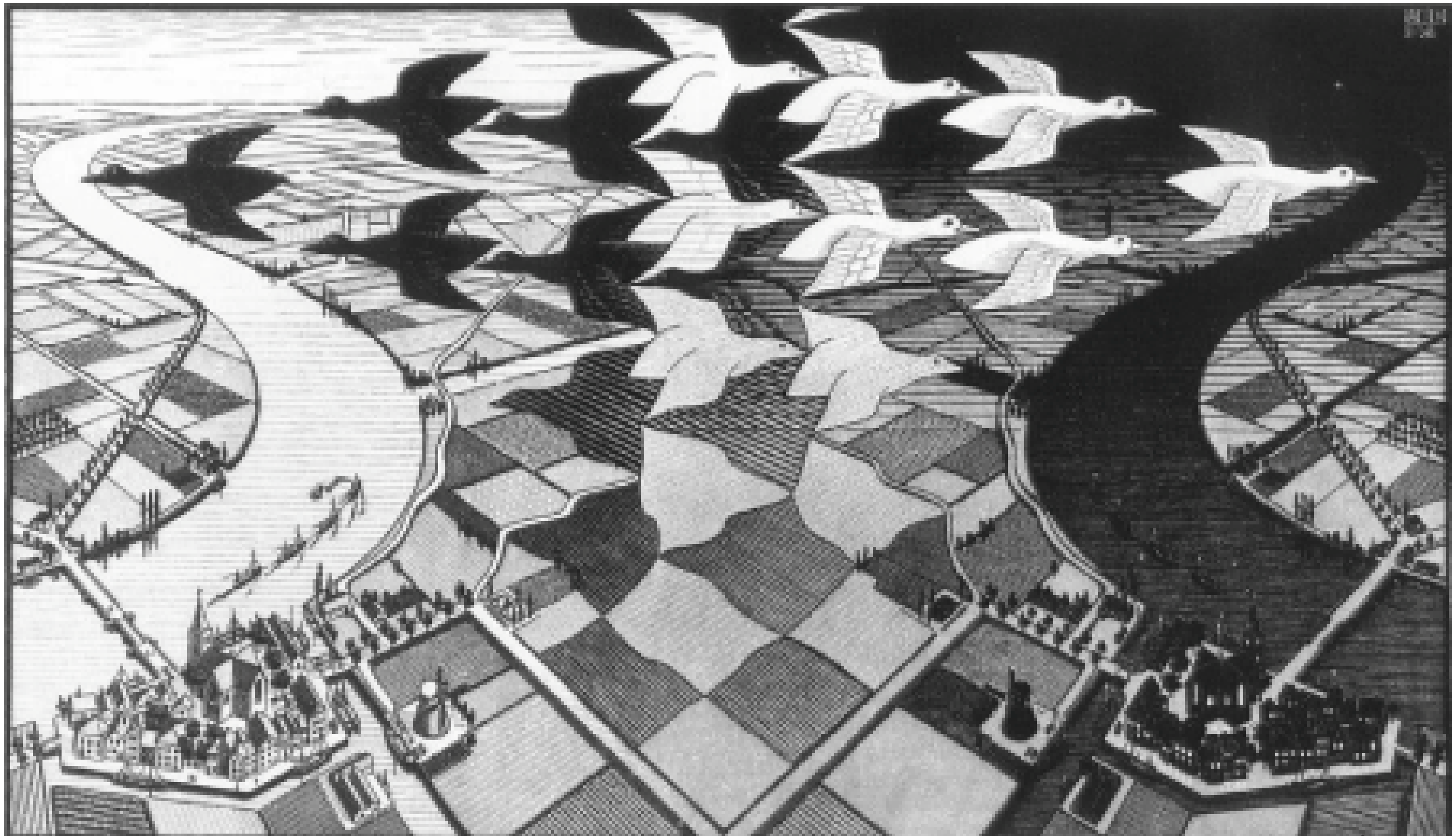
CP Violation

-- Lecture 3 --



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Question from Lecture 1

why does this term appear
in the QCD Lagrangian,

while the corresponding term
does not appear in QED?

$$\boxed{\mathcal{L}_\theta^{CPV} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}}$$

violates $\mathcal{P}$

QED: $F_{\mu\nu}\tilde{F}_{\mu\nu} = -4\boldsymbol{E}\cdot\boldsymbol{B}$

QED and QCD, similarities and differences

QED Lagrangian: $\boxed{\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}} = \frac{1}{2}(E^2 - B^2)$

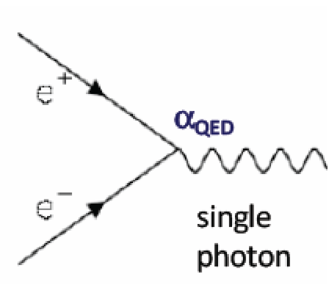
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad \tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\kappa\lambda}F_{\kappa\lambda} \quad F_{\mu\nu}\tilde{F}_{\mu\nu} = -4\boldsymbol{E}\cdot\boldsymbol{B}$$

QCD Lagrangian: $\boxed{\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i\,(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij})\,\psi_j - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu}} + \theta\frac{g_s^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$

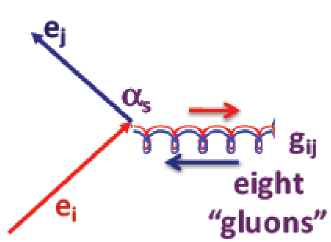
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc}A^b_\mu A^c_\nu \qquad \tilde{G}^{a\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\kappa\lambda}G^{a\kappa\lambda}$$

$a = 1 \to 8$; 8 gluons

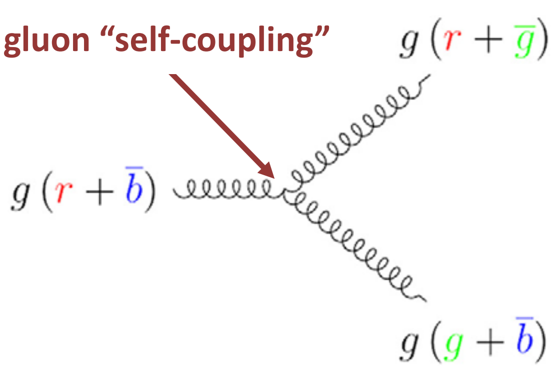
gluon "self-coupling"



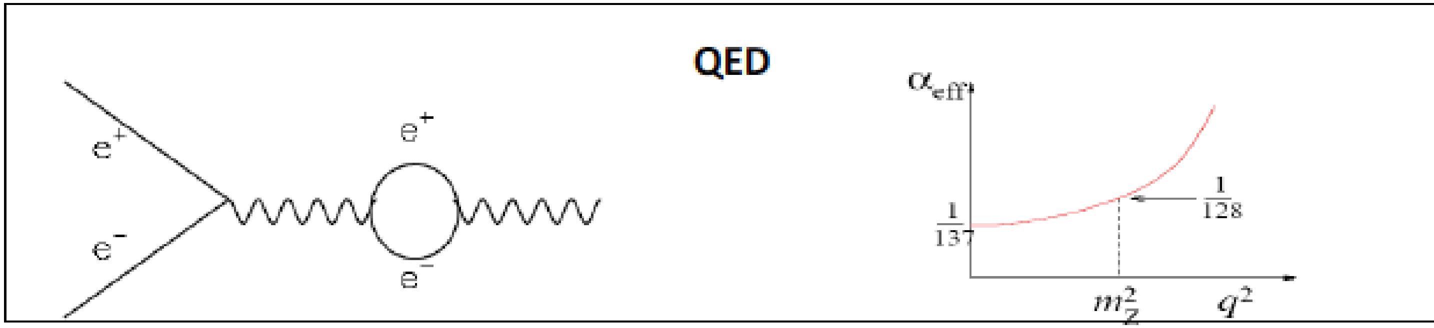
photon is electrically neutral

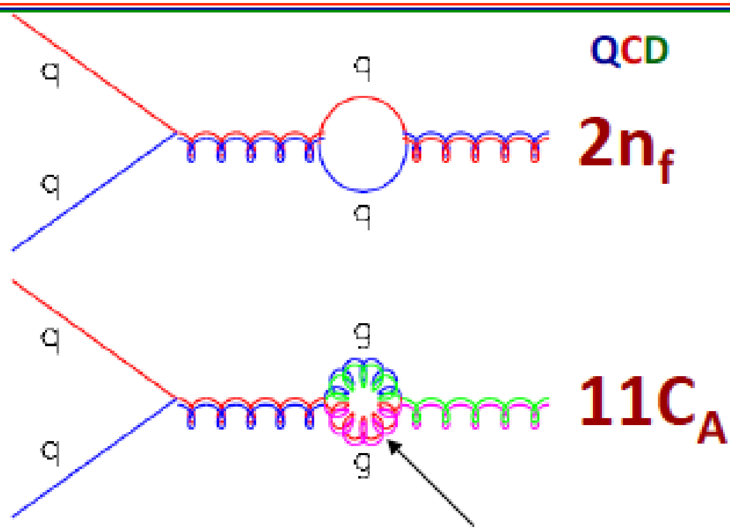


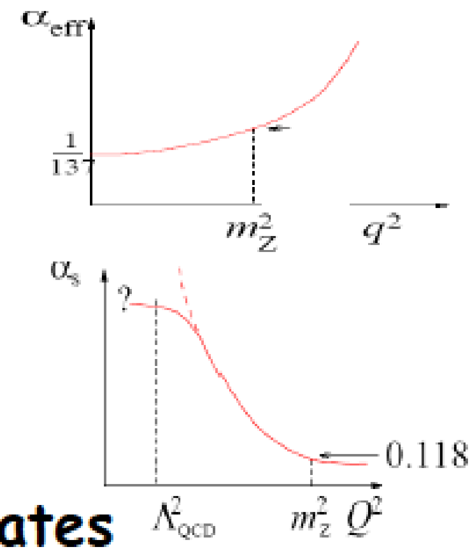
gluons have color charges



Vacuum polarization QED *vs* QCD



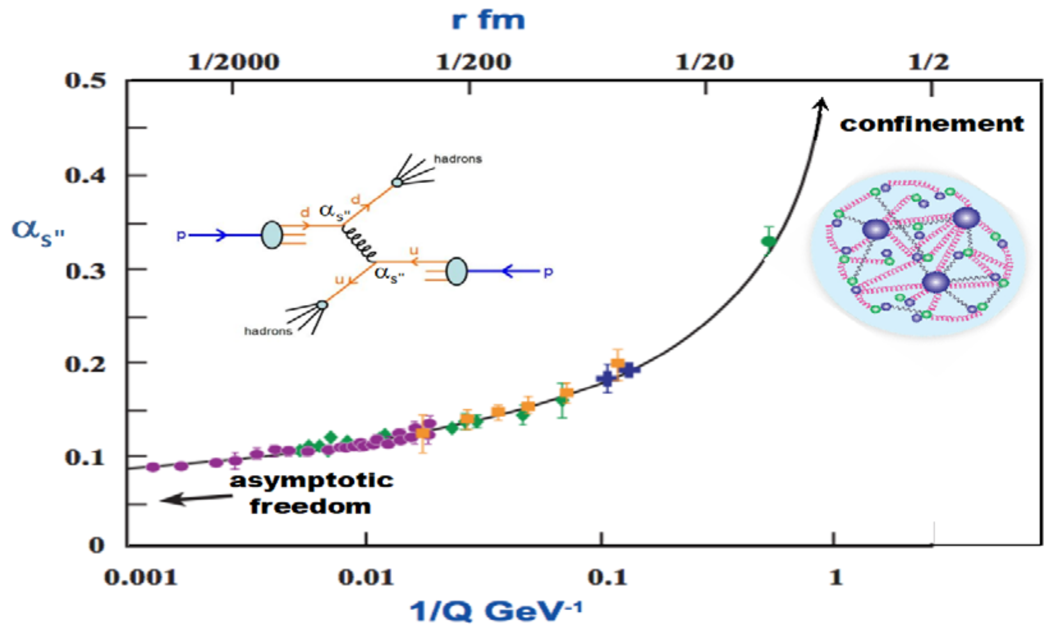


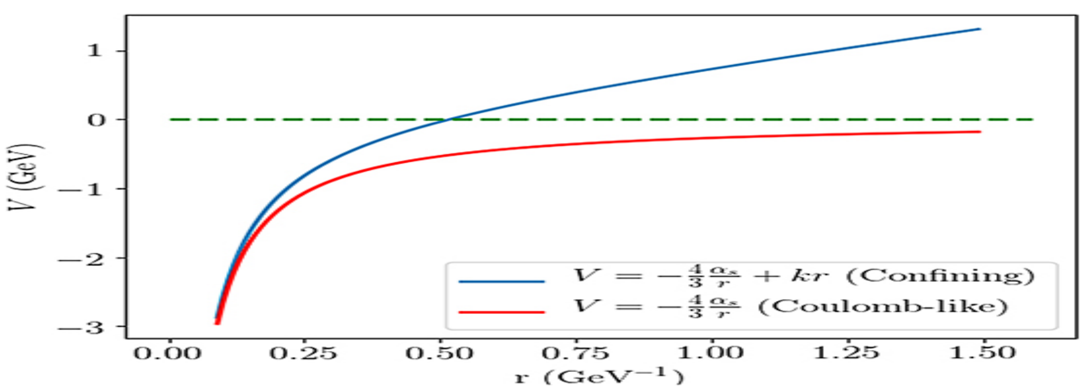


in QCD: C_A=3, & this dominates

α_s increases with distance

QED & QCD long-distance behavior is very different





Technical details

gluon self-couplings produce different behavior as r → infinity:

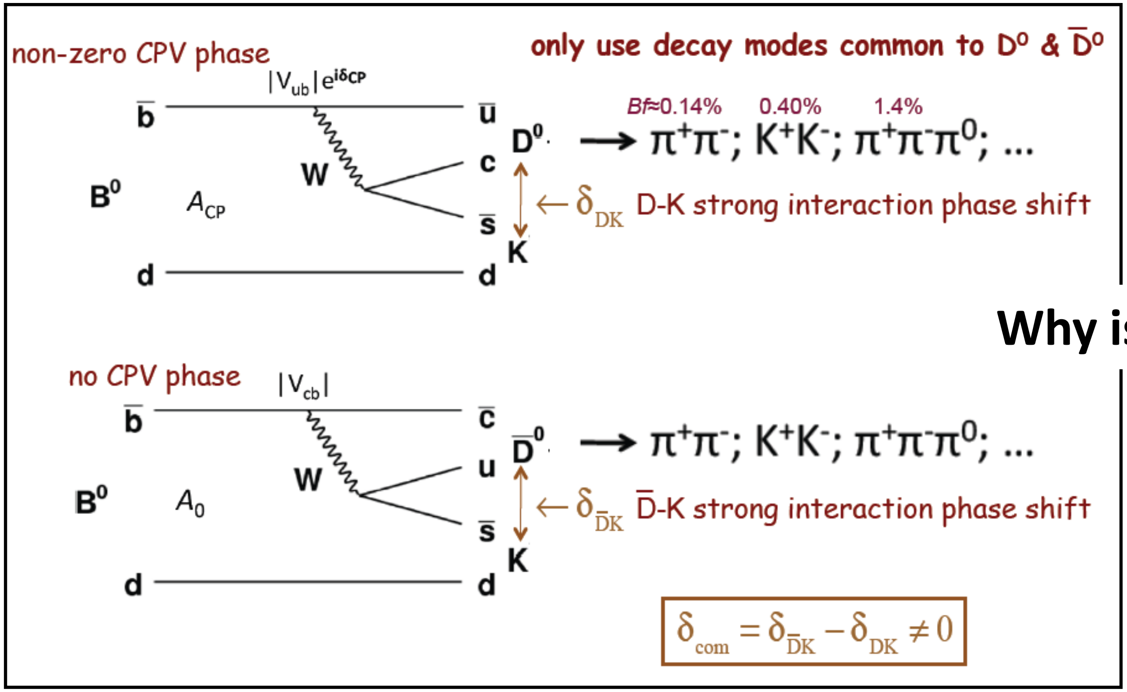
QED: $$\oiint_{r\to\infty} F_{\mu\nu}\tilde{F}_{\mu\nu}\, dA \to 0$$

no effect on dynamics, absent from the Lagrangian

QCD: $$\oiint_{r\to\infty} G^{a}_{\mu\nu}\tilde{G}^{a\mu\nu}\, dA \not\to 0$$

effects the dynamics, must be included in the Lagrangian

Question from lecture 2



Why is $\delta_{\bar{D}K} \neq \delta_{DK}$?

$\bar{q}$ $\qquad\qquad$ q

$\bar{D}K : \begin{pmatrix} c \\ \bar{s} \end{pmatrix}$ resonances $\qquad$ $DK : \begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix}$ no resonances

q $\qquad\qquad$ q

$\bar{K}$p and Kp interactions are different

$K^{-}p:$

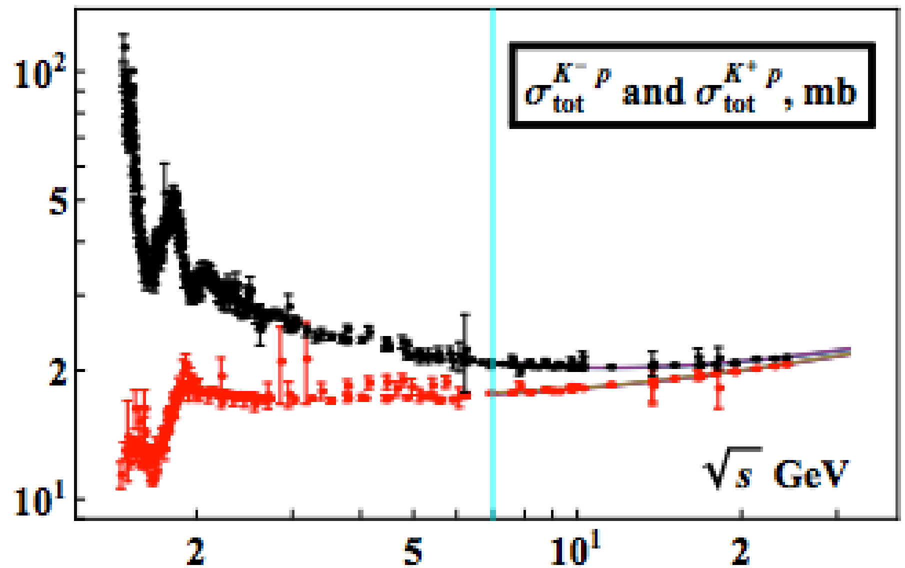
$\bar{u}\, s\, u\, u\, d$

resonances

$K^{+}p:$

$u\, \bar{s}\, u\, u\, d$

no resonances

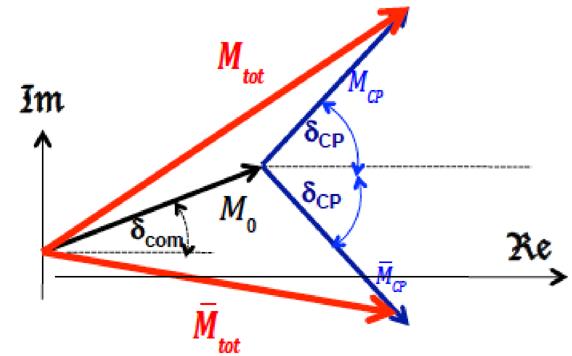


So, we can expect that DK can differ from $\bar{D}$ K.

In fact, LHCb measures $\delta_{KD} - \delta_{K\bar{D}} \approx 110^{\circ}$

Lecture 2 Summary I

δ_{CP} measurements require an interfering process with a non-zero δ_{com}



The $\mathcal{P}$ operator for Dirac spinors is the ©^{0} matrix; $\mathcal{P}^2$ =1

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Fermions and anti-fermions (i.e. spin ½ particles) have opposite $\mathcal{P}$

$\mathcal{C}$ operating on a fermion → an antifermion;

for ψ=fermion-antifermion eigenstate: $CP\psi = (-1)^{S+\ell+1}\psi$

Pions have P=-1

$$P\left|\pi^+\right\rangle = -\left|\pi^+\right\rangle$$

$$P\left|\pi^0\right\rangle = -\left|\pi^0\right\rangle$$

$$P\left|\pi^-\right\rangle = -\left|\pi^-\right\rangle$$

Lecture 2 Summary II

C eigenstates with:

C=+1 ➔ only even number of photons
C=-1 ➔ only odd number of photons

K mesons discovered in a cosmic ray cloud chamber experiment with a magnetic field

The $\tau - \theta$ puzzle was resolved by the discovery of $\mathcal{P}$ violations in the Weak Interactions

C and $\mathcal{P}$ violations in $\pi^{\pm}$ decays were found such that $C\mathcal{P}$ seemed to be conserved

The C-parity of the π^0 has to be +1: $C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$

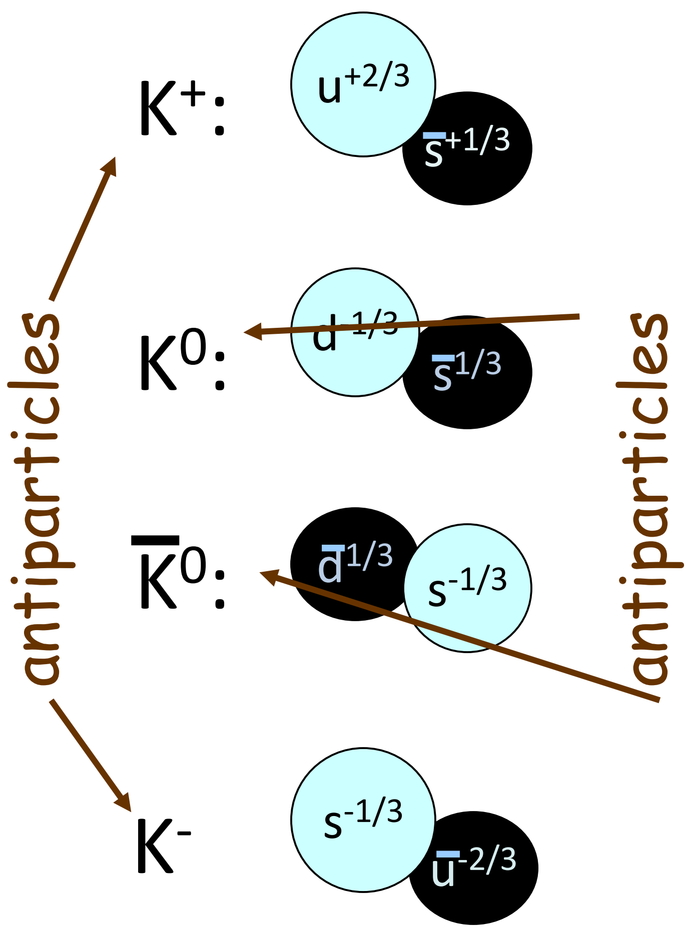
By (our) choice:

$$C\left|\pi^+\right\rangle = +\left|\pi^-\right\rangle$$

$$C\left|\pi^-\right\rangle = +\left|\pi^+\right\rangle$$

The K mesons

K mesons: K^+, K^-, K^0, $\bar{K}^0$



$u \quad \bar{s}$ $\qquad$ $S(\bar{s}\text{-quark})=+1$

Charge (Q) $= 2/3 + 1/3 = 1$

Strangeness (S) $= 0 + 1 = 1$

$d \quad \bar{s}$

$Q = -1/3 + 1/3 = 0$

$S = 0 + 1 = 1$

$s \quad \bar{d}$ $\qquad$ $S(s\text{-quark})=-1$

$Q = -1/3 + 1/3 = 0$

$S = -1 + 0 = -1$

$s \quad \bar{u}$

$Q = -1/3 - 2/3 = -1$

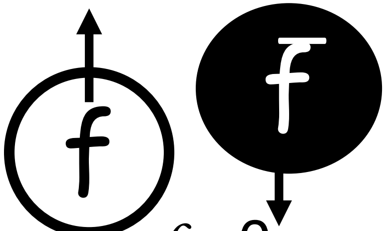
$S = -1 + 0 = -1$

$\mathcal{P}$ of the K mesons

fermion-antifermion "atom"
from Dirac Eqn

S=0

$\mathcal{P}$=-1



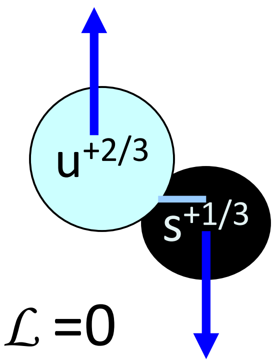
$\mathcal{L}$=0

$\mathcal{C}$=+1

"Para-positronium"

quarks are Dirac particles

K$^+$:

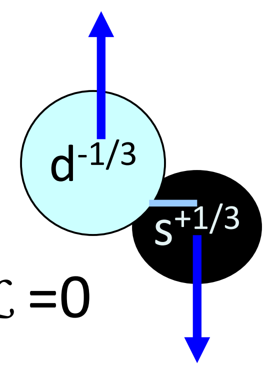


$\mathcal{P}$=-1

$\mathcal{L}$=0

same for K$^-$

K^0:

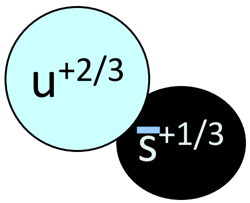


$\mathcal{P}$=-1

$\mathcal{L}$=0

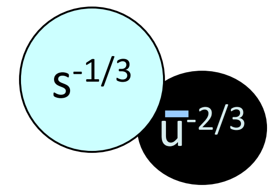
same for $\bar{K}^0$

$\mathcal{C}$-operator on K^+ and K^0?

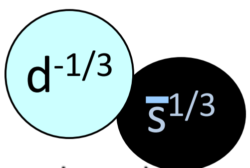


$|\mathrm{K}^+\rangle$

$\mathcal{C}\,\mathrm{K}^+ \rightarrow \xi_+ \mathrm{K}^-$

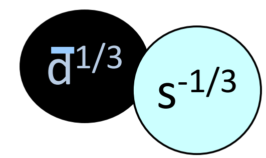


$\xi|\mathrm{K}^-\rangle$



$|\mathrm{K}^0\rangle$

$\mathcal{C}\,\mathrm{K}^0 \rightarrow \xi_0 \overline{\mathrm{K}}^0$



$\xi|\overline{\mathrm{K}}^0\rangle$

ξ_+ and ξ_0 can be either +1 or -1
the choice is arbitrary

I chose both ξ_+=+1 and ξ_0=1, same as the C-parity of the π^0

$$\mathcal{C}|\pi^+\rangle = +|\pi^-\rangle \qquad \mathcal{C}|\pi^-\rangle = +|\pi^+\rangle$$

$\mathcal{C}$, $\mathcal{P}$ & $\mathcal{CP}$ for □ and **K** mesons

Particle	$\mathcal{P}$	$\mathcal{C}$	$\mathcal{CP}$
$\lvert\pi^+\rangle$	-1	$+\lvert\pi^-\rangle$	$-\lvert\pi^-\rangle$
$\lvert\pi^0\rangle$	-1	$+\lvert\pi^0\rangle$	$-\lvert\pi^0\rangle$
$\lvert\pi^-\rangle$	-1	$+\lvert\pi^+\rangle$	$-\lvert\pi^+\rangle$
$\lvert K^+\rangle$	-1	$+\lvert K^-\rangle$	$-\lvert K^-\rangle$
$\lvert K^0\rangle$	-1	$+\lvert\bar{K}^0\rangle$	$-\lvert\bar{K}^0\rangle$
$\lvert\bar{K}^0\rangle$	-1	$+\lvert K^0\rangle$	$-\lvert K^0\rangle$
$\lvert K^-\rangle$	-1	$+\lvert K^+\rangle$	$-\lvert K^+\rangle$
©		-1	-1

$+1$

beware:
some literature uses

$$C\lvert K^0\rangle = -\lvert\bar{K}^0\rangle;\quad \mathcal{CP}\lvert K^0\rangle = +\lvert\bar{K}^0\rangle$$

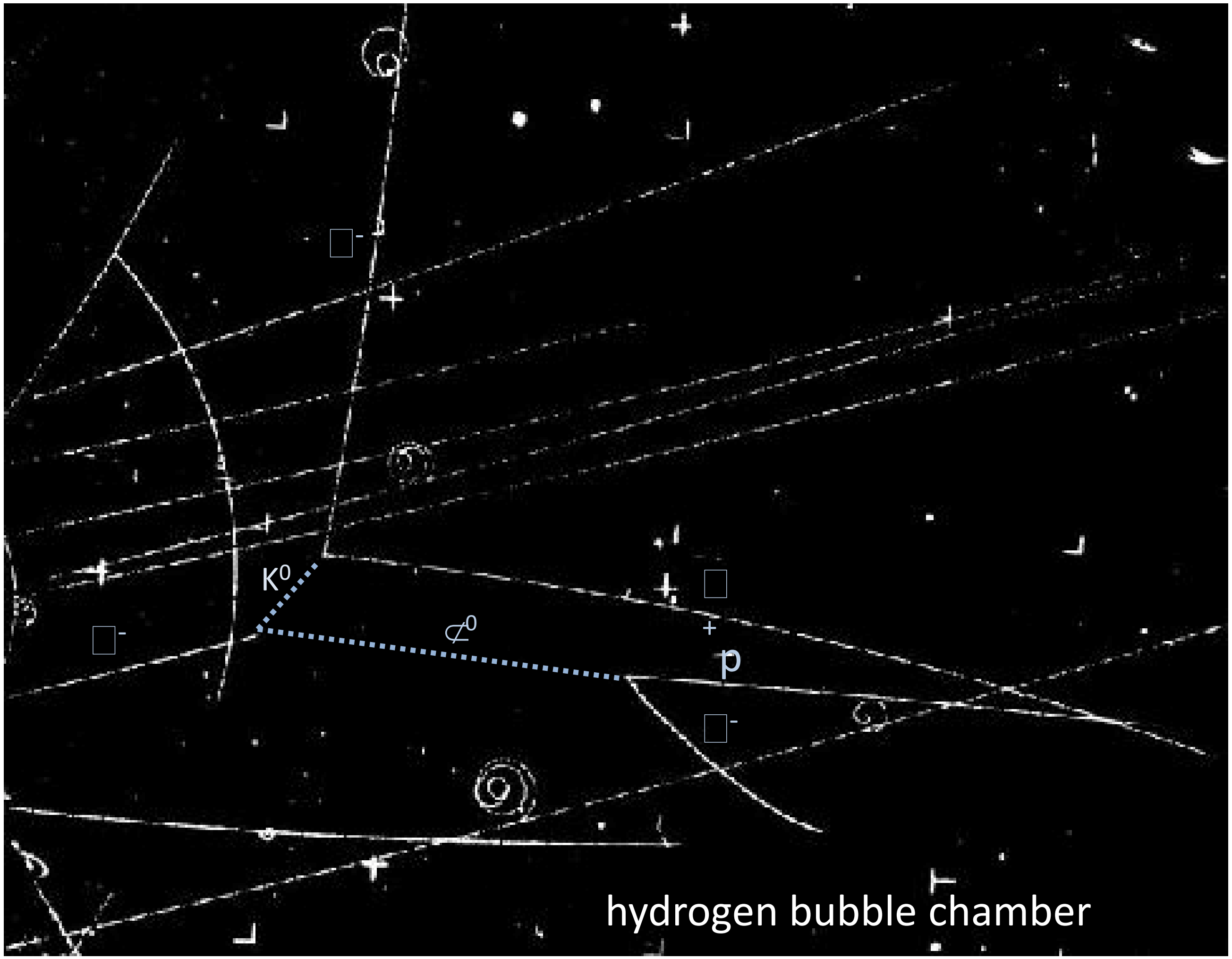
$$C\lvert\bar{K}^0\rangle = -\lvert K^0\rangle;\quad \mathcal{CP}\lvert\bar{K}^0\rangle = +\lvert K^0\rangle$$

But this is not the whole story

$□^{-}p \rightarrow K^{0}(\rightarrow □^{+}□^{-}) + ⊄^{0}(\rightarrow p□^{-})$

S=0

$□^{-}p$



must be

S=+1 ➔ K^{0}

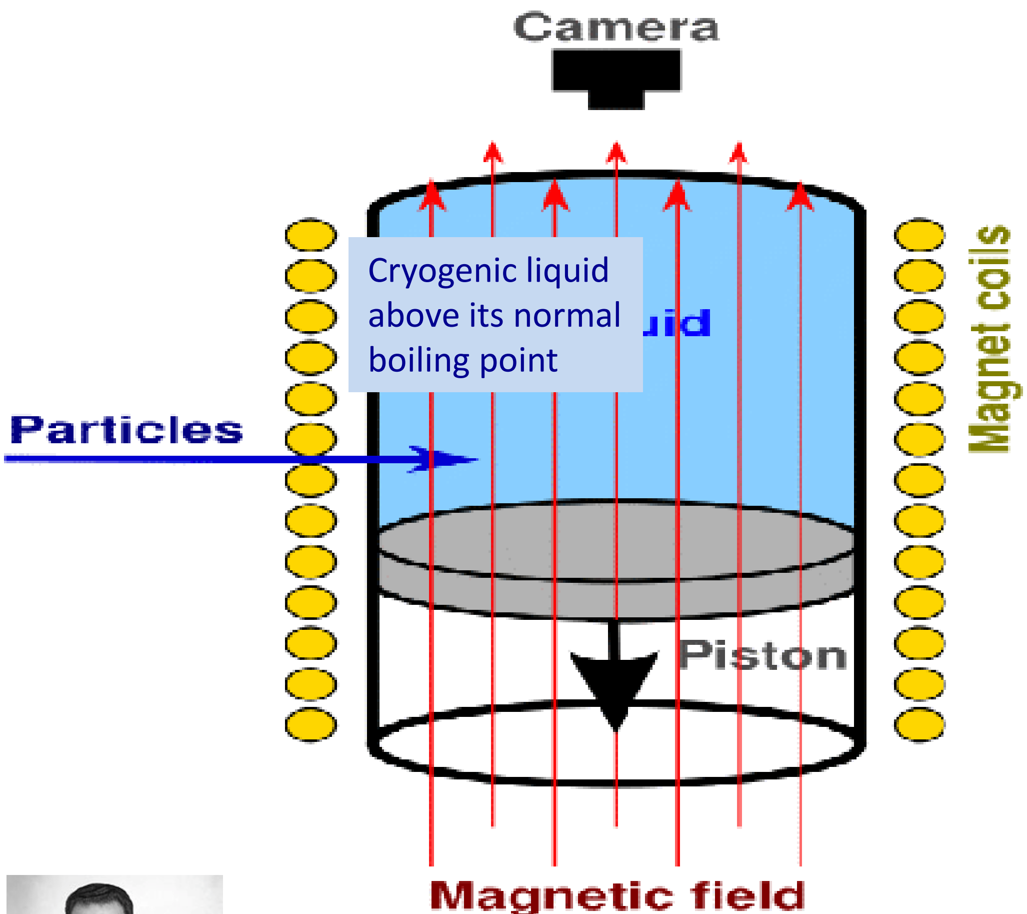
K^{0}?

