Symmetries and heavy flavours

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Part I: C, P and T parities
Flavour physics

- *Selective and biased introduction by an experimental particle physicist*
- *Many simplifications, avoid formalism*
- *Slides of many colleagues used without proper references*

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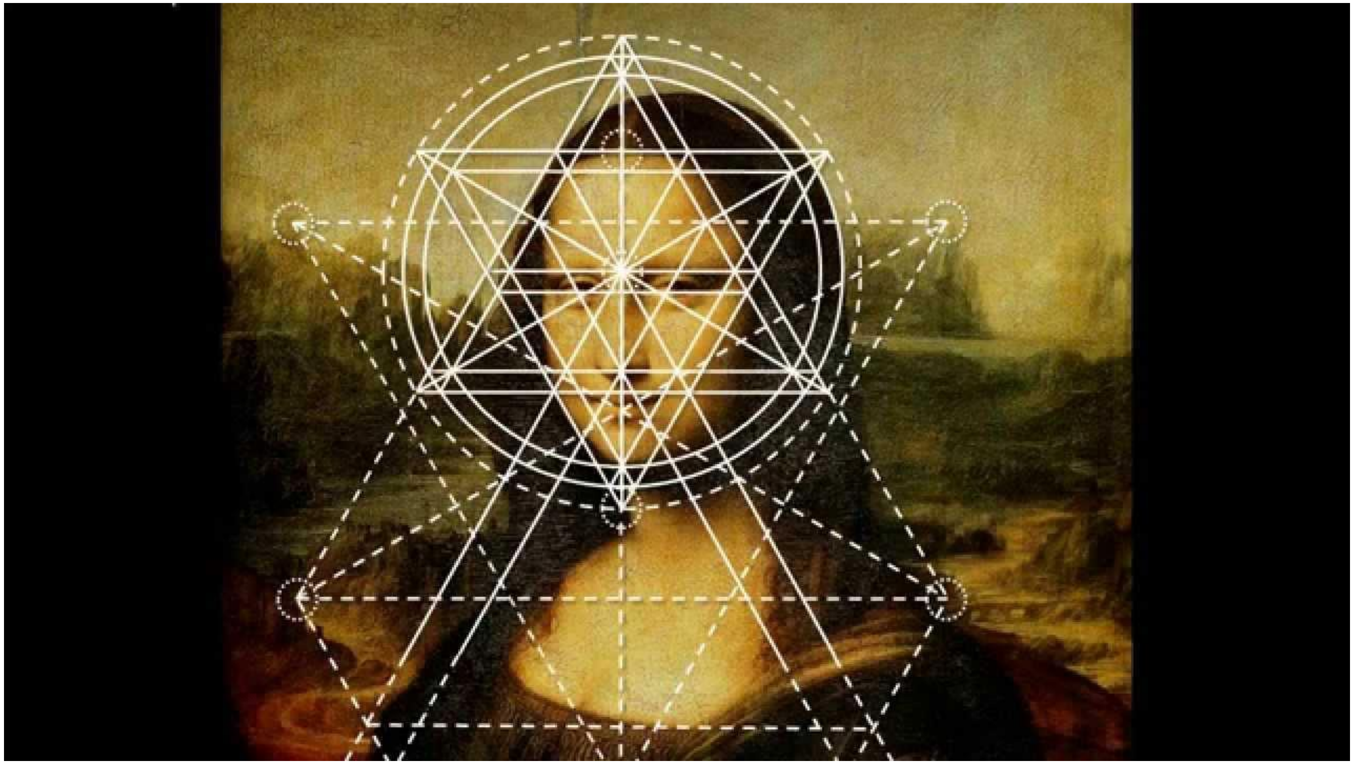
- **Symmetry** (from Greek συμμετρία symmetria "agreement in dimensions, due proportion, arrangement") in everyday language refers to a sense of harmonious and beautiful proportion and balance.

Wikipedia

- People often equate symmetry with beauty.



- There are many types of symmetry and not all of them have to do with the shape of an object:

local, global, space-time, discrete, super, gauge, charge, parity and time symmetries.

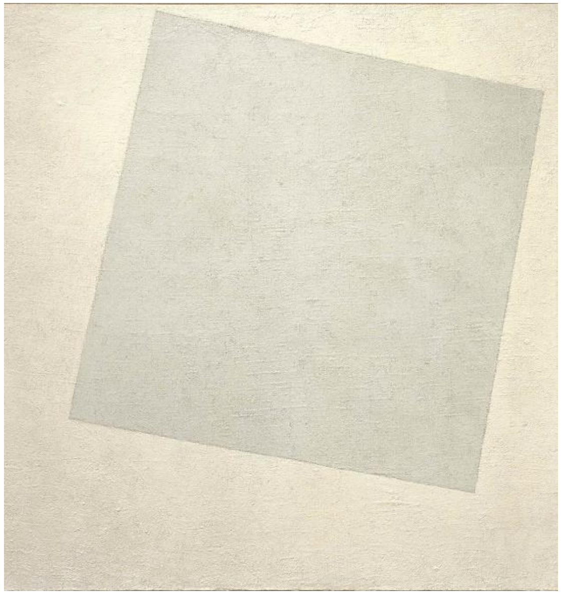
After H.Ekhlas and F.Ruskowski

- **Global symmetry** is one that holds at all points of space-time
- **Local symmetry** is one that only holds on a certain subset of the whole space-time. Local symmetries play an important role in physics, as measurements are performed in a limited region of space (or space-time).

Cathedral in Brixen, Italy

Discrete symmetry

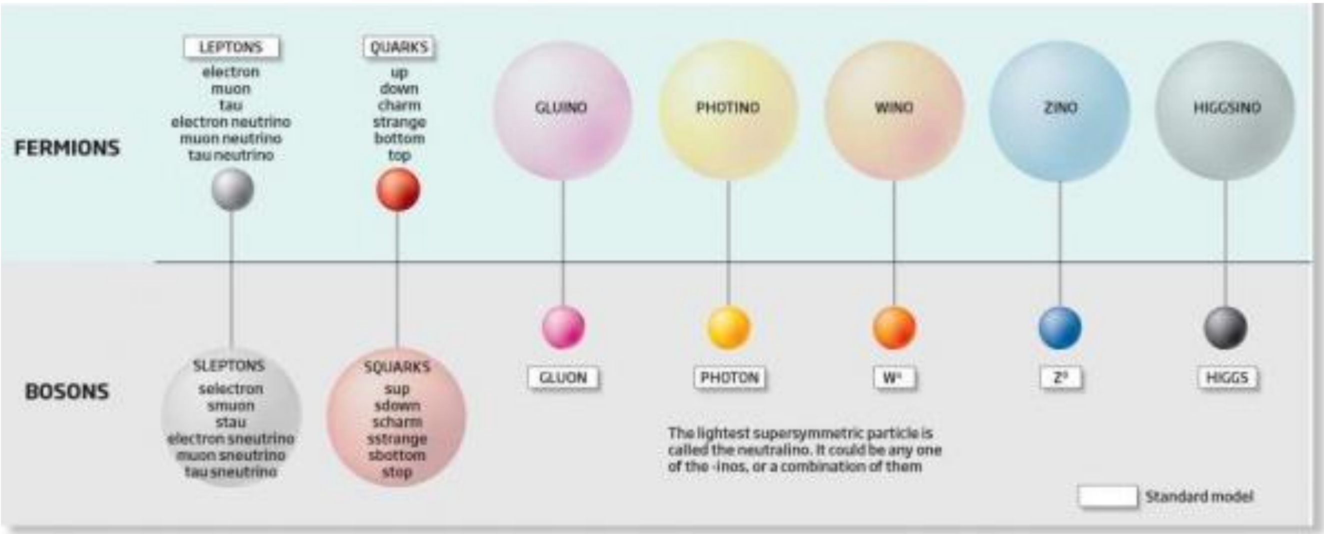
- Symmetry that describes non-continuous changes in a system.
- For example, a square possesses discrete symmetry, as only rotations by integral multiples of 90 degrees will preserve the square's original outlook.



Super Symmetry

- Extensions of symmetry to the concept of supersymmetry used to solve open questions in the Standard Model. Simplified idea: add one remaining physical symmetry beyond those that are well-understood, a symmetry between bosons and fermions, so that each boson would have a symmetry partner fermion, super partner, and vice versa.

If superpartners exist, they must have greater mass than existing particle accelerators have been capable of generating.



Gauge symmetry

- Example: electric charge. It is possible to define an electrostatic potential at any point in space. Voltage of a battery is the difference of potentials. No way to measure the absolute value of the electrostatic potential; only difference between two different points. In the language of symmetry: the **laws** of electrostatics are **invariant under the addition of a value to the potential which is the same everywhere**.

C, P and T symmetries

- **Charge symmetry** states that every particle is replaced with its antiparticle
- **Parity symmetry** states that the universe is reflected as in a mirror
- **Time symmetry** states that the direction of time is reversed

