Flavour oscillations and CP violation in neutral mesons

(a.k.a. a biased introduction to heavy flavour physics)

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Part 1.a

Roma — May 31st & Jun 1st, 2016

Outline

1. Introduction
2. Mixing of neutral mesons

Part 1

3. CP violation phenomenology
4. Put everything in the SM…
5. (and maybe a look beyond)

Part 2

Flavour?

"The term flavour was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at an ice-cream store in Pasadena. **Just as ice cream has both colour and flavour, so do quarks.**"

WIKIPEDIA
The Free Encyclopedia

In particle physics, **flavour** or **flavor** refers to a species of an elementary particle. The Standard Model counts six flavours of quarks and six flavours of leptons. They are conventionally parameterized with *flavour quantum numbers* that are assigned to all subatomic particles, including composite ones. For hadrons, these quantum numbers depend on the numbers of constituent quarks of each particular flavour.

Flavour sector of the SM

Flavour in particle physics

Flavour quantum numbers

- Isospin: **I** or I_3
- Charm: C
- Strangeness: S
- Topness: T
- Bottomness: B'

Related quantum numbers

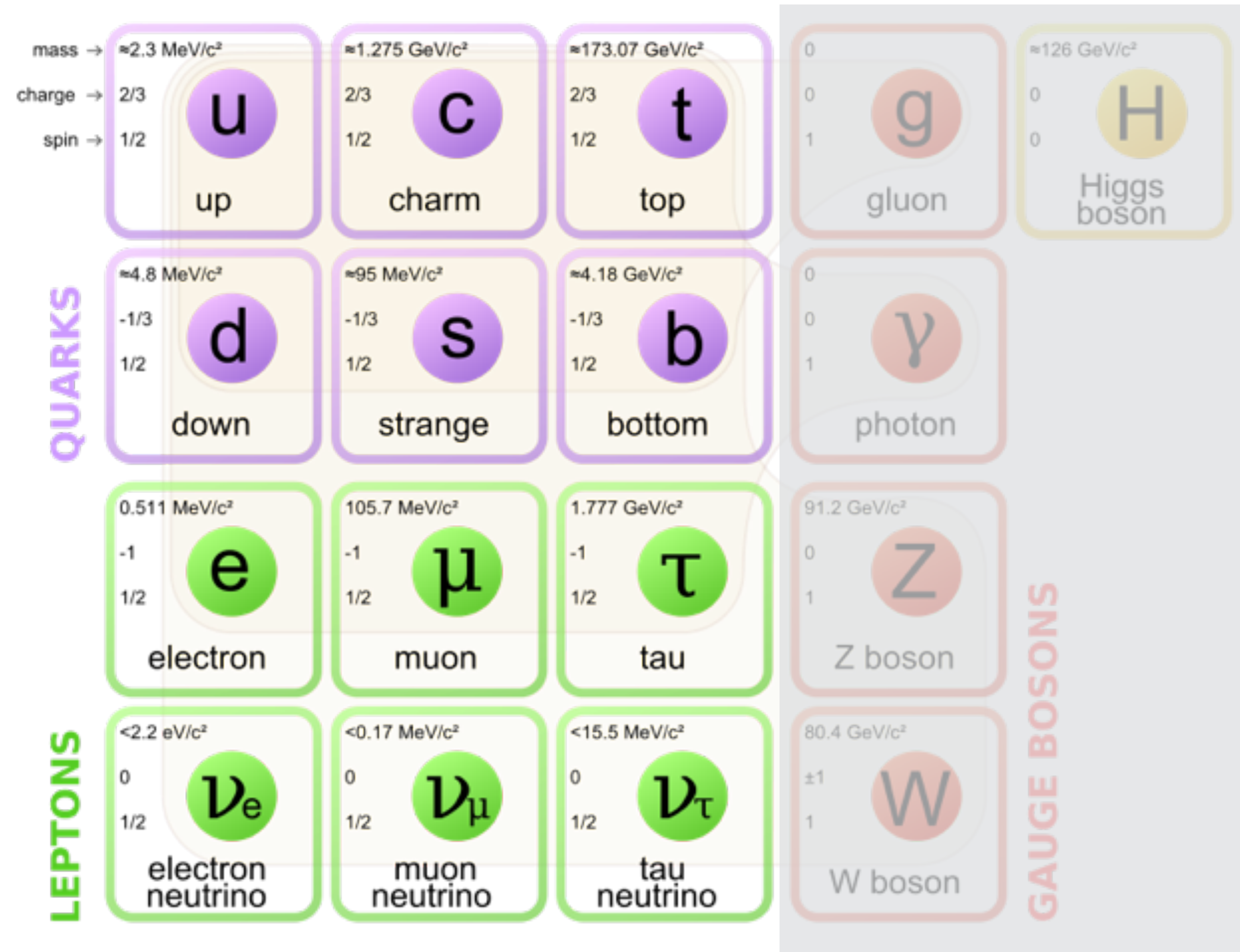
- Baryon number: B
- Lepton number: L
- Weak isospin: **T** or T_3
- Electric charge: Q
- X-charge: X

Combinations

- Hypercharge: Y
  - $Y = (B + S + C + B' + T)$
  - $Y = 2\,(Q - I_3)$
- Weak hypercharge: Y_W
  - $Y_W = 2\,(Q - T_3)$
  - $X + 2Y_W = 5\,(B - L)$

Flavour mixing

- CKM matrix
- PMNS matrix
- Flavour complementarity



Reducing the scope

Flavour in particle physics

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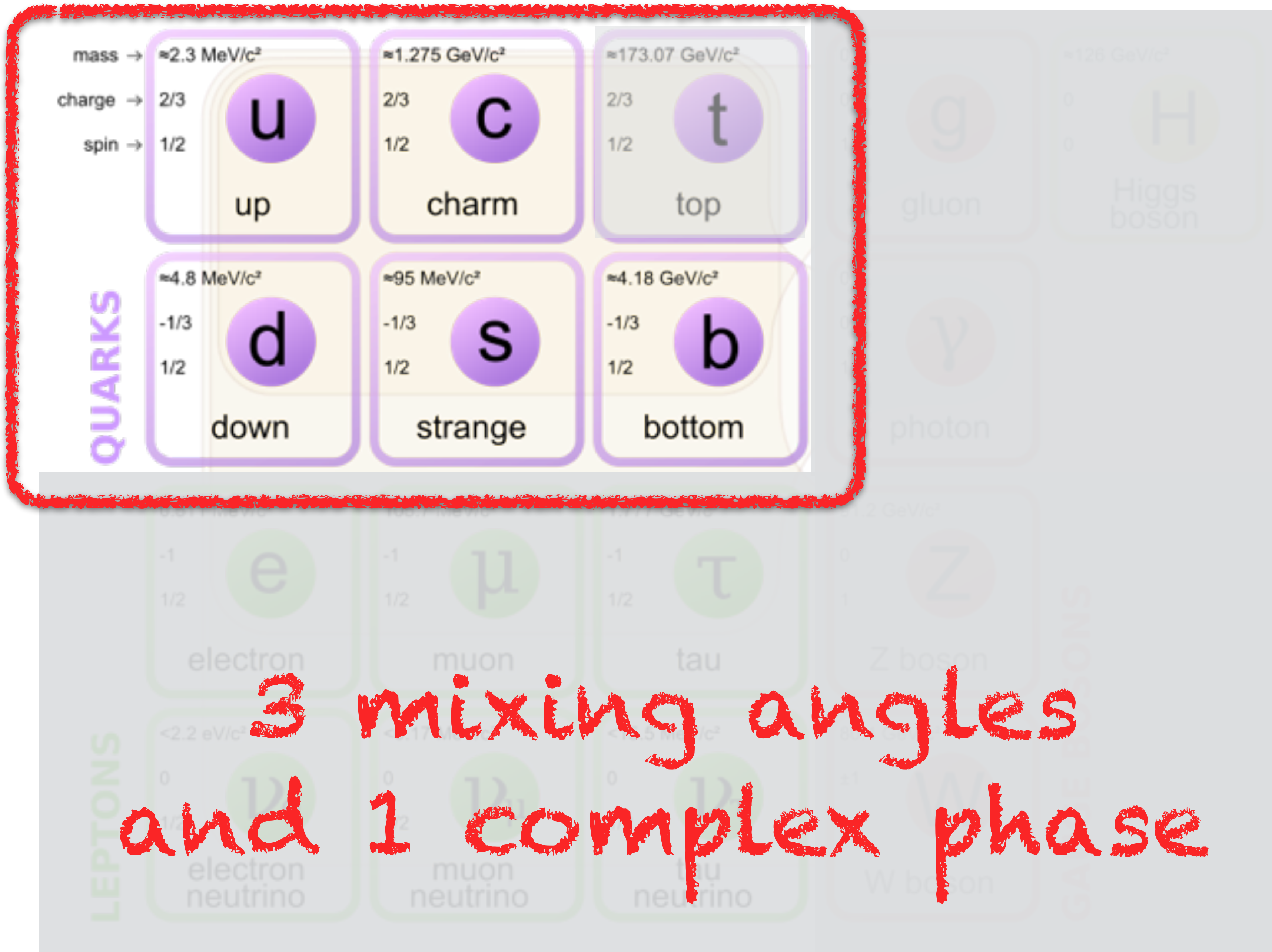


Heavy flavours

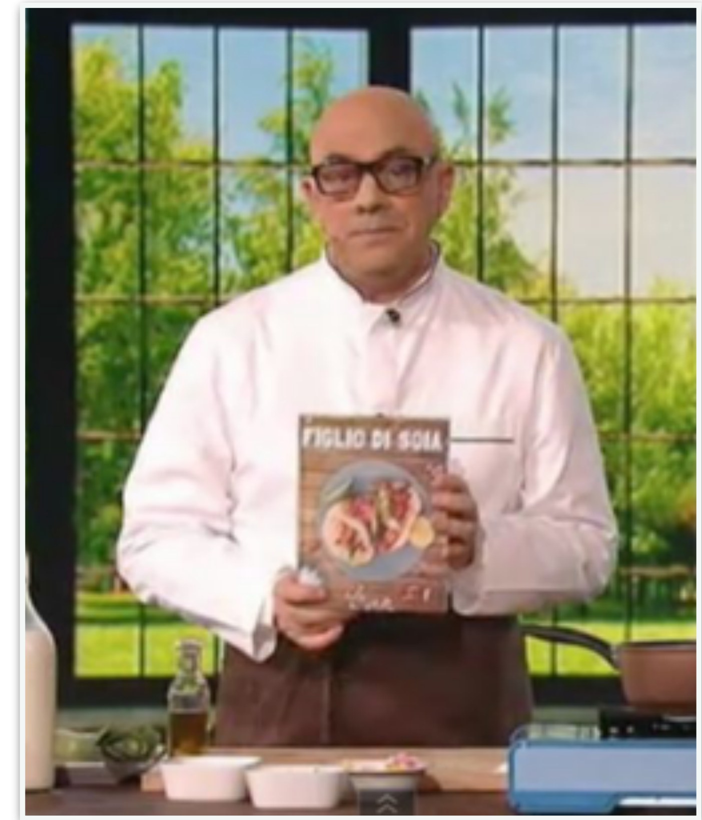
Will explore (some) **flavour-changing interactions of charm and beauty quarks** (heavy flavour), expanding from the physics of kaons (strange quark).

Quarks feel the strong interaction and hadronise… various different strange, charmed and beauty hadrons

+ many, many possible decays to different final states

The hardest part of quark flavour physics is learning the names of all the damned hadrons!

References



I've copied **a lot** from

- **Gerard Raven**, Summer School lectures at CERN (2012)
- **Tim Gershon**, Summer School lectures at CERN (2015)

Standard references (among severals…):

- *CP violation*, I. I. Bigi and A. I. Sanda, Cambridge University Press (2009)
- *The experimental foundations of Particle Physics*, R. Cahn and G. Goldhaber, Cambridge University Press (2009)
- Reviews on flavour physics: arXiv:1002.0900, arXiv:1110.3920, arXiv:1208.3355
- Websites: PDG, HFAG, CKM-Fitter, UT-Fit
- Experiments: LHCb, Babar, Belle and Belle2, CDF, D0, ATLAS, CMS

Quarks

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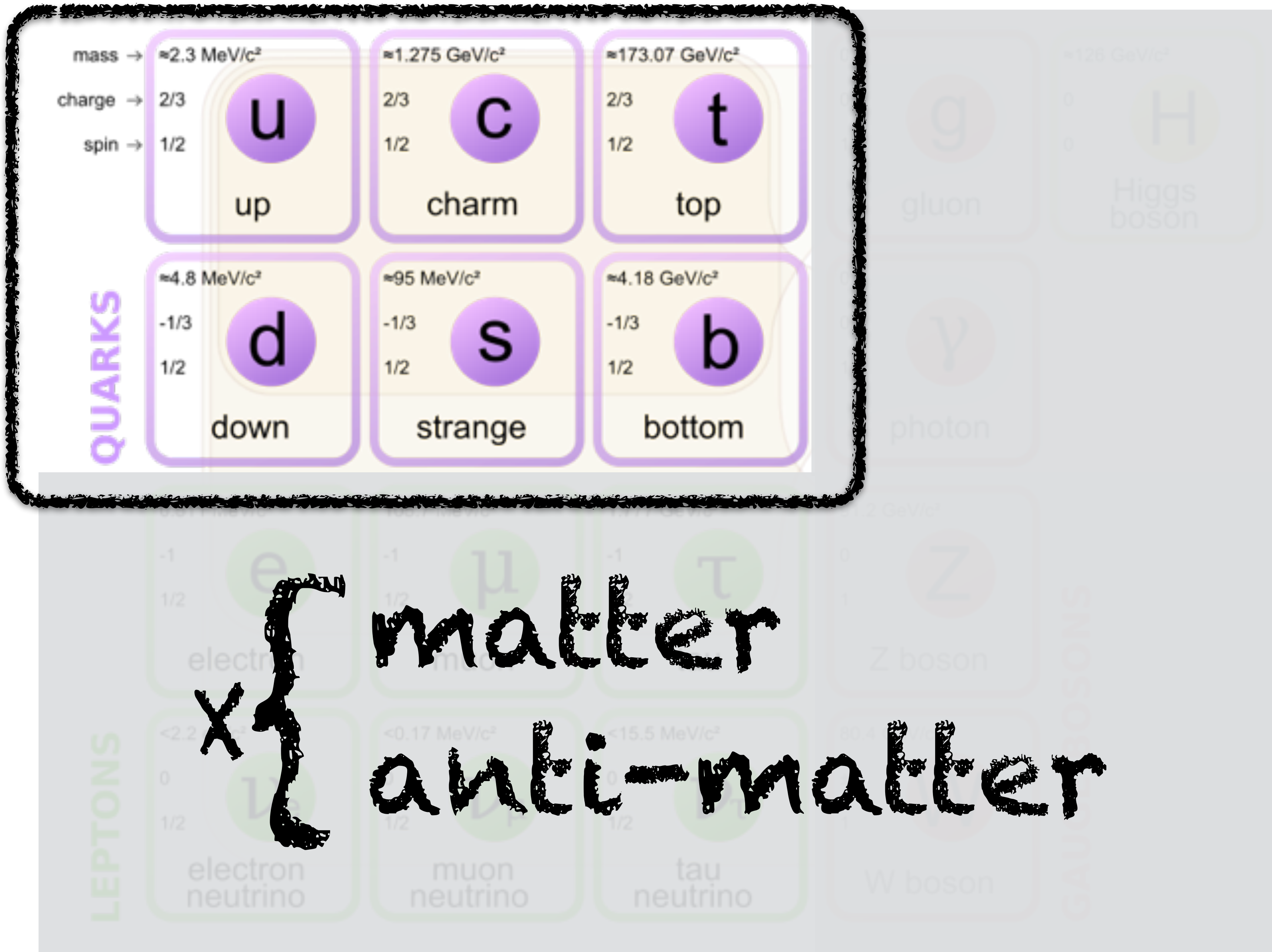