~~$\bar{K}^{0}$?~~

S=-1

$⊄^{0}$

Bubble chambers



Pressurize the liquid to ~10 Atm
to keep it from boiling

Pass particle beam through liquid

Rapidly depressurize the liquid
--it starts to boil around the
track-induced ions.

Allow bubbles to grow for ~3 msec

Flash lamps; take photographs

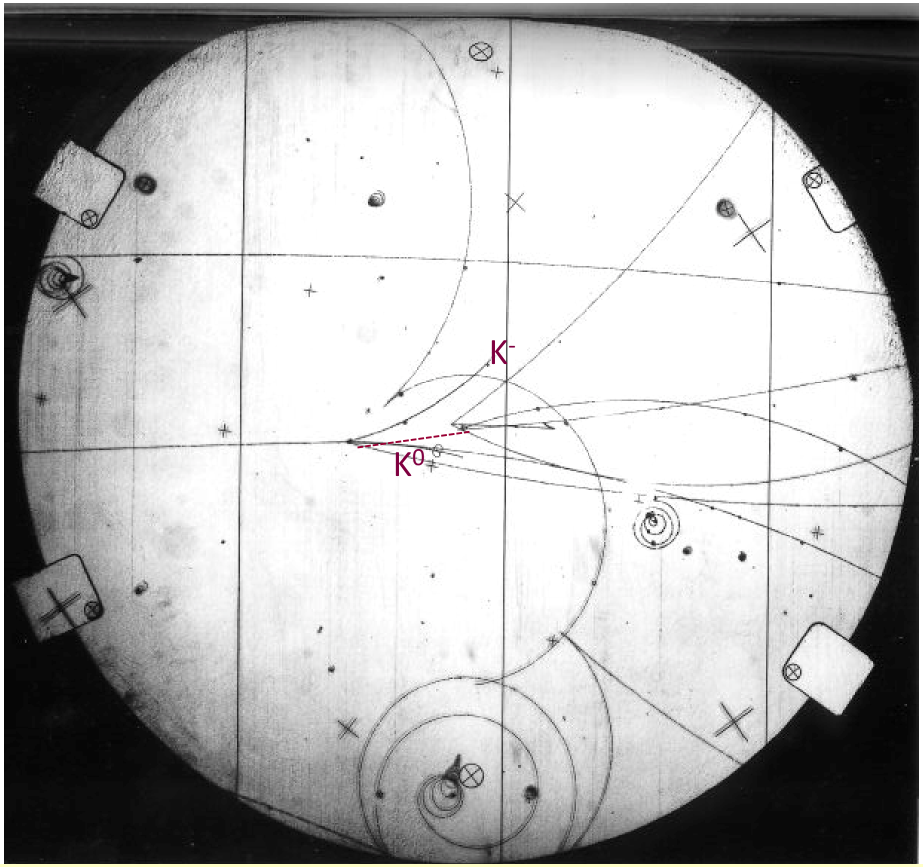
Recompress before general boiling
occurs.

Repeat

Donald Glaser
1926-2013

1959 Nobel physics prize

Bubble chamber event



K^- S=-1

K^0 S=+1

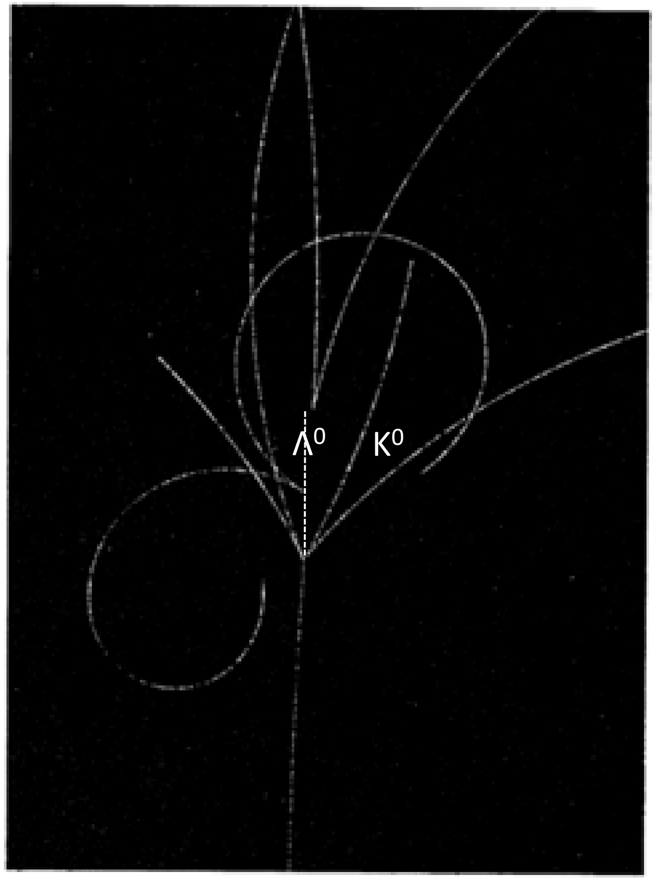
A careful study of this photograph reveals the reaction to be $\bar{p}\,p \rightarrow p\,\pi^+\,K^-\,\pi^-\,\pi^0\,K^0\,\bar{n}$, where

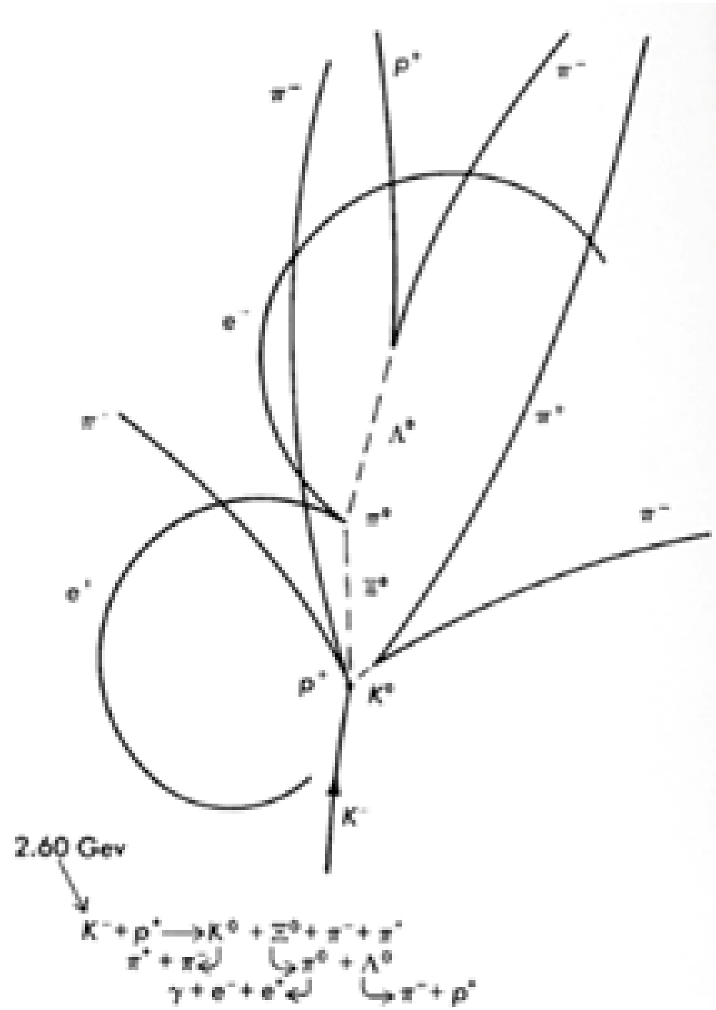
- the slow proton is identifed by its heavier ionisation,
- the K^0 subsequently decays into a pair of charged pions,
- the antineutron annihilates with a proton a short distance downstream from the primary interaction, to produce three charged pions,
- the neutral pion decays into two photons, which (unusually for a hydrogen chamber) both convert into e^+e^- pairs,
- (external particle detectors were used to identify the charged kaon).

Ξ^0 S=-2

$K^- p \rightarrow K^0\ \Xi^0\ \pi^+\ \pi^-$ event

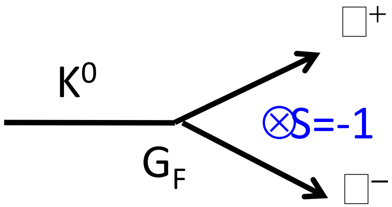
K^- S=-1 K^0 S=+1



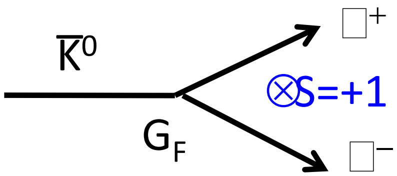


$K^0 \rightarrow \square^+\square^-$ or $\bar{K}^0 \rightarrow \square^+\square^-$?

cannot tell



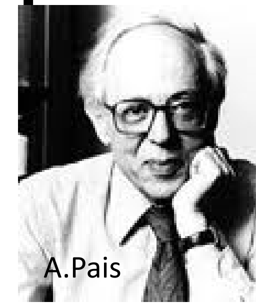
both decays are allowed



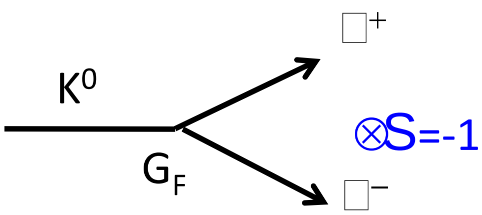
The K^0 and $\bar{K}^0$ mesons are coupled

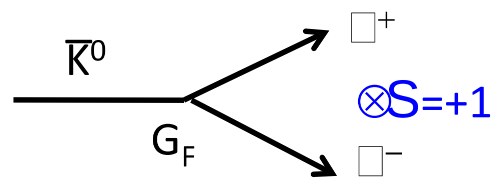
Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann and A. Pais
Phys. Rev. **97**, 1387 – Published 1 March 1955

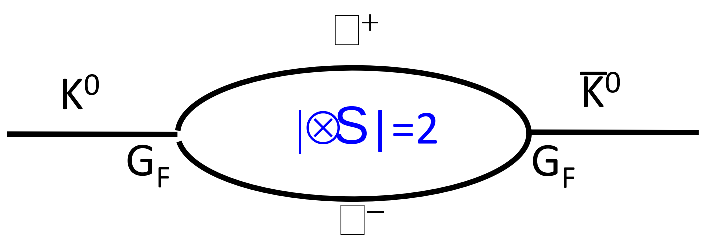


K^0 and $\bar{K}^0$ can both decay to □+□− via a |⊗S|=1 weak interaction





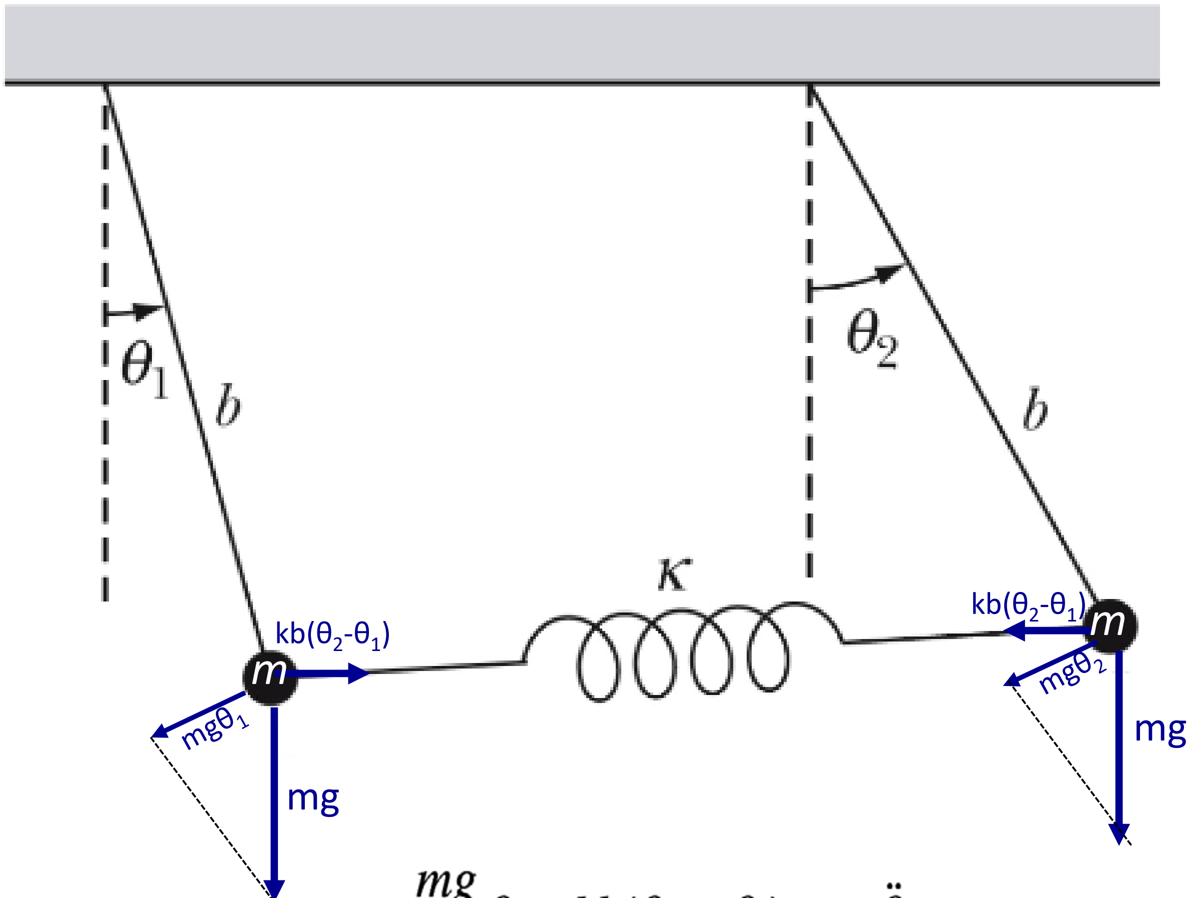
Thus, the K^0 and $\bar{K}^0$ are coupled by a |⊗S|=2, 2nd-order weak interaction



The coupling is very small $(G_F)^2$,
but the K^0 & $\bar{K}^0$ are coupled!!

2nd-order Weak Interaction

Coupled systems in classical physics



equations of motion:

$$-\frac{mg}{b}\theta_1 + kb(\theta_2 - \theta_1) = m\ddot{\theta}_1$$

$$-kb(\theta_2 - \theta_1) + \frac{mg}{b}\theta_2 = m\ddot{\theta}_2$$

Coupled oscillator problem

use:

$$\omega_0^2 = \frac{g}{b}$$

$$\varepsilon = b\frac{k}{m}$$

Equations of motion

$$(\omega_0^2 + \varepsilon)\theta_1 - \varepsilon\theta_2 = -\ddot{\theta}_1$$

$$-\varepsilon\theta_1 + (\omega_0^2 + \varepsilon)\theta_2 = -\hat{\theta}_2$$

matrix form

$$\begin{pmatrix} \omega_0^2 + \varepsilon & -\varepsilon \\ -\varepsilon & \omega_0^2 + \varepsilon \end{pmatrix}\begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix} = -\frac{d^2}{dt^2}\begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix}$$

$$\text{assume solutions of the form: } \theta_i(t) = a_i e^{i\omega t}$$

$$\begin{pmatrix} \omega_0^2 + \varepsilon - \omega^2 & -\varepsilon \\ -\varepsilon & \omega_0^2 + \varepsilon - \omega^2 \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = 0$$

Solve determinant eqn. for eigen-frequencies

$$\begin{vmatrix} \omega_0^2 + \varepsilon - \omega^2 & -\varepsilon \\ -\varepsilon & \omega_0^2 + \varepsilon - \omega^2 \end{vmatrix} = 0$$

pick positive solutions

$$\omega_- = \sqrt{\omega_0^2 + 2\varepsilon}$$

$$\omega_+ = \omega_0$$

Solve for the normal modes

for $\omega_-^2 = \omega_0^2 + 2\varepsilon$

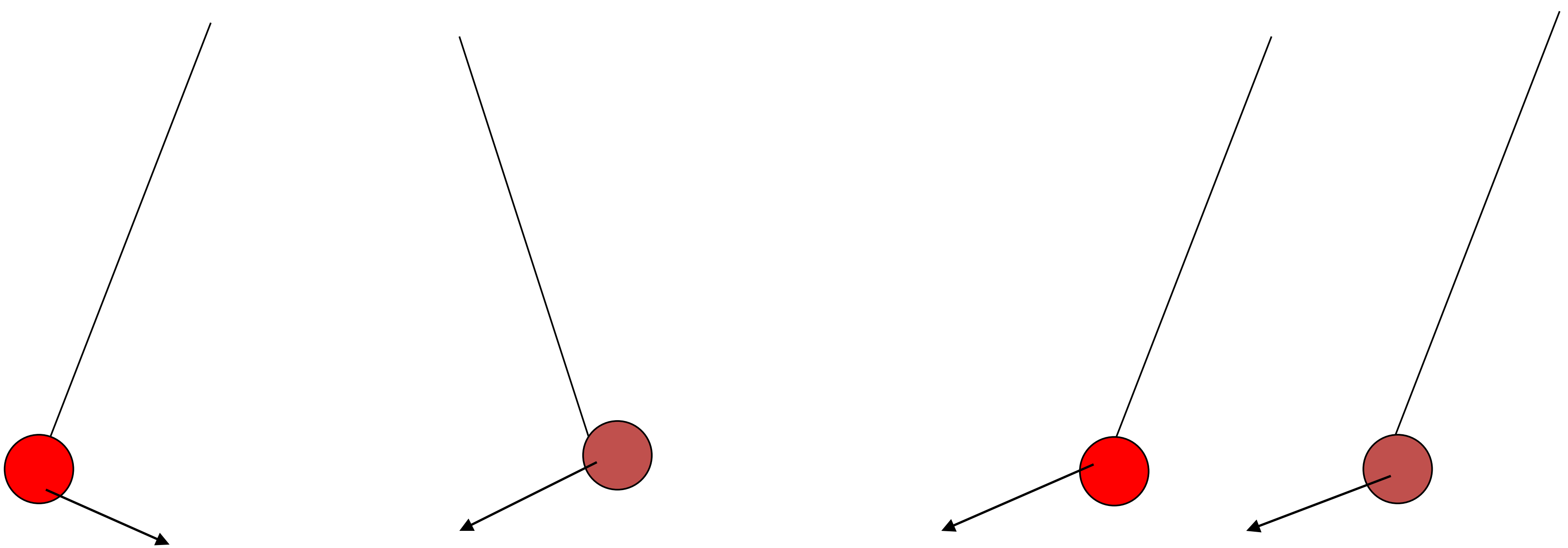
$$\begin{pmatrix} -\varepsilon & -\varepsilon \\ -\varepsilon & -\varepsilon \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = 0$$

$$a_1 = -a_2 \Rightarrow \Theta_-(t) = a\left(\theta_1 - \theta_2\right)e^{i\omega_- t}$$

for $\omega_+^2 = \omega_0^2$

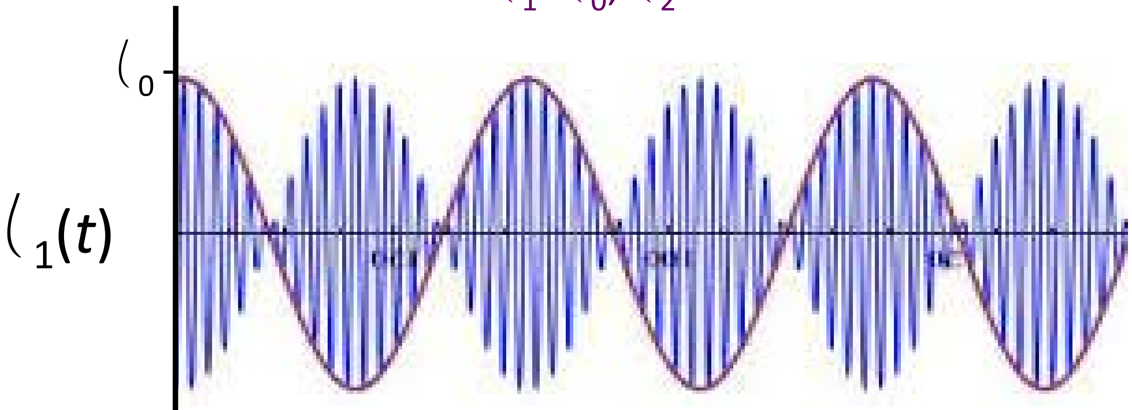
$$\begin{pmatrix} +\varepsilon & -\varepsilon \\ -\varepsilon & +\varepsilon \end{pmatrix}\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = 0$$

$$b_1 = b_2 \Rightarrow \Theta_+(t) = b\left(\theta_1 + \theta_2\right)e^{i\omega_+ t}$$

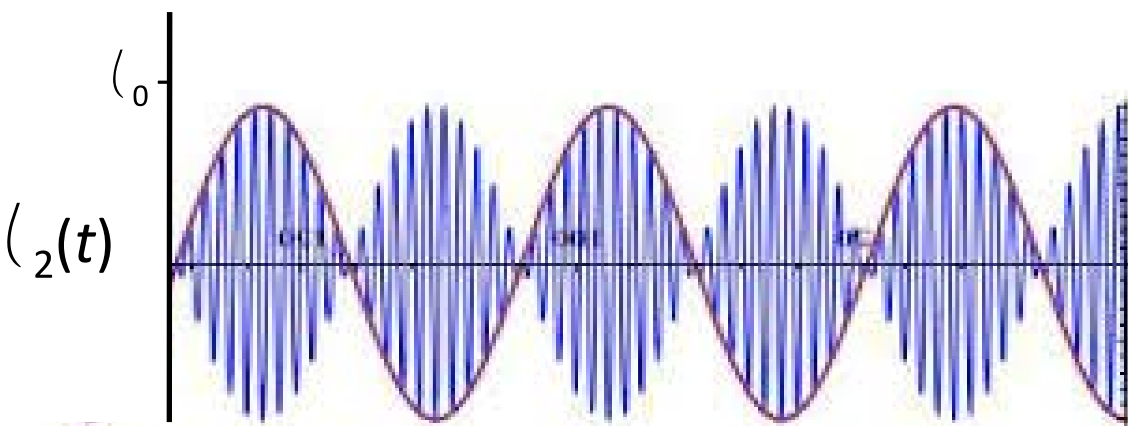


$(_1 - (_2$ mixing

Start with $(_1 = (_0;\ (_2 = 0$



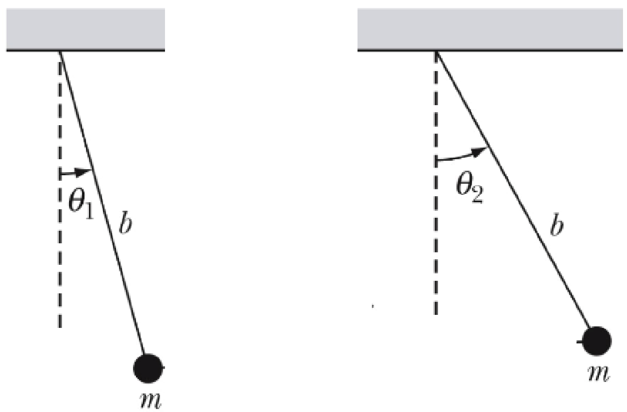
$$\theta_1(t) = \theta_0 \cos(\omega_1 - \omega_2)\mathrm{t} \times \cos\tfrac{1}{2}(\omega_1 + \omega_2)t$$

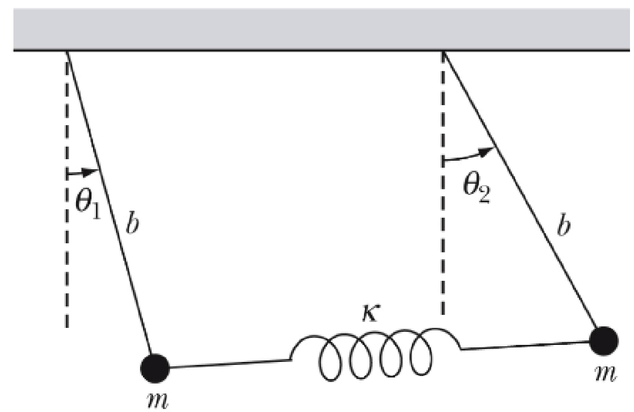


$$\theta_2(t) = \theta_0 \sin(\omega_1 - \omega_2)\mathrm{t} \times \sin\tfrac{1}{2}(\omega_1 + \omega_{2)})t$$

Common feature of coupled systems

a coupling drastically changes the system properties





$$\begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix} \text{are relevant}$$

$$\begin{pmatrix} \theta_1 - \theta_2 \\ \theta \;\; + \theta_2 \end{pmatrix} \text{are relevant}$$

even for very weak couplings

Prediction of a long-lived K^0 meson

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann and A. Pais
Phys. Rev. **97**, 1387 – Published 1 March 1955

... the θ^0 must be considered as a "particle mixture" exhibiting two distinct lifetimes, that each lifetime is associated with a different set of decay modes, and that no more than half of all θ^0's undergo the familiar decay into two pions.

- two neutral K mesons
- they have different lifetimes
- only one of them decays to $\pi^+\pi^-$

Pais Gell-Mann prediction

$$\text{just as}\begin{pmatrix}\theta_1\\ \theta_2\end{pmatrix}\Rightarrow\begin{pmatrix}\theta_1-\theta_2\\ \theta_1+\theta_2\end{pmatrix}\text{in a mechanical system}$$

$$\begin{pmatrix}K^0\\ \overline{K}^0\end{pmatrix}\Rightarrow\begin{pmatrix}K^0-\overline{K}^0\\ K^0+\overline{K}^0\end{pmatrix}\text{in the neutral } K \text{ meson system}$$

$\left(K^0-\bar{K}^0\right)$ and $\left(K^0+\bar{K}^0\right)$ are CP eigenstates with opposite eigenvalues and different masses, decay modes & lifetimes

The $K^0 – \overline{K}^0$ system

In a neutral K meson system, the $K^0 \leftrightarrow \overline{K}^0$ coupling makes it a time-dependent mixture of K^0 and $\overline{K}^0$.

$$\Psi(\mathrm{t}) = a(t)\left|K^0\right\rangle + b(t)\left|\overline{K}^0\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Schrodinger's eqn gives the time dependence:

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathrm{t}) = H\Psi(t)$$

H = Hamiltonian operator, in the K restframe, *H*= "mass matrix:"

$$H = \begin{pmatrix} \left\langle K^0\middle|H\middle|K^0\right\rangle & \left\langle K^0\middle|H\middle|\overline{K}^0\right\rangle \\ \left\langle \overline{K}^0\middle|H\middle|K^0\right\rangle & \left\langle \overline{K}^0\middle|H\middle|\overline{K}^0\right\rangle \end{pmatrix}$$

Properties of the Mass Matrix

-- assuming *CP* symmetry --

I ignore K^0 life-time terms (for now)

$\mathcal{CP}$T symmetry requires: $\langle K^0|H|K^0\rangle = M_{K^o} = M_{\bar{K}^0} = \langle \bar{K}^0|H|\bar{K}^0\rangle = M_K$

$\mathcal{CP}$ symmetry says: $\langle \bar{K}^0|H|K^0\rangle = \mathcal{A}_{K^0\to\bar{K}^0} = \mathcal{A}_{\bar{K}^0\to K^0} = \langle K^0|H|\bar{K}^0\rangle = \delta$

$$H = \begin{pmatrix} \langle K^0|H|K^0\rangle & \langle K^0|H|\bar{K}^0\rangle \\ \langle \bar{K}^0|H|K^0\rangle & \langle \bar{K}^0|H|\bar{K}^0\rangle \end{pmatrix} = \begin{pmatrix} M_K & \delta \\ \delta & M_K \end{pmatrix}$$

assume solutions of the form: $\psi_i(t) = a_i e^{-i\lambda_i t}$

Schrodinger's equation for energy eigenstates;

$$\begin{pmatrix} M_K & \delta \\ \delta & M_K \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t} = i\hbar\frac{\partial}{\partial t}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t}$$

$$\Rightarrow \begin{pmatrix} M_K - \lambda_i & \delta \\ \delta & M_K - \lambda_i \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} = 0 \quad (\hbar = 1)$$

Solutions for ⎠(t)

world's simplest eigenvalue equation:

$$\begin{vmatrix} M_K - \lambda_i & \delta \\ \delta & M_K - \lambda_i \end{vmatrix} = 0$$

eigenvalues   eigenstates

$$i = 1: \quad \lambda_1 = M_K - \delta; \quad \left|K_1\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\overline{K}^0\right\rangle\right)$$

$$i = 2: \quad \lambda_2 = M_K + \delta; \quad \left|K_2\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\overline{K}^0\right\rangle\right)$$

using:

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

$$\boxed{\begin{aligned} CP\left|K_1\right\rangle &= \tfrac{1}{\sqrt{2}}\left(-\left|\overline{K}^0\right\rangle + \left|K^0\right\rangle\right) = +\left|K_1\right\rangle \\ CP\left|K_2\right\rangle &= \tfrac{1}{\sqrt{2}}\left(-\left|\overline{K}^0\right\rangle - \left|K^0\right\rangle\right) = -\left|K_2\right\rangle \end{aligned}}$$

$\mathcal{CP}$ even

$\mathcal{CP}$ odd

Decay modes of the K_1 and K_2 states

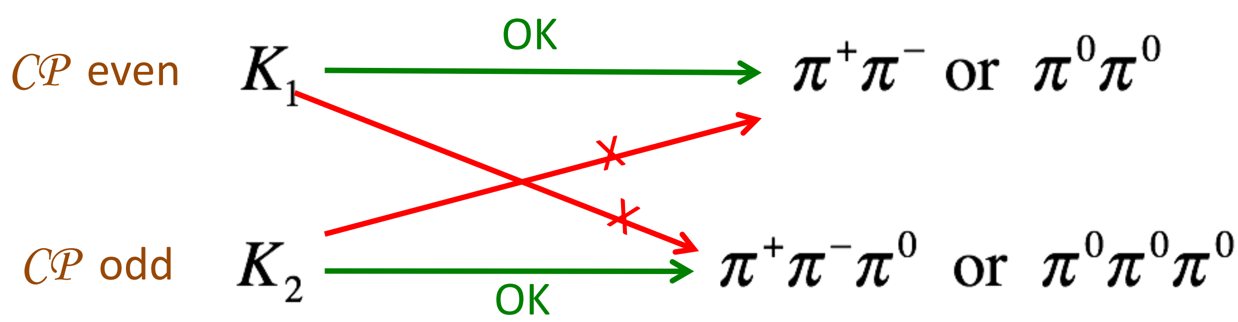
$$CP|\pi^{\pm}\rangle = -1|\pi^{\mp}\rangle$$
$$CP|\pi^{0}\rangle = -1|\pi^{0}\rangle$$

$$\boxed{\begin{aligned} CP\left(|\pi^+\rangle|\pi^-\rangle\right) &= +|\pi^+\rangle|\pi^-\rangle \\ CP\left(|\pi^+\rangle|\pi^-\rangle|\pi^0\rangle\right) &= -|\pi^+\rangle|\pi^-\rangle|\pi^0\rangle \end{aligned}}$$

$\mathcal{CP}$ even

$\mathcal{CP}$ odd

Gell-Mann & Pais:
"...no more than half of all θ^0's...decay into two pions."



