In 2005 NuMI (Neutrinos at the Main Injector)[1] [2] was planned in Fermilab to capture the muon neutrino[3], without digging a tunnel[4]. Firstly MINOS[5], then NOvA[6], would successfully trap thousands of muon neutrinos over the years.

But our story starts earlier with Fermilab scientists Rameika and Byron Lundberg, who recognised a logical flaw in the proposed long-baseline programme for NuMI. Standard quantum theory predicted that neutrinos could change flavour as they propagated, so that after travelling a sufficient distance there would be a probability of detecting a neutrino as an electron, muon or tau neutrino rather than in its original flavour. This phenomenon, later known as neutrino oscillation, implied that the tau neutrino should exist as the third member of the lepton family[7].

However, unlike the electron and muon neutrinos, the tau neutrino had never been directly observed interacting in a detector. Before long-baseline programmes such as NuMI could investigate neutrino oscillations in detail, physicists first needed a direct experimental demonstration that the tau neutrino itself existed.

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[1] https://lss.fnal.gov/archive/design/fermilab-design-1998-01.pdf

[2] https://history.fnal.gov/historical/accelerator/numi_construction_begins.html

[3] https://www.physik.uni-bielefeld.de/~yorks/pro13/PhysRevLett.9.36.pdf

[4] The electron neutrino, the muon neutrino and the tau neutrino are all electrically neutral particles with spin ½ and extremely small masses. Their interactions with matter are so weak that they can pass through enormous thicknesses of material with only a tiny chance of interacting. This last property is the key to understanding why detecting them proved to be such a difficult experimental challenge.

[5] https://summerofscience.wordpress.com/2009/10/10/soudan/

[6] https://en.wikipedia.org/wiki/NOvA

[7] Neutrino oscillation is a quantum-mechanical effect arising because the neutrino flavour states (electron, muon and tau) are not identical to the neutrino mass states. As the mass states propagate, they accumulate different quantum phases, causing the probability of observing each flavour to change with distance (or, equivalently, with time). For neutrinos travelling close to the speed of light, the relevant parameter is the ratio of distance travelled to energy, and the characteristic oscillation length is typically many hundreds to many thousands of kilometres for accelerator neutrinos. By contrast, the DONUT detector was located only about 36 m from the neutrino source. At this distance the probability of flavour oscillation was effectively zero. Consequently, the tau neutrinos observed by DONUT could not have arisen from oscillations of electron or muon neutrinos during flight, and they had to be produced directly in the decay of charmed mesons, followed by the decay of the short-lived tau lepton. This is why DONUT is regarded as the first **direct experimental observation** of the tau neutrino, rather than an observation inferred from neutrino oscillation.

That objective led directly to the DONUT[8] experiment. They submitted a proposal[9] in 1994, and were already taking data in 1997[10].

Before DONUT, physicists already had compelling indirect evidence that the tau neutrino existed because the discovery of the tau lepton implied the existence of an associated neutrino. In 1975, Martin Perl and his collaborators at SLAC discovered the tau lepton[11], the third member of the charged-lepton family, sharing the electron's electric charge and spin but with a mass nearly 3,500 times greater. Since charged leptons participate in weak interactions together with an associated neutrino, the existence of the tau lepton implied the existence of a tau neutrino to preserve lepton number in its production and decay.

For more than two decades after the discovery of the tau lepton, no experiment possessed the combination of capabilities needed to detect the tau neutrino directly. An intense beam of tau neutrinos was first required, yet conventional accelerator neutrino beams consisted almost entirely of muon neutrinos produced in pion decay. Furthermore, a tau neutrino can only be identified by observing the charged-current interaction in which it produces a tau lepton. Because the tau lepton has a mass of 1.777 GeV/c^2, almost 17 times greater than that of the muon, the incident neutrino must have an energy exceeding approximately 3.5 GeV simply to produce the particle, with substantially higher energies required in practice to leave sufficient energy for the recoiling hadrons and for the tau itself to emerge with a detectable track. Finally, because the tau survives for only about 3×10^{-13} seconds before decaying, even a relativistic tau travels only a fraction of a millimetre before decaying, demanding detectors with microscopic

[8] sometime also written as DONuT meaning Direct Observation of NU Tau

[9] https://inspirehep.net/files/3e9544e84a1651da81dd2a66dc4bb583

[10] https://arxiv.org/pdf/hep-ex/0012035

[11] https://www.slac.stanford.edu/pubs/slacpubs/10000/slac-pub-10150.pdf

spatial resolution capable of resolving its characteristic decay kink[12].

