Kaon physics

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PSI Summer School
Zuoz, July 17-22, 2006

Outline

- Express review of K phenomenology
- Neutral K hadronic decays and CP violation
- The measurement of direct CP violation
- More CP violation
- Radiative decays
- Non CPV physics from K
- The new frontier: ultra-rare FCNC K decays

Express review of Kaon phenomenology

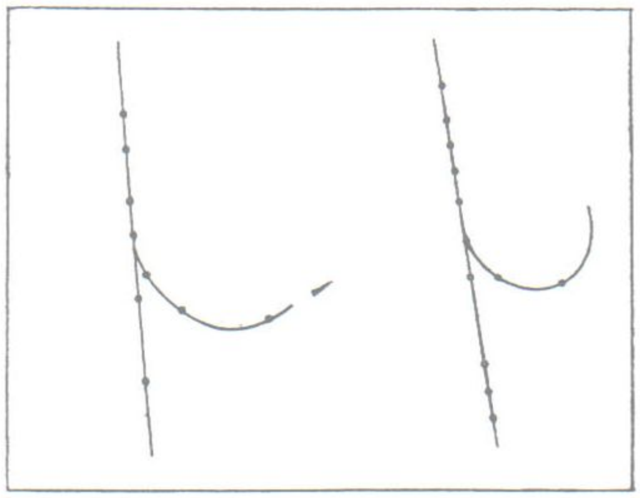
K mesons

Discovered in cosmic rays

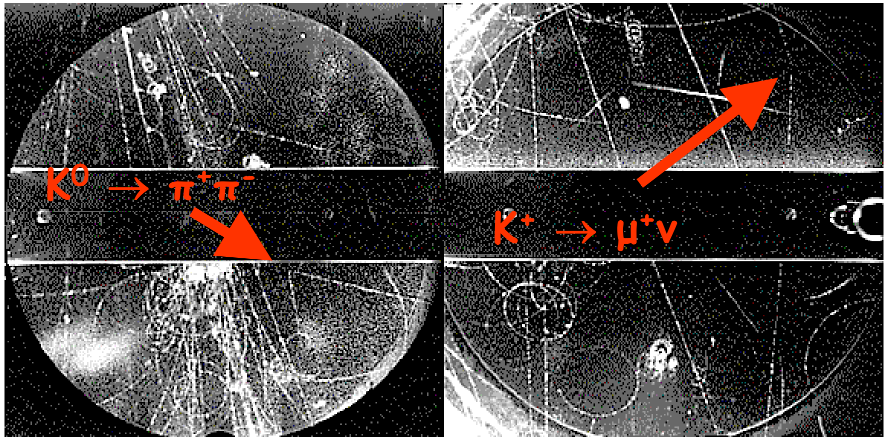
L. Leprince-Ringuet, M. L'Heritier (1944):

Existence probable d'une particule de masse 990 m_0 dans le rayonnement cosmique.

[K^+ scatters elastically on e^- in a cloud chamber]



Dessin stéréoscopique de la collision.



G.D. Rochester, C.C. Butler (1947):

Evidence for the existence of new unstable elementary particles.

[$K^0 \to \pi^+\pi^-$ and $K^+ \to \mu^+\nu$ in a cloud chamber]

Strangeness…

A. Pais, Phys. Rev. **86** (1952) 663
M. Gell-Mann, Phys. Rev. **92** (1953) 833
T. Nakano, K. Nishijima, Prog. Theor. Phys. **10** (1953) 581

"Strange" particles:

◊ copiously produced: $\sigma(\pi^- p \to K^0 \Lambda) \approx 1$ mb $\approx \sigma_{tot}/40$ STRONG

BUT

◊ long lifetime: $\tau(\Lambda \to \pi^- p) \approx 10^{-10}$ s » 10^{-23} s ~ r/c WEAK

Strangeness (S) hypotesis:
a quantum number conserved by strong interactions and *not* by weak interactions:

- Associated production (*strong*):
  $\pi^- p \to K^- p$ not observed
  rate of events with two V-particles above accidental rate
- S-violating decay (*weak*)
  $\Lambda \to \pi^- p \pi^0 \to \pi^- p$ is as slow as $\pi^- p \to \Lambda \pi^0$

… and weirdness

M. Gell-Mann and A. Pais (1955)

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

Some properties are discussed of the θ^0, a heavy boson that is known to decay by the process $\theta^0 \to \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the θ^0 possesses an antiparticle $\bar{\theta}^0$ distinct from itself. Some theoretical implications of this situation are discussed with special reference to charge conjugation invariance. The application of such invariance in familiar instances is surveyed in Sec. I. It is then shown in Sec. II that, within the framework of the tentative schemes under consideration, 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. Some experimental consequences of this picture are mentioned.

- Macroscopic physics laws are C-symmetric [later CP-]
- Two classes of neutral particles; behaviour under C:
  1. $\theta^0 \to \theta^0$ (self C-conjugated, ex. γ, π^0)
  2. $\theta^0 \to \bar{\theta}^0$ (distinct by conserved quantum numbers; ex. n)
- K^0 mesons belong to class (2) with strong interactions only (strangeness conservation) but in weak interactions strangeness is not conserved:
  Possible $K^0 \to \bar{K}^0$ transitions, common decay final states

Change of basis: K^0, $\overline{K}^0$ described by a complex field

$$C\Psi C^{-1} = \Psi^+ \qquad C\Psi^+ C^{-1} = \Psi$$

Use C to characterize physical states (later CP):

Defining:
$$\begin{cases} K_1 = (\Psi + \Psi^+)/\sqrt{2} \\ K_2 = (\Psi - \Psi^+)/\sqrt{2} \end{cases}$$

One gets: $CK_1C^{-1} = +K_1 \qquad CK_2C^{-1} = -K_2$

So: $C(K_1) = +1 \quad C(K_2) = -1$

Physical states are K_1 and K_2, with no transitions among them, with well-defined masses (not a particle-antiparticle pair) and widths (expected to be different because different final states available).

[After 1964: replace C with CP everywhere]

(1) Long-lived K mesons

Observation of Long-Lived Neutral V Particles*

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,
Columbia University, New York, New York
AND
W. CHINOWSKY, *Brookhaven National Laboratory, Upton, New York*
(Received July 30, 1956)

23 V events in 1200 pictures, all but one non-coplanar (at least 3 particles)

Exclude possible backgrounds:
meson pair production, $\pi^0 \to e^+e^-\gamma$,
large-angle lepton pairs and scattering of backward-moving particles

$\pi e \nu$ and $\pi \mu \nu$ decay modes, and occasionally $\pi\pi\pi$, 10^{-9} s $< \tau < 10^{-6}$ s

K_S (*short-lived*), K_L (*long-lived*)
$=K_1$ $=K_2$ For the time being…

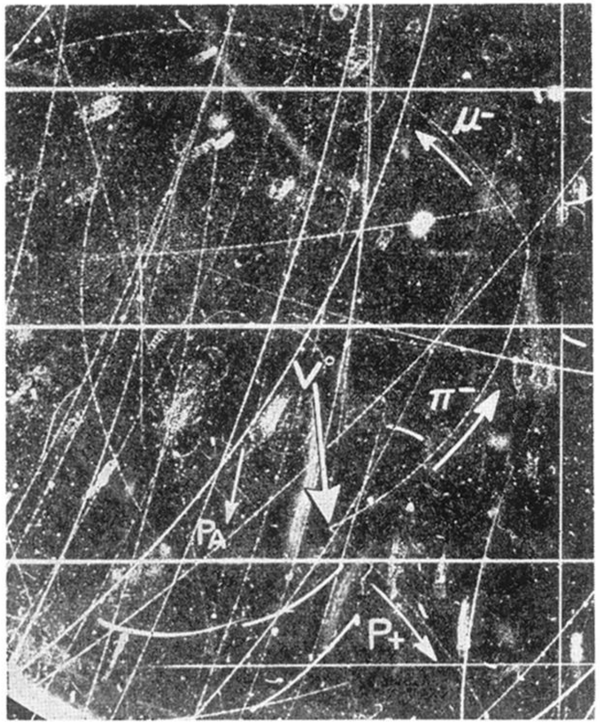


FIG. 2. Example of $K^0 \to \pi^+ + \pi^- +$neutral particle. P_+ is shown to be a pion by ionization measurements. P_A is a proton track used in the ionization calibration.

$\tau(K_S) = 0.89\times10^{-10}$ s
$\tau(K_L) = 5.17\times10^{-8}$ s

Accidental difference by a factor 600 !

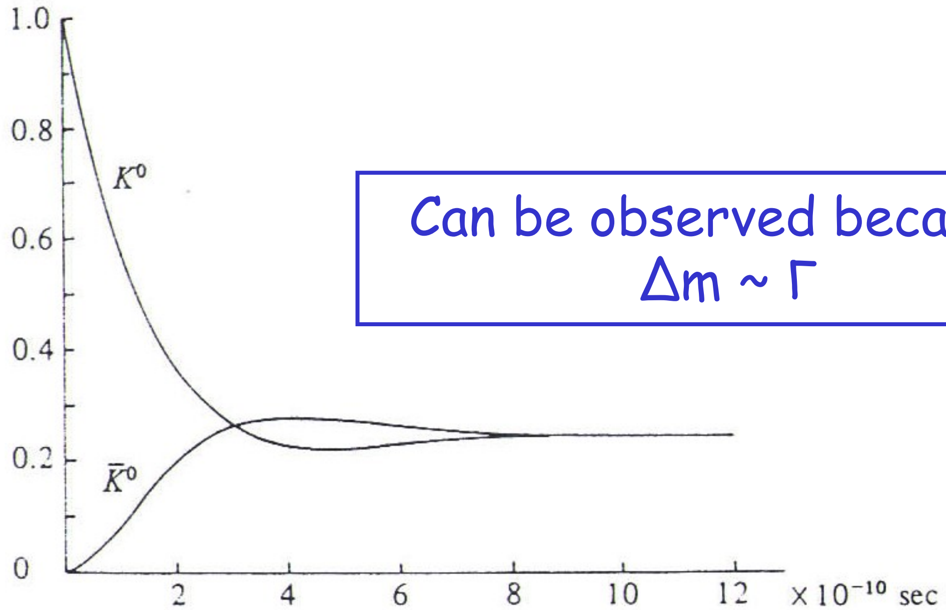
(2) Strangeness oscillations

Producing a state (K^0, $\overline{K}^0$) of definite strangeness at t=0, its strangeness oscillates in time:

$$P[K^0(t=0) \to K^0(t)] = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + 2e^{-(\Gamma_1+\Gamma_2)t/2}\cos(\Delta m t)\right]$$

$$P[K^0(t=0) \to \overline{K^0}(t)] = \frac{1}{4}\left[e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - 2e^{-(\Gamma_1+\Gamma_2)t/2}\cos(\Delta m t)\right]$$

$\Delta m = m_1 - m_2$



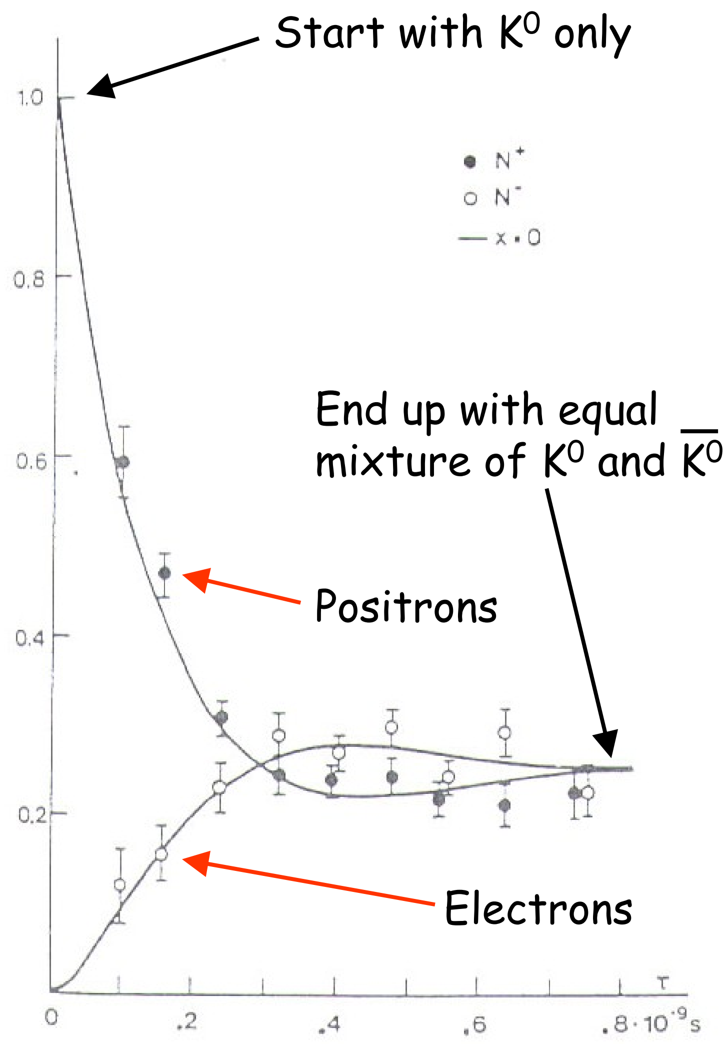
Can be observed because:
$\Delta m \sim \Gamma$

Strangeness oscillations can be measured exploiting flavour-specific decays which are allowed only for K^0 or for $\bar{K}^0$ (*flavour tagging*).

Semi-leptonic decays:
$K^0 \rightarrow \pi^- e^+ \nu_e$ but not $\bar{K}^0 \rightarrow \pi^- e^+ \nu_e$
because of the "$\Delta S = \Delta Q$ rule" (quarks).

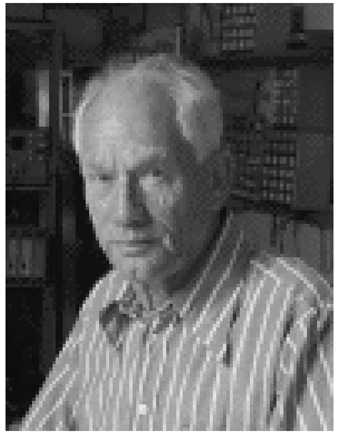
Non-exponential decay into *strangeness eigenstates* (not eigenstates of H): strangeness non-conservation

Ignoring strangeness (lepton charge): exponential decay(s) recovered



(3) Regeneration

[A. Pais, O. Piccioni (1955)]

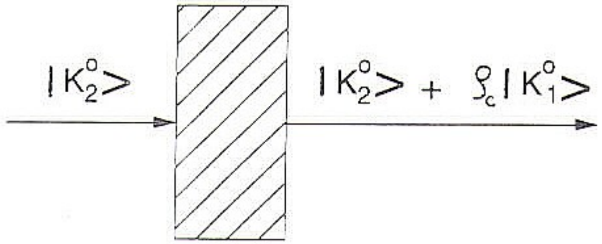


Strong interactions with matter are not strangeness-symmetric:
besides $K^0p \to nK^+$ and $\bar{K}^0n \to pK^-$ also
$\bar{K}^0p \to \Lambda\pi^+$ (hyperon production) gives

$\sigma(\bar{K}^0) \gg \sigma(K^0)$

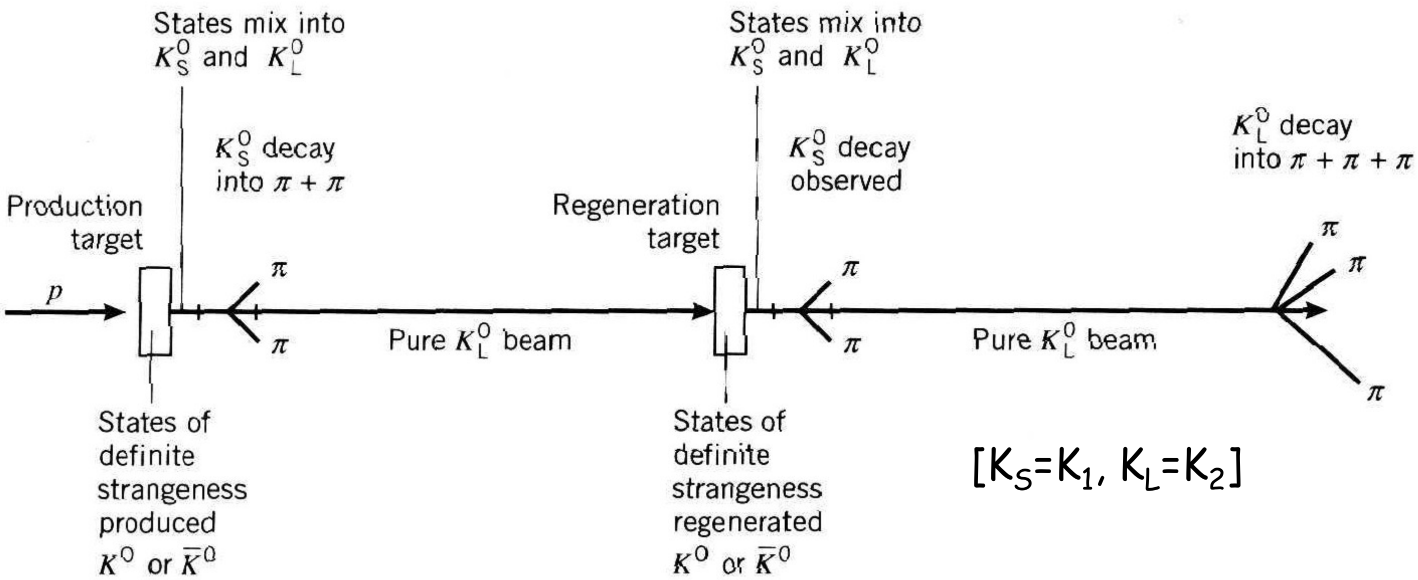
Indeed: $\bar{K}^0p \to \Lambda\pi^+$ has no threshold, while
$K^0p \to \Lambda K^0K^+$ has 1.27 GeV kinetic energy threshold

… even more bizarre manifestations of the mixing of K^0 and $\bar{K}^0$.
(J.D. Jackson, 1958)



Regeneration

K^0 (or $\bar{K}^0$) $\propto K_1 \pm K_2 \rightarrow K_2 \rightarrow \bar{K}^0$ removed in matter $\rightarrow K_1 + K_2$



[$K_S = K_1$, $K_L = K_2$]

"... the only instance where a forward coherently scattered beam can be distinguished from the original beam".

(K^0, K^0) and (K_S, K_L) as

(S_x, S_y) and (S_L, S_R) optical activity or

$(S_y = \pm\frac{1}{2})$ and $(S_x = \pm\frac{1}{2})$ Stern-Gerlach

Regeneration

REGENERATION AND MASS DIFFERENCE OF NEUTRAL K MESONS*

Francis Muller,† Robert W. Birge, William B. Fowler,‡ Robert H. Good, Warner Hirsch,
Robert P. Matsen, Larry Oswald, Wilson M. Powell, and Howard S. White
Lawrence Radiation Laboratory, University of California, Berkeley, California

and

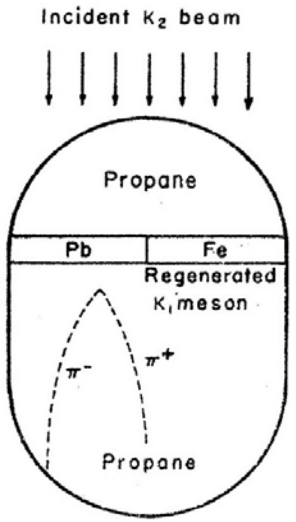
Oreste Piccioni
Brookhaven National Laboratory, Upton, New York
(Received March 29, 1960)

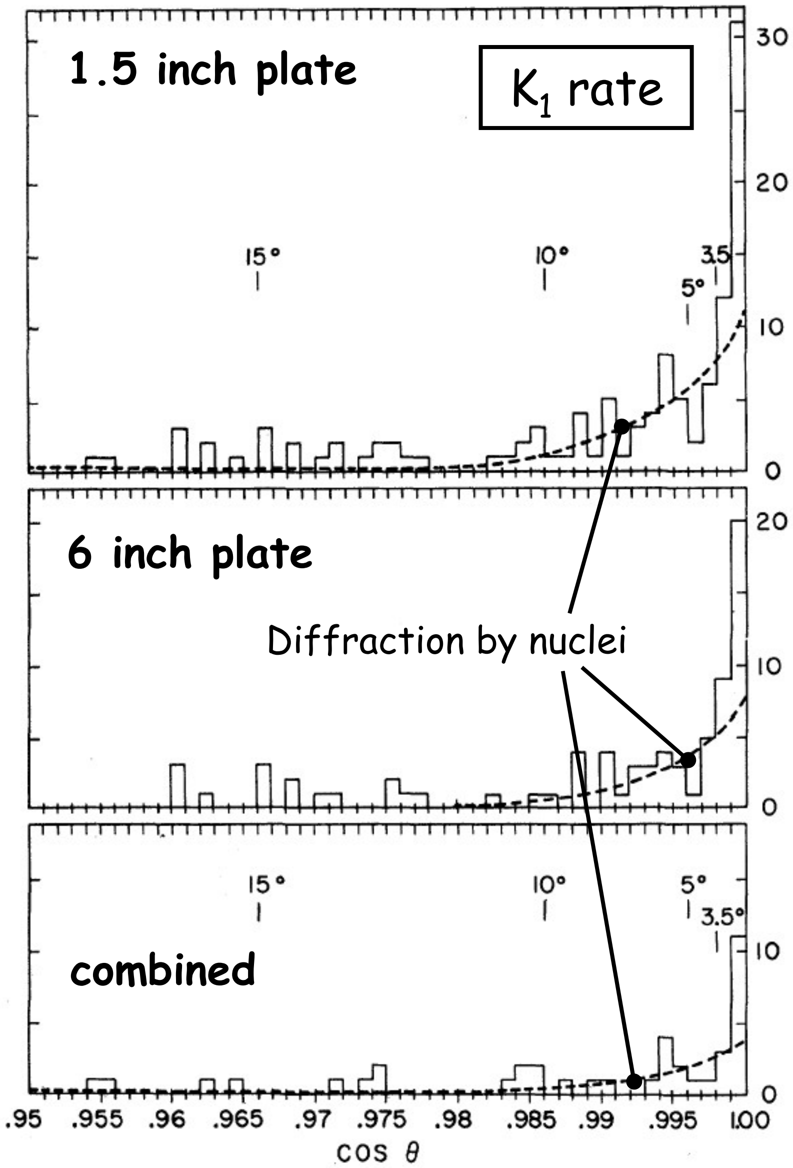
π^- on H_2 target: 670 MeV/c neutral K beam at Berkeley

Travelling ~7.5 m (200 τ_S) before reaching a propane chamber containing an iron plate

200000 pictures, half with 1.5 inch iron plate, half with 6 inch iron plate

Look for 2-track events, close ($2\tau_S$) to plate, with same momentum as incident beam





Two neutral K mesons

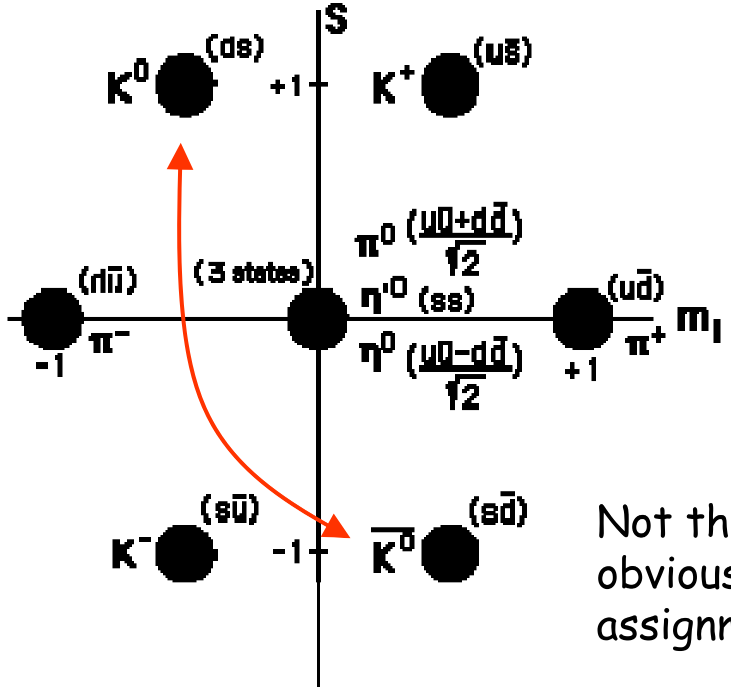
Example: $n \to \Lambda K^0$ and $\overline{K}^0 n \to \Lambda$ occur (strongly)
but if $K^0 n \to \Lambda$ would occur
then $nn \to n\Lambda K^0 \to \Lambda\Lambda$ would also occur (not observed)

$M(K^0) = 497.7\ \text{MeV}/c^2$
$I(J^P) = \frac{1}{2}(0^-)$

In terms of quarks:
$K^0 = (d\bar{s})$ $S = +1$
$\overline{K}^0 = (\bar{d}s)$ $S = -1$
which means:

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

$[\ \pi^0 = (u\bar{u}+d\bar{d})/\sqrt{2} = \overline{\pi}^0\ ]$



Not the most obvious multiplet assignment.

The K meson system is the *minimal flavour laboratory*

A bold, profound and very fruitful conceptual step

"The search for ordering principles at this moment may indeed ultimately have to be likened to a chemist's attempt to build up the periodic system if he were given only a dozen odd elements".
(A. Pais, 1952)

"It is by no means certain that, if the complex ensemble of phenomena concerning the neutral K mesons were known without the benefit of the Gell-Mann – Pais theory, we could, even today, correctly interpret the behavior of these particles.
That their theory, published in 1955, actually preceded most of the experimental evidence known at present, is one of the most astonishing and gratifying successes in the history of the elementary particles".
(R.H. Good *et al.*, 1961)

"Especially interesting is the fact that we have taken the principle of superposition to its ultimately logical conclusion".
"… one of the greatest achievements of theoretical physics".
(R. Feynman)

Two-state formalism

Consider the (non complete) subspace spanned by {K^0,$\overline{K}^0$},
for times » the strong interaction time scale [Weisskopf-Wigner].

$$\left|\psi(t)\right\rangle = e^{-i\mathbf{H}t}\left|\psi(0)\right\rangle$$

Effective Hamiltonian **H** (non-Hermitian), decomposed into a Hermitian part (mass matrix **M**) and an anti-Hermitian part (i/2 decay matrix **Γ**):

$$i\hbar\frac{d}{dt}\left|\psi(t)\right\rangle = \mathbf{H}\left|\psi(t)\right\rangle = \left[\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right]\left|\psi(t)\right\rangle$$

$$\mathbf{M}^{+} = \mathbf{M} \qquad \mathbf{\Gamma}^{+} = \mathbf{\Gamma}$$

$$\left[\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right]\left|K_{S,L}(t)\right\rangle = \lambda_{S,L}\left|K_{S,L}(t)\right\rangle$$

$$\lambda_{S,L} = m_{S,L} - \frac{i}{2}\Gamma_{S,L}$$

$$M_{ij} = m_K\delta_{ij} + \left\langle i\left|H_2\right|j\right\rangle - \wp\sum_k \frac{\left\langle i\left|H_1\right|k\right\rangle\left\langle k\left|H_1\right|j\right\rangle}{E_k - m_K}$$

$$\Gamma_{ij} = 2\pi\sum_k \left\langle i\left|H_1\right|k\right\rangle\left\langle k\left|H_1\right|j\right\rangle\delta(E_k - m_K)$$

H_2: direct transitions $K^0 \leftrightarrow \overline{K}^0$ ($\Delta S=2$)

H_1: weak Hamiltonian ($\Delta S=1$)

Case of CP symmetry

$$\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} \qquad \mathbf{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \qquad \mathbf{H}|\Psi\rangle = (m_K + \delta m)|\Psi\rangle$$

$$CP = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

If CP symmetry is valid: $[\mathrm{H},\mathrm{CP}] = 0$

$$\langle K^0 | \mathbf{H} | K^0 \rangle = \langle K^0 | \mathbf{H}\,\mathbf{CP} | \overline{K}^0 \rangle = \langle K^0 | \mathbf{CP}\,\mathbf{H} | \overline{K}^0 \rangle = \langle \overline{K}^0 | \mathbf{H} | \overline{K}^0 \rangle$$

$$\langle K^0 | \mathbf{H} | \overline{K}^0 \rangle = \langle K^0 | \mathbf{H}\,\mathbf{CP} | K^0 \rangle = \langle K^0 | \mathbf{CP}\,\mathbf{H} | K^0 \rangle = \langle \overline{K}^0 | \mathbf{H} | K^0 \rangle$$

$$H_{11} = H_{22} = m_0 \qquad H_{12} = H_{21} = \delta m$$

$$\mathbf{H} = \begin{pmatrix} m_K + m_0 & \delta m \\ \delta m & m_K + m_0 \end{pmatrix}$$

Mass shift m_0 and *split* $\Delta m = 2\delta m$

Decays: m_0 and δm have an imaginary part

Eigenstates

CP symmetric case

Since C is violated in Nature, physical states need not be C eigenstates or members of a degenerate C-conjugate pair.
Enter CP instead.

Choose (*arbitrary phase convention*):

$$CP|K^0\rangle = (+1)|\overline{K^0}\rangle$$

$$\begin{cases} CP|K_1\rangle = +|K_1\rangle \\ CP|K_2\rangle = -|K_2\rangle \end{cases}$$

$\langle K_1|K_2\rangle = 0$

For the time being...

