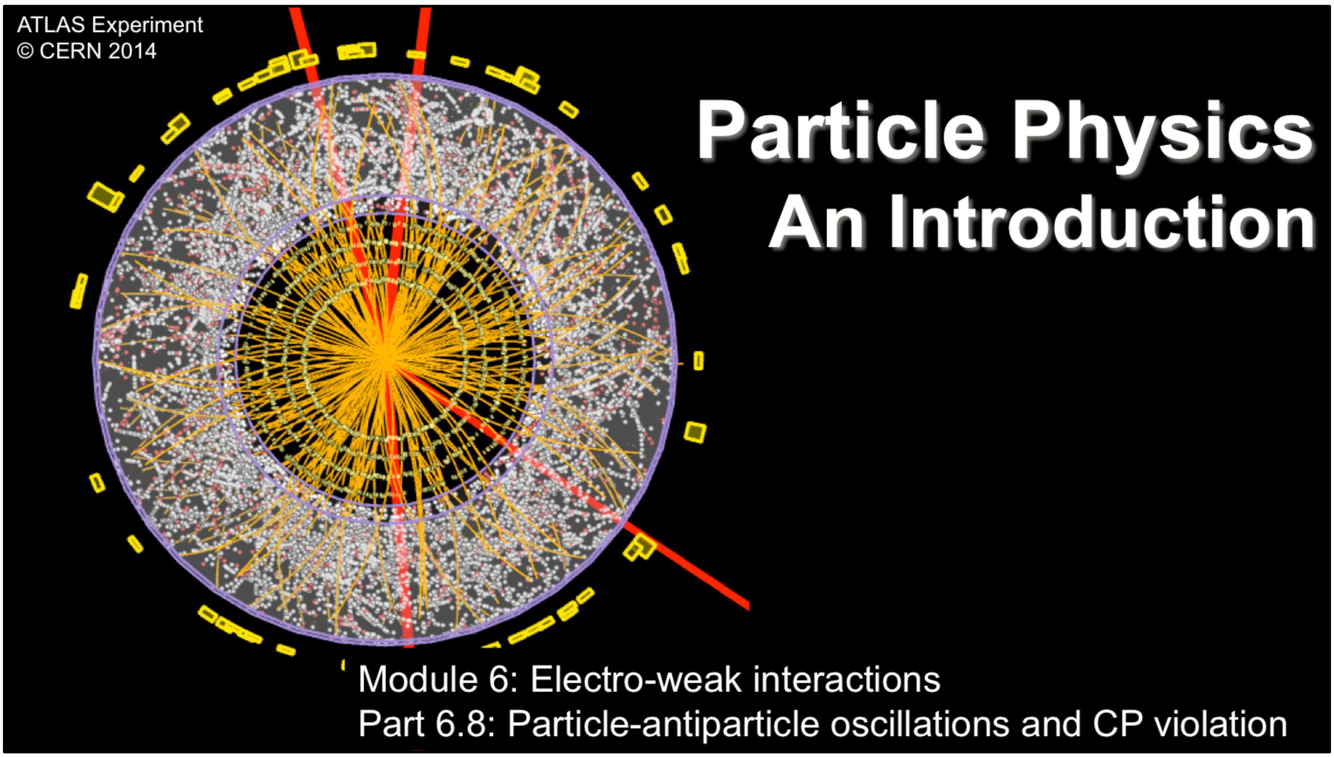