$K_1 \rightarrow \pi\pi \Leftarrow$ phase space large

lifetime is short: $\tau \approx 0.1\text{ns}$

$K_2 \rightarrow \pi\pi\pi \Leftarrow$ phase space small

lifetime is long: $\tau \approx 50\text{ns}$

K_1 & K_2 lifetimes

相空间

$K_2 \rightarrow \square^+ \square^- \square^0$ has little phase space

$$Q_{K_2} = m_K - 3m_{\square} \approx 80 \text{ MeV}$$

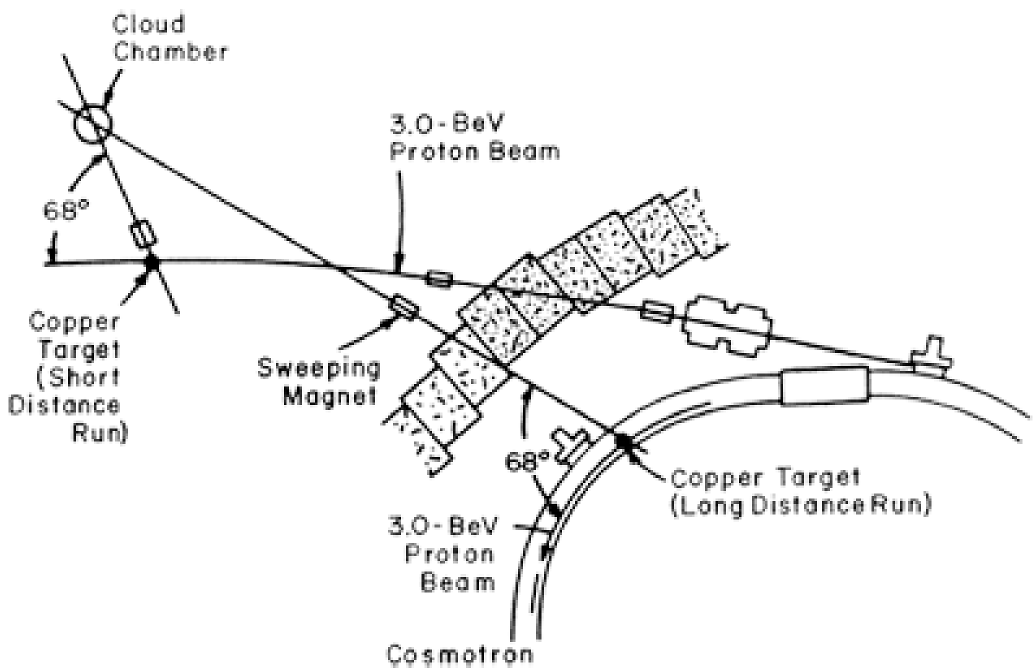
$K_1 \rightarrow \square^+ \square^-$ has more phase space

$$Q_{K_1} = m_K - 2m_{\square} \approx 215 \text{ MeV}$$

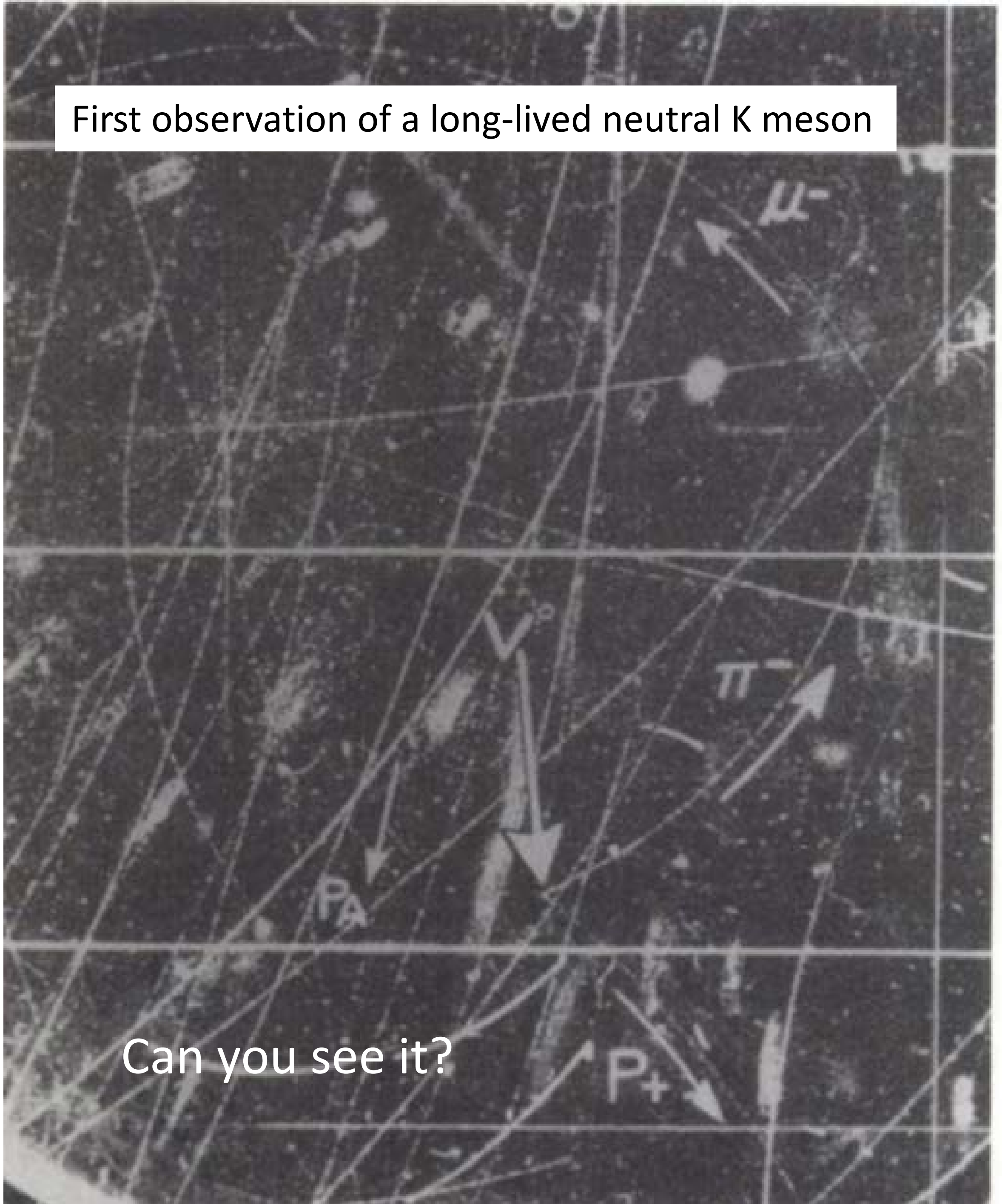
Easier for K_1 to decay $\rightarrow |_{K_1} << |_{K_2}$

1956: Search for long-lived K^0

Brookhaven-Columbia Expt



First observation of a long-lived neutral K meson



Can you see it?

K_S & K_L mesons

Two neutral K mesons were identified:

$K_1 \rightarrow$ □$^+$□$^-$ $\quad |_{K_S} \approx$ 0.1 nanosecs ($\approx 10^{-10}$s)

500x bigger

$K_2 \rightarrow$ □$^+$□$^-$□^{0} $\quad |_{K_L} \approx$ 50 nanosecs ($\approx 5\text{x}10^{-8}$s)

$K_1 \longrightarrow K_S$ "K-Short"

"capital S"

$K_2 \longrightarrow K_L$ "K-long"

"capital L"

K_S & K_L mesons

K_S^0 DECAY MODES		Fraction (Γ_i/Γ)
Hadronic modes		
$\pi^0\pi^0$		(30.69 ± 0.05) %
$\pi^+\pi^-$		(69.20 ± 0.05) %
Semileptonic modes		
$\pi^\pm e^\mp \nu_e$	[p]	$(7.04 \pm 0.08) \times 10^{-4}$

Mean life $\tau = (0.8954 \pm 0.0004) \times 10^{-10}$ s

K_L^0 DECAY MODES		Fraction (Γ_i/Γ)
Semileptonic modes		
$\pi^\pm e^\mp \nu_e$	[p]	(40.55 ± 0.11) %
Called K^0_{e3}.		
$\pi^\pm \mu^\mp \nu_\mu$	[p]	(27.04 ± 0.07) %
Hadronic modes		
$3\pi^0$		(19.52 ± 0.12) %
$\pi^+\pi^-\pi^0$		(12.54 ± 0.05) %

Mean life $\tau = (5.116 \pm 0.021) \times 10^{-8}$ s

$\mathcal{C}$, $\mathcal{P}$ & $\mathcal{CP}$ for □ and **K** mesons

Particle	$\mathcal{P}$	$\mathcal{C}$	$\mathcal{CP}$
$\|\pi^+\rangle$	-1	$+\|\pi^-\rangle$	$-\|\pi^-\rangle$
$\|\pi^0\rangle$	-1	$+\|\pi^0\rangle$	$-\|\pi^0\rangle$
$\|\pi^-\rangle$	-1	$+\|\pi^+\rangle$	$-\|\pi^+\rangle$
$\|K^+\rangle$	-1	$+\|K^-\rangle$	$-\|K^-\rangle$
$\|K_S\rangle$	-1	$-\|K_S\rangle$	$+\|K_S\rangle$
$\|K_L\rangle$	-1	$+\|K_L\rangle$	$-\|K_L\rangle$
$\|K^-\rangle$	-1	$+\|K^+\rangle$	$-\|K^+\rangle$
©		-1	-1

$+1$

K_S & K_L mesons

K_S^0 DECAY MODES		Fraction (Γ_i/Γ)
Hadronic modes		
$\pi^0\pi^0$		(30.69 ± 0.05) %
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$\pi^\pm e^\mp \nu_e$	[p]	$(7.04\pm0.08)\times10^{-4}$

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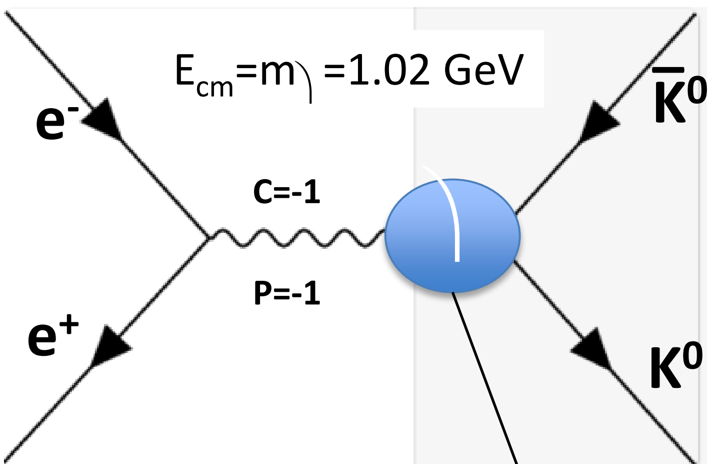
Called K_{e3}^0.		
$\pi^\pm \mu^\mp \nu_\mu$	[p]	$(27.04\ \pm0.07\ )$ %
Hadronic modes		
$3\pi^0$		$(19.52\ \pm0.12\ )$ %
$\pi^+\pi^-\pi^0$		$(12.54\ \pm0.05\ )$ %

Mean life $\tau = (5.116\pm0.021)\times10^{-8}$ s

Production of K_S and K_L mesons

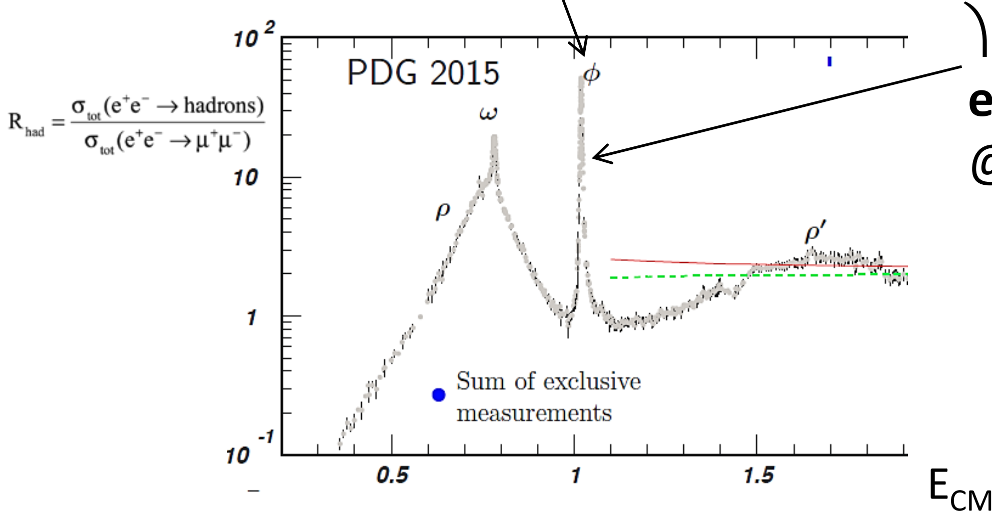
K_L & K_S mesons in e^+e^- annihilation



need K^0 and $\bar{K}^0$ with $J^{PC}=1^{--}$

- J=1 :   K and $\bar{K}$ in a *P*-wave
- P=-1: $(-1)_K\,(-1)_K\,(-1)_{P\text{-wave}}$
- C=-1: $(+1)_{K_S}\,(-1)_{K_L}$

only K_SK_L has C=-1



) -factory:

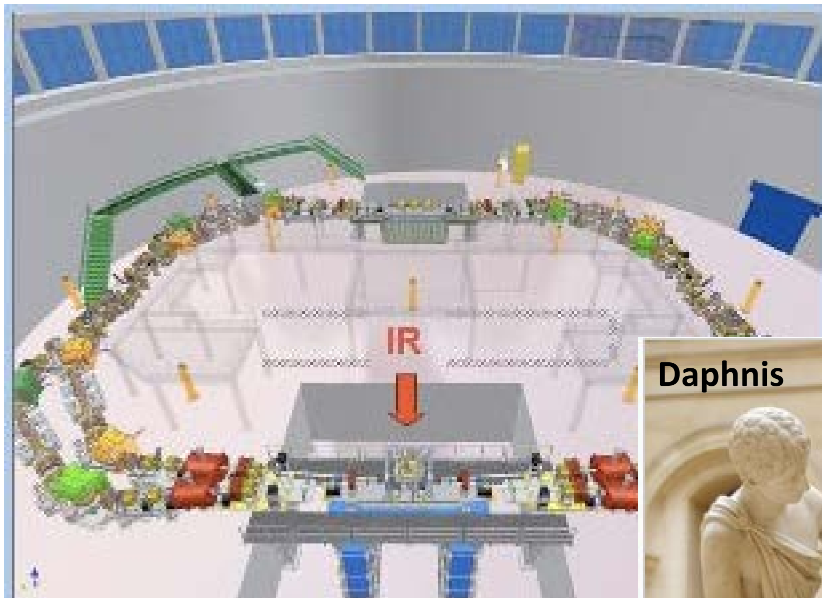
$e^+e^- \to\ ) \to K_SK_L$

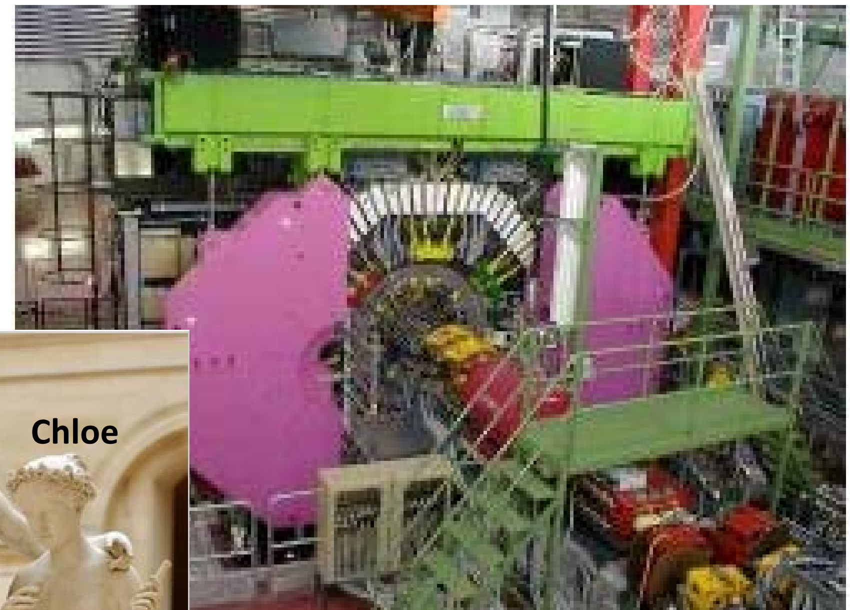
@ E_{CM}=1.02 GeV

e^+e^- ϕ-factory at Frascati, Italy

Daϕne collider

KLOE detector

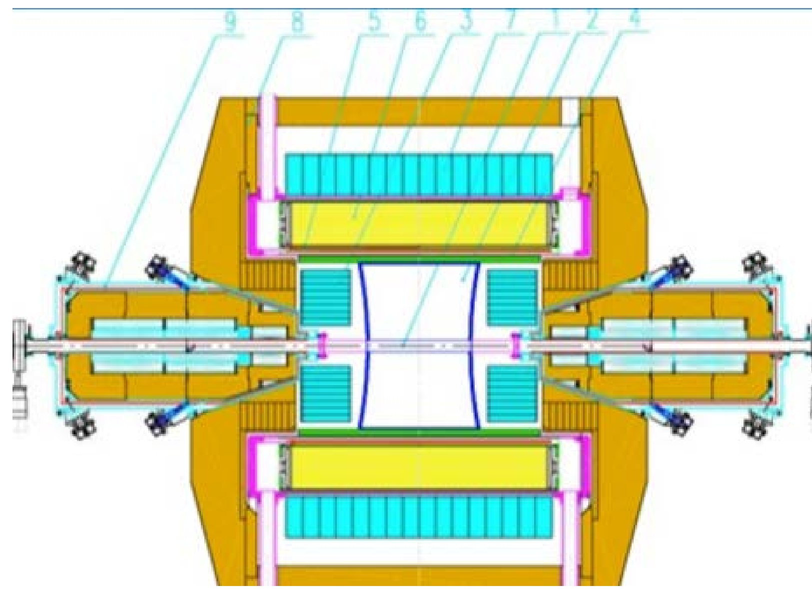




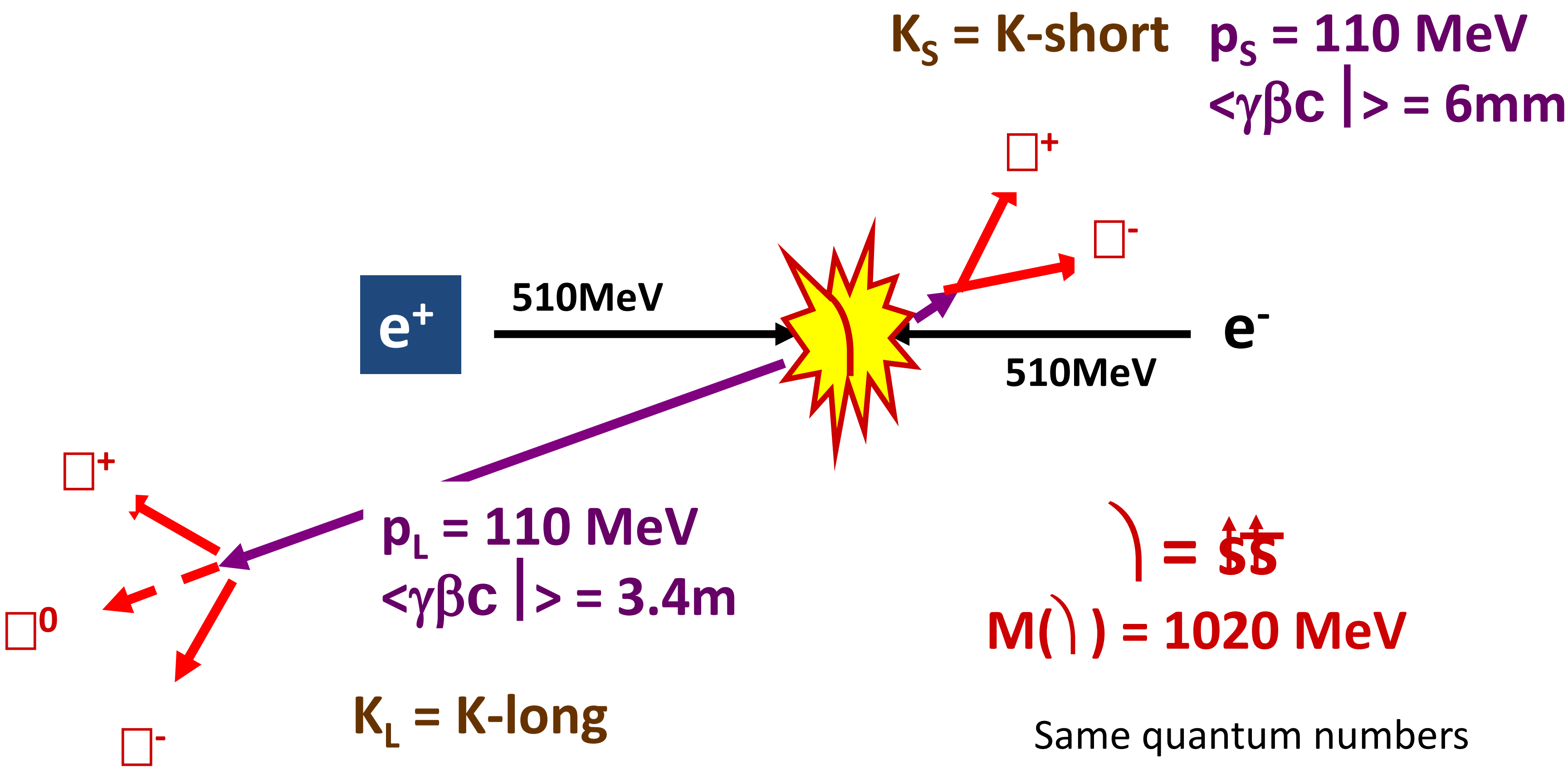
e^+e^- ϕ-factory in Novosibirsk, Russia

VEPP collider

CMD detector



K_L & K_S mesons from an e^+e^-) -factory



Same quantum numbers
As ortho-positronium

$\rightarrow K_L + K_S$

"quantum-correlated" decays

99.9%: □□ $\leftarrow K_S \leftarrow$ ——

of all events $\rightarrow K_L$

$3\pi \approx 32\%$

K^o

$\overline{K}^0$

$\pi^{\mp} e^{\pm} \upsilon \approx 41\% \quad (K^0_{e3})$

$\pi^{\mp} \mu^{\pm} \upsilon \approx 27\% \quad (K^0_{\mu 3})$

"flavor-tagged" decays

0.1%:

of all events

$K_{e^+(\mu^+)3}$ $\leftarrow$ K^o

$K_{e^-(\mu^-)3}$ $\leftarrow$ $\overline{K}^0$

$\overline{K}^o$ $\quad K_S \quad 50\%$

K^0 $\quad K_L \quad 50\%$

CHARM-FACTORIES

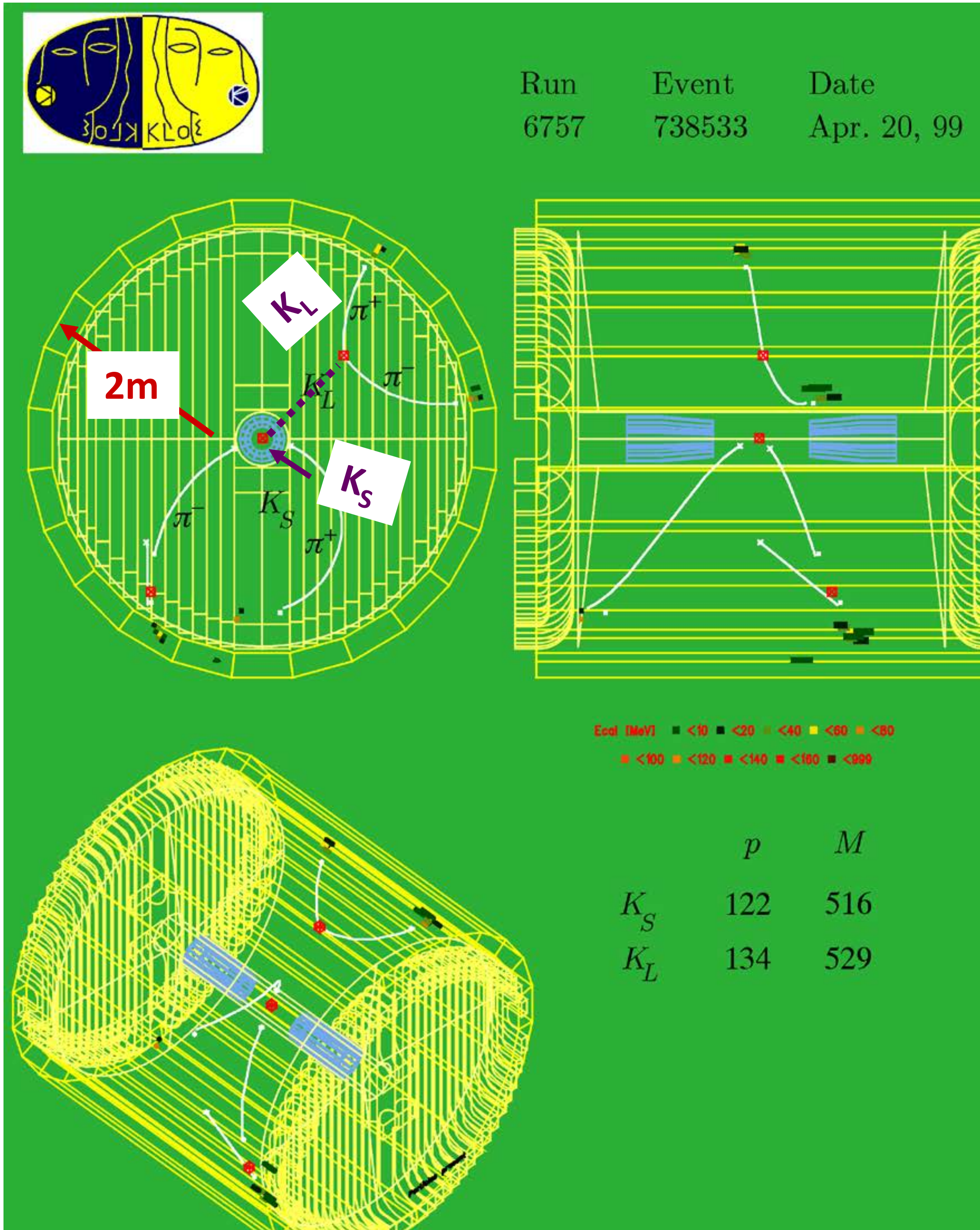
$$\text{BEPC/BES3}: \ \psi'' \begin{array}{l} \rightarrow \text{quantum correlated} \approx \text{few}\% \\ \rightarrow \text{flavor tagged} \approx 95\% \end{array}$$

B-FACTORIES

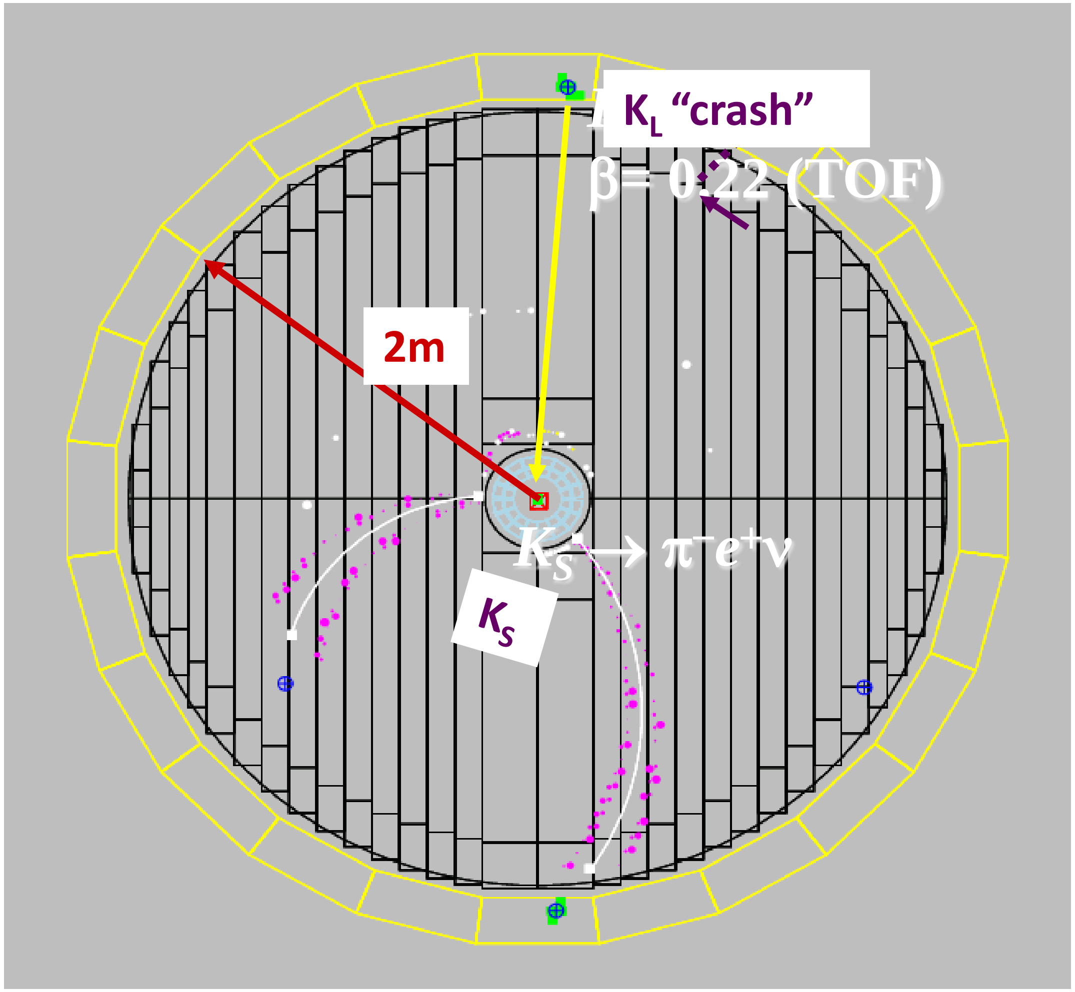
$$\text{Belle/BaBar}: \ \Upsilon(4S) \begin{array}{l} \rightarrow \text{quantum correlated} \approx 1\% \\ \rightarrow \text{flavor tagged} \approx 99\% \end{array}$$

