# Weak interactions do not conserve strangeness: $K^0 \Leftrightarrow \bar{K}^0$ through weak interactions.

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

spring paddle

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

-$K^0$ and $\bar{K}^0$ 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 $\bar{K}^0$.

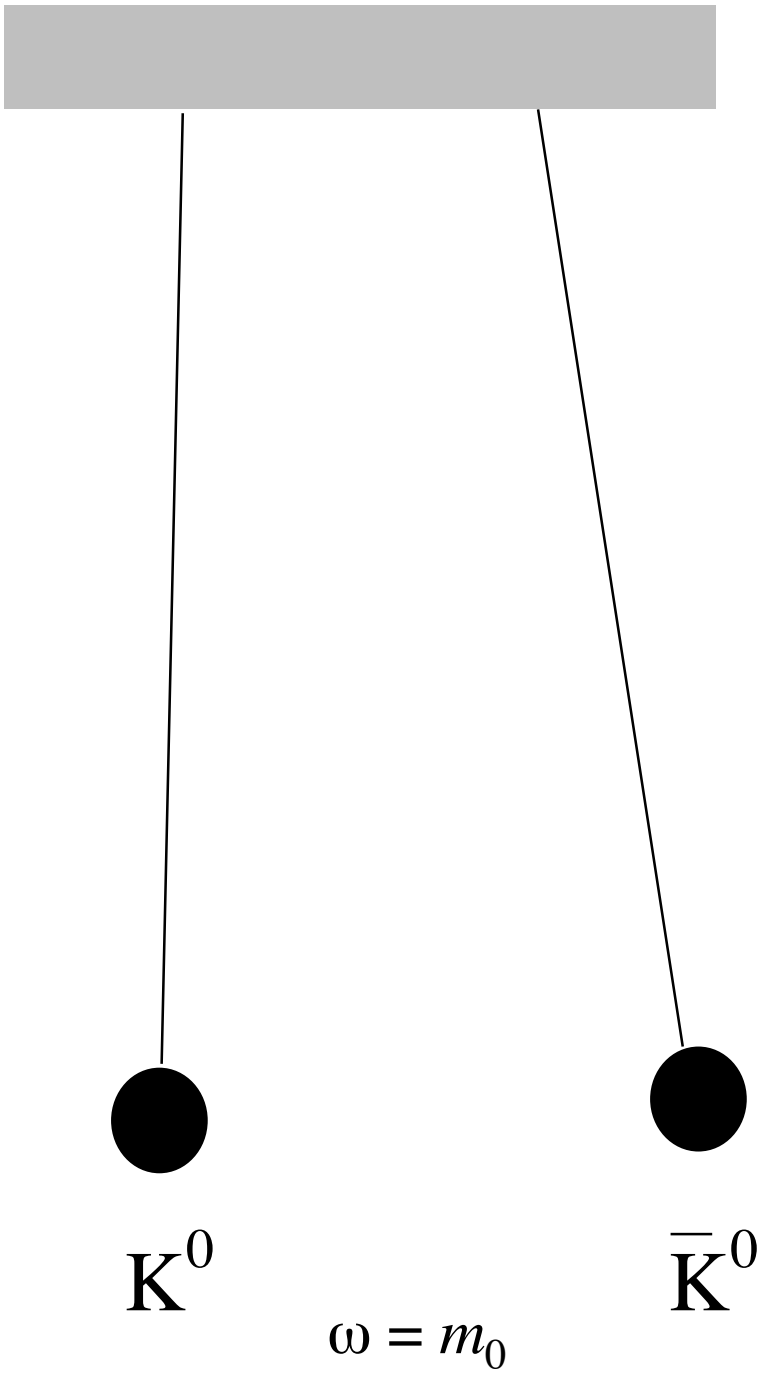
-$K_L$ and $K_S$ with definite masses and decay widths.