Symmetries

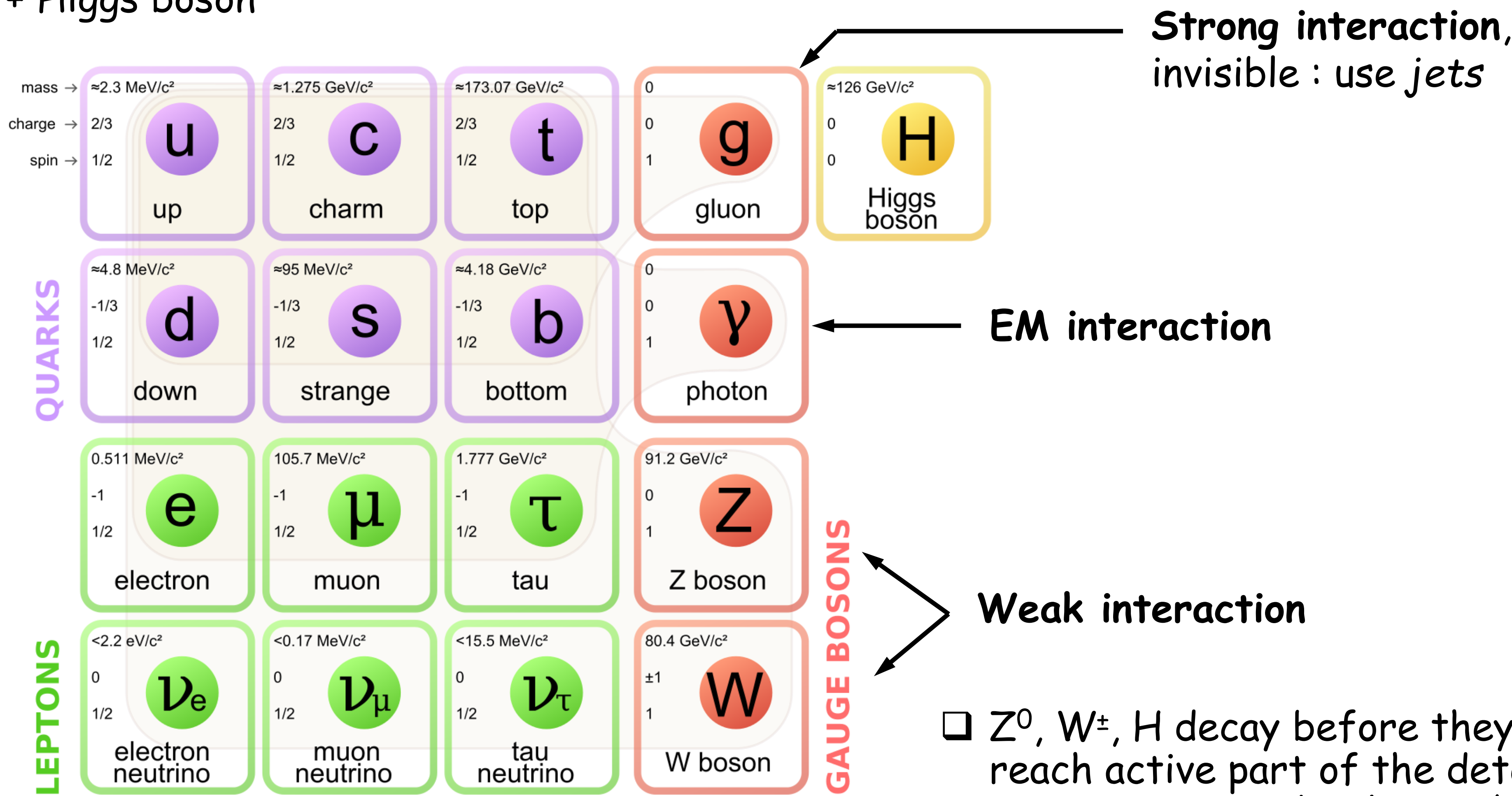
- Symmetry is important because there are all kinds of transformations which leave the laws of physics invariant. E.g. the laws of physics are the same everywhere, i.e. we detect no difference in the results of any self contained experiment which depends on where we do it. I.e. the laws of physics are invariant under a translation transformation. The infinite dimensional group of translation transformations is a symmetry of the laws of physics

- Symmetry and symmetry breaking help to determine how the universe goes from an undifferentiated point to the present complex structure.

- Peter Higgs and François Englert spontaneously violated local non-abelian symmetry to give masses to particles

- You followed the discovery with Damir in his first lecture

- «Truly » elementary particles : **fermions** (leptons and quarks) and **gauge bosons** + Higgs boson

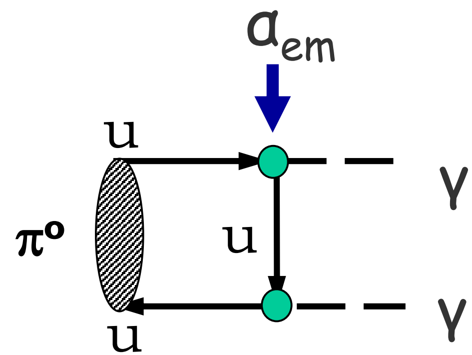


- Z^0, $W^{\pm}$, H decay before they reach active part of the detector: reconstruct via daughters / jets

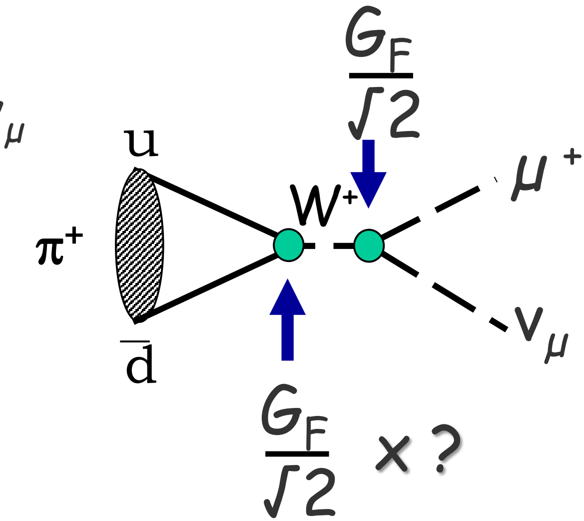
- **Neutrinos** can be seen in the dedicated detector only, or sometimes indirectly. Probability of interaction with matter is small.
- Free **quarks** have not been observed. Quarks form hadrons : mesons ($q\bar{q}$) or baryons (qqq). « Initial » (diagram) quarks can be probed via measurement of jets.

Rules : interactions

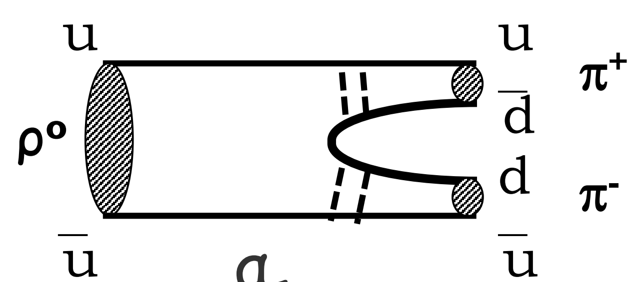
- **Electroweak**
  - electromagnetic (photon), e.g. decay of $\pi^o \rightarrow \gamma\gamma$

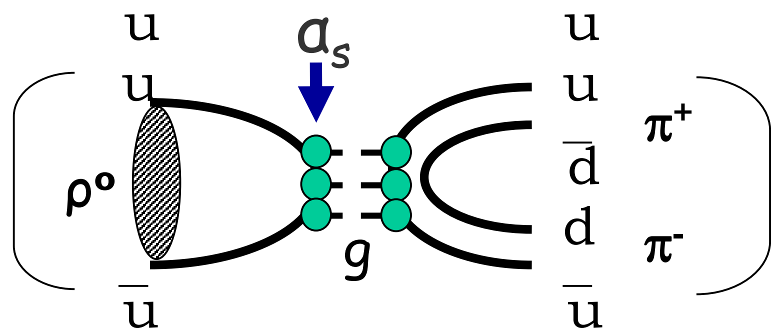


  - and **weak** ($W^{\pm}$ and Z^o bosons), e.g. decay of $\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$
    - ✓ *Violates symmetries*
    - ✓ *Violates universality*
    - ✓ …



- **Strong** (eight colour gluons): keeps quarks bound inside hadrons, responsible for decay of resonances, e.g. $\rho^o \rightarrow \pi^+\pi^-$



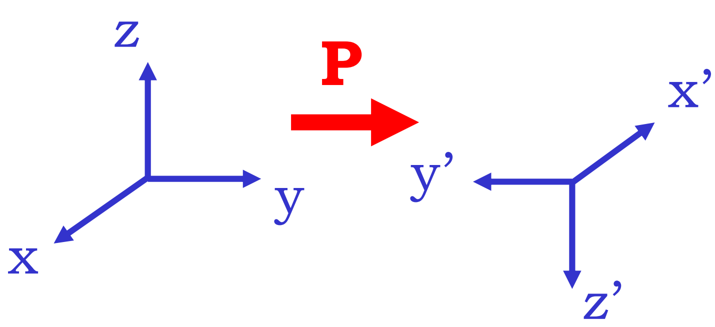


C, P and T parities

Bruno Touschek

P – parity

P - parity



Examples:

$P\vec{r} = -\vec{r}$	vector (parity -1)
$P(\vec{r}\cdot\vec{p}) = \vec{r}\cdot\vec{p}$	scalar (parity +1)
$P(\vec{r}\wedge\vec{p}) = \vec{r}\wedge\vec{p}$	pseudovector (parity +1)
$P[(\vec{r}\wedge\vec{p})\cdot\vec{r}\,'] = -(\vec{r}\wedge\vec{p})\cdot\vec{r}\,'$	pseudoscalar (parity -1)

spin 0	0^+	parity +1	Scalar
	0^-	parity -1	Pseudo-scalar
spin 1	1^+	parity +1	Pseudo-vector
	1^-	parity -1	Vector

Intrinsic parity of a particle :

J^P : Spin$^{\text{parity}}$

(the spin is invariant under P)

$q\bar{q}'$ system with angular momentum L: $P_{q\bar{q}'} = (-1)^{L+1}$

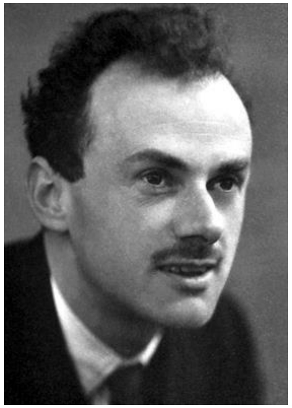
<u>Parity for a two-particles system:</u>

Intrinsic parity of the 2 components + parity of the angular momentum L (the part related to the spin is invariant under P)

$$P_{tot} = P_1\, P_2\, (-1)^L$$

Charge conjugation (C)