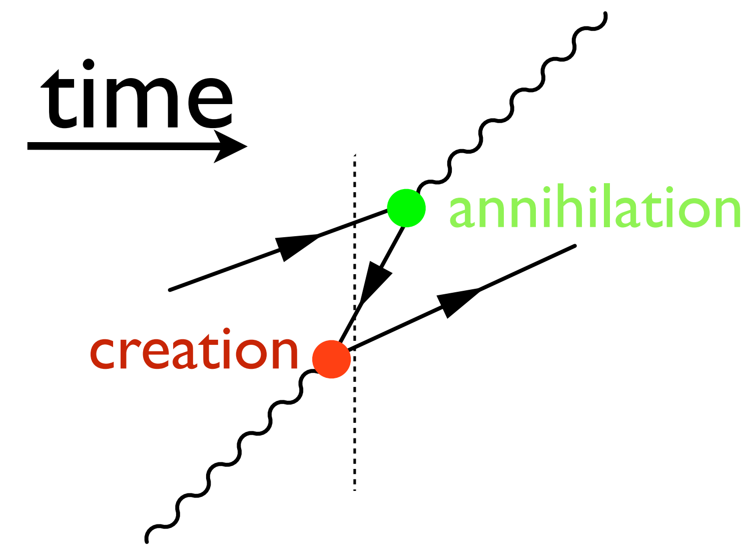
Antiparticles

Quantum mechanics + special relativity lead Dirac to predict 1/2 spin particles with positive and negative energy (1928).

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

Feynman, Stueckelberg:
negative energy solution *as running backwards in time*: consider it as *antiparticle* with *positive* energy, going forward in time.

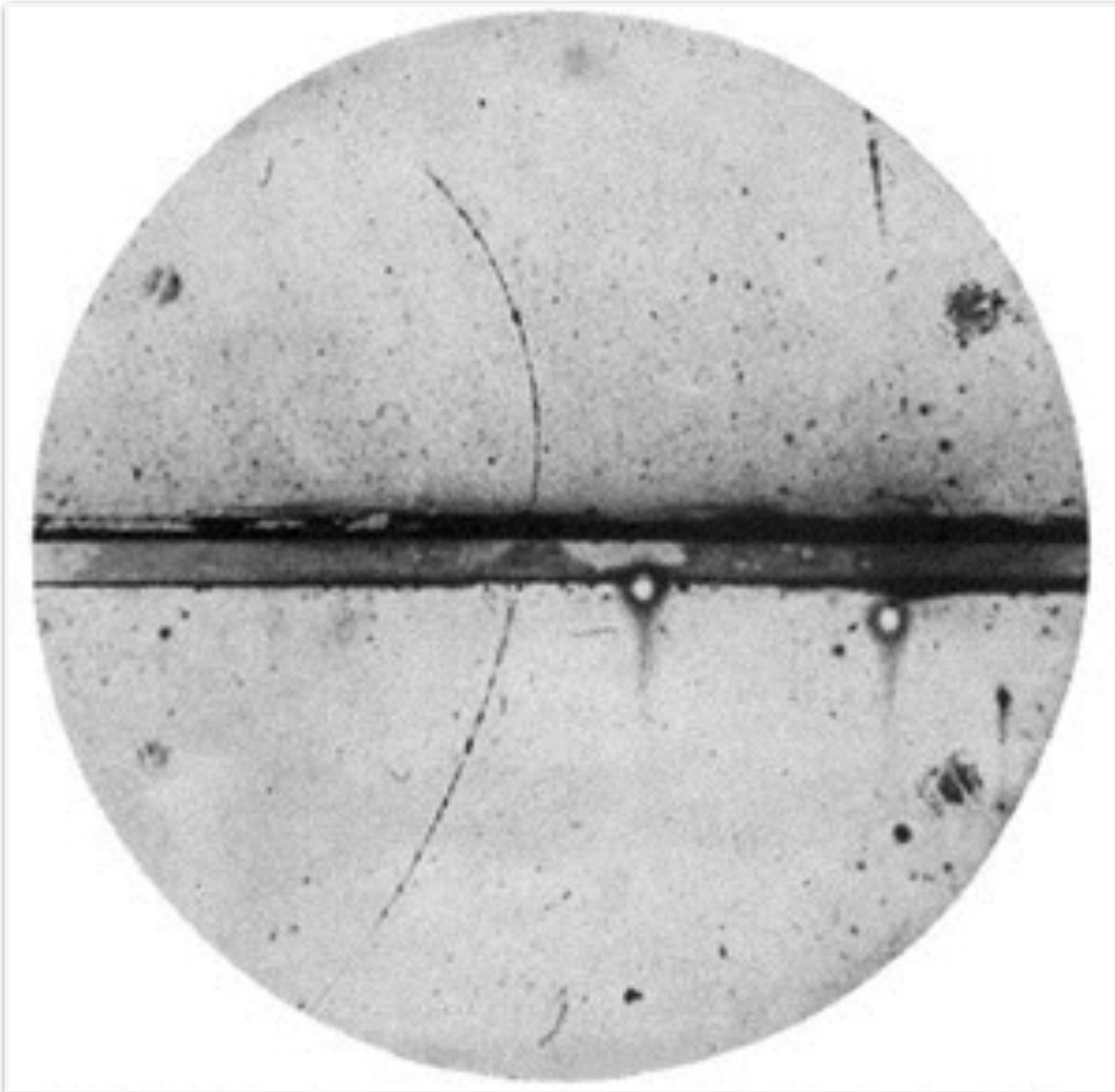
Emission of E>0 antiparticle = absorption of particle E<0



This involves a *CPT* transformation:
flipped charge (*C*),
flipped time (*T*),
must *also* flip the space coordinates (*P*).

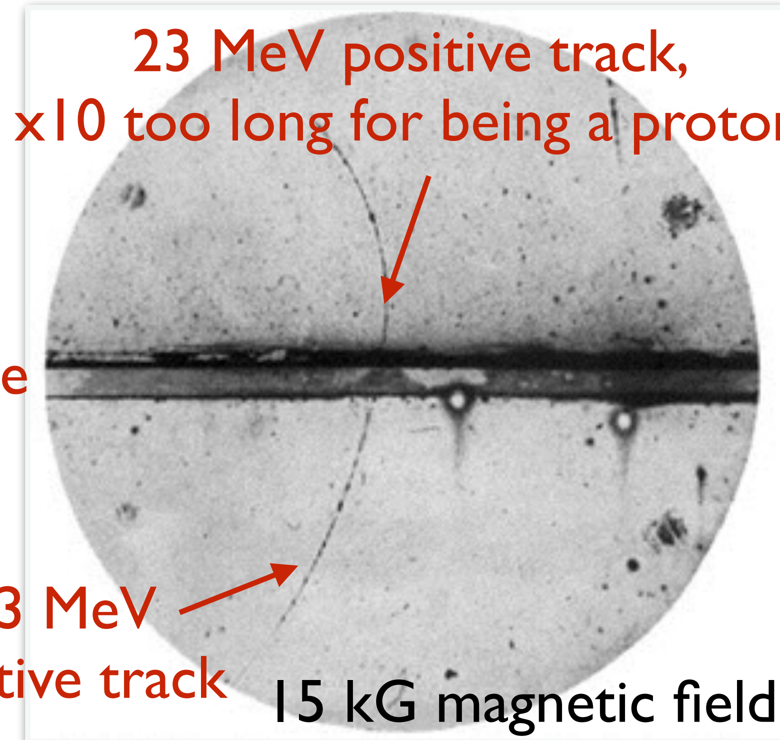
Quantity		*C*	*T*	*P*
Time	t	t	$-t$	t
Space vector	$\boldsymbol{x}$	$\boldsymbol{x}$	$\boldsymbol{x}$	$-\boldsymbol{x}$
Momentum	$\boldsymbol{p}$	$\boldsymbol{p}$	$-\boldsymbol{p}$	$-\boldsymbol{p}$

Antiparticles discoveries

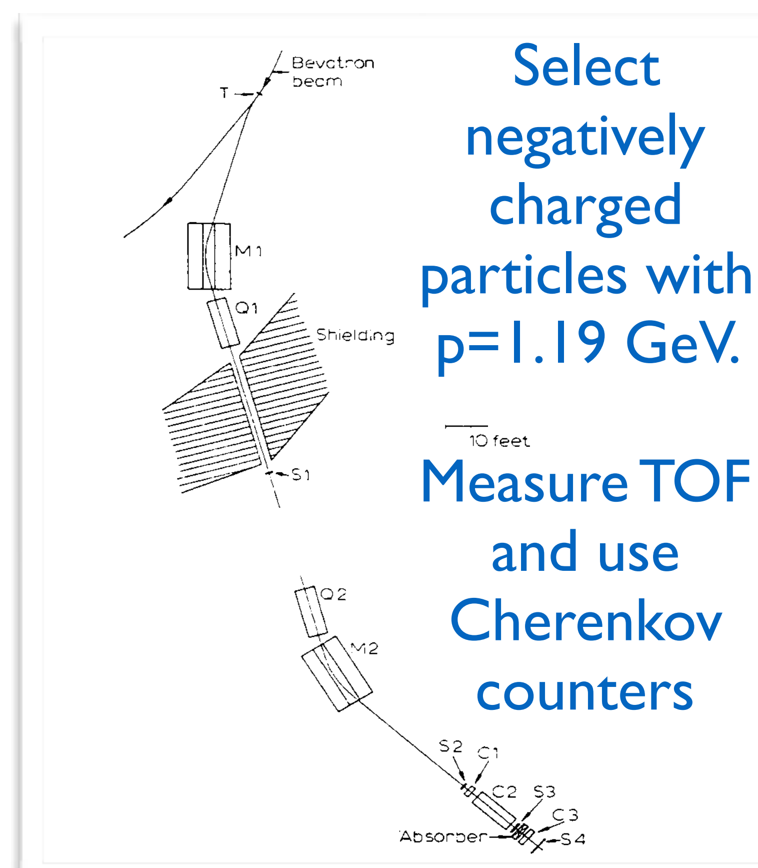


Antiparticles discoveries

1932: Anderson discovers the positron,
by studying cosmic rays with a cloud chambers.
Particles "show up" (temporarily) as
condensation trail in gas volume
(15 tracks out of 1300 photographs!)
Nobel prize in 1936.



1955: discovery of the antiproton by Chamberlain, Segré, Wiegand and Ypsilantis, using the Bevatron (proton) beam of 6.5 GeV. Found 60 negative particles with same mass of the proton within 5%.
Nobel prize in 1959.



Select negatively charged particles with p=1.19 GeV.

