OVERVIEW OF LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENTS

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- 1930: $\nu \rightarrow 1$st predicted by Pauli to satisfy the conservation laws, in beta decay, which occurs in the nucleus and results in 1 e, 1 p and 1 $\bar{\nu}$.
- If the process is $A \rightarrow B + e$, E_e must be at a fixed value. But this should not be the case! *Energy-momentum must be conserved in β decay.*

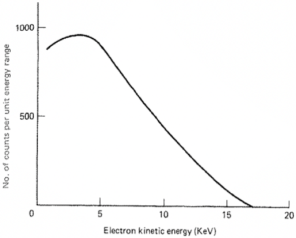
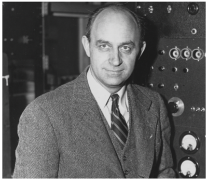


Fig. 1.5 The beta decay spectrum of tritium ($^3_1$H → $^3_2$He).
(*Source*: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

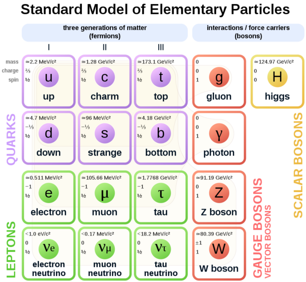
- Pauli thought that energy-momentum conservation should not be violated and suggested the process: $n \rightarrow p^+ + e^- + \bar{\nu}$.
- He desperately suggested *(desperate remedy)*:
  This particle had to be a new 'invisible' particle, which he named *neutron.* Because the lack of electric charge, Pauli thought that it could never be detected.

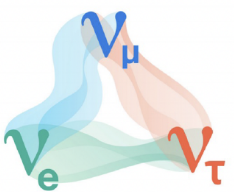


- 1932: Chadwick discovered a particle with a larger mass which is close to the m_p, no charge, he named it also *neutron.*
- Enrico Fermi, the pioneer of the world's first nuclear reactor, found a general formula for β decay involving ν, the first formulation of the weak force, in the mid-1930s → *"Fermi's theory of beta decay": the road to the Standard Model.*
- Fermi coined the name to ν: *"neutrino",* which means *"little neutral one"* in Italian.
- Detection of this particle took 26 years. Cowan and Reines placed a detector near the reactor and observed the inverse beta decay process (a few events/hour) given off by the reactors (Cowan–Reines neutrino experiment, 1956): $\bar{\nu}_e + p \rightarrow n + e^+$. Here: n: n-capture by Cd and e^+: $e^+ + e^- \rightarrow \gamma + \gamma$.

→ Neutrinos are produced during nuclear processes like when atomic nuclei fuse together (like in the sun which is an intense source of ν_e when hydrogen nuclei fuse together) or break apart (as in nuclear reactor which produces pure beams of $\bar{\nu}_e$ when uranium/plutonium nuclei break apart).

Standard Model (SM) & Neutrinos

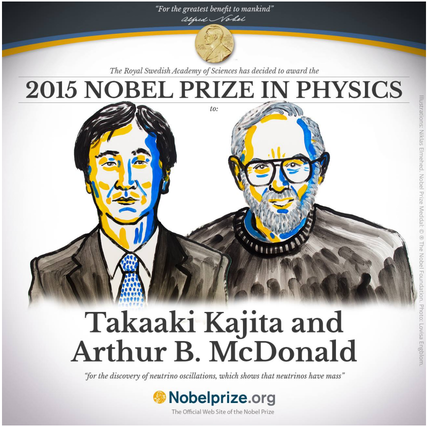




- SM of particle physics explains all elementary particles and their interactions (except gravity).
- In the SM, neutrino masses are exactly zero. → $\boxed{m_{\nu,i} = 0}$
- BUT! with the remarkable *discovery of the atmospheric neutrino oscillations* by the Super-Kamiokande (SK) collaboration, nonzero neutrino masses were confirmed. → $\boxed{m_{\nu,i} \neq 0}$ (massless particles not "experience time")
- Unlike SM, the neutrino oscillations proved that the neutrinos are massive and oscillate from one flavor to another.

2015 Nobel Prize in Physics

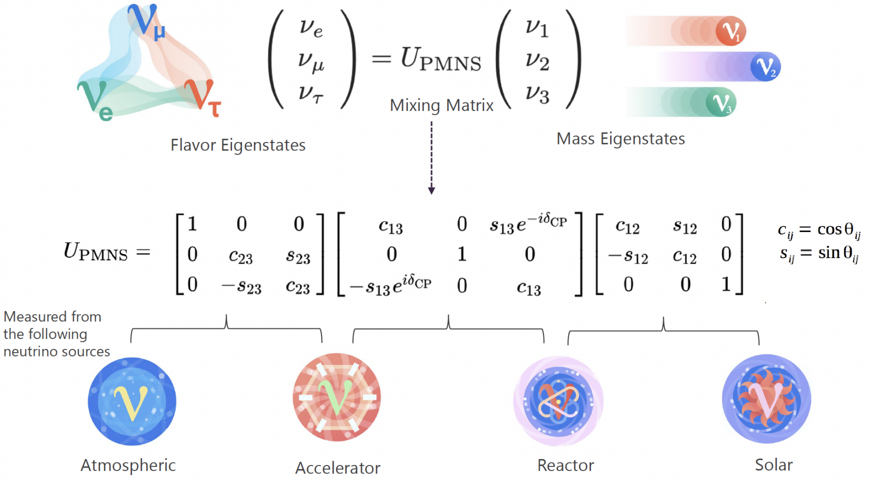
The confirmation of neutrino oscillations has led to new physics research beyond the standard model (BSM) to investigate new physics scenarios.



SK began to work in 1996 and announced the first evidence of neutrino oscillations in 1998. This was the first experimental observation to support the theory that neutrinos have non-zero mass, a possibility that theorists have speculated for years. *The 2015 Nobel Prize in Physics was awarded to Super Kamiokande researcher Takaaki Kajita, along with Arthur McDonald at the Sudbury Neutrino Observatory, for their work confirming neutrino oscillations.*

Neutrino Oscillations: 3-flavor $(\nu_e, \nu_\mu, \nu_\tau)$

credit Zoya Vallari, Neutrino Seminar, Fermilab



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

Image by Symmetry Magazine

$\theta = 0$: Oscillations cannot happen. $\theta = \pi/4$: Oscillations are maximal.

