CP Violation in Experimental Particle Physics

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The Question

"Life, the Universe, and Everything"

D. Adams, *The Hitchhiker's Guide to the Galaxy*

The Universe appears matter-dominant.

- There is much more matter than anti-matter.

"Big-Bang" implies:

- Equal amount of matter and anti-matter must have been created, and
- They should have annihilated with each other.

Then why are we here?

A. Sakharov's 3 conditions (1957):

- CP violation
- Baryon number non-conservation
- Thermal non-equilibrium

What is "*CP* violation"?

Outline

Symmetry

- C, P and T symmetries
- CPT theorem
- Parity Violation

CP Violation

- Neutral kaon system
- Discovery of CP violation
- Direct and indirect CP violation

The Standard Model

- Electroweak theory
- CKM matrix
- Testing the Standard Model

The Next Step

CP violation in K_L decays

- $K_L \to \pi^0 \nu \bar{\nu}$

CP violation in B^0 decays

- B factories
- Proton accelerators

Summary

Outlook

Symmetry

Quantum Mechanics says:

Symmetry of Nature = Invariance of Hamiltonian
$\rightarrow$ Conservation Law

In less philosophical terms:

Symmetry = A transformation under which the law of physics does not change.
(e.g. experiments work the same in Geneva and in California.)

$\rightarrow$ The Hamiltonian H is invariant under the transformation.

$$H(x, y, z) = H(x + \delta x, y + \delta y, z + \delta z).$$

$\rightarrow$ The operator that generates the transformation does not affect H.

$$pH = Hp \text{ where } p = i\hbar\frac{\partial}{\partial x}.$$

The operator is said to "commute with H."

$\rightarrow$ The operator represents a physical quantity that is conserved.

$$i\hbar\frac{dp}{dt} = [p, H] = 0, \text{ i.e. momentum conservation.}$$

C, P and T symmetries

Two classes of symmetries: **continuous** and **discrete.**

- Spatial translation symmetry is continuous.

Three important types of **discrete space-time symmetries:**

C : Charge conjugation = Replacement of particles with antiparticles.

$$e^- \leftrightarrow e^+ \qquad p \leftrightarrow \bar{p} \qquad \gamma \leftrightarrow \gamma$$

P : Parity = Space inversion.

$$x \to -x \qquad y \to -y \qquad z \to -z$$

T : Time reversal.

$$t \to -t$$

What's special about these symmetries?

CPT Theorem

In any relativistic quantum theory:

The combined CPT symmetry is exact.

Consequence:

- If any of the C, P, T symmetries is broken, the combination of the remaining two must also be broken to conserve the CPT symmetry.

This in fact is known to be the case…

Interactions vs. Symmetries

Four fundamental interactions.

Interaction	Object	Medium	Reach	Lifetime
Strong	quarks, hadrons, nuclei	gluon	10^{-15} m	10^{-22}–10^{-24} s
Electromagnetic	charged objects	photon	∞	10^{-16}–10^{-21} s
Weak	anything	$W^{\pm}$, Z^0	10^{-18} m	10^{3}–10^{-13} s
Gravitational	anything	graviton	∞	—

C and P symmetries are broken by weak interactions.

Interaction	*C*	*P*	*T*	*CP*	*CPT*
Strong	✔	✔	✔	✔	✔
Electromagnetic	✔	✔	✔	✔	✔
Weak	✘	✘	?	?	✔

But CP is almost OK. Hence T is OK.

Parity Violation

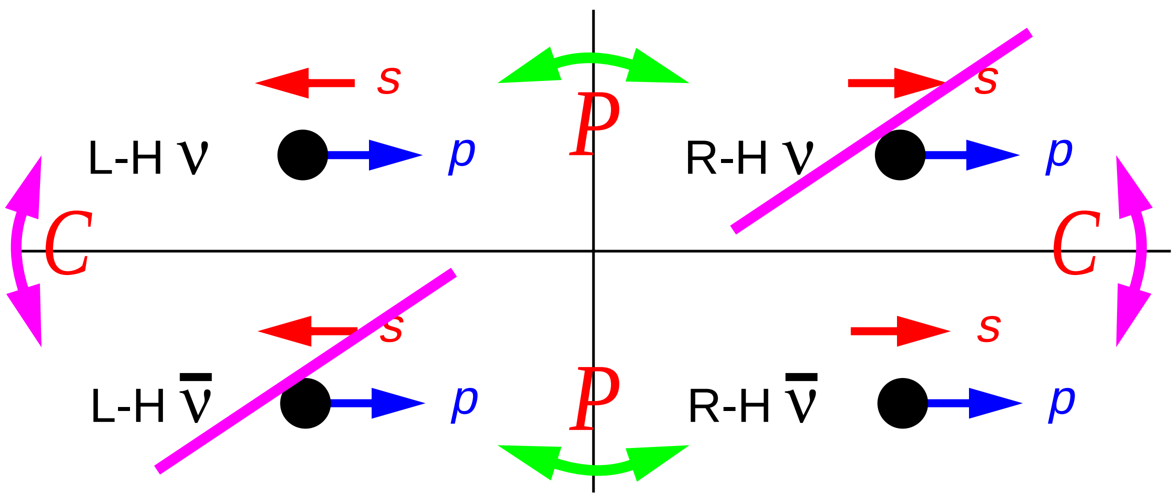
P-invariance was considered trivial before 1956.

Why should Physics distinguish left and right?

Wu *et al.* (Phys. Rev. 105, 1413–1414, 1957) discovered P violation.

- Angular distribution of electrons from β-decay of ^{60}Co.

Consider the neutrinos, which interacts only weakly.



R-H neutrinos and L-H anti-neutrinos do *not* exist.

But the combined *CP*-invariance is still valid.

CP Violation

Discovered in 1964 in K_L decays.

What is K_L and what is special about it?

What have we been studying for 36 years?

Neutral Kaons

Kaons are the lightest "*strange*" particles.

Name	Quark content	Charge	Mass (MeV/c^2)
K^+	$u\bar{s}$	+1	494
K^-	$s\bar{u}$	-1	494
K^0	$d\bar{s}$	0	498
$\bar{K}^0$	$s\bar{d}$	0	498

- They decay via weak interactions. → "Long" lifetime (10^{-8}–10^{-10} s).

K^0 and $\bar{K}^0$ have same mass, charge, spin.

- "Identical twins" except for the quark contents.

Nothing forbids $K^0 \leftrightarrow \bar{K}^0$ transitions, or K^0-$\bar{K}^0$ Mixing.

Neutral Kaons — CP Eigenstates

K^0 and $\overline{K}^0$ are coupled by *CP*.

$$CP\,|K^0\rangle = |\overline{K}^0\rangle \qquad CP\,|\overline{K}^0\rangle = |K^0\rangle$$

CP eigenstates can be formed by linear combinations.

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\overline{K}^0\rangle) \qquad CP\,|K_1\rangle = |K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\overline{K}^0\rangle) \qquad CP\,|K_2\rangle = -|K_2\rangle$$

K_1 and K_2 are *CP* eigenstates with eigenvalues +1 and -1, respectively.

Neutral Kaons — Mass Eigenstates

Since K^0 and $\overline{K}^0$ can convert into each other, they are not eigenstates of the Hamiltonian H.

$$H|K^0\rangle = a|K^0\rangle + b|\overline{K}^0\rangle$$

$$H|\overline{K}^0\rangle = c|K^0\rangle + d|\overline{K}^0\rangle$$

If H is CP-invariant, then $a = d$ and $b = c$. It follows that

$$H|K_1\rangle = (a+c)|K_1\rangle$$

$$H|K_2\rangle = (a-c)|K_2\rangle$$

i.e. K_1 and K_2 are eigenstates of H, with different masses and lifetimes.