KLOE Experiment in Italy

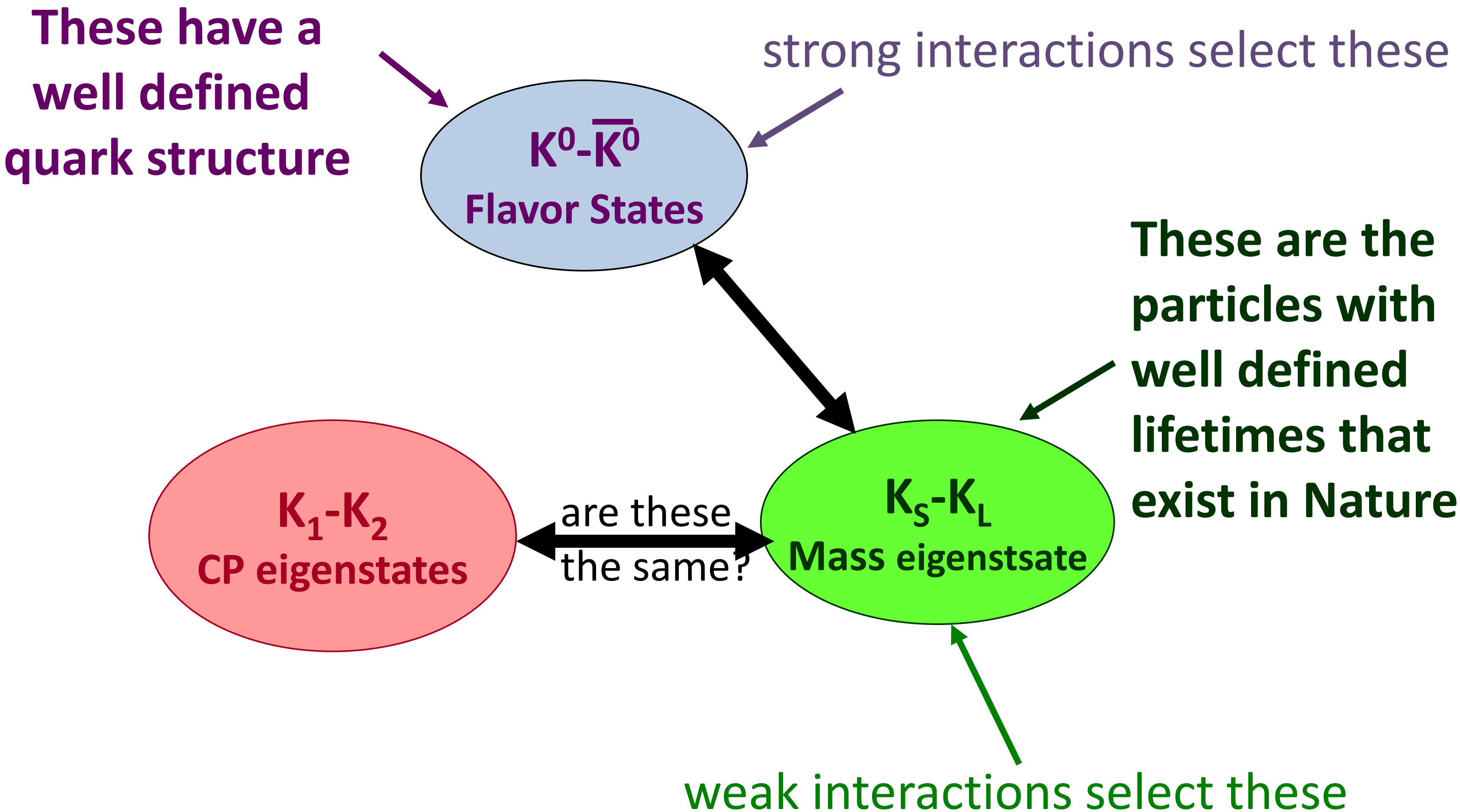
In this event the K_L only travels ~1m before it decays



Usually, the K_L traverses to entire 2m radius of the drift chamber



Neutral K mesons "Basis" sets



$K^0 \leftrightarrow \bar{K}^0$ oscillations (mixing)

Now let us consider decay times

$$|K_L(t)\rangle = e^{-i(M_L+\frac{i}{2}\Gamma_L)t}|K_L(0)\rangle$$
$$|K_S(t)\rangle = e^{-i(M_S+\frac{i}{2}\Gamma_S)t}|K_S(0)\rangle$$

eigenstates

start at t=0 with a K^0:

$$|K^0(t=0)\rangle = -\tfrac{1}{\sqrt{2}}\left(|K_S(t=0)\rangle + |K_L(t=0)\rangle\right)$$

then, at a later time t:

$$|K^0(t)\rangle = -\tfrac{1}{\sqrt{2}}\left(e^{-i(M_S+\frac{i}{2}\Gamma_S)t}|K_S(0)\rangle + e^{-i(M_L+\frac{i}{2}\Gamma_L)t}|K_L(0)\rangle\right)$$
$$= f_+(t)|K^0\rangle + f_-(t)|\bar{K}^0\rangle$$

$$f_\pm(t) = \tfrac{1}{2}\left[e^{-i(M_S+\frac{i}{2}\Gamma_S)t} \pm e^{-i(M_L+\frac{i}{2}\Gamma_L)t}\right]$$

These are the K^0 and $\bar{K}^0$ rates we measure

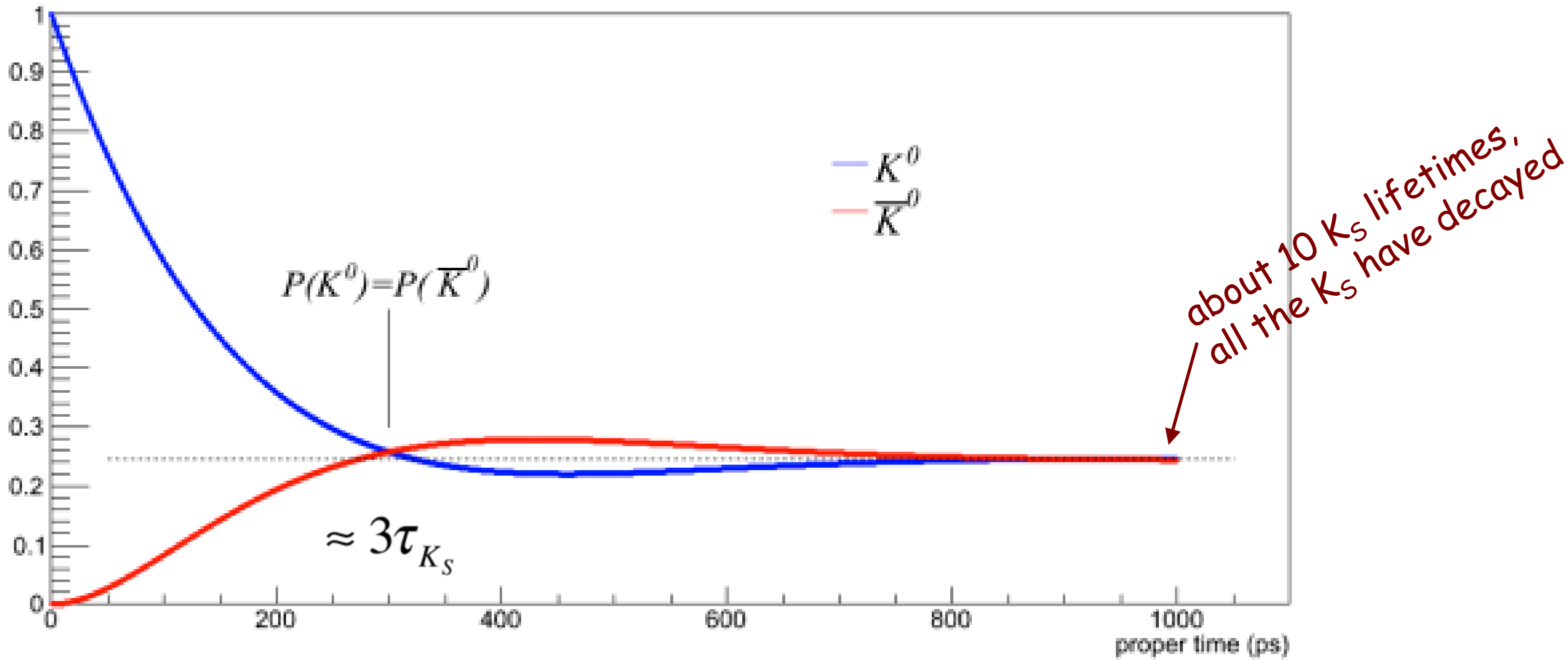
$$I(K^0 \to K^0;t) = I_0\left|\langle K^0|K^0(t)\rangle\right|^2 = I_0\left|f_+(t)\right|^2$$

$$I(K^0 \to \bar{K}^0;t) = I_0\left|\langle \bar{K}^0|K^0(t)\rangle\right|^2 = I_0\left|f_-(t)\right|^2$$

I_0 = beam intensity (# of particles/s)

K^0 survival; $\overline{K}^0$ appearance

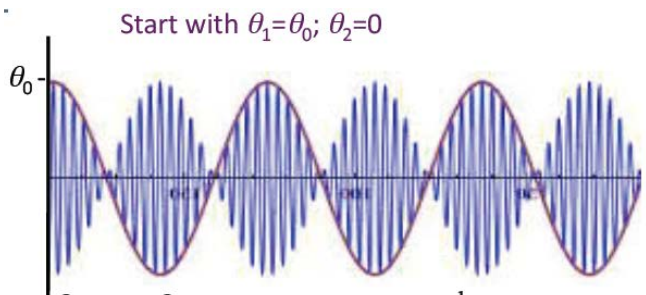
--strangeness oscillations--



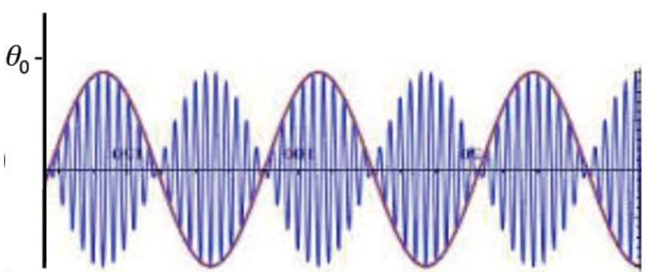
$$I(K^0 \to K^0;t) = \tfrac{1}{4} I_0 \left[e^{-\Gamma_L t} + e^{-\Gamma_S t} + 2e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos \Delta M_K t \right]$$

$$I(K^0 \to \overline{K}^0;t) = \tfrac{1}{4} I_0 \left[e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos \Delta M_K t \right]$$

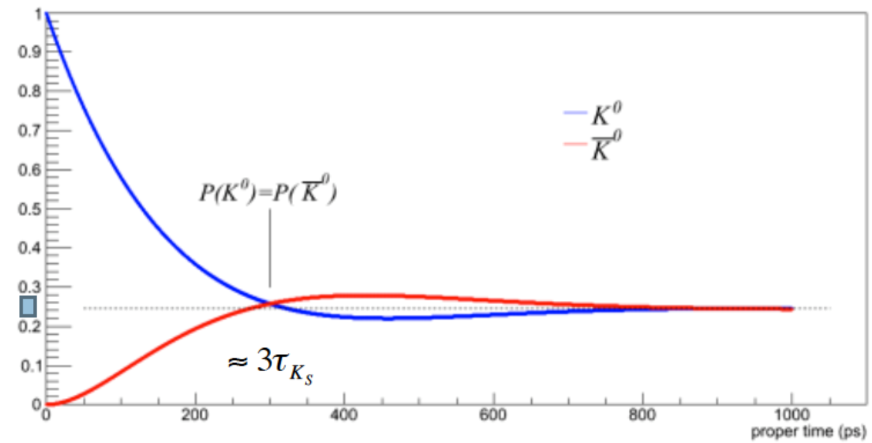
Comparison with classical system



$$\theta_1(t) = \theta_0 \cos(\omega_1 - \omega_2)\text{t} \times \cos\tfrac{1}{2}(\omega_1 + \omega_2)t$$



$$\theta_2(t) = \theta_0 \sin(\omega_1 - \omega_2)\text{t} \times \sin\tfrac{1}{2}(\omega_1 + \omega_{2)})t$$

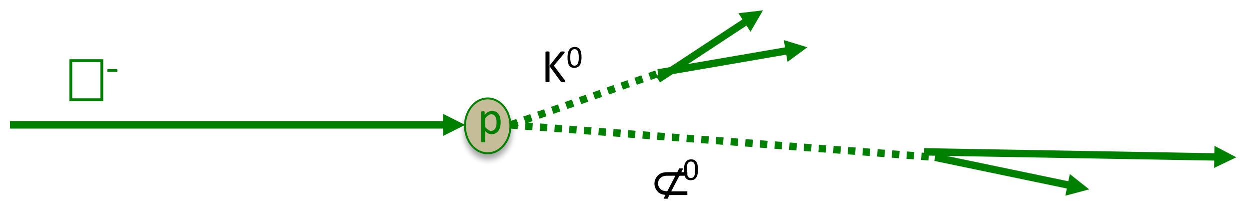


$$I(K^0 \to K^0;t) = \tfrac{1}{4} I_0 \left[e^{-\Gamma_L t} + e^{-\Gamma_S t} + 2e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos \Delta M_K t \right]$$

$$I(K^0 \to K^0;t) = \tfrac{1}{4} I_0 \left[e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos \Delta M_K t \right]$$

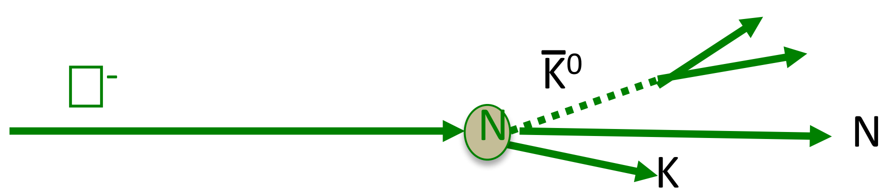
Producing K mesons with □ beams

Threshold for producing a K^0 (or K^+)



$\square^-\ p \rightarrow K^0\ \not\subset^0$: $E_{cm} > 1.61$ GeV; $E_{\square} > 0.9$ GeV

Threshold for producing a $\bar{K}^0$ (or K^-)



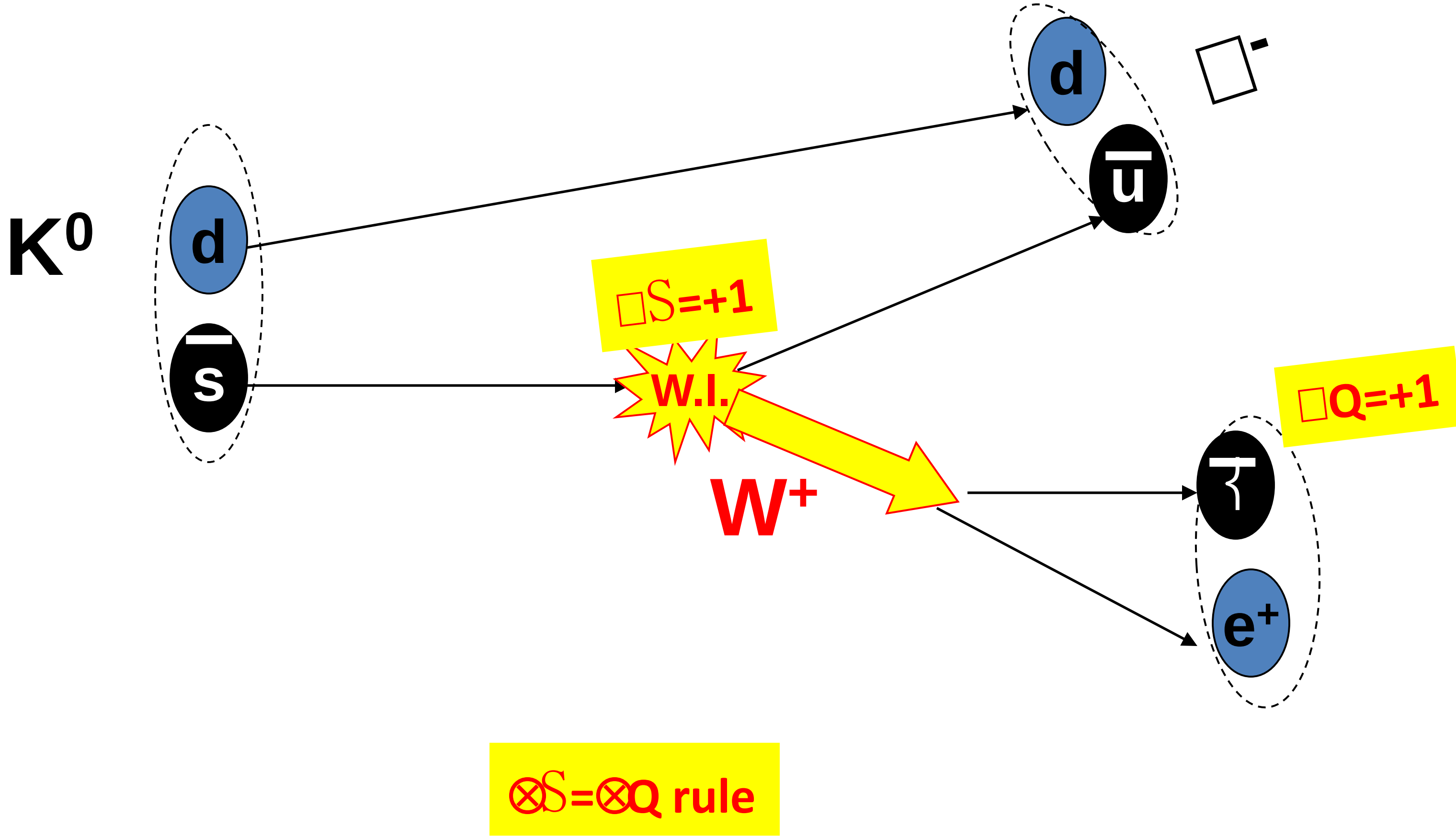
$\square^-\ p \rightarrow \bar{K}^0 K N$: $E_{cm} > 1.93$ GeV; $E_{\square} > 1.41$ GeV

Easier to produce K mesons than $\bar{K}$ mesons at fixed target hadron machines

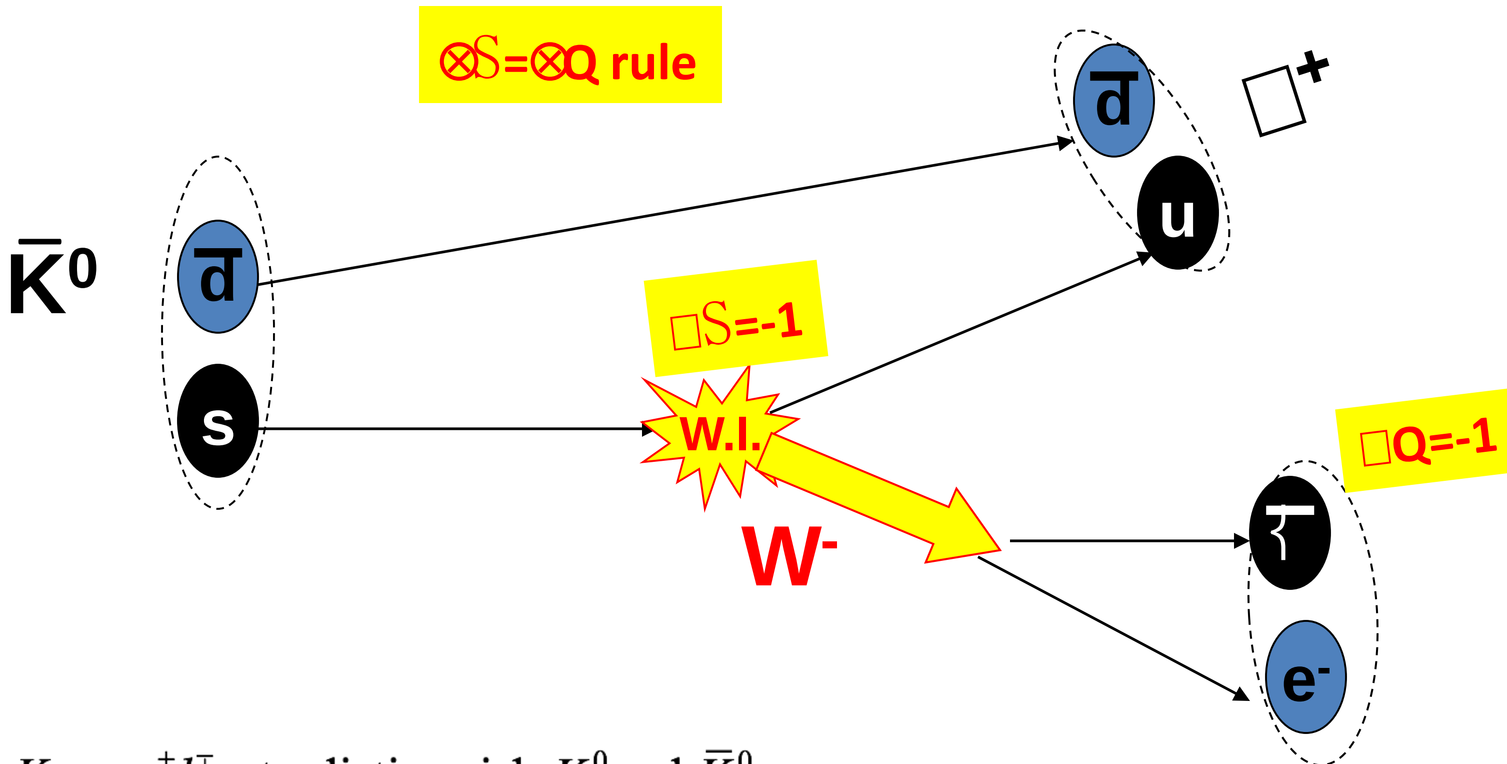
Distinguishing K^0 from $\overline{K}^0$ decays

$$\boxed{\text{The } \Delta S = \Delta Q \text{ rule}}$$

$K^0 \rightarrow$ □$^-e^+${ and not □$^+e^-${



$\bar{K}^0 \rightarrow$ □$^+e^-\nu$ and not □$^-e^+\nu$



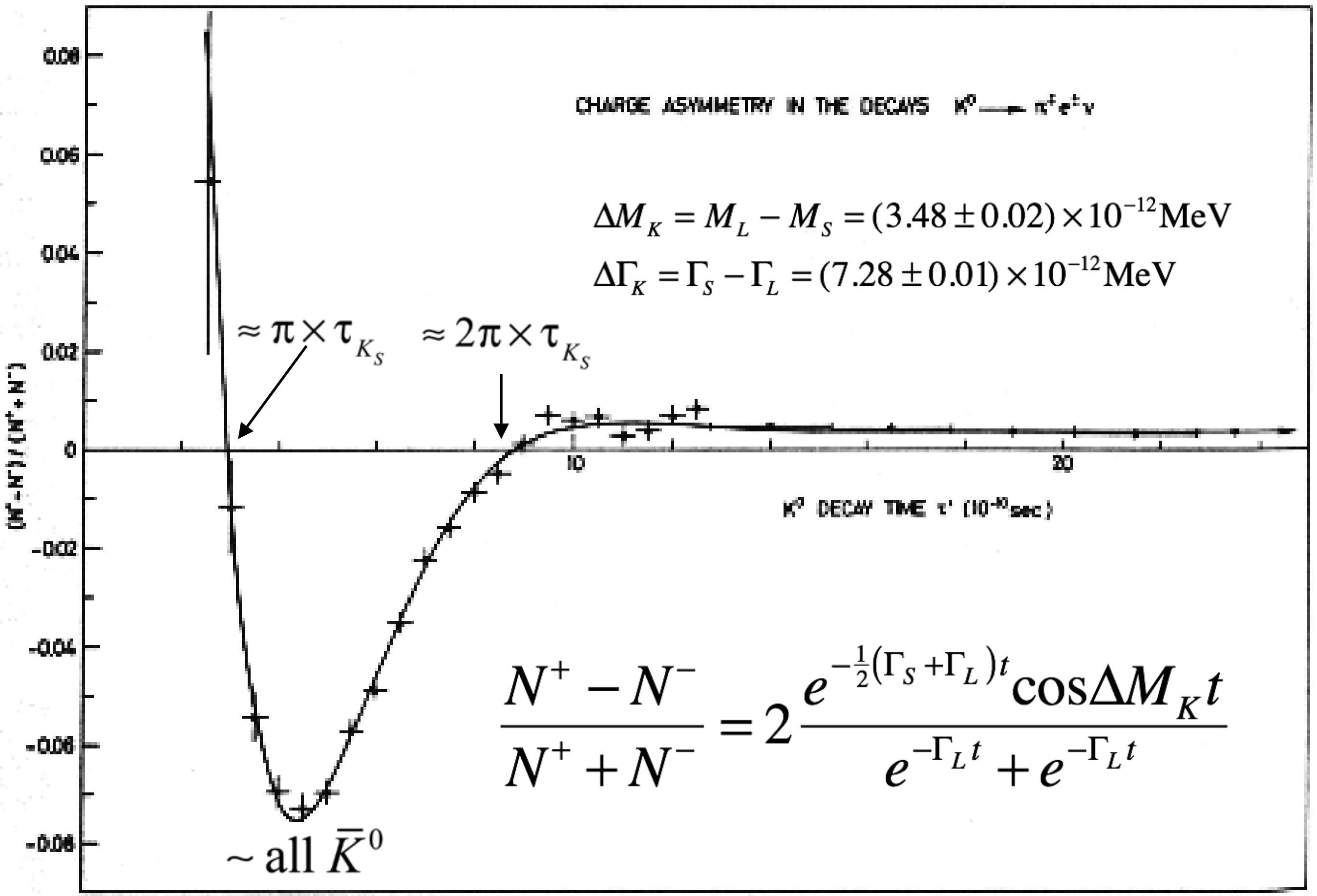
use $K \rightarrow \pi^{\pm} l^{\mp} \nu$ to distinguish K^0 and $\bar{K}^0$

$$\frac{N_{K^0} - N_{\bar{K}^0}}{N_{K^0} + N_{\bar{K}^0}} = \frac{N_{l^+} - N_{l^-}}{N_{l^+} + N_{l^-}} \qquad l^{\pm} = e^{\pm} \text{ or } \mu^{\pm}$$

Detecting K^0 & $\bar{K}^0$ in a neutral kaon beam

start with ≈75% K^0 and ≈25% $\bar{K}^0$

$$\frac{N^+ - N^-}{N^+ + N^-}$$



$$\Delta M_K = M_L - M_S = (3.48 \pm 0.02) \times 10^{-12}\,\mathrm{MeV}$$

$$\Delta \Gamma_K = \Gamma_S - \Gamma_L = (7.28 \pm 0.01) \times 10^{-12}\,\mathrm{MeV}$$

$$\frac{N^+ - N^-}{N^+ + N^-} = 2\frac{e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos \Delta M_K t}{e^{-\Gamma_L t} + e^{-\Gamma_L t}}$$

Let's put in some numbers

$$\Delta M_K = M_L - M_S = (3.48 \pm 0.02)\times 10^{-12}\,\text{MeV}=\omega_K$$

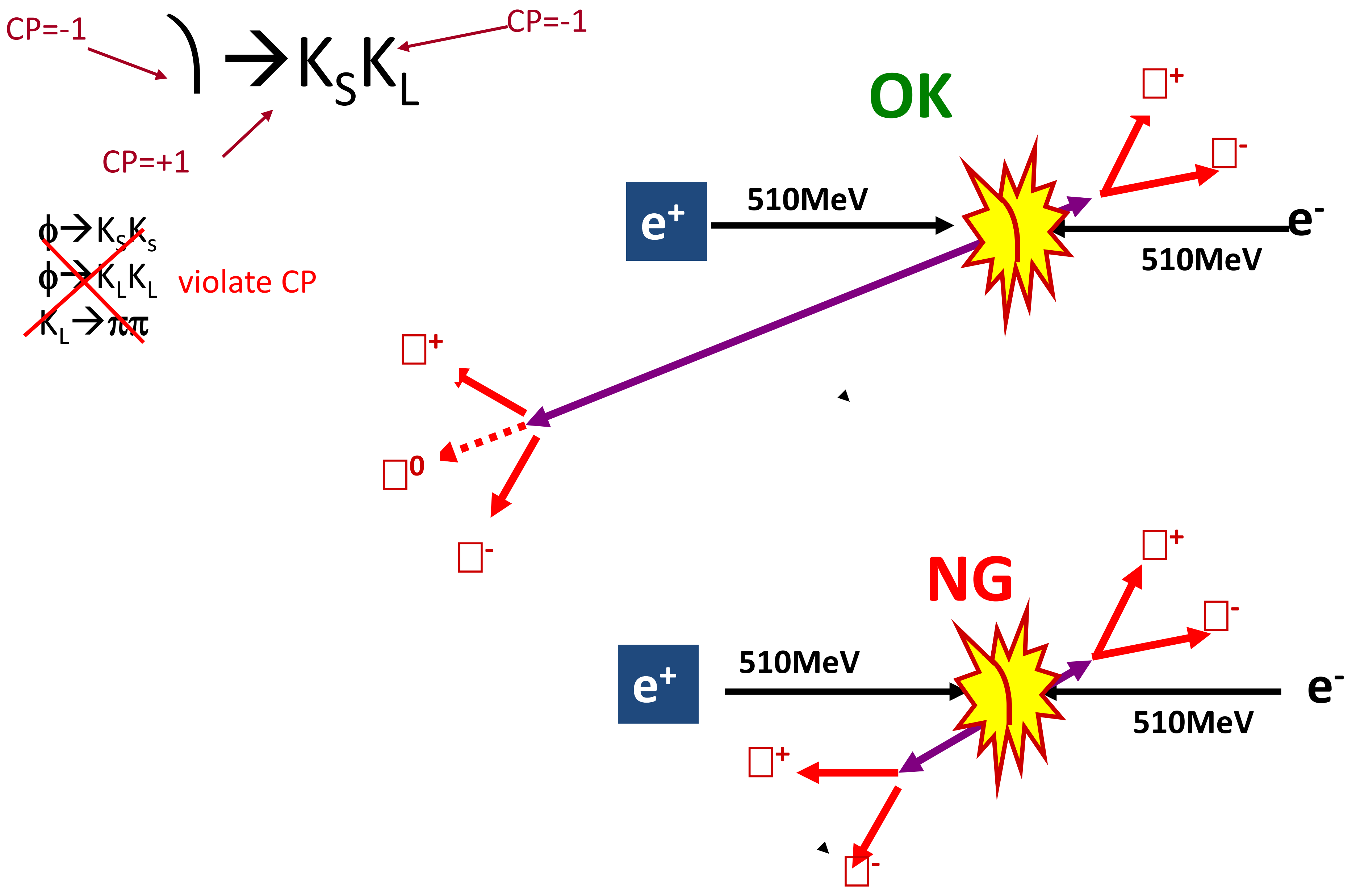
$$\Delta \Gamma_K = \Gamma_S - \Gamma_L = \frac{1}{\tau_S} - \frac{1}{\tau_L} = (7.28 \pm 0.01)\times 10^{-12}\,\text{MeV} \approx \frac{1}{\tau_S}$$

$$\frac{\Delta M_K}{\Delta \Gamma} = 0.48 \Rightarrow \omega_K \approx \frac{0.5}{\tau_S}$$

$$\omega_K T_{1-Oscillation} = \frac{0.5}{\tau_S} T_{1-Oscillation} = 2\pi \Rightarrow T_{1-Oscillation} \approx 4\pi \cdot \tau_S$$

