Violation of Particle Anti-particle Symmetry

CERN Summer Student Lectures

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Geneva Festival ▶

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6) Kaon interferometer

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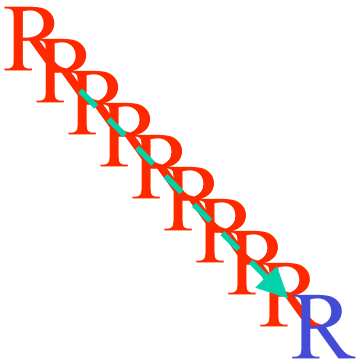
22:00, Saturday 7 August Great Musical Fireworks Display

1) Transformation, symmetries, invariance

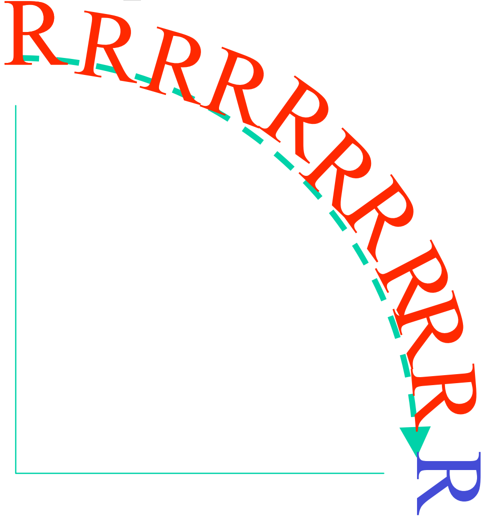
Important concept in physics…

Space translation



continuous

Space rotation



continuous

If system remains invariant ⇒ conservation of

momentum angular momentum

Another classical examples…

time translation → energy conservation

rotation in space-time → Lorenz transformation

There are transformations in “internal” space…

U(1) gauge transformation → electromagnetism

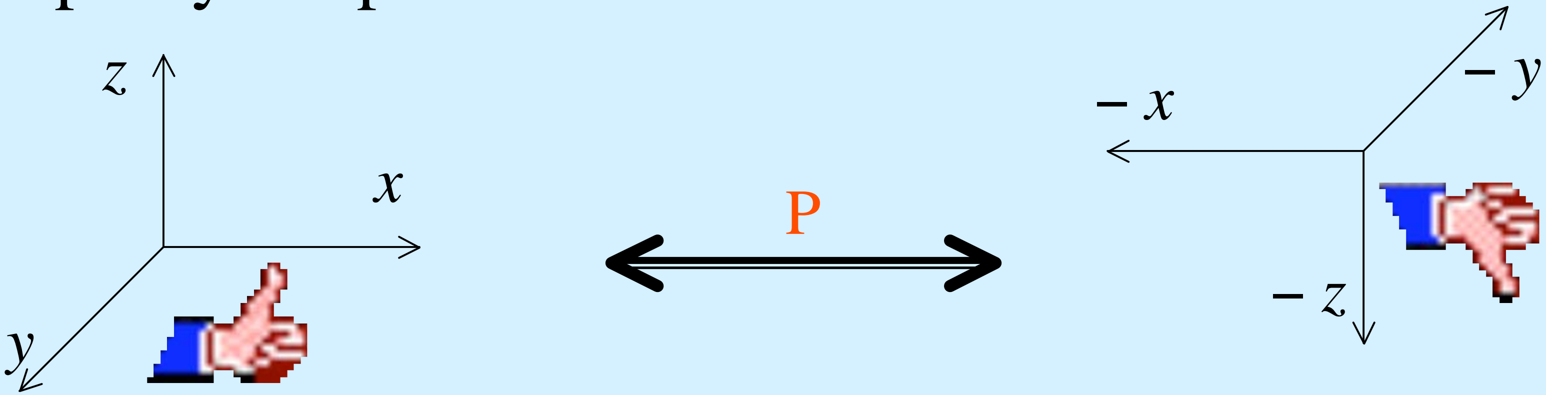
SU(2) gauge transformation → weak interactions

SU(3) gauge transformation → strong interactions

They are all continuous transformation!