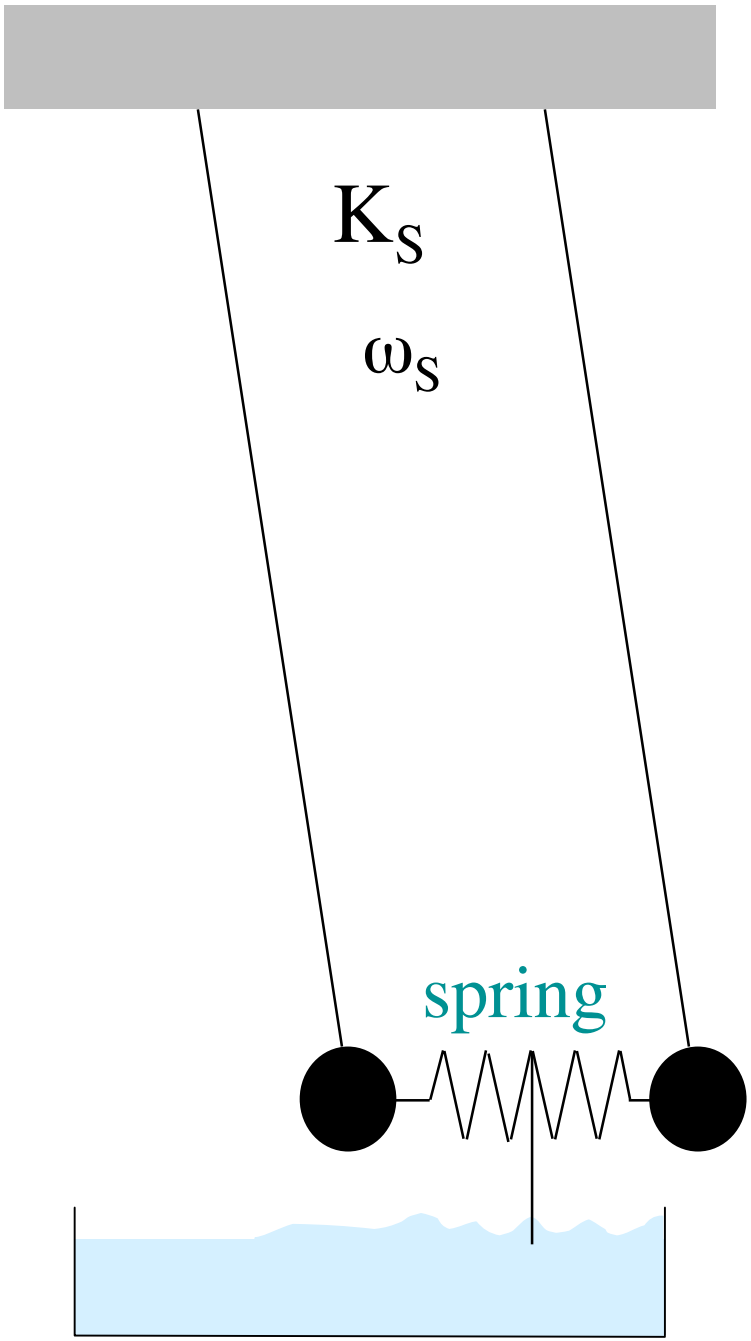
$m_L > m_S$, $\Gamma_S >> \Gamma_L$

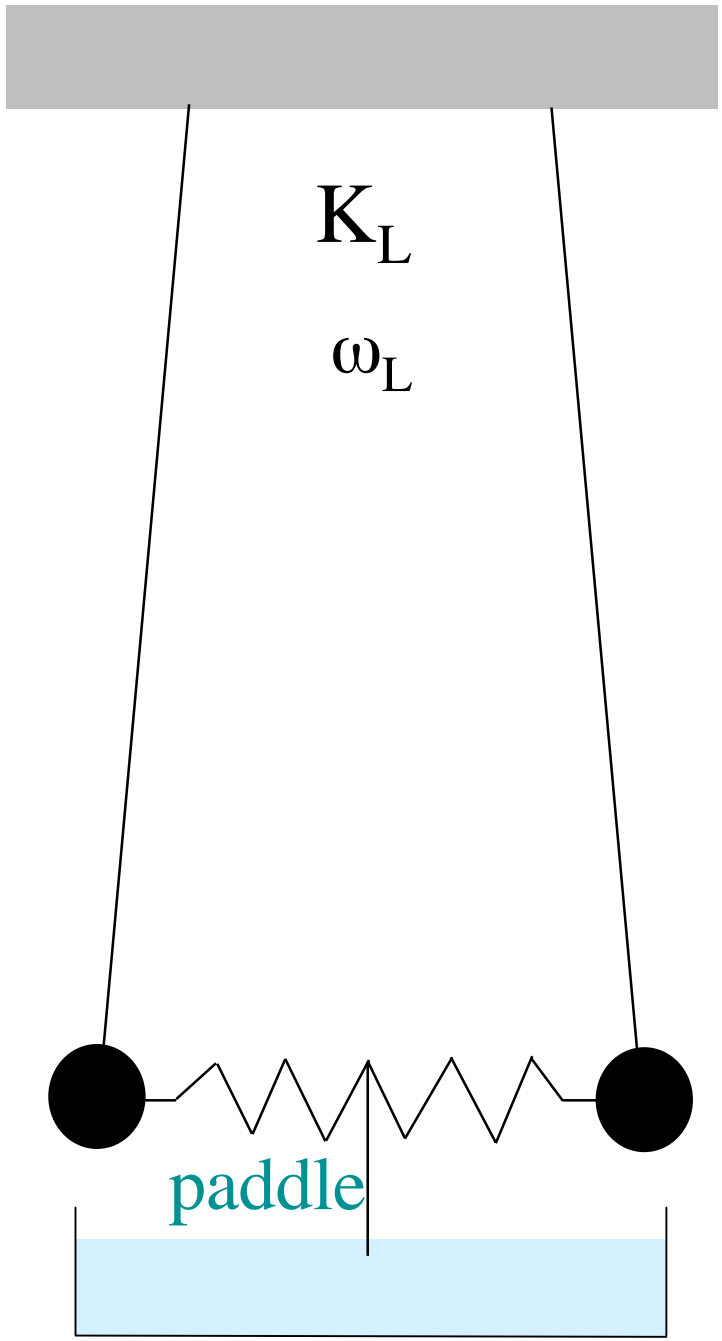
$K_S$ lifetime = $1/\Gamma_S = 8.94\times10^{-11}$s(2.7 cm@$p$ = 450 MeV/$c$)

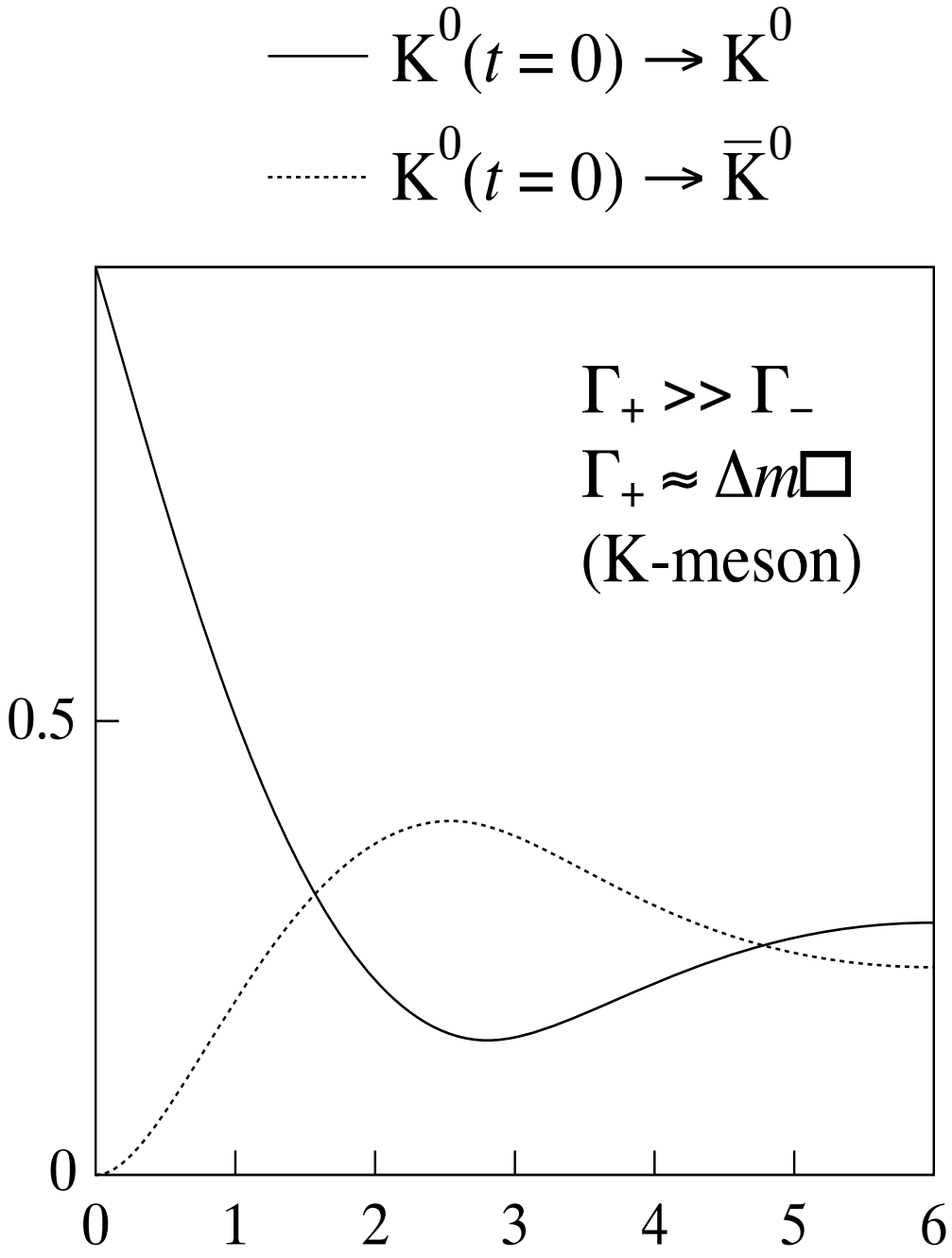
$K_L$ lifetime = $1/\Gamma_L = 5.17\times10^{-8}$s (16 m@$p$ = 450 MeV/$c$)

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


$K^0$
$\bar{K}^0$
$\omega = m_0$


$K_S$
$\omega_S$
spring


$K_L$
$\omega_L$
paddle


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

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

→ 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 $\pi^0$)