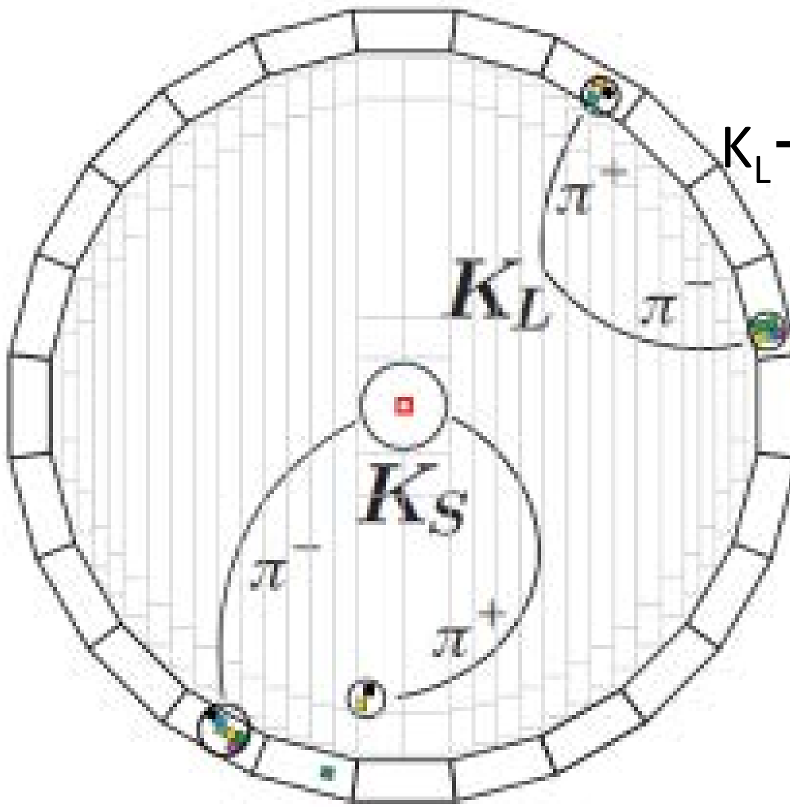
$e^{-t/\|_s}$:	1	0.05	0.0025	10^{-4}	$6\text{x}10^{-6}$
	$\begin{pmatrix} K^0 \\ 0 \end{pmatrix}$	$\rightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix}$	$\rightarrow \begin{pmatrix} 0 \\ \overline{K}^0 \end{pmatrix}$	$\rightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix}$	$\rightarrow \begin{pmatrix} K^0 \\ 0 \end{pmatrix}$
	0	Xπ $\|_S$	X 2π $\|_S$	X 3π $\|_S$	X 4π $\|_S$

revisit the ⎞ -factory



KLOE sees many □□←⎞→□□ events

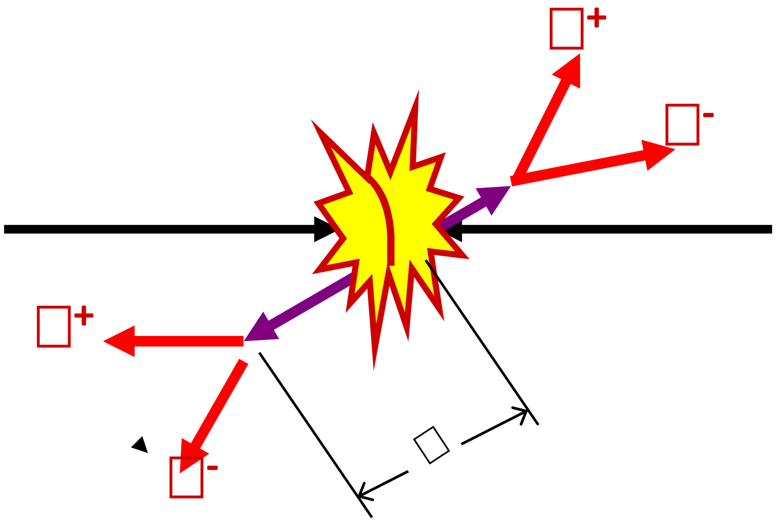
p (K_S)= 110 MeV
<©χ |> = 6mm

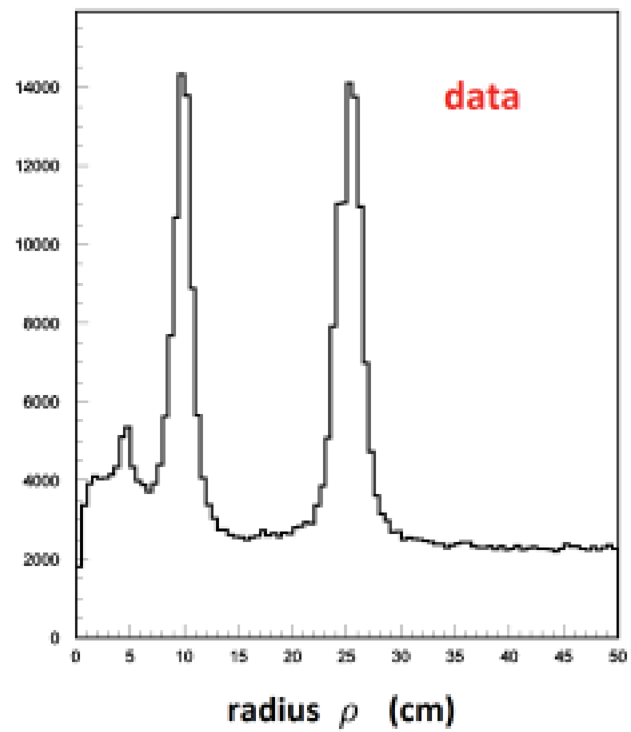


K_L→□□?

Is this CP violation?

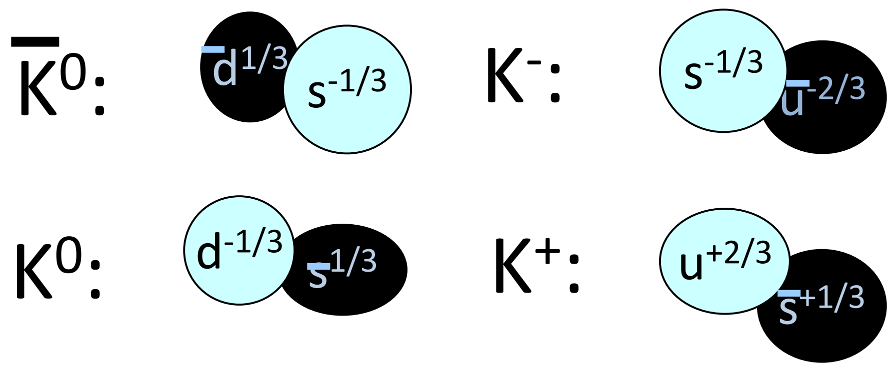
The □□←⎞→□□ events have strange pattern





$\bar{K}^0$ N & K^0 N cross-section differences

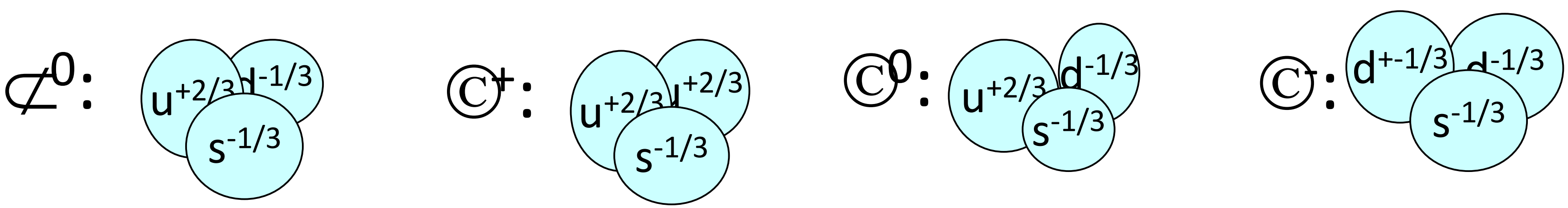
-- N= proton or neutron --



← contain an s-quark

← contain an $\bar{s}$-quark

The ⊄^{0} and ©$^+$, ©^{0}, ©$^-$ all contain an s-quark:



$\bar{K}$ + N→⊄(©) + □ ←allowed

conserves Strangeness

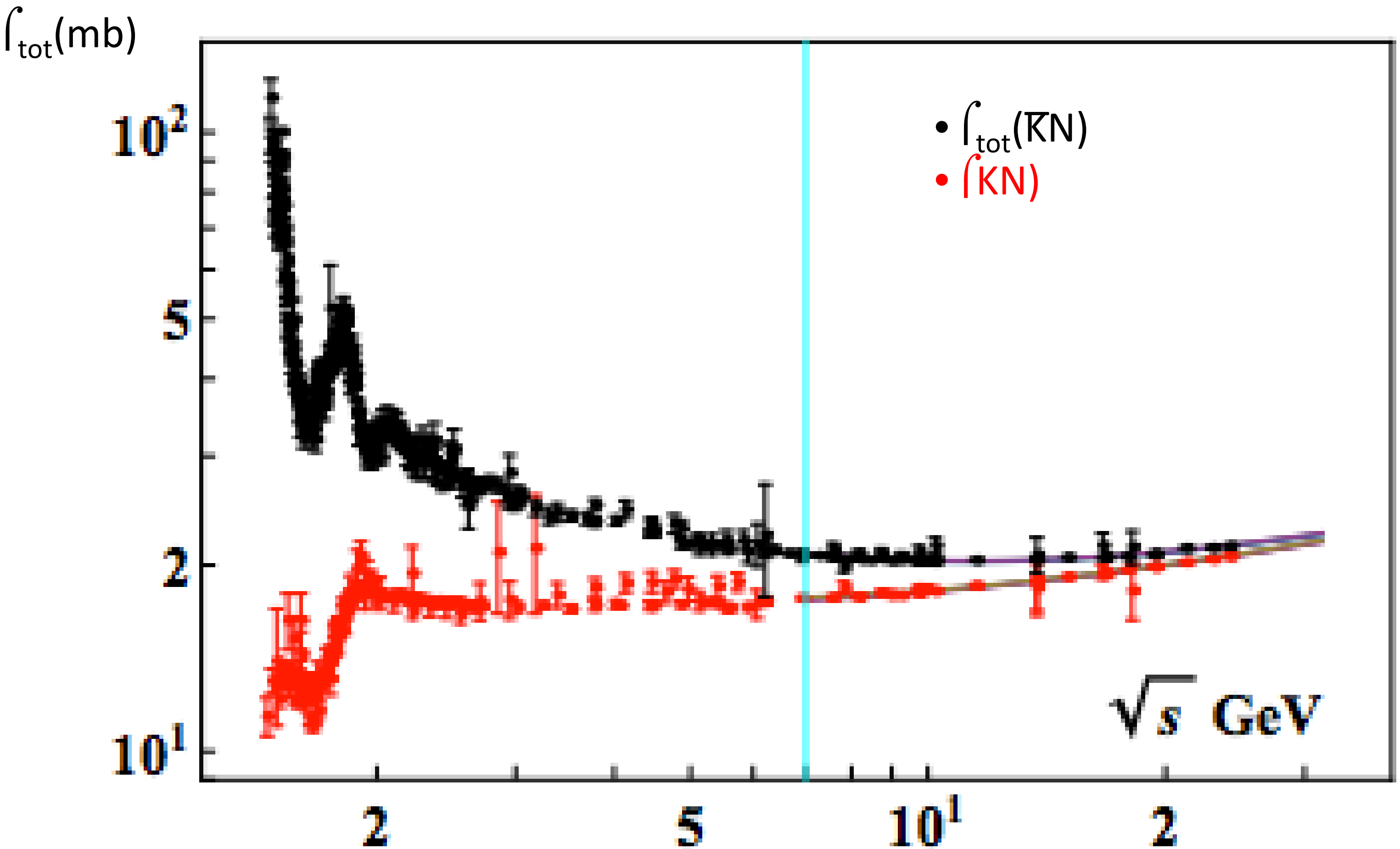
K + N→⊄(©) + □ ← forbidden

violates Strangeness

$\bar{K}$ + N has many possible channels

K + N has only a few channels

$\bar{K}$ N cross-sections larger than KN



When penetrating material $\bar{K}$ is more strongly affected than K

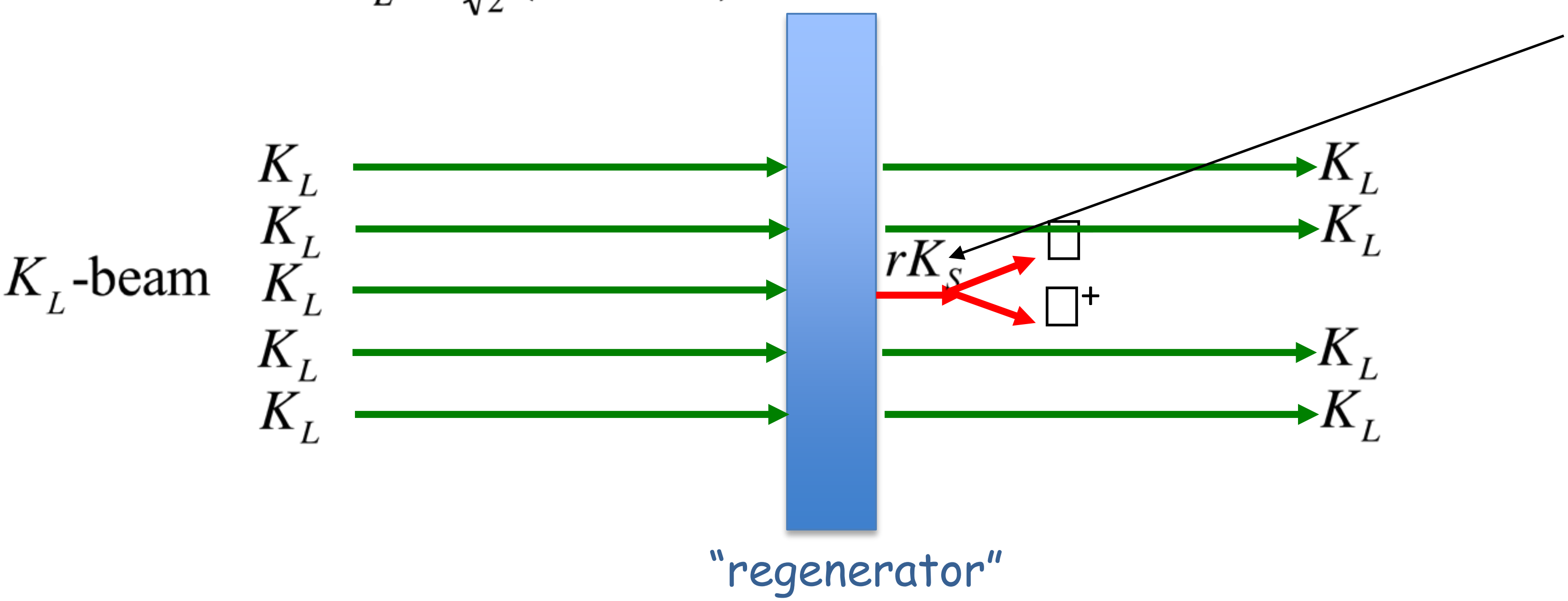
$K_L \rightarrow K_S$ regeneration

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

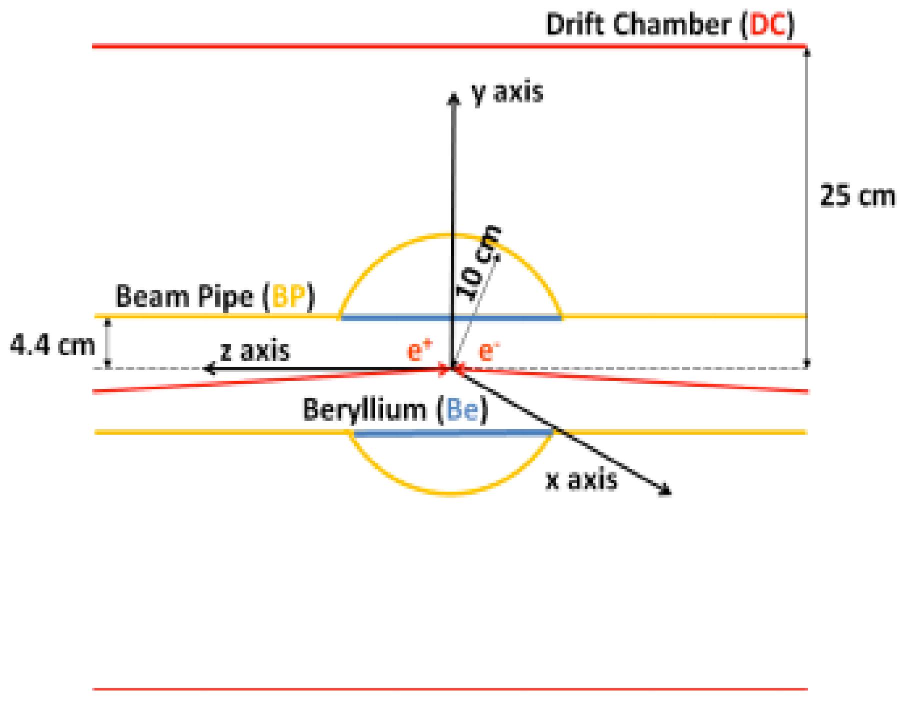
$\bar{K}^0 = \frac{1}{\sqrt{2}}(K_S - K_L)$

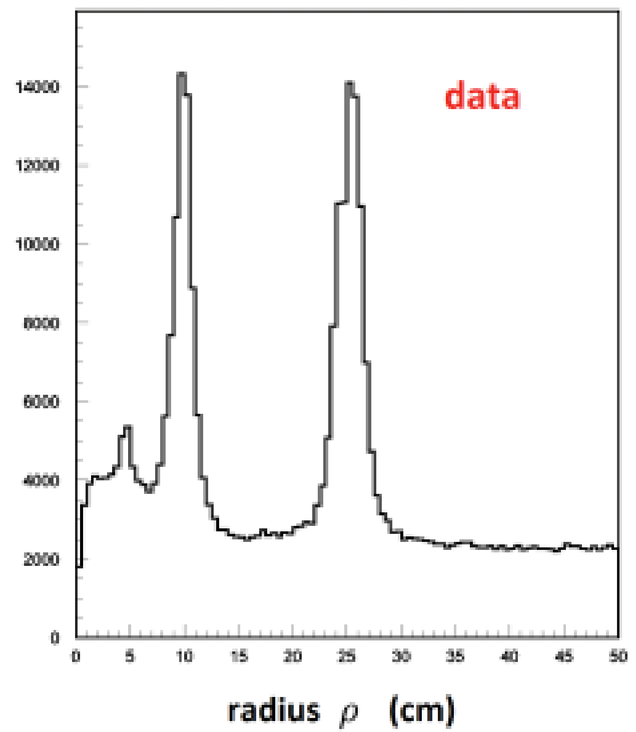
$$K' = \frac{1}{\sqrt{2}}(fK^0 + \bar{f}\,\overline{K}^0)$$

$$K_L = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0)$$



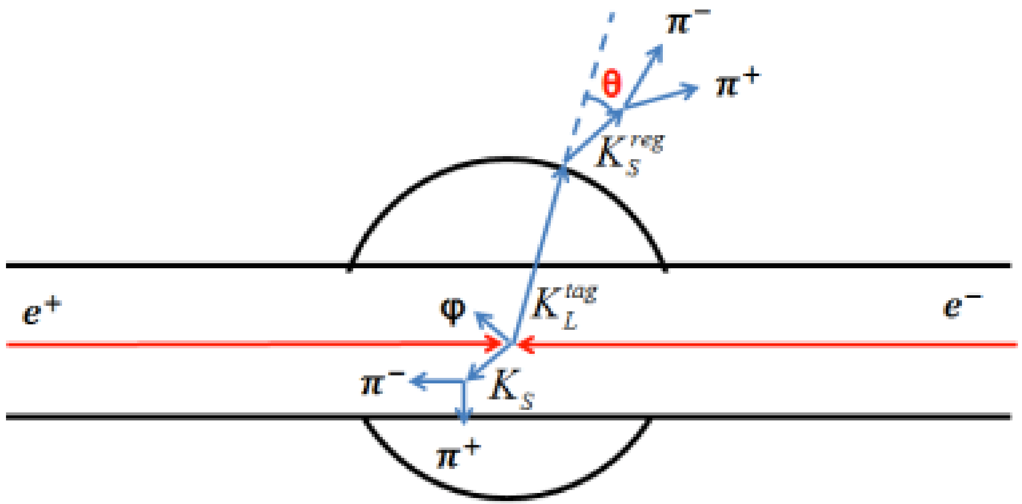
$K_L \rightarrow K_S$ regeneration in KLOE



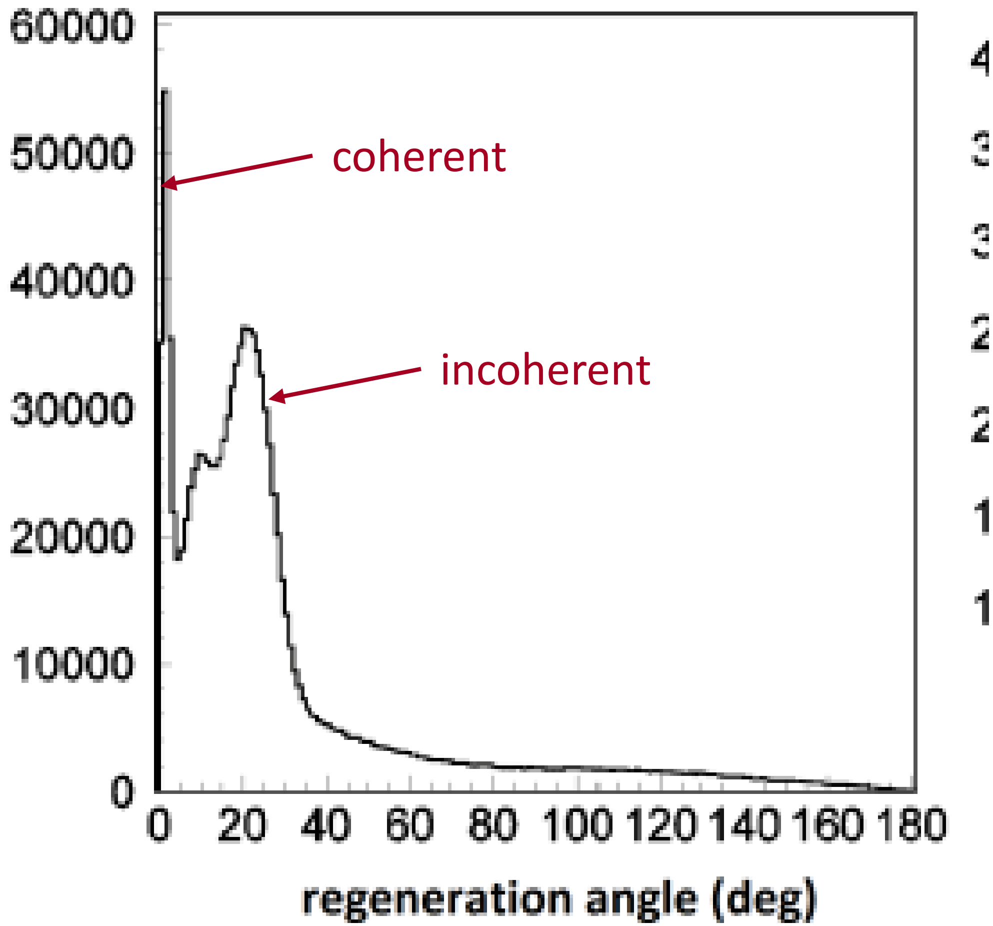


The peaks correspond to the location of material

$K_L \rightarrow K_S$ regeneration in KLOE



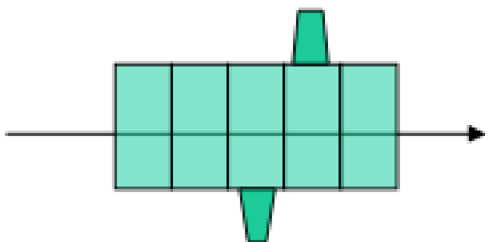
Angular dist for $K_L \rightarrow K_S$ regeneration



Coherent regeneration

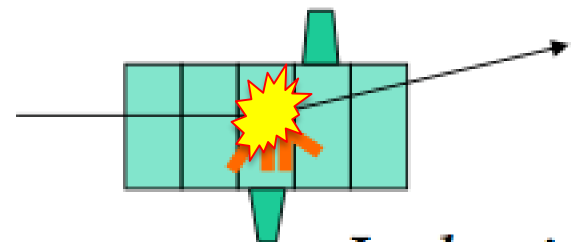
$f = f(\theta = 0)$
remains coherent with initial beam

$f = f(\theta \neq 0)$
Scatters out of initial beam



Coherent

scintillating material



Inelastic

$$K_s = \tfrac{1}{2}(K^0 + \overline{K}^0) \Rightarrow \frac{f+\bar{f}}{\sqrt{2}}(K_L + rK_S)$$

$$I_0 \rightarrow I_0 e^{-\Delta x / \lambda_{incoh}}$$

- dangerous background
- very useful experimental tool

Some K-meson properties

Properties of kaons

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)	Commonly decays to (>5% of decays)
Kaon[1]	K^+	K^-	$u\bar{s}$	493.677 ±0.016	½	0^-	1	0	0	$(1.2380 \pm 0.0021) \times 10^{-8}$	$\mu^+ + \nu_\mu$ or $\pi^+ + \pi^0$ or $\pi^+ + \pi^+ + \pi^-$ or $\pi^0 + e^+ + \nu_e$
Kaon[2]	K^0	$\bar{K}^0$	$d\bar{s}$	497.614 ±0.024	½	0^-	1	0	0	[a]	[a]
K-Short[3]	K^0_S	Self	$\frac{d\bar{s}-s\bar{d}}{\sqrt{2}}$ [b]	497.614 ±0.024[c]	½	0^-	(*)	0	0	$(8.954 \pm 0.004) \times 10^{-11}$	$\pi^+ + \pi^-$ or $\pi^0 + \pi^0$
K-Long[4]	K^0_L	Self	$\frac{d\bar{s}+s\bar{d}}{\sqrt{2}}$ [b]	497.614 ±0.024[c]	½	0^-	(*)	0	0	$(5.116 \pm 0.021) \times 10^{-8}$	$\pi^\pm + e^\mp + \nu_e$ or $\pi^\pm + \mu^\mp + \nu_\mu$ or $\pi^0 + \pi^0 + \pi^0$ or $\pi^+ + \pi^0 + \pi^-$

$$\Delta M_K = M_L - M_S = (3.48 \pm 0.02) \times 10^{-12}\,\mathrm{MeV}$$

$$\Delta\Gamma_K = \Gamma_S - \Gamma_L = (7.28 \pm 0.01) \times 10^{-12}\,\mathrm{MeV}$$

the search for CP violation

Properties of the Mass Matrix

-- slide 26 --

I ignore K^0 life-time terms (for now)

$\mathcal{CPT}$ symmetry requires: $\langle K^0|H|K^0\rangle = M_{K^0} = M_{\bar{K}^0} = \langle \bar{K}^0|H|\bar{K}^0\rangle = M_K$

$\mathcal{CP}$ symmetry says: $\langle \bar{K}^0|H|K^0\rangle = \mathcal{A}_{K^0\to\bar{K}^0} = \mathcal{A}_{\bar{K}^0\to K^0} = \langle K^0|H|\bar{K}^0\rangle = \delta$

Let's not use this condition & assume CP is violated

$$H = \begin{pmatrix} \langle K^0|H|K^0\rangle & \langle K^0|H|\bar{K}^0\rangle \\ \langle \bar{K}^0|H|K^0\rangle & \langle \bar{K}^0|H|\bar{K}^0\rangle \end{pmatrix} = \begin{pmatrix} M_K & \delta \\ \delta & M_K \end{pmatrix}$$

assume solutions of the form: $\psi_i(t) = a_i e^{-i\lambda_i t}$

Schrodinger's equation for energy eigenstates;

$$\begin{pmatrix} M_K & \delta \\ \delta & M_K \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t} = i\hbar \frac{\partial}{\partial t}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t}$$

$$\Rightarrow \begin{pmatrix} M_K - \lambda_i & \delta \\ \delta & M_K - \lambda_i \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} = 0 \quad (\hbar = 1)$$

Hamiltonian operator with decays

$$\boldsymbol{H=M - \tfrac{i}{2}\,\Gamma}$$

-- now we will include decays --

Hermitian

Mass matrix

Decay matrix

$$\left\langle K_j \middle| H \middle| K_i \right\rangle = \left\langle K_j \middle| M \middle| K_i \right\rangle - \tfrac{i}{2}\left\langle K_j \middle| \Gamma \middle| K_i \right\rangle = M_{ij} - \tfrac{i}{2}\Gamma_{ij} = X_{ij}$$

$$\begin{pmatrix} \left\langle K^0 \middle| H \middle| K^0 \right\rangle & \left\langle K^0 \middle| H \middle| \overline{K}^0 \right\rangle \\ \left\langle \overline{K}^0 \middle| H \middle| K^0 \right\rangle & \left\langle \overline{K}^0 \middle| H \middle| \overline{K}^0 \right\rangle \end{pmatrix} = \begin{pmatrix} M_{11} - \tfrac{i}{2}\Gamma_{11} & M_{12} - \tfrac{i}{2}\Gamma_{12} \\ M_{21} - \tfrac{i}{2}\Gamma_{21} & M_{22} - \tfrac{i}{2}\Gamma_{22} \end{pmatrix}$$

$\mathcal{CP}$T symmetry: $M_{11} = M_{22}$ $\quad \Gamma_{11} = \Gamma_{22}$

no assumptions about $\mathcal{CP}$

Hermiticity: $X_{21} = M_{12}^{*} - \tfrac{i}{2}\Gamma_{12}^{*}$

$$H = \begin{pmatrix} M_{11} - \tfrac{i}{2}\Gamma_{12} & M_{12} - \tfrac{i}{2}\Gamma_{12} \\ M_{12}^{*} - \tfrac{i}{2}\Gamma_{12}^{*} & M_{11} - \tfrac{i}{2}\Gamma_{11} \end{pmatrix}$$

Schrodinger's Equation

-- allowing for CP violation and including decays --

to conform to the standard notation:

$$X_{21} = \mathcal{A}_{K^0 \to \overline{K}^0} = \boxed{-ip^2 \quad \left(= M_{12}^* - \tfrac{i}{2}\Gamma_{12}^*\right)}$$

$$X_{12} = \mathcal{A}_{\overline{K}^0 \to K^0} = \boxed{-iq^2 \quad \left(= M_{12} - \tfrac{i}{2}\Gamma_{12}\right)}$$

$$i\hbar \frac{\partial}{\partial t}\Psi(\mathrm{t}) = H\Psi(t)$$

$$\text{assume solutions of the form: } \psi_i(t) = a_i e^{-i\lambda_i t}$$

Schrodinger's equation for energy eigenstates;

$$\begin{pmatrix} X_{11} & -iq^2 \\ -ip^2 & X_{11} \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t} = i\frac{\partial}{\partial t}\begin{pmatrix} a_i \\ b_i \end{pmatrix} e^{-i\lambda_i t}$$

$$\Rightarrow \begin{pmatrix} X_{11} - \lambda & -iq^2 \\ -ip^2 & X_{11} - \lambda_i \end{pmatrix}\begin{pmatrix} a_i \\ b_i \end{pmatrix} = 0$$

Solutions for Ψ(t)

eigenvalue equation:

$$\begin{vmatrix} X_{11}-\lambda_i & -iq^2 \\ -ip^2 & X_{11}-\lambda_i \end{vmatrix} = 0 \qquad X_{11} = M_K - \tfrac{i}{2}\Gamma_K$$

eigenvalues

eigenstates

$$i=1: \quad \lambda_S = M_S - \tfrac{i}{2}\Gamma_S = X_{11} + ipq \qquad |K_S(t)\rangle = \tfrac{1}{\sqrt{p^2+q^2}}\left(p|K^0\rangle - q|\bar{K}^0\rangle\right)e^{-iM_St-\frac{1}{2}\Gamma_St}$$

$$i=2: \quad \lambda_L = M_L - \tfrac{i}{2}\Gamma_L = X_{11} - ipq \qquad |K_L(t)\rangle = \tfrac{1}{\sqrt{p^2+q^2}}\left(p|K^0\rangle + q|\bar{K}^0\rangle\right)e^{-iM_Lt-\frac{1}{2}\Gamma_Lt}$$