Neutrino Oscillations

- The flavor eigenstates of neutrinos (ν_e, ν_μ, ν_τ) are formed by mixing the mass eigenstates (ν_1, ν_2, ν_3):

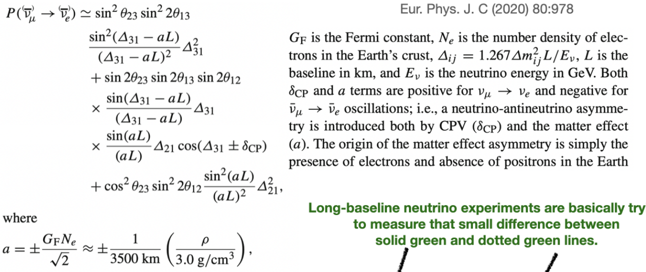
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} \, |\nu_i\rangle \, ,$$

  ν_α: flavor eigenstates, ν_i: mass eigenstates, so the flavor eigenstates are a superposition of the mass eigenstates. The superpositions are described by the unitary matrix, U_{PMNS}.
- Interactions in flavor eigenstates, propagation in the mass eigenstates.
- Probability for neutrino oscillations between neutrino flavors

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\alpha i} \, e^{-im_i^2 L/2E} U_{\beta i} \right|^2 ,$$

  this is governed by PMNS mixing matrix (U) and squared difference in neutrino mass (m^2). Here, L is the propagation distance and E is the neutrino energy.

The oscillation probability of $\nu_\mu \to \nu_e$ through matter in the standard three-flavor model and a constant density approximation is, to first-order



Eur. Phys. J. C (2020) 80:978

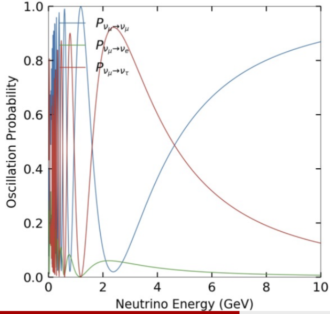
$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq{}& \sin^2\theta_{23}\sin^2 2\theta_{13} \\
& \frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12} \\
& \times \frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31} \\
& \times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{\mathrm{CP}}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

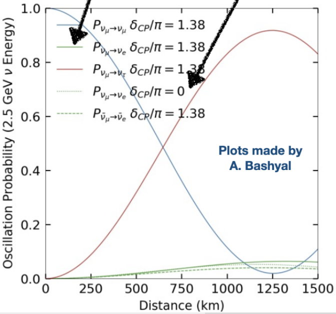
where

$$
a = \pm\frac{G_{\mathrm{F}}N_e}{\sqrt{2}} \approx \pm\frac{1}{3500\ \mathrm{km}}\left(\frac{\rho}{3.0\ \mathrm{g/cm^3}}\right),
$$

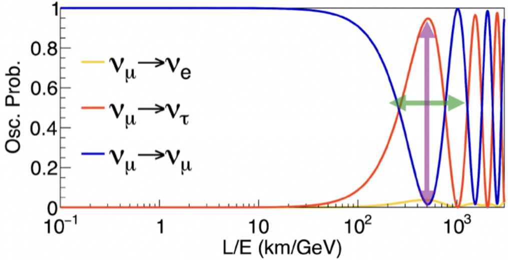
G_{F} is the Fermi constant, N_e is the number density of electrons in the Earth's crust, $\Delta_{ij} = 1.267\Delta m_{ij}^2 L/E_\nu$, L is the baseline in km, and E_ν is the neutrino energy in GeV. Both δ_{CP} and a terms are positive for $\nu_\mu \to \nu_e$ and negative for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations; i.e., a neutrino-antineutrino asymmetry is introduced both by CPV (δ_{CP}) and the matter effect (a). The origin of the matter effect asymmetry is simply the presence of electrons and absence of positrons in the Earth

Long-baseline neutrino experiments are basically trying to measure that small difference between solid green and dotted green lines.





Plots made by A. Bashyal



Oscillation Probability

$$P_{\nu_\alpha \rightarrow \nu_\beta} = |\sum_j U^*_{\beta j} U_{\alpha j} \exp\left(-1.27i \frac{\Delta m^2_{j1} L}{E}\right)|^2$$

For 3-Flavour Oscillations, PMNS Mixing Matrix

$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

6 parameters

Δm^2_{21}, Δm^2_{32}, governs **oscillation frequency**

$\theta_{12}, \theta_{13}, \theta_{23}$, governs **oscillation magnitude**

δ_{CP}, governs $\nu - \bar{\nu}$ **differences**

L (baseline), **E** (energy) are **experimental choices**

L/E is characteristic of oscillations

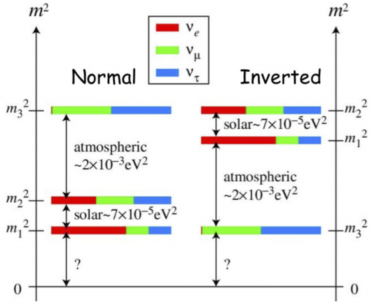
Adam Lister, NuPhys2023 @ Kings College London, 19th December 2023

PMNS matrix and its elements

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} :$$

- 1st matrix comes from the accelerator and atmospheric sectors: θ_{23}.
- 2nd matrix can be measured by the accelerator and reactor neutrino sources. It includes the CP phase. δ_{CP} is only combined with $\sin\theta_{13}$.
- δ_{CP} describes CP violation in ν oscillations. If δ_{CP} is not equal to 0 (or 180 degrees), then CP violation exists in ν oscillation.
- For δ_{CP}, CP conserved values: 0 and π; for all other values, CP is violated. Maximum CP violation at $\pi/2$ and $3\pi/2$, δ_{CP}. The CP-violating phase of the PMNS matrix has only been weakly measured yet and constrained by available data.
- The 3rd matrix comes from the solar and reactor neutrino sources: θ_{12}.
  → Q1: ν *and* $\bar{\nu}$ *violate CP?* (*"Do they oscillate at the same rate?"*)

Mass Hierarchy



- Normal ordering (NO): $\Delta m^2_{31} > 0$,
- Inverted ordering (IO): $\Delta m^2_{31} < 0$.