Measure TOF and use Cherenkov counters

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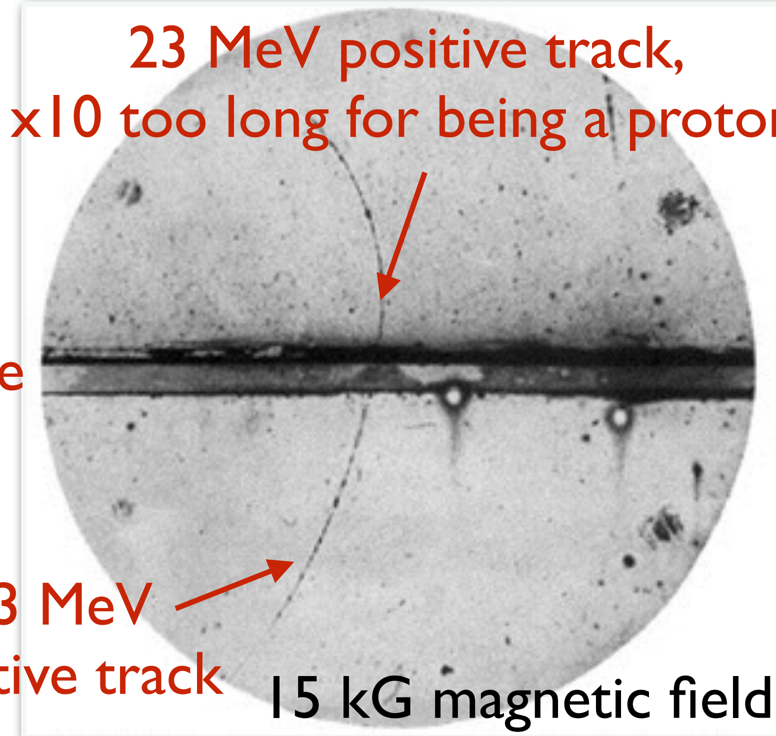

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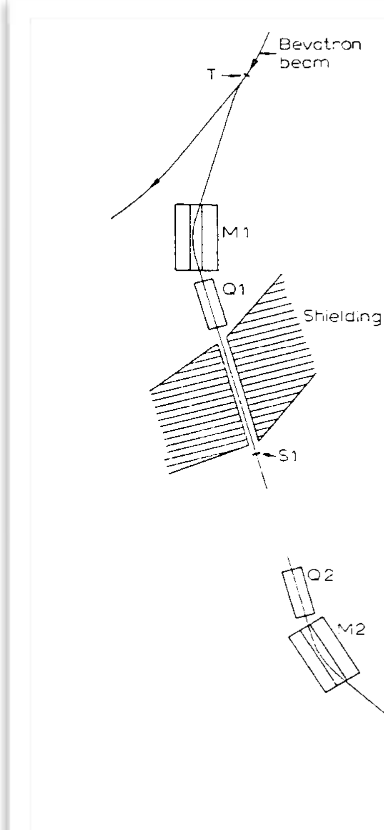
why this energy?
(exercise)



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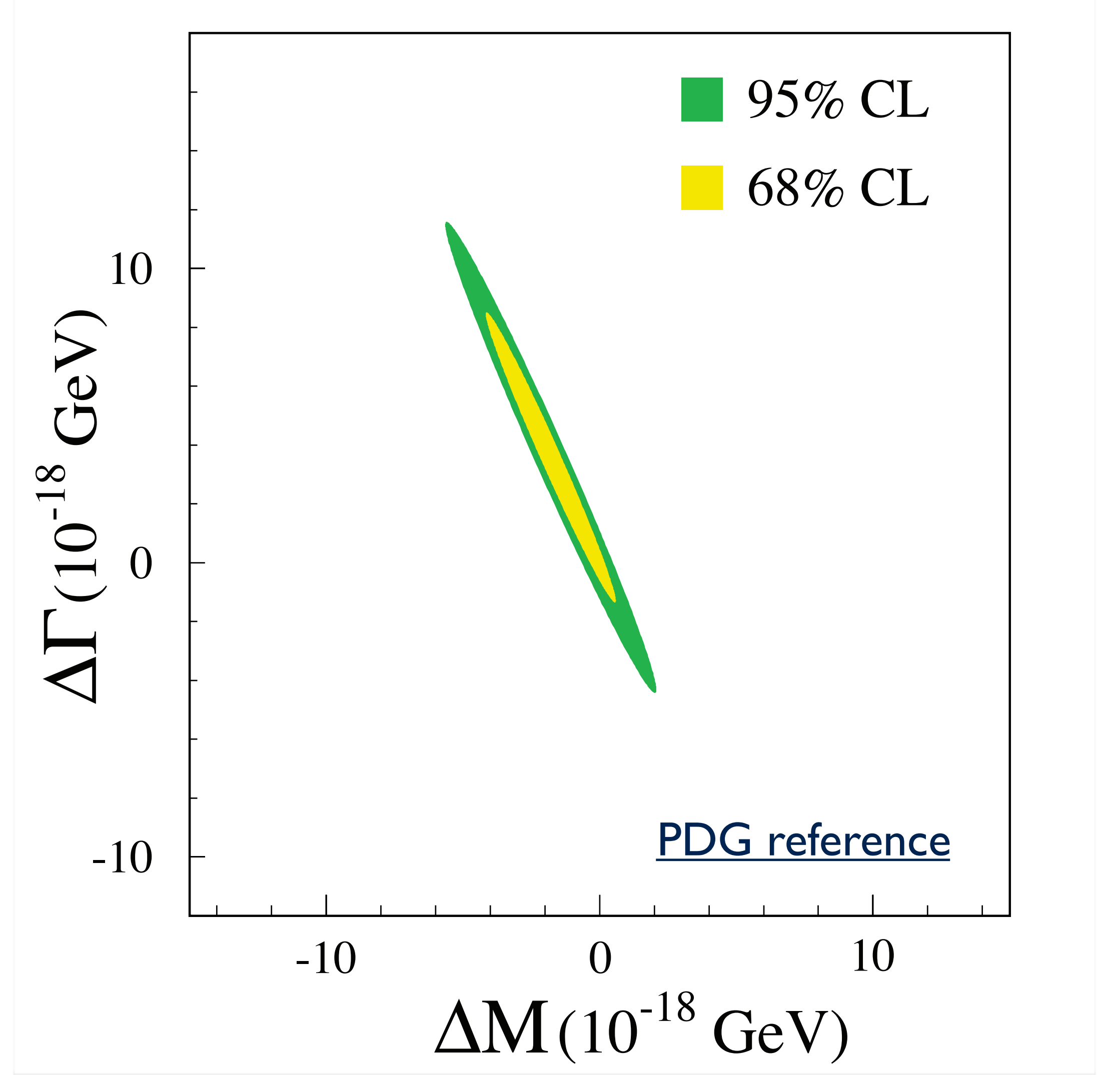
CPT theorem

Any Lorentz-invariant local quantum field theory is invariant under the combined application of a *C*, *P* and *T* transformation

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

Assumptions:

1. Lorentz invariance
2. Principle of locality
3. Vacuum lowest energy



$|m_{K^0} - m_{\overline{K}^0}| \, / \, m_{\text{average}} < 6 \times 10^{-19}$

at 90% CL

Consequences:

1. Fields with integer spin commute and fields with half-numbered spin anti commute (Pauli exclusion principle);

2. Particles and antiparticles have **equal mass and lifetime and opposite quantum numbers**.

Dirac, 1933

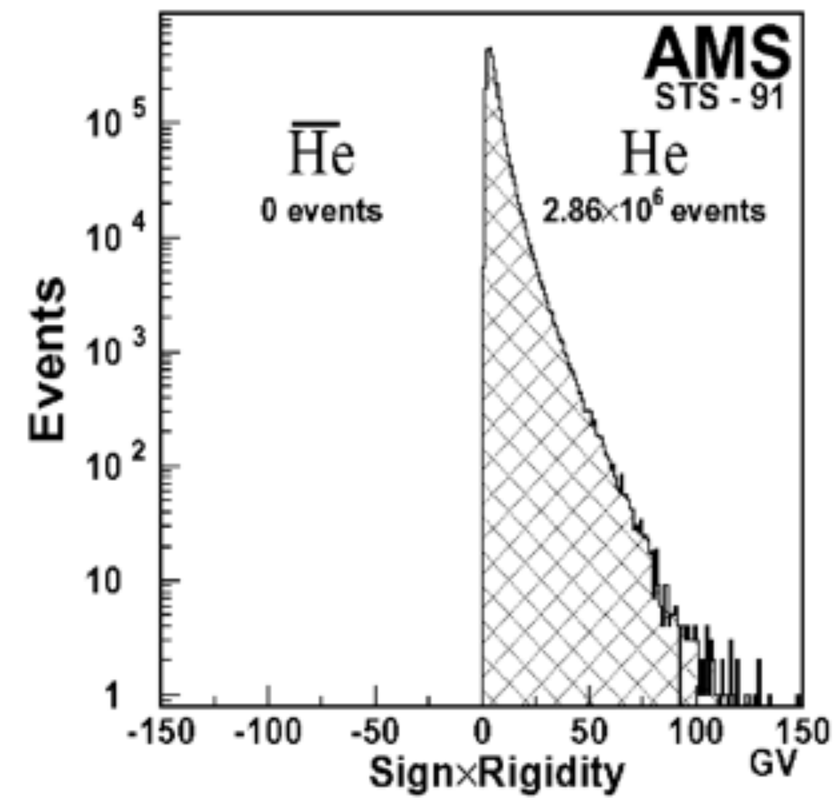
"If we accept the view of **complete symmetry between positive and negative electric charge** so far as concerns the fundamental laws of Nature, we must regard it rather as **an accident** that the Earth (and presumably the whole solar system), contains a **preponderance of negative electrons and positive protons**.

It is quite possible that for **some of the stars it is the other way about**, these stars being built up mainly of positrons and negative protons. **In fact, there may be half the stars of each kind**."

Cosmic antimatter searches

Possible signals:

- photons produced by matter-antimatter annihilation at domain boundaries - not seen.
- Cosmic-rays from anti-stars (best prospect anti-^{4}He nuclei), e.g. searches by AMS.



No evidence for the (primordial) cosmic antimatter, and

$$N(\text{baryons})/N(\text{photons}) \cong 6 \times 10^{-10}$$

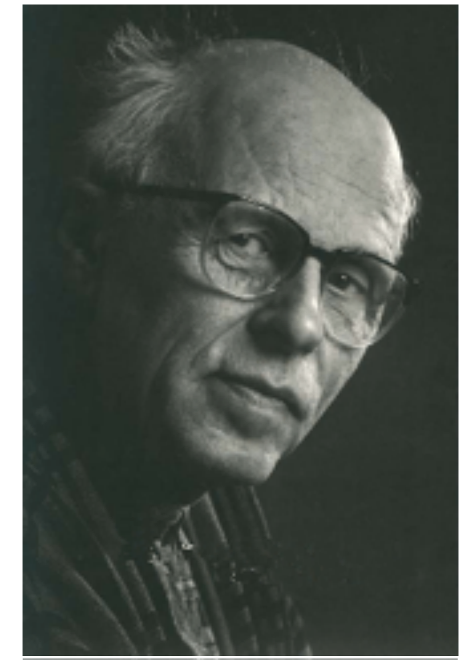
If the Big Bang created an equal amount of matter & antimatter, somewhere along the way one (matter) has been favoured.

Sakharov's conditions

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.



Three requirements for a 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

The question(s)

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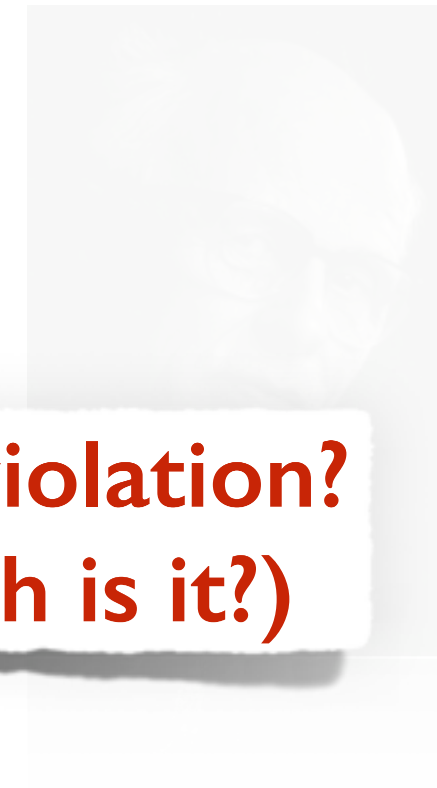

Which is our current knowledge of CP violation?
(where is CP violation in SM? how much is it?)

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So far (so good?)

- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this

Neutral meson mixings,
i.e. matter-antimatter oscillations

Back in the '50s

Observation of something(s) decaying to $\pi\pi$ and $\pi\pi\pi$ (now known as K^+), but whatever decays has, in both cases, the same lifetime, mass, spin=0...

In 1953, Dalitz argued that, since π has parity -1,

- $\pi\pi$ has parity (-1)(-1) = +1
- $\pi\pi\pi$ has parity (-1)(-1)(-1) = -1.

If parity conserved, there must be two distinct particles:

- the 'θ' with parity +1
- the 'τ' with parity -1.

How to explain two distinct particles with the same mass and lifetime (θ-τ puzzle)?

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

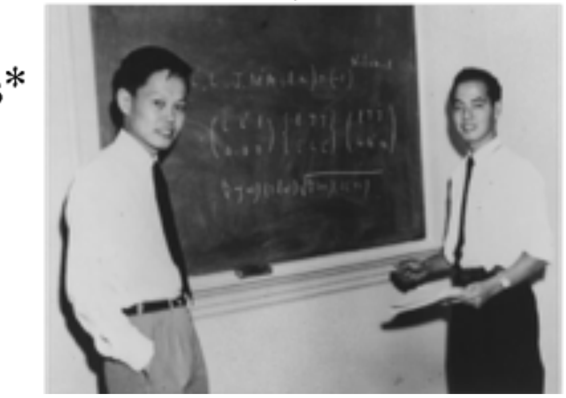
Question of Parity Conservation in Weak Interactions*

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

AND

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

(Received June 22, 1956)



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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