HW

in terms of the CP eigenstates:

$$|K^0\rangle = \tfrac{1}{\sqrt{2}}\left(|K_1\rangle + |K_2\rangle\right)$$

$$|\bar{K}^0\rangle = \tfrac{1}{\sqrt{2}}\left(|K_2\rangle - |K_1\rangle\right)$$

$$|K_S\rangle = \tfrac{p+q}{\sqrt{p^2+q^2}}\left(|K_1\rangle + \tfrac{p-q}{p+q}|K_2\rangle\right) = \tfrac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_1\rangle + \varepsilon|K_2\rangle\right)$$

$$|K_L\rangle = \tfrac{p+q}{\sqrt{p^2+q^2}}\left(|K_2\rangle + \tfrac{p-q}{p+q}|K_1\rangle\right) = \tfrac{1}{\sqrt{1+|\varepsilon|^2}}\left(|K_2\rangle + \varepsilon|K_1\rangle\right)$$

$$\boxed{\varepsilon \equiv \frac{p-q}{p+q}}$$

HW

$$\boxed{\lambda_S - \lambda_L = 2ipq = (M_S - M_L) - \tfrac{i}{2}(\Gamma_S - \Gamma_L)}$$

Decay of the K_L

$$\left|K_L\right\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(\underbrace{\left|K_2\right\rangle}_{\mathcal{CP}\text{ odd}} + \varepsilon\underbrace{\left|K_1\right\rangle}_{\mathcal{CP}\text{ even}}\right)$$

$\left|K_2\right\rangle \xrightarrow{\text{OK}}$ $\mathcal{CP}$ odd: $\pi^+\pi^-\pi^0$ or $\pi^0\pi^0\pi^0$

$\left|K_1\right\rangle \xrightarrow{\text{OK}}$ $\mathcal{CP}$ even: $\pi^+\pi^-$ or $\pi^0\pi^0$

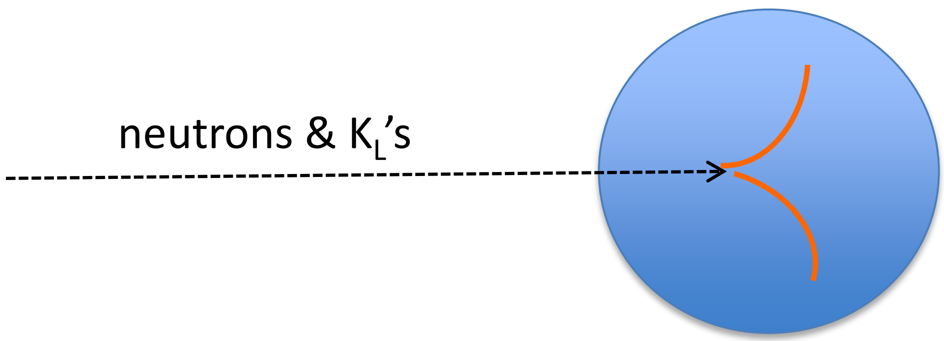
If $\mathcal{CP}$ is violated: K_L contains a $\mathcal{CP}$-even K_1 component

Discovery of K_L decays to $\pi^+\pi^-$

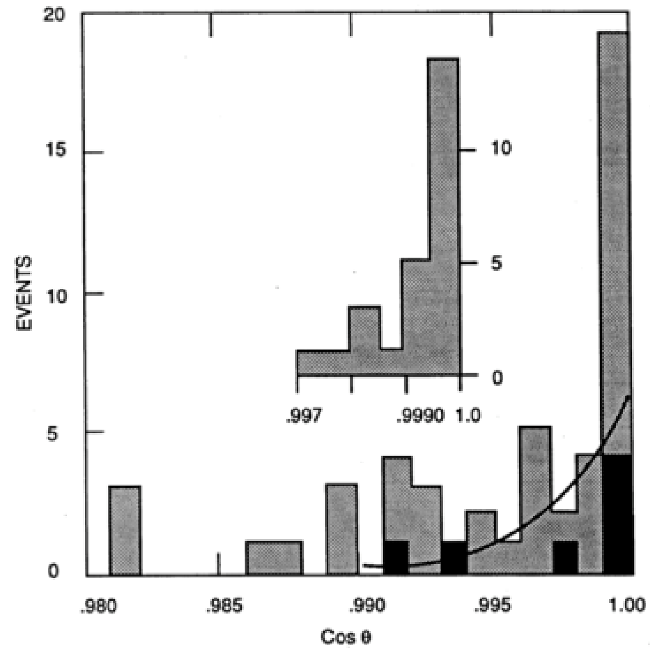
“Hint” for $K_L \rightarrow \pi^+\pi^-$??

a Bubble chamber
in a neutral beam
at Brookhaven saw
some $\pi^+\pi^-$ events

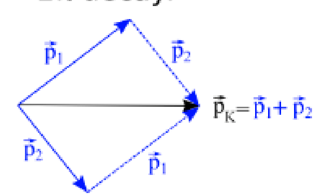
neutrons & K_L’s



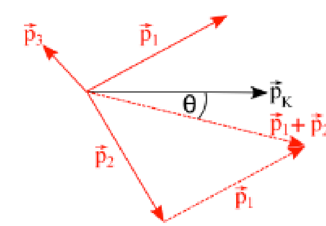
$K_L \rightarrow \pi^+\pi^-$events or $K_L \rightarrow K_S$ via regeneration



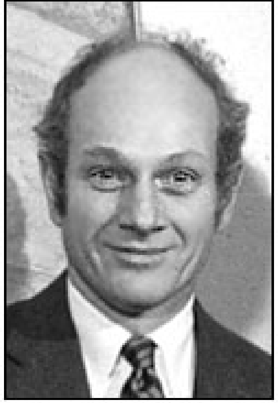
2π decay:



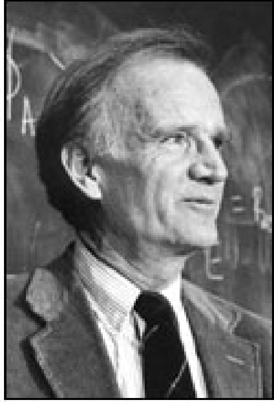
3-body-decay:



proposal



James Cronin



Val Fitch

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXP

J. W. Cronin, V. L. Fitch, R. Turlay

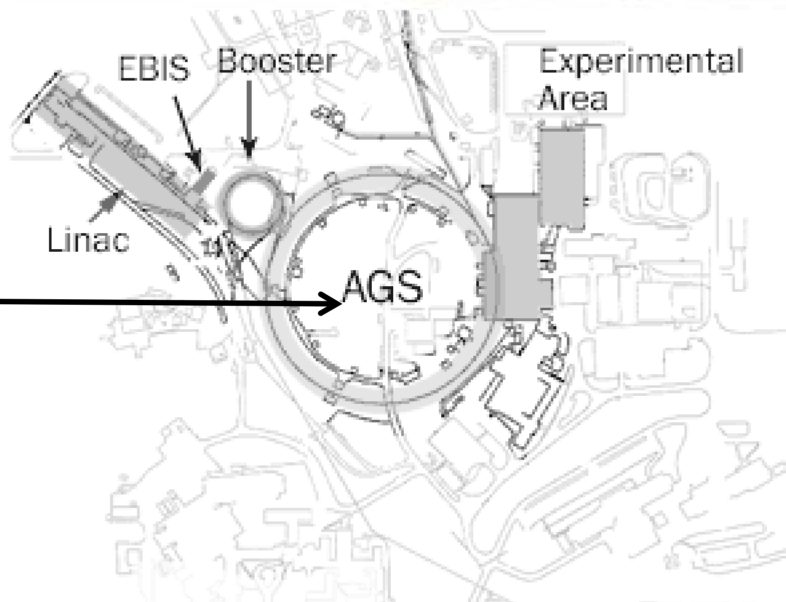
(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

AGS Brookhaven's 2nd HE accelerator

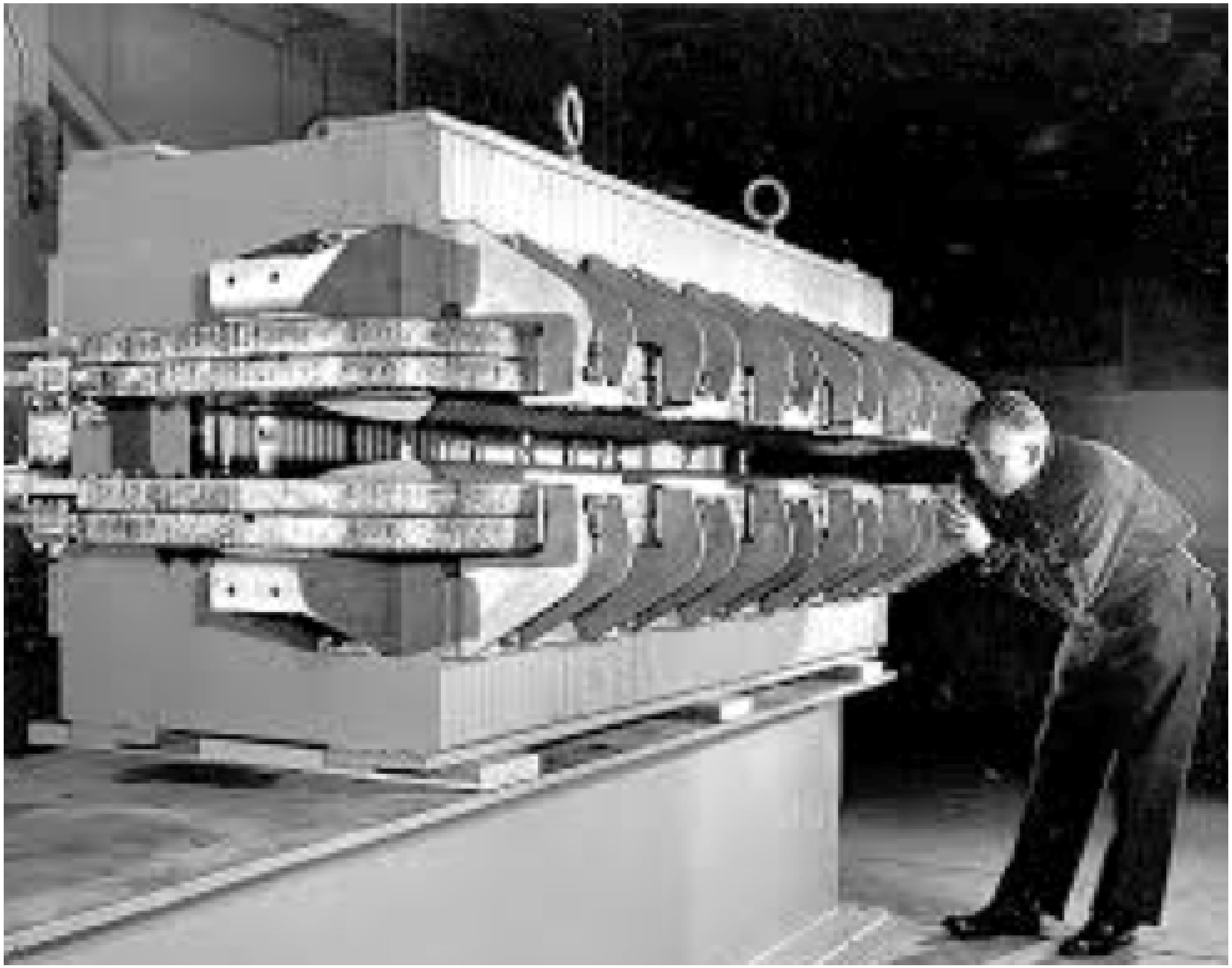
-- world's first strong focusing accelerator, still running, more than 50 years later --



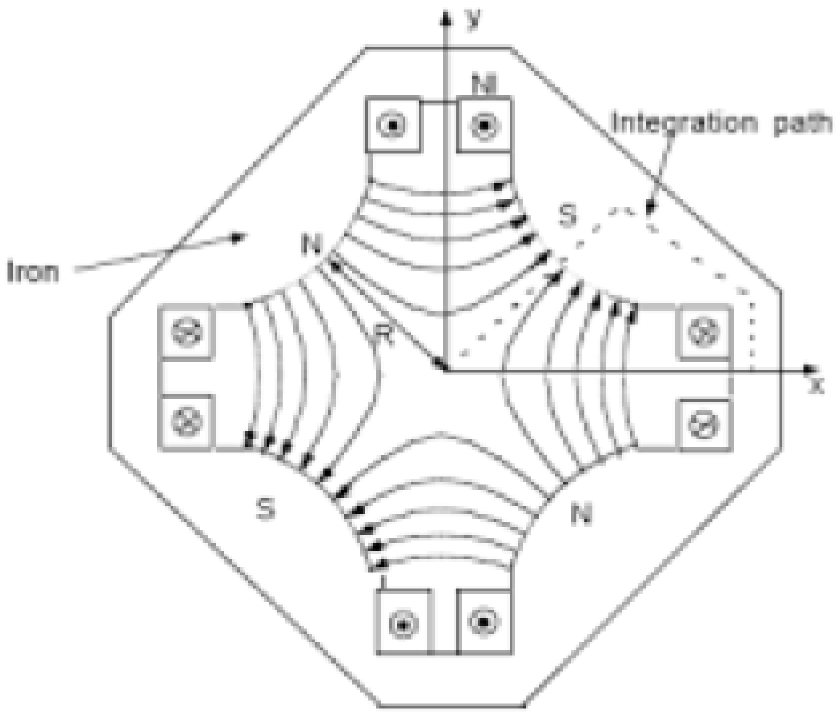
"Inner Mongolia"

BEPC—AGS see the differences?

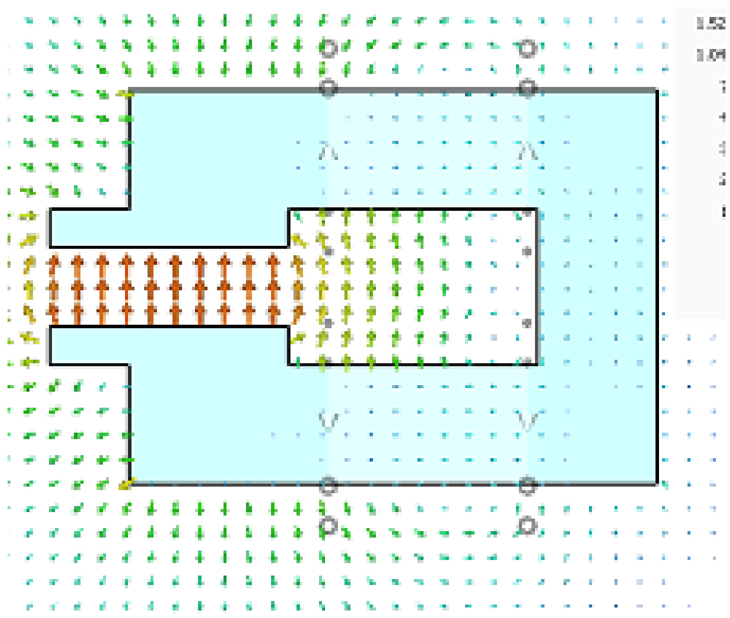
AGS combined function magnets



Quadrupoles & dipoles



Quadrupole



dipole

the “inner Mongolia” beam line

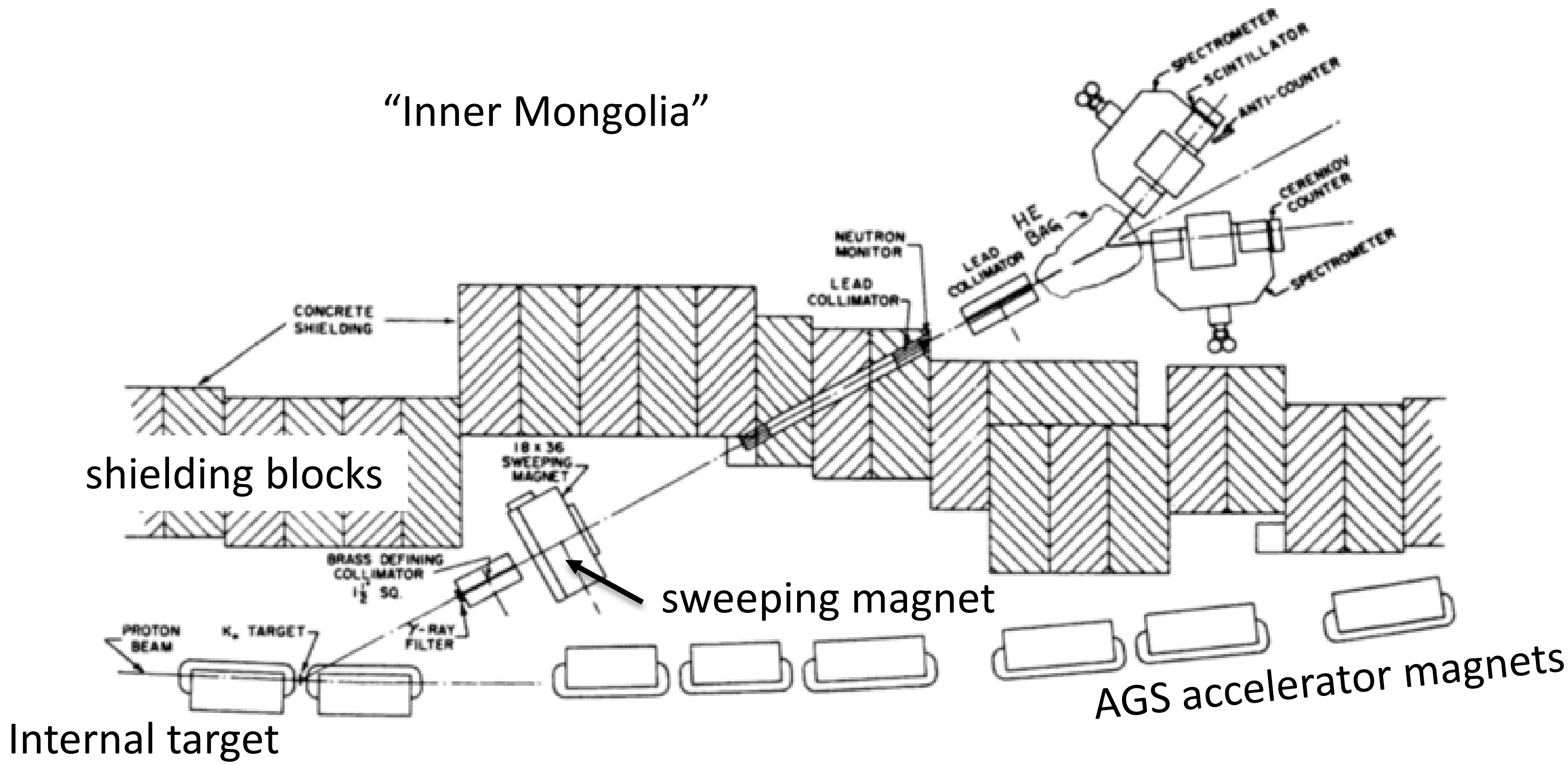
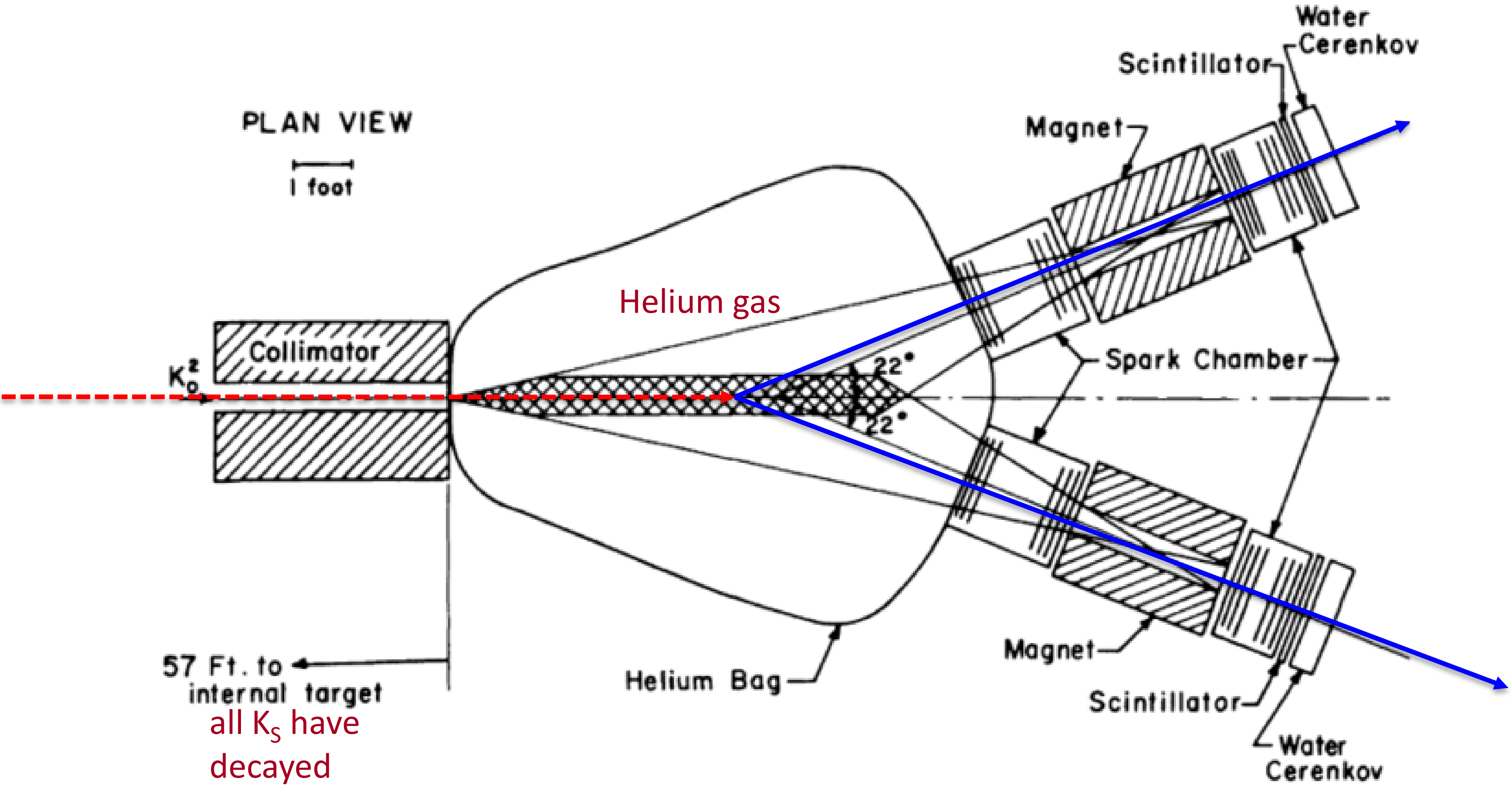


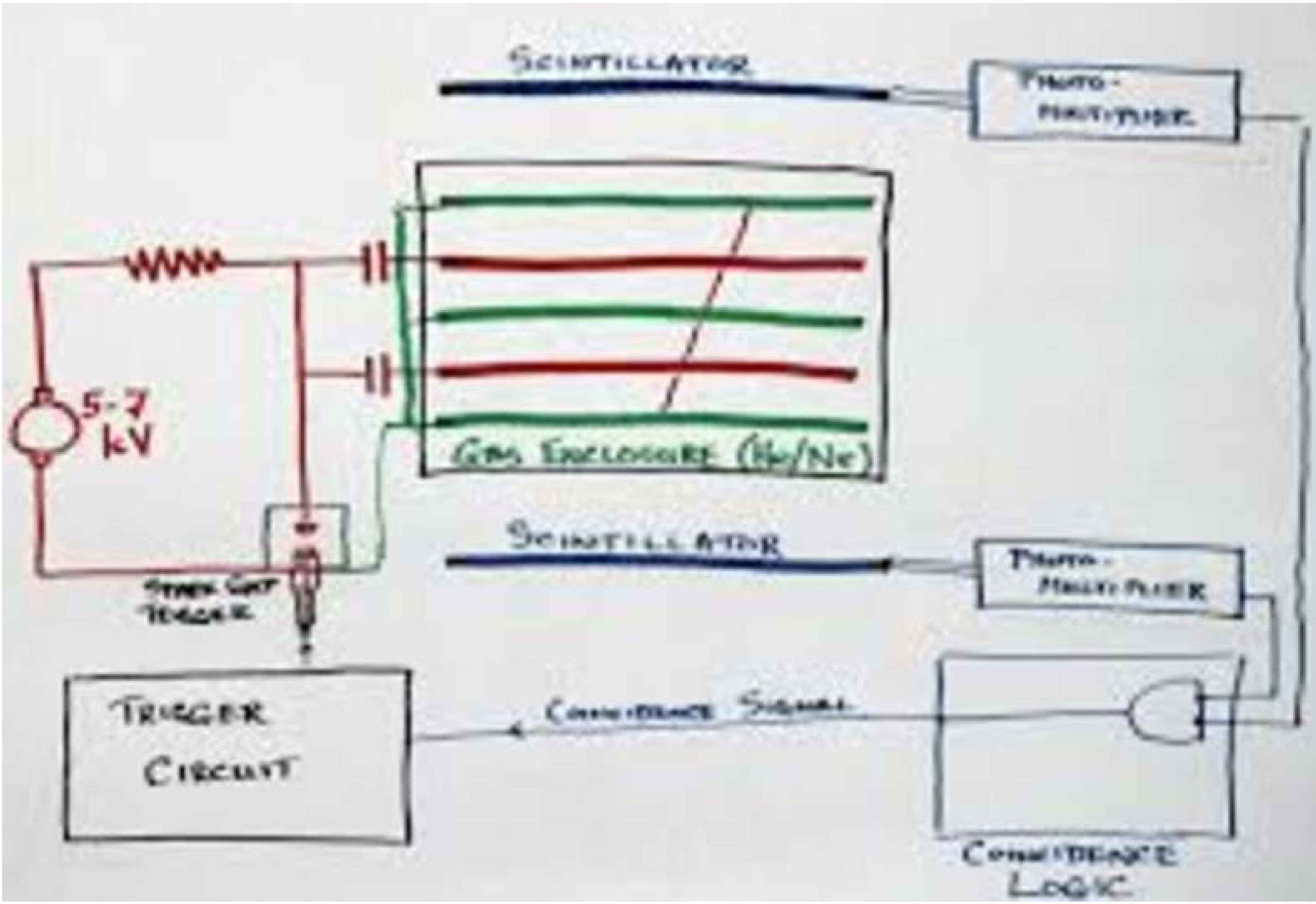
Fig. 7.5. Schematic view of the experimental arrangement for the CP invariance test.

The Fitch-Cronin experiment



Rev. Mod. Phys., Vol. 53, No. 3, July 1981

Spark chamber



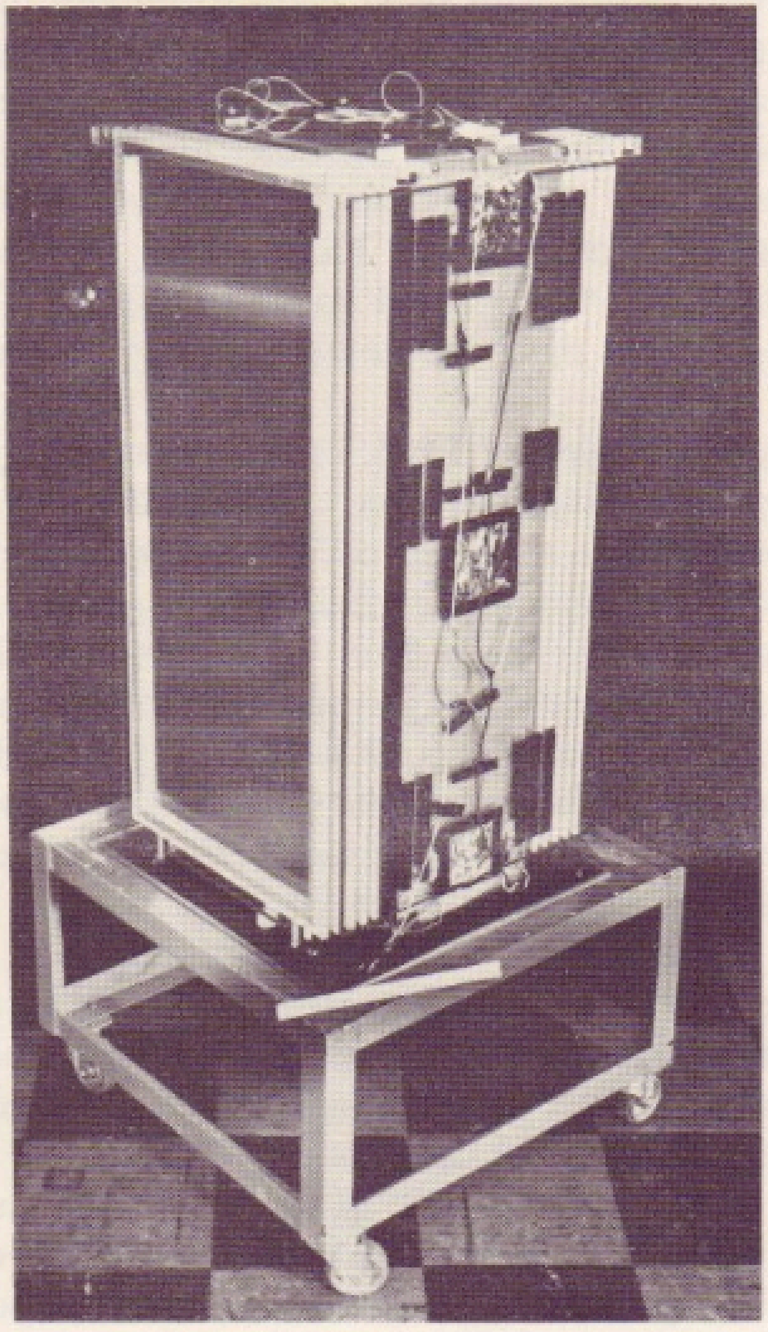
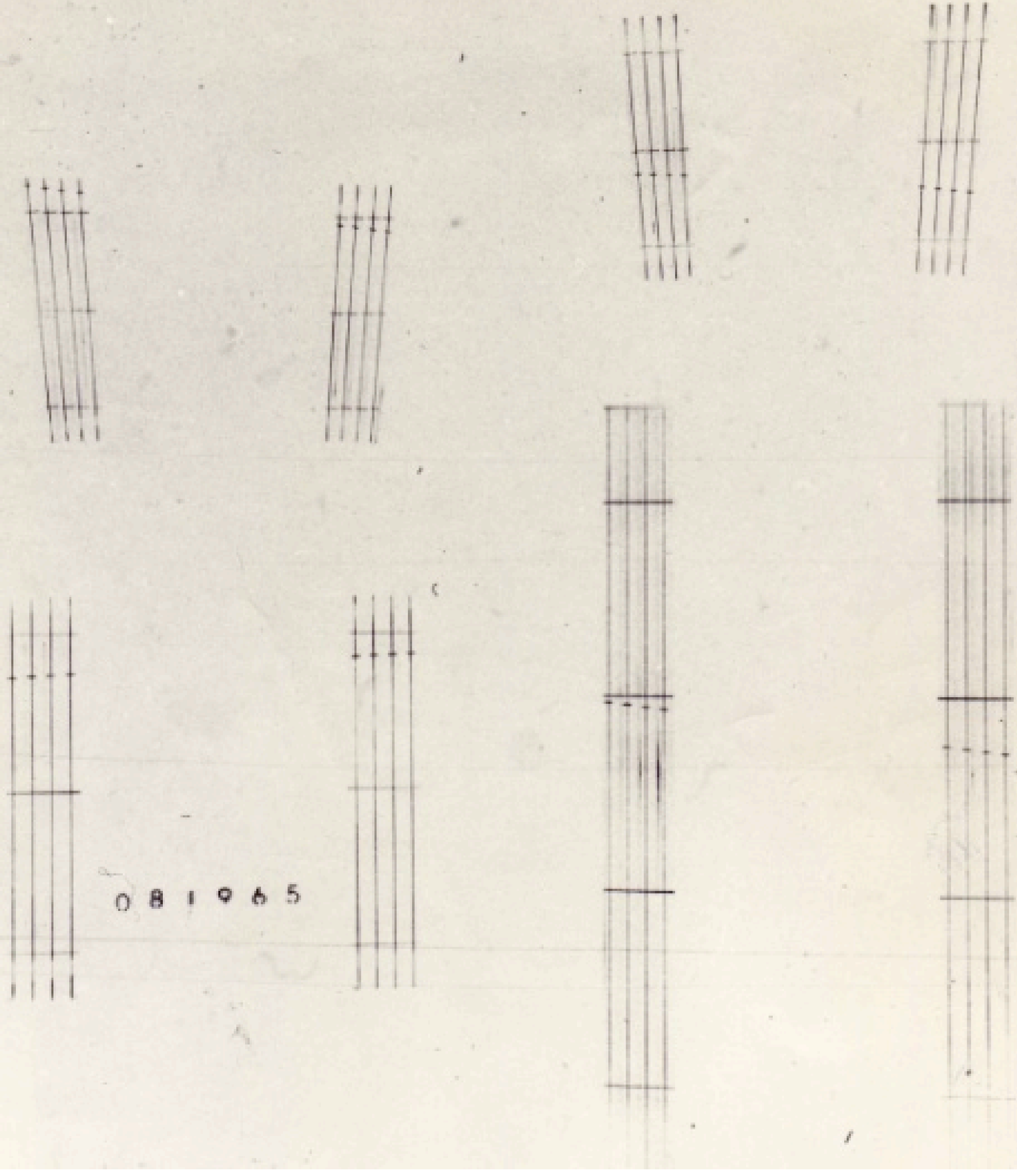
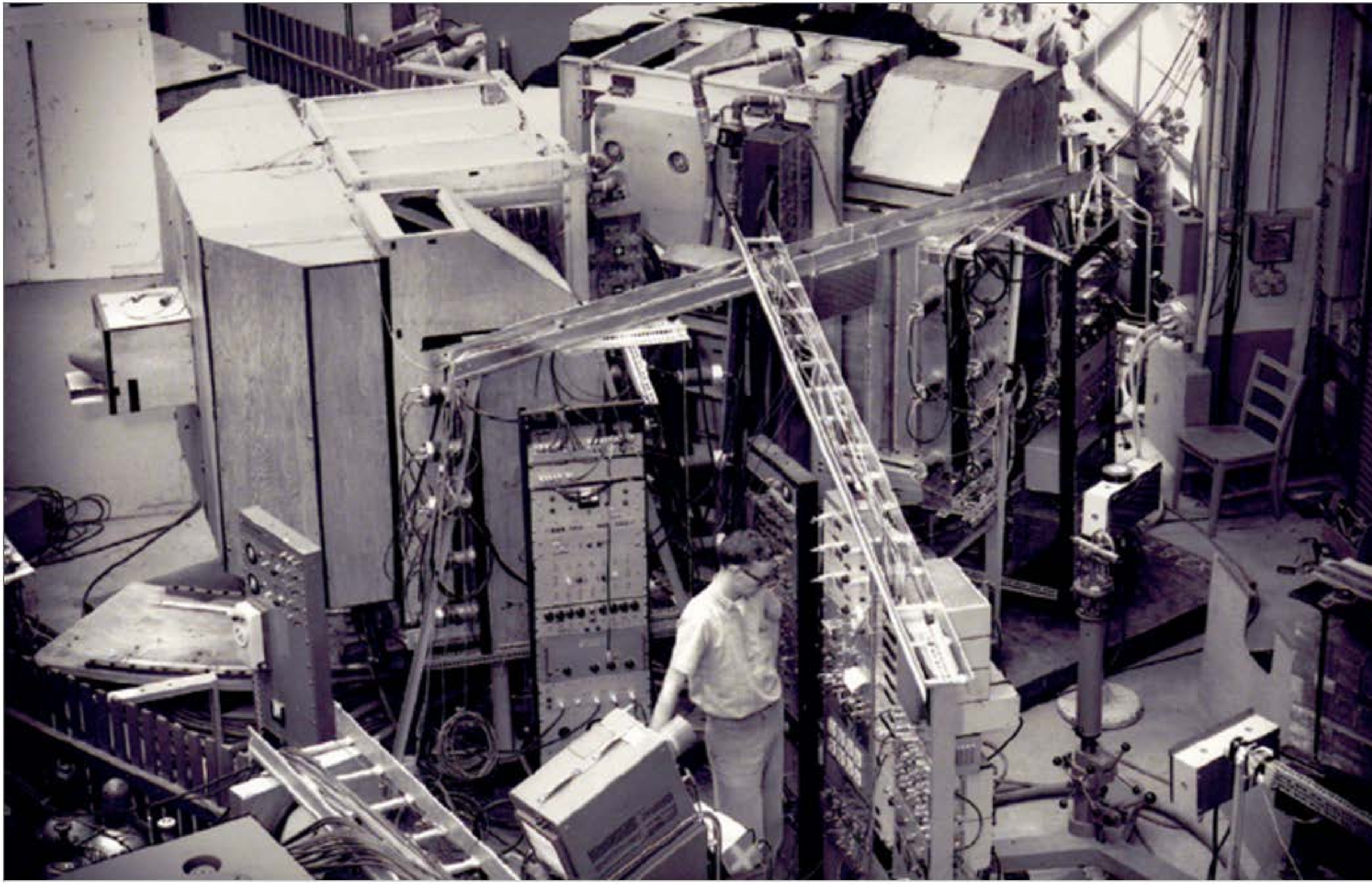