If CP is conserved, physically-observed neutral kaons should be the CP eigenstates K_1 and K_2.

Neutral Kaons — Long and Short

Experimentally, two types of neutral kaons are observed.

Name	**Lifetime**	**Decay Modes**[a]
K_S	8.92×10^{-11} s	$\rightarrow \pi^+\pi^-$ (68.6%) $\rightarrow \pi^0\pi^0$ (31.4%)
K_L	5.17×10^{-8} s	$\rightarrow \pi^0\pi^0\pi^0$ (21.6%) $\rightarrow \pi^+\pi^-\pi^0$ (12.4%) $\rightarrow \pi^+\mu^-\bar{\nu}$ (27.0%) $\rightarrow \pi^+ e^-\bar{\nu}$ (38.7%)

a. Charge conjugations are included

2-π and 3-π final states are CP eigenstates.

$$CP(\pi^0) = -1 \qquad CP(\pi^0\pi^0) = 1 \qquad CP(\pi^0\pi^0\pi^0) = -1$$

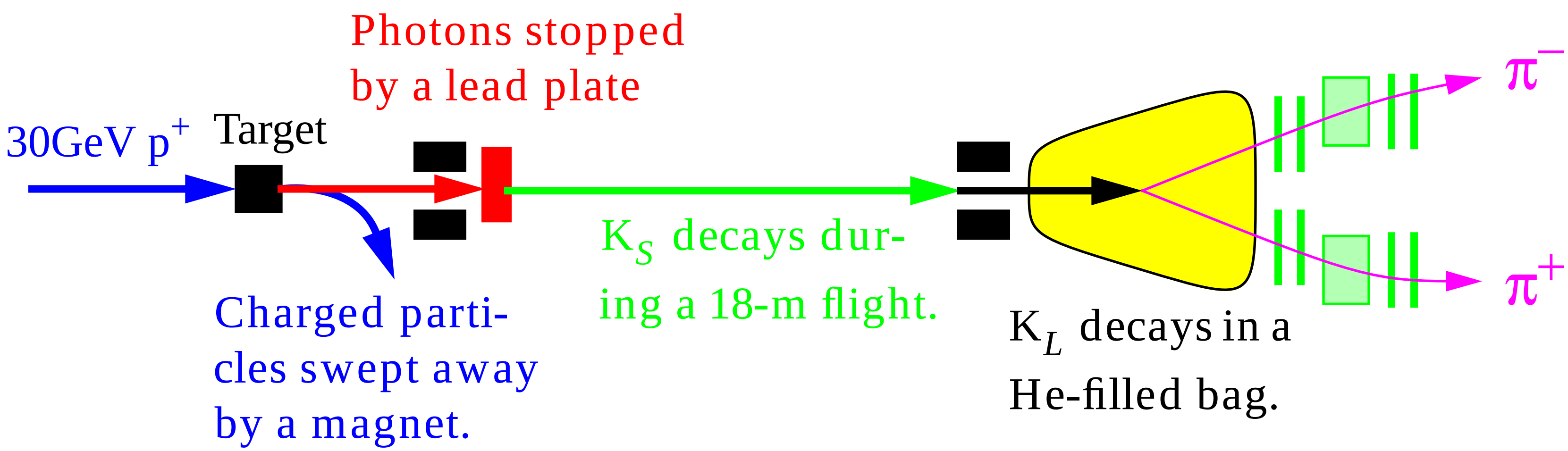
$$CP(\pi^+\pi^-) = 1 \qquad CP(\pi^+\pi^-\pi^0) = -1$$

K_S is CP-even = K_1, K_L is CP-odd = K_2.

CP Violation

Christenson, Cronin, Fitch, Turlay (Phys. Rev. Lett. 13, 138–140, 1964)

Experimental set-up:



Momenta of the π^+ and π^- were measured by two sets of magnets & spark chambers.

- Signals for the decay $K_L \to \pi^+\pi^-$ were found with:
  - Invariant mass of the π^+ and π^- near the K_L mass (494–504 MeV / c^2).
  - Total momentum of the π^+ and π^- parallel to the beam direction.

Discovery of the *CP*-violating decay $K_L \to \pi^+\pi^-$.

CP Violation — Direct or Indirect

Two possible scenarios:

1. **Indirect *CP* violation:**

   The mass eigenstates K_S and K_L are mixtures of the *CP* eigenstates K_1 and K_2.

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(|K_1\rangle - \varepsilon|K_2\rangle)$$

$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}}(\varepsilon|K_1\rangle + |K_2\rangle)$$

2. **Direct *CP* violation:**

   The *CP* eigenstates K_1 and K_2 can decay into final states with opposite *CP*.

$$\frac{\langle\pi^+\pi^-|H|K_2\rangle}{\langle\pi^+\pi^-|H|K_1\rangle} = \varepsilon' \qquad \frac{\langle\pi^0\pi^0|H|K_2\rangle}{\langle\pi^0\pi^0|H|K_1\rangle} = -2\varepsilon'$$

Can we separate ε and ε'?

CP Violation — Direct or Indirect

Compare $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$.

$$\eta_{+-} \equiv \frac{\langle \pi^+\pi^- | H | K_L \rangle}{\langle \pi^+\pi^- | H | K_S \rangle} = \varepsilon + \varepsilon' \qquad \eta_{00} \equiv \frac{\langle \pi^0\pi^0 | H | K_L \rangle}{\langle \pi^0\pi^0 | H | K_S \rangle} = \varepsilon - 2\varepsilon'$$

Experiments measured $|\eta_{+-}| \sim |\eta_{00}| \sim 2 \times 10^{-3} \to |\varepsilon| \gg |\varepsilon'|$.

Indirect *CP* violation dominates.

Does direct *CP* violation exist?

- Standard Model says it should.

$\to$ We must look harder.

Direct CP Violation

Try measuring the double-ratio:

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

The trick is to measure all four decays simultaneously

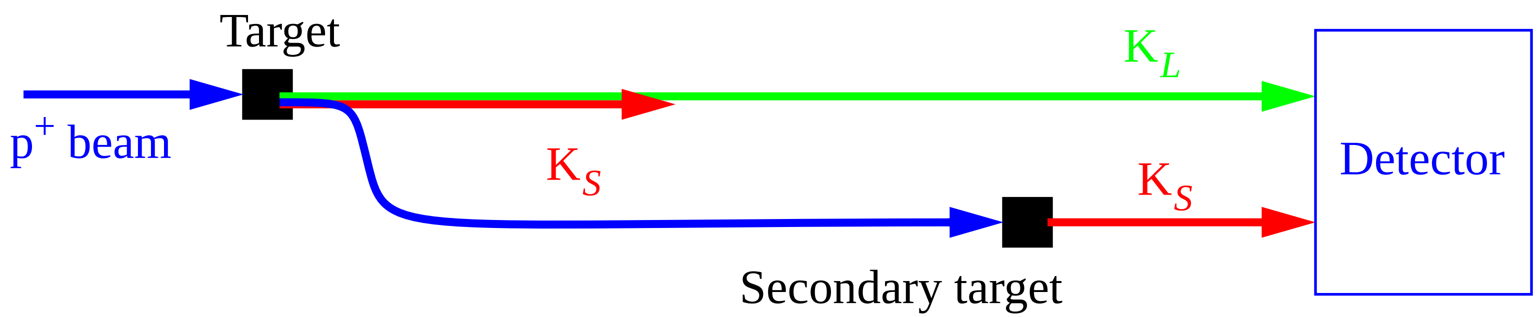
$\rightarrow$ Cancel out experimental systematics, e.g.

