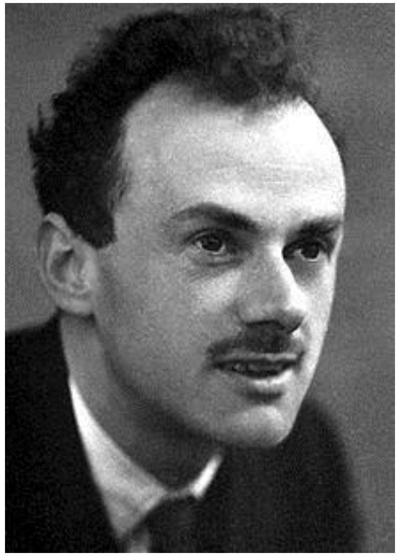
History of Antimatter and CPT Invariance

Dr. Andreas Mooser and Dr. Christian Smorra

Questions…

- How did we learn about antimatter?
- How did we discovery antimatter?
- What is the relation of symmetries within the Standard Model of Particle Physics and antimatter?
- How can we explain the abundance of antimatter?
- How can we search for possible effects explaining the abundance?

The ANTIMATTER story started with a theoretician



… one of the rare situations in physics history, where theory predicted a trailblazing breakthrough!

DIRAC EQUATION

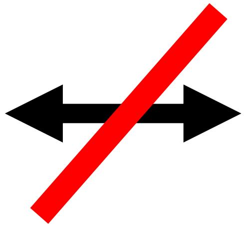
Physics at the beginning of the 19th century

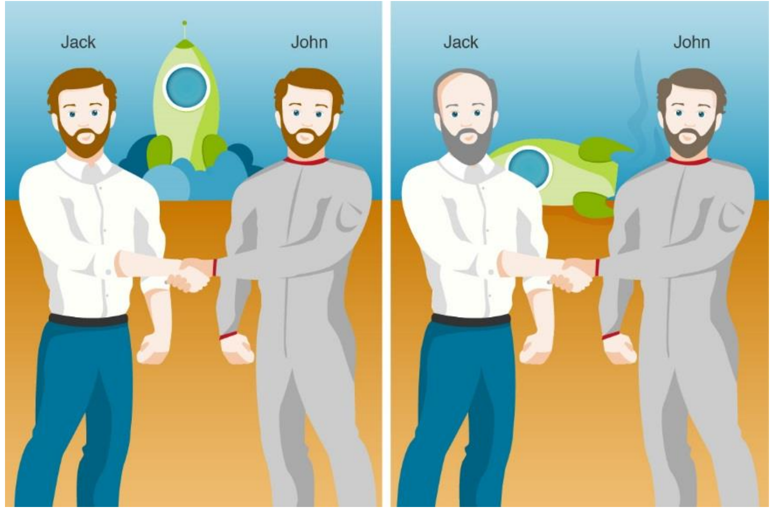
Quantum Mechanics:

- Photoelectric effect
- Blackbody radiation - Planck‘s law
- Atomic theory

Special Relativity:

- Michelson-Morley experiment – no ether for light
- Speed of light independent of reference frame





Search for a unified theory of quantum mechanics and relativity

More details…

1905 Special Relativity → Relativistic wave equation

1920ies Quantum Mechanics

??? What is a relativistic wave equation ???

Wave equation which fulfils the relativistic energy momentum dispersion relation

$$E^2 = p^2c^2 + m^2c^4$$

common substitution $E \to i\hbar\frac{\partial}{\partial t}$ $p \to \frac{\hbar}{i}\nabla$

$$-\hbar^2\frac{\partial^2}{\partial t^2}\psi = (-\hbar^2\Delta + m^2)\,\psi$$

Negative Energy solutions

Negative Probability Densities

Unphysical

Dirac's Ansatz

Construct a wave equation which is linear in energy and momentum but somehow fulfils dispersion relation

$$H\psi = (\alpha_i p_{\boldsymbol{i}} + \beta m)\,\psi \quad \Rightarrow \quad H^2\psi = (\alpha_i p_{\boldsymbol{i}} + \beta m)(\alpha_j p_{\boldsymbol{j}} + \beta m)\psi$$

$$H^2\psi = \Big(\underbrace{\alpha_i^2}_{=1} p_i^2 + \underbrace{(\alpha_i\alpha_j + \alpha_j\alpha_i)}_{=0} p_i p_j + \underbrace{(\alpha_i\beta + \beta\alpha_i)}_{=0} p_i m + \underbrace{\beta^2}_{=1} m^2\Big)\psi$$

$$E^2 = p^2c^2 + m^2c^4$$

So α , β must satisfy:

- $\boldsymbol{\alpha^2 = \beta^2 = 1}$
- **α , β anti-commute**

Solution

Lowest dimensional matrix that has desired behaviour is **4x4**!

$$\vec{\alpha} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix} \qquad \beta = \begin{pmatrix} I & \vec{0} \\ \vec{0} & -I \end{pmatrix}$$

With σ 2x2 Pauli matrices and

I identity matrix

Lowest dimensional solution is a **4**-component vector

$$\mathrm{i}\hbar\frac{\partial\psi}{\partial t} = \left(\frac{\hbar c}{\mathrm{i}}\alpha^k\partial_k + \beta mc^2\right)\psi \equiv H\psi$$

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

Surprising

- One component automatically describes the spin
- Gives g=2 without construction - in Schrödinger/Pauli approach included heuristically
- applied to hydrogen it delivers all energy corrections which have been introduced to describe the atom by the Schrödinger approach
  - Relativistic corrections
  - LS coupling corrections

This highly “intuitive” approach leads to a really “cool” theory

??? BUT…what are the two additional component ???

… SO …

…the fact that this new equation describes the “real world” consistently was so convincing that Dirac did not give up in interpreting it.

Dirac‘s Fight – the History

1928

Since half the solutions must be rejected as referring to the charge $+e$ on the electron, the correct number will be left to account for duplexity phenomena.

Dirac's Fight – the History

1928

Since half the solutions must be rejected as referring to the charge $+e$ on the electron, the correct number will be left to account for duplexity phenomena.