FIG. 26. View of thin foil chamber constructed at Princeton University.


0 8 1 9 6 5



The experiment that discovered CP violation at Brookhaven was set up in a neutral beamline, directed inside the ring of the Alternating Gradient Synchrotron. Visible here are the two spectrometer magnets positioned at 22° to the beam. Spark chambers tracked particles before and after the magnets.
Image credit: Brookhaven National Laboratory.

Data-taking and analysis

THURSDAY – JUNE 20, 1963 — CP INVARIANCE RUN

have removed separator stand and anti and installed Helium bag – bag touches S.C. windows and falls ~6" short of collimator
sag is ≈10" thick – switched New Mon. to new H.V. Supply – same voltage.

126921 126945 .541 .529 .256 — .524 151 1.746 64437 63261

Stopped run because neutron mon not counting – found anti and collector transistors blown in coinc. circuit – replaced – A.O.K.

126945 – 127262 ~~[illegible]~~ 54469 5.3162 2.499 30.011 - 12543 317 1382 15.248 .508 1.023 21.7 .1816 .1772 .0830 10.6 2.390 AT N127355 DIAL 36

3a is now meaningless – won't write

127262 128412 ~~1784~~ ~~2088~~ 17.87 8.098 100.02 41.62 1150 6509 49.192 .492 .179 .179 .081 11.50 2.40 ← Made adjustments Monitor Voltage this run

Should consider changing Pb filter – now $2\frac{9}{16}$" ??

128412 128604 2.78 125 16.41 ~~[illegible]~~ 6.28 997 3588

camera advanced 10 pulses at this point – counts not reset.

128614 129611 18525 18.136 7.994 100.02 41.72 997 5890 49.48 .495 .185 .181 .0884 9.97 2.40.

129611 130805 18.504 18.166 8.262 100.12 41.92 1194 6553 49.823 .498 .185 .182 .0826 11.9 2.40. 13 | 130151 10 pu

130805 131535 12.044 11.754 5.367 64.587 26.894 730 2981 32.215 .498 16.2 .186 ~~[illegible]~~ .1815 .0832 11.3 2.41 63330

II Film ran out some time (?) before this – noticed it at this point — Somewhat before 131700 it would seem! Sorry.

Changed film & began again

131545 132626 — 12686 7.788 76.641 40.162 1081 6897 47.965 .496 (#3 scin) — 14.0 — .183 .0806 11.2 2.40

at 0445 (~131844), noticed rubber diaphragm in camera lens worked off – perhaps pictures taken till now are no good?

found top of Helium bag in beam at end of above run. – put more He in.

132626 133813 — 12.281 7.966 100.019 41.909 1187 6124 49.743 .497 — 16.3 — .183 .080 11.9 2.39 — SAME DIAL – 36

Space at 133100 134650, 136200, change at 137750 — Watch end closely!

N133262 – Spaced film

133813 64451 63253 ~~64530~~ ~~[illegible]~~ DIAL

Note: mag dropped ~~Too~~ – corrected Hall + NMR – don't like it, but so what.

N 134650 – Spaced film – put some Helium in bag at 15:45

63.266

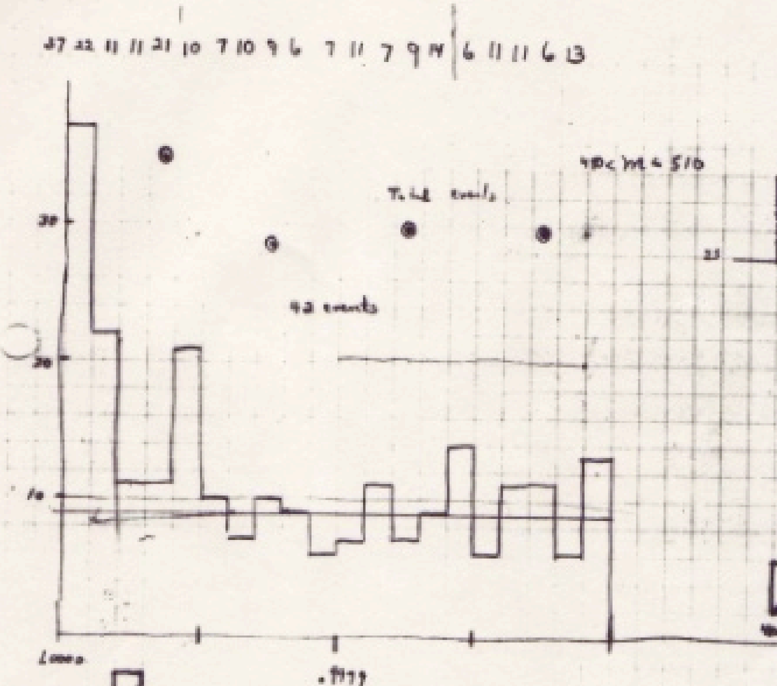
CP limit $\frac{42}{12300} = 3.3 \times 10^{-3}$

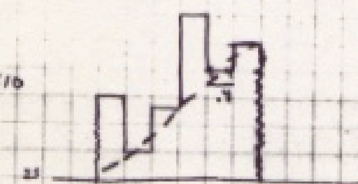
$\approx 1 \times 10^{-3}$

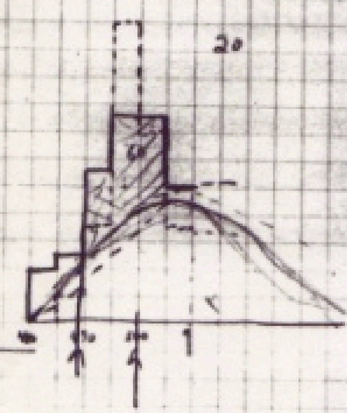
Some plots of 5211 CP events

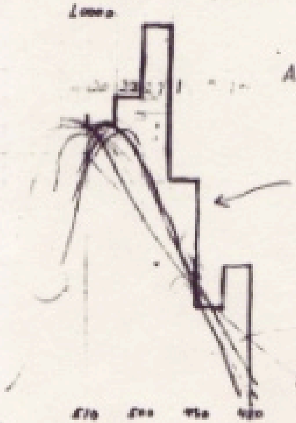
[$K_2^0 \to \pi^+\pi^-\gamma$ | ?? phase space $\frac{1}{\alpha}$

To draw final conclusions we await the remeasurement on the Hybel.
5211



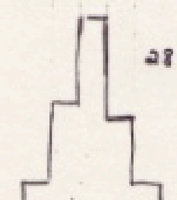






New spectrum

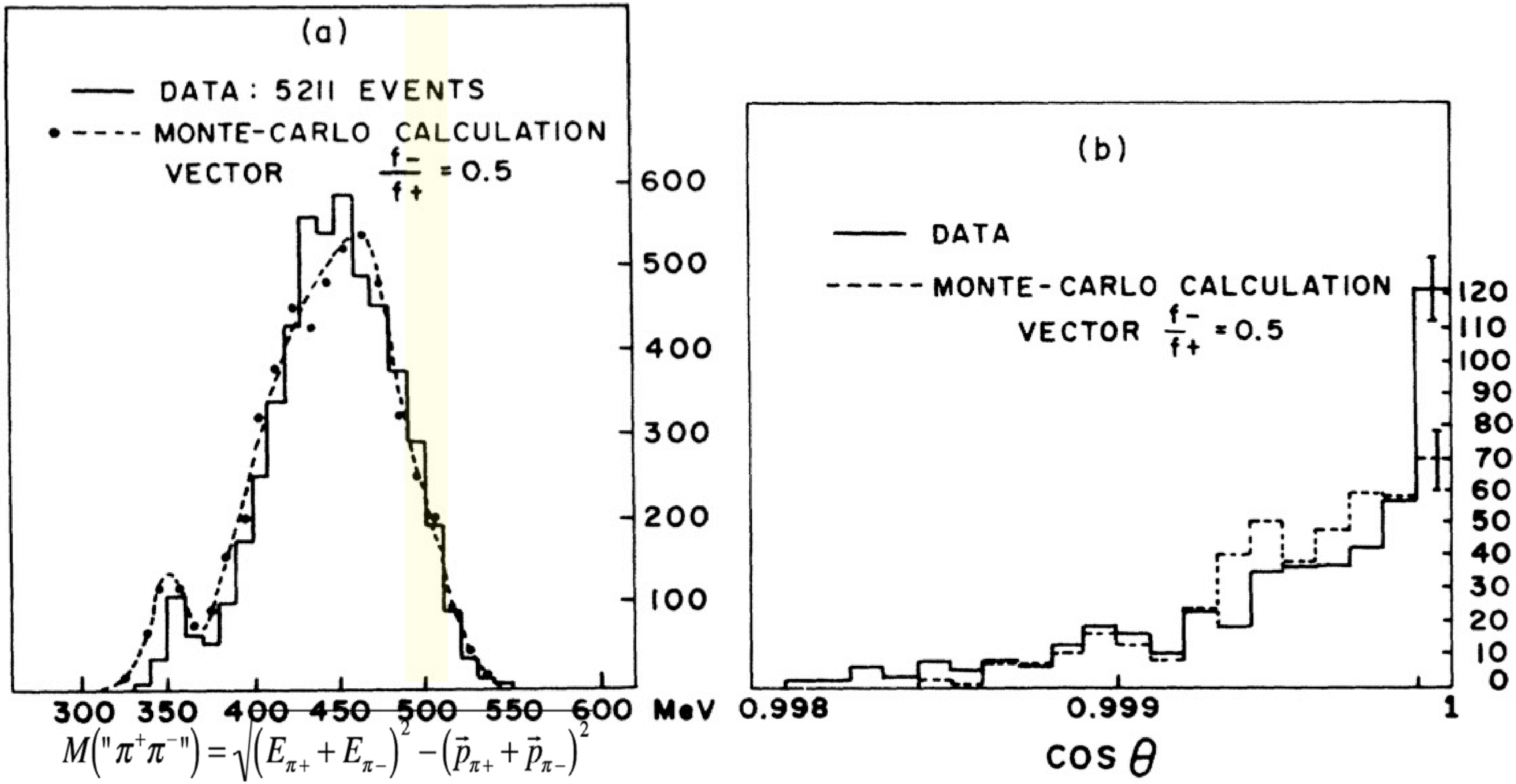
$\cos\theta > .99995$



28 events K_1^0

Tail of $K(e\pi\nu)$ spectrum with zero neutrino momentum

Note scale!



$$M(\text{"}\pi^+\pi^-\text{"})=\sqrt{\left(E_{\pi+}+E_{\pi-}\right)^2-\left(\vec{p}_{\pi+}+\vec{p}_{\pi-}\right)^2}$$

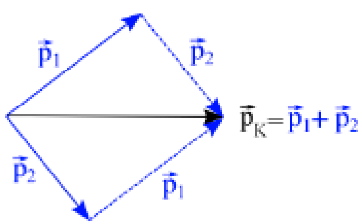
FIG. 2. (a) Experimental distribution in m^* compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events. (b) Angular distribution of those events in the range $490 < m^* < 510$ MeV. The calculated curve is normalized to the number of events in the complete sample.

5211 $K_L \rightarrow \pi^+ + \pi^-$ candidates remeasured on a commercial bubble chamber measuring machine

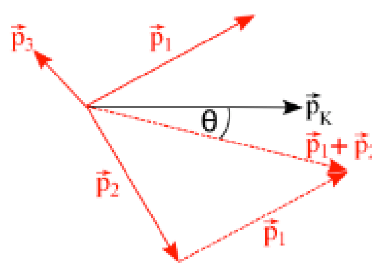
$\pi^+\pi^-$ "invariant mass"

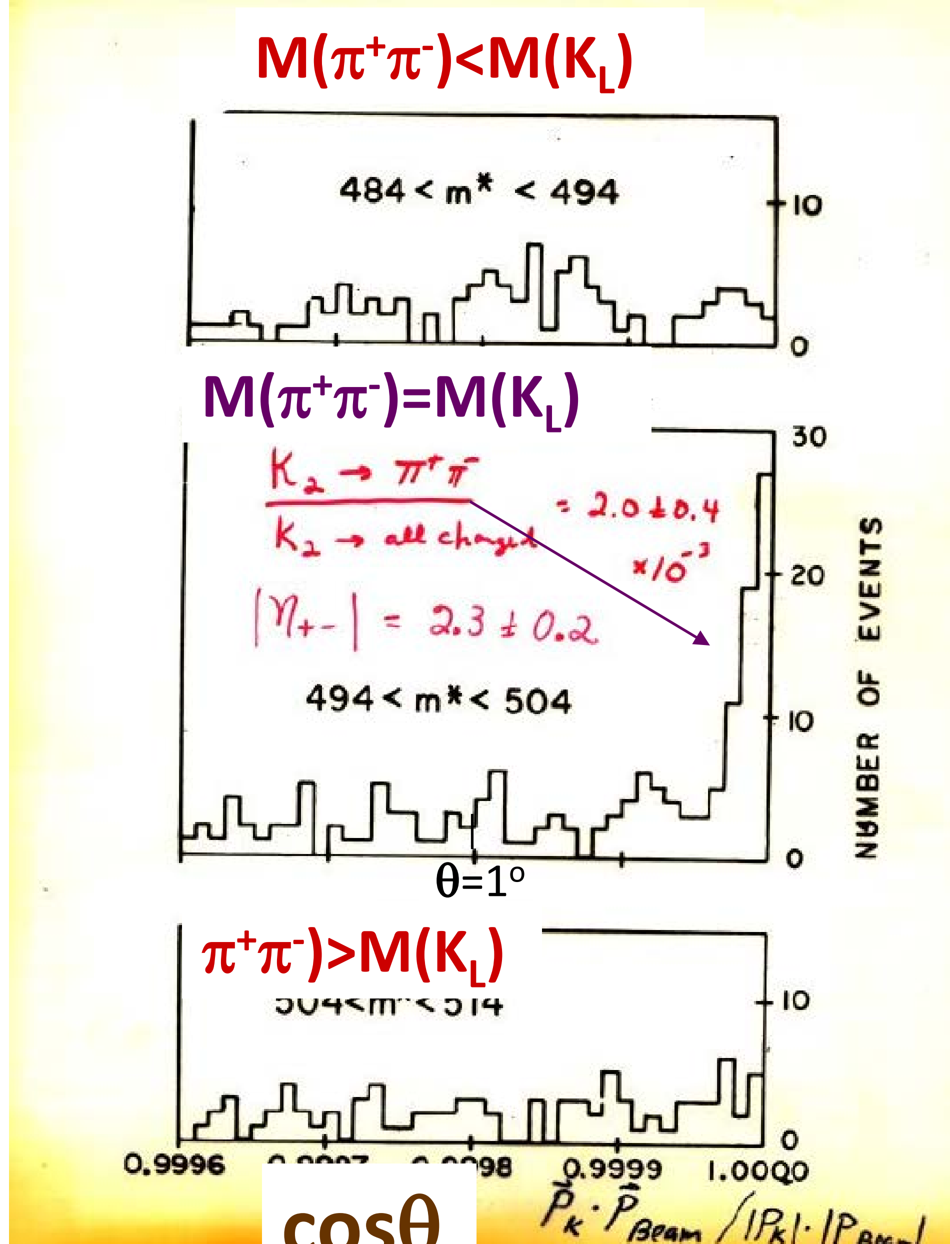
$$M\left(\pi^+\pi^-\right) = \sqrt{\left(E_{\pi+} + E_{\pi-}\right)^2 - \left(\vec{p}_{\pi+} + \vec{p}_{\pi-}\right)^2}$$

2π decay:



3-body-decay:





EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as

Results

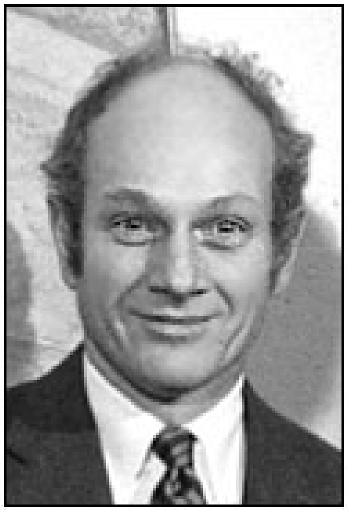
$$\frac{Bf(K_L \to \pi^+\pi^-)}{Bf(K_L \to \text{charged particles})} = 2.0 \pm 0.4 \times 10^{-3}$$

$$|\eta_{+-}| = \sqrt{\frac{Bf(K_L \to \pi^+\pi^-)\Gamma_{tot}^L}{Bf(K_S \to \pi^+\pi^-)\Gamma_{tot}^S}} = \sqrt{\frac{Bf(K_L \to \pi^+\pi^-)\tau_s}{Bf(K_S \to \pi^+\pi^-)\tau_L}}$$

$$|\eta_{+-}| = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \approx |\varepsilon| = 2.3 \pm 0.2 \times 10^{-3}$$

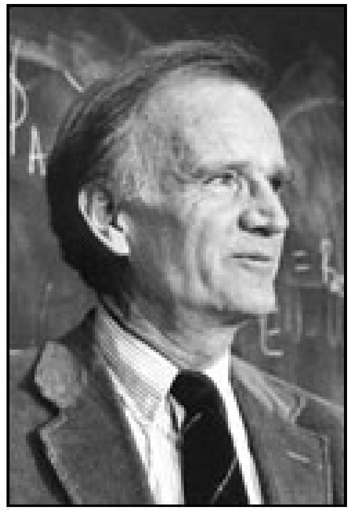
CP is violated!!

James Cronin

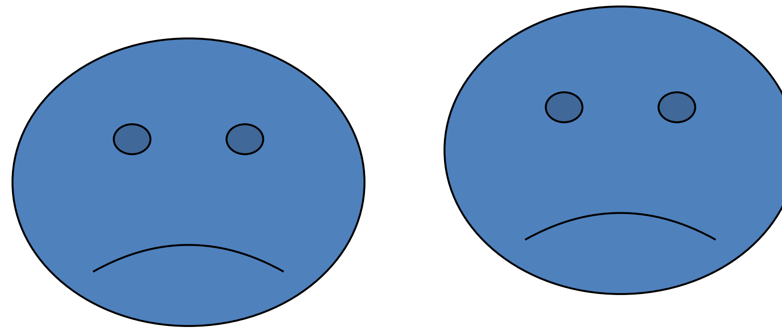


James Cronin

Val Fitch



Val Fitch



1980 Nobel Prize for Physics

No prizes for Christenson or Turlay

From left : Val Fitch, René Turlay, Jim Cronin and Jim Christenson.

Let's look at ε:

definition of ε:

$$\varepsilon \equiv \frac{p-q}{p+q}$$

what we know about $\boldsymbol{p}$ & $\boldsymbol{q}$

$$-ip^2 = \left(M_{12}^* - \tfrac{i}{2}\Gamma_{12}^*\right) \Rightarrow \boxed{p^2 = iM_{12}^* - \tfrac{i}{2}\Gamma_{12}^*}$$

$$-iq^2 = \left(M_{12} - \tfrac{i}{2}\Gamma_{12}\right) \Rightarrow \boxed{q^2 = iM_{12} + \tfrac{i}{2}\Gamma_{12}}$$

$$\lambda_S - \lambda_L = 2ipq = (M_S - M_L) - \tfrac{i}{2}(\Gamma_S - \Gamma_L)$$

$$\Rightarrow \boxed{2pq = i(M_L - M_S) - \tfrac{1}{2}(\Gamma_S - \Gamma_L)}$$

rewrite ε in terms that we know:

$$\varepsilon \equiv \frac{p^2-q^2}{(p+q)^2} \Rightarrow \frac{p^2-q^2}{4pq + (p-q)^2} \approx \frac{p^2-q^2}{4pq}$$

$$(p-q)^2 \sim \varepsilon^2 \Leftarrow small$$

$$\frac{p^2-q^2}{4pq} = \frac{-2\,\mathrm{Im}\,M_{12} + i\,\mathrm{Im}\Gamma_{12}}{2i(M_L - M_S) - (\Gamma_S - \Gamma_L)}$$

$$\varepsilon = \frac{i\,\mathrm{Im}\,M_{12} + \tfrac{1}{2}\mathrm{Im}\Gamma_{12}}{(M_L - M_S) - \tfrac{i}{2}(\Gamma_S - \Gamma_L)}$$

Some comments

$$H \Rightarrow \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{12} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^{*} - \frac{i}{2}\Gamma_{12}^{*} & M_{11} - \frac{i}{2}\Gamma_{11} \end{pmatrix}$$

CP is only violated if the off-diagonal terms are different

$$\varepsilon = \frac{i\,\mathrm{Im}\,M_{12} + \frac{1}{2}\mathrm{Im}\Gamma_{12}}{(M_L - M_S) - \frac{i}{2}(\Gamma_S - \Gamma_L)}$$

Hermiticity: $M_{21}=M_{12}^{*}$ & $\Gamma_{12}=\Gamma_{21}^{*}$
CPV only driven by imaginary terms

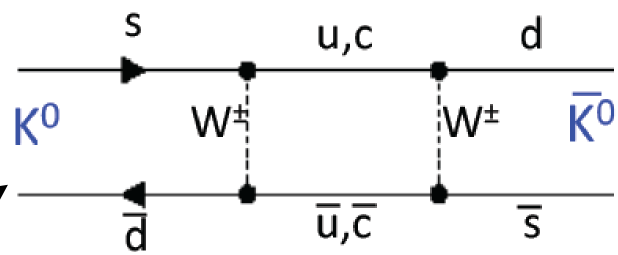
Latest numbers:

$$\frac{Bf(K_L \rightarrow \pi^+\pi^-)}{Bf(K_L \rightarrow \text{all})} = 1.97 \pm 0.01 \times 10^{-3}$$

$$|\eta_{+-}| = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \approx |\varepsilon| = 2.23 \pm 0.01 \times 10^{-3}$$

CPV is very small, $\sim 10^{-3} G_F^2$, far from the maximum that is possible (unlike P and C violations)

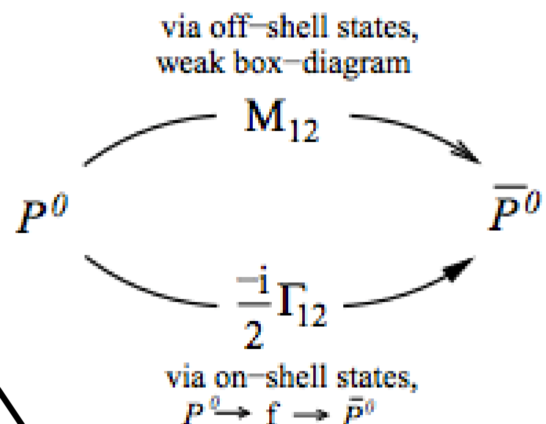
virtual & on-shell K^0--$\bar{K}^0$ couplings

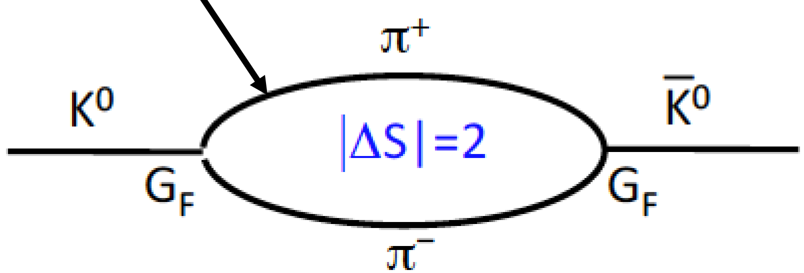


2nd-order quark-level virtual $|\Delta S|=2$ process

"short-distance processes" due to Mass Matrix CPV

$$\varepsilon = \frac{i\,\mathrm{Im}M_{12}+\frac{1}{2}\mathrm{Im}\Gamma_{12}}{(M_L-M_S)-\frac{i}{2}(\Gamma_S-\Gamma_L)}$$





On-shell pion-induced $|\Delta S|=2$ process

"long-distance processes" due to Decay Matrix CPV

Phase of ε (η_{+-})

$$\varepsilon = \frac{i\,\mathrm{Im}\,M_{12} + \frac{1}{2}\mathrm{Im}\Gamma_{12}}{(M_L - M_S) - \frac{i}{2}(\Gamma_S - \Gamma_L)}$$

$$\text{if } \mathrm{Im}\,\Gamma_{12} = 0,\ \varepsilon = \frac{i\,\mathrm{Im}\,M_{12}}{(M_L - M_S) + \frac{i}{2}(\Gamma_S - \Gamma_L)}$$

$$\&\,\phi_{SW} = \tan^{-1}\frac{2\Delta m}{\Delta\Gamma} = 43.30^\circ \pm 0.16^\circ,$$

ϕ_{SW}="Superweak phase"

FIG. 4. Vector diagram showing schematically the difference in the amplitudes for $K^0 \to \overline{K}^0$ and $\overline{K}^0 \to K^0$.