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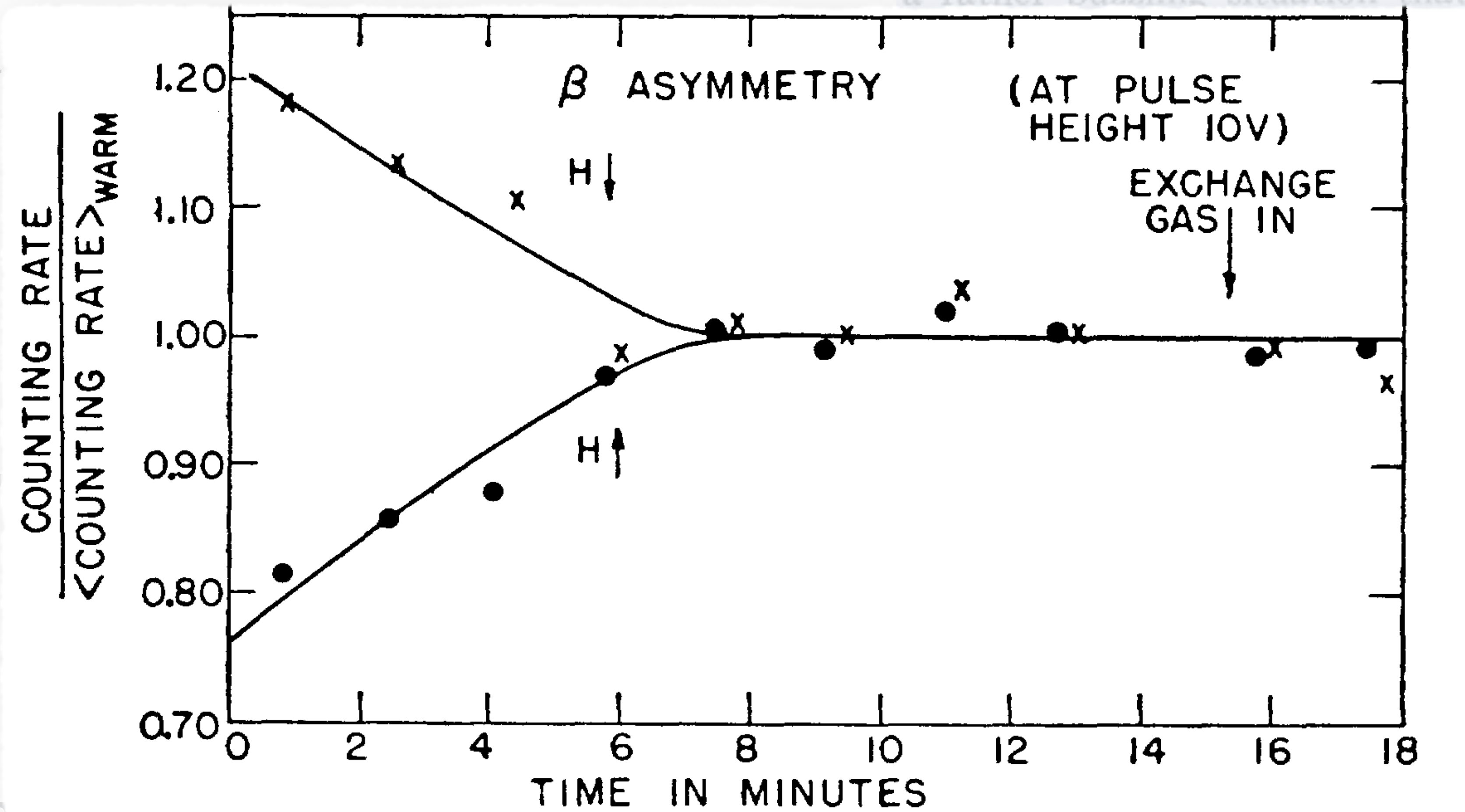

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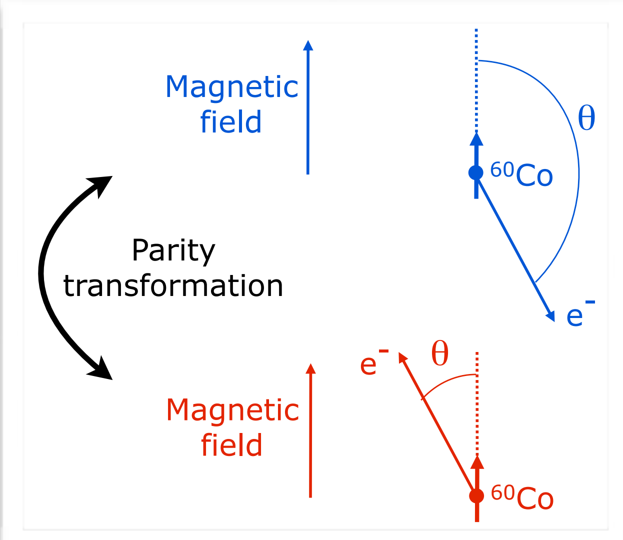


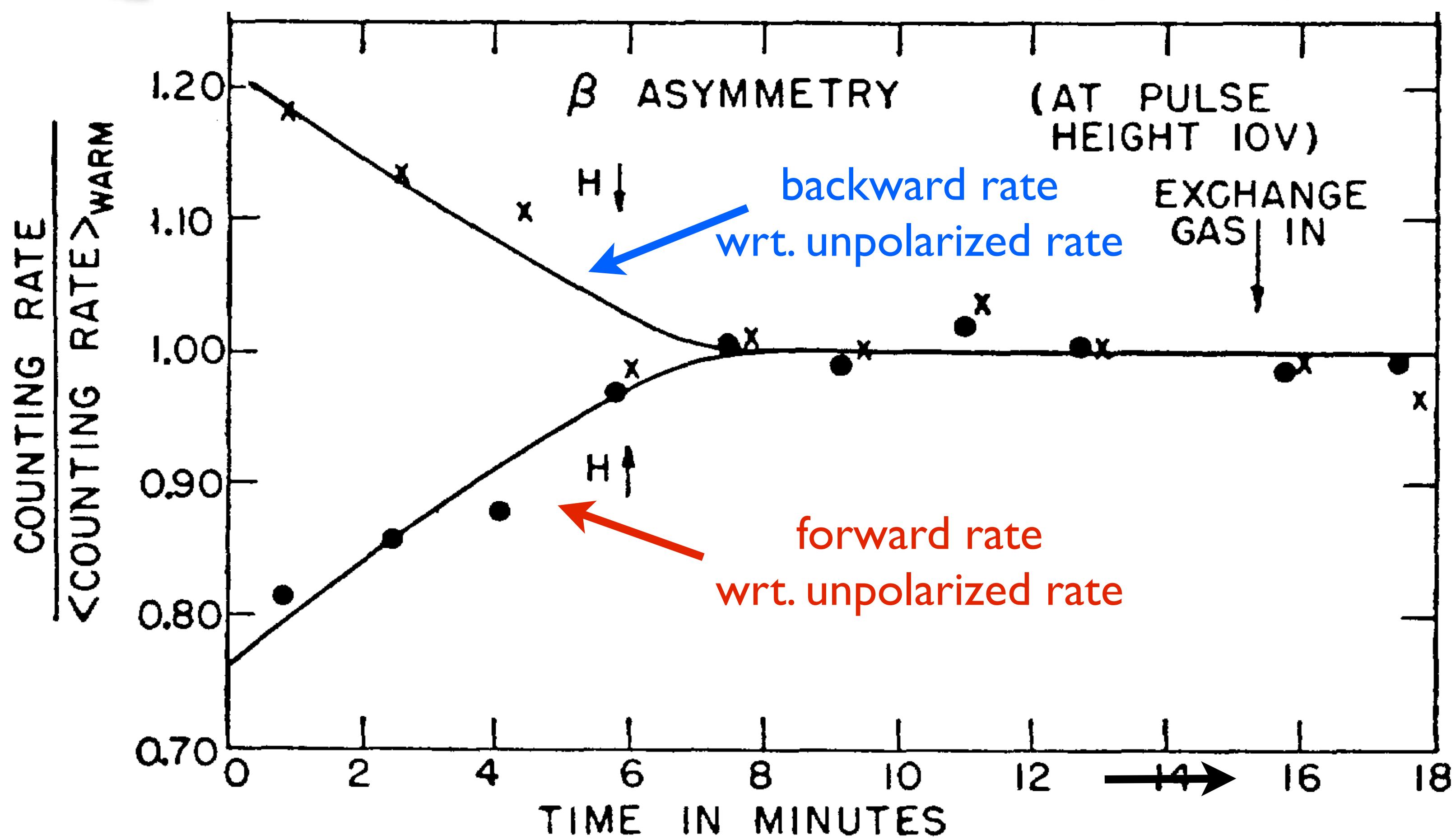
Experimental Test of Parity Conservation in Beta Decay*

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

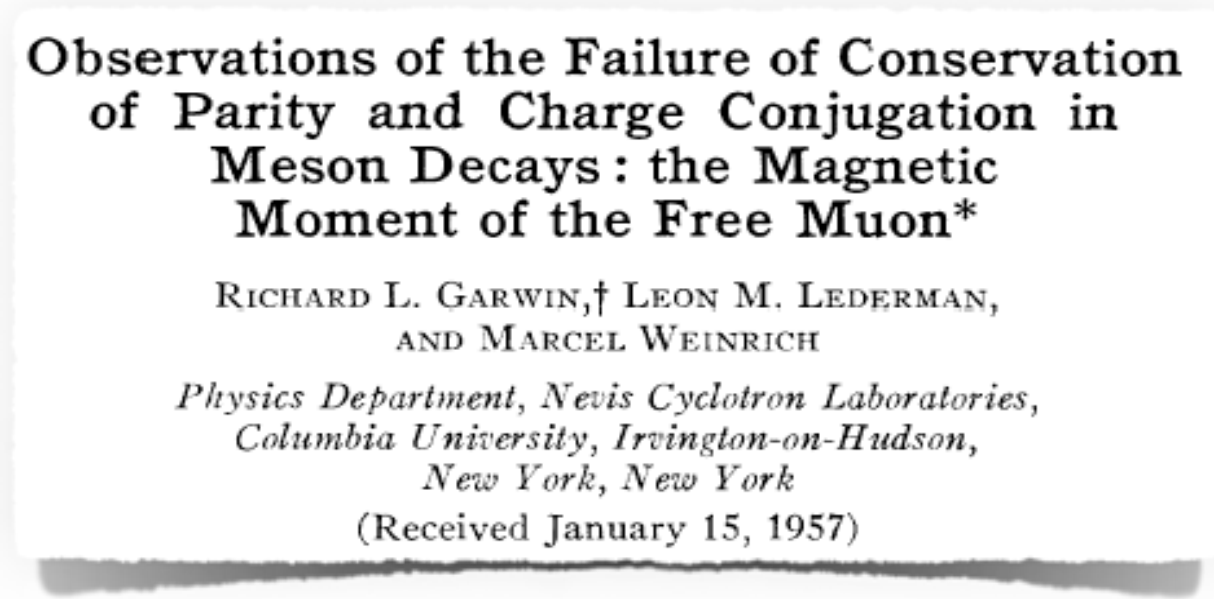
AND

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

(Received January 15, 1957)



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



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

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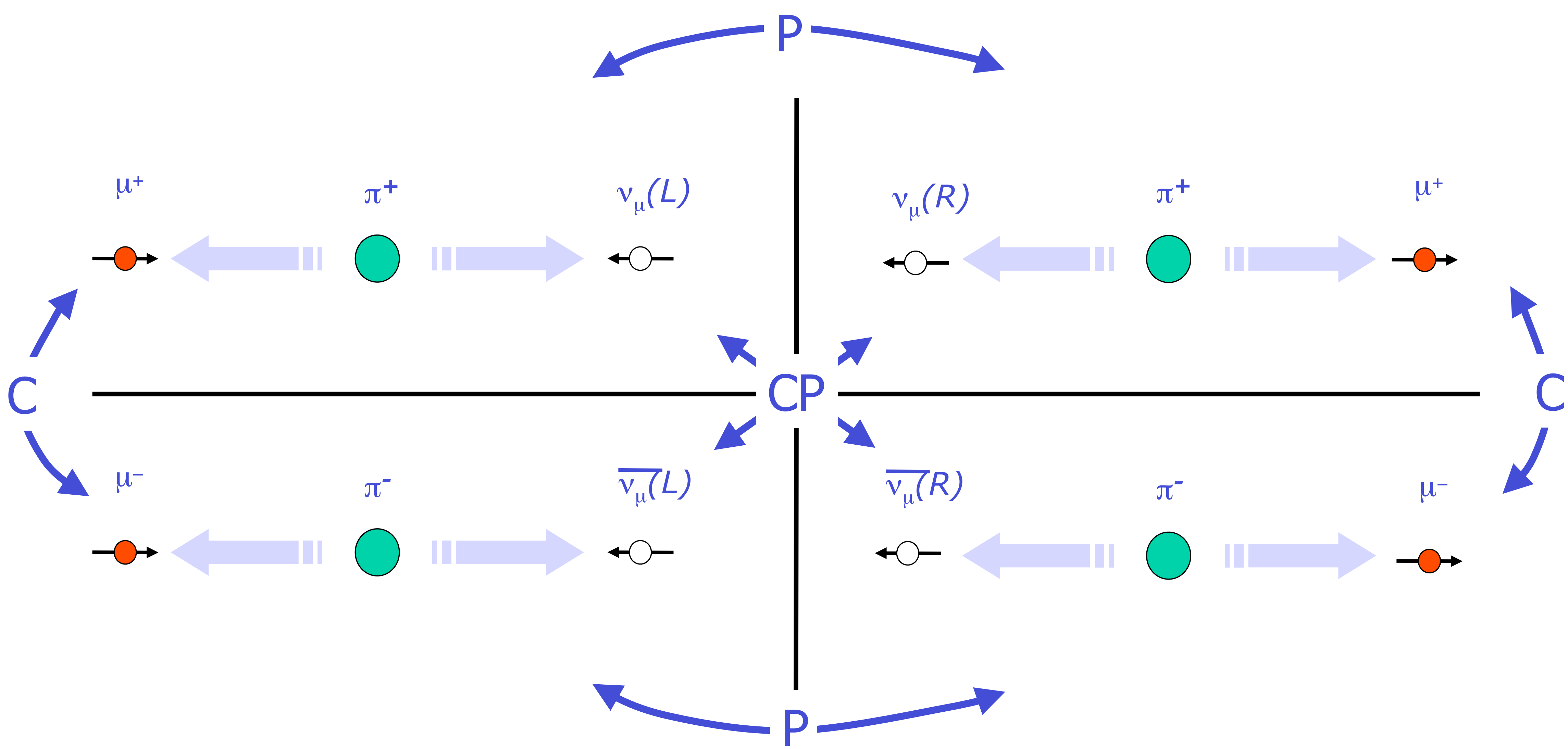

