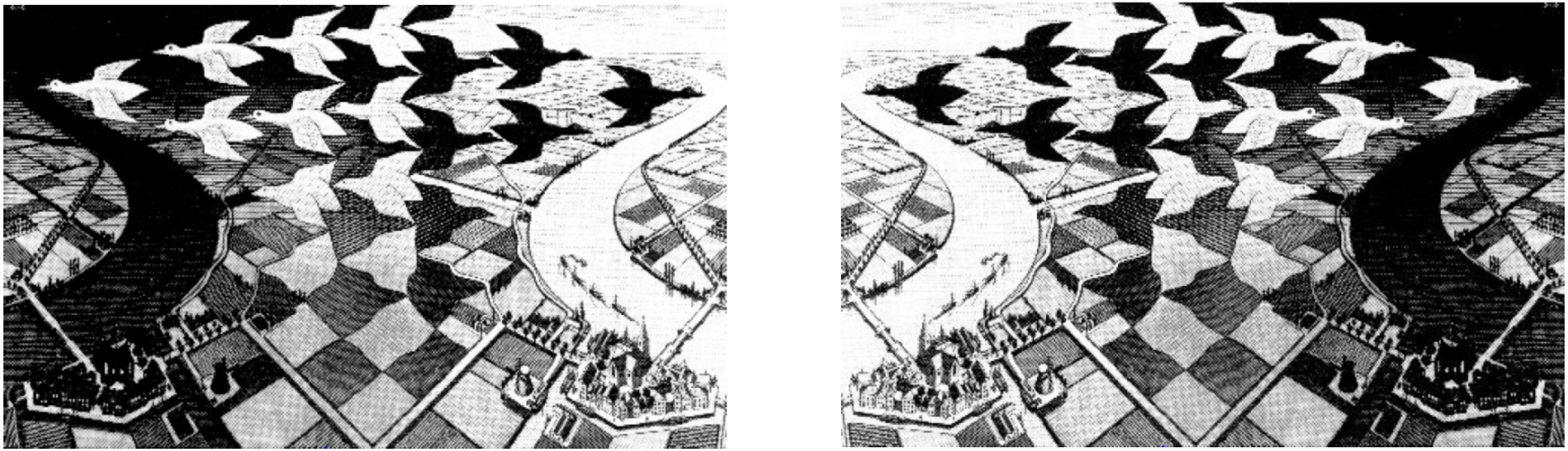


CP Violation

The asymmetry between Matter and AntiMatter

Gerhard Raven, Nikhef and Vrije Universiteit Amsterdam

Outline

1. Antimatter & Big Bang
2. Symmetries and the weak interactions
3. Discovery of CP violation
4. Describing CP violation and the weak interactions
5. CP violation and the Standard Model
6. Testing the Standard Model predictions of CP violation
7. Outlook for future measurements
8. Summary

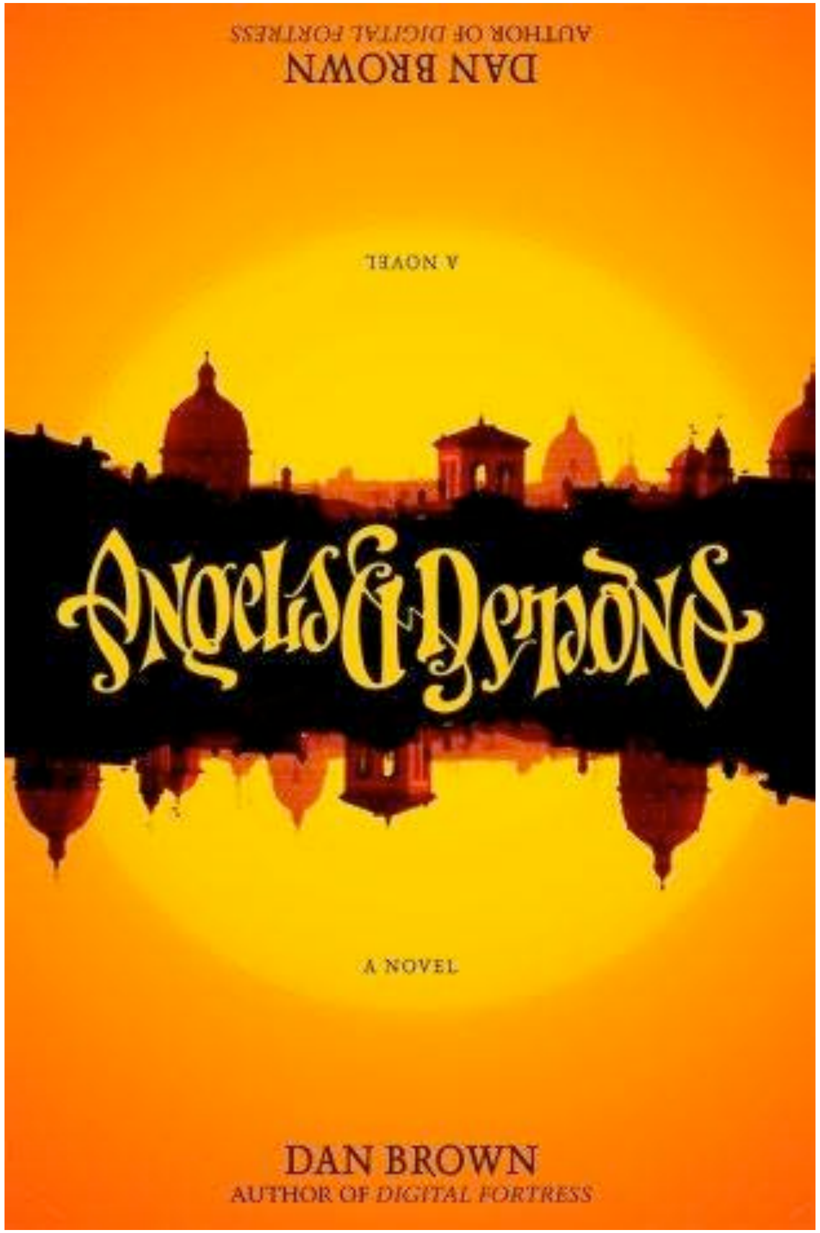
Antimatter

matter and antimatter distinction in different from + versus - charge in electrodynamics

- In Maxwell's theory, if we change all "+" into. "-" and vice-versa, *nothing* happens...

matter & antimatter *can* be distinguished: the "stuff" in the universe is the "matter"

- There must be *some* fundamental difference in the laws of physics...



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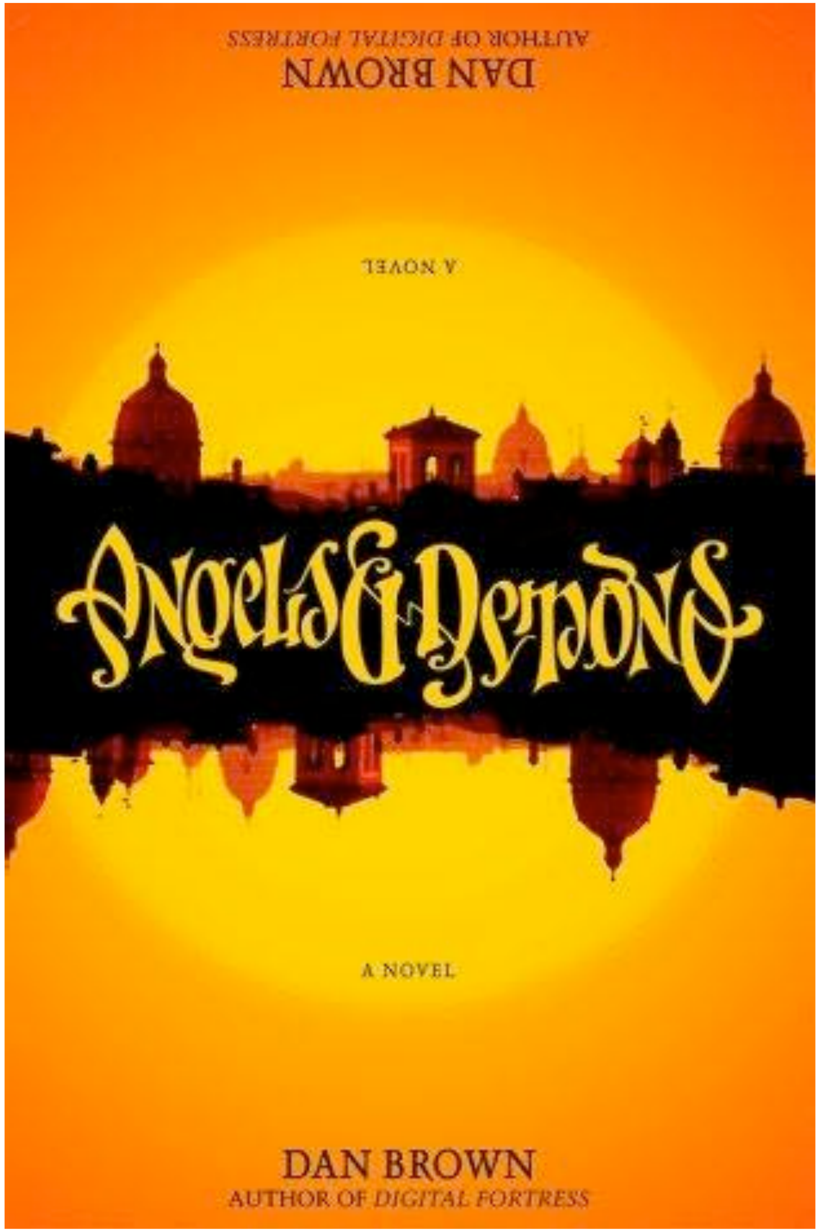
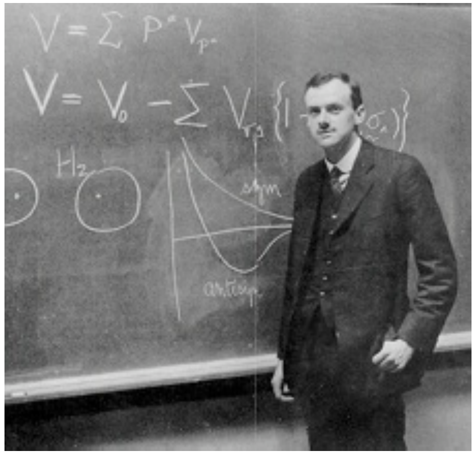


Antiparticles: Dirac's prediction



- Combining quantum mechanics with special relativity, and the wish to *linearize* ∂/∂t, leads Dirac to the equation

$$(i\gamma^\mu \partial_\mu - m)\,\psi(\vec{x}, t) = 0$$

- Solutions describe particles with spin = 1/2

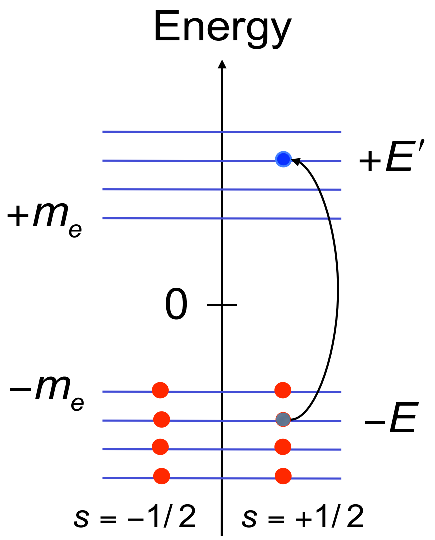
- But half of the solutions have *negative energy*

$$E = \pm\sqrt{\vec{p}^{\,2} + m^2}$$

- Vacuum represents a "sea" of such negative-energy particles (fully filled according to Pauli's principle)

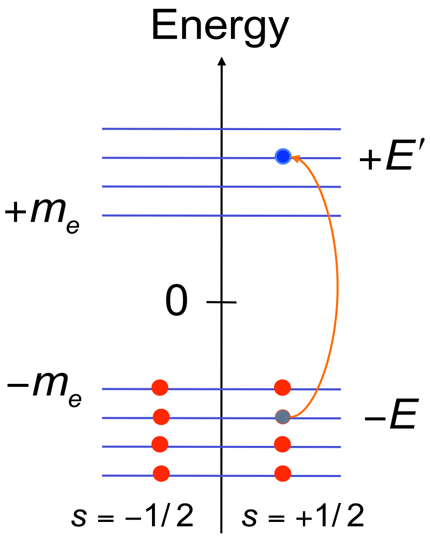
- Dirac identified holes in this sea as "antiparticles" with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought "positrons" would have been discovered already)

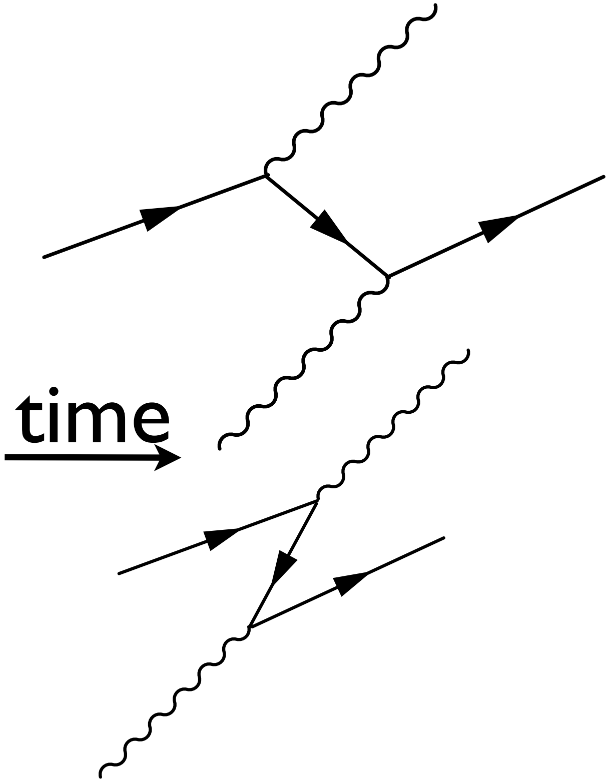
- An electron with energy E can fill this hole, emitting an energy 2E and leaving the vacuum (hence, the hole has effectively the charge +e and positive energy).



This picture fails for bosons !

Antiparticles: Stueckelberg/Feynman





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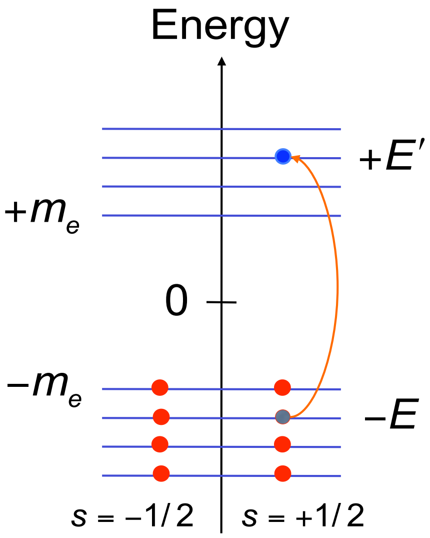
Stueckelberg/Feynman interpretation:

- consider the negative energy solution as *running backwards in time*

Antiparticles: Stueckelberg/Feynman



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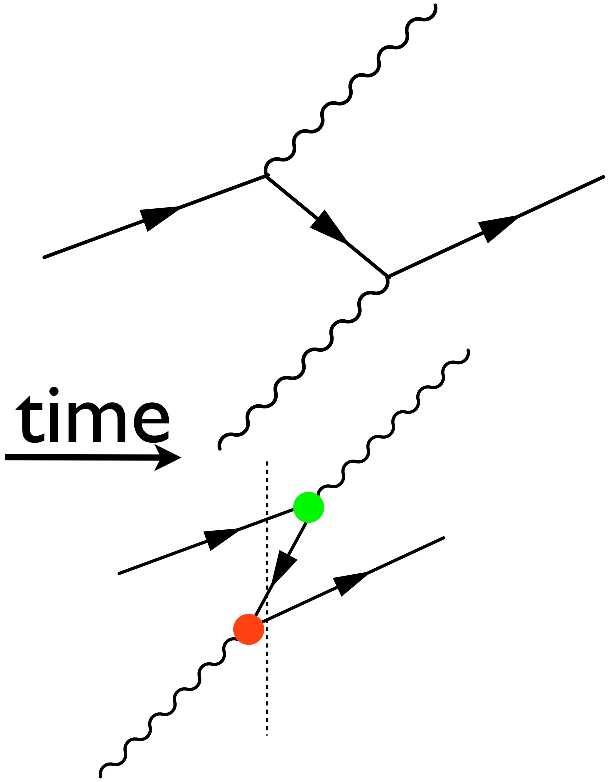
Stueckelberg/Feynman interpretation:



- consider the negative energy solution as *running backwards in time*
- and re-label it as *antiparticle*, with *positive* energy, going forward in time
- emission of E>0 antiparticle = absorption of particle E<0
- Naturally describes *creation* and *annihilation*...
- ... and that particles and antiparticles must have the same mass, spin, ... and opposite charges

Discovery of Antiparticles

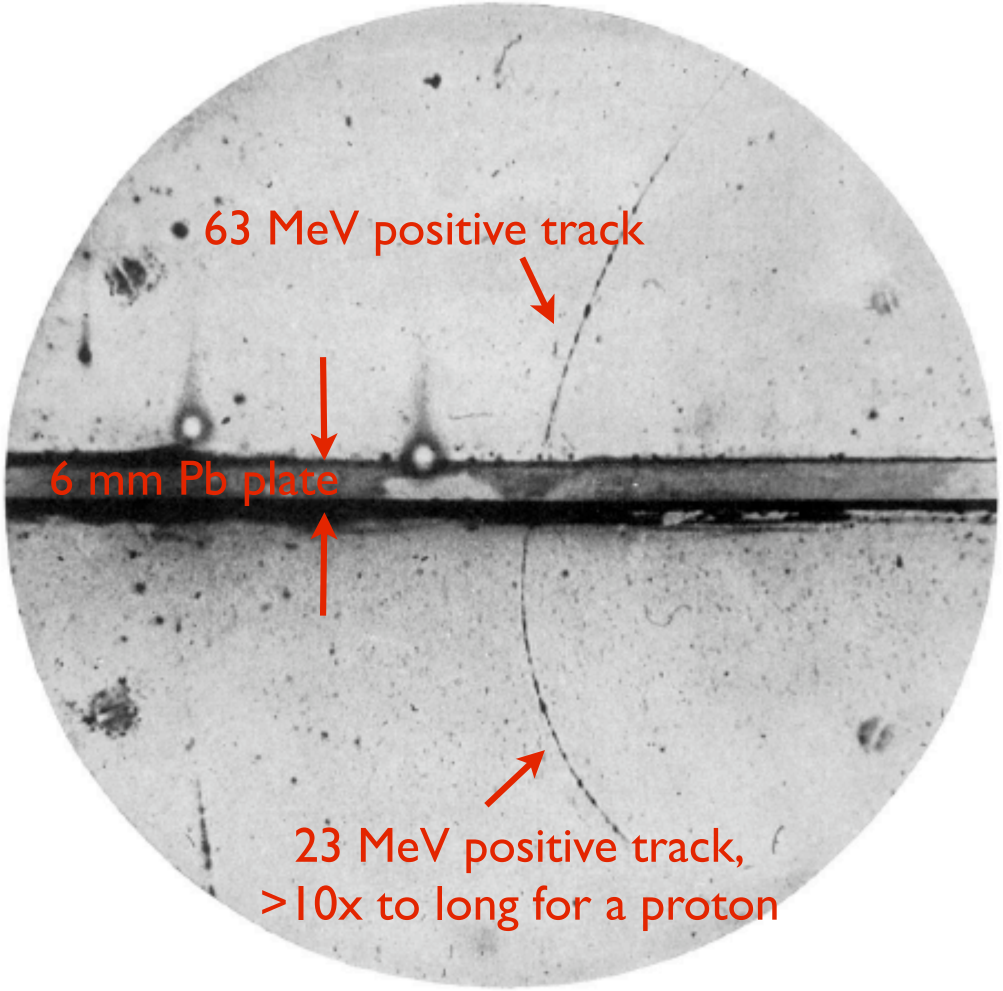
Back to experiment: does antimatter exists, and, if so, where is it?

Carl Anderson studies at cosmic rays on Pikes peak, using a Cloud chamber

Particles will show (temporarily) as condensation trail in gas volume (just like condensation trails of airplanes)

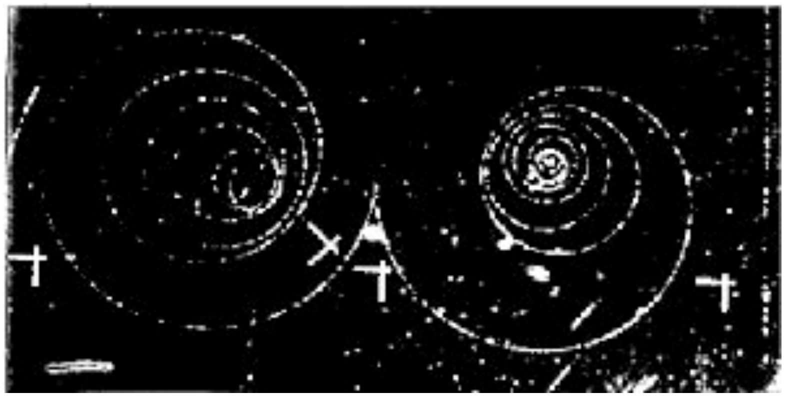
Antiparticles: Anderson’s discovery

- Result: discovery of a positively charged, electron-like particle dubbed the ‘positron’



Antiparticles: Anderson’s discovery

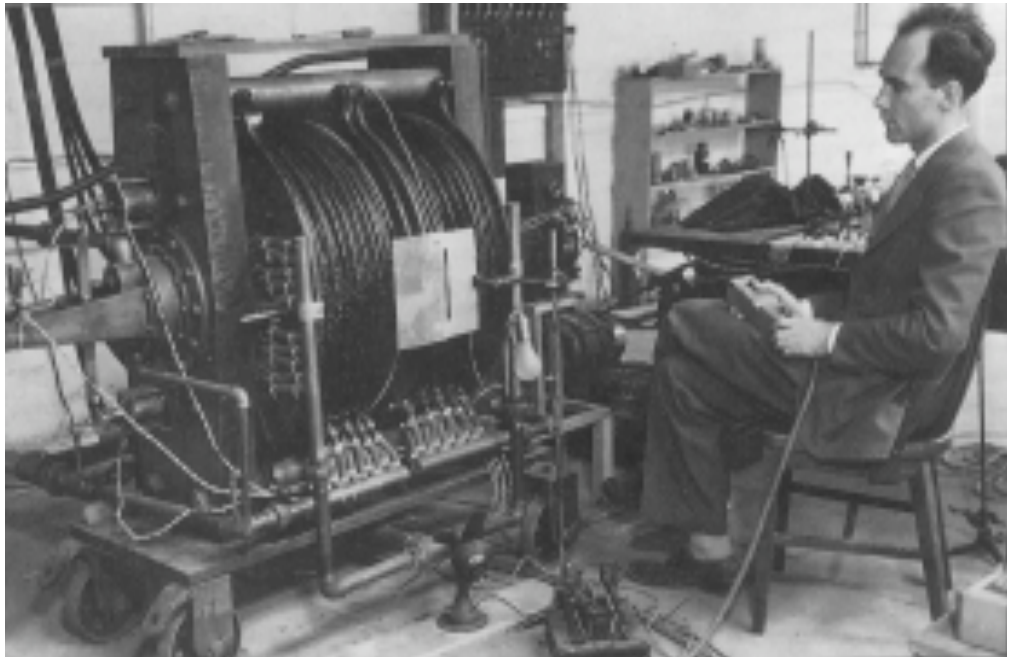
- Confirmed with $\gamma \rightarrow e^+e^-$

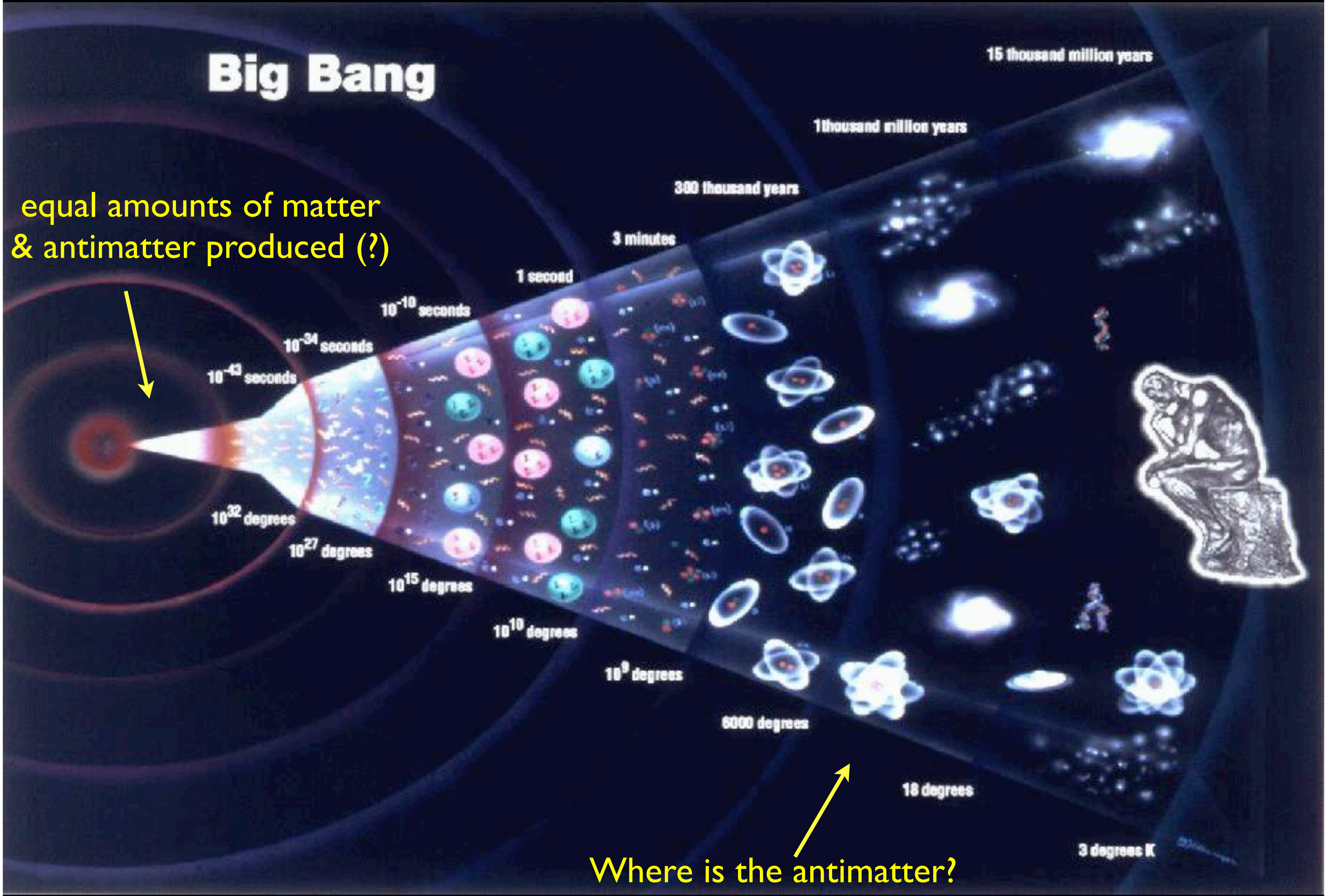


CARL D. ANDERSON

The production and properties of positrons

Nobel Lecture, December 12, 1936

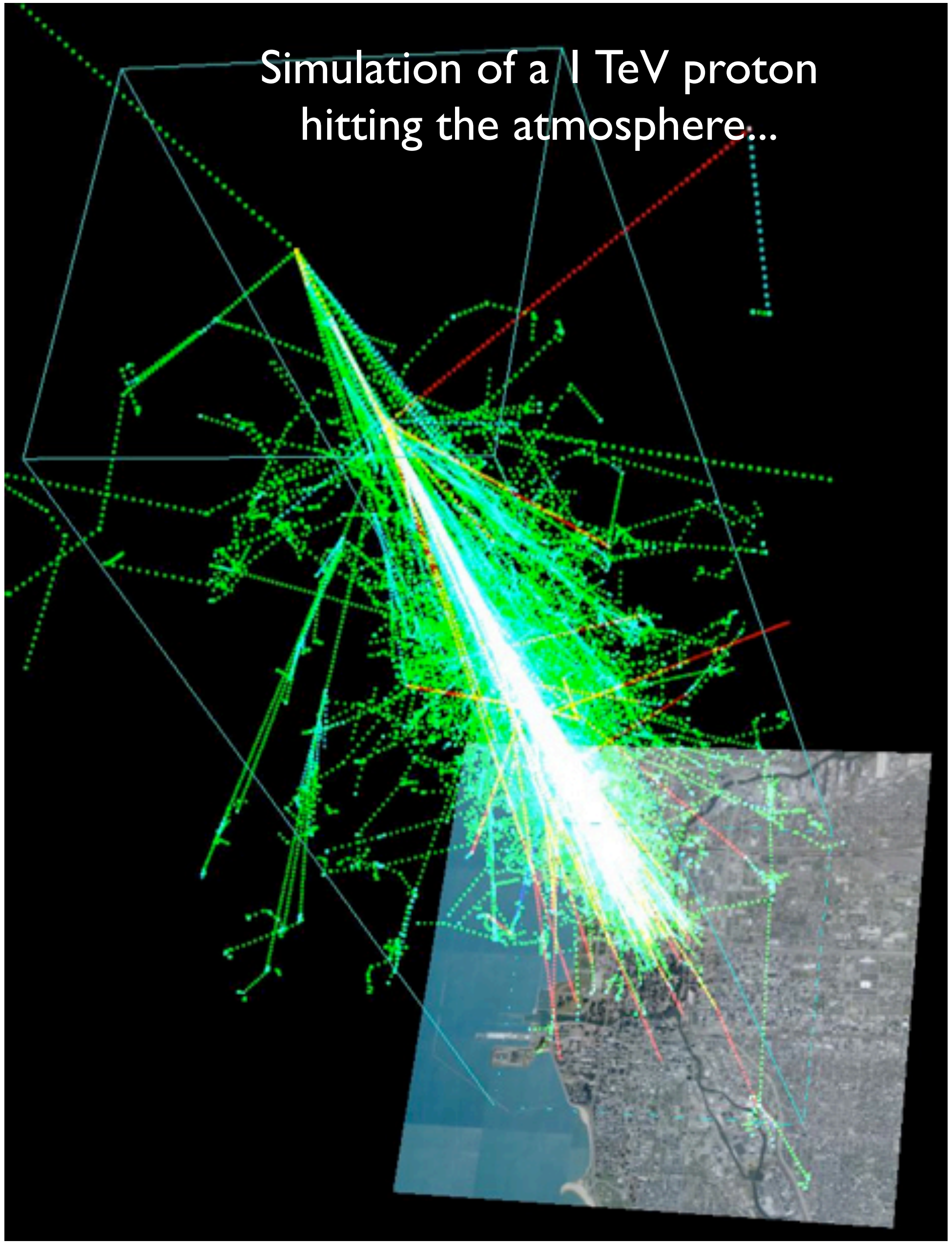




equal amounts of matter
& antimatter produced (?)

Where is the antimatter?

Cosmic Antimatter...


Simulation of a 1 TeV proton hitting the atmosphere...

- Antiparticles appear in cosmic ray showers
- But what about the original incoming (anti?)particle
- Must measure before the shower starts, eg. above the atmosphere..

AntiMatter Searches: AMS

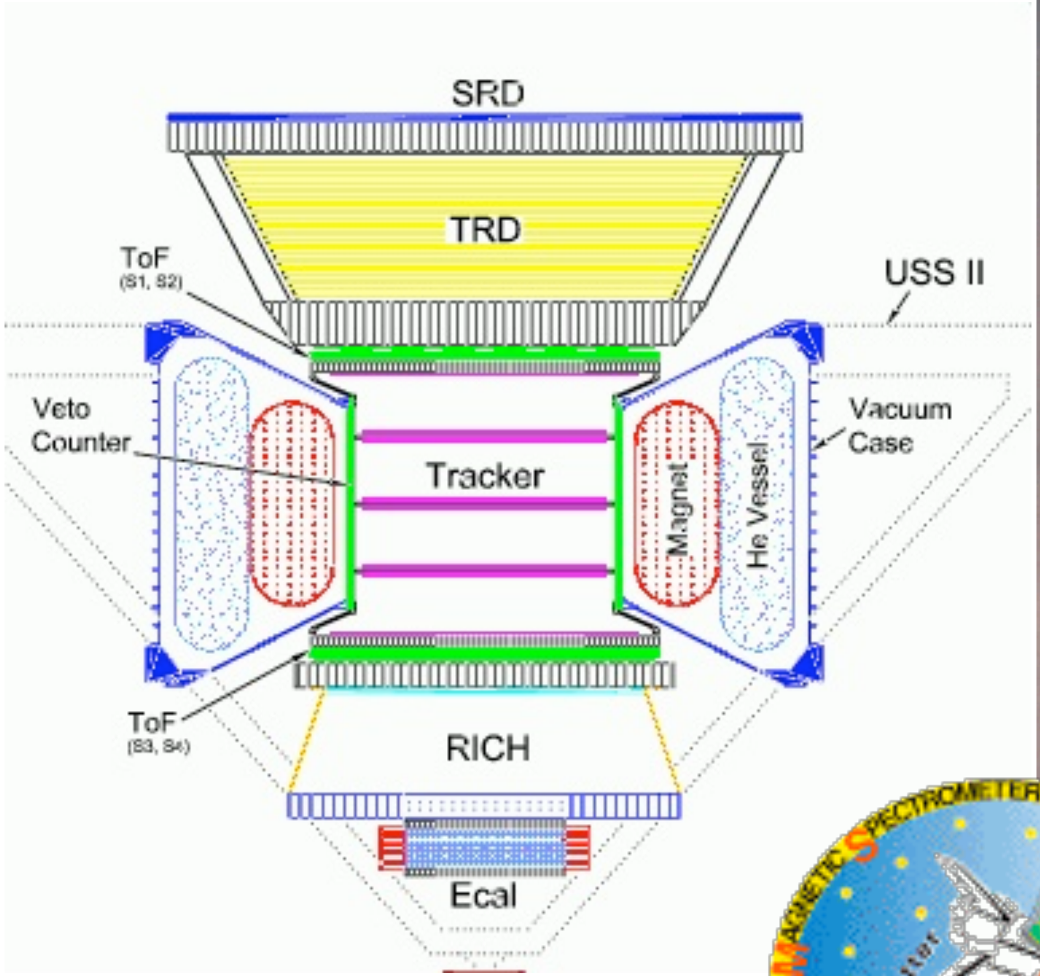
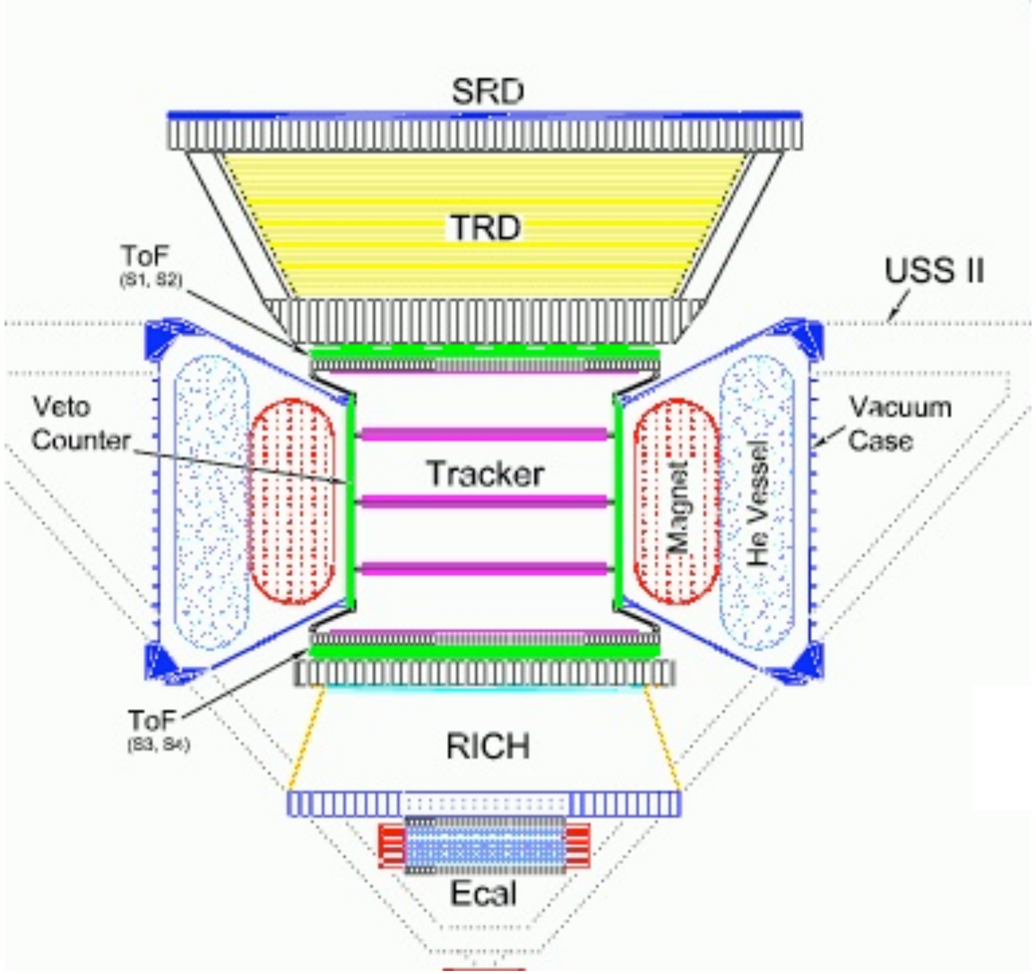
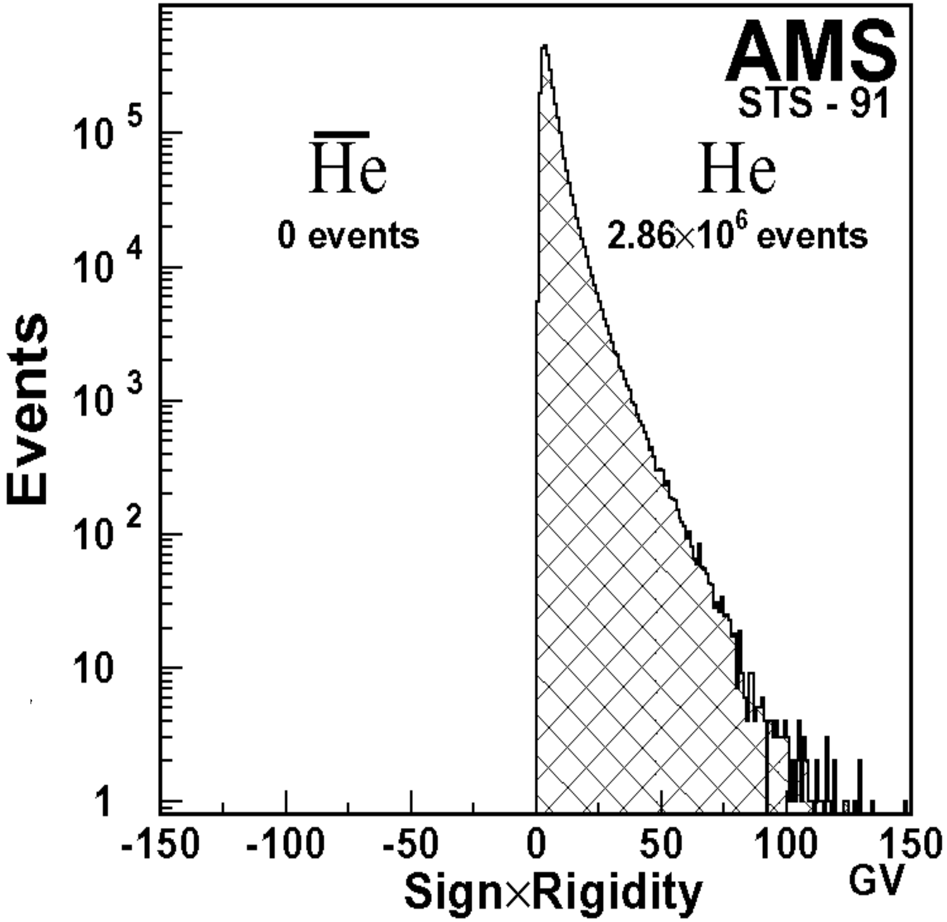


Photo taken from Mir (1998)

AntiMatter Searches: AMS

Look for anti-Helium: very unlikely to have been created as secondary product in collisions...





$$\frac{N_{\overline{\mathrm{He}}}}{N_{\mathrm{He}}} < 1.1 \cdot 10^{-6} \ @ \ 95\% CL$$

AMS-2 currently scheduled for STS-134 (either the last or last but one shuttle flight!) for delivery to the ISS..

