Lectures 1 & 2

The Violation of Symmetry between Matter and Antimatter

Andreas Höcker

CERN

CERN Summer Student Lectures, August 5 – 7, 2008

M.C. Escher

Lectures 1 & 2

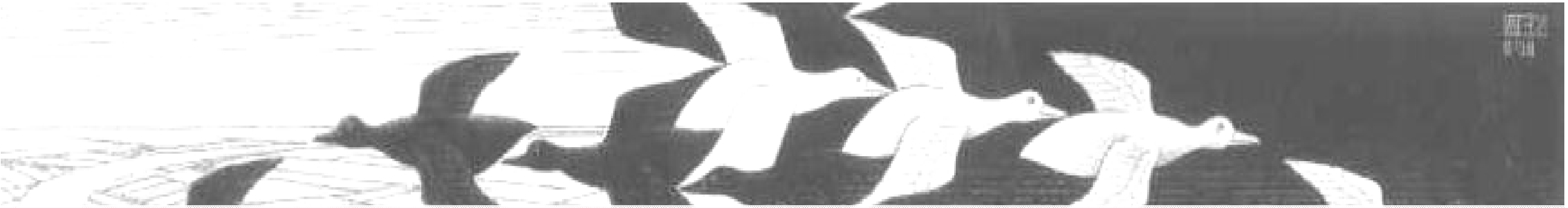
CP Violation

Andreas Höcker

CERN

CERN Summer Student Lectures, August 5 – 7, 2008

M.C. Escher

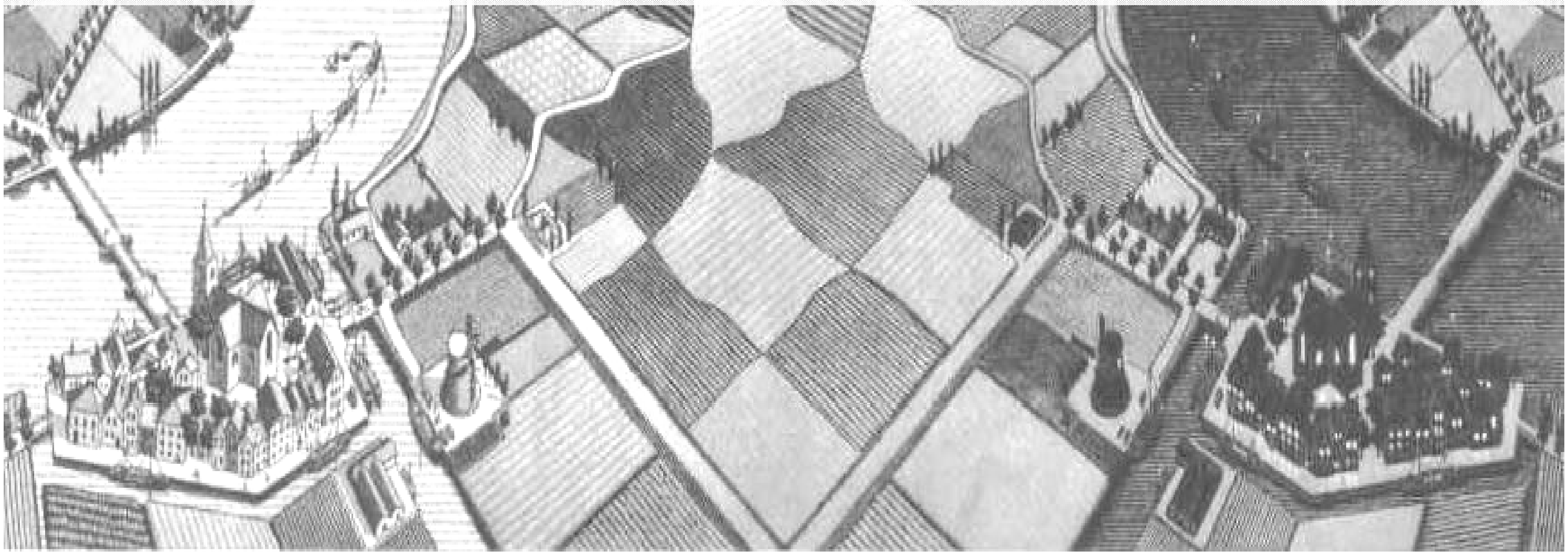


A definition, which we will understand later in this lecture:

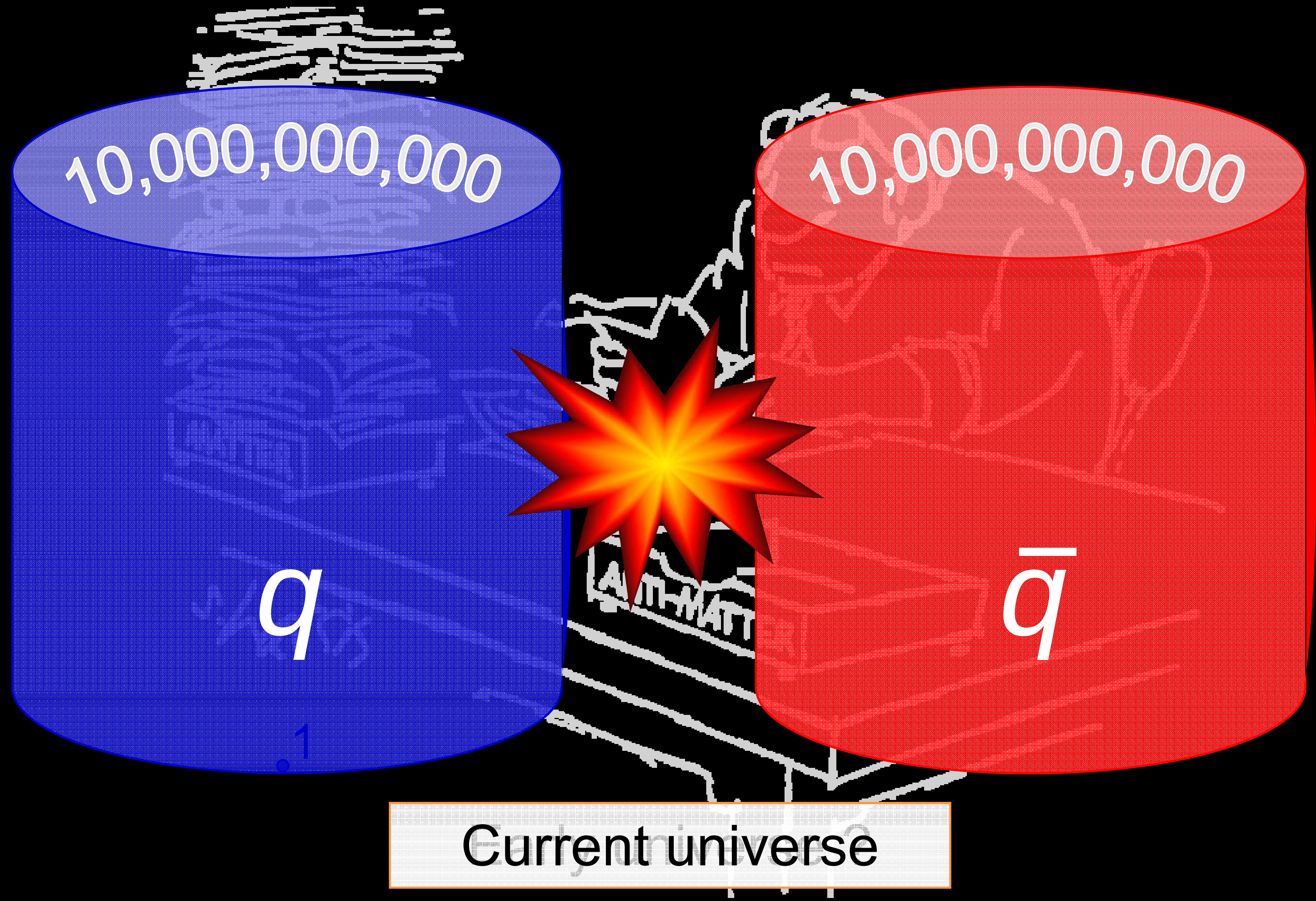
The **matter-antimatter symmetry** violation

in physics reactions corresponds to the breaking of the

so-called *CP* symmetry ➔ ***C·P* Violation**



Matter-Antimatter Asymmetry



Sakharov Conditions

[(*)] Bigi-Sanda, *CP* Violation, 2000

- The Universe is not empty* !
- The Universe is almost empty* !

$$\frac{n_{\text{baryon}} - n_{\overline{\text{baryon}}}}{n_\gamma} \approx \frac{n_{\text{baryon}}}{n_\gamma} \sim O\left(10^{-10}\right)$$

Sakharov conditions (1967) for Baryogenesis

1. Baryon number violation
2. *C* and *CP* violation
3. Departure from thermodynamic equilibrium (non-stationary system)

So, if we believe to have understood CPV in the quark sector, and **if** it cannot account for the observed baryon asymmetry … what does it signify ?

A sheer **accident of nature** ?

What would be the **consequence** of a **different** value for the **CKM phase** ?

Much is Strange Out There …

Note: ring is not necessarily due to dark matter !

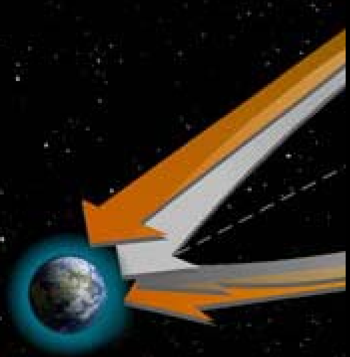
Hubble space telescope picture of Cluster ZwCl0024+1652

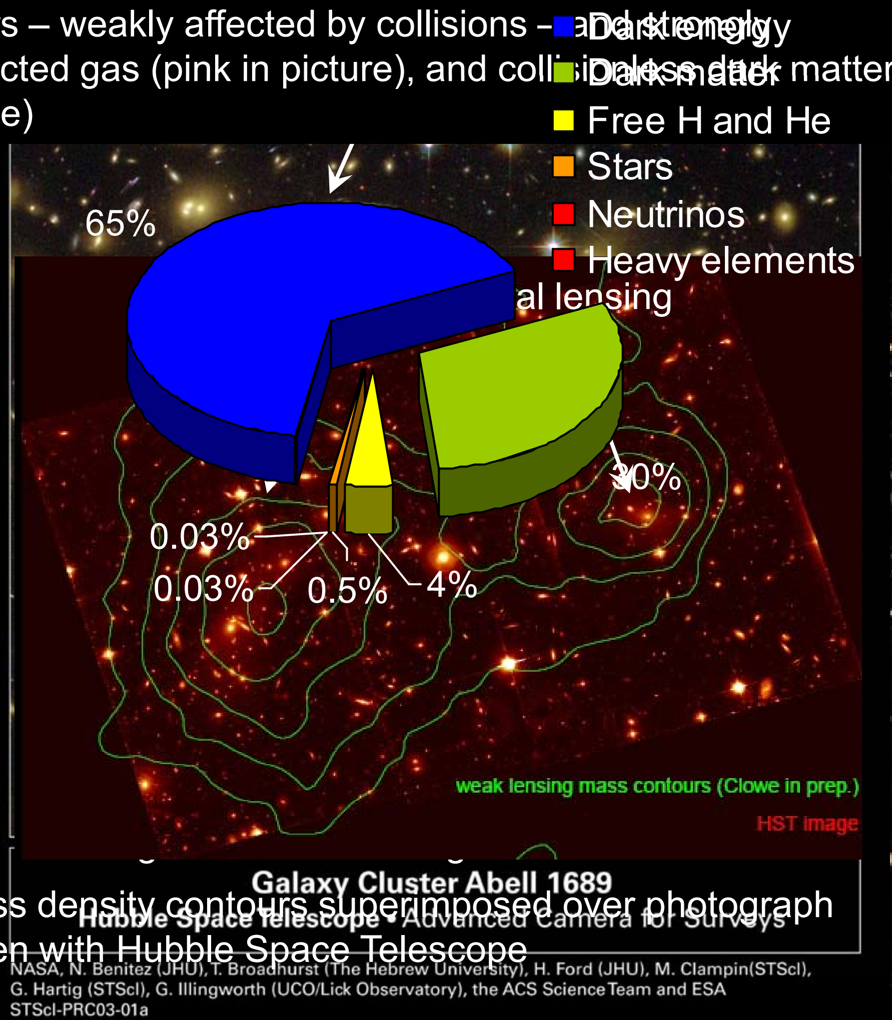
Image: NASA, ESA, M.J. JEE AND H. FORD (Johns Hopkins University)

Much is Strange Out There …

- *Dark matter* does not emit or reflect sufficient electromagnetic radiation to be detected
- Evidence for dark matter stems from:
  - Gravitational lensing
  - Kinetics of galaxies
  - Anisotropy of cosmic microwave background (blackbody) radiation

Bullet cluster: Collision of galaxy clusters: baryonic matter, stars – weakly affected by collisions – and strongly affected gas (pink in picture), and collisionless dark matter (blue)





Mass density contours superimposed over photograph taken with Hubble Space Telescope

