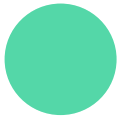
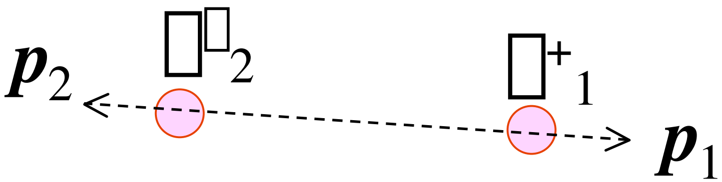
5) CP violation in the neutral kaon system

initial state
K^0



decay process
via weak interactions →

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



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

↕ 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:

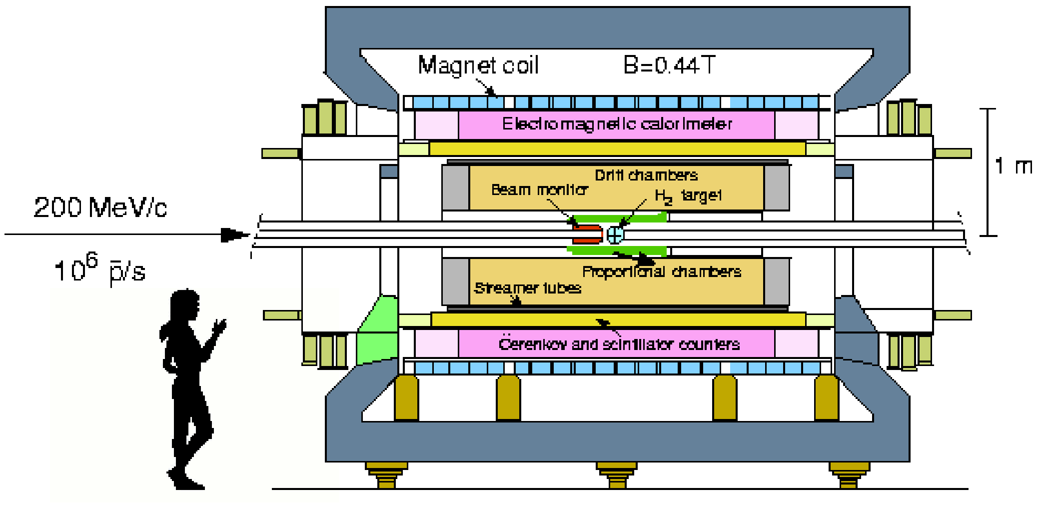
$$K^+ n \ (s = +1) \rightarrow pK^0 \ (s = +1), \quad K^- p \ (s = -1) \rightarrow n\overline{K}^0 \ (s = -1)$$

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

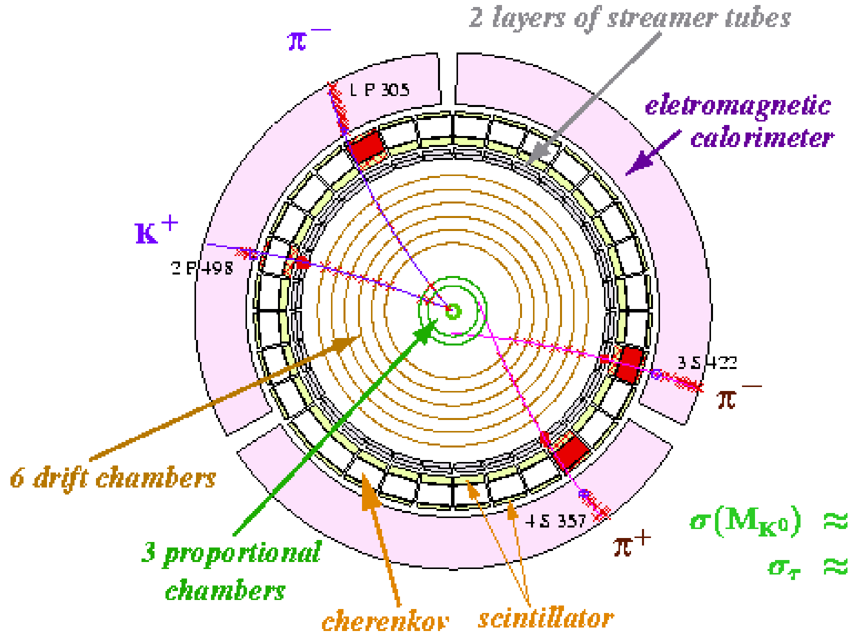
$$\phi \ (s = 0) \rightarrow K^0 \overline{K}^0 \ (s = 0)$$

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

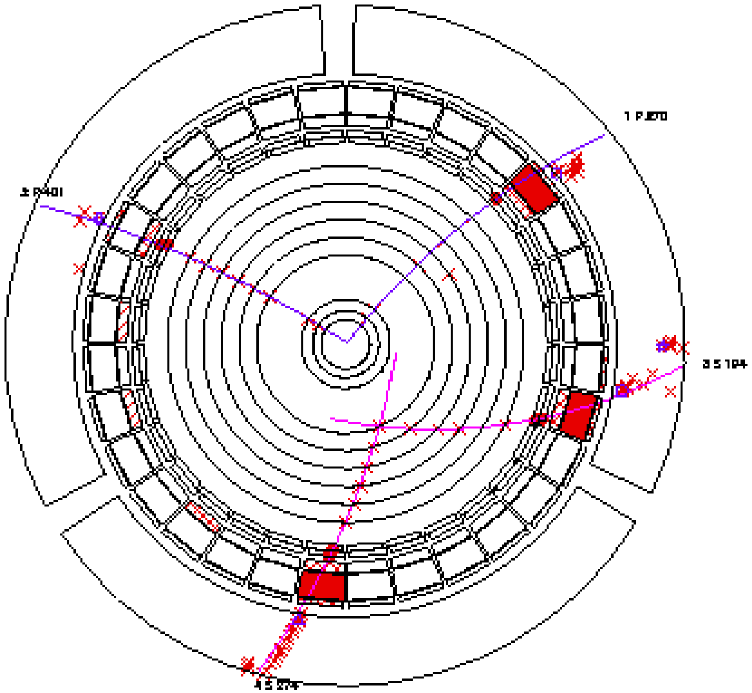
The CPLEAR Detector



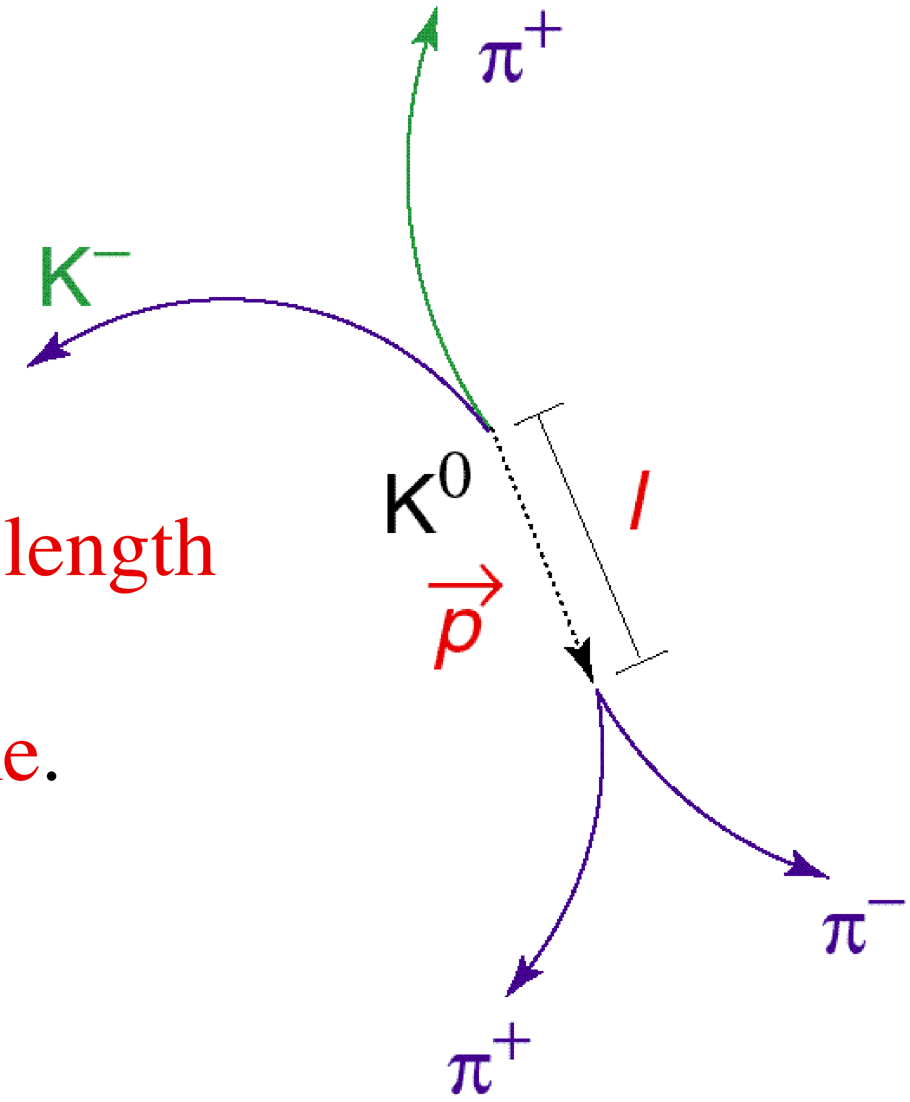
$$p\bar{p} \to K^-K^0\pi^+,\ K^+\bar{K}^0\pi^-$$