1930

would fill it, and will thus correspond to its possessing a charge $+e$. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons*. When an electron of positive energy drops into

Dirac‘s Fight – the History

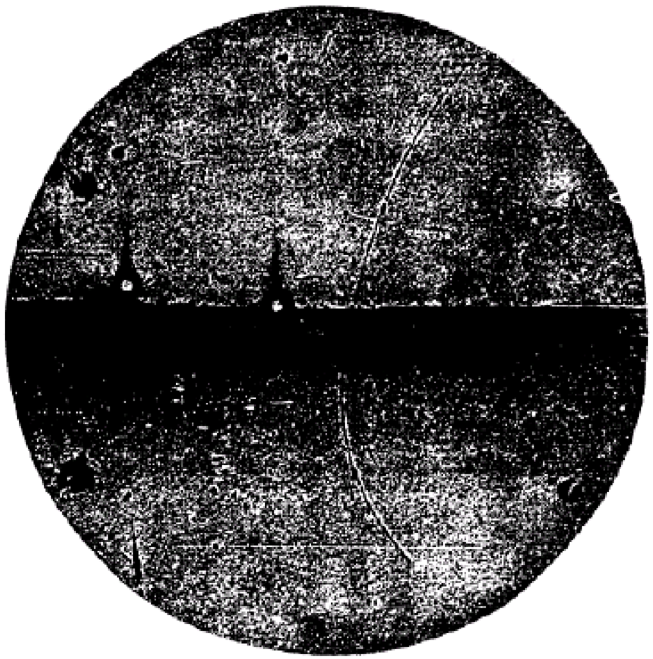
1928 Since half the solutions must be rejected as referring to the charge $+e$ on the electron, the correct number will be left to account for duplexity phenomena.

1930 would fill it, and will thus correspond to its possessing a charge $+e$. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons*. When an electron of positive energy drops into

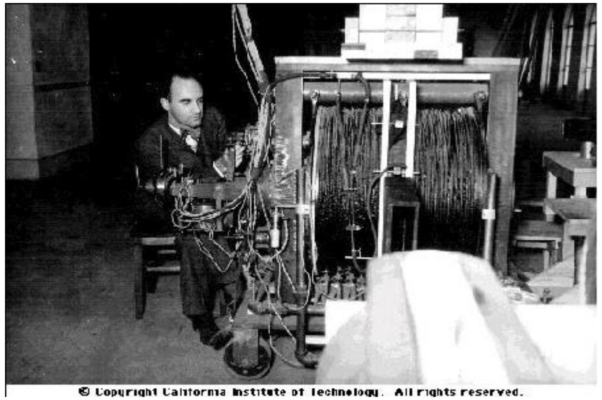
1931 nearly all, of the negative-energy states for electrons are occupied. A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of

Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton.

First observation of antimatter



Carl David Anderson,
Phys.Rev.43(1933)491



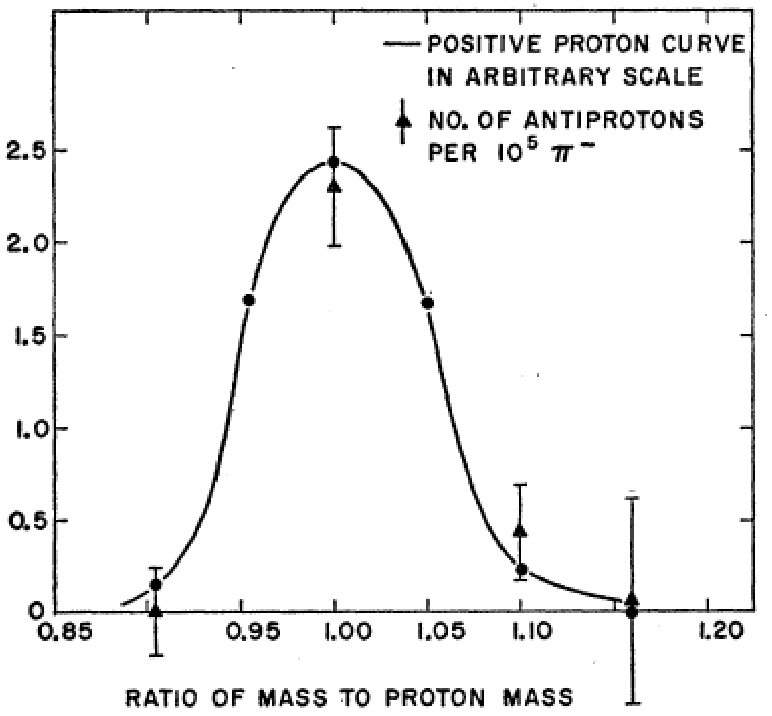
Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the

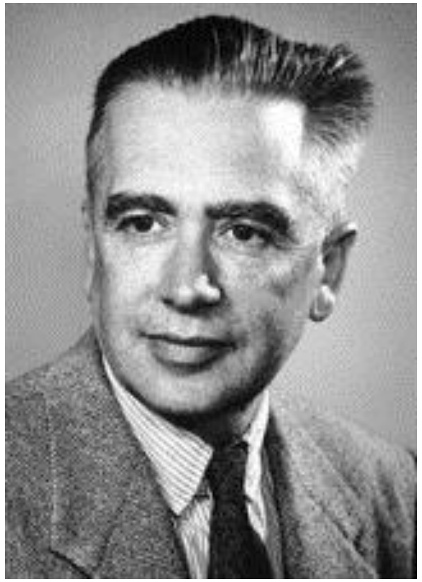
seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the

23 years later

At Bevatron – Proton accelerator at Berkley (California)

Measurement of mass of negatively charges particles – by measurement of velocity and momentum