K^0 -- $\overline{K}^0$ basis states with CPV

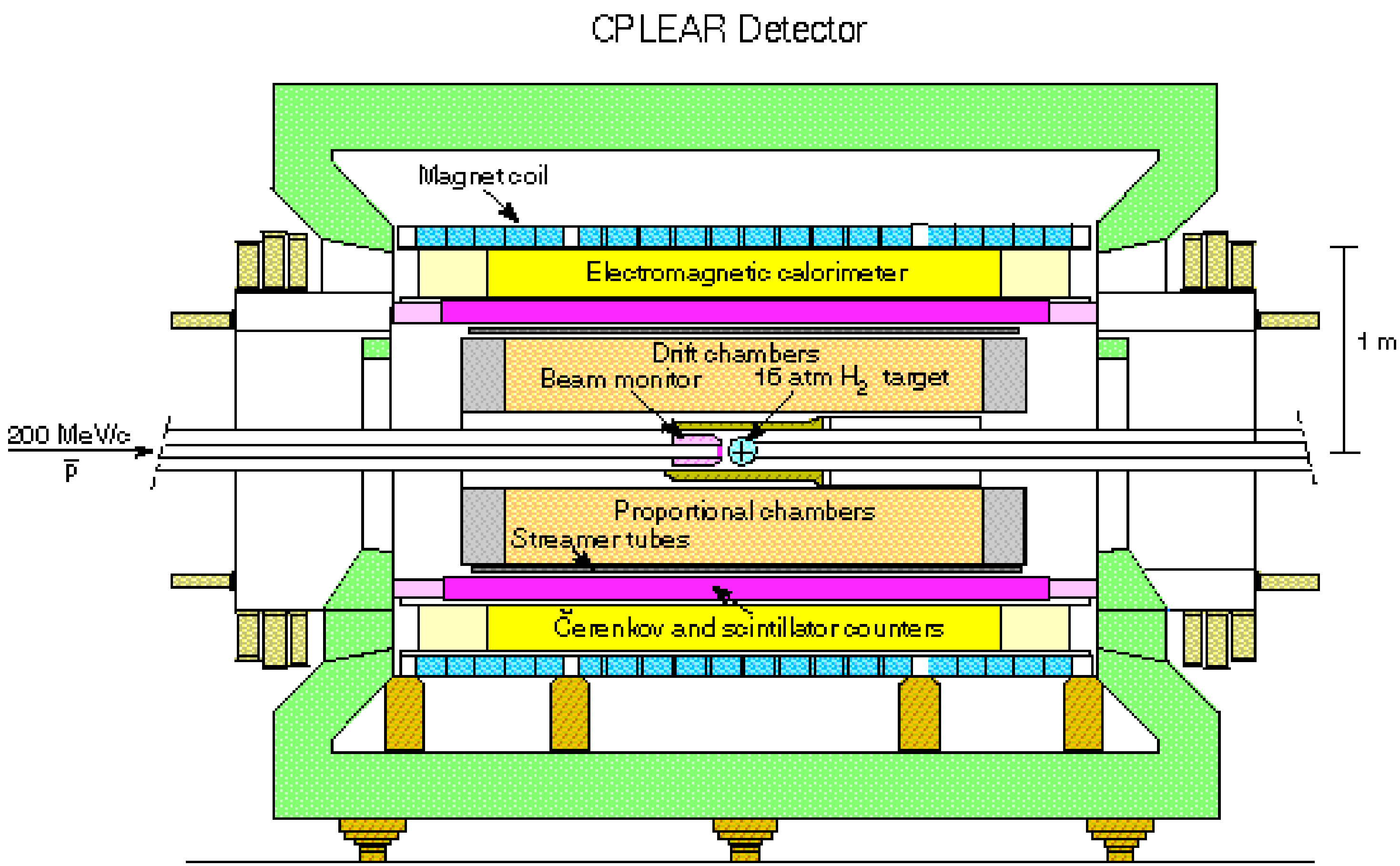
$$\frac{K_S = \frac{1}{\sqrt{2}}\left(K_1 + \varepsilon K_2\right) = \frac{1}{\sqrt{2}}\left((1+\varepsilon)K^0 - (1-\varepsilon)\overline{K}^0\right)}{K_L = \frac{1}{\sqrt{2}}\left(K_2 + \varepsilon K_1\right) = \frac{1}{\sqrt{2}}\left((1-\varepsilon)K^0 + (1+\varepsilon)\overline{K}^0\right)}$$

Solve for K^0 and $\overline{K}^0$

$$K^0 = \frac{1}{\sqrt{2}}\left((1-\varepsilon)K_S + (1+\varepsilon)K_L\right)$$
$$\overline{K}^0 = \frac{1}{\sqrt{2}}\left((1+\varepsilon)K_S - (1-\varepsilon)K_L\right)$$

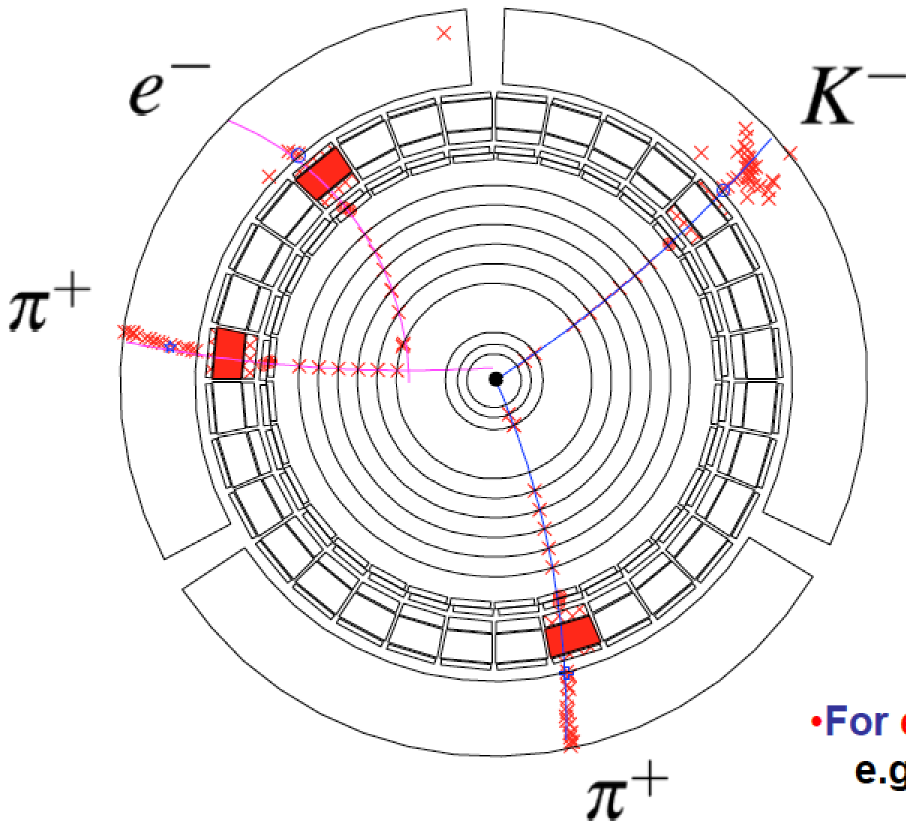
Please check this for HW

The CPLEAR experiment



Strangeness-tagging at CPLEAR

An example of a CPLEAR event



$K^-(s\bar{u})$
$K^0(d\bar{s})$
$\bar{K}^0(s\bar{d})$

Production:

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

Mixing

Decay:

$$\bar{K}^0 \to \boxed{\pi^+e^-}\bar{\nu}_e$$

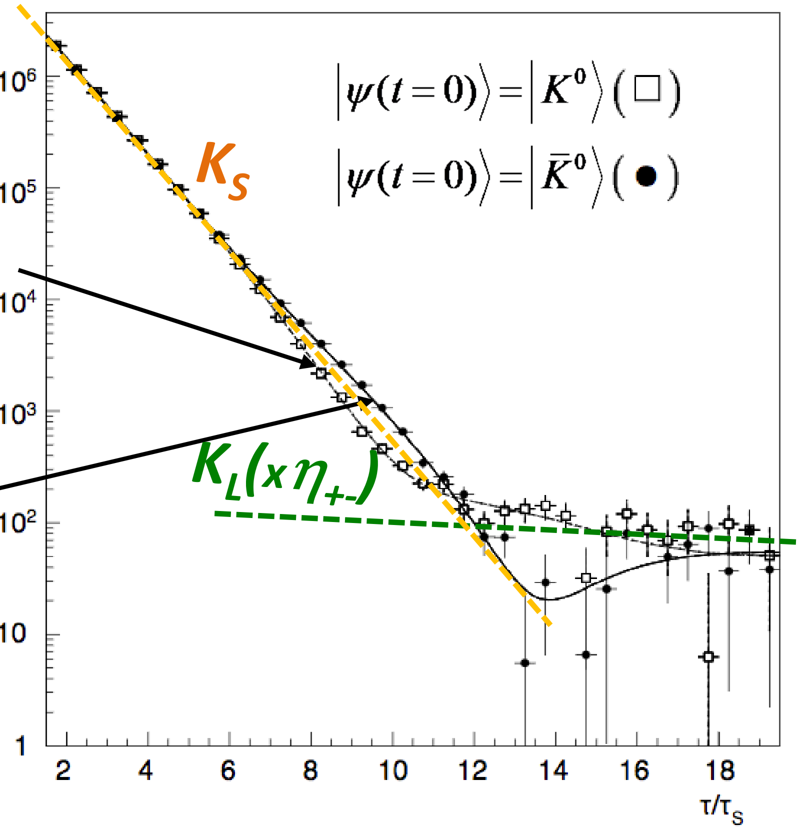
- **For each event know initial wave-function,**
  e.g. here: $|\psi(t=0)\rangle = |K^0\rangle$

$$\text{for } \bar{p}p \to \boxed{K^+\pi^-}K, \quad |\psi(t=0)\rangle = |\bar{K}^0\rangle$$

Time-dependence of $K^0(\bar{K}^0) \rightarrow \pi^+\pi^-$

$$\left|K^0(t)\right\rangle = \tfrac{1}{\sqrt{2}}\begin{pmatrix}(1-\varepsilon)\left|K_S\right\rangle \\ (1+\varepsilon)\left|K_L\right\rangle\end{pmatrix}\begin{matrix} e^{-i(M_s-\frac{i}{2}\Gamma_S)t} \rightarrow \pi^+\pi^- \\ \left|\eta_{+-}\right|e^{-i(M_L-\frac{i}{2}\Gamma_L)t+\phi_{+-}} \rightarrow \pi^+\pi^- \end{matrix}$$

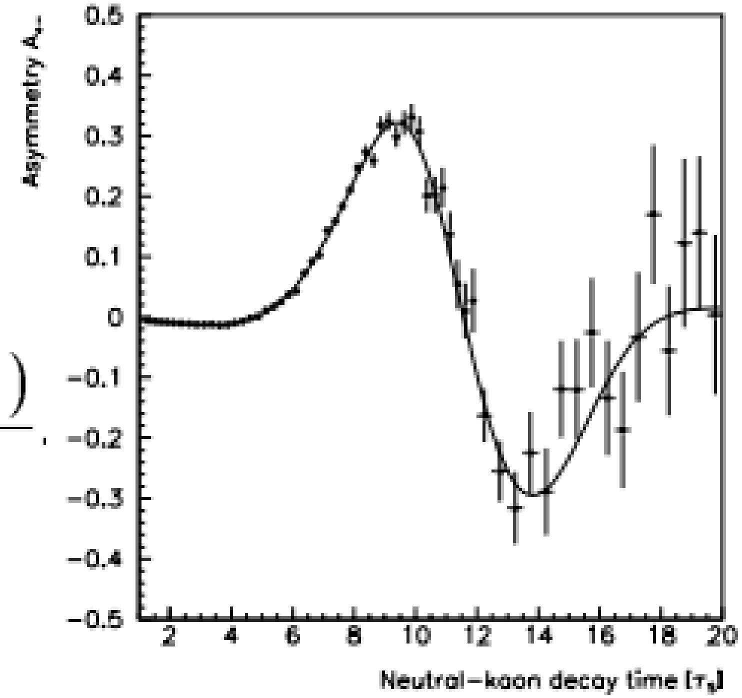
$$\left|\bar{K}^0(t)\right\rangle = \tfrac{1}{\sqrt{2}}\begin{pmatrix}(1+\varepsilon)\left|K_S\right\rangle \\ (\varepsilon-1)\left|K_L\right\rangle\end{pmatrix}\begin{matrix} e^{-i(M_s-\frac{i}{2}\Gamma_S)t} \rightarrow \pi^+\pi^- \\ \left|\eta_{+-}\right|e^{-i(M_L-\frac{i}{2}\Gamma_L)t+\phi_{+-}} \rightarrow \pi^+\pi^- \end{matrix}$$



Phase of (η_{+-}) from CPLEAR

$$A_{+-}(\tau) = \frac{\overline{N}(\tau) - \alpha N(\tau)}{\overline{N}(\tau) + \alpha N(\tau)}$$

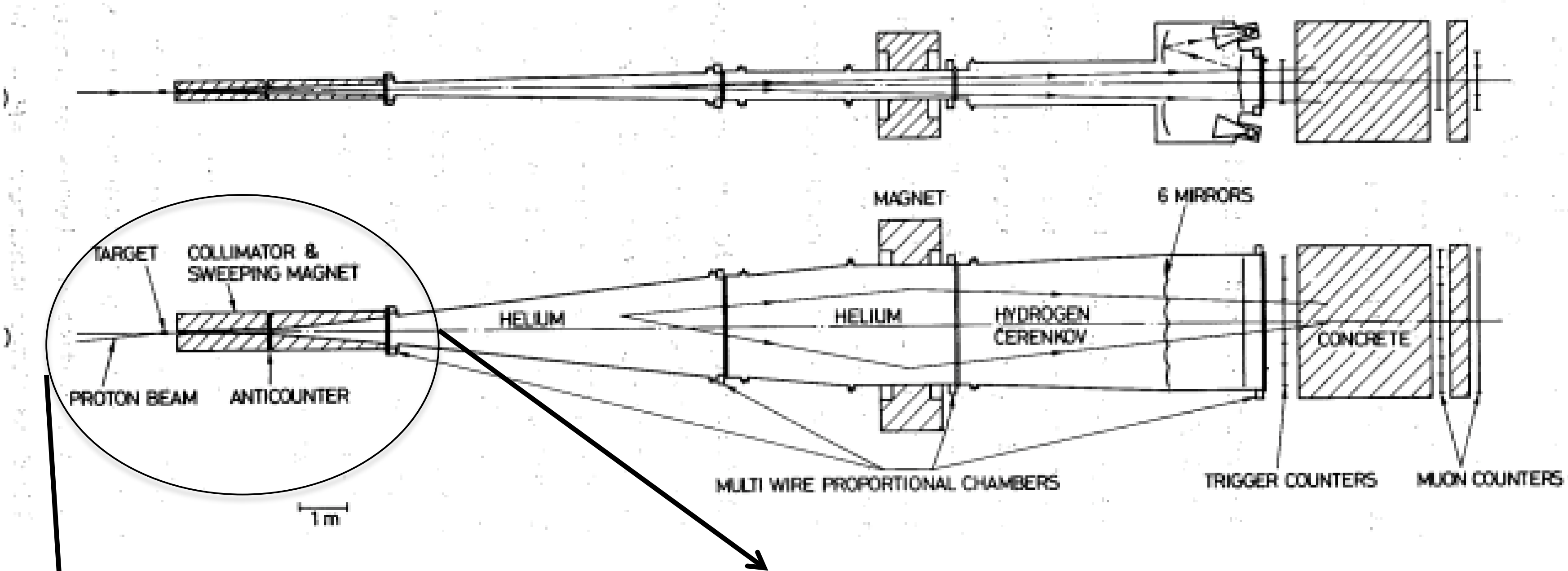
$$= -2\frac{|\eta_{+-}|e^{\frac{1}{2}(\tau/\tau_{\rm S}-\tau/\tau_{\rm L})}\cos(\Delta m\tau - \phi_{+-})}{1+|\eta_{+-}|^2 e^{(\tau/\tau_{\rm S}-\tau/\tau_{\rm L})}}.$$

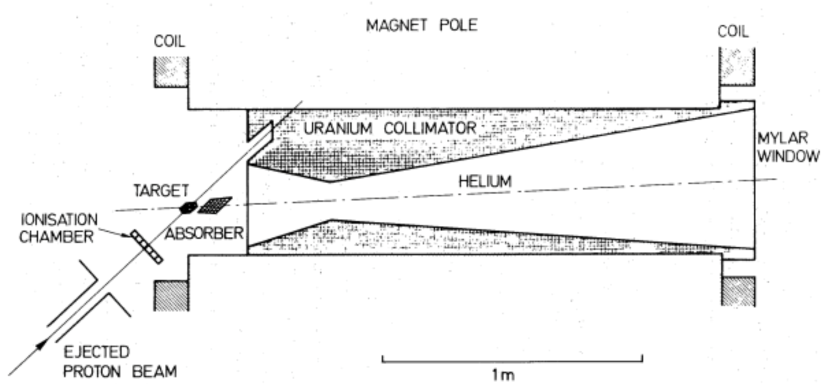


$$\begin{aligned} |\eta_{+-}| &= (2.312 \pm 0.043_{\rm stat.} \pm 0.030_{\rm syst.} \pm 0.011_{\tau_{\rm S}}) \times 10^{-3} \\ \phi_{+-} &= 42.7^\circ \pm 0.9^\circ_{\rm stat.} \pm 0.6^\circ_{\rm syst.} \pm 0.9^\circ_{\Delta m}\ . \end{aligned}$$

CPLEAR Phys. Lett. B458, 545 (1999)

Neutral Kaon spectrometer @ CERN



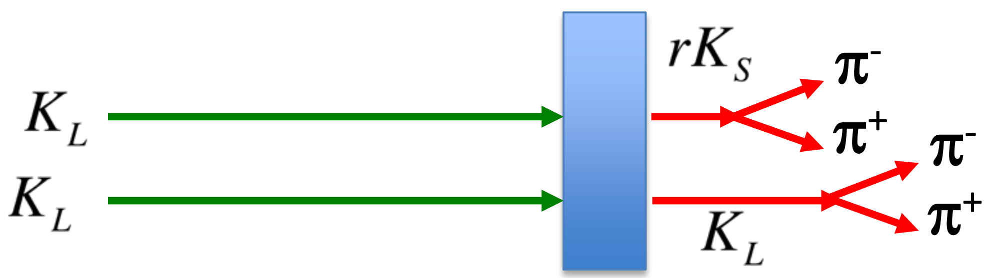


expanded view of target region

Exploit $K_L \rightarrow K_S$ coherent regeneration

$$K_L = \tfrac{1}{\sqrt{2}}(K^0 + \overline{K}^0)$$

$$K' = \tfrac{f+\bar{f}}{\sqrt{2}}(K_L + rK_S)$$

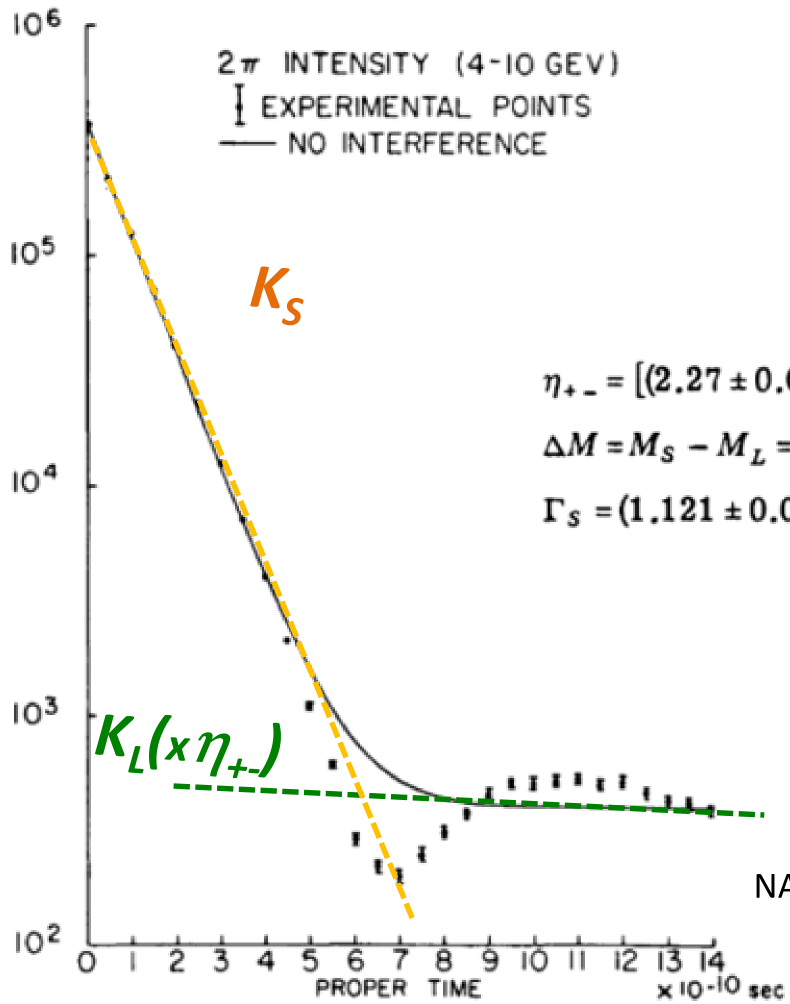


Need to know regeneration phase

$$r \cdot e^{-i(M_S - \frac{i}{2}\Gamma_S)t + \phi_{reg}}$$

$$|\eta_{+-}| e^{-i(M_L - \frac{i}{2}\Gamma_L)t + \phi_{\eta+-}}$$

ΔM and $\phi(\eta_{+-})$ measured via regeneration



$$\eta_{+-} = [(2.27 \pm 0.02)\times 10^{-3}]\exp[i(44.7^\circ \pm 1.2^\circ)],$$

$$\Delta M = M_S - M_L = -(0.535 \pm 0.002)\times 10^{10}\ \text{sec}^{-1},$$

$$\Gamma_S = (1.121 \pm 0.003)\times 10^{10}\ \text{sec}^{-1}.$$

NA31 Phys. Lett. B237, 303 (1990)

FIG. 2. Yield of $\pi^+\pi^-$ events as a function of proper time downstream from an 81 cm carbon regenerator placed in a K_L beam

$K^0 \leftrightarrow \overline{K}^0$ oscillations (mixing);no CPV→CPV

$$|K_L(t)\rangle = e^{-i(M_L - \frac{i}{2}\Gamma_L)t}|K_L(0)\rangle$$

$$|K_S(t)\rangle = e^{-i(M_S - \frac{i}{2}\Gamma_S)t}|K_S(0)\rangle$$

eigenstates

start at t=0 with a K^0: $$|K^0(t=0)\rangle = \tfrac{1}{\sqrt{2}}\left((1-\varepsilon)|K_S(t=0)\rangle + (1+\varepsilon)|K_L(t=0)\rangle\right)$$

then, at a later time t: $$|K^0(t)\rangle = \tfrac{1}{\sqrt{2}}\left((1-\varepsilon)e^{-i(M_S - \frac{i}{2}\Gamma_S)t}|K_S(0)\rangle + (1+\varepsilon)e^{-i(M_L - \frac{i}{2}\Gamma_L)t}|K_L(0)\rangle\right)$$

$$= f_+(t)|K^0\rangle + f_-(t)|\overline{K}^0\rangle$$

$$f_\pm(t) = \tfrac{1}{2}\left[e^{-i(M_S - \frac{i}{2}\Gamma_S)t} \pm e^{-i(M_L - \frac{i}{2}\Gamma_L)t}\right]$$

These are the K^0 and $\overline{K}^0$ rates we measure

$$I(K^0 \to K^0;t) = I_0\left|\langle K^0|K^0(t)\rangle\right|^2 = I_0|f_+(t)|^2$$

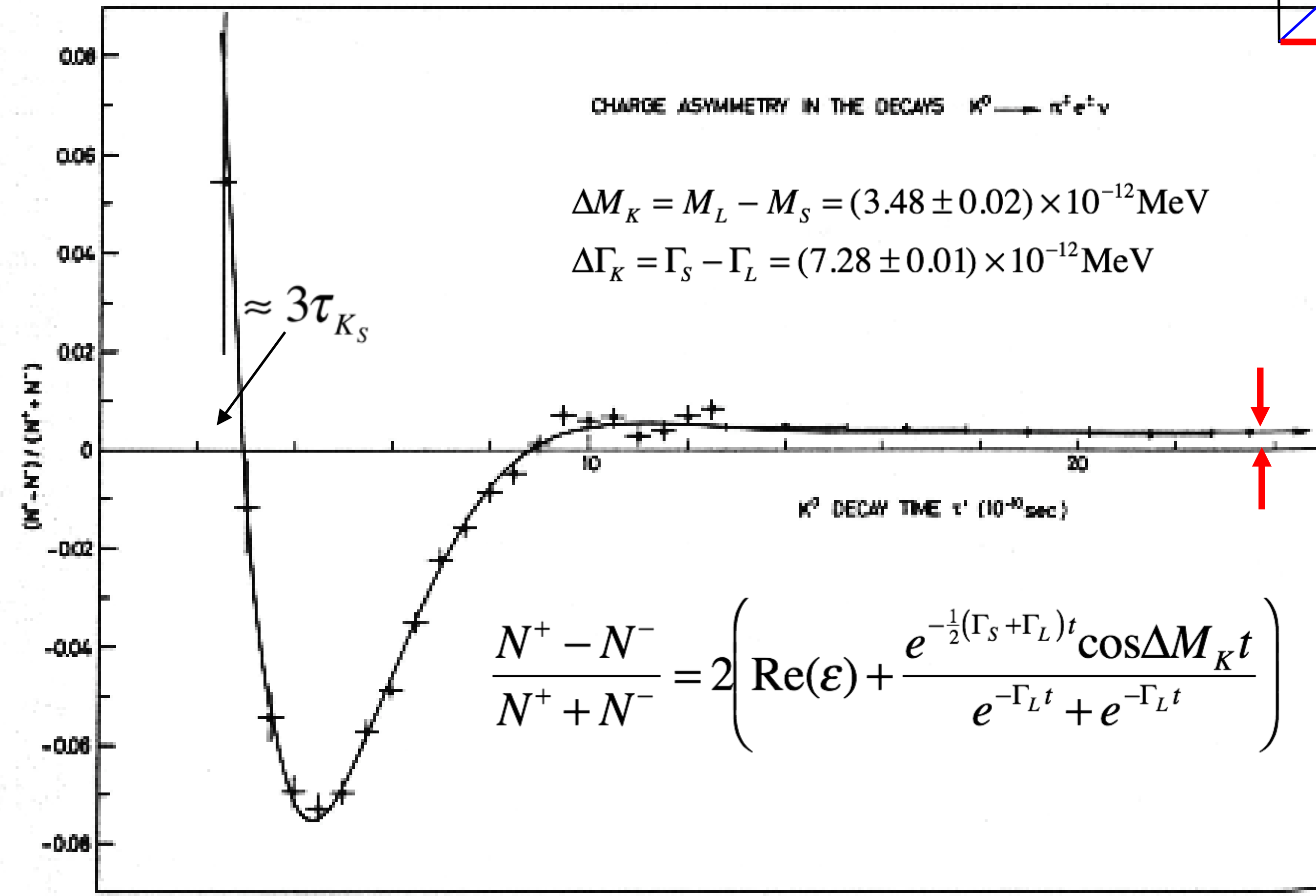
$$I(K^0 \to \overline{K}^0;t) = I_0\left|\langle \overline{K}^0|K^0(t)\rangle\right|^2 = I_0|f_-(t)|^2$$

I_0 = beam intensity (particles/s)

$K^0 \leftrightarrow \bar{K}^0$ in a neutral K beam with CPV

start with ≈75% K^0 and ≈25% $\bar{K}^0$

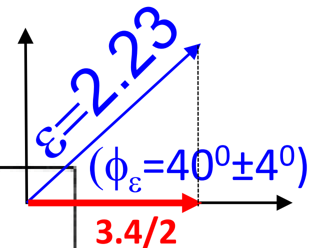
$$\frac{N^+ - N^-}{N^+ + N^-}$$



$$\Delta M_K = M_L - M_S = (3.48 \pm 0.02) \times 10^{-12}\,\mathrm{MeV}$$

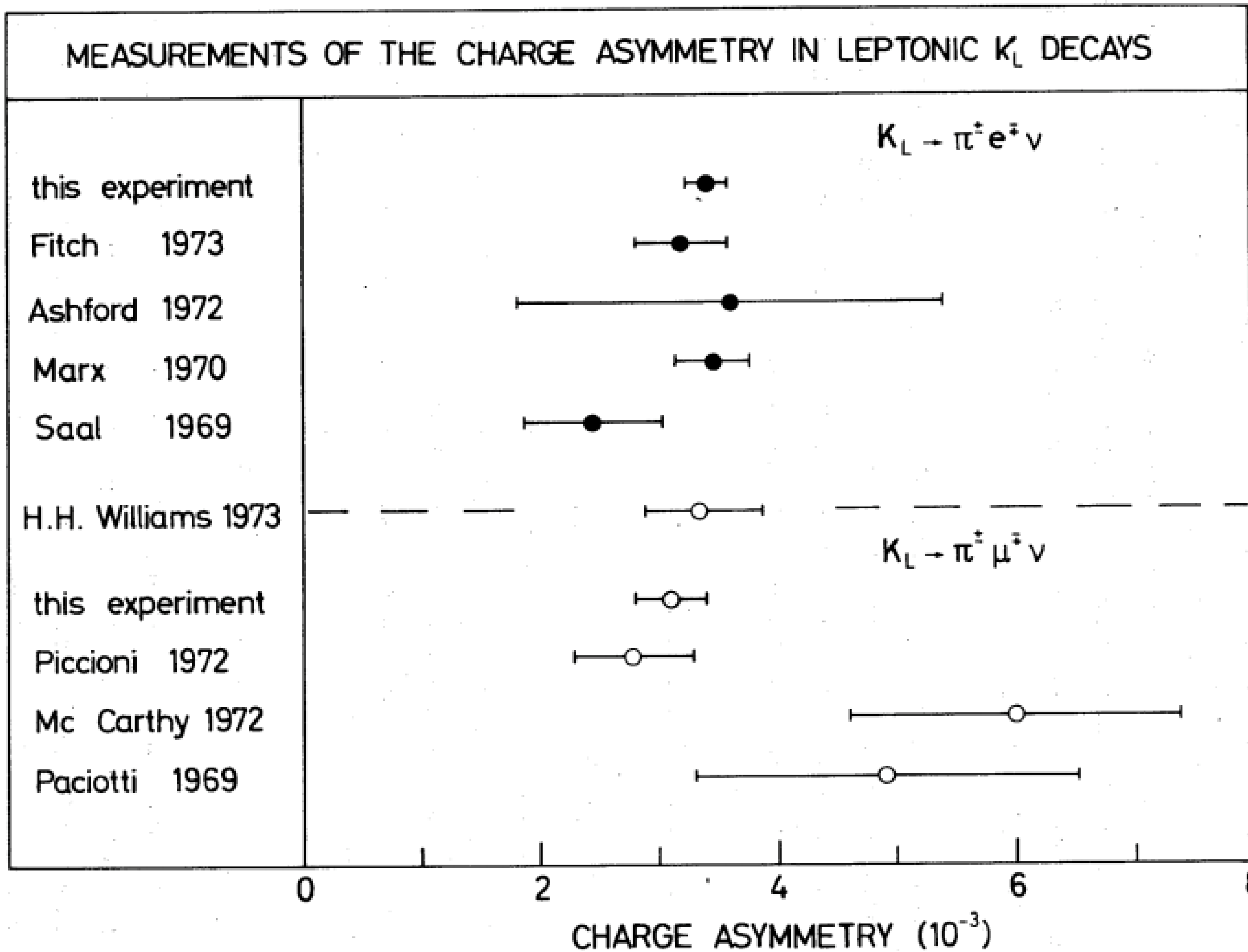
$$\Delta\Gamma_K = \Gamma_S - \Gamma_L = (7.28 \pm 0.01) \times 10^{-12}\,\mathrm{MeV}$$

$$\frac{N^+ - N^-}{N^+ + N^-} = 2\left(\mathrm{Re}(\varepsilon) + \frac{e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \cos \Delta M_K t}{e^{-\Gamma_L t} + e^{-\Gamma_L t}} \right)$$



2Reε= $3.4 \pm 0.2 \times 10^{-3}$

Measurements of 2Reε (circa 1974)



Recent values of K-meson CPV parameters

Quantity(units)	Fit w/o CPT	Fit w/ CPT
$\phi_{+-}(^\circ)$	43.4 ± 0.5 (S=1.2)	43.51 ± 0.05 (S=1.2)
$\Delta m(10^{10}\hbar\,\mathrm{s}^{-1})$	0.5289 ± 0.0010	0.5293 ± 0.0009 (S=1.3)
$\tau_S(10^{-10}\mathrm{s})$	0.89564 ± 0.00033	0.8954 ± 0.0004 (S=1.1)
$\phi_{00}(^\circ)$	43.7 ± 0.6 (S=1.2)	43.52 ± 0.05 (S=1.3)
$\Delta\phi(^\circ)$	0.34 ± 0.32	0.006 ± 0.014 (S=1.7)
$\phi_\epsilon(^\circ)$	43.5 ± 0.5 (S=1.3)	43.52 ± 0.05 (S=1.2)
χ^2	16.4	20.0
# Deg. Free.	14	16

consistent with $\mathrm{Im}\Gamma_{12}$=0,
& ImM_{12} responsible for all of the CPV

Summary of Lecture 3

- K^0 and $\overline{K}^0$ mesons are not mass eigenstates; K_S and K_L are mass eigenstates
- K_L mesons discovered at Brookhaven Laboratory
- a K^0 will oscillate into a $\overline{K}^0$ and vice versa
- neutral K mesons produced in ϕ decay are ~100% "quantum correlated"
- K_S mesons are "regenerated" when a K_L passes through matter

- Discovery of $K_L \rightarrow \pi^+\pi^-$ decays proved that CP symmetry is violated
- Measurements consistent with $K_L = K_2 + \varepsilon K_1$; $\varepsilon = 2.2 \times 10^{-3}$
- Phase of ε consistent with CPV originating from short-distance Mass-Matrix terms
- Many beautiful, high-statistics measurements of CPV interference effects reported