Antimatter Searches: Summary

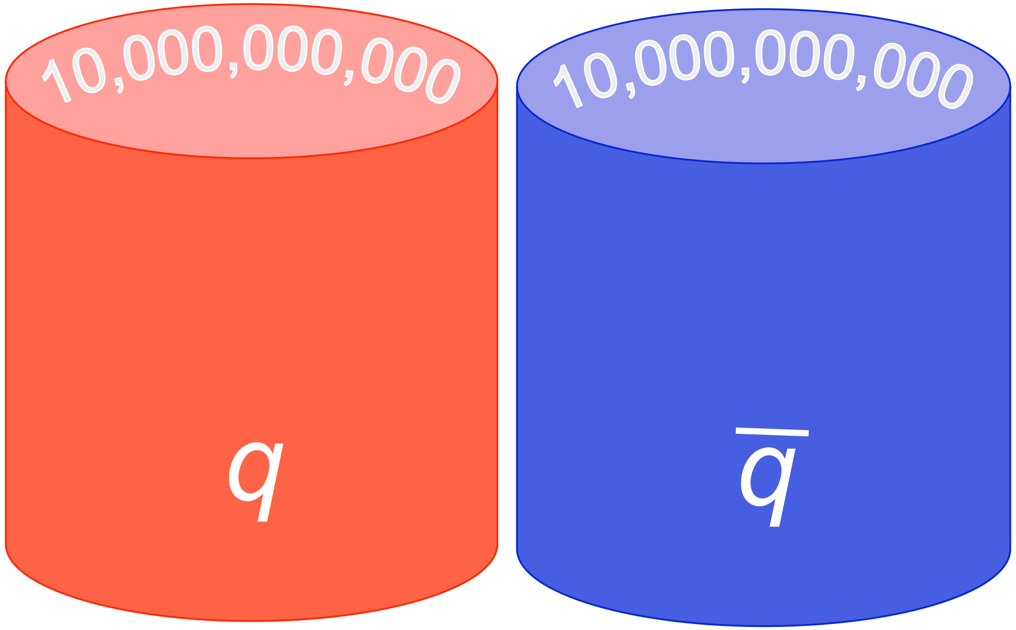
No evidence for the original, “primordial” cosmic antimatter:

- Absence of anti-nuclei amongst cosmic rays in our galaxy
- Absence of intense γ−ray emission due to annihilation of distant galaxies in collision with antimatter

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter

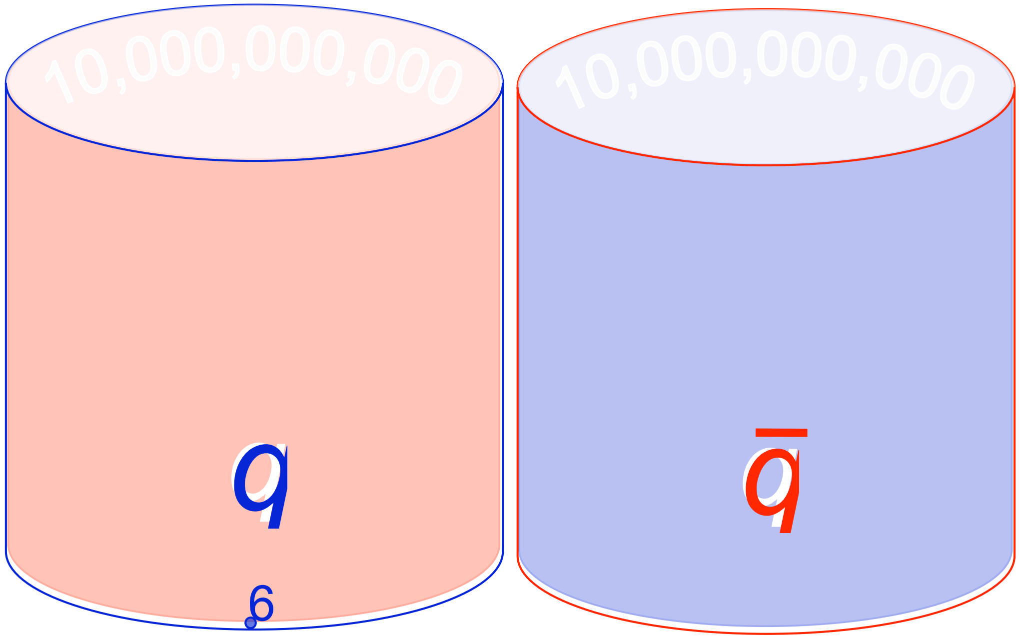


Early universe

Antimatter & the Big Bang

Big Bang:

- Create equal amounts of matter & antimatter
- Somewhere along the way, one (matter) is favored
- Final result : a bit of matter and *lots* of photons
  - $N_{baryons}/N_{photons} \cong 6\ 10^{-10}$



Current universe

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov

Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

Sakharov's conditions on the Big Bang

- In 1967, Sakharov formulated three necessary conditions to generate universe with a baryon asymmetry:

  1. a process that violates baryon number
  2. C and CP violation, i.e. breaking of the C and CP *symmetries*
  3. 1 & 2 should occur during a phase which is NOT in thermal equilibrium

- These lectures will focus on 2.

Andrei Sakharov
"Father" of Soviet hydrogen bomb
& Nobel Peace Prize Winner

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter

Symmetries

Instructions by the VOC (Dutch East India Company) in Aug 1642:

"Since many rich mines and other treasures have been found in countries north of the equator between 15° and 40° latitude, there is no doubt that countries alike exist south of the equator. The provinces in Peru and Chili rich of gold and silver, all positioned south of the equator, are revealing proofs hereof."

Abel Tasman discovered Tasmania (Nov. 1642), New Zealand (Dec. 1642), Fiji (Jan 1643), ...

From the point of view of the VOC, this was a disappointment..

Abel Tasman

Symmetries & "Hidden Observables"

"The root to all symmetry principles lies in the assumption that it is impossible to observe certain basic quantities; the non-observables"

1. Space translation symmetry:
   Hidden observable: **Absolute position**
   Conserved quantity: momentum

2. Time shift symmetry:
   Hidden observable: **Absolute time**
   Conserved quantity: Energy

3. Rotation symmetry:
   Hidden observable: **Absolute orientation**
   Conserved quantity: Angular momentum

T.D. Lee

See Noether's theorem for more details

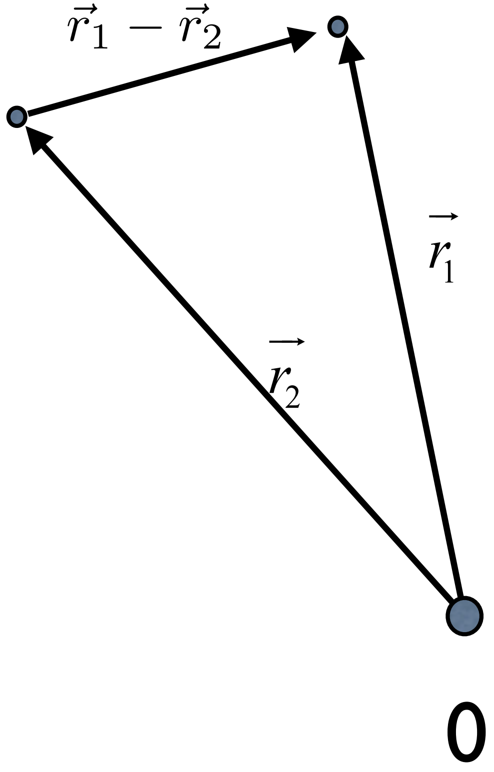
Symmetry & "Hidden Observable"

- Example: Potential energy between two charged particles:

$$V = V\left(\vec{r_1} - \vec{r_2}\right)$$

- translate origin by $\vec{d}$:

$$\begin{aligned} \vec{r}_1 &\longrightarrow \vec{r}_1 - \vec{d} \\ \vec{r}_2 &\longrightarrow \vec{r}_2 - \vec{d} \end{aligned}$$



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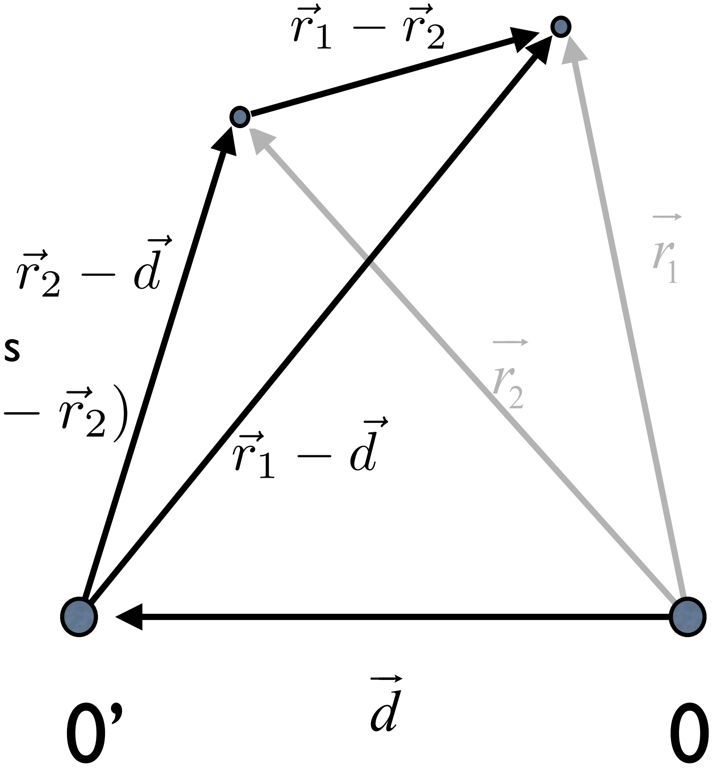
$$\vec{r}_1 \quad \longrightarrow \quad \vec{r}_1 - \vec{d}$$
$$\vec{r}_2 \quad \longrightarrow \quad \vec{r}_2 - \vec{d}$$

- V is *invariant* under translations

$$V\left(\vec{r_1} - \vec{r_2}\right) \rightarrow V\left(\vec{r_1} - \vec{r_2}\right)$$

- System is *symmetric* under translations



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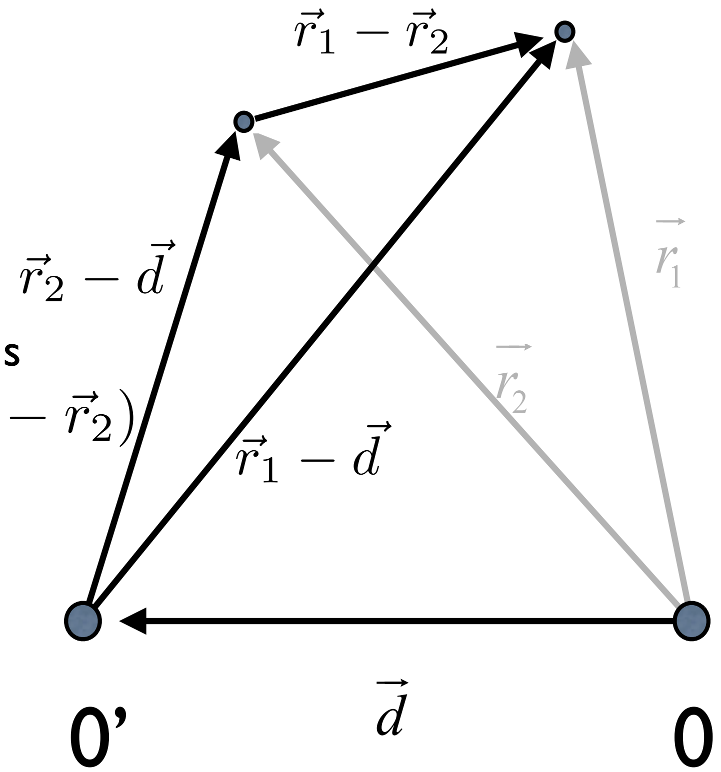

- Absolute position is a non-observable: the interaction is independent of the choice of origin.

- Result: total momentum is conserved

$$\frac{d}{dt}\left(\vec{p}_1 + \vec{p}_2\right) = -\left(\vec{\nabla}_1 + \vec{\nabla}_2\right) V\left(\vec{r_1} - \vec{r}_2\right) = 0$$

See Noether's theorem for more details

Symmetry & "Hidden Observable"

- Example: Potential energy between two charged particles:

$$V = V\left(\vec{r_1} - \vec{r_2}\right)$$

- translate particles by $\vec{d}$:

$$\vec{r}_1 \quad \rightarrow \quad \vec{r}_1 + \vec{d}$$
$$\vec{r}_2 \quad \rightarrow \quad \vec{r}_2 + \vec{d}$$

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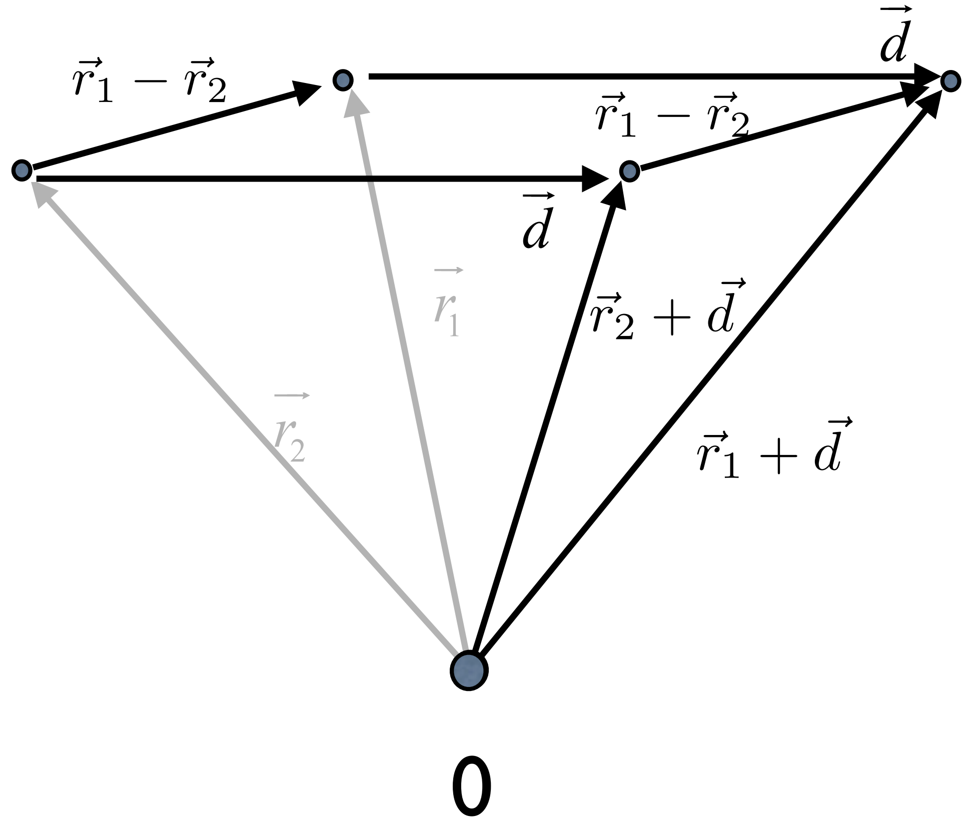

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See Noether's theorem for more details

Discrete Symmetries

- Space, time translation & orientation symmetries are all *continuous* symmetries
  - Each symmetry operation associated with one ore more continuous parameter
- There are also *discrete* symmetries
  - Spatial sign flip (x,y,z → -x,-y,-z) : P
  - Charge sign flip (Q → -Q) : C
  - Time sign flip (t → -t) : T
- Are these discrete symmetries exact symmetries that are observed in nature?
  - Key issue of these lectures

Quantity		P	C	T
Space vector	$\mathbf{x}$	$-\mathbf{x}$	$\mathbf{x}$	$\mathbf{x}$
Time	t	t	t	$-t$
Momentum	$\mathbf{p}$	$-\mathbf{p}$	$\mathbf{p}$	$-\mathbf{p}$
Spin	$\mathbf{s}$	$\mathbf{s}$	$\mathbf{s}$	$-\mathbf{s}$
Electrical field	$\mathbf{E}$	$-\mathbf{E}$	$-\mathbf{E}$	$\mathbf{E}$
Magnetic field	$\mathbf{B}$	$\mathbf{B}$	$-\mathbf{B}$	$-\mathbf{B}$

Discrete Symmetries

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In particle physics:

$$P\left|e_L^-\right\rangle = \left|e_R^-\right\rangle$$

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

$$P\left|n\right\rangle = +\left|n\right\rangle$$

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

$$C\left|u\right\rangle = \left|\overline{u}\right\rangle$$

$$C\left|d\right\rangle = \left|\overline{d}\right\rangle$$

$$C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$

note: the definition of a 'left handed' particle will follow in 'a few slides' time

Discrete Symmetries

- *No* evidence that electromagnetic & strong forces break C, P or T
- Example: π^0 decay into photons

$$\pi^0 = \frac{1}{\sqrt{2}}\left[u\overline{u} - d\overline{d}\right]_{L=0,S=0} \quad \Rightarrow \quad C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$
$$C \cdot \vec{B} = -\vec{B}; C \cdot \vec{E} = -\vec{E} \quad \Rightarrow \quad C\left|\gamma\right\rangle = -\left|\gamma\right\rangle$$

- π^0 decays to two photons, but not three!
- Initial *and* final states are C even, thus C is conserved!
- Experimental test of P and C conservation in EM interaction:
  - C invariance: $Br(\pi^0 \rightarrow \gamma\gamma\gamma) < 3.1\ 10^{-5}$
  - P invariance: $Br(\eta \rightarrow \pi^0 \pi^0 \pi^0 \pi^0) < 6.9\ 10^{-7}$
- Experimental test of C invariance in strong interaction:
  - compare rates of positive and negative particles in eg. $p\overline{p} \longrightarrow \pi^+\pi^- X, K^+K^- X, \ldots$

CPT theorem

"Any Lorentz-invariant local quantum field theory is invariant under the successive application of *C*, *P* and *T* "

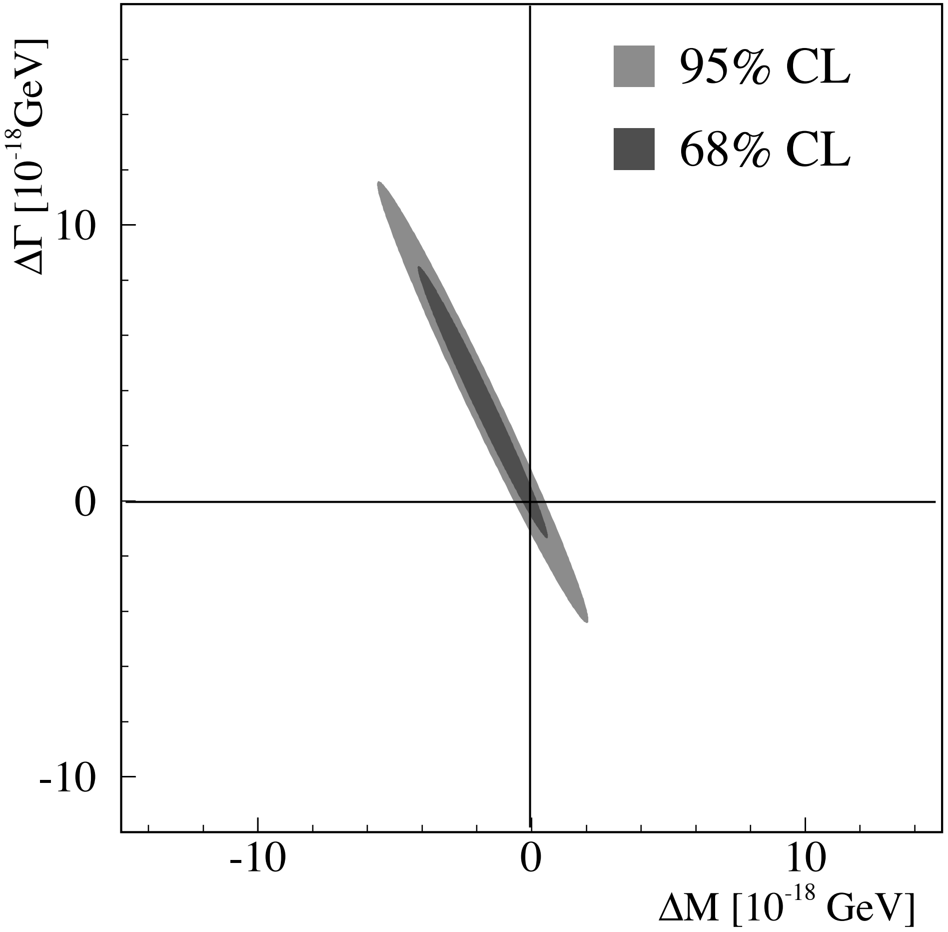
G. Lüders, W. Pauli (1954); J. Schwinger (1951)

Assumptions:

1. Lorentz invariance
2. "principle of locality"
3. Causality
4. Vacuum lowest energy
5. Flat space-time
6. Point-like particles

Consequences:

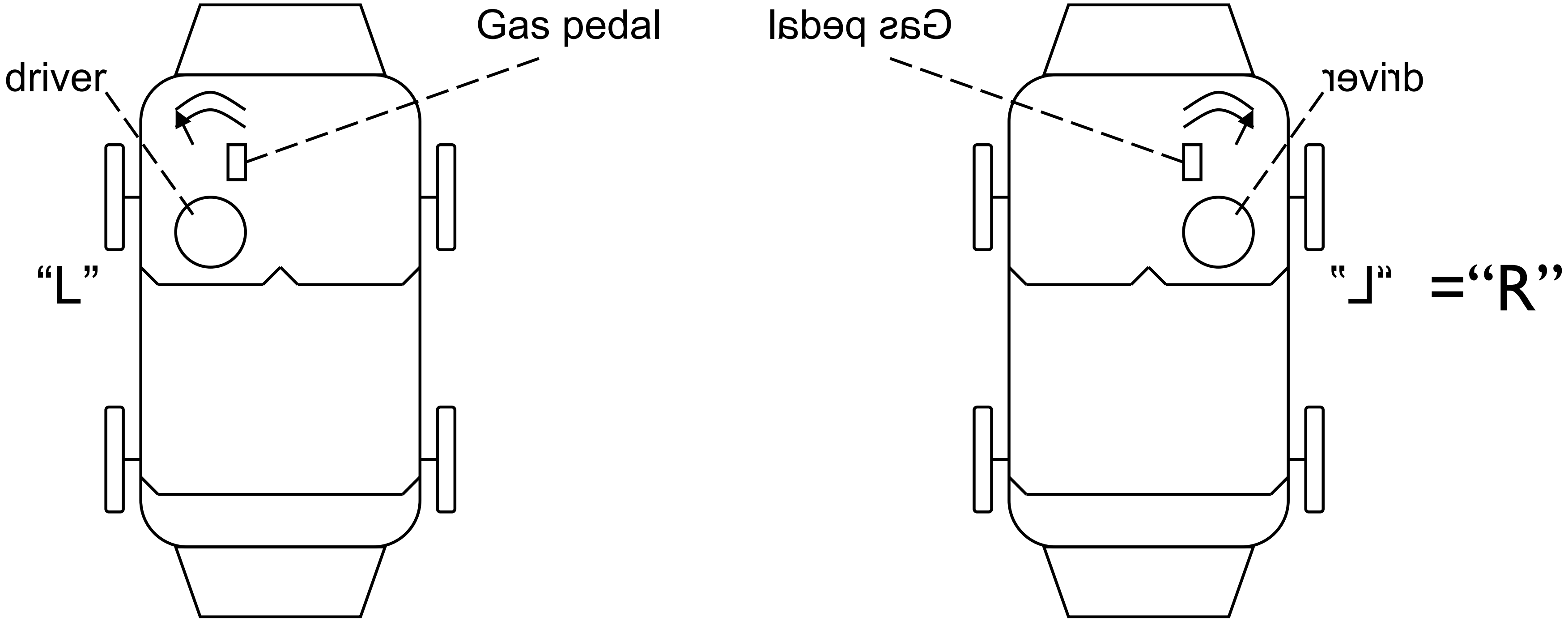
1. Relation between spin and statistics: fields with integer spin commute and fields with half-numbered spin anticommute; Pauli exclusion principle
2. Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**



$$\frac{M(K^0) - M(\overline{K^0})}{\left(M(K^0) + M(\overline{K^0})\right)/2} < 10^{-17}(95\%CL)$$

Parity

- Before 1956 physicists were *convinced* that the laws of nature were left-right symmetric. Strange?
  - A “gedanken” experiment:
    Consider two perfectly mirror symmetric cars:



What would happen if the ignition mechanism uses, say, ^{60}Co β decay?

The θ-τ puzzle

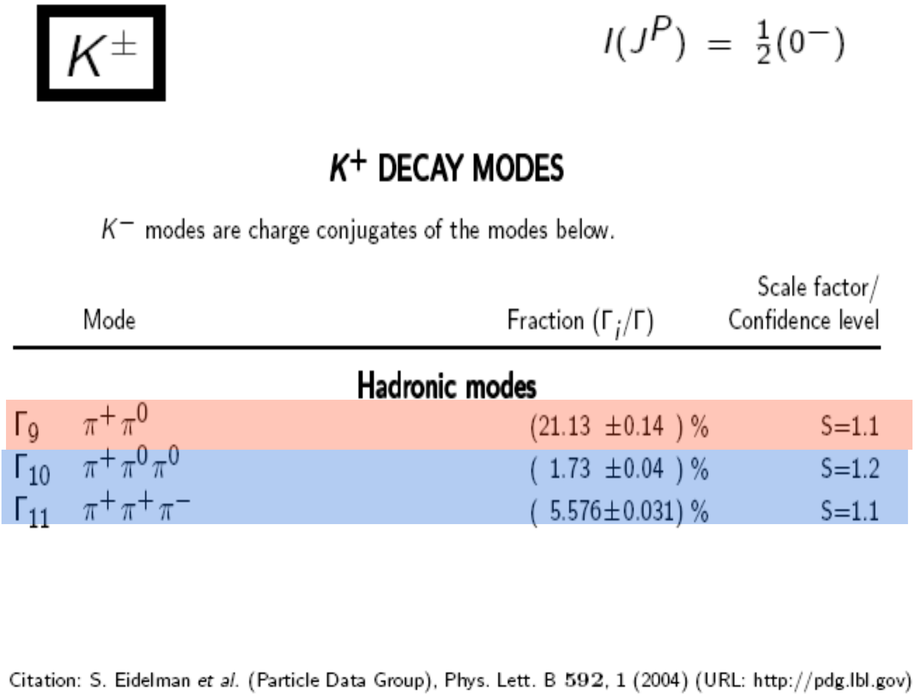
Observation of decays to two pions and three pions, but whatever decays (now known as K^+), has, in both decays, the same lifetime, mass, spin=0...

In 1953, Dalitz argued that since the pion has parity of -1,

- two pions (*) would combine to produce a net parity of (-1)(-1) = +1,
- and three pions (*) would combine to have total parity of (-1)(-1)(-1) = -1.

Hence, if conservation of parity holds, there are two *distinct* particles with parity +1 (the ‘θ’) and parity -1 (the ‘τ’)(**).

But how to explain the fact that the mass and lifetime are the same?



$K^\pm$ $I(J^P) = \frac{1}{2}(0^-)$

K^+ DECAY MODES

K^- modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Hadronic modes		
Γ_9	$\pi^+\pi^0$	(21.13 ±0.14) %	S=1.1
Γ_{10}	$\pi^+\pi^0\pi^0$	(1.73 ±0.04) %	S=1.2
Γ_{11}	$\pi^+\pi^+\pi^-$	(5.576±0.031) %	S=1.1

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

(*) produced in the decay of a spin=0 mother

(**) Warning: do not confuse this ‘τ’ with what is now known as the τ lepton...

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

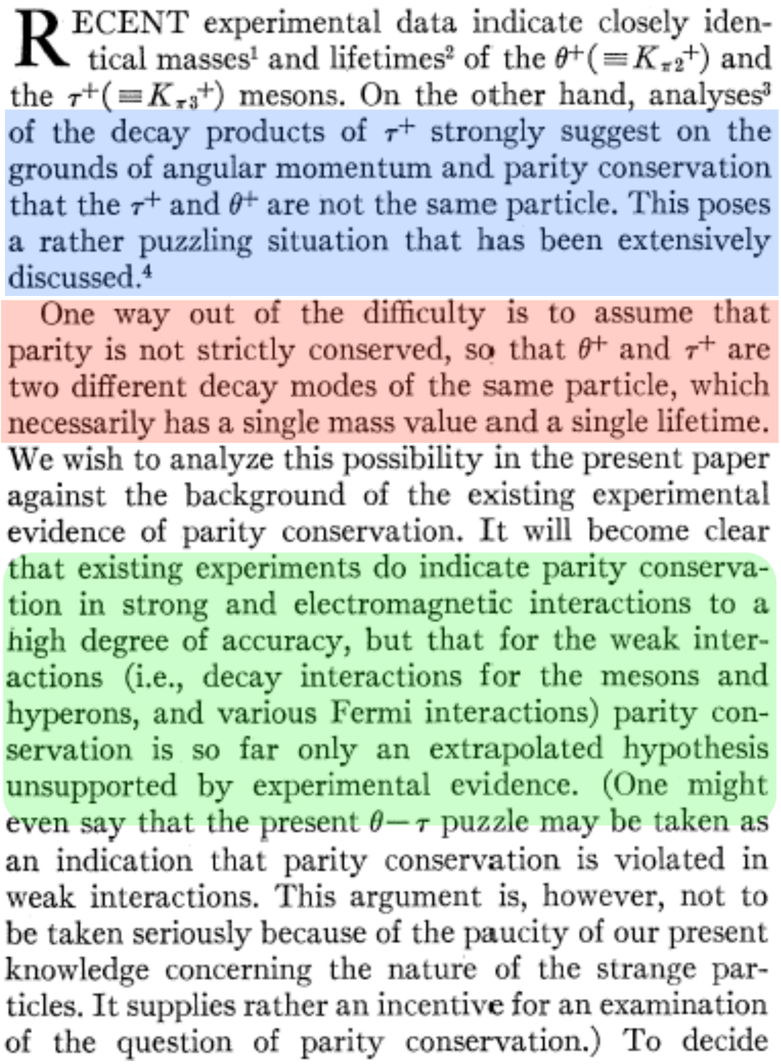
T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

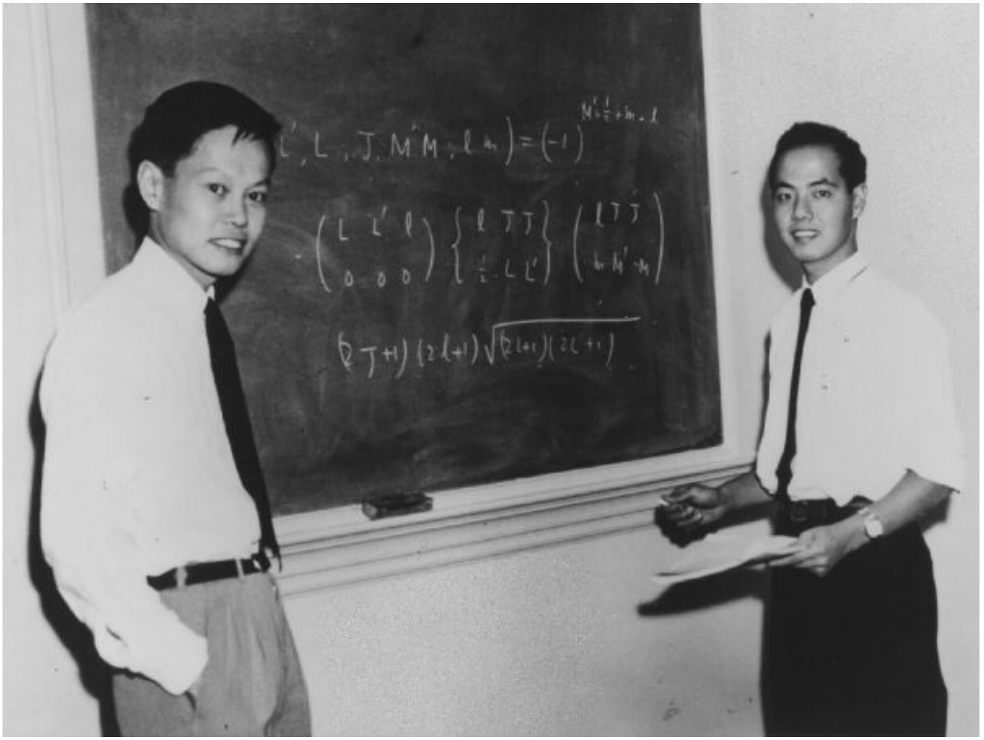
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.



RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

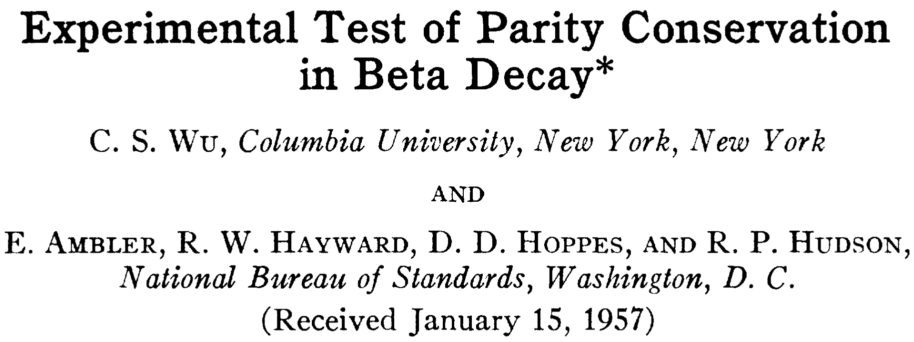
One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as an indication that parity conservation is violated in weak interactions. This argument is, however, not to be taken seriously because of the paucity of our present knowledge concerning the nature of the strange particles. It supplies rather an incentive for an examination of the question of parity conservation.) To decide



The Nobel Prize in Physics 1957

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

The Exprimental (Re)Solution...



Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

Idea for experiment in collaboration with Lee and Yang: *Look at spin of decay products of polarized radioactive nucleus*

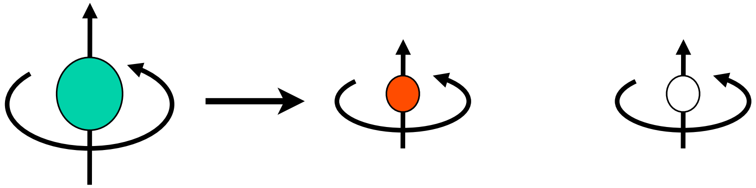
- Production mechanism involves exclusively weak interaction

Mme. Chien-Shiung Wu

Parity & Spin

How does the decay of a particle with spin tell you something about parity?

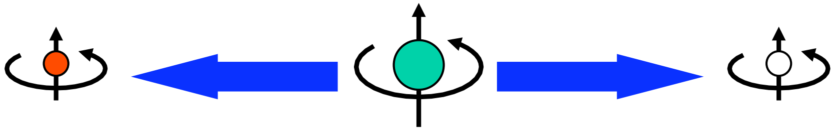
Gedanken-experiment: decay of a spin-1 particle to two spin-½ particles



- Spin: $|1,1\rangle \rightarrow |\frac{1}{2}, \frac{1}{2}\rangle + |\frac{1}{2}, \frac{1}{2}\rangle$
- It is important that initial state is maximally polarized: only then there is a single solution for the spin of the decay products. If not, e.g.
  - $|1,0\rangle \rightarrow |\frac{1}{2}, +\frac{1}{2}\rangle + |\frac{1}{2}, -\frac{1}{2}\rangle$
  - $|1,0\rangle \rightarrow |\frac{1}{2}, -\frac{1}{2}\rangle + |\frac{1}{2}, +\frac{1}{2}\rangle$

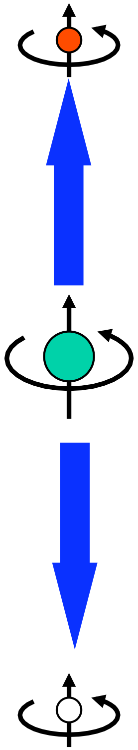
Parity & Spin

- A possible orientation



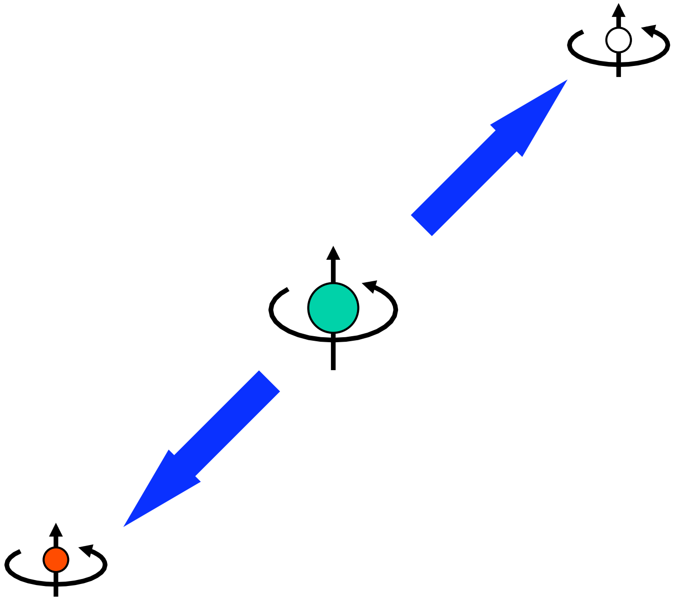
Parity & Spin

- A possible orientation
- And another...



Parity & Spin

- A possible orientation
- And another...
- And another...



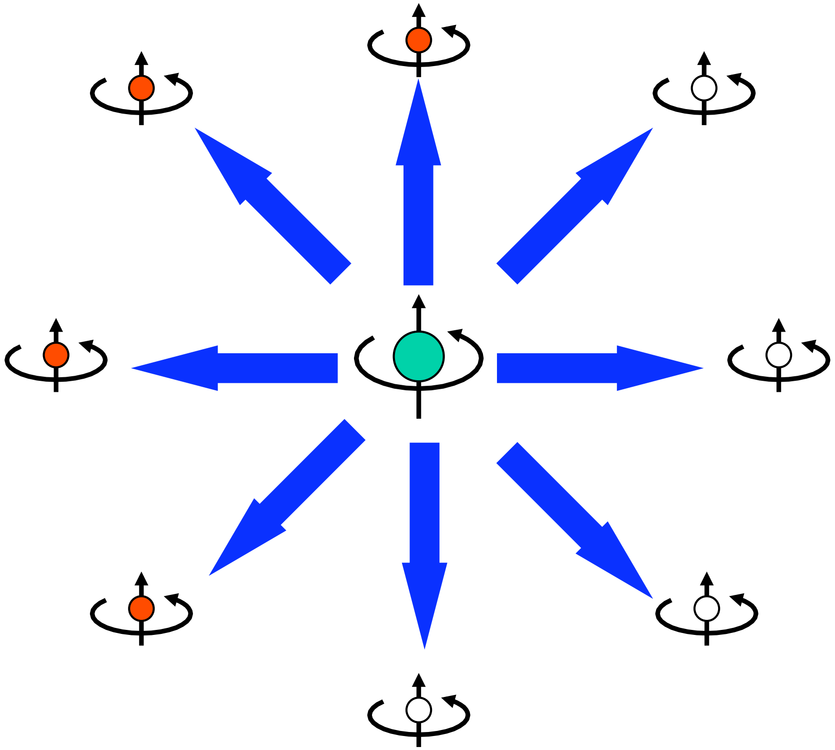
Parity & Spin: Helicity

- A possible orientation
- And another...
- And another...
- Introduce projection of spin on momentum, the helicity, to distinguish:

$$H = \frac{\vec{S}\cdot\vec{P}}{\left|\vec{S}\cdot\vec{P}\right|}$$

- Under parity transform H→-H
- If parity conserved, no reason to favour one value of H over another

$$H = +1 \;\; \text{"Right Handed"}$$

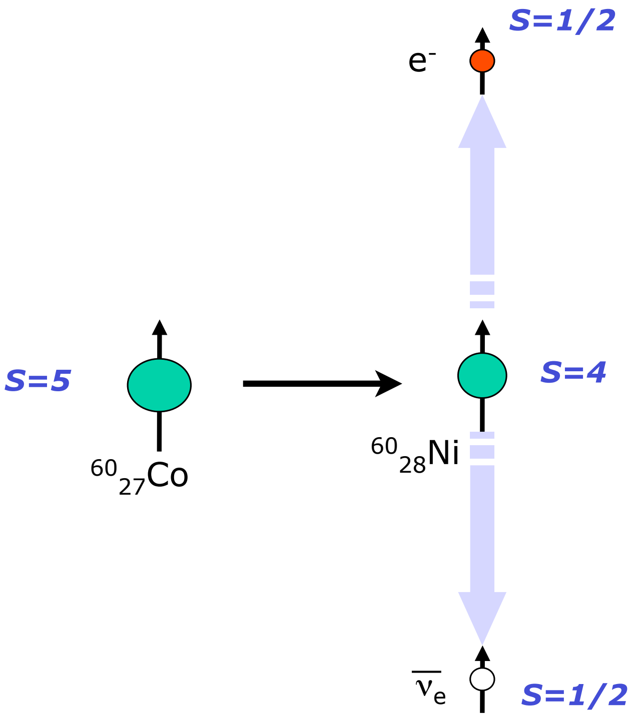


$$H = -1 \;\; \text{"Left Handed"}$$

warning:
helicity assignment is not Lorentz invariant for massive particles: an observer can boost 'past' such that p changes direction.

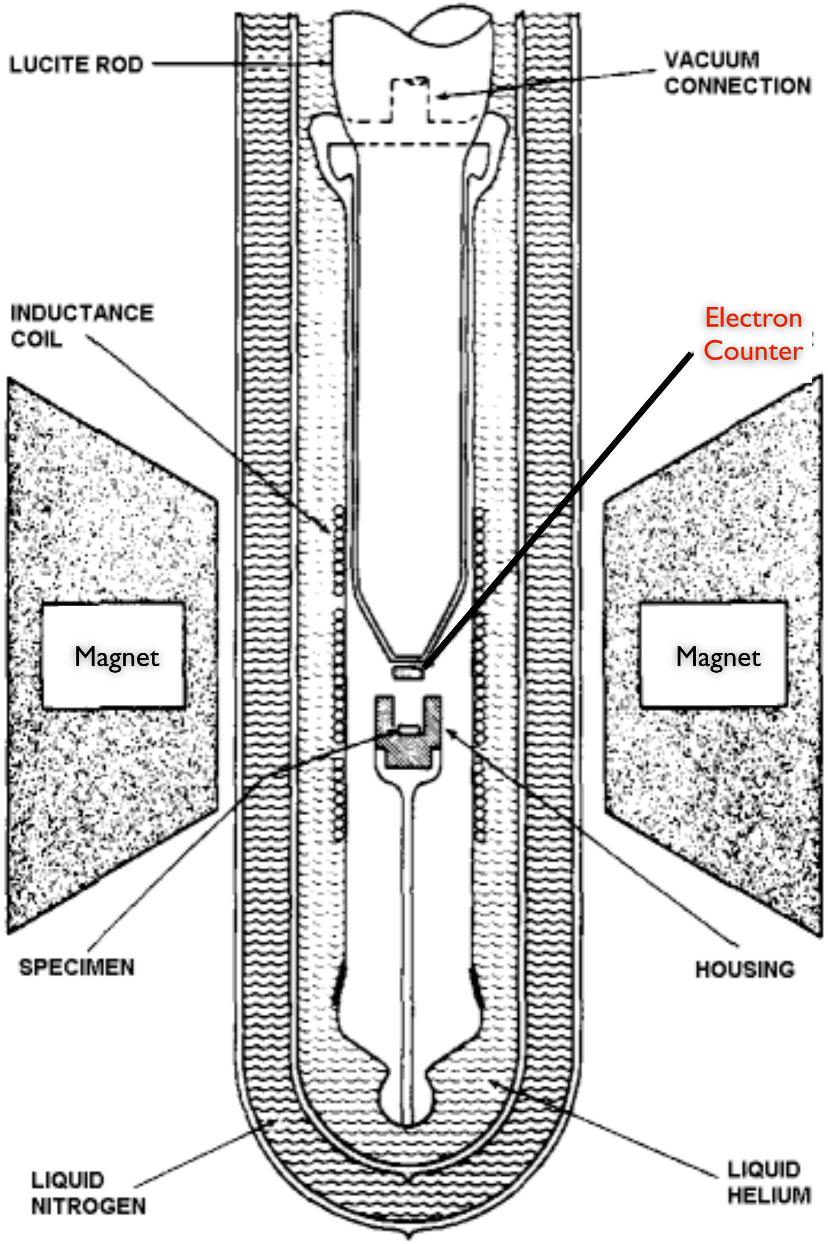
For more details, please check on the difference between 'chirality' and 'helicity'

Mme Wu’s Experiment : setup



- How do you obtain a sample of ^{60}Co with spins aligned in one direction, and compare to non-aligned case?