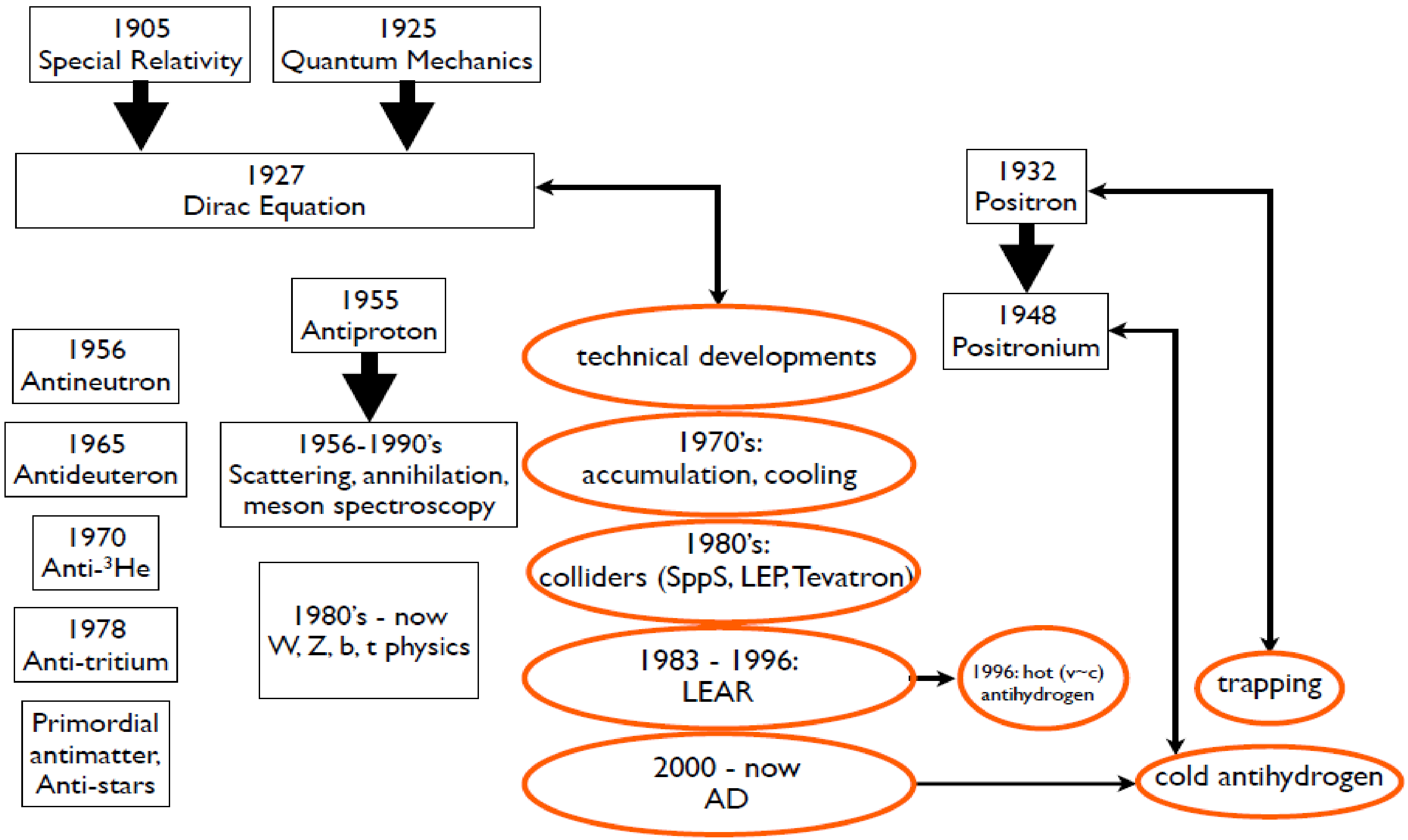
Emilo Serge

Owen Chamberlain

Nobelprize 1959 for the dicovery of the antiproton

Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis Phys. Rev. 100, 947 (1955)

History of Antimatter



Difficulty with antimatter

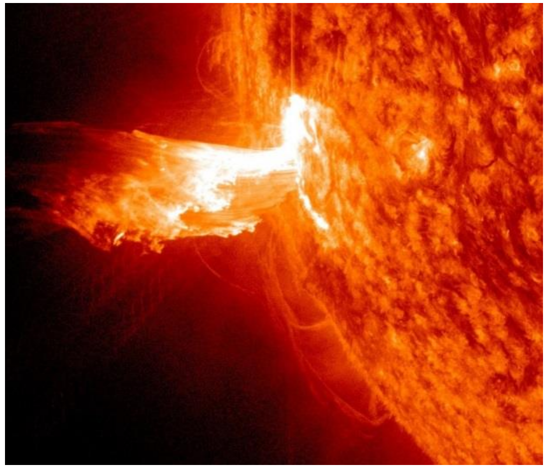
Our universe started with the BIG BANG

Which should have produced the same amount of matter and antimatter

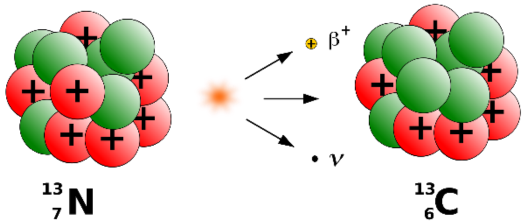
However

We do observe antimatter only under very exotic conditions

Cosmic rays



Radioactive decays



Accelerator facilities

Where is the antimatter – how did it get lost?

