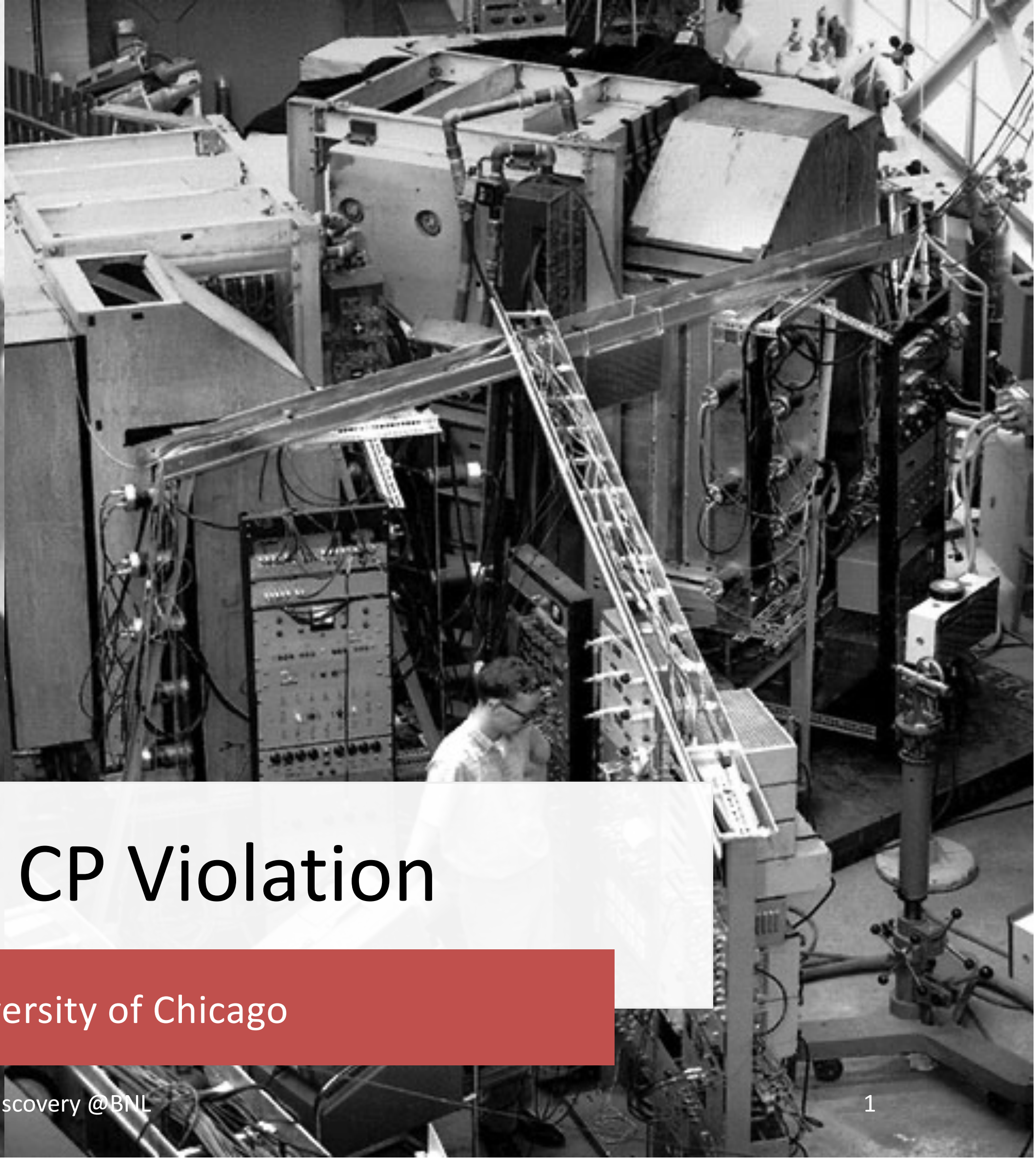


Discovery of CP Violation

Ed Blucher, University of Chicago

Outline

- Background
- The 1963 Experiment
- Experimental and theoretical efforts to understand what they observed
- Summary

Discrete Symmetries

C: Charge conjugation — particle→antiparticle
P: Parity — x,y,z →-x,-y,-z
T: Time reversal — t → -t

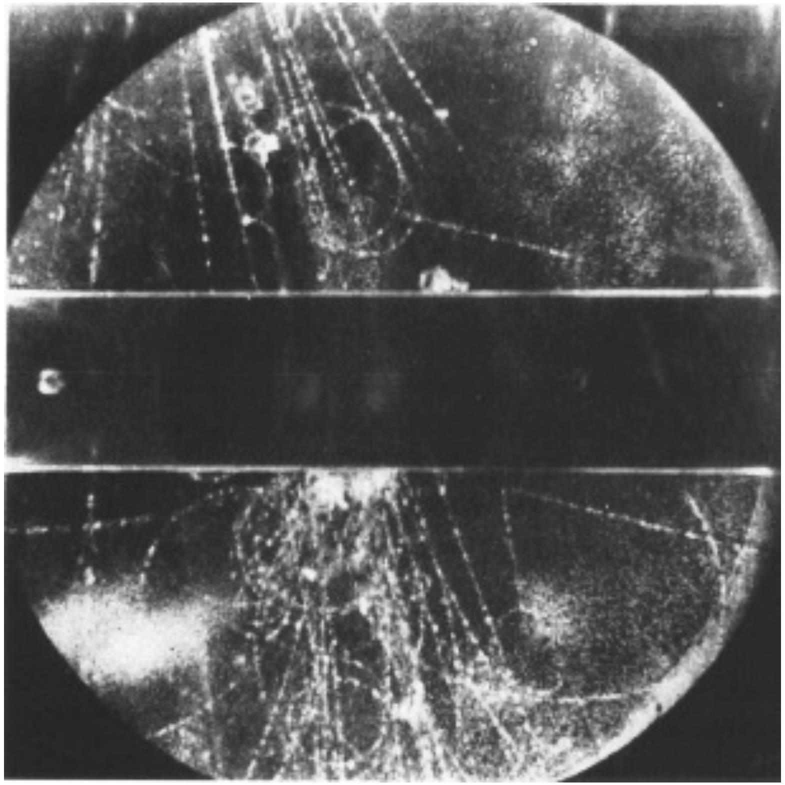
Until late 1950s, all three were assumed to be good symmetries.

Only CPT has a general proof: Relativistic quantum field theories require CPT invariance.

$$m_{particle} = m_{\overline{particle}}$$

$$\tau_{particle} = \tau_{\overline{particle}}$$

1957: Parity violated in weak interactions … but CP appeared to be conserved.



Neutral K discovered in 1946
by Rochester and Butler

Two neutral K mesons are produced in strong interactions:

$$K^0\ (\bar{s}d)\ \text{and}\ \bar{K}^0\ (s\bar{d})$$

Weak interactions do not conserve strangeness:

- Decay: $K^0, \bar{K}^0 \to \pi\pi$ $\quad \Delta s = 1$
- Mixing: $K^0 \to \pi\pi \to \bar{K}^0$ $\quad \Delta s = 2$

In spring of 1954, Jim Cronin was a student in Murray Gell-Mann's class at the University of Chicago.

Ryerson Laboratory, University of Chicago

Fermi asked "if both K^0 and $\overline{K}^0$ both decay to the same final state, how can they be distinct?"

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)

Weak eigenstates (assuming CP invariance):

$$K_{even} \sim K^0 + \overline{K}^0 \qquad CP|K_{even}\rangle = +|K_{even}\rangle$$

$$K_{odd} \sim K^0 - \overline{K}^0 \qquad CP|K_{odd}\rangle = -|K_{odd}\rangle$$

$K_{even} \rightarrow \pi\pi$ allowed; $K_{odd} \rightarrow \pi\pi$ forbidden

At any rate, the point to be emphasized is this: a neutral boson may exist which has the characteristic θ^0 mass but a lifetime $\neq \tau$ and which may find its natural place in the present picture as the second component of the θ^0 mixture.

One of us, (M. G.-M.), wishes to thank Professor E. Fermi for a stimulating discussion.