$$K_S \propto K^0 + \overline{K}^0,\ K_L \propto K^0 - \overline{K}^0$$

with CP quantum numbers +1 and −1 respectively

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

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

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

$$K_L(CP = -1) \not\rightarrow \pi^+\pi^-(CP = +1)$$

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

**-discovery of CP violation-**

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

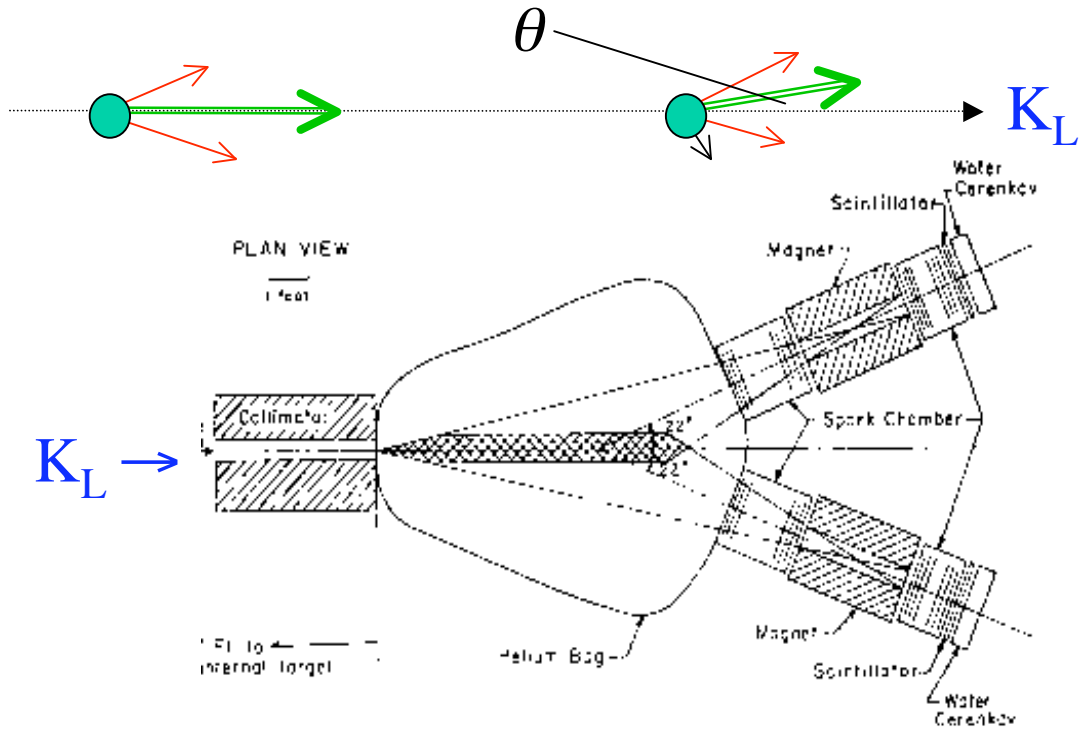
$K_L \rightarrow \pi^+\pi^- + X$

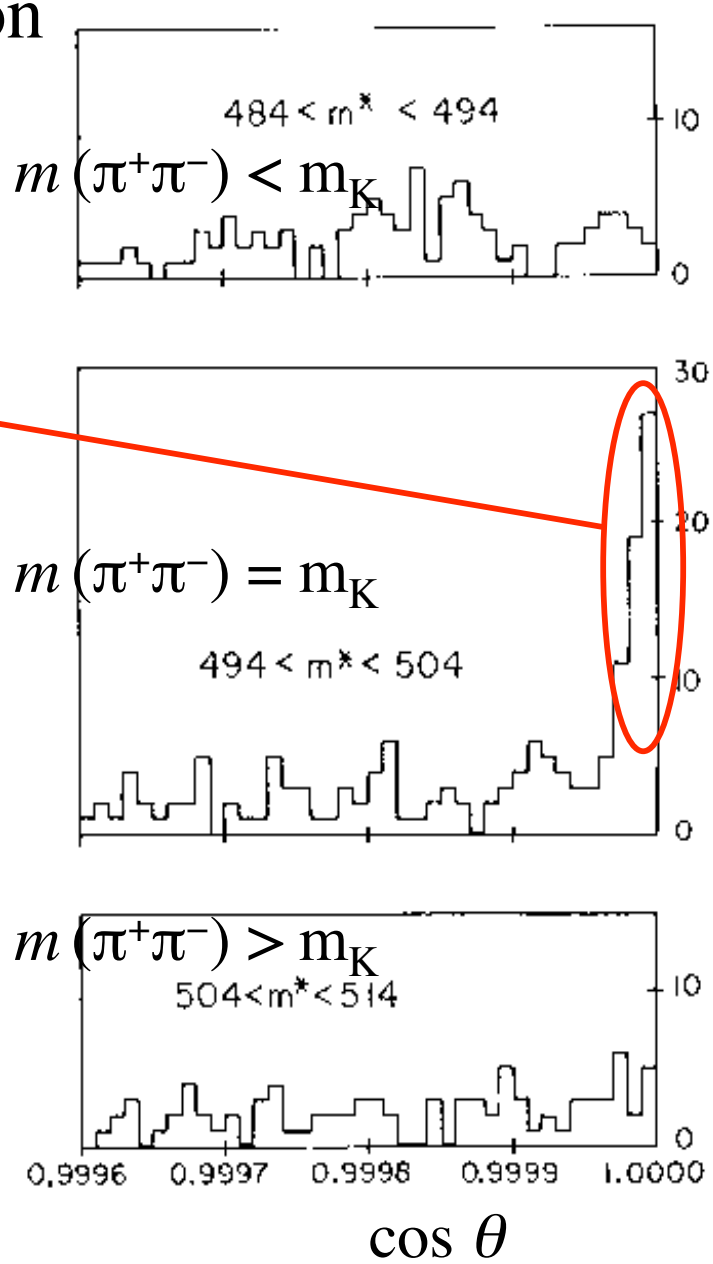
$\boldsymbol{p}_{+-} = \boldsymbol{p}_{\pi+} + \boldsymbol{p}_{\pi-}$

$\theta$ = angle between $\boldsymbol{p}_{KL}$ and $\boldsymbol{p}_{+-}$

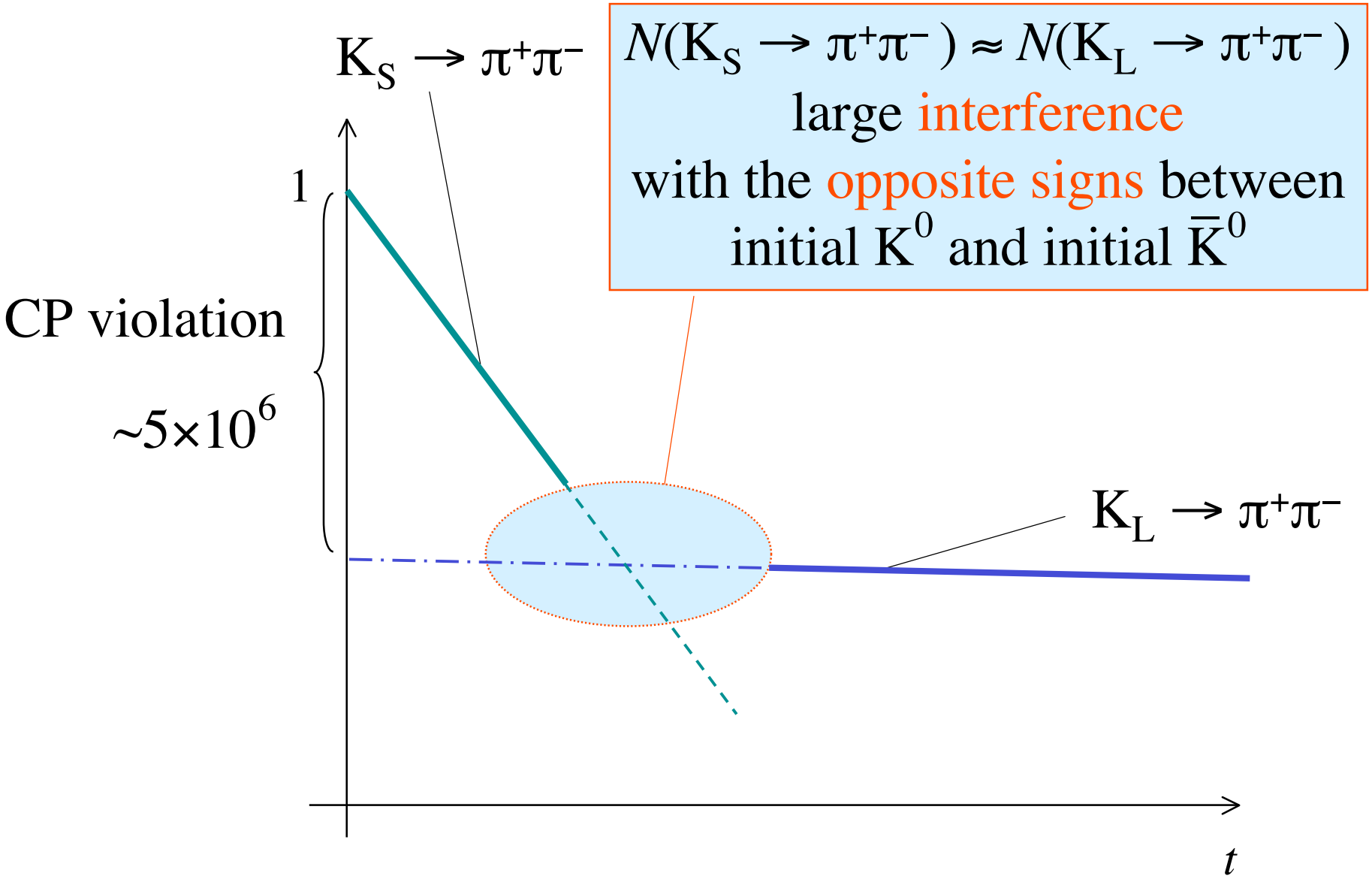
If $X = 0$, $\boldsymbol{p}_{+-} = \boldsymbol{p}_{KL}$ : $\cos\theta = 1$

If $X \neq 0$, $\boldsymbol{p}_{+-} \neq \boldsymbol{p}_{KL}$ : $\cos\theta \leq 1$



# What you see in CPLEAR is



CP violation parameters often refereed:

$$\eta_{+-} = \frac{K_L \to \pi^+\pi^- \text{ decay amplitude}}{K_S \to \pi^+\pi^- \text{ decay amplitude}} \cancel{CP}$$

$$= (2.286 \pm 0.017) \times 10^{-3} \times e^{i(43.7 \pm 0.7)^\circ}$$

<1% error

$$\eta_{00} = \frac{K_L \to \pi^0\pi^0 \text{ decay amplitude}}{K_S \to \pi^0\pi^0 \text{ decay amplitude}} \cancel{CP}$$

$$= (2.280 \pm 0.026) \times 10^{-3} \times e^{i(43.7 \pm 0.8)^\circ}$$

direct measurements

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

(but not quite...)

