

# V. CP violation

In 1956, T.D.Lee & Chen Ning Yang suggested non-conservation of parity in weak processes, evident in e.g. kaon decays (known then as the “*theta-tau puzzle*”), proposed a  $\beta$ -decay experiment

❖ Some known decays of  $K^+$  were:



Called in 50-ies: “*theta meson*” and “*tau meson*”

Intrinsic parity of a pion  $P_\pi = -1$ , and for the  $\pi^0\pi^+$ ,  $\pi^+\pi^+\pi^-$  states parities are

$$P_{0+} = P_\pi^2 (-1)^L = 1, \quad P_{++-} = P_\pi^3 (-1)^{L_2 + L_3} = -1$$

where  $L=0$  since kaon has spin-0.

❖ One of the  $K^+$  decays **violates** parity!

❖ 1957: a group lead by Chien-Shiung Wu demonstrated parity violation in  $\beta$ -decay

- $^{60}\text{Co}$   $\beta$ -decay into  $^{60}\text{Ni}^*$  was studied (cooled to 0.01 K to prevent thermal disorder)
- Sample was placed in a magnetic field  $\Rightarrow$  nuclear spins aligned with the field direction

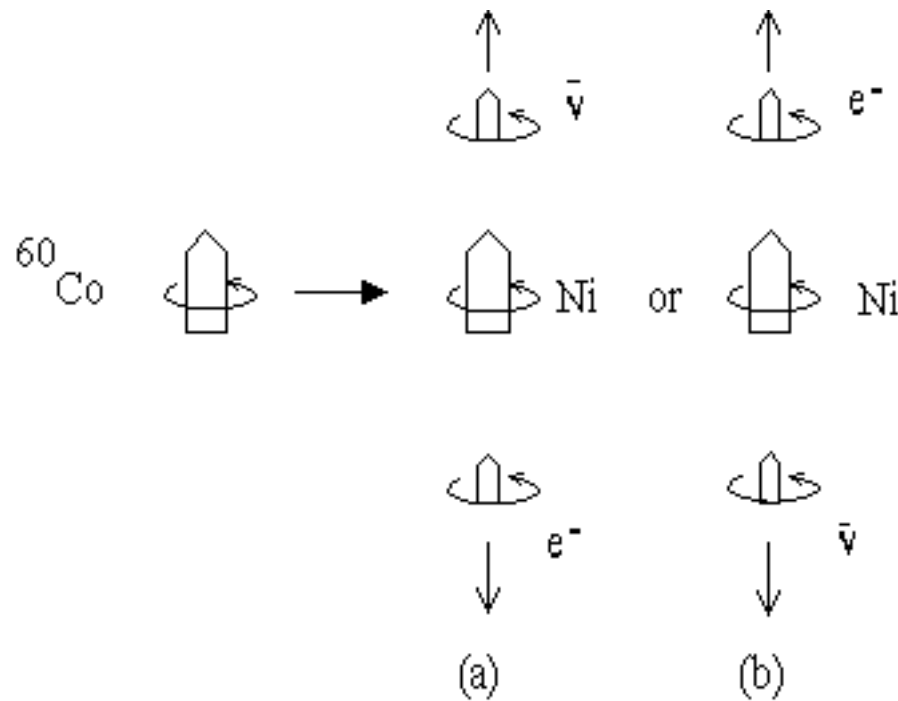


Figure 75: Possible  $\beta$ -decays of  $^{60}\text{Co}$ : case (a) is preferred.

- If parity is conserved, processes (a) and (b) must have equal rates

🎯 *Electrons were emitted predominantly in the direction opposite the  $^{60}\text{Co}$  spin*

