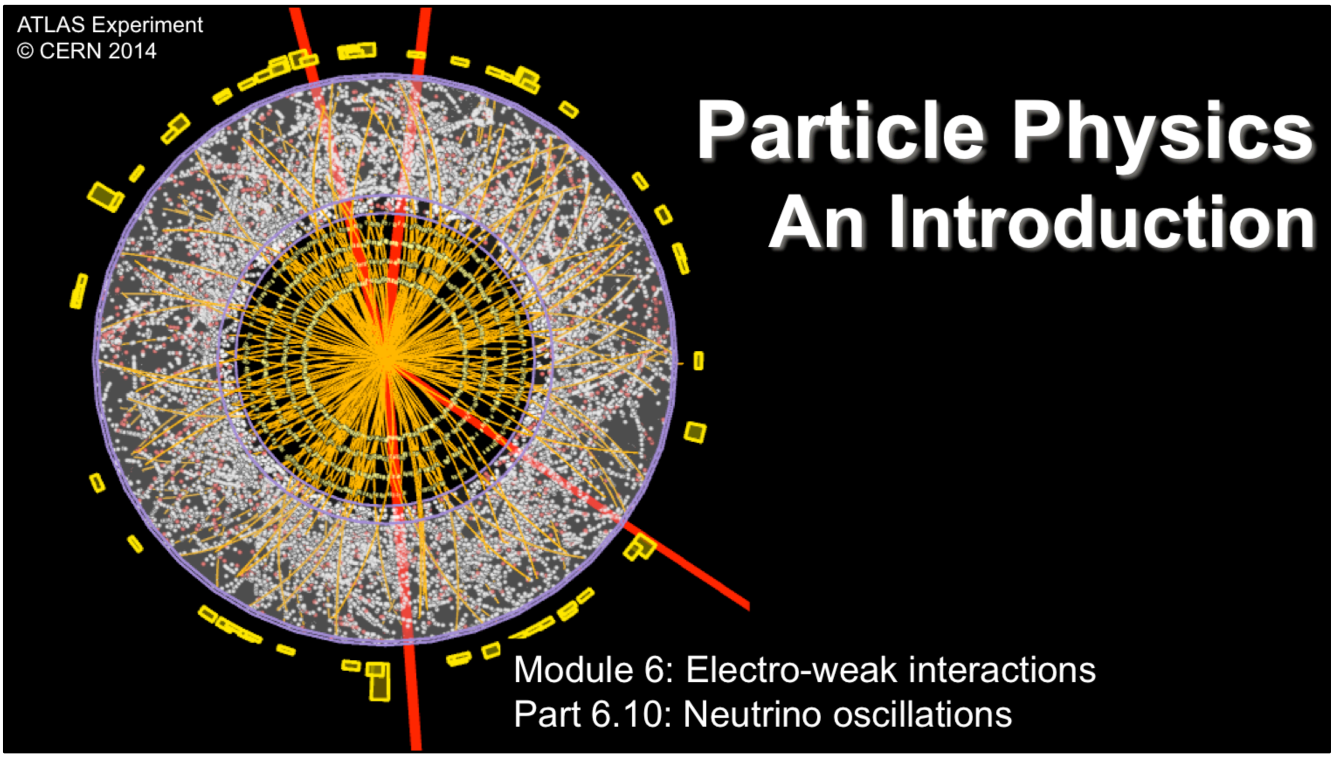


In this sixth module, weak interactions are discussed.

In this 10th video we talk about oscillations between different neutrino flavors.

After following this video you will know:

- How to describe the quantum mechanism of oscillation between neutrinos of different generations;
- The key methods used to detect such oscillations.

	Spin	# bar.	# lept.	Q elec.	T, T_3 weak[1]	C strong
Leptons:						
ν_L, ν_M, ν_H	$1/2$	0	$+1$	0	$1/2, +1/2$	0
e^-, μ^-, τ^-	$1/2$	0	$+1$	-1	$1/2, -1/2$	0
Quarks:						
u, c, t	$1/2$	$+1/3$	0	$+2/3$	$1/2, +1/2$	R, G, B
d, s, b	$1/2$	$+1/3$	0	$-1/3$	$1/2, -1/2$	R, G, B
Gauge Bosons:						
γ	1	0	0	0	0	0
Z, $W^\pm$	1	0	0	$0, \pm 1$	$1, (0, \pm 1)$	0
Gluons	1	0	0	0	0	$C\bar{C}$
Vacuum:						
Higgs	0	0	0	0	0	0

[1] Mind helicities and mixtures!