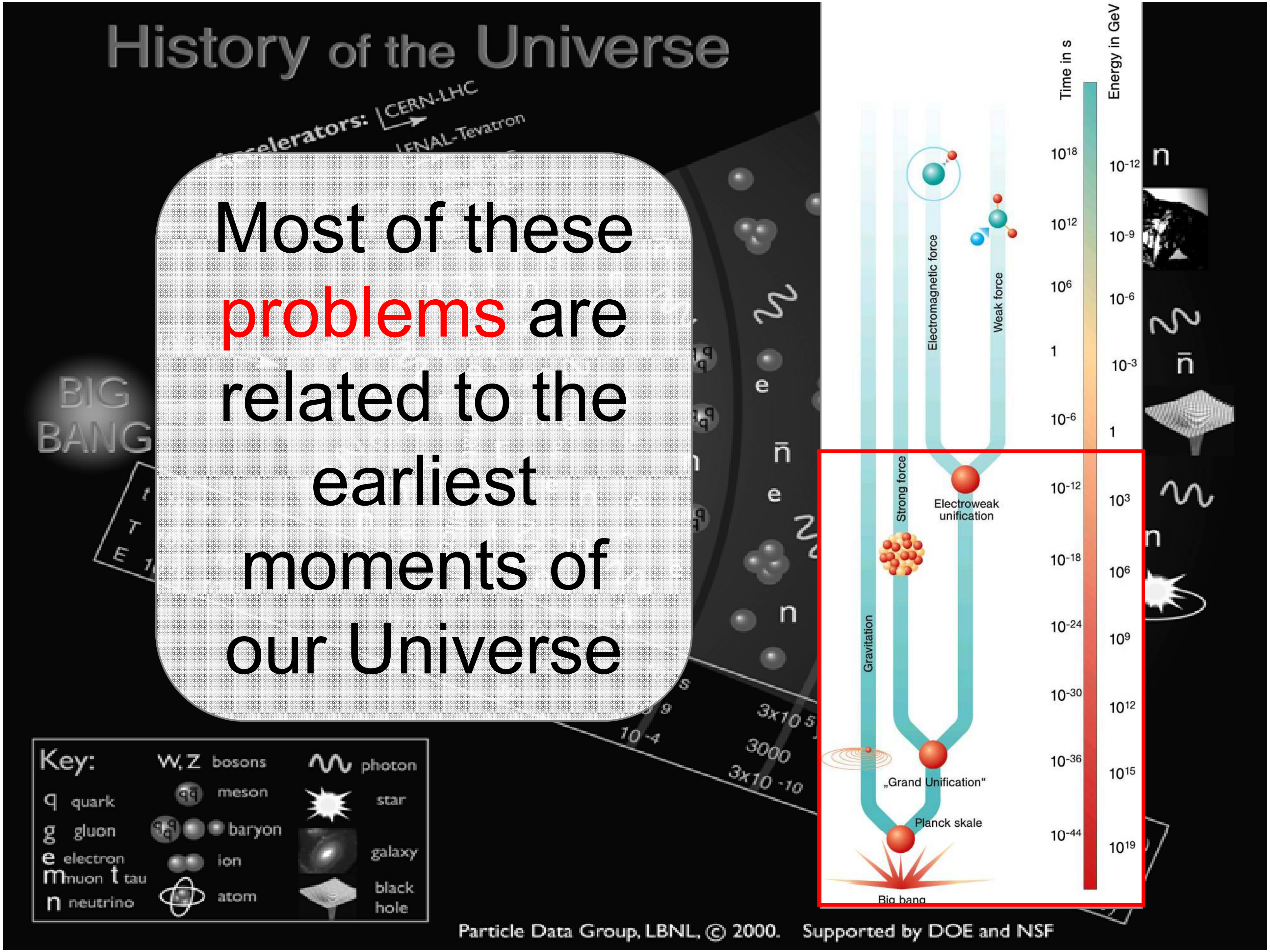
And: There is Much More Strangeness …

Empirical and Theoretical

Limitations of the

Standard Model

- Dark matter (and, perhaps, dark energy)
- Baryogenesis (CKM CPV too small)
- Grand Unification of the gauge couplings
- The gauge hierarchy Problem (Higgs sector, NP scale ~ 1 TeV)
- The strong *CP* Problem (why is $\theta \sim 0$?)
- Neutrino masses
- Gravitation



Most of these **problems** are related to the earliest moments of our Universe

The understanding of **matter-antimatter symmetry violation** is **crucial** if we want to move closer into the heart of the **Big Bang**

Lecture Themes

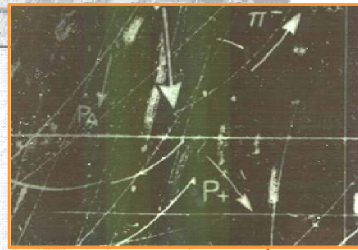
I. Introduction
- Antimatter
- Discrete Symmetries

II. The Phenomena of *CP* Violation
- Electric and weak dipole moments
- The strong *CP* problem
- The discovery of *CP* violation in the kaon system

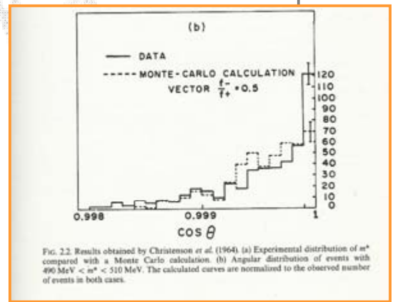
III. *CP* Violation in the Standard Model
- The CKM matrix and the Unitarity Triangle
- *B* Factories
- *CP* violation in the *B*-meson system and a global CKM fit
- Penguins

IV. *CP* Violation and the Genesis of a Matter World
- Baryogenesis and *CP* violation
- Models for Baryogenesis

digression: *CP* Violation, a Family History of Flavour

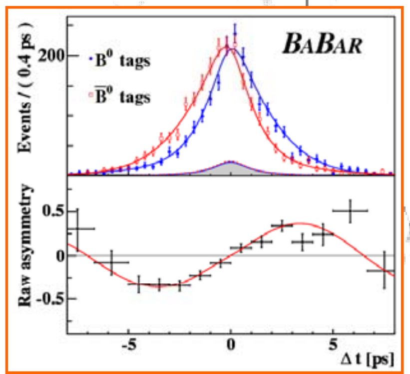


- Discovery of strange particles (Rochester, Butler) (1946-47)
- Neutral kaons can mix (Gell-Mann, Pais) (1952)
- K_L discovery (Lederman *et al.*) (1956)
- Parity (*P*) violation: possible explanation (Lee, Yang) (1956)
- *P* Violation found in β decay (Wu *et al.*) (1957)
  later: maximum *P* and *C* violation, but *CP* invariance
- Cabibbo-Theory (1963)
- **→ *CP* violation (CPV) discovered (Cronin, Fitch *et al.*) (1964)**
- GIM-Mechanism (Glashow, Illiopolous, Maiani) (1970)
- J/ψ Resonance: *c* quarks (Ting, Richter) (1974)



digression: CP Violation, a Family History of Flavour

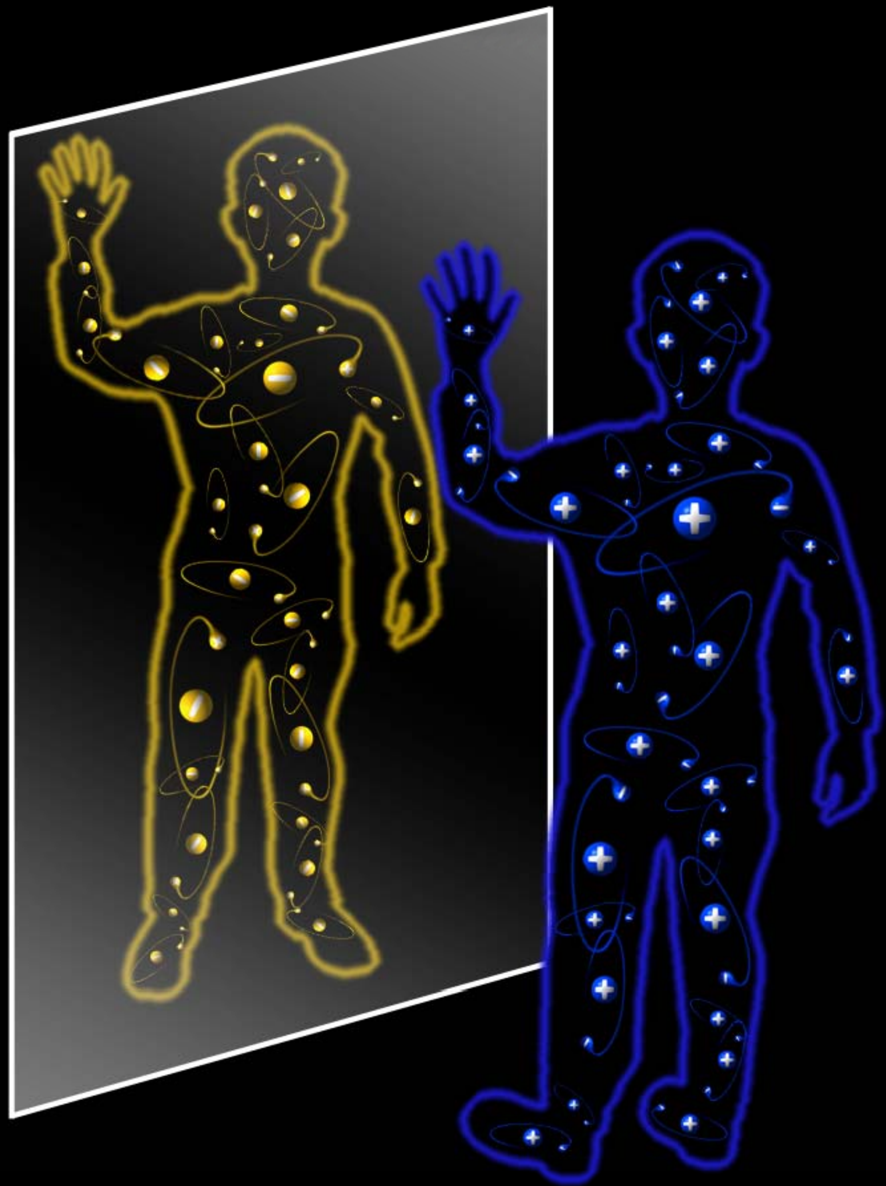
- CPV Phase requires 3 families (Kobayashi-Maskawa) (1973)
- Discovery of τ lepton: 3rd family (Perl et al.) (1975)
- Υ resonance: *b* quarks (Lederman *et al.*) (1977)
- Neutral B_d mesons mix (ARGUS) (1987)
- *t*-Quark discovery (CDF) (1995)
- ν-Oscillation discovery (Super-K) (1998)
- Direct *CP* violation in *K* system (NA31, NA48, KTeV) (1999)
- Start of B_d Factories: BABAR (PEP II), Belle (KEKB) (1999)
- **CPV in B_d system** : $\sin(2\beta) \neq 0$ **(BABAR, Belle)** **(2001)**
- Direct CPV in B_d system (BABAR, Belle) (2004)
- B_s mesons oscillate (CDF) (2006)
- D^0 mesons oscillate (BABAR & Belle) (2007)



Evolution of working conditions (example BABAR, discovery of *CP* violation in *B* system, 2001) :

… 623 physicists (in 2005).

BABAR: PRL 87, 091801 (2001)
Belle: PRL 87, 091802 (2001)

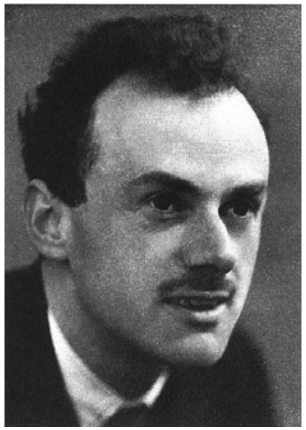


Through the Looking Glass

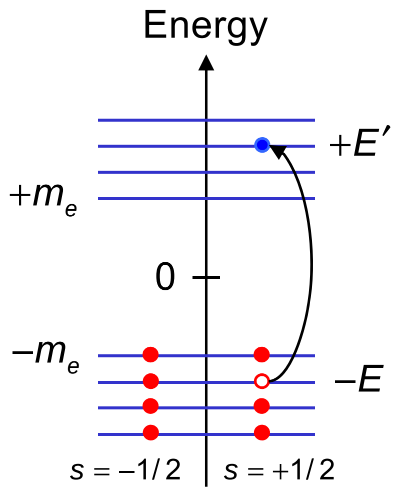
What's the Matter with Antimatter ?

David Kirkby, APS, 2003

Paul Dirac (1902 – 1984)



Dirac, imagining holes and seas in 1928



This picture fails for bosons !