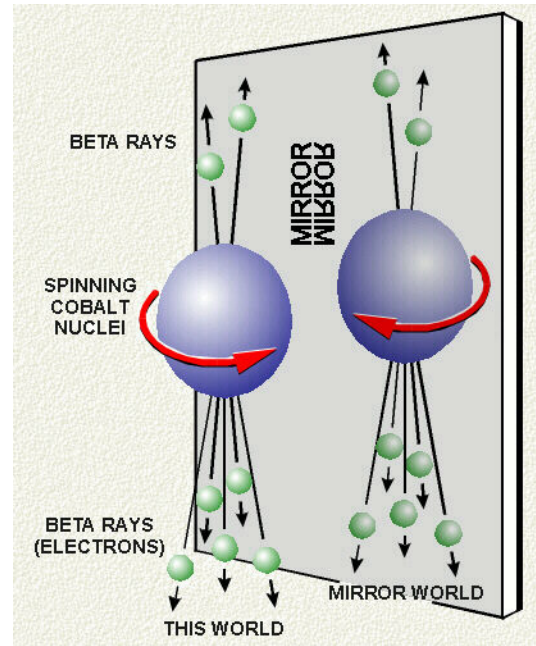


Figure 76: Artistic representation of the effect. In the mirror, the direction of spin is reversed, while the direction in which most beta rays are emitted remains unchanged. Parity transformation would turn the mirror upside down, to return the spin to the original direction. But then the electrons will be emitted upwards, which is not the case: parity is not conserved.

***NB! Parity transformation does not change spin!***

❖ Another case of parity and C-parity violation was observed in muon decays:

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (75)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (76)$$

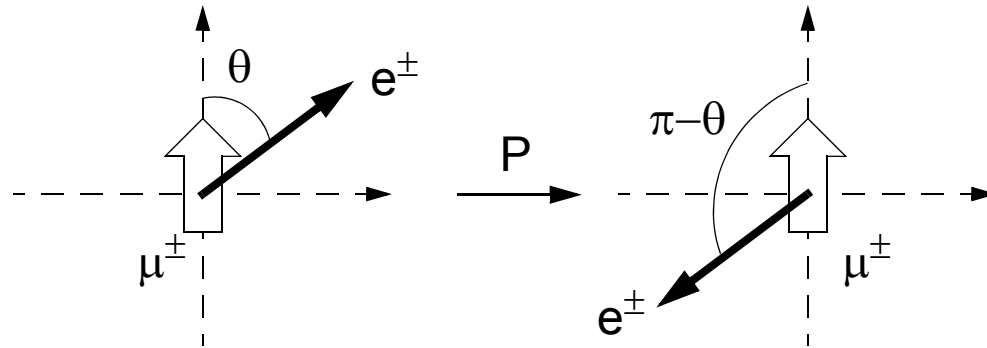


Figure 77: Effect of a parity transformation on the muon decays (75) and (76)

Angular distribution of  $e^-$  ( $e^+$ ) emitted in  $\mu^-$  ( $\mu^+$ ) decay has a form of:

$$\Gamma_{\mu^\pm}(\cos\theta) = \frac{1}{2}\Gamma_\pm \left( 1 - \frac{\xi_\pm}{3} \cos\theta \right)$$

– here  $\xi_\pm$  are constants – “*asymmetry parameters*”, and  $\Gamma_\pm$  are total decay rates (thus inverse lifetimes)

$$\Gamma_{\pm} = \int_{-1}^1 \Gamma_{\pm}(\cos\theta) d\cos\theta \equiv \frac{1}{\tau_{\pm}} \quad (77)$$

☉ If the process is invariant under charge conjugation (C-invariance)  $\Rightarrow$

$$\Gamma_{+} = \Gamma_{-} \quad \xi_{+} = \xi_{-} \quad (78)$$

(rates and angular distributions are the same for  $e^{-}$  and  $e^{+}$ )

☉ If the process is P-invariant, then angular distributions in forward and backward directions are the same:

$$\Gamma_{\mu^{\pm}}(\cos\theta) = \Gamma_{\mu^{\pm}}(-\cos\theta) \quad \xi_{+} = \xi_{-} = 0 \quad (79)$$