- ➤ Detector efficiency
- ➤ Detector acceptance
- ➤ Beam intensity

Direct CP Violation — Competition

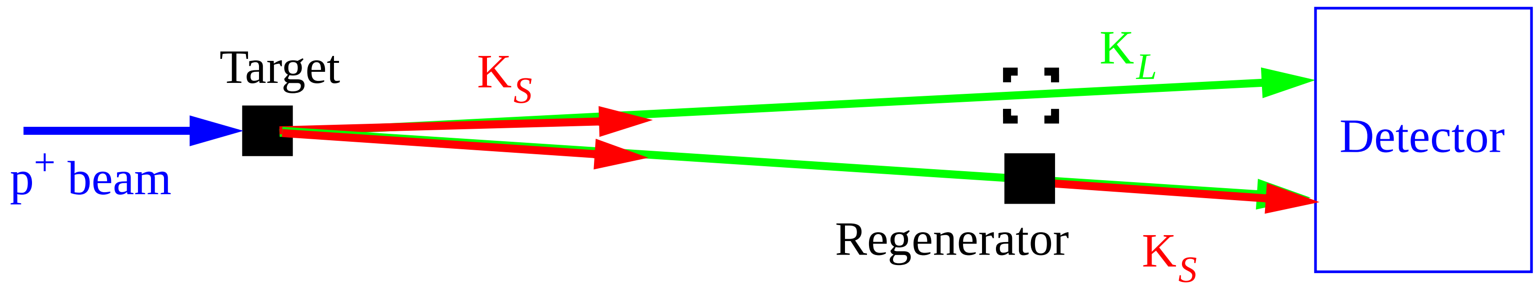
Two competing series of experiments.

CERN (NA31 → NA48)



- Part of the proton beam hits the second target.

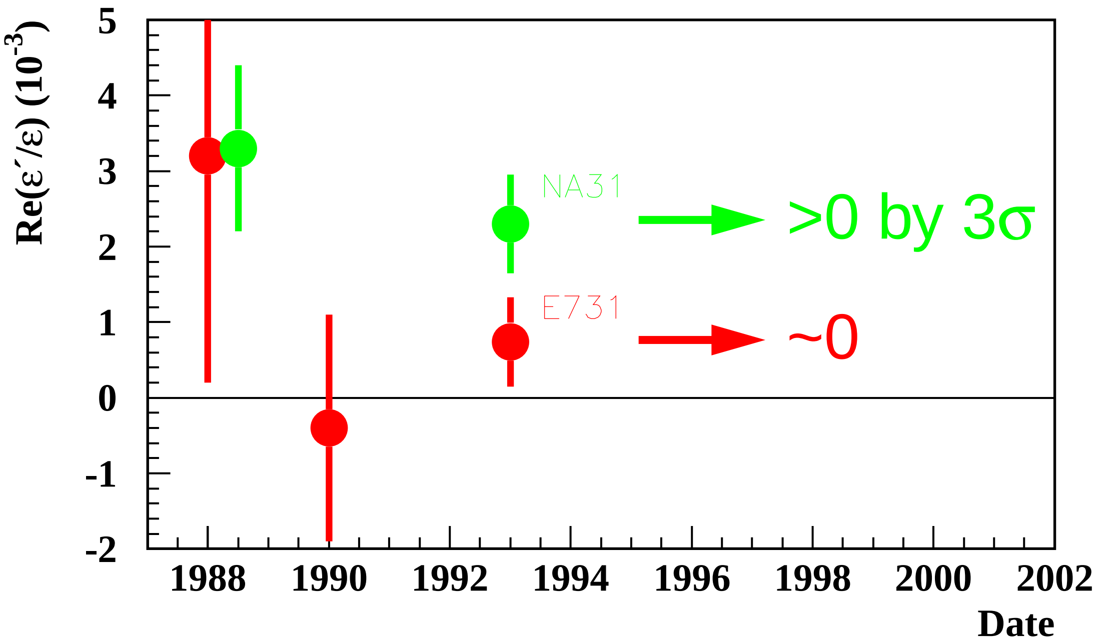
Fermilab (E731 → KTeV)



- One of the two K_L beams hits the regenerator.
- The regenerator moves between the two beams every beam "spill."

Direct CP Violation — Confusion

History of ε'/ε has been interesting.

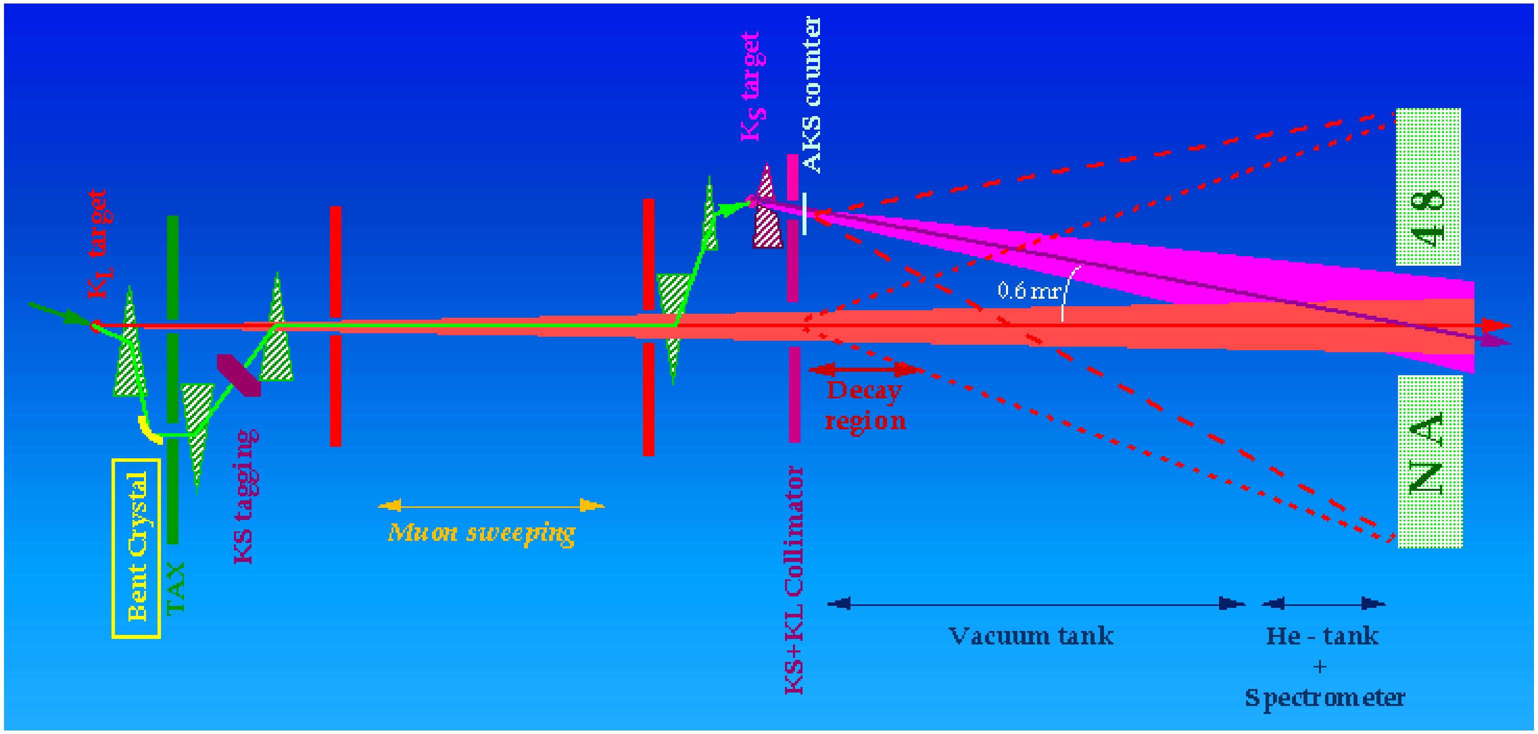


Two experiments found inconsistent results.