2) P, T and C transformation

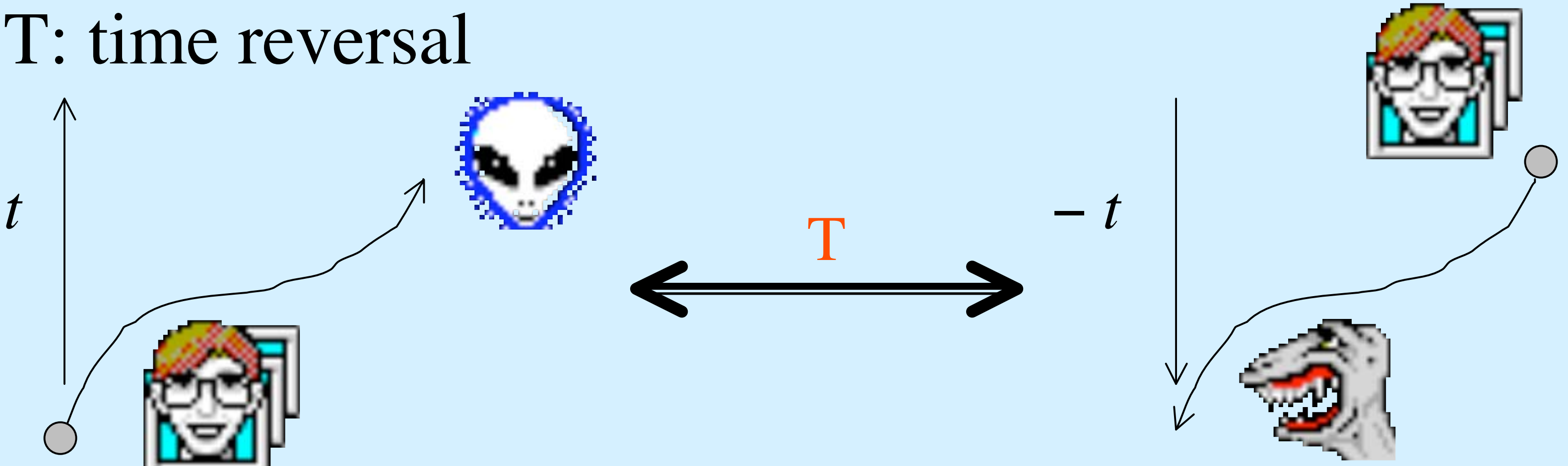
P: parity or space reflection



left handed system

right handed system

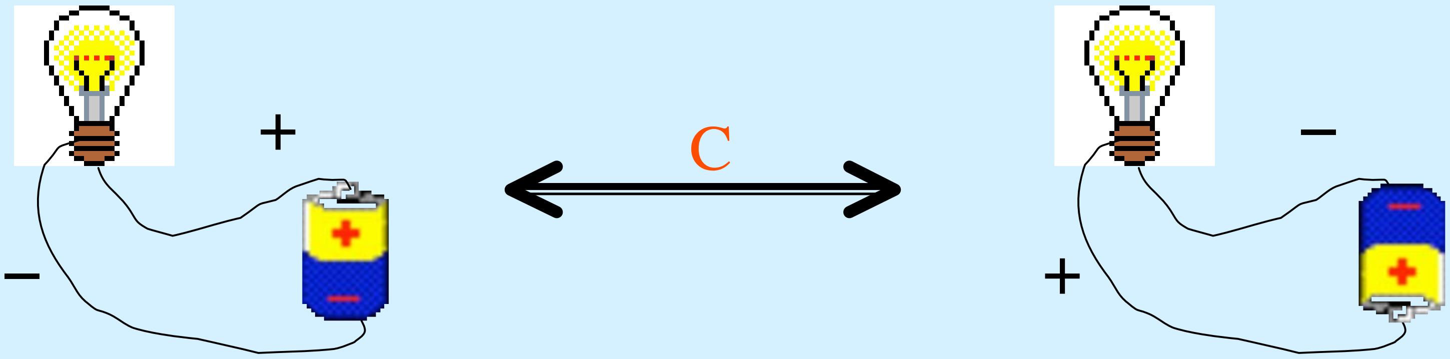
T: time reversal



forward moving

backward moving

C: charge conjugation



In particle physics reversing internal quantum numbers

charged states

e^- (electron) ⇔ e^+ (positron)

p (proton) ⇔ $\bar{p}$ (anti proton)

π^+ (positive pion) ⇔ π^- (negative pion)

u (u quark) ⇔ $\bar{u}$ (anti u quark)

neutral states

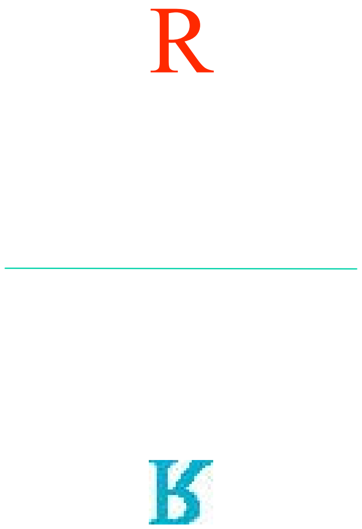
n (neutron) ⇔ $\bar{n}$ (anti neutron)

K^0 (k-zero meson) ⇔ $\bar{K}^0$ (anti k-zero meson)

π^0 (neutral pion) ⇔ π^0 (neutral pion)

C, P and T are discrete transformations

Reflection
(parity)



discrete

3) Conservation of symmetries

If no difference seen between

"this world" and "space reflected world"

⇒ We say:

•parity is conserved,

•P symmetry is conserved,

•world is invariant under P transformation

•etc.

example ▶

More "professional" description,

$\hat{H}$ Hamiltonian operator describing a system

$\hat{P}$ Parity transformation operator

$\hat{P}^{\dagger}\hat{H}\hat{P} = \hat{H}^{\mathrm{P}}$ parity transformation of Hamiltonian

If $\hat{H}^{\mathrm{P}} \neq \hat{H}$

Parity violation, Parity non-conservation etc. etc.