❖ Experimental results:

$$\Gamma_{+} = \Gamma_{-} \quad \xi_{+} = -\xi_{-} = 1.00 \pm 0.04 \quad (80)$$

**Both C- and P-invariance are violated, on daily basis!**

❖ An idea: combined operation CP is conserved

$$\Gamma_{\mu^+}(\cos\theta) = \Gamma_{\mu^-}(-\cos\theta) \quad (81)$$

⇓

$$\Gamma_+ = \Gamma_- \quad \xi_+ = -\xi_- \quad (82)$$

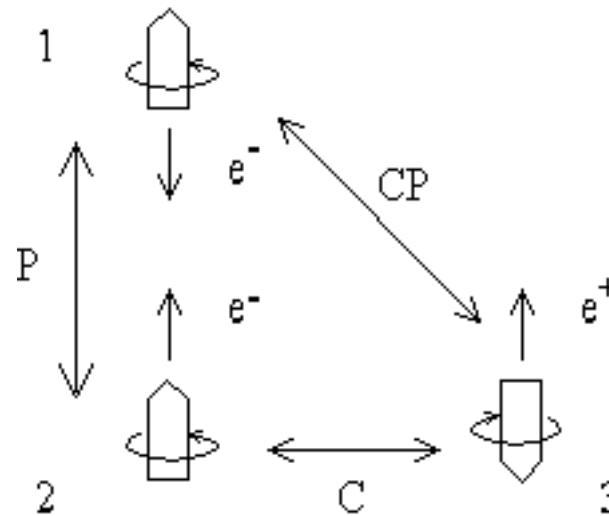


Figure 78: P-, C- and CP-transformation of an electron

❖ It appears that electrons prefer to be emitted with momentum opposite to their spin (left-handed)

Corresponding observable: *helicity* – projection of particle's spin to its direction of motion

$$\Lambda = \frac{\vec{J} \cdot \vec{p}}{|\vec{p}|} = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} \quad (83)$$

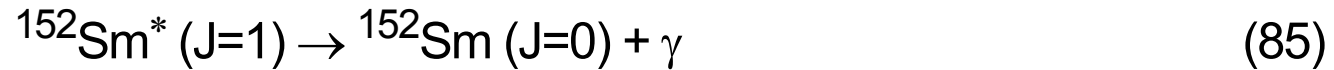
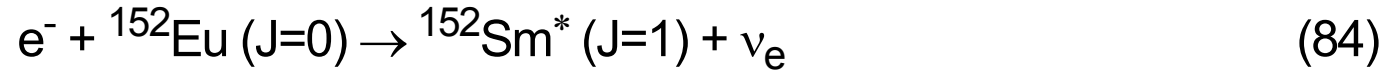
Eigenvalues of helicity are  $h = -s, -s+1, \dots, +s$ ,  $\Rightarrow$  for a spin-1/2 electron it can be either -1/2 or 1/2



Figure 79: Helicity states of spin-1/2 particle

## Helicity of neutrino

❖ 1958: Goldhaber et al. measured helicity of neutrino using the reaction of orbital electron capture in Eu:



In the reaction (84),  ${}^{152}\text{Sm}^*$  and  $\nu_e$  recoil in opposite directions



Figure 80: Spin of  ${}^{152}\text{Sm}^*$  has to be opposite to the neutrino spin (parallel to the electron spin)

In the initial state, electron has spin-1/2,  ${}^{152}\text{Eu}$  – spin-0, in final state:  ${}^{152}\text{Sm}^*$  has spin-1 and  $\nu_e$  – spin-1/2  $\Rightarrow$  spin of  ${}^{152}\text{Sm}^*$  is parallel to the electron spin and opposite to the neutrino spin.



