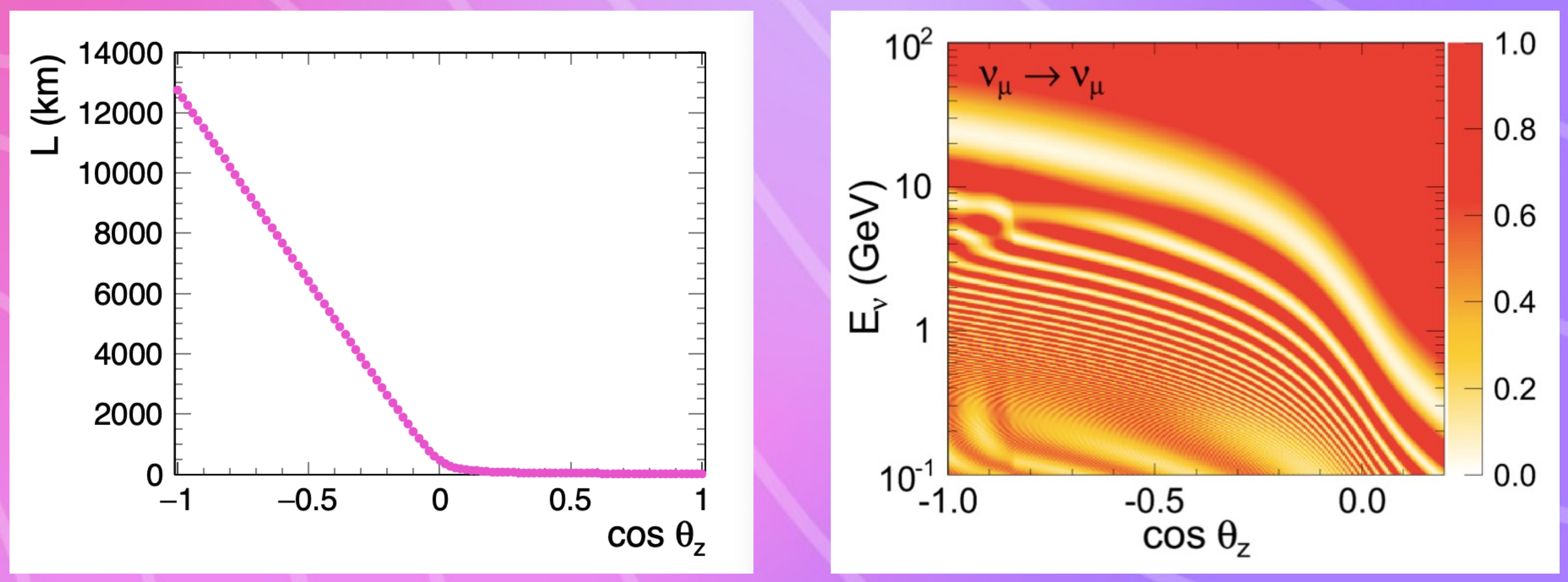
where θ is the mixing angle between two mass states, Δm^2 is the mass splitting between two mass states, L is the neutrino propagation distance and E is the neutrino energy.

Oscillation types

A range of neutrino oscillation modes are observed in nature. Solar and atmospheric neutrinos provide some of the most common modes, with solar neutrino oscillations being defined as $\upsilon_e \rightarrow \upsilon_\mu$, and atmospheric neutrino oscillations defined as $\upsilon_\mu \rightarrow \upsilon_\tau$. Oscillations can also be observed in man-made neutrino sources, such as particle accelerators and nuclear reactors.

Tau neutrino appearance at DUNE

The DUNE far detector will be sensitive to oscillations in neutrinos produced by cosmic ray interactions in the atmosphere. This provides a great source of muon neutrinos, and we can search for their oscillations into tau neutrinos. Atmospheric neutrinos have a broad range of L and E enabling a significant tau neutrino signal to be observed. Figures 5a and 5b highlight the key oscillation properties.



a) Distance of travel against angle as a function of angle of incidence for atmospheric neutrinos in the DUNE far detector. Demonstrated here is a great range of L, allowing us to take good measurements of atmospheric neutrino oscillation.

b) Energy as a function of angle of incidence for atmospheric neutrinos in the DUNE far detector. Larger energies correspond to a smaller oscillation probability, as predicted by Equation 2.

Figures 5a and 5b: Atmospheric neutrino oscillation parameters demonstrating the large ranges of E and L essential for taking significant measurements.

To assess the capability of DUNE to measure tau neutrino appearance, we developed a computer simulation of atmospheric tau neutrinos at DUNE. This simulation was used to calculate event rates, considering both signal and background processes. With this simulation, we determined that DUNE will be sensitive to tau neutrinos at high statistical significance, as shown below.

Signal (no. of υ_τ CC interactions in 400 kt-yrs) = 408

Background (no. of NC interactions above 3.5 GeV) = 1426

$$\frac{S}{\sqrt{B}} \sim 10 \text{ std. deviations!}$$

References

[1] *Meszéna, Balázs. "Neutrino Oscillations". Wolfram Demonstrations Project. Retrieved 8 October 2015.*

[2] Deep Underground Neutrino Experiment. Dune Detector Schematic [Internet]. 2020 [cited 4 April 2022]. Available from: https://www.dunescience.org/wp-content/uploads/2016/12/LBNE_Graphic_061615_2016.jpg

[3] Abi B et al. First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform. JINST. 2020.