- Adiabatic demagnitization of ^{60}Co in a magnetic field at very low temperatures (~0.01 K!). Extremely challenging in 1956!



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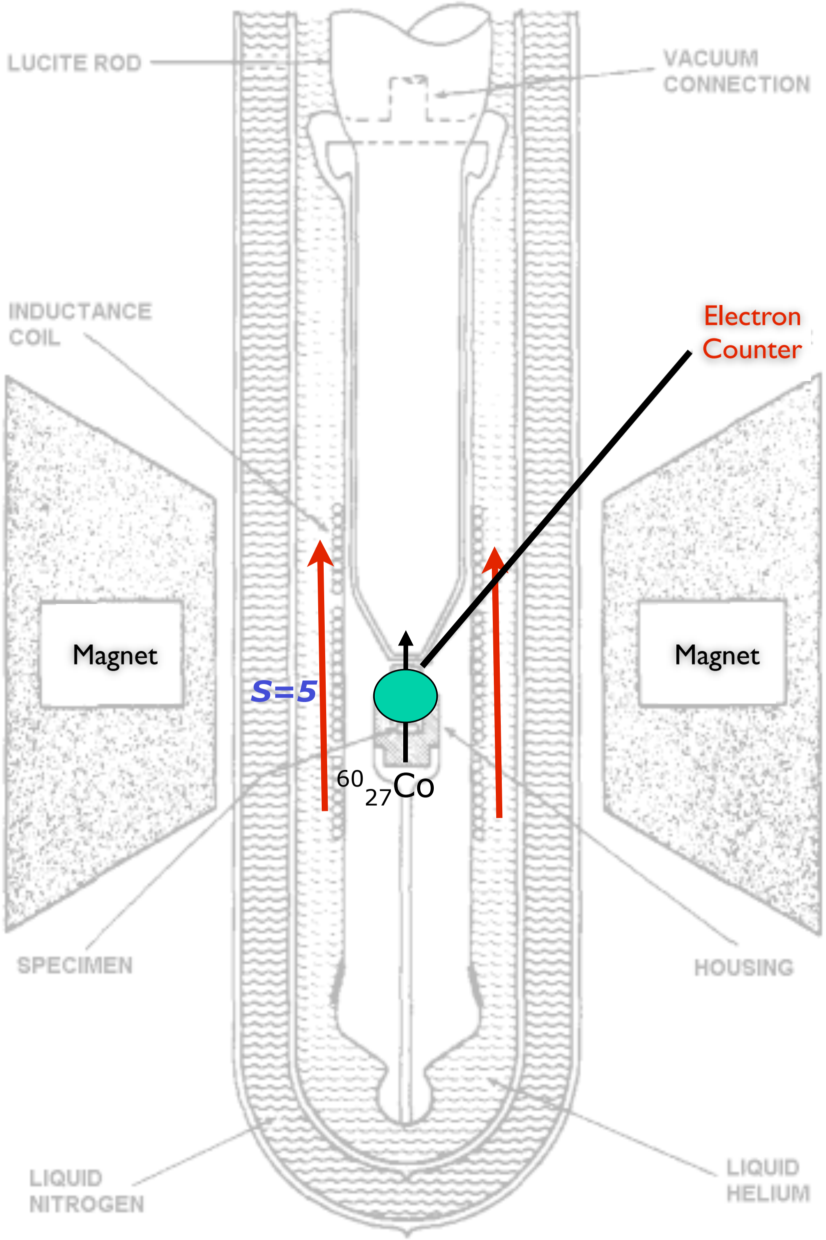

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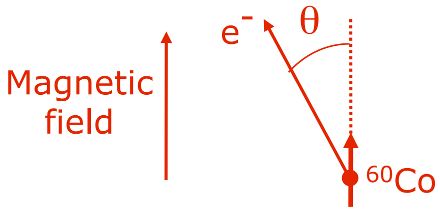

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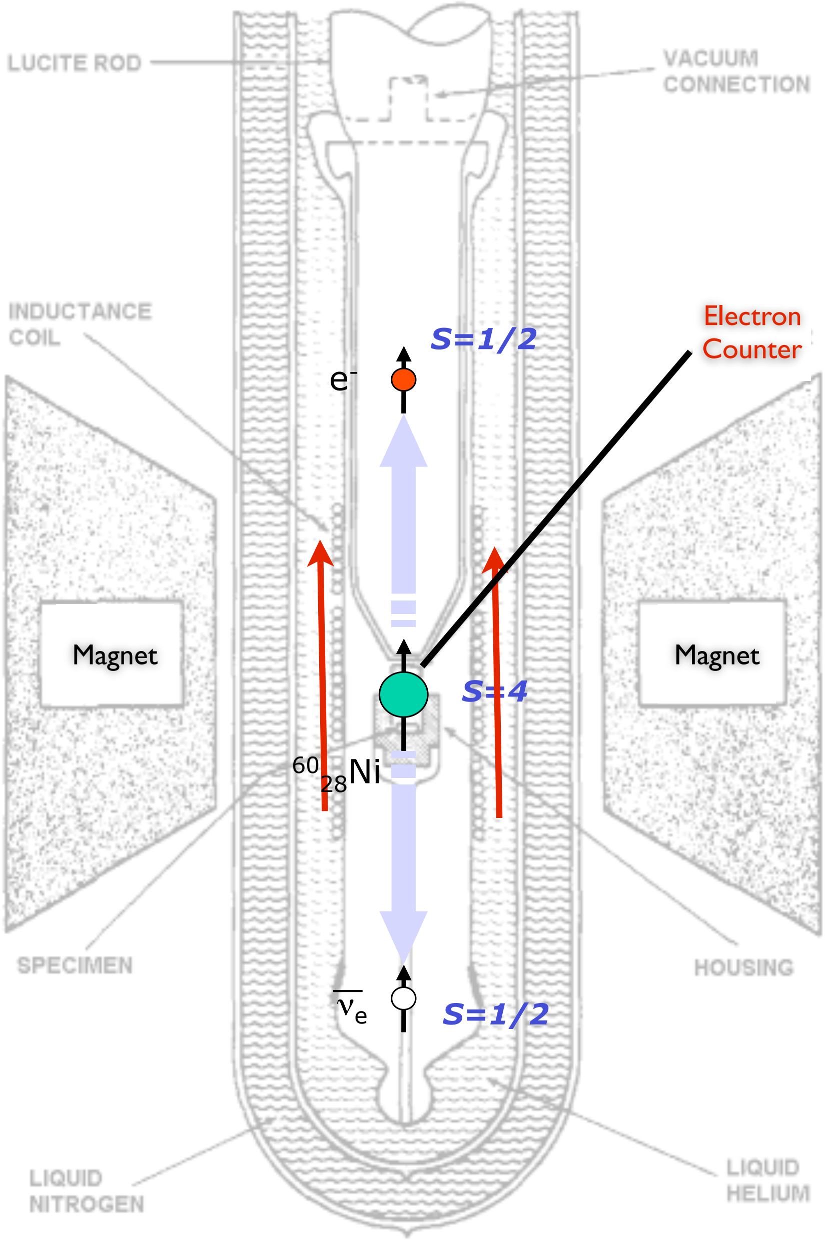

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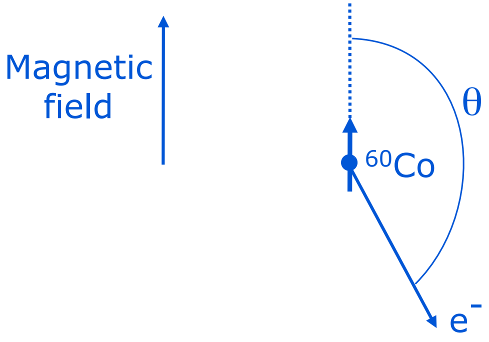

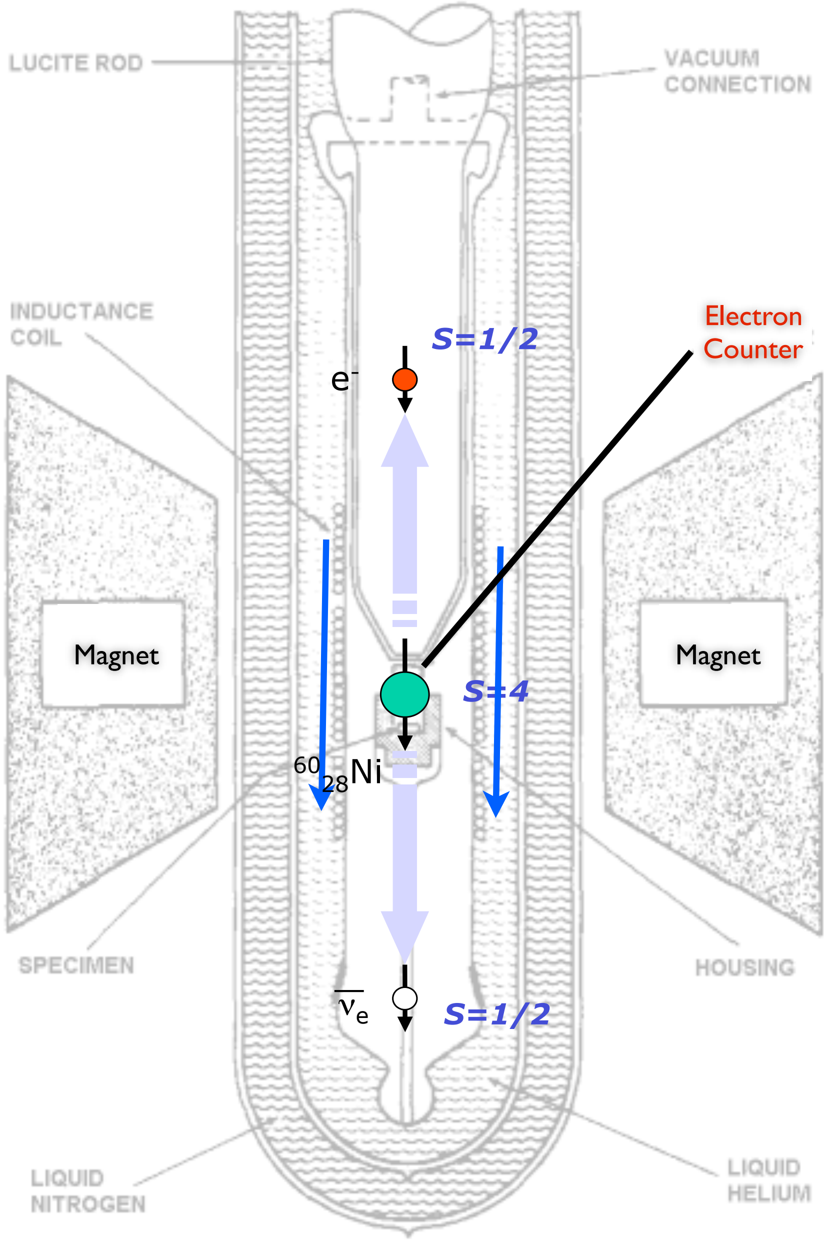

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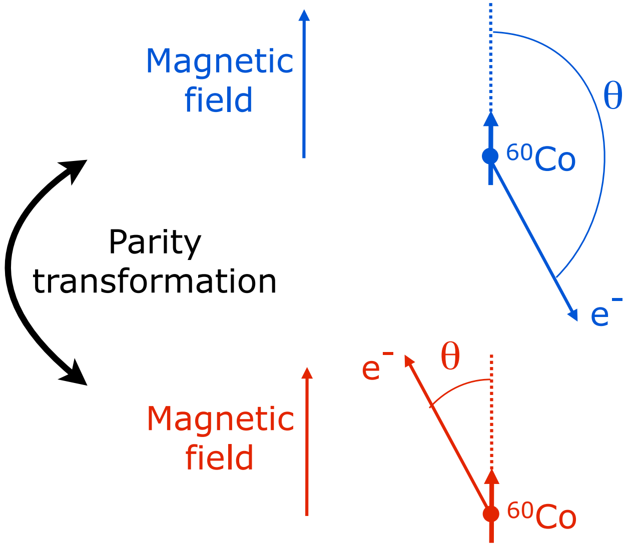
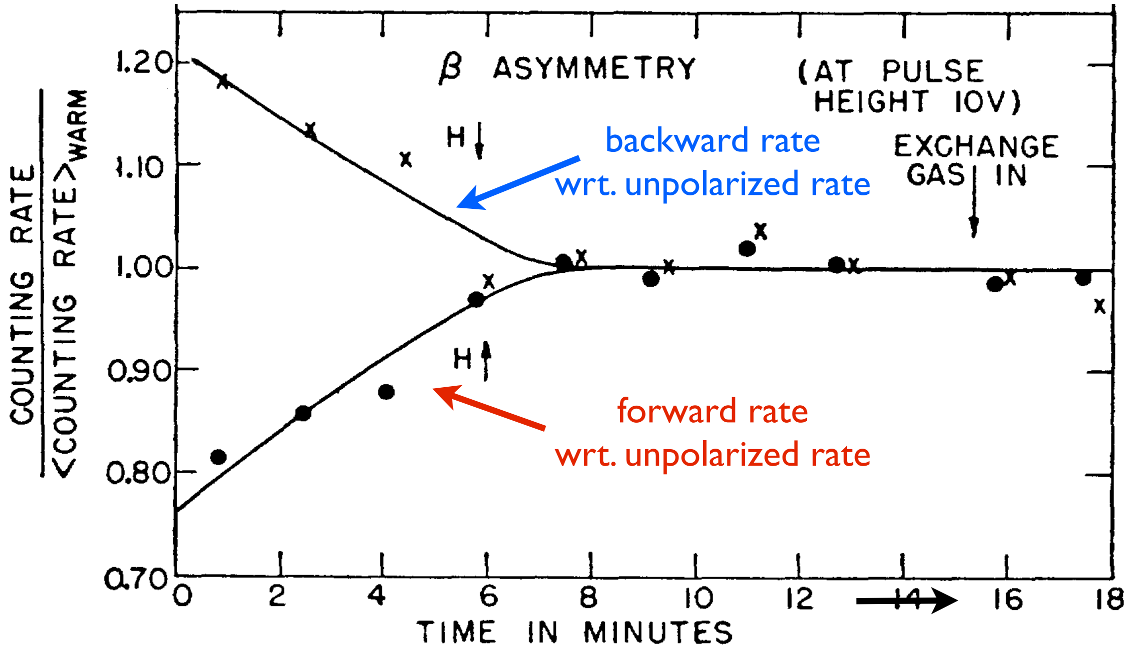
Mme Wu's Experiment : result

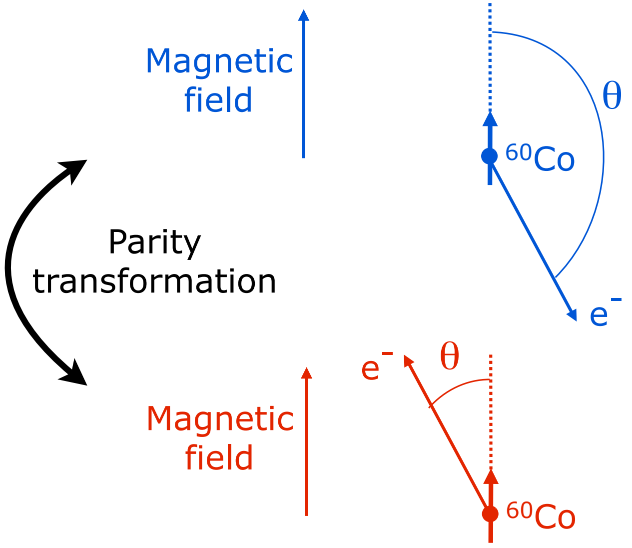


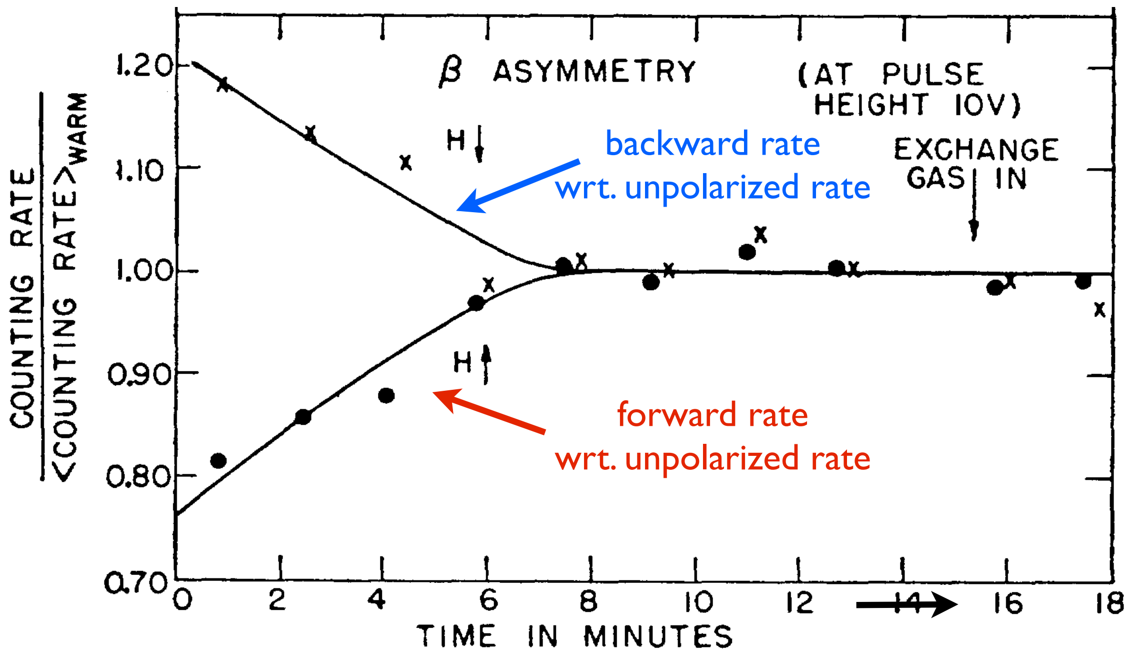


^{60}Co polarization decreases as a function of time as the temperature increases

- The counting rate in the polarized case is different from the unpolarized case
- Changing the direction of the B-field changes the counting rate!
- Electrons are preferentially emitted in the direction opposite the ^{60}Co spin!

Mme Wu's Experiment : conclusion





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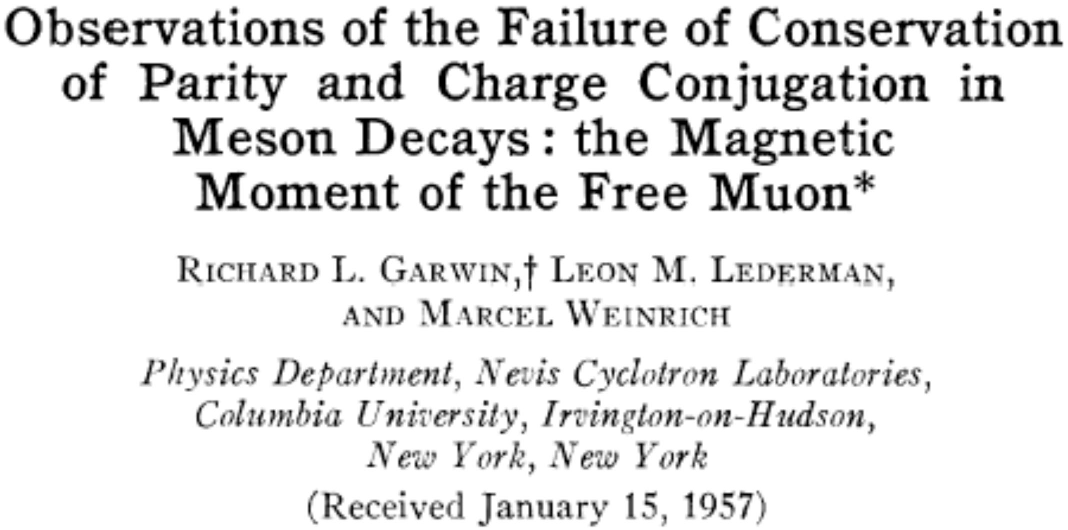
- The counting rate in the polarized case is different from the unpolarized case
- Changing the direction of the B-field changes the counting rate!
- Electrons are preferentially emitted in the direction opposite the ^{60}Co spin!
- Analysis of the results shows that data consistent with the emission of only left-handed (i.e. H = -1) electrons ....
- ... and thus only *right-handed anti-neutrinos*

From P to C,P and C P



Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

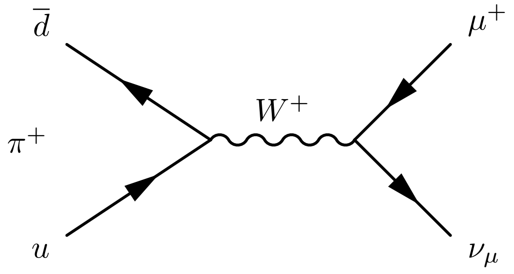
RICHARD L. GARWIN,† LEON M. LEDERMAN,
AND MARCEL WEINRICH

*Physics Department, Nevis Cyclotron Laboratories,
Columbia University, Irvington-on-Hudson,
New York, New York*

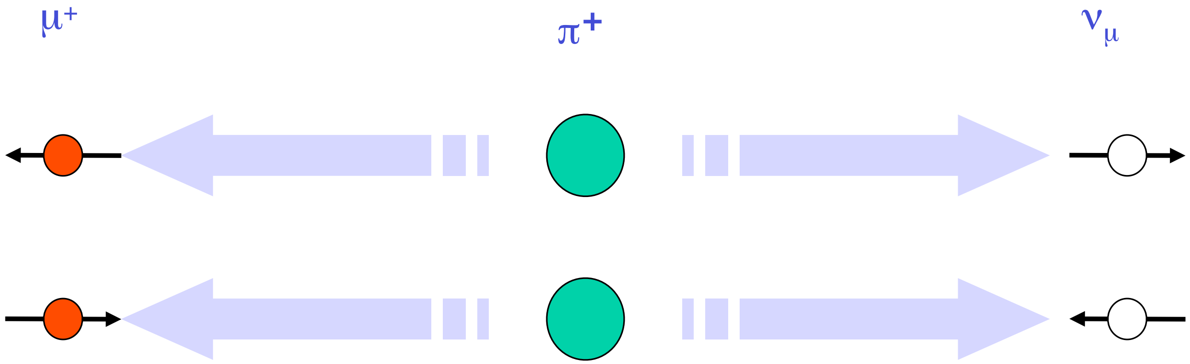
(Received January 15, 1957)

Leon M. Lederman

From P to C,P and CP



- Lederman et al.: Look at decay $\pi^+ \to \mu^+ \nu_\mu$
    - Pion has spin 0; μ,ν_μ both have spin ½
      → spin of decay products must be *oppositely* aligned
      → Helicity of muon is the *same* as that of neutrino.



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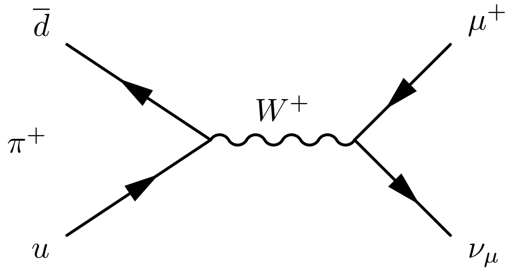

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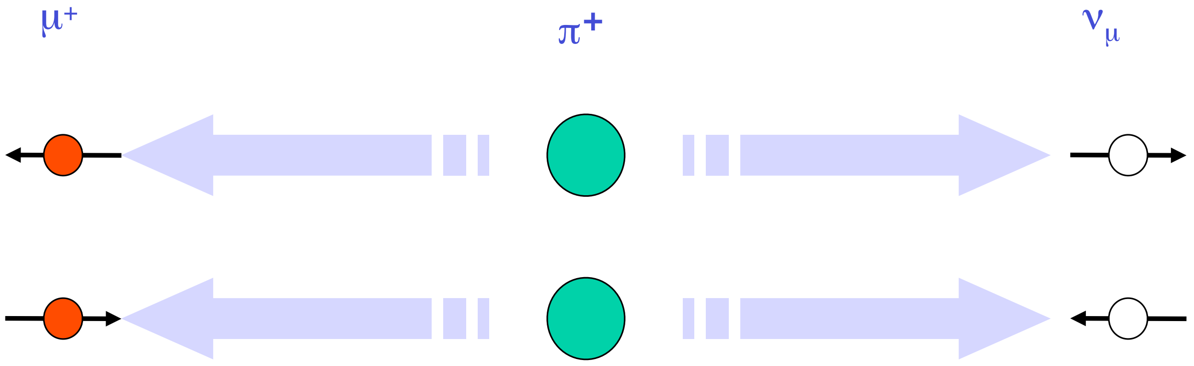
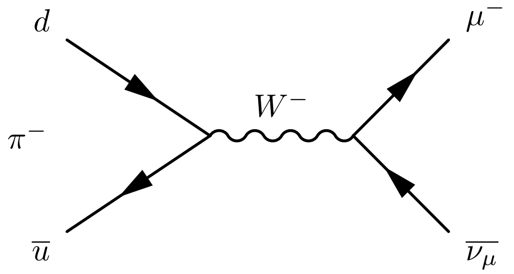
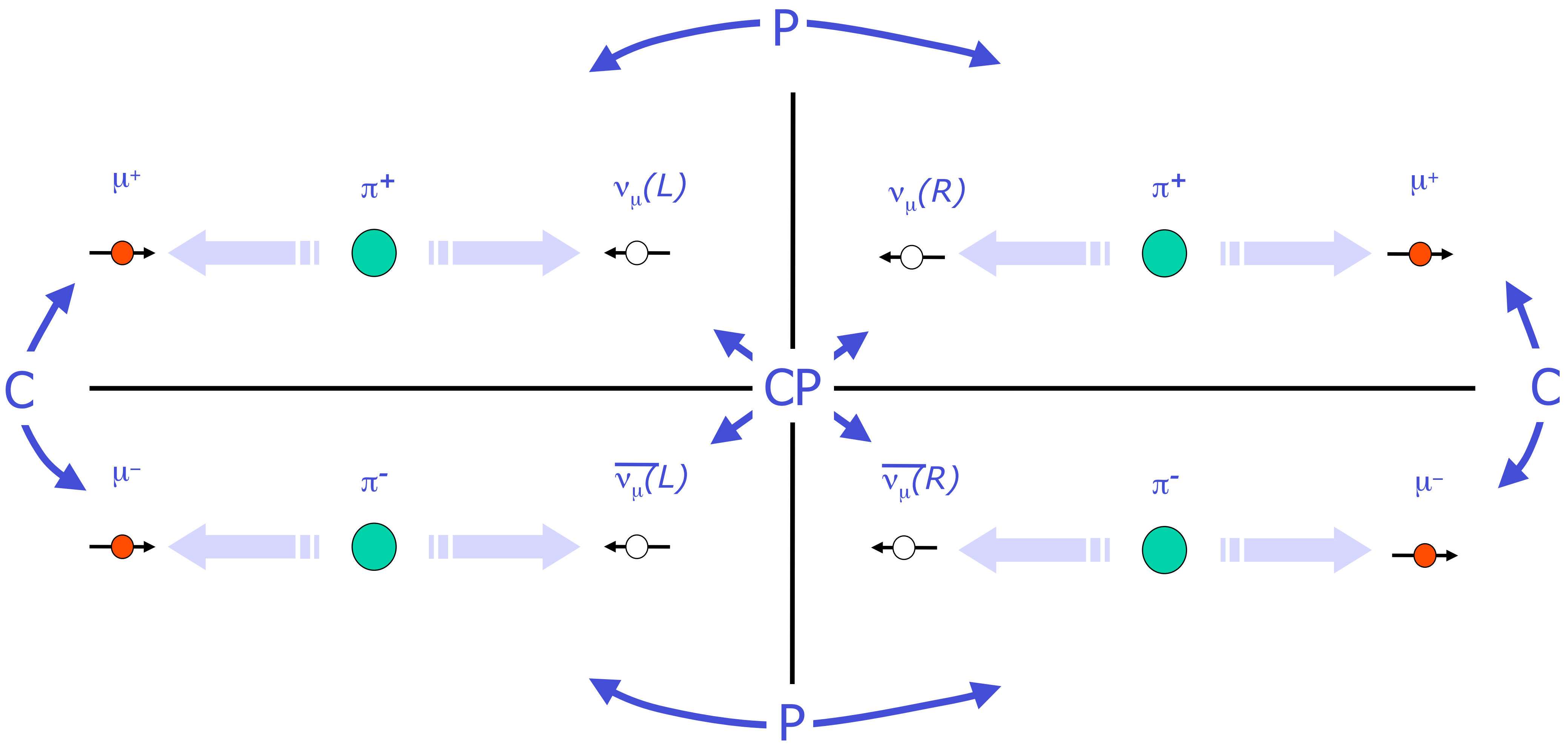




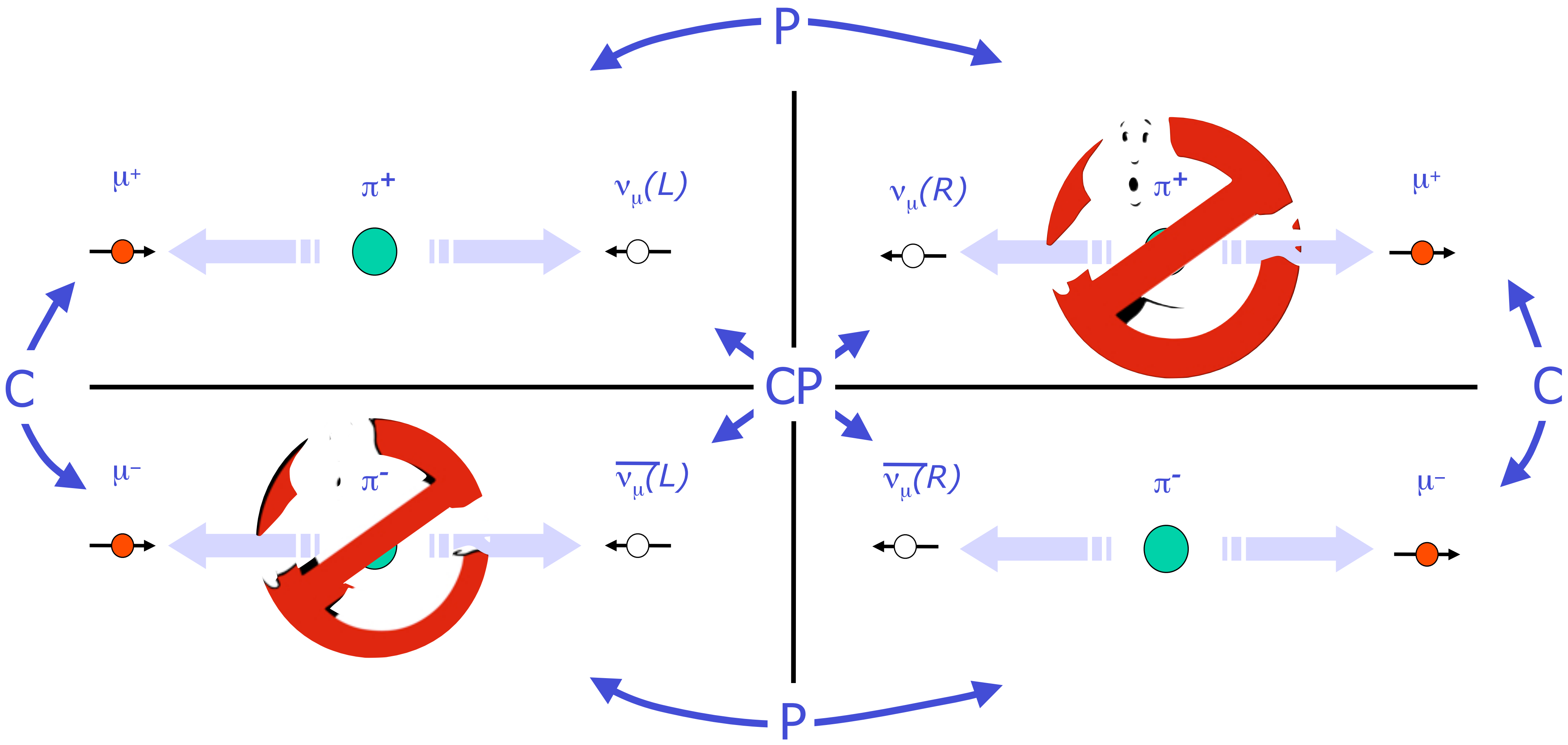
- Nice bonus: can also measure polarization of both neutrino (π^+ decay) and anti-neutrino (π^- decay)
- Result: All neutrinos produced are left-handed and all anti-neutrinos are right-handed

C,P and CP



P
μ^+
π^+
$\nu_\mu(L)$
$\nu_\mu(R)$
π^+
μ^+
C
CP
C
μ^-
π^-
$\overline{\nu_\mu}(L)$
$\overline{\nu_\mu}(R)$
π^-
μ^-
P

C,P and CP



C broken, P broken, but CP *appears* to be preserved in weak interaction!

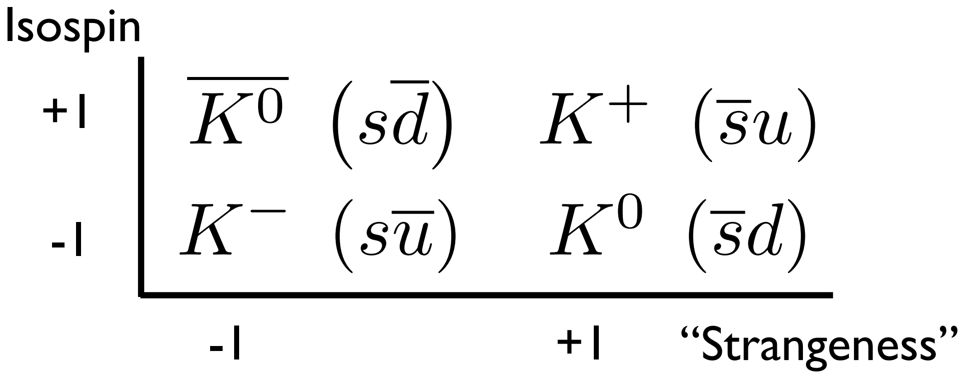
Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...

Kaons...

m_K ~ 494 MeV/c^2
No strange particles lighter than kaons exist
⇒Decay must violate "strangeness"

Strong force conserves "strangeness"
⇒Decay is a pure weak interaction



Isospin		
+1	$\overline{K^0}\ (s\bar{d})$	$K^+\ (\bar{s}u)$
-1	$K^-\ (s\bar{u})$	$K^0\ (\bar{s}d)$
	-1	+1 "Strangeness"

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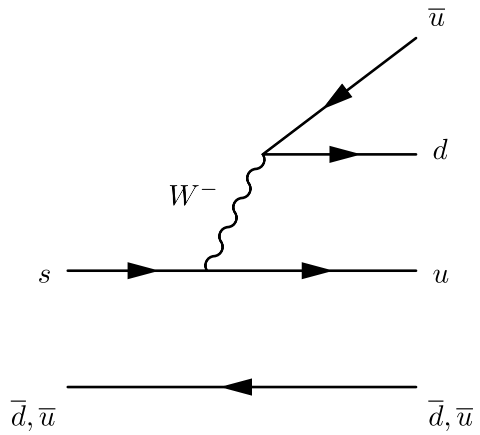

hadronic decays:

$$\begin{array}{lcl} K^+ & \longrightarrow & \pi^+\pi^0,\ \pi^+\pi^-\pi^+,\ \pi^+\pi^0\pi^0 \\ K^- & \longrightarrow & \pi^-\pi^0,\ \pi^-\pi^+\pi^-,\ \pi^-\pi^0\pi^0 \\ K^0 & \longrightarrow & \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0 \\ \overline{K^0} & \longrightarrow & \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0 \end{array}$$

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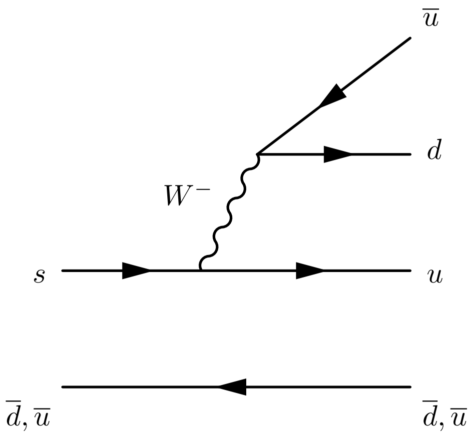

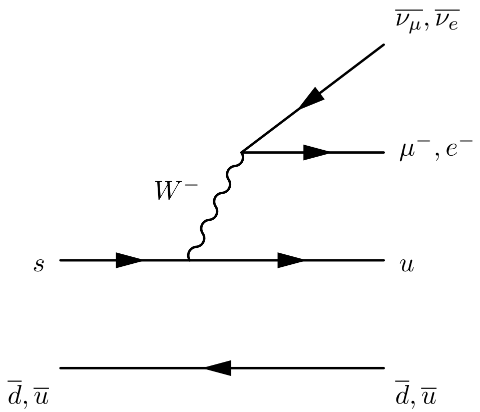

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semi-leptonic decays:

$$K^+ \rightarrow \pi^0\mu^+\nu_\mu,\ \pi^0e^+\nu_e$$
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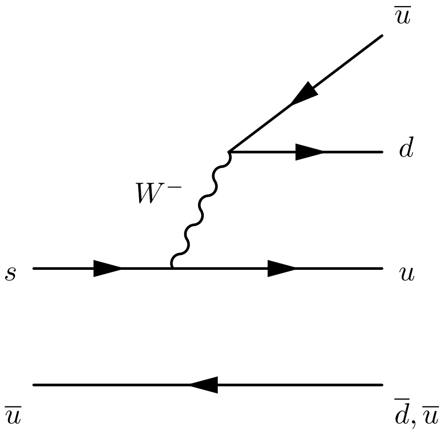

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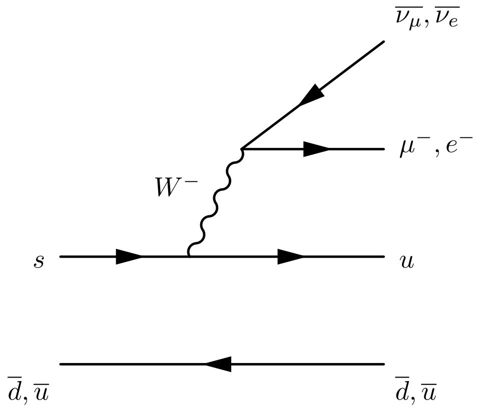

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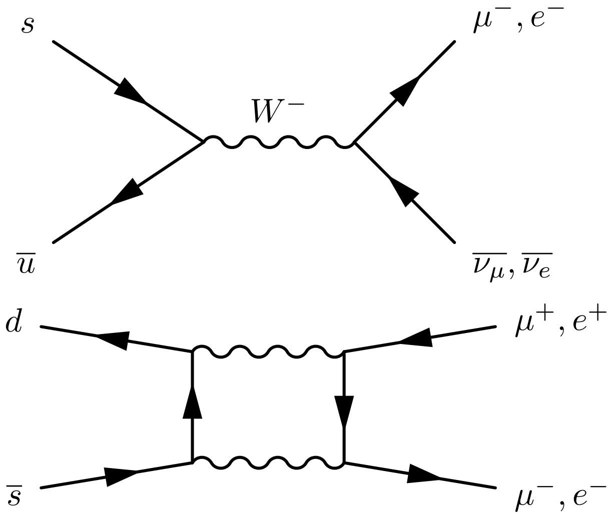

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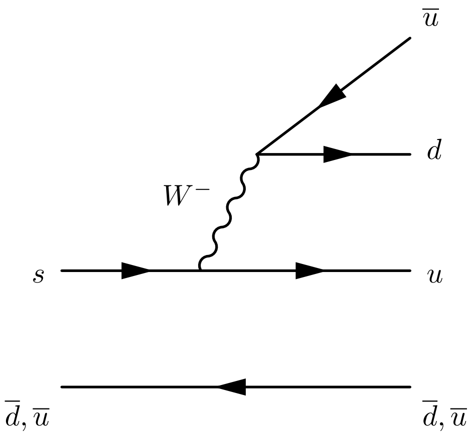

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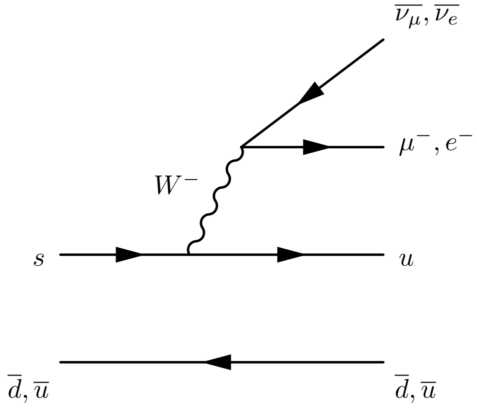

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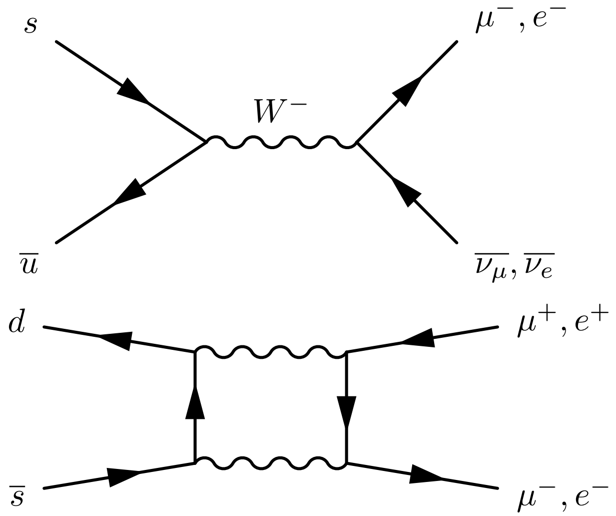

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Hadronic and leptonic decays:
particle and anti-particle behave the same

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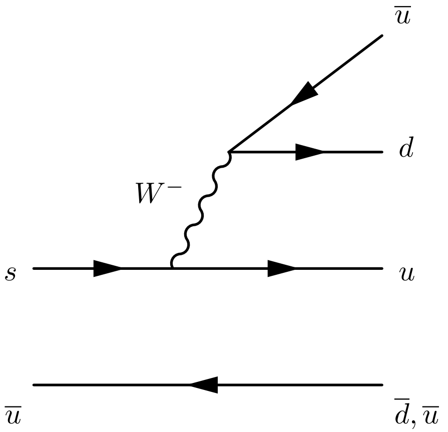

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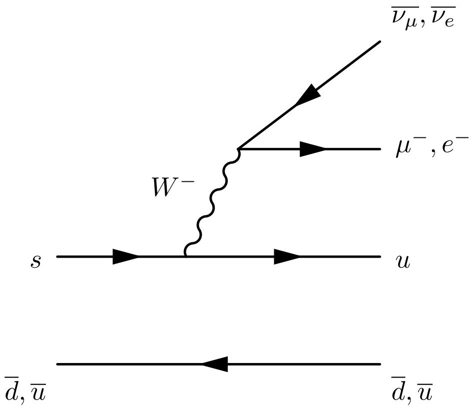

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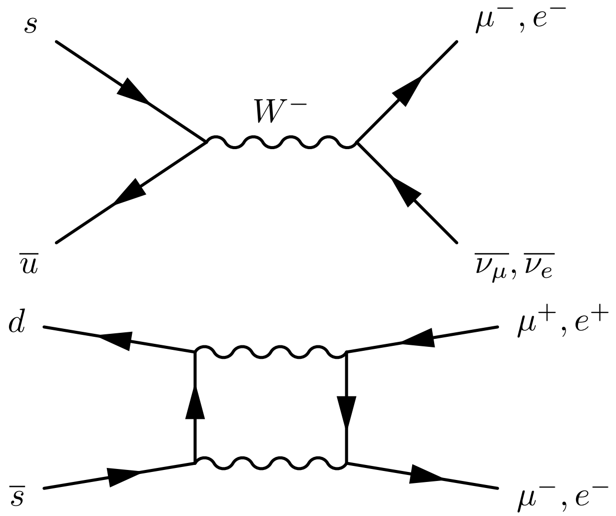

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Hadronic and leptonic decays:
particle and anti-particle behave the same

Semi-leptonic decays:
particle and anti-particle are distinct!
"ΔQ=ΔS rule"

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 $\theta^0 \rightarrow \pi^+ + \pi^-$. 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.