To overcome this problem, DONUT used the 800 GeV proton beam from Fermilab's Tevatron[13]. The proton beam was directed into a 1 m-thick, water-cooled tungsten beam dump. Although its primary purpose was to absorb the proton beam safely, the intense collisions within the tungsten produced a wide variety of secondary particles, including charmed mesons. Among these, the D_s meson was particularly important because it can decay into a tau lepton and a tau neutrino, providing the source of tau neutrinos required by the experiment.

The crucial decay sequence was

$$D_s^+ \rightarrow \tau^+ + \nu_\tau$$

followed almost immediately by

$$\tau^+ \rightarrow \nu_\tau + X$$

where X represents one or more additional particles. The charge-conjugate[14] decays occur equally for negatively charged particles. Every D_s decay therefore produced at least one tau neutrino, and the subsequent decay of the tau produced a second tau neutrino. This provided the first accelerator beam with a useful flux of tau neutrinos. Almost everything else produced in the tungsten target was unwanted. Hadrons were absorbed in massive shielding, while magnets swept away charged particles. Only weakly interacting neutrinos were able to pass through the shielding and continue towards the detector. Although the beam still consisted

[12] In particle physics, a *kink* is the abrupt change in direction of a charged particle's track when it decays in flight into another charged charged particle and one or more undetected particles, usually neutrinos. Because the neutrinos carry away momentum without leaving a visible track, the daughter particle emerges at a different angle, producing the characteristic "kink" seen in high-resolution detectors such as nuclear emulsions.

[13] The Tevatron, which supplied the 800 GeV proton beam for the DONUT experiment, was shut down in 2011. Fermilab subsequently shifted its emphasis from high-energy proton–antiproton collisions to high-intensity neutrino physics.

[14] Jargon meaning replace every particle in the reaction with its corresponding antiparticle.

predominantly of muon neutrinos, it now contained enough tau neutrinos that direct observation became feasible.

The detector combined several complementary technologies, namely a stacks of nuclear emulsion sheets interleaved with thin steel plates. The steel served as the target in which neutrinos occasionally interacted with atomic nuclei. When a tau neutrino underwent a charged-current interaction, it produced a tau lepton

$$\nu_\tau + N \rightarrow \tau^- + X$$

where N denotes a nucleus and X the accompanying hadronic particles.

The tau lepton survived for only about 2.9×10^{-13} seconds before decaying, typically travelling less than a millimetre. The nuclear emulsion acted like an extremely fine photographic film, recording the trajectories of charged particles with a spatial resolution of about 1 μm. Under a microscope, physicists searched for the distinctive kink where the short tau track abruptly ended and its decay products emerged in a different direction. Electronic scintillating-fibre trackers and spectrometers identified the interaction location and measured particle momenta, allowing the emulsion data to be reconstructed efficiently.

The success of DONUT depended on two complementary innovations, firstly an accelerator beam capable of producing a measurable flux of tau neutrinos through D_s meson decay, and then a detector with sufficient spatial resolution to record the microscopic decay signature of the short-lived tau lepton[15]. Together, these made possible the first direct observation of tau neutrino interactions. In July 2000, after analysing millions of particle tracks, the DONUT collaboration announced that it had identified four events[16] in which a neutrino interaction was

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[15] https://www.sciencedirect.com/science/article/abs/pii/S0168900202015553
The automated Ultra Track Selector (UTS) microscope system and the associated NETSCAN software, developed at Nagoya University, Japan, made the DONUT experiment practical by enabling the rapid scanning and reconstruction of millions of particle tracks in nuclear emulsion.

[16] https://news.fnal.gov/2025/07/how-an-experiment-at-fermilab-fixed-a-hole-in-the-standard-model/

immediately followed by the characteristic "kink" of a decaying tau lepton[17]. The long-sought tau neutrino had finally been observed directly.

The discovery of the tau neutrino did more than complete the third generation of leptons. It established the final missing neutrino flavour experimentally and opened the way for a new generation of experiments. In 2015, the OPERA collaboration[18] reported the first direct observation of muon neutrinos oscillating into tau neutrinos after travelling 730 km from CERN to the Gran Sasso National Laboratory, confirming that neutrino oscillations produce tau neutrinos exactly as predicted[19]. In 2024, the IceCube Neutrino Observatory announced the identification of seven astrophysical tau neutrinos originating from some of the most energetic processes in the Universe, demonstrating that tau neutrinos are produced naturally over cosmological distances[20].