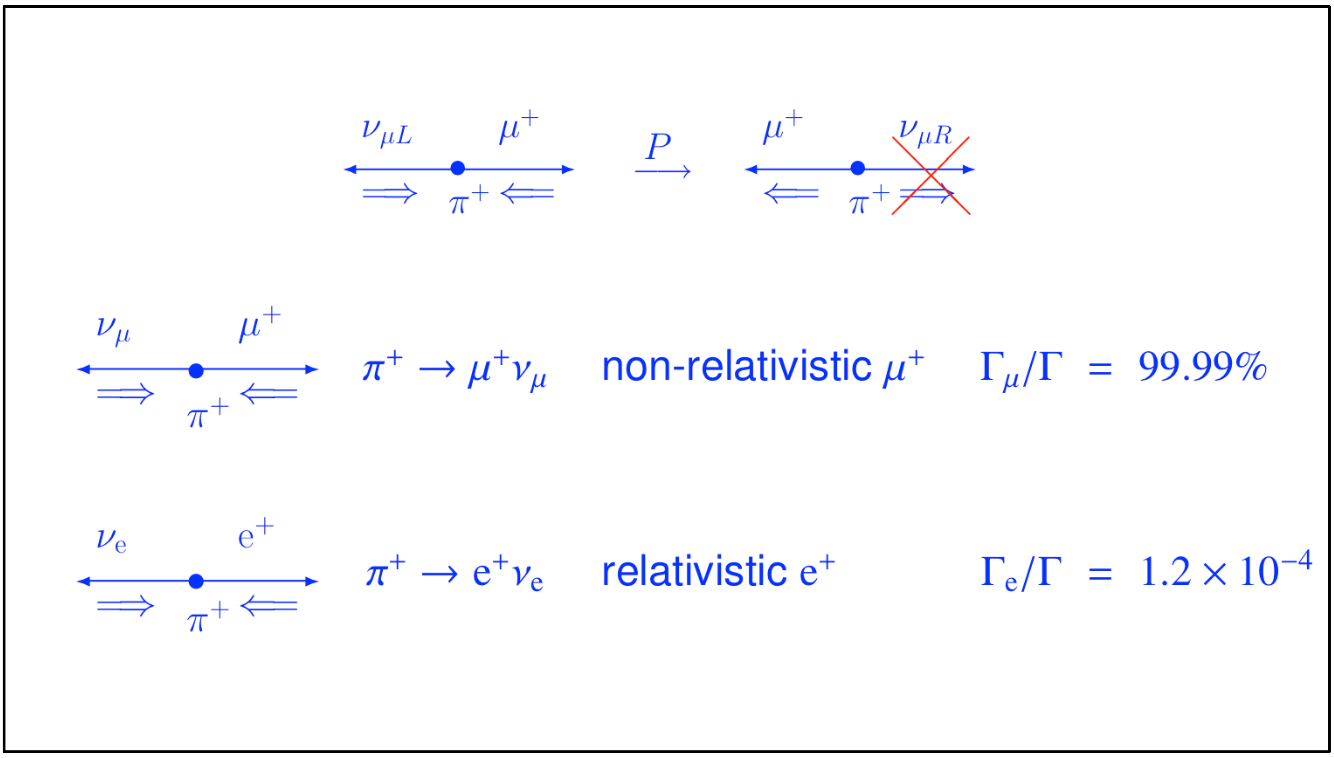