Particle ↔ antiparticle, e.g. electron ↔ positron



Dirac 1928

Anderson 1932

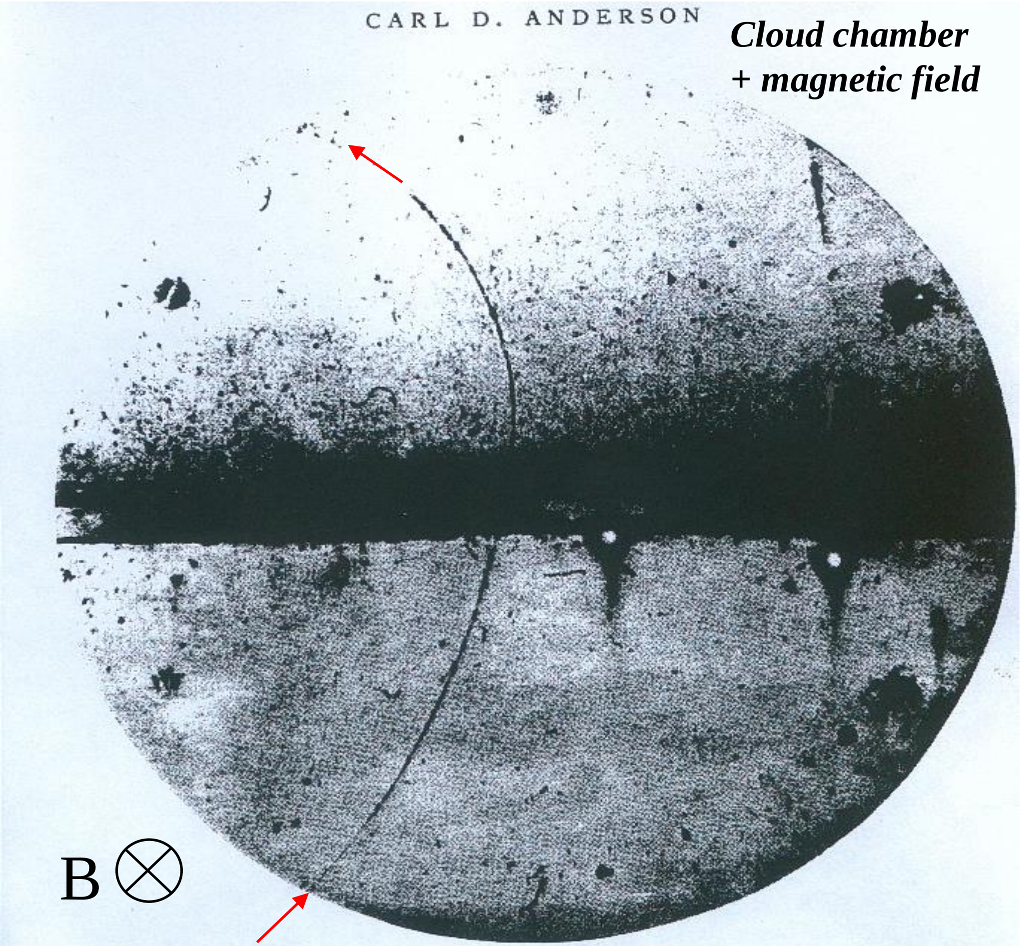


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

- Particle with positive curvature and minimum ionisation (size of the droplets)
- **Track length incompatible with a proton in the air, mass incompatible with a proton**
- Energy loss in a 6 mm of Pb : **compatible with that of electron**
- **Hypothesis (discovery !) :**

  particle with mass ~m_e and charge +1, the positron

- *First anti-particle*
- **Charge conjugation, or C-parity** $C_{q\bar{q}'} = (-1)^{L+s}$ defined for $q\bar{q}$ (q=q') states only
- Not defined in many cases: $C|\pi^+\rangle \rightarrow |\pi^-\rangle \neq \pm|\pi^+\rangle$ (with $\pi^+ = u\bar{d}$, $\pi^- = \bar{u}d$) E.g. fermions are not C-eigenstates
- C can be defined for a neutral boson or for a particle-antiparticle system $(\gamma, Z^0, \pi^0, \rho, \eta, \ldots)$

C, P, T Transformations :

Quantity	*P*	*C*	*T*
space vector	−*x*	*x*	*x*
time	*t*	*t*	−*t*
momentum	−*p*	*p*	−*p*
spin	*s*	*s*	−*s*
electrical field	−*E*	−*E*	*E*
magnetic field	*B*	−*B*	−*B*

- Electromagnetic and strong interactions are (so far) *C*, *P* and *T* invariant

Example: neutral pion decays via electromagnetic (EM) interaction : $\pi^0 \to \gamma\gamma$ but not $\pi^0 \to \gamma\gamma\gamma$

$$\pi^0 = \frac{1}{\sqrt{2}}\left[u\bar{u} - d\bar{d}\right]_{L=0,S=0} \quad \Rightarrow \quad C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$

$$C \cdot \vec{B},\vec{E} = -\vec{B},-\vec{E} \quad \Rightarrow \quad C\left|\gamma\right\rangle = -\left|\gamma\right\rangle$$

the initial (π^0) *and* final ($\gamma\gamma$) states are *C* even: hence, *C* is conserved !

Experimentally :

$$\frac{BR\left(\pi^0 \to \gamma\gamma\gamma\right)}{BR\left(\pi^0 \to \gamma\gamma\right)} < 3.1 \cdot 10^{-8} \quad 90\ \%\ \mathrm{CL}$$

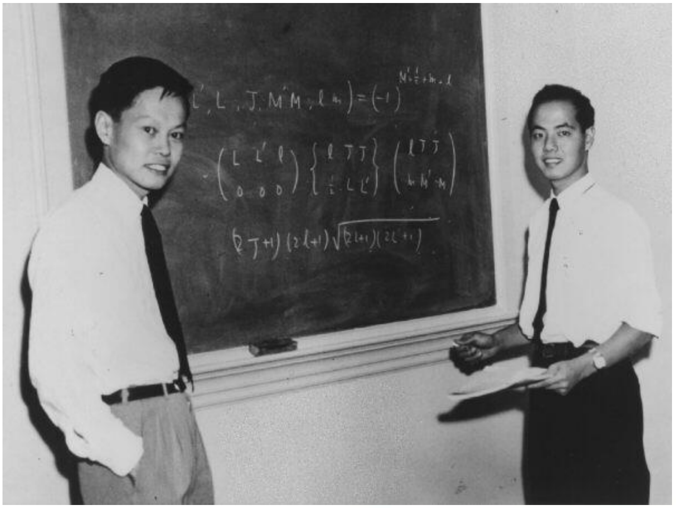
❑ Weak decays do not conserve *C*, *P* and *T* parity

The way to parity violation:

- Before 1956: the physics laws should not change under Parity transformation

- Was tested already for strong and electromagnetic interactions

- 1956: Lee and Yang postulated:
  - Weak decays violate parity,
  i.e. can distinguish between left- and right-handed coordinate systems
  - Proposed an experiment to test it

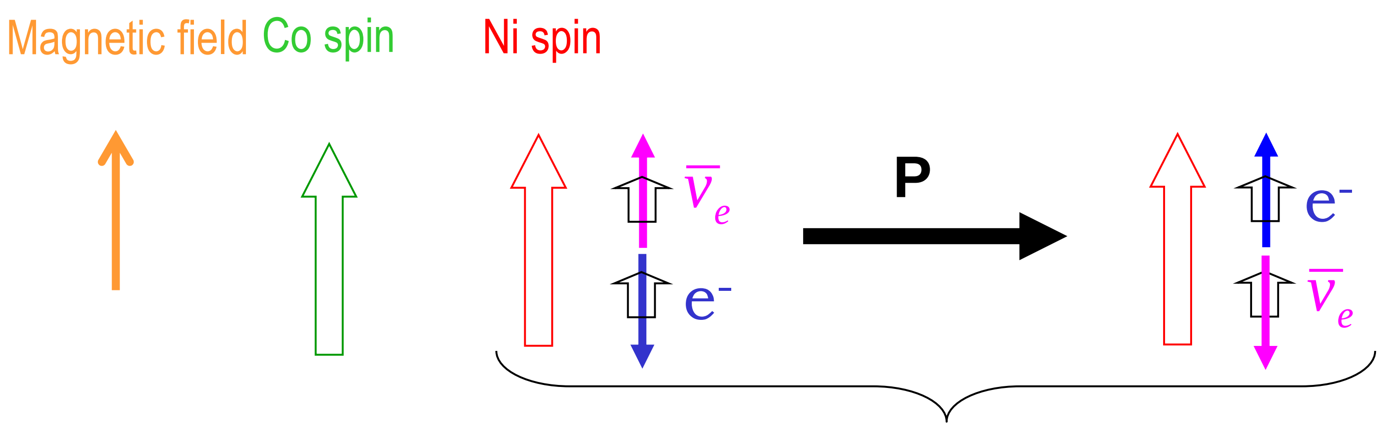


- Done by C. S. Wu and collaborators:
the ^{60}Co experiment, discovery of parity violation in β-decay

Phys. Rev. 105, 1413-1414 (1957)

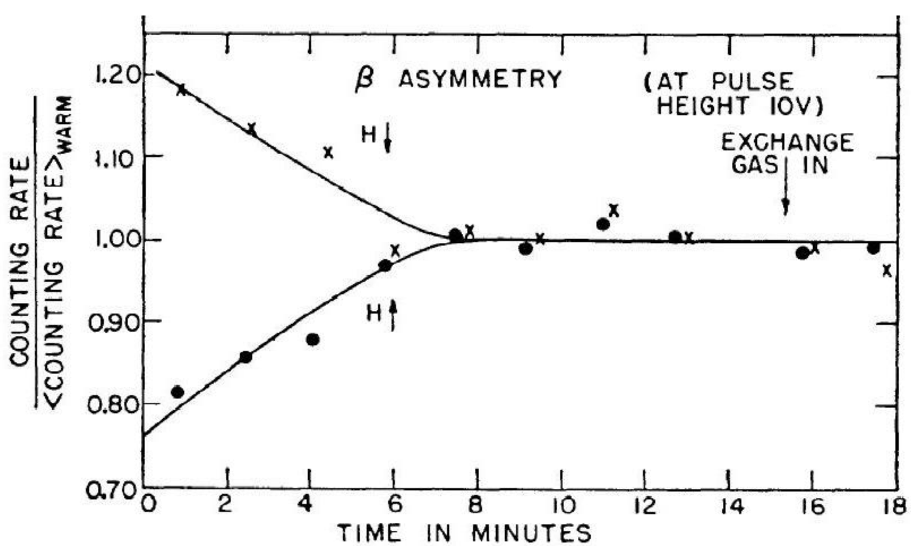
Schematic overview of the Co^{60} experiment

- β decay : $Co^{60}\ (J=5) \rightarrow Ni^{60*}\ (J=4)\, e^- \bar{\nu}_e$ $\quad n \rightarrow p\, e^- \bar{\nu}_e$
- Wu's experiment :
  - The spin of the Co^{60} atoms are aligned by a magnetic field
  - Operate at low temperature T = 0.01 K
  - Use scintillator to record the direction of the emitted electrons



Result of the experiment: the e^- are preferentially emitted in the direction opposite to the Co spin (asymmetry)

IF P is conserved, these two configurations should have the same probability



The magnetic field direction is changed and the rate for the electrons emission is measured in the two configurations. The asymmetry is reversed.

Parity is violated by the weak interaction

Goldhaber *et al*

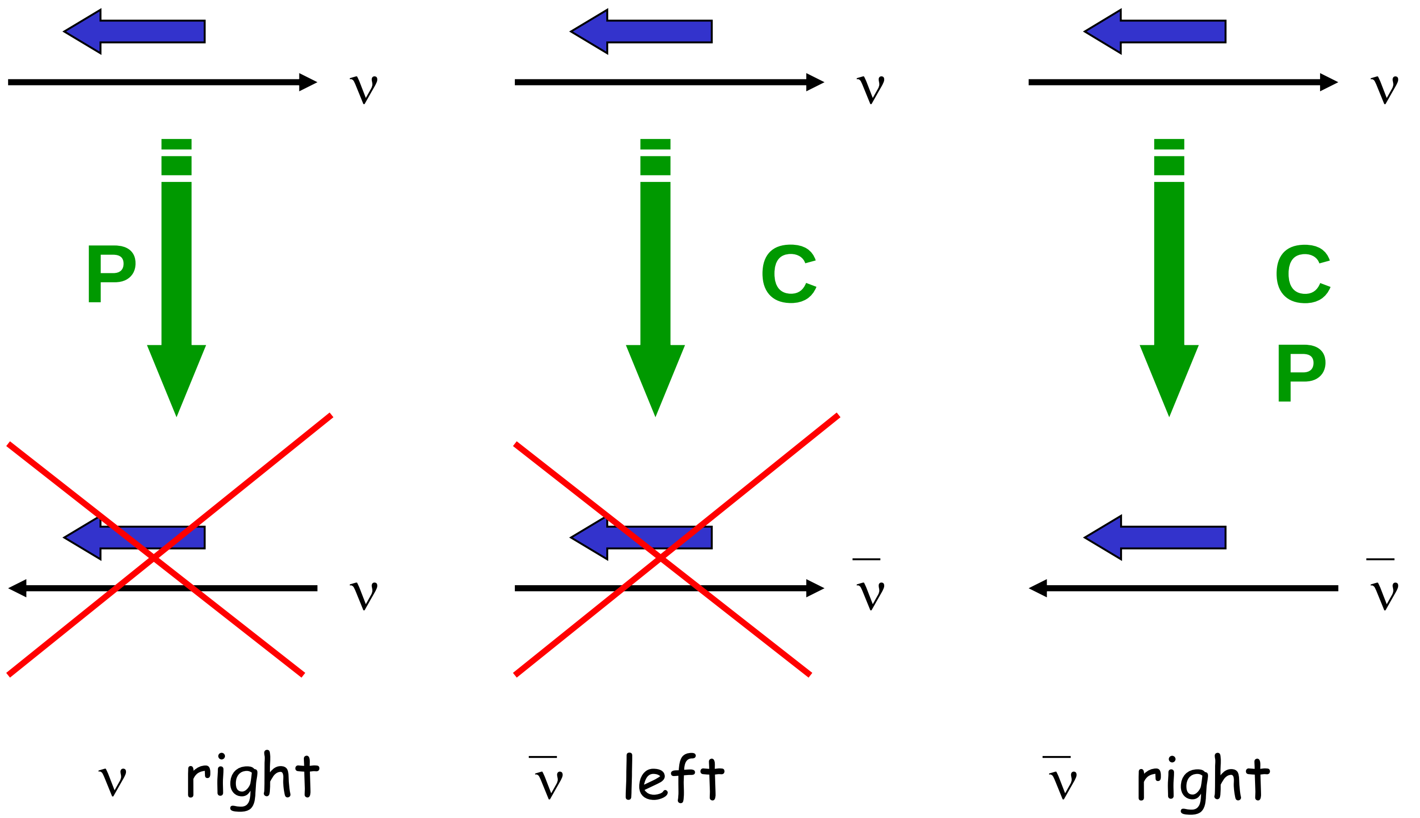
Phys. Rev. 109, 1015-1017 (1958)

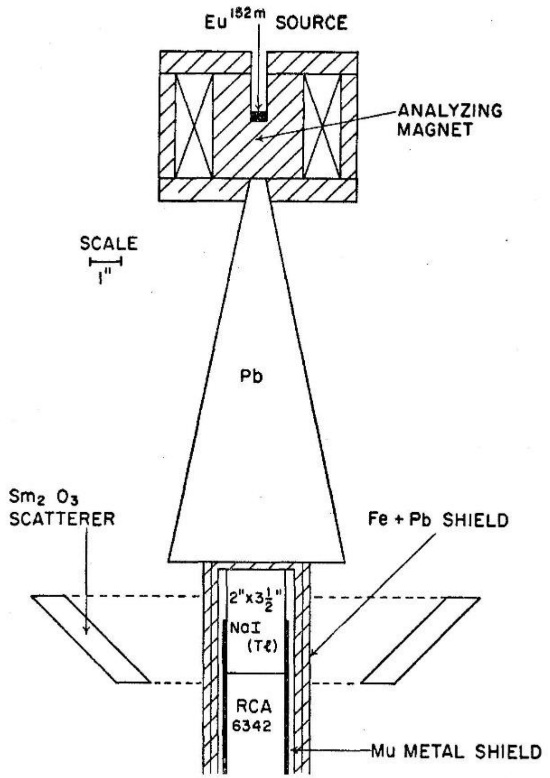
$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu$$

(K capture)

$$\hookrightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma$$

- Neutrino helicity probed by measuring photon helicity using magnetic material
- ***C*** and **P** automatically violated in weak decays involving neutrinos





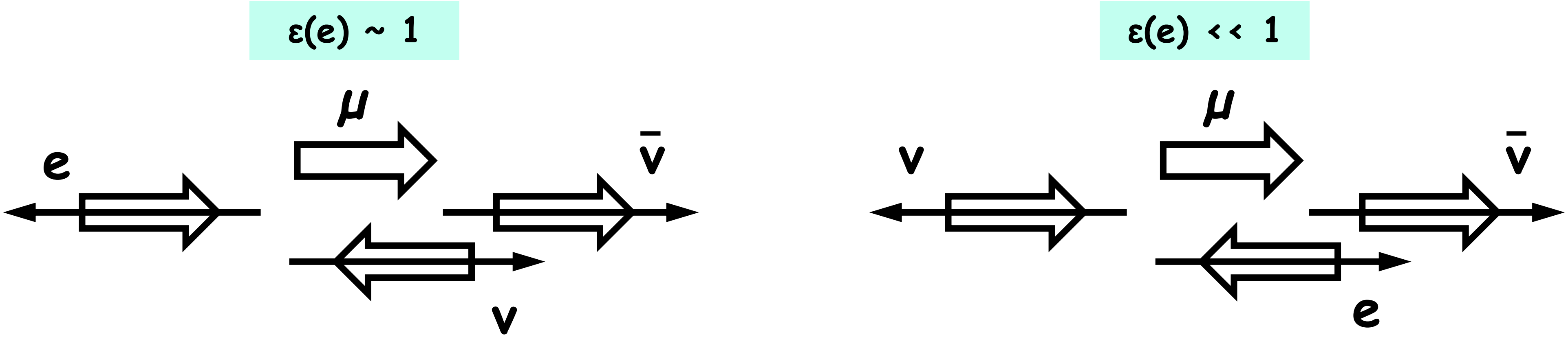
- Thus the anti-particles helicity is the opposite to the particles helicity.

The ν is left handed (the anti-neutrino is right handed)

P and C Violation in Weak Interactions

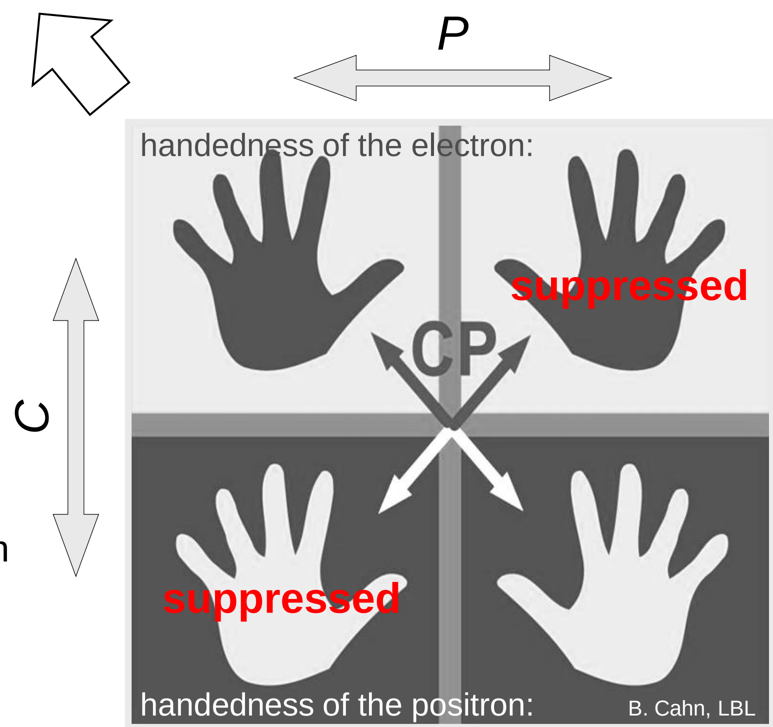
- Weak interaction violates both C and P symmetries
- Consider the collinear decay of a polarized muon: $\mu^-_{\text{polarized}} \rightarrow e^- + \nu_\mu + \bar{\nu}_e$

Angular asymmetry in muon decay



The preferred emission direction of the light left-handed electron is opposite to the muon polarization.

Similar situation for C transformation (i.e. replace all particles with their antiparticles).



P transformation (i.e. reversing all three directions in space) yields constellation that is suppressed in nature.

Applying CP, the resulting reaction—in which an antimuon preferentially emits a positron in the same direction as the polarization—is observed.

The *CPT* theorem (1954): "Any Lorentz-invariant local quantum field theory is invariant under the successive application of *C*, *P* and *T*"

proofs: G. Lüders, W. Pauli; J. Schwinger

(Lorentz invariance and the Principle of locality in the interaction of quantum fields)

$$CPT = 1$$

Consequences of CPT symmetry :

- **CP-violation = T-violation**
- A **"mirror-image" of our universe** —

objects having their positions P-reflected,

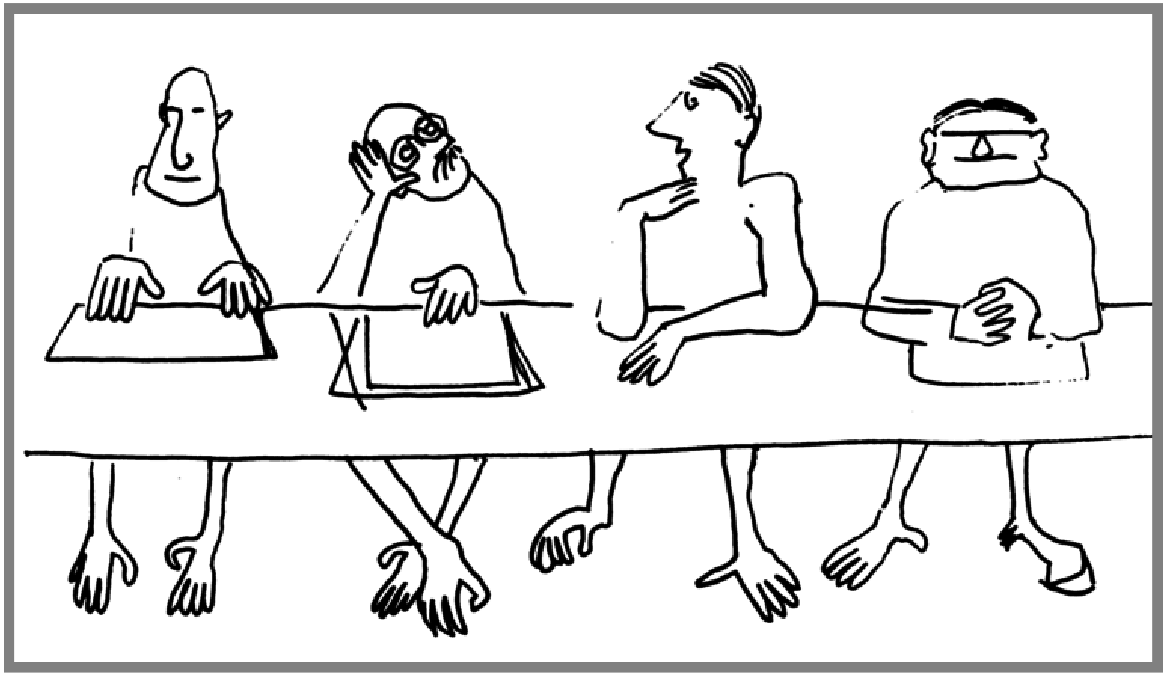
momenta reversed (corresponding to a T-inversion),

matter replaced by anti-matter (corresponding to a charge inversion)

— would **evolve under exactly the same physical laws**.

The CPT transformation turns our universe into its "mirror image" and vice versa.

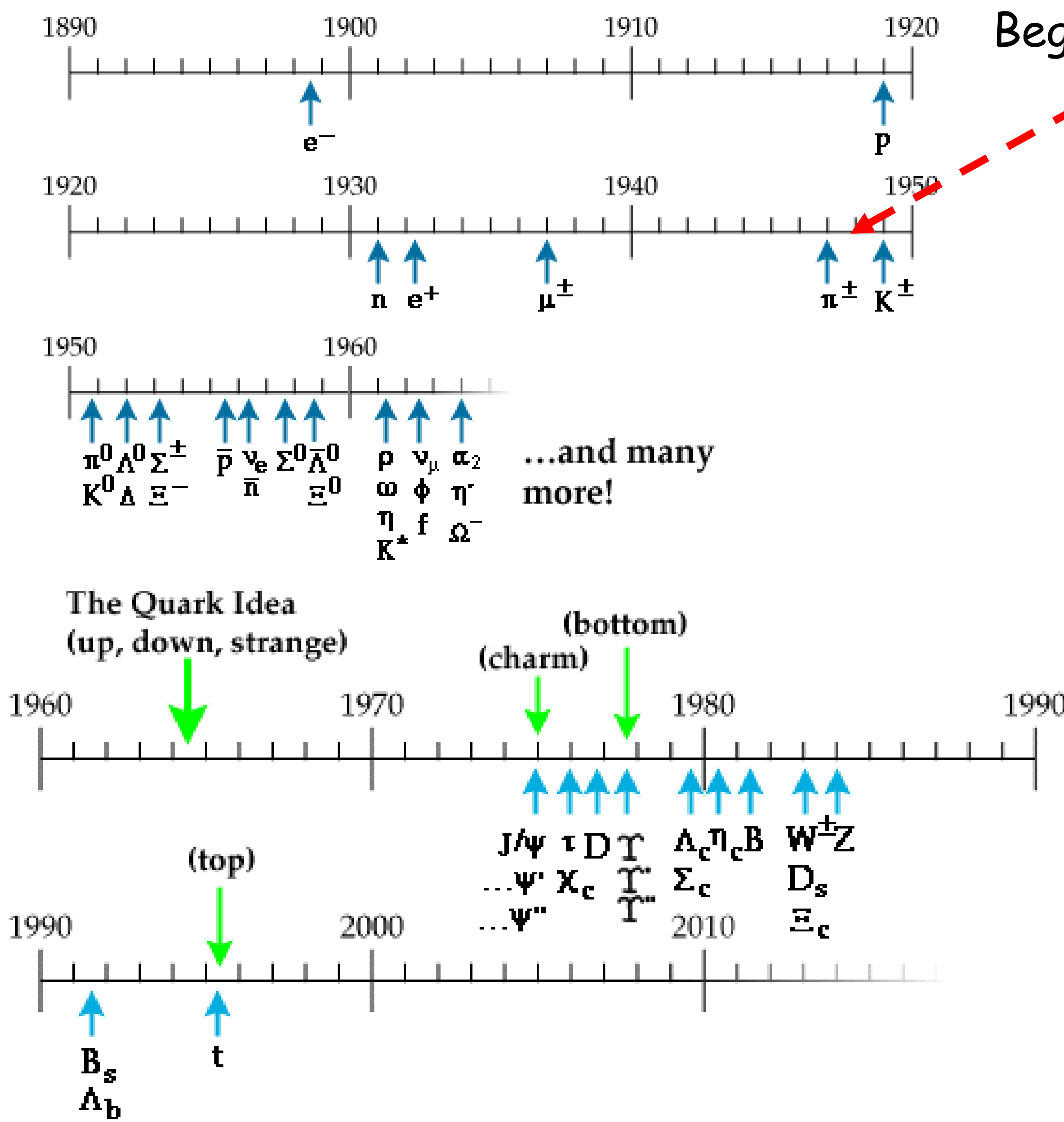
Flavour physics



Bruno Touschek

- Fundamental role of strange particles in the development of flavour physics.

Beginning of flavour physics



- The strangeness is the quantum number associated to a new quark :

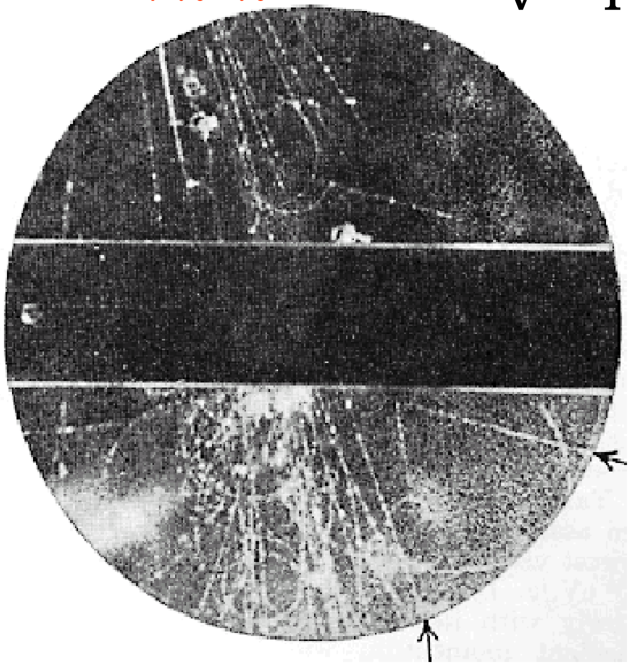
the strange quark s

Bubbles Chamber ~1947

1955 Walker *et al* (Berkeley)

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

V - Particle

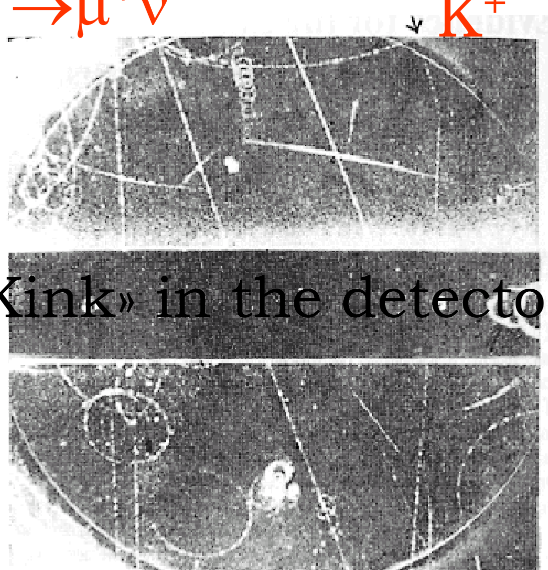


π^+

π^-

$K^+ \to \mu^+\nu$

K^+



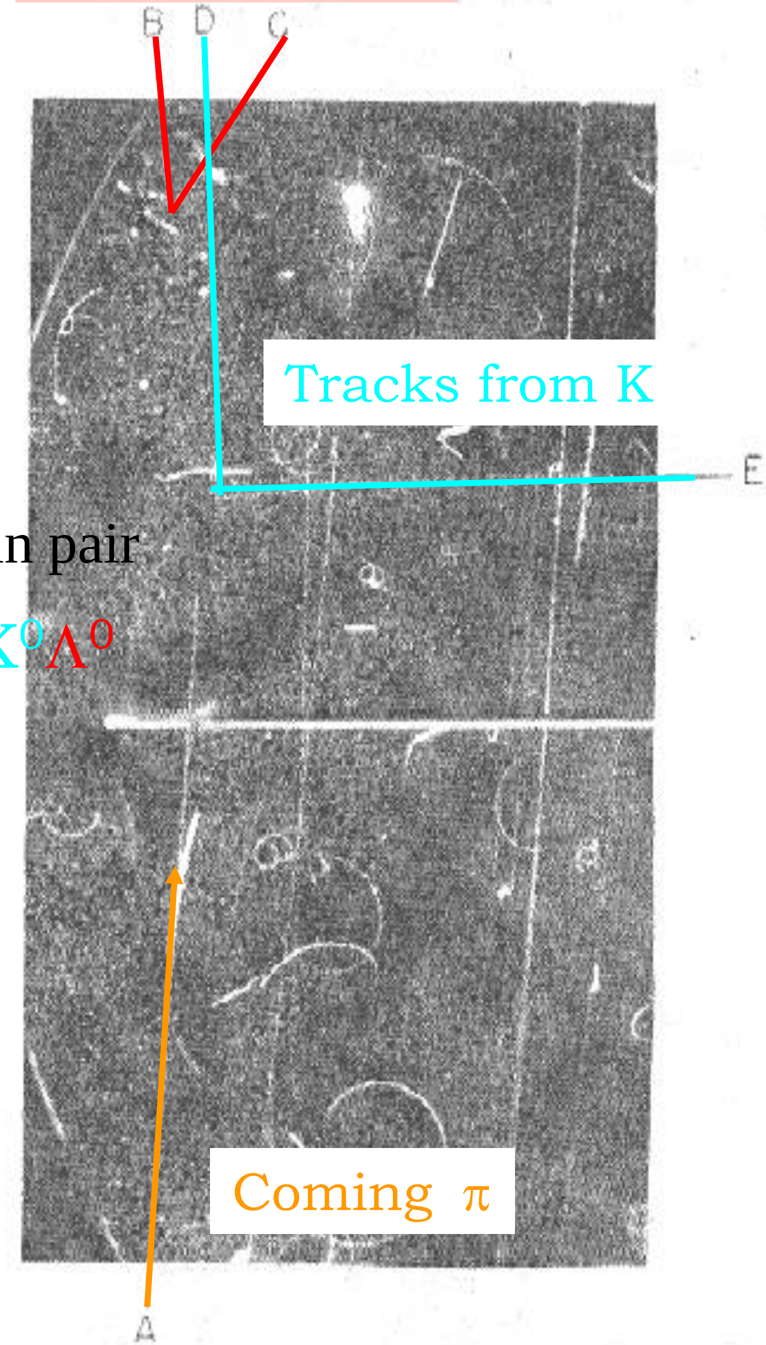
«Kink» in the detector

μ^+

Tracks from Λ

Tracks from K

Coming π



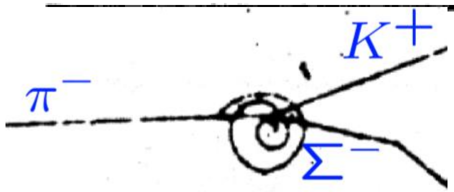
Produced in pair

$\pi^- \; p \to K^0 \Lambda^0$

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 86, NO. 5 JUNE 1, 1952



"V particle": particles that are produced in pairs and thus leaves a 'v' trial in a bubble chamber picture

Some Remarks on the *V*-Particles*

A. PAIS
Institute for Advanced Study, Princeton, New Jersey

(Received January 22, 1952)

It is qualitatively investigated whether the abundance of *V*-particle production can be reconciled with their long lifetime by using only interactions of a conventional structure. This is possible, provided a *V*-particle is produced together with another heavy unstable particle (Sec. II). Two distinct groups of interactions are needed: for one, the coupling is strong (II); for the other, it is very weak (III). Two kinds of *V*-particles are considered, Fermions of mass $\sim 2200m$ and Bosons ($\sim 800m$). The arguments are somewhat different, according to whether the latter are nonpseudoscalar (III) or pseudoscalar (V). The competition with processes involving μ-mesons is discussed (IV). Possible connections with the τ-meson are commented on in Sec. V. The preliminary nature of the present analysis is stressed (VI).

Observations:

1. **High production cross-section**
2. **Long lifetime**

Conclusion:

must always be produced in pairs!

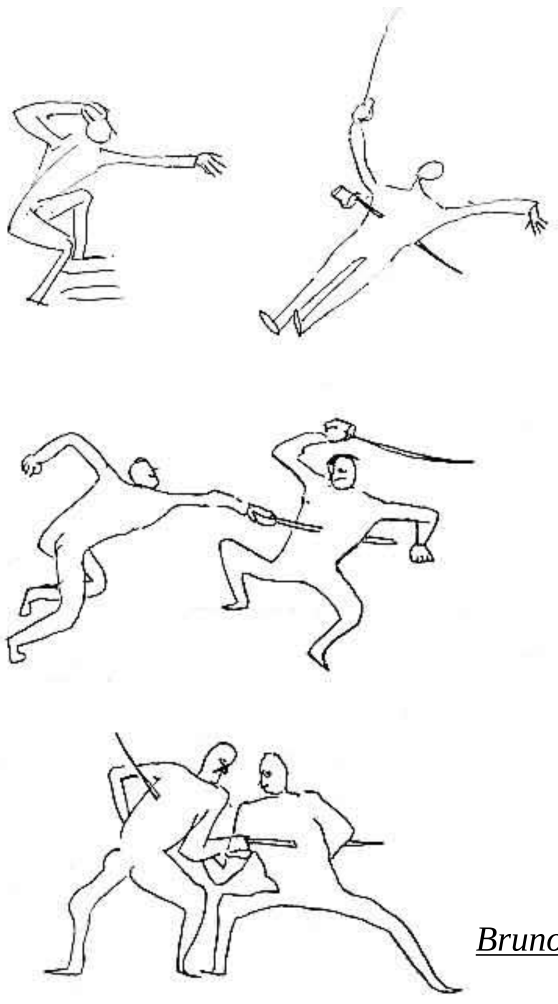
Details: create a new quantum number, "strangeness" which is conserved by the production process (pair production)

however, the decay must violate "strangeness"

if only weak force is "strangeness violating" then it is responsible for the decay process

hence (relatively) long lifetime…

Neutral kaons: CP parity and mixing



Bruno Touschek

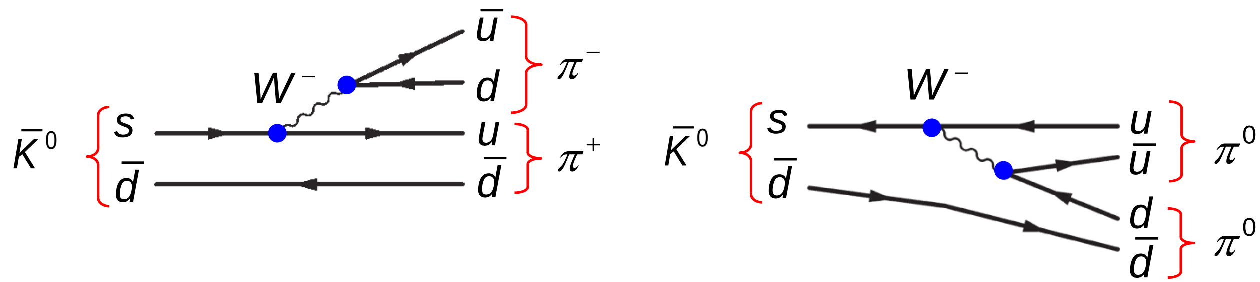
Neutral kaon decays into $\pi\pi$ and $\pi\pi\pi$ systems

Neutral kaons

$K^0 = d\bar{s}$ $\quad \bar{K}^0 = \bar{d}s$

Decays: $K \rightarrow \pi\pi$ and $K \rightarrow \pi\pi\pi$

Tree diagrams for
$K \rightarrow \pi\pi$ decay:



CP-counting

$\pi\pi$ system: $CP(\pi^0\pi^0) = (CP(\pi^0))^2 = (-1)^2 = +1$

$CP(\pi^+\pi^-) = C(\pi^+\pi^-) \times P(\pi^+\pi^-) = (-1)^l \times (-1)^l = +1,$

l – orbital momentum of the $\pi\pi$ system

$\pi\pi\pi$ system: $CP(\pi^0\pi^0\pi^0) = -1$

$CP(\pi^+\pi^-\pi^0) = (-1)^{l+1}$

CP parity of **K^o and $\bar{K}^o$** not defined …

$CP|K^0\rangle = |\bar{K}^0\rangle$

$CP|\bar{K}^0\rangle = |K^0\rangle$

… but defined for linear superposition …

$K_1 = \dfrac{K^0 + \bar{K}^0}{\sqrt{2}} \qquad K_2 = \dfrac{K^0 - \bar{K}^0}{\sqrt{2}}$

$CP|K_1\rangle = +|K_1\rangle \qquad CP|K_2\rangle = -|K_2\rangle$

➔ **Favoured are $K_1 \rightarrow \pi\pi$ and $K_2 \rightarrow \pi\pi\pi$**

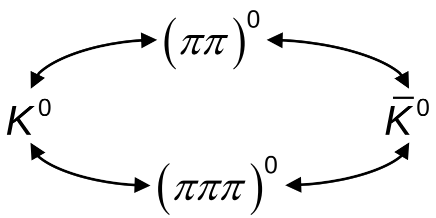
Probability($K_1 \rightarrow \pi\pi$) / Probability($K_2 \rightarrow \pi\pi\pi$) ~ 1000

$\tau \sim 10^{-11}$ s $\qquad \tau \sim 5 \times 10^{-8}$ s

correspond to K_S and K_L mass eigenstates

Neutral kaons can "mix" through the charged weak current, which does not conserve strangeness, and neither *P* nor *C*. **Weak interaction cannot distinguish** K^0 **from** $\bar{K}^0$

Simple picture: they mix through common virtual states:



Mass difference:

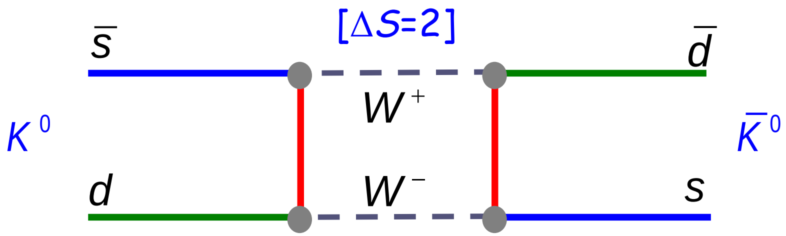
$$\Delta m = m1 - m2 = \langle K1|H|K1\rangle - \langle K2|H|K2\rangle = \left\langle \frac{K^0 + \bar{K}^0}{\sqrt{2}} \right| H \left| \frac{K^0 + \bar{K}^0}{\sqrt{2}} \right\rangle - \left\langle \frac{K^0 - \bar{K}^0}{\sqrt{2}} \right| H \left| \frac{K^0 - \bar{K}^0}{\sqrt{2}} \right\rangle$$

$$= \langle K^0|H|\bar{K}^0\rangle + \langle \bar{K}^0|H|K^0\rangle$$

$$\Delta m = 3.5 \times 10^{-12} \text{ MeV}$$

➔ **Mass difference is due to transitions $K^0 \leftrightarrow \bar{K}^0$**

These oscillations are described by ΔS = 2 Feynman "box" diagrams:



- An initially pure K^0 state will evolve into a superposition of states: $|K(t)\rangle = g(t)|K^0\rangle + h(t)|\bar{K}^0\rangle$

- The **time dependence** is obtained by solving the time-dependent Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|K^0(t)\rangle \\ |\bar{K}^0(t)\rangle\end{pmatrix} = \left(M - \tfrac{i}{2}\Gamma\right)\begin{pmatrix}|K^0(t)\rangle \\ |\bar{K}^0(t)\rangle\end{pmatrix}$$

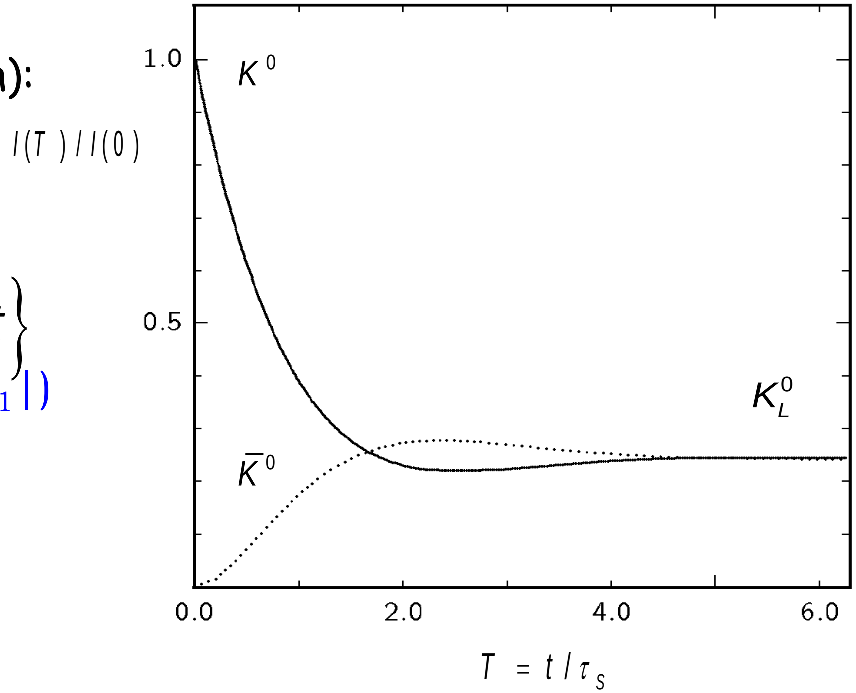
with 2x2 matrices M, Γ

off-diagonals ~ Δm, $\Delta\Gamma$ govern the mixing

- If having pure K^0 sample at T=0, the respective time-dependent intensities (neglecting CP violation):

$$I(|K^0\rangle) = \frac{1}{4}\left\{e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-[(\Gamma_S+\Gamma_L)/2]t}\cos\Delta m t\right\}$$

$-$ for $\bar{K}^0$ $\quad (\Delta m = |m_2 - m_1|)$

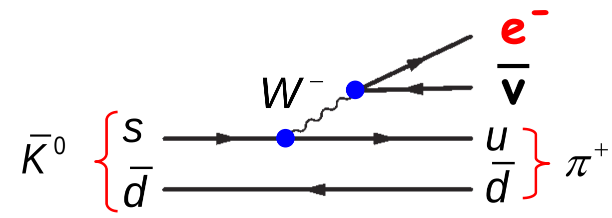


- **After several K_S lifetimes, only K_L are left**

- **Flavor eigenstates** distinguishable when produced via strong or EM interaction ("s" conserved)
  E.g. : pure K^0 beam (**at production**) from $\pi^- + p \rightarrow \Lambda + K^0$

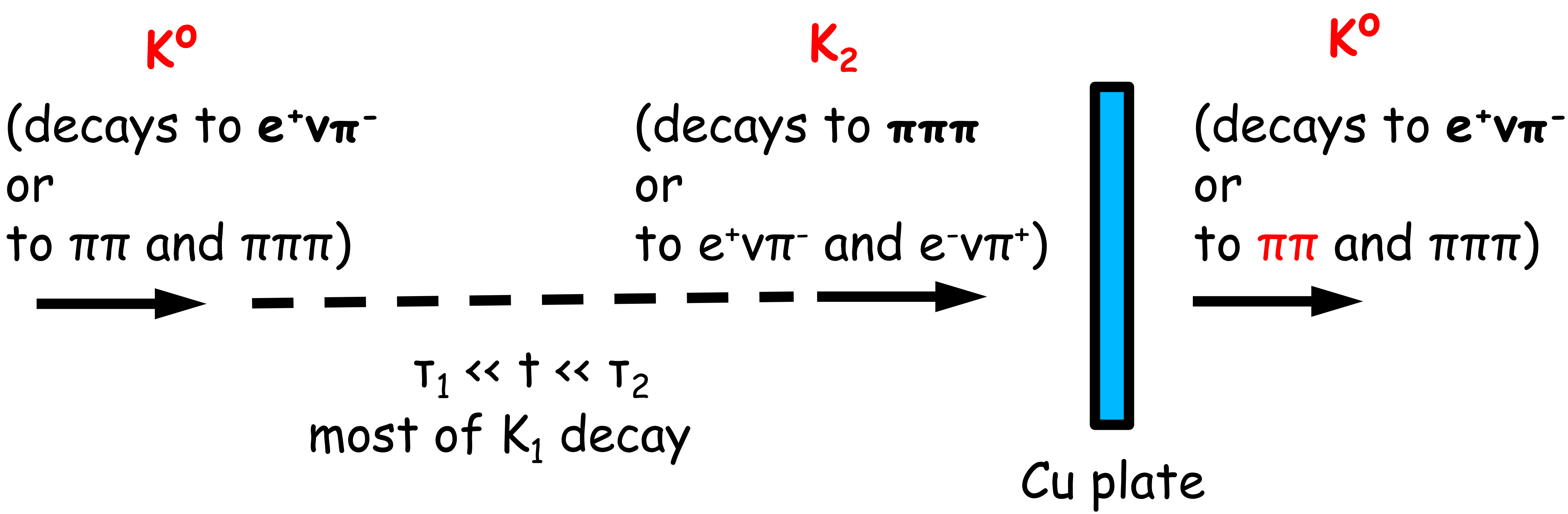
  K flavour tagging at decay: $K^0 \rightarrow e^+ \nu \pi^-$ $\bar{K}^0 \rightarrow e^- \bar{\nu} \pi^+$

  or in matter plane : $\bar{K}^0 + p \rightarrow \Lambda + \pi^+$



- **CP eigenstates are distinguishable by their decay into ππ or πππ system**
- **Weak and CP eigenstates are NOT defined simultaneously**

- Difference of strong interactions for K^0 and $\bar{K}^0$: **regeneration** effect observed.

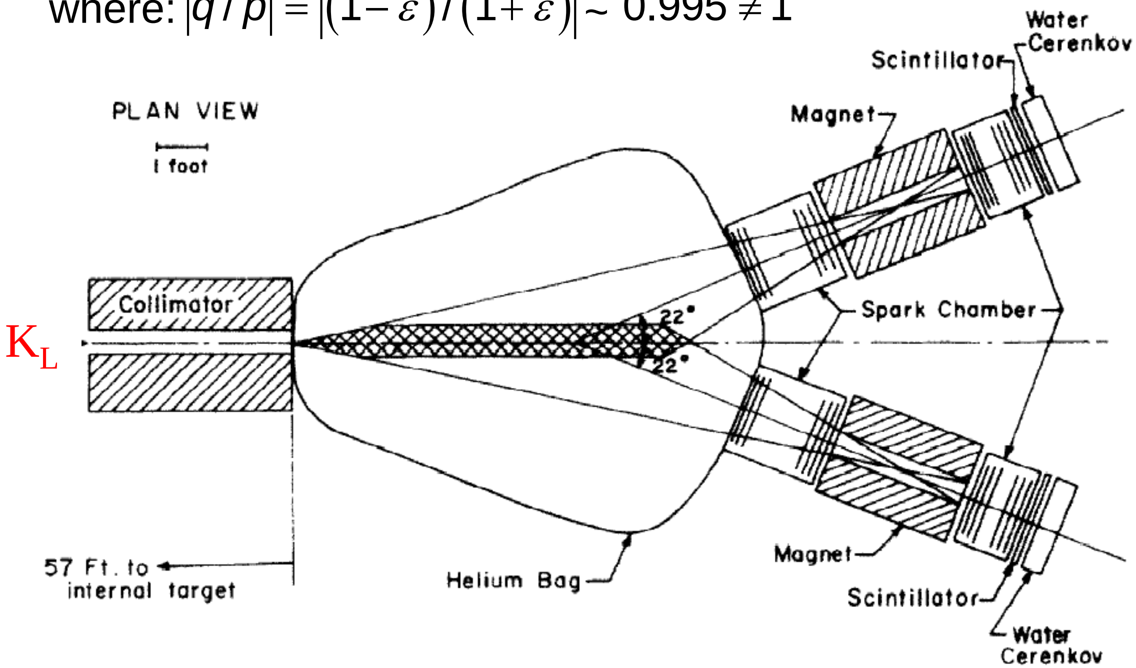


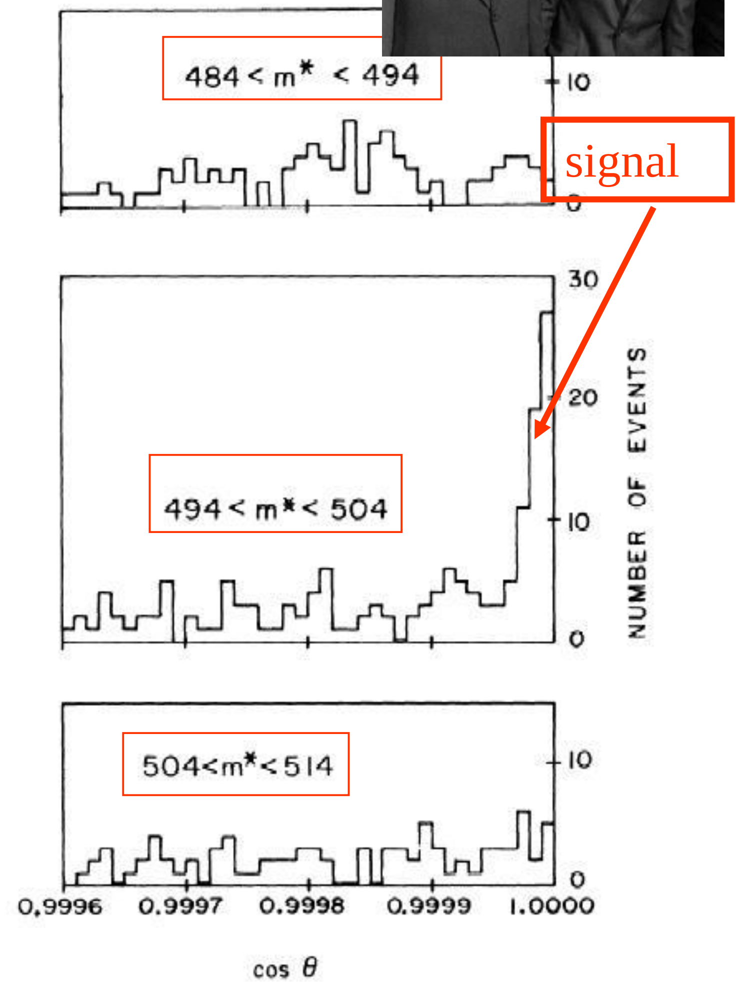
Discovery by Cronin, Fitch et al., 1964, the CP-violating decay: $K_L \rightarrow 2\pi$

- If there is CP violation, the **mass eigenstates are not exactly** the **CP eigenstates**:

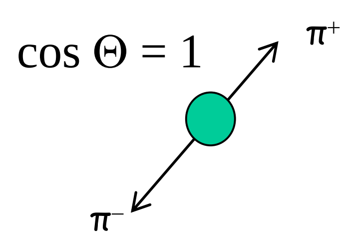
$$\begin{pmatrix} |K_S\rangle \\ |K_L\rangle \end{pmatrix} = \frac{1}{\sqrt{1+|\varepsilon|^2}} \begin{pmatrix} |K_1\rangle + \varepsilon|K_2\rangle \\ -\varepsilon|K_1\rangle + |K_2\rangle \end{pmatrix} = \sqrt{\frac{1}{2}} \begin{pmatrix} p & q \\ p & -q \end{pmatrix} \circ \begin{pmatrix} |K^0\rangle \\ |\bar{K}^0\rangle \end{pmatrix}$$

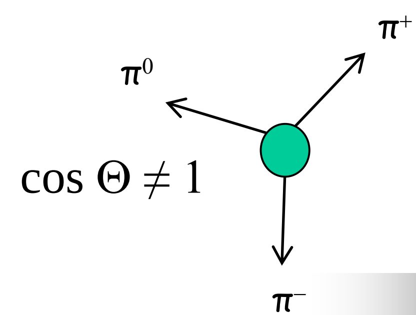
where: $|q/p| = |(1-\varepsilon)/(1+\varepsilon)| \sim 0.995 \neq 1$





- 2-body decay : the two π are back-to-back: $|\cos\Theta| = 1$





- Level of CP violation :

$$|\eta_{+-}| = \frac{A(|K_L^0\rangle \rightarrow 2\pi)}{A(|K_S^0\rangle \rightarrow 2\pi)} = (2.27 \pm 0.02)10^{-3}$$

The Discovery of *CP* Violation in the Decay

- To allow for (*small*) direct CPV modify previous definitions:

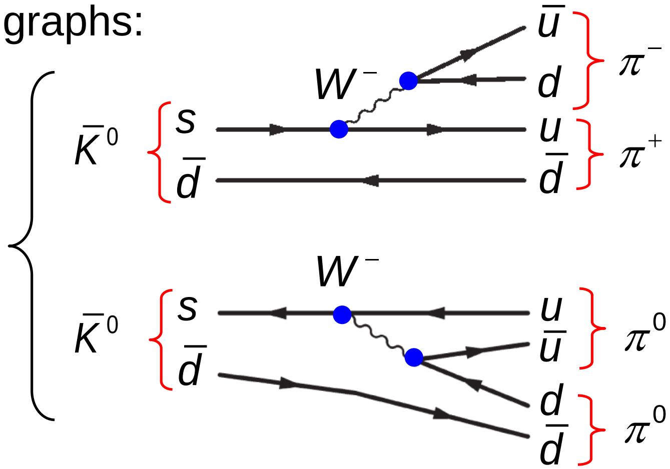
$$|\varepsilon+\varepsilon'|^2=\frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_S\to\pi^+\pi^-)}$$

$$\frac{\Gamma(K_L\to\pi^0\pi^0)}{\Gamma(K_S\to\pi^0\pi^0)}\Bigg/\frac{\Gamma(K_L\to\pi^+\pi^-)}{\Gamma(K_S\to\pi^+\pi^-)}=\left|\frac{\varepsilon-2\varepsilon'}{\varepsilon+\varepsilon'}\right|^2\sim 1-6\times\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

The observable

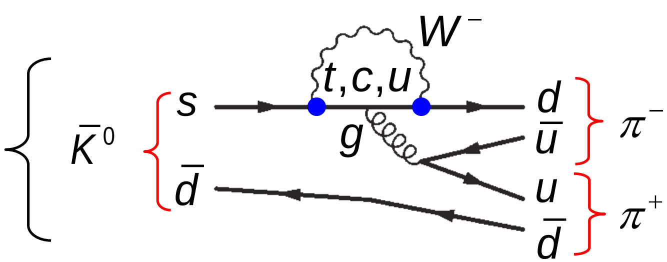
- Feynman graphs:

"Tree" (born-level) amplitudes



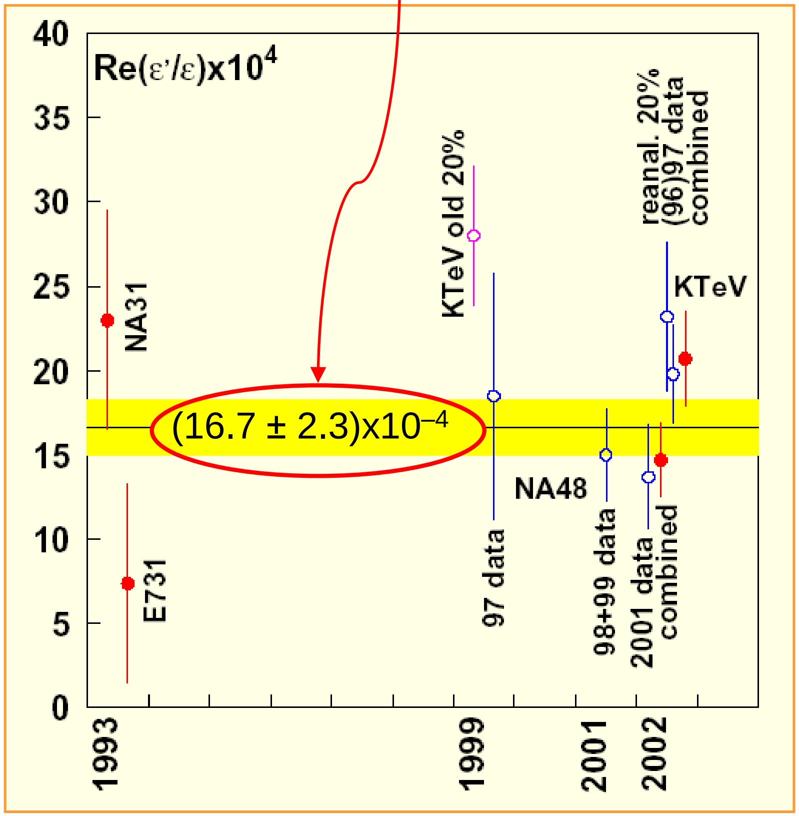
Interference

"Penguin" (loop-level) amplitude



Experimental average

Indeed, a *very* small CPV effect !



Three types of *CP* violation

- The *CP* violation discovered by Cronin, Fitch *et al*. involves two types of CPV:
  - *CP* Violation in mixing:

$$\text{Prob}(K^0 \to \bar{K}^0) \neq \text{Prob}(\bar{K}^0 \to K^0)$$

  - *CP* Violation in interference between decays with and without mixing:

$$\text{Prob}(K^0(t) \to \pi^+\pi^-) \neq \text{Prob}(\bar{K}^0(t) \to \pi^+\pi^-)$$

} indirect CPV

- Conceptually "simpler" *CP* violation:
  - *CP* Violation in the decay:

$$\text{Prob}(K \to f) \neq \text{Prob}(\bar{K} \to \bar{f})$$

} direct CPV

Always two different paths !

as in the double-slit experiment