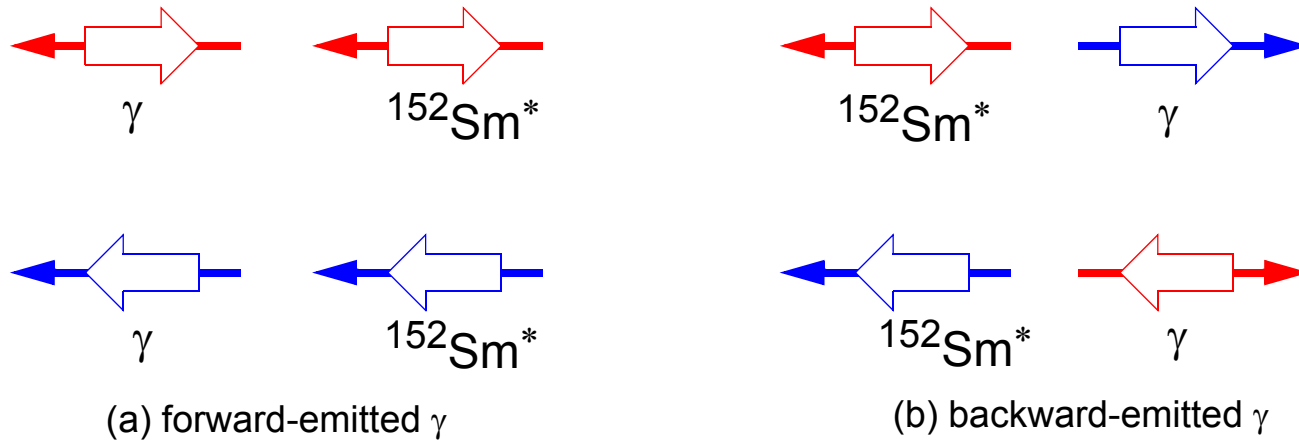


Figure 81: Forward-emitted  $\gamma$  has the same helicity as  $\nu_e$

Events with  $\gamma$  emitted in the direction of motion of  $^{152}\text{Sm}^*$  were selected.

– Polarization of photons was determined by studying their absorption in magnetized iron.

- ❖ It turned out that neutrinos can be only **left-handed!**
- ❖ Antineutrinos were found to be always right-handed.

## V-A interaction

- ❖ V-A interaction theory was introduced by Fermi as an analytic description of spin dependence of charged current interactions.
  - ☉ It denotes “polar Vector - Axial vector” interaction
  - *Polar vector* is any which direction is reversed by parity transformation: momentum  $\vec{p}$
  - *Axial vector* is that which direction is not changed by parity transformation: spin  $\vec{s}$  or orbital angular momentum  $\vec{L} = \vec{r} \times \vec{p}$
  - ☉ Weak current has both vector and axial components, hence parity is not conserved in weak interactions
- ❖ Main conclusion: if velocity  $v \approx c$ , only left-handed fermions  $\nu_L, e_L^-$  etc. are emitted, and right-handed antifermions.
- ❖ *The very existence of preferred states violates both C- and P-invariance*

- ⊙ Neutrinos (antineutrinos) are always relativistic and hence always are left(right)-handed
- ⊙ For other (massive) fermions, preferred states are left-handed, and right-handed states are not completely forbidden, but *suppressed* by factors

$$\left(1 - \frac{v}{c}\right) \approx \frac{m^2}{2E^2} \quad (86)$$

Consider pion decay modes (pion at rest):

$$\pi^+ \rightarrow l^+ + \nu_l \quad (l=e, \mu) \quad (87)$$

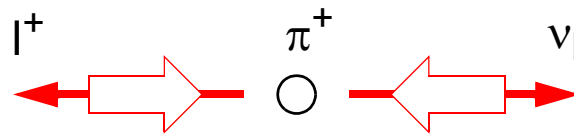


Figure 82: Helicities of leptons emitted in a pion decay

- $\pi^+$  has spin-0,  $\Rightarrow$  spins of charged lepton and neutrino must be opposite
- Neutrino is always left-handed  $\Rightarrow$  charged lepton has to be left-handed as well. BUT:  $e^+$  and  $\mu^+$  as antileptons ought to be right-handed!

❖ It follows that a relativistic charged lepton can not be emitted at all in a pion decay!

☉ Muons are rather heavy  $\Rightarrow$  non-relativistic  $\Rightarrow$  can be left-handed (see Eq.(86))

☉ Decays of pions to positrons ought to be *suppressed* by a factor of  $10^{-5}$

Measured ratio:

$$\frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)} = (1.230 \pm 0.004) \times 10^{-4} \quad (88)$$

❖ Muons emitted in pion decays are always polarized ( $\mu^+$  are left-handed)

This can be used to measure muon decay (75), (76) symmetries by detecting highest-energy (relativistic) electrons with energy

$$E = \frac{m_\mu}{2} \left( 1 + \frac{m_e^2}{m_\mu^2} \right) \gg m_e \tag{89}$$