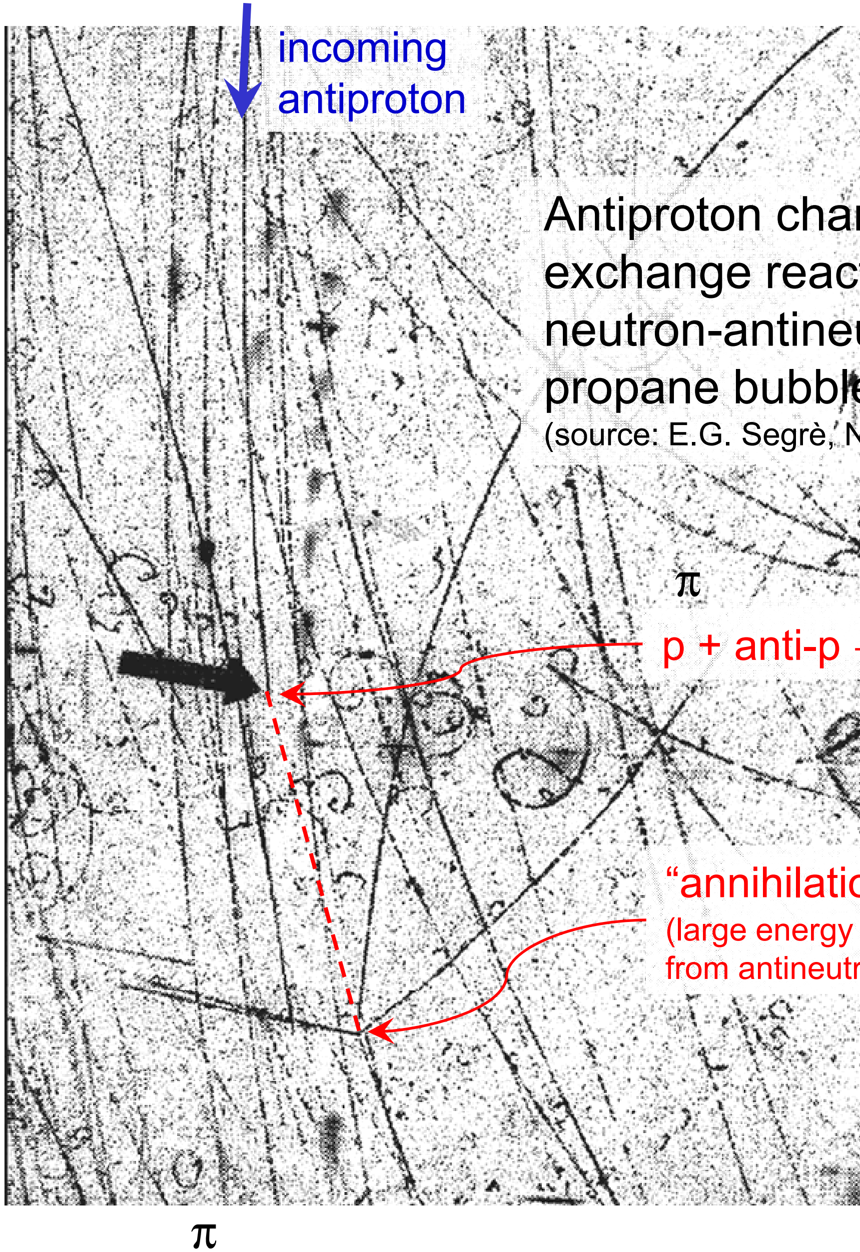
- Combining quantum mechanics with special relativity, and the wish to linearize $\partial/\partial t$, leads Dirac to the equation

$$i\gamma^{\mu}\partial_{\mu}\psi(x,t)-m\psi(x,t)=0 \qquad (1928)$$

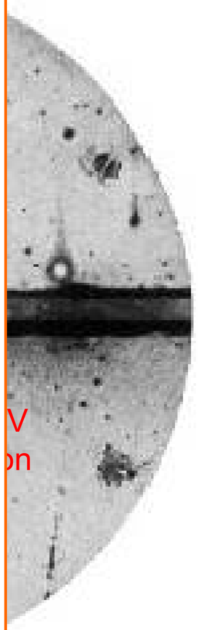
for which **solutions with negative energy** appear

- 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).

Antineutron discovery 1956



Antiproton charge-exchange reaction into neutron-antineutron pair in propane bubble chamber
(source: E.G. Segrè, Nobel Lecture)



D

H

H

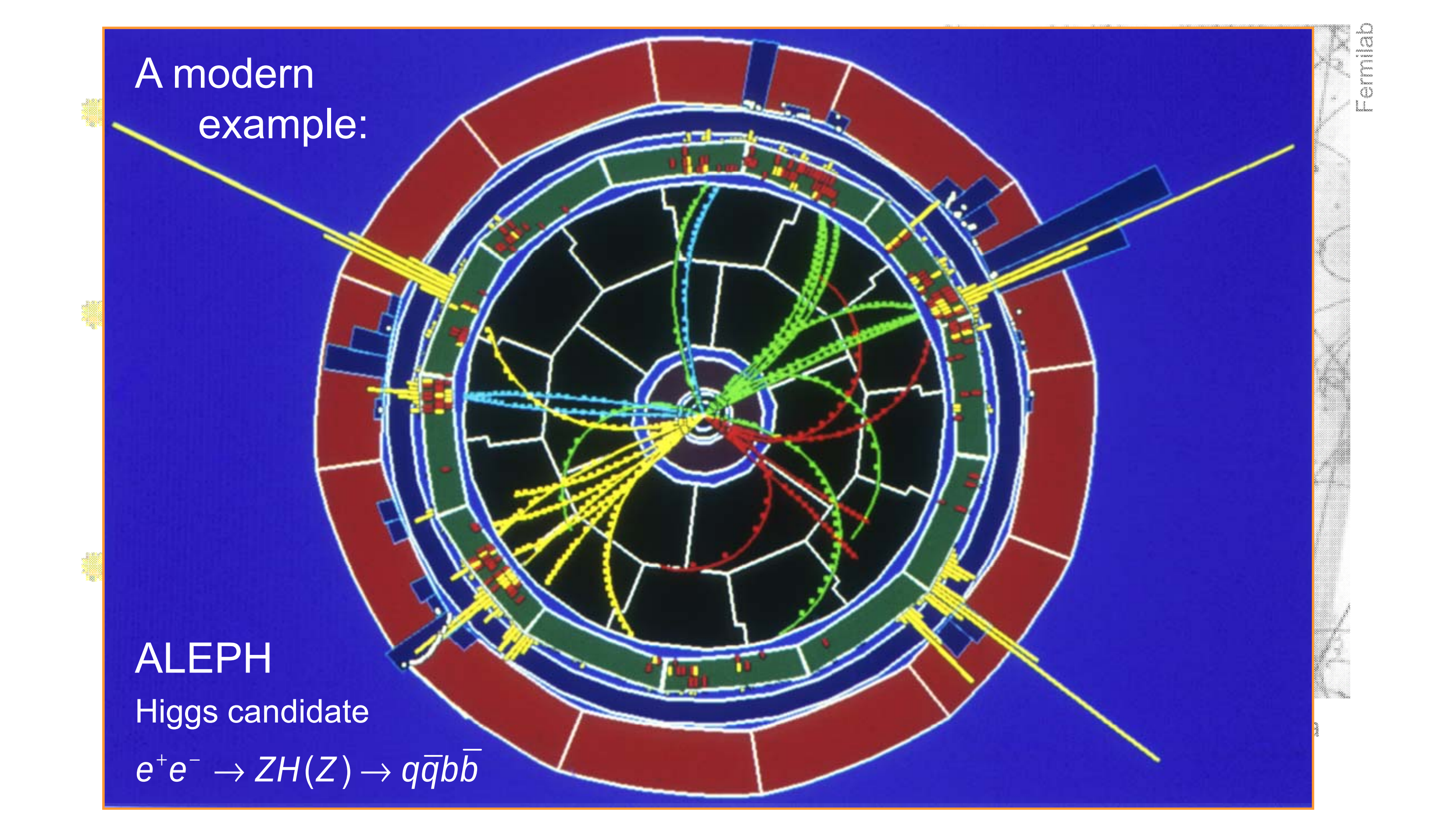
V

on

!

Particles and Antiparticles Annihilate

What happens if we bring particles and antiparticles together ?



Symmetries

A symmetry is a change of something that leaves the physical description of the system unchanged.

1. Physical symmetries:
   - People are approximately bilaterally symmetric
   - Spheres have rotational symmetries
2. Laws of nature are symmetric with respect to mathematical operations,
   that is: an observer cannot tell whether or not this operation has occurred

Pollen of the hollyhock exhibits spherical symmetry (magnification x 100,000)

Continuous Symmetries and Conservation Laws

- In classical mechanics we have learned that to each continuous symmetry transformation, which leaves the scalar Lagrange density invariant, can be attributed a conservation law and a constant of movement (E. Noether, 1915)

- Continuous symmetry transformations lead to additive conservation laws

Symmetry	Invariance under movement in time	Homogeneity of space	Isotropy of space
Transformation	Translation in time	Translation in space	Rotation in space
Conserved quantity	Energy	Linear momentum	Angular momentum

→ No evidence for violation of these symmetries seen so far

digression: Symmetry of Reference Systems

Another type of symmetry has to do with reference frames moving with respect to one in which the laws of physics are valid (inertial reference frames):

> Physical laws are unchanged when viewed in any reference frame moving at constant velocity with respect to one in which the laws are valid

- Note that while laws are unchanged between reference frames, quantities are not
- The fact that the laws of motion are unchanged between frames, plus the fact that the speed of light is always the same lead to the theory of *special relativity* with two consequences
  - Two events that are simultaneous in one reference frame are not necessarily simultaneous in a reference frame moving with respect to it
  - There are some quantities (called Lorentz scalars) that have values independent of the reference frame in which their value is calculated

Continuous Symmetries and Conservation Laws

In general, if U is a symmetry of the Hamiltonian H, one has: $[H,U]=0 \;\Rightarrow\; H=U^{\dagger}HU$

$$\langle f'|H|i'\rangle = \langle Uf|H|Ui\rangle = \langle f|U^{\dagger}HU|i\rangle = \langle f|H|i\rangle$$

- Accordingly, the Standard Model Lagrangian satisfies local gauge symmetries (the physics must not depend on local (and global) phases that cannot be observed):

U(1) gauge transformation	→	**Electromagnetic interaction**
SU(2) gauge transformation	→	**Weak interaction**
$SU(3)_C$ gauge transformation	→	**Strong interaction (QCD)**

- Conserved additive quantum numbers:
  - Electric charge (processes can move charge between quantum fields, but the sum of all charges is constant)
  - Similar: color charge of quarks and gluons, and the weak charge
  - Quark (baryon) and lepton numbers (however, no theory for these, therefore believed to be only approximate symmetries) → evidence for lepton flavor violation in "neutrino oscillation"

Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

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

- Time reversal ***T*** :

  The time arrow is reversed in the equations;
  T invariance → if a movement is allowed by a the physics law, the movement in the opposite direction is also allowed

$$C\left|d\right\rangle = \left|\bar{d}\right\rangle$$
$$C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$

Time reversal symmetry (invariance under change of time direction) does certainly not correspond to our daily experience. The macroscopic violation of *T* symmetry follows from maximising thermodynamic entropy (leaving a parking spot has a larger solution space than entering it). In the microscopic world of single particle reactions thermodynamic effects can be neglected, and *T* invariance is realised.

The *CPT* Theorem

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 (1954);
J. Schwinger (1951)
Derived from Lorentz invariance and the "principle of locality"

- Fundamental consequences:
  - Relation between spin and statistics: fields with integer spin ("bosons") commute and fields with half-numbered spin ("fermions") anticommute → Pauli exclusion principle
  - Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

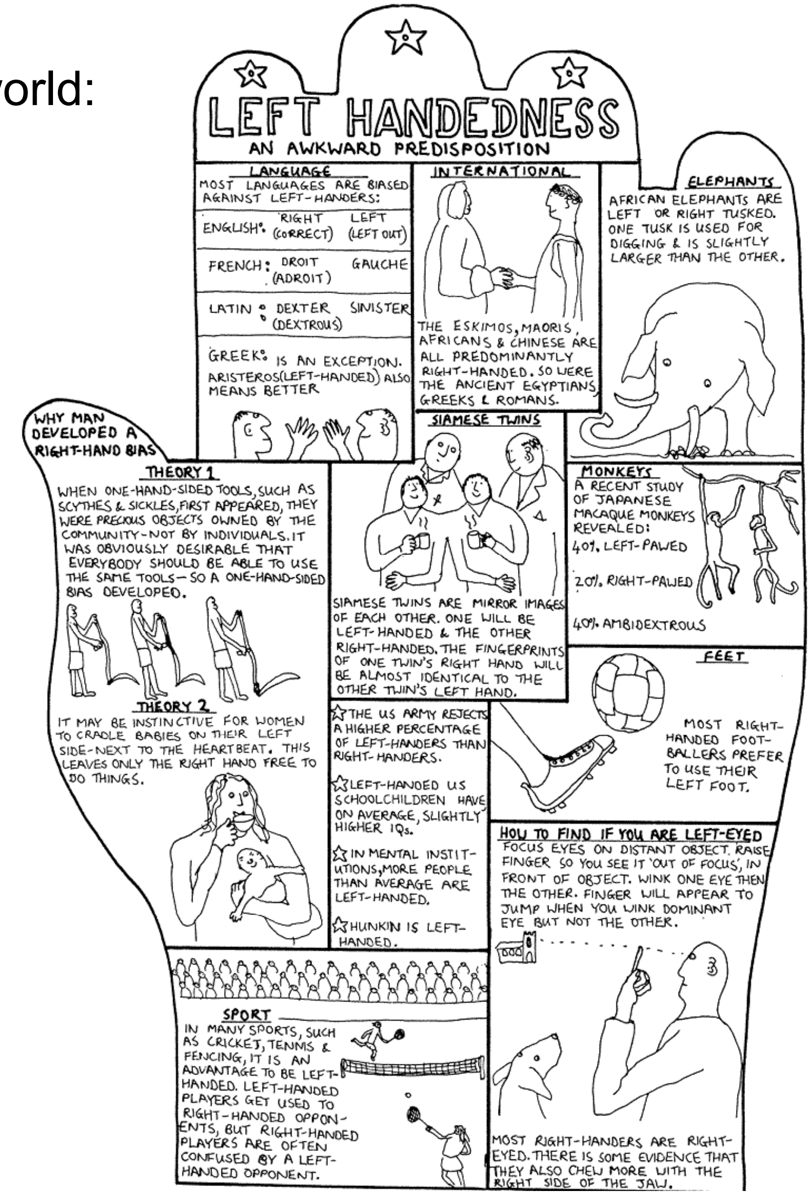
- Best experimental test: $\left|\left(m_{K^0} - m_{\overline{K}^0}\right)/m_{K^0}\right| < 10^{-18}$

If *CPT* is Conserved, how about *P*, *C* and *T* ?