In this sixth module, weak interactions are discussed.

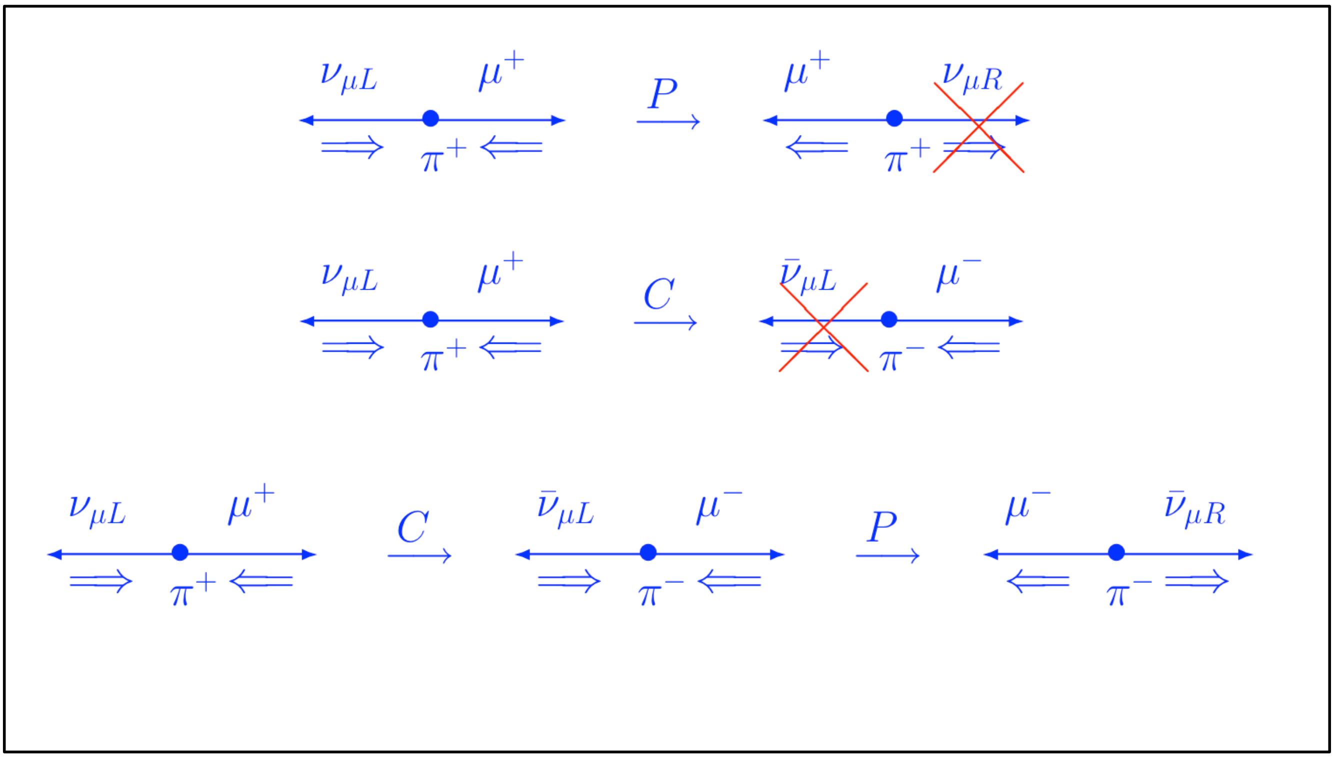
In this 8th video, we will talk about the violation of the CP symmetry between particles and antiparticles, by weak interactions.

After following this video you will be able to:

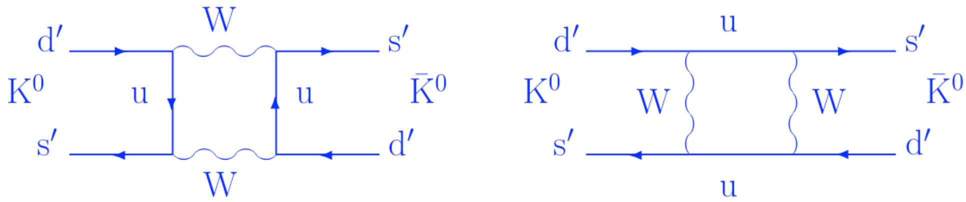
- Describe the conditions for oscillations between particles and antiparticles and their mechanism;
- Explain the violation of the joint symmetry CP in the quark sector.