Two most recent experiments:

NA48@CERN, KTeV@FNAL

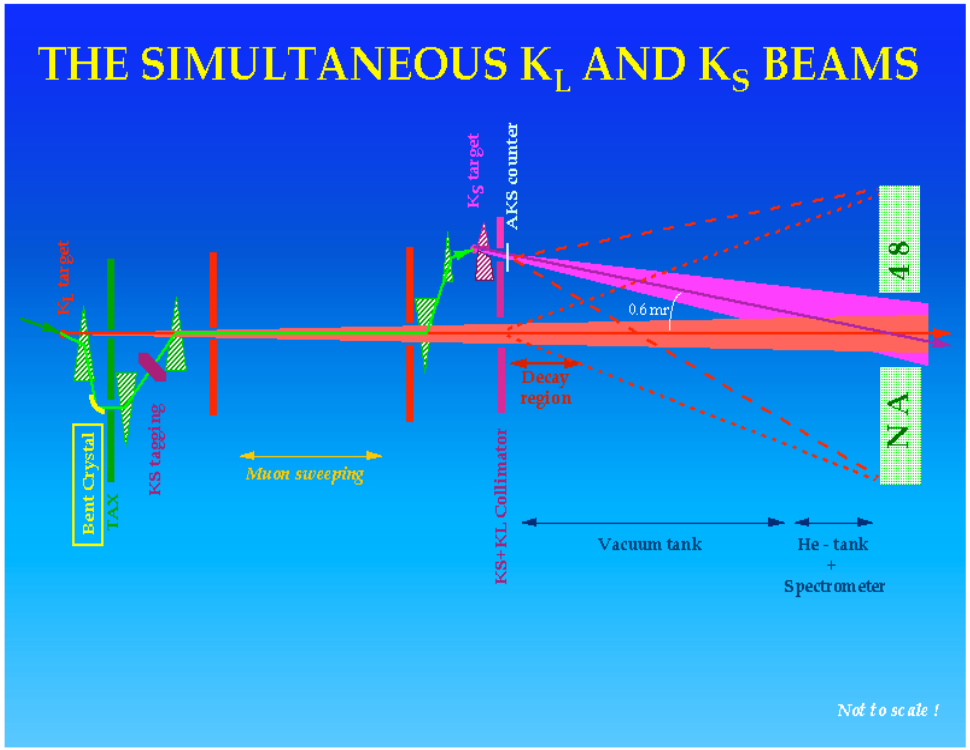
$$|\eta_{+-}|^2 = \frac{N(K_L \to \pi^+\pi^-)}{N_L^{+-}} \Big/ \frac{N(K_S \to \pi^+\pi^=)}{N_S^{+-}}$$

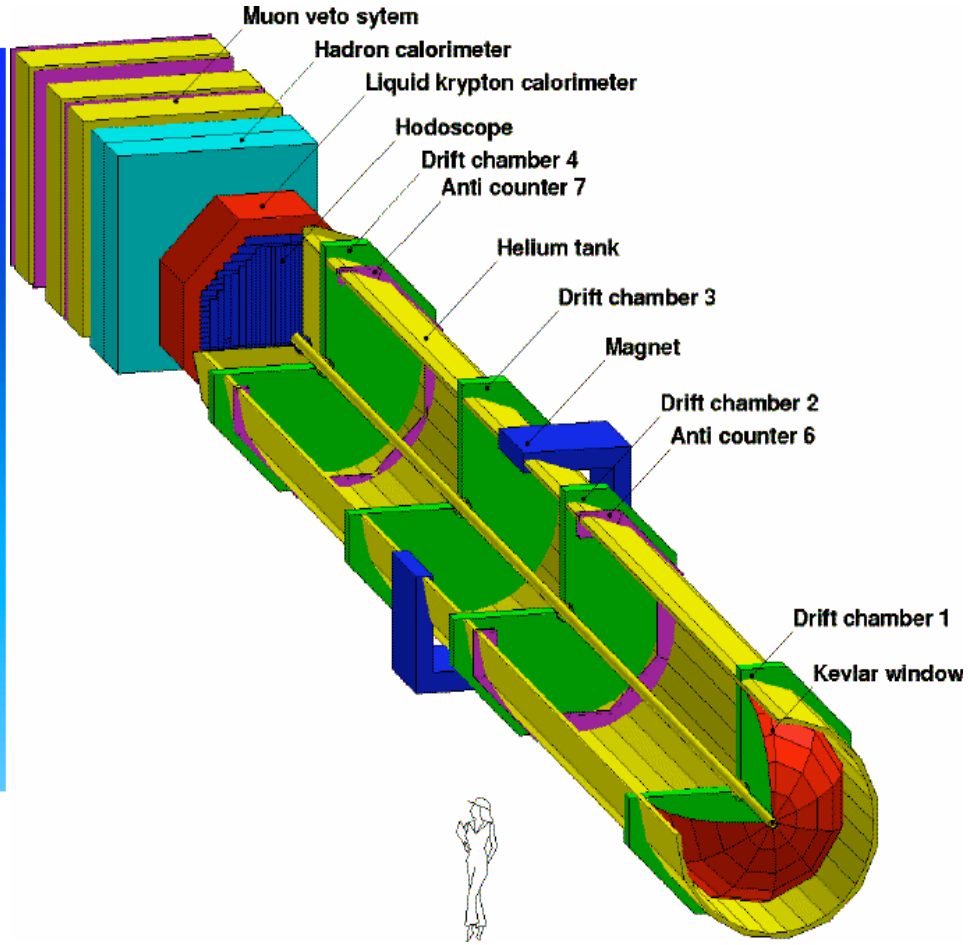
$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{N_S^{00} N_L^{+-}}{N_L^{00} N_S^{+-}} \frac{N\left(K_L \to \pi^0\pi^0\right) N\left(K_S \to \pi^+\pi^-\right)}{N\left(K_S \to \pi^0\pi^0\right) N\left(K_L \to \pi^+\pi^-\right)}$$