Looking ahead, the Deep Underground Neutrino Experiment (DUNE)[21] will send an intense beam of muon neutrinos from Fermilab to detectors 1,300 km away in South Dakota. By measuring how these neutrinos oscillate during their journey, including the appearance of tau neutrinos, DUNE aims to determine the ordering of neutrino masses and to investigate whether neutrinos violate charge-parity (CP) symmetry, a possible clue to why the Universe contains far more matter than antimatter[22].

[17] My understanding is that one film would register approximately between 10,000 and 100,000 microscopic track segments, or microtracks, in each scanned emission volume. Probably around approximately 600–2,000 particle tracks were reconstructed, and a total of 203 neutrino interactions were identified, four of which were isolated as neutrino interactions followed almost immediately by the characteristic kink produced by the decay of a tau lepton.

[18] https://www.lngs.infn.it/en/news-fisica/tau-neutrino-appearance

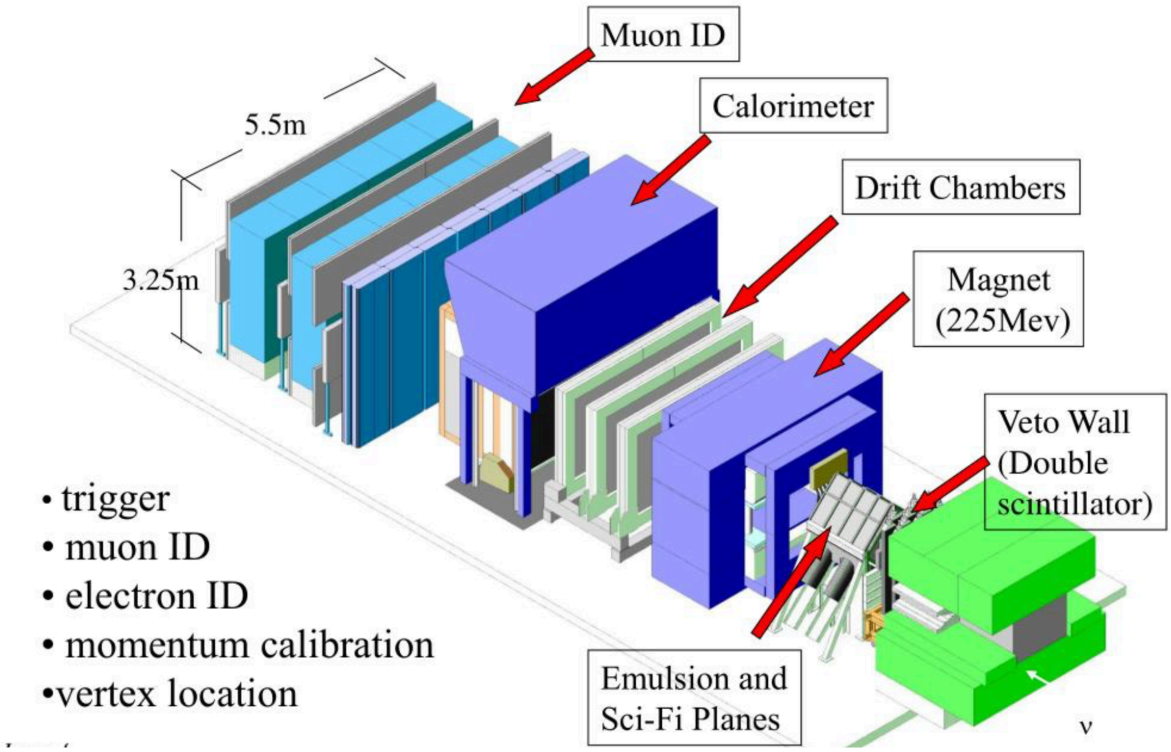
[19] https://www.sciencedirect.com/science/article/pii/S055032131600105X

[20] https://www.researchgate.net/publication/389627868_Highlights_from_the_IceCube_Neutrino_Observatory

[21] https://www.dunescience.org/

[22] https://www.sciencedirect.com/science/article/abs/pii/S0146641019300626

Annex



Simplified layout of the DONUT detector. The neutrino beam entering from the right, first passed through the veto wall before reaching the emulsion target, where the rare neutrino interactions occurred. Downstream detectors then reconstructed the emerging particles: scintillating-fibre (Sci-Fi) planes predicted the interaction location, drift chambers measured particle trajectories, the analysing magnet determined their momenta, the calorimeter measured deposited energy, and the muon detector identified penetrating muons. Combining information from all these systems allowed the characteristic decay of the short-lived tau lepton to be identified.