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Known:

-$K^0 \rightarrow \pi^+ \pi^-$

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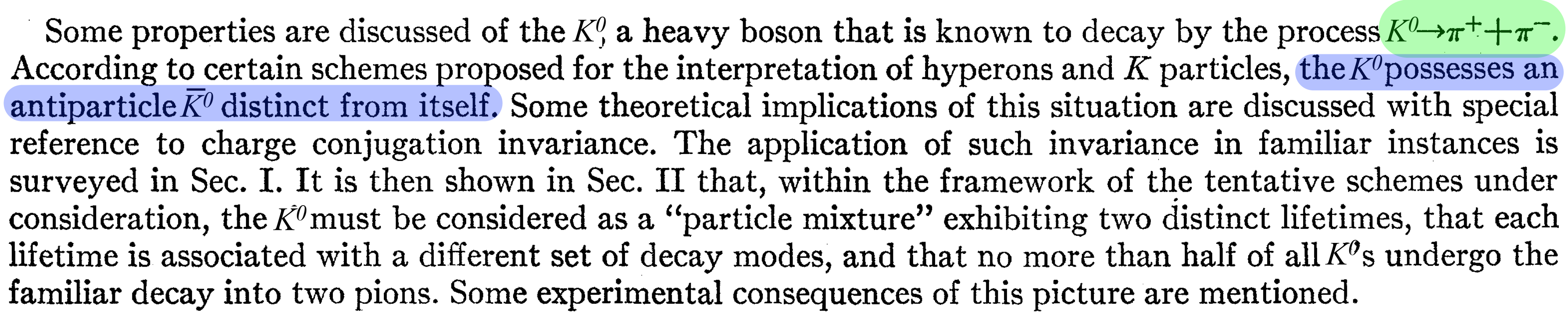

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Known:
-$K^0 \rightarrow \pi^+\pi^-$

Hypothesis:
-$\overline{K}^0$ is *not* equal to K^0

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Known:

-$K^0 \rightarrow \pi^+\pi^-$

Hypothesis:

-$\bar{K}^0$ is *not* equal to K^0

Use C (actually, CP) to deduce:

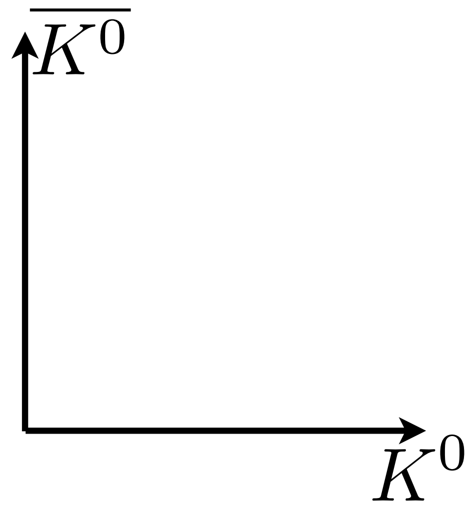
1. K^0 ($\bar{K}^0$) is an 'admixture' with two distinct lifetimes
2. Each lifetime associated to a distinct set of decay modes
3. No more than 50% of K^0 will decay to two pions...

Neutral Meson Mixing

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

$$i\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

$$\hat{H} = \begin{pmatrix} M_K & 0 \\ 0 & M_K \end{pmatrix}$$



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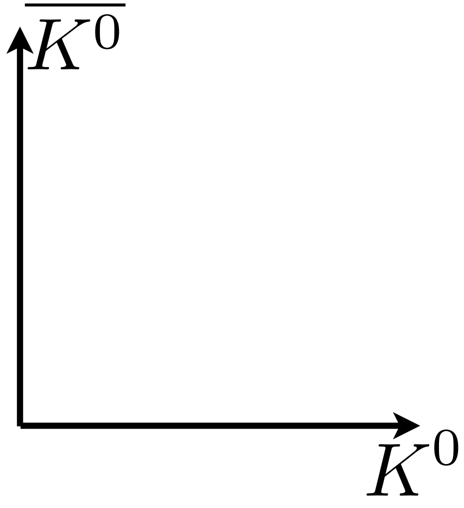

As (eventually) K^0 and $\overline{K^0}$ decay, add an *antihermitic* part to the Hamiltonian

$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & 0 \\ 0 & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$

$$\frac{d}{dt}\left(|a|^2 + |b|^2\right) = -\begin{pmatrix} a^* & b^* \end{pmatrix}\begin{pmatrix} \Gamma_K & 0 \\ 0 & \Gamma_K \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

Can identify Γ_K as the decay width ($=1/\tau_K$)

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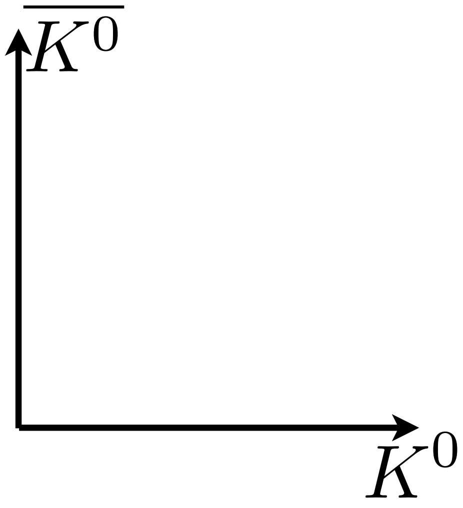

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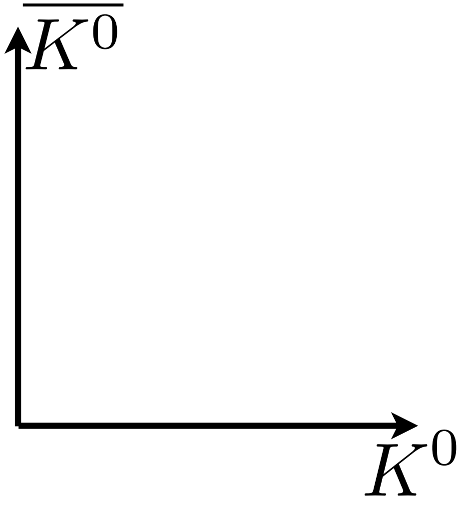

Now consider the effect of CP symmetry:

$$\text{CP}\quad \begin{array}{ccc} K^0 & \leftrightarrow & \pi^+\pi^- \\ \overline{K^0} & \leftrightarrow & \pi^+\pi^- \end{array} \quad \Longleftrightarrow \quad K^0 \leftrightarrow \overline{K^0}$$

$$\hat{H} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & \Delta \\ \Delta & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$

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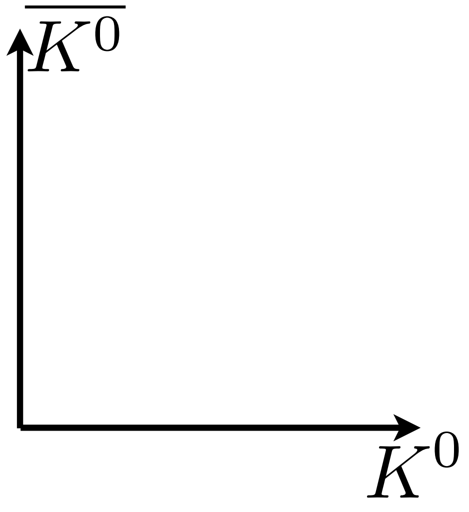

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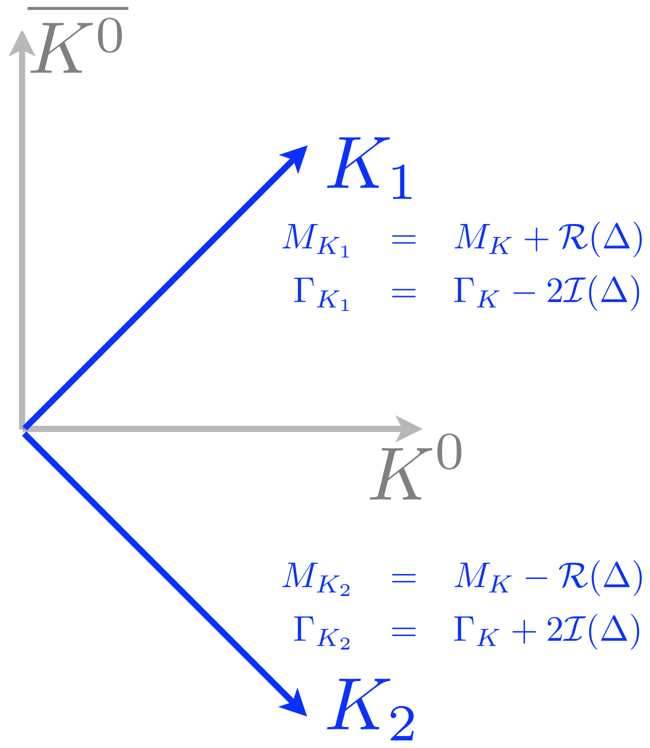


$$\begin{aligned} M_{K_1} &= M_K + \mathcal{R}(\Delta) \\ \Gamma_{K_1} &= \Gamma_K - 2\mathcal{I}(\Delta) \end{aligned}$$

$$\begin{aligned} M_{K_2} &= M_K - \mathcal{R}(\Delta) \\ \Gamma_{K_2} &= \Gamma_K + 2\mathcal{I}(\Delta) \end{aligned}$$

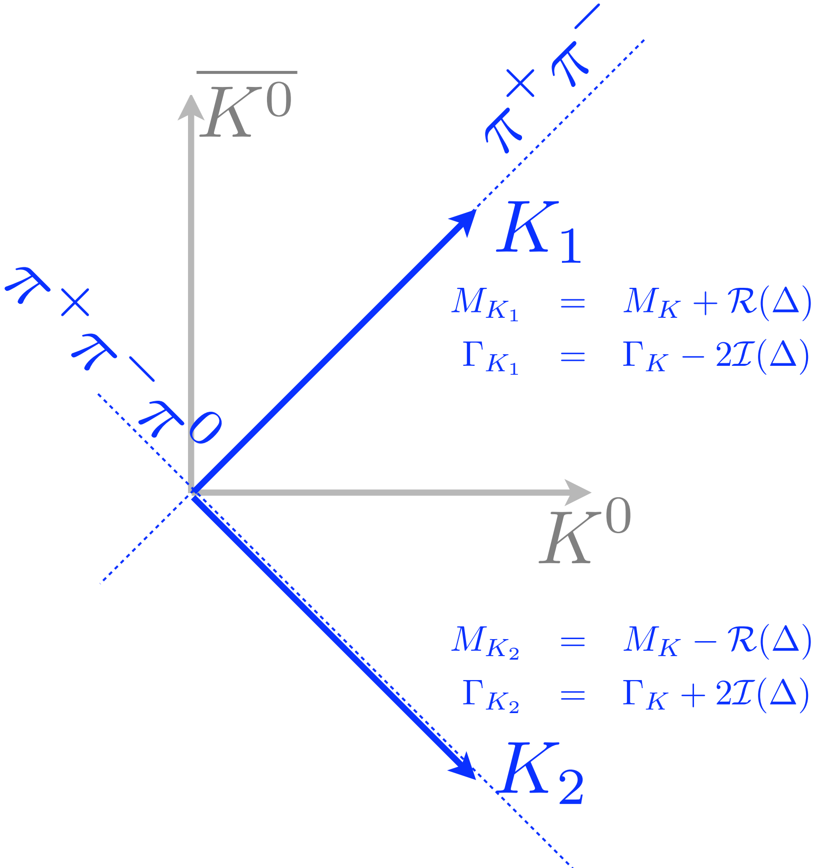
K^0 and $\overline{K^0}$ are *no longer* eigenstates of H
their *sum* (K_1) & *difference* (K_2) are eigenstates...
and K_1 and K_2 have *different* masses and lifetimes

Neutral Kaon Mixing

- K_1 and K_2 are their *own* antiparticle, but one is CP even, the other CP odd
- *Only* the CP even state can decay into 2 pions
  - $|K_1>$ (CP=+1) → ππ (CP=-1 * -1 =+1)
- The CP odd state will decay into 3 pions instead
  - $|K_2>$ (CP=-1) → ππ π (CP = -1*-1*-1 = -1)
- There is a huge difference in available phasespace between the two (~600x!) → the CP *even* state will decay much faster
  - Difference due to $M(K^0) \cong 3M(\pi)$
  - Δ has a large imaginary component!

$$|K_1\rangle = \frac{|K^0\rangle + |\overline{K^0}\rangle}{\sqrt{2}}$$

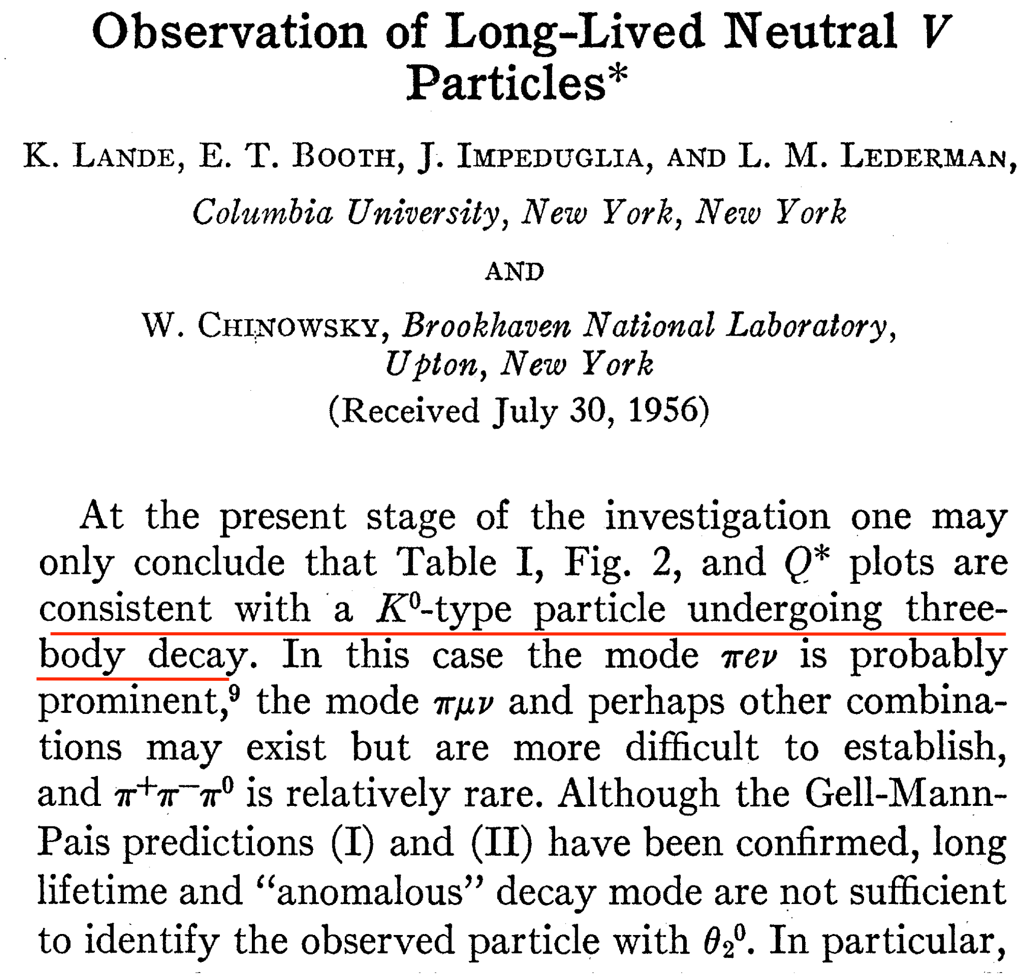
$$|K_2\rangle = \frac{|K^0\rangle - |\overline{K^0}\rangle}{\sqrt{2}}$$



$$\begin{aligned} M_{K_1} &= M_K + \mathcal{R}(\Delta) \\ \Gamma_{K_1} &= \Gamma_K - 2\mathcal{I}(\Delta) \end{aligned}$$

$$\begin{aligned} M_{K_2} &= M_K - \mathcal{R}(\Delta) \\ \Gamma_{K_2} &= \Gamma_K + 2\mathcal{I}(\Delta) \end{aligned}$$

Experimental confirmation...



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)

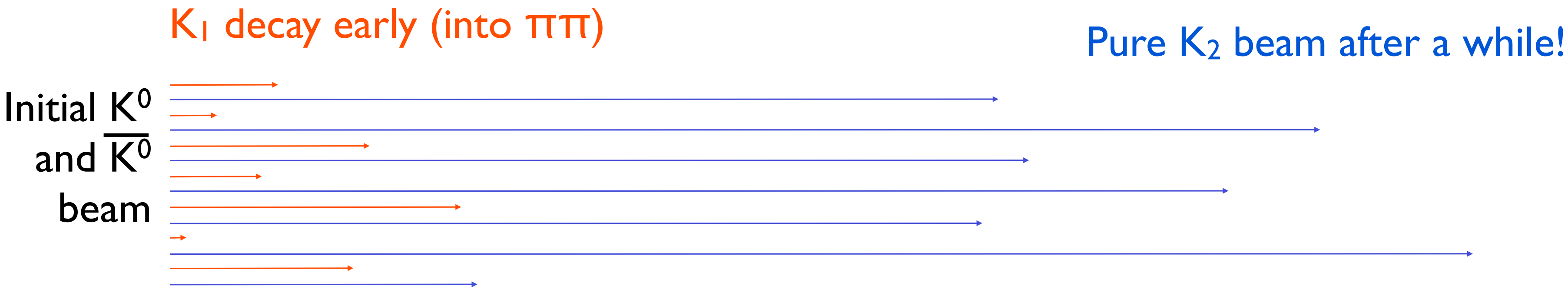
At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e \nu$ is probably prominent,[9] the mode $\pi \mu \nu$ and perhaps other combinations may exist but are more difficult to establish, and $\pi^+\pi^-\pi^0$ is relatively rare. Although the Gell-Mann-Pais predictions (I) and (II) have been confirmed, long lifetime and "anomalous" decay mode are not sufficient to identify the observed particle with θ_2^0. In particular,

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP (!) eigenstates of the Hamiltonian

Designing a CP violation experiment

- How do you obtain a pure 'beam' of K_2 particles?
- Exploit that decay of K_1 into two pions is *much* faster than decay of K_2 into three pions
  - $\tau_1 = 0.89 \times 10^{-10}$ sec
  - $\tau_2 = 5.2 \times 10^{-8}$ sec (~600 times larger!)
- Beam of neutral Kaons automatically becomes beam of $|K_2>$ as all $|K_1>$ decay very early on…



K_1 decay early (into $\pi\pi$)

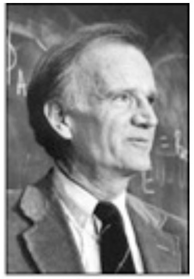
Pure K_2 beam after a while!

Initial K^0
and $\overline{K^0}$
beam

The Cronin & Fitch Experiment

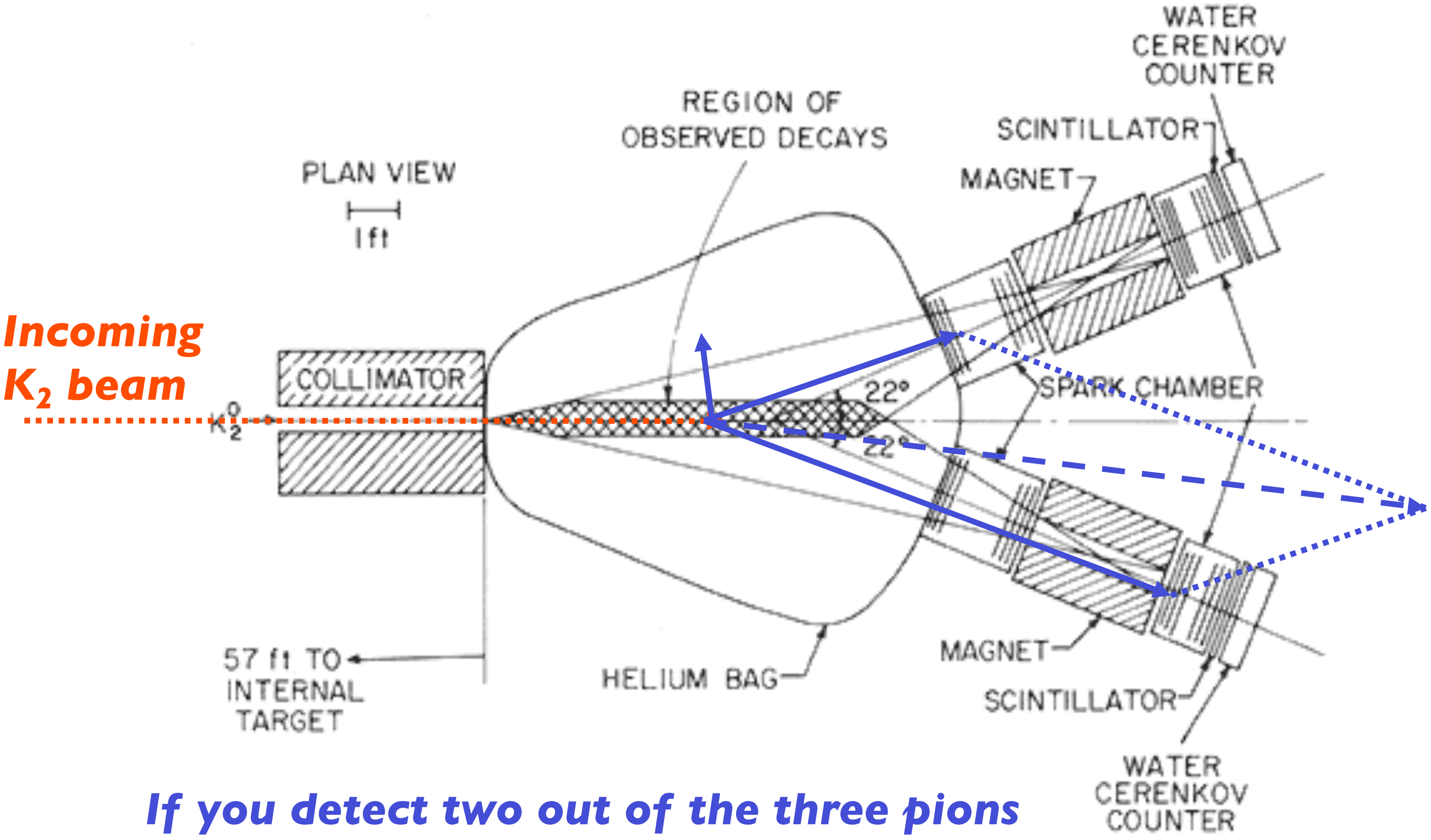
Essential idea: Look for (CP violating)
$K_2 \rightarrow \pi^+\pi^-$ decays 20 meters away from
K^0 production point

James Cronin



Val Fitch

Decay of K_2 into 3 pions



If you detect two out of the three pions of a $K_2 \rightarrow \pi\pi\pi$ decay their combined momentum will generally not point along the beam line

The Cronin & Fitch Experiment

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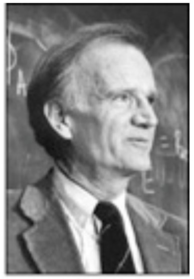
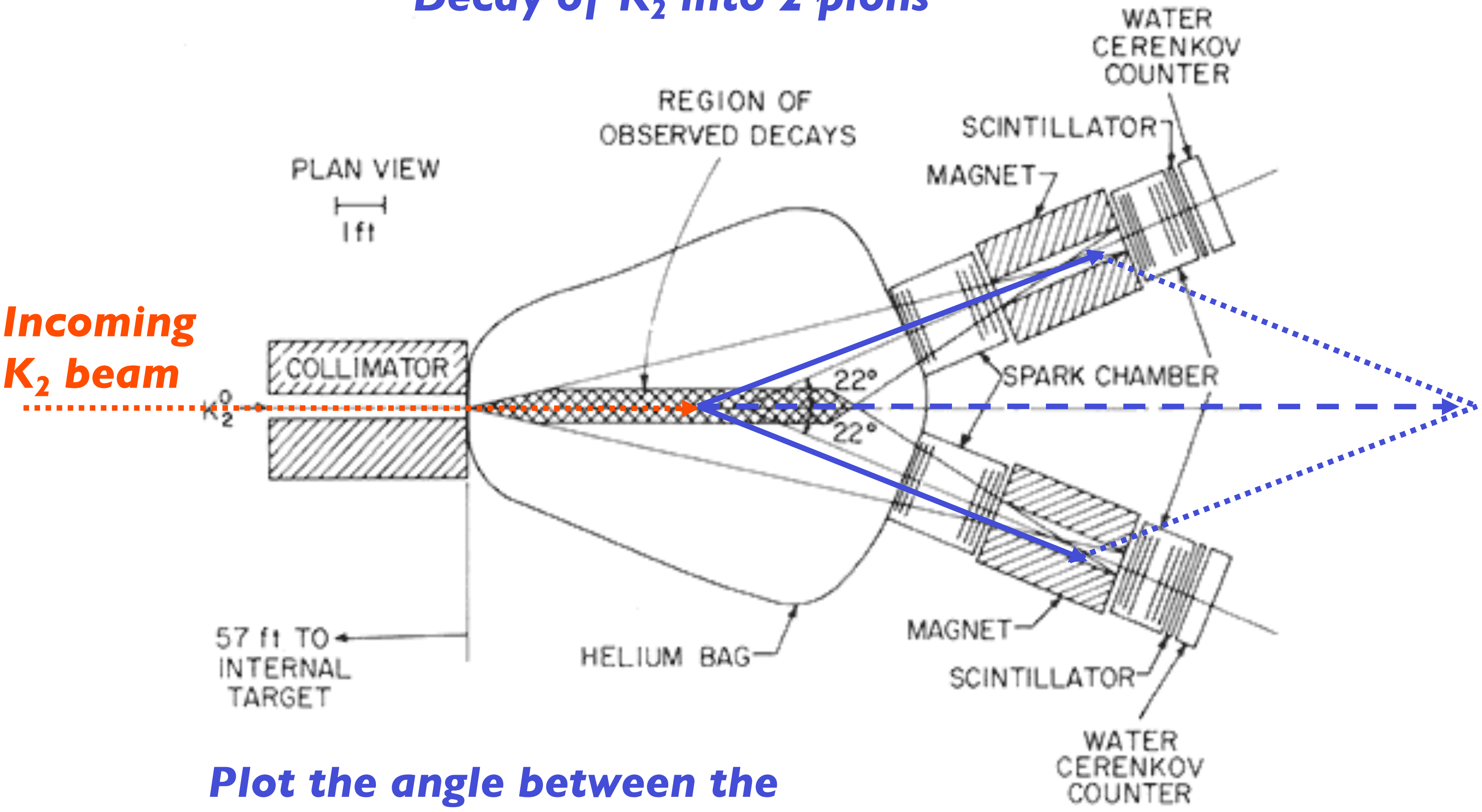


Val Fitch

Decay of K_2 into 2 pions

Incoming K_2 beam



Plot the angle between the momentum direction of two pions and the beamline

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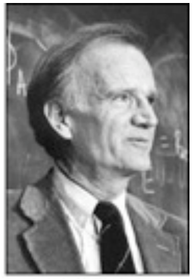
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EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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

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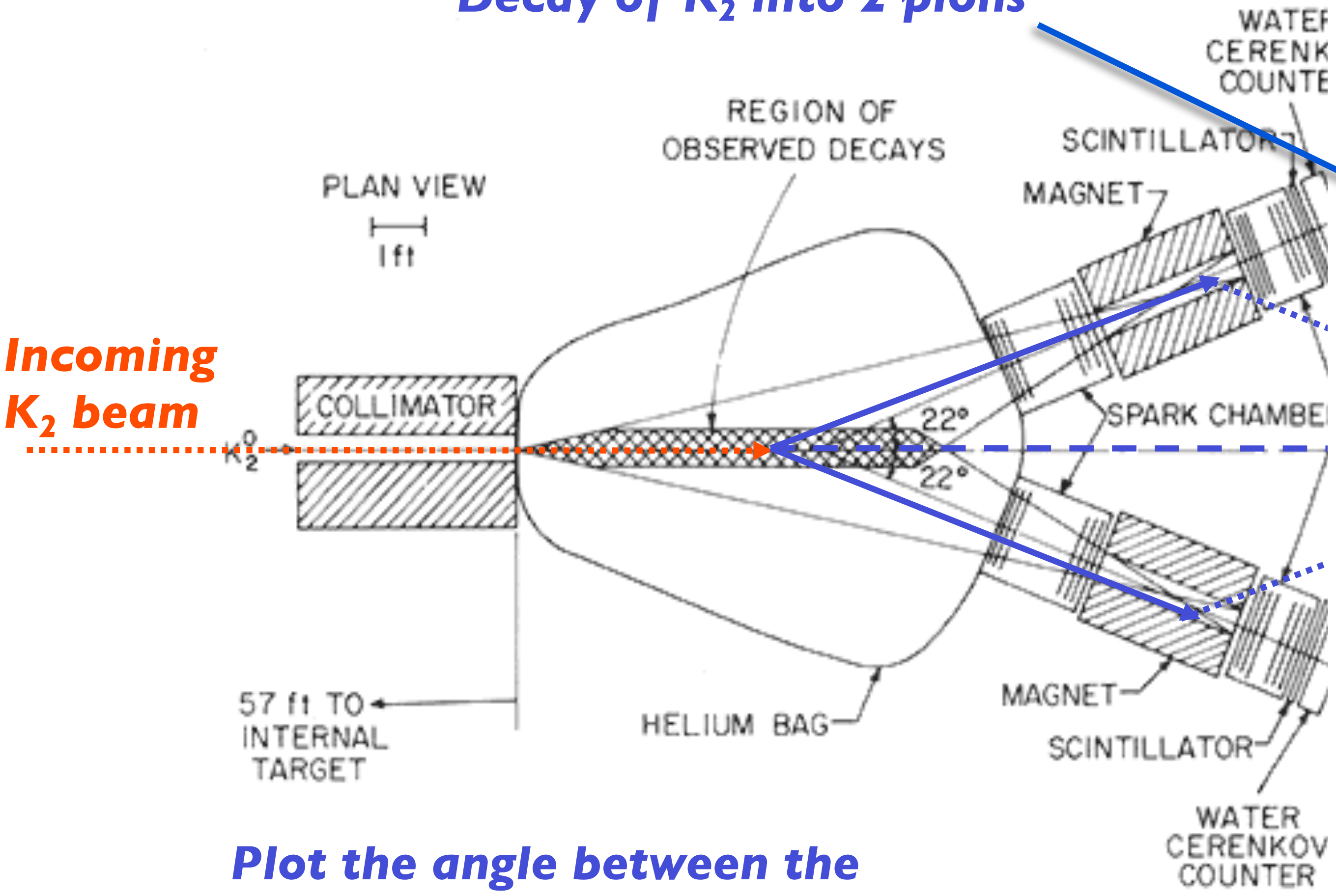

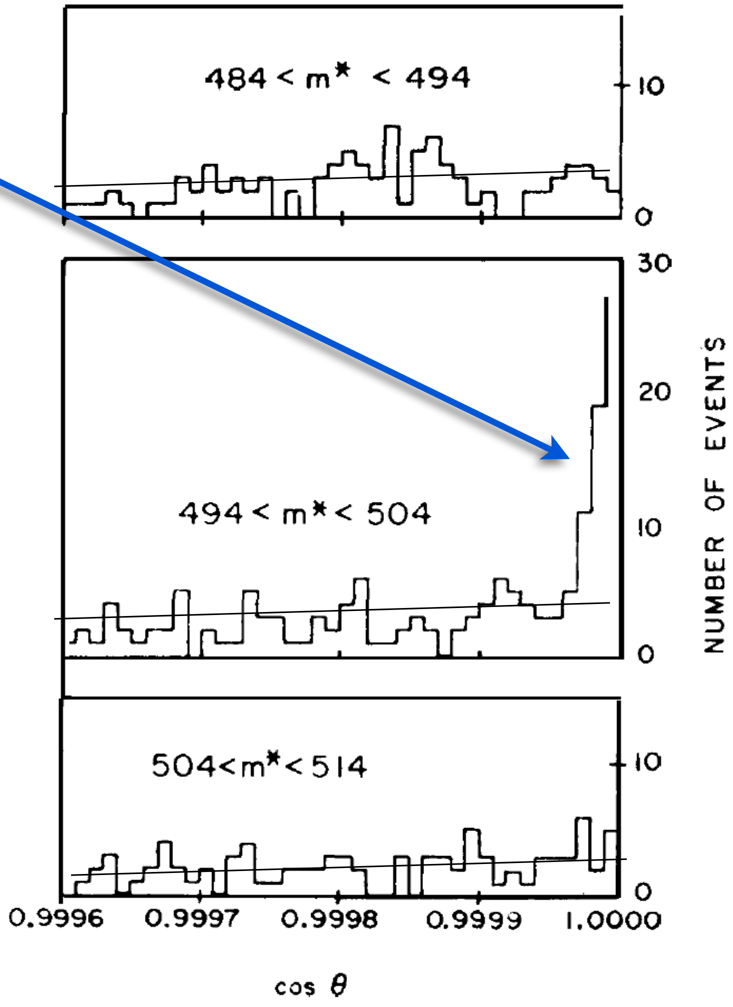

Plot the angle between the momentum direction of two pions and the beamline

Nobel Prize 1980

"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

“The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments.”

CP is (a bit) broken by weak decays...

Conclusion: **weak decay violates CP** (as well as C and P)

- But effect is tiny! (~0.2%)
- Maximal (100%) violation of P symmetry "easily" interpretable as absence of right-handed neutrino,

how to construct a physics law that violates a symmetry just a tiny bit?

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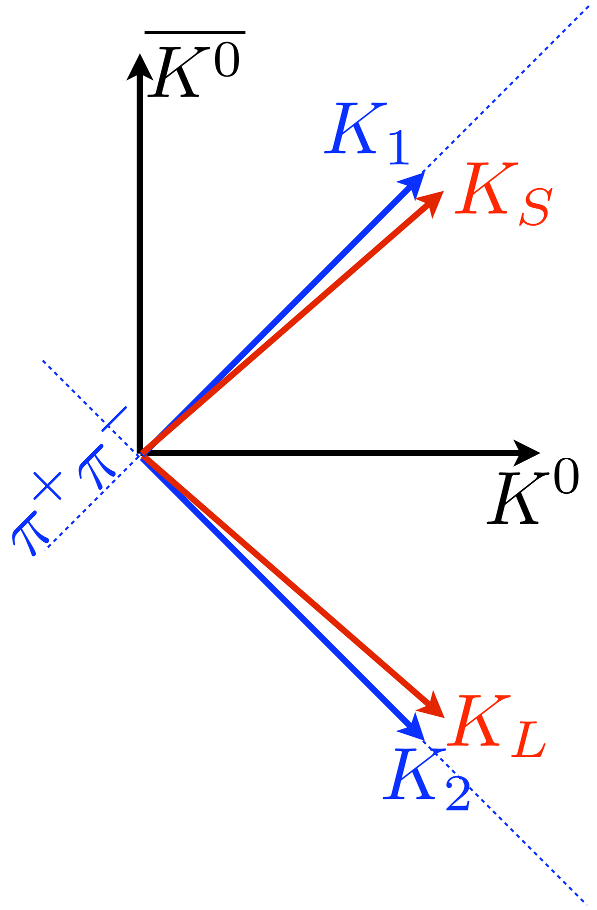
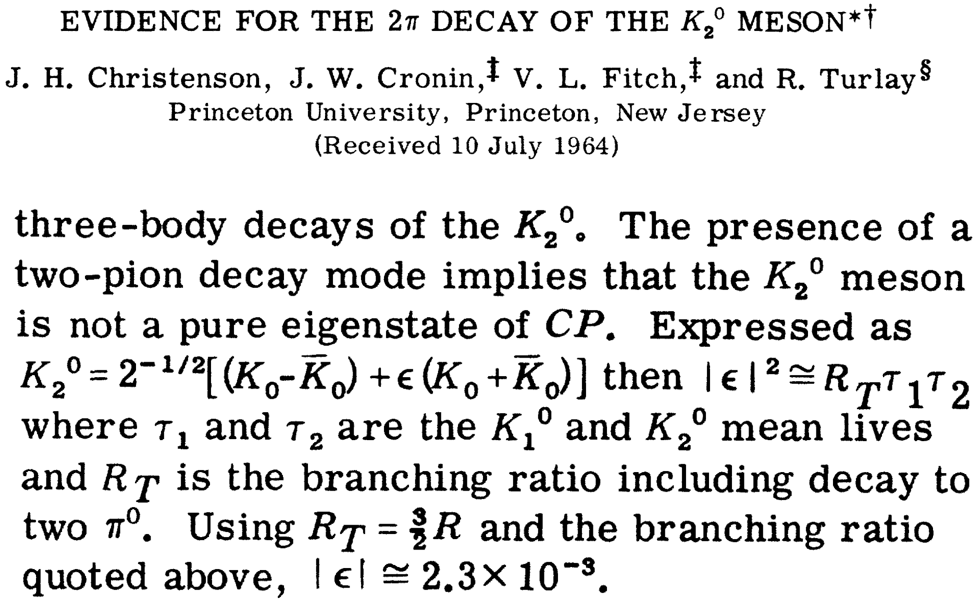
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!

How to describe this?





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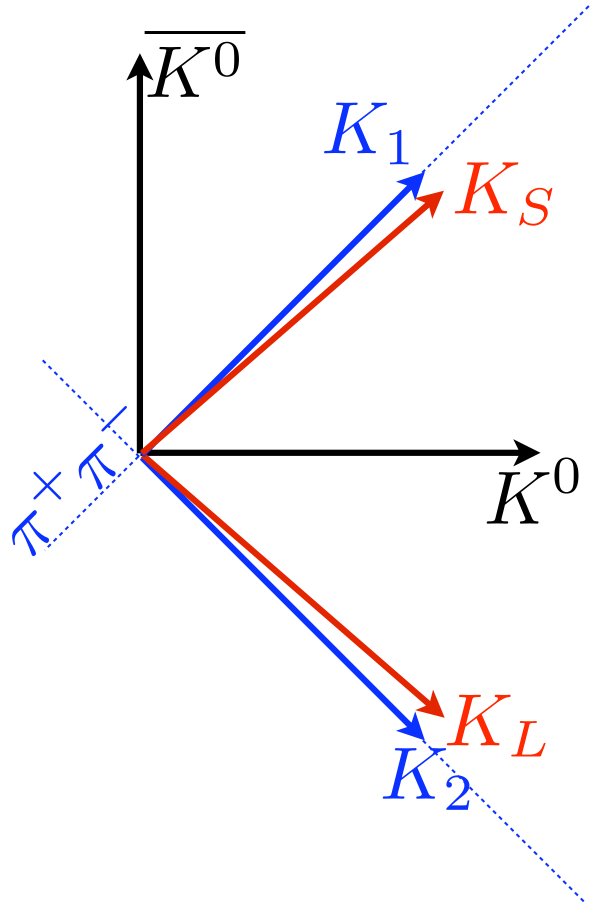
three-body decays of the $K_2{}^0$. The presence of a two-pion decay mode implies that the $K_2{}^0$ meson is not a pure eigenstate of CP. Expressed as $K_2{}^0 = 2^{-1/2}[(K_0-\bar{K}_0)+\epsilon(K_0+\bar{K}_0)]$ then $|\epsilon|^2 \cong R_T\tau_1\tau_2$ where τ_1 and τ_2 are the $K_1{}^0$ and $K_2{}^0$ 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, $|\epsilon| \cong 2.3\times 10^{-3}$.

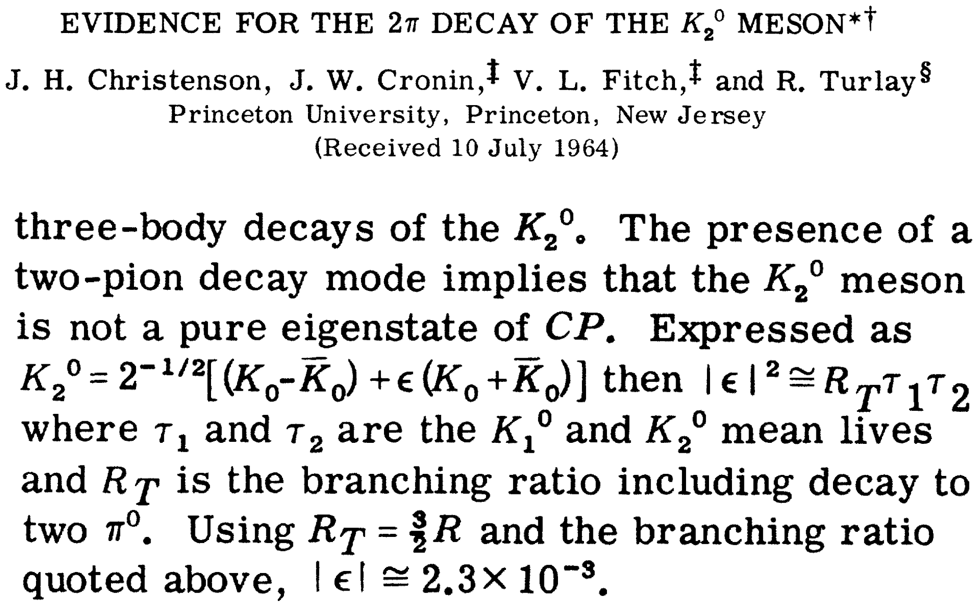
$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$

$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

with $|\epsilon| << 1$

How to describe this?