C and CP 🟩

Violation of Parity

World

90%

10%

Mirror World

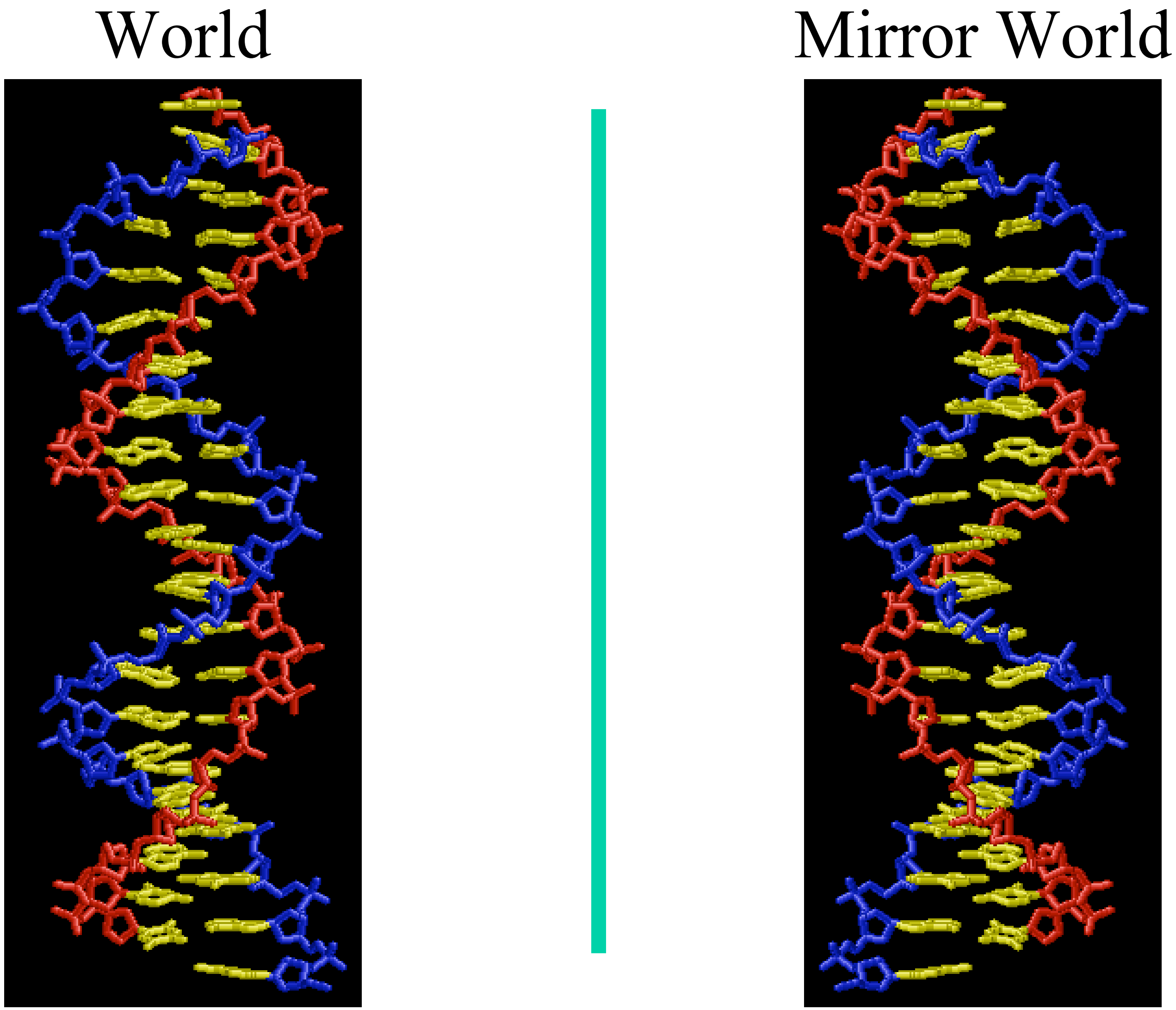
10%

90%

World ≠ Mirror World

(parity violation)

DNA

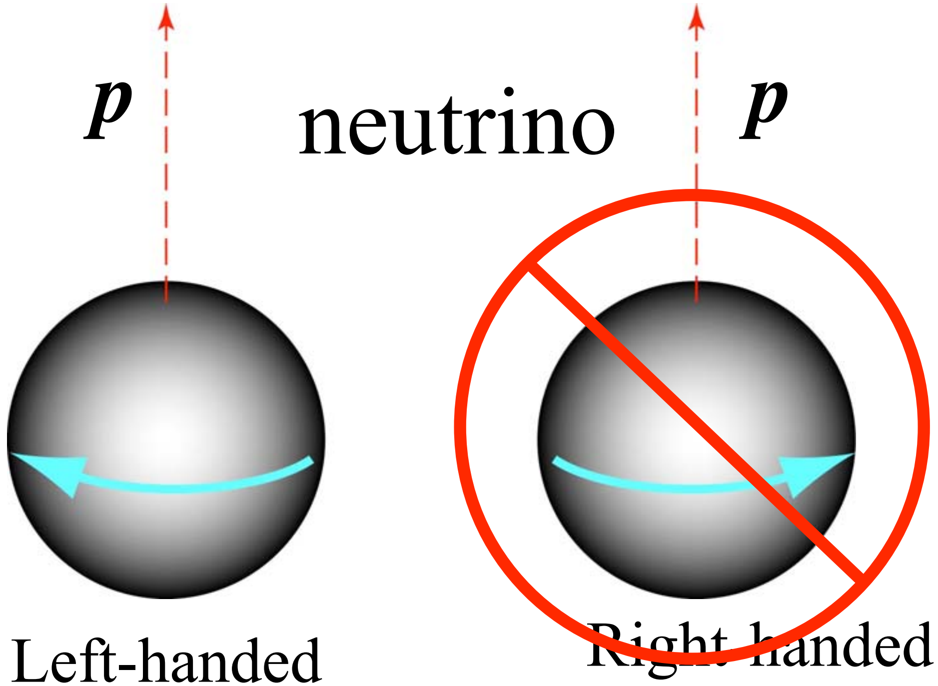


World

Mirror World

World ≠ Mirror World by 100%
Parity is fully violated.

And in elementary particle world



neutrino

Left-handed

Right-handed

does not exist

theory of
parity
violation

1956, T.D. Lee and C.N.Yang

experiment of
parity
violation

1957, C.S.Wu

back to list
🟩

A similar terminology applies to C and T.

Strong and electromagnetic interactions conserve:
flavour quantum numbers,
C, P, T, CP, CT, PT and CPT

Particle physics example: pion decay via electromatnetic int.