- Does direct CP violation exist or not?

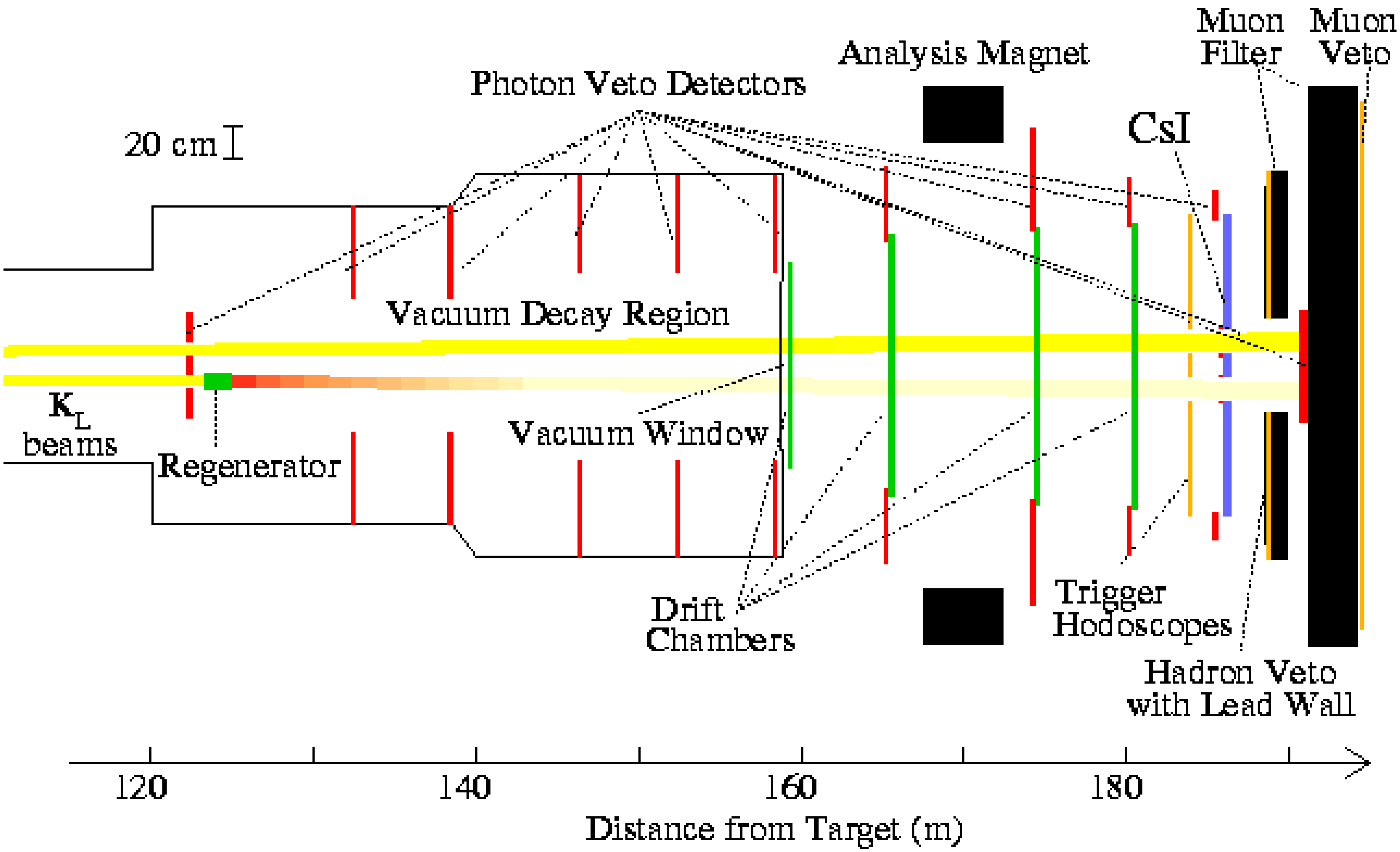
→ Both groups embarked on new, bigger, and much more sensitive experiments.

NA48 at CERN



- Part of the incident proton beam is transferred along with the K_L beam.
- K_S beam is generated at the secondary target.
- K_L and K_S decays in a 90 m-long vacuum tank.

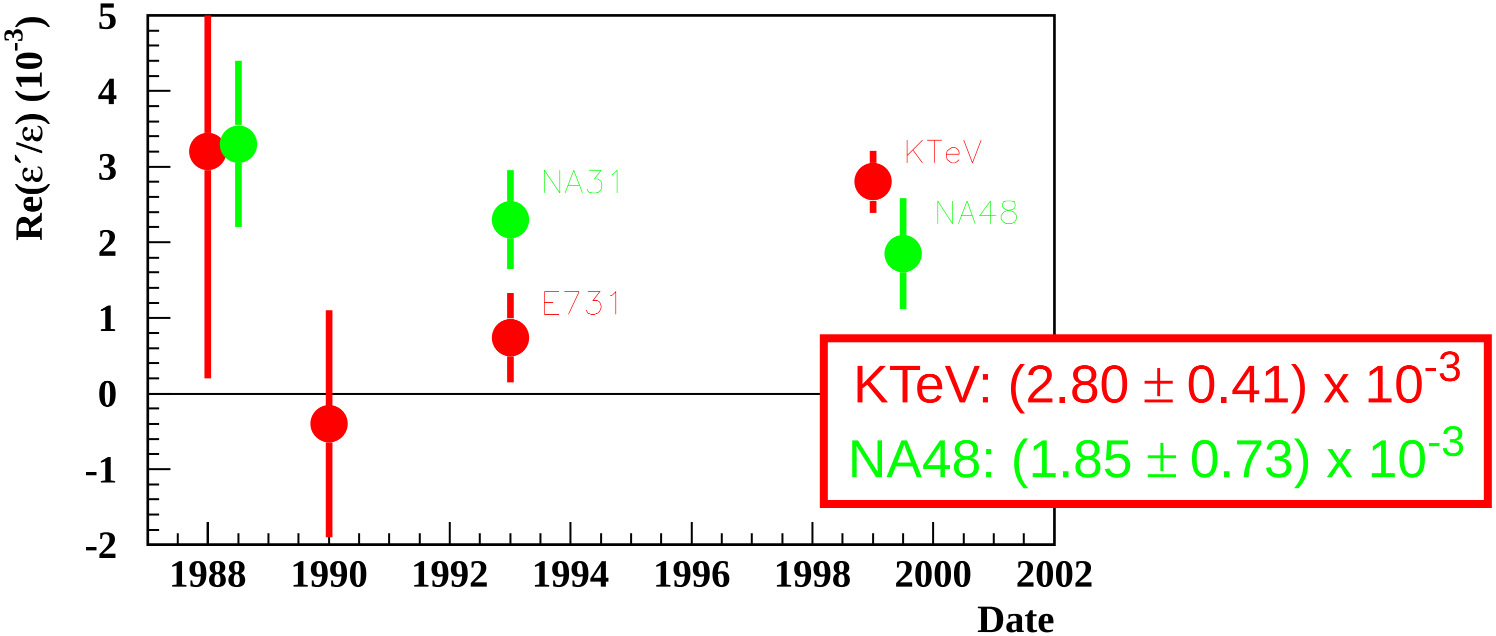
KTeV (E832) at Fermilab



- Two near-parallel K_L beams. A moving regenerator regenerates K_S.
- Vacuum decay region 122–159 m from the K_L production target.