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$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$

$$|K_S\rangle = |K_1\rangle + \epsilon\,|K_2\rangle$$

with $|\epsilon| << 1$

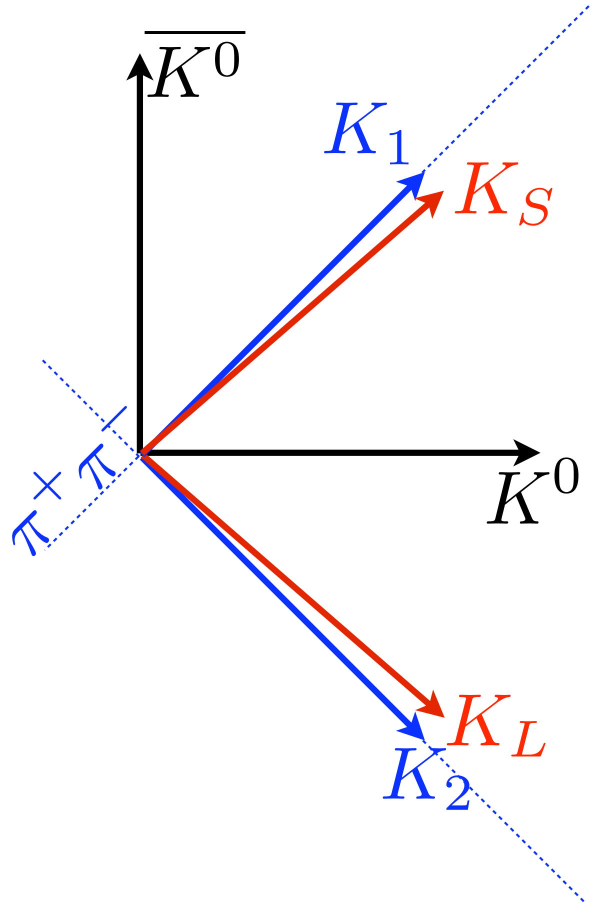
Have a *choice* when 'parameterizing' K_S and K_L:

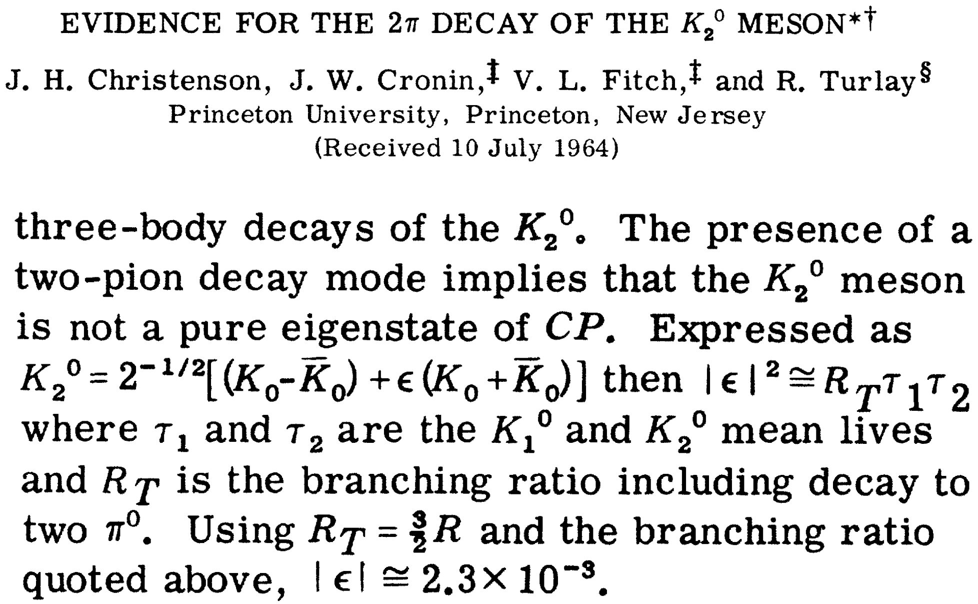
1. in terms of K^0 and $\overline{K^0}$
2. in terms of K_1 and K_2

Historically, 'kaon physics' has chosen 2, but in in 'B physics' (next lectures!), the equivalent of 1 is very much dominant...

This tends to be *very* confusing...

How to describe this?





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$$|K_L\rangle = p\left|K^0\right\rangle - q\left|\overline{K^0}\right\rangle$$

$$|K_S\rangle = p\left|K^0\right\rangle + q\left|\overline{K^0}\right\rangle$$

$$\langle K_L|\,K_L\rangle \equiv 1 \Rightarrow |q|^2 + |p|^2 = 1$$

eg. $$\begin{aligned} p &= 1+\epsilon \\ q &= 1-\epsilon \end{aligned} \quad \text{with } |\epsilon| << 1$$

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2. in terms of K_1 and K_2

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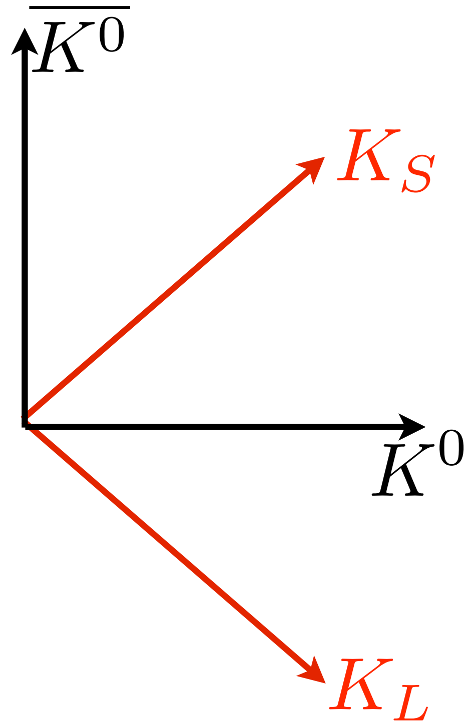
Time Evolution of K^0 and $\overline{\text{K}^0}$...

$$\begin{pmatrix} K_S(0) \\ K_L(0) \end{pmatrix} = \begin{pmatrix} +q & +p \\ +q & -p \end{pmatrix} \begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix}$$

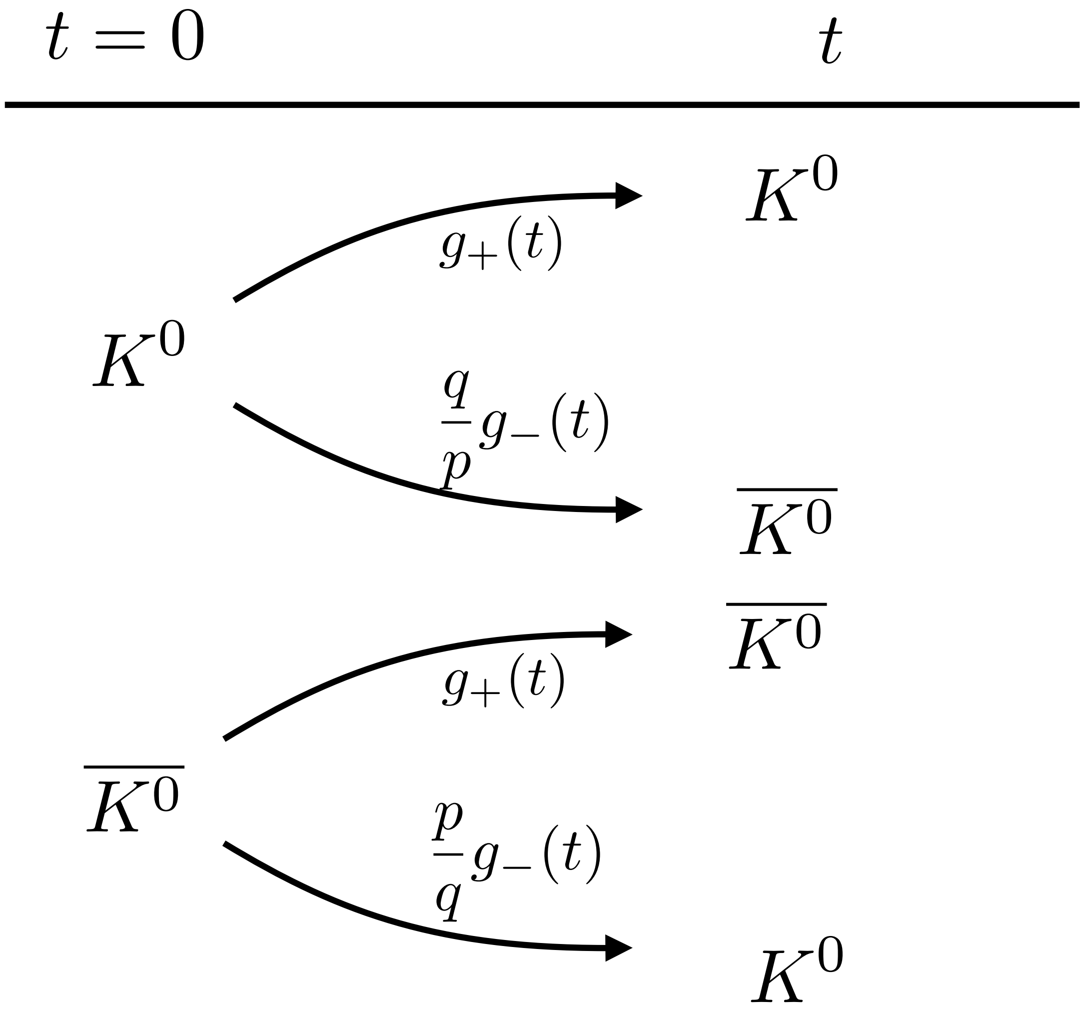


$$\begin{pmatrix} K_S(t) \\ K_T(t) \end{pmatrix} = \begin{pmatrix} e^{-i\omega_S t} & 0 \\ 0 & e^{-i\omega_L t} \end{pmatrix} \begin{pmatrix} K_S(0) \\ K_L(0) \end{pmatrix}$$

$$\begin{pmatrix} K^0(t) \\ \overline{K^0}(t) \end{pmatrix} = \begin{pmatrix} +1/2q & +1/2q \\ +1/2p & -1/2p \end{pmatrix} \begin{pmatrix} K_S(t) \\ K_L(t) \end{pmatrix}$$

Time Evolution of K⁰ and $\overline{K^0}$...

$$\begin{pmatrix} K^0(t) \\ \overline{K^0}(t) \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{p}{q}g_-(t) \\ \frac{q}{p}g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix} \qquad g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$



$t = 0$

t

K^0 $\xrightarrow{g_+(t)}$ K^0

K^0 $\xrightarrow{\frac{q}{p}g_-(t)}$ $\overline{K^0}$

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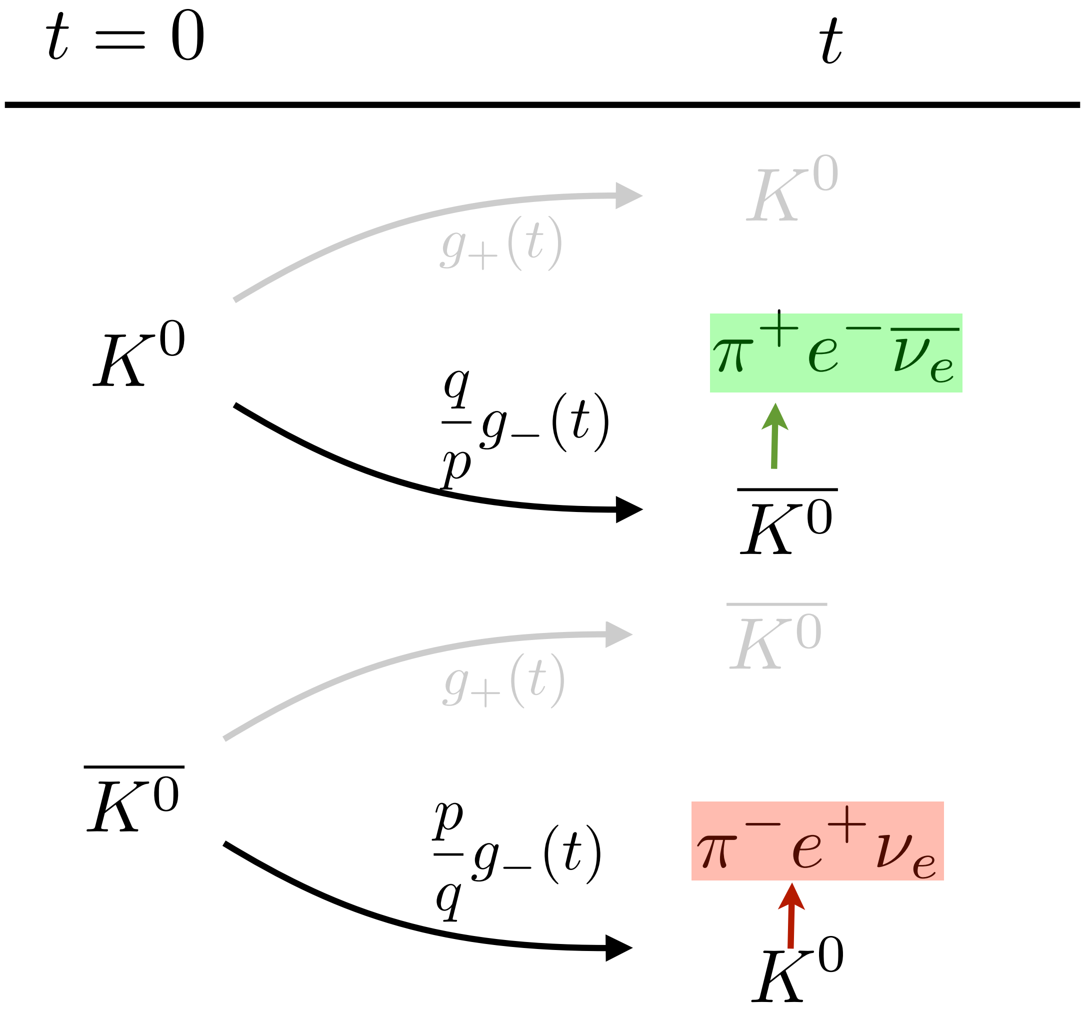

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t

K^0 $\xrightarrow{g_+(t)}$ K^0

K^0 $\xrightarrow{\frac{q}{p}g_-(t)}$ $\overline{K^0}$ $\rightarrow$ $\pi^+ e^- \overline{\nu_e}$

$\overline{K^0}$ $\xrightarrow{g_+(t)}$ $\overline{K^0}$

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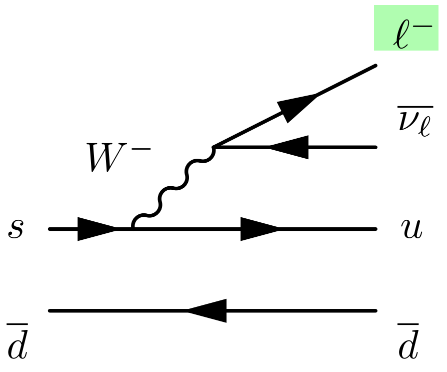
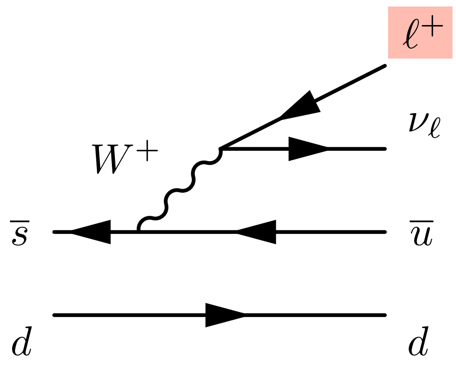
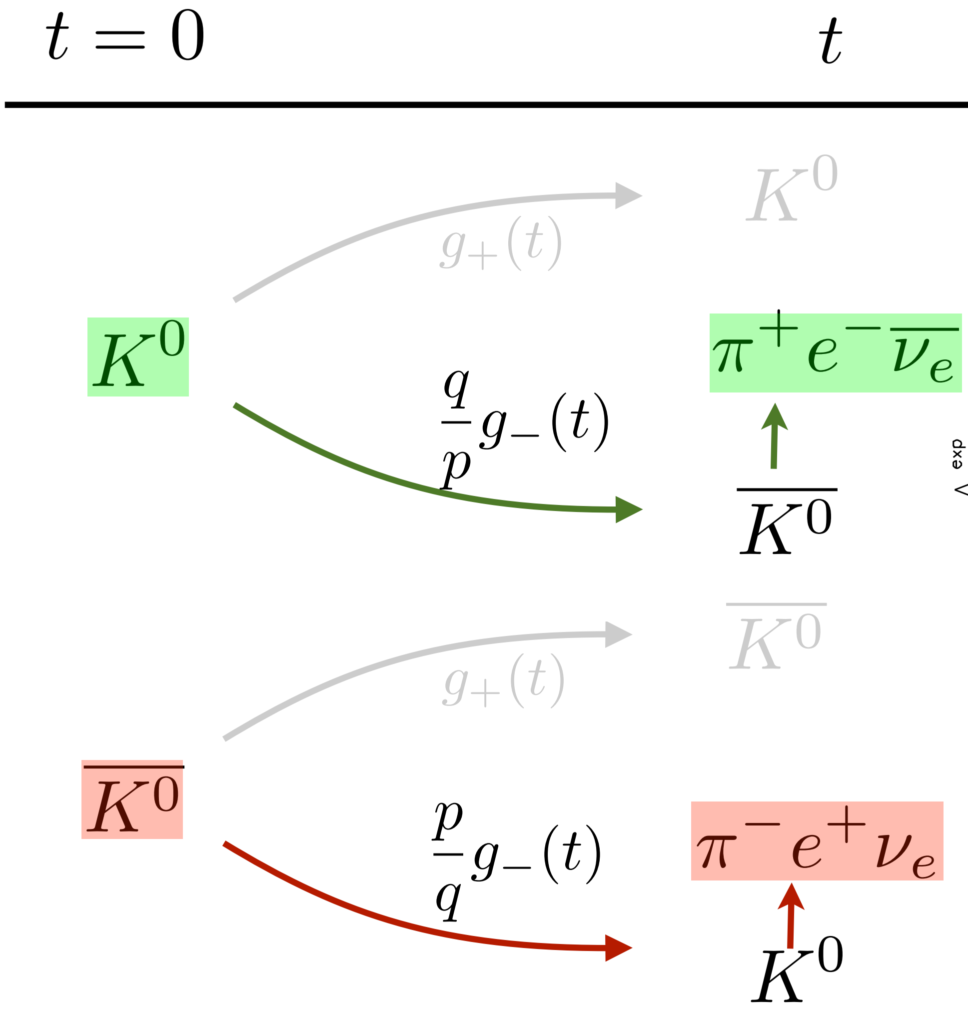




Time Evolution of K^0 and $\overline{K^0}$...



$t = 0$

t

K^0

$g_+(t)$

K^0

$\pi^+ e^- \overline{\nu_e}$

$\frac{q}{p} g_-(t)$

$\overline{K^0}$

$\overline{K^0}$

$g_+(t)$

$\overline{K^0}$

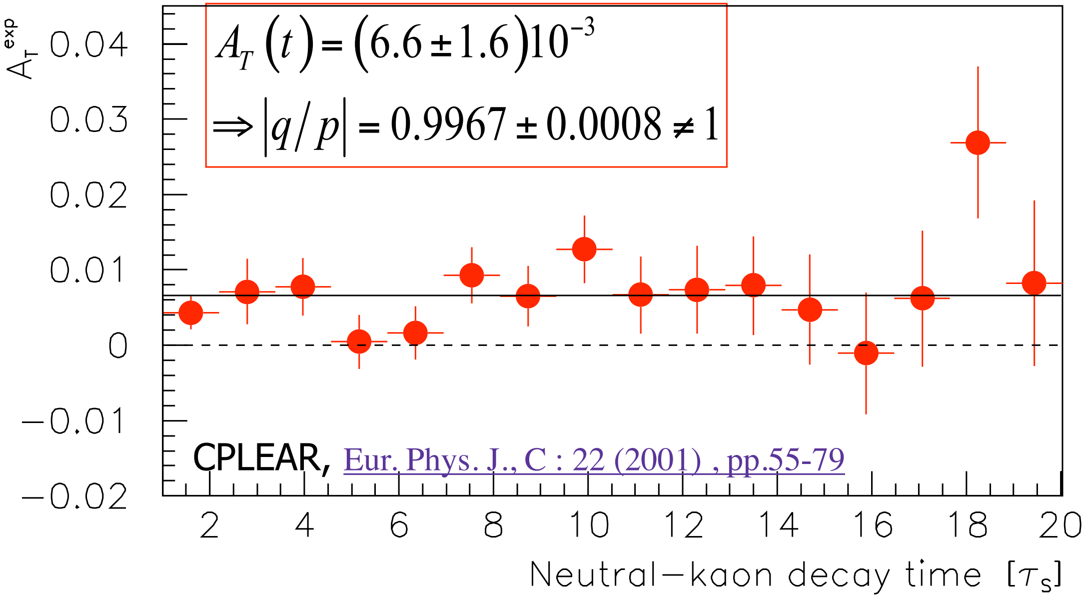
$\pi^- e^+ \nu_e$

$\frac{p}{q} g_-(t)$

K^0

$$A_T(t) = \frac{\overline{I}_{\pi^- e^+ \nu}(t) - I_{\pi^+ e^- \overline{\nu}}(t)}{\overline{I}_{\pi^- e^+ \nu}(t) + I_{\pi^+ e^- \overline{\nu}}(t)}$$

$$= \frac{1 - |q/p|^4}{1 + |q/p|^4} = 4\mathcal{R}\epsilon$$



$A_T(t) = (6.6 \pm 1.6)10^{-3}$

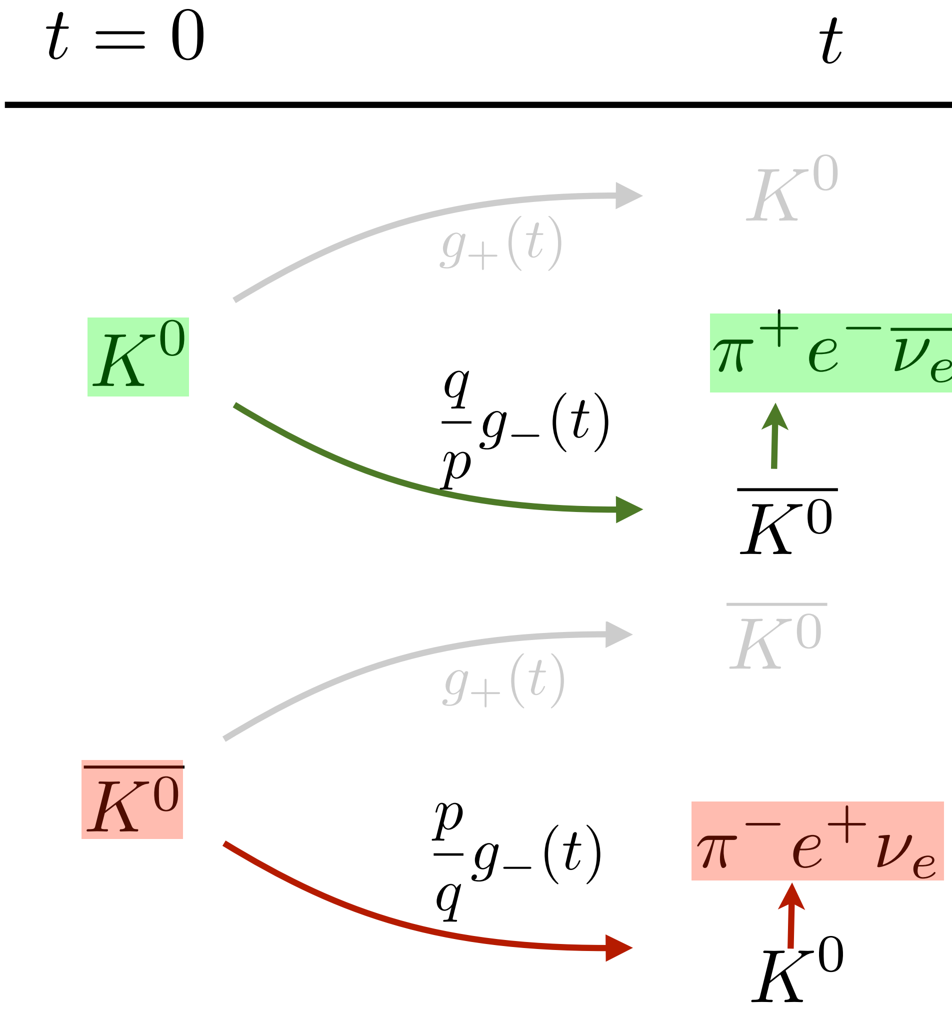
$\Rightarrow |q/p| = 0.9967 \pm 0.0008 \neq 1$

CPLEAR, Eur. Phys. J., C : 22 (2001) , pp.55-79

Time Evolution of K^0 and $\overline{K^0}$...

This measurement allows one to make an *ABSOLUTE* distinction between matter and anti-matter

- *Positive charge is the charged carried by the lepton preferentially produced in the decay of the neutral K meson*



$t = 0$

t

K^0

$g_+(t)$

K^0

$\frac{q}{p} g_-(t)$

$\pi^+ e^- \overline{\nu_e}$

$\overline{K^0}$

$\overline{K^0}$

$g_+(t)$

$\overline{K^0}$

$\frac{p}{q} g_-(t)$

$\pi^- e^+ \nu_e$

K^0

$$A_T(t) = \frac{\overline{I}_{\pi^- e^+ \nu}(t) - I_{\pi^+ e^- \overline{\nu}}(t)}{\overline{I}_{\pi^- e^+ \nu}(t) + I_{\pi^+ e^- \overline{\nu}}(t)}$$

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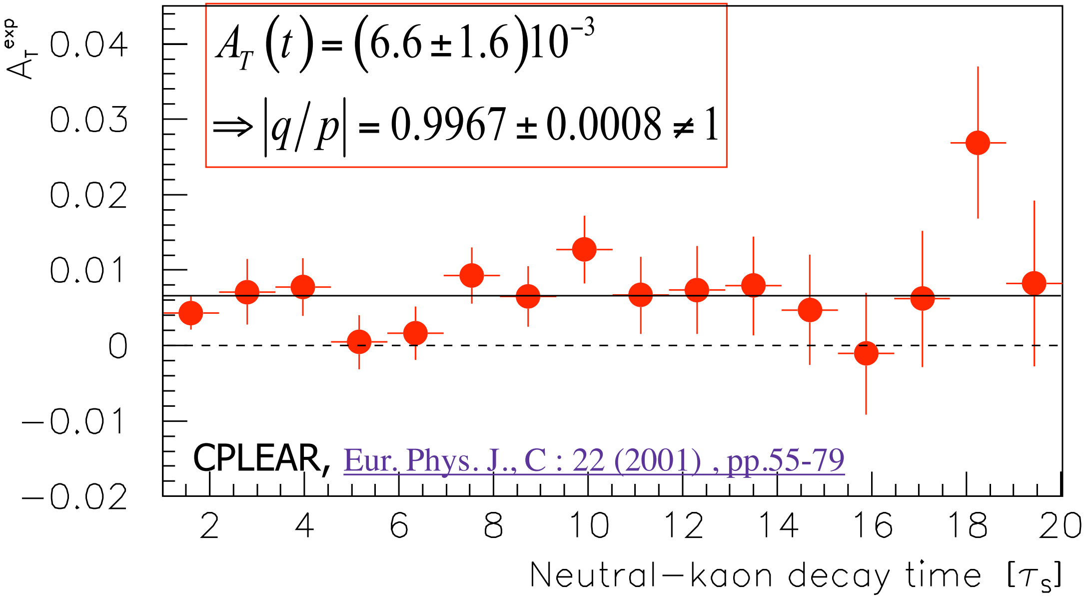

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$\Rightarrow |q/p| = 0.9967 \pm 0.0008 \neq 1$

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Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
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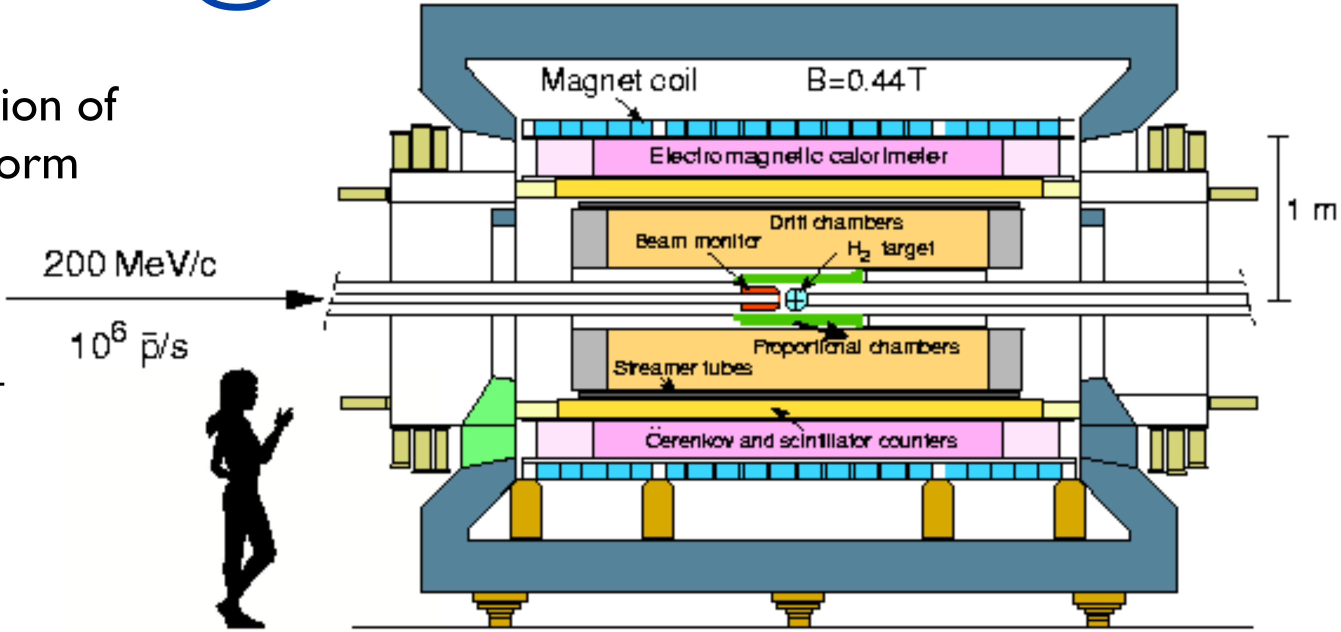
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter

CPLEAR Detector@CERN

Use the strangeness conservation of the strong interactions to perform *tagged* K^0 and $\overline{K^0}$ production:

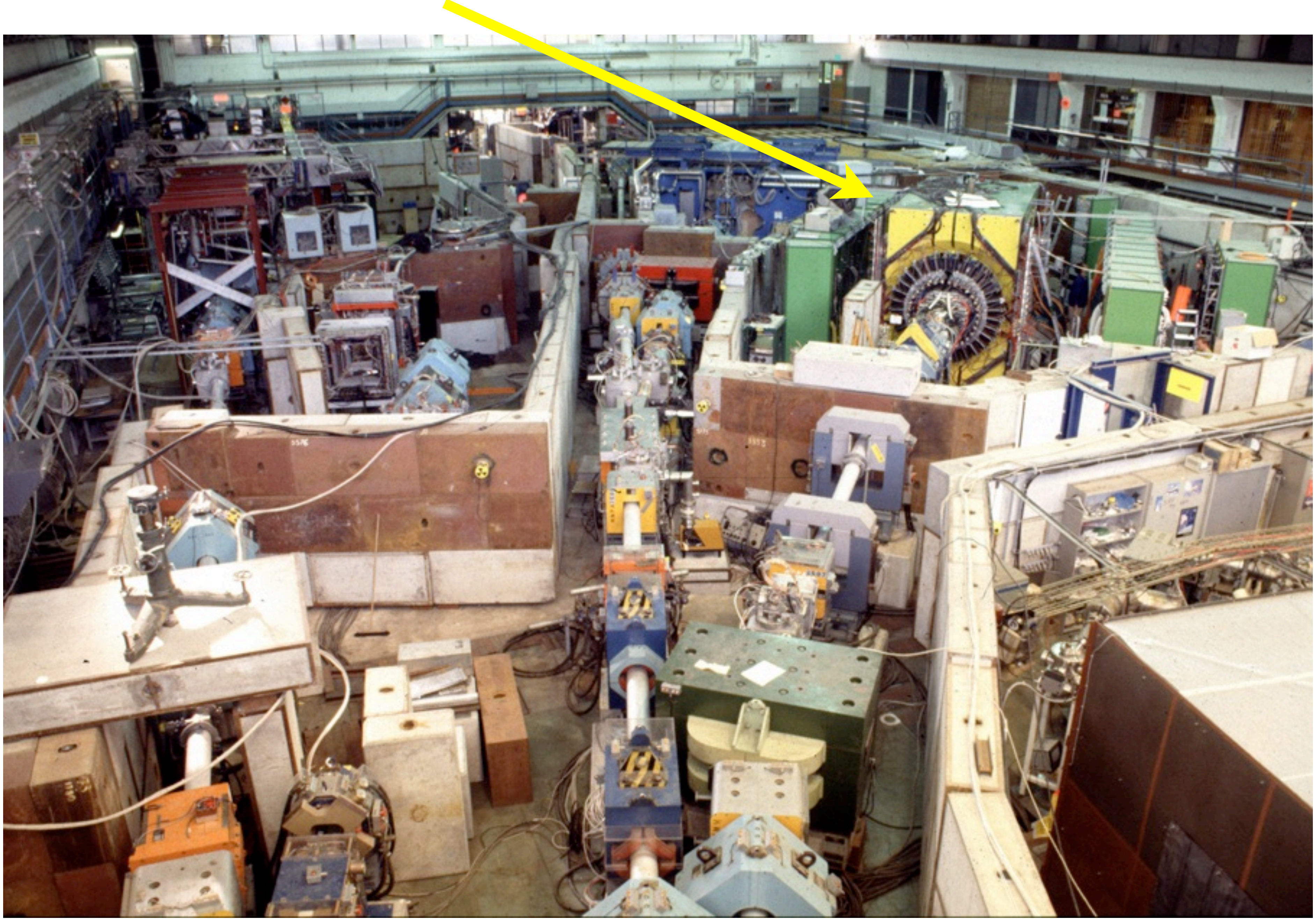
$$p\overline{p} \to \begin{cases} \pi^- K^+ \overline{K^0} \\ \pi^+ K^- K^0 \end{cases}$$



At *t=0*, events with a

- K^+ 'tag' are a pure $\overline{K^0}$ sample
- K^- 'tag' are a pure K^0 sample

CPLEAR Detector@CERN



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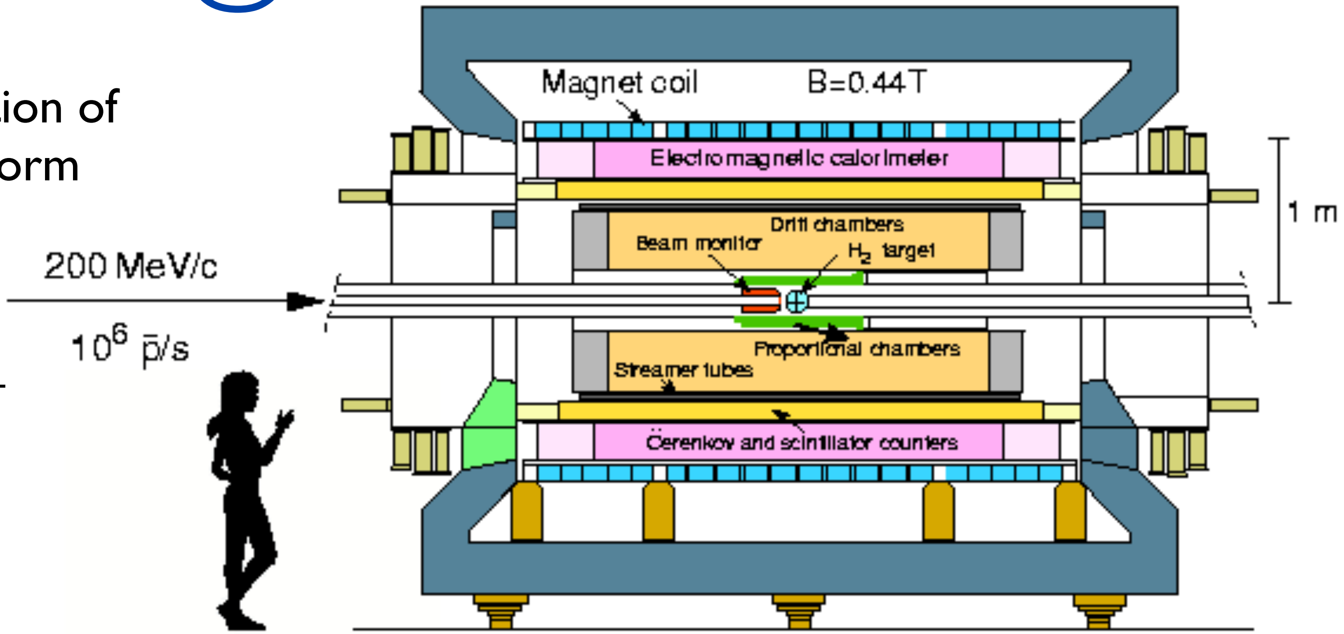
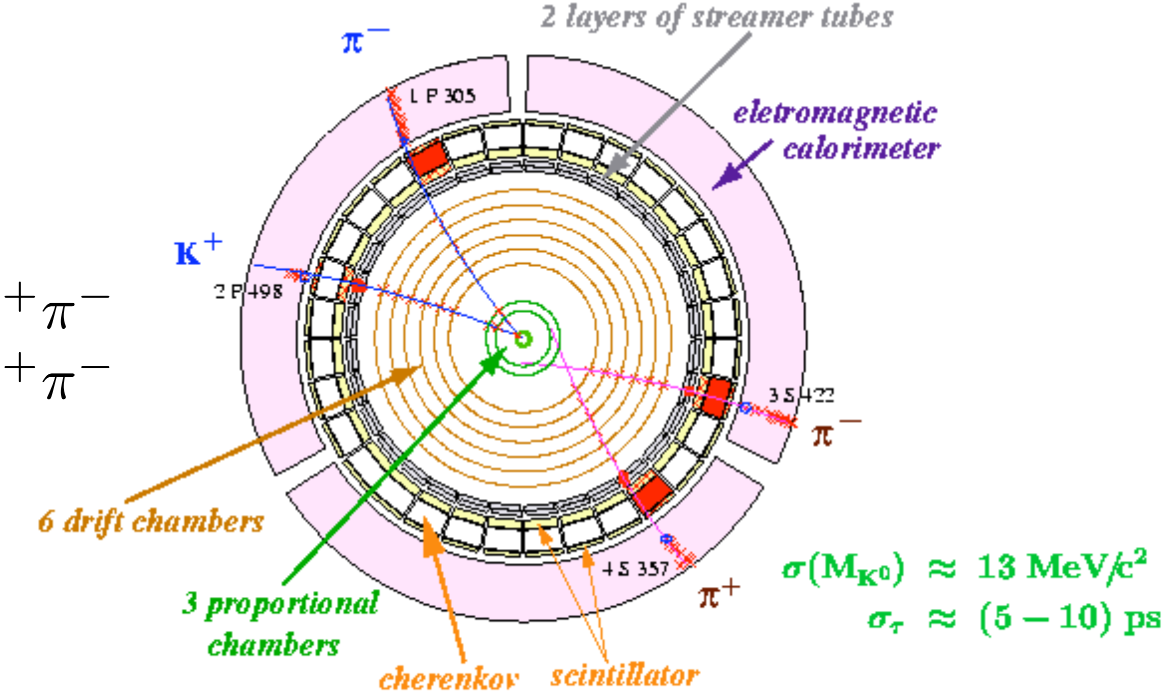


$$p\overline{p} \longrightarrow \begin{cases} \pi^- K^+ \overline{K^0} \\ \pi^+ K^- K^0 \end{cases}$$

At *t=0*, events with a

- K$^+$ ‘tag’ are a pure $\overline{\mathrm{K}^0}$ sample
- K$^-$ ‘tag’ are a pure K^0 sample

$$p\overline{p} \longrightarrow \begin{cases} \pi^- K^+ \overline{K^0} & \longrightarrow \pi^- K^+ \, \pi^+ \pi^- \\ \pi^+ K^- K^0 & \longrightarrow \pi^+ K^- \, \pi^+ \pi^- \end{cases}$$



$$\sigma(\mathrm{M}_{\mathrm{K}^0}) \approx 13\ \mathrm{MeV/c^2}$$

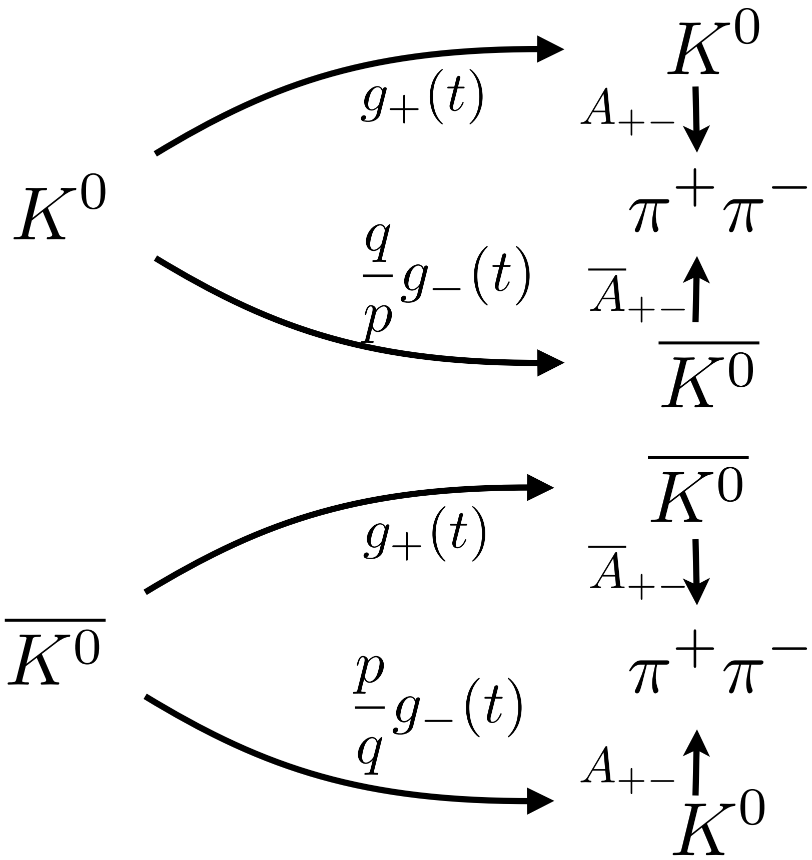
$$\sigma_\tau \approx (5-10)\ \mathrm{ps}$$

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

$$A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle$$
$$\overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle$$

$t = 0$ | t | **Amplitude**



$$g_+(t)A_{+-} + \frac{q}{p}g_-(t)\overline{A}_{+-}$$

$$g_+(t)\overline{A}_{+-} + \frac{p}{q}g_-(t)A_{+-}$$

Interference!