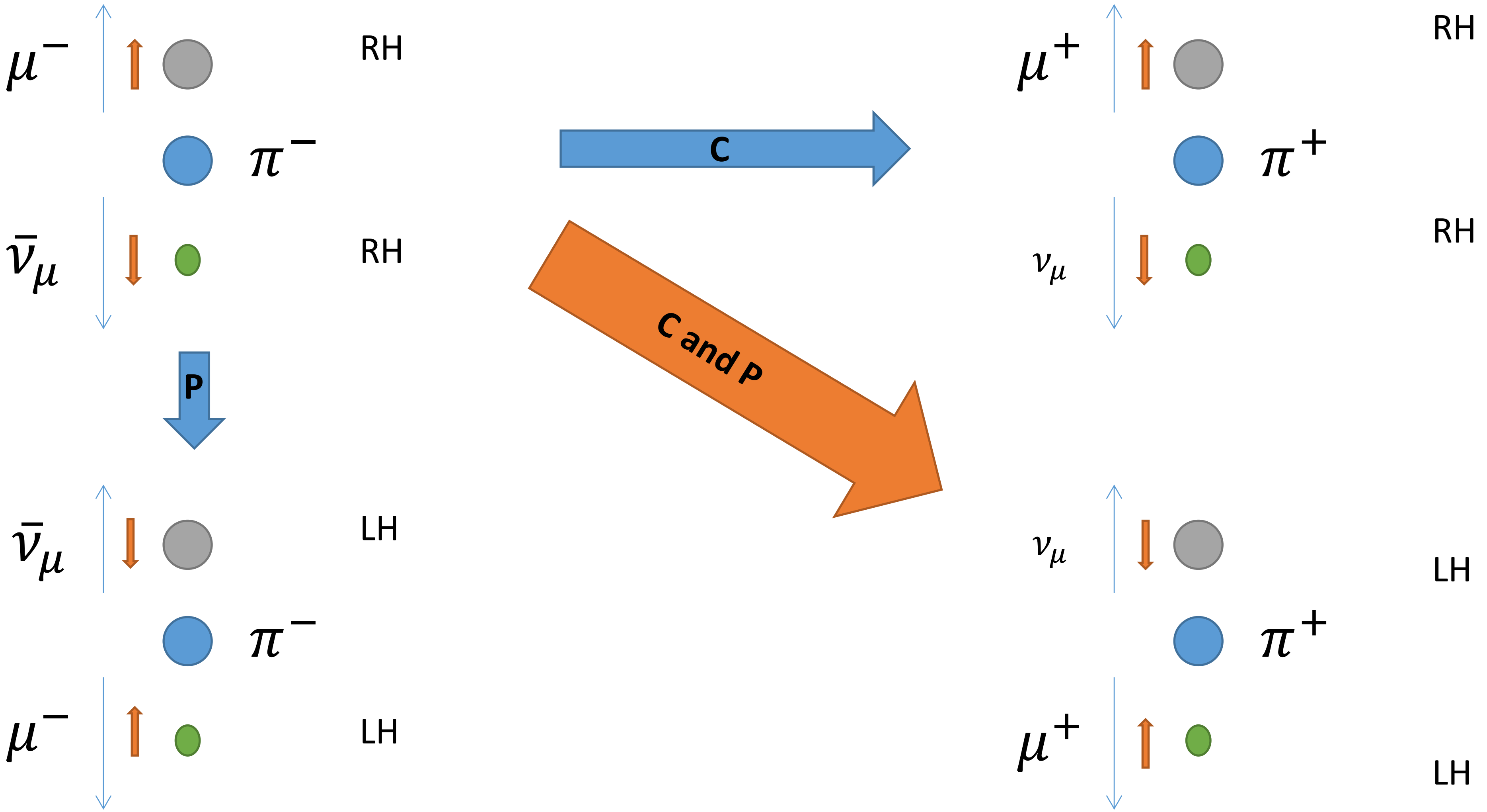
Why do we pose this question?

The Standard Model and Symmetries

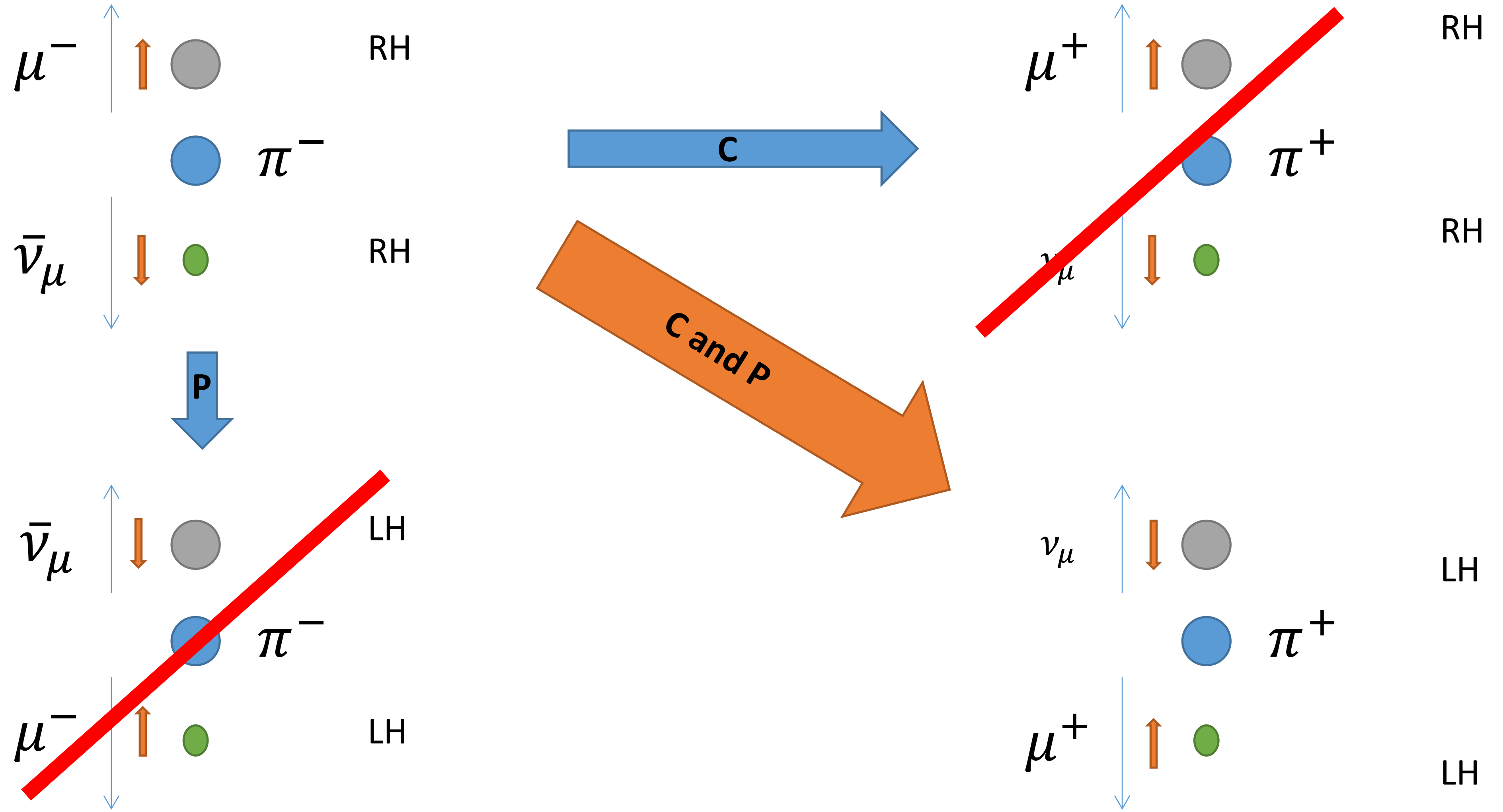
Breaking of all discrete symmetries observed in the Standard Model (SM):

- C (charge) transformation: Particle into antiparticle
- P (parity) transformation: Point transformation in (0,0,0,0)
- T (time) reversal

Which one is allowed?