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



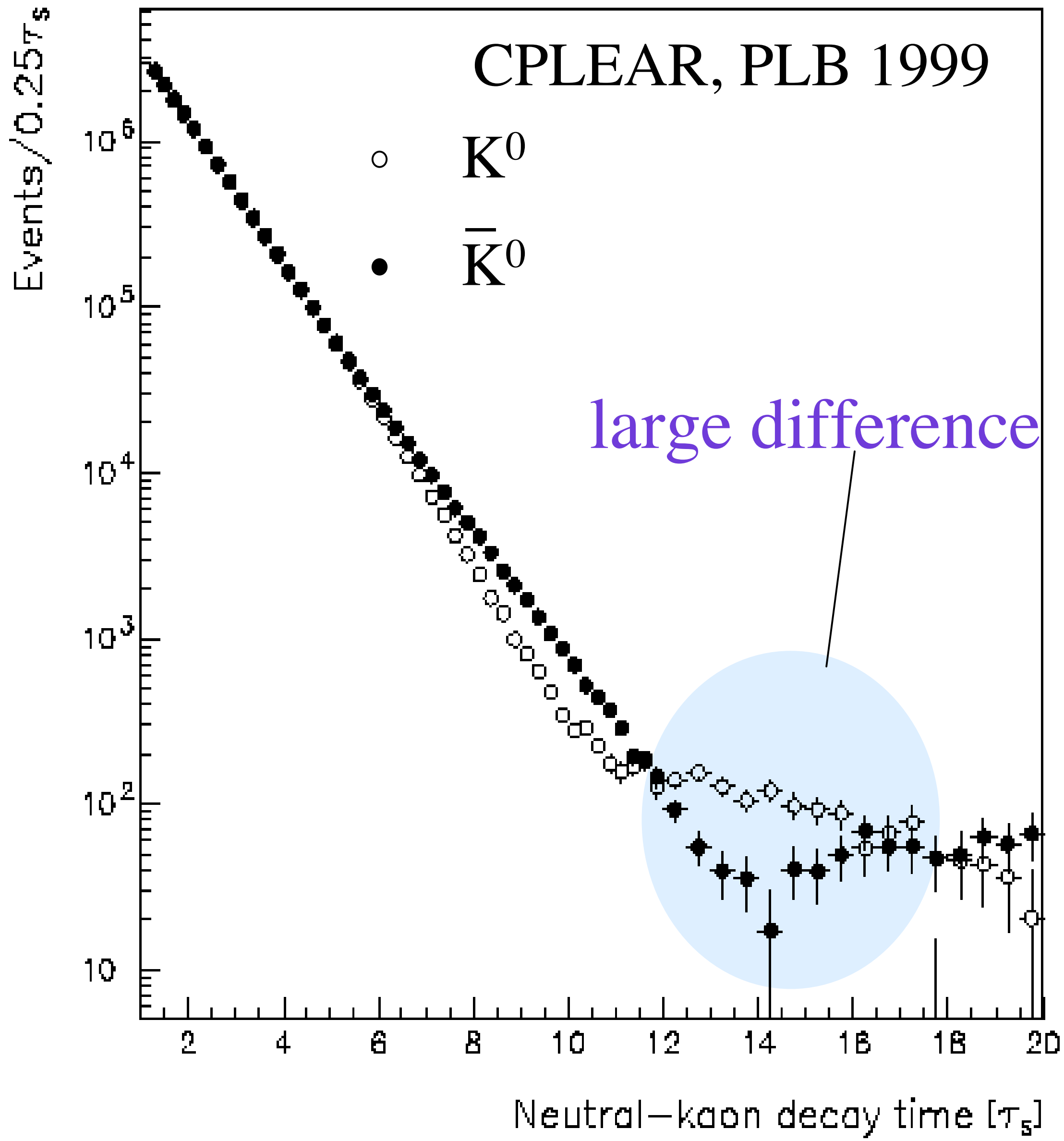
By measuring the decay length and momentum, determine the decay time.



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????

back

Weak interactions do not conserve strangeness: $K^0 \leftrightarrow \overline{K}^0$ through weak interactions.

-see demonstration with the coupled pendulum-
elastic (dispersive) and non-elastic (absorptive) coupling.

spring paddle

K^0 and $\overline{K}^0$ are not the eigen-modes.

-K^0 and $\overline{K}^0$ have neither definite mass nor decay width,
i.e. they oscillate to each other.

Two eigen-modes are the linear combinations of K^0 and $\overline{K}^0$.

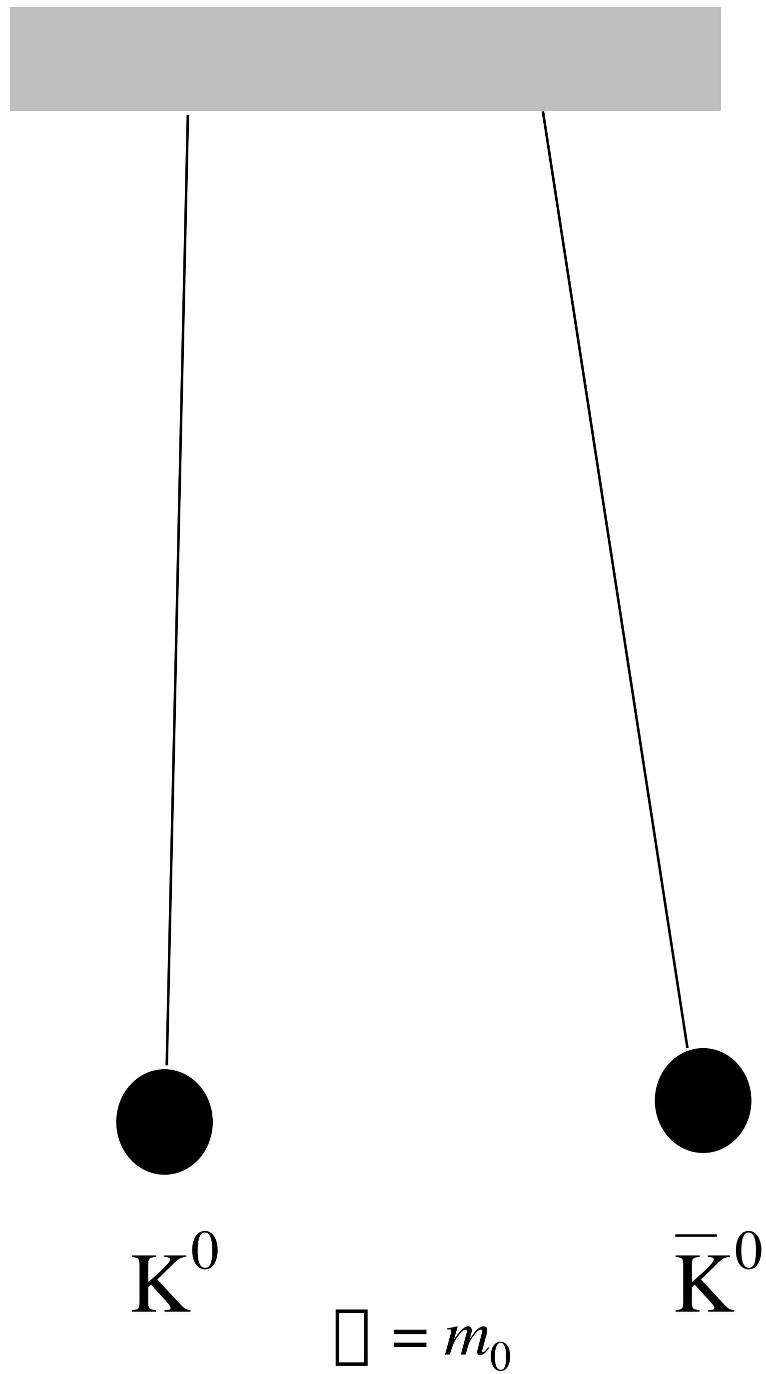
-K_L and K_S with definite masses and decay widths.