- The CKM matrix must be unitary, but not necessarily real. This allows a **non-trivial complex phase**, which cannot be removed by a global rotation in flavor space. The existence of such a phase has very important consequences, that we will discuss in the following.
- But first a reminder: We already saw in video 6.3 that the **weak interaction maximally violates parity P**. A good example is π^+ decay.
- The dominant decay channel is $\pi^+ \rightarrow \mu^+ \nu_{\mu L}$. The **neutrino** produced in the decay must be **left-handed** because of the structure of the interaction. As the pion is a scalar particle, the μ^+ must also be left-handed, which is allowed to the extent that its mass is non-negligible and allows it to have the "wrong" helicity.
- The **mirror decay,** on the contrary, which would produce a μ^+ of the "right" helicity, is not observed at all, because the W does not interact with right-handed neutrinos.
- This explains why the **decay into an electron** $\pi^+ \rightarrow e^+ \nu_{eL}$ is so much disfavored, despite its much larger phase space factor: the small mass of the electron requires it much more to have the "right" helicity and thus suppresses the amplitude of this process.



- The decay of the charged pion **violates** at the same time the **charge conjugation symmetry, C**. Under this operation, we obtain a reaction that is forbidden by the fact that the W does not couple at all to the left-handed antineutrino, but only to ν-Bar-R.
- Since symmetries C and P are thus both violated in a maximum fashion by charged weak interactions, one might expect that the **combined symmetry CP** would be respected. This is indeed the case in the example shown so far.
- For the pion, it is simple to verify that the operation CP converts the π^+ decay into the π^- decay with the "good" helicity for the neutrinos, but the "bad" one for muons, only admitted because muons are non-relativistic. These processes are **therefore CP eigenstates with the same amplitude.**



$$\mathbf{P}\phi_{K^0} = -\phi_{K^0} \quad ; \quad \mathbf{P}\phi_{\bar{K}^0} = -\phi_{\bar{K}^0}$$

$$\mathbf{C}\phi_{K^0} = \phi_{\bar{K}^0} \quad ; \quad \mathbf{C}\phi_{\bar{K}^0} = \phi_{K^0}$$

$$\phi_{K_1} = \frac{1}{\sqrt{2}}(\phi_{K^0} - \phi_{\bar{K}^0}) \quad ; \quad \mathbf{CP}(\phi_{K_1}) = +\phi_{K_1}$$

$$\phi_{K_2} = \frac{1}{\sqrt{2}}(\phi_{K^0} + \phi_{\bar{K}^0}) \quad ; \quad \mathbf{CP}(\phi_{K_2}) = -\phi_{K_2}$$

- But this is not the case for all the **inter-generation weak processes** mediated by the W boson. Let's look at the neutral mesons like K^0 (d,s-bar), or B^0 (d,b-bar). These can be converted into their own anti-particle by a second order process. This reaction is obviously only possible for particles that do not carry any kind of charge.
- The pseudoscalar meson **K^0**, for example, is an **eigenstate of P, but not of C**, because this operation changes its strangeness. K^0 contains an antiquark s-bar, so it has strangeness +1. K^0-bar contains a quark s, so it has strangeness -1.
- Therefore, neither K^0 nor K^0-bar are eigenstates of CP. But one can construct **linear combinations K_1 and K_2**, that are eigenstates of CP.
- If CP is conserved, it should thus be these two states which decay by weak interactions.

$$\phi_{K_1} = \frac{1}{\sqrt{2}}(\phi_{K^0} - \phi_{\bar{K}^0}) \quad ; \quad \mathbf{CP}(\phi_{K_1}) = +\phi_{K_1}$$

$$\phi_{K_2} = \frac{1}{\sqrt{2}}(\phi_{K^0} + \phi_{\bar{K}^0}) \quad ; \quad \mathbf{CP}(\phi_{K_2}) = -\phi_{K_2}$$

$$K_1 \rightarrow \pi^+\pi^- \quad ; \quad K_2 \rightarrow \pi^+\pi^-\pi_0$$

$$K_S \simeq K_1 \quad ; \quad K_L \simeq K_2$$

$$\Delta m = m_L - m_S \simeq 3.5 \times 10^{-6}\text{eV}$$

- If the **eigenvalue of CP** were conserved by weak interactions, the eigenstates K_1 and K_2 would decay by the weak force into final states K_1➔2π and K_2➔3π, respectively. These final states have the right CP properties.
- This is **approximately true**. The states K_1 and K_2 are almost identical to the **particles K^0_S and K^0_L** found in the lists of the Particle Data Group. Because of the two very different **phase space** factors, one finds that the **lifetime** of the K_S is much shorter than that of K_L, which explains the notation "K short" and "K long".
- But the identification $K_S \approx K_1$ and $K_L \approx K_2$ is **not perfect**:
    - First, the two masses are not quite the same, they differ by some micro-eV. The mass difference produces **oscillations** between particles and antiparticles in time, because both states are not evolving with the same velocity when their energy is the same.