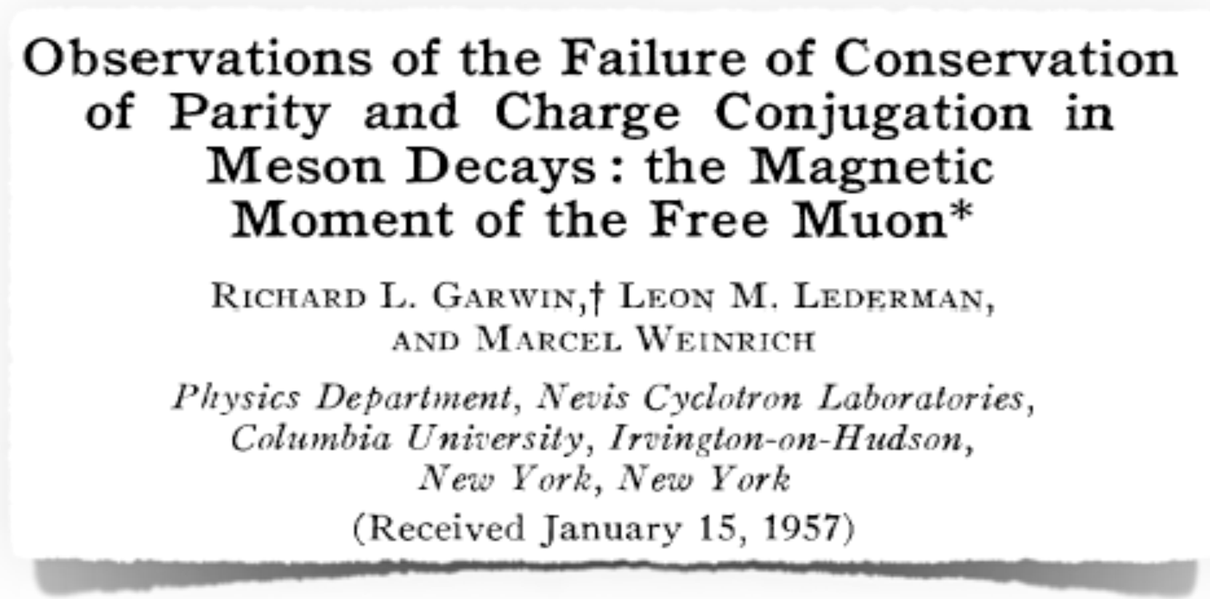

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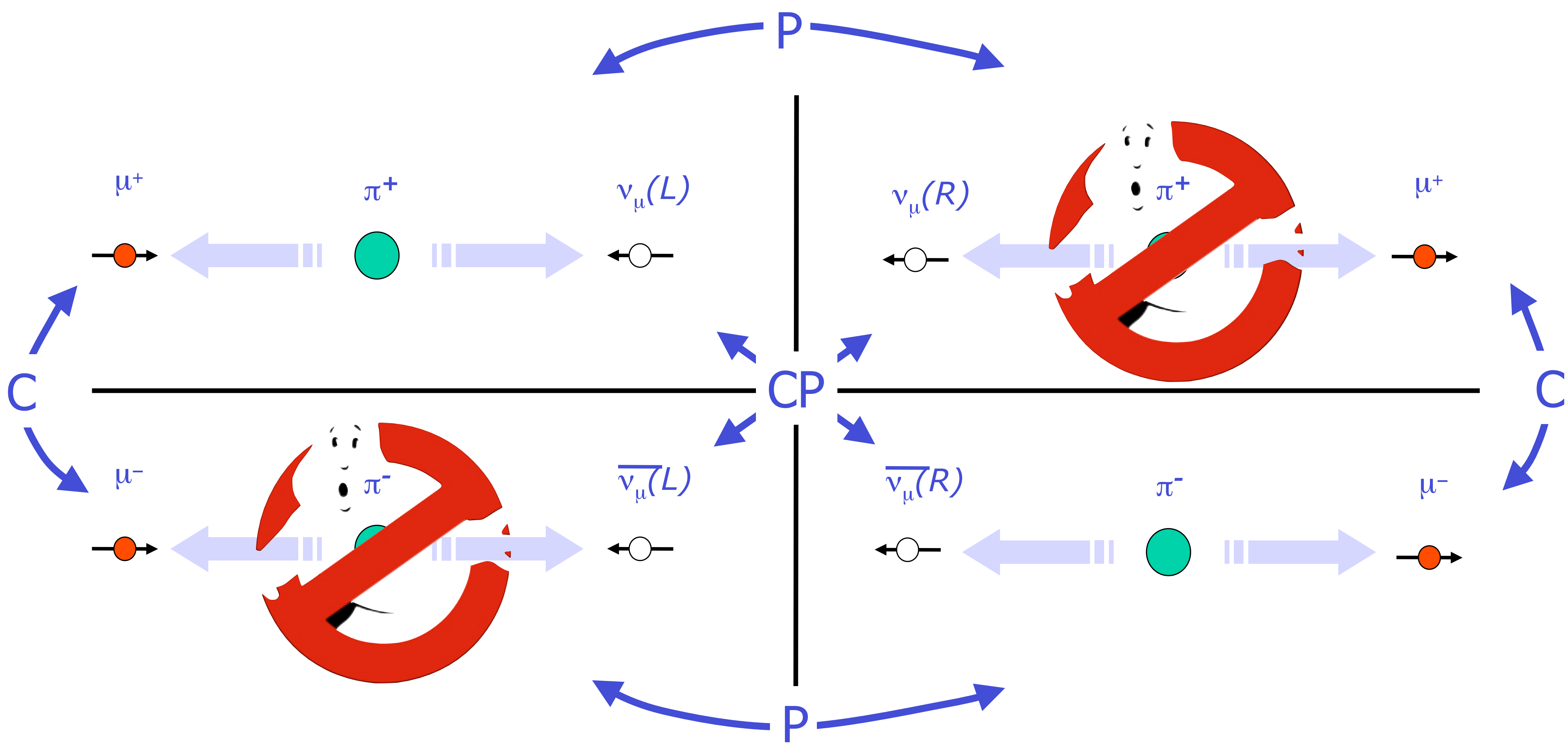

Strangeness

Yet, another puzzle: particles (like the θ-τ) produced in strong interactions and decaying with **very long lifetimes (inconsistent with strong decays)** to strongly interacting particles.

Pais/Gell-Mann: these particles can be produced only in pairs, and a **new (additive) quantum number** is associated to them, the **strangeness**, which is **conserved in strong interaction, but not in weak ones**.

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:

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

leptonic decays:

$$\begin{array}{lcl} K^+ & \rightarrow & \mu^+\nu_\mu,\ e^+\nu_e \\ K^- & \rightarrow & \mu^-\overline{\nu_\mu},\ e^-\overline{\nu_e} \\ K^0 & \rightarrow & \mu^-\mu^+,\ e^-e^+ \\ \overline{K^0} & \rightarrow & \mu^+\mu^-,\ e^+e^- \end{array}$$

Hadronic and leptonic decays:
particle and antiparticles behave the same

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K^0 &\rightarrow \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0 \\
\overline{K^0} &\rightarrow \pi^0\pi^0,\ \pi^0\pi^0\pi^0,\ \pi^+\pi^-,\ \pi^+\pi^-\pi^0
\end{aligned}$$

semi-leptonic decays:

$$\begin{aligned}
K^+ &\rightarrow \pi^0\mu^+\nu_\mu,\ \pi^0 e^+\nu_e \\
K^- &\rightarrow \pi^0\mu^-\overline{\nu_\mu},\ \pi^0 e^-\overline{\nu_e} \\
K^0 &\rightarrow \pi^-\mu^+\nu_\mu,\ \pi^- e^+\nu_e \\
\overline{K^0} &\rightarrow \pi^+\mu^-\overline{\nu_\mu},\ \pi^+ e^-\overline{\nu_e}
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leptonic decays:

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\end{aligned}$$

Hadronic and leptonic decays:
particle and antiparticles behave the same

Semi-leptonic decays:
particle and antiparticles are different!
"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.

Behavior of Neutral Particles under Charge Conjugation

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(Received November 1, 1954)

Some properties are discussed of the K^0, a heavy boson that is known to decay by the process $K^0 \rightarrow \pi^+ + \pi^-$. According to certain schemes proposed for the interpretation of hyperons and K particles, the K^0 possesses an antiparticle $\bar{K}^0$ 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 K^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 K^0's undergo the familiar decay into two pions. Some experimental consequences of this picture are mentioned.

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

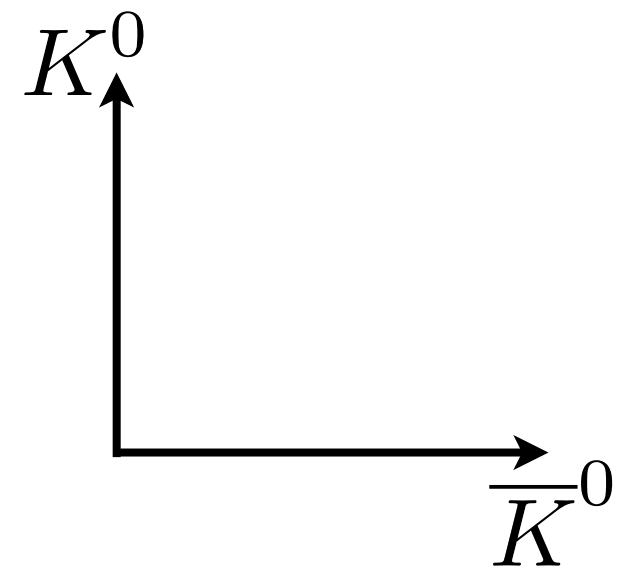
Hypothesis:
- $\bar{K}^0$ is *not* equal to K^0

The fact that a neutral meson is not its own antiparticles was very weird at that time (think about pions)

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...

Only strong interactions



Superposition state

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

Time evolution

$$i\frac{\partial}{\partial t}\psi(t) = \hat{H}\psi(t)$$

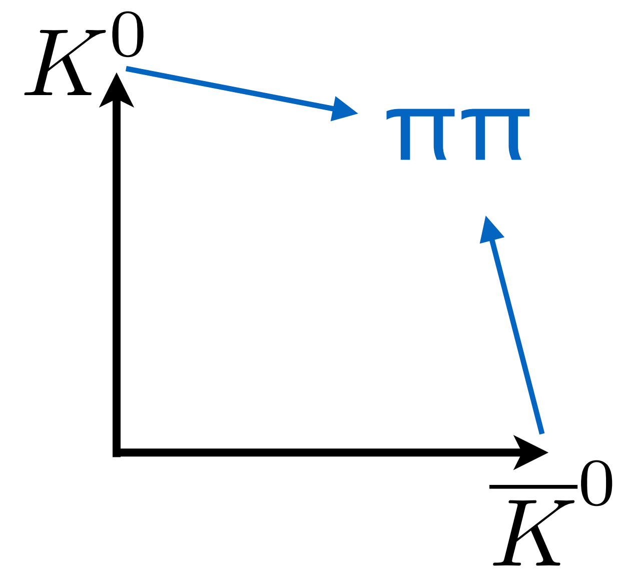
Hamiltonian

Mass

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

K^0 and anti-*K^0* eigenstates of the strong interaction.
If *no weak* interaction, they are stable and have equal mass:
they are the physical states.

With weak interactions



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Time evolution

$$i\frac{\partial}{\partial t}\psi(t) = \hat{H}\psi(t)$$

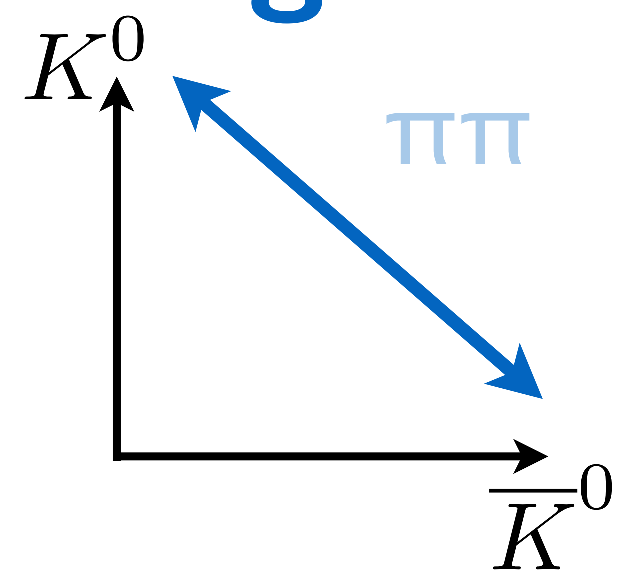
***K*⁰ and anti-*K*⁰ can decay to the same final state (CP eigenstate)**

Hamiltonian

Decay-width

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

With weak interactions: mixing



Superposition state

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

Time evolution

$$i\frac{\partial}{\partial t}\psi(t) = \hat{H}\psi(t)$$

The weak interaction breaks the degeneracy: add *off-diagonal elements*

Hamiltonian

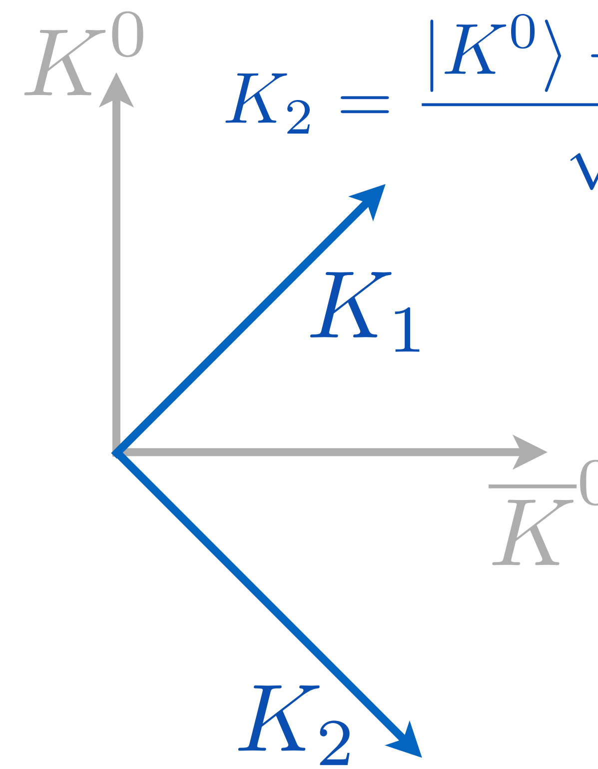
$$\hat{H} = \hat{M} - \frac{i}{2}\hat{\Gamma} = \begin{pmatrix} M_K - \frac{i}{2}\Gamma_K & \Delta \\ \Delta & M_K - \frac{i}{2}\Gamma_K \end{pmatrix}$$