$N_{S(L)}^{+-(00)}$: 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

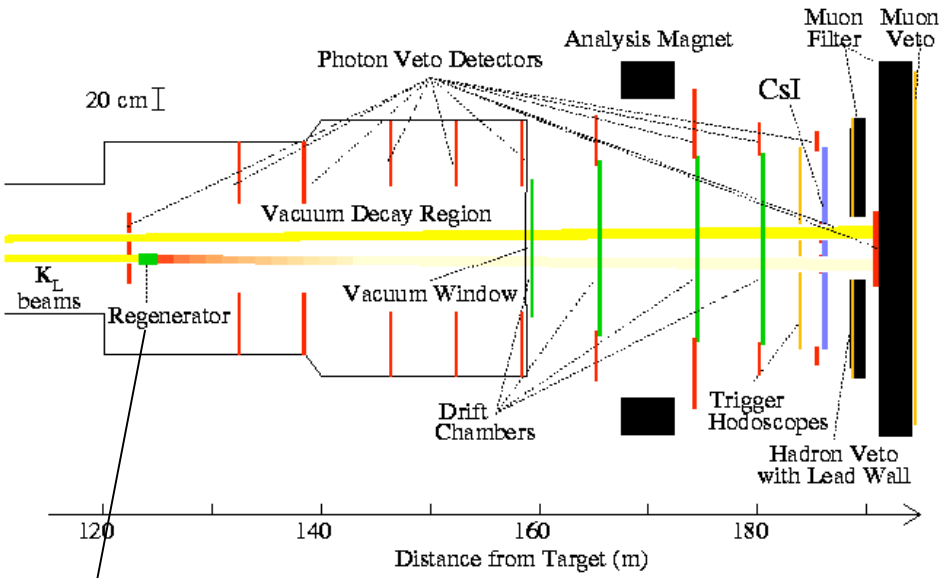
# NA48 @ CERN

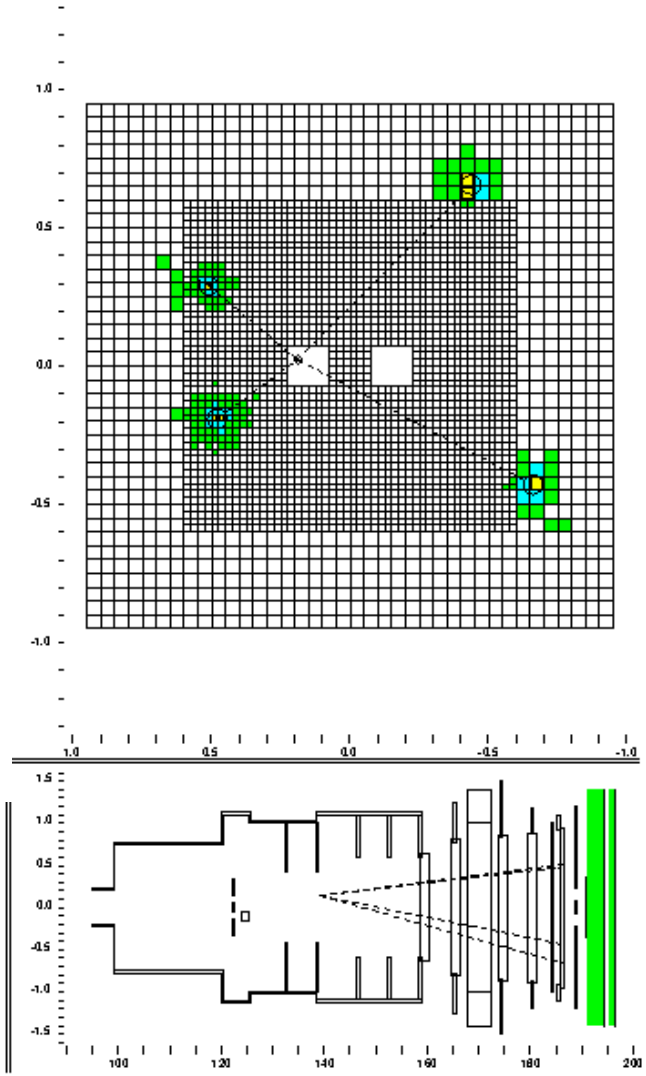



$K_S$ and $K_L$ beam

# KTeV @ FNAL




$K_S$ is produced by the regeneration of $K_L$.

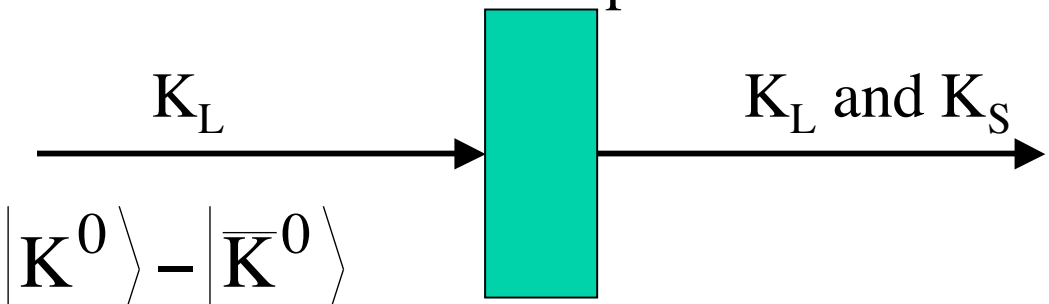
# Regeneration

$$\sigma_{\overline{K}n}, \sigma_{\overline{K}p} > \sigma_{Kn}, \sigma_{Kp}$$

$$K^0 = (d\bar{s})$$
$$\overline{K}^0 = (\bar{d}s)$$

$$p = (uud), \; n = (udd)$$

material = p and n




$$\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle$$

$$\left|K^0\right\rangle - \alpha\left|\overline{K}^0\right\rangle$$

$$= \frac{1-\alpha}{2}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right) + \frac{1+\alpha}{2}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right)$$

$$= \frac{1-\alpha}{2}\left|K_S\right\rangle + \frac{1+\alpha}{2}\left|K_L\right\rangle$$

$$\alpha = \sqrt{\frac{\sigma_{\overline{K}N}}{\sigma_{KN}}} \neq 1$$

Measure

$\pi^+\pi^-$ and $\pi^0\pi^0$ at the same time: $N_S^{00} = N_S^{+-}$, $N_L^{00} = N_L^{+-}$

NA48

definition

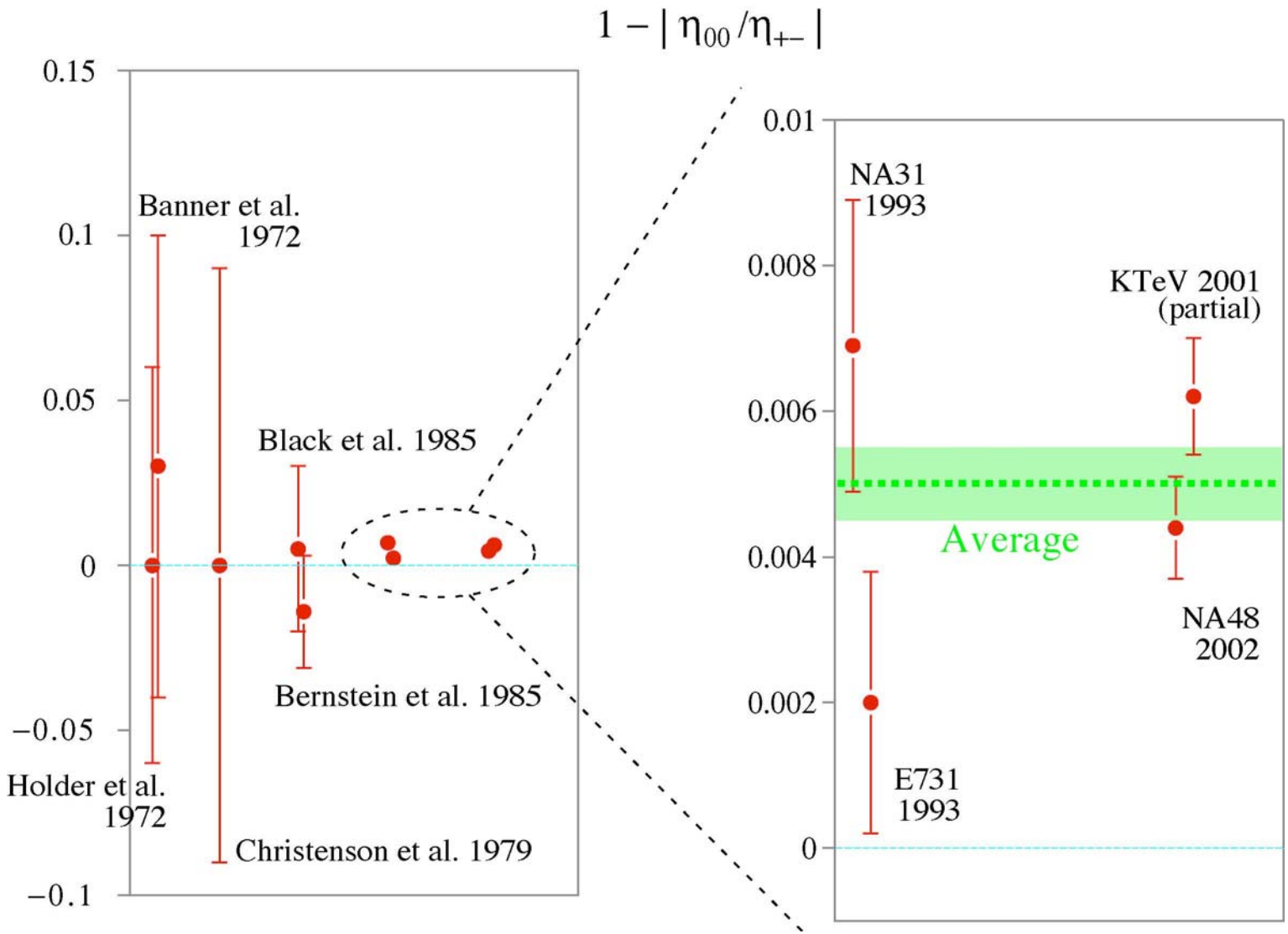
$K_L$ is regenerated from $K_S$: $N_L^{00} = rN_S^{00}$, $N_L^{+-} = rN_S^{+-}$

