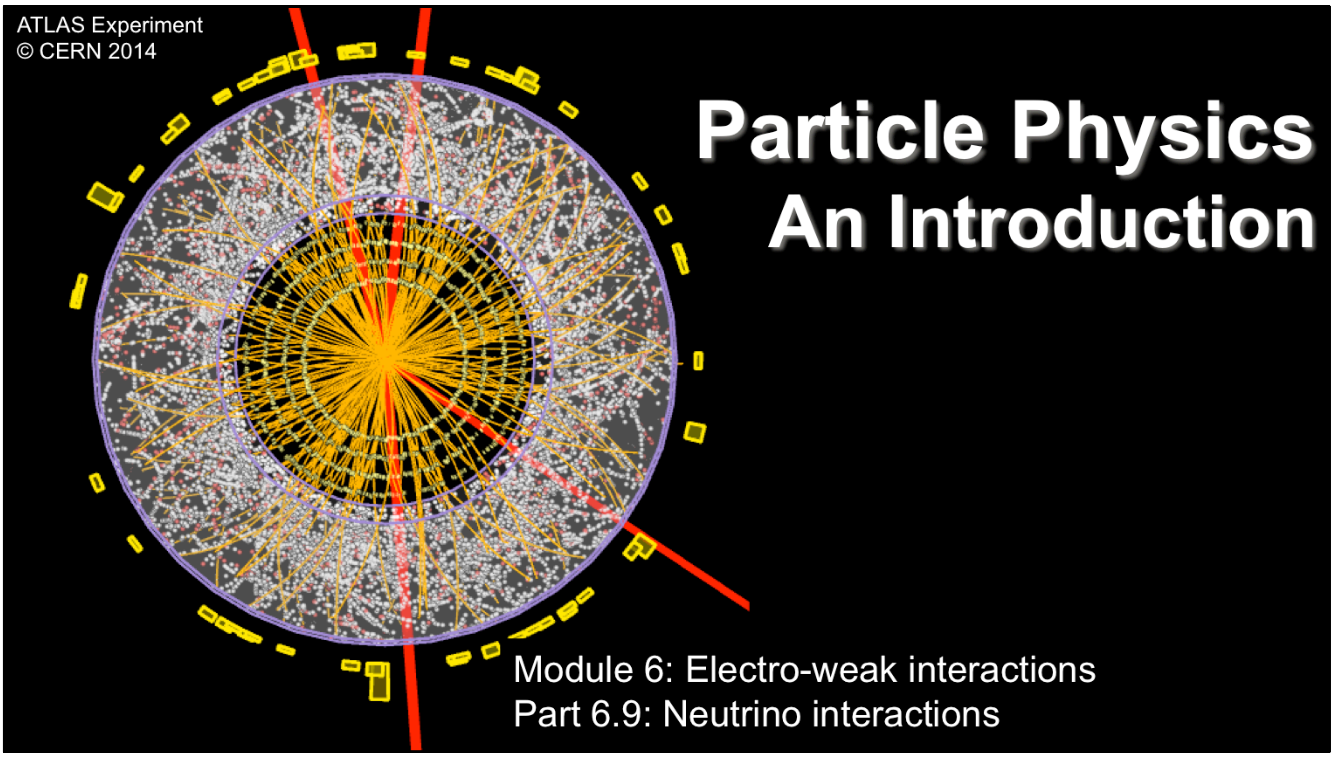
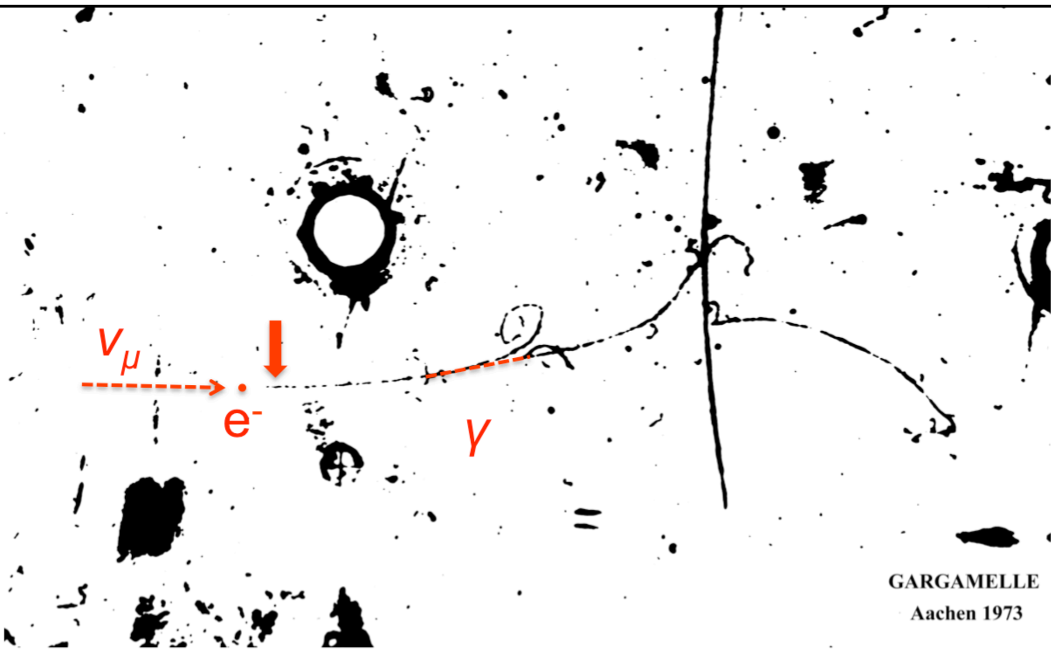