Direct CP Violation — Confirmation

New results arrived last year:



- World average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (2.13 \pm 0.46) \times 10^{-3}$.

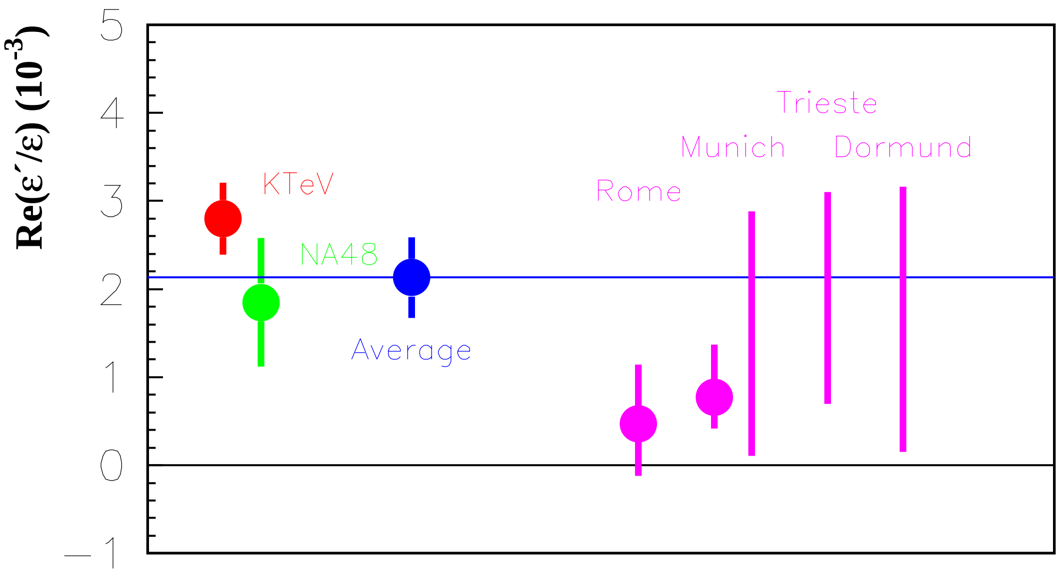
Existence of direct CP violation established at last.

Direct CP Violation — Theory

Problem:

Lack of reliable theoretical calculation.

Recent predictions scatter between 0 and 3 x 10^{-3}.



$\rightarrow$ Theoretical uncertainty today > Experimental errors.

We must wait for theorists to catch up.

Direct CP Violation — Future

Experiments continue to improve.

- KTeV and NA48 have more data to analyze.
- New experiment: KLOE at DAΦNE.
  - "ϕ Factory": Collides e^+ and e^- to produce $\phi \to K^0\overline{K}^0$.

$\to$ Error on $\mathrm{Re}(\varepsilon'/\varepsilon) < 1 \times 10^{-4}$ in the next few years.

Theoretical uncertainty ($\geq 10^{-3}$ today) must shrink.

Lattice-QCD promises to improve.

- Parallel supercomputers with 100 $\to$ 1000 $\to$ 10000 GFLOPS.
- First result from RIKEN-BNL-Columbia: -1×10^{-2} (!?)

$\to$ Wait and see what comes.

The Standard Model

What is the Standard Model?

How does it explain CP violation?

How do we test it?

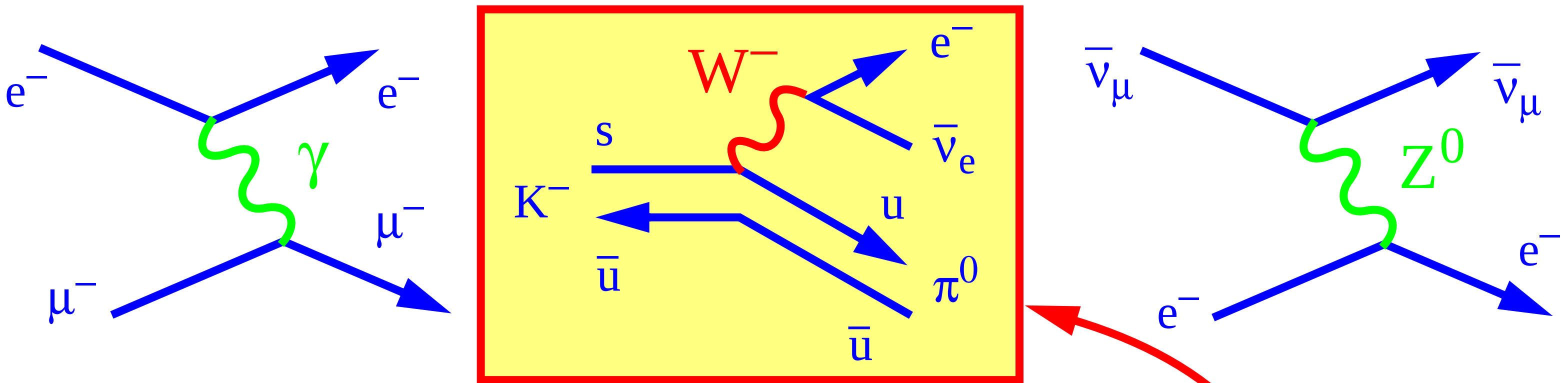
The Standard Model

Electroweak Model (S.L. Glashow, A. Salam, S. Weinberg)

- Matter is made of leptons and quarks that come in pairs.

$$\begin{bmatrix} e^- \\ \nu_e \end{bmatrix} \begin{bmatrix} \mu^- \\ \nu_\mu \end{bmatrix} \begin{bmatrix} \tau^- \\ \nu_\tau \end{bmatrix} \qquad \begin{bmatrix} u \\ d \end{bmatrix} \begin{bmatrix} c \\ s \end{bmatrix} \begin{bmatrix} t \\ b \end{bmatrix} \begin{matrix} \leftarrow Q = +2/3 \\ \leftarrow Q = -1/3 \end{matrix}$$

- Electromagnetic and weak interactions are mediated by:



➤ Photons (γ) mediate electromagnetic interactions.

➤ $W^\pm$ bosons mediate “charged-current” interactions.

➤ Z^0 bosons mediate “neutral-current” interactions.

CP violation occurs only in the charged-current interaction.

CKM Matrix

Charged-current interaction converts

- leptons to neutrinos, and vice versa.
- Q = +2/3 quarks (u, c, t) to Q = –1/3 quarks (d, s, b), and vice versa.

Coupling between the quarks has a general form:

$$\begin{bmatrix} u & c & t \end{bmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix} \qquad V^{\dagger}V = 1$$

Kobayashi and Maskawa (Prog. Theor. Phys. 49, 652, 1973)

- If there are 3 generations of quarks, the matrix V contains 1 imaginary phase, which causes *CP* violation.

V is called “the Cabibbo-Kobayashi-Maskawa matrix.”

CKM Matrix

Coupling between (u, c, t) and (d, s, b) quarks:

- 2 generations: $\begin{array}{cc} & \\ \begin{array}{c} u \\ c \end{array} & \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \\ & \begin{array}{cc} d \quad & \quad s \end{array} \end{array}$ $\to$ 2-d rotation.