$$\phi_{K_1}(t) = \phi_{K_1}(0)e^{im_1 t}e^{-\Gamma_1 t/2}$$

$$\phi^*_{K_1}(t)\phi_{K_1}(t) = \left|\phi_{K_1}(0)\right|^2 e^{-\Gamma_1 t}$$

$$\phi_{K_1}(0) = \phi_{K_2}(0) = \frac{1}{\sqrt{2}}$$

$$\begin{aligned}\phi^*_{K^0}(t)\phi_{K^0}(t) &= \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2e^{-\frac{\Gamma_1+\Gamma_2}{2}} \cos \Delta m t\right] \\ \phi^*_{\bar{K}^0}(t)\phi_{\bar{K}^0}(t) &= \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-\frac{\Gamma_1+\Gamma_2}{2}} \cos \Delta m t\right]\end{aligned}$$

- Imagine a **K_1 meson at *t* = 0**, at rest in vacuum. Its wave function evolves according to its mass m_1 and width Γ_1. The probability density to find the K_1 at time *t* is given by the evolution equation for free particles.
- The same reasoning is valid for **K_2**, but with mass m_2 and width Γ_2.
- Since strong interactions conserve flavors, including strangeness, a state produced by strong interactions will have a **definite strangeness**, like K^0 or K^0-bar. If one produces, e.g., a K^0 at *t* = 0, we will have a mixture of **equal quantities of K_1 and K_2** at that time.
- Now the two components are evolving differently because of the small mass difference *Δm*. At a **later time** *t* we therefore find a **different mixture**! If we thus measure the strangeness of the state as a function of time (again by a strong interaction, for example), we find that it **oscillates** between K^0 and K^0-bar with a frequency *Δm*.

$$\phi_{K_L} = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(\phi_{K_2} + \epsilon\,\phi_{K_1}\right)$$

$$|\epsilon| \simeq 2.3 \times 10^{-3}$$

$$\mathbf{V}_{CKM} = \begin{pmatrix} |V_{11}| & |V_{12}|e^{i\delta} & |V_{13}|e^{i\delta} \\ |V_{12}|e^{i\delta} & |V_{22}| & |V_{23}|e^{i\delta} \\ |V_{13}|e^{i\delta} & |V_{23}|e^{i\delta} & |V_{33}| \end{pmatrix}$$

- So far, the **combined symmetry CP** is still respected. But one finds that the long lived particle, $K^0_L \approx K_2$, has a low probability to decay into $\pi^+\pi^-$, a state with the **wrong CP eigenvalue**!
- One must thus admit that **K^0_L also contains a small amplitude of K_1**. The coefficient $|\varepsilon| \approx 2.3\times10^{-3}$ is certainly small but not zero.
- Consequently, charged **weak interactions violate also the combined symmetry CP,** but only a little bit.
- This means that the **amplitudes** of charged weak interactions for **matter and antimatter** are slightly different. Nature has therefore foreseen an objective way to distinguish them.
- A **complex phase in the CKM matrix** allows to introduce this little asymmetry in the mixing of quark states involved in weak interactions, with a phase angle of $\delta \approx 45°$. This describes the phenomenon using the CKM matrix, but does not explain it. CP violation in weak interactions is a subject of active research in the kaon sector as well as in the decays of the B^0.

- The next video will discuss neutrino interactions, which are among the most rare processes in particle physics.