In this sixth module, weak interactions are discussed.

In this 9th video we talk about neutrinos, the only particles which interact exclusively by weak interactions.

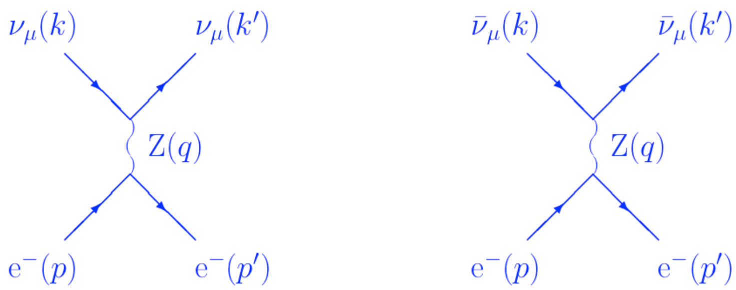
After following this video you will know about:

- The basic properties of neutrinos and
- Their fabulously small interaction cross sections with matter.



http://cerncourier.com/cws/article/cern/28875

- The processes involving **neutrinos** are only due to weak interactions, because neutrinos carry neither electric nor color charge. The process through which weak neutral interactions have been discovered is **elastic neutrino-electron scattering**, $\nu_\mu e^- \rightarrow \nu_\mu e^-$.
- This picture taken with the **Gargamelle bubble chamber** at CERN in 1973 documents the 1rst observation of this interaction type, it is in fact the very first observation of a weak neutral current event. The neutrino enters from the left and interacts with an atomic electron of the liquid. A single visible track leaves the interaction vertex. It is due to a minimum ionizing particle as shown by the low bubble density. The particle also causes bremsstrahlung, it is therefore clearly an electron.
- Since the observation of this reaction, the neutrino has become a **precious tool** for the study of weak interactions, particularly the interactions of the Z and W with matter.