- Parity is often violated in the macroscopic world:

	Strongly Left-sided	Strongly Right-sided	Mixed Sided
Handedness	5%	72%	22%
Footedness	4%	46%	50% (?)
Eyedness	5%	54%	41%
Earedness	15%	35%	60%

Porac C & Coren S. Lateral preferences and human behavior. New York: Springer-Verlag, 1981

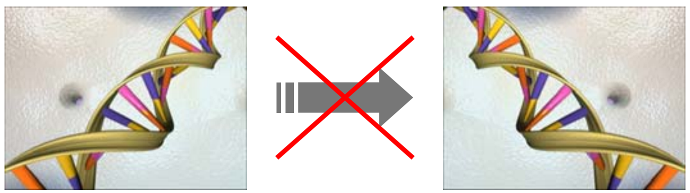


- About 25% of the population drives on the left side: why ?

In ancient societies people walked (rode) on the left to have their sword closer to the middle of the street (for a right-handed man) !?

- The DNA is an oriented double helix

Two right-handed polynucleotide chains that are coiled about the same axis:



Not so in the microscopic World ?

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 states ($\gamma\gamma$) are *C* even: hence, ***C*** **is conserved** !

- Generalization: $P\left|q\bar{q}'\right\rangle = (-1)^{L+1}\left|q\bar{q}'\right\rangle$, $C\left|q\bar{q}\right\rangle = (-1)^{L+S}\left|q\bar{q}\right\rangle$, $G\left|u\bar{u}(\bar{d})\right\rangle = (-1)^{L+S+I}\left|u\bar{u}(\bar{d})\right\rangle$

- Experimental tests of *P* and *C* invariance of the EM interaction:

$$C \text{ invariance: BR}\left(\pi^0 \to 3\gamma\right) < 3.1\times10^{-8}$$

$$P \text{ invariance: BR}\left(\eta \to 4\pi^0\right) < 6.9\times10^{-7}$$

- Experimental tests of *C* invariance of **strong interaction**: compare rates of positive and negative particles in reactions like: $p\bar{p} \to \pi^+\pi^- X,\ K^+K^- X$

And … the Surprise in Weak Interaction !

Lee & Yang:

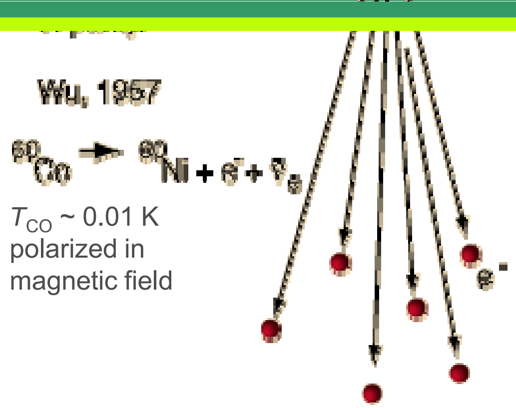
"Past experiments on the weak interactions had actually no bearing on the question of parity conservation."

"In strong interactions, ... there were indeed many experiments that established parity conservation to a high degree of accuracy..."

"To decide unequivocally whether parity is conserved in weak interactions, one must perform an experiment to determine whether weak interactions differentiate the right from the left."

Yang, C. N., *The law of parity conservation and other symmetry laws of physics,* Nobel Lectures Physics: 1942-1962, 1964.
Lee, T. D., and C. N. Yang, *Question of Parity Conservation in Weak Interactions*, The Physical Review, 104, Oct 1, 1956.

$$\alpha = \begin{cases} -1 & \text{for electron} \\ +1 & \text{for positron} \end{cases}$$



T_{CO} ~ 0.01 K
polarized in
magnetic field

- Parity is *maximally* violated in weak interactions !

P and *C* Violation in Weak Interaction

- Goldhaber *et al*. demonstrated in 1958 that in the β decay of the nucleus, the **neutrino (e⁻) is left-handed**, while the **antineutrino (e⁺) is right-handed**:

$$\begin{array}{lcccc} \text{Particle:} & e^- & e^+ & \nu & \bar{\nu} \\ \text{Helicity:} & -v/c & +v/c & -1 & +1 \end{array} \qquad (\rightarrow C \text{ violation ! })$$

- In the Dirac theory, fermions are described as 4-component spinor wave functions upon which 4×4 Operators Γ_i apply, which are classified according to their space reflection properties :

$$\underbrace{\bar{\psi}(4\times4)\psi}_{\text{Lorentz-covariant bilinear}} \text{ current } \begin{cases} \bar{\psi}\psi \equiv \psi^\dagger\gamma^0\psi & \text{scalar } (S) & P\text{-even} \\ \bar{\psi}\gamma_5\psi & \text{pseudoscalar } (P) & P\text{-odd} \\ \bar{\psi}\gamma^\mu\psi & \text{vector } (V) & P\text{-even} \\ \bar{\psi}\gamma^\mu\gamma_5\psi & \text{axial vector } (A) & P\text{-odd} \\ \bar{\psi}\underbrace{\left(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right)}_{-2i\sigma^{\mu\nu}}\psi & \text{tensor } (T) & \text{antisymmetric tensor} \end{cases}$$

P and *C* Violation in Weak Interaction

- Let's consider the β reaction: $n + \nu \rightarrow e^- + p$

  - General ansatz for the current-current matrix element :

some constants

$$M = \frac{G_F}{\sqrt{2}} \sum \left[\bar{\psi}_p \Gamma_i \psi_n \right] \left[\bar{\psi}_{e^-} \Gamma_i \left(C_i + \gamma_5 C_i' \right) \psi_\nu \right]$$

One transparency with a bit of math

… sorry …

won't happen again (almost) …

s

$$=1$$

while for a scalar interaction: $\bar{u}_L u_R = \frac{1}{2} \bar{u}(1+\gamma_5) u \neq 0$ and similar for *P*, *T*

  - Consider a (weak interaction) ***V – A*** neutrino-electron current in the relativistic limit:

$$\bar{u}_e (V - A) u_\nu = \bar{u}_e \gamma^\mu \frac{1}{2} (1 - \gamma_5) u_\nu = \left(\bar{u}_{e,L} + \bar{u}_{e,R} \right) \gamma^\mu u_{\nu,L} = \bar{u}_{e,L} \gamma^\mu u_{\nu,L}$$

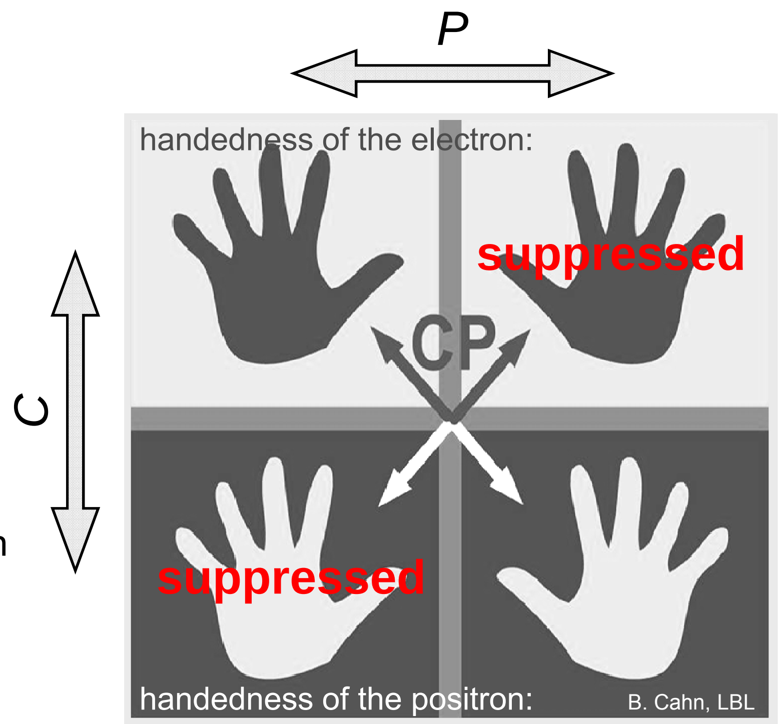
➡ It projects upon the left handed helicities, and hence violates *P* maximally, as required !

P and *C* Violation in Weak Interaction

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

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.

… and **tomorrow**, we will **see**


CP

CP Violation

CP Symmetry requires that **processes and** their **anti-processes have** the **same rates**

1. Due to the *CPT* theorem, *CP* symmetry also requires *T* symmetry
2. *CP violation* would enable us to distinguish between particles and antiparticles, and between past and future in an absolute way !

Dipole moments

- Can there be *CP* violation in the electromagnetic or neutral weak current ?

Let's modify the Standard Model Lagrangian to allow for *CP* violation through electromagnetic and weak dipole moments:

$$L_{CP} = -\frac{i}{2}\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell\left(d_\ell^{\mathrm{EM}} F_{\mu\nu} + d_\ell^{\mathrm{weak}} Z_{\mu\nu}\right)$$

where $F_{\mu\nu}$ and $Z_{\mu\nu}$ are electric and weak field strength tensors.

In the nonrelativistic limit one obtains the Pauli equation with the additional terms:

$$L_{CP} \to d_\ell^{\mathrm{EM}}\vec{\sigma}\vec{E} + d_\ell^{\mathrm{weak}}\vec{\sigma}\vec{Z}$$

A shift in the energy of the system when applying an external electric or weak field

But…. why do these dipole moments violate *CP* symmetry ?

Dipole Moments and *CP* Violation

- Spin is the only explicit "direction" of an elementary particle. Hence the dipole moment must be proportional to it

$$\boxed{\vec{d} \propto \vec{s}}$$

- The electric dipole moment is the average of a charge density distribution → polar vector

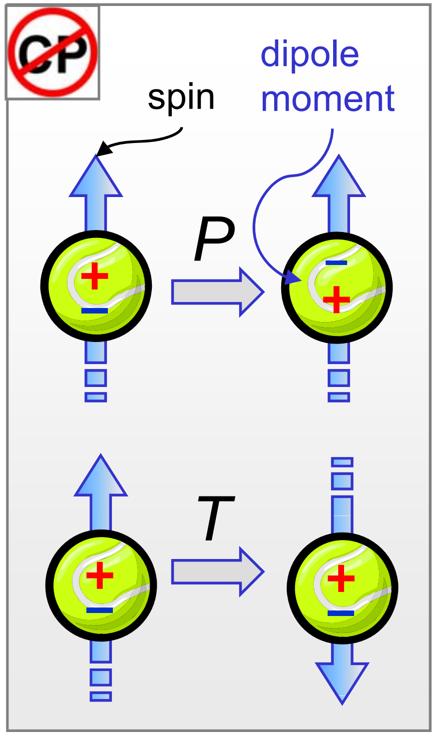
$$\vec{d} = \int d^3x \cdot \rho(\vec{x}) \cdot \vec{x}$$