With weak interactions

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

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

K^0 and anti-K^0 are no longer eigenstates of H.
K_1 and K_2, superposition of K^0 and anti-K^0, are eigenstates and have different mass and lifetime **(physical states)**



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

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

Hamiltonian

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

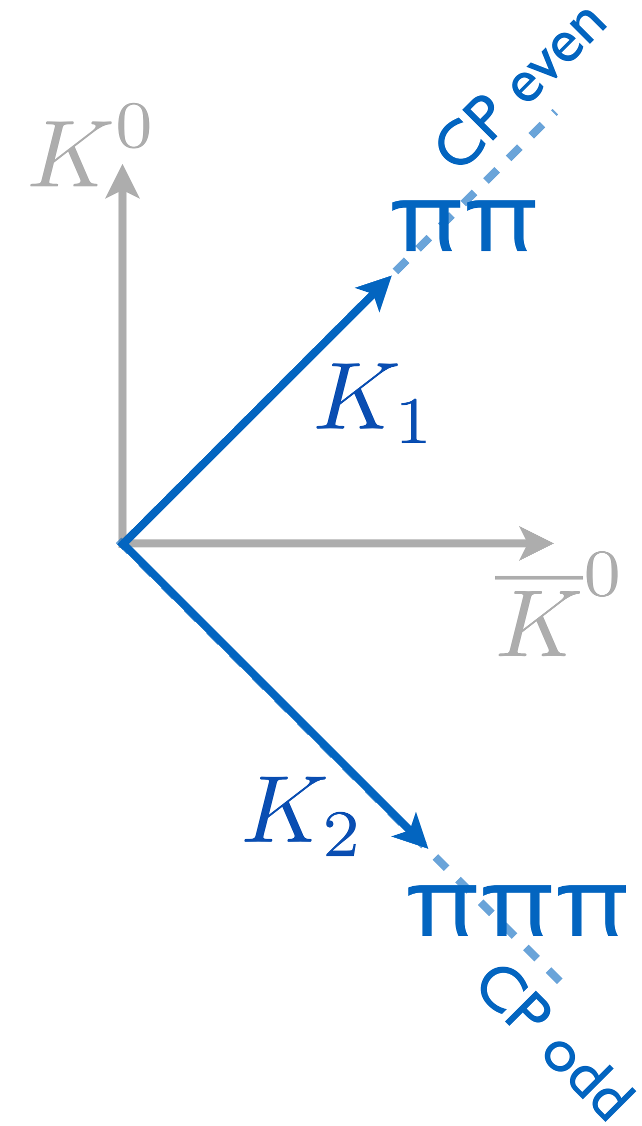
If CP is conserved

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

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

[with the phase convention: $CP|K^0\rangle = |\overline{K}^0\rangle$]

K_1 and K_2 are their own antiparticles, one CP even, and one CP odd.



Only CP-even state (K_1) decay to ππ
K_1: CP=+1 => ππ: CP=(-1)(-1)=+1

CP-odd state (K_2) decay into πππ
K_2: CP=-1 => πππ: CP=(-1)(-1)(-1)=-1

Huge difference in phase space, the CP even will decay much faster!

- difference due to M(K)~3M(π)
- Δ must have large Im component

$\tau_1 = 0.89 \times 10^{-10}$ s, $\tau_2 = 5.2 \times 10^{-8}$ s

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)

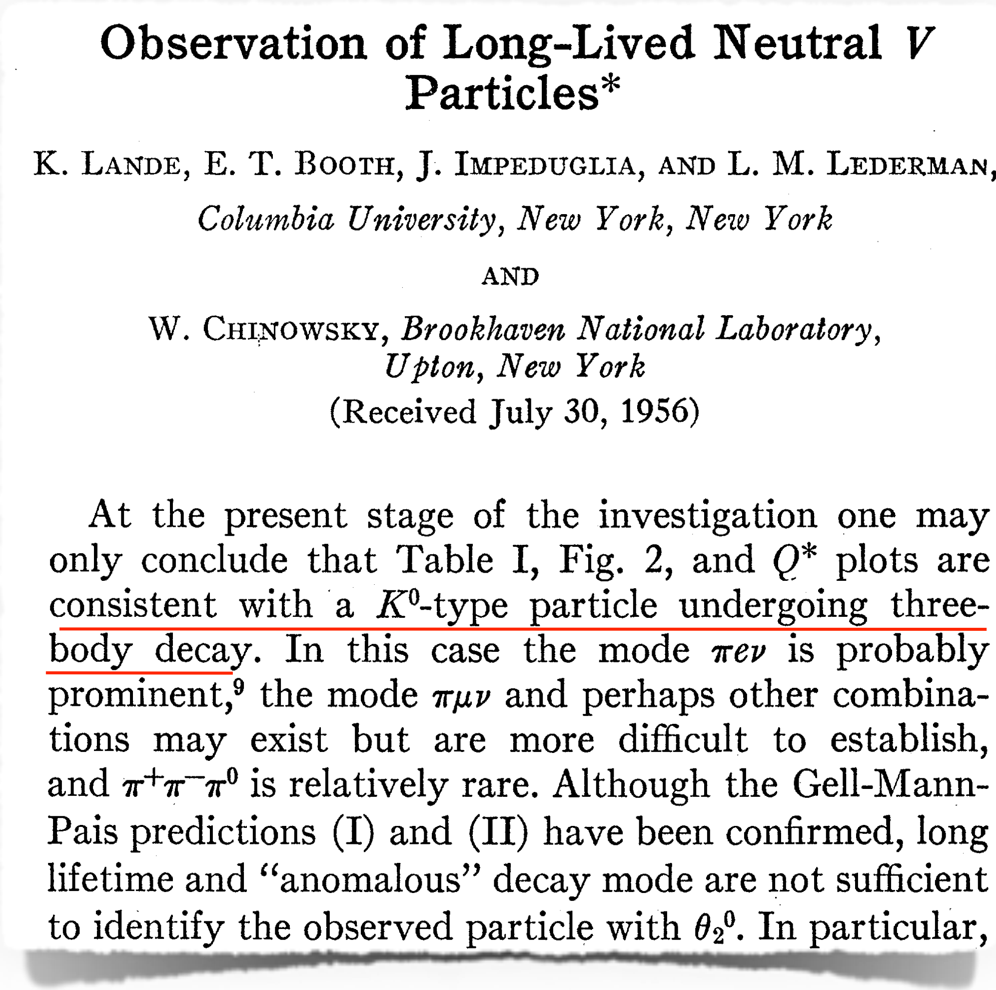
At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e\nu$ is probably prominent,[9] the mode $\pi\mu\nu$ and perhaps other combinations may exist but are more 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,

A cloud chamber 6 m from the interaction point (3-GeV p beam on a copper target):

- all K_l (and Lambda) decay before
- observed forked tracks kinematically compatible with $\pi e\nu$ and $\pi\mu\nu$ from **long lived K_2 (estimated lifetime in 10^{-9}-10^{-6} s).**

More systematic confirmation later:

Experimental confirmation



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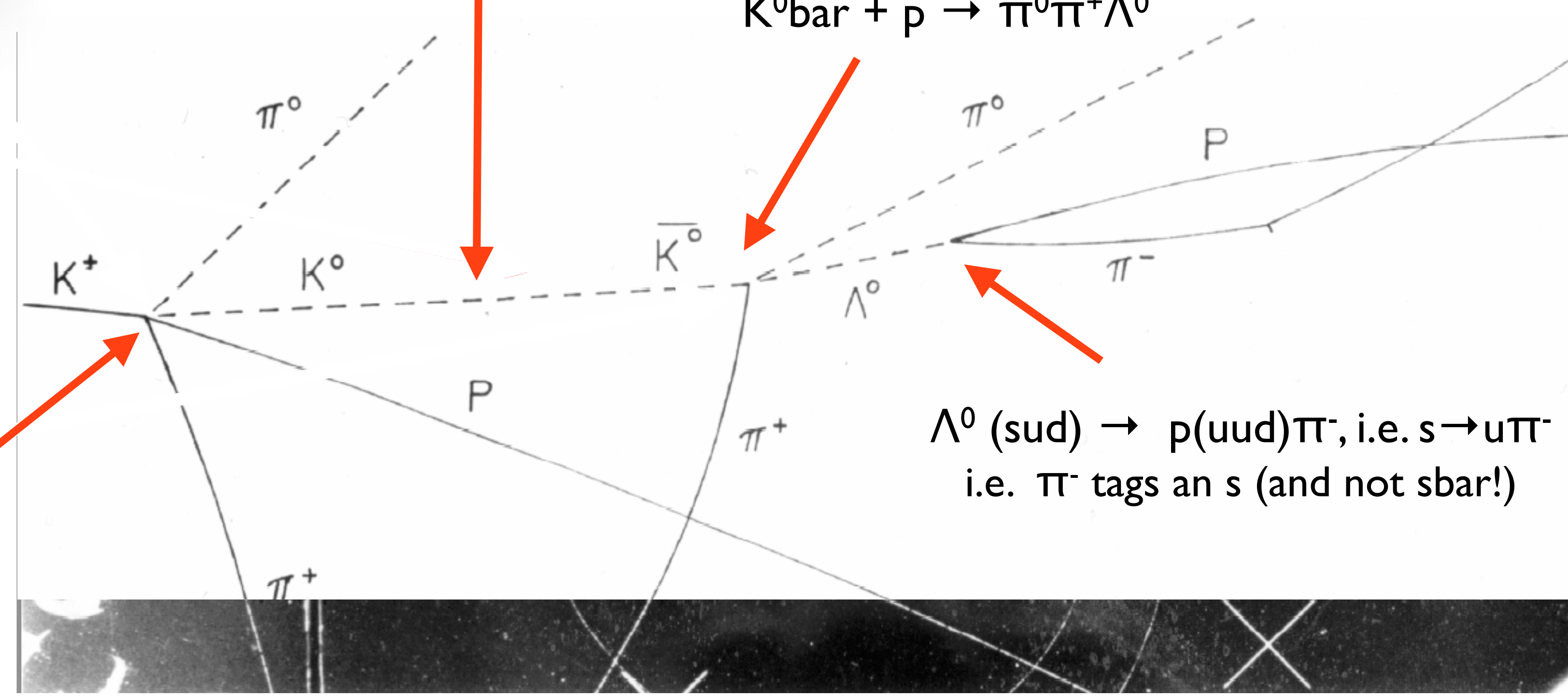
More systematic confirmation later:

K^0bar + p → $\pi^0\pi^+\Lambda^0$



Λ^0 (sud) → $p(uud)\pi^-$, i.e. s→uπ^-
i.e. π^- tags an s (and not sbar!)

Incoming K^+ (sbar) produces K^0 (sbar):
$K^+p \rightarrow p\pi^0\pi^+K^0$

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- ★ Need breaking of CP symmetry to explain this
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  the physical states are not the flavour eigenstates.

More general

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

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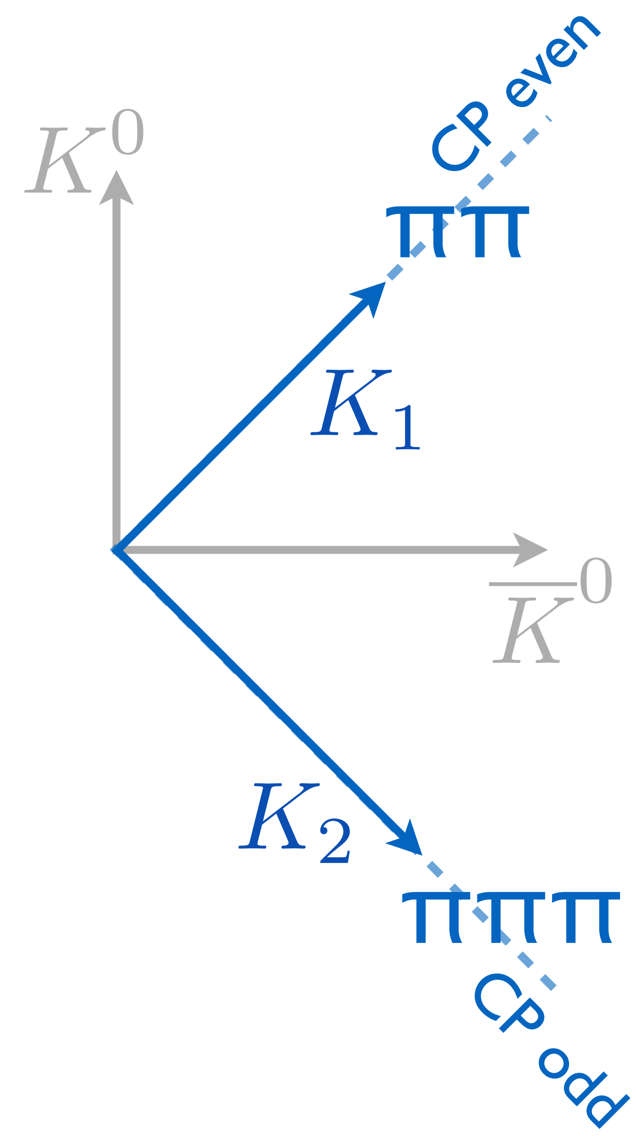
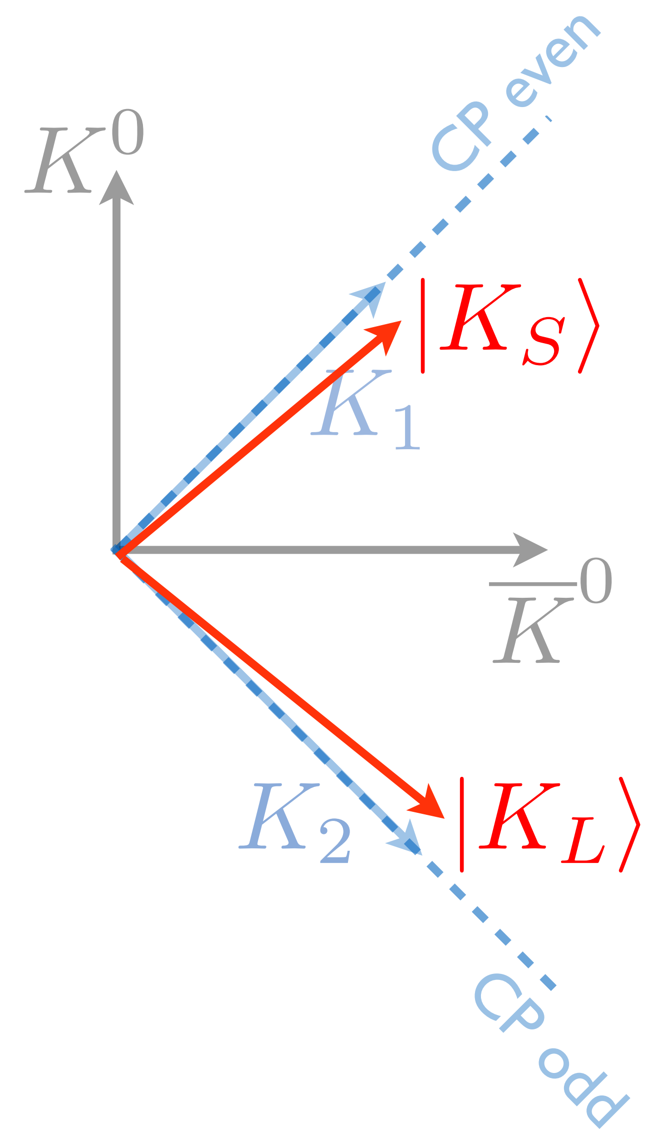