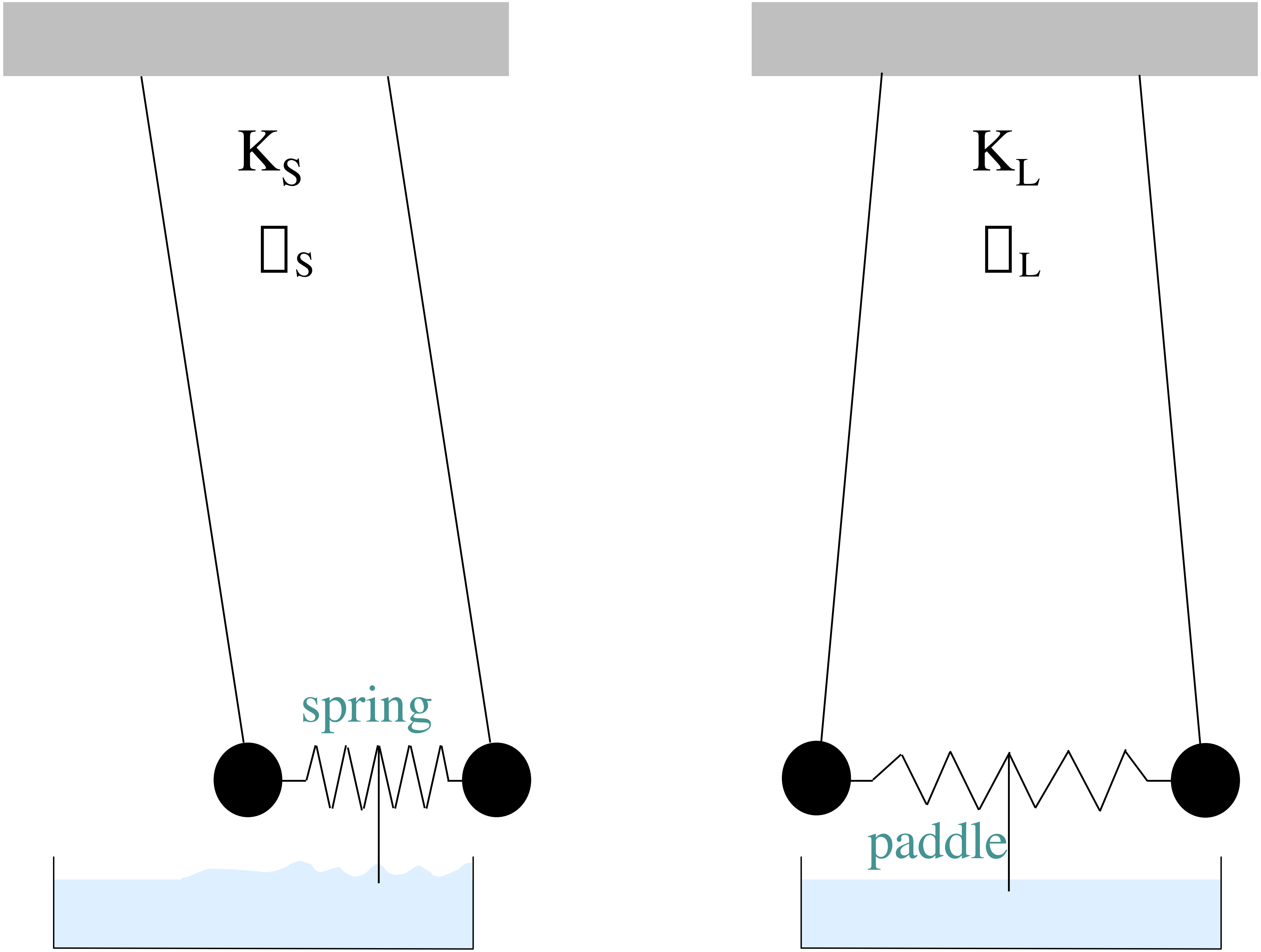
$m_L > m_S$, $\Gamma_S >> \Gamma_L$

K_S lifetime $= 1/\Gamma_S = 8.94 \times 10^{-11}$ s (2.7 cm @ p = 450 MeV/c)

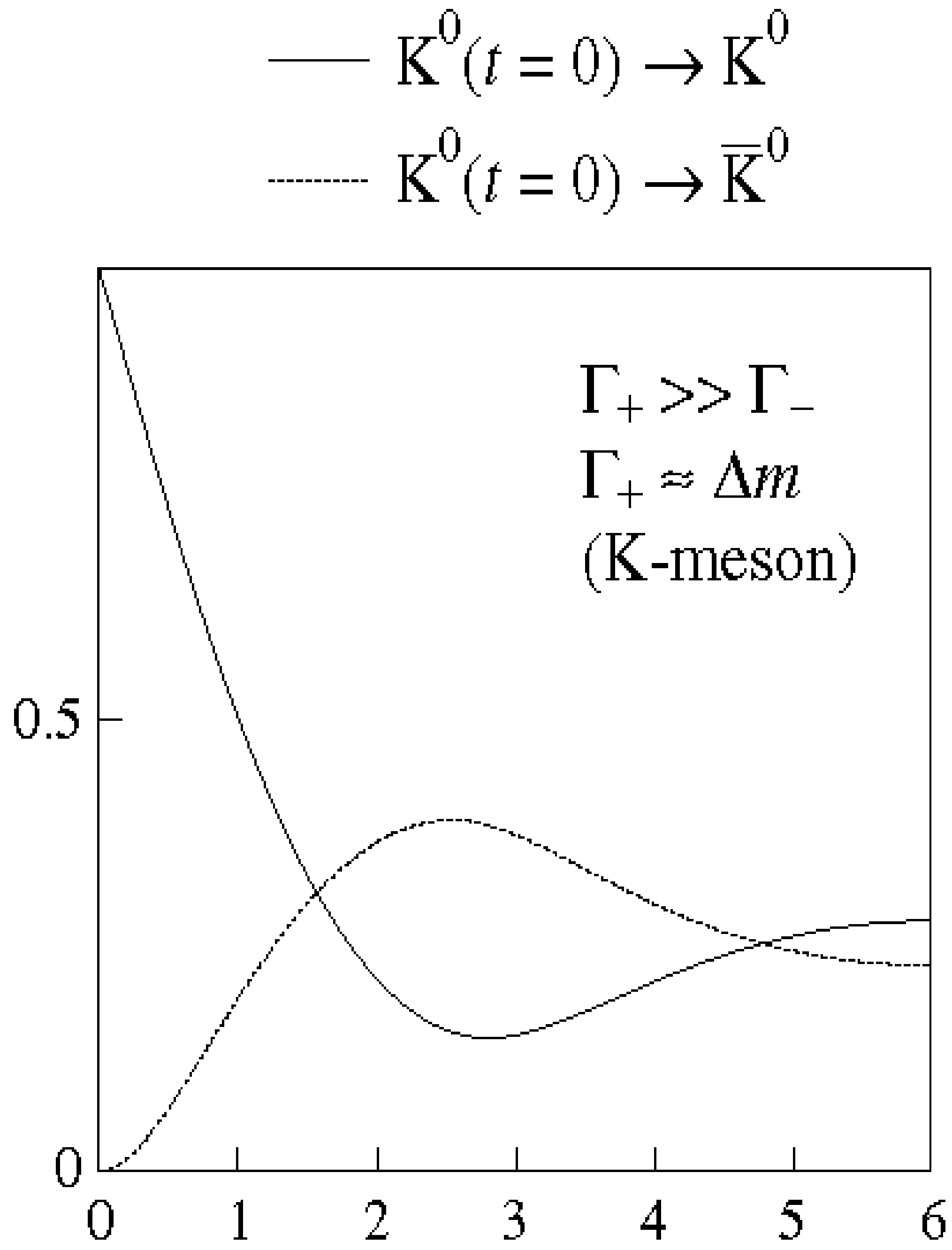
K_L lifetime $= 1/\Gamma_L = 5.17 \times 10^{-8}$ s (16 m @ p = 450 MeV/c)

K_L beam is "easy" to make: wait long enough!


K^0
$\bar{K}^0$
□ = m_0



K S
spring
K L
paddle



$K^0(t=0) \to K^0$
$K^0(t=0) \to \overline{K}^0$
$\Gamma_+ >> \Gamma_-$
$\Gamma_+ \approx \Delta m$
(K-meson)
0.5
0
0
1
2
3
4
5
6

•K^0 and $\bar{K}^0$: CP (and C) transformed states to each other

$\Rightarrow$ What are the CP (and C) transformed states of K_S and K_L?