Observation of Long-Lived Neutral V Particle

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)

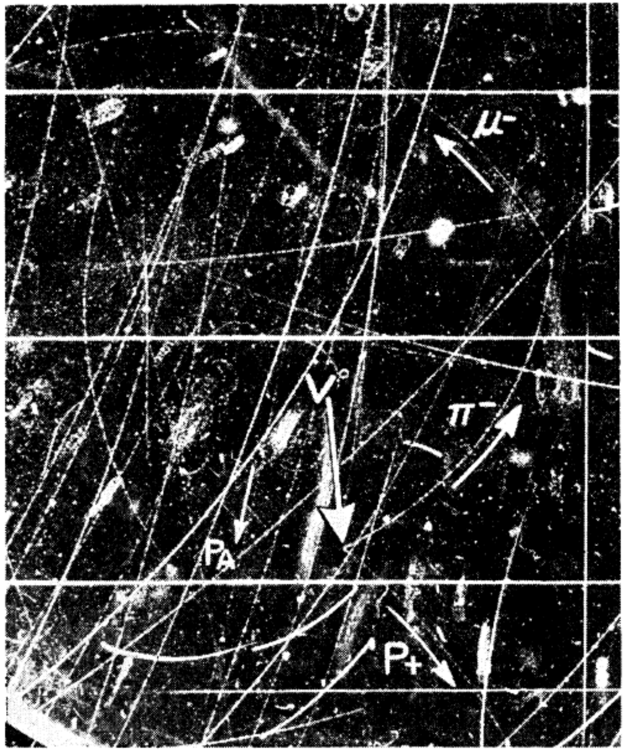


Fig. 2. Example of $K^0 \to \pi^+ + \pi^- +$neutral particle. P_+ is shown to be a pion by ionization measurements. P_A is a proton track used in the ionization calibration.

- Multiple 3-body decays were identified
- "No evidence is found for 2-body disintegrations."

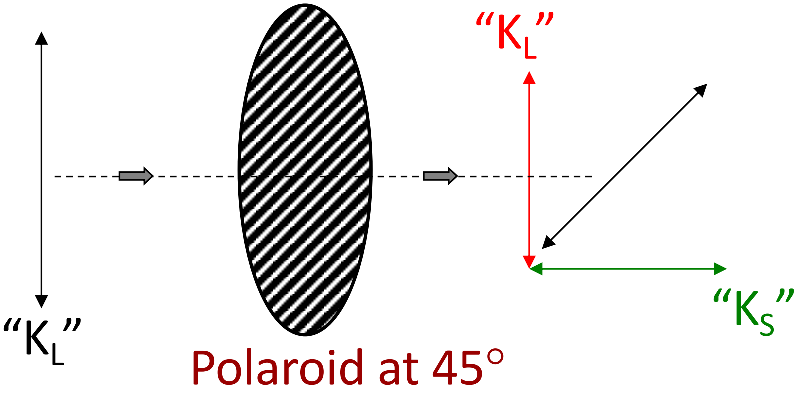
$$\tau(K_{odd}) \sim 580\ \tau(K_{even})$$

$$(K_2^0) \qquad\qquad (K_1^0)$$

Kaon Regeneration

$$K_L \sim K^0 - \bar{K}^0 \Rightarrow \boxed{\begin{array}{l}\sigma(\bar{K}^0 N) \\ > \sigma(K^0 N)\end{array}} \Rightarrow K_L + \rho K_S$$

Process is analogous to passing polarized light through a filter that transmits at 45°.



Note on the Decay and Absorption of the θ^0†

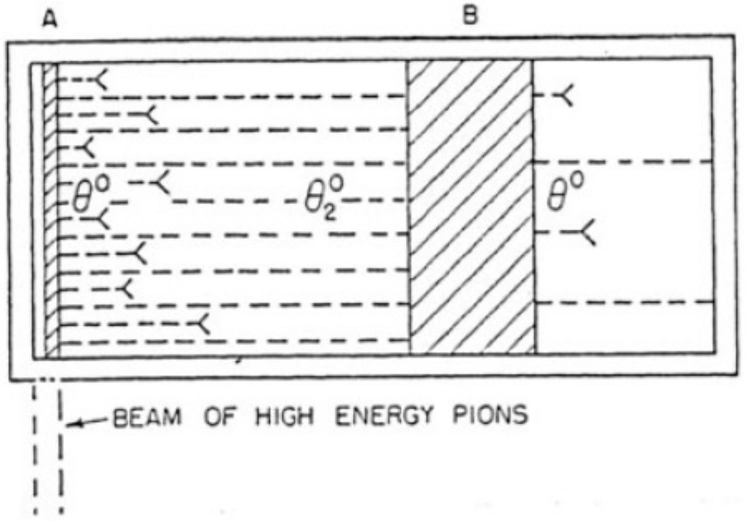
A. Pais,* *Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York*

AND

O. Piccioni, *Brookhaven National Laboratory, Upton, New York*

(Received July 5, 1955)

A suggestion is made on how to verify experimentally a recent theoretical suggestion that the θ^0 meson is a "particle mixture."



Anomolous Regeneration

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.

- They observed 10-20 times the number of K_1 events expected
- Bubble chamber was quite small, so E resolution and angular resolution were rather poor.

Cronin-Fitch Collaboration

- In 1963, Val Fitch was finishing an experiment on the pion form factor at the AGS, and Jim Cronin was completing an experiment on ρ production at the BNL Cosmotron:
- Fitch, who was very experienced with kaons, suggested that they use Cronin's spectrometer to look for Adair's regeneration.
- René Turlay and Jim Christenson joined Cronin and Fitch on experiment.

ρ production detector of Clark, Christenson, Cronin, Turlay

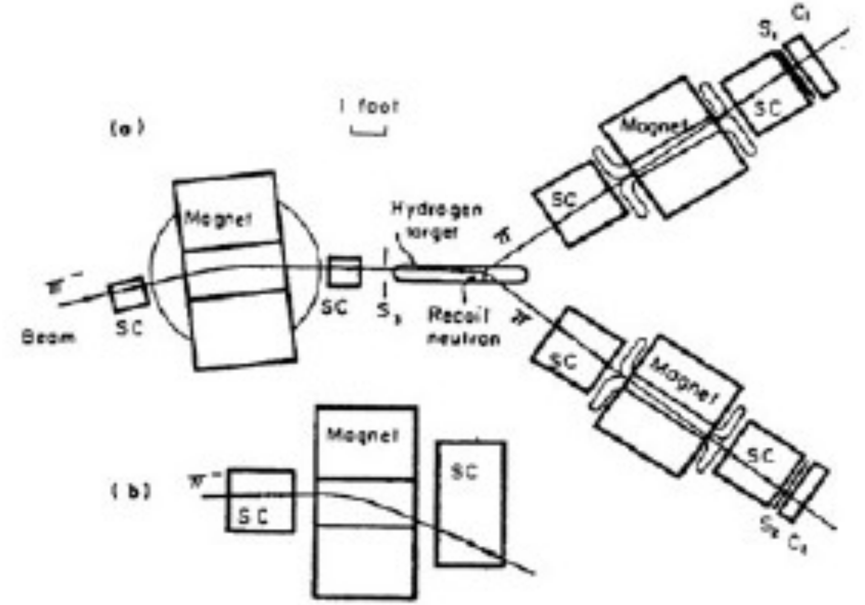


FIG. 1. Schematic views of the experimental apparatus. (a) Plan view, showing all spark chambers and analyzing magnets; (b) side view of one decay pion spectrometer. "SC" denotes spark chamber.