KTeV

Only the measured decay rates are required.

$$|\eta_{+-}/\eta_{00}|^2 - 1 = 6\,\mathrm{Re}\,(\varepsilon'/\varepsilon)$$

$$|\eta_{+-}/\eta_{00}| \neq 1$$
$$\Rightarrow \mathrm{Re}\,(\varepsilon'/\varepsilon) \neq 0$$




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

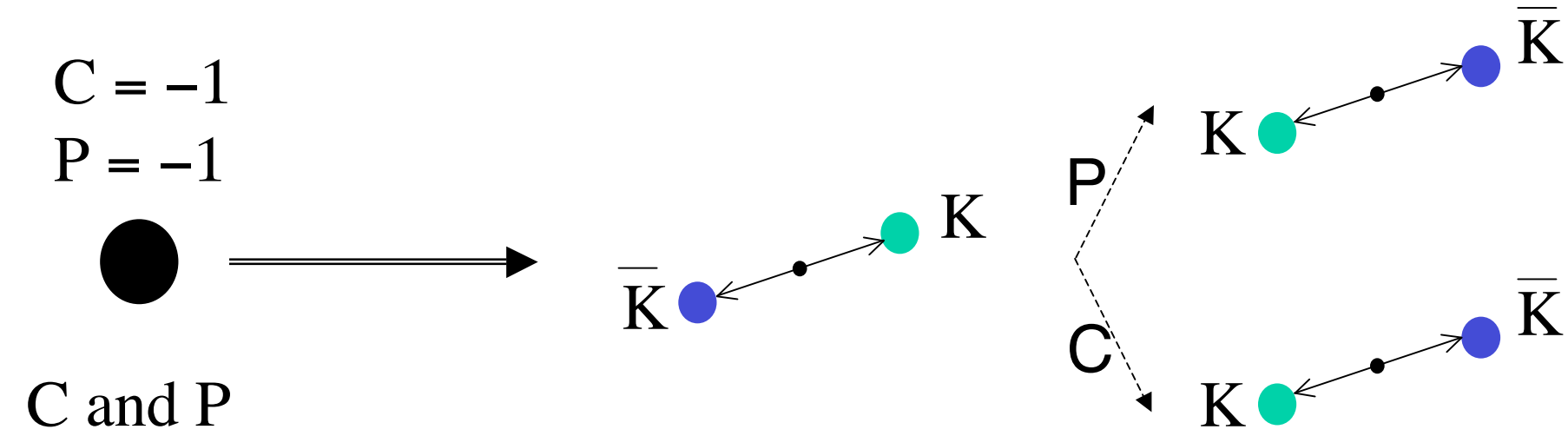
**The Standard Model prediction is 1) + 2) [but 1)>>2)] and the observation is consistent with this prediction.**

# 6) Kaon interferometer

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

all due to electromagnetic interactions

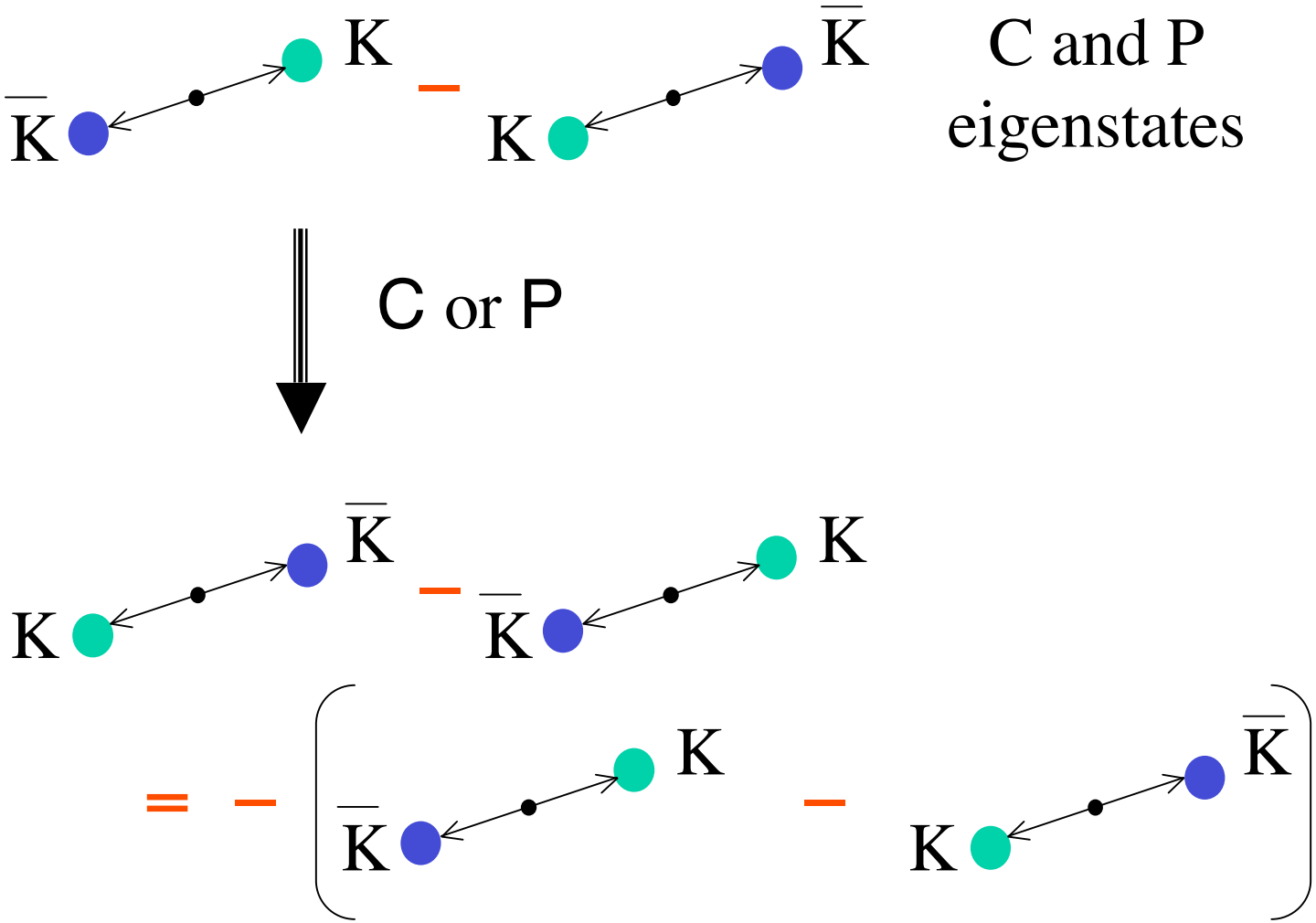
$\phi(1020) \rightarrow \bar{K}\,K$




not P eigenstate

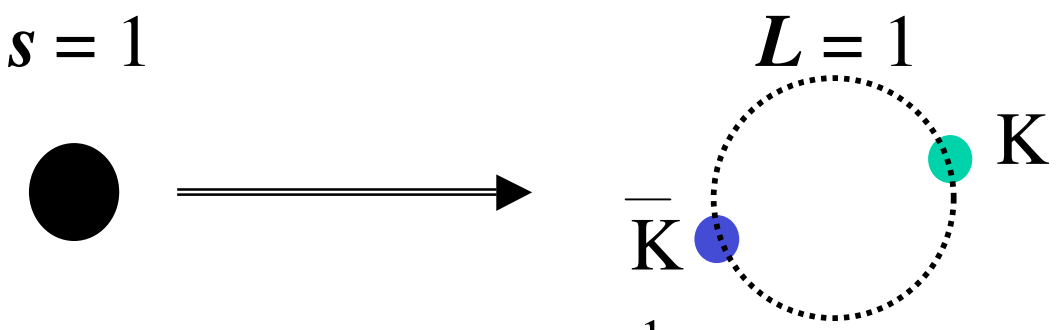
not C eigenstate

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

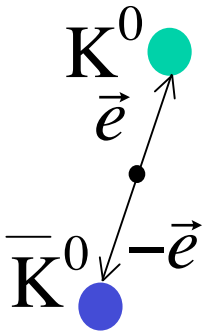



final state $\begin{matrix} C = -1 \\ P = -1 \end{matrix}$ = initial state (C and P conserved)