Which one is allowed?



The Standard Model and Symmetries

Nowadays combined CPT symmetry believed to hold

CPT Theorem

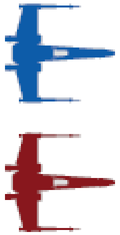
It can be shown that any quantum field theory within the SM is invariant under CPT transformations (Wolfgang Pauli and Gerhart Lüders)

CPT theorem: consequence of

- Lorentz-invariance
- local interactions
- unitarity
  - *Lüders, Pauli, Bell, Jost 1955*

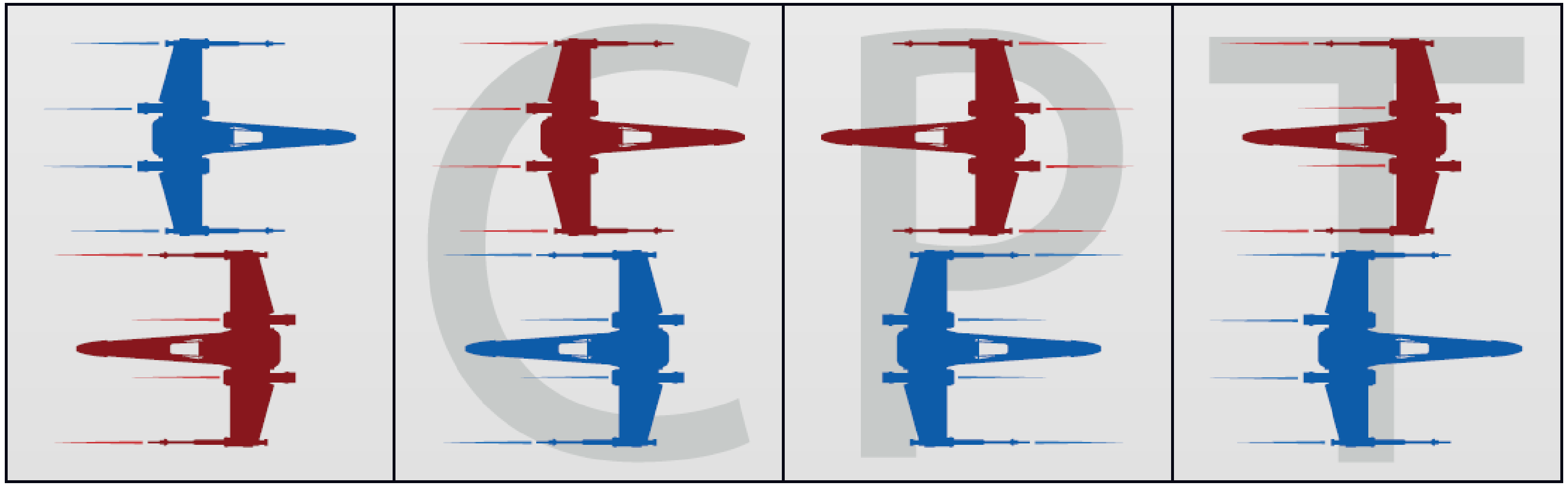
The Standard Model and Antimatter

<u>What does this mean?</u>



Matter

Antimatter



The Standard Model and Antimatter

Formal: $H|\psi\rangle = E|\psi\rangle \xrightarrow{\text{CPT}} H'|\psi'\rangle = \Theta H \Theta^{-1}\Theta|\psi\rangle$

CPT Theorem:

$$H' = \Theta H \Theta^{-1} = H \longrightarrow H'|\psi'\rangle = H\Theta|\psi\rangle = \Theta H|\psi\rangle$$

$$[\Theta, H] = 0 \qquad H'|\psi'\rangle = \Theta E|\psi\rangle = E|\psi'\rangle$$

<u>The Consequence:</u> Particles and Antiparticles share the same Eigenvalue

The Standard Model and Antimatter

Particle at rest:

$\Rightarrow$ $\bar{m} = m$

Spin in magnetic field:

$$e \rightarrow -e,\ \boldsymbol{s} \rightarrow -\boldsymbol{s},\ m \rightarrow \bar{m},\ g \rightarrow \bar{g},\ \boldsymbol{B} \rightarrow \boldsymbol{B}$$

$$E = m - g\left(\frac{e\hbar}{2mc}\right)\boldsymbol{s}\cdot\boldsymbol{B} \qquad E = \bar{m} - \bar{g}\left(\frac{e\hbar}{2\bar{m}c}\right)\boldsymbol{s}\cdot\boldsymbol{B}$$

$\Rightarrow$ $\bar{g} = g$

<u>Coupling constant for particles and antiparticles are equal</u>

Properties of particles and antiparticle are equal e.g. mass, lifetime, charge (sign) AND Particles-Antiparticle pairs created in equal amounts

How to produce an antimatter/matter imbalance – Possibility I

The three Sakharov conditions (only quantitative picture):

1. Baryon number violation

   If every interaction conserves the B-number, it will always be conserved globally. Need process

$$X \rightarrow Y + B$$

How to produce an antimatter/matter imbalance – Possibility I

The three Sakharov conditions (only quantitative picture):

1. Baryon number violation

   If every interaction conserves the B-number, it will always be conserved globally. Need process

$$X \rightarrow Y + B$$

2. C and CP Violation

   If C conserved every B-number violating process has C conjugated process at same rate. Avoid

$$\text{Rate}(X \rightarrow Y + B) = \text{Rate}(\overline{X} \rightarrow \overline{Y} + \overline{B})$$

How to produce an antimatter/matter imbalance – Possibility I

The three Sakharov conditions (only quantitative picture):