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

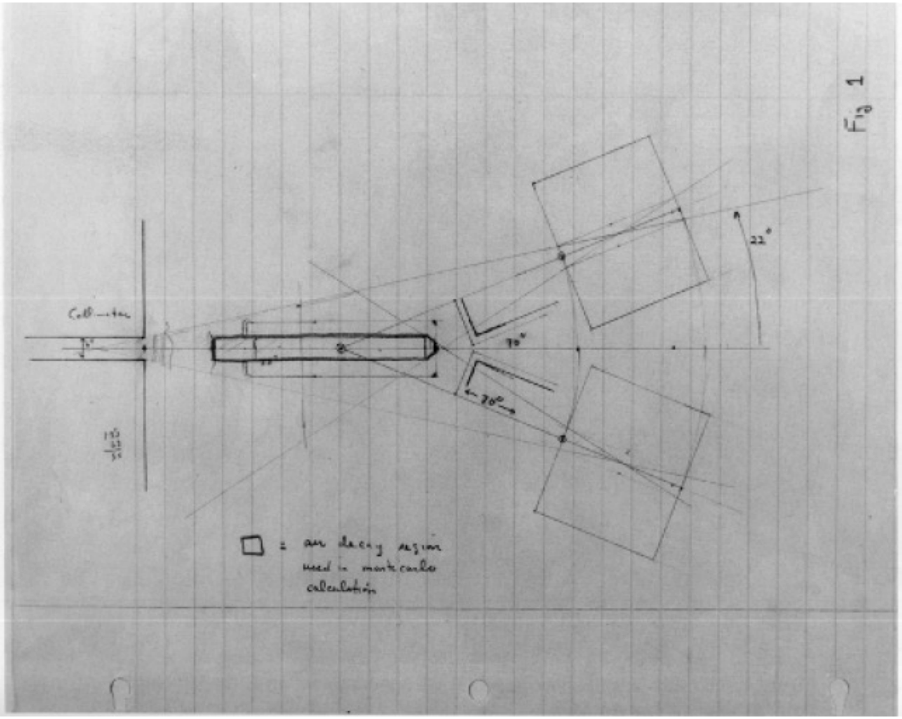
J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

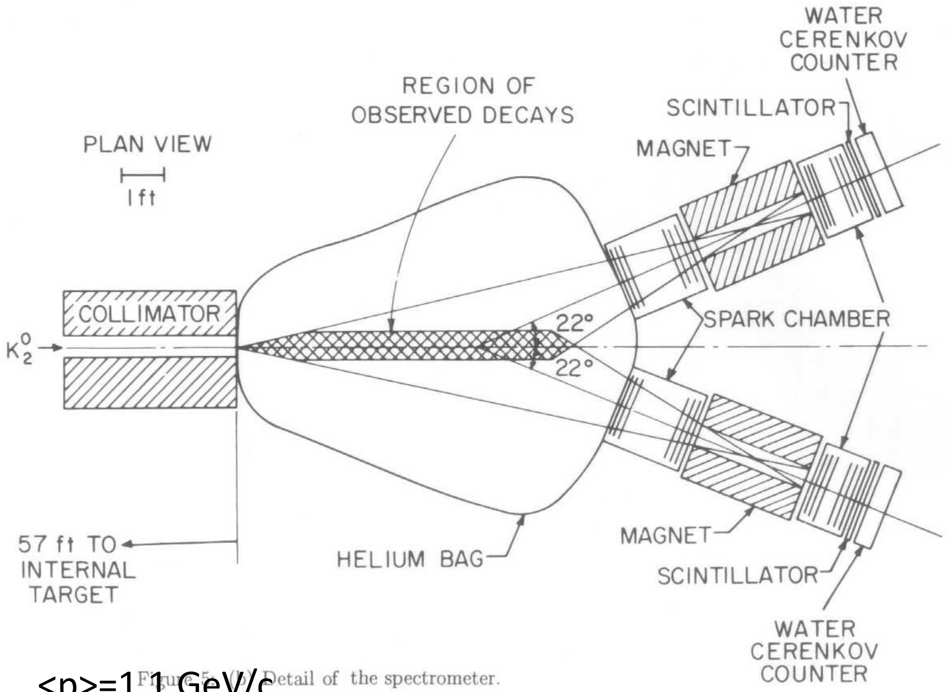
I. INTRODUCTION

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.