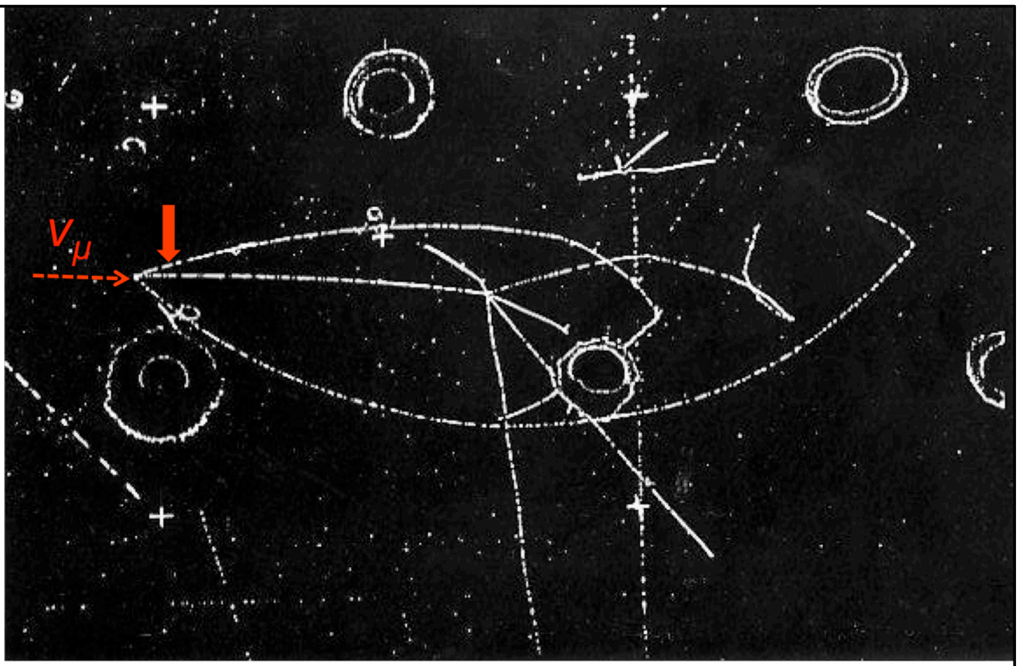


$$\sigma(\nu_\mu e^- \to \nu_\mu e^-) = \frac{G_F^2 s}{3\pi}(g_V^{e2} + g_V^e g_A^e + g_A^{e2}) \simeq 1.6 \times 10^{-49} \left(\frac{E_\nu}{1\mathrm{MeV}}\right) \mathrm{m}^2$$

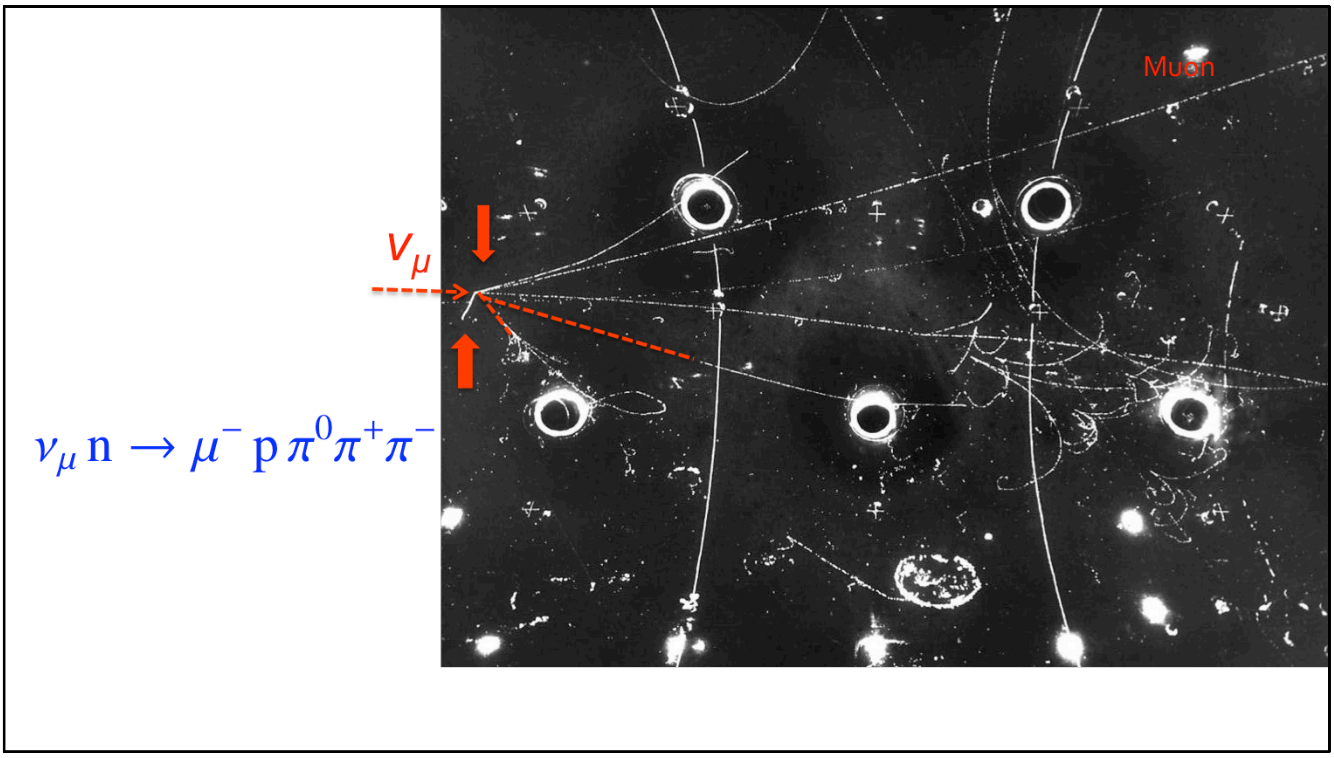
$$\sigma(\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-) = \frac{G_F^2 s}{3\pi}(g_V^{e2} - g_V^e g_A^e + g_A^{e2}) \simeq 1.3 \times 10^{-49} \left(\frac{E_\nu}{1\mathrm{MeV}}\right) \mathrm{m}^2$$