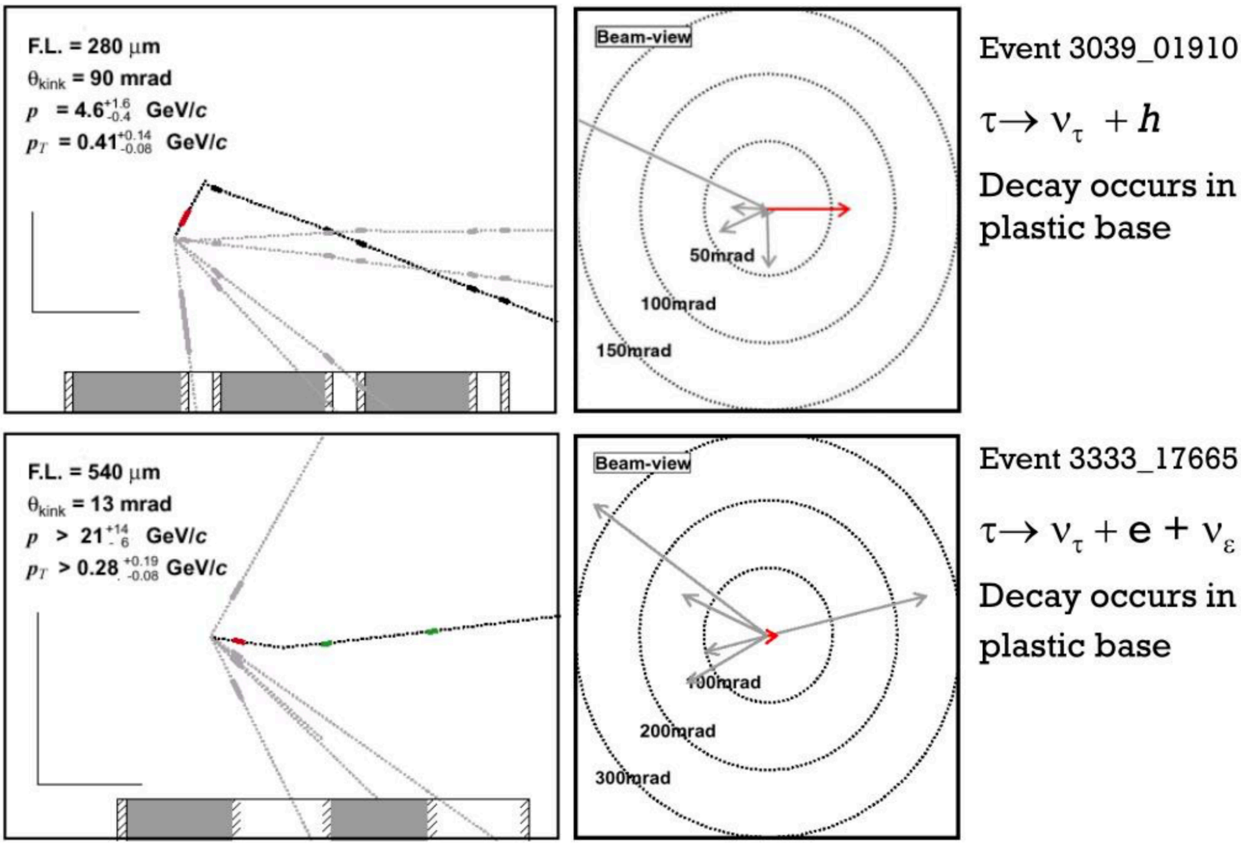
The **two-plane plastic scintillator veto wall** is particularly important because it was positioned immediately upstream of the emulsion target. Charged particles traversing both scintillators produced light signals that generated an electronic veto, identifying the event as background. Since neutrinos passed through the scintillators without interacting, only events with no veto signal were accepted as neutrino candidates and examined further.

I guess **225 MeV magnet** means 225 MeV/c of momentum. So an analysing magnet designed to bend charged particles, and from the amount of curvature the experiment could determine their momenta.

Drift chambers are gas-filled tracking detectors used to measure the trajectories of charged particles. Each chamber contains a carefully selected gas mixture, typically argon with a small proportion of a quenching gas such as carbon dioxide or methane, together with thousands of parallel wires arranged in alternating layers. The fine sense wires, held at a high positive voltage, are interleaved with thicker field wires, which shape a uniform electric field throughout the chamber.
As a charged particle passes through the gas, it ionises the gas molecules, producing free electrons and positive ions along its path. The electrons drift towards the nearest sense wire under the influence of the electric field. Close to the sense wire, where the electric field becomes extremely strong, each electron initiates an avalanche of further ionisations, producing a measurable electrical pulse. Because the electron drift velocity in the gas is precisely known, the time taken for the electrons to reach the sense wire determines the distance of the particle's trajectory from that wire.
A particle typically traverses many successive wire planes, each providing an independent position measurement. By combining these measurements, the detector reconstructs the particle's trajectory with a spatial precision of about 100–200 μm. In the DONUT experiment, the drift chambers provided the electronic tracking needed to connect the microscopic particle tracks recorded in the nuclear emulsion to the downstream analysing magnet, where the curvature of the tracks was used to determine the momentum and electric charge of the particles produced in the neutrino interaction.

The **muon identifier** consisted of alternating layers of thick steel absorber plates and plastic scintillation counters. As charged particles emerging from the neutrino interaction passed through the detector, the steel absorber plates progressively removed their energy. Electrons rapidly lost energy through electromagnetic interactions, while hadrons such as pions and protons underwent strong nuclear interactions and were absorbed within the steel.

Muons, however, interact only electromagnetically and through the weak force, and because of their relatively large mass (about 207 times that of the electron) they lose energy much more slowly. Consequently, they were able to penetrate several successive steel layers, producing light signals in each of the intervening scintillation counters. This distinctive pattern of penetration identified the particle as a muon. The ability to recognise muons was particularly important because charged-current interactions of muon neutrinos produce an outgoing muon. Identifying these events allowed the collaboration to distinguish ordinary muon-neutrino interactions from the much rarer candidate interactions initiated by tau neutrinos.



Above we have two candidate tau-neutrino interactions recorded by the DONUT experiment. The left-hand panels show side views reconstructed from the nuclear emulsion, while the right-hand panels show the same events viewed along the beam direction. In both cases the incoming tau lepton travelled only a few hundred micrometres before decaying, producing the characteristic kink that distinguished it from an ordinary charged-particle track.

In the upper event (3039_01910), the tau lepton travelled 280 μm before decaying within the plastic base separating two emulsion layers. At the decay vertex the outgoing charged hadron departed at an angle of 90 mrad (approximately 5°) relative to the original tau trajectory. The missing momentum carried away by the invisible tau neutrino caused the daughter particle to emerge in a different direction, producing the unmistakable kink. The measured momentum of the charged daughter particle was 4.6 GeV/c, with a transverse momentum of 0.41 GeV/c, consistent with the decay

$$\tau^- \rightarrow \nu_\tau + h^-$$

where *h* denotes a charged hadron, typically a pion.

The lower event (3333_17665) shows a different tau decay mode. Here the tau lepton travelled 540 μm before decaying, again within the plastic base between emulsion layers. The kink angle was much smaller, only 13 mrad (approximately 0.75°), demonstrating that not all tau decays produce large deflections. Nevertheless, the event satisfied the DONUT selection criteria because the daughter particle had a momentum exceeding 21 GeV/c and sufficient transverse momentum. The decay was identified as a tau decaying into an electron accompanied by two neutrinos.

The concentric circles in the beam-view panels are angular reference markers (50, 100, 150 mrad, etc.), allowing the deflection of the daughter particle to be measured in projection along the beam axis. In the side views, the short red segment marks the reconstructed tau-lepton track between its production at the neutrino interaction vertex and its decay point. The black track is the charged decay product, while the grey tracks are other charged particles emerging from the original neutrino interaction.

These events illustrate why the DONUT experiment required nuclear emulsion. The tau lepton has a mean lifetime of only 2.9×10^{-13} s, so even at relativistic energies it travels only a few hundred micrometres before decaying. Conventional electronic detectors could not resolve such short distances.