- The spin has the form of angular momentum → axial vector

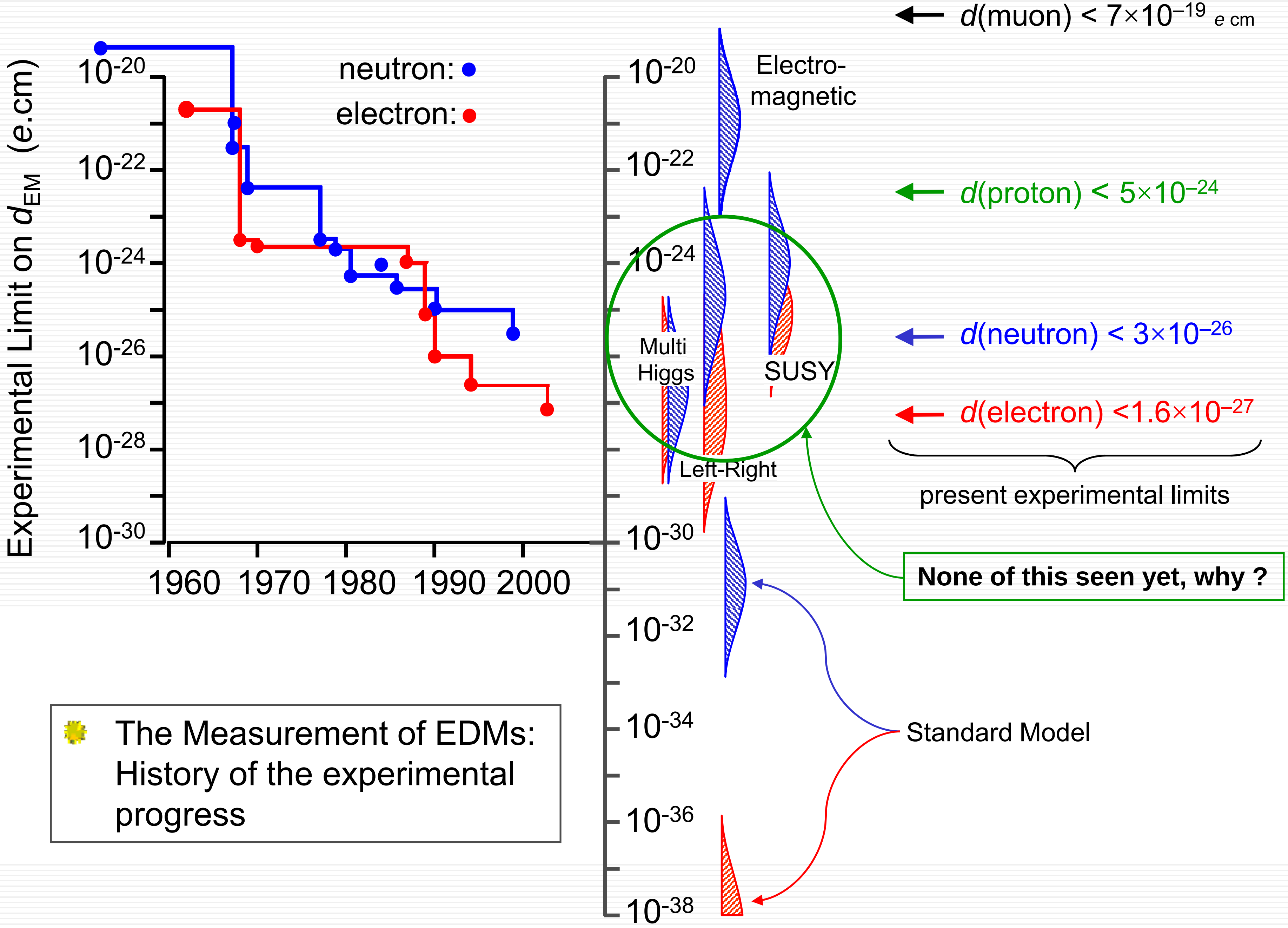
$$\vec{s} \propto \vec{r} \times \vec{p}$$

- Parity transformation gives: $P\vec{d} = -\vec{d}\ ,\quad P\vec{s} = \vec{s} \quad \underbrace{\Rightarrow}_{P\ \text{invariance}} \quad \vec{d} = 0$

- Time reversal transformation gives: $T\vec{d} = \vec{d}\ ,\quad T\vec{s} = -\vec{s} \quad \underbrace{\Rightarrow}_{T\ \text{invariance}} \quad \vec{d} = 0$



→ **Non-vanishing electric or weak dipole moments require the presence of a *P*- and *T*-violating (=*CP*-violating) interaction**



- The Measurement of EDMs: History of the experimental progress

digression: CP Violation in the QCD Lagrangian

- It was found in 1976 that the perturbative QCD Lagrangian was missing a term L_θ

$$L_{\rm QCD} = \underbrace{L_{\rm pQCD}}_{\text{perturbative QCD}} + \underbrace{L_\theta}_{P,T\text{-violating}}, \quad \text{where:} \quad L_\theta = \theta \frac{\alpha_s}{8\pi} \underbrace{G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}}_{\text{Gluon field tensors}}, \text{ and } \underbrace{\tilde{G}^{\mu\nu,a} = \frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}G^{\alpha\beta,a}}_{\textit{dual}\text{ field tensor}}$$

that breaks through an axial triangle *anomaly* diagram the $U(1)_A$ symmetry of $L_{\rm pQCD}$, which is not observed in nature

when classical symmetries are broken on the quantum level, it is denoted an *anomaly*

- The term $G^a_{\mu\nu}G^{\mu\nu,a}$ contained in $L_{\rm pQCD}$ is *CP*-even, while $G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$ is *P*-and *T*-odd, since:

$$G G \propto \sum_a \left(\left|\vec{E}_a\right|^2 + \left|\vec{B}_a\right|^2\right) \xrightarrow{P,T} \sum_a \left(\left|\vec{E}_a\right|^2 + \left|\vec{B}_a\right|^2\right)$$

$$G\tilde{G} \propto \sum_a \left(\vec{E}_a \cdot \vec{B}_a\right) \xrightarrow{P,T} -\sum_a \left(\vec{E}_a \cdot \vec{B}_a\right)$$

color electric and magnetic fields

Relativistic invariants, similar to electric field tensors: $F_{\mu\nu}F^{\mu\nu}$, $F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\underbrace{\partial_\mu F^{\mu\nu} = j^\nu, \; \partial_\mu \tilde{F}^{\mu\nu} = 0}_{\text{Maxwell equations}}$$

- This *CP*-violating term contributes to the EDM of the neutron:

$$\underbrace{d_n \approx \theta \cdot 5\times 10^{-16}\ e\text{cm, so that } \theta \text{ tiny or zero}}_{\text{"Strong } CP \text{ (finetuning) Problem"}}$$

digression: The Strong *CP* Problem

- Remarks:
  - If at least one quark were massless, L_θ could be made to vanish; if all quarks are massive, one has uncorrelated contributions, which have no reason to disappear
  - Peccei-Quinn suggested a new global, chiral $U_{PQ}(1)$ symmetry that is broken, with the "axion" as pseudoscalar Goldstone boson; the axion field, ϕ_a ,compensates the contribution from L_θ :

$$L_\theta = \left(\theta - \frac{\phi_a}{f_a}\right)\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

axion coupling to SM particles is suppressed by symmetry-breaking scale (= decay constant)

QCD nonperturbative effects ("instantons") induce a potential for ϕ_a with minimum at $\phi_a = \theta \cdot f_a$

- The axion mass depends on the $U_{PQ}(1)$ symmetry-breaking scale f_a

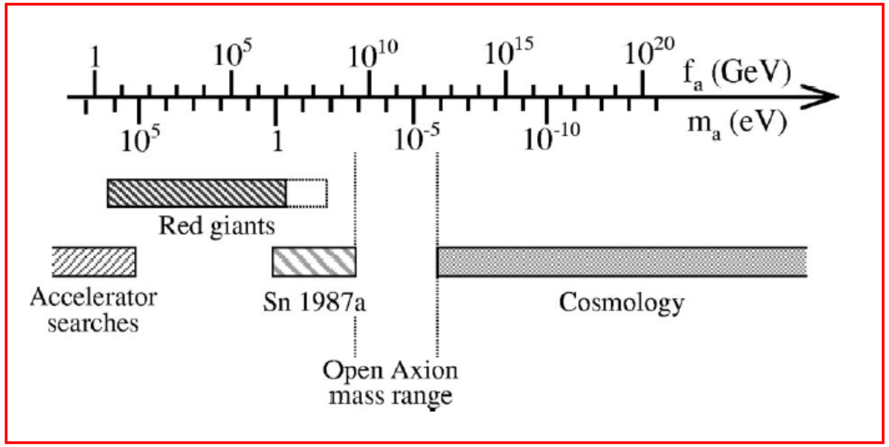
$$m_a \approx \left(\frac{10^7\ \text{GeV}}{f_a\ (\text{GeV})}\right) \times 0.62\ \text{eV}\,,$$

and axion coupling strength: $g_a \propto m_a$

  - If f_a of the order of the EW scale (v), m_a~250 keV → excluded by collider experiments

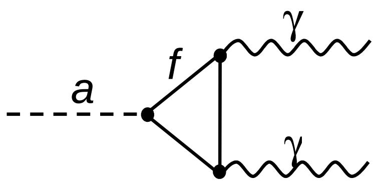
digression: The Search for Axions (a dark matter candidate !)

- The axion can be made “invisible” by leaving scale and coupling free, so that one has: $m_a \sim 10^{-12}$ eV up to 1 MeV → 18 orders of magnitude !

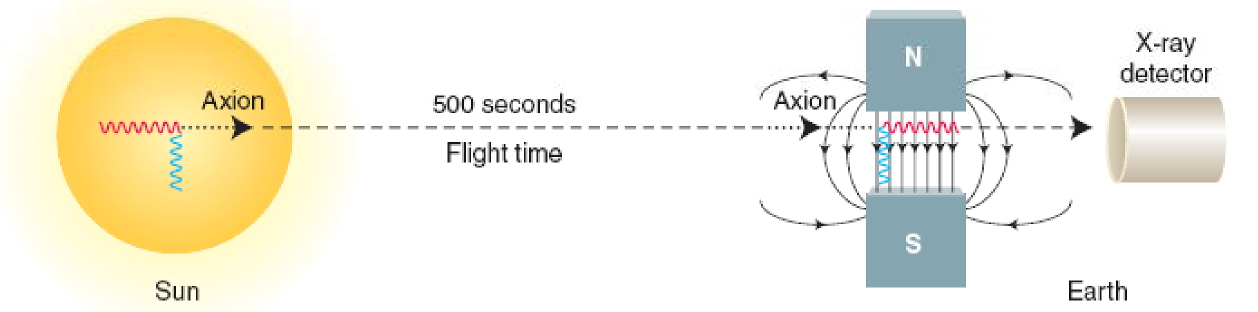


Axion scale and mass, together with the exclusion ranges from experimental non-observation

- Axion decays to 2γ, just as for the π^0, or in a static magnetic field:



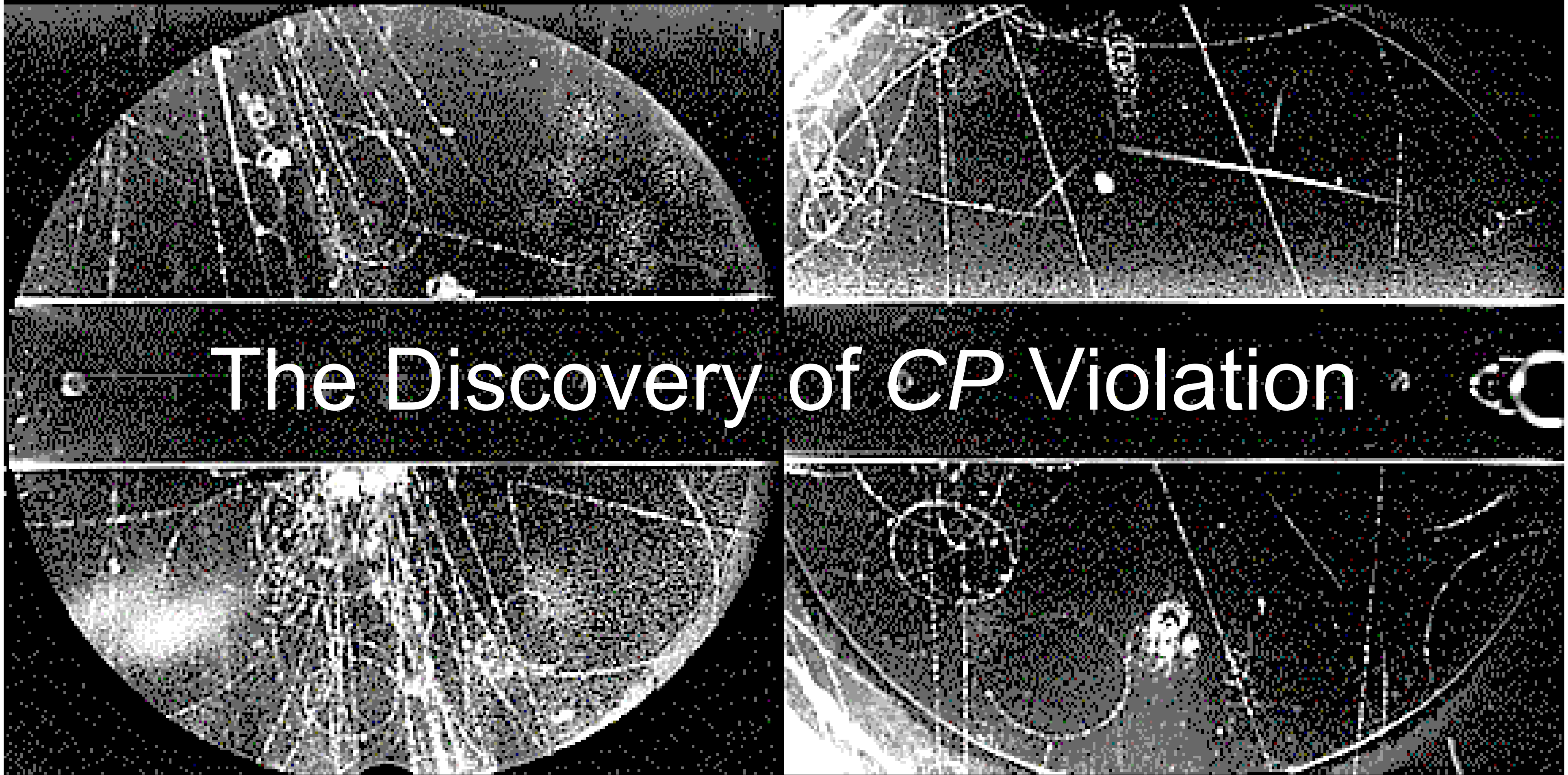
Schematic view of CAST experiment at CERN:



Axion source

Axion detection (LHC dipole magnet)