More general

No assumption on CP conservation, take a more general basis

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

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



with the normalisation condition

$$|p|^2 + |q|^2 = 1$$

Solving the Schroedinger equation

$$|K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$$
$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$$

Eigenvectors of the Schoeridenger equation:

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

From the eigenvectors calculation:

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

Evolution of the eigenvectors:

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

$$\omega_S = M + \frac{1}{2}\Delta m + \frac{i}{2}(\Gamma - \Delta\Gamma)$$
$$\omega_L = M - \frac{1}{2}\Delta m + \frac{i}{2}(\Gamma + \Delta\Gamma)$$

Δm and ΔΓ follow from the eigenvalues:

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

The key mixing parameters

$$\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$$

$\left|\frac{q}{p}\right| = 1$ if $\Gamma_{12} = 0$

$$x = \frac{\Delta m}{\Gamma} = \frac{M_S - M_L}{(\Gamma_L + \Gamma_S)/2}$$

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_L - \Gamma_S}{(\Gamma_L + \Gamma_S)}$$

zero if $\Gamma_{12} = 0$

Time evolution

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

t=0: physical superposition of "flavour" states

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

time evolution of physical states

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

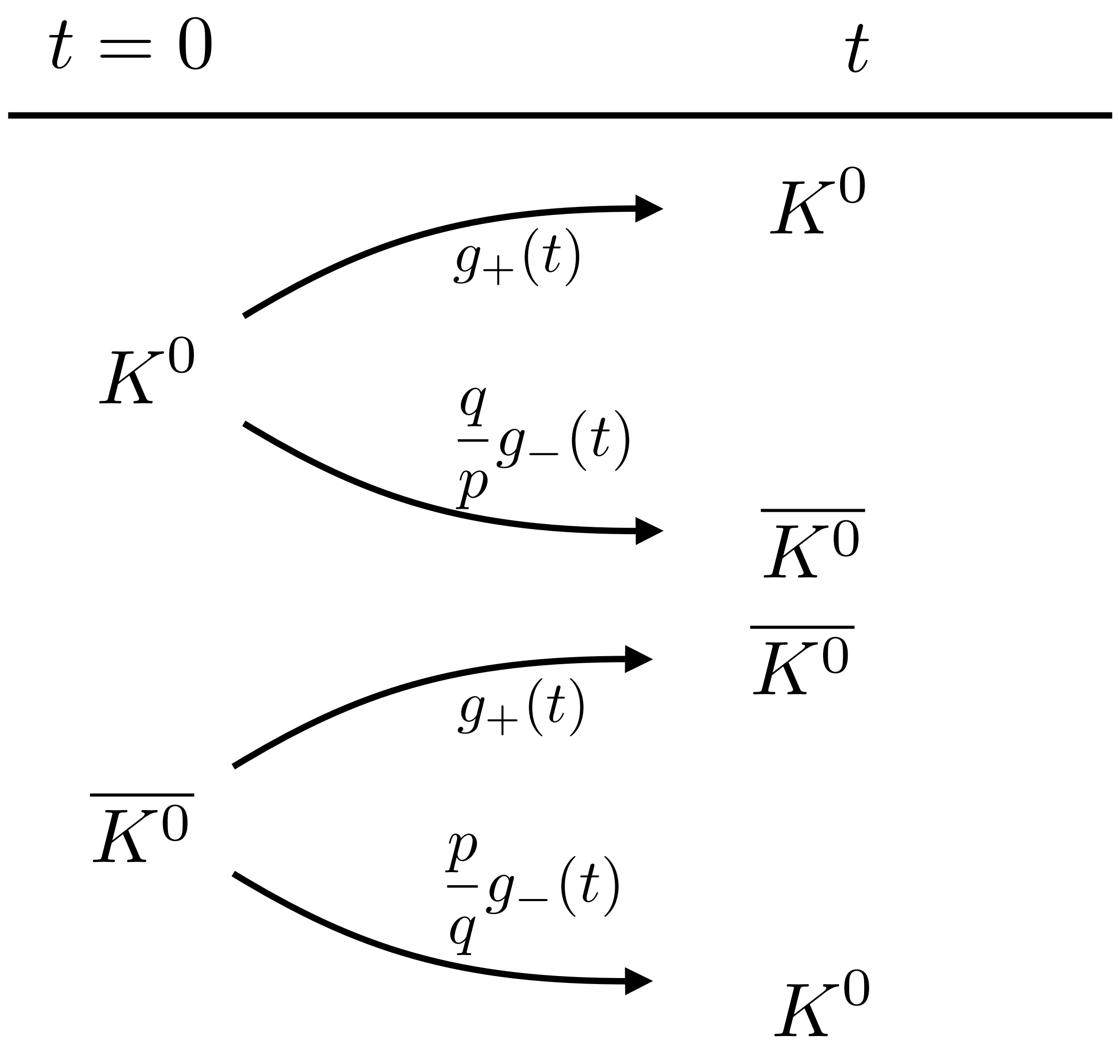
time evolution of "flavour" states
from evolution of physical states

$$\begin{pmatrix} K^0(t) \\ \overline{K^0}(t) \end{pmatrix} = \underbrace{\begin{pmatrix} +\frac{1}{2q} & +\frac{1}{2q} \\ +\frac{1}{2p} & -\frac{1}{2p} \end{pmatrix} \begin{pmatrix} e^{-i\omega_S t} & 0 \\ 0 & e^{-i\omega_L t} \end{pmatrix} \begin{pmatrix} +q & +p \\ +q & -p \end{pmatrix}} \begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix}$$

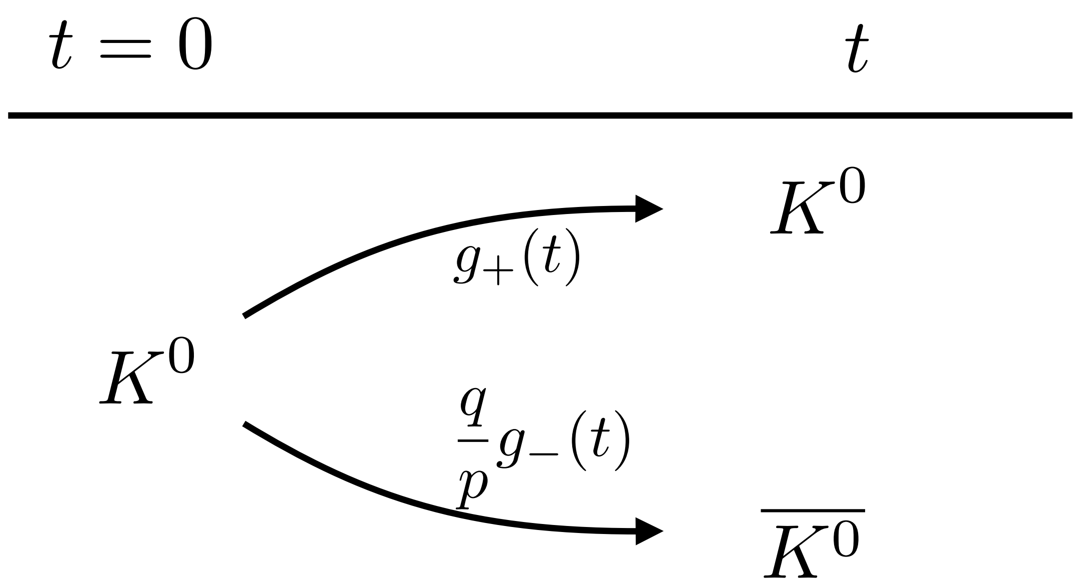
$$= \begin{pmatrix} g_+(t) & \frac{p}{q} g_-(t) \\ \frac{q}{p} g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} K^0(0) \\ \overline{K^0}(0) \end{pmatrix}$$

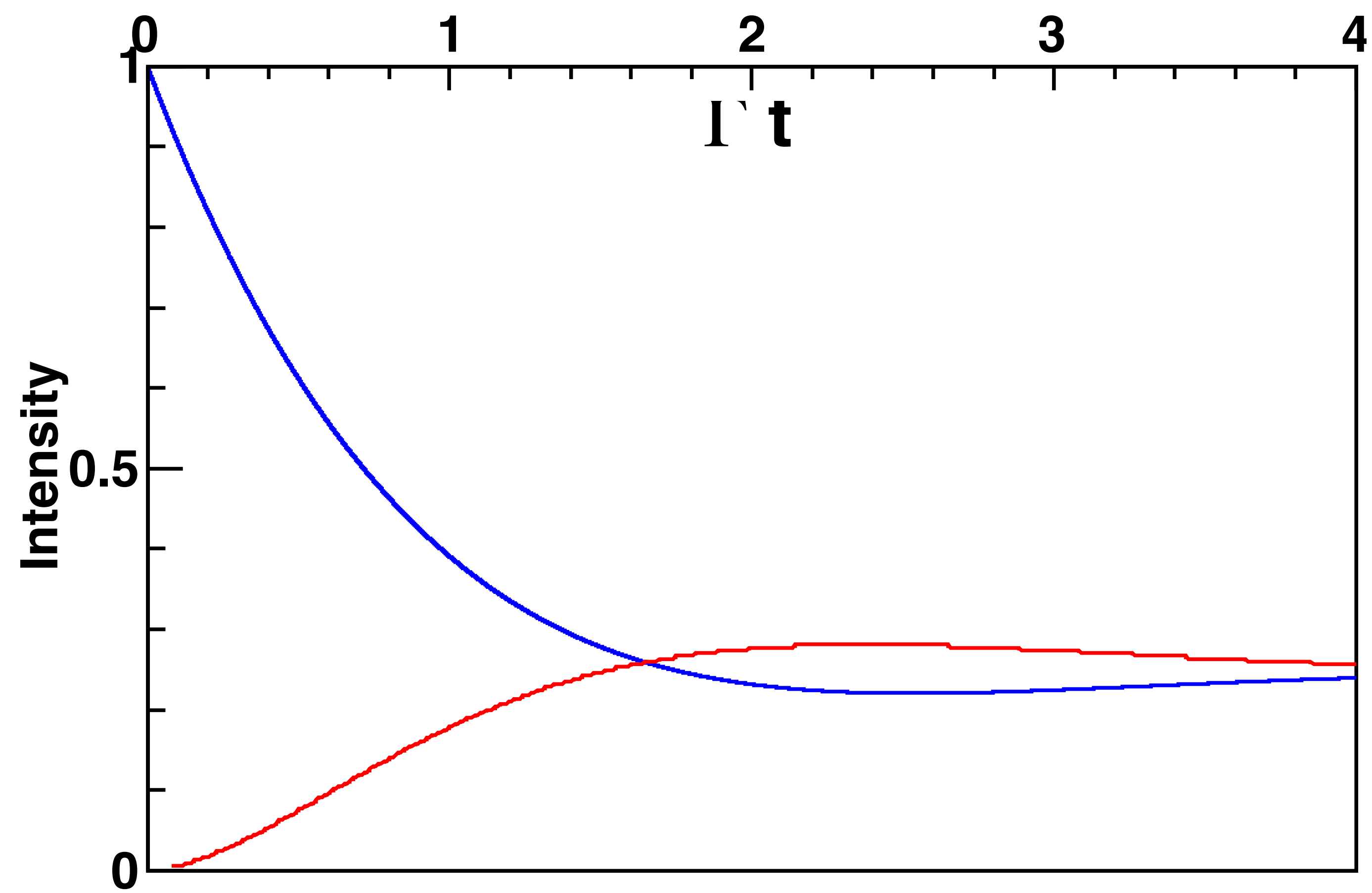
$$g_\pm(t) = \frac{e^{-i\omega_S t} \pm e^{-i\omega_L t}}{2}$$