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




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




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

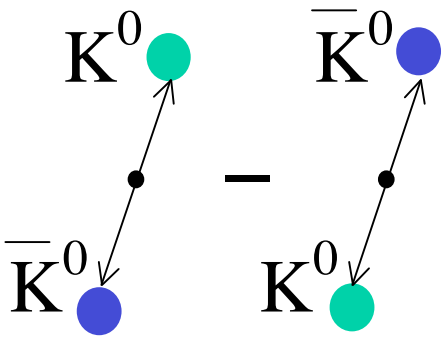
$$\vec{e} = \vec{e}\,' \qquad\qquad \vec{e} = -\vec{e}\,'$$

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

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

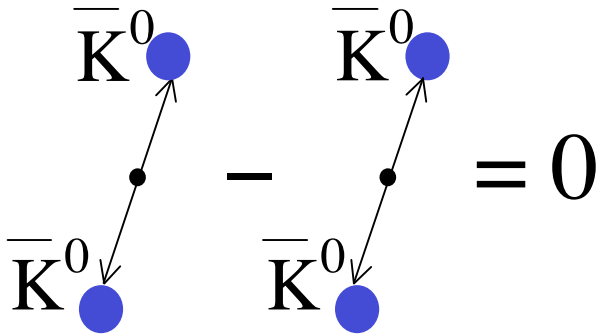
# For neutral kaons, they oscillates, but....

$t = 0$

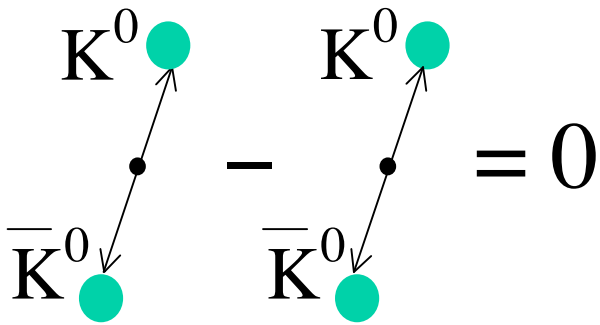



sometime later...

$K^0 \rightarrow \overline{K}^0$

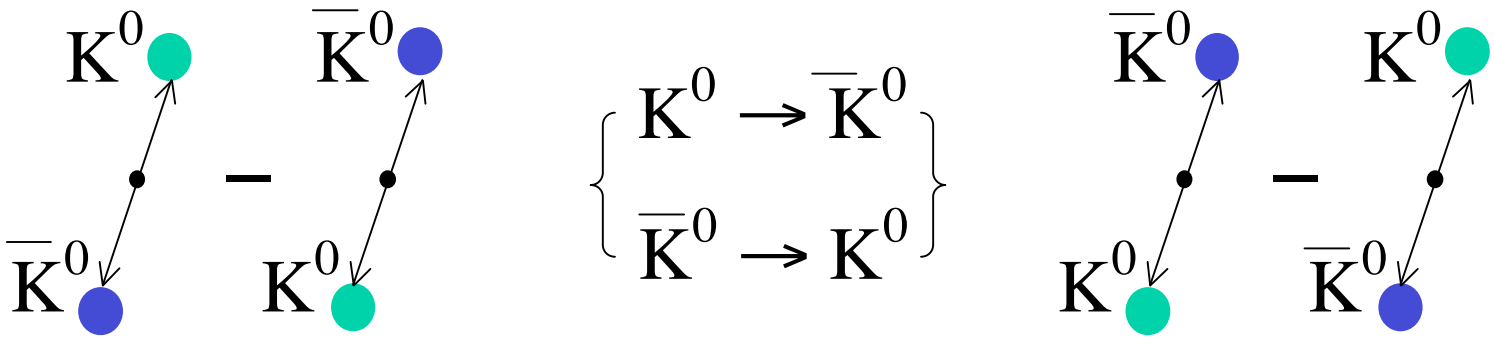



$\overline{K}^0 \rightarrow K^0$



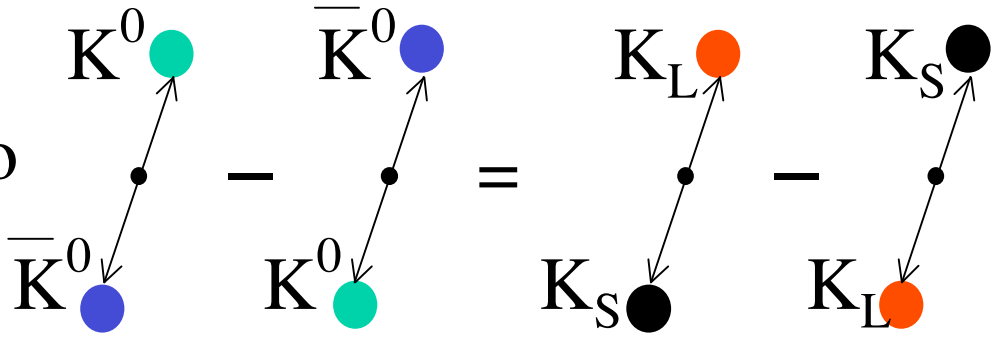
Only the allowed oscillations are

$t = 0$ sometime later...



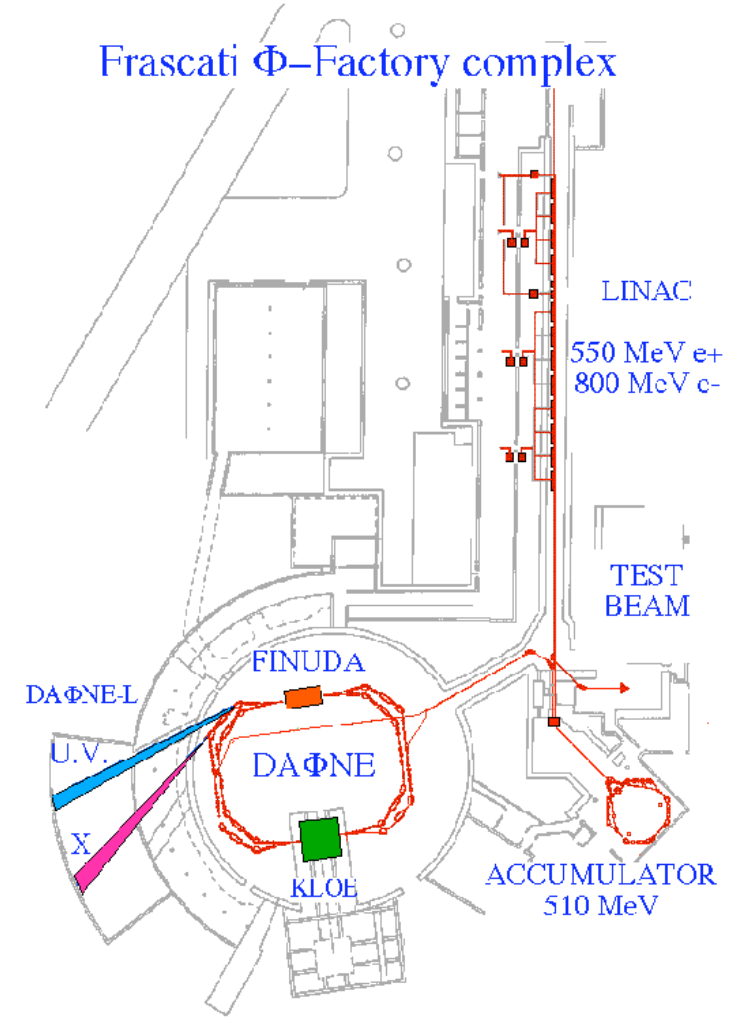

One kaon seems to know what the other does!!