- 3 generations:

$$\begin{array}{cc} \begin{array}{c} u \\ c \\ t \end{array} & \begin{bmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & -c_1 s_2 c_3 - c_2 s_3 e^{i\delta} & -c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{bmatrix} \\ & \begin{array}{ccc} d & \qquad\qquad s & \qquad\qquad b \end{array} \end{array}$$

  - $c_i = \cos\theta_i \qquad s_i = \sin\theta_i \qquad i = 1, 2, 3.$

$\to$ Added degree of freedom allows 1 imaginary phase.

$\to$ CP violation.

CKM Matrix

Predictions:

1. If there are 3 generations, CP violation is naturally expected.
2. The CP violation occurs due to a single imaginary phase in the CKM matrix (if there are only 3 generations).

Discovery of the third generation.

- τ lepton (1975), b quark (1977), t quark (1994).

Testing the Standard Model

***CP* violation in the Standard Model has a single origin: the imaginary phase in the CKM matrix.**

This implies:

If the Standard Model is correct, all CP violating effects must be explained using a single parameter.

With >1 experimental measurements, we can *over-constrain* this parameter; in other words, we can test if the Standard Model is correct in explaining the CP violation.

How many experiments do we have?

All We Know about CP Violation

CP violation has been observed only in the K^0-$\overline{K}^0$ system.

$$\delta = \frac{\Gamma(K_L^0 \to \pi^- l^+ \nu) - \Gamma(K_L^0 \to \pi^+ l^- \bar{\nu})}{\Gamma(K_L^0 \to \pi^- l^+ \nu) + \Gamma(K_L^0 \to \pi^+ l^- \bar{\nu})}$$

$$\eta_{+-} = A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-) = |\eta_{+-}|e^{i\phi_{+-}}$$

$$\eta_{00} = A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0) = |\eta_{00}|e^{i\phi_{00}}$$

Measurements say

$$|\eta_{+-}| \approx |\eta_{00}| = 2.28 \times 10^{-3} \qquad \phi_{+-} \approx \phi_{00} = 44^\circ \qquad \delta = 3.3 \times 10^{-3}$$

The problem is: They are all measuring the same old ε !

The only exception is ε'/ε

- But it cannot be reliably calculated from the CKM matrix.

The Standard Model cannot be tested using kaons alone.

Why Do We Have to Test the SM?

1) Because it's not been tested well enough.

- The Standard Model has been extremely successful in explaining all the experimental data.
- CP violation is one of the least tested aspects of the Standard Model.

2) Because it's not the *Ultimate Theory of Everything*.

- Lack of unification between strong, electroweak and gravitational interactions.
- Eighteen (18) free parameters.
- Attractive new models (SUSY, etc.) predict new CP violating effects.

3) Because it doesn't explain the matter-dominant universe.

- CP violation predicted by the Standard Model is too small.
- Baryon number is conserved in the Standard Model.

The SM is flawed, but we need an evidence!

The Next Step

How can we make a new measurement of CP violation that tests the validity of the Standard Model?

Where to Look

Other K_L^0 decays.

- We need something different from ε.
- It must be reliably calculated from the CKM matrix.

$\rightarrow$ $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$.

Outside the K^0-$\overline{K}^0$ system.

- Look for "interference" phenomena similar to the K^0-$\overline{K}^0$ mixing.
- Reliable theoretical prediction is necessary.
- Large CP-violating effect is desirable.

$\rightarrow$ The B^0-$\overline{B}^0$ system.

HEP Seminar, 1/25, 4:00 PM, 318 Willamette Hall

"First Year of BABAR/PEP-II"

CP-Violating Decay $K_L \to \pi^0 \nu\bar{\nu}$

Theorists love this decay.

- Neutrinos "feel" only weak interactions. $\to$ Simplifies calculation.
- Can use well-measured decay $K^+ \to \pi^0 l^+ \nu$ for "calibration."

$\to$ The branching ratio is directly related to the imaginary phase in the CKM matrix.

- Theoretical uncertainty is only 2–3%.

Expected branching ratio ~ 3 x 10^{-11}.

Very difficult to detect.

- Neutral particle (K_L) decaying into two photons (π^0) and nothing ($\nu\bar{\nu}$).

Main background is $K_L \to \pi^0\pi^0$ when one π^0 is undetected.

- This is CP violating. BR is 3 x 10^7 times (!) larger.

$\to$ Big (daunting?) experimental challenge.

Search for $K_L \to \pi^0 \nu\bar{\nu}$

Present limit: BR($K_L \to \pi^0 \nu\bar{\nu}$) < 5.9 x 10^{-7} (90% C.L.)

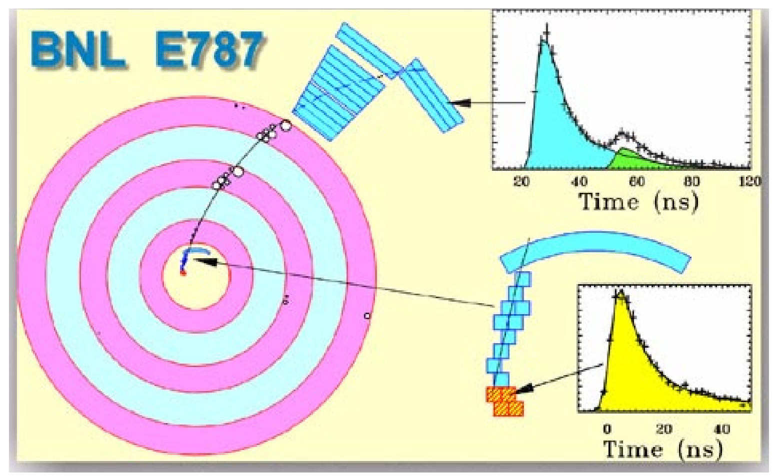
- KTeV Collaboration. Soon to appear in Phys. Rev. D.
- KEK E391a plans to reach 5 x 10^{-10}.

$\to$ Still a far cry from 3 x 10^{-11}...

Similar decay $K^+ \to \pi^+ \nu\bar{\nu}$ has been found.

- E787 Collaboration, S. Adler *et al.*, Phys. Rev. Lett. 79 (1997) 2204-2207.
- Just 1 event:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (4.2^{+9.7}_{-3.2}) \times 10^{-10}.$$



$K_L \to \pi^0 \nu\bar{\nu}$ is another order rarer, and harder to detect.

Search for $K_L \to \pi^0 \nu\bar{\nu}$

Future experiments: Reach and *measure* BR ~ 3 x 10^{-11}.

Experiment	Fermilab KAMI	BNL E926
Sensitivity	1.0 x 10^{-12}	0.4 x 10^{-12}

Hermetic photon veto detector to remove $K_L \to \pi^0\pi^0$.

- Detect photons from $\pi^0 \to \gamma\gamma$ decays. Efficiency >99.99%.

BNL experiment benefits from additional information.

- Beam arrives in very short (100 ps) pulses.
  - Time of flight gives the K_L decay point.
- Calorimeter measures photon direction as well as energy.
  - Decay point of the π^0 can be reconstructed.

Both are very aggressive projects.

But the physics motivation merits the effort.

Neutral B System

The K^0 system is a great place to study CP violation.

- K^0 and $\overline{K}^0$ can mix with each other to form CP eigenstates.

Are there anything similar?

$\rightarrow$ Look at heavier quarks!

Quark	strange	charm	bottom	top
Lightest neutral meson	$K^0 = d\bar{s}$	$D^0 = c\bar{u}$	$B^0 = d\bar{b}$	—

- D^0 system is expected to have only small mixing.
- Top quark does not live long enough to form a useful “system.”

$\rightarrow$ How about the B^0 system?