$\pi^0 \rightarrow \gamma\gamma$ but not $\gamma\gamma\gamma$

$$\pi^0 = (u\bar{u}+d\bar{d})_{L=0,\ S=0} \longrightarrow C(\pi^0) = +1$$

$$\vec{B},\ \vec{E} \xrightarrow{C} -\vec{B},\ -\vec{E} \longrightarrow C(\gamma)=-1$$

initial state $C(\pi^0) = +1$,

final state $C(\gamma\gamma) = (-1)^2 = +1$, $C(\gamma\gamma\gamma) = (-1)^3 = -1$

Conservation of C in π^0 decays

Or... calculating decay amplitudes

$$A_{\gamma\gamma\gamma} = <\gamma\gamma\gamma|\underbrace{C^{-1}C}_{\mathbf{1}}\ H\ \underbrace{C^{-1}C}_{\mathbf{1}}|\pi^0> = -<\gamma\gamma\gamma|C\ H\ C^{-1}|\pi^0>$$

$$= -<\gamma\gamma\gamma|\ H\ |\pi^0> = -A_{\gamma\gamma\gamma}$$

$$\mathrm{A}_{\gamma\gamma\gamma} = 0$$

weak interactions interact with neutrinos…

$$\left.\begin{array}{l}\text{Neutrio is only left-handed}\\ \text{Antineutriono is only right-handed}\end{array}\right\}\rightarrow \text{C nor P conserved}$$

pion decays via weak interaction

$$\begin{tikzcd}
\pi^+ \to \mu^+_R + \nu_L \arrow[r, "P"] \arrow[d, "C"] \arrow[dr, "CP"] & \pi^+ \to \mu^+_L + \cancel{\nu}_R \\
\pi^- \to \mu^-_R + \cancel{\overline{\nu}}_L & \pi^- \to \mu^-_L + \overline{\nu}_R
\end{tikzcd}$$

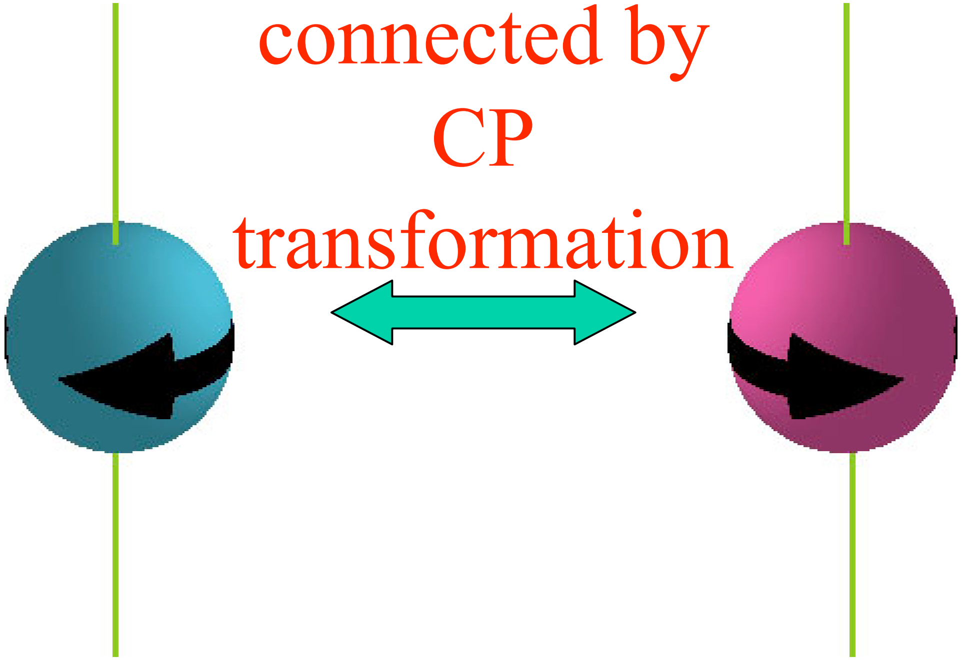
ν_R or $\overline{\nu}_L$ do not exist

P or C transformed decay processes do not exist:
→ P and C violation. (**if you can see handedness**)

CP

It looks like there is no CP violation.