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad \begin{aligned} A_{+-} &\equiv \langle \pi^+\pi^- | K^0 \rangle \\ \overline{A}_{+-} &\equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \end{aligned} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$t = 0$ $\quad$ t $\quad$ **Amplitude**

$$\begin{tikzcd}
 & K^0 \arrow[d, "A_{+-}"'] \\
K^0 \arrow[ur, bend left, "g_+(t)"'] \arrow[dr, bend right, "\frac{q}{p}g_-(t)"] & \pi^+\pi^- \\
 & \overline{K^0} \arrow[u, "\overline{A}_{+-}"]
\end{tikzcd}$$

$$A_{+-}\,[\, g_+(t) + \lambda_{+-} g_-(t)\,]$$

$$\begin{tikzcd}
 & \overline{K^0} \arrow[d, "\overline{A}_{+-}"'] \\
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 & K^0 \arrow[u, "A_{+-}"]
\end{tikzcd}$$

$$\overline{A}_{+-}\left[\, g_+(t) + \frac{1}{\lambda_{+-}} g_-(t)\,\right]$$

Interference!

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$t = 0$ t **Rate**

$$\begin{tikzcd}
 & K^0 \arrow[d, "A_{+-}"'] \\
K^0 \arrow[ur, bend left, "g_+(t)"'] \arrow[dr, bend right, "\frac{q}{p}g_-(t)"] & \pi^+\pi^- \\
 & \overline{K^0} \arrow[u, "\overline{A}_{+-}"]
\end{tikzcd}$$

$$\propto |A_{+-} \, [\, g_+(t) + \lambda_{+-} g_-(t) \,] \,|^2$$

$$\begin{tikzcd}
 & \overline{K^0} \arrow[d, "\overline{A}_{+-}"'] \\
\overline{K^0} \arrow[ur, bend left, "g_+(t)"'] \arrow[dr, bend right, "\frac{p}{q}g_-(t)"] & \pi^+\pi^- \\
 & K^0 \arrow[u, "A_{+-}"]
\end{tikzcd}$$

$$\propto \left| \overline{A}_{+-} \left[g_+(t) + \frac{1}{\lambda_{+-}} g_-(t) \right] \right|^2$$

Three ways to break CP...

$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2} \qquad \begin{array}{l} A_{+-} \equiv \langle \pi^+\pi^- | K^0 \rangle \\ \overline{A}_{+-} \equiv \left\langle \pi^+\pi^- | \overline{K^0} \right\rangle \end{array} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\Gamma\left(K^0 \to \pi^+\pi^-\right) \propto |A_{+-}|^2 \left[|g_+(t)|^2 + |\lambda_{+-}|^2 |g_-(t)|^2 + 2\mathcal{R}\left(\lambda_{+-} g_+^*(t) g_-(t)\right)\right]$$

$$\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) \propto |\overline{A}_{+-}|^2 \left[|g_+(t)|^2 + \frac{1}{|\lambda_{+-}|^2} |g_-(t)|^2 + \frac{2}{|\lambda_{+-}|^2}\mathcal{R}\left(\lambda_{+-}^* g_+^*(t) g_-(t)\right)\right]$$

1. CP violation in decay $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$
2. CP violation in mixing: $\left|\frac{q}{p}\right| \neq 1$
3. CP violation in interference mixing/decay: $\mathcal{I}(\lambda_f) = \mathcal{I}\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0$

Write in terms of observables...

$$\eta_{+-} = \frac{1-\lambda}{1+\lambda} = \frac{pA - q\bar{A}}{pA + q\bar{A}} = \frac{\langle \pi^+\pi^- | K_L \rangle}{\langle \pi^+\pi^- | K_S \rangle} \qquad \eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} \qquad \lambda_{+-} \equiv \frac{q}{p}\frac{\overline{A}_{+-}}{A_{+-}}$$

$$\begin{aligned}
\Gamma\left(K^0 \to \pi^+\pi^-\right) &= N\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2e^{-\Gamma t}|\eta_{+-}|\cos\left(\Delta m t - \phi_{+-}\right)\right] \\
\Gamma\left(\overline{K^0} \to \pi^+\pi^-\right) &= \overline{N}\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} - 2e^{-\Gamma t}|\eta_{+-}|\cos\left(\Delta m t - \phi_{+-}\right)\right]
\end{aligned}$$

K_S $\qquad$ K_L $\qquad$ K_S-K_L interference

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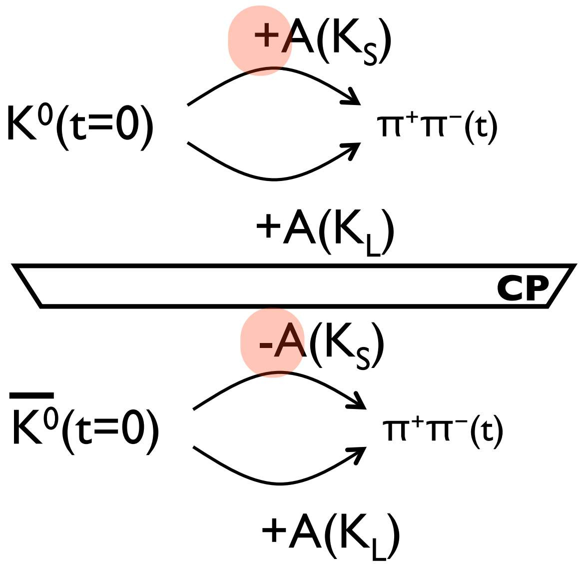
\end{aligned}$$

K_S $\qquad$ K_L $\qquad$ K_S-K_L interference

Interference term has a *sign difference* because:

$$\begin{aligned}
|K^0\rangle &= \frac{1}{2p}\left(|K_L\rangle + |K_S\rangle\right) \\
|\overline{K^0}\rangle &= \frac{1}{2q}\left(|K_L\rangle - |K_S\rangle\right)
\end{aligned}$$

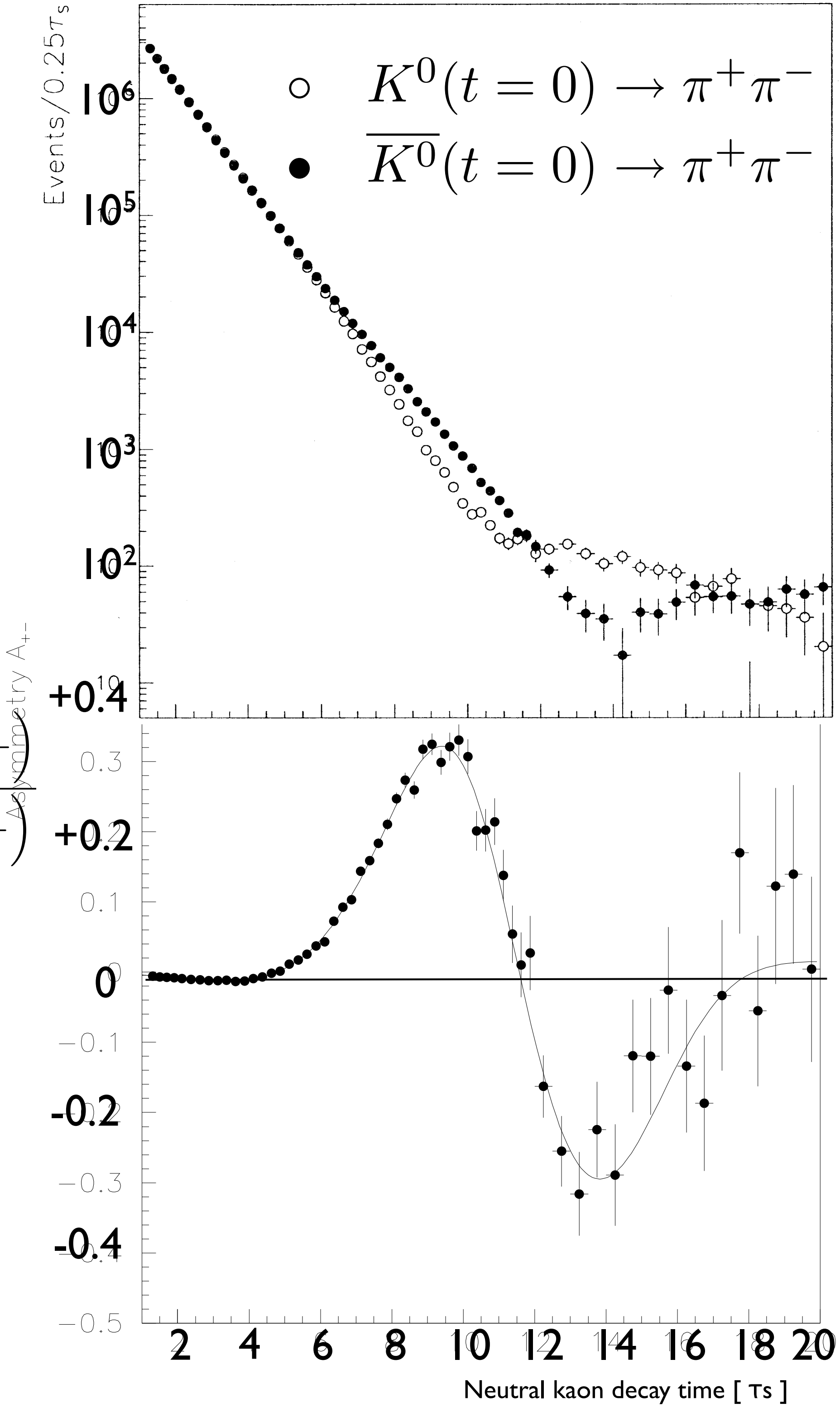


A determination of the CP violation parameter η_{+-} from the decay of strangeness-tagged neutral kaons

CPLEAR Collaboration

A. Apostolakis [a], E. Aslanides [k], G. Backenstoss [b], P. Bargassa [m], O. Behnke [q],
A. Benelli [i], V. Bertin [k], F. Blanc [g,m], P. Bloch [d], P. Carlson [o], M. Carroll [i],
E. Cawley [i], M.B. Chertok [c], M. Danielsson [o], M. Dejardin [n], J. Derre [n], A. Ealet [k],
C. Eleftheriadis [p], W. Fetscher [q], M. Fidecaro [d], A. Filipčič [j], D. Francis [c], J. Fry [i],
E. Gabathuler [i], R. Gamet [i], H.-J. Gerber [q], A. Go [o], A. Haselden [i], P.J. Hayman [i],
F. Henry-Couannier [k], R.W. Hollander [f], K. Jon-And [o], P.-R. Kettle [m], P. Kokkas [d],
R. Kreuger [f], R. Le Gac [k], F. Leimgruber [b], I. Mandić [j], N. Manthos [h], G. Marel [n],
M. Mikuž [j], J. Miller [c], F. Montanet [k], A. Muller [n], T. Nakada [m], B. Pagels [q],
I. Papadopoulos [p], P. Pavlopoulos [b], G. Polivka [b], R. Rickenbach [b], B.L. Roberts [c],
T. Ruf [d], L. Sakeliou [a], M. Schäfer [q], L.A. Schaller [g], T. Schietinger [b],
A. Schopper [d], L. Tauscher [b], C. Thibault [l], F. Touchard [k], C. Touramanis [i],
C.W.E. Van Eijk [f], S. Vlachos [b], P. Weber [q], O. Wigger [m], M. Wolter [q], C. Yeche [n],
D. Zavrtanik [j], D. Zimmerman [c]

$$\mathcal{A} = \frac{\Gamma\left(K^0 \to \pi + \pi -\right) - \Gamma\left(\overline{K^0} \to \pi + \pi -\right)}{\Gamma\left(K^0 \to \pi + \pi -\right) + \Gamma\left(\overline{K^0} \to \pi + \pi -\right)}$$



Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
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- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
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- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!

CP and the Standard Model

Sofar:

- seen that Weak Interaction breaks both C and P ‘completely’ and CP ‘a bit’
- described what happens in very generic terms...

Next:

1. towards the Standard Model description of the Weak Interaction
2. how CP violation is integrated into the Standard Model
3. how can we test the Standard Model description of CP violation?

Leptons & Quarks

In the sixties, it seemed that there were

- 4 types of lepton: e, ν_e, μ, ν_μ
- 3 types of quark: u, d, s
  - but many (most!) considered quarks a mathematical trick to explain the zoo of observed particles...

Let's sort them by their electrical charge:

0: ν_e, ν_μ +⅔: u

-1: e, μ -⅓: d, s

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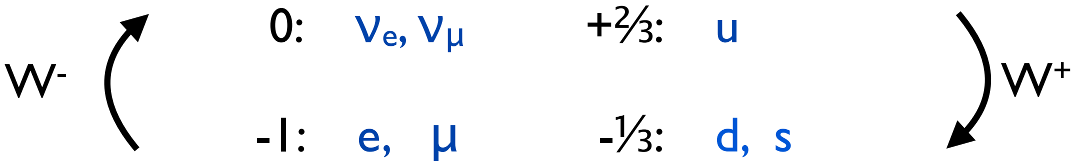
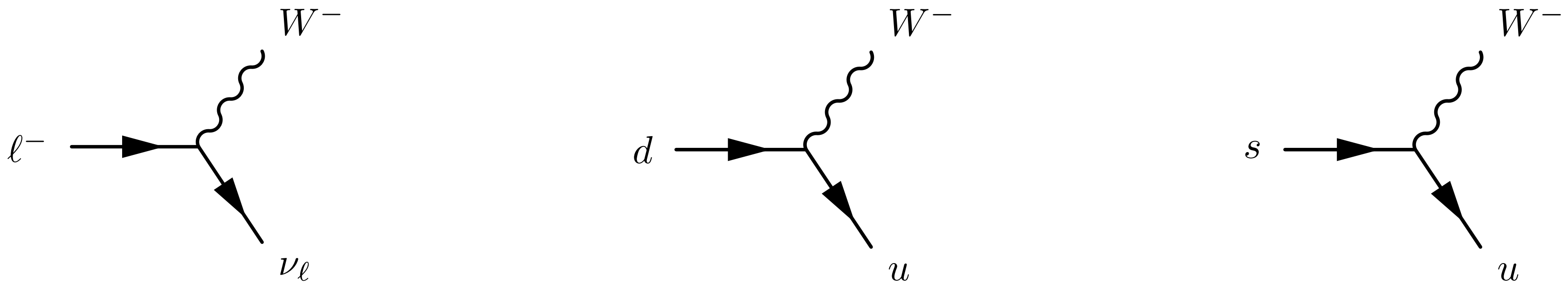


0: ν_e, ν_μ +⅔: u

-1: e, μ -⅓: d, s

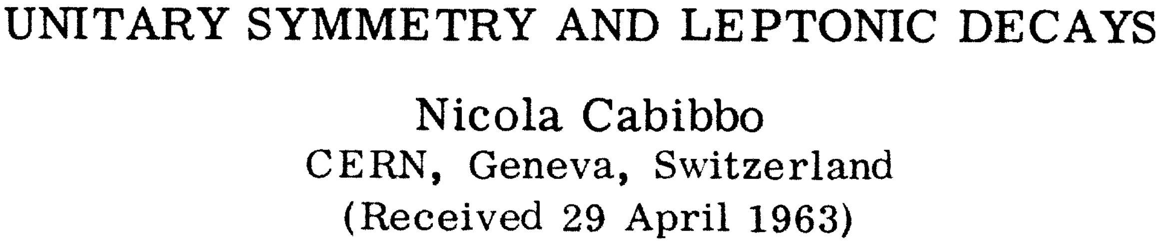
Weak Interaction: Leptons vs Quarks

- Problem: using the measured muon lifetime, the *predicted* neutron lifetime is a bit too short -- and the *predicted* lifetime of strange particles way too short...



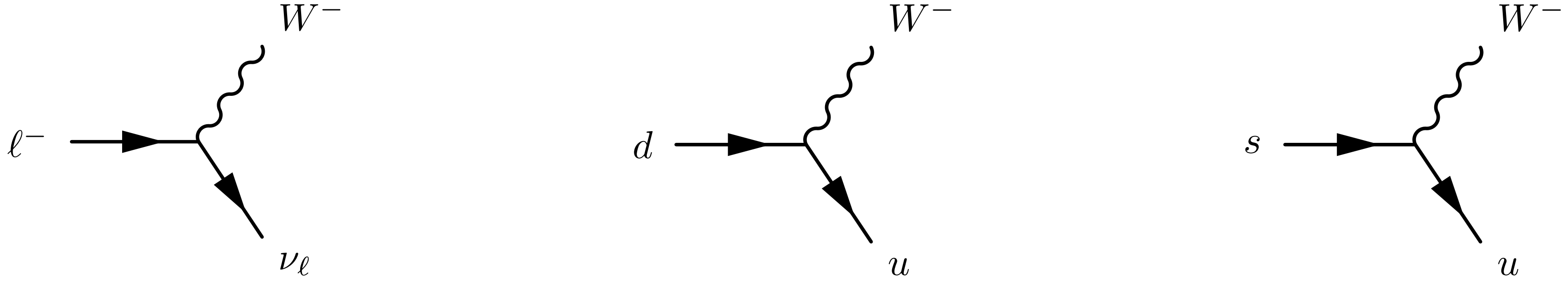
$$g \qquad > \qquad g' \qquad >> \qquad g''$$

- Conclusion: measured strength (coupling constant) of weak interaction is systematically (!) different when measured in different types of processes???
- Or maybe we just overlooked something?



UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)



$$g \quad > \quad g\cos\theta_C \quad >> \quad g\sin\theta_C$$

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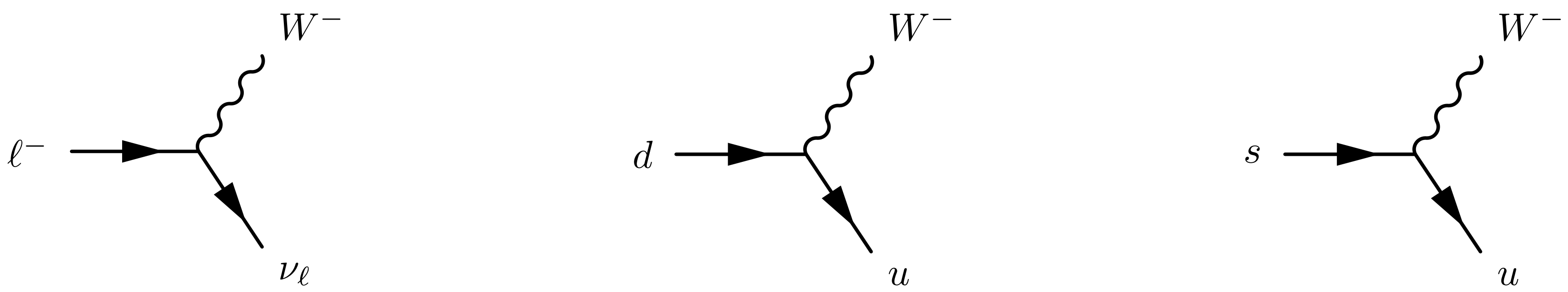


$$g \quad > \quad g\cos\theta_C \quad >> \quad g\sin\theta_C$$

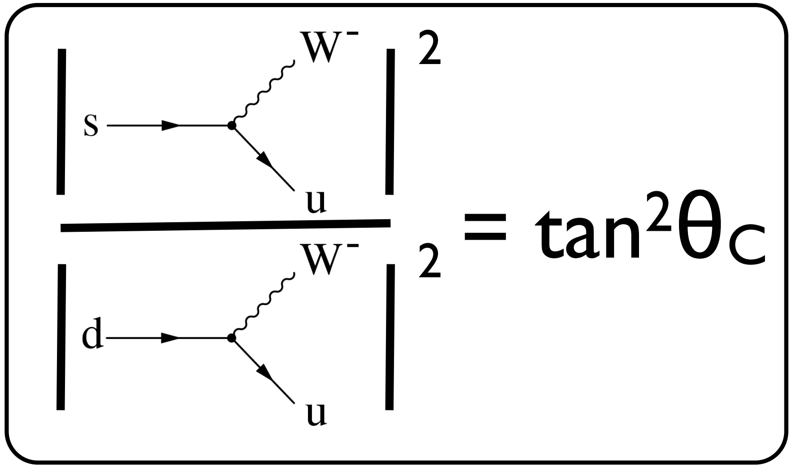
To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$

$$= \tan^2\theta M_K(1 - M_\mu^{\ 2}/M_K^{\ 2})^2/M_\pi(1 - M_\mu^{\ 2}/M_\pi^{\ 2})^2. \quad (3)$$

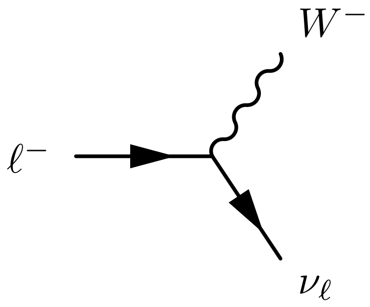
From the experimental data, we then get[5,6]

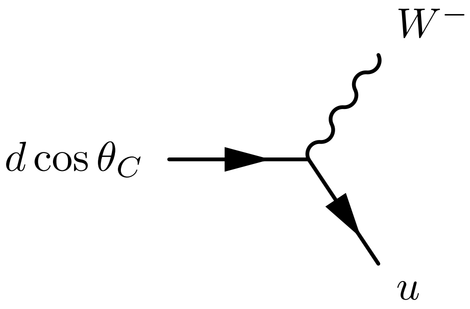
$$\theta = 0.257. \quad (4)$$

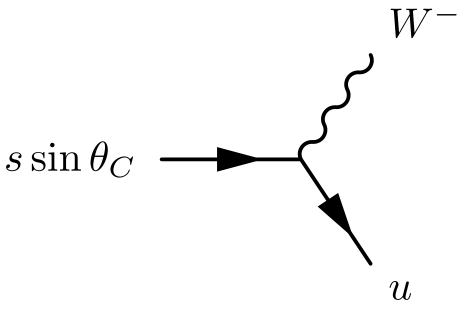


$= \tan^2\theta_C$

Weak Interaction: Universality

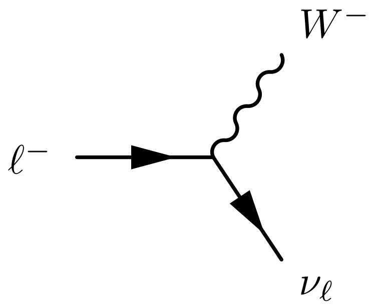


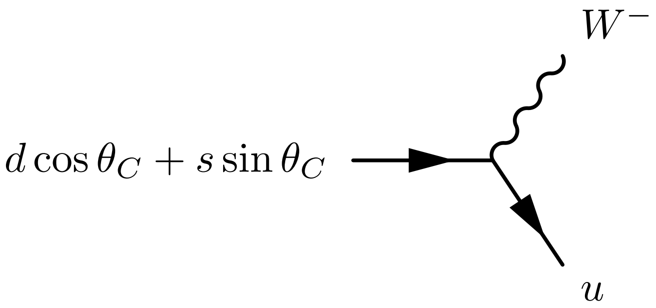




$$g \qquad = \qquad g \qquad = \qquad g$$

Weak Interaction: Universality





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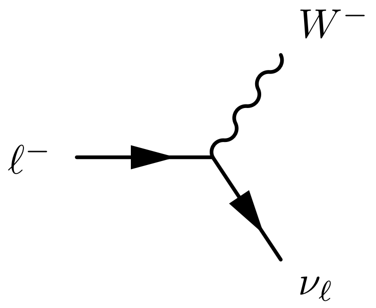
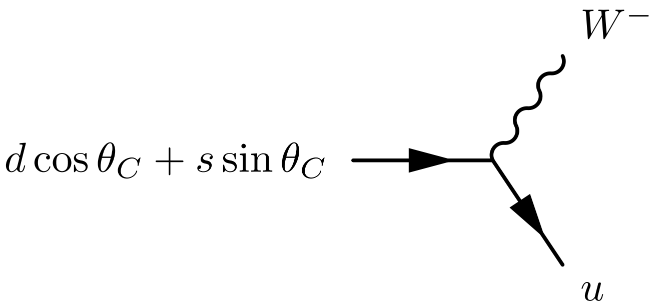


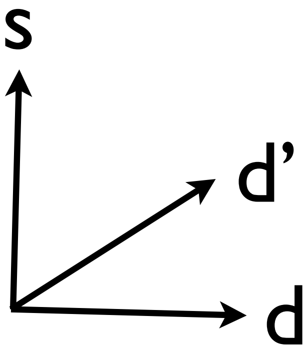


$$g \qquad = \qquad g$$

The d quark as ‘seen’ by the W, the *weak* eigenstate d’, is *not* same as the *mass* eigenstate (the d)...

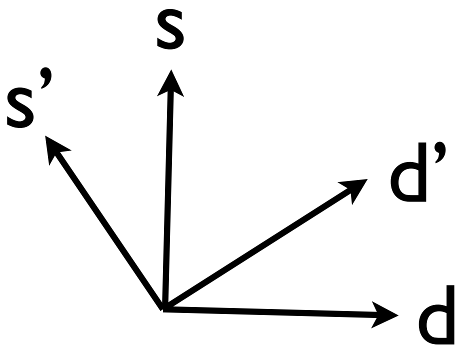
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} u \\ d' \end{pmatrix}_L = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}_L$$

Weak Interaction: Universality



The d' seen by the W is a *superposition* of the d and s...

Weak Interaction: Universality



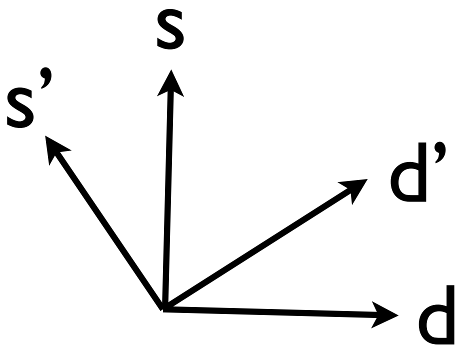
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

The d’ seen by the W is a *superposition* of the d and s...

- If d’ is a superposition of the d and s, shouldn’t there be an s’ as well? (*)
- If so, we can write d’ and s’ as *rotated* versions of d and s

(*) yes: coupling of Z to d’ *without* matching s’ causes a tree-level flavour changing neutral current, which is incompatible with eg. observed Br($K_L \to \mu\mu$)

Weak Interaction: Universality



$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

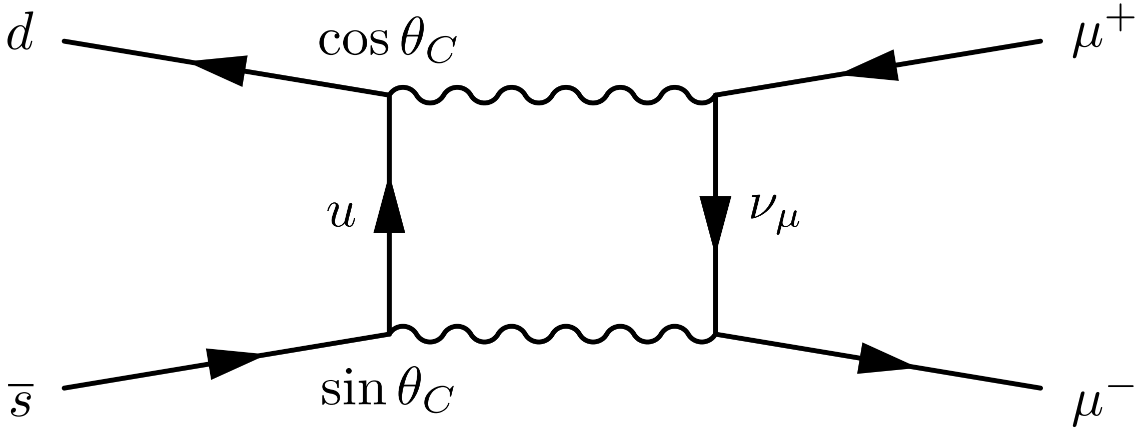
The d' seen by the W is a *superposition* of the d and s...

- If d' is a superposition of the d and s, shouldn't there be an s' as well? (*)
- If so, we can write d' and s' as *rotated* versions of d and s
- And if there is an s', why no u-like partner for it?

(*) yes: coupling of Z to d' *without* matching s' causes a tree-level flavour changing neutral current, which is incompatible with eg. observed Br($K_L \to \mu\mu$)

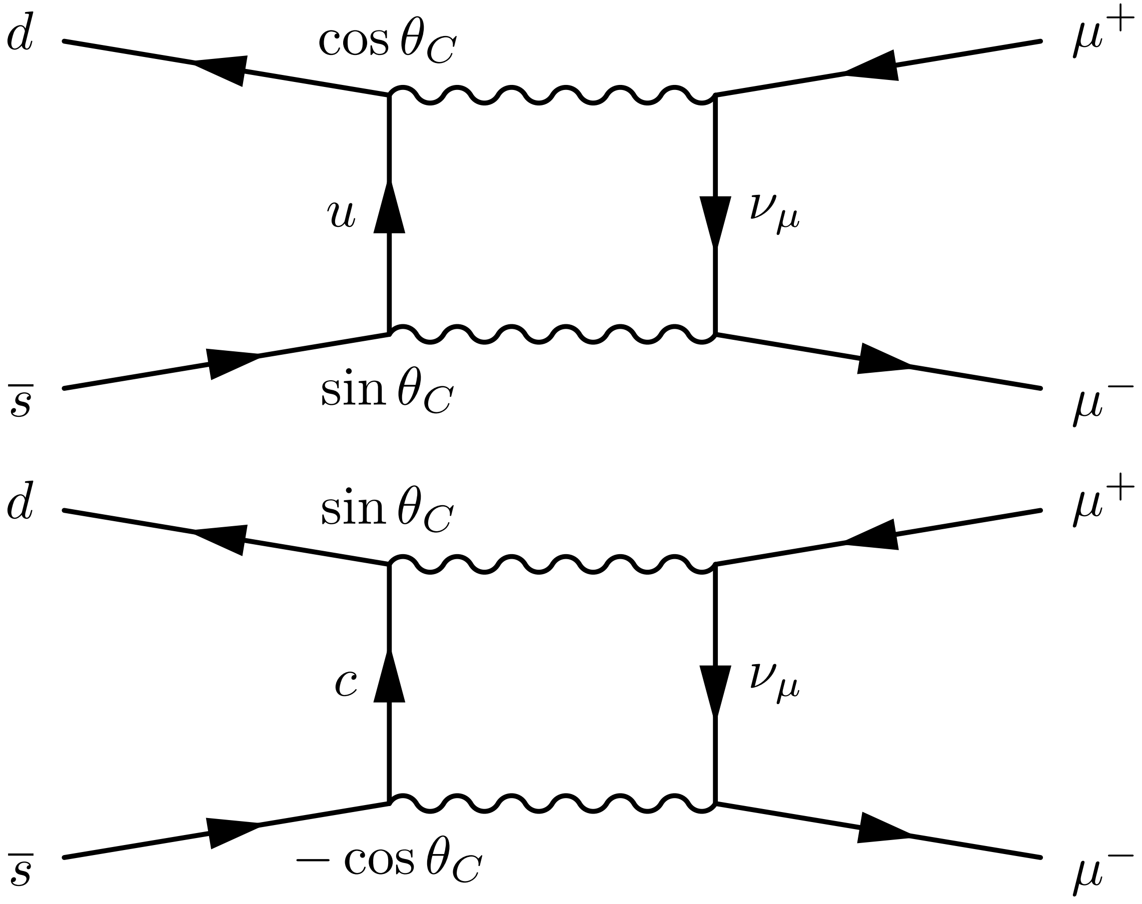
Cabibbo and the charm quark

- There was however one major exception which Cabibbo could not describe: $K^0 \rightarrow \mu^+ \mu^-$
  - Observed rate much lower than expected from Cabibbos rate correlations (expected rate ∝ $g^8 \sin^2\theta_c \cos^2\theta_c$)

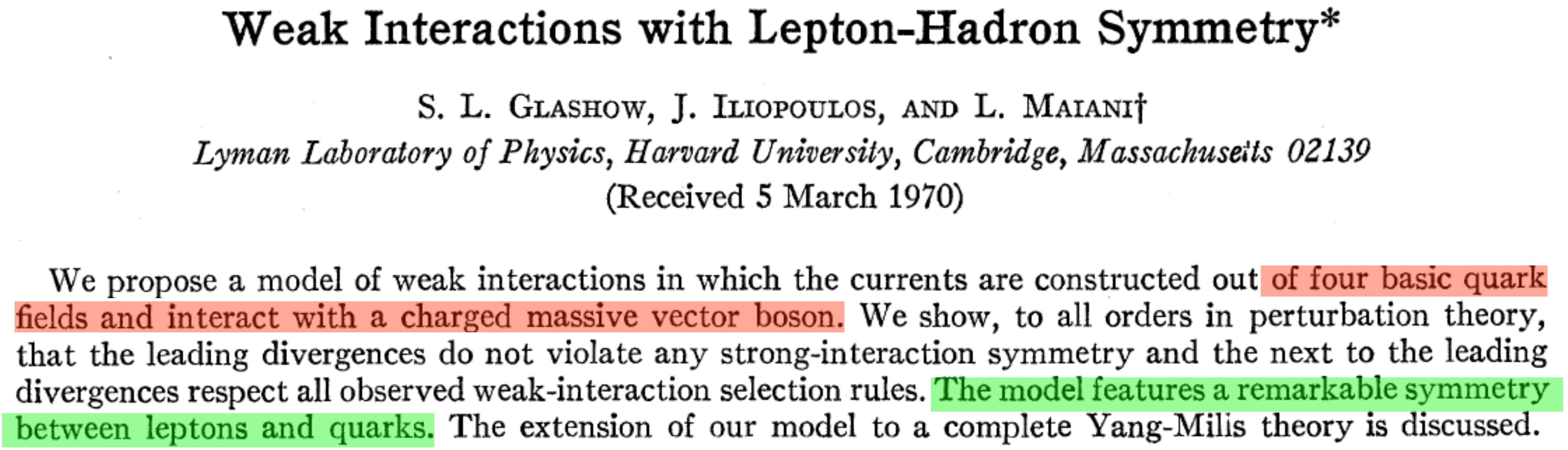


GIM and the charm quark

- How does it solve the $K^0 \rightarrow \mu^+\mu^-$ problem?
  - Second decay amplitude added that is almost identical to original one, but has relative minus sign ⇒ (Almost) fully destructive interference



  - Cancellation not perfect because u, c mass not quite the same...



Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)

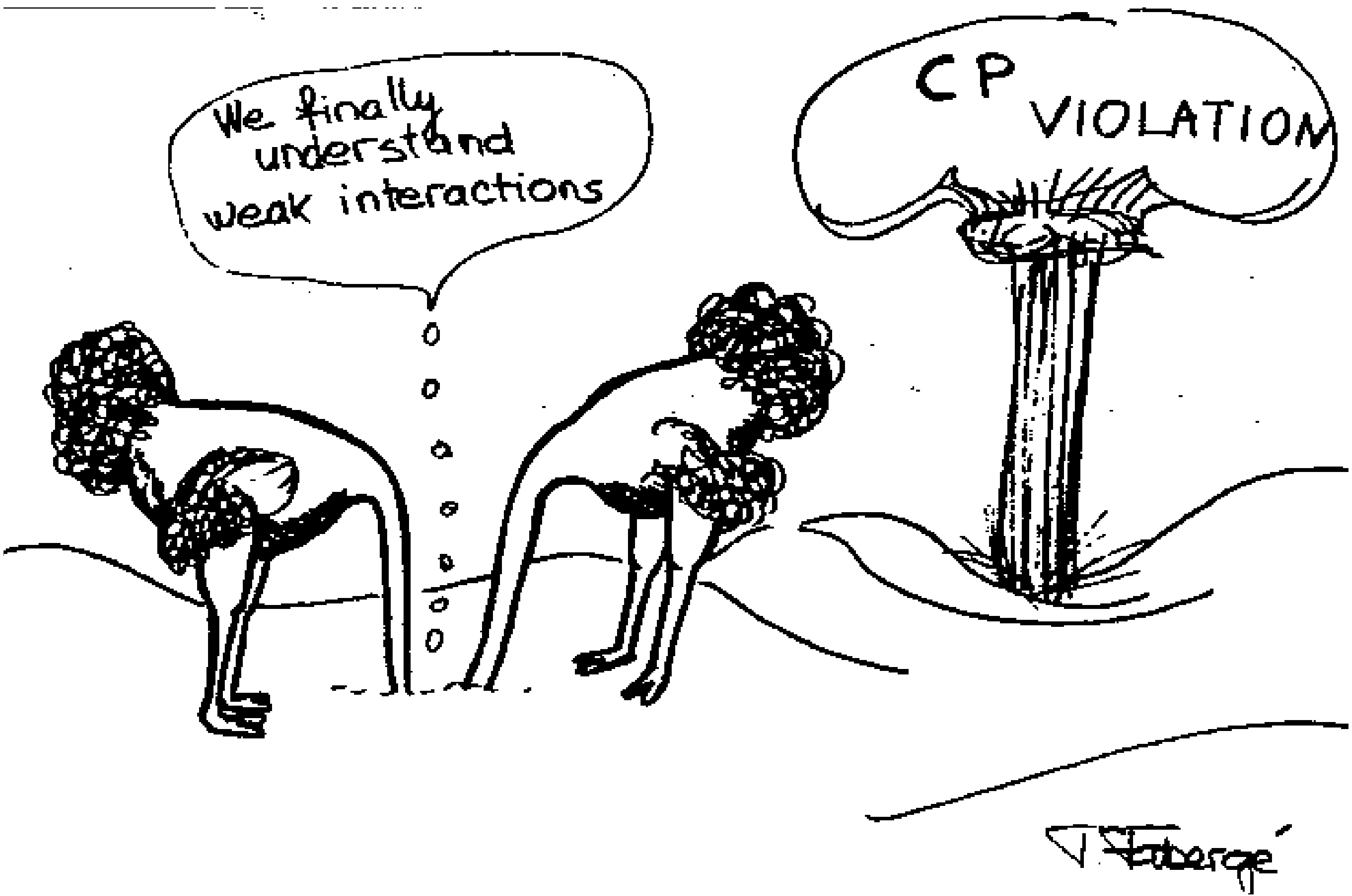
We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

One 'tiny' problem: no experimental evidence for a fourth quark...

...until 1974: Ting, Richter (Nobel prize 1976)



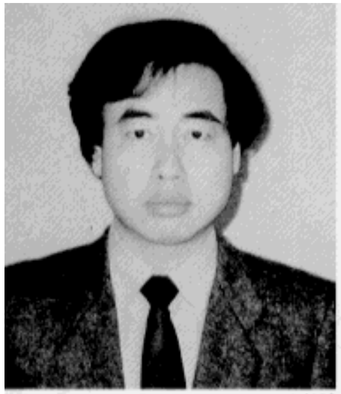
Cartoon shown by N. Cabibbo in 1966…

since then, there was tremendous progress in the understanding (better: describing) *CP* violation

⇒ **next topic!**

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...



小林誠

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

益川敏英

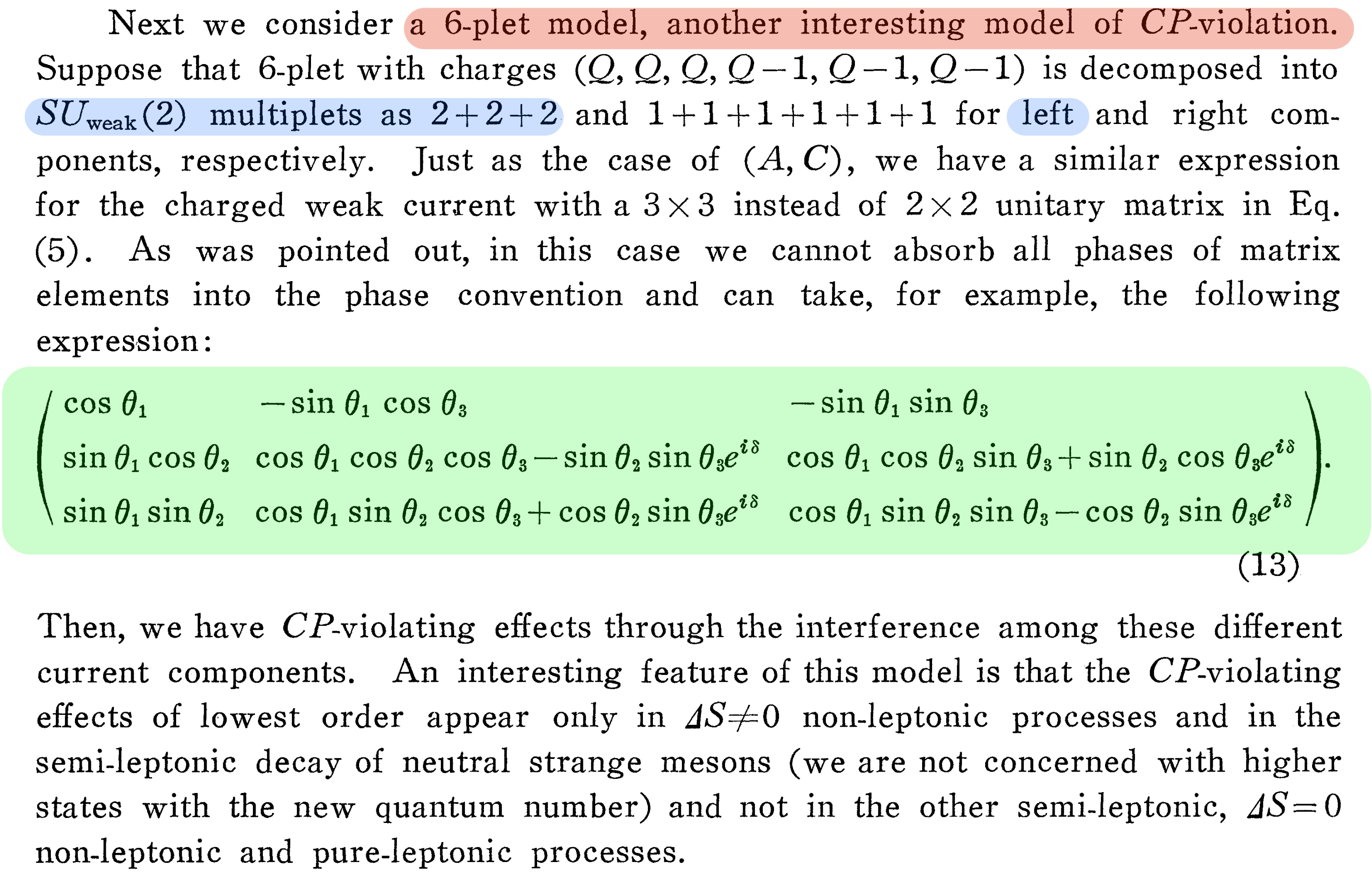
Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

The Nobel Prize winning part



Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq 0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L \text{ with} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

How many 'physical' parameters in V_{CKM}?