If CP and C are conserved in weak interactions:

K_S and K_L are self-conjugate (like π^0)

$K_S \quad K^0 + \bar{K}^0, \; K_L \quad K^0 - \bar{K}^0$

with CP quantum numbers +1 and −1 respectively

$CP(K_S) = + K_S, \; CP(K_L) = - K_L$

$\Rightarrow$

$K_S(CP = +1) \rightarrow \pi^+\pi^-(CP = +1)$

but $K_L(CP = -1) \nrightarrow \pi^+\pi^-(CP = +1)$

$K_L \rightarrow \pi^+\pi^-$ decays were observed in 1964

-discovery of CP violation-

$K_L(CP = -1) \rightarrow \pi^+\pi^-\pi^0, \; \pi^0\pi^0\pi^0 \; (CP = -1)$

J.H. Christenson et al., PRL 1964
Discovery of CP violation

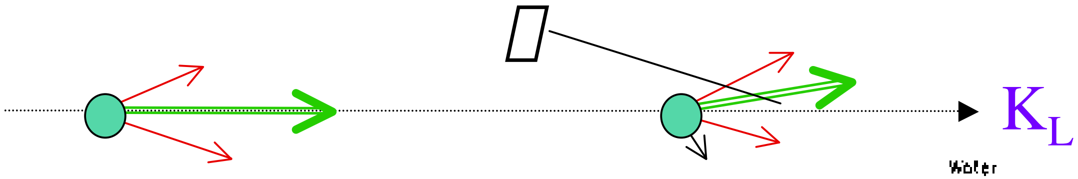
$K_L \to \pi^+\pi^- + X$

$p_{+-} = p_{\pi+} + p_{\pi-}$

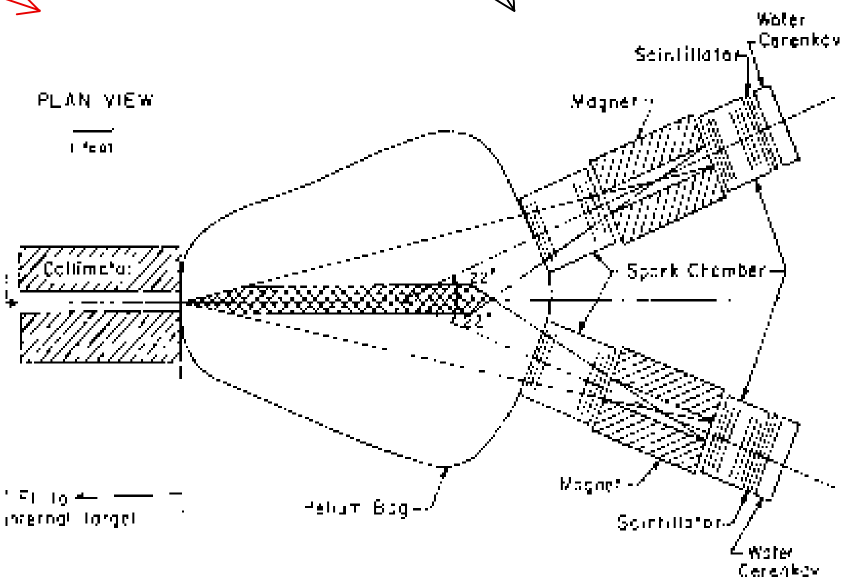
θ = angle between p_{KL} and p_{+-}

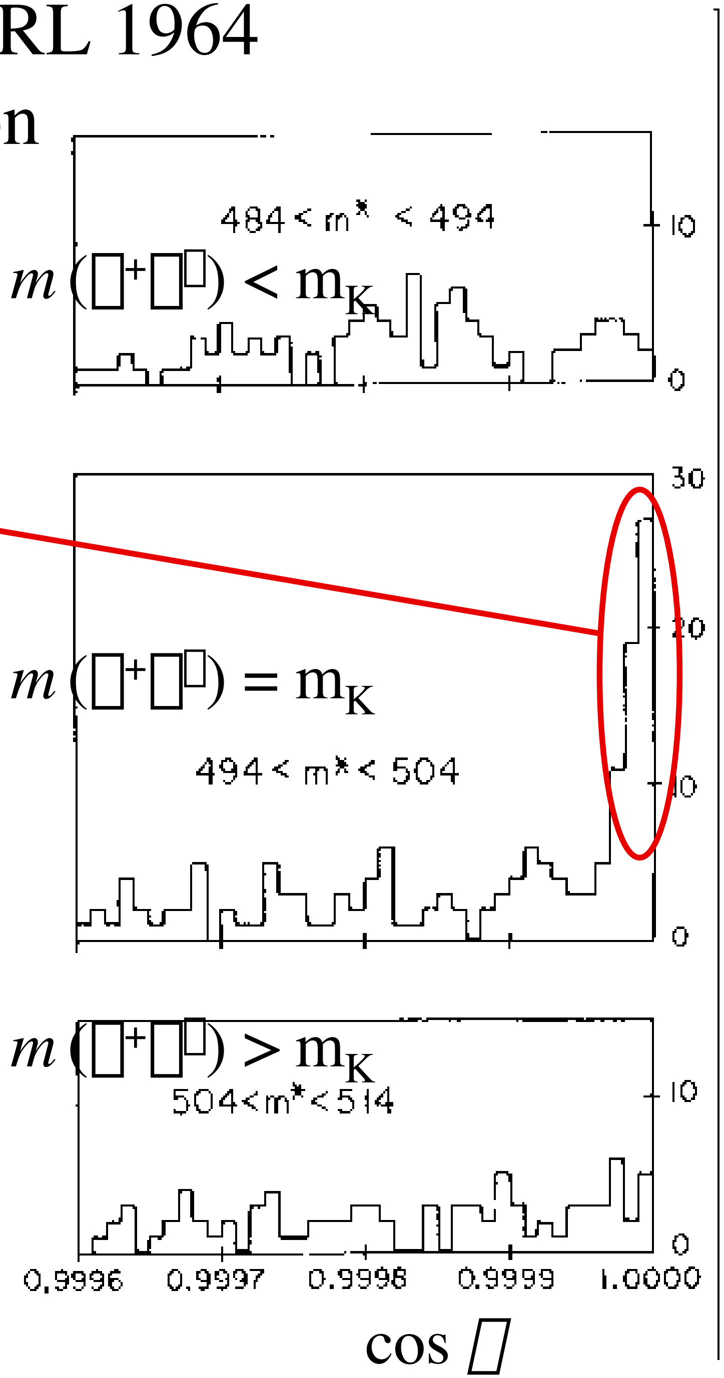
If $X = 0$, $p_{+-} = p_{KL}$: $\cos\theta = 1$