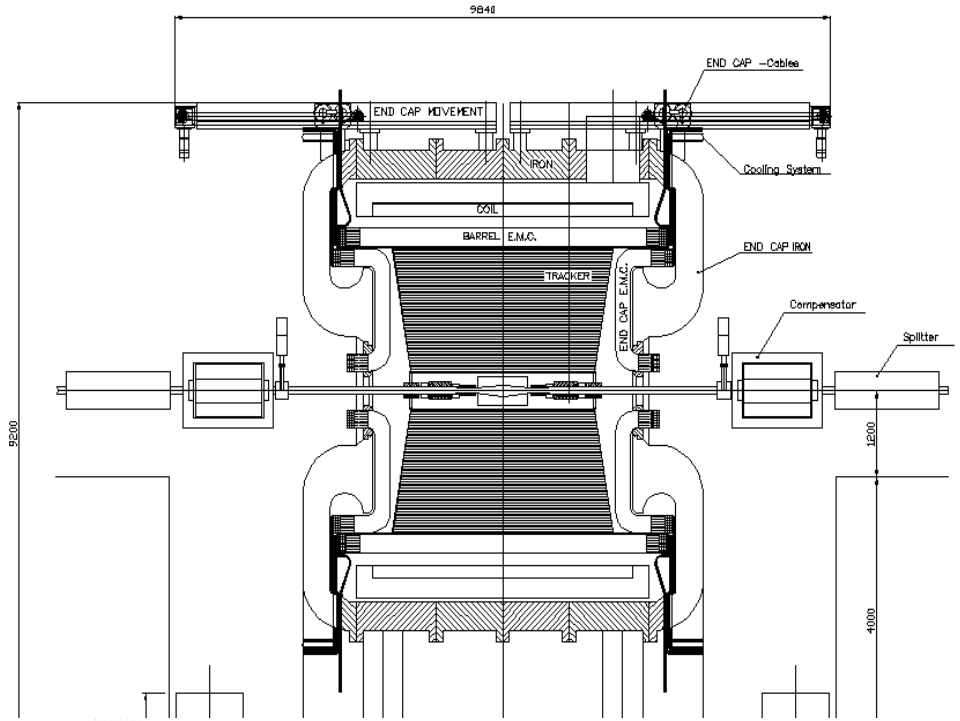
Also

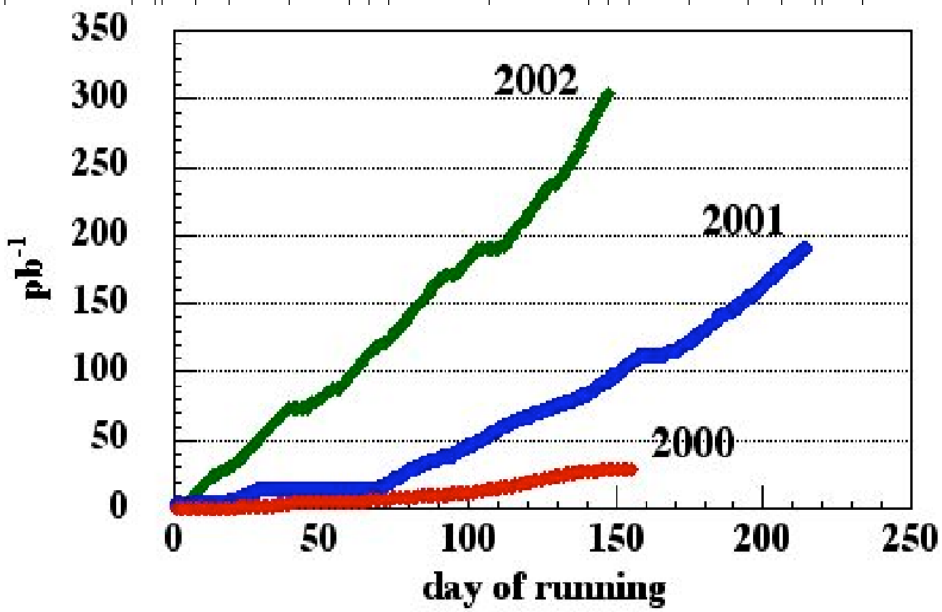



but no $K_S K_S$ or $K_L K_L$

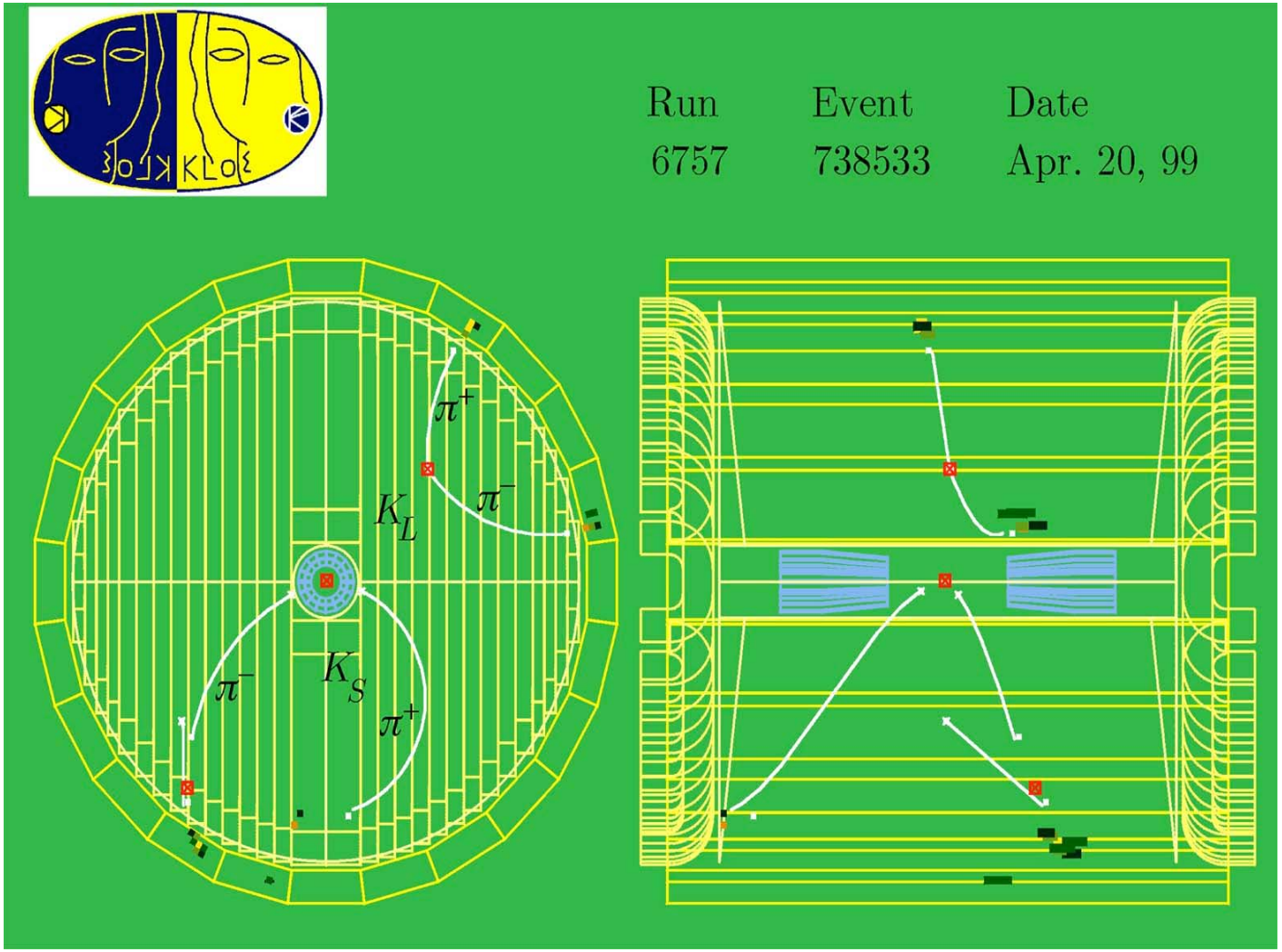
# KLOE experiment at DAFNE storage ring (@Frascati)



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




An ideal way to produce $K_S$ beam

1) Identify $K_L$ decay with the decay time.

2) opposite side is $K_S$.