The Discovery of *CP* Violation



Ingredients … *Strange* Particles

- Strange mesons have an "*s*" valence quark
  - Non-strange particles: $(\pi,\rho,\ldots)_{I=1}:\ u\bar{d},\ (u\bar{u}-d\bar{d})/\sqrt{2}$
    $(\eta,\omega,\ldots)_{I=0}:\ (u\bar{u}+d\bar{d})/\sqrt{2}+\ldots$
    Neutral particles are eigenstates of *C* operator
  - Strange particles: $(K,K^*,\ldots)_{I=1/2}:\ K^+=u\bar{s},\ K^-=\bar{u}s,\ \underbrace{K^0=d\bar{s},\ \bar{K}^0=\bar{d}s}$
    Neutral strange particles are not eigenstate of *C* operator

- Production of strange particles via strong or electromagnetic interaction has to respect conservation of the *S* ("strangeness") quantum number
  (Strange particles are "eigenstates" of these interactions)

$$\left(\pi^-_{S=0}p_{S=0}\right)_{S=0}\rightarrow\left(\Lambda_{S=-1}K^0_{S=+1}\right)_{S=0}$$
$$\left(\pi^+_{S=0}p_{S=0}\right)_{S=0}\rightarrow\left(p_{S=0}K^+_{S=+1}\bar{K}^0_{S=-1}\right)_{S=0}$$
$$\left(p_{S=0}\bar{p}_{S=0}\right)_{S=0}\rightarrow\left(\pi^+_{S=0}K^-_{S=-1}K^0_{S=+1}\right)_{S=0},\ \left(\pi^-_{S=0}K^+_{S=+1}\bar{K}^0_{S=-1}\right)_{S=0}$$
$$\left(e^-_{S=0}e^+_{S=0}\right)_{S=0}\rightarrow\phi_{S=0}\rightarrow\left(K^0_{S=+1}\bar{K}^0_{S=-1}\right)_{S=0}$$

- Kaons are lightest *s*-particles → can only decay via *s*-changing **weak** interaction

The Discovery of *CP* Violation

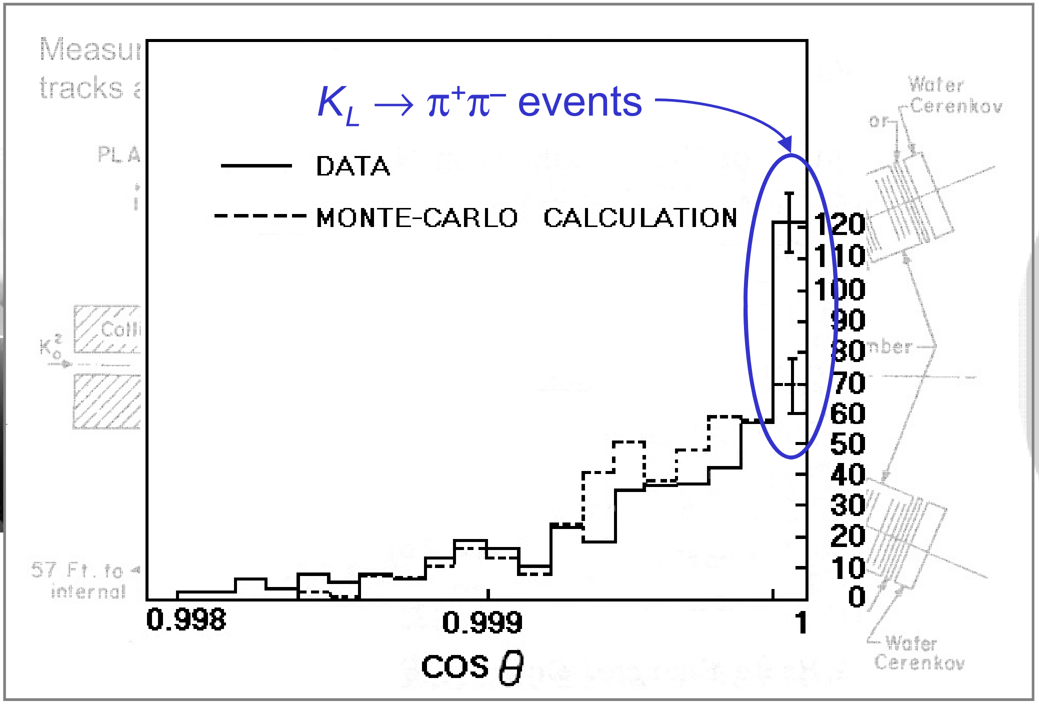
- Empirically (in the experiment) one does however not observe the neutral "flavor eigenstates" K^0 and $\bar{K}^0$ but rather long- and short-lived neutral states: K_L and K_S
  - Their observed pionic decays are: $K_S \to (\pi\pi)^0$ and $K_L \to (\pi\pi\pi)^0$
  - And it was believed that: $CP|K_S\rangle = +|K_S\rangle$ and $CP|K_L\rangle = -|K_L\rangle$

Larger phase space of 2π decay:
$\Rightarrow \tau_{K_L} / \tau_{K_S} \approx 580$

- However, Cronin, Fitch et al. (BNL) discovered in 1964 the *CP*-violating decay $K_L \to \pi^+\pi^-$

Jim Cronin

Val Fitch

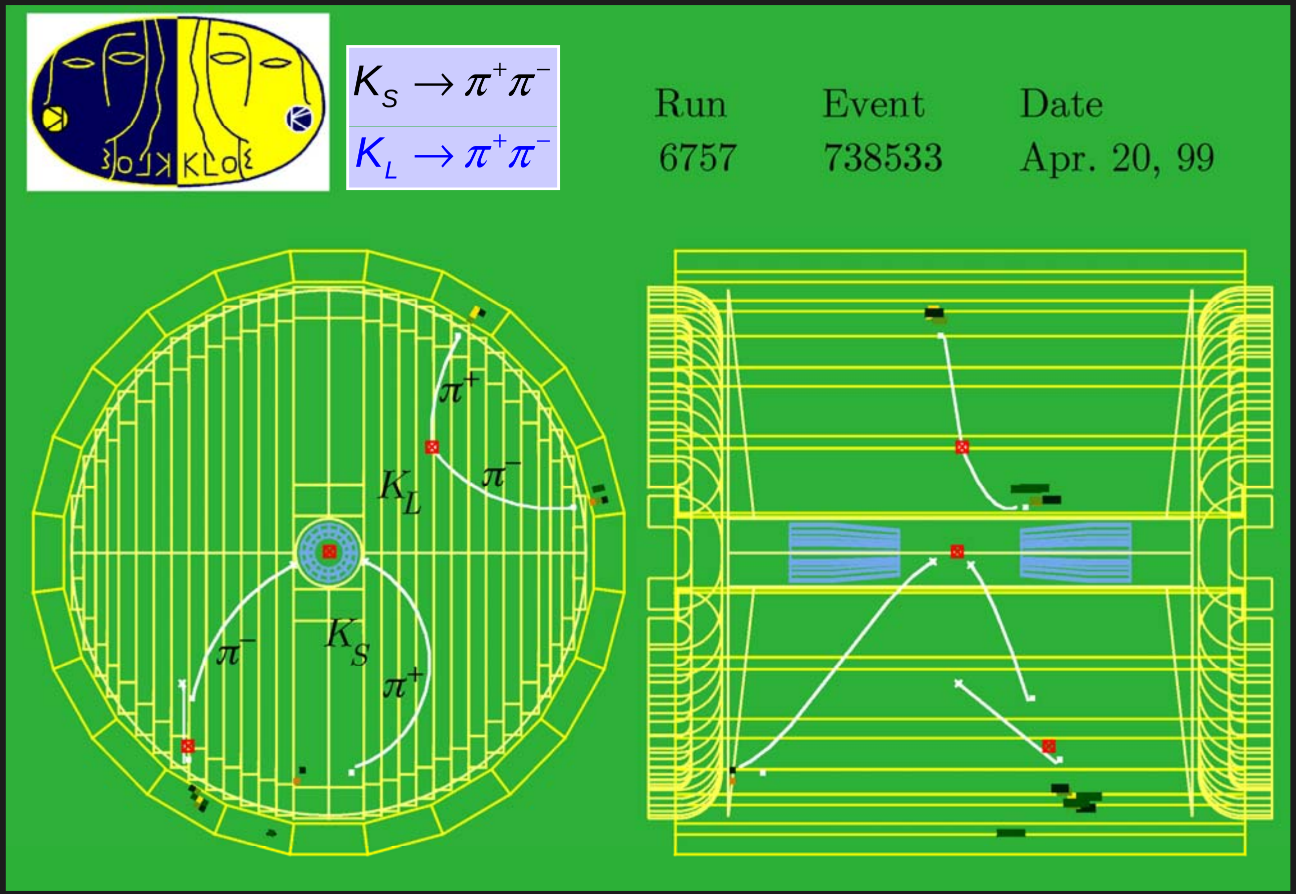


Today's most precise measurement of amplitude ratio:

$$|\varepsilon| = \left| \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \right| = (2.282 \pm 0.017) \times 10^{-3}$$

The KLOE experiment at the ϕ Factory DAΦNE (Frascati, Italy) can detect **single** *CP*-violating decays:

$e^+e^- \to \phi \to K^0\bar{K}^0$ and equivalently: $e^+e^- \to \phi \to K_S K_L$



Note that the quantum coherence is broken after the decay of one of the two K^0's

The Discovery of *CP* Violation in the Charged Weak Current

- To understand the observed *CP* violation from the flavour perspective, let us *construct CP* eigenstates with *CP* eigenvalues   1:

$$
\begin{aligned}
|K_1\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)\ , \qquad [CP = +1] \\
|K_2\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)\ , \qquad [CP = -1]
\end{aligned}
$$

- While the flavour eigenstates are defined by the production, the *CP* eigenstates are distinguished by their decay into an even and odd number of pions.

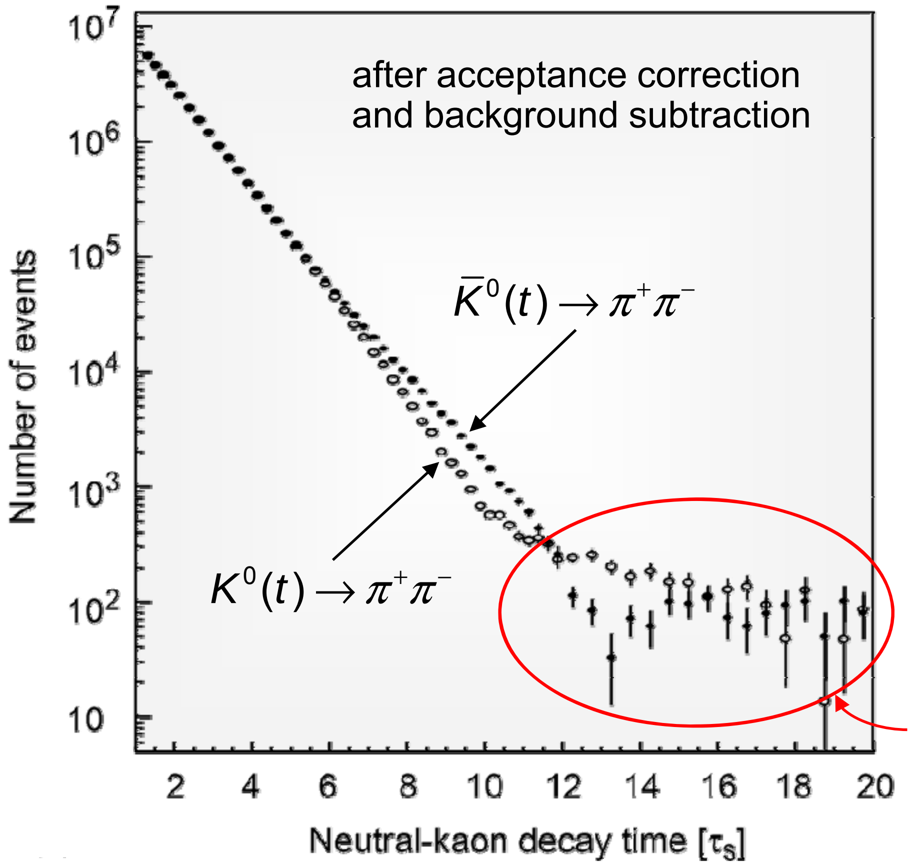
- Since there is *CP* violation, the physical states ("mass eigenstates") are **not exactly the same as the *CP* eigenstates**:

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

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

CP Violation and Neutral Kaon Mixing

- CPLEAR (CERN) measured the rates of $K^0, \bar{K}^0(t) \to \pi^+\pi^-$ (using initial state strangeness tagging) as a function of the decay time, and finds quite a surprise:



- *s*-tagging at production:

$$p\bar{p} \to \begin{Bmatrix} K^-\pi^+K^0 \\ K^+\pi^-\bar{K}^0 \end{Bmatrix} \text{ charge of } K^\pm$$

- Rates are different for the two flavor states

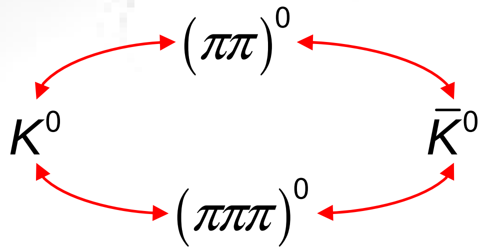
- Also *T* violation measured by looking at time-dependent asymmetry of
- There is a non-exponential component (?)