If $X \neq 0$, $p_{+-} \neq p_{KL}$: $\cos\theta < 1$

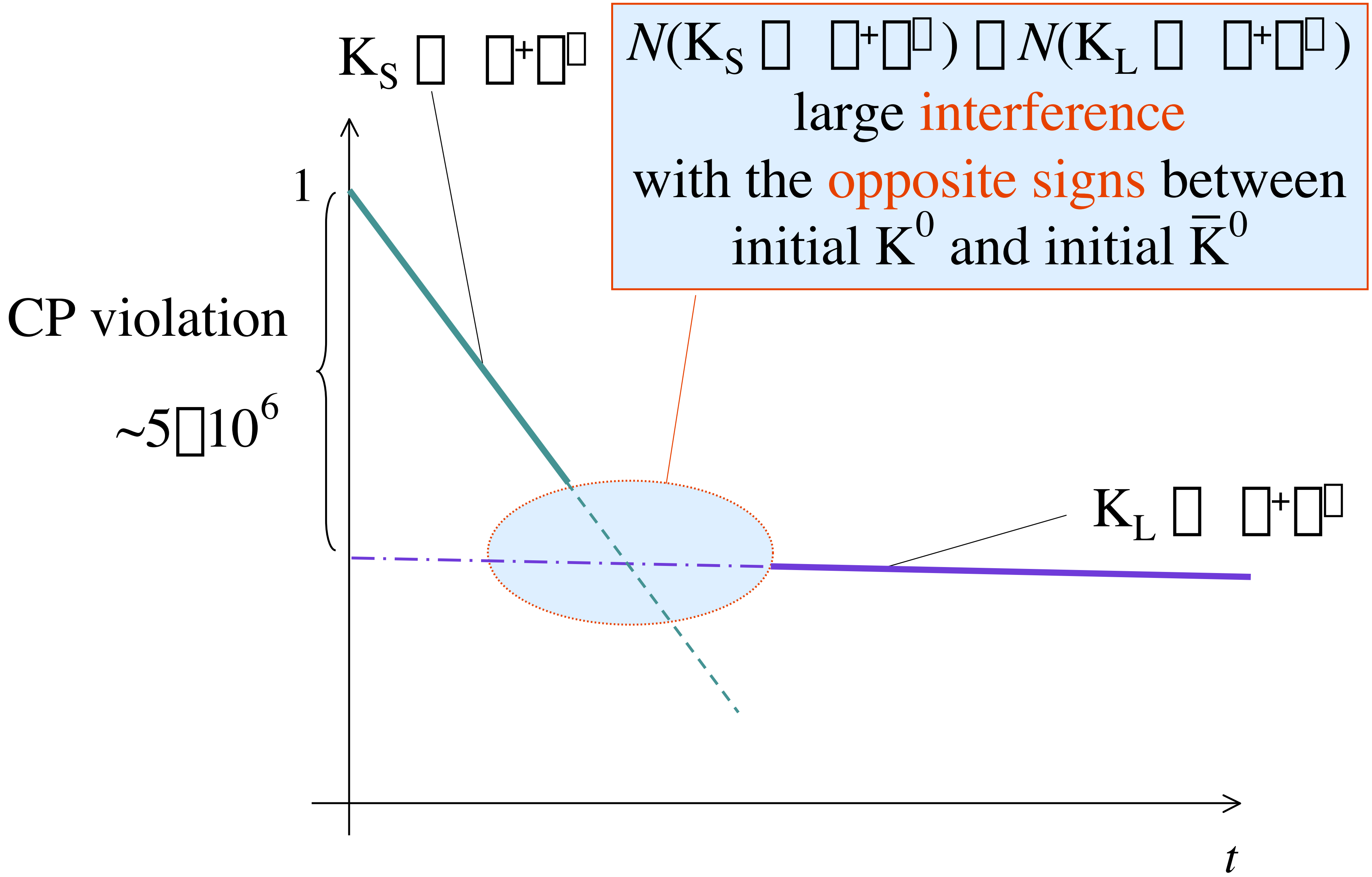


$K_L \to$





What you see in CPLEAR is



CP violation parameters often refereed:

$$\eta_{+-} = \frac{K_L \to \pi^+\pi^- \text{ decay amplitude}}{K_S \to \pi^+\pi^- \text{ decay amplitude}} \quad \not{CP}$$

$$= (2.284 \pm 0.018) \times 10^{-3} \times e^{i(43.3\pm0.5)^\circ}$$

<1% error

$$\eta_{00} = \frac{K_L \to \pi^0\pi^0 \text{ decay amplitude}}{K_S \to \pi^0\pi^0 \text{ decay amplitude}} \quad \not{CP}$$

$$= (2.23 \pm 0.11) \times 10^{-3} \times e^{i(43.2\pm1.0)^\circ}$$

direct measurements

$$\eta_{+-} \approx \eta_{00}$$

(but not quite...)

Two most recent experiments:

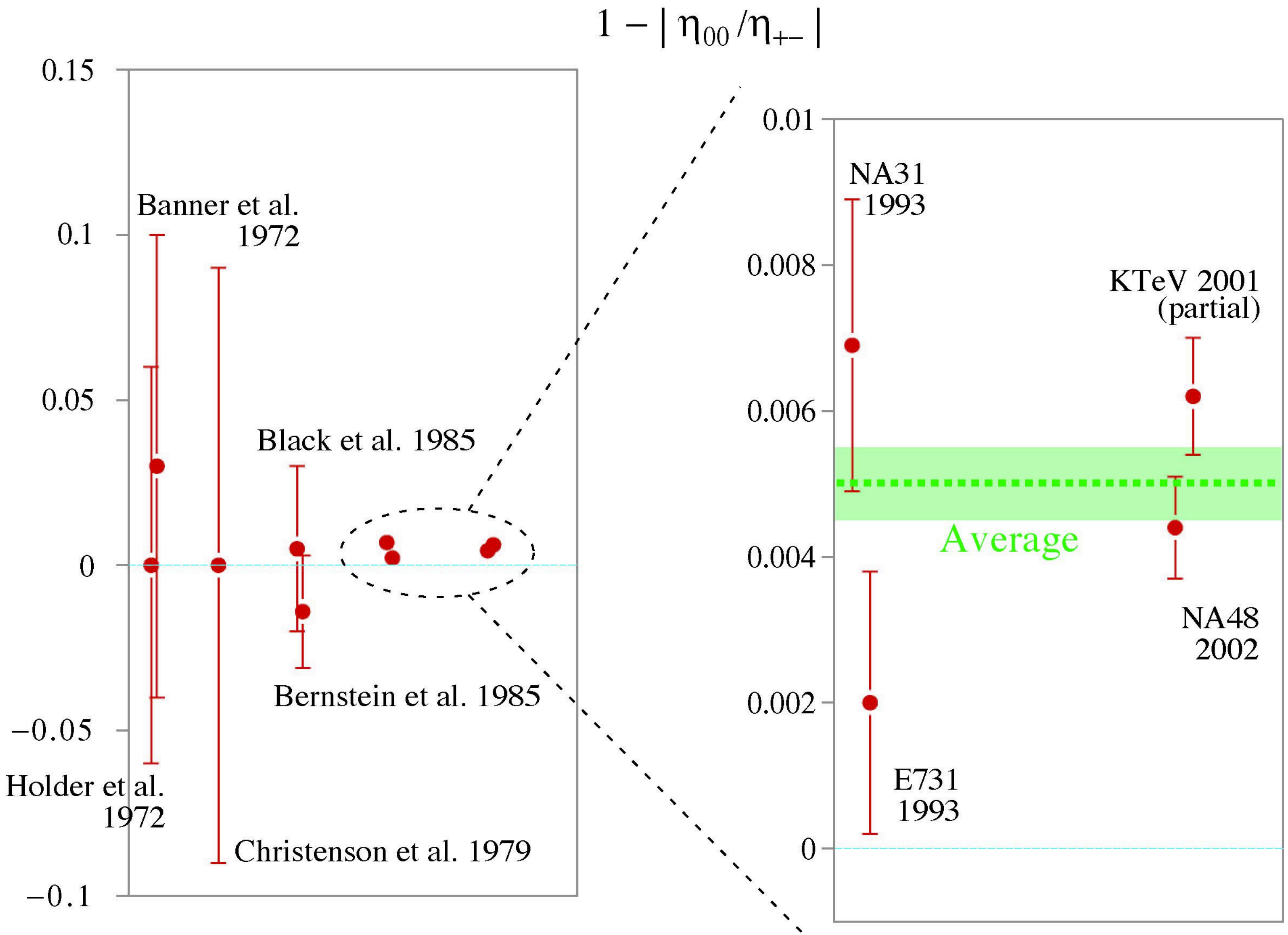
NA48@CERN, KTeV@FNAL

$$|\eta_{+-}|^2 = \frac{N(K_L \to \pi^+\pi^-)}{N_L^{+-}} \bigg/ \frac{N(K_S \to \pi^+\pi^-)}{N_S^{+-}}$$

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{N_S^{00} N_L^{+-}}{N_L^{00} N_S^{+-}} \frac{N\left(K_L \to \pi^0\pi^0\right) N\left(K_S \to \pi^+\pi^-\right)}{N\left(K_S \to \pi^0\pi^0\right) N\left(K_L \to \pi^+\pi^-\right)}$$

$N_{S(L)}^{+-(00)}$: number of $K_{S(L)}$ used to measure $K_{S(L)} \to \pi^+\pi^-(\pi^0\pi^0)$ decays

$N(K_{S(L)} \to \pi^+\pi^-(\pi^+\pi^-))$: number of observed $K_{S(L)} \to \pi^+\pi^-(\pi^0\pi^0)$ decays



Effort over 30 years!

$$0.0050 \pm 0.0005 \neq 0 \;\Rightarrow\; |\eta_{+-}| \neq |\eta_{00}|$$

You will often hear $\frac{\varepsilon'}{\varepsilon}$: Just remember, $3\,\mathrm{Re}\,\frac{\varepsilon'}{\varepsilon} = |\eta_{+-}/\eta_{00}| - 1$

Why is $|\eta_{+-}/\eta_{00}| \neq 1$ so important?

K_L can decay into $\pi^+\pi^-$ if

1) K_L is not a state with CP = −1

or/and

2) CP is not conserved in $K_L \rightarrow \pi^+\pi^-$ decays.