❖ Highest-energy electrons are emitted in decays when both  $\nu_\mu$  and  $\bar{\nu}_e$  are emitted in the direction opposite to  $e^-$ :

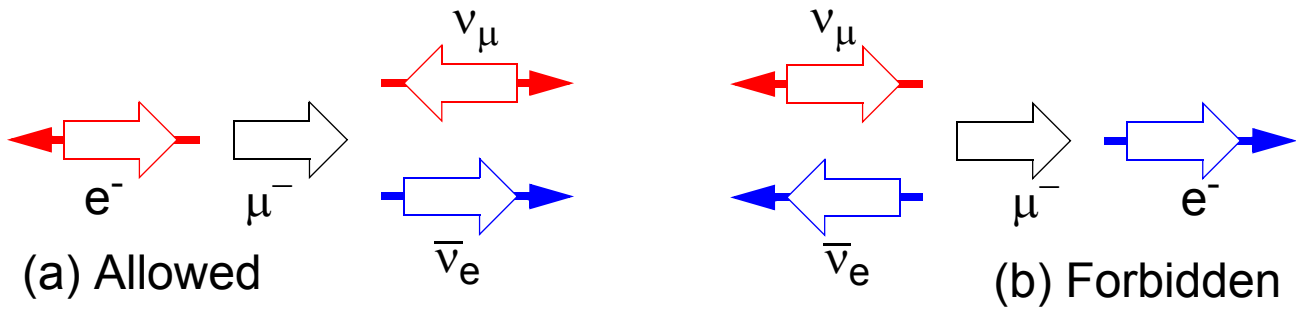


Figure 83: Muon decays at rest with highest-energy electron emission

🎯 Electron must have spin parallel to the muon spin  $\Rightarrow$  configuration (a) is strongly preferred  $\Rightarrow$  observed experimentally forward-backward asymmetry (80)

## Neutral kaons

❖ CP symmetry apparently can be violated in weak interactions

☉ Neutral kaons  $K^0(498)=(d\bar{s})$  and  $\bar{K}^0(498)=(s\bar{d})$  can be converted into each other because they have same quantum numbers

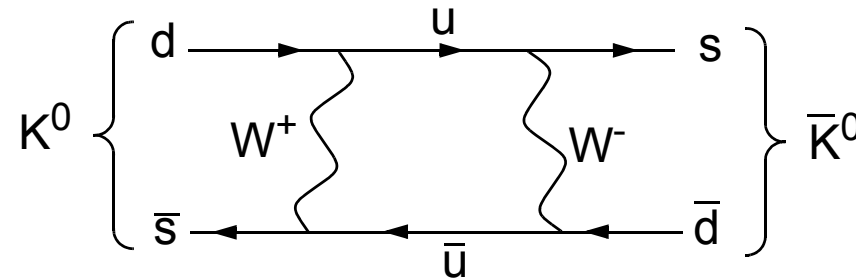


Figure 84: Example of a process converting  $K^0$  to  $\bar{K}^0$ .

❖ Phenomenon of  $K^0-\bar{K}^0$  mixing: observed physical particles are linear combinations of  $K^0$  and  $\bar{K}^0$ , since there is no conserved quantum number to distinguish them

☉ The same is true for neutral B-mesons:  $B^0 = d\bar{b}$ ,  $\bar{B}^0 = b\bar{d}$ ,  $B_s = s\bar{b}$  and  $\bar{B}_s = b\bar{s}$ , and for neutral D-mesons  $D^0 = c\bar{u}$  and  $\bar{D}^0 = u\bar{c}$ .

C-transformation changes a quark into antiquark  $\Rightarrow$

$$C|K^0, \vec{p}\rangle = -|\bar{K}^0, \vec{p}\rangle \quad \text{and} \quad C|\bar{K}^0, \vec{p}\rangle = -|K^0, \vec{p}\rangle \quad (90)$$

– Here signs are chosen for further convenience and do not affect physical predictions