Neutral B System

B mesons have very similar structure as K mesons.

Name	Quark content	Charge	Mass (MeV/c^2)
B^+	$u\bar{b}$	+1	5279
B^-	$b\bar{u}$	-1	5279
B^0	$d\bar{b}$	0	5279
$\bar{B}^0$	$b\bar{d}$	0	5279

Difference: larger mass (x10) and shorter lifetime.

- All B mesons have lifetime ~ 1.6×10^{-12} s.
- K_S lifetime = 8.9×10^{-11} s. K_L lifetime = 5.2×10^{-8} s.

Mixing between B^0 and $\bar{B}^0$ was observed in 1987.

- ARGUS Collaboration, H. Albrecht *et al*., Phys. Lett. B192 (1987) 245.

$\rightarrow$ Opportunity to observe CP violation.

CP Violation in the B^0 System

Two good news from the ever-optimistic theorists:

1. CP violation in the B^0 system will be large.
2. It can be reliably calculated in many cases.

Example:

- Look for $B^0 \to J/\psi\, K_S$ decay (a.k.a. Gold-Plated Decay).

$$\frac{\Gamma(B^0 \to J/\psi K_S) - \Gamma(\overline{B}^0 \to J/\psi K_S)}{\Gamma(B^0 \to J/\psi K_S) + \Gamma(\overline{B}^0 \to J/\psi K_S)} = -\sin 2\beta \cdot \sin(\Delta m \cdot t)$$

  - Δm = B^0 mixing frequency = 0.47 / ps. t = decay time.
  - $-\sin 2\beta$ = CP asymmetry. Expected to be about –70%. (c.f. 0.2% in K^0.)
  - β is an imaginary phase in the CKM matrix.

→ Measurement of the time-dependent CP asymmetry gives direct information on the CKM matrix.

Experimental Challenges

B^0 is not as easy to make as K^0.

B^0 decays in many different ways.

- Most of the decay "channels" are not useful.
- $BR(B^0 \to J/\psi\, K_S) = 4 \times 10^{-4}$. Only 1/1000 events are gold-plated.

$\to$ Biggest obstacle is the statistics!

How to produce enough ($>10^7$) B^0's.

- e^+e^- collision at E_{CM} = 10.58 GeV. (Cornell, SLAC, KEK)
- Proton accelerators. (Fermilab, DESY, CERN)

B Factories

Collide e^+ and e^- at E_{CM} = 10.58 GeV = $m(\Upsilon_{4S})$.

- Υ_{4S} is a bound state of b and $\bar{b}$ quarks. Decays into B^+B^- or $B^0\bar{B}^0$.

Probability of collision (cross-section) is small.

→ Accelerator must deliver high-intensity beams.

Three on-going projects:

Accelerator	CESR	PEP-II	KEKB
Scheme	Symmetric	Asymmetric	Asymmetric
Where	Cornell	SLAC	KEK
Experiment	CLEO-III	BABAR	Belle
Design L (cm^{-2}s^{-1})	2×10^{33}	3×10^{33}	1×10^{34}
B^0 / year ($\times 10^6$)	20	30	100
Achieved L (cm^{-2}s^{-1})	0.8×10^{33}	1.4×10^{33}	0.6×10^{33}

→ 10 million B^0's this year. 100 million in 3 years.

Asymmetric B Factories

The "gold-plated" signal is time-dependent.

$$\frac{\Gamma(B^0 \to J/\psi K_S) - \Gamma(\bar{B}^0 \to J/\psi K_S)}{\Gamma(B^0 \to J/\psi K_S) + \Gamma(\bar{B}^0 \to J/\psi K_S)} = -\sin 2\beta \cdot \sin(\Delta m \cdot t)$$

- We need to measure the decay time t of the B^0's.

At the B factories, B^0's are produced almost at rest.

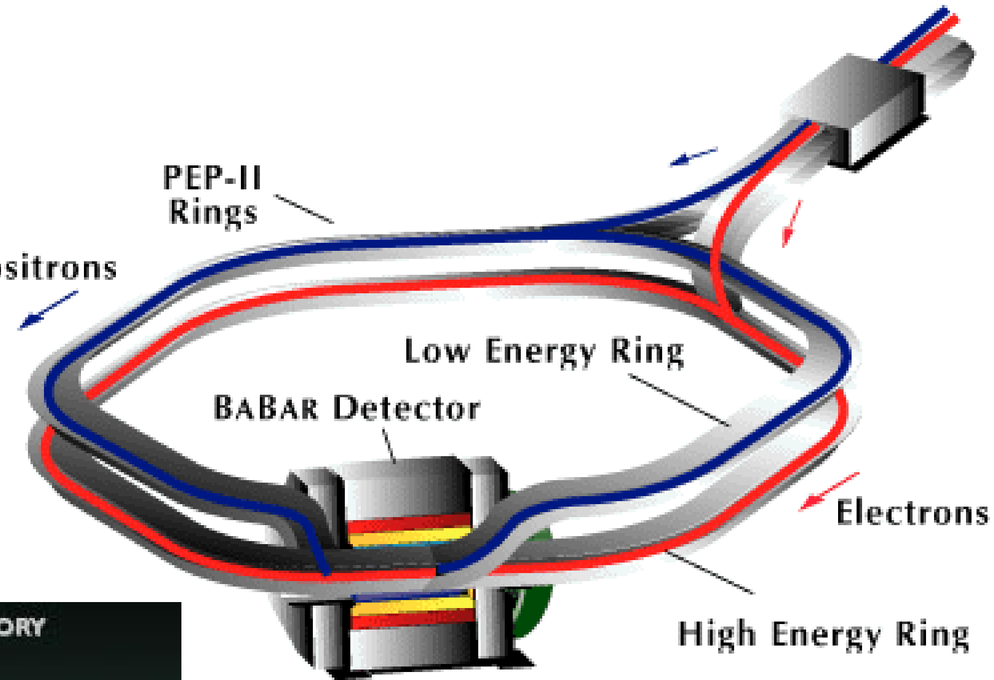
- Average flight = 30 microns → Too short to measure.

→ Why don't we produce them moving?

PEP-II and KEKB are "asymmetric" B factories.