- For **energies much lower than the Z boson mass**, the cross section depends on the coupling constants g_V and g_A of the electron; those of the neutrino are fixed to ½. These coupling constants have already been discussed in video 6.6.
- This cross section is valid for **neutrinos of the second and third generation**, ν_μ and ν_τ.
- For the **anti-neutrino**, the cross section is indicated below, it differs from the neutrino cross section in the sign of the interference term between vector and axial-vector contributions.
- Neutrino-electron cross sections are **extremely small**. The proportionality to E_ν comes from $s = (p+k)^2 \cong 2E_\nu m_e$. It is regularized at high energy by the Z propagator, hidden in the Fermi coupling G_F. At 1 GeV the cross sections are of the order of **attobarn.** The rates are thus desperately low.

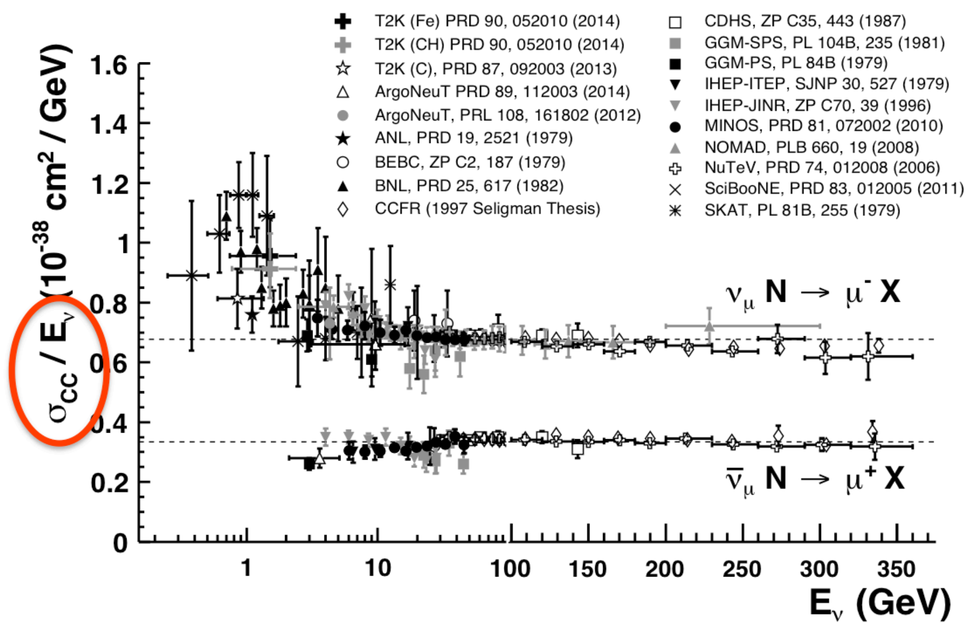
$\nu_\mu \mathrm{p} \rightarrow \nu_\mu \mathrm{p} \pi^+ \pi^-$



- Obviously, the neutrino can also interact with **quarks** through the exchange of a Z boson.
- This image was taken with the same Gargamelle bubble chamber in the CERN neutrino beam, here we show the original **negative**.
- The neutrino enters from the left and interacts with a proton of the liquid. There are three hadrons coming out of the vertex, two positively charged and one negative, as shown by the curvature of the tracks in the magnetic field. The **proton** in the middle interacts with a nucleus of the liquid. Both **pions** are slowed down by dE/dx and absorbed. The **neutrino** escapes without leaving a track.