Intrinsic parity of a kaon is  $P_K = -1 \Rightarrow$  for  $\vec{p} = (0, 0, 0)$

$$P|K^0, \vec{p}\rangle = -|K^0, \vec{p}\rangle \quad \text{and} \quad P|\bar{K}^0, \vec{p}\rangle = -|\bar{K}^0, \vec{p}\rangle \quad (91)$$

and the CP transformation is

$$CP|K^0, \vec{p}\rangle = |\bar{K}^0, \vec{p}\rangle \quad \text{and} \quad CP|\bar{K}^0, \vec{p}\rangle = |K^0, \vec{p}\rangle \quad (92)$$

While  $K^0$  and  $\bar{K}^0$  are not CP eigenstates, these two combinations are:

$$|K_1^0, \vec{p}\rangle = \frac{1}{\sqrt{2}} \{ |K^0, \vec{p}\rangle + |\bar{K}^0, \vec{p}\rangle \} \quad (93)$$

$$|K_2^0, \vec{p}\rangle = \frac{1}{\sqrt{2}} \{ |K^0, \vec{p}\rangle - |\bar{K}^0, \vec{p}\rangle \} \quad (94)$$

with eigenvalues 1 and -1, such that:

$$CP|K_1^0, \vec{p}\rangle = |K_1^0, \vec{p}\rangle \text{ and } CP|K_2^0, \vec{p}\rangle = -|K_2^0, \vec{p}\rangle$$

❖ Experimentally observed are two types of neutral kaons:  $K_S^0$  (“S” for “short”, lifetime  $\tau = 0.9 \times 10^{-10} s$ ) and  $K_L^0$  (“long”,  $\tau = 5 \times 10^{-8} s$ ).

🎯  $K_S^0$  is identified with  $K_1^0$  CP-eigenstate, and  $K_L^0$  – with  $K_2^0$

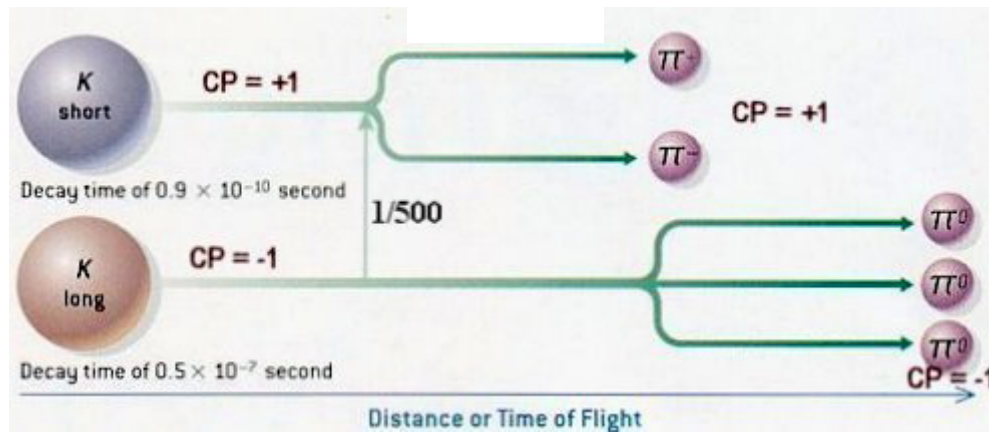


Figure 85: Decays of K-short and K-long



❖ If CP-invariance holds for neutral kaons,  $K_S^0$  should decay only to states with CP=1, and  $K_L^0$  – to states with CP=-1:

$$K_S^0 \rightarrow \pi^+ \pi^-, \quad K_S^0 \rightarrow \pi^0 \pi^0 \quad (95)$$

– Parity of a two-pion state is  $P = P_\pi^2 (-1)^L = 1$  (kaon has spin-0)

– C-parity of  $\pi^0 \pi^0$  state is  $C = (C_{\pi^0})^2 = 1$ , and of a  $\pi^+ \pi^-$  state:  $C = (-1)^L = 1$ ,

$\Rightarrow$  for final states in (95) CP=1

$$K_L^0 \rightarrow \pi^+ \pi^- \pi^0, \quad K_L^0 \rightarrow \pi^0 \pi^0 \pi^0 \quad (96)$$

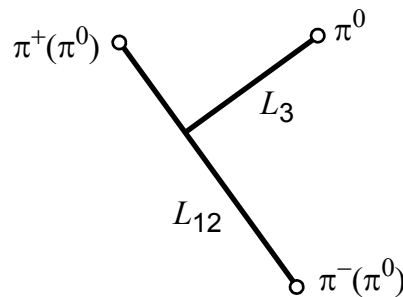


Figure 86: Angular momenta in a 3-pion system

– Parity of a 3-pion state is  $P = P_{\pi}^3 (-1)^{L_{12} + L_3} = -1$

– C-parity of  $\pi^0\pi^0\pi^0$  is  $C = (C_{\pi^0})^3 = 1$ , and of the state  $\pi^+\pi^-\pi^0$ :

$C = C_{\pi^0}(-1)^{L_{12}} = (-1)^{L_{12}}$ .  $L_{12}$  can be defined experimentally:  $L_{12}=0 \Rightarrow$  for final states in (96)  $CP=-1$

❖ However, the *CP-violating* decay



was observed in 1964, with a branching ratio  $B \approx 10^{-3}$  (Cronin & Fitch)

⊙ In general, physical states  $K_S^0$  and  $K_L^0$  don't have to correspond to CP-eigenstates  $K_1^0$  and  $K_2^0$ :  $K_S^0$  has admixture of  $K_2^0$  and  $K_L^0$  – of  $K_1^0$ .

⊙ There can be different mechanisms for CP-violation, esp. in  $B^0$ - $\bar{B}^0$  systems; dedicated experiments (BaBar, Belle) are observing this

❖ CP violation in B systems is even larger than for kaons!