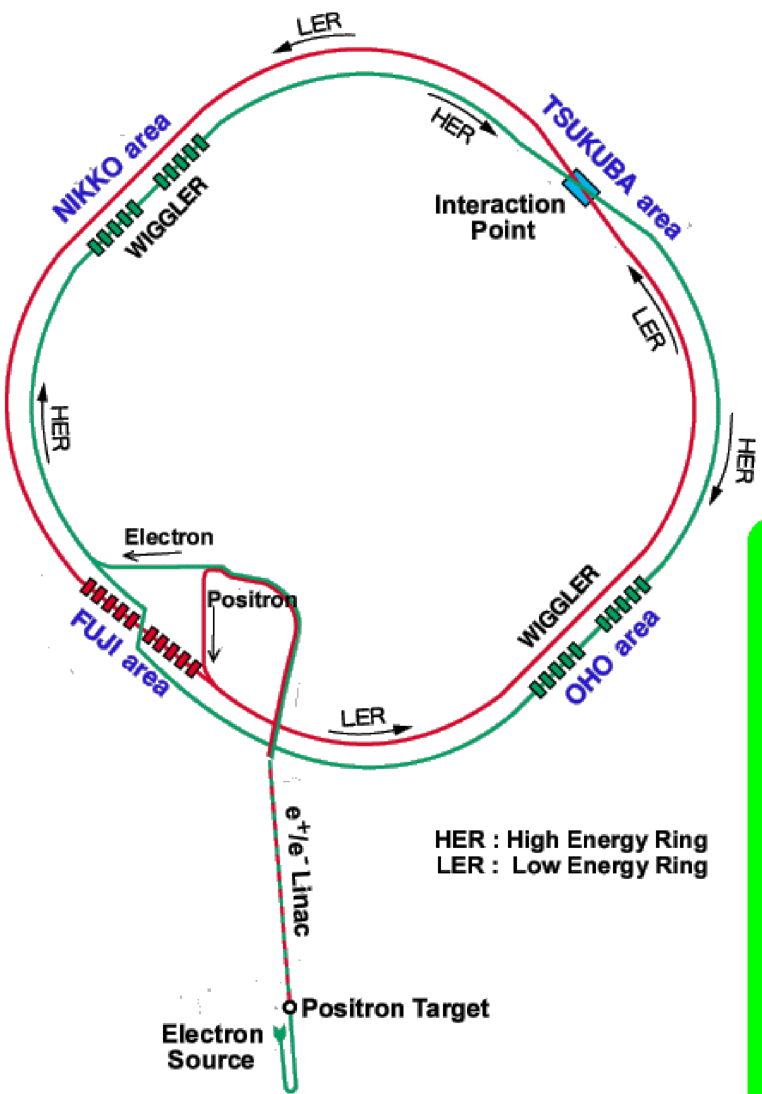
Accelerator	PEP-II	KEKB
e^- energy (GeV)	9.0	8.0
e^+ energy (GeV)	3.1	3.5
Boost $\beta\gamma$ of the CMS	0.56	0.43
B^0 flight length (μm)	270	210

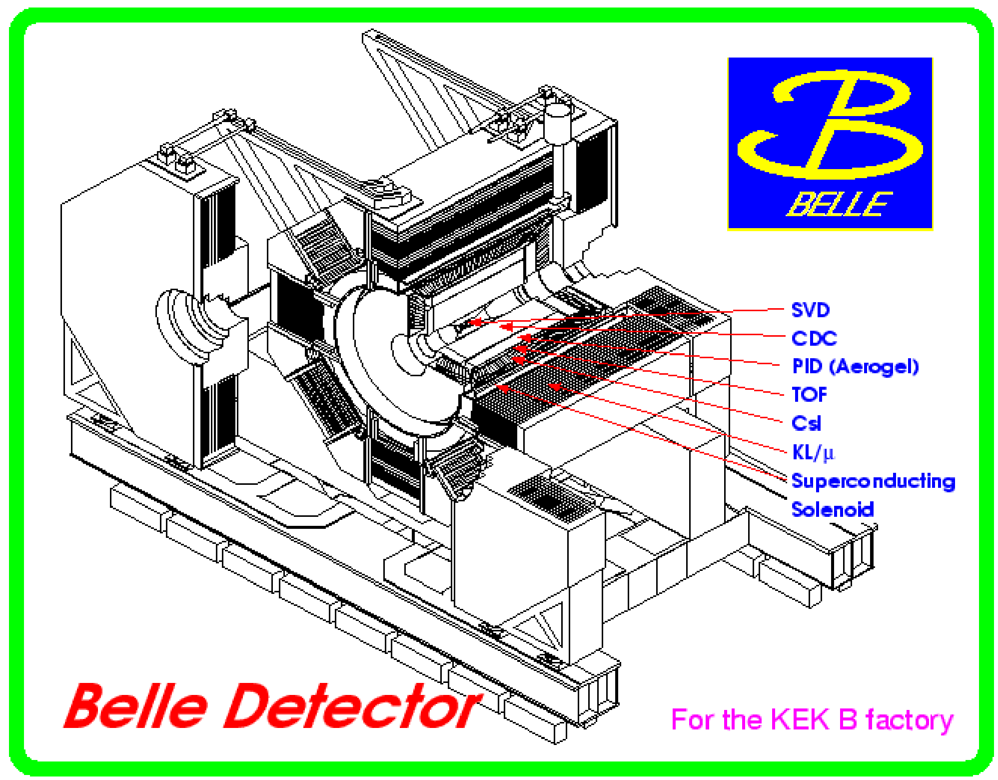
PEP-II/BaBar



BABAR TM & L de Brunhoff

KEKB/Belle


LER
HER
NIKKO area
WIGGLER
TSUKUBA area
Interaction Point
LER
HER
HER
Electron
Positron
FUJI area
LER
WIGGLER
OHO area
e+/e- Linac
HER : High Energy Ring
LER : Low Energy Ring
Positron Target
Electron Source


BELLE
SVD
CDC
PID (Aerogel)
TOF
CsI
KL/μ
Superconducting
Solenoid
Belle Detector
For the KEK B factory

B Factories — Status

PEP-II / BaBar and KEKB / Belle started taking data in 1999.

- Will compete for the first observation of CP violation in the B system in summer 2000.

→ First *real* test of the Standard Model prediction.

- Will need ~10 million B^0's. Too early to predict a winner.

CESR / CLEO-III is in commissioning.

- Test data taken in November 1999.
- Not a direct competitor (symmetric collider). Will try to detect time-integrated CP asymmetry.

Next few years will be exciting.

Proton Accelerators

Advantage: Statistics

- B^0's generated ~50000 times more often at Tevatron than at B factories.

Disadvantage: Signal / Noise

- Background is ~1000 times larger than the signal.

Tevatron ($p\bar{p}$ collision at 800 GeV each) proved principle.

- CDF (FERMILAB-Pub-99/225-E)

$$\sin 2\beta = 0.79^{+0.41}_{-0.44}$$

from $B^0 \to J/\psi\, K_S$ decays.

Proton Accelerators

(Near-)Future Experiments

Experiment	CDF	D∅	HERA-B	LHCb	BTeV
Where	Fermilab		DESY	CERN	Fermilab
Accelerator	Tevatron		HERA	LHC	Tevatron
Collision	1 TeV p on 1 TeV $\bar{p}$		920 GeV p on wire target	7 TeV p on 7 TeV p	1 TeV p on 1 TeV $\bar{p}$
Starting	Oct. 2000		Feb. 2000	2005	2005

CDF and D∅ are upgrading the detectors for Run-II.

- Tevatron is also upgraded with 20 times more luminosity.

HERA-B is completing the detector.

- Schedule very tight due to HERA upgrade plan.

LHCb and BTeV promise to be "ultimate."

- Huge statistics will allow many independent CP measurements.

$\rightarrow$ More exciting results in the next 10–15 years.

Summary

Violation of the CP invariance is of fundamental importance for our understanding of Physics.

- The CPT theorem.
- Matter-dominant Universe.

Thirty-six years of experimental and theoretical studies led to a model—the Standard Model—that explains all known CP-violating effects with a single parameter.

- Three generation of quarks $\rightarrow$ the CKM matrix.

The model, however, has yet to be tested.

- Experimental evidences limited to the neutral kaon system.

Experimental pursuit of new CP-violating phenomena continues to be a very active area of research.

Outlook

What to watch for:

1. **CP violation in the B system.**
   - ➤ First observation as early as this summer.
   - ➤ First independent test of the predictive power of the Standard Model.
   - ➤ Prolific physics programs for the next 10–15 years.
2. **CP violating decay $K_L \to \pi^0 \nu \bar{\nu}$.**
   - ➤ Another independent, clear-cut test of the Standard Model.
   - ➤ Experimental challenge is great, but not insurmountable.
3. **Improved calculation of ε'/ε.**
   - ➤ Will lattice-QCD deliver?

We will learn a great deal more about CP violation in this decade, probably in just a few years.

Will CP violation change our view of physics?

Who knows?