$$K^0 / \bar{K}^0(t) \to e^{+/-}\pi^{-/+}\nu$$

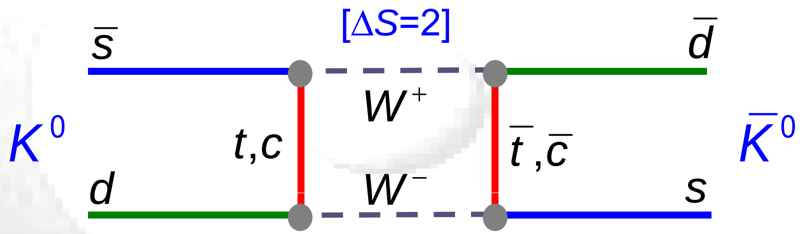
Neutral Kaon Mixing

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

- Simple picture: they mix through common virtual states:



- These oscillations are described in QCD by Δ*S* = 2 Feynman "box" diagrams:



- Because $\Delta m(K) = m(K_L) - m(K_S) = 3.5 \times 10^{-12}$ MeV > 0, a K^0 will change with time into a $\bar{K}^0$ and vice versa

Neutral Kaon Mixing

- 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 from the time-dependent Schrödinger equation:

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

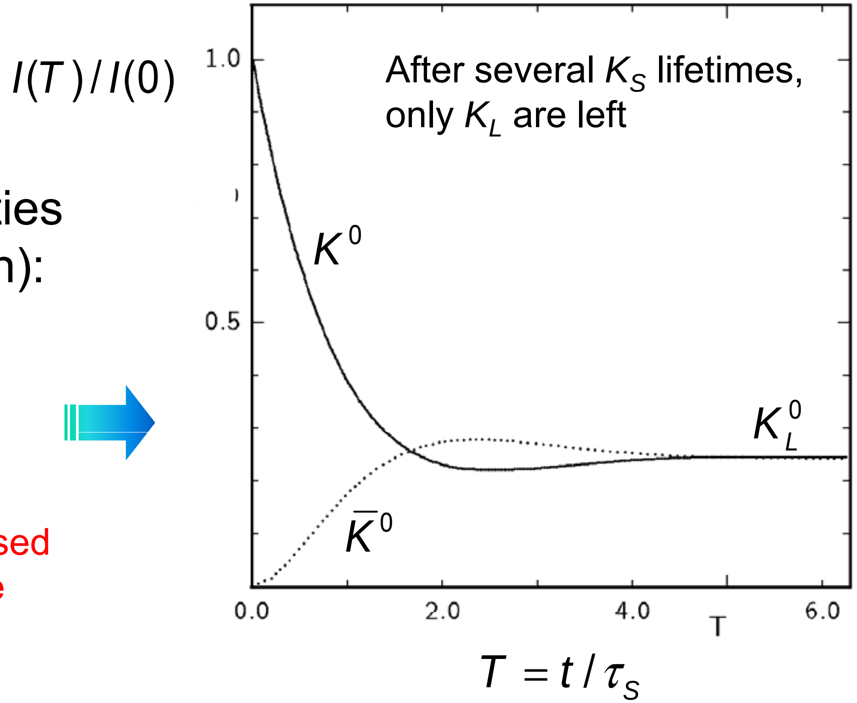
With 2×2 matrices M, Γ, of which the off-diagonals $\propto \Delta m$, $\Delta\Gamma$ govern the mixing

- The respective time-dependent intensities are found to be (neglecting *CP* violation):

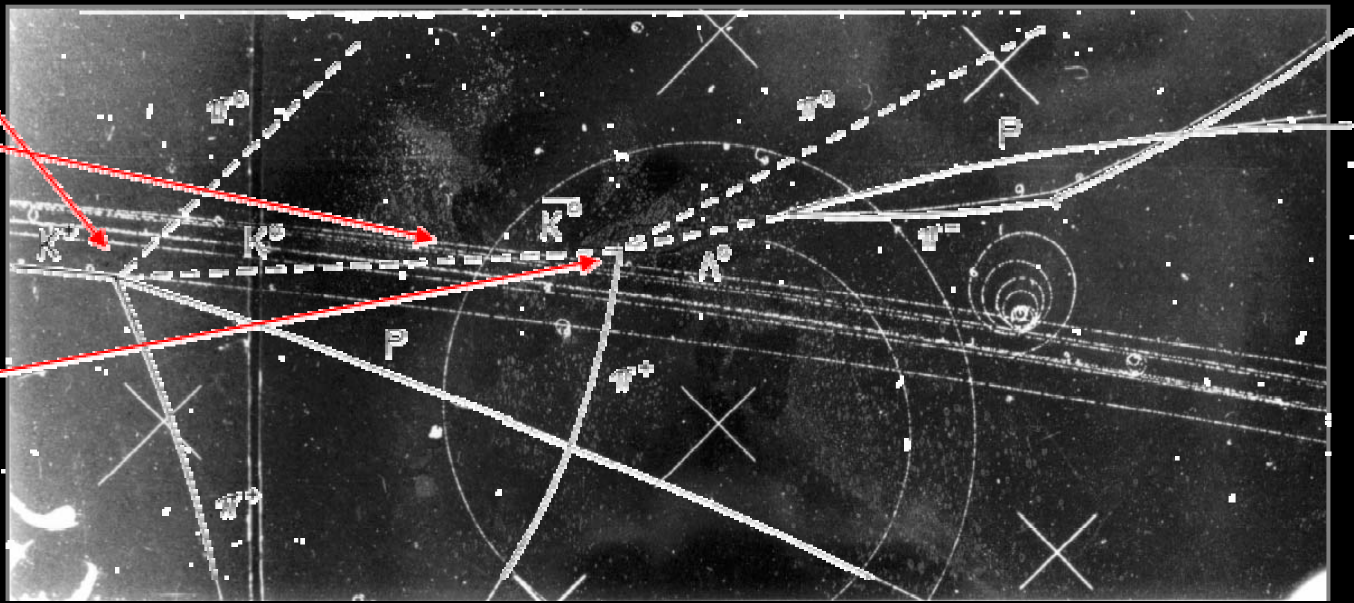
$$I_{K^0}(t) \propto e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m \cdot t)$$

$$I_{\bar{K}^0}(t) \propto e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m \cdot t)$$

cos terms caused by interference



Observing K^0 Mixing



The $\bar{s}$ in the K^+ is transferred to the K^0

The $\bar{s}$ in the K^0 mixes to a s making a $\bar{K}^0$

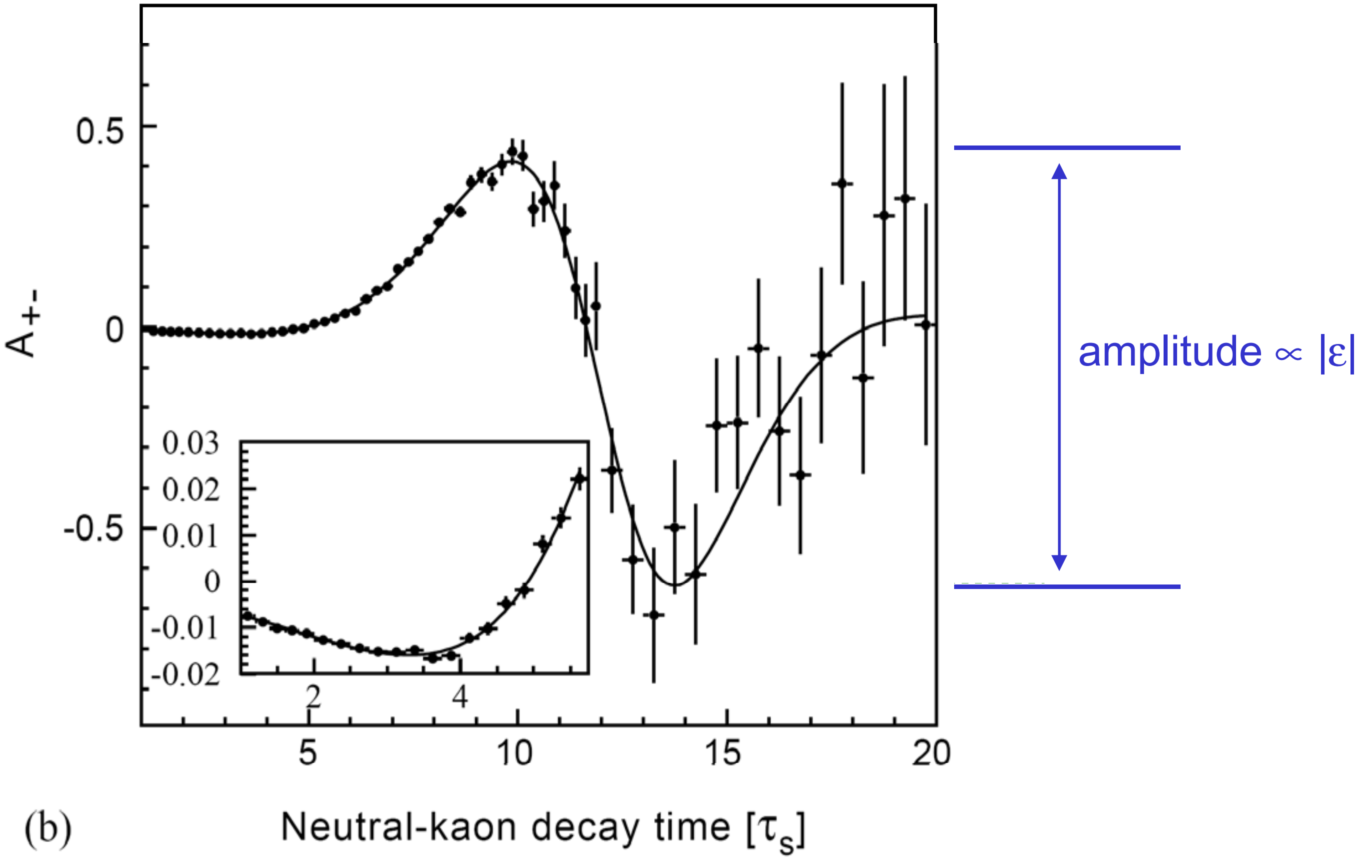
The s is transferred to a Λ^0 (uds baryon)

Neutral Kaon Mixing and *CP* Violation

- Since K_S and K_L are **not** *CP* eigenstates, the time dependence has to be slightly modified by the size of ε, giving rise to an additional sine term.

  - Asymmetry: $$A_{\pi\pi} = \frac{\Gamma\left(\bar{K}^0 \to \pi^+\pi^-\right) - \Gamma\left(K^0 \to \pi^+\pi^-\right)}{\Gamma\left(\bar{K}^0 \to \pi^+\pi^-\right) + \Gamma\left(K^0 \to \pi^+\pi^-\right)} \propto |\varepsilon| \cos\left(\Delta m \cdot t - \varphi\right)$$

Neglecting other sources of *CP* violation & assuming arg(ε) = π/4.



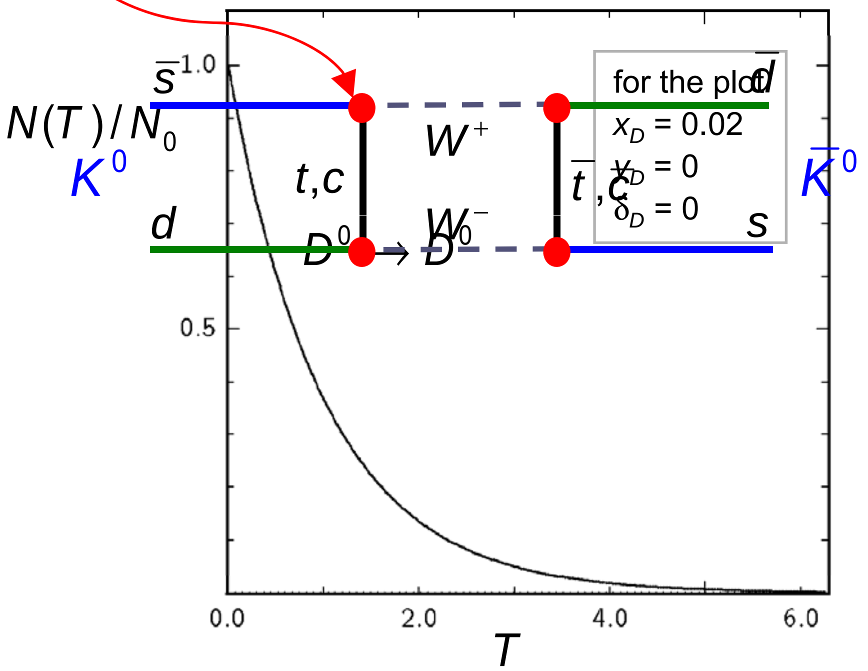
There are in Fact Four Meson Systems with Mixing

- Pairs of self-conjugate mesons that can be transformed to each other via flavor changing weak interaction transitions are:

$$|K^0\rangle = |\bar{s}d\rangle \qquad |D^0\rangle = |c\bar{u}\rangle \qquad |B_d^0\rangle = |\bar{b}d\rangle \qquad |B_s^0\rangle = |\bar{b}s\rangle$$

All measured by now !