(~~CP~~ in decay amplitude)

If 1) ⇒ CP violation ($\pi^+\pi^-$) must be = CP violation ($\pi^0\pi^0$)

$|\eta_{+-}/\eta_{00}| = 1$

⇒ No CP violation in the charged kaon system,

If 2) ⇒ CP violation ($\pi^+\pi^-$) could be ≠ CP violation ($\pi^0\pi^0$)

may be $|\eta_{+-}/\eta_{00}| \neq 1$.

The Standard Model prediction is 1) + 2) [but 1)>>2)] and the observation is consistent with this prediction.

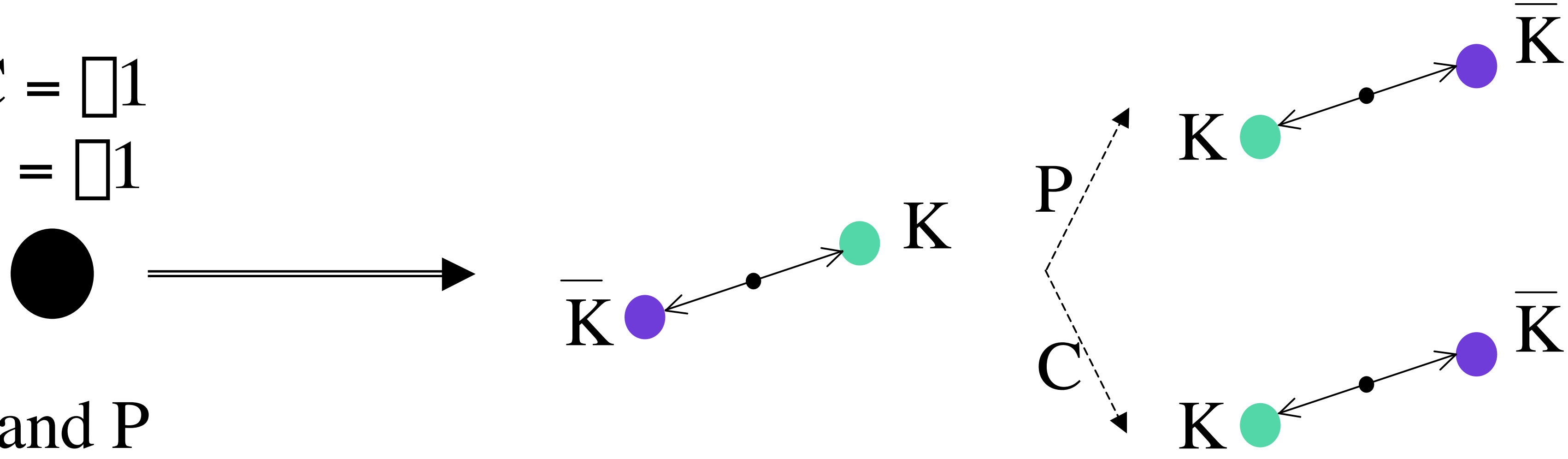
6) Kaon interferometer

e^+e^- (@1GeV) $\rightarrow$ virtual $\gamma \rightarrow$ $\phi(1020) \rightarrow \bar{K}\, K$

all due to electromagnetic interactions

$\phi(1020) \rightarrow \bar{K}\, K$

C = -1
P = -1

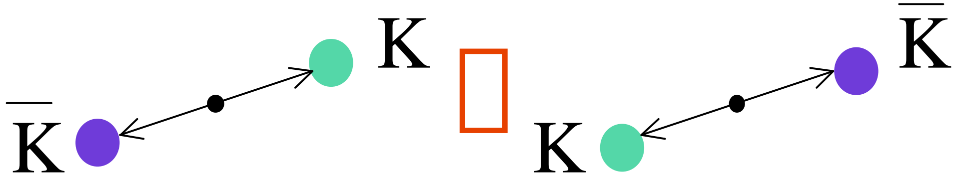


C and P eigenstate

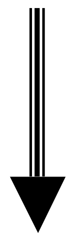
not P eigenstate

not C eigenstate

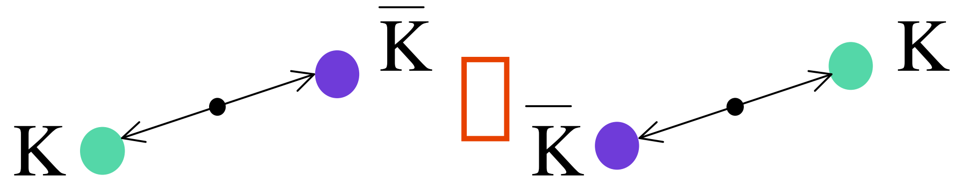
$K\bar{K}$ final state must be a quantum superposition

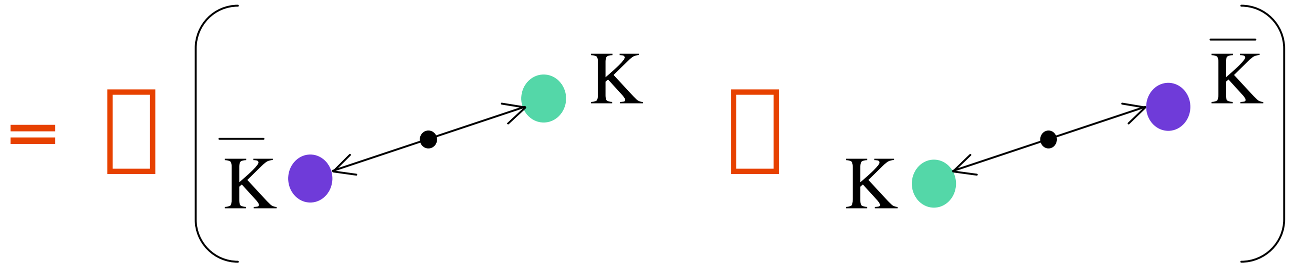


C and P eigenstates



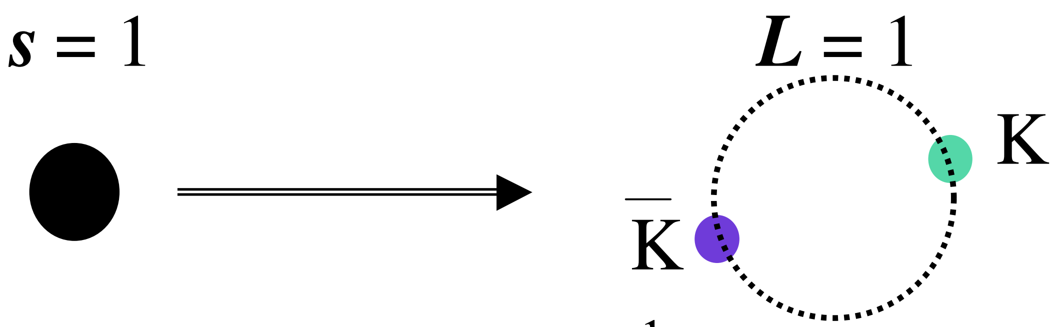
C or P



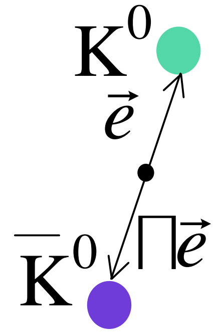


final state $C = \square 1$, $P = \square 1$ = initial state (C and P conserved)

Or... $\phi(1020) \rightarrow K\bar{K}$



$$\left|K\bar{K}_{L=1}\right\rangle = \int d\Omega \sum_{m=-1}^{1} Y_{1m}(\vec{e}) \left|K_{\vec{e}}\right\rangle \left|\bar{K}_{-\vec{e}}\right\rangle$$