- Another riddle about neutrinos: *'absolute masses'* because currently we only know the differences of the squared of their masses.

$$\boxed{\Delta m^2_{21} \equiv m^2_2 - m^2_1 \sim 10^{-5}\text{eV}^2} \qquad \boxed{|\Delta m^2_{31}| \equiv |m^2_3 - m^2_1| \sim 10^{-3}\text{eV}^2}$$

- We know: $\Delta m^2_{21} > 0$, but the sign of Δm^2_{31} has not been known yet.
- This is known as the "Mass ordering problem".
  → Q2: Is the mass order 'Normal' or 'Inverted'?

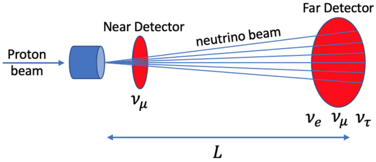
Maximal Mixing: θ_{23}

- There is large uncertainty in the mixing angle θ_{23}.
- Upper octant: $\theta_{23} > 45°$?, Maximal mixing: $\theta_{23} = 45°$?, Lower octant: $\theta_{23} < 45°$?
  → Q3: $\nu_\mu = \nu_\tau$ in the ν_3 mass state? θ_{23} : Is the mixing maximal?

Currently the main topics of neutrino oscillation experiments:

- Does the symmetry that determines the mass of charged leptons affect ν_1 being the lightest neutrino, or is it the other way around?
  $\longrightarrow$ *Oscillation experiments have excellent sensitivity to measure this with next generation experiments.*
- Neutrino mass order and θ_{23} octant,
- CP Phase δ_{CP}, why more matter than antimatter in the universe?
  $\longrightarrow$ *Do neutrinos and antineutrinos oscillate differently, violating CP symmetry?* $\delta_{\mathrm{CP}} = 0$?
- We see ν flavors but we want to measure ν eigenstates to infer physics.
- Accelerator-based neutrino oscillation experiments are among the most studied topics in order to comprehend these important questions.

Accelerator-based neutrino oscillation experiments



- Accelerator-based neutrino experiments allow exploration of the following regions: $\Delta m^2 \geq 2 \times 10^{-3}$eV^2, $E \sim 1$ GeV and long distances L.

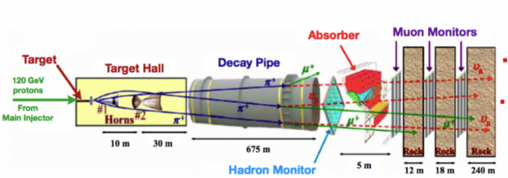
$$\frac{L}{E} \lesssim 10^3 \text{ km/GeV} \qquad \Longrightarrow \qquad \Delta m^2 \gtrsim 10^{-3}\text{eV}^2.$$

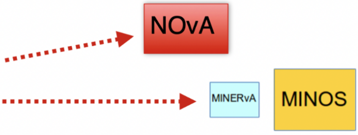
- The probability of two neutrino oscillation states is in SI, for $p \sim E$

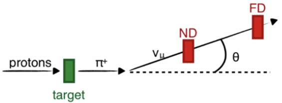
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \qquad \alpha \neq \beta,$$

'1.27' assumes that L is in km, E is in GeV, and Δm^2 is in units of eV^2/c^4.

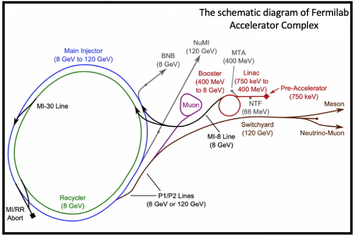
Fermilab NuMI beamline and neutrino experiments



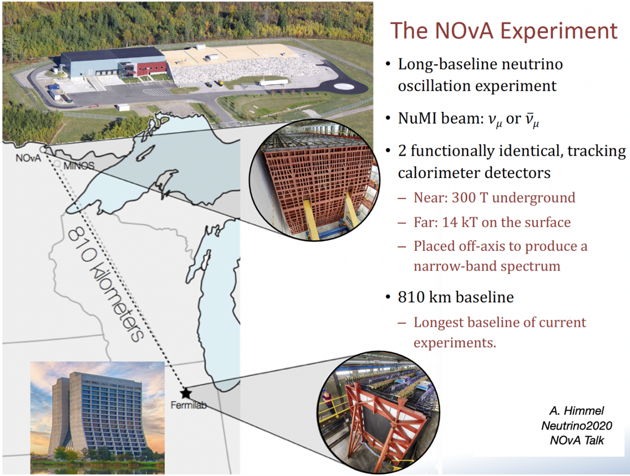




- 120 GeV protons hit the target and π^+ produced
- Magnetic horns to focus π^+
- π^+ decay to $\mu^+\nu$ in long low-density He-filled pipe
- ν beam travels through earth to experiment
- MINERvA (Main Injector Experiment for ν - A)
  → On-axis experiment located at Fermilab
  → It completed physics run in 2019
- NOvA (NuMI Off-axis ν_e Appearance)
  → Off-axis angle 14.6 mrad
  → Near Detector at Fermilab and Far Detector at Ash River


The schematic diagram of Fermilab Accelerator Complex

NOvA: NuMI Off-axis ν_e Appearance Experiment @Fermilab



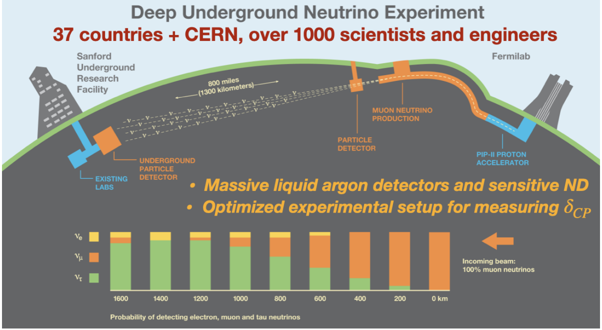
The NOvA Experiment

- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

A. Himmel
Neutrino2020
NOvA Talk

- To measure $P(\nu_\mu \to \nu_\mu)$ and $P(\nu_\mu \to \nu_e)$ in ν's and $\bar{\nu}$'s. δ_{CP}.
- Over long baselines to separate hierarchy and δ effects. Δm^2_{32}, $\sin^2\theta_{23}$.