1. Baryon number violation

If every interaction conserves the B-number, it will always be conserved globally. Need process

$$X \rightarrow Y + B$$

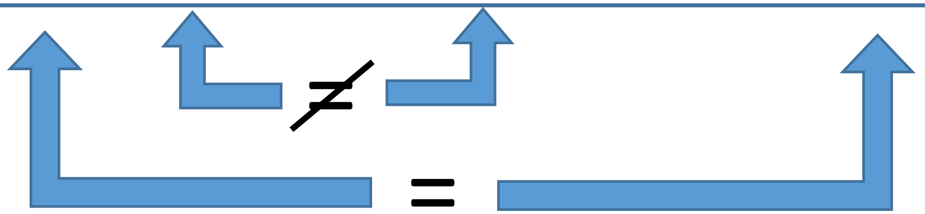
2. C and CP Violation

If C conserved every B-number violating process has C conjugated process at same rate. Avoid

$$\text{Rate}(X \rightarrow Y + B) = \text{Rate}(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

If CP conserved every B-number violating process has CP conjugated process at same rate. Avoid

$$\text{Rate}(X \rightarrow q_l q_l) + \text{Rate}(X \rightarrow q_r q_r) = \text{Rate}(\bar{X} \rightarrow \bar{q}_r \bar{q}_r) + \text{Rate}(\bar{X} \rightarrow \bar{q}_l \bar{q}_l)$$



How to produce an antimatter/matter imbalance – Possibility I

The three Sakharov conditions (only quantitative picture):

1. Baryon number violation

   If every interaction conserves the B-number, it will always be conserved globally. Need process

$$X \rightarrow Y + B$$

2. C and CP Violation

   If C conserved every B-number violating process has C conjugated process at same rate. Avoid

$$\text{Rate}(X \rightarrow Y + B) = \text{Rate}(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

   If CP conserved every B-number violating process has CP conjugated process at same rate. Avoid

$$\text{Rate}(X \rightarrow q_l q_l) + \text{Rate}(X \rightarrow q_r q_r) = \text{Rate}(\bar{X} \rightarrow \bar{q}_r \bar{q}_r) + \text{Rate}(\bar{X} \rightarrow \bar{q}_l \bar{q}_l)$$

3. Thermodynamic Non-Equilibrium

$$\text{Rate}(X \rightarrow Y + B) \neq \text{Rate}(Y + B \rightarrow X)$$

CP violation in the Kaon system

Neutral Kaon can decay in 2 or 3 pions

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

$$J^P(\pi^\pm) = 0^- \quad J^{PC}(\pi^0) = 0^{-+}$$

Produkt	C	P	CP
$\pi^0\pi^0$	$+1$	$+1$	$+1$
$\pi^+\pi^-$	$+1$	$+1$	$+1$
$\pi^0\pi^0\pi^0$	$+1$	-1	-1
$\pi^+\pi^-\pi^0$	$+1$	-1	-1

Construct CP eigenstates

$$|K_1\rangle := \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \quad CP = +1$$

$$|K_2\rangle := \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \quad CP = -1$$

Decay of K_2 into 3 pions long-lifed

$$W = \frac{2\pi}{\hbar} |\mathcal{M}_{fi}|^2 \cdot \varrho(E') \,.$$

CP violation in the Kaon system

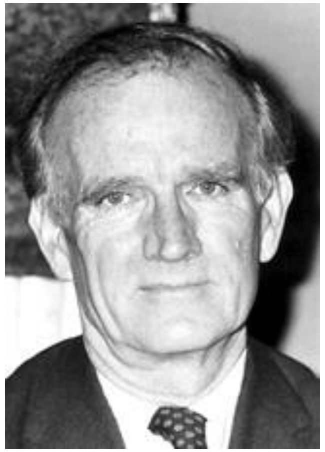
Brookhaven

$\tau(K_1) = 0{,}9 \cdot 10^{-10}$ s

$\tau(K_2) = 0{,}5 \cdot 10^{-7}$ s

Nobel Prize 1980

James Watson Cronin



Val Logsdon Fitch

But observed decay of long-lived state into 2 pions

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

There are several processes possible

		Size of effect
Parity violation	1956 Theory: Lee & Yang 1957 ß-decay Wu et al. $\pi \to \mu \to e$ decay	100%
CP violation	1964 K_0 decays: Cronin & Fitch 2001 B decays: BELLE, BaBar	$\varepsilon \sim 2.3 \times 10^{-3}$

So far experimentally observed CP violation cannot explain the large baryon asymmetry

- **Search for CP violation in other systems – e.g. neutrino oscillations**
- **Try to describe asymmetry by other process**

How to produce an antimatter/matter imbalance – Possibility II

Kostelecy (only quantitative picture):

1. Baryon number violation

   If every interaction conserves the B-number, it will always be conserved globally. Need process

$$X \rightarrow Y + B$$

2. CPT Violation

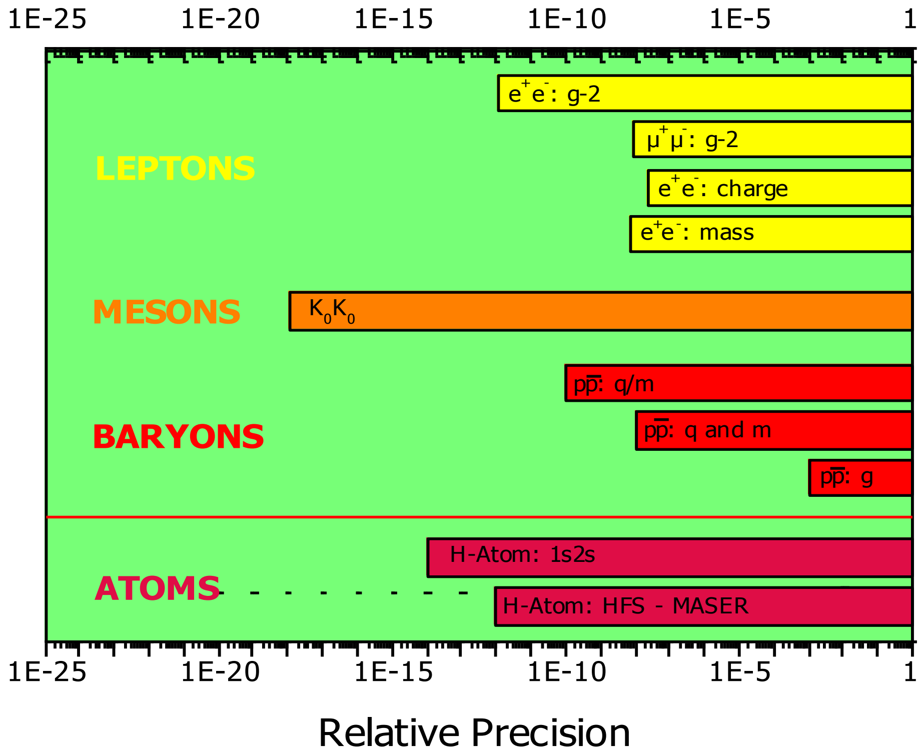
$$\text{Rate}(X \rightarrow Y + B) \neq \text{Rate}(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

$$\text{Rate}(X \rightarrow Y + B) \neq \text{Rate}(Y + B \rightarrow X)$$

3. Thermodynamic Equilibrium

The strategy

Compare matter and antimatter with ultra high precision….