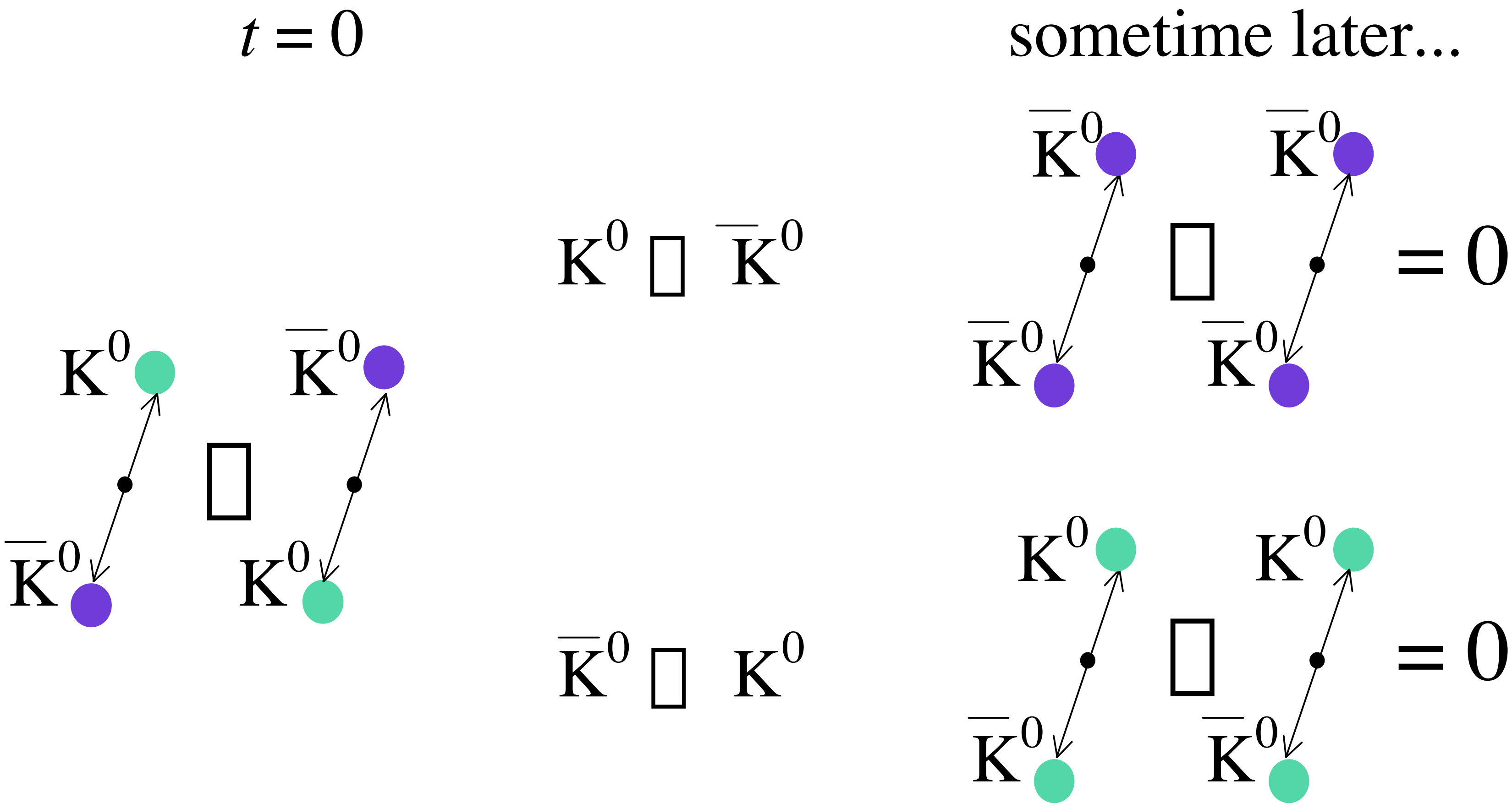
Projection to a momentum state $\left\langle K_{\vec{e}} \right| \left\langle \bar{K}_{-\vec{e}} \right|$

$$\vec{e} = \vec{e}' \qquad\qquad \vec{e} = -\vec{e}'$$

$$\sum_{m=-1}^{1} \left\{ Y_{1m}(\vec{e}) \left|K_{\vec{e}}\right\rangle \left|\bar{K}_{-\vec{e}}\right\rangle + Y_{1m}(-\vec{e}) \left|K_{-\vec{e}}\right\rangle \left|\bar{K}_{\vec{e}}\right\rangle \right\}$$

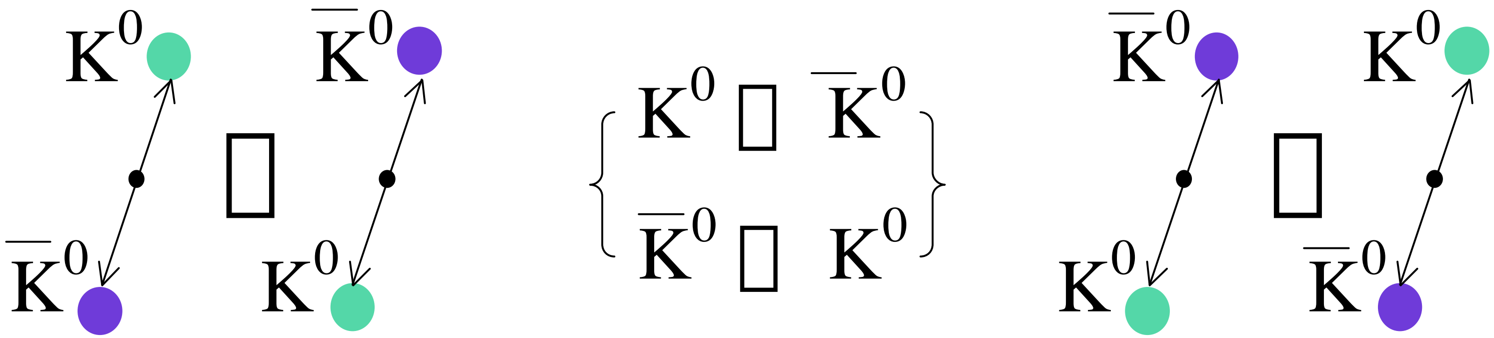
$$= \sum_{m=-1}^{1} Y_{1m}(\vec{e}) \left\{ \left|K_{\vec{e}}\right\rangle \left|\bar{K}_{-\vec{e}}\right\rangle - \left|K_{-\vec{e}}\right\rangle \left|\bar{K}_{\vec{e}}\right\rangle \right\}$$

For neutral kaons, they oscillates, but....



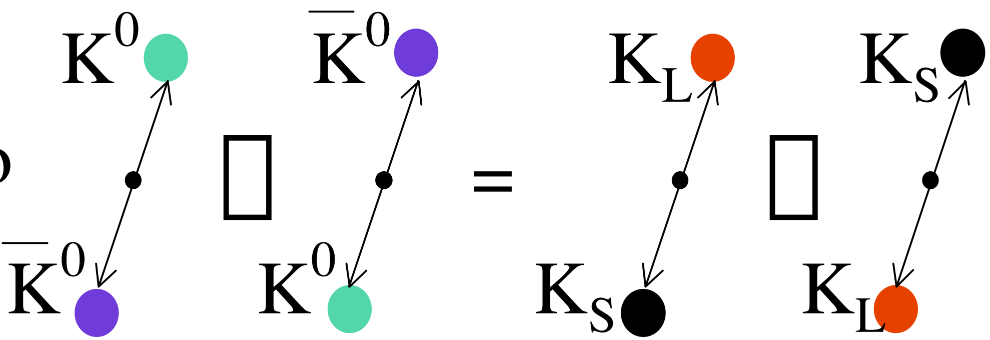
Only the allowed oscillations are

$t = 0$ sometime later...



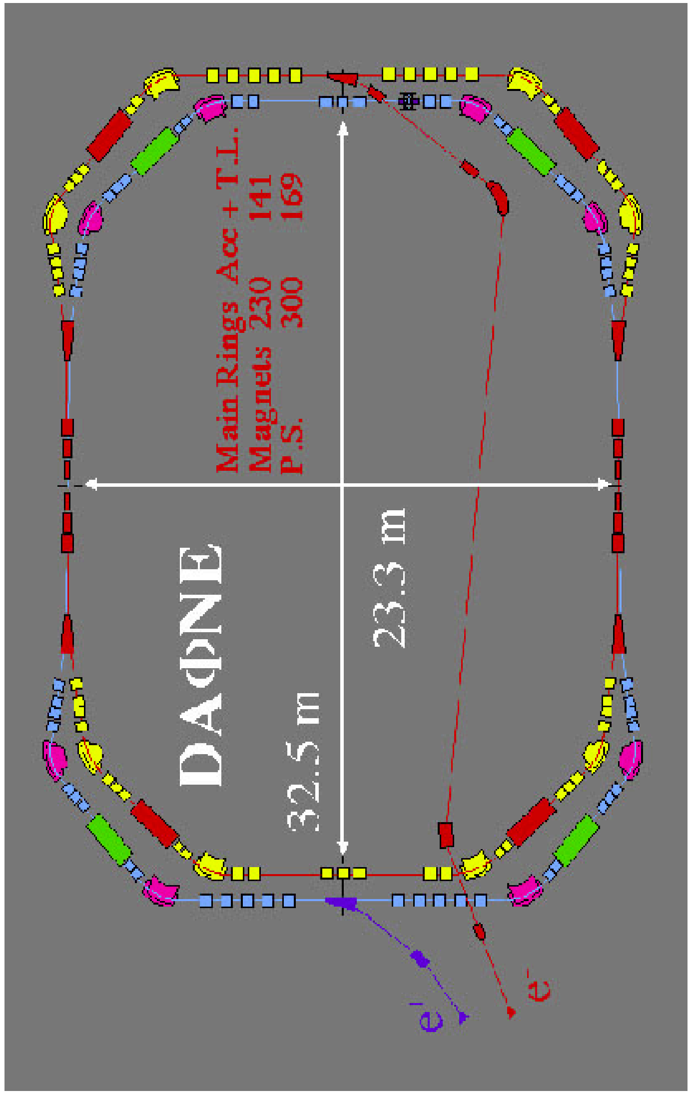
One kaon seems to know what the other does!!