DUNE: Deep Underground Neutrino Experiment @Fermilab

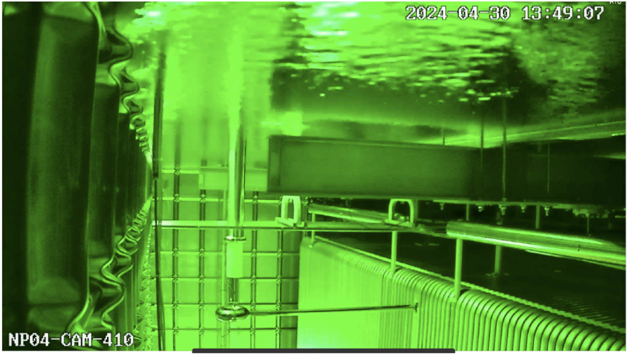


- DUNE will consist of two neutrino detectors placed to obtain the world's most intense neutrino beam.
- Near Detector @Fermilab: for beam characterization
- Far Detector @SURF, South Dakota: 1.5 km underground: 4×10 kton Liquid Argon TPCs. For the measurements of neutrino oscillations
- The baseline (distance between ν source and the FD) is $\sim$ 1300 km.

ProtoDUNE LArTPC @Experimental Hall North 1 (EHN1)

→ ProtoDUNE started in 2018 with ProtoDUNE Single-Phase (SP) and ProtoDUNE Dual-Phase (DP).
→ Both detectors are TPCs. Also, ProtoDUNE-SP is a horizontally drifting LArTPC, same as the DUNE FD Module planned. ProtoDUNE Horizontal Drift is now full and ProtoDUNE Vertical Drift planned.
→ One may think of ProtoDUNE Horizontal Drift as ProtoDUNE-SP's successor.
→ Collecting test-beam data to understand/calibrate response of detector to various particle species.
→ Approving design from viewpoint of basic detector performance.

NP04 the ProtoDUNE Horizontal Drift prototype at the CERN Neutrino Facility is now full!

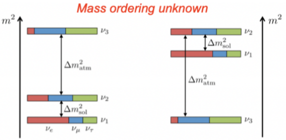


Detector full since 30 April 2024.
Argon fill

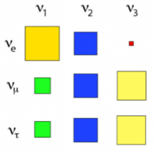
ProtoDUNE-SP just utilizes liquid argon.

The inner cryostat dimensions are: width = 8.548 m, length = 8.548 m and height = 7.900 m. This corresponds to a total volume of 580 m^3.

LBNF/DUNE Science Program



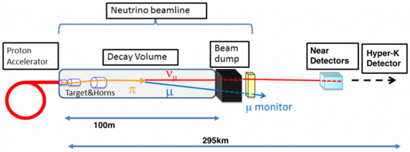
Credit: JUNO Collaboration / JGU-Mainz



Credit: Sheldon Stone

- Neutrino Oscillation Physics
  → Leptonic (neutrino) CP violation
  → Mass hierarchy
  → Precise oscillation physics: Parameter measurements (θ_{23} octant), Testing the existing 3-neutrino model, Non-Standard Interactions, ...
- Nucleon Decay
  → Especially precision for $p \to K + \bar{\nu}$
- Supernova physics and astrophysics
- Also many other important topics for research
  neutrino interaction physics, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.

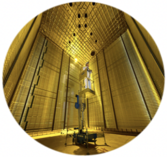
T2K and Hyper-K Experiments @Japan



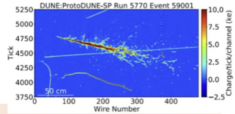
- High intensity 30 GeV proton beam hits 90 cm Carbon target
- The primary goal is to produce the ν_μ or $\bar{\nu}_\mu$ beam, ($\sim 2.5°$) an off-axis experiment, $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$ oscillation measurements
- Hadrons are focused in 3 electromagnetic focusing horns
- $\pi \to \mu\nu$ in the 100 m decay volume.
- T2K has a 50 kt Water Cherenkov FD. 3rd next-generation massive water Cherenkov detector is being built in Japan that Hyper-K will use.
- Hyper-Kamiokande will address the biggest unsolved questions in physics through a ten-year research program starting in 2027.

Differences between DUNE and Hyper-K

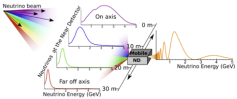
DUNE



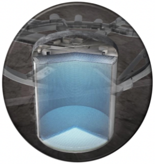
- Fermilab - SURF: ~ 1295 km
- Liquid Argon TPC detector with 40 kt fiducial volume
- Off-axis movable ND
- 1.2 MW (upgradable to 2.4 MW) PIP-II beam
- Very well particle identification and spatial resolution by LArTPC technology



DUNE PRISM



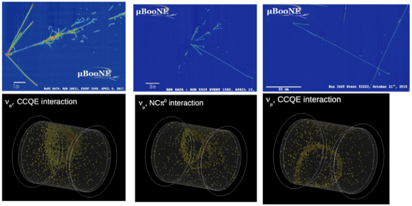
Hyper-K

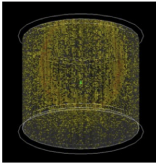


- Tokai - Kamioka: 295 km
- Water Cherenkov detector with 187 kt fiducial volume
- Cherenkov rings to separate muon and electron rings
- 1.3 MW J-PARC beam
- Very well timing resolution (~ ns)