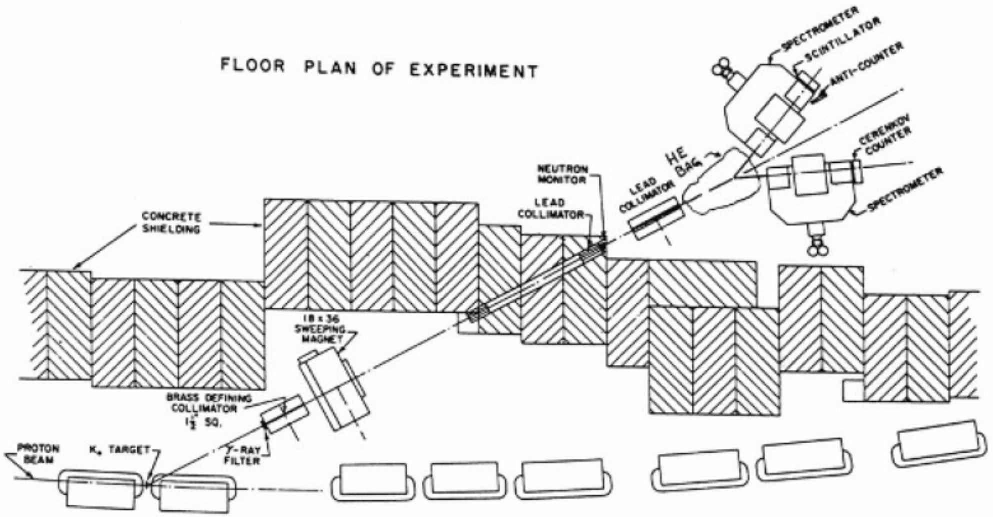
Detector for K_2^0 Experiment

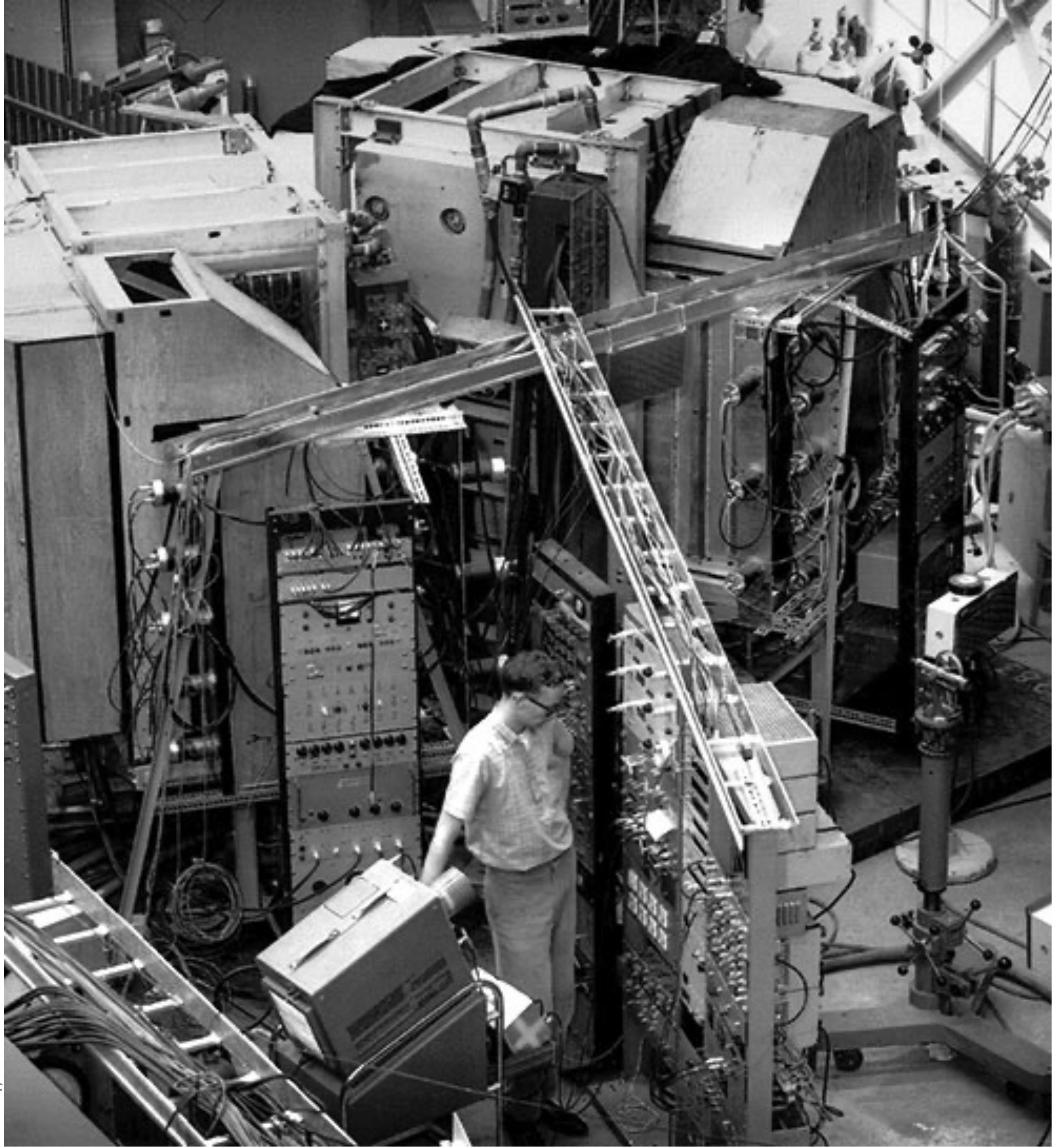


From Cronin's notebook



<p>=1.1 GeV/c
Detector ~ 300 K_1 decay lengths
From target

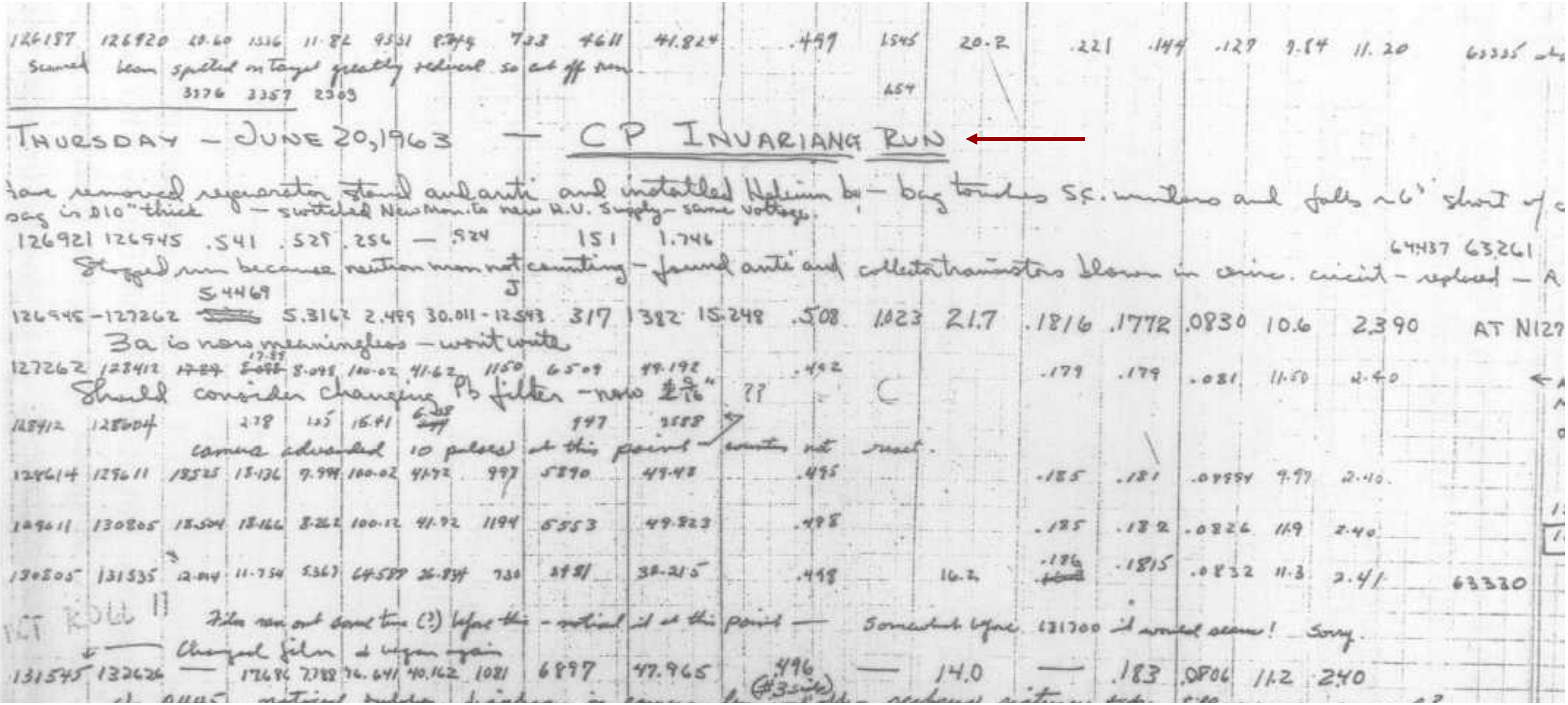

FLOOR PLAN OF EXPERIMENT
SPECTROMETER
SCINTILLATOR
ANTI-COUNTER
CERENKOV COUNTER
SPECTROMETER
HE BAG
LEAD COLLIMATOR
NEUTRON MONITOR
LEAD COLLIMATOR
CONCRETE SHIELDING
18 x 36 SWEEPING MAGNET
BRASS DEFINING COLLIMATOR
1½" SQ.
γ-RAY FILTER
PROTON BEAM
K₀ TARGET



K_2^0 Decay and Interaction Experiment

- Proposal submitted on April 12, 1963
- Proposal approved for ~ 200 hours on May 6; allotted time had to be used between May 27 and July 22.
- Detector moved from cosmotron to AGS and debugging started on June 2.
- Data taking began with regenerator runs.
- CP Invariance run began on June 20, 1962 and lasted for one week.