- You may have wondered why the **particles ν_L, ν_M and ν_H,** which we have introduced in Module 1, do not appear in reactions mediated by the weak force. The reason is that just like for quarks, the neutrinos which interact with the W are **superpositions** of these real particles.
- Consequently, a phenomenon analogous to quark oscillations happens in the family of neutrinos. Vacuum **oscillations between different neutrino flavors** can occur if neutrinos have a non-zero mass and if this mass varies from generation to generation. And these two conditions are indeed met.

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{MH} & \sin\theta_{MH} \\ -\sin\theta_{MH} & \cos\theta_{MH} \end{pmatrix} \begin{pmatrix} \nu_M \\ \nu_H \end{pmatrix}$$

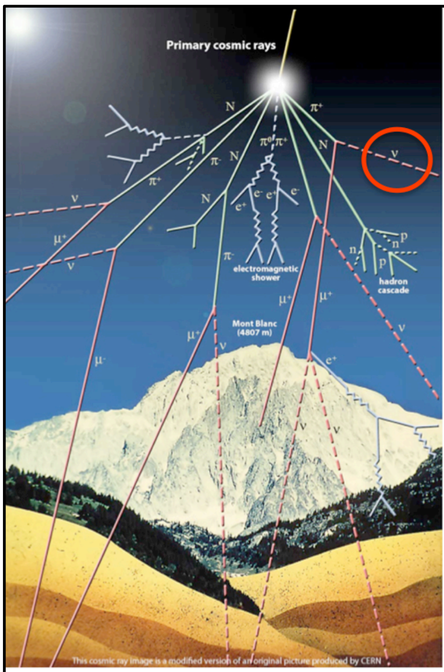
$$t = 0 \;:\; \phi(0) = \phi_{\nu_\mu} = \phi_M(0)\cos\theta_{MH} + \phi_H(0)\sin\theta_{MH}$$

$$\phi_i(t) = \phi_i(0)e^{-i(Et-p_i z)} \underset{p_i \simeq E - m_i^2/2E}{\simeq} \phi_i(0)e^{-im_i^2 z/(2E)}$$

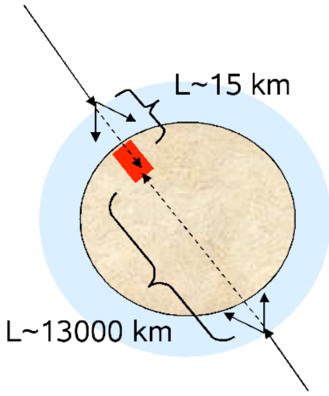
$$t = z \;:\; \phi(z) = \phi_M(0)\cos\theta_{MH}e^{-im_M^2 z/(2E)} + \phi_H(0)\sin\theta_{MH}e^{-im_H^2 z/(2E)}$$

$$P_{\nu_\mu\to\nu_\tau}(z) = \left|\cos\theta_{MH}\sin\theta_{MH}\left(e^{im_M^2 z/(2E)} - e^{im_H^2 z/(2E)}\right)\right|^2 = \underbrace{\sin^2(2\theta_{MH})}_{\text{amplitude}}\sin^2\underbrace{\left(1.27\delta m_{MH}^2\frac{z}{E}\right)}_{\text{phase}}$$

- Let us first consider **two flavors** of neutrinos, ν_μ and ν_τ for example, involved in weak interactions, and **two mass eigenstates** – two real particles ν_M and ν_H with masses m_M and m_H
- The relation between the two classes are **unitary rotations in flavor space**. The angle ϑ_{MH} is the equivalent of the Cabibbo angle in the quark sector, which we introduced in video 6.7.
- The two particles ν_M and ν_H **propagate** in the *z* direction, for example, with different wave functions because of their different masses.
- The second equation is valid in the **ultra-relativistic approximation** $p = E - m^2/2E$ and $t = z$. Now take a **ν_μ beam at $t = 0$**, created by the decay $\pi^+ \rightarrow \mu^+ \nu_\mu$ for example. At a later time *t*, so at a distance *z* from its origin, this beam will be composed differently.
- The **probability to find a ν_τ** in this beam will therefore not be zero. The factor 1.27 takes into account the constants as well as the conversion of units, such that we can put $\delta m^2 = m_H^2 - m_M^2$ in eV^2, E^2 in GeV^2 and *z* in km.
- The two factors in the equation correspond to the **amplitude and phase of an oscillation**. By choosing a distance *z*, which is of the same order of magnitude as $\delta m^2/4E$, *one* can thus make a part of the ν_μ disappear and convert them into ν_τ.