LAr → TPC

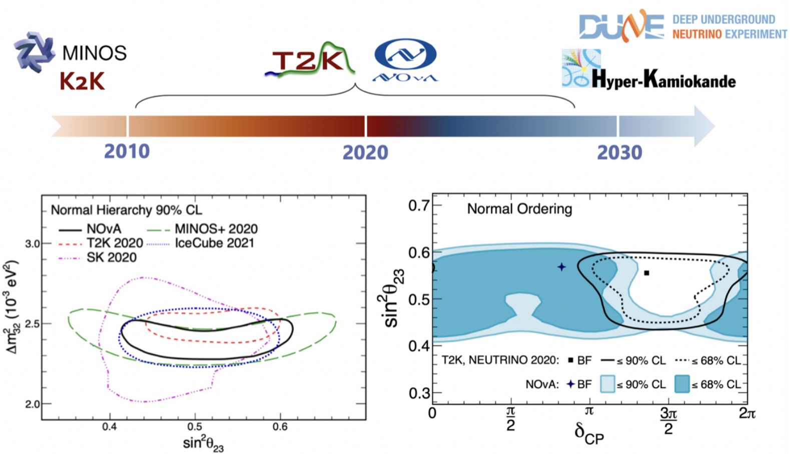
Water → Cerenkov





Where are we?

credit: Zoya Vallari, The 7th Symposium on Neutrinos and Dark Matter in Nuclear Physics (NDM22)



→ While the global measurements for Δm^2_{32} and θ_{23} agree well, there is an inconsistency for the δ_{CP} measurements.

PMNS latest constraints: T2K *Nature 580, 339–344 (2020).*

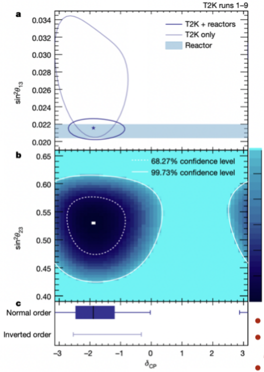
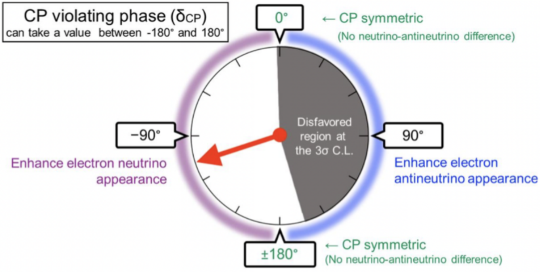


Fig. 4 | Constraints on PMNS oscillation parameters



- *The SK is a 50 kt water detector equipped with photomultiplier tube light sensors*
- *An ν interaction with the es or nuclei of water can produce a charged particle that moves faster than the c in water but slower than the c in vacuum.*
- *This creates a cone of light known as Cherenkov radiation.*
- *Charged particles produce Cherenkov light, which is detected by PMTs.*
- *In SK, Cherenkov light is produced by charged particles above the momentum threshold traveling through water.*
- *This light is emitted in a ring shape, which is detected by light sensors.*
- *Because of their lower mass. electrons scatter much more frequently (both elastically and inelastically) than muons, so Cherenkov rings are blurred.*
- *This blurring is used to describe the flavor of the charged lepton.*

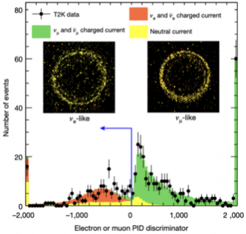
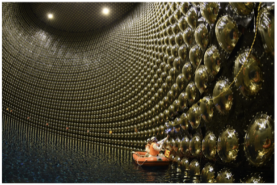


Fig. 2 | Particle identification in the SK detector.



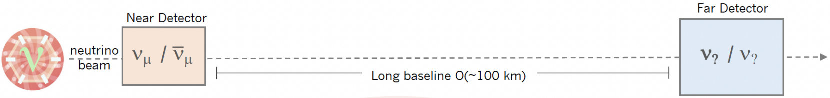
Inside the Super-Kamiokande, the far detector of T2K. Image credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

Summary

- The latest constraints for the leptonic sector: $\sin^2\theta_{23} = 0.53^{+0.03}_{-0.04}$ for both mass orders, NO(IO). Also for the NO(IO): $\Delta m^2_{32} = 2.45 \pm 0.07 \times 10^{-3} eV^2/c^4 (\Delta m^2_{13} = 2.43 \pm 0.07 \times 10^{-3} eV^2/c^4)$. $\delta_{CP}\ 3\sigma : [-3.41, -0.03]$ (NO) and $[-2.54, -0.32]$ (IO). *Both CP conserving points, 0 and π, are ruled out at 95% CL.*
- Today, some of the main goals are to determine the neutrino masses, how ν's interact with matter, how do ν's get their mass, and whether the neutrino is its own antiparticle or not (Neutrinos: Majorana or Dirac?) etc.
- DUNE will resolve neutrino mass ordering and measuring δ_{CP} over a wide range of parameter space. DAQ will begin in $\sim$ 2031.
- DUNE will use θ_{13}, θ_{23}, Δm^2_{32} to test the 3-flavor paradigm and precisely measure 3-flavor oscillations. DUNE will also provide important information for the Physics beyond the Standard Model (BSM).
- DUNE will have the highest hierarchy sensitivity due to larger baseline, Hyper-K will have the best CP sensitivity due to large number of events. Combined analysis will be important for CPν discovery and hierarchy.

Long-baseline neutrino oscillation experiments

credit Zoya Vallari Neutrino Seminar, Fermilab, 2023



T2K collects first beam data.

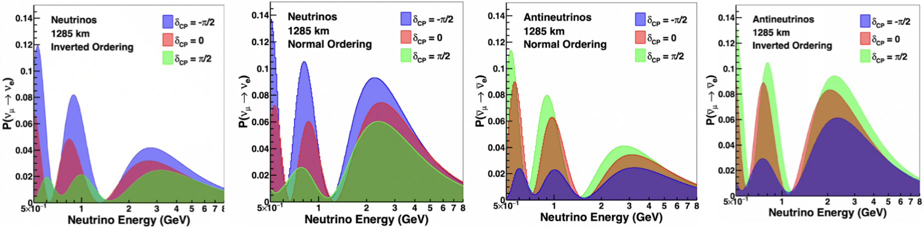
NOvA collects first beam data.

Published data until 2020 by both experiments. More data has since been collected and analyses are in progress!

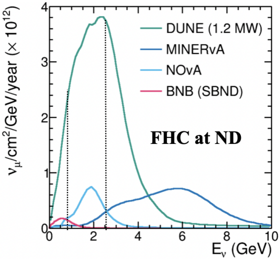
Both NOvA and T2K are scheduled to run until ~ 2026-27. Hyper-K takes beam data?

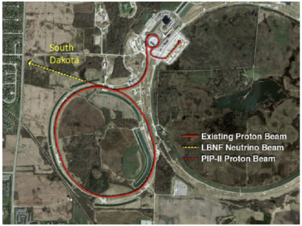
DUNE takes beam data?

DUNE neutrino oscillations: Eur. Phys. J. C 80 10, 978 (2020).



- The effect of mass ordering, CP violation, θ_{23} octant, has different shapes as a function of L/E.
- Measuring oscillations as a continuous function of energy helps resolve degeneracies.
  $\rightarrow$ This is unique to DUNE and is complementary to other experiments with narrow flux spectra (e.g. Hyper-K).
- DUNE will be able to determine mass order and δ_{CP} over the full range of possible outcomes.

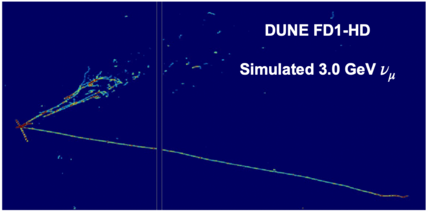


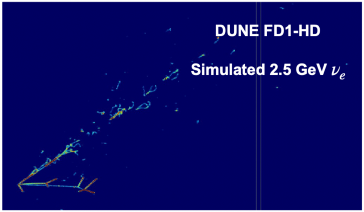


- The peak of the first oscillation maximum (2.5 GeV) is a significant neutrino flux between the first and second maximum (0.8 GeV).
- Since the leading term depends on Δ_{31}, the physical characteristic of experiments $\nu_\mu \to \nu_e$ is that the mixing between states ν_1 and ν_3 is maximum, L. Also, it is determined by E_ν. For the oscillation term of $P^{\nu}_{\mu e}$, we obtain oscillation maximum in this equation: $\Delta m^2_{31} L/4E = (2n-1)\frac{\pi}{2}$,

  $\to$ where n is an integer and $n = 1; 2; ...$ means the maximum oscillations occurring in the first, second, … $L/E \simeq 500, 1500$, .. km/GeV etc.

⋆ LAr is an excellent scintillating medium and the photon detection system is used to obtain additional event information from the photons produced by particles traversing the detector.
⋆ TPC is a device that measures the energy loss and signatures of charged particles in a gas.



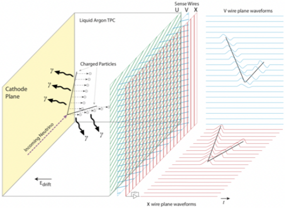


- LArTPC provides excellent imaging for particle identity.
  → Clear separation for ν_μ and ν_e CC events

- Low thresholds for charged particles:
  → High-precision reconstruction of lepton and hadronic energy
  → Reconstruction of neutrino energy over a wide energy range

Time Projection Chamber (TPC) technologies

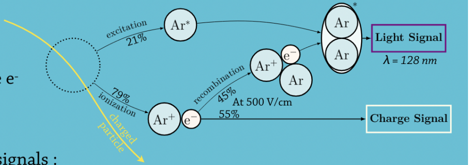
- DUNE utilizes LArTPC technology for the massive, but extremely sensitive neutrino detector for the DUNE FD
- FD comprises of detector systems for charge and light delivered by an ionization event in the LArTPC
- Charged particles going through the detector ionize the argon atoms, and the ionization electrons drift in the E field to the anode wall on a timescale of milliseconds. This anode comprises of layers of active wires forming a grid



- High spatial and calorimetric resolutions
- Each module has a total mass of 17 kton, situated 1.5 km underground

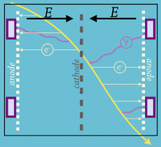
Liquid Argon TPC

Charge particles excite and ionize LAr
-> Produces a charge & light signal
An electric field suppresses the recombination and allow to collect the e- at the anode



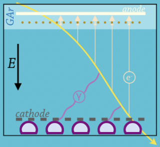
Different TPC designs to collect both signals :

Single-Phase
Horizontal drift



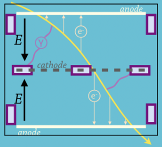
- Two drift volumes
- Anode made of wires
- Light collected with X-ARAPUCAs behind the anodes

Dual-Phase



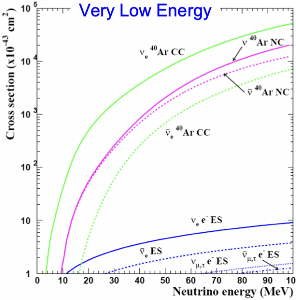
- Single drift volume
- Electron cloud amplified in gas argon layer with thick GEM
- Anode made of PCBs
- Light collected with PMTs below the cathode

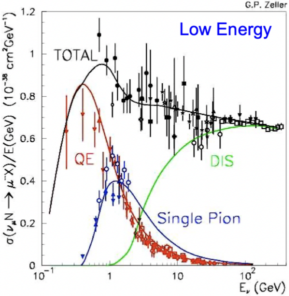
Vertical drift



- Two drift volumes
- Anode made of drilled PCBs
- Light collected with X-ARAPUCAs on the cathode and behind the field cage

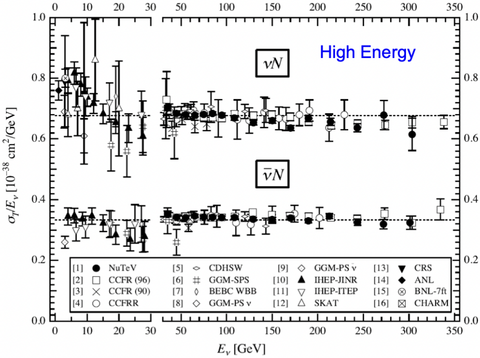
Neutrino Cross Sections





Neutrino – electron scattering

$$
\begin{aligned}
\sigma(\nu_e e^- \rightarrow \nu_e e^-) &= 9.20 \times 10^{-45} E_{\nu_e}(\mathrm{MeV}) \quad \mathrm{cm}^2 \\
\sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-) &= 3.83 \times 10^{-45} E_{\bar{\nu}_e}(\mathrm{MeV}) \quad \mathrm{cm}^2 \\
\sigma(\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-) &= 1.57 \times 10^{-45} E_{\nu_{\mu,\tau}}(\mathrm{MeV}) \quad \mathrm{cm}^2 \\
\sigma(\bar{\nu}_{\mu,\tau} e^- \rightarrow \bar{\nu}_{\mu,\tau} e^-) &= 1.29 \times 10^{-45} E_{\bar{\nu}_{\mu,\tau}}(\mathrm{MeV}) \quad \mathrm{cm}^2
\end{aligned}
$$

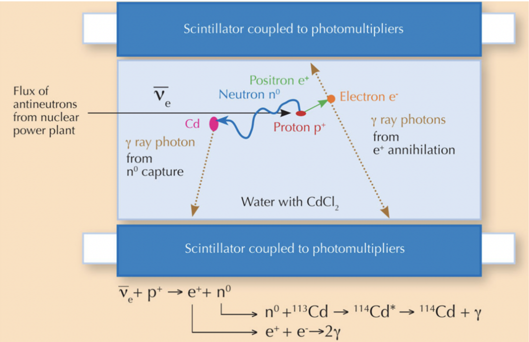


$$\sigma^{\nu\, Iso}/E_\nu = (0.677 \pm 0.014) \times 10^{-38} \mathrm{cm}^2/\mathrm{GeV}$$

$$\sigma^{\bar{\nu}\, Iso}/E_{\bar{\nu}} = (0.334 \pm 0.008) \times 10^{-38} \mathrm{cm}^2/\mathrm{GeV}$$

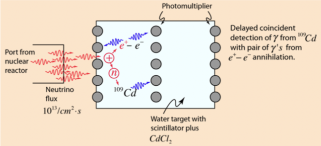
Deney, bir nükleer reaktörün yakınında sıvı bir sintilatör olarak çalışan, su ve kadmiyumla dolu büyük bir etkileşim hacminden oluşuyordu. Kaydedilen sinyal iki bölümden oluşuyordu: hızla yok olan pozitron sinyali ve kadmiyumdaki bir nötronun yakalanması, nükleer de-excitation bir foton imzasına neden oldu.

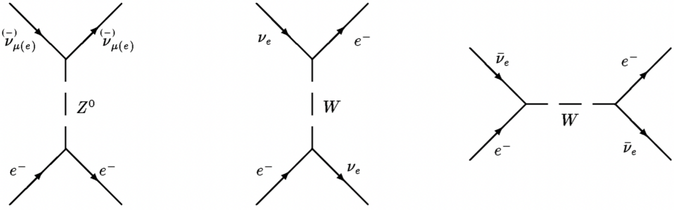
https://www.scienceinschool.org/article/2011/neutrinos/



Reines and Cowan at the Savannah River Reactor

http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/cowan.html

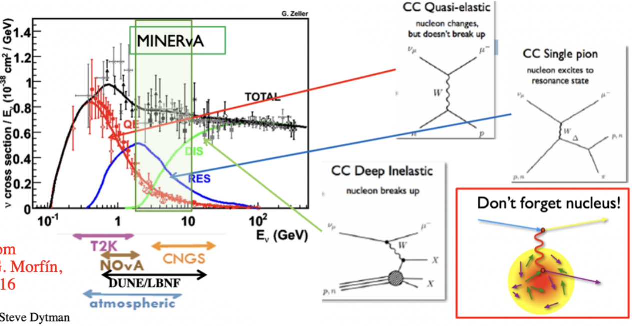




(a) (b) (c)

Figure 1: *Feynman diagrams for the processes of neutral current (NC) νe-scattering (a), and charged current (CC) ν_ee-scattering via the exchange of a W-Boson (b,c).*

CC interactions: $\nu_l + n \rightarrow l + p$, NC interactions: $\nu_l + n \rightarrow \nu_l + n$



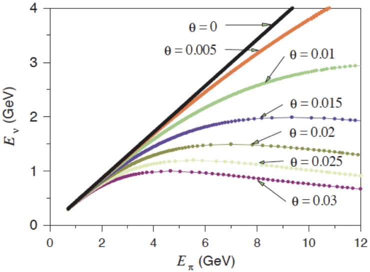
Talk from
Jorge G. Morfín,
NuFact16

Thanks to Steve Dytman

credit: Mark Thomson, Neutrinos: Lecture 2 Beam Oscillation Experiments

For a particular off-axis angle, neutrino energies peak around

$$E_\nu = \frac{0.43\frac{m_\pi}{\theta}}{2} \Rightarrow \boxed{E_\nu/\mathrm{GeV} = \frac{0.03}{\theta}}$$



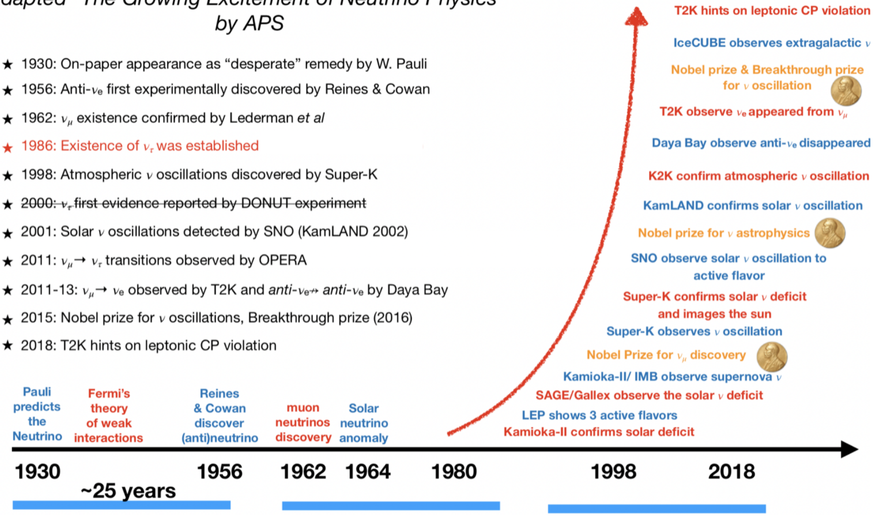
On-axis: neutrino beam with spectrum of pions from the target $E_\nu = 0.43 E_\pi$

Off-axis: neutrino beam peaked around a certain energy $E_\nu/\mathrm{GeV} = \frac{0.03}{\theta}$

credit APS

Adapted "The Growing Excitement of Neutrino Physics" by APS

- ★ 1930: On-paper appearance as "desperate" remedy by W. Pauli
- ★ 1956: Anti-ν_e first experimentally discovered by Reines & Cowan
- ★ 1962: ν_μ existence confirmed by Lederman *et al*
- ★ 1986: Existence of ν_τ was established
- ★ 1998: Atmospheric ν oscillations discovered by Super-K
- ★ ~~2000: ν_τ first evidence reported by DONUT experiment~~
- ★ 2001: Solar ν oscillations detected by SNO (KamLAND 2002)
- ★ 2011: $\nu_\mu \to \nu_\tau$ transitions observed by OPERA
- ★ 2011-13: $\nu_\mu \to \nu_e$ observed by T2K and *anti-*$\nu_e \nrightarrow$ *anti-*ν_e by Daya Bay
- ★ 2015: Nobel prize for ν oscillations, Breakthrough prize (2016)
- ★ 2018: T2K hints on leptonic CP violation



T2K hints on leptonic CP violation

IceCUBE observes extragalactic ν

Nobel prize & Breakthrough prize for ν oscillation

T2K observe ν_e appeared from ν_μ

Daya Bay observe anti-ν_e disappeared

K2K confirm atmospheric ν oscillation

KamLAND confirms solar ν oscillation

Nobel prize for ν astrophysics

SNO observe solar ν oscillation to active flavor

Super-K confirms solar ν deficit and images the sun

Super-K observes ν oscillation

Nobel Prize for ν_μ discovery

Kamioka-II/ IMB observe supernova ν

SAGE/Gallex observe the solar ν deficit

LEP shows 3 active flavors

Kamioka-II confirms solar deficit

Pauli predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrino

muon neutrinos discovery

Solar neutrino anomaly

1930

~25 years

1956

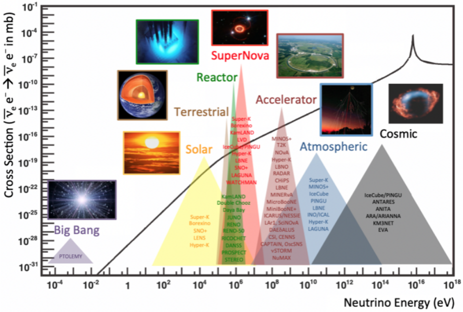
1962

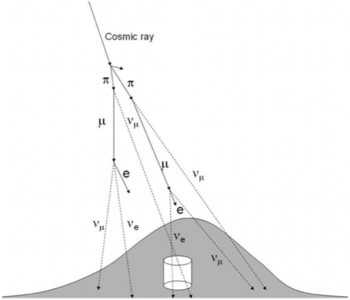
1964

1980

1998

2018

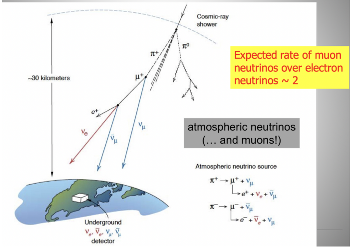




Decay	Chanel	Branching ratio (%)
1	$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	99.9877
2	$\pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e)$	0.0123
3	$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	63.55
4	$K^\pm \rightarrow \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$	5.07
5	$K^\pm \rightarrow \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	3.353
6	$K_L^0 \rightarrow \pi^\pm + e^\mp + \nu_e$	40.55
7	$K_L^0 \rightarrow \pi^\pm + \mu^\mp + \nu_\mu$	27.04
8	$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$	100.0

The main decay modes that create neutrinos and the branching ratios.

Atmospheric Neutrinos

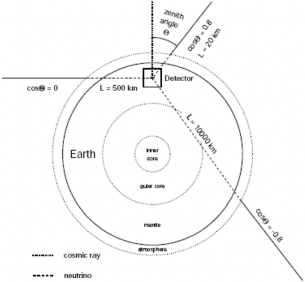


Expected rate of muon neutrinos over electron neutrinos ~ 2

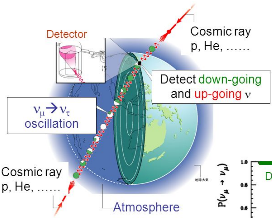
atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



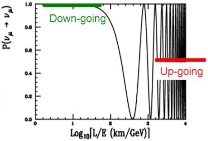
Atmospheric neutrinos and neutrino oscillations



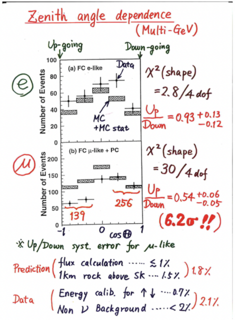
Detect down-going and up-going ν

$\nu_\mu \rightarrow \nu_\tau$
oscillation

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Discovery of atmospheric neutrino oscillation



Zenith angle dependence
(Multi-GeV)

χ^2(shape)
$= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape)
$= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1%
1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7%
Non ν Background …..< 2%) 2.1%

It was revealed that the number of neutrinos coming from the other side of the earth was smaller, and solid evidence of neutrino oscillations was shown to the world.