… where any difference would directly hint to physics beyond the SM

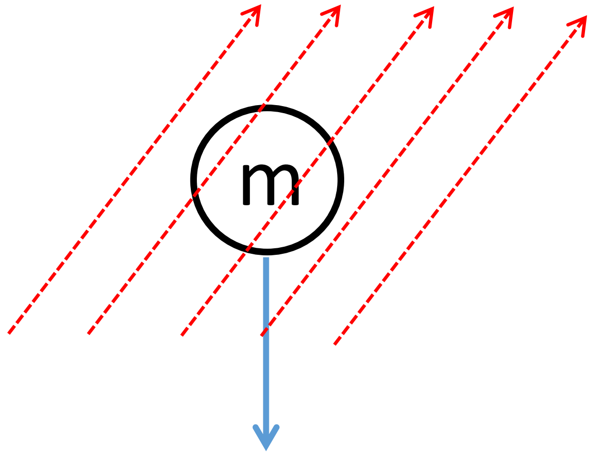
What could be the origin of CPT vilation?

Described by so-called Standard Model Extension:

Which implements CPT violation and Lorentz-violation via non-dynamical background-fields

Example:

$$\vec{F} = m\vec{a} + \vec{b} \times \vec{a} + \cdots$$



Extend SM for CPT Lorentz violating fields

Why Lorentz transformation?

- It has been shown that CPT violation always causes Lorentz-violation
- But Lorentz-violation does not necessarily imply CPT violation

The Standardmodel Extension (SME)

Dirac equation within framework of SME

$$\left(i\gamma^{\mu}D_{\mu} - m_e - a^e_{\mu}\gamma^{\mu} - b^e_{\mu}\gamma_5\gamma^{\mu} - \tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^{\mu}D^{\nu} + id^e_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu}\right)\psi = 0 .$$

CPT & Lorentz violation

Lorentz violation

D. Colladay and V.A. Kostelecky, PRD 55 (1997) 6760.

a_μ, b_μ: CPT and Lorentz-violating background-fields

Meaning for a simple matter-antimatter system?

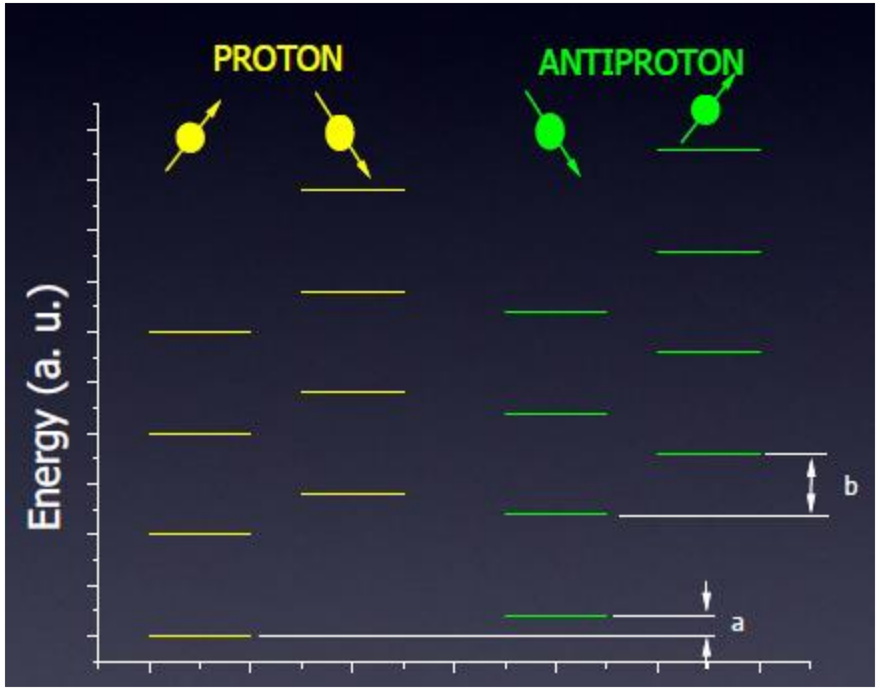
SME in a Penning trap I

SME reduces to

$$\left(i\gamma^{\mu}D_{\mu}-m-a_{\mu}\gamma^{\mu}-b_{\mu}\gamma^{5}\gamma^{\mu}\right)\psi=0$$

a – shifts levels, no measurable effect in Penning trap
b – modification of anomaly frequency

$$r_g=\frac{E_p-E_{\bar{p}}}{E_p}=\frac{\delta\omega_a}{m}$$



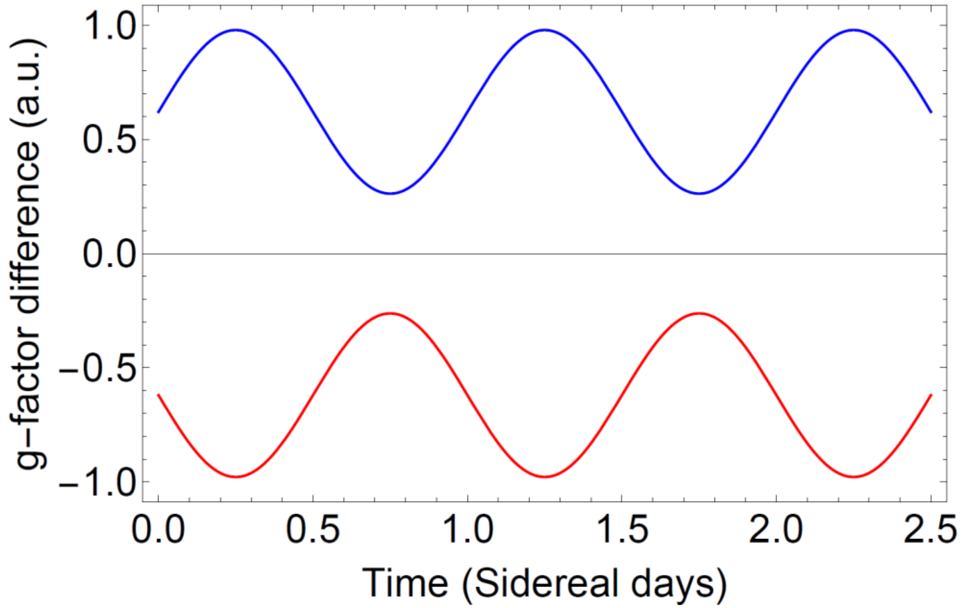
SME in a Penning trap II

Frequencies become dependent on the experiment orientation relative to the SME fields