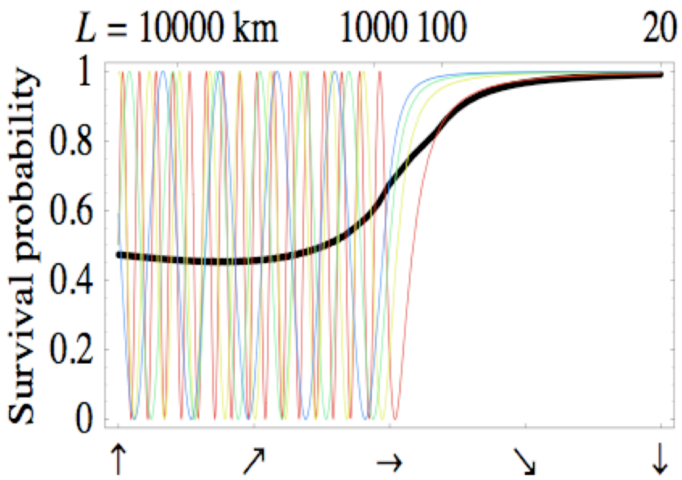
$$\pi^+ \to \mu^+\nu_\mu \;\; ; \;\; \mu^+ \to e^+\nu_e\bar{\nu}_\mu$$
$$\pi^- \to \mu^-\bar{\nu}_\mu \;\; ; \;\; \mu^- \to e^-\bar{\nu}_e\nu_\mu$$

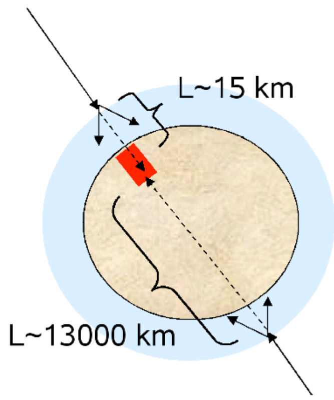


Super-Kamiokande Coll., Y Fukuda et al., Phys. Rev. Lett. 81 (1998) 1562

- This **ν_μ disappearance** was first observed for so-called "atmospheric" neutrinos. Cosmic rays incident on the Earth atmosphere are mostly protons. The hadron shower they cause in the atmosphere is dominated by pions. In their decay, pions produce ν_μ and ν_e in a relative proportion of 2 to 1.
- Thus, there ought to be **twice as many ν_μ and ν_μ-bar** in atmospheric showers than ν_e and ν_e-bar.
- If, on the other hand, neutrinos undergo oscillation, the **ratio of both neutrino flavors should vary with distance.** Fortunately, Earth itself provides the means to vary the distance between source and target without moving the experiment. Neutrinos from the nadir travel a distance larger by the Earth diameter, compared to those from the zenith.
- As the primary flux of cosmic protons is homogeneous and isotropic, and since low energy neutrinos hardly interact with the terrestrial matter, any change in the ratio of ν_μ to ν_e with the zenith angle indicates oscillations.

$$P_{\nu_\mu\to\nu_\mu}(z) = 1 - \sin^2(2\theta_{MH})\,\sin^2\left(1.27\delta m^2_{MH}\frac{z}{E}\right)$$

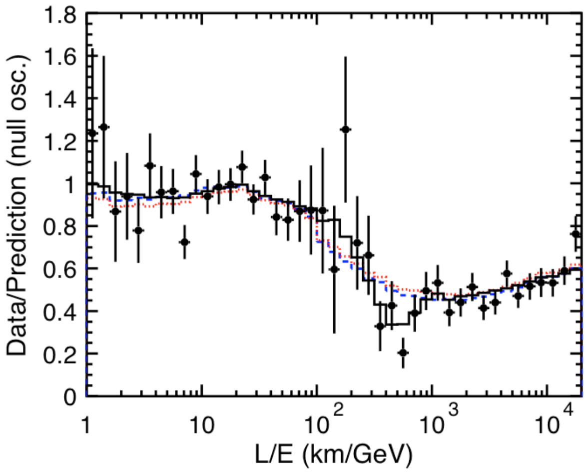




- It is evident from the unitarity of the operation, that for the **probability of survival** is $P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau)$
- Experimentally, one **averages over the unknown neutrino energy** at a known propagation distance. The oscillation curves for different energies, shown here by different colors, are thus averaged over the spectrum of neutrinos. This gives the black curve as a function of distance, indicated on the top scale, or as a function of the angle of incidence, indicated on the bottom.

$$P_{\nu_\mu \to \nu_\mu}(z) = 1 - \sin^2(2\theta_{MH}) \sin^2\left(1.27 \delta m^2_{MH} \frac{z}{E}\right)$$

$$\boxed{\sin^2 2\theta_{MH} = 1^{+0.0}_{-0.2}}$$



$\nu_\mu \mathcal{N} \rightarrow \mu^- +$ hadrons

$\nu_e \mathcal{N} \rightarrow e^- +$ hadrons

T2K Collab., K. Abe et al., Phys. Rev. Lett. 112 (2014) 181801

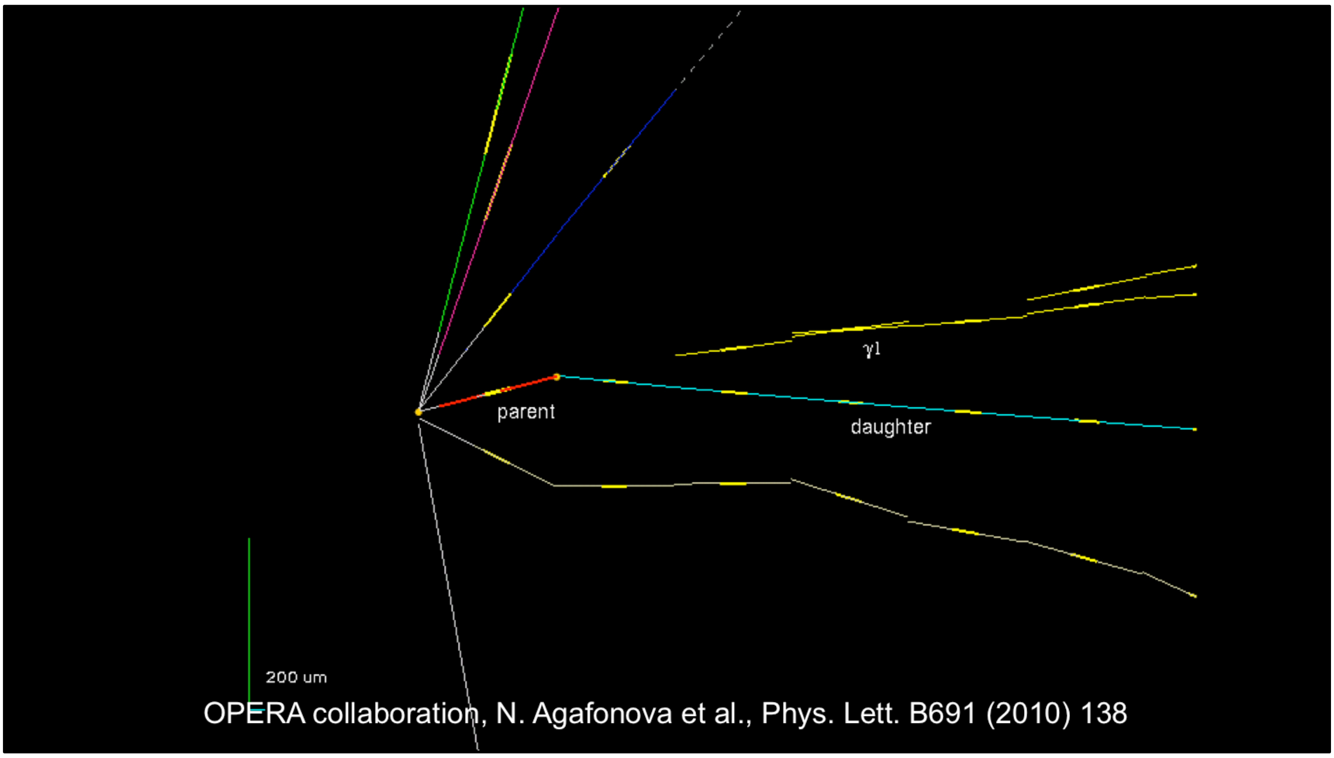
- The **neutrino flux** is measured and their flavor identified by measuring the reaction rate of charged current interactions, which produce either a muon or an electron in the final state. With a known cross section, the reaction rate is proportional to the incident neutrino flux. One finds experimentally that the observed flux ratio is compatible with the calculated oscillation probability. Please note, that the scale of length over energy in this plot is the opposite of the one that we have shown just before.
- The observed **oscillation amplitude** is quite large and therefore corresponds to an angle ϑ_{MH} = 45°±13°. The difference of squared masses is of the order of 3×10^{-3} eV^2 and thus extremely small. As the indices indicate, it is considered more likely that the oscillations of atmospheric neutrinos happen between the second and third generation, i.e. between ν_μ and ν_τ.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = \begin{pmatrix} V_{eL} & V_{eM} & V_{eH} \\ V_{\mu L} & V_{\mu M} & V_{\mu H} \\ V_{\tau L} & V_{\tau M} & V_{\tau H} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_M \\ \nu_H \end{pmatrix}$$