K decay



particle world

antiparticle world

neutrino

antineutrino

connected by
CP
transformation

Left-handed

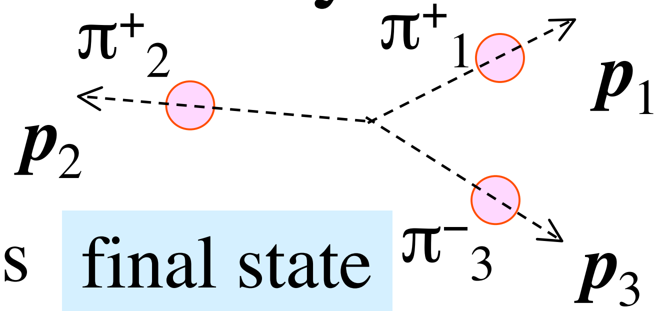
Right-handed

pi decay 🟩

4) CP violation in the charged kaon system

initial state
K^+

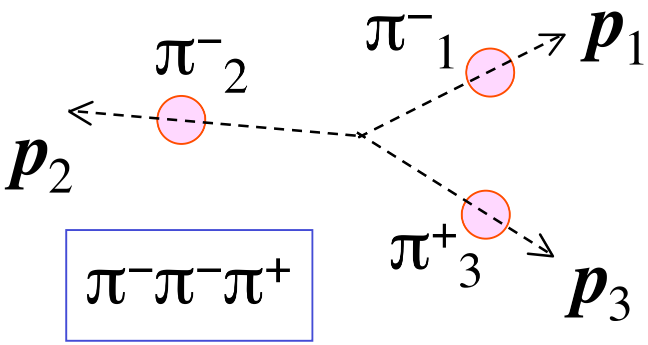
decay process
via weak interactions



final state
$\pi^+\pi^+\pi^-$

C transformation

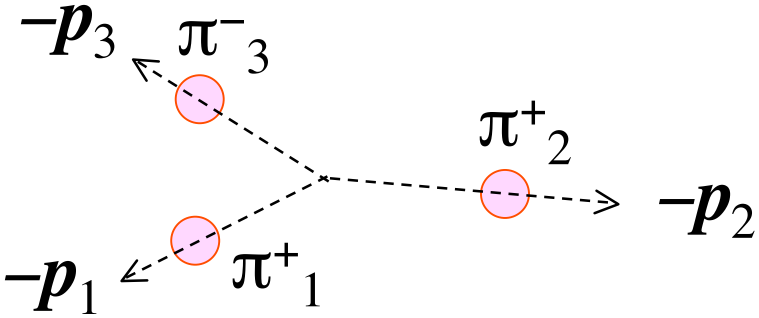
K^-



$\pi^-\pi^-\pi^+$

P transformation

K^+



$\pi^-\pi^-\pi^+$

Partial decay width for $K^+ \rightarrow \pi^+\pi^+\pi^-$

$$\Gamma_{K^+\rightarrow\pi^+\pi^+\pi^-} = \int d^3p_1 \int d^3p_2 \int d^3p_3 \Gamma_{\pi_1^+,\pi_2^+,\pi_3^-}(\vec{p}_1, \vec{p}_2, \vec{p}_3)$$

◁

C transformed partial decay width

$$\Gamma^C_{K^+\rightarrow\pi^+\pi^+\pi^-} = \int d^3p_1 \int d^3p_2 \int d^3p_3 \Gamma_{\pi_1^-,\pi_2^-,\pi_3^+}(\vec{p}_1, \vec{p}_2, \vec{p}_3)$$

$$\equiv \Gamma_{K^-\rightarrow\pi^-\pi^-\pi^+}$$

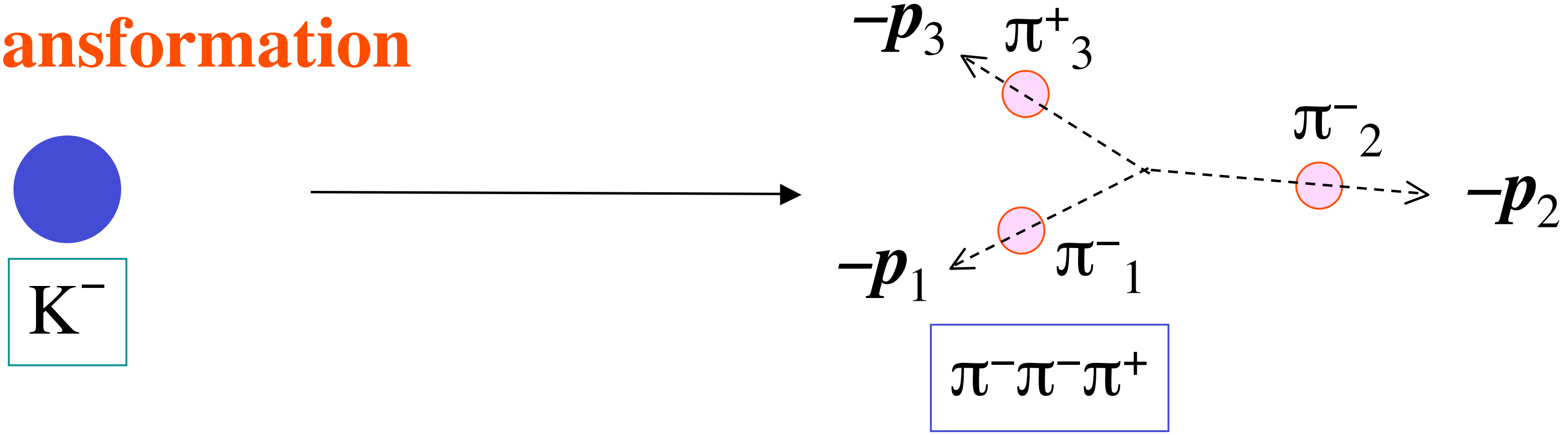
P transformed partial decay width

$$\Gamma^P_{K^+\rightarrow\pi^+\pi^+\pi^-} = -\int d^3p_1 \int d^3p_2 \int d^3p_3 \Gamma_{\pi_1^+,\pi_2^+,\pi_3^-}(-\vec{p}_1, -\vec{p}_2, -\vec{p}_3)$$

$$= \Gamma_{K^+\rightarrow\pi^+\pi^+\pi^-}$$

P does not affect phase space integrated decay width.

CP transformation



CP transformed partial decay width

$$\begin{aligned}\Gamma^{CP}_{K^+\to\pi^+\pi^+\pi^-} &= -\int d^3p_1\int d^3p_2\int d^3p_3\,\Gamma_{\pi_1^-,\pi_2^-,\pi_3^+}(-\vec{p}_1,-\vec{p}_2,-\vec{p}_3)\\ &= \int d^3p_1\int d^3p_2\int d^3p_3\,\Gamma_{\pi_1^-,\pi_2^-,\pi_3^+}(\vec{p}_1,\vec{p}_2,\vec{p}_3)\\ &= \Gamma_{K^-\to\pi^-\pi^-\pi^+}\end{aligned}$$

Partial decay width: $\Gamma_{K^+ \to \pi^+\pi^+\pi^-}$ and $\Gamma_{K^- \to \pi^-\pi^-\pi^+}$
are CP and C transformed to each other