CP Invariance Run

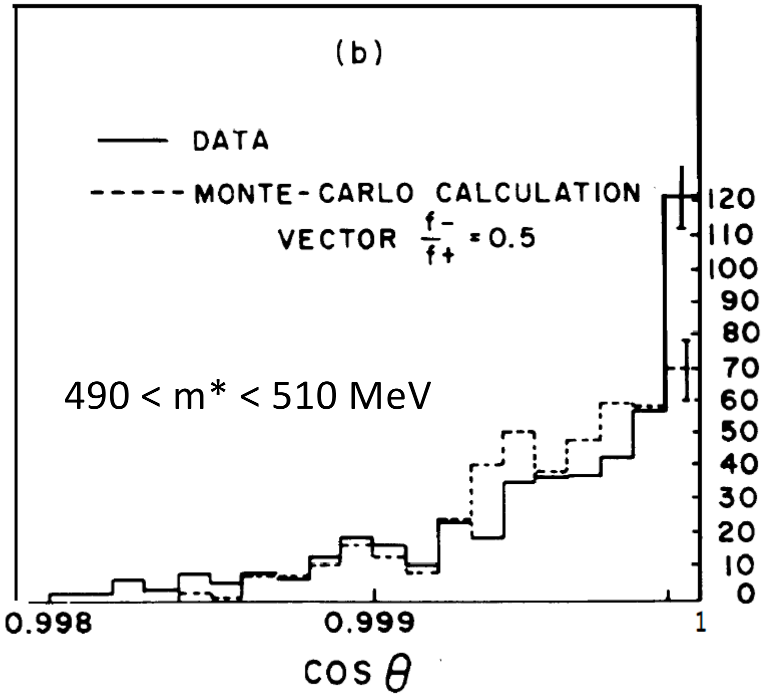

126157 126920 20.60 1336 11.82 9331 8.749 7.28 4611 41.824 .497 1545 20.2 .221 .144 .129 9.84 11.20 63335
Scanned beam spotted on target greatly reduced so cut off run
3376 3357 2309 654
THURSDAY — JUNE 20, 1963 — CP INVARIANCE RUN
Have removed regenerator stand and anti and installed Helium bag — bag touches S.C. windows and falls ~6" short of
bag is .010" thick — switched New Mon. to new H.V. supply — same voltage.
126921 126945 .541 .525 .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
5.4469
126945–127262 5.3162 2.489 30.011 - 12.543 317 1382 15.248 .508 1023 21.7 .1816 .1772 .0830 10.6 2.390 AT N127
3a is now meaningless — won't write
127262 128412 17.55 8.098 100.02 41.62 1150 6509 49.192 .492 .179 .179 .081 11.50 2.40
Should consider changing Pb filter — now 3/16" ??
128412 128604 278 125 15.41 6.28 147 3588
camera advanced 10 pulses at this point — counters not reset.
128614 129611 18525 18.136 7.994 100.02 41.72 997 5890 49.48 .495 .185 .181 .08954 9.97 2.40
129611 130805 18.504 18.166 8.262 100.12 41.92 1194 5553 49.823 .498 .185 .182 .0826 11.9 2.40
130805 131535 12.014 11.754 5.363 64.587 26.894 730 3481 32.215 .498 16.2 .186 .1815 .0832 11.3 2.41 63330
1st ROLL 11 Film ran out some time (?) before this — noticed it at this point — Somewhat before 131700 it would seem! Sorry.
Changed film at beginning again
131545 132626 — 17.686 7.788 76.641 40.162 1081 6897 47.965 .496 (#3 side) — 14.0 — .183 .0806 11.2 2.40

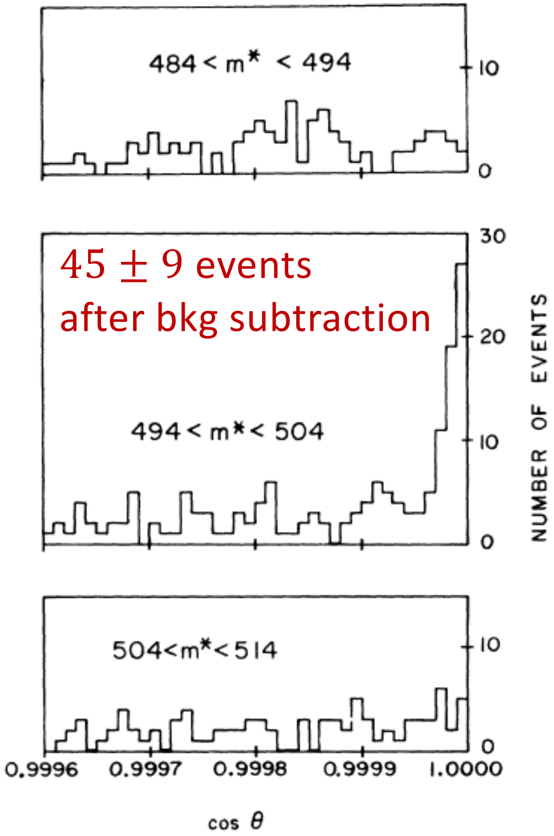
Analysis

- They stopped data taking at the end of June, and immediately began analysis of anomalous regeneration data. The CP invariance limit was not a high priority.
- René Turlay was in charge of measurements taken with the helium bag.
- By early 1964, events from the CP run had been measured with a homemade angular encoder, and showed clear forward peak for events with $490 < m_{\pi\pi} < 510$ MeV/c^2.
- By spring 1964, all events were remeasured with a commercial bubble chamber scanning machine and the forward peak remained.

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)



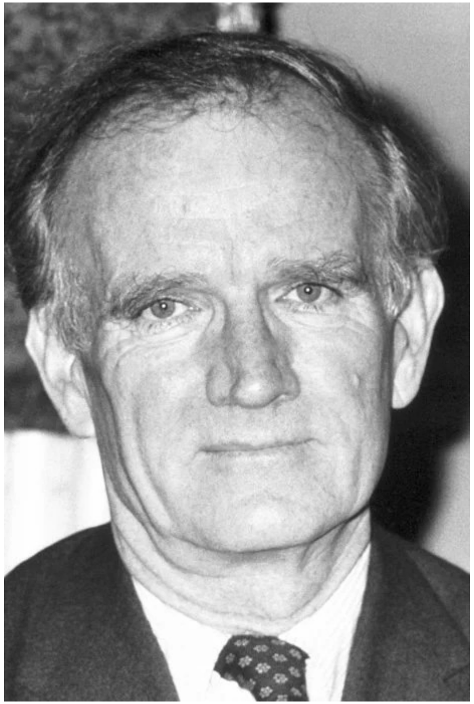


EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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 $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives and R_T is the branching ratio including decay to two π^0. Using $R_T = \frac{3}{2} R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3 \times 10^{-3}$.

1980 Nobel Prize in Physics

Awarded to James Cronin and Val Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"



Crucial Role of Regeneration in CP Discovery

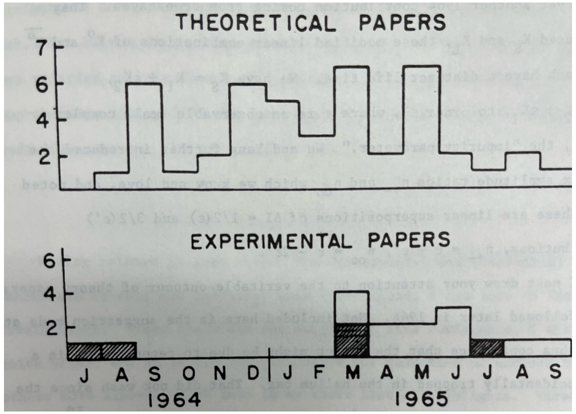
- Anomalous regeneration provided motivation for experiment.
- Measured regeneration rates in tungsten, copper, carbon, and liquid hydrogen targets allowed them to estimate regeneration in He (negligible).
- Coherently regenerated K_1^0 events provided calibration (tungsten regenerator moved to 5 different spots along decay region to approximate K_2^0 distribution).
- In 1965, Fitch did experiment that observed constructive interference between $K_L \to \pi\pi$ and regenerated $K_S \to \pi\pi$ events:

EVIDENCE FOR CONSTRUCTIVE INTERFERENCE BETWEEN COHERENTLY REGENERATED AND CP-NONCONSERVING AMPLITUDES*

V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 3 June 1965)

What happened next?

- Following 1964 result, there was a flurry of theoretical and experimental activity.



Cronin plot from 1965 ANL Workshop: papers on CP violation. Cross hatched experiments are those specifically measuring $K_2 \to \pi\pi$.

- Two of these theory papers are particularly notable:
  - The paper of Wu and Yang in August worked out most of the phenomenology used for for CP violation in neutral kaons to this day, including the ideas of indirect and direct CP violation
  - Lincoln Wolfenstein proposed that a new very weak interaction with $\Delta s=2$ was responsible for CP violation in mixing. This “superweak” model survived for 35 years.

Later Theory Developments

1967: Sakharov described conditions required for universe with baryon number = 0 (equal matter and antimatter) to evolve to one with net baryon number: baryon number violation, C and CP violation (direct), and out of equilibrium conditions.

1973: Kobayashi and Maskawa pointed out that electroweak theory with 2 generations was automatically CP conserving, but 3 generation theory allowed CP violation, with a single CP-violating quantity. (In 1973, only 3 quarks had been detected!)