- In general, the relationship between the states participating in leptonic weak interactions, ν_e, ν_μ and ν_τ, and the eigenstates of the mass operator, ν_L, ν_M and $\nu_{H,}$ is described by a unitary matrix of 3×3 elements, analogous to the Cabibbo-Kobayashi-Maskawa matrix for hadronic currents. For leptons, it is called the **Pontecorvo-Maki-Nakagawa–Sakata matrix**.
- Like the matrix for quarks, the one for leptons may contain a non-trivial phase that would **violate CP** symmetry if it existed. Future neutrino experiments will show its existence or not.

- Atmospheric ν_μ disappearance:
  Super-Kamiokande Collab., K. Abe *et al.*, Phys. Rev. D83, 052010 (2011)
- Accelerator ν_μ disappearance:
  K2K Collaboration, M.H. Ahn *et al.*, Phys. Rev. D74 (2006) 072003.
- Appearance of ν_τ in a ν_μ beam:
  OPERA collaboration, N. Agafonova *et al.*, Phys. Lett. B691 (2010) 138
- Appearance of ν_e in a ν_μ beam:
  MINOS Collab., P. Adamson *et al.*, Phys. Rev. Lett. 112 (2014) 191801
- Disappearance of ν_e from nuclear power plants:
  Daya Bay Collaboration, F.P. An *et al.*, Phys. Rev. Lett. 108 (2012) 171803

- Different **types of neutrino oscillations** have been observed to date. A non-exhaustive list:
  - Disappearance of atmospheric ν_μ;
  - Disappearance of the ν_μ produced at accelerators;
  - Appearance of ν_τ and ν_e in a ν_μ beam produced at accelerators;
  - Disappearance of ν_e abundantly produced in nuclear power plants.
- For each of these measurements, we give here a **source of information** that you can use to find more details.



- As an example we show here the interaction of a **ν_τ, appearing in a ν_μ beam** produced at CERN and observed in the **OPERA** detector situated in the Gran Sasso underground laboratory in Italy. The neutrino interactions are observed using photographic emulsions which are then developed. The *dE/dx* of charged particles thus becomes visible.
- This **animation** show an enlargement around the vertex of the neutrino interaction. The reconstruction shows in the final state a charged τ lepton in red, which decays into a π^- (in cyan) and a π^0. The kink between the parent and daughter tracks is a clear signal of a tau lepton decay. The converted photons from the π^0 are shown in yellow; they point to the decay vertex.
- This topology is a clear signature of a ν_τ interaction, which had appeared in the ν_μ beam by **flavor oscillation**.
- Neutrino oscillations are a very **lively research** sector in the United States, Europe and Asia. We can expect spectacular results by experiments which are in progress and under construction.

In the next video we discuss the fact that mass is not an intrinsic property of particles, but that it is dynamically generated by the Higgs mechanism.