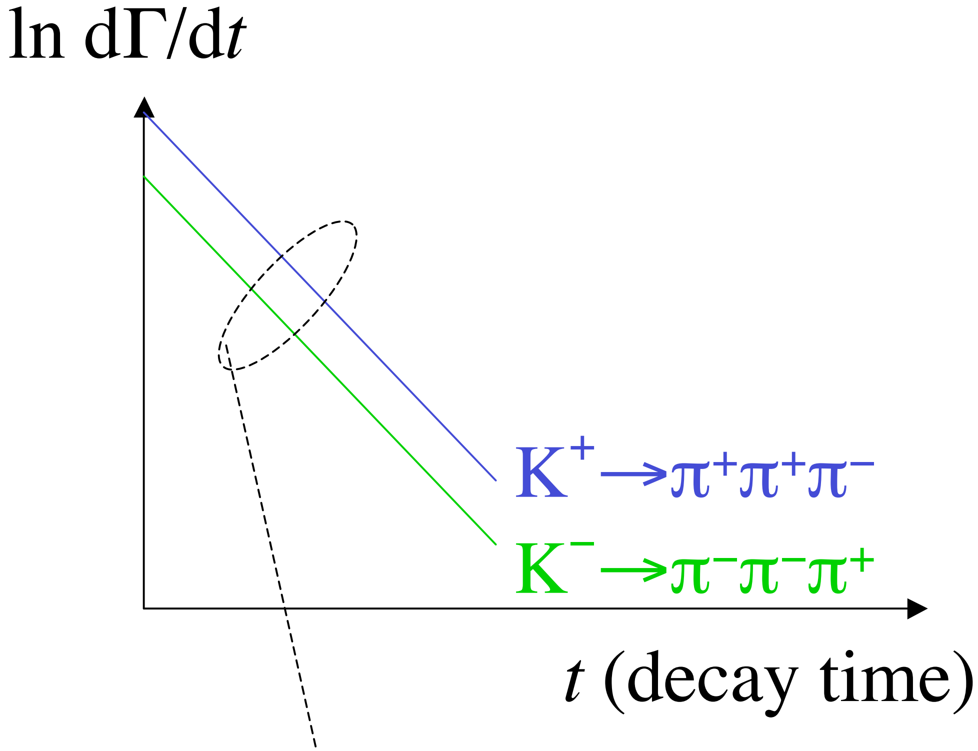
If $\Gamma_{K^+ \to \pi^+\pi^+\pi^-} \neq \Gamma_{K^- \to \pi^-\pi^-\pi^+} \to \cancel{CP}$ and $\cancel{C}$!

NB: these differences can appear in Γ or $d\Gamma/dt$

In general,
$\cancel{C}$ and $\cancel{CP}$ are needed in order to generate partial decay widths differences between particles and anti particles.

Total widths between K^+ and K^- must be identical
CPT

If there were $\cancel{CP}$ and $\cancel{C}$, we would observe



Not seen yet!

Exponential decays

(K± have definite masses and decay widths)

Slopes are given by the total decay widths:

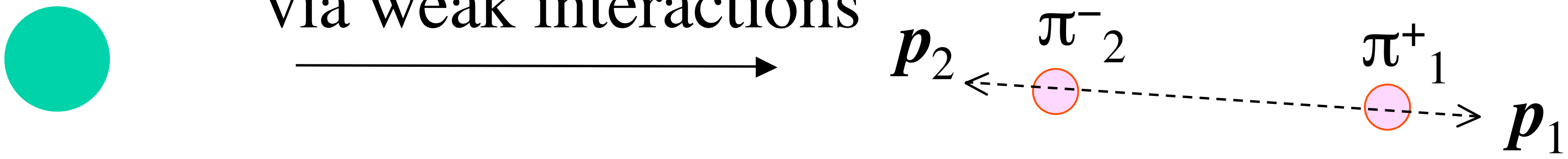
CPT theorem guarantees that they are identical.

5) CP violation in the neutral kaon system

initial state
K^0

decay process
via weak interactions

final state
$\pi^+\pi^-$



$\Gamma_{K^0\to\pi^+\pi^-}$ and $d\Gamma_{K^0\to\pi^+\pi^-}/dt$

$\Big\Updownarrow$ CP and C transformed

initial $\overline{K}^0$ decaying into $\pi^+\pi^-$

$\Gamma_{\overline{K}^0\to\pi^+\pi^-}$ and $d\Gamma_{\overline{K}^0\to\pi^+\pi^-}/dt$

How do we produce K^0 and $\overline{K}^0$?

Strong and electromagnetic interactions conserve strangeness:

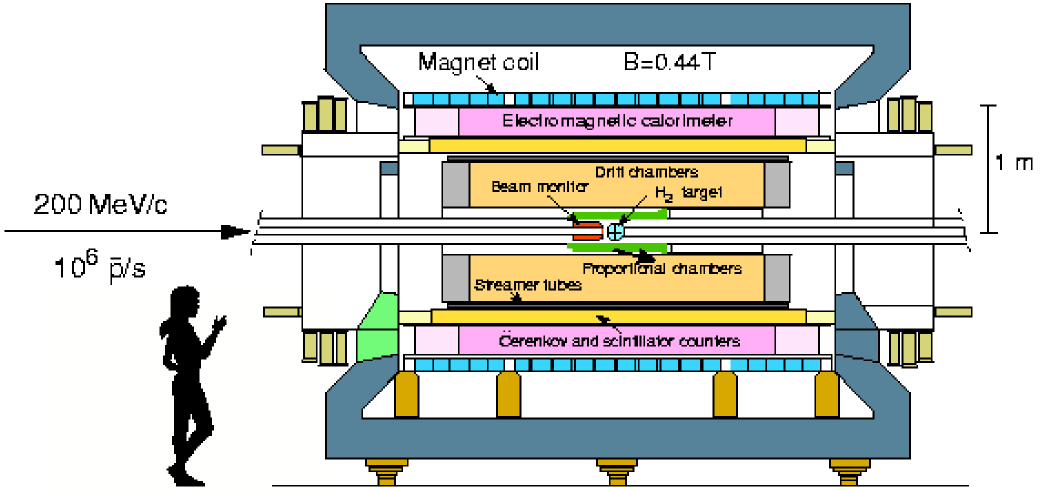
$$K^+n\ (s = +1) \rightarrow pK^0\ (s = +1),\ K^-p\ (s = -1) \rightarrow n\overline{K}^0\ (s = -1)$$

$$p\overline{p}\ (s = 0) \rightarrow K^-K^0\pi^+,\ K^+\overline{K}^0\pi^-\ (s = 0)$$

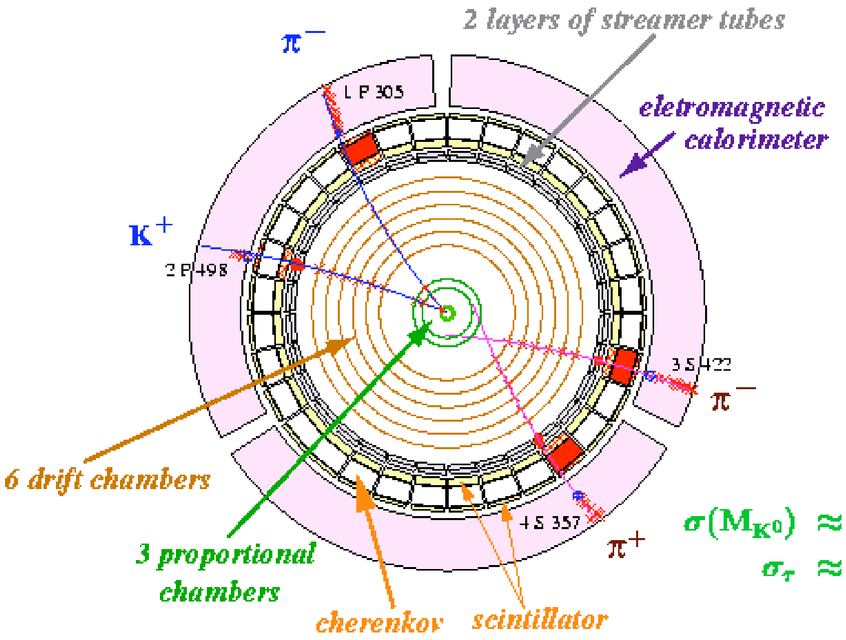
$$\phi\ (s = 0) \rightarrow K^0\overline{K}^0\ (s = 0)$$

(Neutral kaons are generally produced as “flavour eigenstate”.)

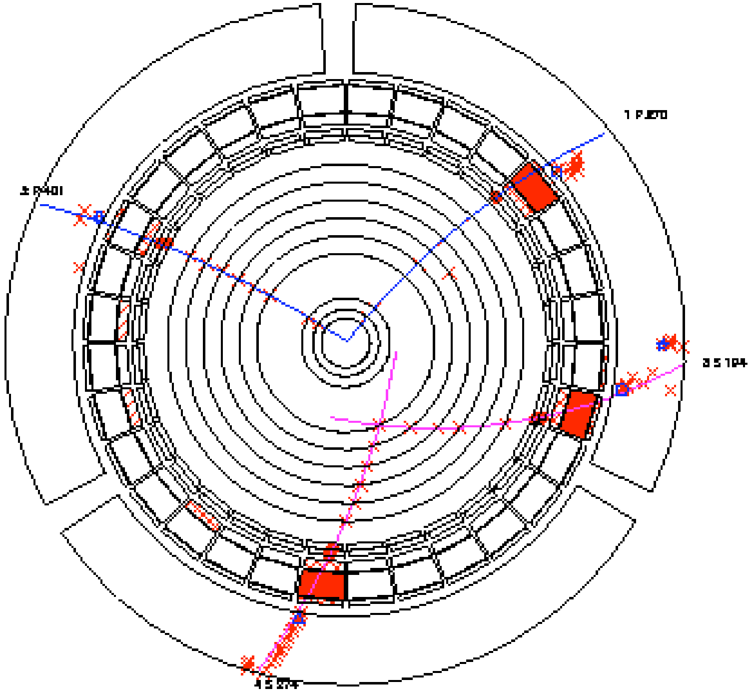
The CPLEAR Detector



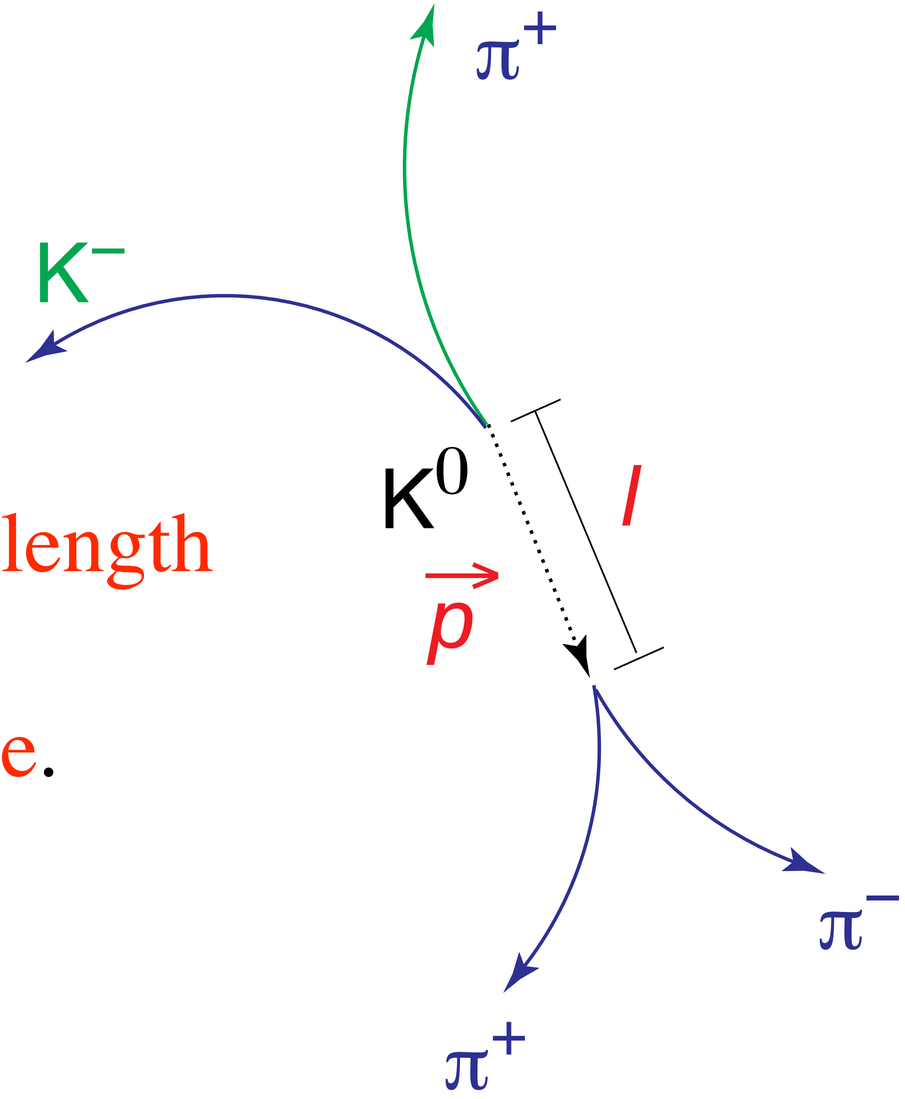
$$p\bar{p} \rightarrow K^-K^0\pi^+,\ K^+\bar{K}^0\pi^-$$