Sidereal variation of the measured frequencies occur
Hypothetical signature of CPT violation:

SME figure of merit: $$\frac{\delta E}{E} = \frac{h\,\Delta v}{m\,c^2}$$

High sensitivity: Antihydrogen GS-HFS,
Muon (g-2),
Antiproton g-factor



The Standardmodel Extension (SME) - Details

- Idea was: Add CPT violating extension to Hamiltonian of Standard Model
  Treat CPT violating terms perturbative

$$H' = H_{SM} + H_{SME}$$

Perturbative expansion →

$$< \psi^* | H_{SME} | \psi >= \Delta E$$

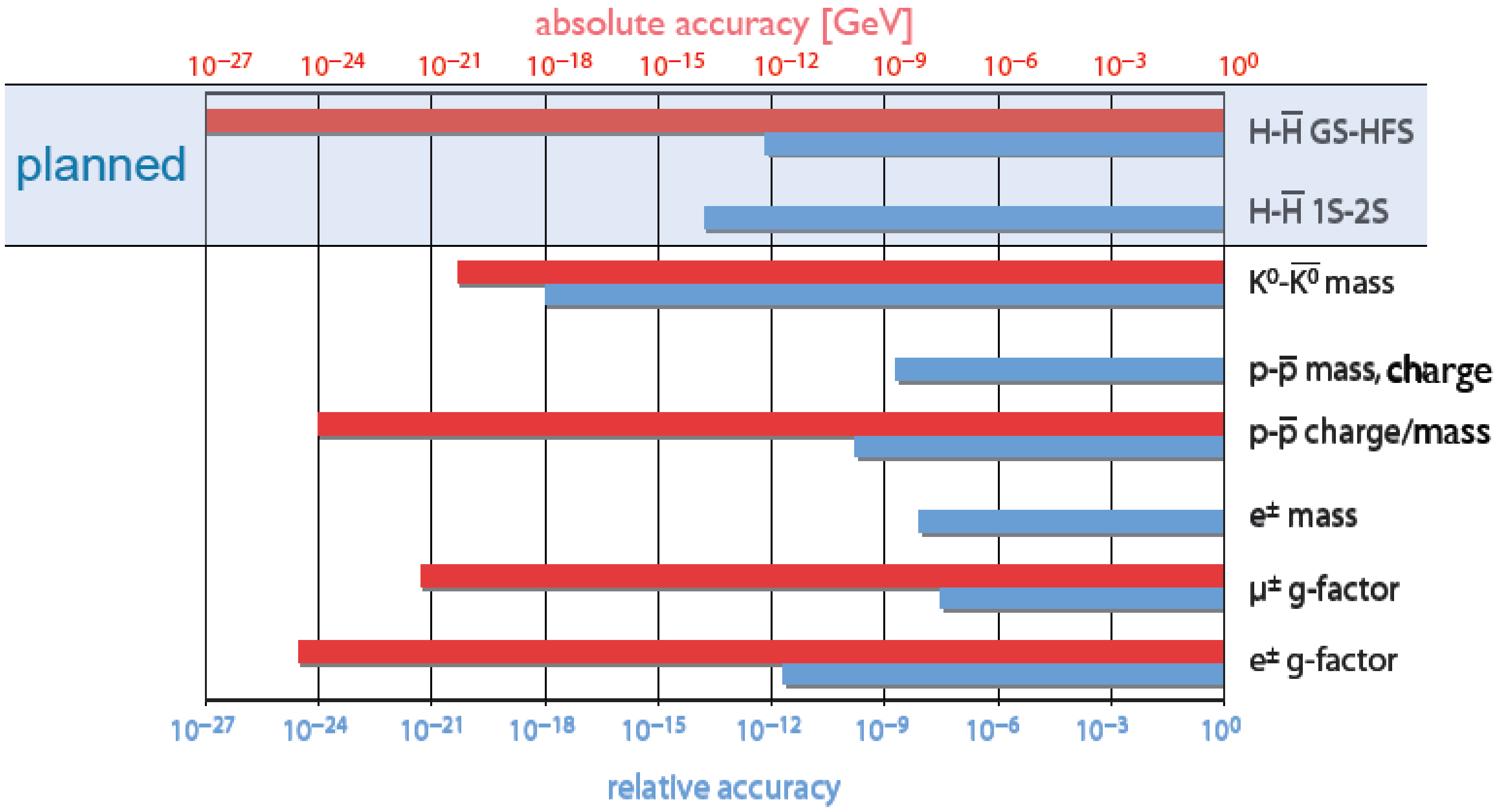
System based on SM (H_{SM})

CPT violating term – not observed yet, must be small (H_{SME})

- Contributions at absolute energy scale -
  ⇒ Absolute energy resolution is appropriate measure of sensitivity with respect to CPT violation

- High sensitivity - precise measurement at small intrinsic energy
  ⇒ precise measurement of frequencies at mueV-energy scales

SME applied to measurements



Blue: Achieved Precision

Red: Sensitivity to CPT violation

Summary

- Historical Introduction
- Dirac Equation
- Discovery of Antimatter

- Symmetries within the Standard Model of Particle Physics
- Motivation on Antimatter Physics
- Standard Model Extension
- Possible Experiments for a Search of CPT violation

A comment

I think that the discovery of antimatter was perhaps the biggest jump of all the big jumps in physics in the 20th century.

W.Heisenberg in “The physicist’s conception of Nature”, 1972