- They have very different oscillation frequencies that can be understood from the "CKM couplings" (→ tomorrow !) occurring in the box diagrams



mixing probability:

$\chi \sim 2\times10^{-6}$

Three Types of *CP* Violation

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

  - ***CP* Violation in mixing:**

$$\mathrm{Prob}(K^0 \to \overline{K}^0) \neq \mathrm{Prob}(\overline{K}^0 \to K^0)$$

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

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

also called:
"indirect CPV"

- There is another, conceptually "simpler" type of *CP* violation:

  - ***CP* Violation in the decay:**

$$\mathrm{Prob}(K \to f) \neq \mathrm{Prob}(\overline{K} \to \overline{f})$$

also called:
"direct CPV"

"Direct" *CP* Violation = *CP* Violation in Decay

- General signature: rate differences between *CP*-conjugated processes:

$$\Gamma\left(|i\rangle \to |f\rangle\right) \neq \bar{\Gamma}\left(|\bar{i}\rangle \to |\bar{f}\rangle\right)$$

- It **must** involve interference of amplitudes contributing to the processes.
  - To obtain interference, we need **phases that change sign under *CP***
  - Example: if the decay amplitudes are given by: $\{a_{1,2}, \phi_{1,2} \in \mathbb{R}\}$

$$A\left(|i\rangle \to |f\rangle\right) = a_1 e^{i\theta_1} e^{i\phi_1} + a_2 e^{i\theta_2} e^{i\phi_2}$$

$$\bar{A}\left(|\bar{i}\rangle \to |\bar{f}\rangle\right) = \left(a_1 e^{i\theta_1} e^{-i\phi_1} + a_2 e^{i\theta_2} e^{-i\phi_2}\right) \underbrace{e^{-2i(\xi_i - \xi_f)}}_{\text{unphysical phase}}$$

ϕ_j Alters sign under *CP* ("weak phase")

θ_j *CP* invariant ("strong phase")

where: $\Gamma\left(|i\rangle \to |f\rangle\right) \propto \left|A\left(|i\rangle \to |f\rangle\right)\right|^2$ and $\bar{\Gamma}\left(|\bar{i}\rangle \to |\bar{f}\rangle\right) \propto \left|\bar{A}\left(|\bar{i}\rangle \to |\bar{f}\rangle\right)\right|^2$

We can define the following *CP* asymmetry A_{CP}:

$$\boxed{A_{CP} = \frac{\bar{\Gamma}\left(|\bar{i}\rangle \to |\bar{f}\rangle\right) - \Gamma\left(|i\rangle \to |f\rangle\right)}{\bar{\Gamma}\left(|\bar{i}\rangle \to |\bar{f}\rangle\right) + \Gamma\left(|i\rangle \to |f\rangle\right)} = \frac{2a_1 a_2 \sin(\theta_1 - \theta_2)\sin(\phi_1 - \phi_2)}{a_1^2 + a_2^2 + 2a_1 a_2 \cos(\theta_1 - \theta_2)\cos(\phi_1 - \phi_2)}}$$

CP Violation in the Kaon Decay

- We have seen that **at least two** amplitudes with **different weak <u>and</u> strong** phases must contribute to the decay for direct CPV. This suppresses this type of CPV, so that the observable effect should be small compared to ε.

The Discovery of *CP* Violation in the Decay

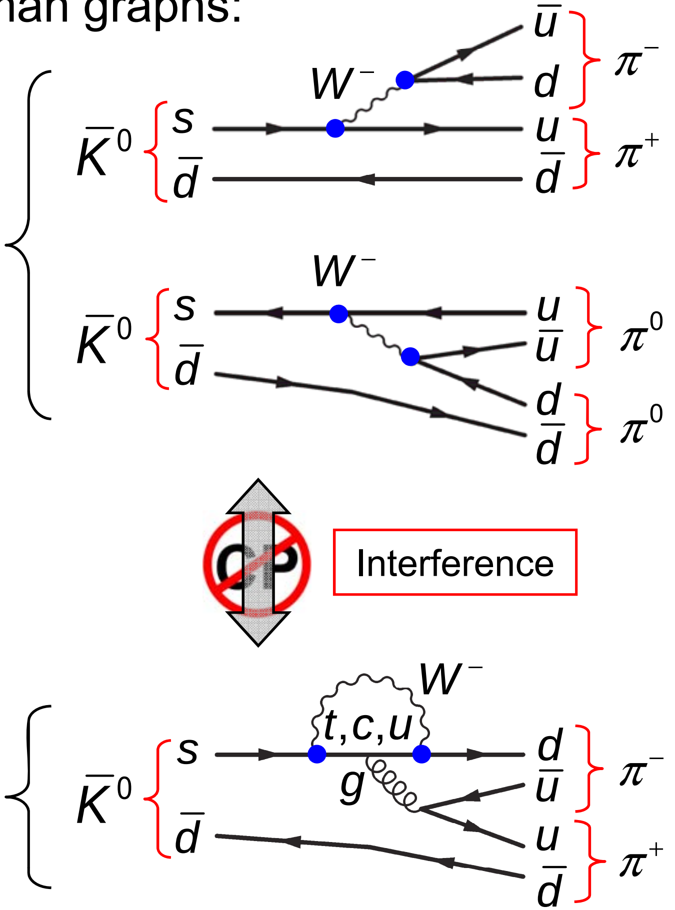
- It took several experiments and **over 30 years** of effort to establish the existence of direct CPV

$$\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \overset{\varepsilon' \ll \varepsilon}{\simeq} 1 - 6 \times \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

- Feynman graphs:

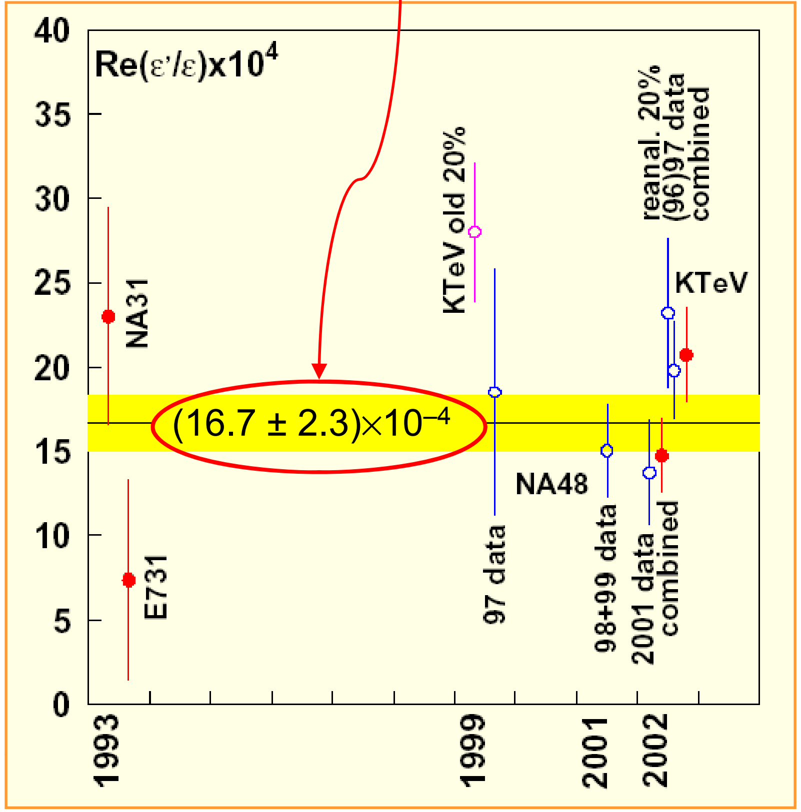
"Tree" (born-level) amplitudes

"Penguin" (loop-level) amplitude

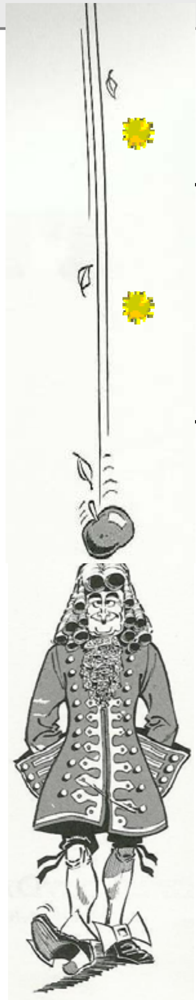


Experimental average

Indeed, a *very* small CPV effect !

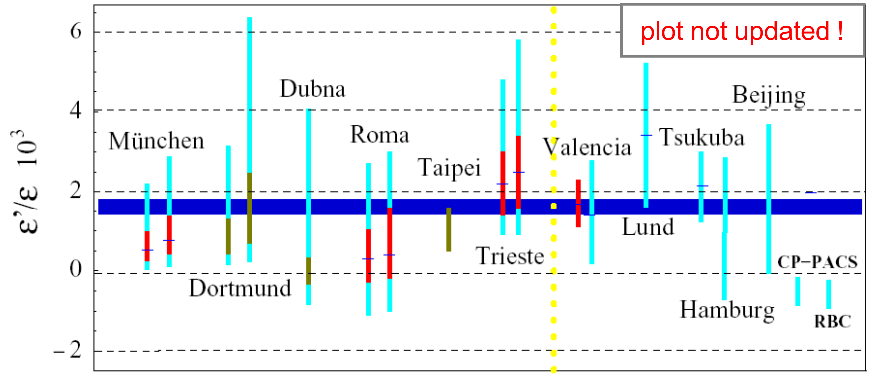


And the Theory ?



- Direct *CP* violation is in general very hard to calculate due to its sensitivity to the relative size and phase of different amplitudes of similar size
- Many theoretical groups have put efforts into this. All agree that the effect is much smaller than the indirect CPV (a success for the Standard Model !), but the theory uncertainties are larger than the measurement errors

Theoretical pre(post)dictions



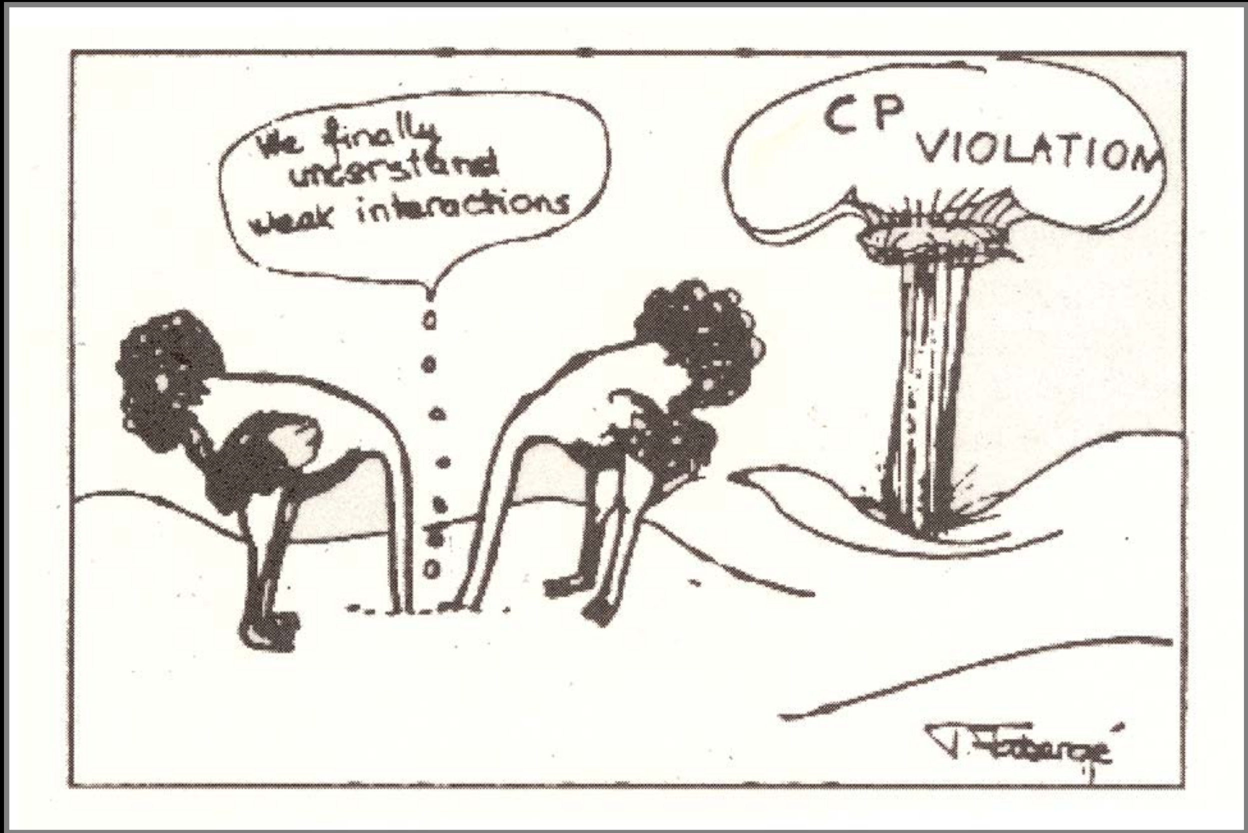
...the ball is on the theory side

courtesy:
G. Hamel de Monchenault

e n d o f L e c t u r e 1 & 2

Conclusions of the first two Lectures

- No *CP* violation without antimatter !
- *CP* violation is a vital ingredient for the creation of a matter universe
- *CPT* Symmetry is a fundamental property of quantum field theories
- *P*, *C*, *T* are good symmetries of electromagnetic and strong interactions
- *P*, *C* are maximally violated in weak interaction
- *CP*, *T* are broken symmetries of weak interaction
- *CP* violation has been first discovered in the kaon system, and both, direct and indirect *CP* violation have been observed
- No other source of *CP* violation has been found so far



Cartoon shown by N. Cabibbo in 1966… since then, there was tremendous progress in the understanding (better: describing) *CP* violation → **next lecture !**