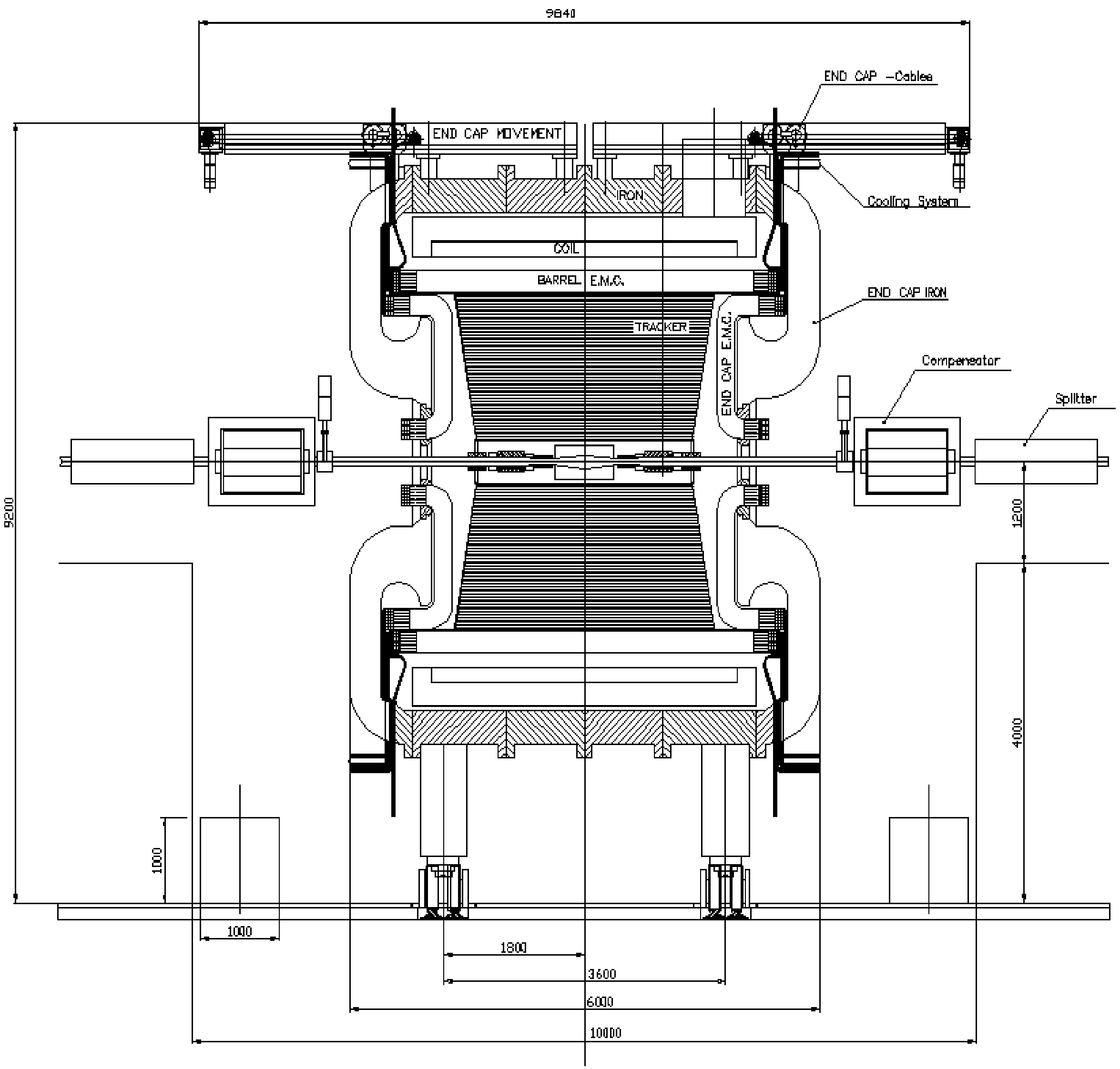
Also



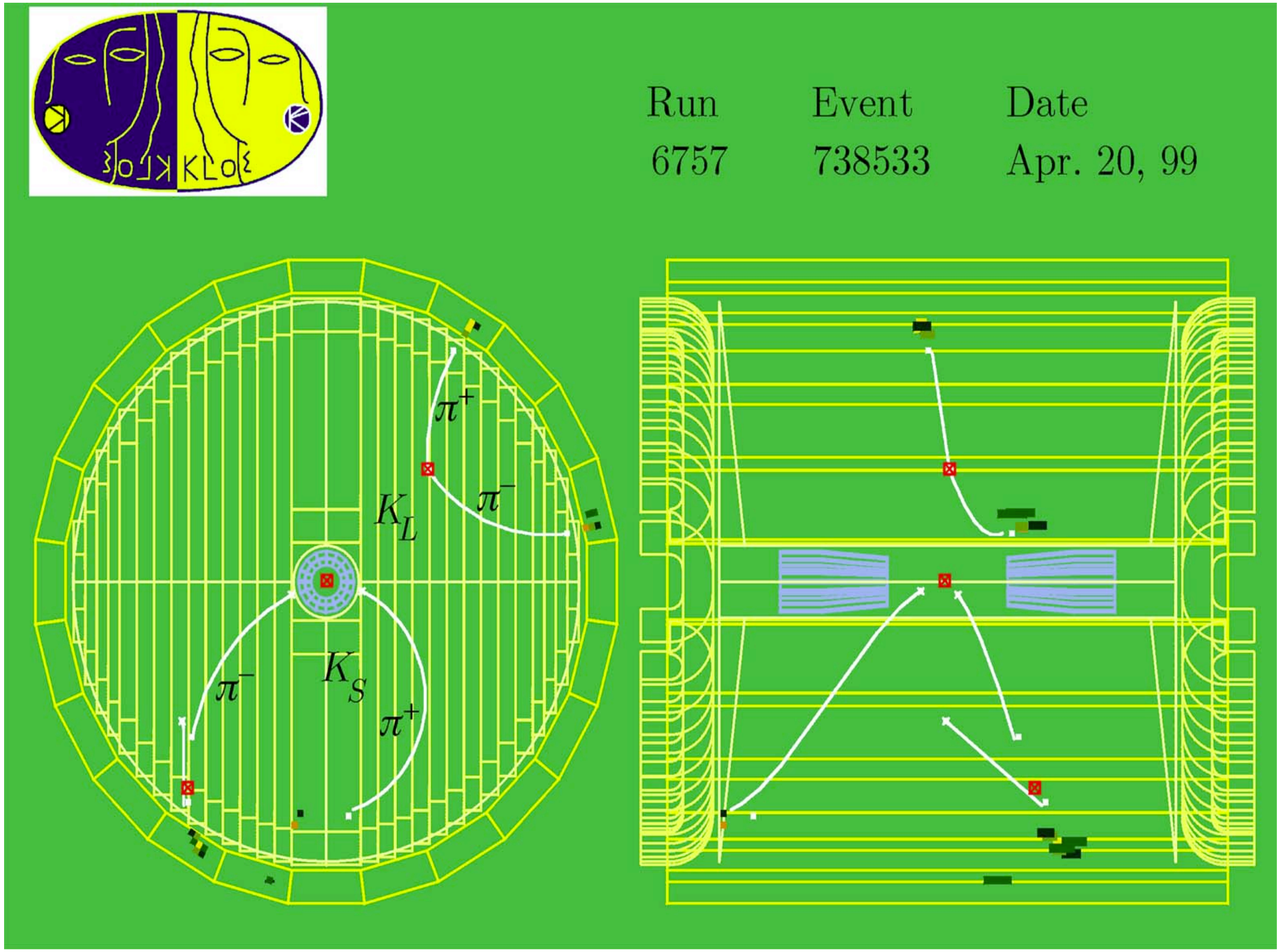
but no $K_S K_S$ or $K_L K_L$

KLOE experiment at DAFNE storage ring (@Frascati)





$K_S \to \pi^+\pi^-$, $K_L \to \pi^+\pi^-$ CP violating decays!!



An ideal way to produce K_S beam

1) Identify K_L decay with the decay time.

2) opposite side is K_S.