Very different (Q-values/m_K): 0.432 vs. 0.157
(Q = 215 MeV vs. Q = 78 MeV). $\tau(\pi\pi) \ll \tau(\pi\pi\pi)$

Since: $CP|\pi\pi\rangle_{J=0} = +|\pi\pi\rangle$ $\quad CP|\pi\pi\pi\rangle_{J,L=0} = -|\pi\pi\pi\rangle$

one identified: $|K_S\rangle \equiv |K_1\rangle$ $\quad |K_L\rangle \equiv |K_2\rangle$

CP conserved (commutes with H): physical states = CP eigenstates

Time evolution

CP symmetric case

Dual description:

(1) K^0 and $\overline{K}^0$: strangeness eigenstates

$\pi^- p \to \Lambda K^0$ $\quad K^+ n \to p\overline{K}$ [strong interactions]

(2) K_1 and K_2: physical states (definite mass and lifetime) *and CP*:

[weak interactions]

$$|K_1(t)\rangle = e^{-iE_1 t}|K_1(0)\rangle = e^{-i(m_1 - i\Gamma_1)t}|K_1(0)\rangle$$

$$|K_2(t)\rangle = e^{-iE_2 t}|K_2(0)\rangle = e^{-i(m_2 - i\Gamma_2)t}|K_2(0)\rangle$$

Uncoupled time evolution

$$\begin{cases} |K_1\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K^0}\rangle\right] \\ |K_2\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K^0}\rangle\right] \end{cases}$$

$\Delta m = m(K_L) - m(K_S) = (3.483 \pm 0.007) \cdot 10^{-6}$ eV

Arises from tiny difference in (weak) interactions of K_1,K_2

$$\Delta m \cong 2\,\mathrm{Re}\,M_{12} \qquad \Delta\Gamma \cong 2\,\mathrm{Re}\,\Gamma_{12}$$

Measured through oscillations, e.g. ($K^+n \to K^0p$) $K^0 \to \overline{K}^0$ ($\overline{K}^0p \to \Lambda\pi^+$) or regeneration.

Neutral K hadronic decays and CP violation

Brookhaven, A.D. 1963

PHYSICAL REVIEW VOLUME 132, NUMBER 5 1 DECEMBER 1963

Anomalous Regeneration of K_1^0 Mesons from K_2^0 Mesons*

L. B. LEIPUNER, W. CHINOWSKY,† AND R. CRITTENDEN
Brookhaven National Laboratory, Upton, New York

AND

R. ADAIR,‡ B. MUSGRAVE,§ AND F. T. SHIVELY†
Yale University, New Haven, Connecticut

(Received 13 March 1963; revised manuscript received 27 August 1963)

A beam of 1.0-BeV/c K_2^0 mesons passing through liquid hydrogen in a bubble chamber was seen to generate K_1^0 mesons with the momentum and direction of the original beam. The intensity of K_1^0 production was far greater than that anticipated from conventional mechanisms, and the suggestion is made that the K_1^0 mesons are produced by coherent regeneration resulting from a new weak long-range interaction between protons and K mesons.

"The probability that the peak arises purely as a statistical fluctuation is $\approx 10^{-6}$ ".

"The possibility of interpreting the events as two-pion decays of K_2^0, which would be allowed if *CP* invariance were violated, is excluded by the result of observation of 411 K_2^0 decays in cloud chambers[5,6], none of which were consistent with two-pion decays".

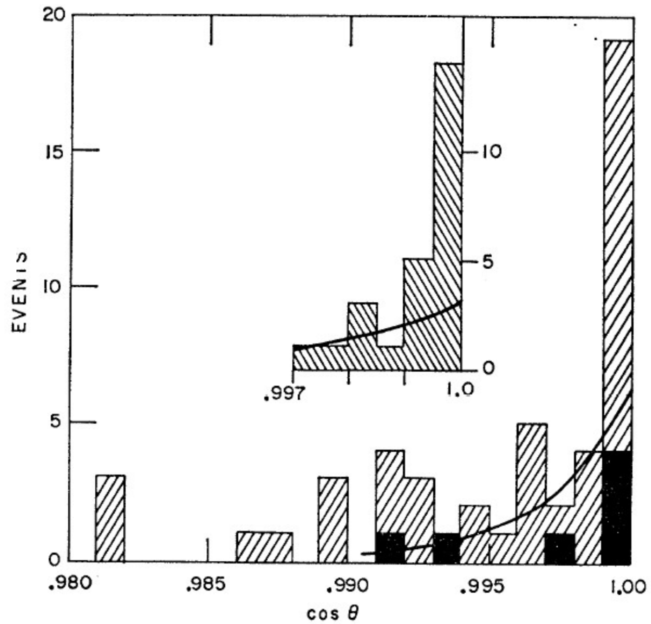


FIG. 3. Angular distribution of events which have a 2π-decay Q value consistent with K_1^0 decay, and a momentum consistent with the beam momentum. θ is the angle between the total visible momentum and the incident beam. All events are plotted for which 180 MeV$\leq Q \leq$270 MeV, $p\geq$800 MeV/c. The black histogram presents those events in front of the thin window. The solid curve represents the contribution expected from K_2^0 decays.

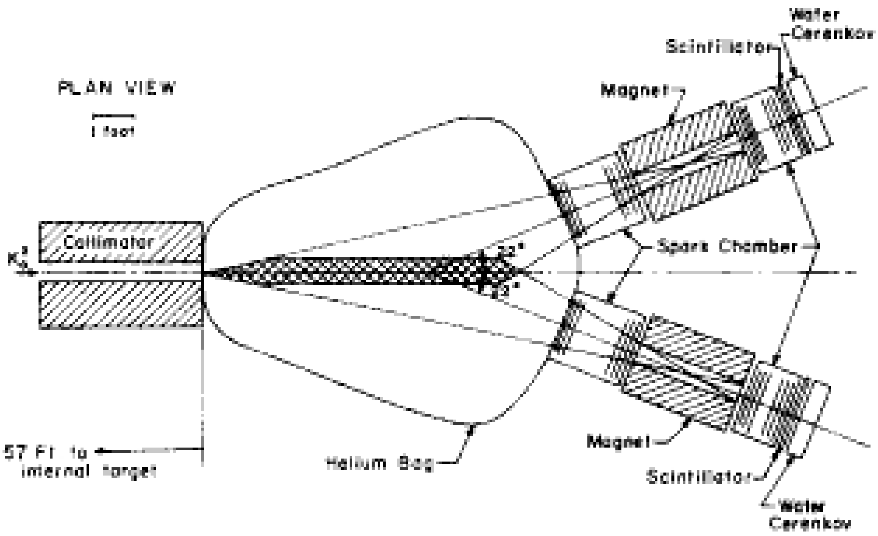
A new coherent regeneration mechanism?

The experiment

J.H. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay (1964)

Experiment to study the anomalous forward regeneration found by Leipuner *et al.* at the 30 GeV synchrotron.

Secondary part of the program: improve limits on $K_L \to \pi\pi$



- 30 GeV p on Be target, neutral beam ~ 1 GeV/c @ 30°
- Pb absorber, collimator, sweeping
- "He bag" after 17 m ($\beta\gamma c\tau$ ~ 2.3 cm, only K_L left)
- Two-arm spark chamber spectrometer triggered by H_2O Čerenkov counter and scintillators
- Measure invariant mass and pT of $\pi+\pi-$ pair (3-body decays do not give peak)
- Calibration with thick tungsten regenerator and anti-coincidence

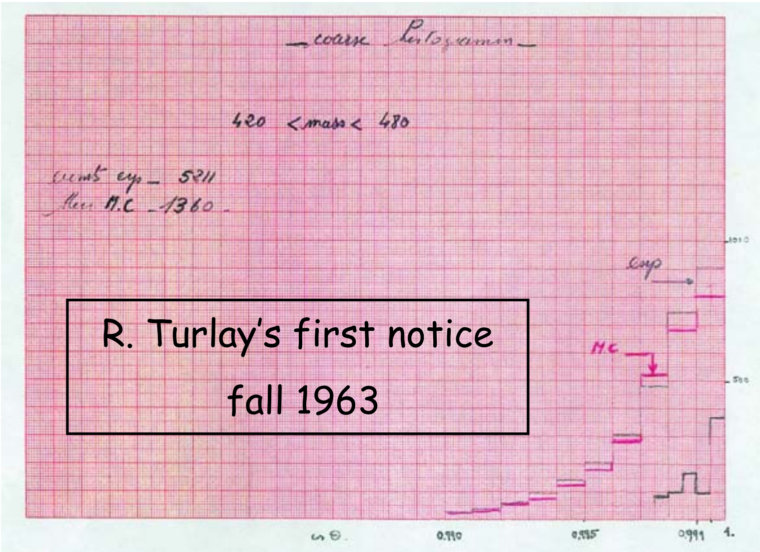
Spark chambers:
higher track resolution and selective triggering

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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)

Letter of Intent: April 1963
Agreement of BNL directorate: May 1963
Apparatus ready: June 2nd 1963
40 days+nights of running: end July 1963



(45 ± 9)/22700

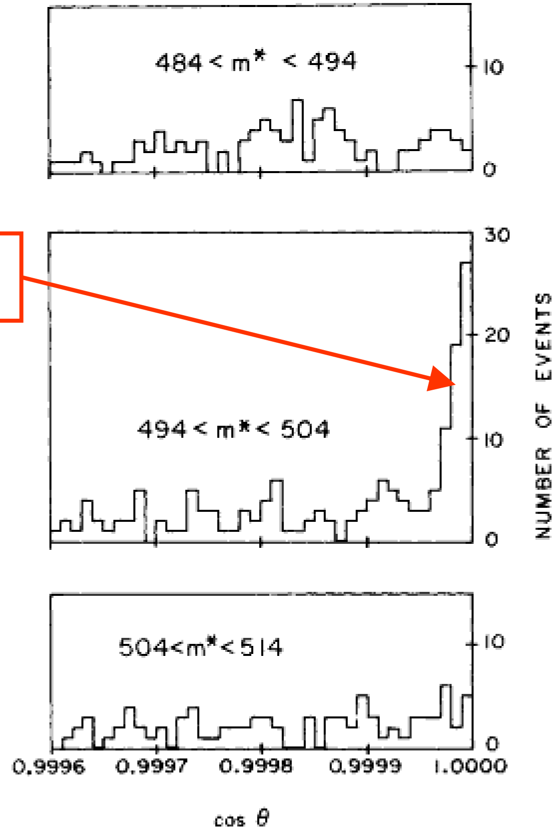


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

After 6 months of scrutiny: reject alternative explanations: Coherent regeneration in He, 3-body $\pi\mu\nu$ or $\pi e\nu$ decay, $\pi\pi\gamma$ decay

Conclusive proof: K_S - K_L interference studying the ππ decay rate in vacuum and with regenerator, V. Fitch et al. (BNL 1965)

There exists a pair (K_S,K_L) of non-degenerate states (Δm≠0), one of them decaying into two states with opposite CP

Evidence of CP SYMMETRY VIOLATION

$$\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_L \to charged)} = (2.0 \pm 0.4)\cdot 10^{-3}$$

New York Times, August 6th 1964: "High energy physics experiment finds time reversal may affect physics laws".

"… a purely experimental discovery, a discovery for which there were no precursive indications, either theoretical or experimental." (V. Fitch)

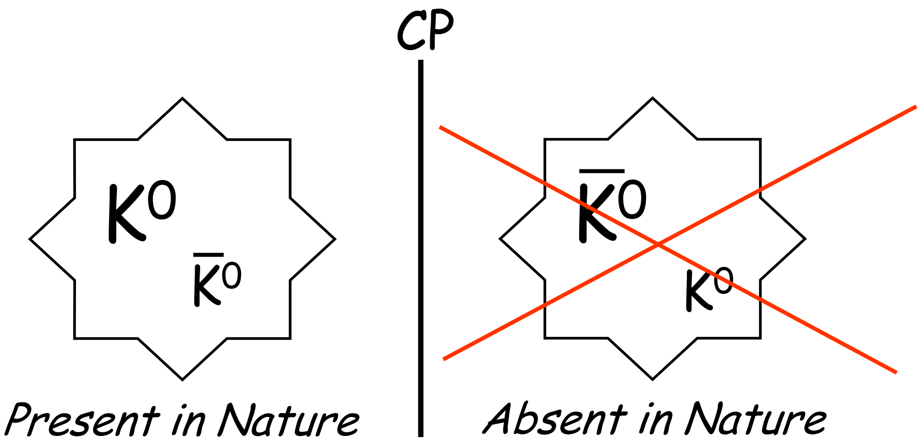
The new paradigm

Physical states (definite mass, lifetime) *are not* CP eigenstates:

$K_S, K_L \neq K_1, K_2$

K_L is a coherent superposition of strangeness eigenstates, with a **tiny** (0.002) unbalance in favour of K^0.

CP invariance as a near "miss"



K^0, $\overline{K}^0$: Eigenstates of strangeness, produced by strong interactions, particle anti-particle pair (equal masses by CPT), common decay modes (not orthogonal), not defined lifetime (non-exponential decay)

K_1, K_2: Eigenstates of CP, almost coincident with physical states, not particle-antiparticle pair, different masses and (almost completely) decay modes, almost orthogonal

K_S, K_L: Physical states, not particle-antiparticle pair, different masses and (almost completely) decay modes, almost orthogonal

"… there is scarcely a physical system which contains so many of the elements of modern physics".
(V. Fitch, 1980)

Physical states

The physical states (definite mass and lifetime) are still "almost" CP eigenstates:

$$\begin{cases} |K_S\rangle = \dfrac{1}{\sqrt{1+|\varepsilon_S|^2}}\left[|K_1\rangle + \varepsilon_S|K_2\rangle\right] = \dfrac{1}{\sqrt{2\left(1+|\varepsilon_S|^2\right)}}\left[(1+\varepsilon_S)|K^0\rangle + (1-\varepsilon_S)|\overline{K^0}\rangle\right] \\ |K_L\rangle = \dfrac{1}{\sqrt{1+|\varepsilon_L|^2}}\left[|K_2\rangle + \varepsilon_L|K_1\rangle\right] = \dfrac{1}{\sqrt{2\left(1+|\varepsilon_L|^2\right)}}\left[(1+\varepsilon_L)|K^0\rangle - (1-\varepsilon_L)|\overline{K^0}\rangle\right] \end{cases}$$

$$\begin{cases} |K_S\rangle = \dfrac{1}{\sqrt{2\left(1+\left|\bar{\varepsilon}^2 - \delta^2\right|\right)}}\left[(1+\bar{\varepsilon}-\delta)|K^0\rangle + (1-\bar{\varepsilon}+\delta)|\overline{K^0}\rangle\right] \\ |K_L\rangle = \dfrac{1}{\sqrt{2\left(1+\left|\bar{\varepsilon}^2 + \delta^2\right|\right)}}\left[(1+\bar{\varepsilon}+\delta)|K^0\rangle + (1-\bar{\varepsilon}-\delta)|\overline{K^0}\rangle\right] \end{cases}$$

$$\bar{\varepsilon} \equiv (\varepsilon_S + \varepsilon_L)/2$$

$$\delta \equiv (\varepsilon_L - \varepsilon_S)/2$$

If $\varepsilon_S, \varepsilon_L \neq 0$ CP symmetry is not valid (physical states ≠ CP eigenstates)

$$\langle K_L | K_S \rangle = 2\,\mathrm{Re}\,\bar{\varepsilon} - 2i\,\mathrm{Im}\,\delta$$

7 parameters: $\lambda_{S,L}$(4), Re($\bar{\varepsilon}$), δ(2)

Diagonalizing the effective Hamiltonian:

$$\bar{\varepsilon} = \frac{\mathrm{Im}\, M_{12} - (i/2)\,\mathrm{Im}\,\Gamma_{12}}{i\Delta m - \Delta\Gamma/2}$$

$$\delta = \frac{(M_{22} - M_{11}) - i(\Gamma_{22} - \Gamma_{11})}{2\left[\Delta m - (i/2)\Delta\Gamma\right]}$$

Note 1. Definitions: $\Delta m \equiv m_L - m_S > 0$ and $\Delta\Gamma \equiv \Gamma_S - \Gamma_L > 0$

Note 2. the phase of ε is not physical, only its real part is.

Re($\bar{\varepsilon}$) really

If $\bar{\varepsilon} \neq 0$ or $\delta \neq 0$ CP symmetry is violated
(physical states are not CP eigenstates)

If $\bar{\varepsilon} \neq 0$ T symmetry
is violated:
$M_{12} \neq M_{21}$ $\Gamma_{12} \neq \Gamma_{21}$

If $\delta \neq 0$ CPT symmetry
is violated:
$M_{11} \neq M_{22}$ $\Gamma_{11} \neq \Gamma_{22}$

[δ=0 assumed herafter]

The measurement of direct CP violation

The *superweak* hypotesis

VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)

L. Wolfenstein (1964):
A hypotetical new interaction inducing $K^0 \leftrightarrow \bar{K}^0$ transitions ($\Delta S=2$) in first order, with coupling ~ $10^{-7}\, G_F$ (!) could explain the effect, and be *practically undetectable* anywhere else.

$$\bar{\varepsilon} = \frac{\mathrm{Im}\, M_{12} - (i/2)\,\mathrm{Im}\,\Gamma_{12}}{i\Delta m - \Delta\Gamma/2}$$

$$|\bar{\varepsilon}| \propto \frac{G_{SW}}{\Delta m} = \frac{\alpha\, G_F}{\Delta m}$$

$$|\bar{\varepsilon}| \approx \frac{\alpha\, G_F}{G_F^2}\,\frac{m_p^2}{m_p^4} \approx 2 \cdot 10^{-3}$$

It would appear as a *property of the physical states* K_S, K_L (*indirect* CP violation).
Not a real dynamical hypotesis, more an *ansatz*, which only failed after 35 years of scrutiny.

Types of CP violation (1)

CP violation in $\Delta S=2$ transitions is called

INDIRECT CP VIOLATION

CP violation in $\Delta S=1$ interactions is called

DIRECT CP VIOLATION

Types of CP violation (2)

CP violation due to the CP-impurity ($\bar{\varepsilon}$) in the physical states, determined by K^0-$\bar{K}^0$ virtual transitions, is named

CP VIOLATION IN THE MIXING

$$K_L \propto K_2 + \bar{\varepsilon}\, K_1$$

$K_1 \rightarrow \pi\pi$

It is *indirect* CP violation
(arising in the effective Hamiltonian **H**)

Actually proportional to Re($\bar{\varepsilon}$)

CP violation in a physical decay process is named

CP VIOLATION IN THE DECAY

$$K_L \propto K_2 + \bar{\varepsilon}\, K_1$$

$$\hookrightarrow \pi\pi$$

It is *direct* CP violation
(arising in the (weak) interaction driving the decay)

Transition from a CP eigenstate to another one with opposite eigenvalue:

$$K_2\ (CP=-1) \rightarrow \pi\pi\ (CP=+1)$$

It reveals an intrinsic property of the weak interactions
(as opposed to a property of the peculiar decaying states)

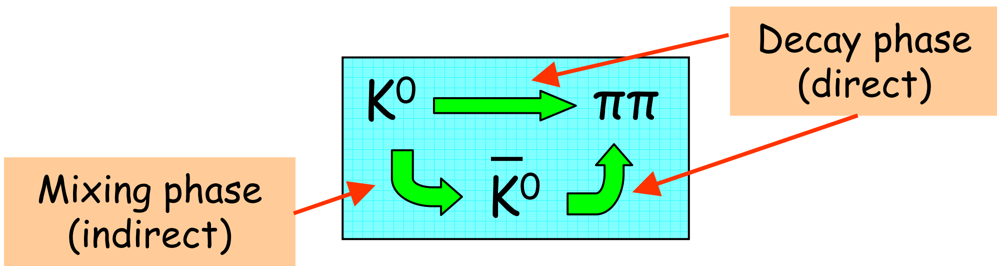
It requires at least 2 interfering amplitudes,
with different (weak) phases AND different FSI (strong) phases,
of comparable magnitude to have large effects

Not present in the superweak scenario

A non flavour-specific final state is accessible to both K^0 and $\bar{K}^0$
The decay can occur both *with* and *without* strangeness oscillation.
If the mixing and decay phases are different the two amplitude can result in CP violation.

This is named

CP VIOLATION IN THE INTERFERENCE OF MIXING AND DECAY

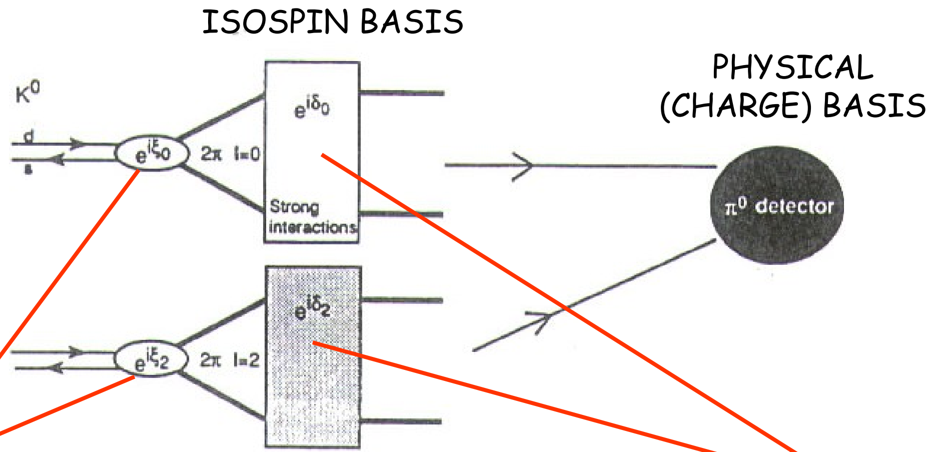


For a *single* decay mode it cannot be unambiguously called *direct or indirect*

CPV in decay: $K^0 \rightarrow \pi\pi$

Isospin I=0

Isospin I=2



Different weak phases: CP violation

Different strong phases: interference

The two decay amplitudes in I=0, I=2 final states can interfere (if they have different phases) in *different* ways for $\pi^+\pi^-$ and $\pi^0\pi^0$

(1) Direct CP violation is intrinsically *suppressed* by $\Delta I=1/2$ "rule"

(2) If $\eta_{+-} \neq \eta_{00}$ different CP violation in different decay modes

(3) The strong phases are actually known experimentally: from Fermi-Watson theorem they are the $\pi\pi$ elastic scattering phase shifts

CP violation in $K^0 \to \pi\pi$

$$\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \frac{\varepsilon'}{1+\omega/\sqrt{2}} \approx \varepsilon + \varepsilon'$$

$$\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - \frac{2\varepsilon'}{1-\omega\sqrt{2}} \approx \varepsilon - 2\varepsilon'$$

$$\varepsilon = \bar{\varepsilon} + i\frac{\mathrm{Im}(a_0)}{\mathrm{Re}(a_0)}$$

$$\varepsilon' = \frac{i}{\sqrt{2}} \frac{\mathrm{Re}(a_2)}{\mathrm{Re}(a_0)} \left[\frac{\mathrm{Im}(a_2)}{\mathrm{Re}(a_2)} - \frac{\mathrm{Im}(a_0)}{\mathrm{Re}(a_0)} \right] e^{i(\delta_2 - \delta_0)}$$

$$\omega = \frac{A[K_S \to \pi\pi(I=2)]}{A[K_S \to \pi\pi(I=0)]} \approx 1/22$$

$\Delta I=1/2$ "rule": hadronic amplitudes with $\Delta I > 1/2$ are smaller: $\Gamma(K^+ \to \pi^+\pi^0) \ll \Gamma(K_S \to \pi^+\pi^-)$

Direct CP violation

For *35 years* :
CP violation seen *only* in $K^0 \rightarrow \pi\pi$ decays (despite impressive experimental campaign), and described by *a single parameter* (ε) related to K^0-$\overline{K}^0$ virtual mixing.

Compatible with a "superweak" ansatz.
The K^0 system exhibits an *extremely tiny* mass difference.

The SM (not superweak) emerged.
Still, no other sign of CPV elsewhere.

"At present our experimental understanding of CP violation can be summarized by the statement of a single number". (J. Cronin, 10.12.1980)

Questions:

Is CP violation really a universal property of weak interactions?
Is it a peculiarity of the bizarre K^0 *system?*
Is it something related to particle mixtures or does it occur in other weak processes (e.g. weak particle decays)?
Is the way CPV is "accomodated" in the SM (CKM) sound?

Searching for direct CPV

Any *difference* in CP violation to different final states cannot be ascribed to an intrinsic property of the decaying system.

Search for a difference between $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$, i.e. $\varepsilon' \neq 0$.

First comparisons of the two modes in the late 60s: $\varepsilon' \ll \varepsilon$

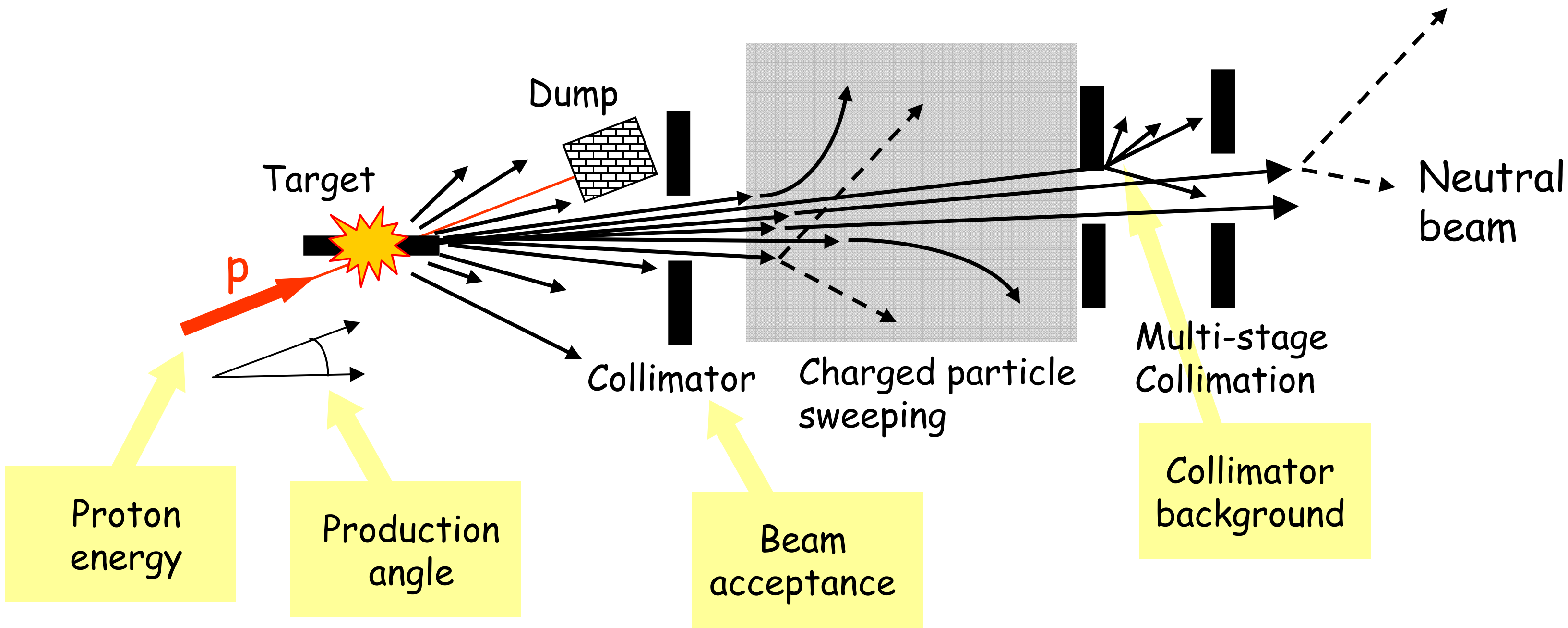
Late 70s: theory says ε'/ε could be *significantly large* and measurable

Pioneering dedicated experiments (inconclusive)

Dedicated programs at FNAL (E731) and CERN (NA31):
disagreement, no firm conclusion

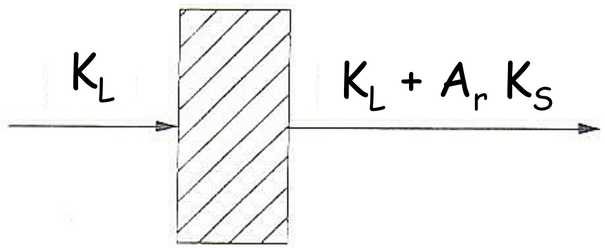
Late 80s: realize that penguin cancellations for large top mass can suppress ε'/ε to very small values

K_L ($+K_S$) beams



High energy p (~ 10-500 GeV), largest yield for $p_K \sim 0.3\ p_p$, long decay beam line (up to ~ 100 m), long decay volumes (up to ~ 100 m): long "skinny" experimental setups

K_S by regeneration

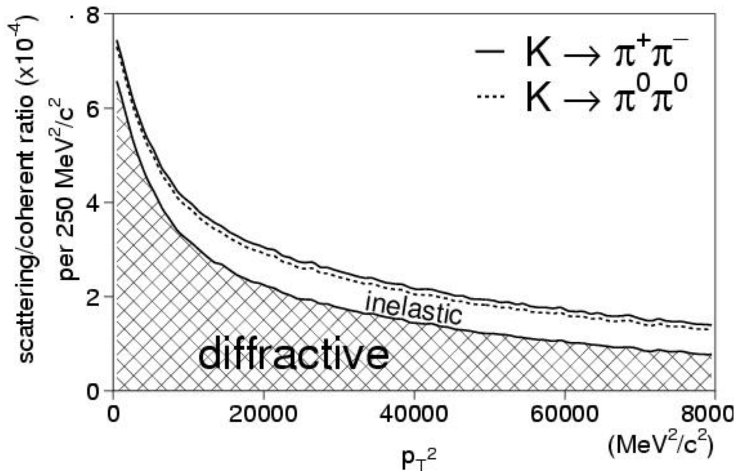


Coherent regeneration (transmission): same momentum and angle as incident beam

Diffractive regeneration:
interaction on nuclei, small angle

Inelastic regeneration:
interaction on nucleons, any angle
(scattered particles can be detected)

KTeV regenerator:
84 10x10x2 cm^2 scintillator modules (fully active),
170 cm long
$|A_r| \sim 0.03$
Diffractive/coherent: 0.09
Inelastic/coherent: 100 before veto



The double ratio method

Comparing the CP-violating K_L decay widths.
Avoid isospin factors, normalize to the CP-conserving K_S decay widths:
measure and $|\eta_{00}|^2$ and $|\eta_{+-}|^2$:

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

Need to measure accurately four decay widths:
$\Gamma(K_S \to \pi^+\pi^-)$, $\Gamma(K_S \to \pi^0\pi^0)$, $\Gamma(K_L \to \pi_+\pi^-)$, $\Gamma(K_L \to \pi^0\pi^0)$.