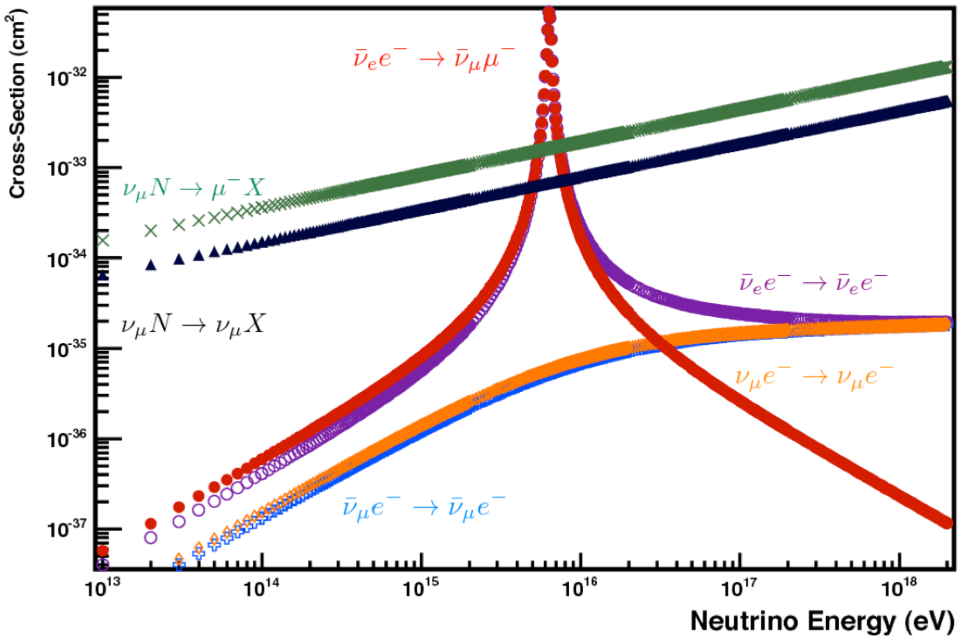


- Neutrinos also interact via W exchange in **charged weak interactions** like in this example.
- The neutrino once again enters from the left and interacts with a neutron. A $\boldsymbol{\mu^-}$ leaves the chamber with minimal ionization. A highly ionizing **proto**n is visible at the vertex. A $\boldsymbol{\pi^0}$ decays into two photons, which in turn are converted into e^+e^- pairs. The **two charged pions** interact with the nuclei of the liquid by the strong force and produce other hadrons.
- You see by these examples that **bubble chamber images** contain a lot of information and are very graphical. They are easily interpreted to identify a reaction and its final state. It were in fact photos of this type, which awakened my fascination with particle physics in the 1970's. But this analogue technology is of course no longer in use today.



http://pdg.lbl.gov/2016/reviews/rpp2016-rev-nu-cross-sections.pdf

- We had seen that for neutrino-electron interactions, the **cross section is proportional to the neutrino energy**. This is true in general, both for purely leptonic interactions and interactions between neutrinos and quarks, and for charged as well as neutral currents.
- Here you see the **compilation** of the Particle Data Group of neutrino- and antineutrino-nucleon charged current cross sections, divided by the neutrino energy to better appreciate the proportionality.
- You may wonder, if a cross section, which increases with energy, will not violate the **unitarity limit** at some point. Indeed, the neutrino cross sections are regularized by the propagators of the W and Z bosons at very high q^2.



Formaggio, J.A. and Zeller, G.P., Rev.Mod.Phys. 84 (2012) 1307

- But to see the effect of the propagator, we need **fabulously high energies** beyond 10^{15} eV in the laboratory frame, that is to say 1000 TeV.
- This graph shows a **calculation** of the cross sections at very high energy. The Z resonance is clearly visible for reactions which involve ***s*-channel Z** exchange. Beyond the resonance, the propagator regularizes the cross section, such that it will eventually tend to zero, as it should.
- For reactions involving **W exchange in the *t*-channel**, regularization takes much higher energies, since only a small fraction of the neutrino energy is transmitted to the target.

- In the next video we will discuss oscillations between different neutrino species.