Indirect vs. Direct CP Violation

- "Indirect" - asymmetric $K^0 - \bar{K}^0$ oscillations

$$K_s \sim (1+\varepsilon)K^0 + (1-\varepsilon)\bar{K}^0$$
$$\sim K_{even} + \varepsilon K_{odd}$$
$$K_L \sim (1+\varepsilon)K^0 - (1-\varepsilon)\bar{K}^0$$
$$\sim K_{odd} + \varepsilon K_{even}$$

$\varepsilon K_{even} \rightarrow \pi\pi$

$|\varepsilon|=2.28\text{x}10^{-3}$

- "Direct" - CP violation in decay amplitude

$K_{odd} \rightarrow \pi\pi$, parameterized by ε'

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

Two approaches have been used to understand the nature of the observed $K_L \rightarrow \pi\pi$ decays:

1) The semileptonic charge asymmetry
2) The comparison of CP violation in $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^0\pi^0$ (ϵ'/ϵ)

Semileptonic Charge Asymmetry

- Semileptonic kaon decays obey ΔS=ΔQ rule, so lepton charge uniquely identifies K^0 or $\bar{K}^0$:

$$K_L \sim (1+\varepsilon)K^0 - (1-\varepsilon)\bar{K}^0$$

$$K^0 \rightarrow \pi^- e^+ \nu \qquad \bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}$$

- The charge asymmetry is defined as

$$\delta_L = \frac{\Gamma(K_L \rightarrow \pi^- e^+ \nu) - \Gamma(K_L \rightarrow \pi^+ e^- \nu)}{\Gamma(K_L \rightarrow \pi^- e^+ \nu) + \Gamma(K_L \rightarrow \pi^+ e^- \nu)}$$

$$= \frac{|1+\varepsilon|^2 - |1-\varepsilon|^2}{|1+\varepsilon|^2 + |1-\varepsilon|^2} = 2\,\mathrm{Re}(\varepsilon)$$

Charge asymmetry results

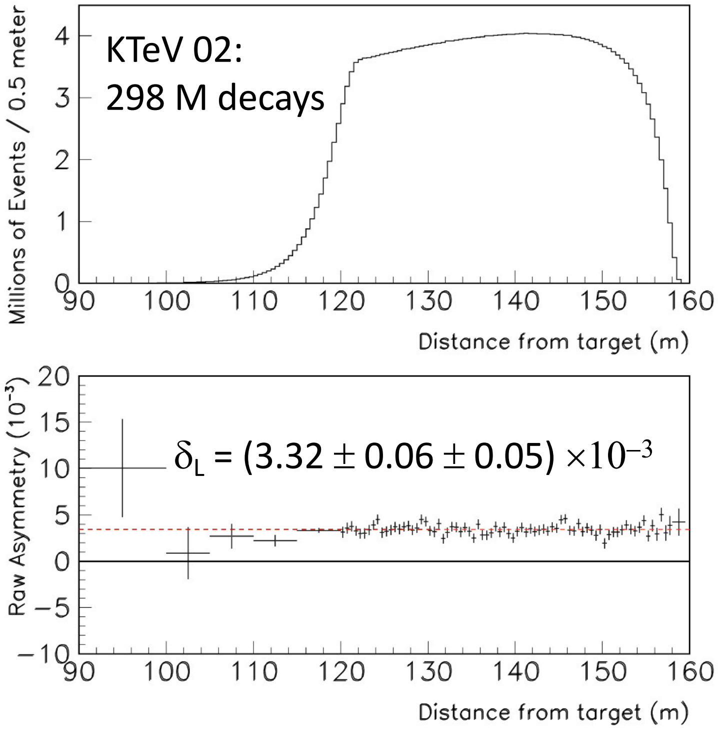
- First measurements of the charge asymmetry (1967):
  - Bennett et al. (Steinberger)

$$\delta_L^e = (2.24 \pm 0.36) \times 10^{-3}$$

  - Dorfan et al.

$$\delta_L^\mu = (4.03 \pm 1.34) \times 10^{-3}$$

- Current world Ave. $\delta_L = (3.30 \pm 0.07) \times 10^{-3}$



Expectation from $K \rightarrow \pi\pi$ with only indirect CP violation: ($\delta_L = 3.32 \pm 0.03$) $\times 10^{-3}$

Indirect vs. Direct CP Violation

To distinguish between direct and indirect CP violation, we can compare level of CP violation in different decay modes:

If $$\frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} \neq \frac{K_L \to \pi^0\pi^0}{K_S \to \pi^0\pi^0}$$ then CP is violated in decay amplitude.

$$\mathrm{Re}(\varepsilon'/\varepsilon) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1\right]$$

$\epsilon'/\epsilon \neq 0$ ➡ Direct CP violation

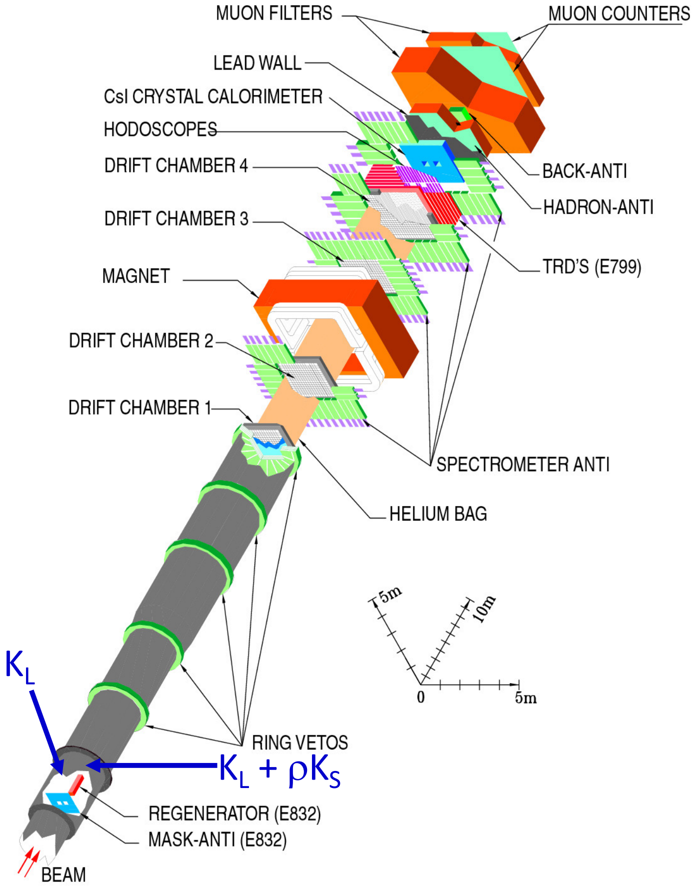
Predictions:

- Superweak Model (Wolfenstein) predicts no direct CP violation ($\epsilon'/\epsilon = 0$)
- "Standard" CKM model predicts both direct and indirect CP violation ($\epsilon'/\epsilon \neq 0$), although level of direct CP violation difficult to calculate.

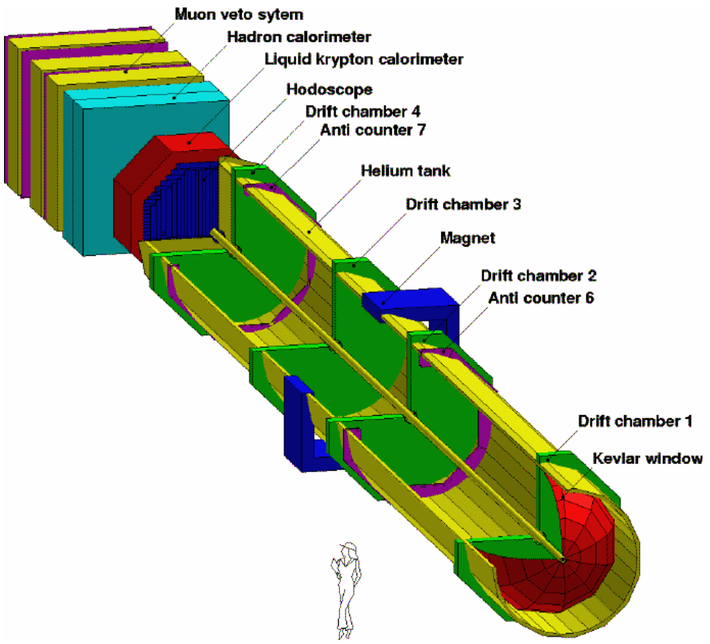
$K_L \to \pi^0\pi^0$

- $K_L \to \pi^0\pi^0$ presented a considerable challenge in the 1960s
- First observations in 1967 yielded results in disagreement with later measurements.
- First real measurements of ϵ'/ϵ were published in 1972 and were consistent with no direct CP violation (with ~6% uncertainty).
- First calculation of ϵ'/ϵ in from Standard Model in 1976 by Ellis, Gaillard, and Nanopoulos ($\sim 2\times 10^{-3}$) ultimately inspired several new efforts: E617,E731,KTeV (FNAL); NA31,NA48, CPLEAR (CERN); KLOE (LNF)
- Effort culminated in KTeV at Fermilab and NA48 at CERN detecting direct CP violation