- complex NxN matrix: $2N^2$ parameters
- must be unitary:
  - eg. t must decay to either b, s or d, so $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$
  - in general: $V^{*T} V = I \rightarrow N^2$ constraints
- freedom to change phase of quark fields $|q_j\rangle \longrightarrow e^{i\phi_j} |q_j\rangle$
  - 2N-1 phases are irrelevant:

$$\langle q_i| V_{ij} |q_j\rangle \longrightarrow \langle q_i| e^{-i\phi_i} V_{ij} e^{i\phi_j} |q_j\rangle$$

$$V_{ij} \longrightarrow e^{i(\phi_j - \phi_i)} V_{ij}$$

- number of 'physical' parameters = N^2-2N+1

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$$V_{ij} \longrightarrow e^{i(\phi_j - \phi_i)} V_{ij}$$

- number of 'physical' parameters = N^2-2N+1
- how many can be rotation angles? N(N-1)/2
- For N=2 : 1 parameter, with 1 rotation angle (Cabbibo!)
- For N=3: 4 parameters = 3 rotations + 1 *irreducible* complex phase!

Complex phases & CP

What does *CP* (or, equivalently *T*) conjugation do with the Hamiltonian *H* ?

$$[\hat{x}, \hat{p}] = i\hbar$$

$$T\,[\hat{x}, \hat{p}]\,T^{-1} = TiT^{-1}\hbar \xrightarrow{\begin{aligned} T\hat{x} &= \hat{x} \\ T\hat{p} &= -\hat{p} \end{aligned}} TiT^{-1} = -i$$

Complex phases & CP

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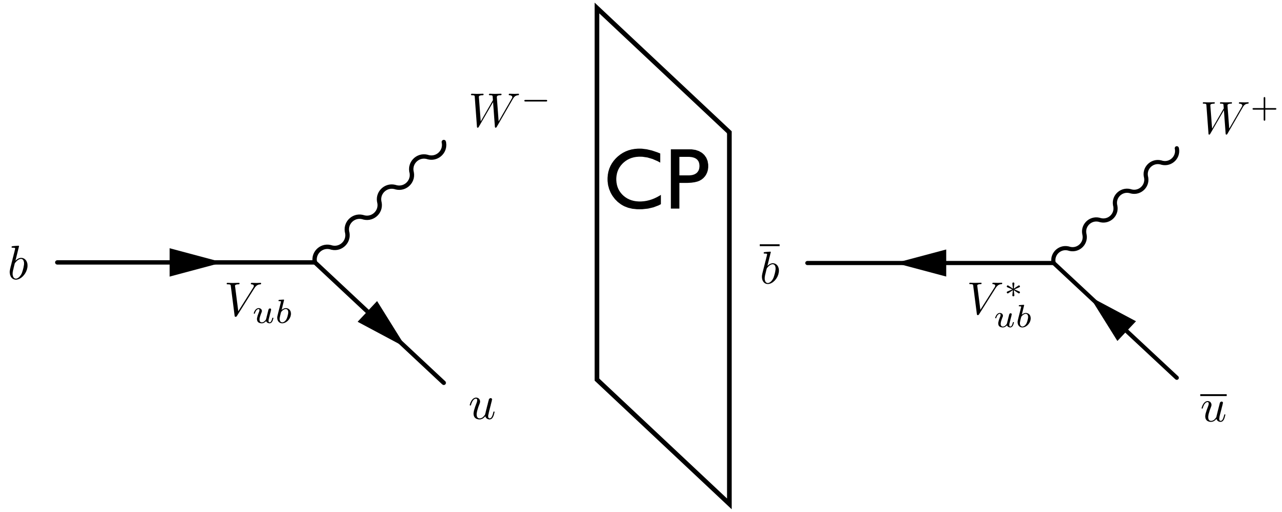
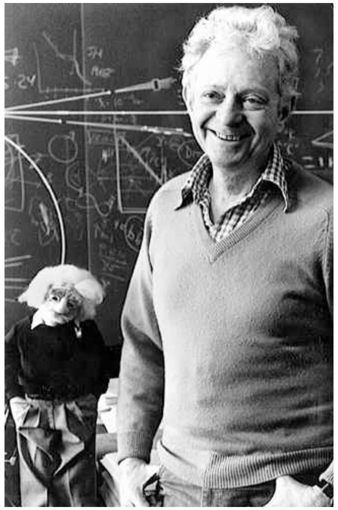
The *T* (and *CP*) operations must be **anti-unitary**, which implies **complex conjugation** !

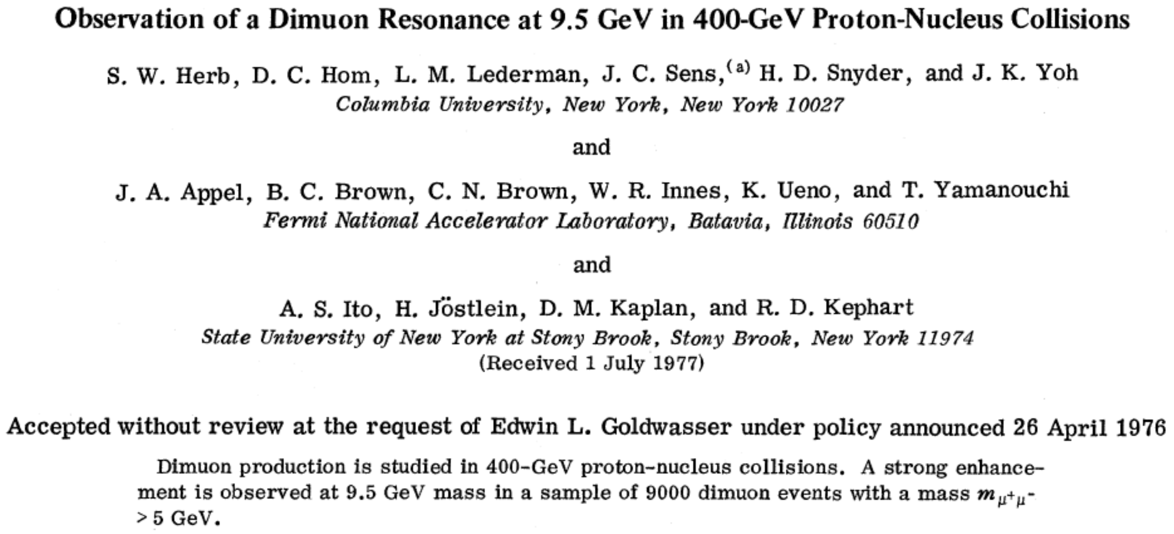


With 3 (or more) generations V_{CKM} can be complex
→ ***CP violation possible***

Are there really 3 generations?

- Discovery of 5th quark in 1977
  - Named ‘b’ for beauty/bottom
  - Mass around 4.5 GeV
  - Start of the 3rd generation of quarks!





Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
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and

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Fermi National Accelerator Laboratory, Batavia, Illinois 60510

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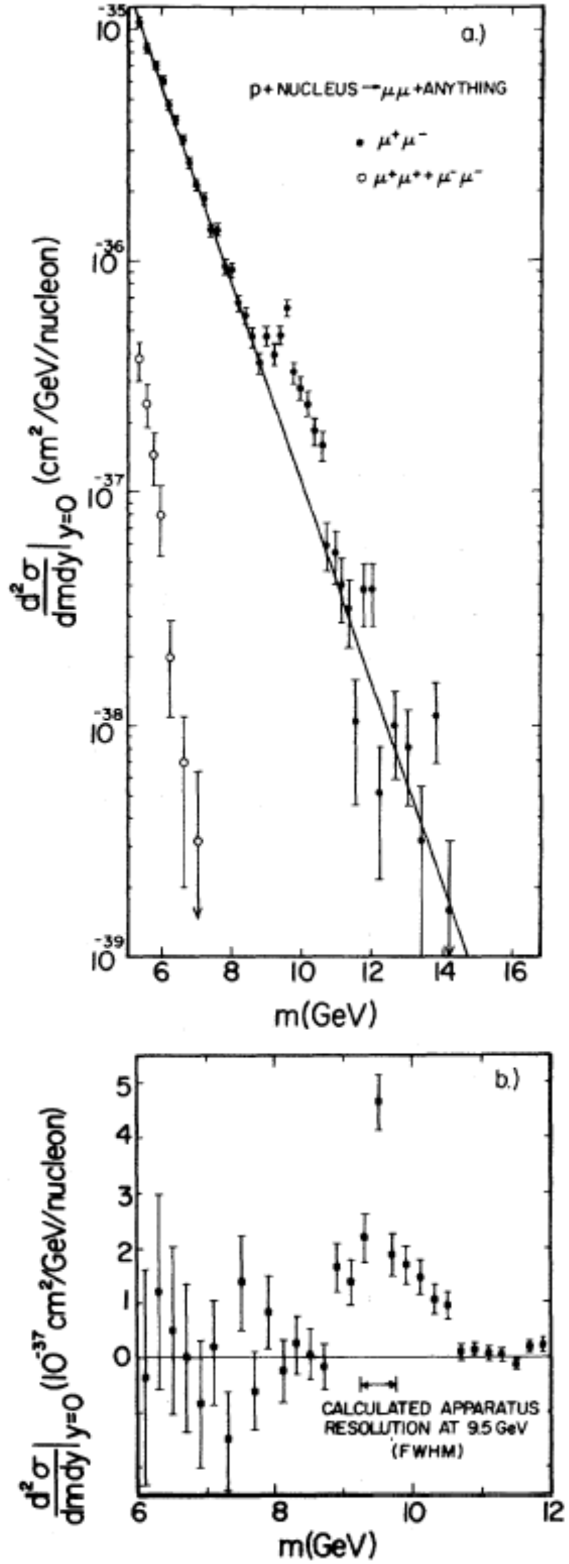
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

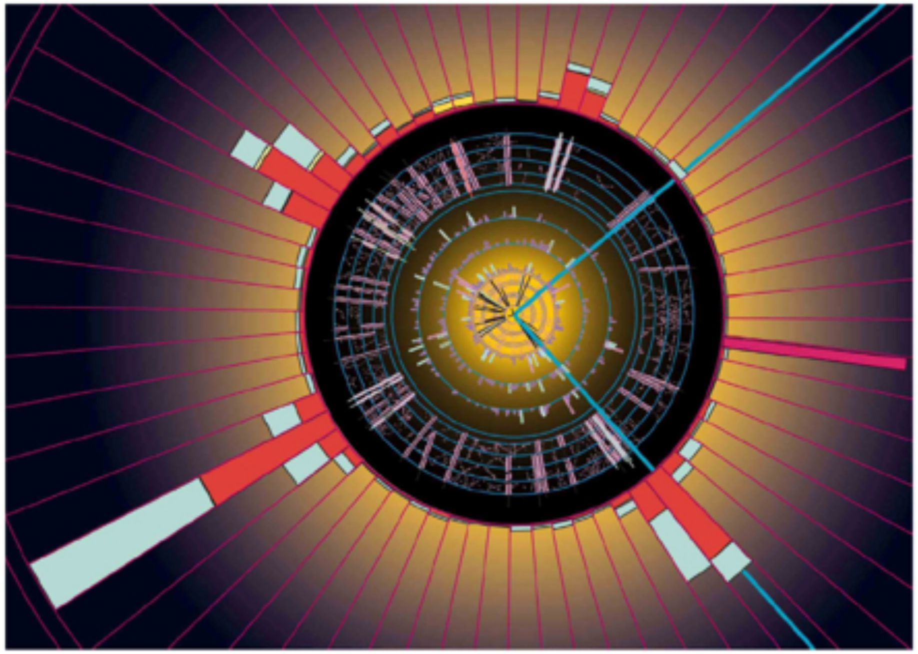
Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

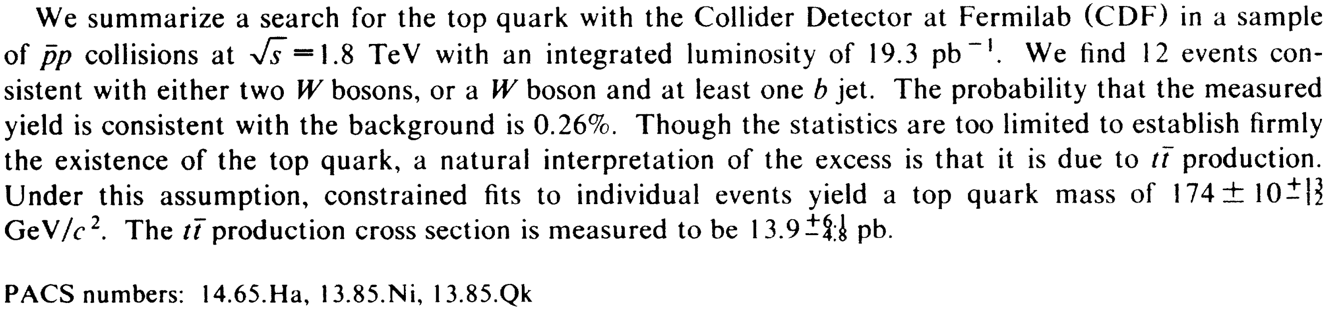


Discovery of the 6th quark

- Discovery of top quark complete 3-generation picture
- Took a long time (1994) because t quark is *very* heavy: ~175 GeV/c^2!

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV



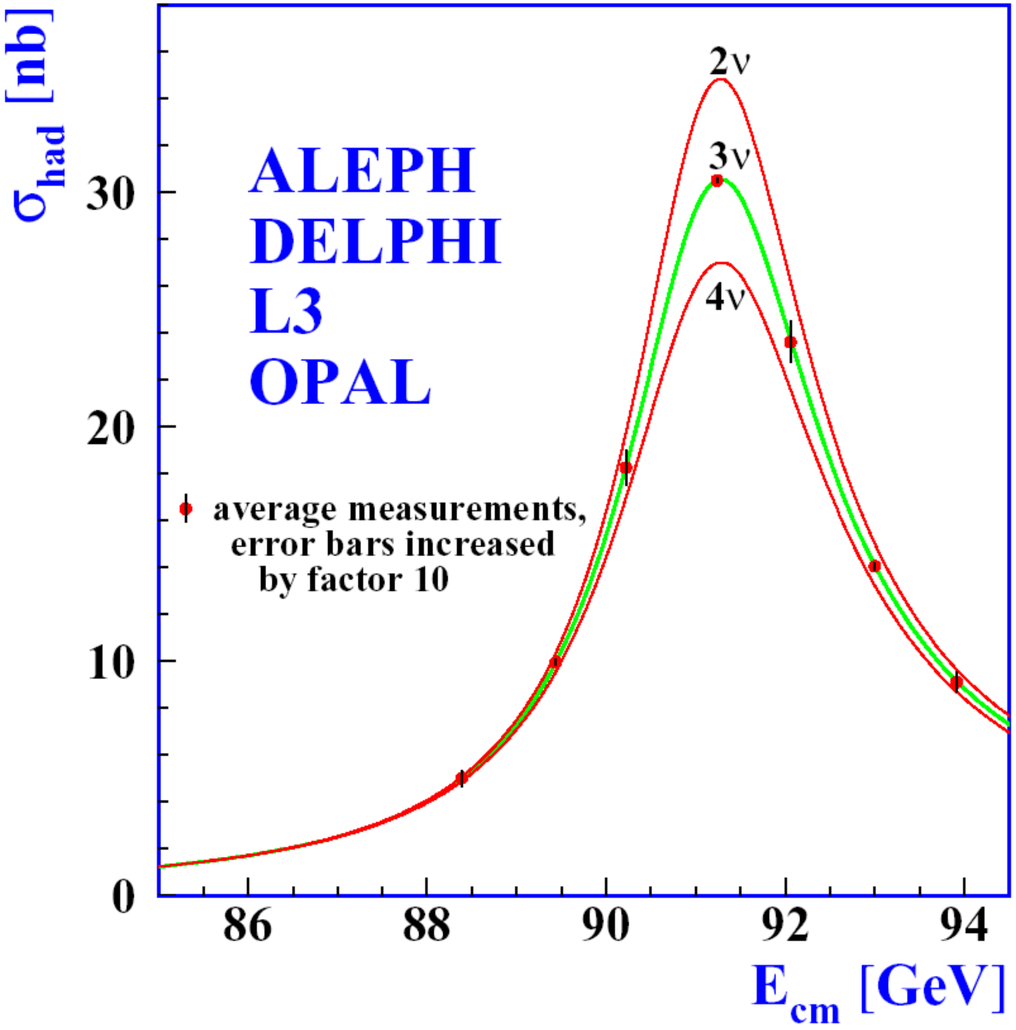


We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

PACS numbers: 14.65.Ha, 13.85.Ni, 13.85.Qk

Are there *more* than three generations?

- Surprisingly, you can actually say something about that…
  - Measure decay rate of Z boson into all quarks, compare to total Z boson decay rate
  - Because Z can decay into $\nu\bar{\nu}$ each additional generation with a light neutrino increases the *fraction* of Z decaying to $\nu\bar{\nu}$, and thus decreases the *fraction* of hadronic decays....
  - Shows conclusively that there are only 3 generations (of neutrinos, of the type we know, with mass < $M_Z/2$)



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- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same... related by V_{CKM}
- with 3 or more families, one *can* have a complex phase(s) in V_{CKM} and thus CP violation is possible!

Three generations, four parameters...

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

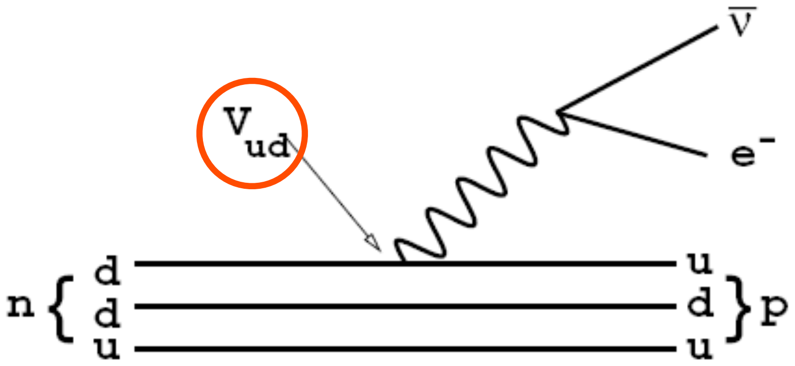
with $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$
so with four parameters $\theta_{12}, \theta_{23}, \theta_{13}, \delta$

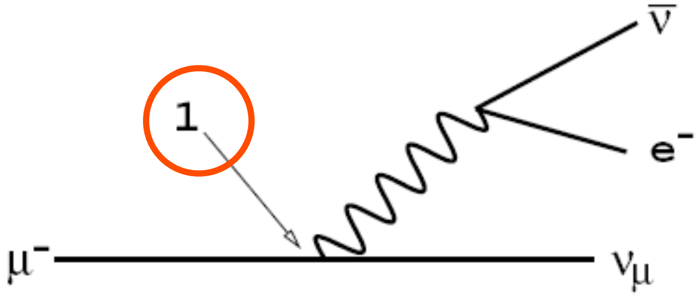
... and many more observables!

How do you measure those numbers?

- *Magnitudes* are typically determined from *ratio* of decay rates
- Example 1 – Measurement of $|V_{ud}|$
  - Compare decay rates of neutron decay and muon decay
  - Ratio proportional to $|V_{ud}|^2$
  - $|V_{ud}| = 0.9735 \pm 0.0008$
  - V_{ud} of order 1

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

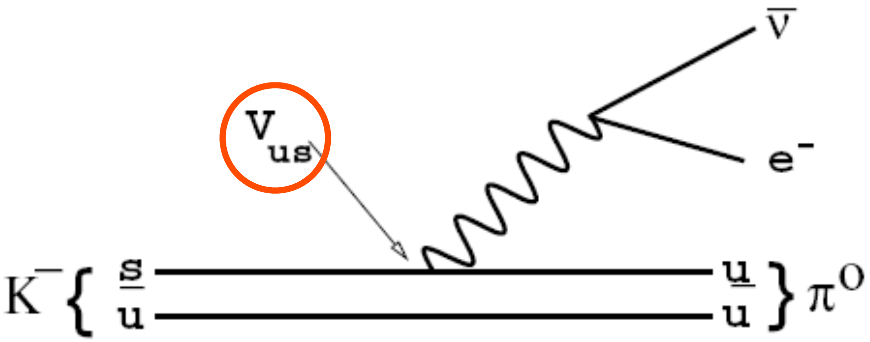


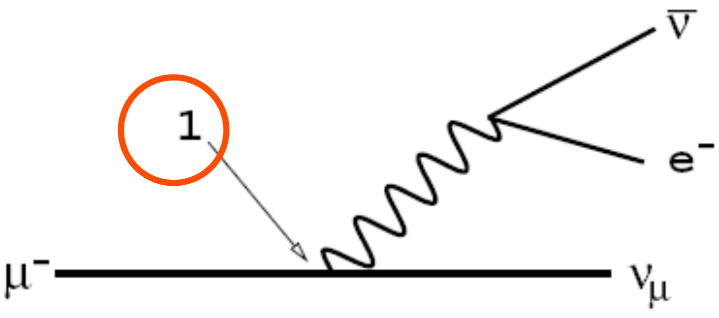


How do you measure those numbers?

- Example 2 – Measurement of $|V_{us}|$
  - Compare decay rates of semileptonic K^- decay and muon decay
  - Ratio proportional to $|V_{us}|^2$
  - $|V_{us}| = 0.2196 \pm 0.0023$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

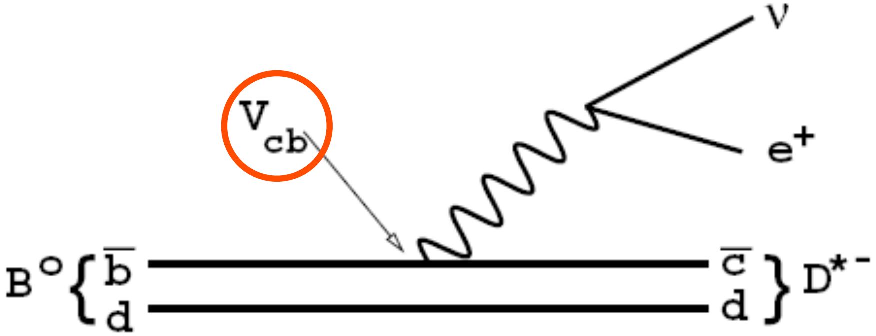


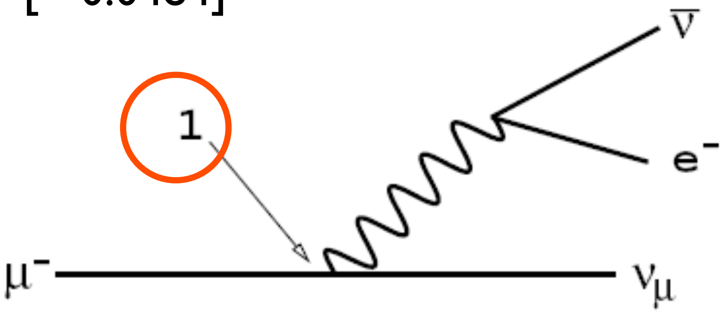


How do you measure those numbers?

- Example 3 – Measurement of V_{cb}
  - Compare decay rates of $B^0 \rightarrow D^{*-} l^{+} \nu$ and muon decay
  - Ratio proportional to V_{cb}^2
  - $|V_{cb}| = 0.0402 \pm 0.0019$
  - $|V_{cb}|$ is almost (but not quite) equal to $\cos(\theta_c)^2$ [= 0.0484]

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

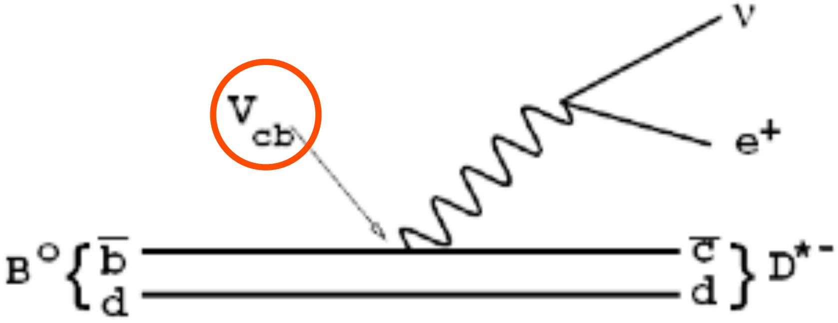


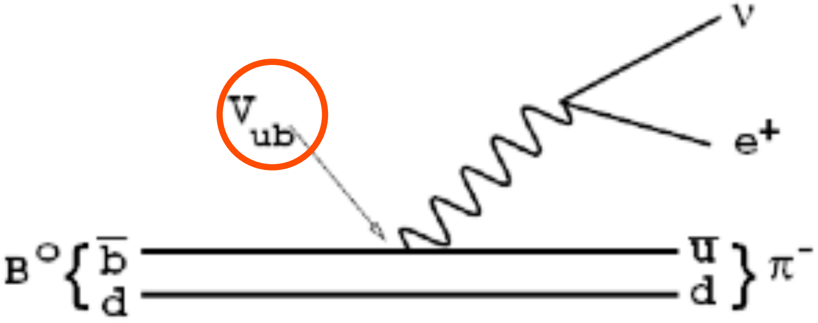


How do you measure those numbers?

- Example 4 – Measurement of V_{ub}
  - Compare decay rates of $B^0 \rightarrow D^{*-} l^+ \nu$ and $B^0 \rightarrow \pi^- l^+ \nu$
  - Ratio proportional to $(V_{ub}/V_{cb})^2$
  - $|V_{ub}/V_{cb}| = 0.090 \pm 0.025$

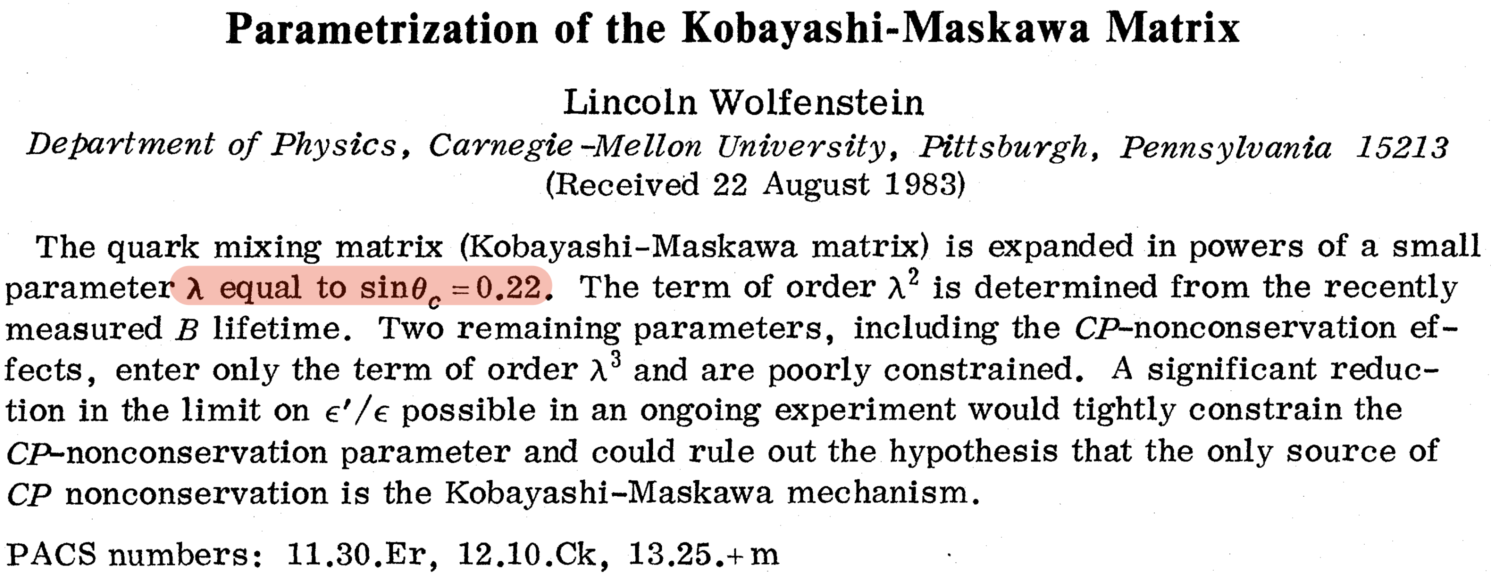
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





Hierarchy...

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



Parametrization of the Kobayashi-Maskawa Matrix

Lincoln Wolfenstein
Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

(Received 22 August 1983)

The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured B lifetime. Two remaining parameters, including the *CP*-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the *CP*-nonconservation parameter and could rule out the hypothesis that the only source of *CP* nonconservation is the Kobayashi-Maskawa mechanism.

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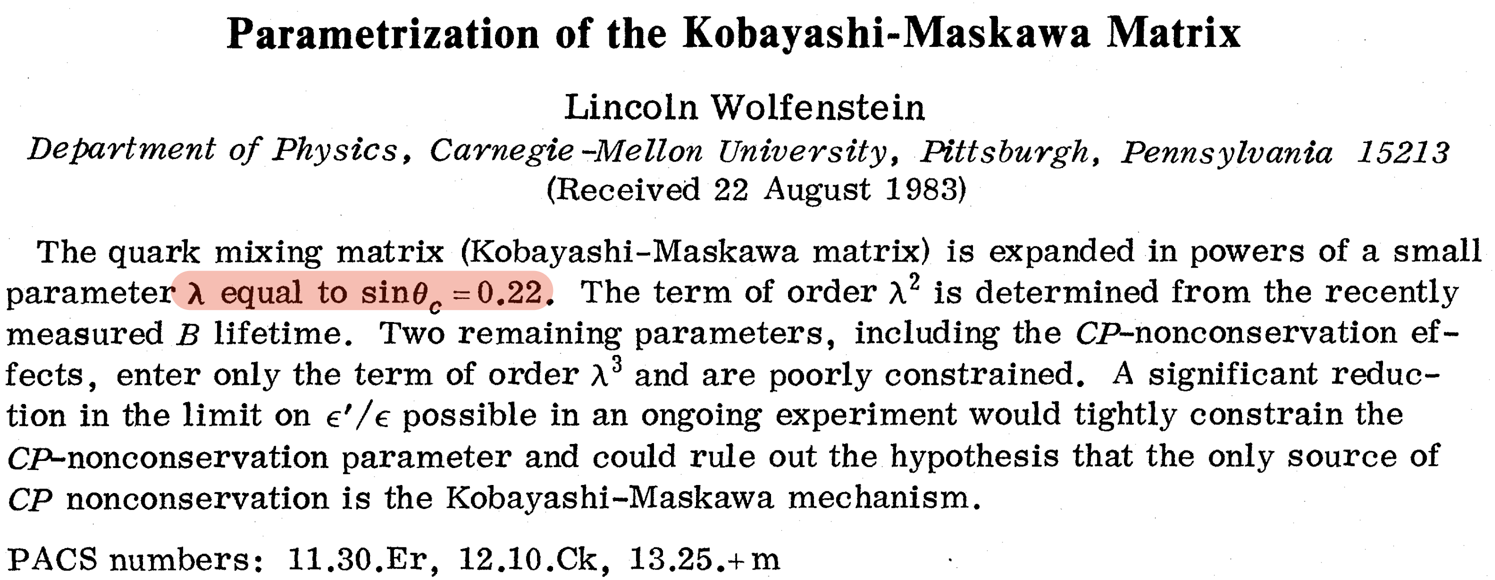

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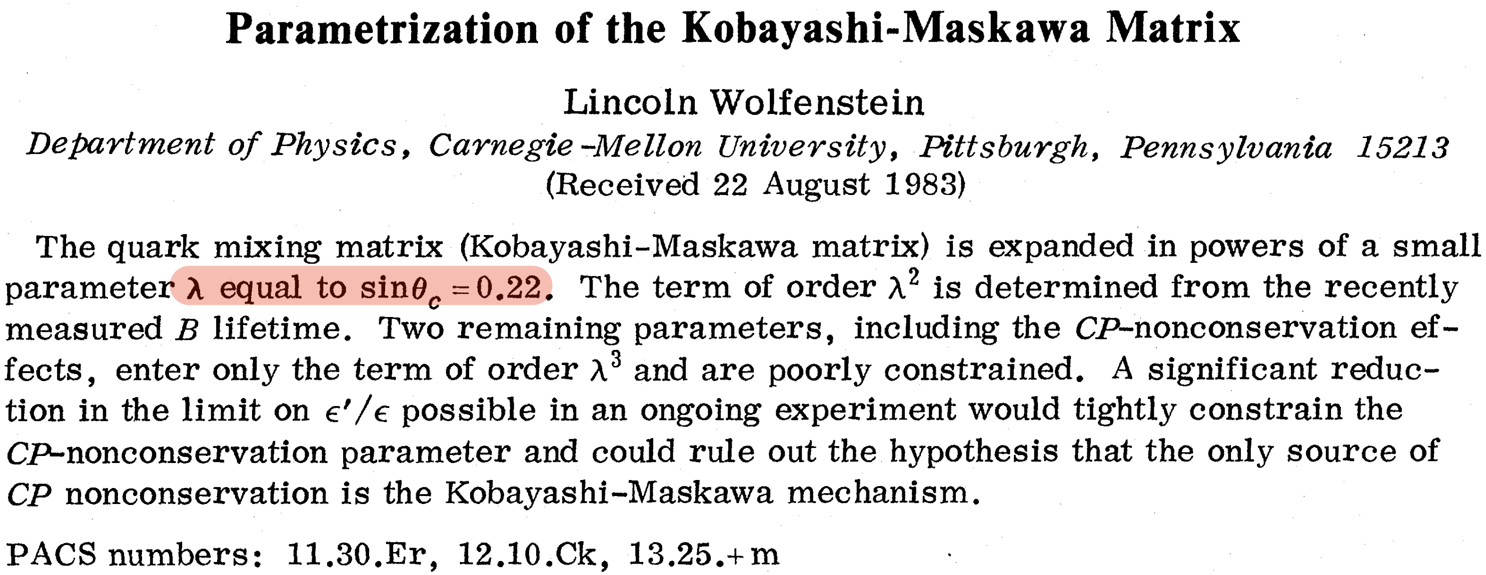

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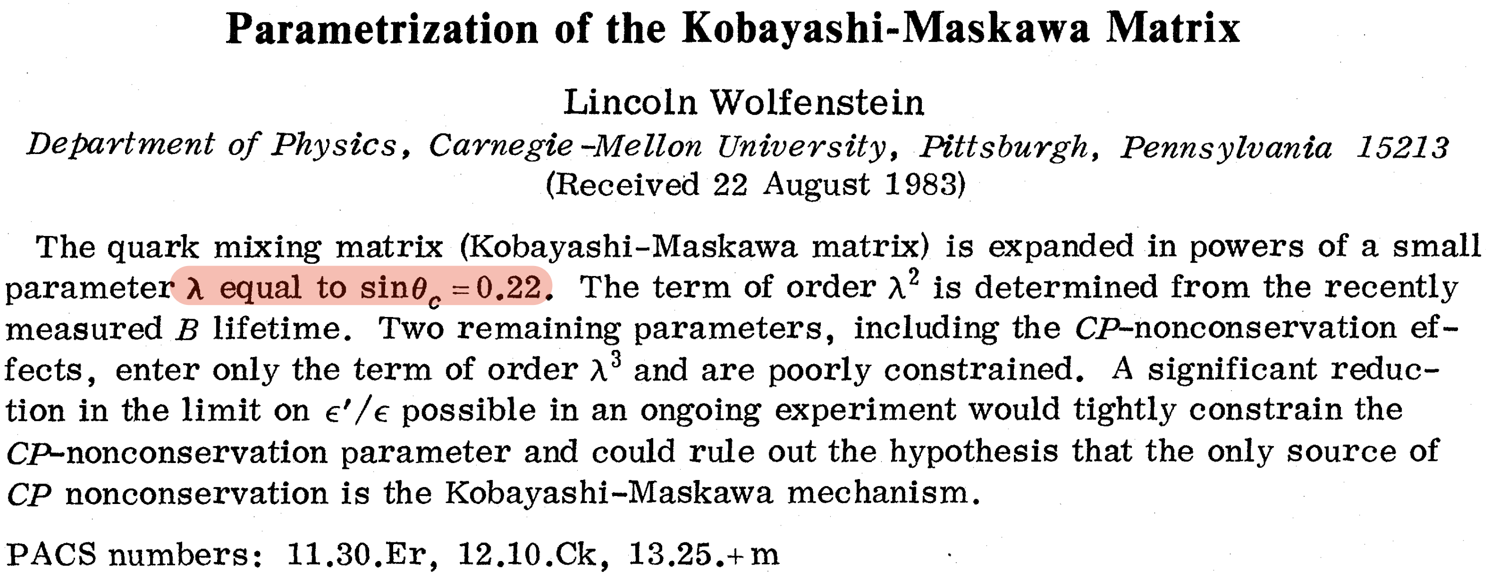

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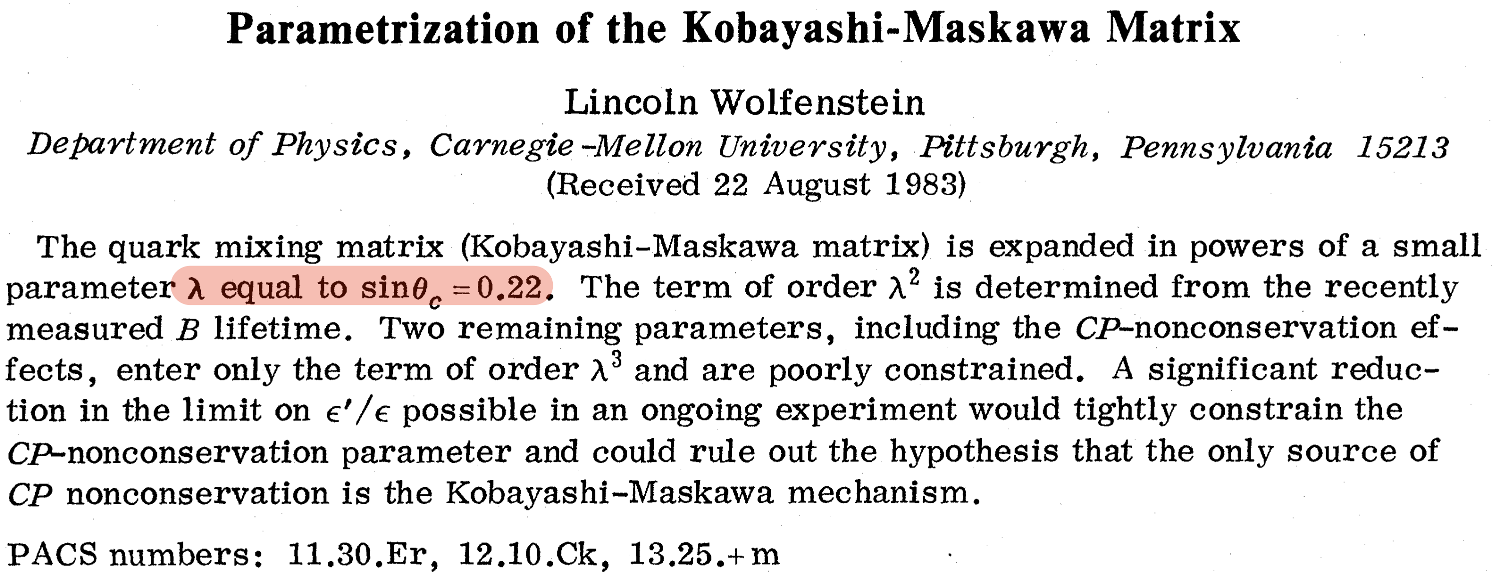

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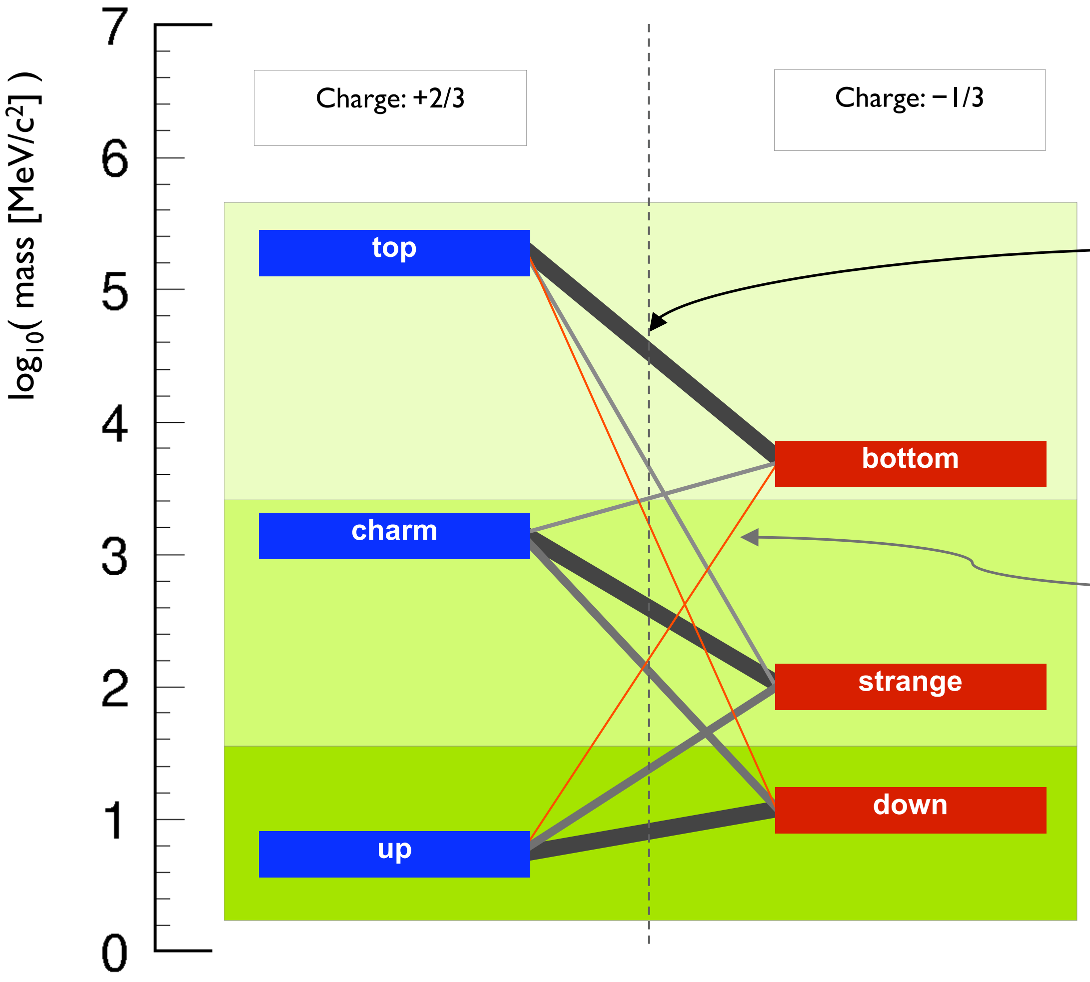
Hierarchy...