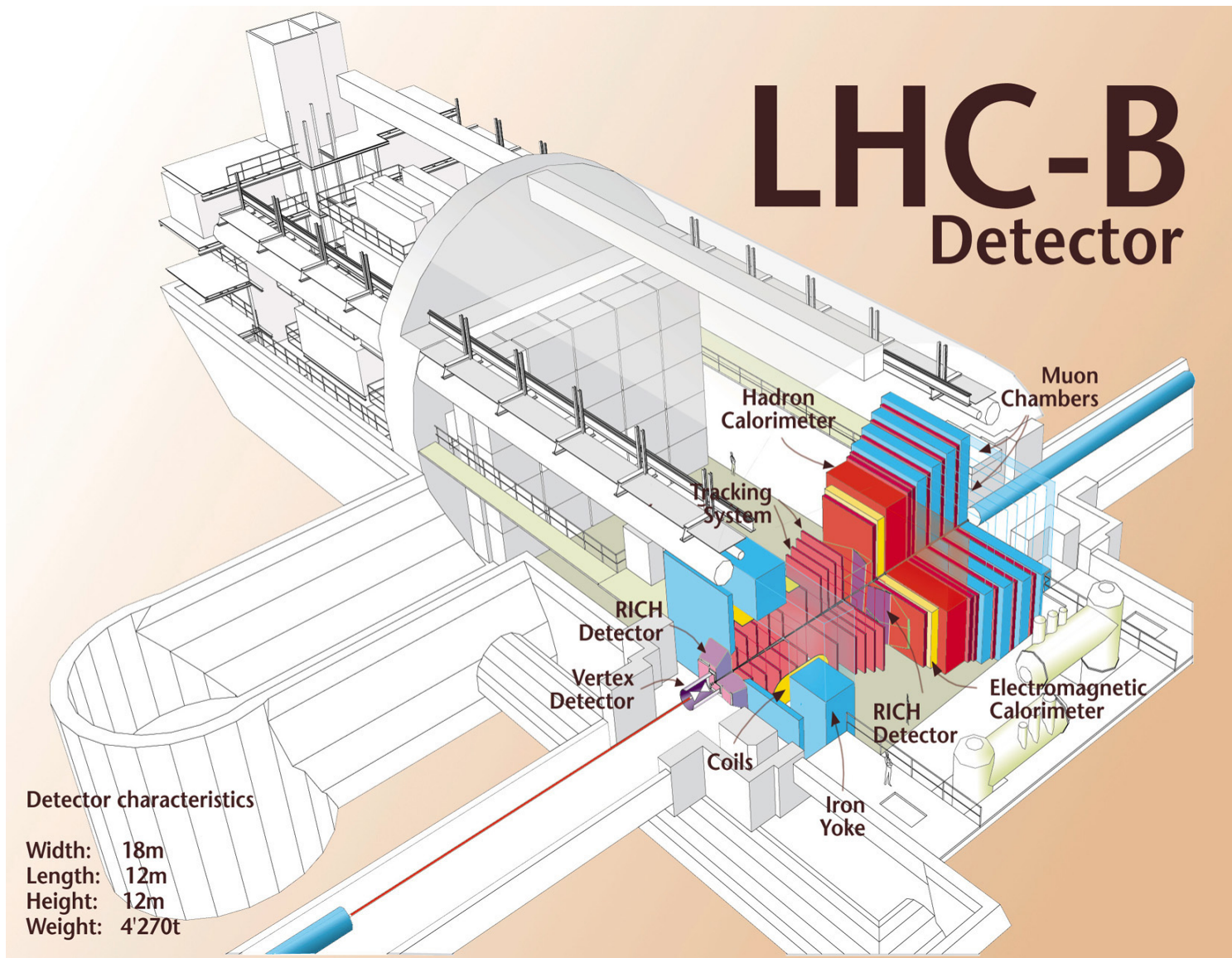


Figure 87: LHCb, the B-physics experiment at CERN

## Flavor oscillation

Kaons created at  $t=0$  can be represented as:

$$K^0(0) = \frac{1}{\sqrt{2}} \{K_S^0(0) + K_L^0(0)\} \quad \bar{K}^0(0) = \frac{1}{\sqrt{2}} \{K_S^0(0) - K_L^0(0)\} \quad (98)$$

With time, the “mixture” changes as:

$$K^0(t) = \frac{1}{\sqrt{2}} \left( e^{-iE_S t} e^{-\Gamma_S t/2} K_S^0(0) + e^{-iE_L t} e^{-\Gamma_L t/2} K_L^0(0) \right) \quad (99)$$

$$\bar{K}^0(t) = \frac{1}{\sqrt{2}} \left( e^{-iE_S t} e^{-\Gamma_S t/2} K_S^0(0) - e^{-iE_L t} e^{-\Gamma_L t/2} K_L^0(0) \right) \quad (100)$$

- ☉ If the time is measured in the restframe of the kaons, then  $E_S = m_S$  and  $E_L = m_L$  are the masses of the  $K_S$  and  $K_L$  and  $\Gamma_S$  and  $\Gamma_L$  are the decay rates with  $\Gamma = 1/\tau$  as usual

This gives:

$$K^0(t) = A(t)K^0(0) + B(t)\bar{K}^0(0) \quad (101)$$

# ❖ Strangeness oscillation: a $K^0$ beam partly turns into a $\bar{K}^0$ beam

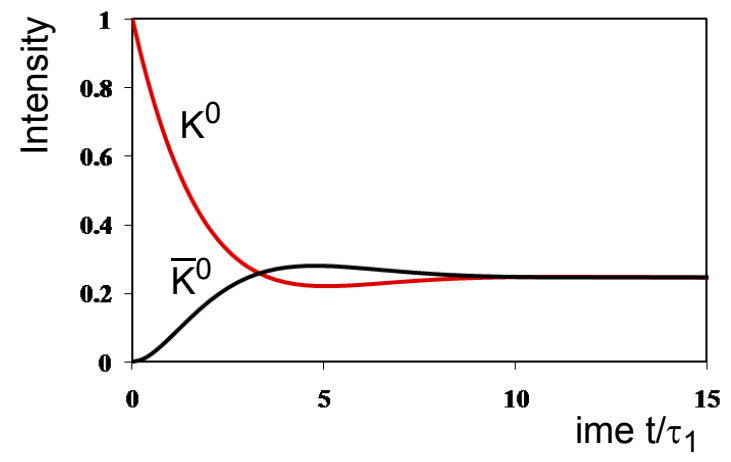


Figure 88: Strangeness oscillation in neutral kaons

Even faster oscillations are observed in B mesons ( $\sim 3 \cdot 10^{12}$  Hz); LHCb provides most precise measurement so far.

Oscillations in D mesons are also observed, though 37 times slower than in B.