KTeV Detector

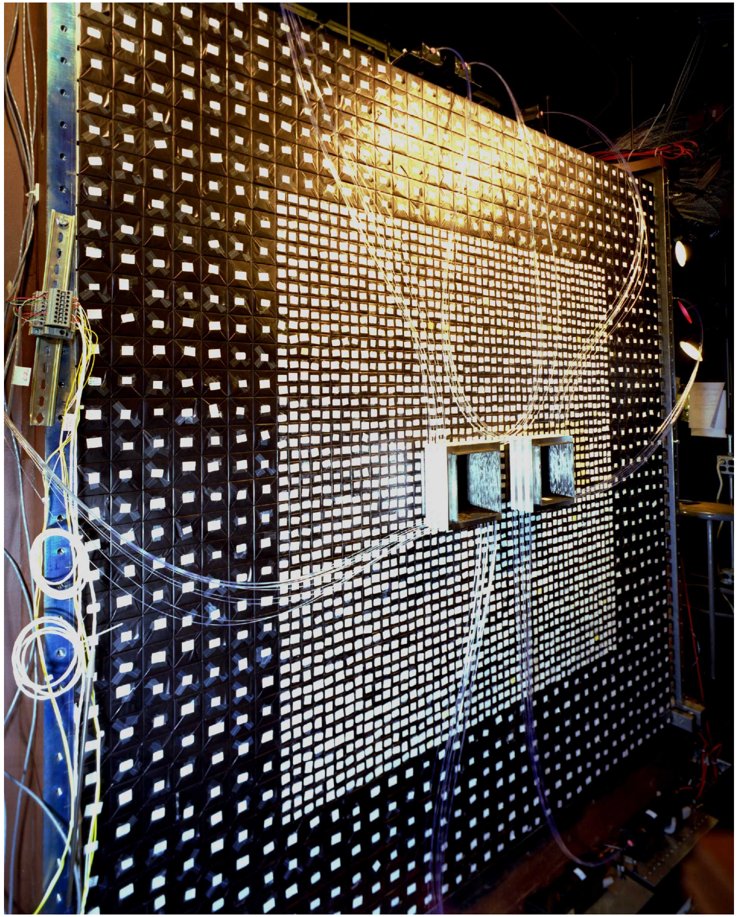


NA48 Detector

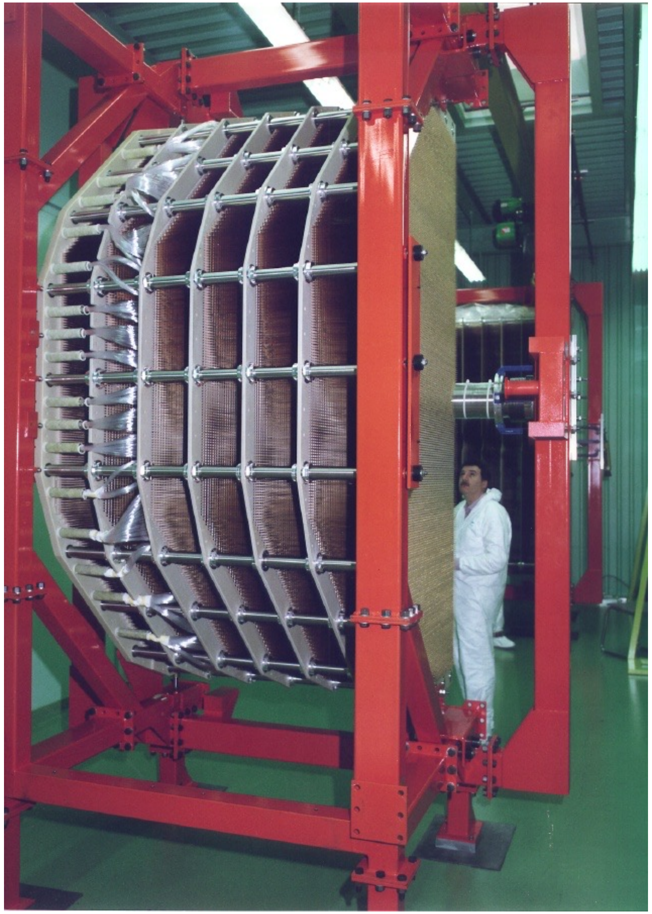


Experiments designed to measure Re(ε′/ε)