$$\sigma(M_{K^0}) \approx 13\ \mathrm{MeV}/c^2$$
$$\sigma_\tau \approx (5-10)\ \mathrm{ps}$$



By measuring the decay length and momentum, determine the decay time.



K^0 flight time = $f(\, l, \vec{p}\,)$

$$d\Gamma_{K^0\to\pi^+\pi^-}/dt \neq d\Gamma_{\overline{K}^0\to\pi^+\pi^-}/dt$$

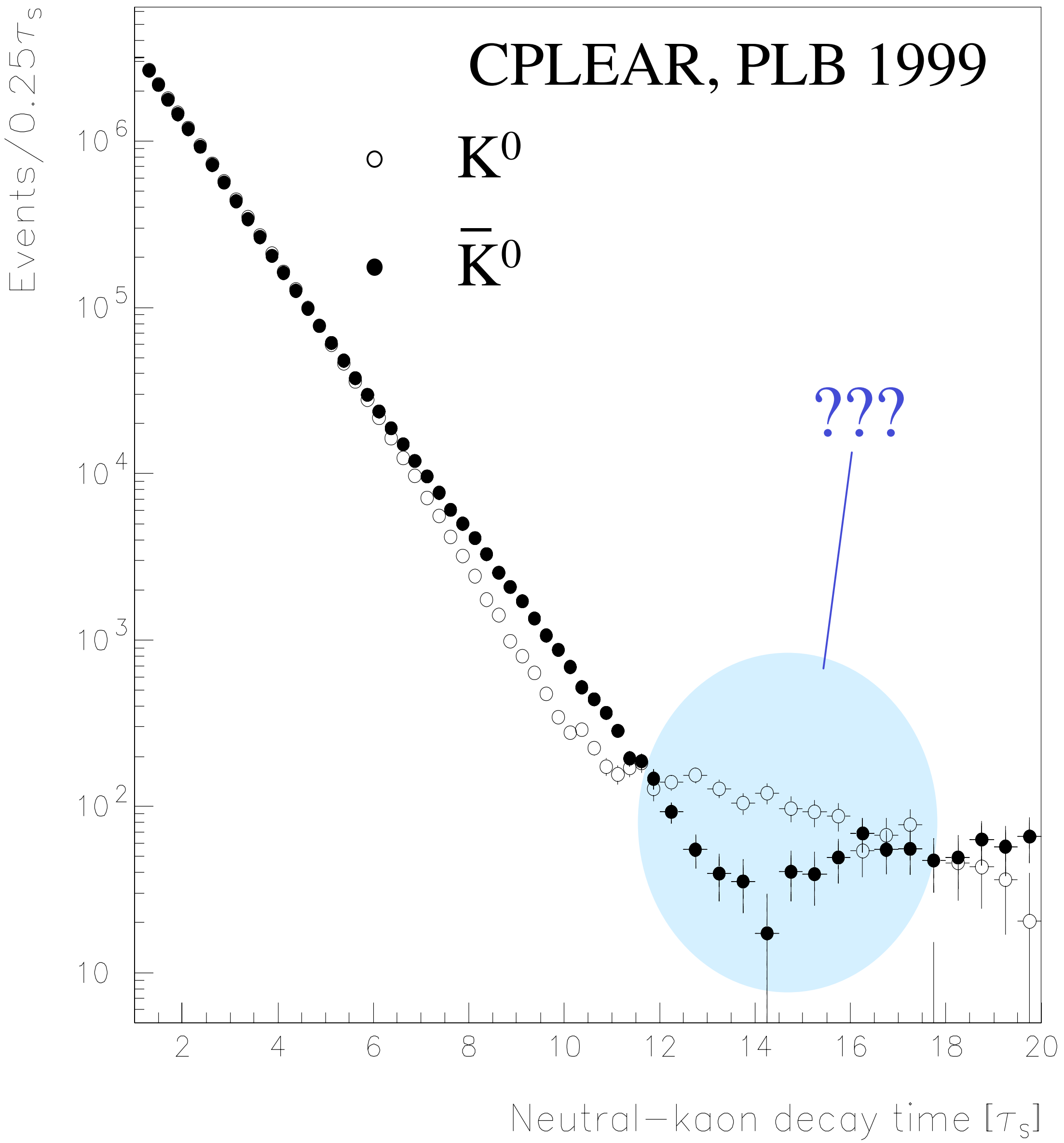
~~C~~ and ~~CP~~ !!!

Also...

non exponential

decays!!!

Why????



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