(1) **Statistics**: $BR(K_L \to \pi\pi) \sim 1 \div 2 \cdot 10^{-3}$ requires *intense K_L beam*

(2) **Systematics**: exploit *cancellations*

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)}$$

If concurrent $\pi^+\pi^-$ and $\pi^0\pi^0$: the K fluxes ($K_S \neq K_L$) do cancel

If concurrent K_S and K_L: detector inefficiencies ($\pi^+\pi^- \neq \pi^0\pi^0$) do cancel

From widths to counts

We need:

$\Gamma(K\to\pi\pi) = \int |M(K\to\pi\pi)|^2\, d(PS)$

We measure:

$N(K\to\pi\pi) = \int_{EXP} |M(K\to\pi\pi)|^2\, d(PS)\, dt =$

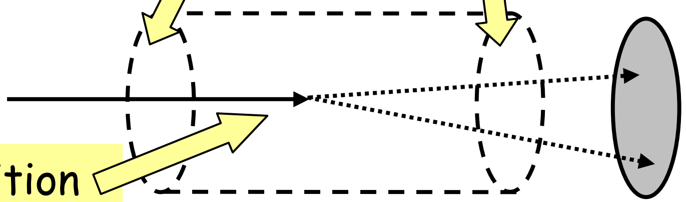
$$\int_{EXP} dt\, [\int_{EXP} d(PS_{ext})]\, [\int_{EXP} |M(K\to\pi\pi)|^2\, d(PS_{int})]$$

Time dependence of cuts and response

$d(PS_{ext}) \propto d^3x\, d^3p/h^3$

Same cuts: cancellation

Position scale

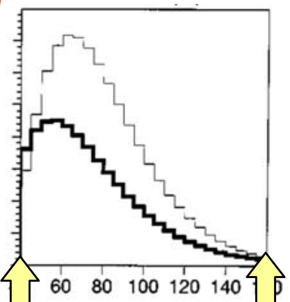


Decay position resolution and distortions

Fiducial decay volume

Detector

Geometrical acceptance



Transverse momentum cut

Momentum scale

Direct CPV: 1996 A.D.

$Re(\varepsilon'/\varepsilon) = (7.4 \pm 6.0) \cdot 10^{-4}$

Not disproving superweak

$Re(\varepsilon'/\varepsilon) = (23.0 \pm 6.5) \cdot 10^{-4}$

Inconsistent with superweak

The press…

The NA31 result is more interesting in that it tends to disagree with the latest predictions from the Standard Model. On the other hand, the E731 result is in the range favored by the Standard Model and as well it doesn't quite rule out the Superweak Model ($\mathrm{Re}\,\varepsilon'/\varepsilon = 0$) with any confidence. The results differ by about two standard deviations; nevertheless, the conclusions are sufficiently different that it would not be appropriate to average the results prior to the establishment of a non-zero effect.

However, a result consistent with zero will not rule out the standard model, because of the uncertainties in the prediction.

The E731 result does not confirm the non-zero result of NA31 nor does it significantly disagree with it.

What are we to conclude from these experiments? The most important conclusion is that they must be continued to still higher accuracy. The point is not to find the exact value of ε'; the point is to make absolutely sure that ε' is non-zero. The NA31 experiment has wounded the superweak theory. The time has come to really kill it.

In any case, while the average is well within the range expected in the standard model, the evidence for a nonzero effect is less than two standard deviations.

so that we cannot as yet claim that direct CP violation is established.

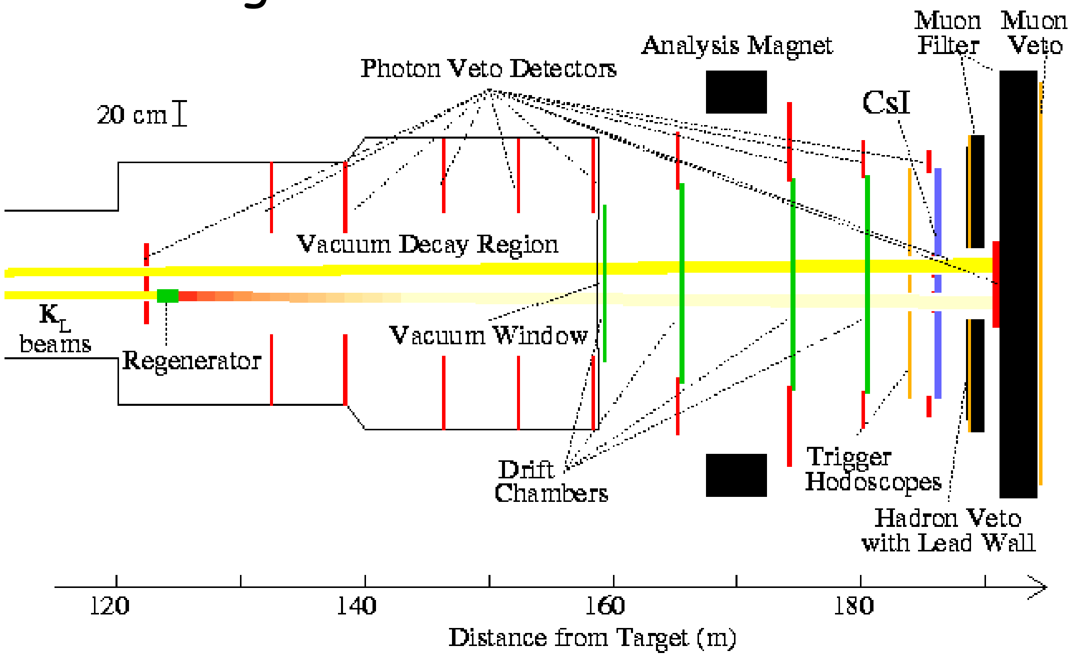
The new fixed-target experiments

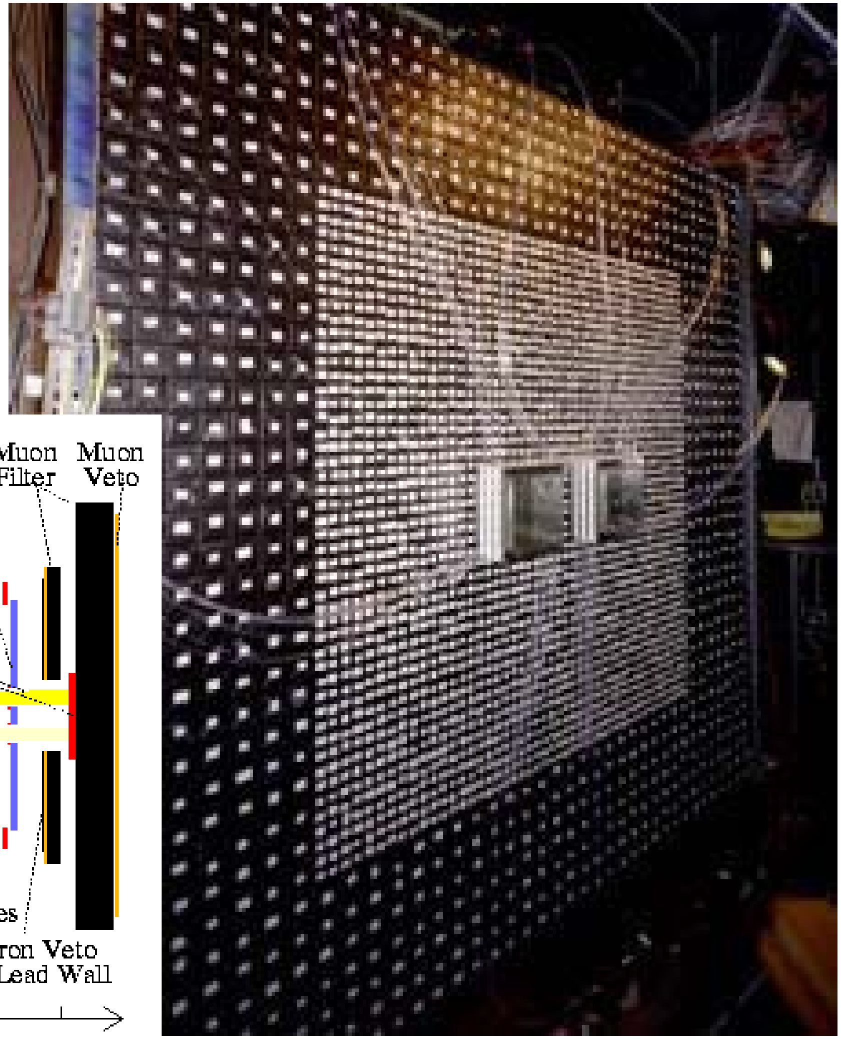
- KTeV at FNAL (evolution of E731): 12 institutions (USA, Japan),
  about 100 physicists
- NA48 at CERN (evolution of NA31): 16 European institutions,
  about 130 physicists
- Started at end of 80s, data-taking in late 90s, first results in 1999
- All 4 modes collected simultaneously
- Higher beam intensities
- Faster detectors and readout (pile-up)
- Important R&D on several aspects
- Higher-resolution detectors (calorimetry), stability
- Large DAQ bandwidths and fast triggers
- Goal: reaching $1\div2\cdot10^{-4}$ precision on ε'/ε

KTEV
Kaons at the Tevatron

KTeV at Fermilab

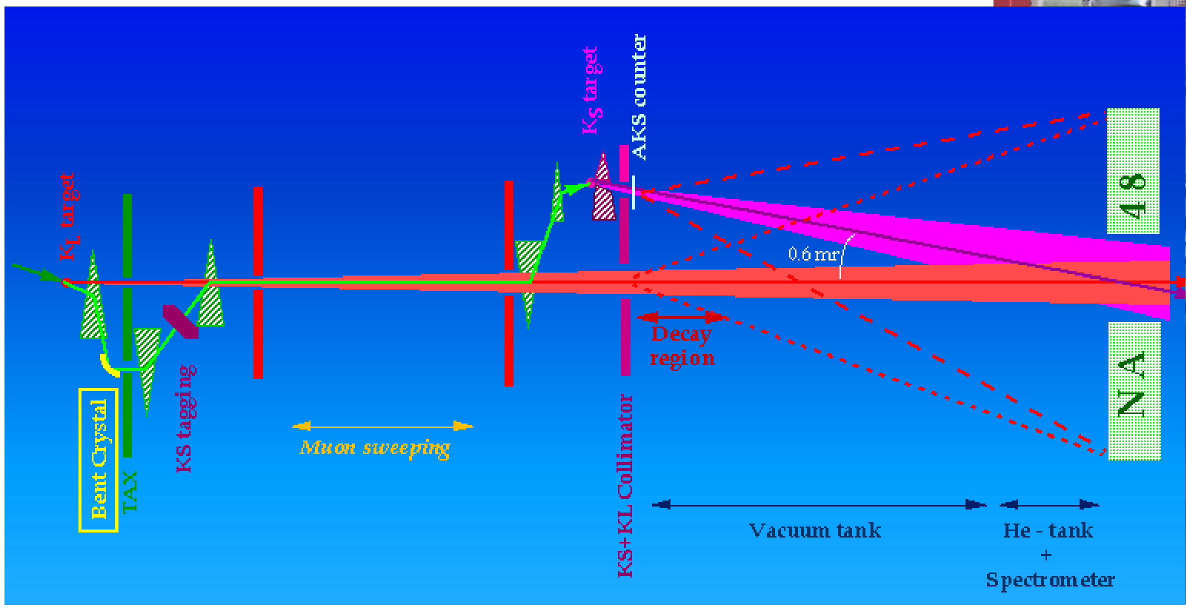
Main Injector (120 GeV) p
Double K_L beam (<p>=70 GeV/*c*)
Regenerated K_S
Pure CsI calorimeter
Data taking in 1997 and 1999

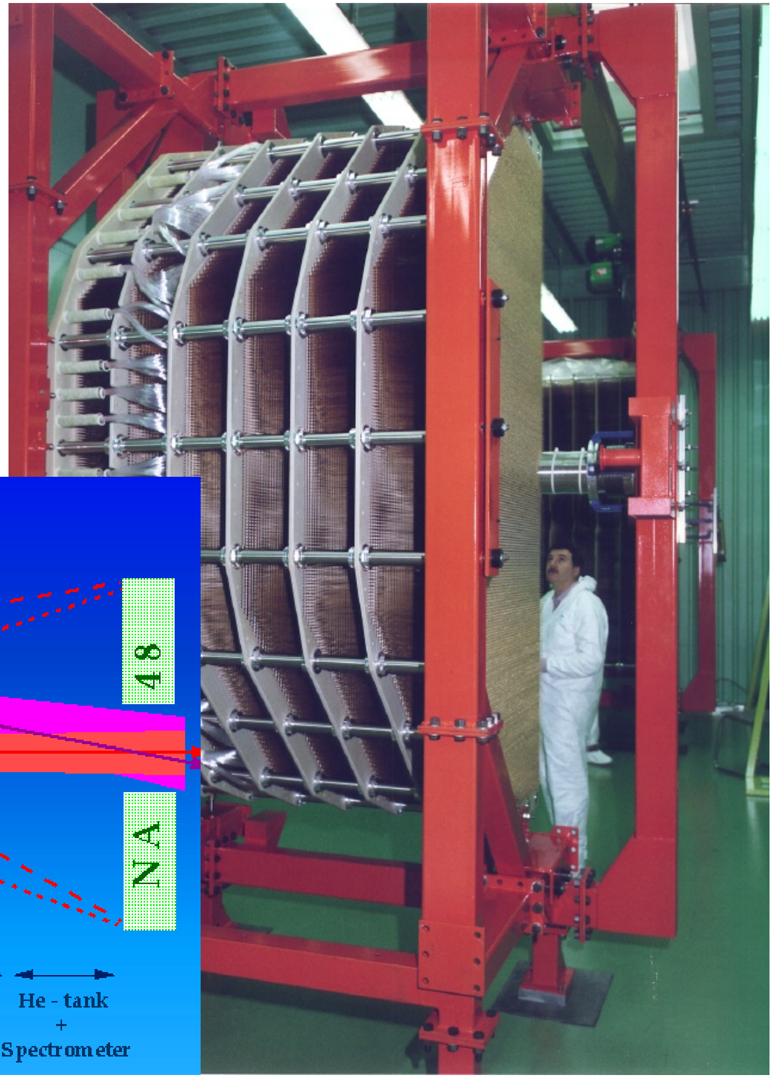




NA48 at CERN

SPS (450 GeV) p
K_S and K_L beams (<p>=100 GeV/c)
K_S tagging by time-of-flight
Liquid Krypton calorimeter
Data-taking 1998-1999-2001





Direct CP violation: ε'/ε

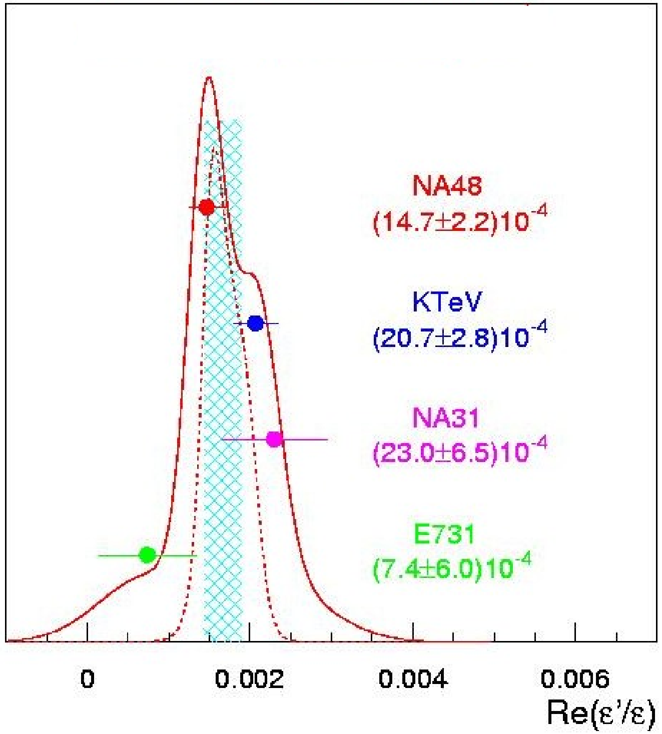
1999: proof of direct CP violation (after 36 years!) at >7 σ

World average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.3 \pm 2.2) \cdot 10^{-4}$

NA48 (1997-2001): final result
KTeV (1997-1999): ½ statistics (1997)
KLOE: working (interferometry?)
χ^2=6.2/3, consistency 10%
Room for improvement

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K}^0 \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K}^0 \to \pi^+\pi^-)} = (5.04 \pm 0.82) \times 10^{-6}$$

After the KTeV and NA48 results, the NA31 collaboration received the 2005 EPS prize for what is *a posteriori* recognized as the first evidence of direct CP violation



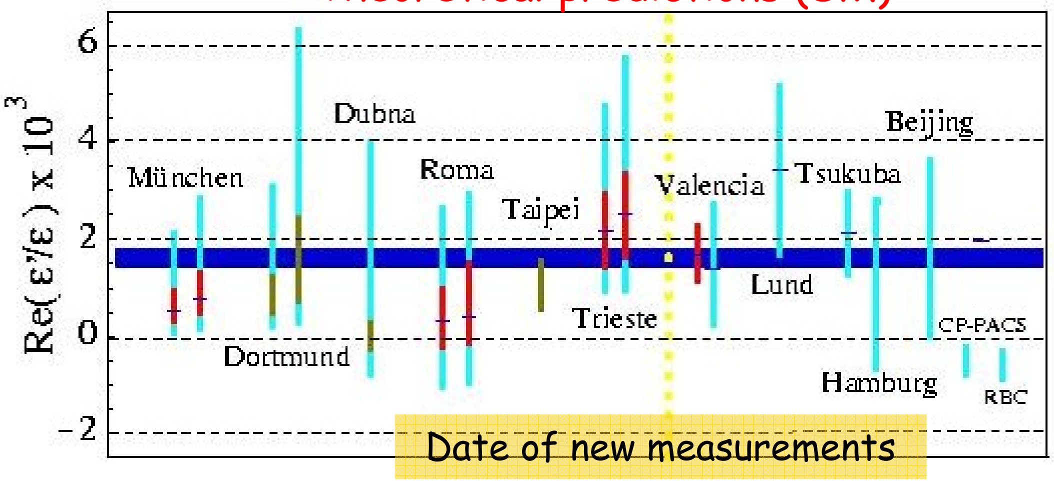
ε'/ε why ?

The *qualitative* importance of ε'/ε ≠ 0 *trascends* the theoretical difficulties of computing such parameter in the Standard Model:

- CP violation no longer described by a *single* number
- It is a property of *weak interactions* (no superweak)
- It is not a peculiarity of *neutral K mesons* (see also B-mesons, sin2β in 1999)
- Qualitative confirmation of *CKM paradigm*

Theory:
Consistent with SM?
No! Yes! Maybe…
SM is *accidentally* a quasi-superweak model.
Waiting for lattice QCD:
ε'/ε may become a quantitative test of SM.

Theoretical predictions (SM)



Other ways of measuring CP violation

K: decays

K^0_L DECAY MODES

Mode		Fraction (Γ_i/Γ)
$\pi^{\pm} e^{\mp} \nu_e$ Called K^0_{e3}.		(38.81 ± 0.27) %
$\pi^{\pm} \mu^{\mp} \nu_\mu$ Called $K^0_{\mu 3}$.		(27.19 ± 0.25) %
$3\pi^0$		(21.05 ± 0.23) %
$\pi^+ \pi^- \pi^0$		(12.59 ± 0.19) %
$\pi^+ \pi^-$	*CPV*	$(2.090 \pm 0.025) \times 10^{-3}$
$\pi^0 \pi^0$	*CPV*	$(9.32 \pm 0.12) \times 10^{-4}$

K^0_S DECAY MODES

Mode		Fraction (Γ_i/Γ)
$\pi^0 \pi^0$		(31.05 ± 0.14) %
$\pi^+ \pi^-$		(68.95 ± 0.14) %
$\pi^+ \pi^- \pi^0$		$(3.2 ^{+1.2}_{-1.0}) \times 10^{-7}$
$\pi^+ \pi^- \gamma$		$(1.79 \pm 0.05) \times 10^{-3}$
$\pi^{\pm} e^{\mp} \nu_e$		$(6.9 \pm 0.4) \times 10^{-4}$
$\pi^{\pm} \mu^{\mp} \nu_\mu$		
$3\pi^0$	*CP*	$< 1.4 \times 10^{-5}$

K^+ DECAY MODES

Mode	Fraction (Γ_i/Γ)
$\mu^+ \nu_\mu$	(63.43 ± 0.17) %
$\pi^0 e^+ \nu_e$ Called K^+_{e3}.	(4.87 ± 0.06) %
$\pi^0 \mu^+ \nu_\mu$ Called $K^+_{\mu 3}$.	(3.27 ± 0.06) %
$\pi^+ \pi^0$	(21.13 ± 0.14) %
$\pi^+ \pi^0 \pi^0$	(1.73 ± 0.04) %
$\pi^+ \pi^+ \pi^-$	(5.576 ± 0.031) %

Relatively few major branching ratios, several in the 10% range (compare B). A "simple" system

(PDG2004)

Searching for CP violation

	For kaons
Transitions among CP eigenstates with opposite eigenvalues	$K_2 \to \pi\pi$
Search for physical states not being CP eigenstates (non-exponential decay of CP eigenstates)	$K_L \to \pi\pi$ and $K_L \to \pi\pi\pi$
Differences in the partial decay widths or decay properties of particles and antiparticles	$\Delta\Gamma(K \to 3\pi)$ $\Delta g(K \to 3\pi)$
Test of time-reversibility (plus CPT)	$P(K^0 \to \overline{K}^0) \neq P(\overline{K}^0 \to K^0)$
Measure of non-zero CP-odd quantities	$P_T(K_{\mu 3})$

K vs B

$s\bar{s}$ pairs produced by strong and EM interactions

(1) Wider range of experimental approaches possible with K (experiments with flavour and physical eigenstates, possibility of beams, stopped K)

(2) Short B lifetime poses considerable experimental challenges

(3) Higher mass is an advantage for "factories"

(4) B have many more final states available (more rich, more complicated, much smaller BR, higher backgrounds)

(5) CPV effects of the same size (in the SM); asymmetries on suppressed decays can be larger in B

(6) All 3 types of CPV observed in K; "decay" and "interference" types in B ("mixing" type is dominant in K and negligible in B); TRV also observed in K.

(7) In a larger number of cases the higher mass B allow better theoretical control and extraction of SM parameters ($\sin 2\beta$ vs. ε)

(A) Experimenting with strangeness eigenstates

(Compare to B experiments at hadron machines, CDF/D0, LHC-b)

Hadronic production: strangeness eigenstates

By exploiting specific reactions strangeness tagging at production is possible:
$p\bar{p} \to K^+\bar{K}^0\pi^-$ and $p\bar{p} \to K^-K^0\pi^+$ (0.4% of $\sigma_{tot}(p\bar{p})$ at rest)

Known strangeness at production time
Measure strangeness ($\pi e\nu$) or CP ($\pi\pi$) at decay time

$$A_T = \frac{\left|\langle K^0 | e^{-iHt} | \bar{K}^0 \rangle\right|^2 - \left|\langle \bar{K}^0 | e^{-iHt} | K^0 \rangle\right|^2}{\left|\langle K^0 | e^{-iHt} | \bar{K}^0 \rangle\right|^2 + \left|\langle \bar{K}^0 | e^{-iHt} | K^0 \rangle\right|^2}$$

T violation (Kabir test)

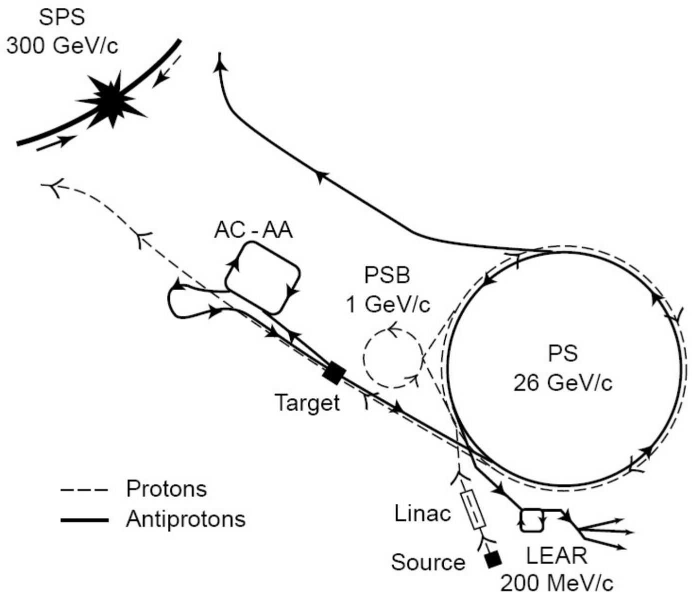
$$A_{CPT} = \frac{\left|\langle \bar{K}^0 | e^{-iHt} | \bar{K}^0 \rangle\right|^2 - \left|\langle K^0 | e^{-iHt} | K^0 \rangle\right|^2}{\left|\langle \bar{K}^0 | e^{-iHt} | \bar{K}^0 \rangle\right|^2 + \left|\langle K^0 | e^{-iHt} | K^0 \rangle\right|^2}$$

CPT violation

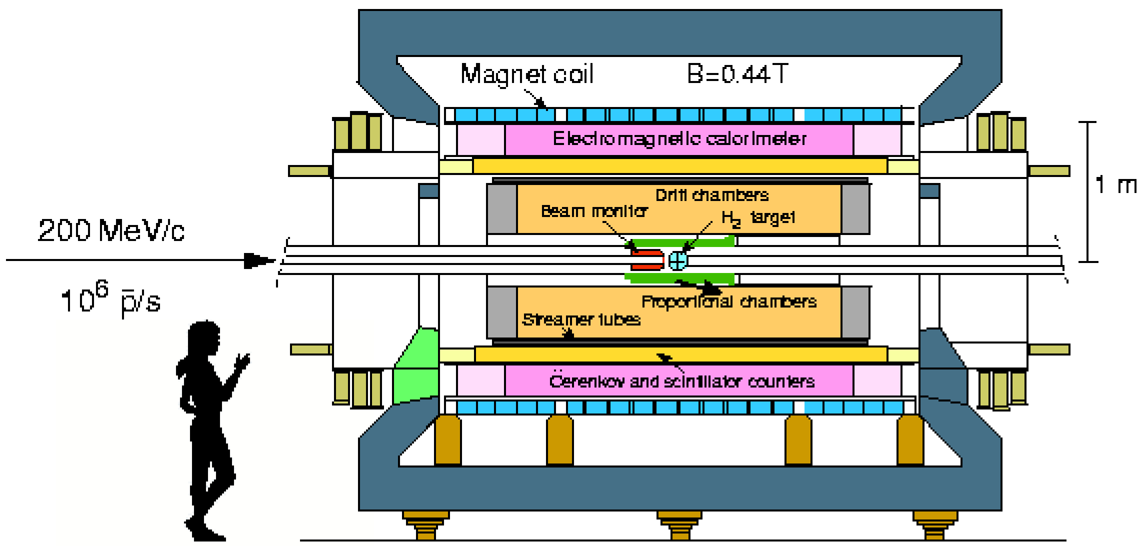
$$A_{CP} = \frac{\left|\langle f_{CP} | e^{-iHt} | \bar{K}^0 \rangle\right|^2 - \left|\langle f_{CP} | e^{-iHt} | K^0 \rangle\right|^2}{\left|\langle f_{CP} | e^{-iHt} | \bar{K}^0 \rangle\right|^2 + \left|\langle f_{CP} | e^{-iHt} | K^0 \rangle\right|^2}$$

CP violation parameters

CPLEAR experiment (CERN: 1990-96)



26 GeV p on target
Collect 3.6 GeV/c $\bar{p}$, store, decelerate and cool them down to 200 MeV/c
10^6 p/s in 1 h spills



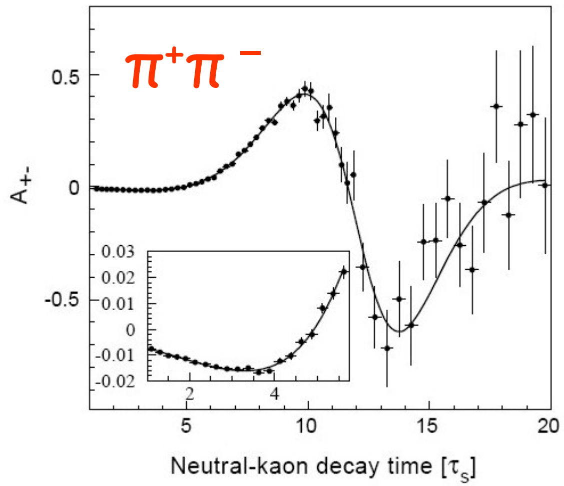
Interaction at rest: 4π detector
Kaon ID: Čerenkov, dE/dx, time-of-flight
Tracking: r ~ 20 λ_S ~ 60 cm
Minimize material (regeneration)
"High" rate (1 MHz): fast trigger

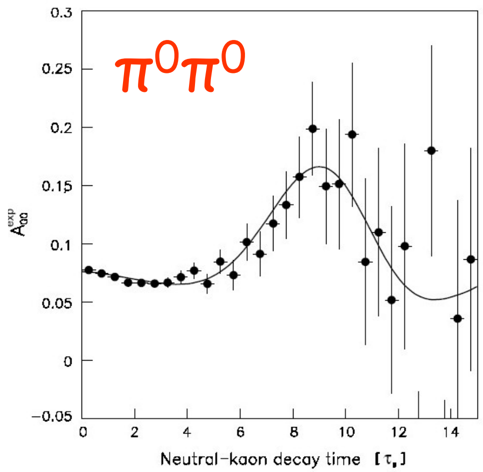
Lifetime resolution:
5-10 fs (with tracks)
70 fs ($\pi^0\pi^0$)