KTeV CsI Calorimeter



NA48 LKr Calorimeter



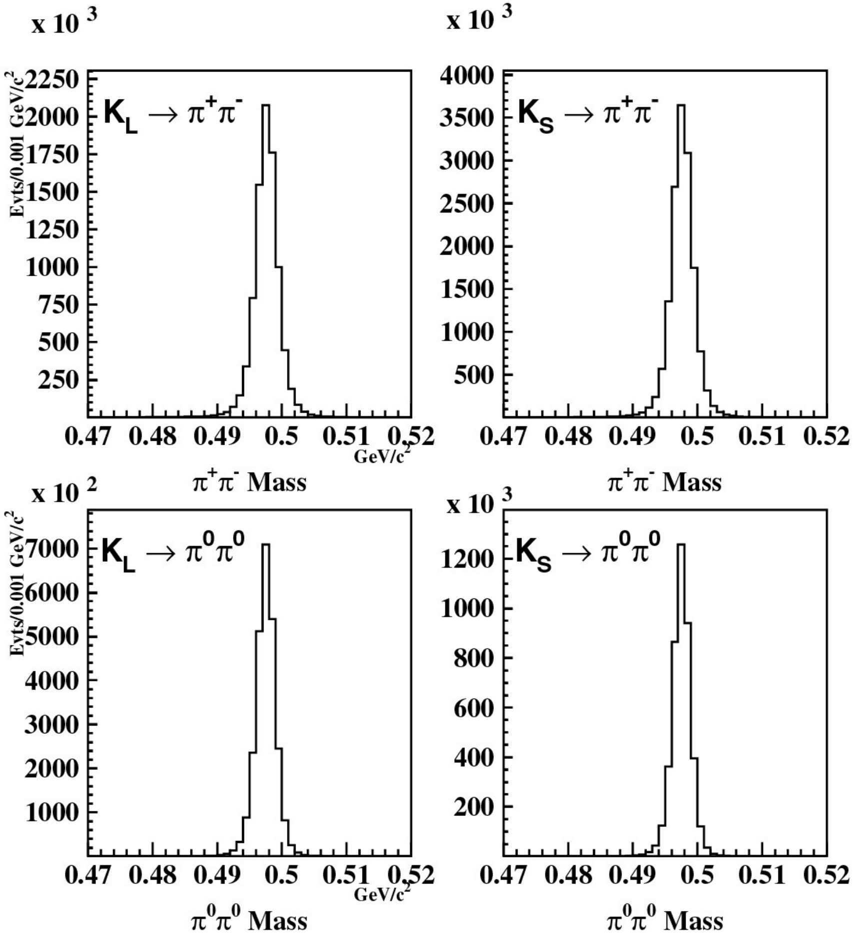
Both had

$\sigma_E < 1\%$

and

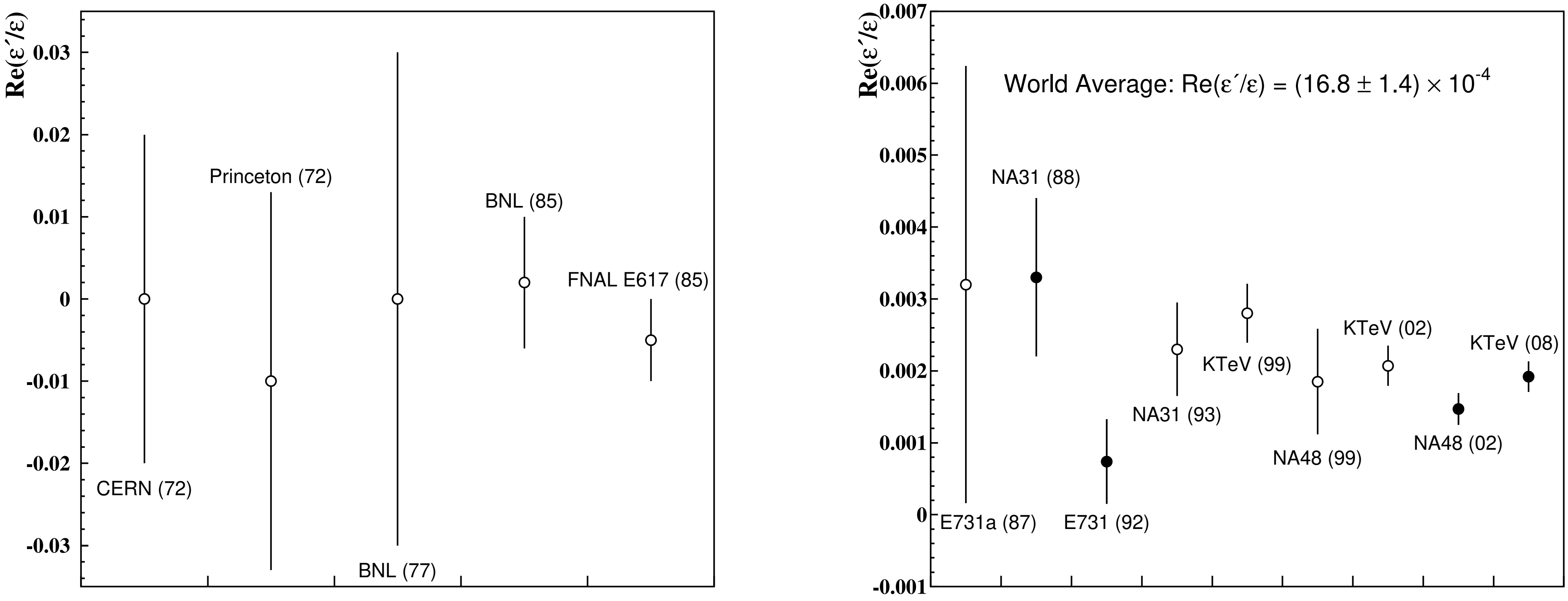
$\sigma_{pos} \sim 1$ mm

KTeV $K_L, K_S \to \pi^+\pi^-, \pi^0\pi^0$ invariant mass distributions



Mass resolution is ~1.5 MeV/c^2 for both charged and neutral decay modes.

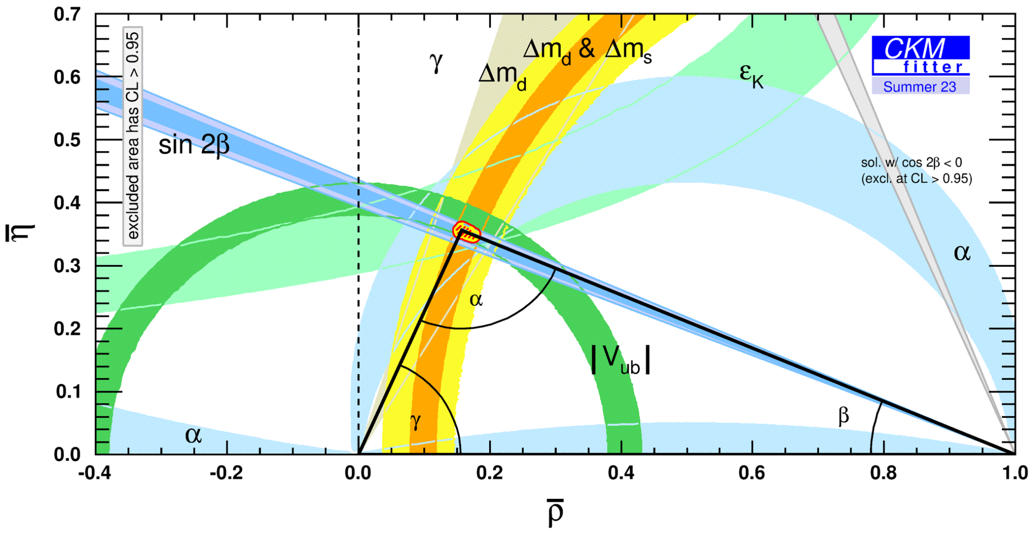
History of ϵ'/ϵ



KTeV and NA48 definitively observed direct CP violation, ruling out the Superweak Model as the sole source of CP violation and supporting the CKM model.

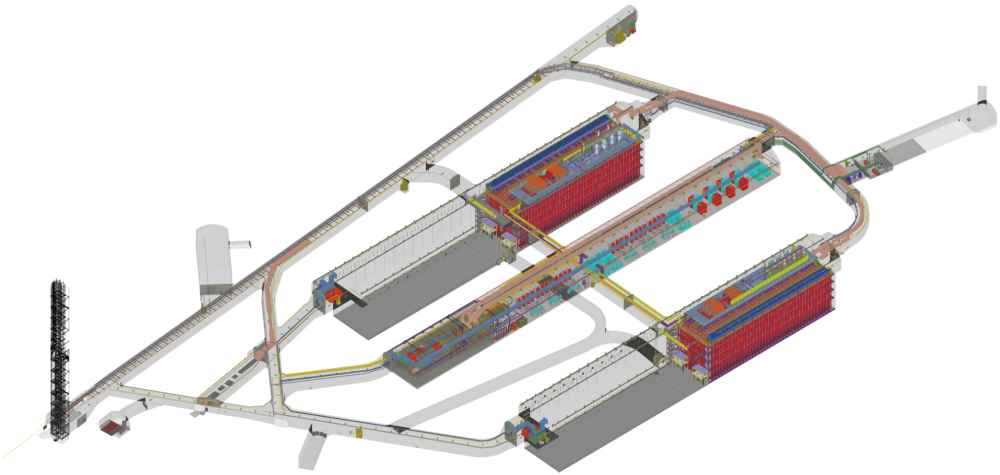
CP Violation in B Decay

- In 2001, BaBar and Belle observed CP violation in B decays.
- B decays have an extremely rich pattern of CP violation; all consistent with CKM model.
- Studies continue with LHCb and Belle II.

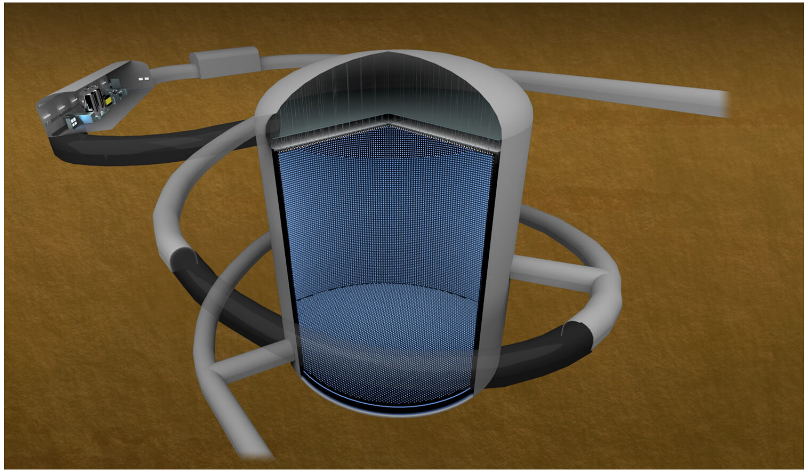


Next frontier: CP Violation in Neutrinos

- CP violation in neutrino oscillations would provide important evidence of the viability of leptogenesis.
- DUNE and HyperK detectors now under construction



DUNE



HyperK

From left : Val Fitch, René Turlay, Jim Cronin and Jim Christenson. Château de Beauregard. Courtesy of Count du Pavillon.

Summary

- For the 60 years since the discovery of CP violation, the effort to understand CP violation and its connection to the matter-antimatter asymmetry has been a central theme of particle physics and cosmology.
- It seems likely that this focus will continue for many more decades.