Flavour-changing transition by charged weak current (boldness indicates transition probability ∝ $|V_{ij}|$)

Smallest couplings are complex → ***CP* violation**

What is the explanation for this structure?
We don't know!

- Transition within generation favored
- Transition from 1st to 2nd generation suppressed by $\lambda=\sin(\theta_c)$
- Transition from 2nd to 3rd generation suppressed by $\lambda^2=\sin^2(\theta_c)$
- Transition from 1st to 3rd generation suppressed by $\lambda^3=\sin^3(\theta_c)$

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No 'primordial' antimatter observed
- Need something called 'CP' symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can 'mix' (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM

How to measure $|V_{td}|$ and $|V_{ts}|$?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Intermezzo: Neutral Meson Mixing

	u	c	t
$\overline{u}$	$\times$	D^0	$\diamond$
$\overline{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\overline{t}$	$\diamond$	$\diamond$	$\times$

	d	s	b
$\overline{d}$	$\times$	K^0	B^0
$\overline{s}$	$\overline{K^0}$	$\times$	B_s
$\overline{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

- Need to be neutral and have distinct anti-particle (x)
- Needs to have a non-zero lifetime
  - top is so heavy, it decays long before it can even form a meson ($\diamondsuit$)
- That leaves four distinct cases...

Note: for (much!) more detail, see eg. arXiv:hep-ex/0103016v1

Intermezzo: Describing Mixing…

Time evolution of B⁰ and $\overline{\text{B}}{}^0$ can be described by an effective Hamiltonian:

$$i\frac{\partial}{\partial t}\Psi = H\Psi$$

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

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

what is the
difference between
M_{12} and Γ_{12}?

Intermezzo: Describing Mixing…

Time evolution of B^0 and $\overline{B^0}$ can be described by an effective Hamiltonian:

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what is the
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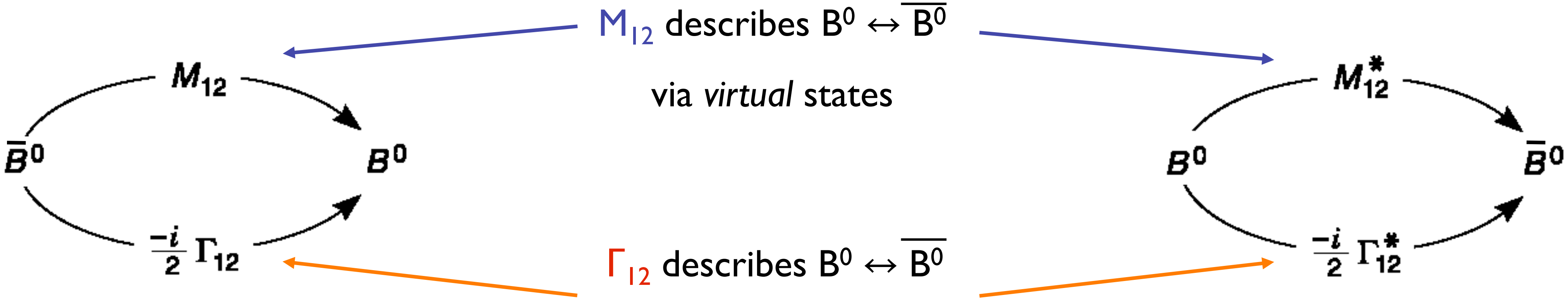
Remember: antihermitian part describes the ‘leaking’ out of the (sub)space spanned by B^0 and $\overline{B^0}$

$$\frac{d}{dt}\left(|a|^2+|b|^2\right) = -\begin{pmatrix} a^* & b^* \end{pmatrix}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$



M_{12} describes $B^0 \leftrightarrow \overline{B^0}$

via *virtual* states

Γ_{12} describes $B^0 \leftrightarrow \overline{B^0}$

via *real* states, eg ππ

For details, look up “Wigner-Weisskopf” approximation…

Solving the Schrödinger Equation

$$i\frac{\partial}{\partial t}\psi(t)=\begin{pmatrix} M-\frac{i}{2}\Gamma & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M-\frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

Solution (in terms of eigenvectors):

$$\psi(t) = a\,|B_H(t)\rangle + b\,|B_L(t)\rangle$$

(a and b determined by initial conditions)

Eigenvectors:

$$|B_H\rangle = p|B\rangle + q|\overline{B}\rangle$$

$$|B_L\rangle = p|B\rangle - q|\overline{B}\rangle$$

Evolution of eigenvectors:

$$|B_H(t)\rangle = |B_H\rangle\, e^{-i\left(M+\frac{1}{2}\Delta m-\frac{i}{2}(\Gamma-\Delta\Gamma)\right)t}$$

$$|B_L(t)\rangle = |B_L\rangle\, e^{-i\left(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma)\right)t}$$

From the eigenvector calculation:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^{*} - \frac{i}{2}\Gamma_{12}^{*}}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

Δm and ΔΓ follow from the eigenvalues:

$$\Delta m + \frac{i}{2}\Delta\Gamma = 2\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^{*} - \frac{i}{2}\Gamma_{12}^{*}\right)}$$

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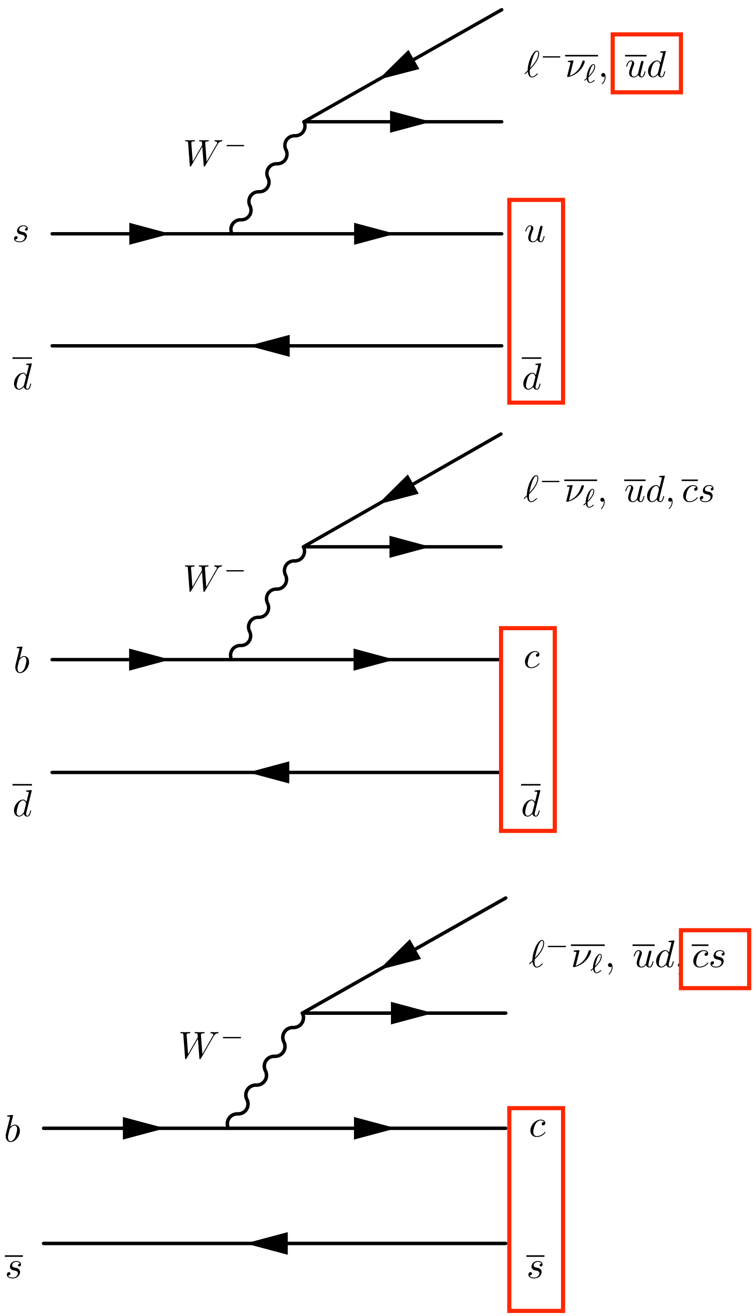
if: $\Gamma_{12}=0 \Rightarrow \Delta\Gamma=0, \left|\frac{q}{p}\right|=1$

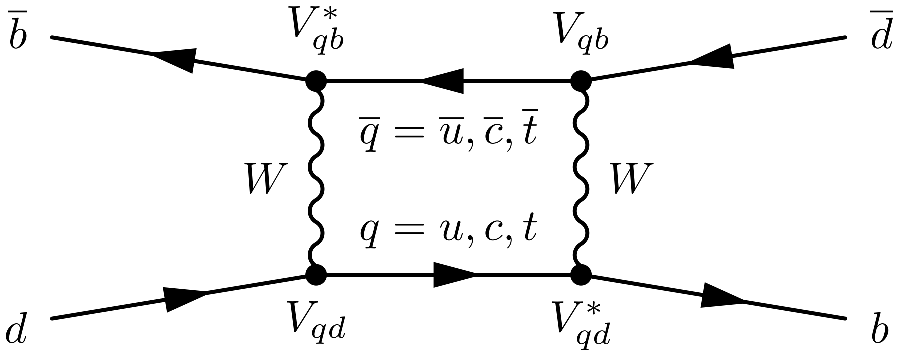
Mixing: Kaons vs. B mesons

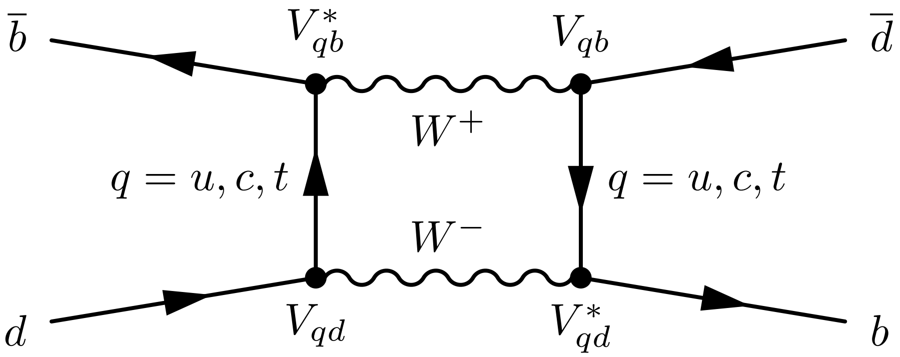
- The difference between K mixing and 'the rest': Γ_{12}
- A **large** fraction of Kaon decays produce CP eigenstates:
  - all decays *without* leptons are CP eigenstates..
- the CP even ones have more phase-space
  - Hence the lifetime difference (large Γ_{12}!)
- For B^0, (and, to a somewhat lesser extent B_s), the dominant decays are *not* CP eigenstates
  - hence $\Delta\Gamma$=0 (smallish), and Γ_{12} does *not* contribute to B^0 mixing
  - note: as a result labeling eigenstates as 'S'hort and 'L'ong doesn't make sense -- hence the 'H'eavy and 'L'ight
- so do B^0 (B_s) mesons actually mix?



Dominant decay amplitudes

Mixing: Box Diagrams





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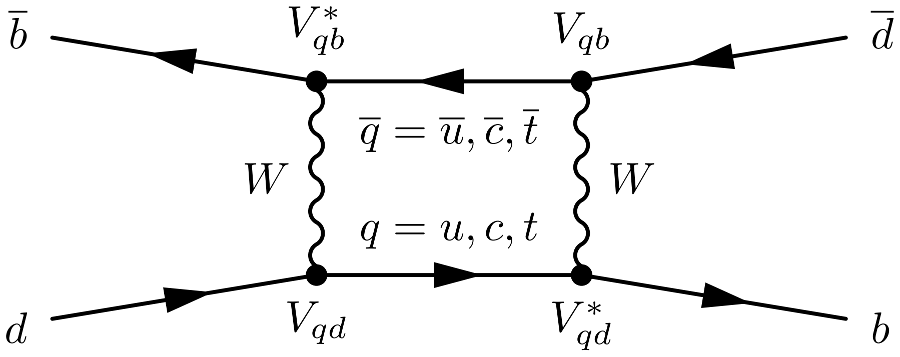

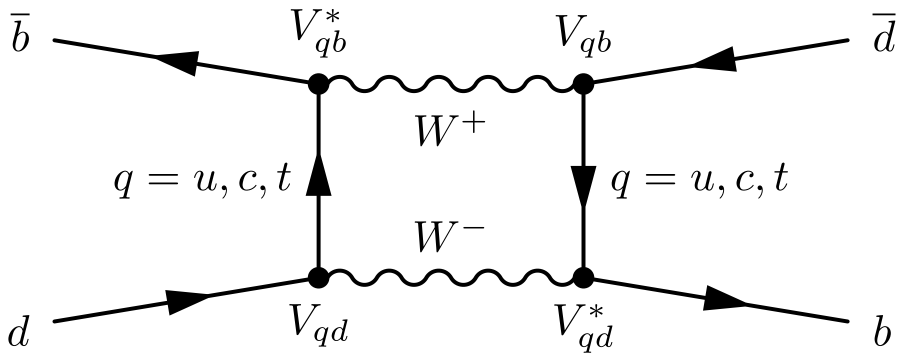

GIM(V_{CKM} unitarity):
if u,c,t same mass, everything
cancels *by construction*!

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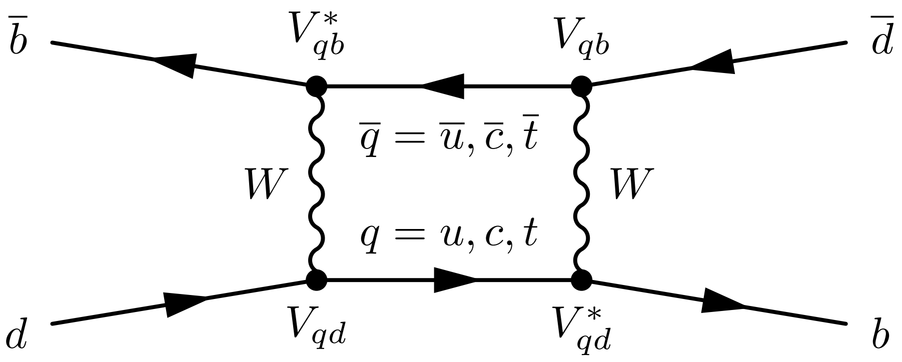

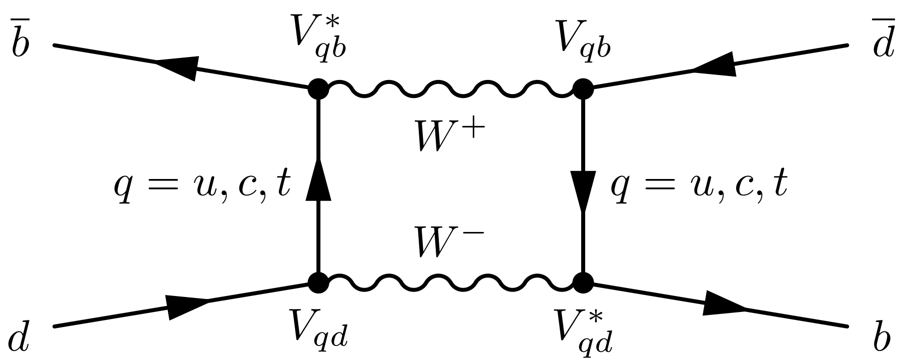

$$t - \bar{t}: \quad \propto m_t^2 \left|V_{tb} V_{td}^*\right|^2 \quad \propto m_t^2 \lambda^6$$

$$c - \bar{c}: \quad \propto m_c^2 \left|V_{cb} V_{cd}^*\right|^2 \quad \propto m_c^2 \lambda^6$$

$$c - \bar{t}, \bar{c} - t: \quad \propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^* \propto m_c m_t \lambda^6$$

GIM(V_{CKM} unitarity):
if u,c,t same mass, everything
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$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_w^2 \eta_B S_0(m_t^2 / m_W^2) m_{B_d} |V_{td}|^2 B_{B_d} f_{B_d}^2$$

Dominated by top quark mass: $$\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$$

reference: τ_B ~1.5 ps

Before you decay, you’ve gotta ask yourself one question:

“do I feel like oscillating?”

well, do ya?

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B^0 Mixing: ARGUS, 1987

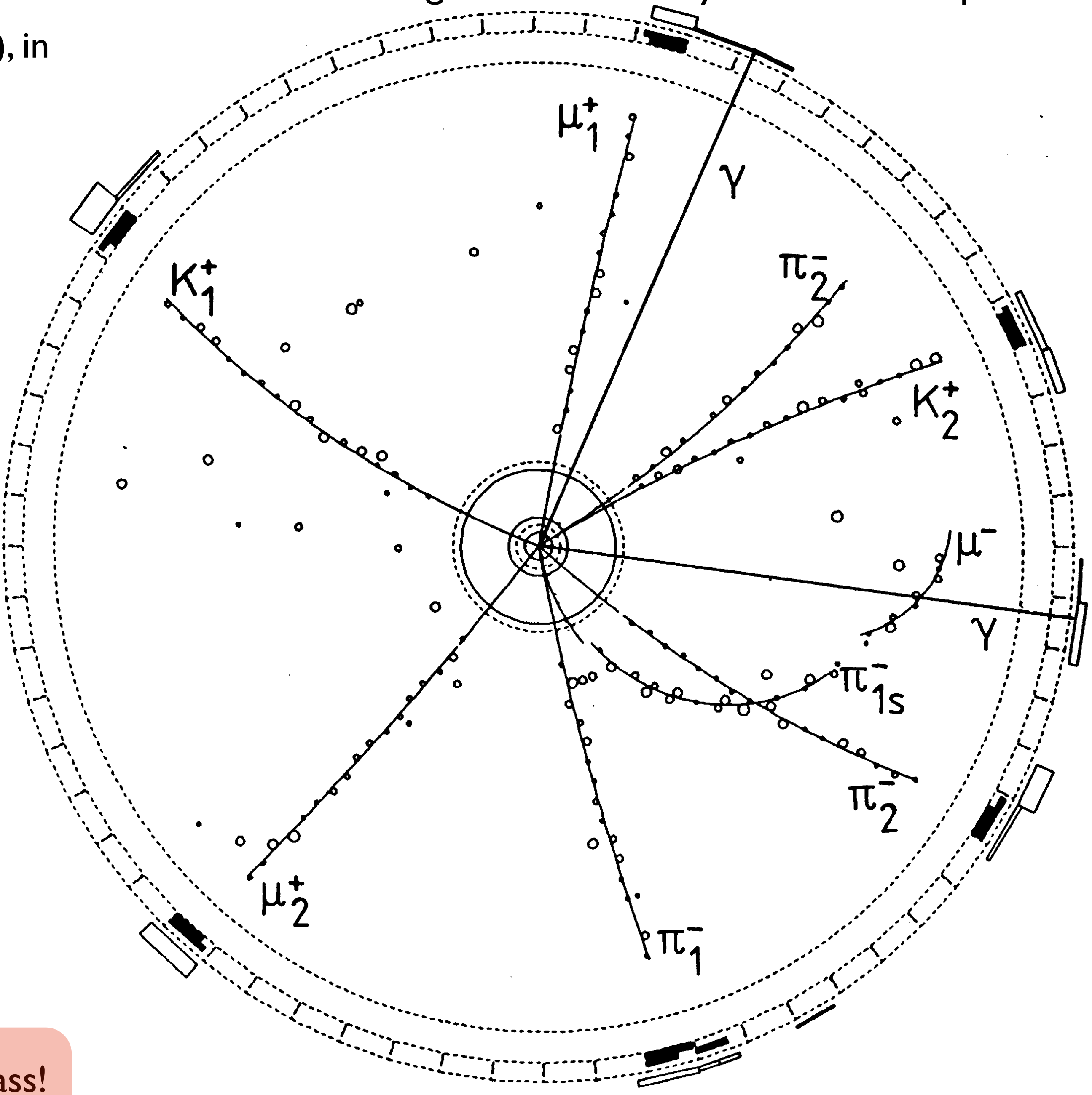
- Produce an $b\overline{b}$ bound state, ϒ(4S), in e^+e^- collisions:
  - $e^+e^- \to \Upsilon(4S) \to B^0\overline{B^0}$
- and then observe:

$$\begin{aligned} B_1^0 \to \quad & D_1^{*-}\mu_1^+\nu_1 \\ & D_1^{*-} \to \quad \overline{D^0}\pi_{1s}^- \\ & \qquad\qquad \overline{D^0} \to K_1^+\pi_1^- \end{aligned}$$

$$\begin{aligned} B_2^0 \to \quad & D_2^{*-}\mu_2^+\nu_2 \\ & D_2^{*-} \to \quad D^-\pi^0 \\ & \qquad\qquad D^- \to K_2^+\pi_2^-\pi_2^- \\ & \qquad\qquad \pi^0 \to \gamma\gamma \end{aligned}$$

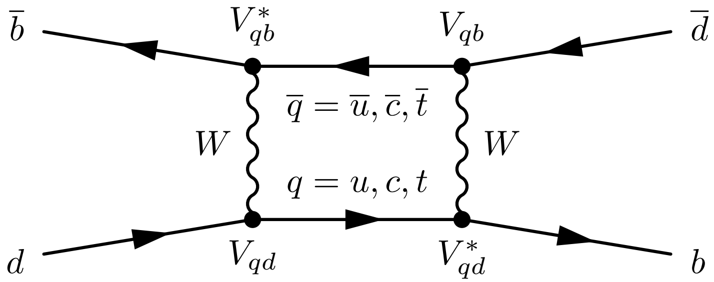
- measure that ~17% of B^0 and $\overline{B^0}$ mesons oscillate before they decay
  - $\tau_B \sim 1.5$ ps ⇒ $\Delta m_d \sim 0.5$/ps,

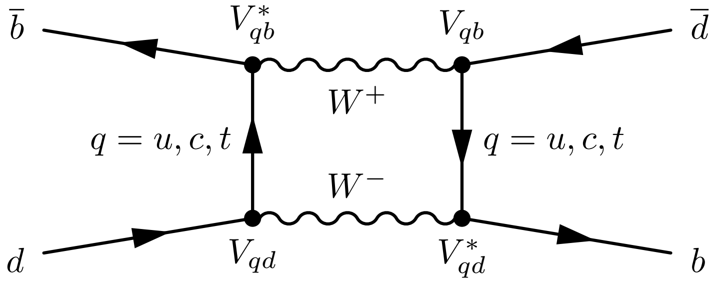
Integrated luminosity 1983-87: 103 pb-1



First evidence of a really large top mass!

B_s mixing:



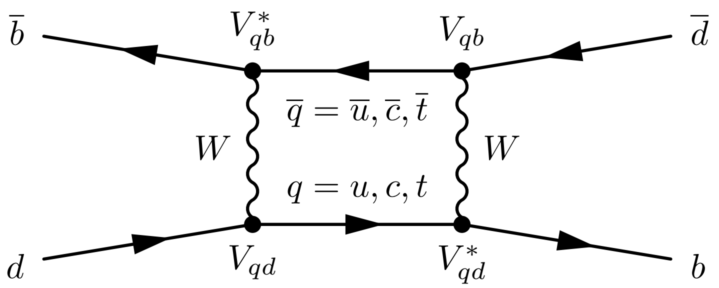


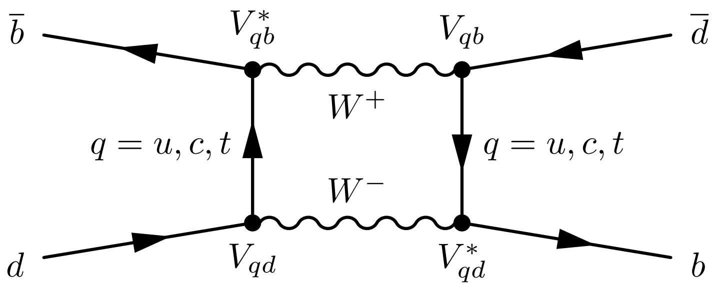
most important difference with B^0:
replace $V_{td} \rightarrow V_{ts}$

$$\left.\begin{array}{l} \dfrac{\Delta m_d}{\Delta m_s} \approx \dfrac{|V_{td}|^2}{|V_{ts}|^2} \approx \dfrac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04 \\ \\ \Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1} \end{array}\right\} \Rightarrow \Delta m_s \approx 12 \text{ ps}^{-1}$$

A more complete calculation leads to the
SM expectation of ~18/ps

B_s mixing: CDF, 2006





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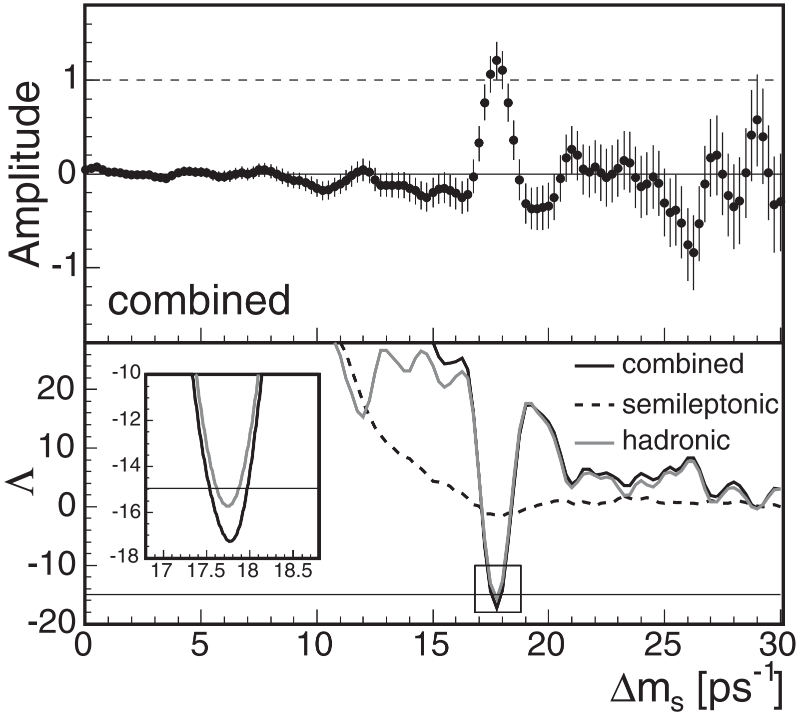
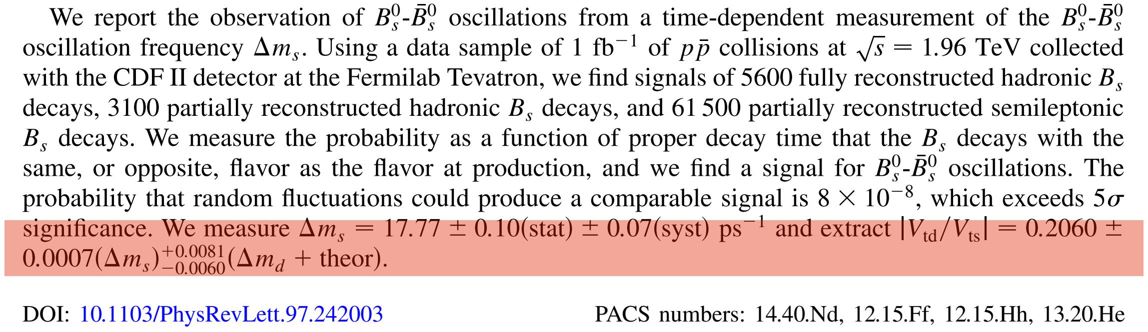
replace $V_{td} \rightarrow V_{ts}$

$$\left.\begin{array}{l} \dfrac{\Delta m_d}{\Delta m_s} \approx \dfrac{|V_{td}|^2}{|V_{ts}|^2} \approx \dfrac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04 \\ \Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1} \end{array}\right\} \Rightarrow \Delta m_s \approx 12 \text{ ps}^{-1}$$

A more complete calculation leads to the SM expectation of ~18/ps

Observation of $B_s^0 - \bar{B}_s^0$ Oscillations





We report the observation of B_s^0-$\bar{B}_s^0$ oscillations from a time-dependent measurement of the B_s^0-$\bar{B}_s^0$ oscillation frequency Δm_s. Using a data sample of 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61 500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B_s^0-$\bar{B}_s^0$ oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8}, which exceeds 5σ significance. We measure $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ ps^{-1} and extract $|V_{\text{td}}/V_{\text{ts}}| = 0.2060 \pm 0.0007(\Delta m_s)^{+0.0081}_{-0.0060}(\Delta m_d + \text{theor})$.

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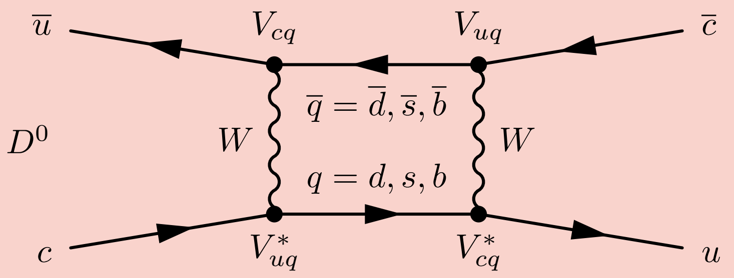
D^0 mixing

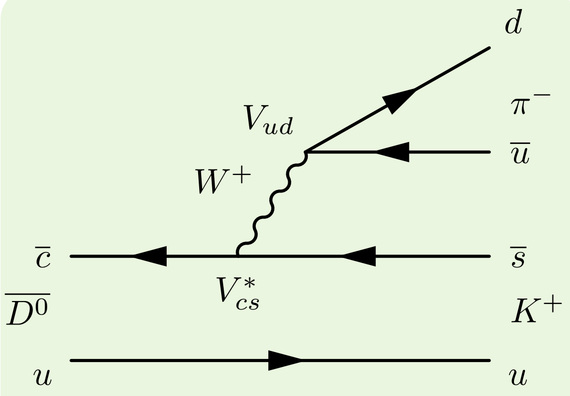
Look for 'wrong sign' D^0 decays

$$D^0 \longrightarrow K^+\pi^-$$

D^0 mixing



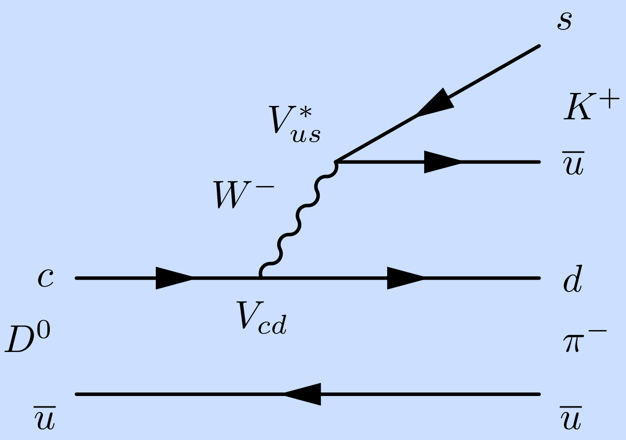
d,s,b 'in the loop' instead of u,c,t
⇒ GIM (almost) kills this amplitude...



$$|V^*_{cs} V_{ud}| = \mathcal{O}(1)$$

Look for 'wrong
sign' D^0 decays

$$\begin{tikzcd} D^0 \arrow[r] \arrow[rr, bend right] & \overline{D^0} \arrow[r, Rightarrow] & K^+\pi^- \end{tikzcd}$$



$$|V_{cd} V^*_{us}| = \mathcal{O}(\lambda^2) \approx 0.04$$

D^0 mixing: BaBar, 2007

PRL **98,** 211802 (2007) PHYSICAL REVIEW LETTERS week ending 25 MAY 2007

Evidence for D^0-$\overline{D}^0$ Mixing

$$\boxed{D^0 \longrightarrow K^+\pi^-}$$

We present evidence for D^0-$\overline{D}^0$ mixing in $D^0 \to K^+\pi^-$ decays from 384 fb^{-1} of e^+e^- colliding-beam data recorded near $\sqrt{s} = 10.6$ GeV with the *BABAR* detector at the PEP-II storage rings at the Stanford Linear Accelerator Center. We find the mixing parameters $x'^2 = [-0.22 \pm 0.30(\text{stat}) \pm 0.21(\text{syst})] \times 10^{-3}$ and $y' = [9.7 \pm 4.4(\text{stat}) \pm 3.1(\text{syst})] \times 10^{-3}$ and a correlation between them of -0.95. This result is inconsistent with the no-mixing hypothesis with a significance of 3.9 standard deviations. We measure R_D, the ratio of doubly Cabibbo-suppressed to Cabibbo-favored decay rates, to be $[0.303 \pm 0.016(\text{stat}) \pm 0.010(\text{syst})]\%$. We find no evidence for CP violation.

DOI: 10.1103/PhysRevLett.98.211802 PACS numbers: 13.25.Ft, 11.30.Er, 12.15.Ff, 14.40.Lb

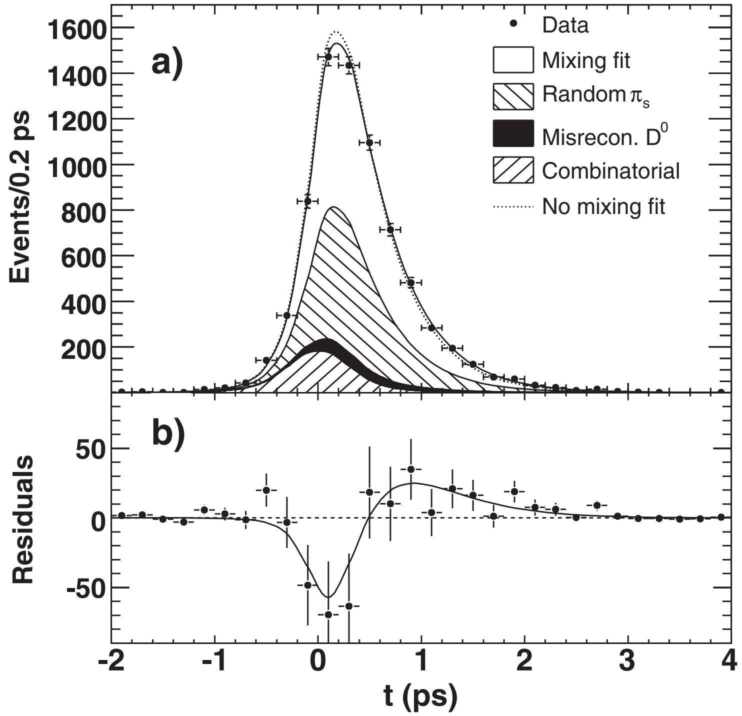
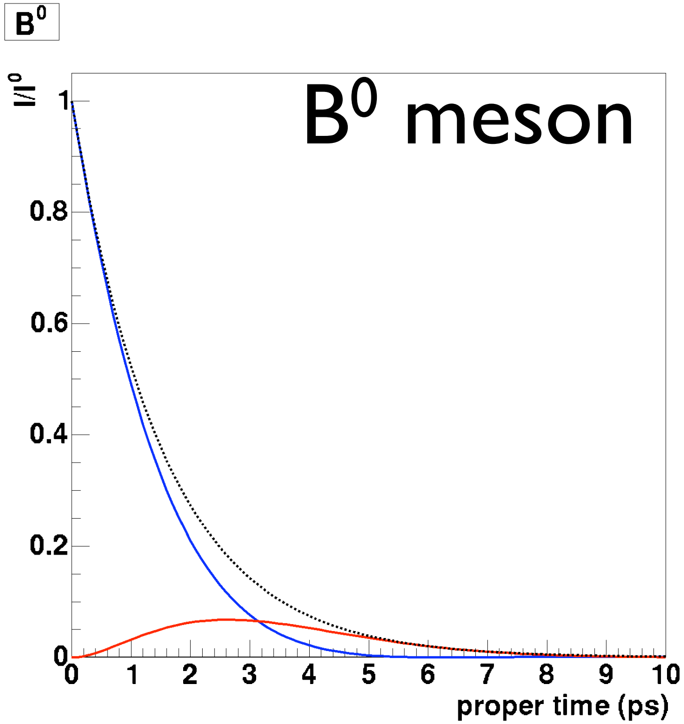
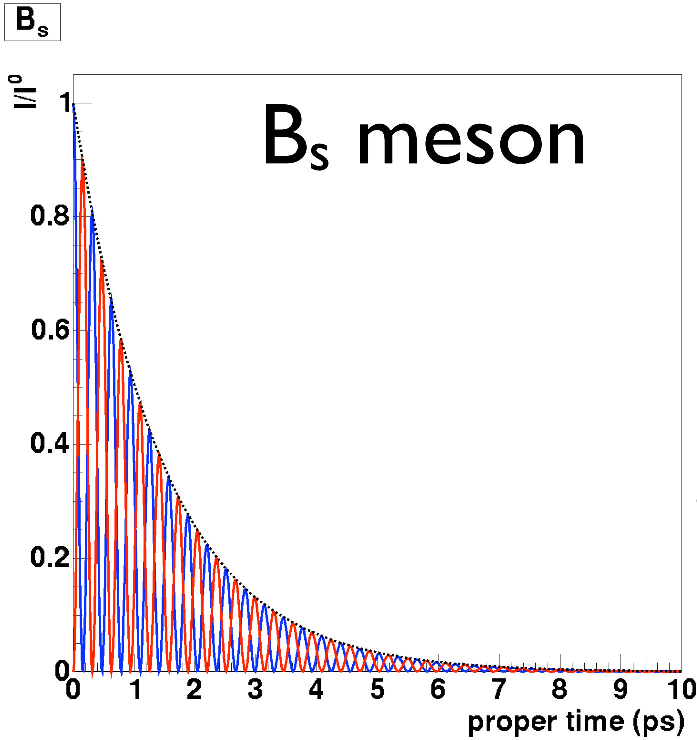
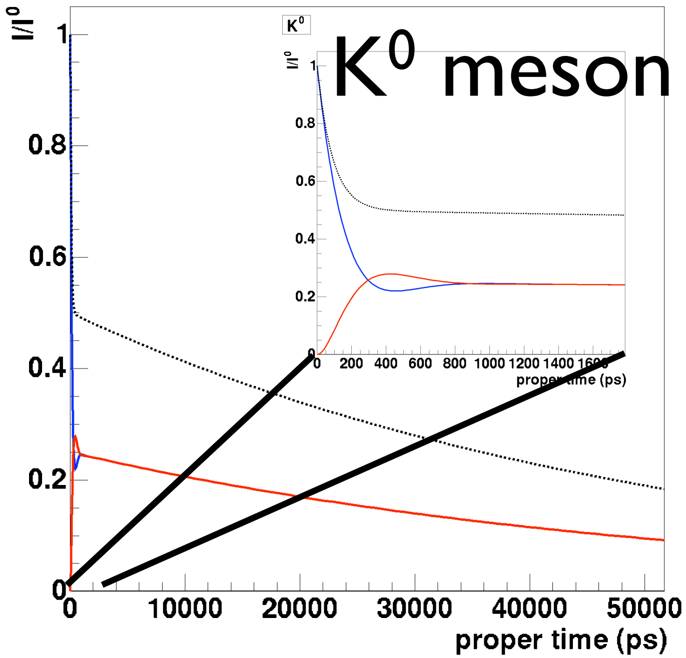


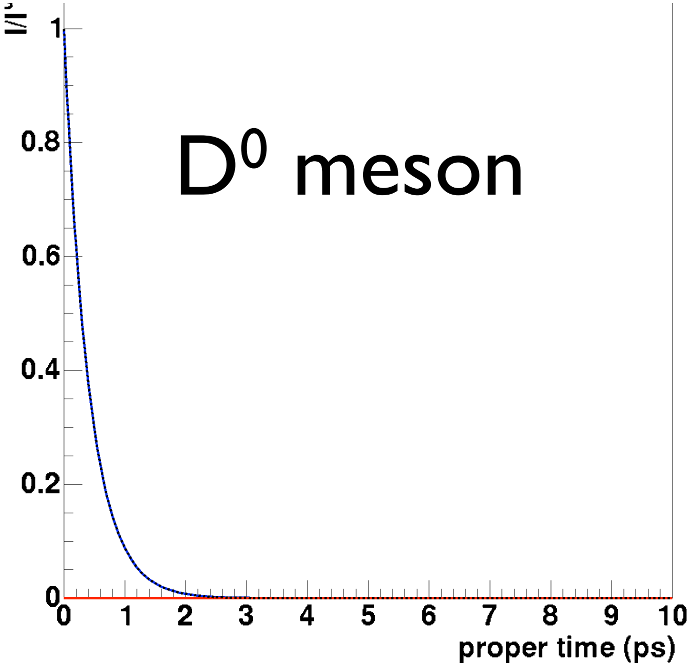
FIG. 2. (a) Projections of the proper-time distribution of combined D^0 and $\overline{D}^0$ WS candidates and fit result integrated over the signal region $1.843 < m_{K\pi} < 1.883\ \text{GeV}/c^2$ and $0.1445 < \Delta m < 0.1465\ \text{GeV}/c^2$. The result of the fit allowing (not allowing) mixing but not CP violation is overlaid as a solid (dashed) curve. (b) The points represent the difference between the data and the no-mixing fit. The solid curve shows the difference between fits with and without mixing.

Summary of Neutral Meson Mixing









	d	s	b
$\bar{d}$	$\times$	K^0	B^0
$\bar{s}$	$\overline{K^0}$	$\times$	B_s
$\bar{b}$	$\overline{B^0}$	$\overline{B_s}$	$\times$

	u	c	t
$\bar{u}$	$\times$	D^0	$\diamond$
$\bar{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\bar{t}$	$\diamond$	$\diamond$	$\times$

Blue:
given a P^0, at t=0,
the probability of
finding a P^0 at t.

Red:
given a P^0, at t=0,
the probability of
finding a P^0bar at t.

Summary

- Existence of antimatter is a consequence of the combination of special relativity and quantum mechanics
- No ‘primordial’ antimatter observed
- Need something called ‘CP’ symmetry breaking to explain the absence of antimatter
- CPT is a very good symmetry
- C,P and CP are conserved in strong & EM interactions
- C,P completely broken by weak interactions, CP looks healthy...
- neutral kaons can ‘mix’ (oscillate) into their antiparticles
- and this can causes lifetime & mass differences of the CP eigenstates of the Hamiltonian
- CP is (a bit) broken in the neutral kaon system!
- And we can use this to unambiguously distinguish matter and antimatter
- There are actually three ways in which CP can be broken!
- the weak and mass eigenstates of quarks are not the same...
- with 3 (or more) families, one can have a complex phase in the CKM matrix that defines the weak eigenstates, and this allows for CP violation!
- There is a clear (and unexplained!) hierarchy in the CKM
- All four neutral mesons can mix -- and do, but some faster(slower) than others...
- Heavy top quark needed for B mixing