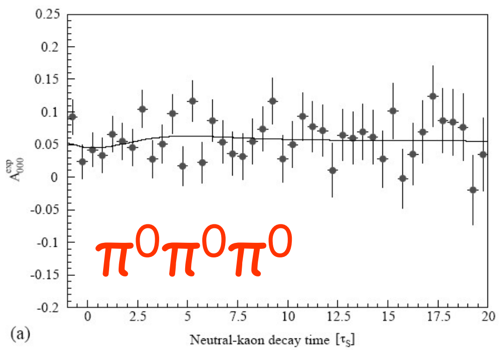
5×10^9 events collected

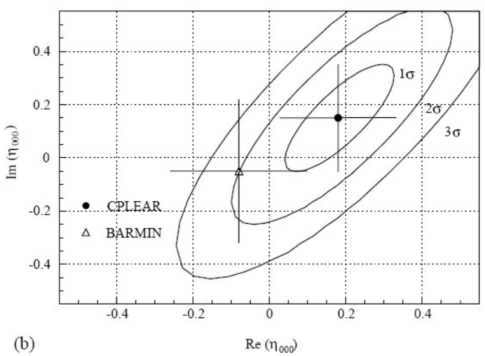
CPLEAR Asymmetries

Non flavour-specific final states







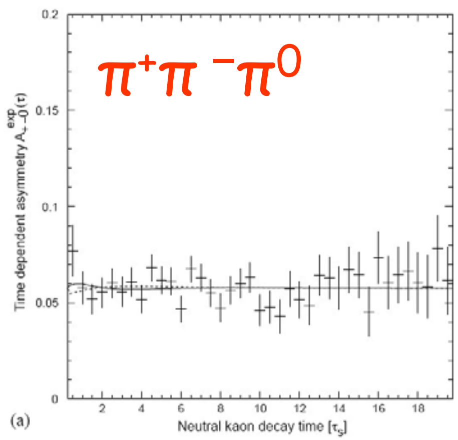


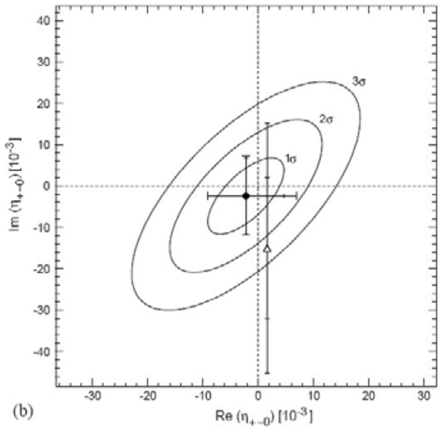
$$A_{CP} = \frac{\left|\left\langle f_{CP}\left|e^{-iHt}\right|\overline{K}^0\right\rangle\right|^2 - \left|\left\langle f_{CP}\left|e^{-iHt}\right|K^0\right\rangle\right|^2}{\left|\left\langle f_{CP}\left|e^{-iHt}\right|\overline{K}^0\right\rangle\right|^2 + \left|\left\langle f_{CP}\left|e^{-iHt}\right|K^0\right\rangle\right|^2} = 2\,\mathrm{Re}(\varepsilon) - \frac{2\left|\eta_f\right| e^{(\Gamma_S-\Gamma_L)t/2}\cos(\Delta m t - \phi_f)}{1+\left|\eta_f\right|^2 e^{(\Gamma_S-\Gamma_L)t}}$$

Acceptance cancellation

Rate difference

Measure η





(B) Experimenting with correlated K pairs

(Compare to B factory experiments Babar, Belle)

Kaon factories [Lipkin (1968)]

$e^+e^- \to \Phi \to K\bar{K}$ at resonance $\sigma = 3.1\ \mu b$

$J^{PC}(\Phi) = 1^{--} \Rightarrow C(K\bar{K}) = -1$ coherent state

($\Phi \to K\bar{K}\gamma$, opposite C, negligible)

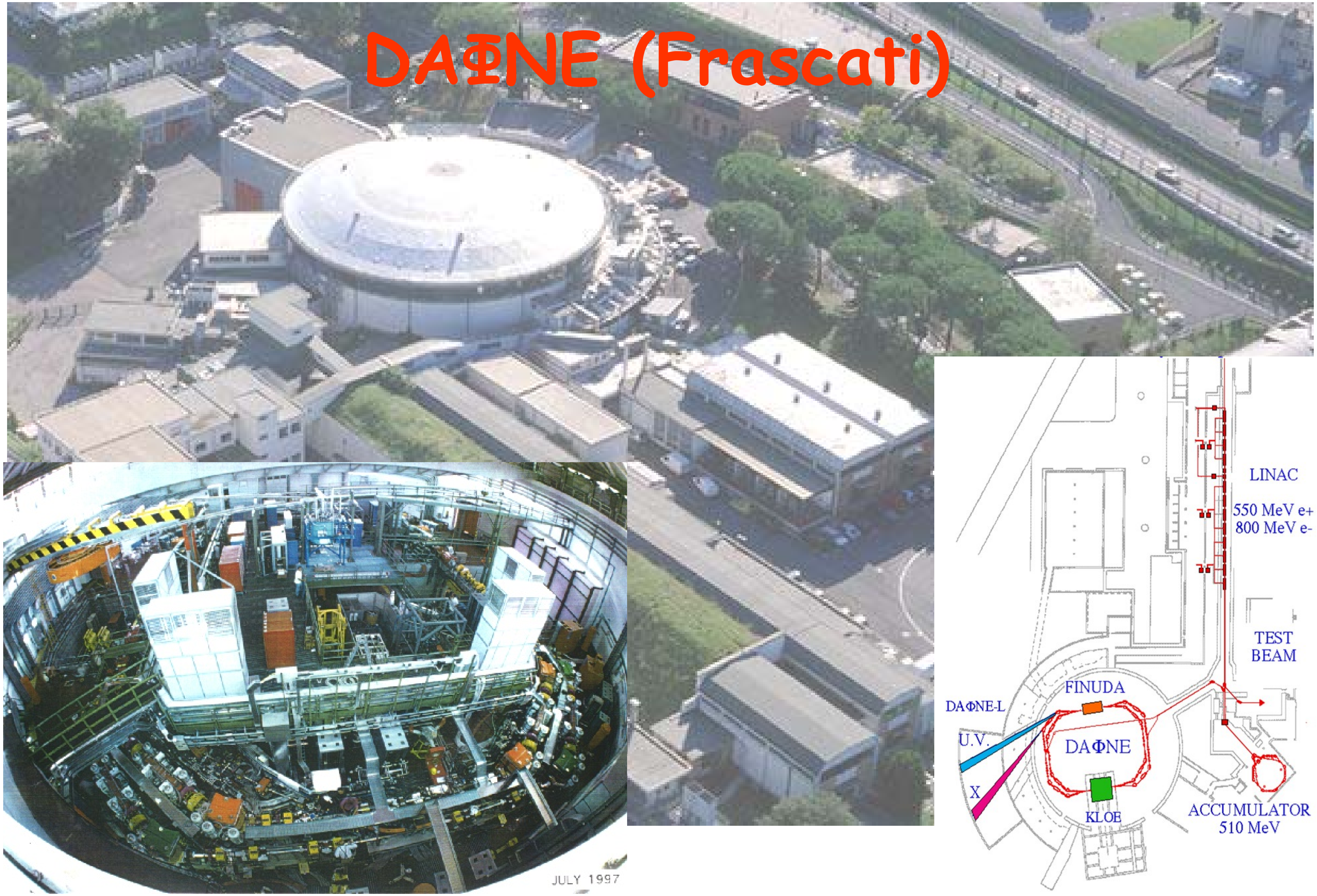
Bose statistics $\Rightarrow$ Even with strangeness oscillations, the two K have to be always distinct (until one decays), i.e. $K_S K_L$ or $K^0\bar{K}^0$ (and K^+K^-), but never $K_S K_S$, $K^0 K^0$,…

EPR correlation:

$$|i\rangle \propto \frac{1}{\sqrt{2}}\left(|K_L, \mathbf{p}\rangle |K_S, -\mathbf{p}\rangle - |K_L, -\mathbf{p}\rangle |K_S, \mathbf{p}\rangle\right)$$

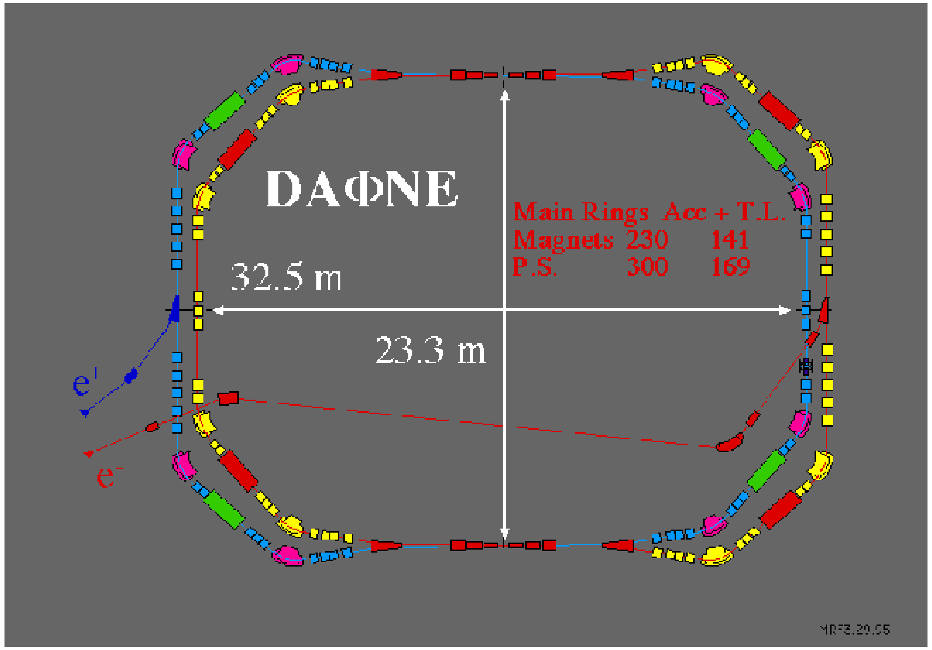
- Tagging: observation of $K_S(K_L)$ signals presence of $K_L(K_S)$: unique "K_S beam" (almost monochromatic, kinematical constraints)
  - Absolute BR measurements
  - Rare K_S decay searches
- QM correlation: allows interference measurements

DAΦNE (Frascati)



DAΦNE (Frascati)

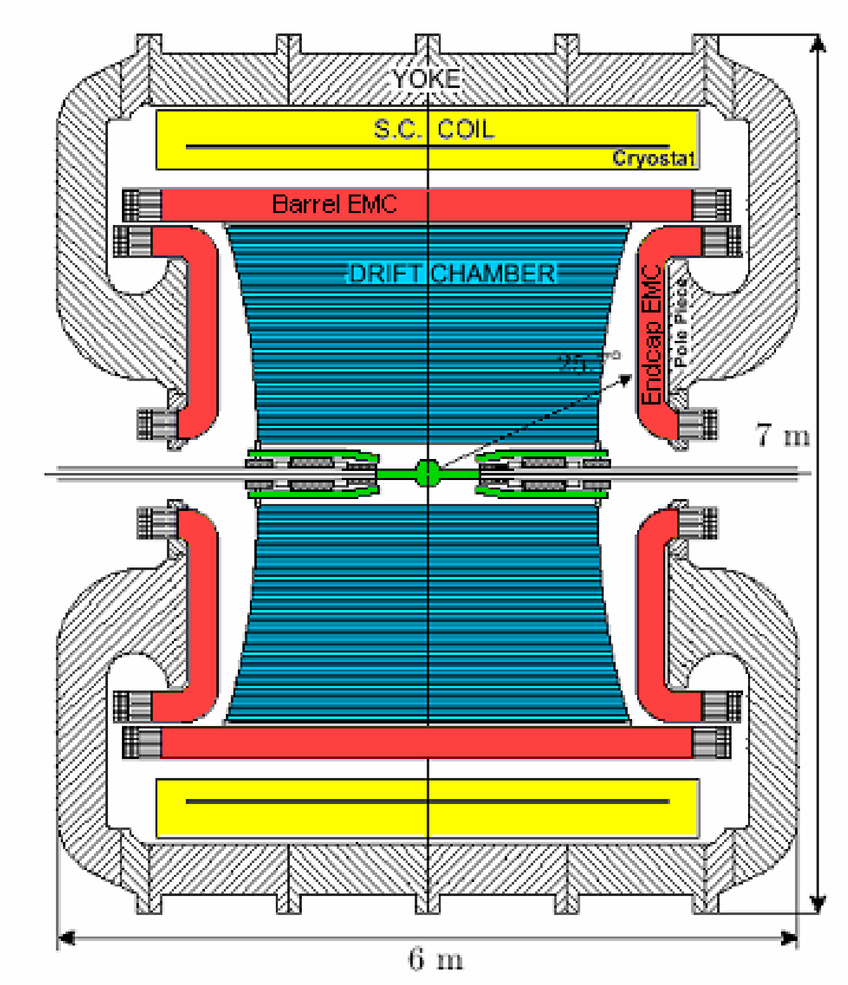
- e^+e^- collider @ $\sqrt{s}$ = m(Φ) = 1019.4 MeV
- 2 interaction regions (KLOE – DEAR/FINUDA)
- Separate e^+ e^- rings to minimize beam-beam interactions
- Crossing angle: 12.5 mrad (p(Φ) ~ 12.5 MeV/*c*)



Design luminosity: $5 \cdot 10^{32}$ cm^{-2} s^{-1}
(1.41 reached so far)

Integrated luminosity:
~ 2.3 fb^{-1} 1999-2006
($7 \cdot 10^9$ Φ decays)

KLOE experiment



K^+K^-: 1.5 $\times 10^6$ /pb^{-1}
p* = 127 MeV/c
λ = 95 cm

$K_L K_S$: 10^6 /pb^{-1}
p* = 110 MeV/c
λ_S = 6 mm K_S decays near interaction point
λ_L = 3.4 m Need large detector (r ~ 0.3 λ_L)

Be beam pipe
Spherical, small (10 cm ∅), thin (0.5 mm)
Instrumented permanent magnet quadrupoles

Drift chamber
Light (MS), large (tracking)

Electromagnetic calorimeter
Inside coil. hermeticity, high resolution in E and time

Superconducting coil
(B = 0.52 T)

KLOE physics

•"K_S beam":
Rare decays (incl. CP-violating $K_S \to \pi^0\pi^0\pi^0$,
$K_S \to \pi \ell \nu$ and its CP-violating charge asymmetry)
Cabibbo angle

•"K_L beam":
Branching ratios, lifetime
Cabibbo angle

•"K_S and K_L":
Direct CP violation (double ratio method)

(The three items above are grouped by a brace: More indirect CP, CPT tests)

•"Entangled K_S and K_L":
CP, T, CPT tests, QM tests

•"$K^{\pm}$ beams":
Branching ratios, lifetime
Direct CP violation searches

(C) Experimenting with charged K beams

CPV in charged K decays

Direct CP violation seen in K^0:
look for CPV in charged particle decays
(no mixing, *any* CPV is direct)

Any difference among K^+ and K^-: CP violation
(except when equality is enforced by CPT, e.g. total decay widths)

Hadronic production: charged K

$K^{\pm}$ beams readily obtained as secondary beams

Magnetic selection based on charge and momentum:

unseparated positive beam contains: $p, \pi^+, K^+, \mu^+, e^+, \ldots$ ($\pi/K \sim 0.1$)

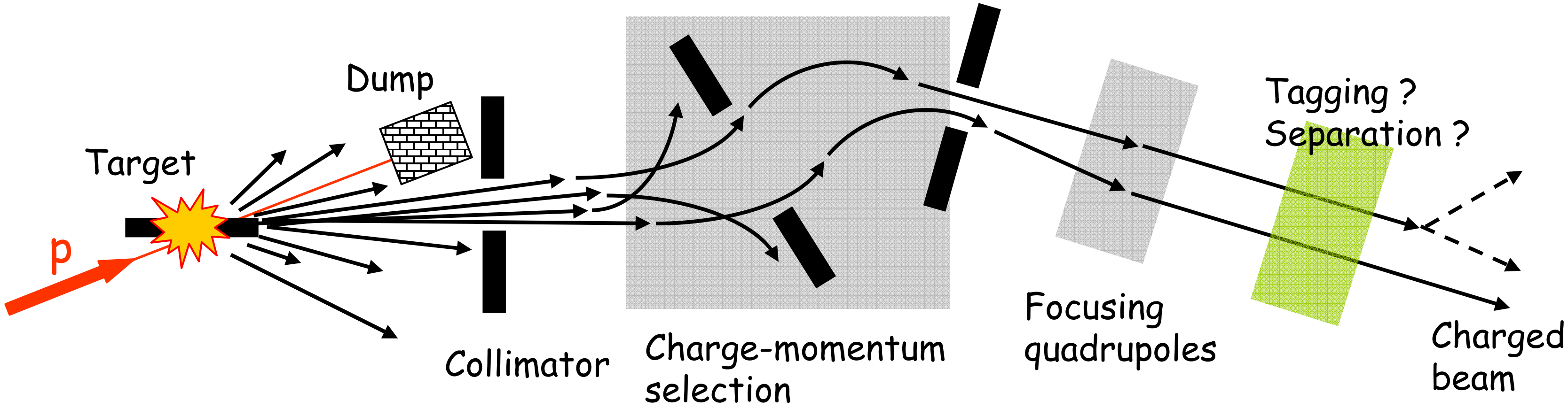
K can be *tagged* by velocity measurement, e.g. TOF or Čerenkov

Beams can be *separated* to enrich K component with:

Electrostatic separators ≈ 1 GeV/c

RF separators (Panofsky) ≈ 10-60 GeV/c

to obtain e.g. $K/\pi \sim 3$ to 10



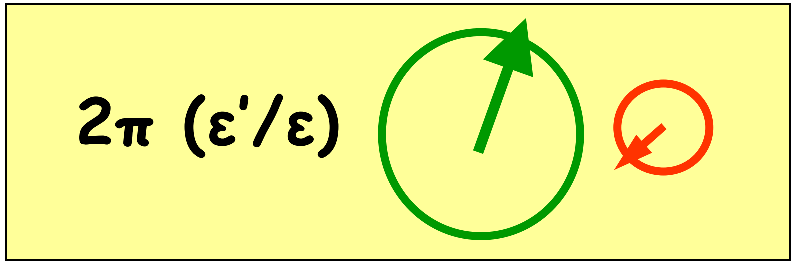
CP violation in $K_{\pi 3}$ (why)

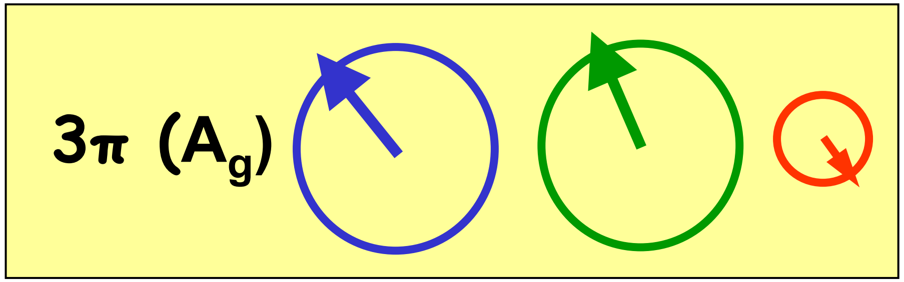
$K^\pm \to \mu^\pm \nu$ ✗

$K^\pm \to \pi^\pm \pi^0$ ✗

$K^\pm \to 3\pi$ ✓

No intrinsic $\Delta I=1/2$ amplitude suppression (as for ε'/ε)





But…

Hadronic uncertainties

Small rescattering phases

→ Small in SM

Width asymmetries suppressed

$K_{\pi 3}$ decays

$BR(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}) = 5.57\%$ "charged"

$BR(K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}) = 1.73\%$. "neutral"

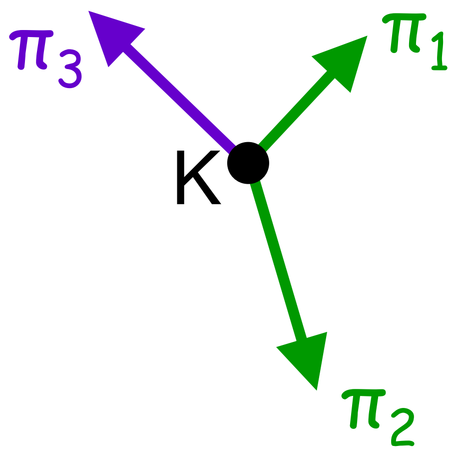
Kinematics:

$s_i = (P_K - P_{\pi i})^2$ *i=1,2,3 (3=odd π)*

$s_0 = (s_1+s_2+s_3)/3$

$u = (s_3-s_0)/m_\pi^2 = 2m_K\,(m_K/3-E^*_{odd})/m_\pi^2$

$v = (s_2-s_1)/m_\pi^2 = 2m_K(E^*_1-E^*_2)/m_\pi^2$



Matrix element:

$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$

Naïve Taylor expansion

$K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ $g = -0.2154 \pm 0.0035$

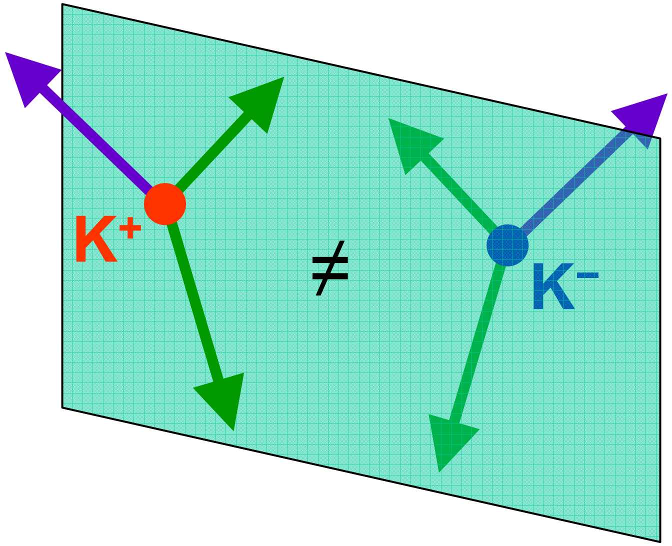
$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$ $g = 0.652 \pm 0.031$

$|h|, |k| << |g|$

CP violation in $K_{\pi 3}$

Potentially large statistics
Simple selection
Low backgrounds

No absolute K flux measurement: compare only Dalitz plot shapes

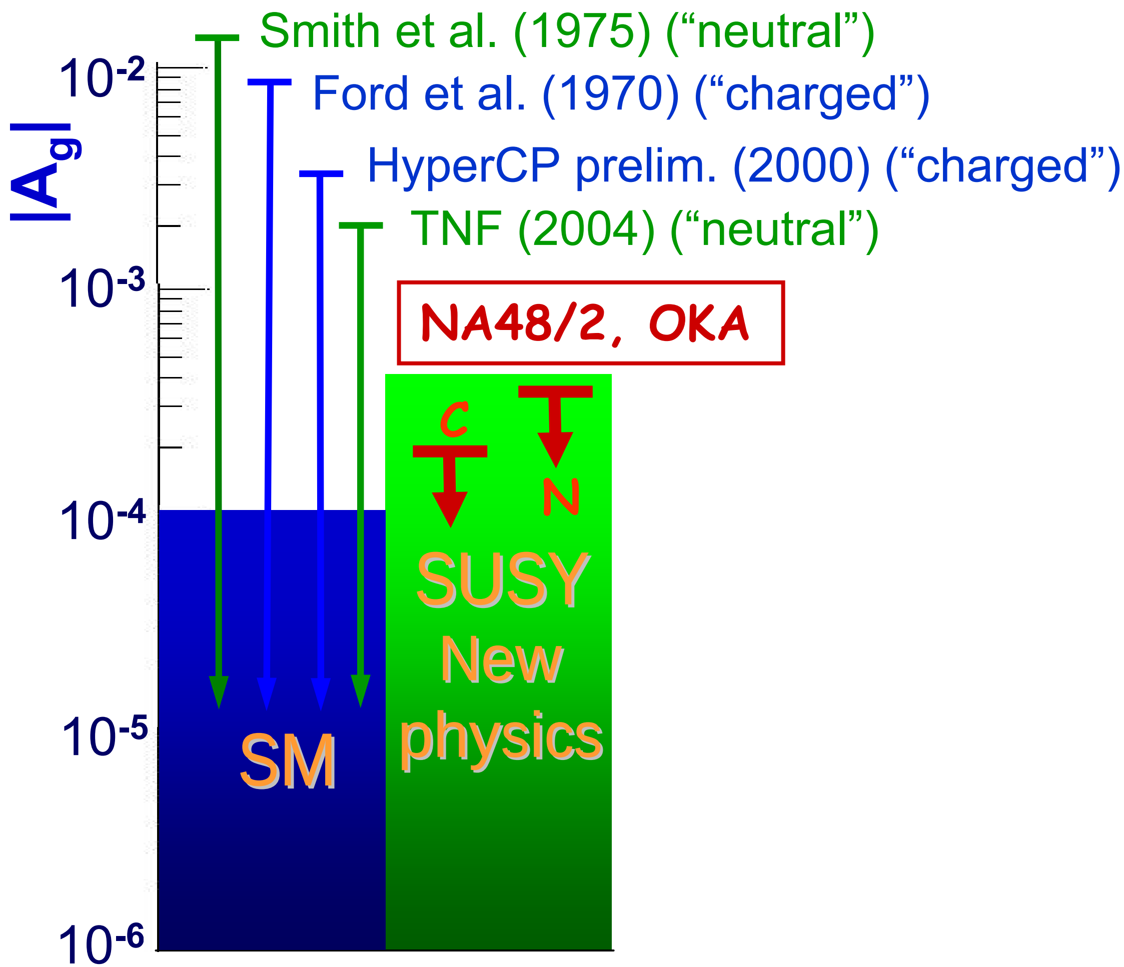


$$A_g = (g_+ - g_-)/(g_+ + g_-) \neq 0\ ?$$

NA48/2 (2003-04): maximal cancellations (robustness)

- Simultaneous K^+ and K^- beams, superimposed in space, with narrow momentum spectra
- Detect asymmetry only from slopes of ratios of normalized u distributions
- Equalize averaged K^+ and K^- acceptances by frequently alternating polarities of relevant magnets

$K^{\pm}$ asymmetries: status



THEORY:

SM contribution: many theoretical computations from several groups
Large uncertainties (~1 order of magnitude) esp. for "neutral"

Some enhancements possible beyond SM

- $A_g \sim 10^{-5}$

Compatible with SM

- $A_g > 1 \cdot 10^{-4}$

SUSY / New Physics

SM contribution (Prades et al.)

- Δg_C dominated by Im G_8 (NLO effects $\simeq (20-30\%)$)
  - Final uncertainty mainly from $\mathrm{Im}\, G_8$

$$\Delta g_C = -(2.4 \pm 1.2) \times 10^{-5}$$

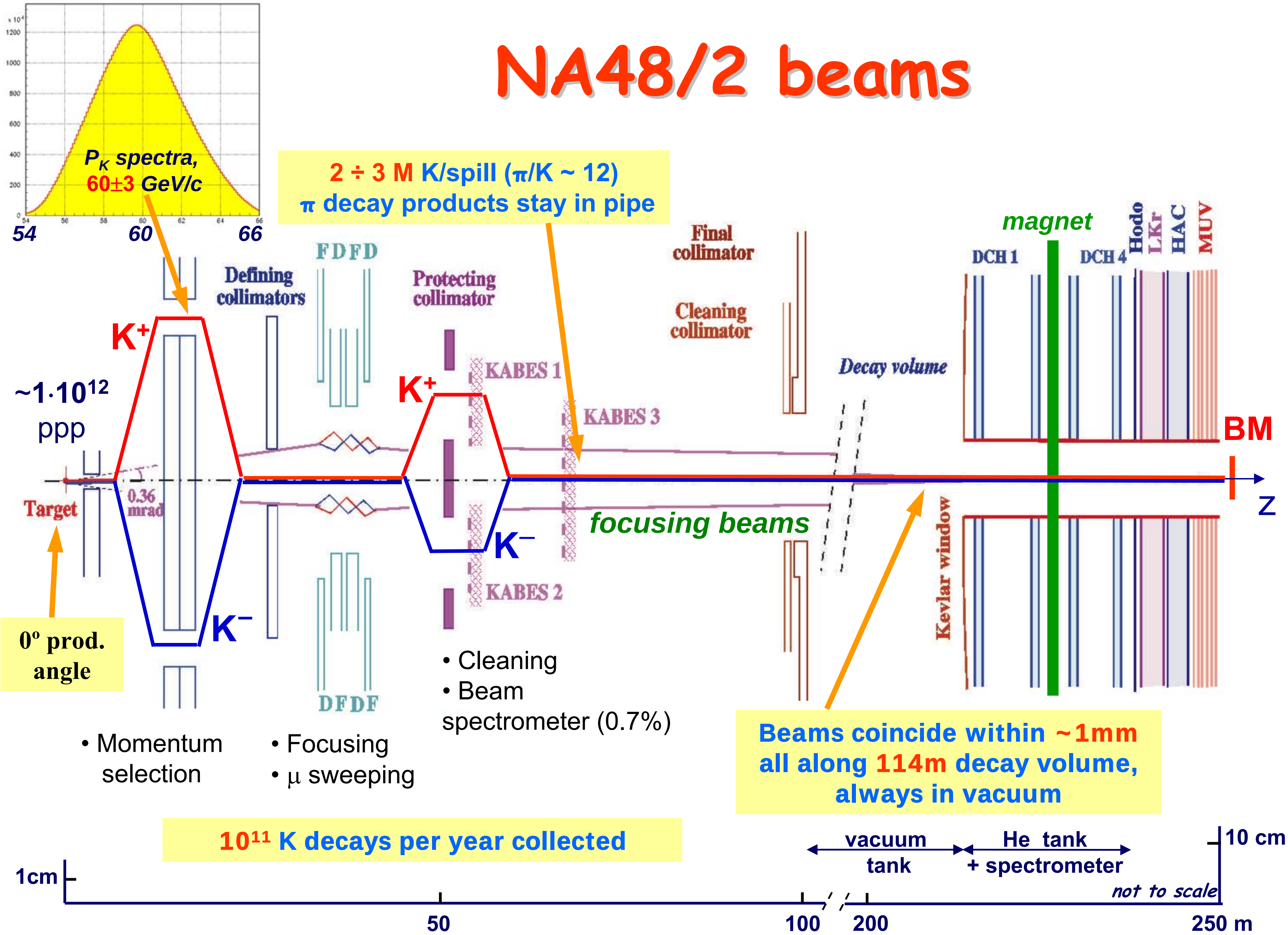
Measurement ⇨ Check of consistency with ε'_K !

- SM prefers values of $(-0.1 > \Delta g_C > -0.4) \times 10^{-4}$

If experimental limit $\leq -1 \times 10^{-4}$ or $\geq 0.5 \times 10^{-4}$
⇨ New Physics

$= A_g$

NA48/2 beams



P_K spectra,
60±3 GeV/c
54
60
66
2 ÷ 3 M K/spill (π/K ~ 12)
π decay products stay in pipe
FDFD
Defining collimators
Protecting collimator
Final collimator
Cleaning collimator
magnet
DCH 1
DCH 4
Hodo
LKr
HAC
MUV
K+
K−
~1·10^12 ppp
Target
0.36 mrad
KABES 1
KABES 2
KABES 3
Decay volume
Kevlar window
BM
Z
focusing beams
0° prod. angle
DFDF
• Cleaning
• Beam spectrometer (0.7%)
• Momentum selection
• Focusing
• μ sweeping
Beams coincide within ~1mm
all along 114m decay volume,
always in vacuum
10^11 K decays per year collected
vacuum tank
He tank + spectrometer
not to scale
1cm
10 cm
50
100
200
250 m

Detector asymmetry cancellation

Detector left-right asymmetry cancels
in 4 ratios of K^+ over K^- u distributions:

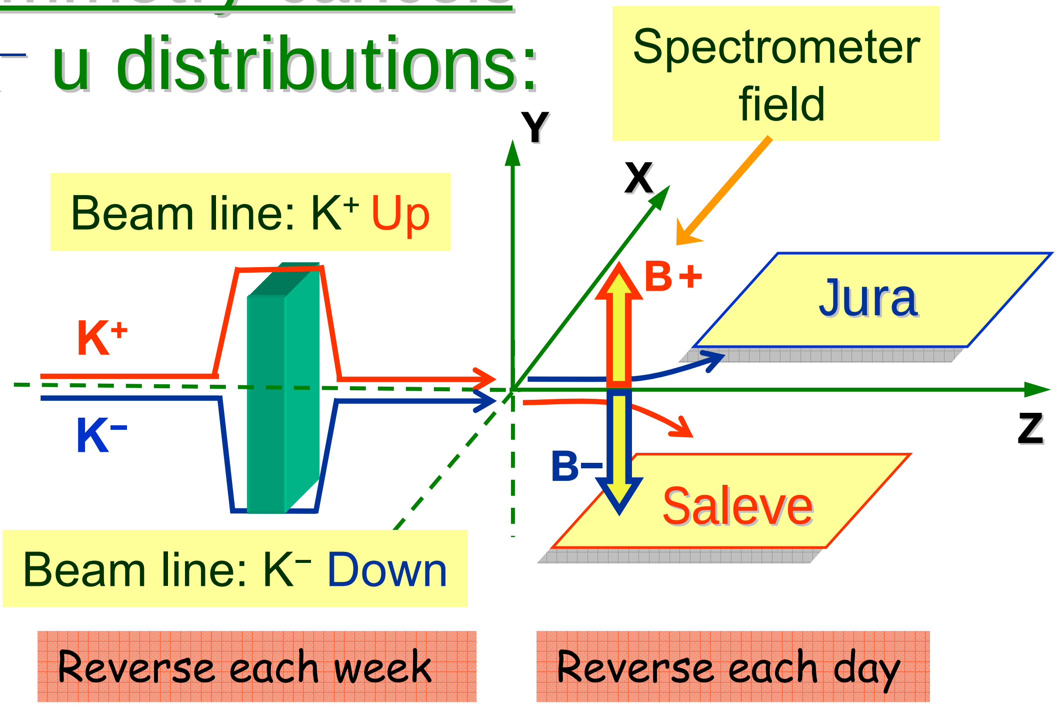
(same deviation by spectrometer in numerator and denominator)

$$R_{US} = \frac{N(A+B+K+)}{N(A+B-K-)}$$

$$R_{UJ} = \frac{N(A+B-K+)}{N(A+B+K-)}$$

$$R_{DS} = \frac{N(A-B+K+)}{N(A-B-K-)}$$

$$R_{DJ} = \frac{N(A-B-K+)}{N(A-B+K-)}$$

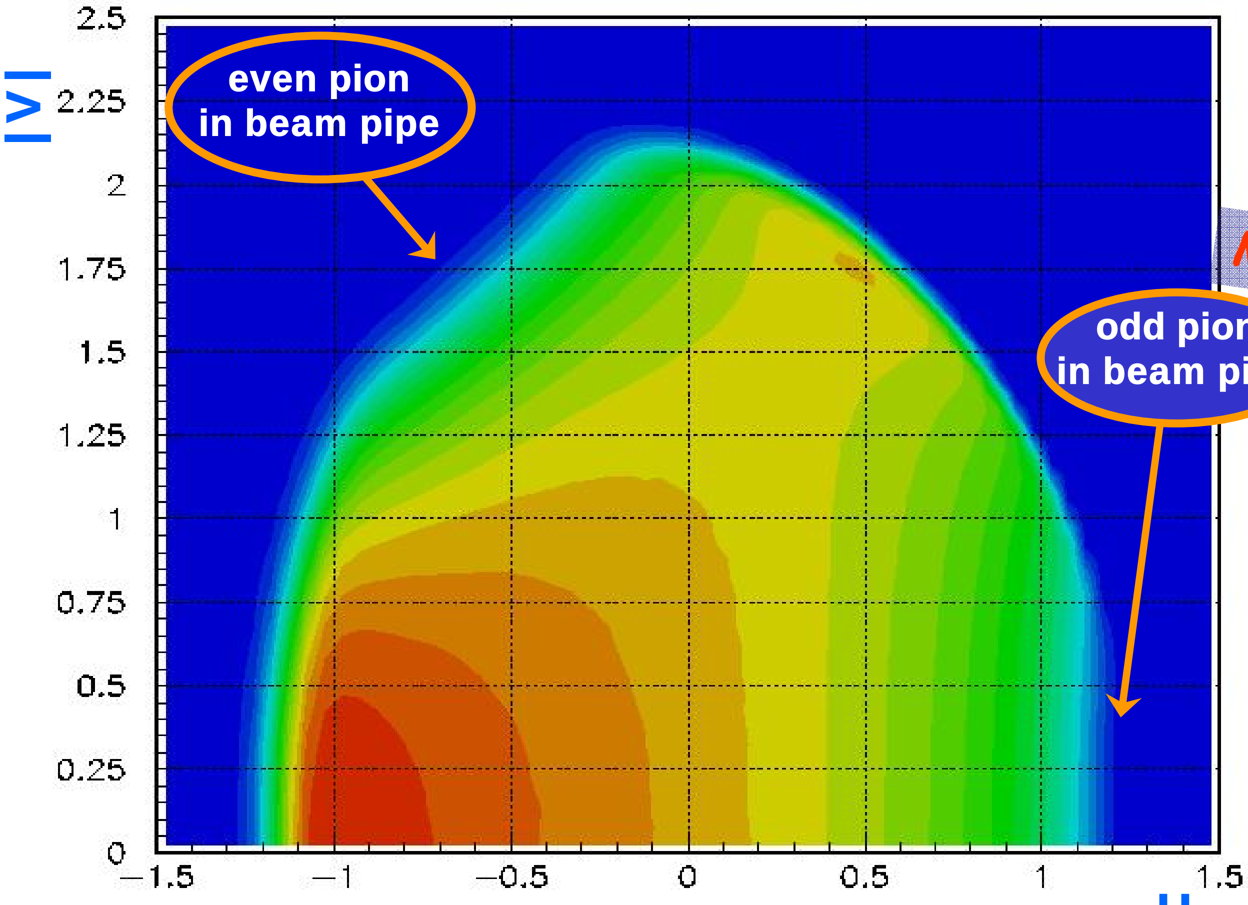


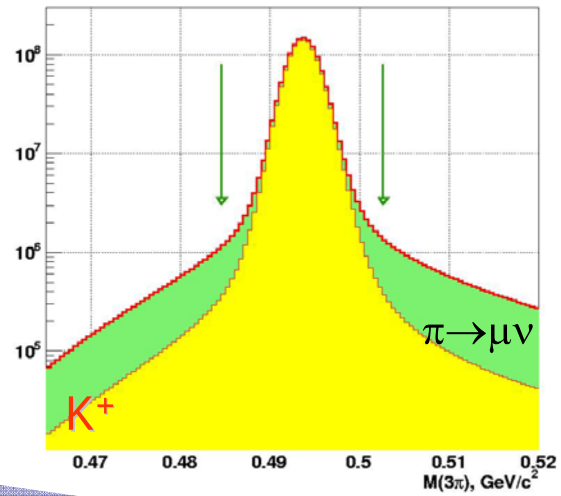
Indexes correspond to
- beamline polarity (U / D)
- direction of kaon deviation in spectrometer (S / J)

NA48/2: $\pi^{\pm}\pi^{+}\pi^{-}$ mode

Data-taking 2003-04:

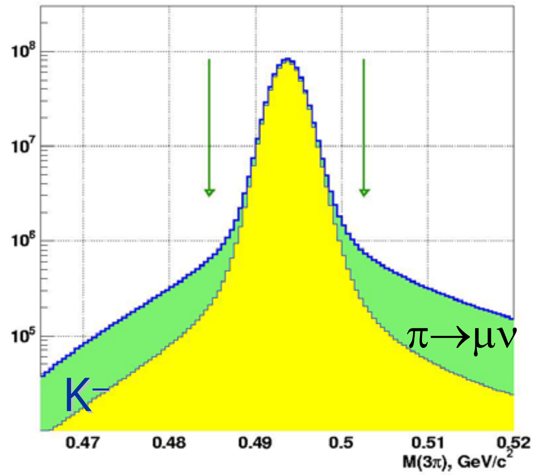
3x10^9 *events selected (K^+ / K^- ≈ 1.8)*



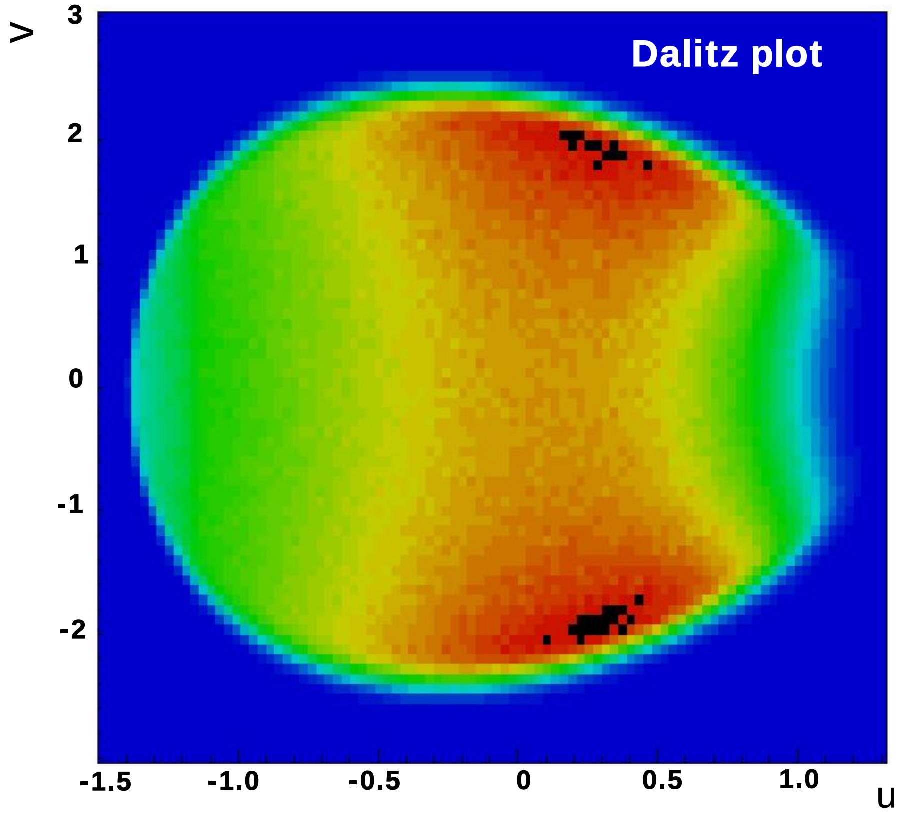


Magnetic spectrometer only

No significant background



NA48/2: $\pi^{\pm}\pi^{0}\pi^{0}$ mode



EM calorimeter only

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ also available: lower statistics, comparable sensitivity.

Kinematic variable reconstructed from $\pi^{0}\pi^{0}$: only calorimeter used – complementary.

NA48/2: CPV asymmetry results

$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ mode full statistics:
$3.1 \cdot 10^9$ decays
Preliminary result on full statistics (2003+04):

$A_g = (-1.3 \pm 2.3) \cdot 10^{-4}$

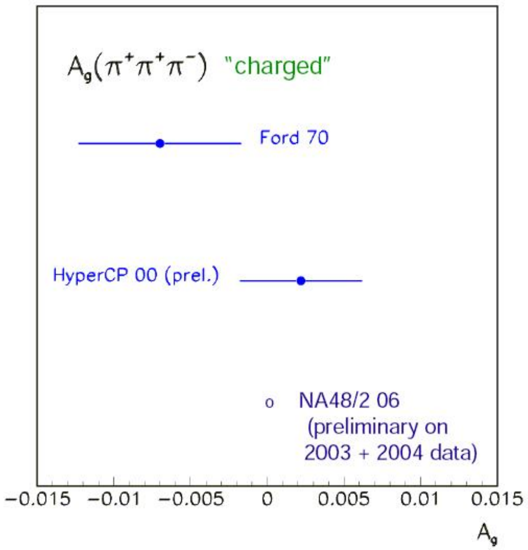
2003 result in PLB 634 (2006) 474

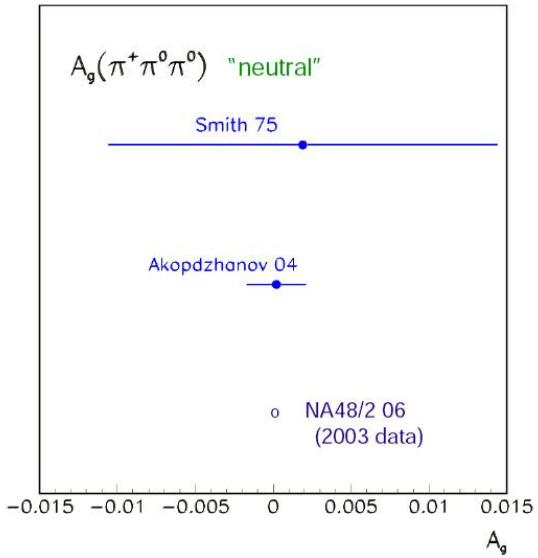
$K^{\pm} \to \pi^{\pm}\pi^{-}\pi^{0}$ mode full statistics:
$0.11 \cdot 10^9$ decays
Preliminary result on full statistics (2003+04):

$A_g = (2.1 \pm 1.9) \cdot 10^{-4}$

2003 result in PLB 638 (2006) 22

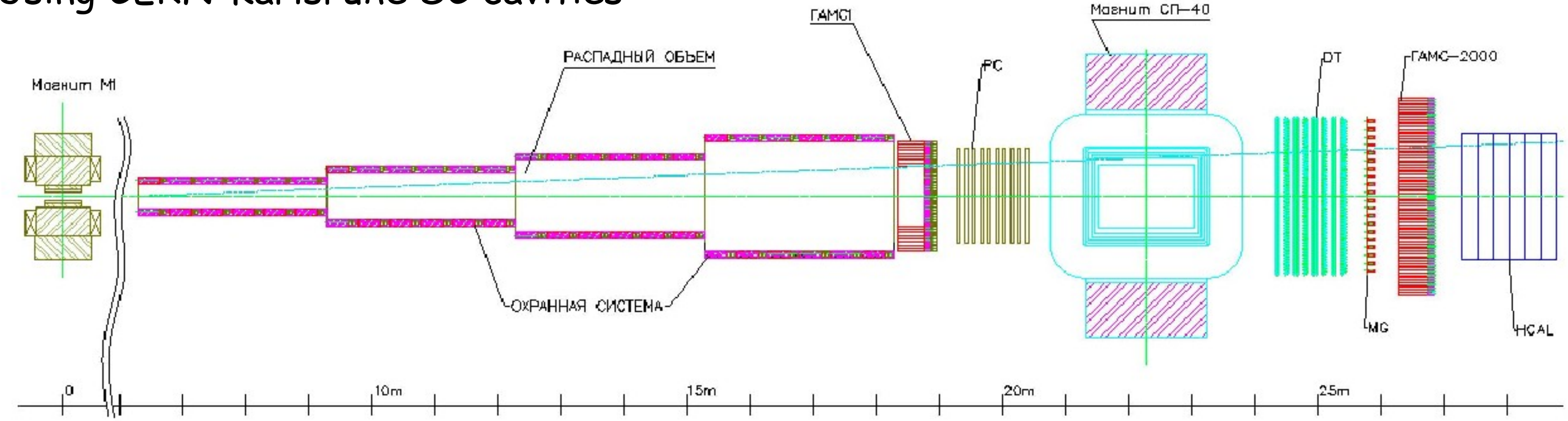
Errors dominated by statistics. No CPV found.
NP window "closed", part of SUSY model parameter space excluded





OKA at Protvino (in preparation)

Using CERN-Karlsruhe SC cavities



RF-separated charged K beam in preparation at U-70 PS in Protvino.
10^{13} ppp (70 GeV)
$8 \cdot 10^{6}$ particles/pulse (>50% K)
15 GeV/c K^{+} or K^{-} alternated.
Commissioning for OKA experiment.

Alternate beam charge

Program:
Vus, radiative and rare decays,
3π asymmetries,
T-odd correlations, …

More CP violation

CP violation parameters (2005)

charge asymmetry in $K^0_{\ell 3}$ decays	
δ_L = weighted average of $\delta_L(\mu)$ and $\delta_L(e)$	$(0.327 \pm 0.012)\%$
$\delta_L(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \overline{\nu}_\mu)]/\text{sum}$	$(0.304 \pm 0.025)\%$
$\delta_L(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \overline{\nu}_e)]/\text{sum}$	$(0.333 \pm 0.014)\%$
parameters for $K^0_L \to 2\pi$ decay	
$\|\eta_{00}\| = \|A(K^0_L \to 2\pi^0) / A(K^0_S \to 2\pi^0)\|$	$(2.276 \pm 0.014) \times 10^{-3}$
$\|\eta_{+-}\| = \|A(K^0_L \to \pi^+\pi^-) / A(K^0_S \to \pi^+\pi^-)\|$	$(2.288 \pm 0.014) \times 10^{-3}$
$\|\epsilon\| = (2\|\eta_{+-}\| + \|\eta_{00}\|)/3$	$(2.284 \pm 0.014) \times 10^{-3}$
$\|\eta_{00}/\eta_{+-}\|$	0.9950 ± 0.0008 (S = 1.6)
$\text{Re}(\epsilon'/\epsilon) = (1-\|\eta_{00}/\eta_{+-}\|)/3$	$(1.67 \pm 0.26) \times 10^{-3}$ (S = 1.6)
Assuming *CPT*	
ϕ_{+-}, phase of η_{+-}	$(43.52 \pm 0.06)^\circ$ (S = 1.3)
ϕ_{00}, phase of η_{00}	$(43.50 \pm 0.06)^\circ$ (S = 1.3)
$\phi_\epsilon = (2\phi_{+-} + \phi_{00})/3$	$(43.51 \pm 0.05)^\circ$ (S = 1.2)
CP asymmetry *A* in $K^0_L \to \pi^+\pi^- e^+ e^-$	$(13.8 \pm 2.2)\%$
β_{CP} from $K^0_L \to e^+ e^- e^+ e^-$	-0.23 ± 0.09
γ_{CP} from $K^0_L \to e^+ e^- e^+ e^-$	-0.09 ± 0.09
parameters for $K^0_L \to \pi^+\pi^-\gamma$ decay	
$\|\eta_{+-\gamma}\| = \|A(K^0_L \to \pi^+\pi^-\gamma, CP \text{ violating})/A(K^0_S \to \pi^+\pi^-\gamma)\|$	$(2.35 \pm 0.07) \times 10^{-3}$
$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$	$(44 \pm 4)^\circ$
$\Gamma(K^0_L \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$(2.090 \pm 0.025) \times 10^{-3}$ (S = 1.1)
$\Gamma(K^0_L \to \pi^0\pi^0)/\Gamma_{\text{total}}$	$(9.32 \pm 0.12) \times 10^{-4}$ (S = 1.1)

Indirect (blue underline)

Direct (red underline)

(A) K_S decays

CPV in K_S decays

Recall: $\pi^0\pi^0\pi^0$ is CP-odd, $\pi^+\pi^-\pi^0$ is predominantly CP-odd

$K_S \to \pi^0\pi^0\pi^0$ (I=1,3) would indicate (mostly *indirect*) CP violation

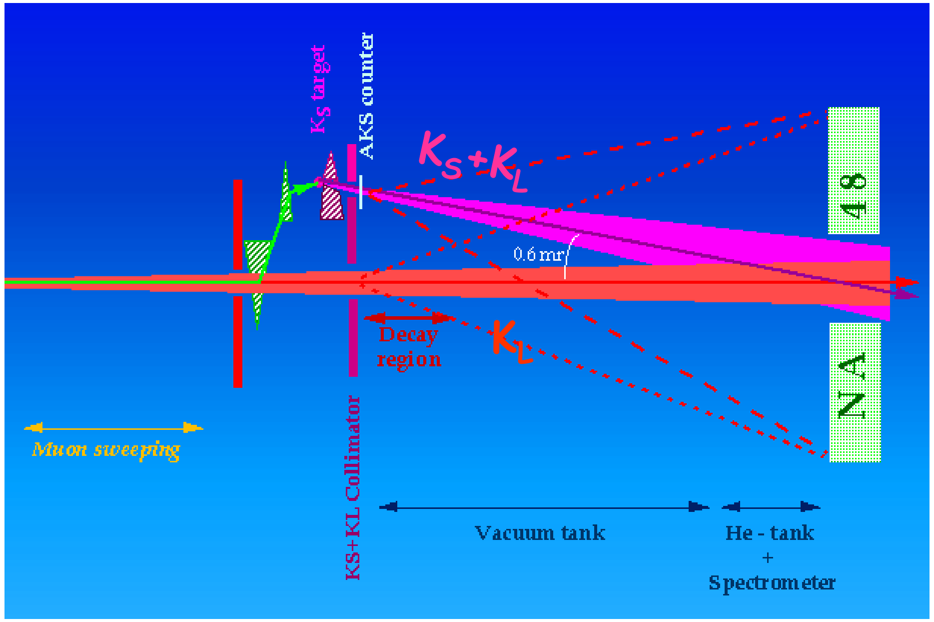
SM prediction: $\Gamma_S(3\pi) \approx \Gamma_L(3\pi)|\eta|^2$, or

$BR(K_S \to 3\pi^0) \approx BR(K_L \to 3\pi^0)\ |\varepsilon|^2\ (\tau_S/\tau_L) \approx 1.9 \cdot 10^{-9}$

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \cong \varepsilon + \varepsilon'_{000}$$

ε'_{000} estimated to be of same order of ε'

$K_S \to \pi^0\pi^0\pi^0$ at hadron machines



NA48: "close" to production target, look for interfering $K_S, K_L \to \pi^0\pi^0\pi^0$ starting from a mixture of $K^0, \overline{K^0}$

Take ratio with a K_L run ("far target") to cancel acceptance and efficiencies

$$f(E,t) = \frac{NEAR}{FAR} =$$

$$A(E)\left[1 + |\eta_{000}|^2 e^{(\Gamma_L - \Gamma_S)t} + 2D(E) e^{\frac{1}{2}(\Gamma_L - \Gamma_S)t} \left(\mathrm{Re}\,\eta_{000} \cos\Delta m t - \mathrm{Im}\,\eta_{000} \sin\Delta m t\right)\right]$$

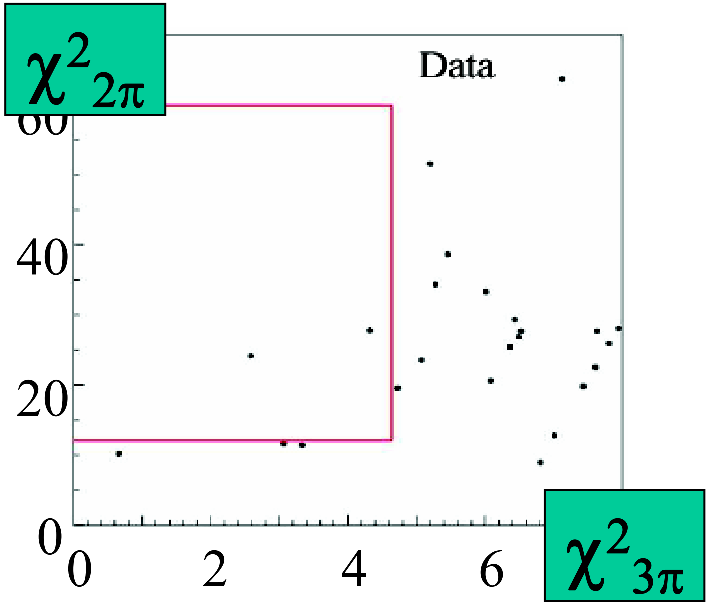
"Dilution factor": $D(E) = \dfrac{N(K^0,E) - N(\overline{K}^0,E)}{N(K^0,E) + N(\overline{K}^0,E)}$ (incoherent production)

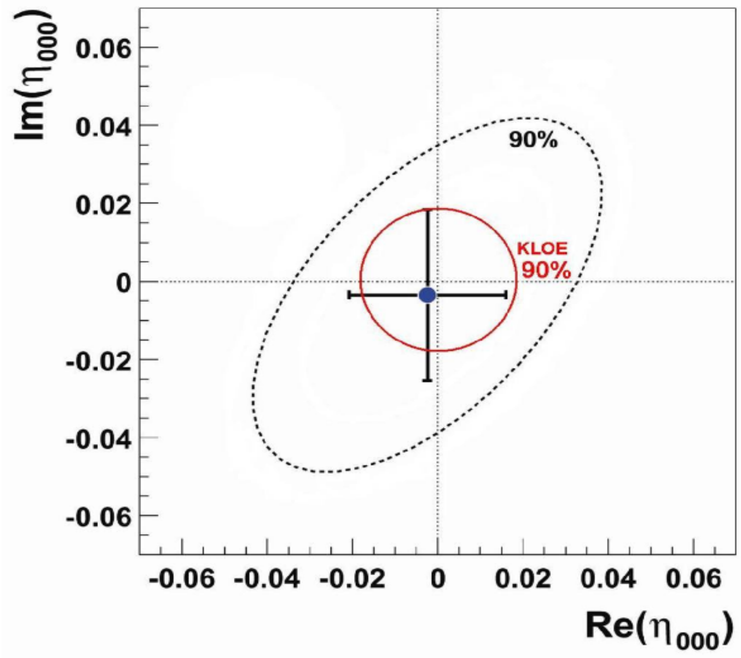
NA48/1: Near target beam: $4.9 \cdot 10^6$ $3\pi^0$
Far target beam: $109 \cdot 10^6$ $3\pi^0$

Assuming CPT:

$BR(K_S \to 3\pi^0) < 2.3 \times 10^{-7}$ (90% CL)

$K_S \to \pi^0\pi^0\pi^0$ at KLOE





450 pb^{-1} (2001+2002 data)

Kinematic fit to $2\pi^0$ and $3\pi^0$

2 signal events w. $3.13 \pm 0.82_{stat} \pm 0.37_{syst}$ expected background

N(3π0) < 3.45 at 90% CL

$$BR(K_S \to \pi^0\pi^0\pi^0) = \frac{N_{3\pi} / \varepsilon_{3\pi}}{N_{2\pi} / \varepsilon_{2\pi}} BR(K_S \to \pi^0\pi^0) < 1.2\ 10^{-7}$$

$|\eta_{000}| < 1.8 \cdot 10^{-2}$ at 90% CL

No CPV seen yet

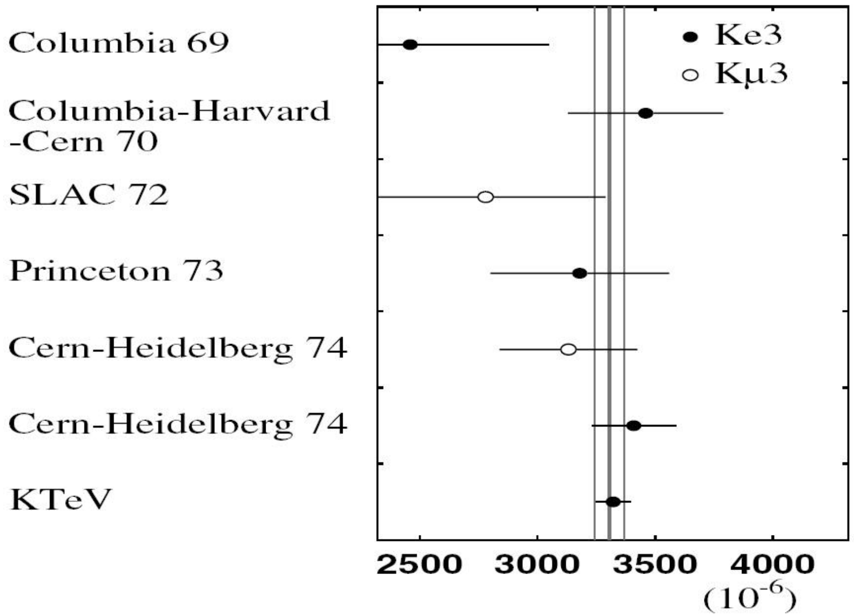
(B) Semi-leptonic charge asymmetries

Semi-leptonic charge asymmetry

Indirect CP violation:
2÷3 ·10^8 events (KTeV, NA48):

$$\delta_L(e) = (3.32 \pm 0.07) \times 10^{-3}$$

It measures ε
(hard to compute, *input* for theory),
systematics limited



Also K_S semi-leptonic decays, first detected by KLOE:
BR($K_S \to \pi e \nu$) ≈ $7 \cdot 10^{-4}$ ($K_S \to \pi \mu \nu$ also observed at KLOE)
charge asymmetry expected to be equal to K_L one by CPT

KLOE (2006): $\delta_S(e) = (1.5 \pm 9.6 \pm 2.9) \cdot 10^{-3}$
(410 pb^{-1} data, still far from significative CPT test)

(C) T-odd correlations

T-odd correlations (1)

Tri-linear quantities such as $\mathbf{p}_a \times \mathbf{p}_b \cdot \mathbf{s}_a$ are odd under T

Muon polarization transverse to the decay plane in
$K_L \rightarrow \pi^+\mu^-\nu$ decay or $K^+ \rightarrow \pi^0\mu^+\nu$ decay

Effect arises from relative phase of two form factors
$\xi = f_-/f_+$ (Im $\xi \neq 0$ is T-violating)

Muon decay mode because f_- is proportional to lepton mass

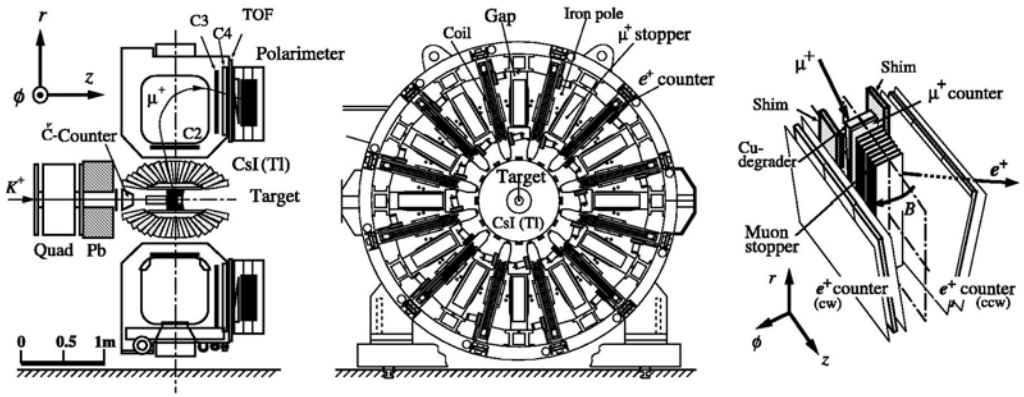
FSI can fake the effect: more relevant for K_L (limit reached in the 70s).
K^+ also allows stopped K technique.

T- violation: KEK E246

T-violation first measured by **CPLEAR**, compatible with indirect CP violation.

$P_T(\mu)$ orthogonal to decay plane in 3-body decays (T-odd correlation).
Tiny FSI (EM) in SM: sensitive to New Physics
Stopped K experiments: systematics from detector mis-alignment, magnetic fields asymmetries and (large) in-plane polarization.

KEK E246:
660 MeV/*c* K^+ stopped in active fibre target.
Final result (8.3M $\pi^0\mu^+\nu$ decays, 1996-2000):



$P_T(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$ $\text{Im}\,\xi = (-5.3 \pm 7.1 \pm 3.6) \times 10^{-3}$

$\text{Im}\,\xi = (-5.3 \pm 7.1 \pm 3.6) \times 10^{-3}$

Experiment concluded. Also 10^5 $\mu^+\nu\gamma$ decays (larger background, different sensitivity to New Physics) in 1996-98.
Plans for improved experiment (x10) at J-PARC.

T-odd correlations (2)

Tri-linear quantities such as $\mathbf{p}_a \times \mathbf{p}_b \cdot \mathbf{s}_a$ are odd under T
To avoid measuring polarizations: $\mathbf{p}_a \times \mathbf{p}_b \cdot \mathbf{p}_c$ but need 4-body final state:

K_{e4} ($K \to \pi\pi e\nu$) BR $\approx 4 \cdot 10^{-5}$ or

$K_{e3\gamma}$ ($K \to \pi e \nu \gamma$) BR $\approx 3 \cdot 10^{-4}$

$$\xi = \frac{\left(\vec{p}_\pi \times \vec{p}_\mu\right) \cdot \vec{p}_\gamma}{\left|\vec{p}_\pi \times \vec{p}_\mu\right| \left|\vec{p}_\gamma\right|} \qquad A_\xi = \frac{N(\xi > 0) - N(\xi < 0)}{N(\xi > 0) + N(\xi < 0)}$$

Final State Interactions can contribute: $A_\xi \approx (0.5\text{-}1) \cdot 10^{-4}$ in the SM
NP models: $A_\xi \approx$ few 10^{-4}

ISTRA+ (2005): $A_\xi = 0.015 \pm 0.021$ (1400 events)
OKA, NA48/2: >10^4 events
NA48/2: Cancellation of FSI effects by K+/K– comparison (!)

ISTRA+ (2006): BR($K \to \pi\mu\nu\gamma$) $\approx 9 \cdot 10^{-5}$ $A_\xi = -0.03 \pm 0.13$ (400 events)

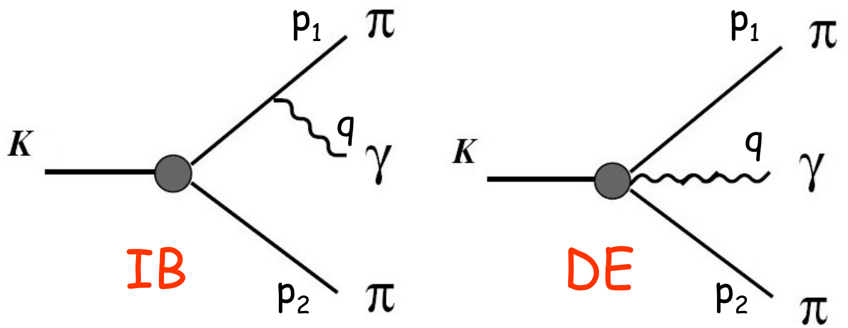
Radiative decays

$K \to \pi\pi\gamma$

Two classes of contributions:

Inner *bremsstrahlung* (IB)

Direct emission (DE)



IB computed by QED, proportional to the corresponding $\pi\pi$ decay, usually dominant, $1/q$ *bremsstrahlung* spectrum for γ, peaked at low E

DE depends on the details of the K

Depending on the multipolarity of the EM radiation the decay can be CP-conserving or CP-violating.

$$A \propto \varepsilon_\mu(q)\left[(p_1 q p_2^\mu - p_2 q p_1^\mu)\, E + \varepsilon^{\mu\nu\rho\sigma} p_{1\nu} p_{2\rho} q_\sigma\, M\right]$$

"electric" (IB+DE) "magnetic" (DE)

CP-violation asymmetries require two interfering amplitudes:
one CP-conserving and one CP-violating.

When summing over (unmeasured) γ helicities, E and M *do not* interfere.
IB can interfere with the electric part of DE.

Considering lowest order (dipole E1, M1):
$\pi\pi\gamma$ (electric) is CP-even:
$K_S \to \pi^+\pi^-\gamma$ dominated by IB
$\pi\pi\gamma$ (magnetic) is CP-odd:
$K_L \to \pi^+\pi^-\gamma$ the M1 DE can compete with the CP-violating IB

$$\eta_{+-\gamma} = \frac{A(K_L \to \pi^+\pi^-\gamma, CP-violating)}{A(K_S \to \pi^+\pi^-\gamma)}$$

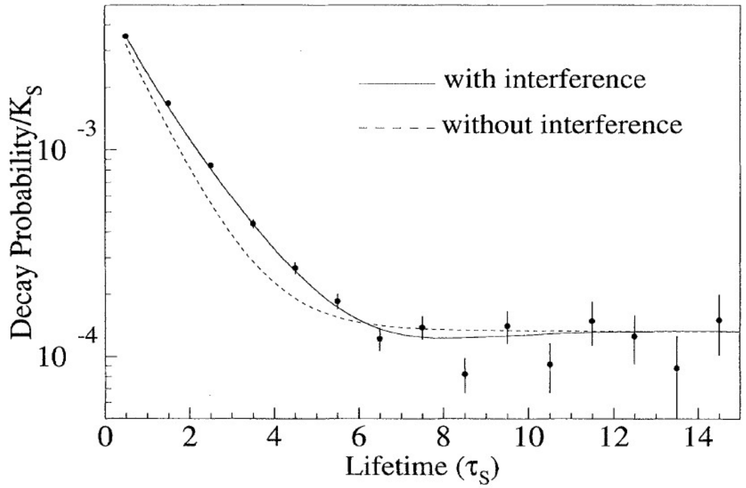
K_S-K_L CPV *interference* arises largely from interference of the two E1 IB:
in this case $\eta_{+-\gamma} = \eta_{+-}$

If an E1 DE component (CP-violating) is present for K_L it can interfere with the (CP-conserving) E1 IB and modify $\eta_{+-\gamma}$ (*direct* CP violation)

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

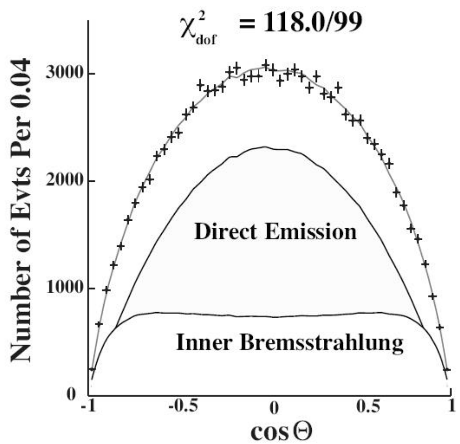
FNAL E731 (1995):
8K events fitted
after regenerator

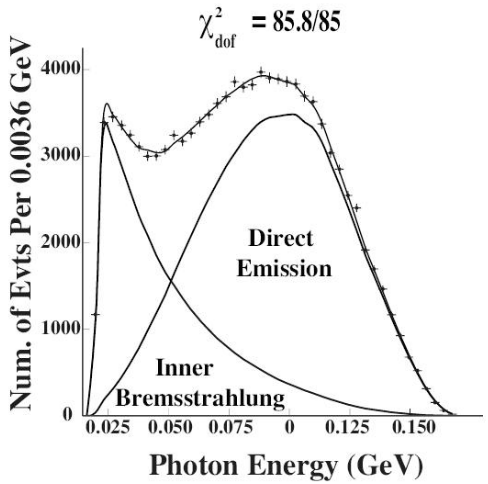
$|\eta_{+-\gamma}| = (2.359 \pm 0.062) \cdot 10^{-3}$
$\varphi_{+-\gamma} = (43.8 \pm 3.5)°$
Fully consistent with η_{+-}:
$|\varepsilon'_{+-\gamma}|/|\varepsilon| < 0.3$ (90% CL)



New KTeV direct measurement
(2006, 40% data sample)
$112 \cdot 10^3$ events

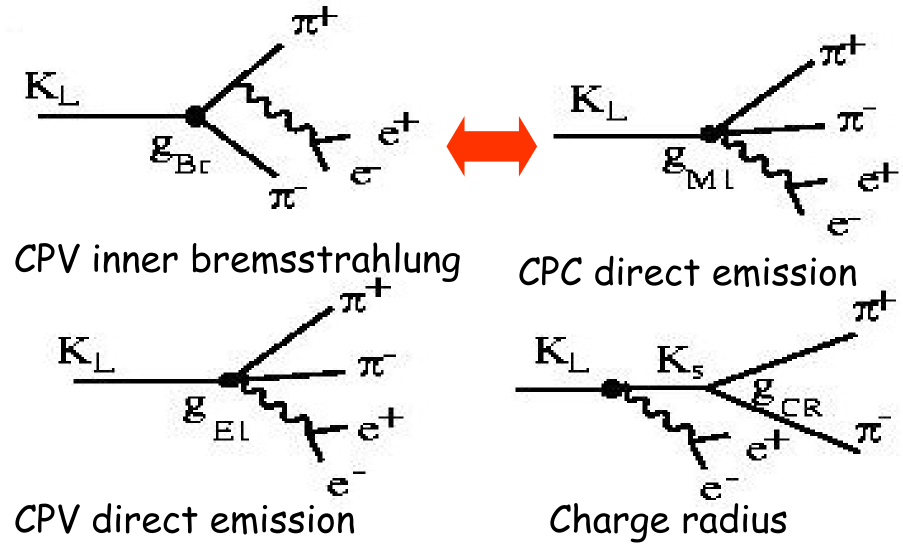
DE/(IB+DE) = 0.689 ± 0.021
for $E_\gamma > 20$ MeV





K_L itself

If one would observe γ helicity, interference among E1 IB (CPV) and M1 DE (CPC) – of comparable magnitude - could be observed.



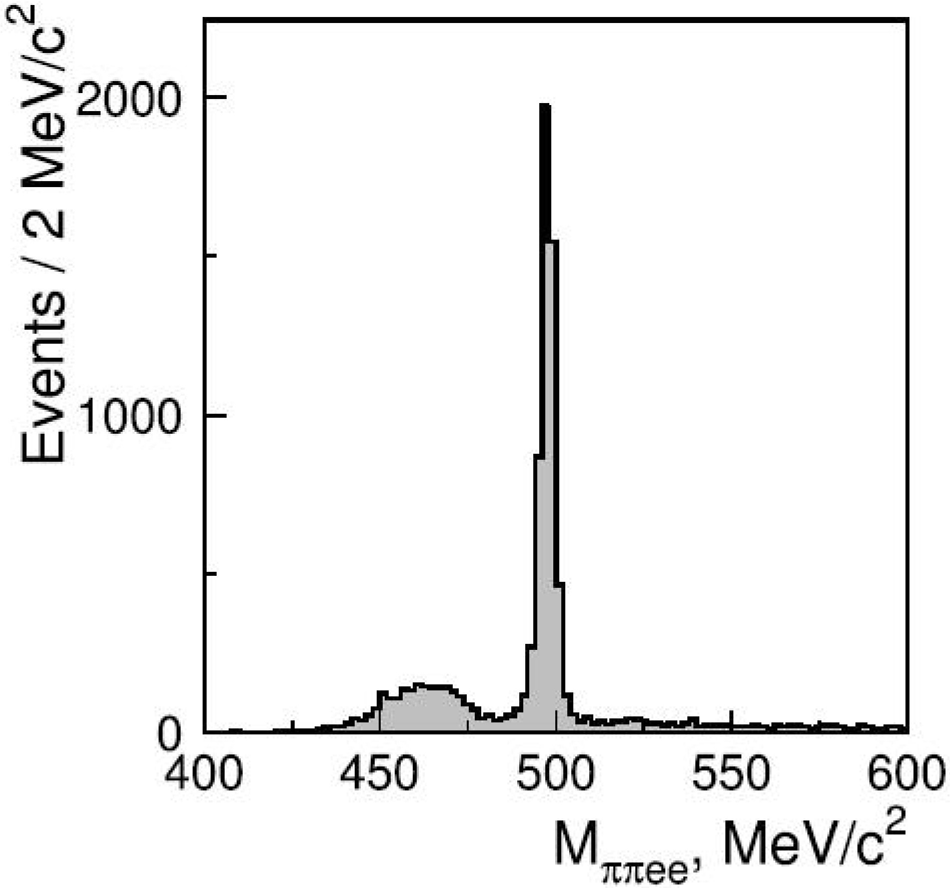
In $\gamma \to e^+e^-$ the lepton plane orientation is correlated to the photon helicity (cmp. π^0 parity determination)

Interference gives *indirect CP-violating* asymmetry in the orientation of $\pi^+\pi^-$ and e^+e^- decay planes: large ($\approx$ 14%) asymmetry predicted

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

KTeV first observation
and NA48

BR = $(3.08 \pm 0.20) \times 10^{-7}$

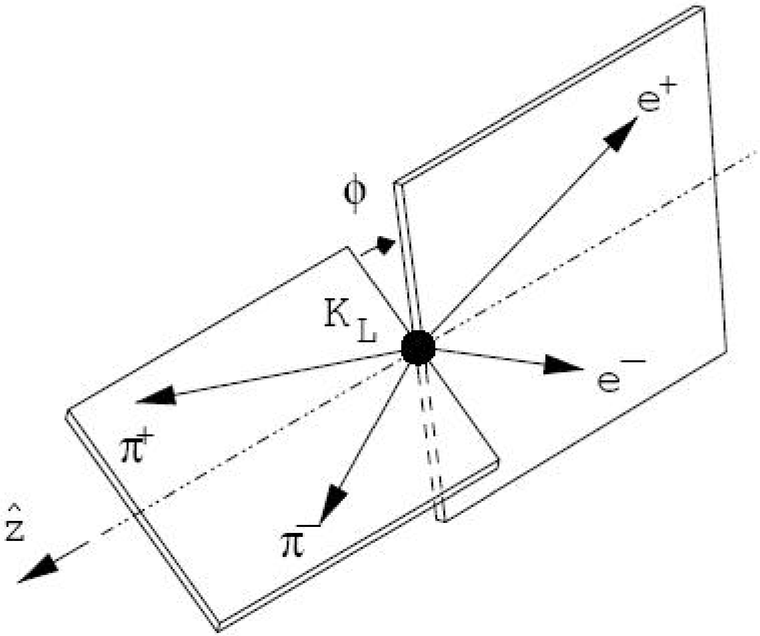


KTeV full data set
5200 events
(4% background)

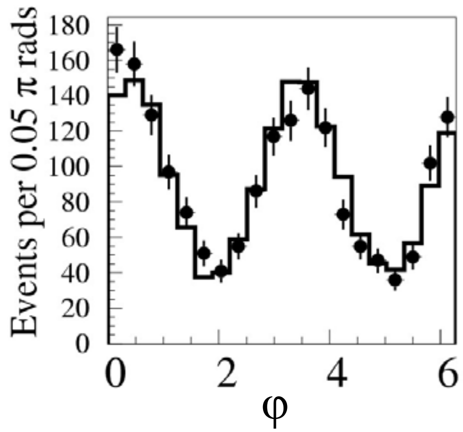
E1 DE term (if any) is
small:

E1/M1 < 0.04 (90% CL)

$K_L \to \pi^+\pi^-e^+e^-$ and CPV

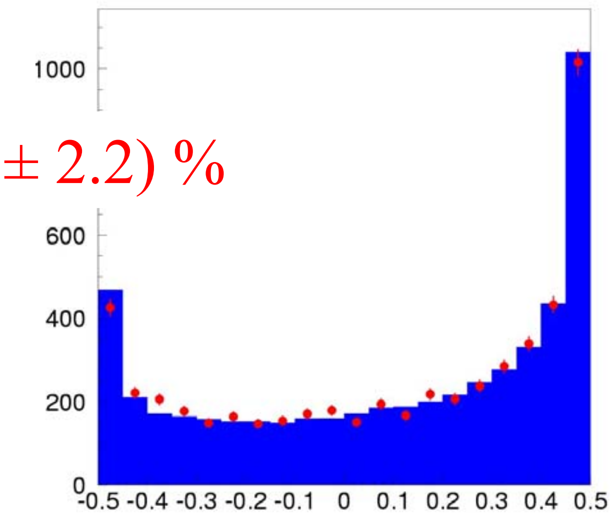


Asymmetry in angle φ between ππ and ee planes, in agreement with theory (indirect CPV)



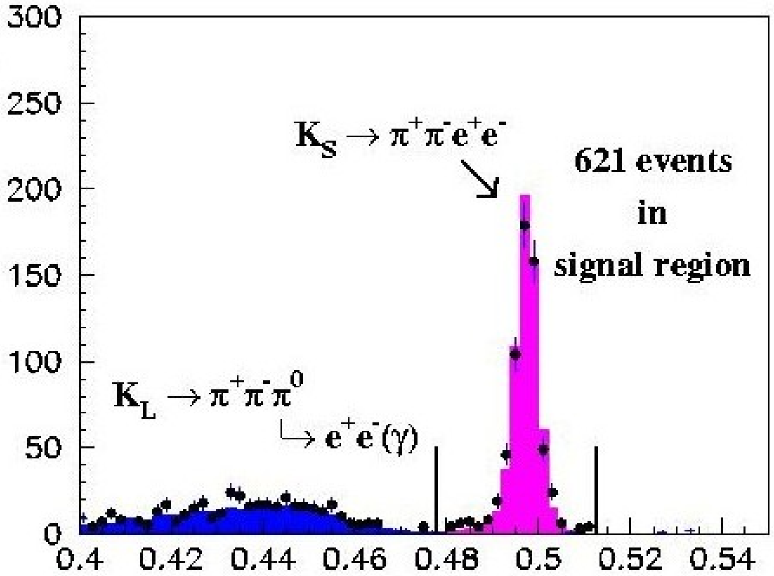
$$A_\Phi = (13.8 \pm 2.2)\ \%$$

KTeV and NA48 average

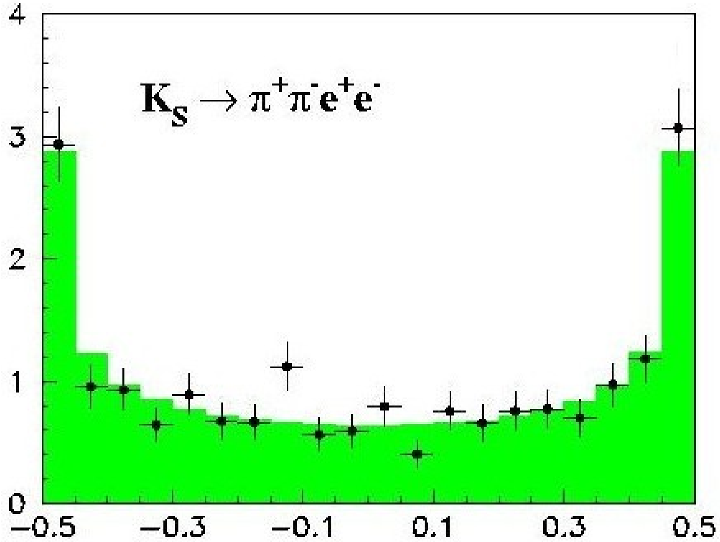


$K_S \to \pi^+\pi^-e^+e^-$

NA48 first observation
600 events
Background = 0.1%



$BR = (4.71 \pm 0.32) \times 10^{-5}$

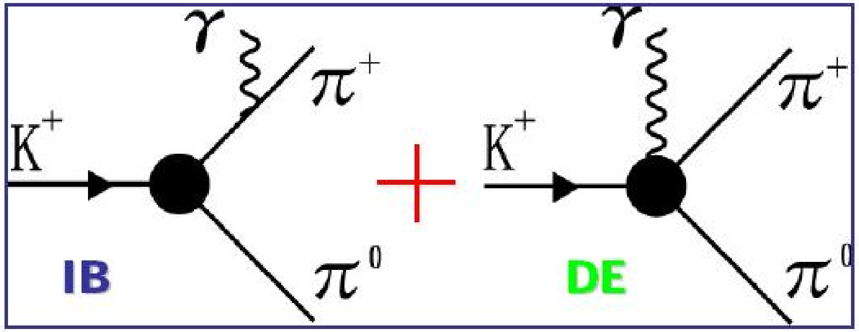


$A_\Phi = (0.5 \pm 4.3)\ \%$

No asymmetry for K_S
as expected

$K^\pm \to \pi^+\pi^0\gamma$

BR ~ $3{\cdot}10^{-4}$ Similar to previous cases, IB dominates, DE measured, interference term not yet



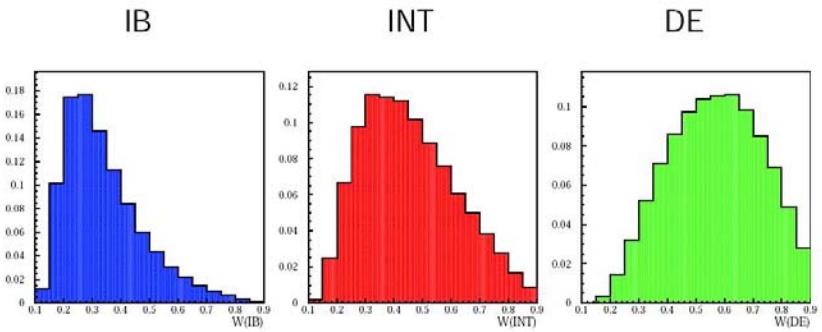
$$\frac{d\Gamma^\pm}{dW} \simeq \underbrace{\left(\frac{d\Gamma^\pm}{dW}\right)_{IB}}_{\text{IB}} \left[1 + \underbrace{2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| cos((\delta_1 - \delta_0) \pm \phi)}_{\text{INT}} + \underbrace{\left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)}_{\text{DE}}\right]$$

INT term could give CPV asymmetry

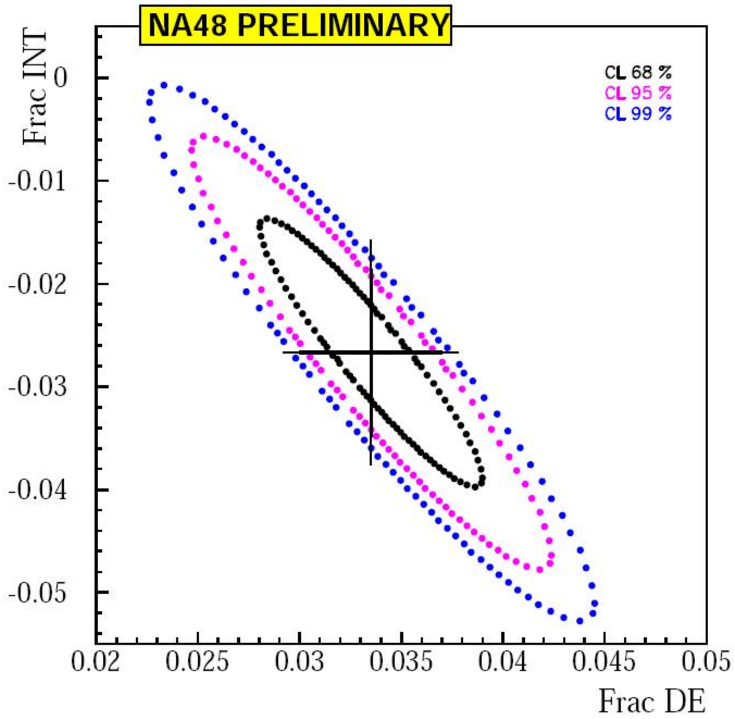
$|\varepsilon'_{+0\gamma}|$ <~ 10^{-4}

$$A_\Gamma = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ - \Gamma^-} \propto \varepsilon'_{+0\gamma} \tan(\Delta\delta) \qquad \Gamma^\pm = \int dE_\gamma \left[\frac{\partial\Gamma}{\partial E_\gamma} - \left.\frac{\partial\Gamma}{\partial E_\gamma}\right|_{IB}\right]$$

$K^{\pm} \rightarrow \pi^{+}\pi^{0}\gamma$



Separation by photon spectrum



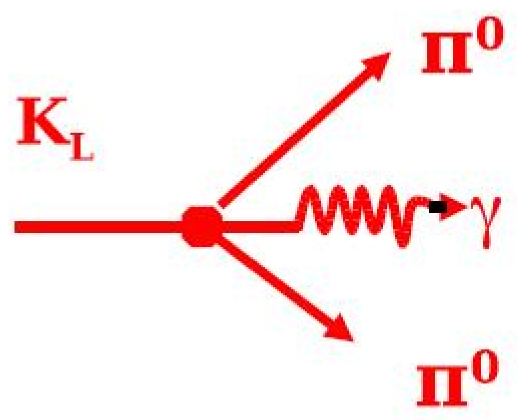
NA48/2 (2006): First indication of INT

$$Frac(DE)_{0<T_{\pi}^{*}<80\,MeV} = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\%$$

$$Frac(INT)_{0<T_{\pi}^{*}<80\,MeV} = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\%$$

$K_L \to \pi^0\pi^0\gamma$

DE only, lowest possible multipole is E2
Not observed yet
Expectations: BR ~ $7{\cdot}10^{-11}$ at first $O(p^6)$ order in CHPT



New KTeV limit (2006): BR < $2.52 \cdot 10^{-7}$ (90% CL)
(0 events found, 1.66 ± 0.59 expected background)

$K_L \to \pi^+\pi^-\pi^0\gamma$

Dominated by IB
Expectations: BR ~ $1.7 \cdot 10^{-4}$ (E_γ > 10 MeV)

First observation by KTeV (2006): BR = $(1.70 \pm 0.03 \pm 0.04 \pm 0.03) \cdot 10^{-4}$
(preliminary, 5700 candidates)

$K_L \to \pi^+\pi^-\pi^0 e^+e^-$

First observation by KTeV (2006): BR = $(1.60 \pm 0.18) \cdot 10^{-7}$
(preliminary, 132 candidates)

Radiative semileptonic decays

- K_L and $K^{\pm}$ semileptonic radiative decays give information on kaon structure

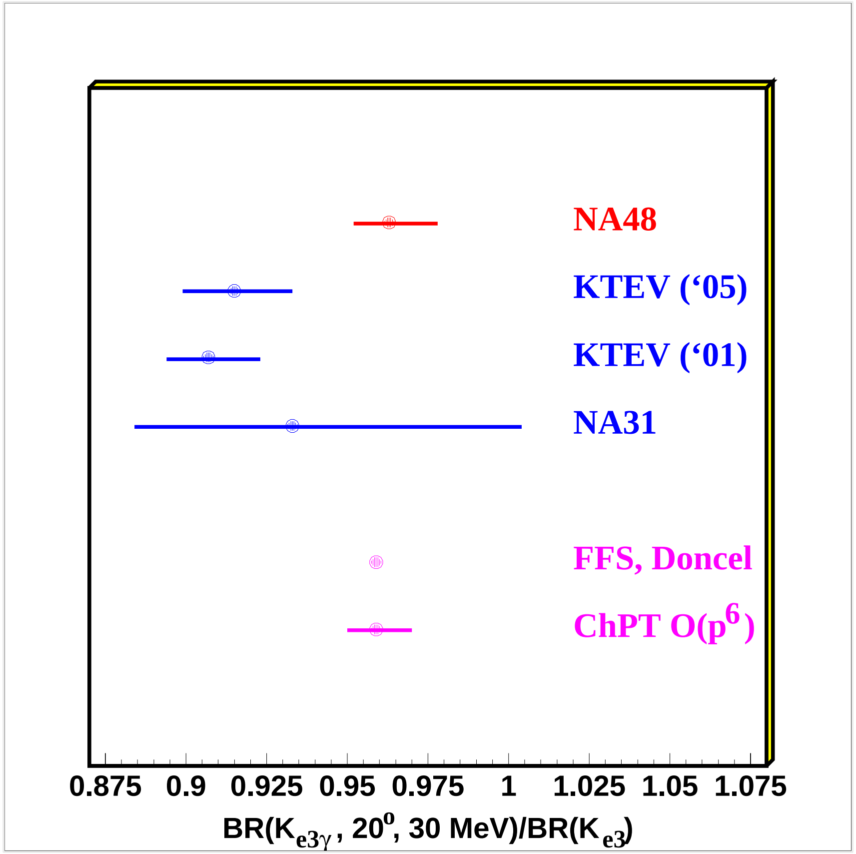
  In $K^{\pm}$ also T-odd variables → CPV...
- Ratio R (with constraints to avoid divergences) is predicted to be between 0.95% and 0.99%
- Theoretical approaches
  - Current algebra (Fearing, Fischbach, Smith) (Doncel)
  - χPT (continuosly improved): latest estimate $(0.96 \pm 0.01)\%$

$$R = \frac{\Gamma(K_{e3\gamma}, E^*_{\gamma} > 30\,MeV, \theta^*_{e\gamma} > 20^{\circ})}{\Gamma(K_{e3})}$$

- A recent measurement from KTeV gives $R = (0.908 \pm 0.008^{+0.013}_{-0.012})\%$, in disagreement with the prediction

Radiative semileptonics

- NA48 results
  - 10K K_{e3g} events
  - 6M K_{e3} events
  - Less than 1% background
- $R=(0.964\pm0.008^{+0.011}{}_{-0.009})\%$
- In full agreement with the predictions
- Analysis in progress by NA48 on $K^{\pm}$ radiative semileptonic decay



Non CPV physics from K

Vus and CKM unitarity test

Unitarity of CKM matrix tests existence of extra quark generations and possible existence of new physics

Most precise test of unitarity from 1st row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \sim |V_{ud}|^2 + |V_{us}|^2 \equiv 1 - \Delta$$

PDG 2004:

$|V_{ud}|^2 = 0.9483 \pm 0.0010$ (nuclear decays)

$|V_{us}|^2 = 0.0482 \pm 0.0010$ (K semi-leptonic decays)

$|V_{ub}|^2 = 0.000011 \pm 0.000003$ (B meson decays)

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 =$ **0 9965±0.0015 (~ 2.3 σ deviation)**

Situation called for more precise K (and nuclear) measurements

V_{us} (the Cabibbo angle)

$$\frac{G^2 m_K^5}{192\pi^3}[1/2]$$

Rate from experiment

EW, Isospin-breaking, EM corrections: few percent

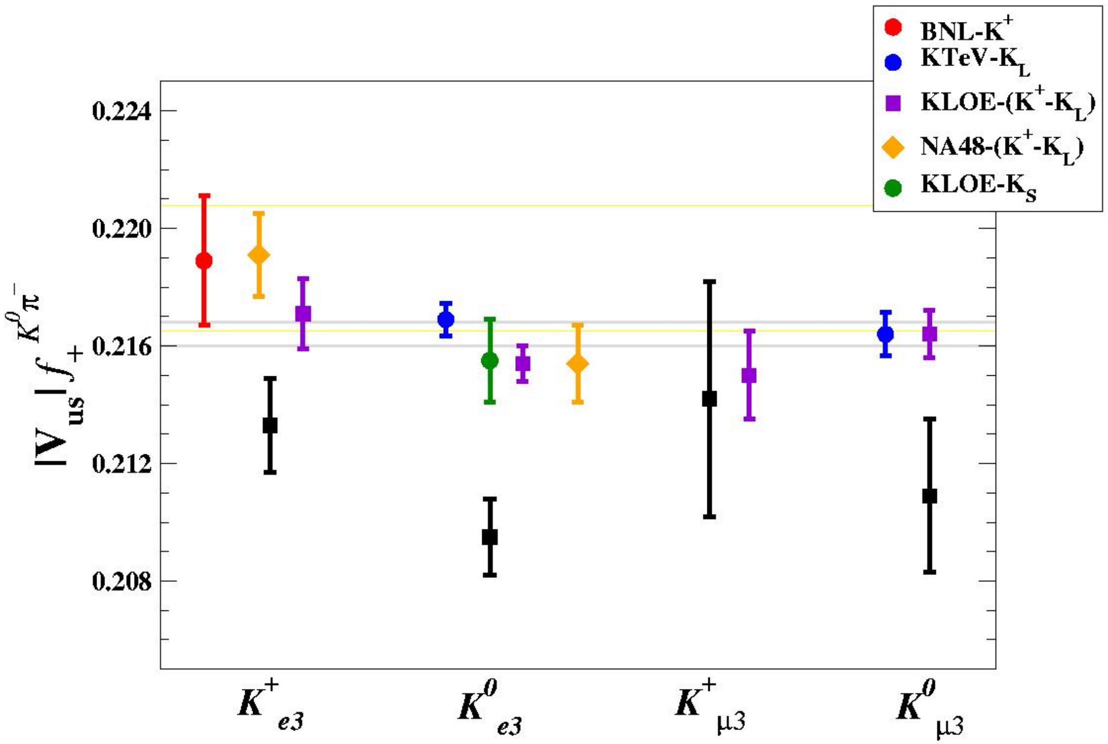
$$|V_{us}| \cdot f_+^{K^0\pi^-}(0) = \left[\frac{\Gamma_i}{\mathcal{N}_i\, S_{ew}\, I_i(\lambda_+, \lambda_0, 0)}\right]^{1/2} \frac{1}{1 + \delta^i_{SU(2)} + \delta^i_{e^2p^2} + \frac{1}{2}\Delta I_i(\lambda_+, \lambda_0)}$$

Form factor at 0 momentum transfer: purely from theory

Form factor slopes from experiment

Phase space integral

V_{us} measurements



Black: pre-2004 measurements

$\langle |V_{us}| \times f_+(0) \rangle_{\text{WORLD AVG.}} = 0.2164(4)$

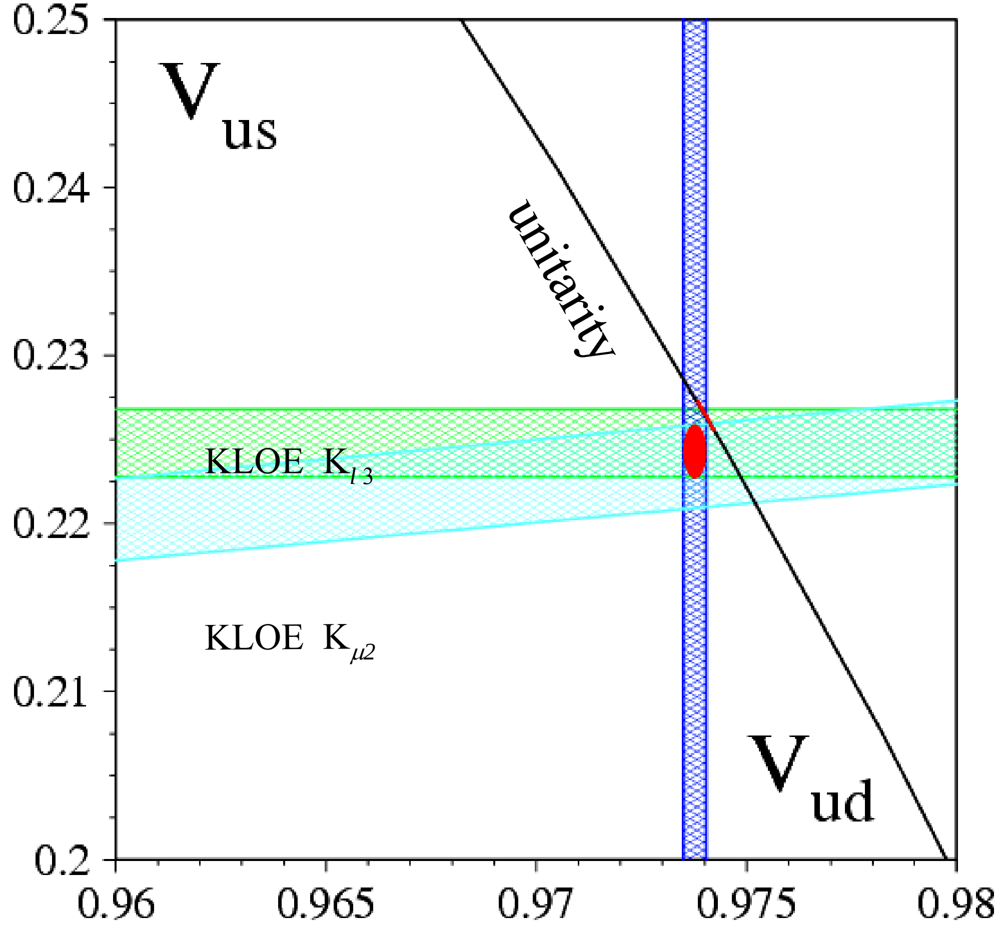
CKM matrix unitary within ~ 1σ

Vus some more

Using f_K / f_π from Lattice QCD (MILC, 2005)
and KLOE BR($K^+ \to \mu+\nu$) :
V_{us}/V_{ud} = 0.2294 ± 0.0026

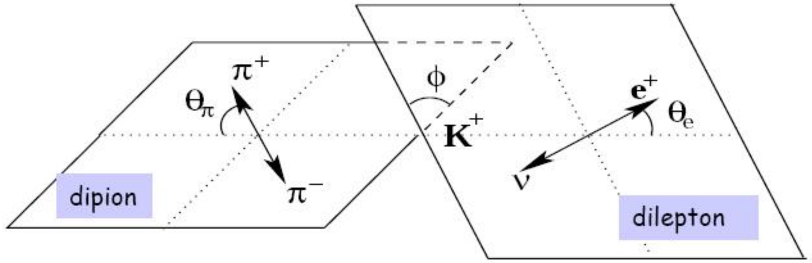
Fit of the above results:
V_{us} = 0.2242 ± 0.0016
V_{ud} = 0.97377 ± 0.00027

Fit assuming unitarity:
V_{us} = 0.2264 ± 0.0009



$K^+ \to \pi^+\pi^- e\nu$ (Ke4) decays

The Ke4 decay are described using 5 kinematic variables (defined by Cabibbo-Maksymowicz): S_π ($M^2_{\pi\pi}$), S_e ($M^2_{e\nu}$), $\cos\theta_\pi$, $\cos\theta_e$ and ϕ.



Using a partial wave expansion:

$F = F_s\, e^{i\delta s} + F_p\, e^{i\delta p} \cos\theta_\pi$ + d-wave term...

$G = G_p\, e^{i\delta g}$ + d-wave term...

$H = H_p\, e^{i\delta h}$ + d-wave term...

Keeping only s and p waves (S_π is small in Ke4) , rotating phases by δ_p and assuming $(\delta_g-\delta_p) = 0$ and $(\delta_h-\delta_p) = 0$, only 5 form factors are left:

$F_s \quad F_p \quad G_p \quad H_p$ and $\delta = \delta_s - \delta_p$

developing in powers of q^2 ($q^2 = (S_\pi - 4m_\pi^2)/4m_\pi^2$), S_e...

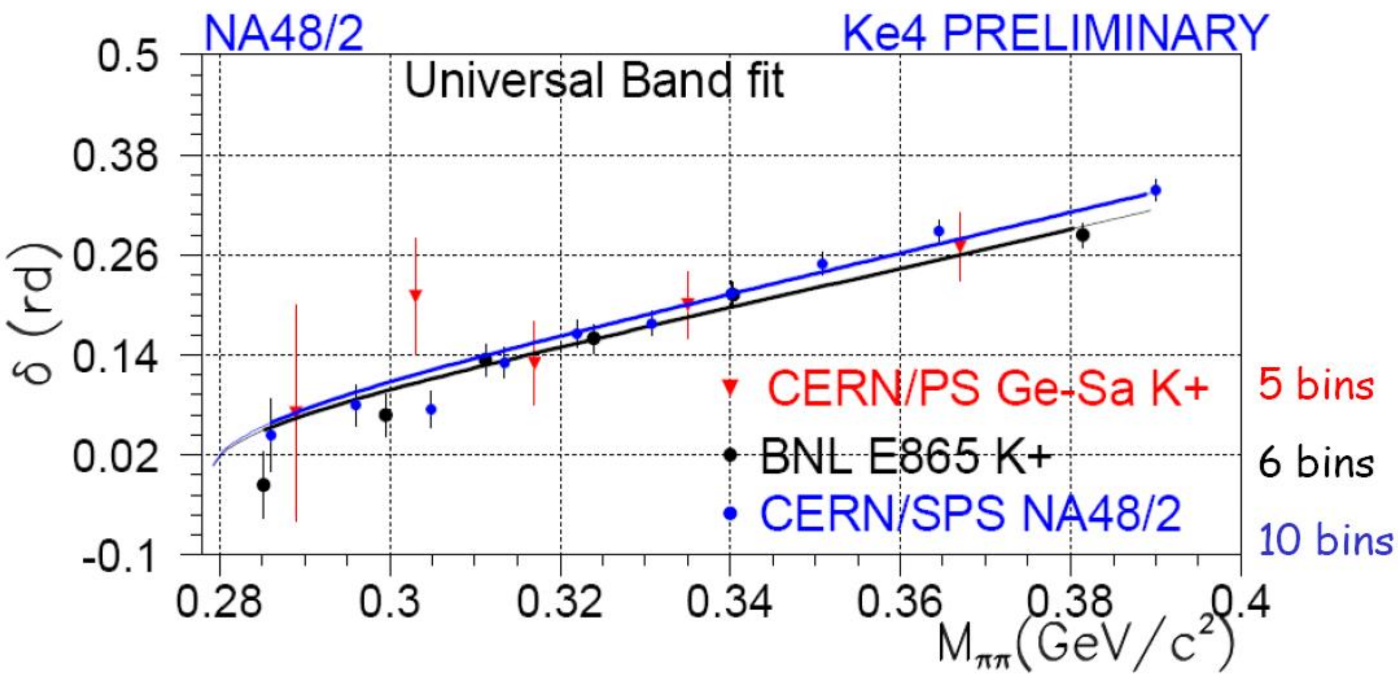
$$F_s = f_s + f_s' q^2 + f_s'' q^4 + f_e\left(S_e/4m_\pi^2\right) + ..$$

$$F_p = f_p + f_p' q^2 + ..$$

$$G_p = g_p + g_p' q^2 + ..$$

$$H_p = h_p + h_p' q^2 + ..$$

Ke4 results



Extraction of well predicted (a2-a0) QCD parameter
(difference of S-wave $\pi\pi$ scattering lengths)
using theoretical input.

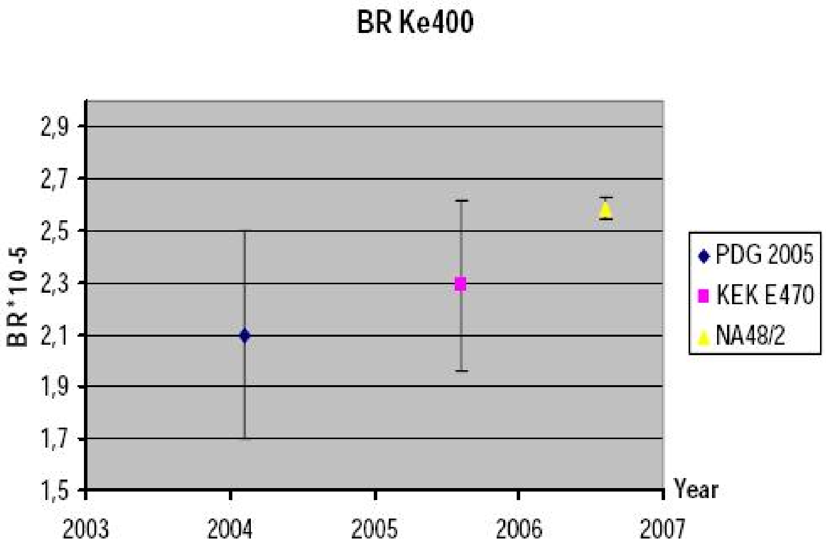
New NA48/2 prelim. (350K events): a0 = 0.256±0.008±0.007±0.018
and a2 = -0.031±0.015±0.015±0.009

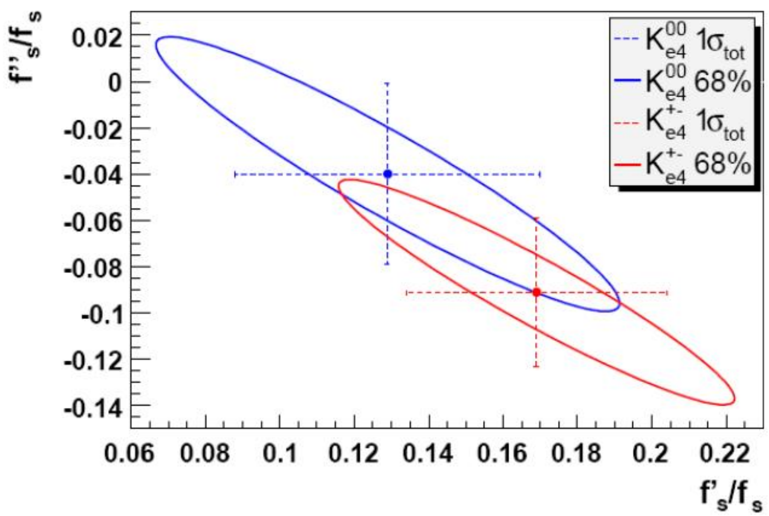
$K^+ \to \pi^0\pi^0 e\nu$

Only 1 form factor in this case
New measurement by NA48/2 (2006)

$$BR(K_{e4}^{00}) = (2.587 \pm 0.026_{stat} \pm 0.019_{syst} \pm 0.029_{ext}) \cdot 10^{-5}$$

(9600 events).
Form factors (37K events) consistent with charged Ke4.

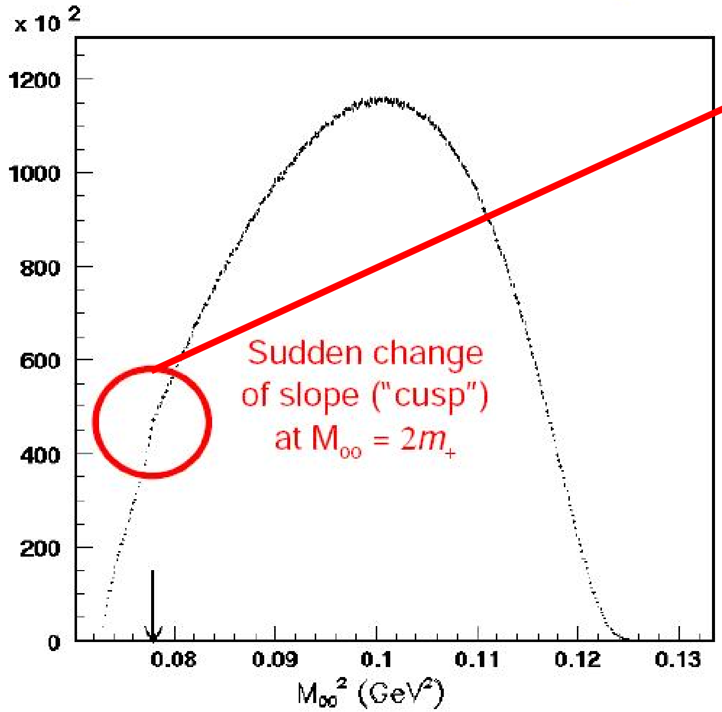


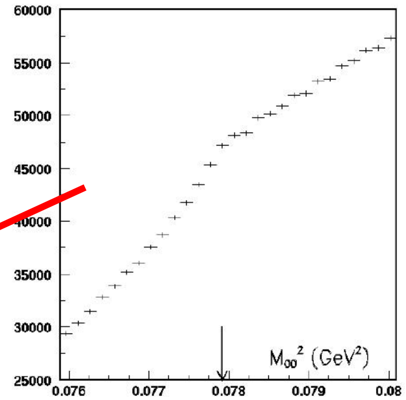


ππ scattering in K→3π decays

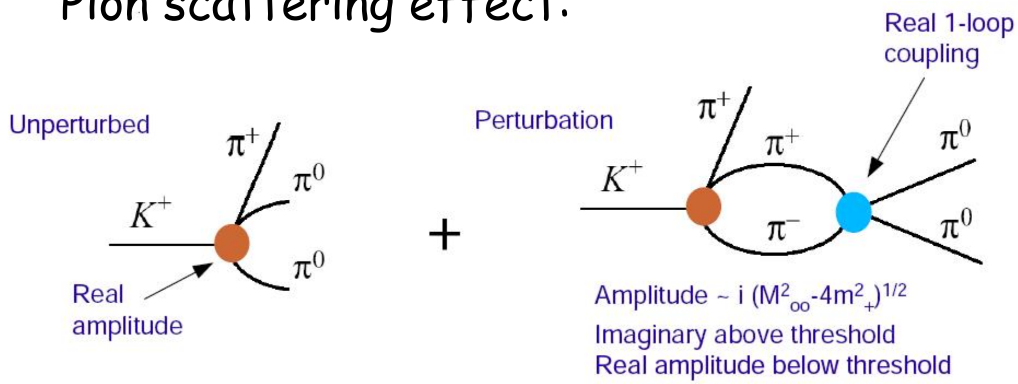
NA48/2: $K^\pm \to \pi^\pm \pi^0 \pi^0$ events

Experimental M_{oo}^2 distribution
for 23 x 10^6 $K^\pm \to \pi^\pm \pi^\circ \pi^\circ$ decays





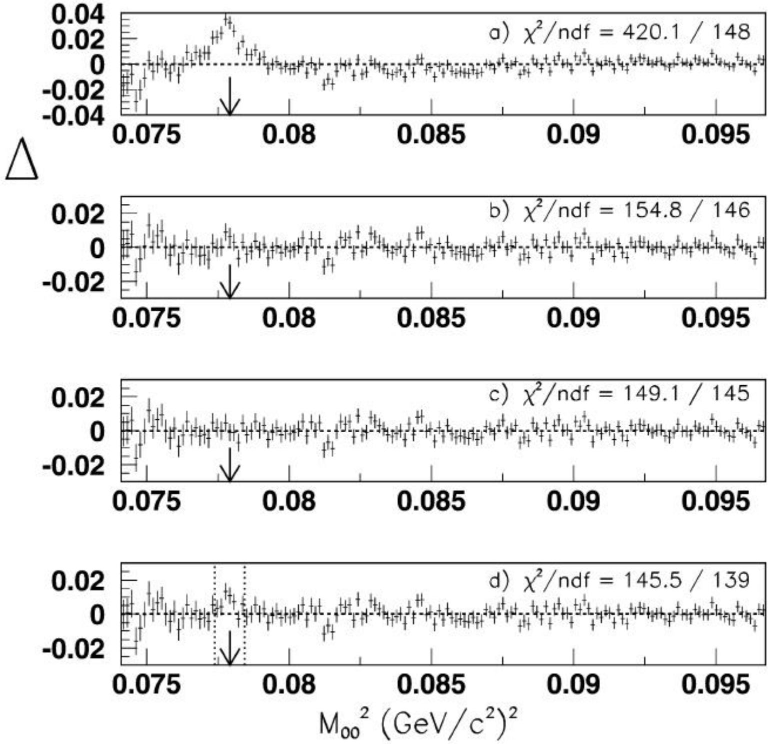
Pion scattering effect:



ππ scattering in K→3π decays

Stimulated much theoretical work
(Cabibbo, Isidori, Gasser et al., Scimemi et al.)

NA48/2



1-loop rescattering

2-loop rescattering

2-loop rescattering + pionium

2-loop rescattering not fitting cusp region

$\pi\pi$ scattering in $K \to 3\pi$ decays

The magnitude of the discontinuity (cusp) is directly related to the (a0-a2) difference in $\pi\pi$ scattering lengths

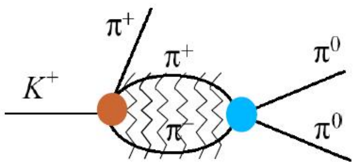
$(a_0 - a_2) m_\pi = 0.268 \pm 0.010 \pm 0.004 \pm 0.013$

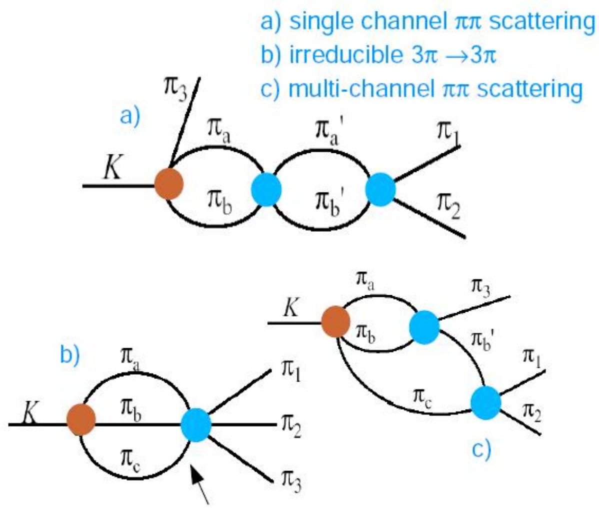
NA48/2

$a_2\ m_\pi = 0.041 \pm 0.022 \pm 0.014$

This new approach, potentially very powerful, is alternative to the one using Ke4 and the one using ionization of pionium (DIRAC experiment at CERN)

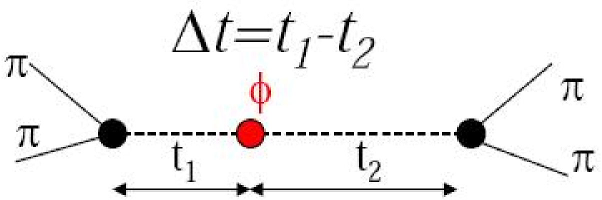
Evidence for pionium formation, sensitivity to higher-order effects…



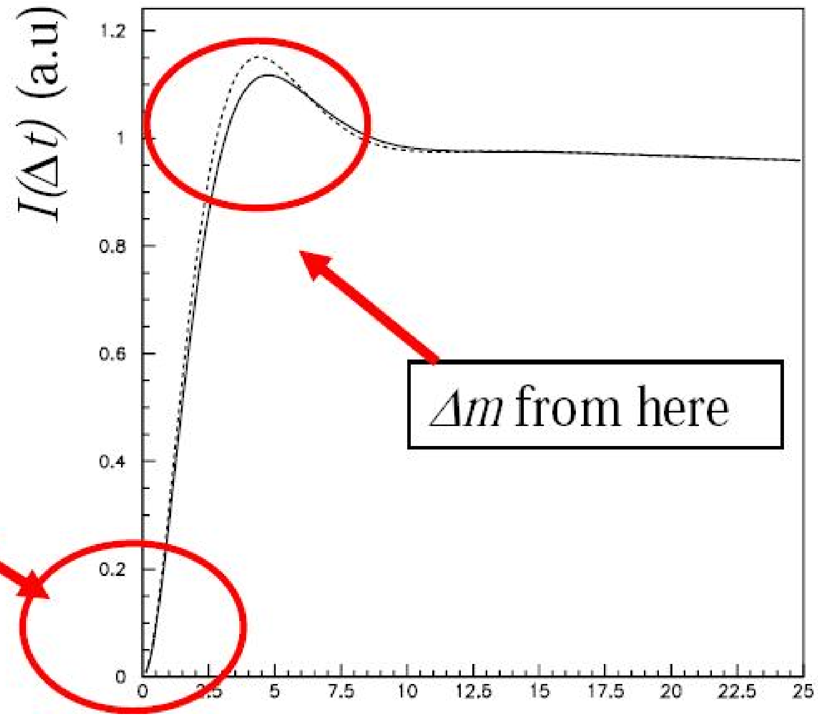


Tests of QM with correlated KK

$$I\left(\pi^+\pi^-,\pi^+\pi^-;|\Delta t|\right)\propto\left\{e^{-\Gamma_L|\Delta t|}+e^{-\Gamma_S|\Delta t|}-2\cdot e^{-(\Gamma_S+\Gamma_L)|\Delta t|/2}\cos\left(\Delta m|\Delta t|\right)\right\}$$

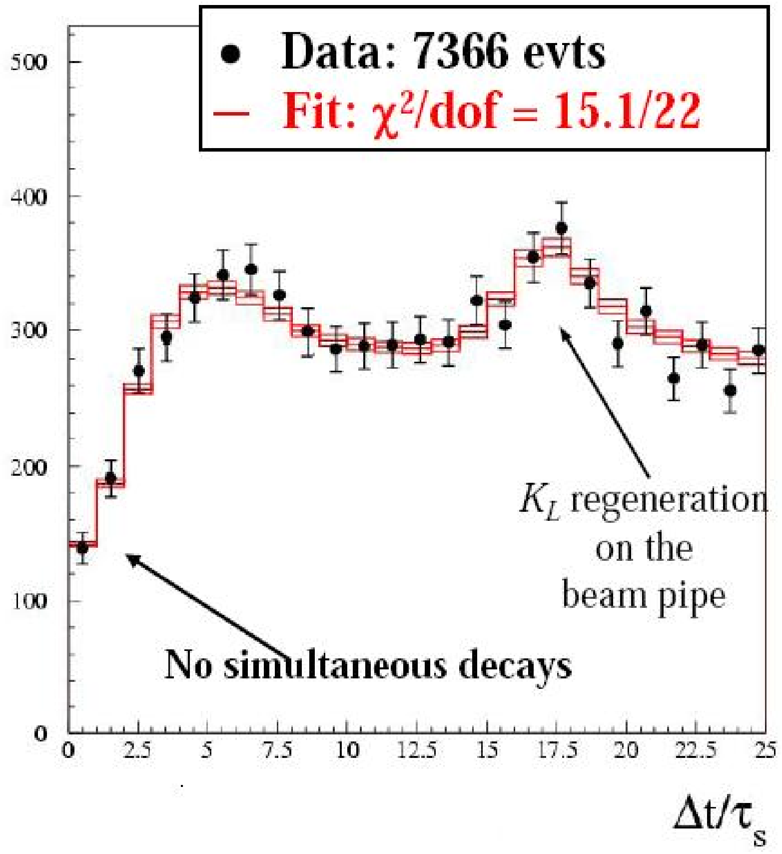


no simultaneous decays (Δt=0) in the same final state due to the destructive quantum interference



Δm from here

KLOE: interference

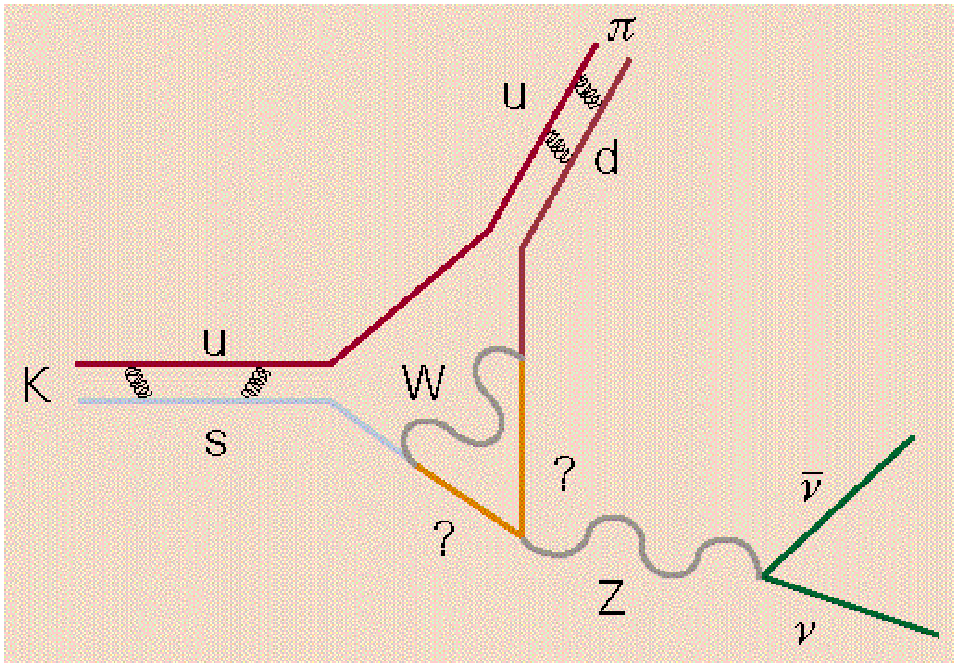


The new frontier:
ultra-rare FCNC K decays

The (new) holy grail: $K \to \pi\ell\bar{\ell}$

(1) Semileptonic: main problem of estimating matrix element avoided (using known $K_{\ell 3}$)

(2) Short distance physics dominates in loop: perturbative, SM under control at NLO, very sensitive to New Physics



(3) For $\ell = \nu$: no long-distance contributions from $\gamma\gamma$

(4) For K_L (and $\ell = \nu$): CP-violating, only top loop contributing (very accurate prediction)

$K \to \pi \ell \bar{\ell}$

Experimental problems:

BR ≈ 10^{-11}, few (or no) kinematic constraints,
backgrounds with BR x 10^7

$K_L \to \pi^0 e^+ e^-$	10^{-11} (CPV_{dir} $3 \cdot 10^{-12}$)	< 2.8 $\cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV, eeγγ bkg. 3 ev. (2.05 bkg)
$K_L \to \pi^0 \mu^+ \mu^-$	10^{-11} (CPV_{dir} $1 \cdot 10^{-12}$)	< 3.8 $\cdot 10^{-10}$ (FNAL KTeV)	CPC+CPV 2 ev. (0.87 bkg)
$K^+ \to \pi^+ \nu \bar{\nu}$	$8 \cdot 10^{-11}$ (at 7%)	$1.47^{+1.30}_{-0.89} \cdot 10^{-10}$ (BNL E787+E949)	Dedicated expt. 3 evt. (bkg. 0.45)
$K_L \to \pi^0 \nu \bar{\nu}$	$2.8 \cdot 10^{-11}$ (at 2%)	< 5.9 $\cdot 10^{-7}$ (KTeV, Dalitz decay)	CPV dir "*Nothing to nothing*"

Dedicated experiments required

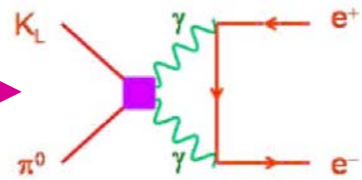
$K_L \to \pi^0 \ell^+ \ell^-$

KTeV limits (90% CL):

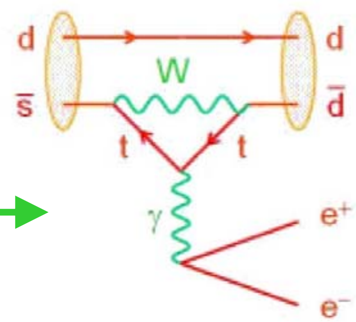
$BR(K_L \to \pi^0 e^+ e^-) < 2.8\times10^{-10}$
$BR(K_L \to \pi^0 \mu^+ \mu^-) < 3.8\times10^{-10}$

Complex situation: 3 contributions

- **CP-allowed**: not predicted, derived from $K_L \to \pi^0 \gamma\gamma$ (NA48/KTeV)



- **Indirect CP violating**: not predicted, measured by $K_S \to \pi^0 \ell^+ \ell^-$ (NA48/1)
- **Direct CP violating**: predicted and proportional to CKM phase

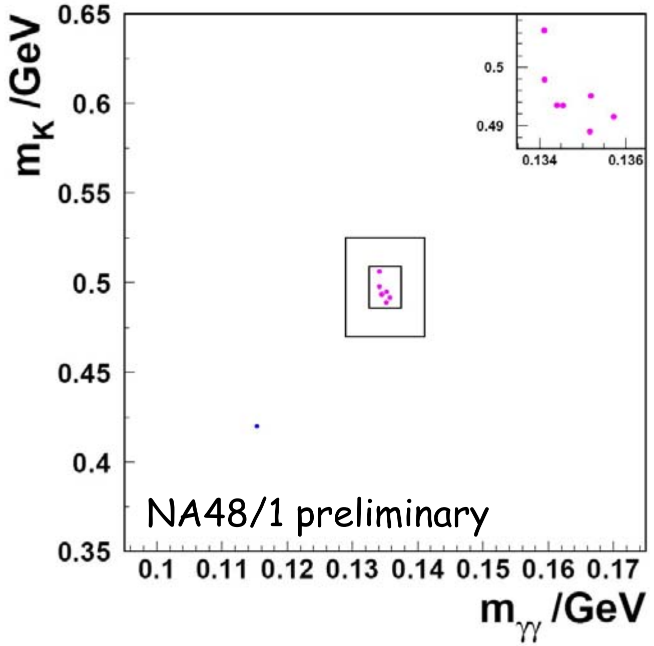


$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \approx 10^{-12}\left[15.3 a_S^2 - 6.8 a_S \,\mathrm{Im}(\lambda_t)\times10^{-4} + 2.8\,\mathrm{Im}(\lambda_t)^2 \times 10^{-8}\right]$$

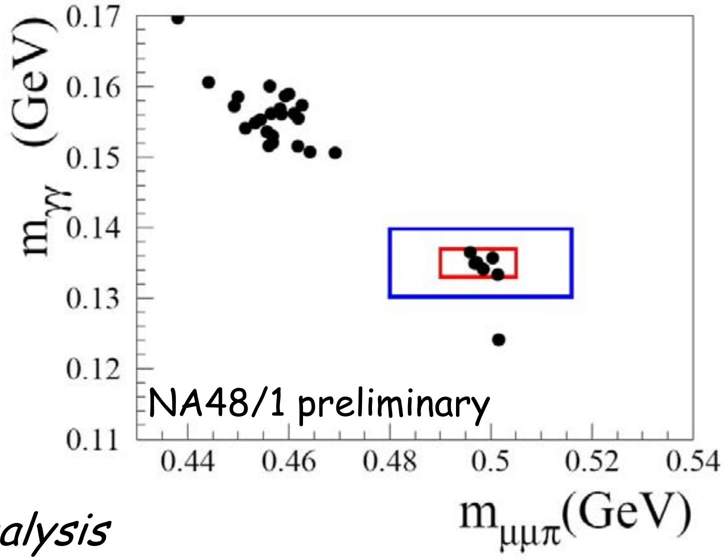
$\lambda_t = V_{ts}^* V_{td}$ $\quad |a_S| \approx 1 \div 1.5$ measured by K_S (sign ?)

NA48/1: $K_S \to \pi^0 \ell^+ \ell^-$

$K_S \to \pi^0 e^+ e^-$



$K_S \to \pi^0 \mu^+ \mu^-$



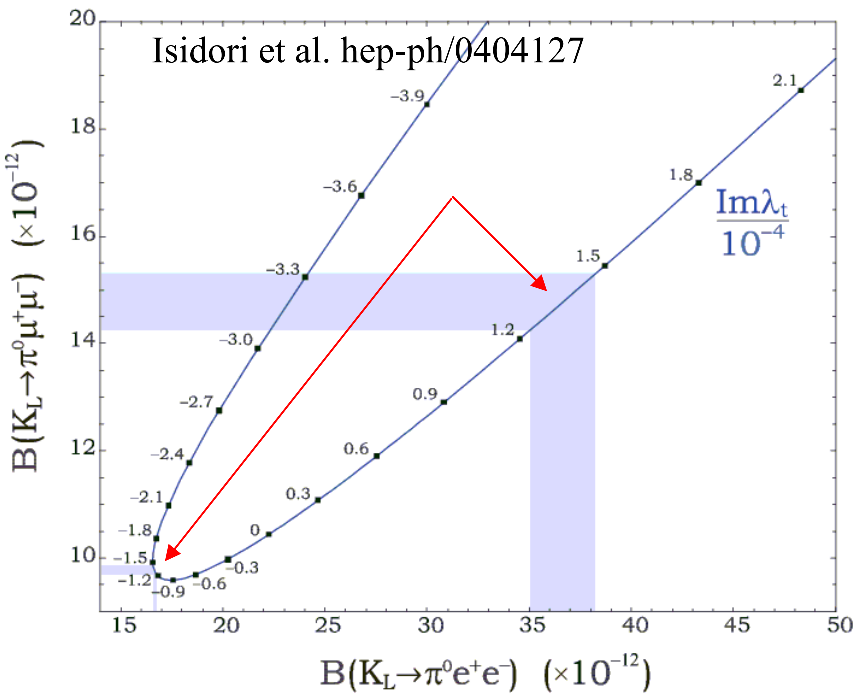
Blind analysis
Background-free

First measurement: 7 events
Bkg. 0.15 $^{+0.10}_{-0.04}$ ($K_L \to ee\gamma\gamma$ and accid.)
BR = $(5.8\ ^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$

First measurement: 6 events
Bkg. 0.22 $^{+0.19}_{-0.12}$ (accid.)
BR = $(2.8\ ^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$

$K_L \to \pi^0 \ell^+ \ell^-$

- K_L measurements: CP-allowed contribution is *small*.
- K_S measurements: indirect CP-violating term *dominates*.
- Sensitivity of BR to CKM phase depends on the (unmeasurable) *relative sign* of the two CP-violating terms. Theoretical predictions: *constructive* interference.

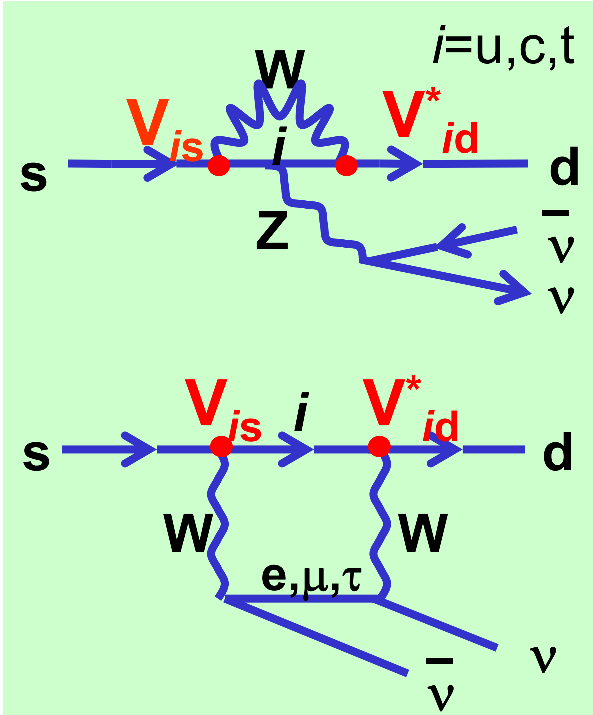


$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \times 10^{12} \approx 17 \text{ (ind)} \pm 9 \text{ (interf)} + 4 \text{ (dir)}$

$BR(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \times 10^{12} \approx 8 \text{ (ind)} \pm 3 \text{ (interf)} + 2 \text{ (dir)}$

K→πνν in the SM

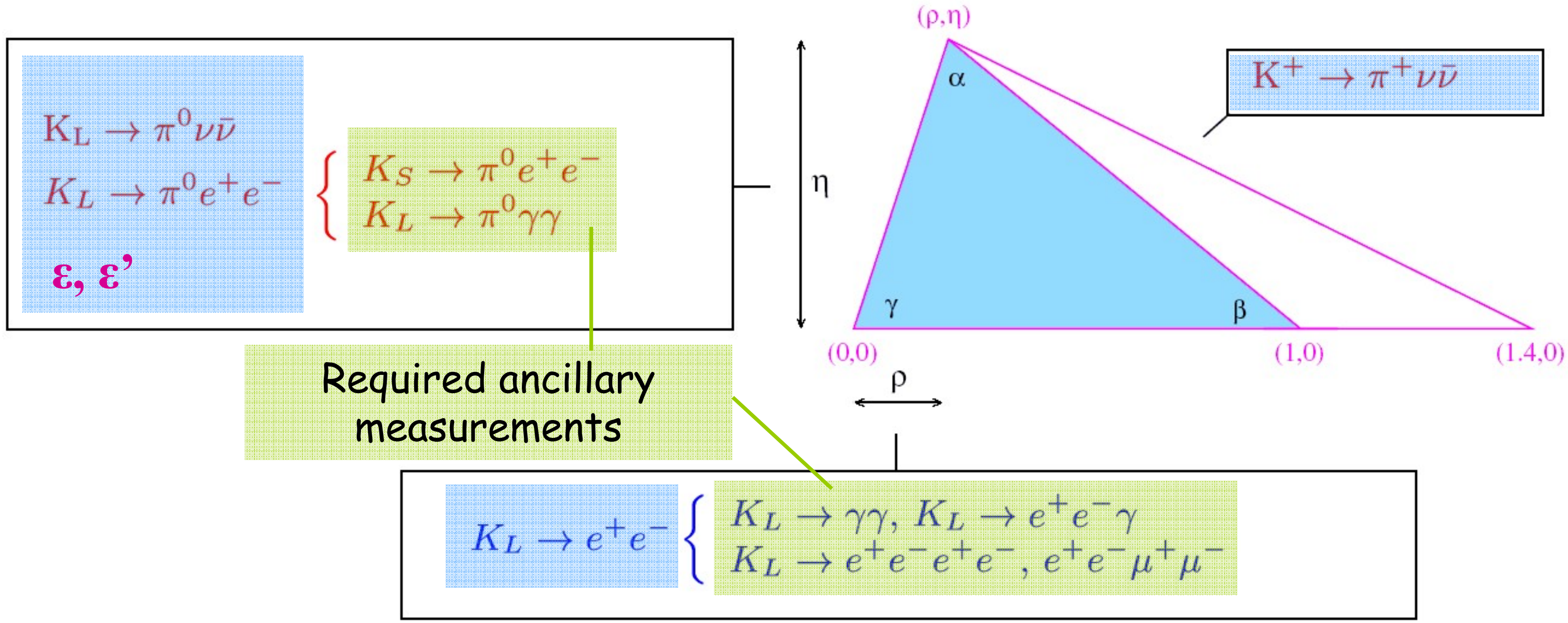
- Z(γ) penguin and box diagrams
- Top in the loop, sensitive to V_{td}
- Small theoretical uncertainty



$$B(K^+ \to \pi^+ \nu\nu) \approx 1.0\times 10^{-10} A^4 \left(\eta^2 + (\rho_0 - \rho)^2\right)$$
$$= (8.0 \pm 1.1)\times 10^{-11}$$

$$B(K_L \to \pi^0 \nu\nu) = 2.2\times 10^{-10} \left(\frac{\mathrm{Im}(V^*_{ts} V_{td})}{\lambda^5} X(x_t) \right)^2$$
$$= (2.8 \pm 0.4)\times 10^{-11}$$

Unitarity triangle from K



$$V^*_{us} V_{ud} + V^*_{cs} V_{cd} + V^*_{ts} V_{td} = \lambda_u + \lambda_c + \lambda_t = 0$$

Height: Im(λ_t)

Ke3 — $K \to \pi \nu \bar{\nu}$ — $K_L \to \pi^0 \nu \bar{\nu}$

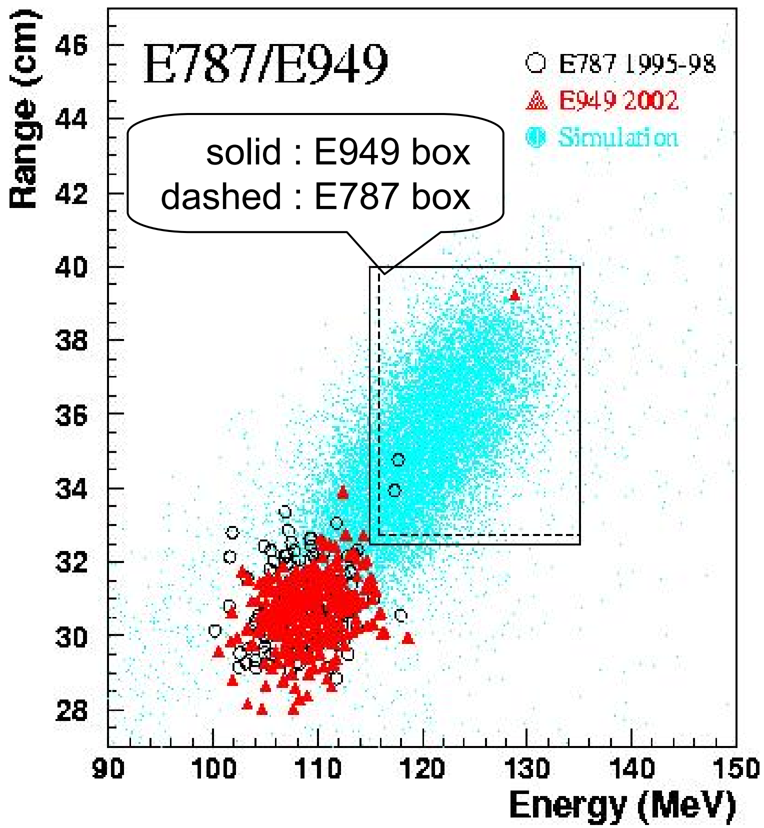
$K^+ \to \pi^+ \nu\nu$: E787-E949 (Brookhaven)

Low-energy K+ stopped in active target
Time reconstruction of $\pi \to \mu \to e$ decay
Pion range vs energy plot

Experiment no longer taking data

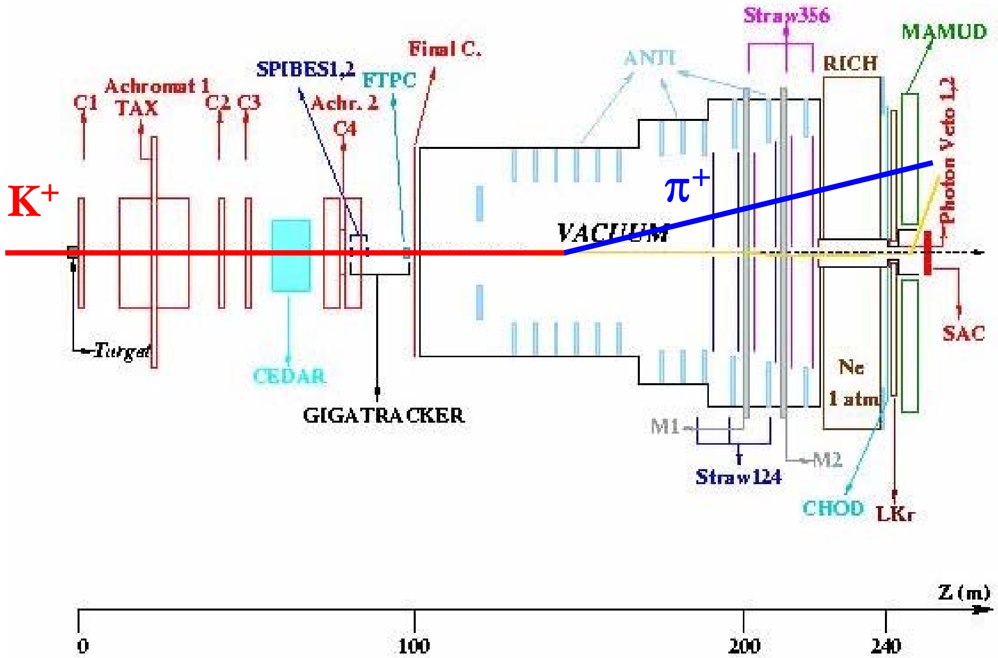
Combined E787/E949
(3 events observed):

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$



$K^+ \to \pi^+ \nu\nu$: P-326 (CERN-SPS)

- Proposal in view of approval, based on NA48 detector
- Decay in flight (75 GeV unseparated K beam)
- Background rejection:
  - K^+ tracking in 1 GHz
  - PID(p/m) by RICH
  - High E p^0, low ineff.
  - Missing mass cut
- Expect 80 SM events in 2 years (data-taking 2010?)

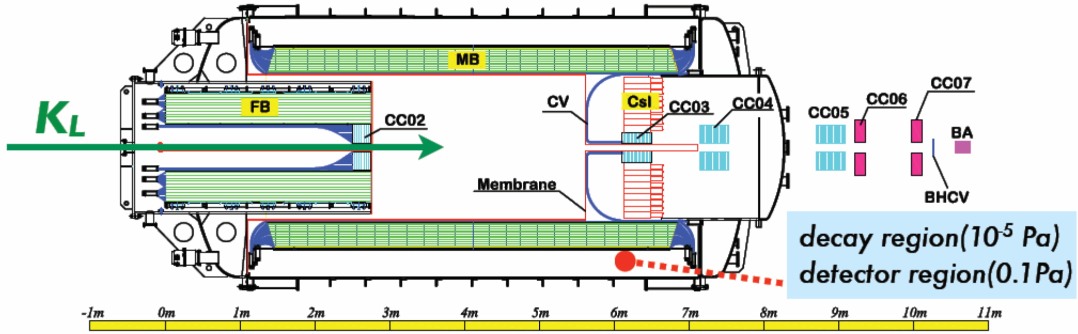


$K_L \to \pi^0 \nu\nu$: E391a pilot project (KEK)

detect 2γ ($\pi^0 \to \gamma\gamma$) + require no other particles

w/ new ideas (1,2,3)

1. *Hermetic photon veto*
   - suppress bkg. involving extra particles (ex. $K_L \to 2\pi^0$, ~~2γ~~)



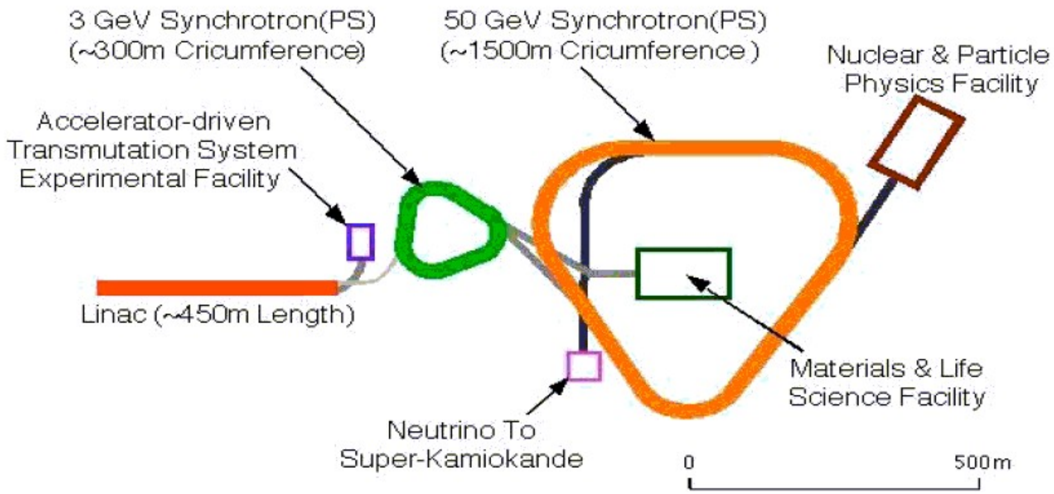
2. *clean/narrow beam*
   - 8cm @ 16 m from target (calorimeter)
3. *vacuum decay region*
   - suppress neutron interactions w/ residual gas

Ran in 2004-2005

From 1 week data: BR < 2.1×10^{-7} (90% C.L.)

$K_L \to \pi^0 \nu\nu$: Future project (J-PARC)

J-PARC proton synchrotron in construction at Tokai:
30 / 50 GeV, 3×10^{14} ppp - First beam expected in 2008



Re-using KTeV EM calorimeter and improving E391a detector:

Step 1 (2010-12): 5 SM events with shared beam line

Step 2: >100 SM events with dedicated beam line

Conclusions (?)

The K system, as the "minimal flavour laboratory" shaped the SM as we know it (P violation, Cabibbo angle, CP violation, GIM, prediction of charm, direct CP violation)

As the Phoenix, every time it appears to have exhausted its potential as a source of information on Nature, it provides something new.

Experimental investigations on it never stopped, and actually keep providing a vast and diverse wealth of information.

Now, if only theoreticians were able to fully tame it…

Thank-you for your attention !

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CP violation (including MUCH more than K):

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- K. Kleinknecht – CP violation – Springer (2003)
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- Proceedings of the "E. Fermi" school, Varenna – SIF and IOP (2006)

or, if you want to read more about beautiful experiments

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Direct CP violation in K meson decays:

- B. Winstein, L. Wolfenstein – Rev. Mod. Phys. 65 (1993) 1113
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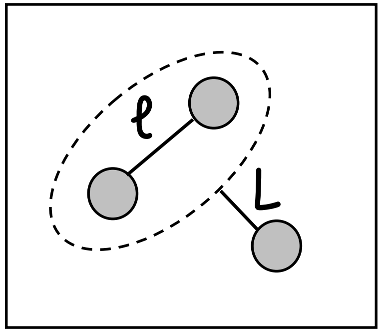
Appendixes

CP-ology

- $J^P(K) = 0^-$
- $J^P(\pi) = 0^-$ $C(\pi^0) = +1$ $[\pi^0 \to \gamma\gamma$ and $C(\gamma) = -1]$

- $\pi\pi$:
  $P(\pi\pi) = P(\pi)^2 (-1)^\ell = (-1)^\ell$ $[\pi^0\pi^0$: even $\ell]$
  $C(\pi^0\pi^0) = +1,\ C(\pi^+\pi^-) = P(\pi^+\pi^-) = (-1)^\ell$
  Exchange = CP $\Rightarrow$ $CP(\pi\pi) = +1$
- $K \to \pi\pi$:
  $J(\pi\pi) = \ell(\pi\pi) = 0 \Rightarrow P(\pi\pi) = +1,\ C(\pi\pi) = +1$

- $\pi\pi\pi$:
  $|\ell-L| \leq J(\pi\pi\pi) \leq |\ell+L|$
  $P(\pi\pi\pi) = P(\pi)^3 (-1)^\ell (-1)^L = (-1)^{\ell+L+1}$ $[\pi^0\pi^0\pi^0$: even ℓ, $P=(-1)^{L+1}]$
  $C(\pi^0\pi^0\pi^0) = +1,\ C(\pi^+\pi^-\pi^0) = (-1)^\ell$
- $K \to \pi\pi\pi$:
  $J(\pi\pi\pi) = 0 \Rightarrow \ell = L \Rightarrow P(\pi\pi\pi) = -1$
  $CP(\pi^0\pi^0\pi^0) = -1$ $CP(\pi^+\pi^-\pi^0) = (-1)^{\ell+1}$
  $\ell>0$ is kinematically suppressed



The Bell-Steinberger relation

$$\left|\Psi\right\rangle = a_S e^{-i\lambda_S t}\left|K_S\right\rangle + a_L e^{-i\lambda_L t}\left|K_L\right\rangle$$

$$\left\langle\Psi\middle|\Psi\right\rangle = \left|a_S\right|^2 e^{-\Gamma_S t} + \left|a_L\right|^2 e^{-\Gamma_L t} +$$
$$a_S^* a_L e^{i(\lambda_S^* - \lambda_L)t}\left\langle K_S\middle|K_L\right\rangle + a_L^* a_S e^{i(\lambda_L^* - \lambda_S)t}\left\langle K_L\middle|K_S\right\rangle$$

Unitarity requires $$-\frac{d}{dt}\left\langle\Psi\middle|\Psi\right\rangle = \sum_f \left|A_{S,L}^f\right|^2 = \sum_f \left|\left\langle f\middle|\mathbf{T}\middle|K_{S,L}\right\rangle\right|^2$$

and therefore: $$\Gamma_S = \sum_f \left|A_S^f\right|^2 \quad \Gamma_L = \sum_f \left|A_L^f\right|^2$$

$$\left[-i\Delta m + (\Gamma_S + \Gamma_L)/2\right]\left\langle K_L\middle|K_S\right\rangle = \sum_f A_L^{f*} A_S^f = \sum_f \eta_f^* \, \Gamma(K_S \to f)$$

A relation linking CP- (and CPT-) violating parameters
to all the physical decay amplitudes

$$\left|\sum_f A_L^{f*} A_S^f\right|^2 \le \sum_f \left|A_L^f\right|^2 \sum_f \left|A_S^f\right|^2$$

$$\left|\langle K_S | K_L \rangle\right|^2 \le \frac{\Gamma_S \Gamma_L}{\left(\Gamma_S + \Gamma_L\right)^2 / 4 + \left(\Delta m\right)^2} \approx \left(0.06\right)^2$$

Lee-Wolfenstein relation
CP violation is small (K_S,K_L are *almost* orthogonal)

Experimentally: $\Gamma_L \ll \Gamma_S$

$\Gamma_S(K_{\ell 3}) \approx \Gamma_L(K_{\ell 3}) \approx \Gamma_L(3\pi) \approx 10^{-3}\,\Gamma_S$

$$\left[i\Delta m / \Gamma_S + 1/2\right]\langle K_L | K_S \rangle \approx \eta_{\pi\pi}$$

$$\eta_{\pi\pi}\Gamma_S = \eta_{+-}\Gamma(K_S \to \pi^+\pi^-) + \eta_{00}\Gamma(K_S \to \pi^0\pi^0)$$

- If CPT is valid (δ=0): $\varphi_{\pi\pi} \approx \mathrm{atan}(2\Delta m/\Gamma_S) \approx 44°$
- If T is valid ($\bar{\varepsilon}$=0) : $\varphi_{\pi\pi} \approx \mathrm{atan}(2\Delta m/\Gamma_S) + \pi/2$

Experiment: $\varphi_{\pi\pi} = (43.5 \pm 1)°$ $\Rightarrow$ CPT is (largely) OK !