Time evolution



Time evolution

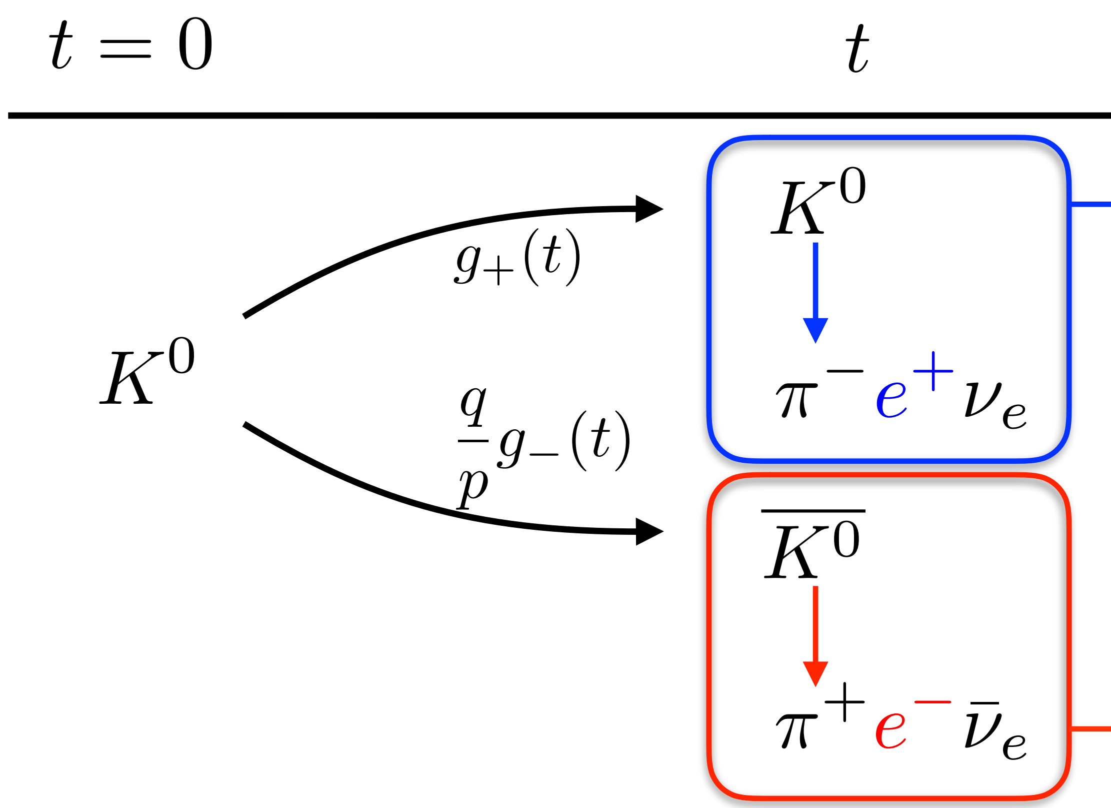




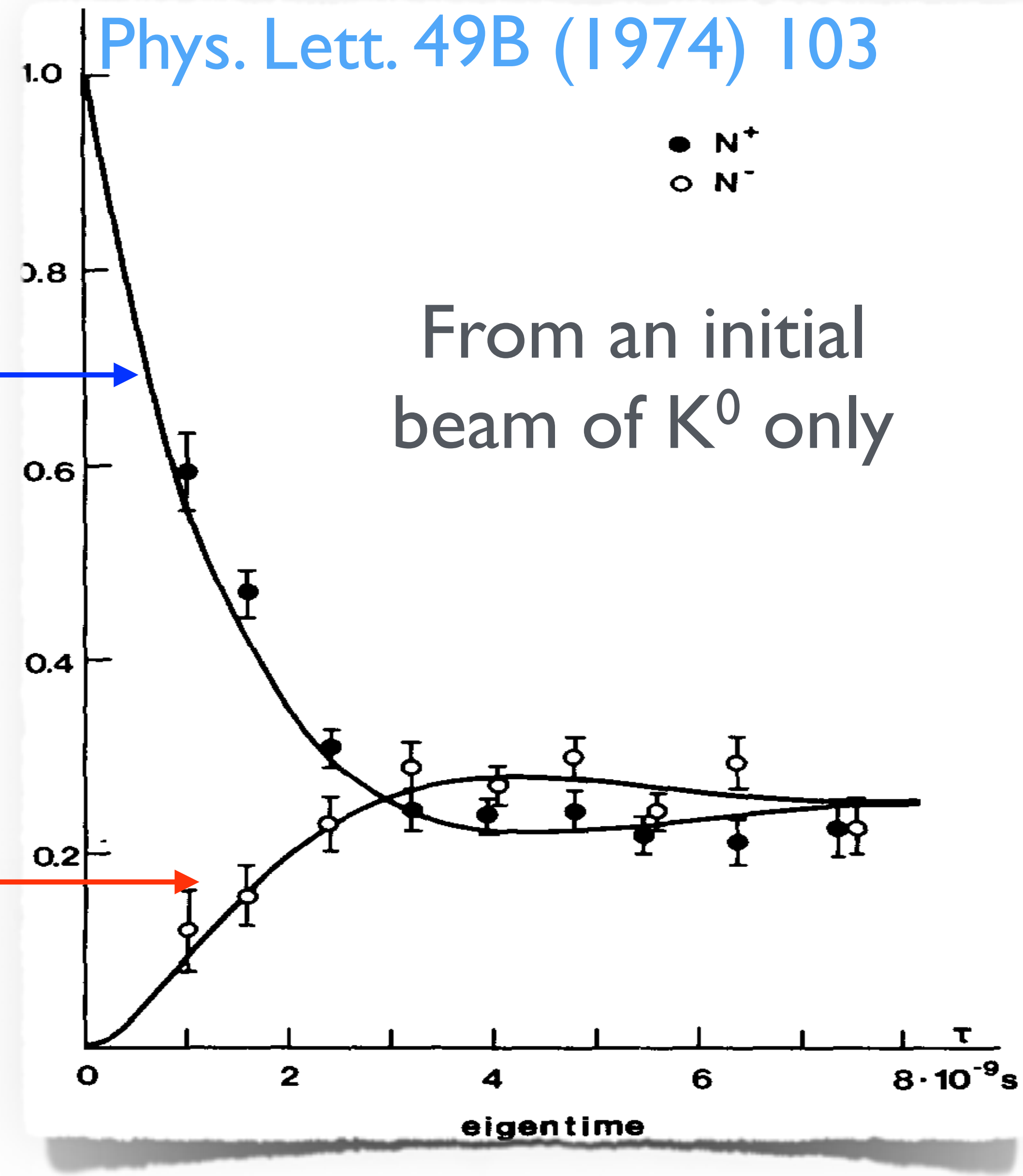
$$|\langle K^0(0)|K^0(t)\rangle|^2 = |g_+(t)|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle K^0(0)|\overline{K}^0(t)\rangle|^2 = |(q/p)\, g_-(t)|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

Time evolution



Use "flavour specific" decays!

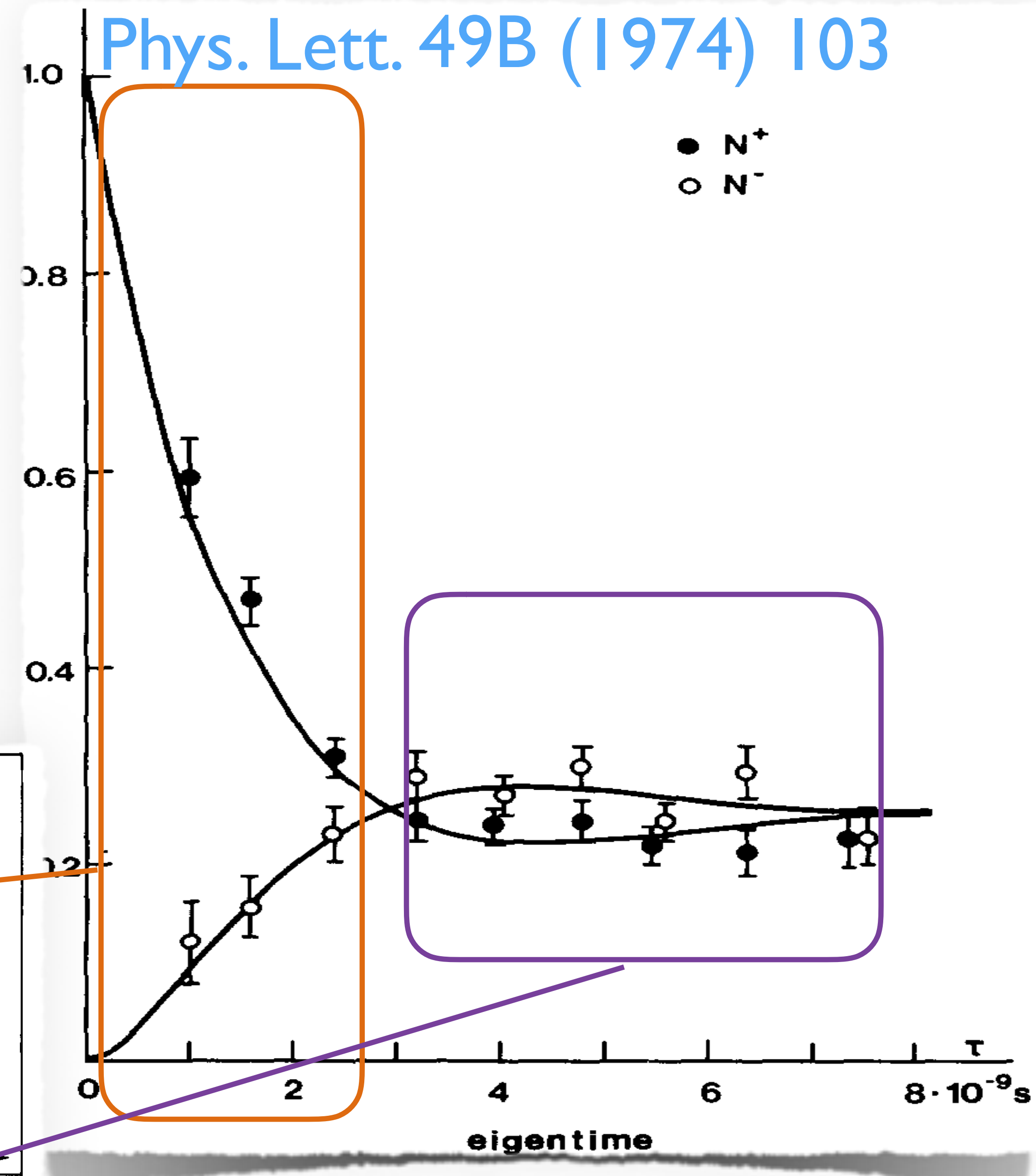


$$|\langle K^0(0)|K^0(t)\rangle|^2 = |g_+(t)|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$|\langle K^0(0)|\overline{K}^0(t)\rangle|^2 = |(q/p)\, g_-(t)|^2 \propto e^{-\Gamma t}[\cosh(y\Gamma t) - \cos(x\Gamma t)]$$

Mixing asymmetry

$$\mathcal{A}_{\rm mix} = \frac{N^+ - N^-}{N^+ + N^-} \propto \cos(x\Gamma t)$$



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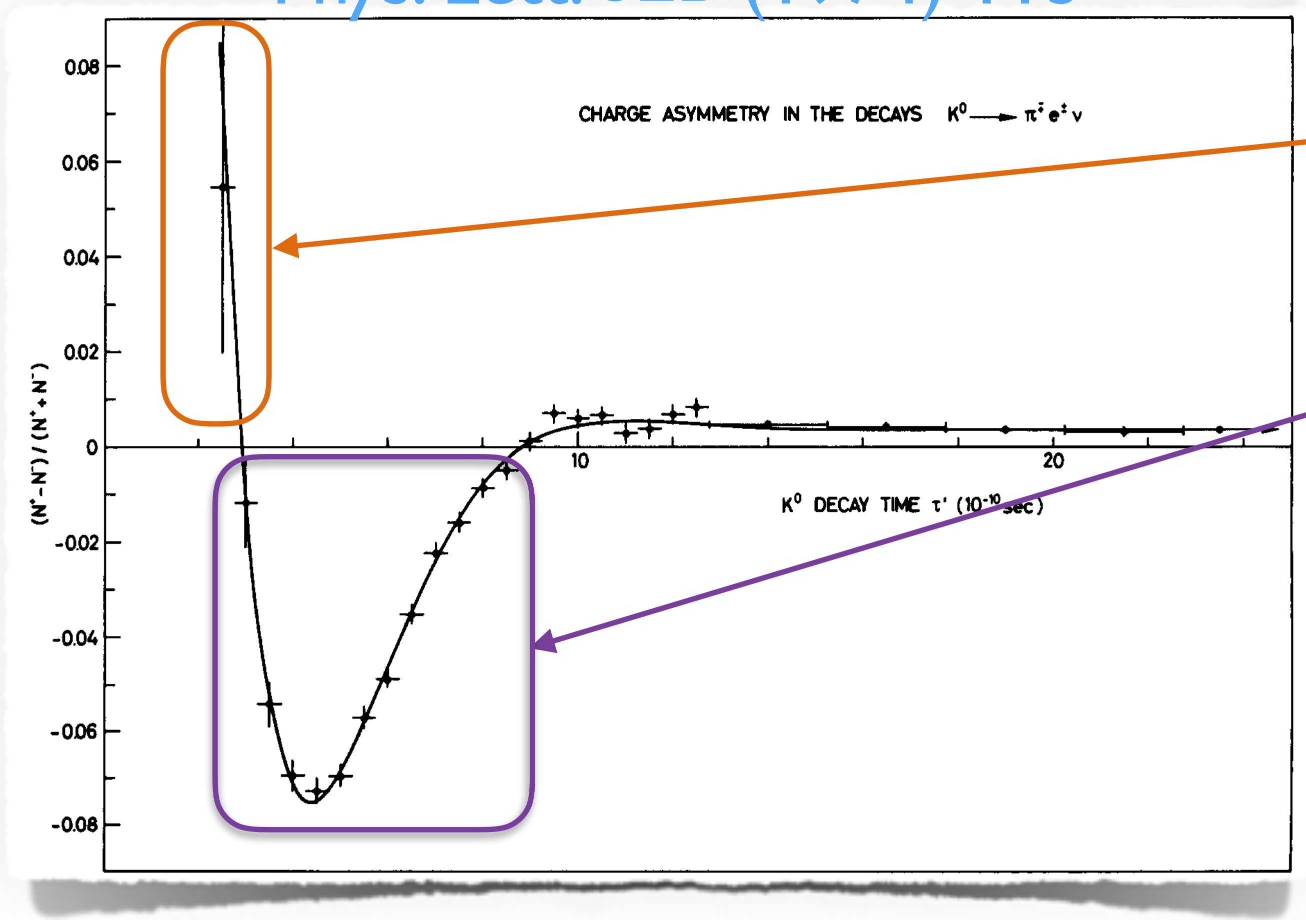

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- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy…)
- ★ Matter-antimatter oscillations: K^0 can turn into anti-K^0; the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations