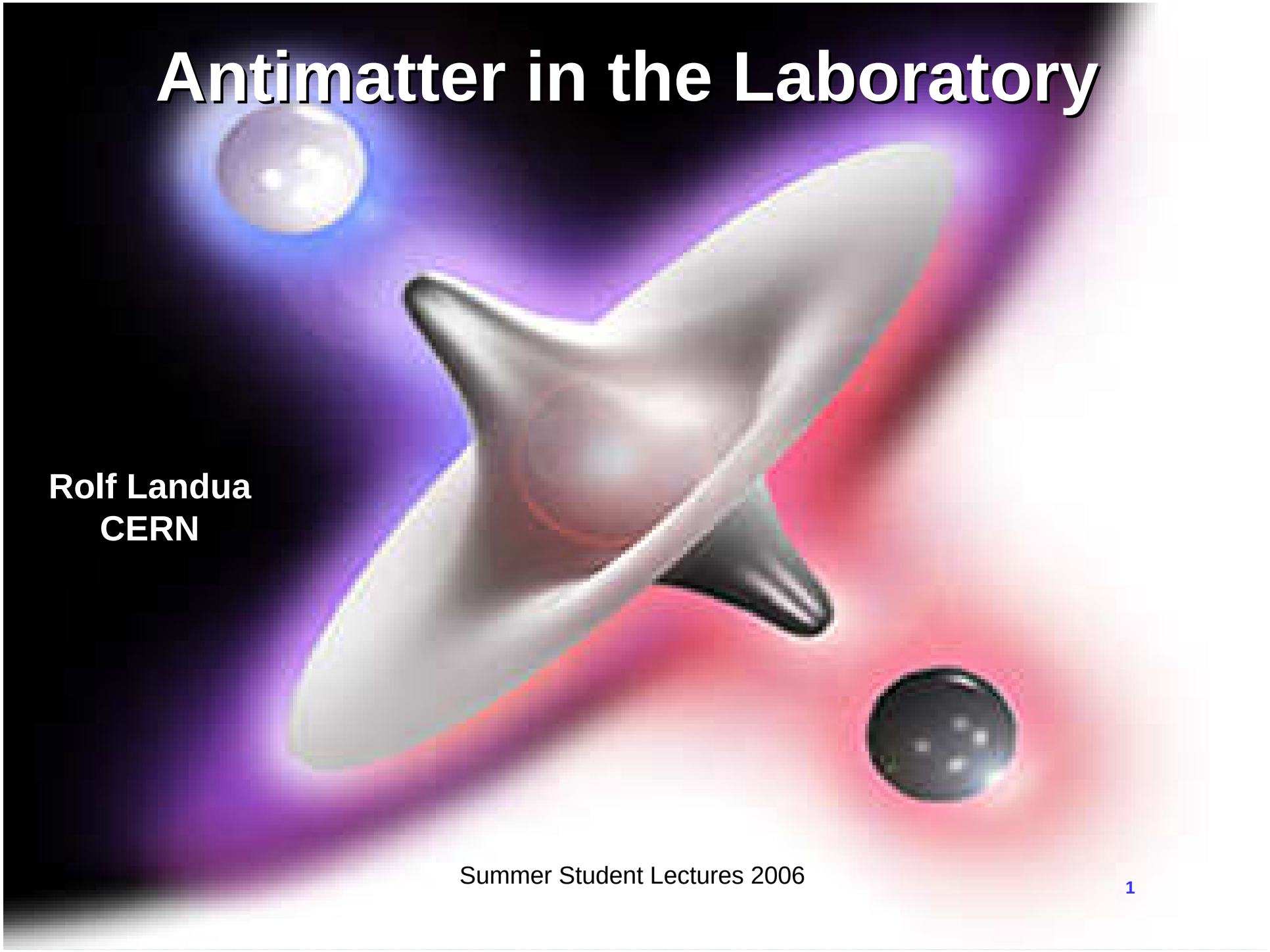
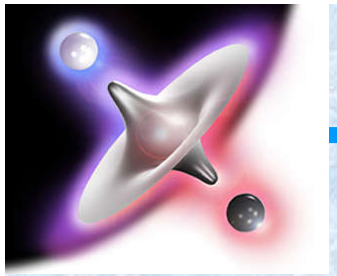
Antimatter in the Laboratory



Rolf Landua
CERN



Anti-Plan

Introduction	Einstein, Dirac, Feynman, CPT
Precision Experiments	Muon magnetic moment (g-2) Antiproton inertial mass
Antimatter 'Factory'	How are antiprotons made?
Antihydrogen	Short history ATHENA and ATRAP Making antihydrogen Future developments
Antimatter technology	PET Antiproton therapy? Rocket propulsion??

How antimatter @ CERN *really* became famous

1996
First Antihydrogen Atoms
Made at LEAR


2 BLICK • Samstag, 6. Januar 1996 AKTUELL

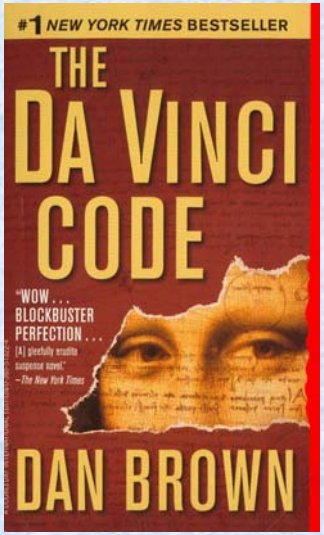
E.T., wir kommen!

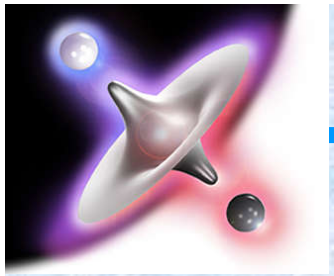
In Genf wurde Wunder-Energie entdeckt

VON WERNER BUCHER

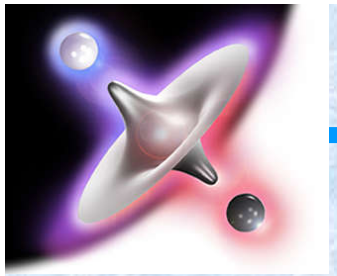
2000
CERNs 'Antimatter Factory' AD


QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.





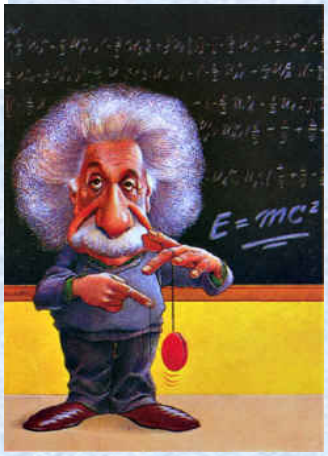
I. Introduction



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

Werner Heisenberg

Theory of special relativity



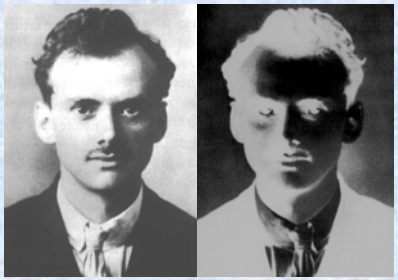
A. Einstein (1905)

Mass is condensed energy

(c^2 = exchange rate!)

$1\ kg = 9 \cdot 10^{16}\ J = 2.5 \cdot 10^{10}\ kWh = 2.85\ GW \cdot year$

Relativity + Quantum Theory = Antimatter



Paul A.M. Dirac (1928)

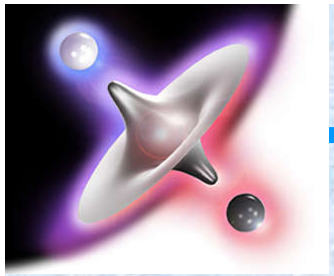
$$\psi_+ = \begin{pmatrix}1\\0\\0\\0\end{pmatrix} \text{ or } \begin{pmatrix}0\\1\\0\\0\end{pmatrix} e^{-imt}$$

$$\psi_- = \begin{pmatrix}0\\0\\1\\0\end{pmatrix} \text{ or } \begin{pmatrix}0\\0\\0\\1\end{pmatrix} e^{+imt}$$

Electron: spin 1/2

Another spin-1/2 particle??

- For $v \neq 0$, upper and lower components mix
- 1929: Positive electron = proton ????
- 1931: m(e-) = m(e+) ! Annihilation possible …



Positron discovery- why so late ?

C. D. Anderson.
Phys. Rev., **43**, 491 (1933).

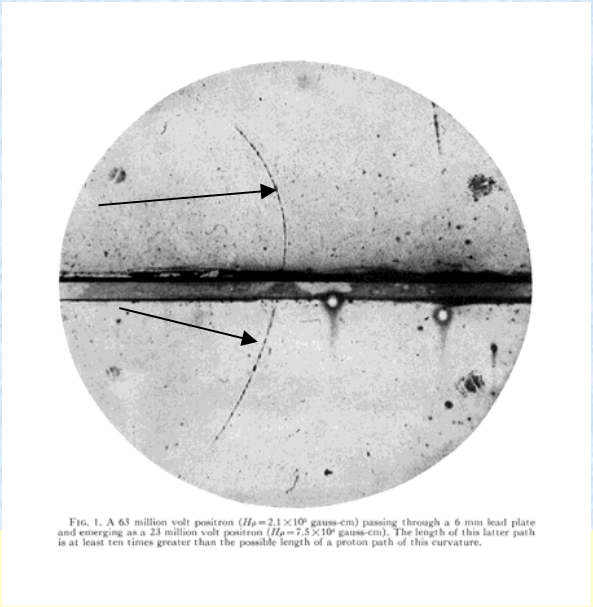


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^5$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Dirac (1932):

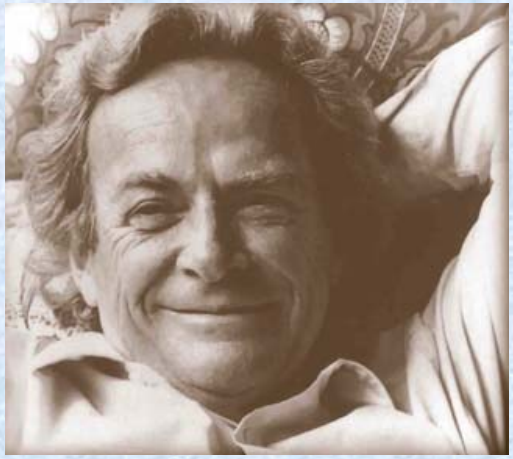
"Why did the experimentalists not see them? Because they were prejudiced against them.

The experimentalists … sometimes saw the opposite curvature, and interpreted the tracks as electrons which happened to be moving into the source, instead of the positively charged particles coming out.

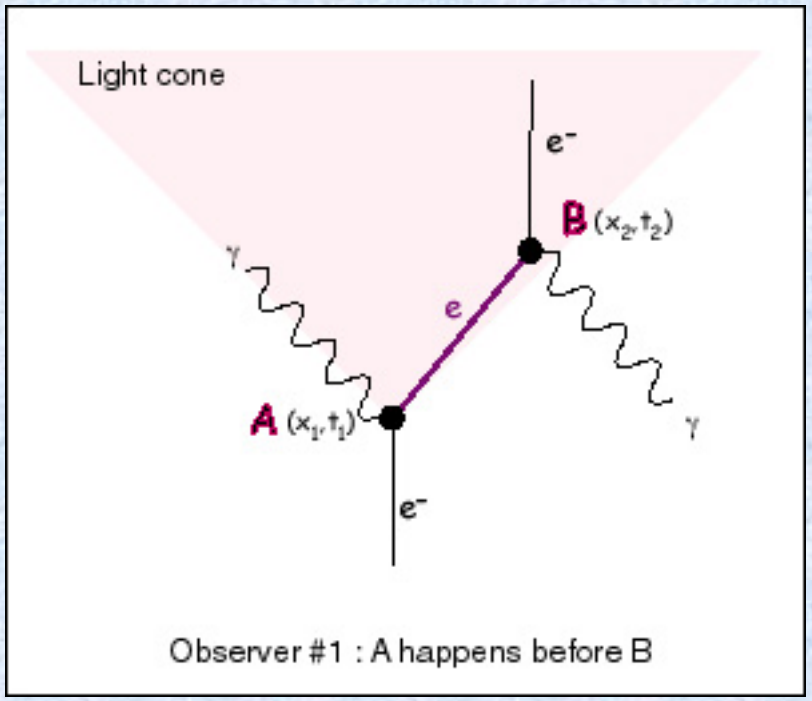
People were so prejudiced against new particles that they never examined the statistics of these particles entering the source to see that there were really too many of them."

Antimatter in Quantum Field Theory

The electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



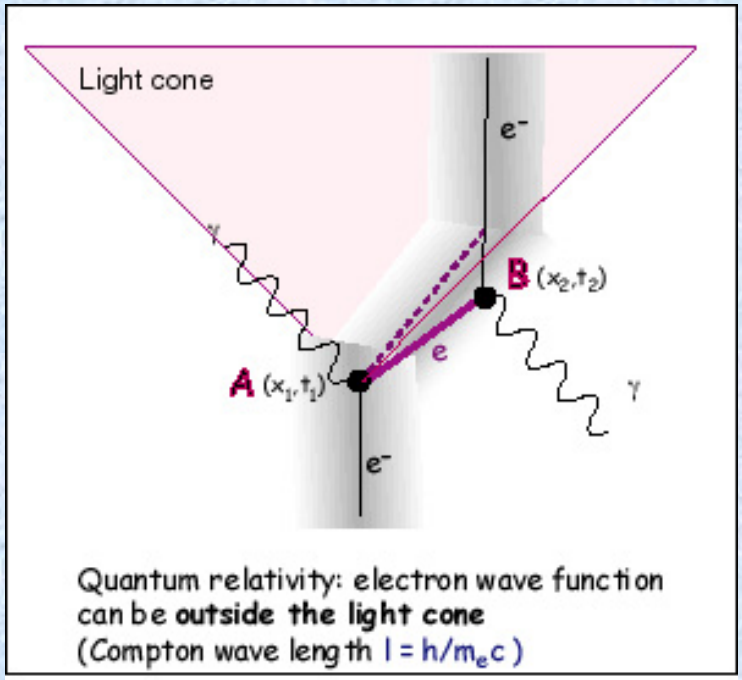
R. P. Feynman



An electron can emit a photon at A, propagate a certain distance, and then absorb another photon at B.

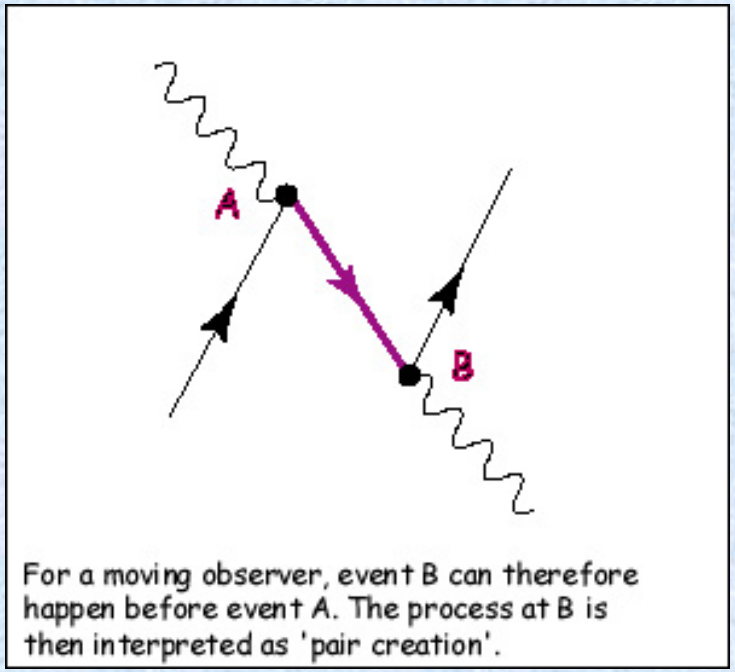
Why antimatter must exist in quantum theory

Wave function only localized within Compton wave length ($\lambda \sim 1/m$).



Quantum relativity: electron wave function can be **outside the light cone** (Compton wave length $l = h/m_e c$)

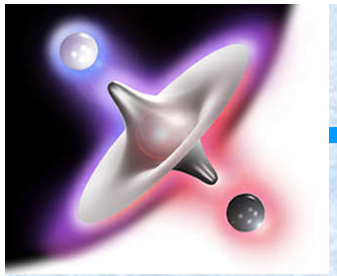
t



For a moving observer, event B can therefore happen before event A. The process at B is then interpreted as 'pair creation'.

"One observer's electron is the other observer's positron".

The presence of antiparticles is necessary to restore the **causal structure** to the process seen in another inertial system.

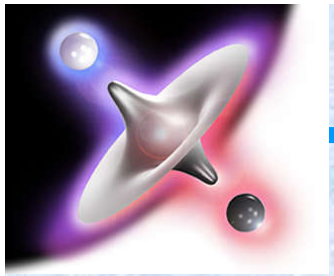


Therefore:

Every particle has an antiparticle

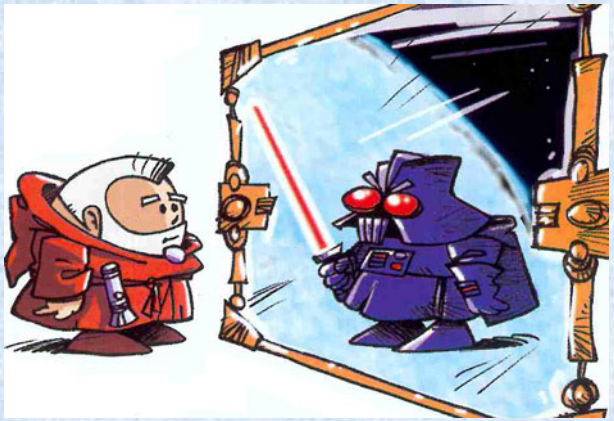
Electron Neutrino Up-Quark Down-Quark	⟷	Positron Anti-Neutrino Anti-Up-Quark Anti-Down-Quark
Muon …	⟷	Anti-Muon …
Tau …	⟷	Anti-Tau …

After Dirac, the fundamental spectrum of particles doubled
In 1973, supersymmetry made a similarly bold prediction …



Particles and antiparticles

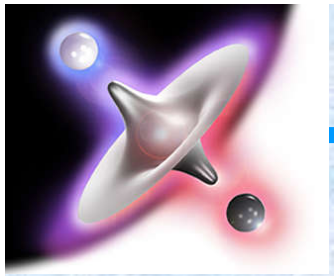
How can we imagine an 'anti-particle'?



Electron

Positron

Particles and anti-particles are two manifestations of the same underlying, but yet unknown, physical structure (superstrings??).



CPT Theorem *

IF :

1) Locality	(no action at a distance)
2) Lorentz invariance	(all inertial frames are equivalent)
3) Causality	(no interaction between two space-time points outside each other's light cone)
4) Vacuum is lowest energy state	(spin-statistics connection)

Then:

Particles and antiparticles must have

- equal masses
- equal lifetimes
- equal magnitude (opposite sign) of quantum numbers, e.g. charge
- equal energy levels of bound states

*1955 - Proof of CPT theorem by Pauli (following work by Schwinger and Lüders)

Why should we test CPT symmetry?

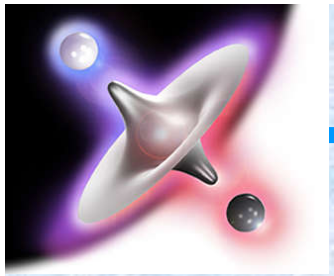
Dirac's Vision (from his Nobel lecture, 1933)

"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. The two kind of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

From his Nobel lecture (12 December 1933)

Is CP-violation the reason for cosmological imbalance? May be.

But: CPT theorem is a formidable challenge for experimentalists!
CPT Violation could give an alternative explanation.

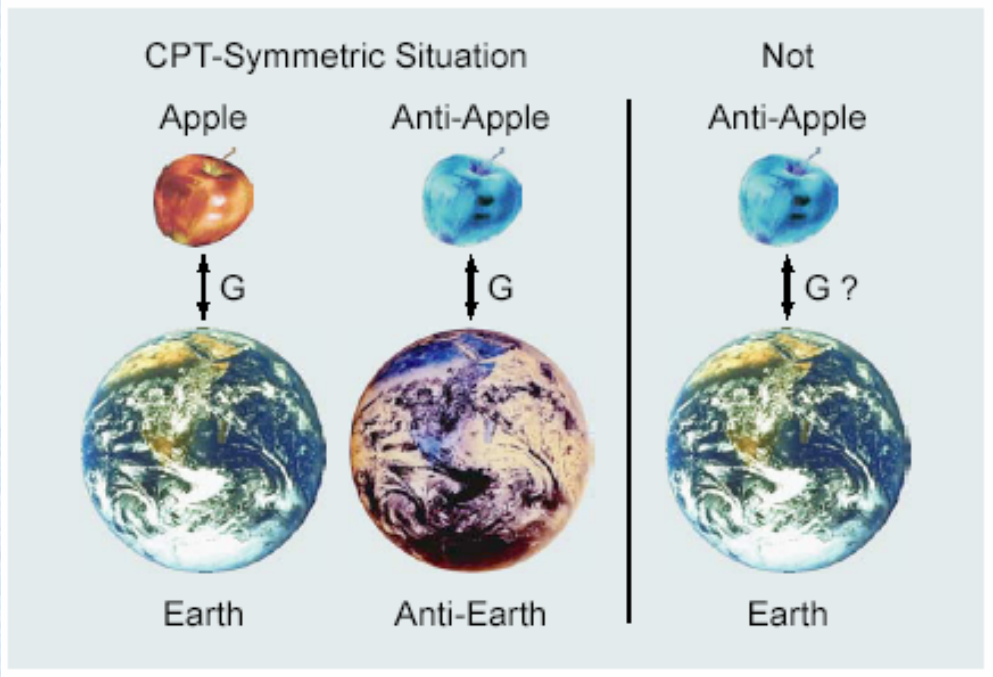


Antimatter gravitation is not constrained by CPT

"Weak" equivalence principle:

The world-line of a free falling body is independent of its composition or structure

Gravitational = Inert mass



Possible violations:

-Additional components of gravitational field (baryon number dependent)
-Short-range deviations (<< mm) from inverse square-law (e.g. due to extra-dimensions)

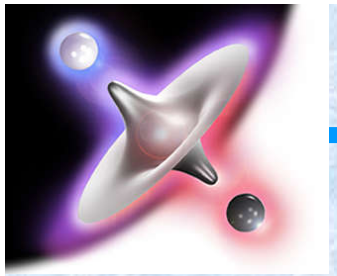
Technology in development:

Measurement of gravitational acceleration by dropping atoms

Achim Peters, Keng Yeow Chung & Steven Chu

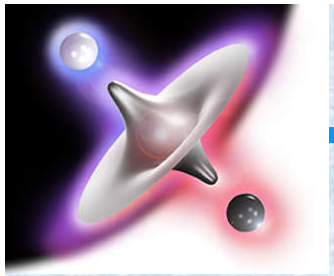
Physics Department, Stanford University, Stanford, California 94305-4060, USA

A. Peters et al., Nature 400 (1999) 849



II.

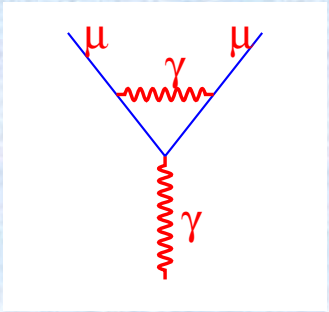
PRECISION EXPERIMENTS WITH ANTIMATTER



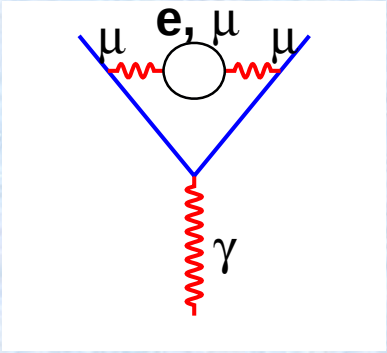
Muon (and antimuon) magnetic moment

μ_μ B = g (e/2m) B
Dirac: g = 2
QED: g = 2 (1+a)

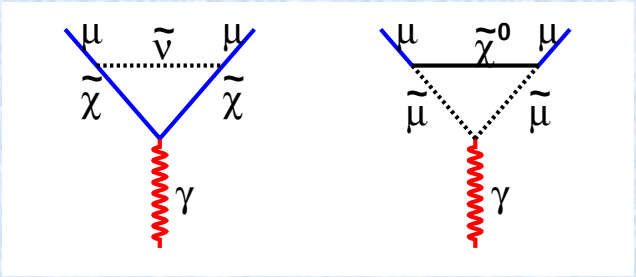
a :



Photons



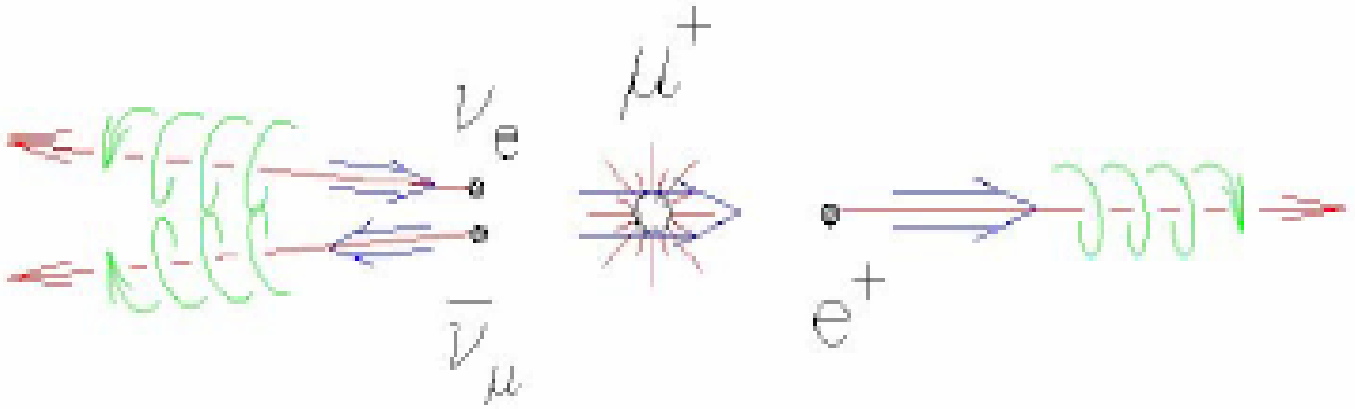
Leptons
Quarks

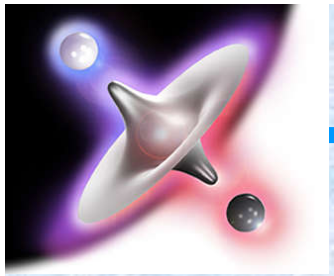


New particles?

Muon: born polarized, decaying polarized

- Muon is born polarized: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Muon shows its polarization when it dies: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

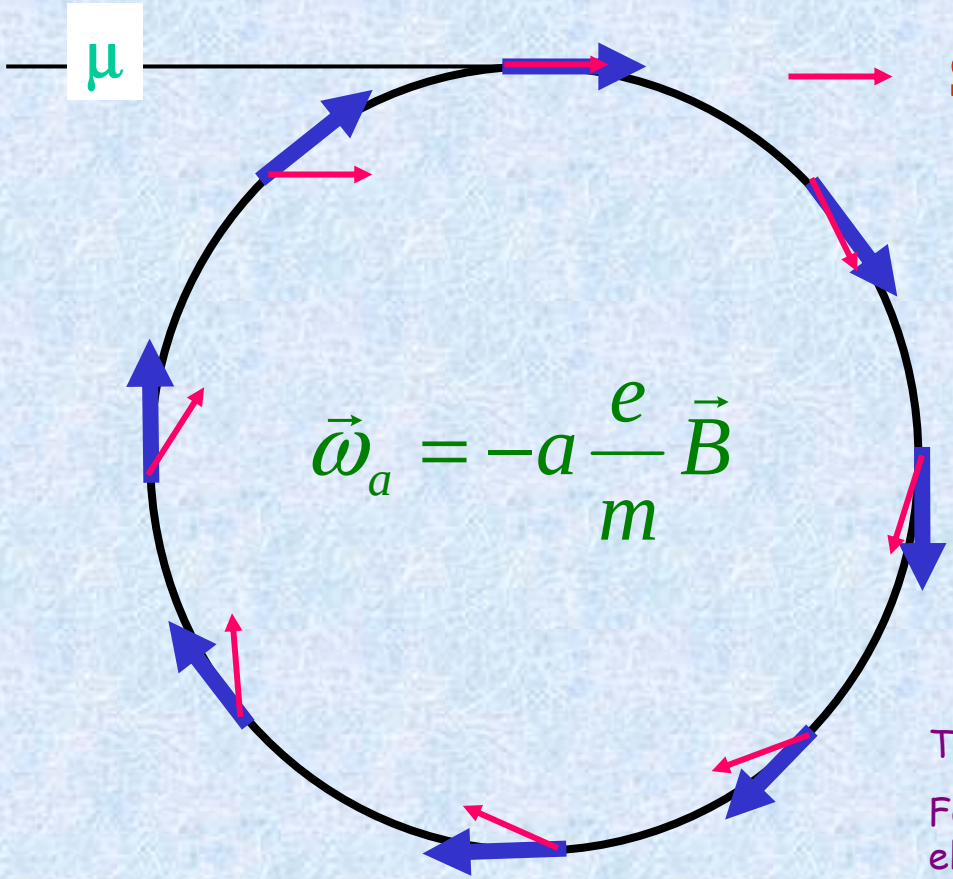




Spin Precession in storage ring

Momentum vector

Spin vector



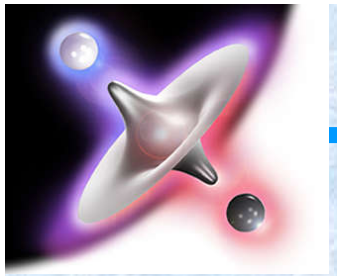
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

$$\vec{\omega}_a = -a\frac{e}{m}\vec{B}$$

$\omega_c = e/m\ B$

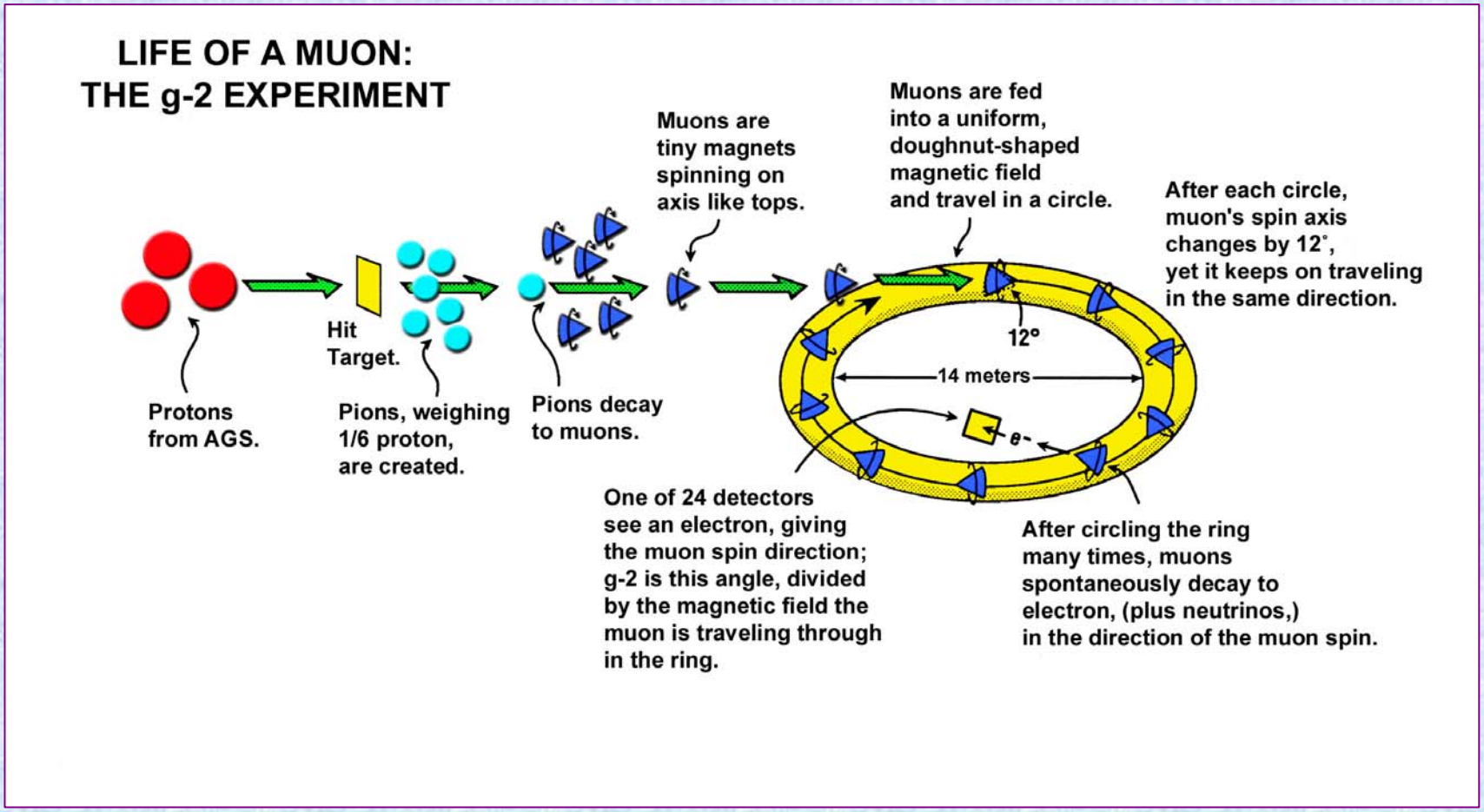
Trap with B = 1.4 T

Focus with quadrupole electric field



Principle of experiment

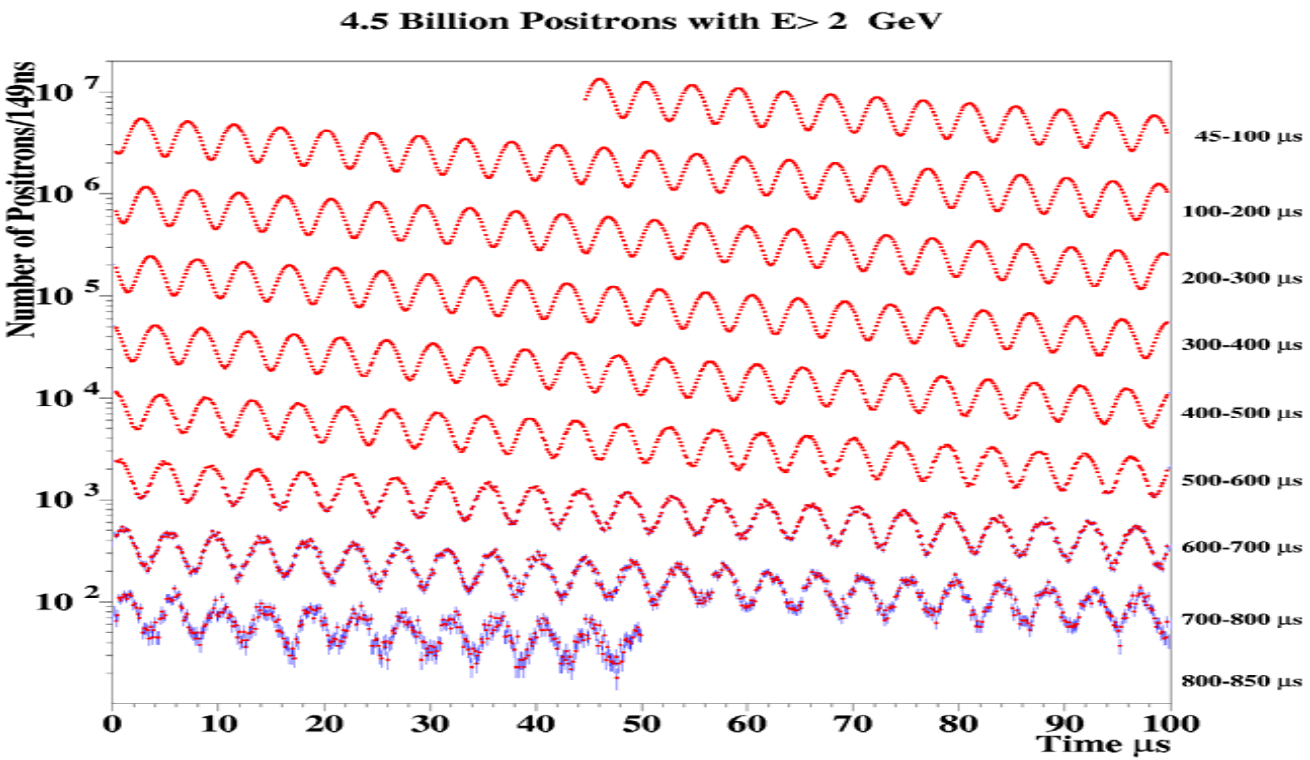
BNL 821 Brookhaven "g-2"



Muons (antimuons) circulate and decay in storage ring

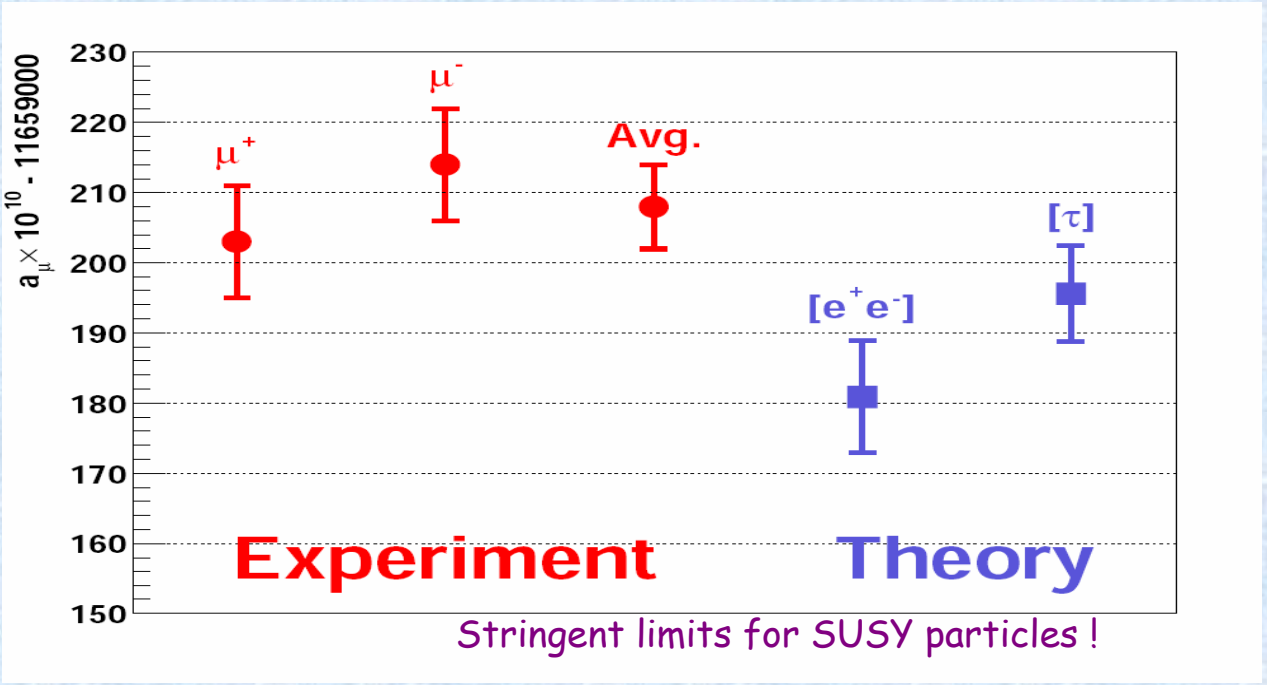
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Electron counting rate from muon decay



Results

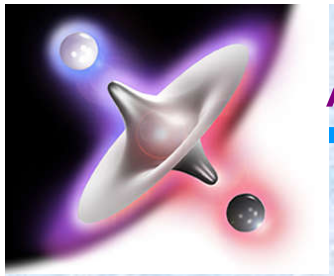
Experiment vs Theory (for negative muons):



Stringent limits for SUSY particles !

Test of CPT (positive vs negative muons):

$$(g_{\mu+} - g_{\mu-}) / g_{av} = (-2.6 \pm 1.6) \times 10^{-8}$$



A short break to think about precision measurements

Precision of a measurement increases with observation time

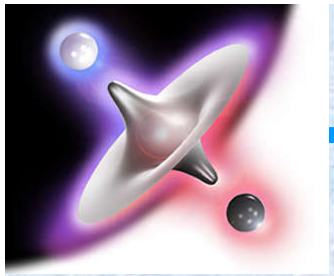
↓

Presence of other particles may decrease precision

↓

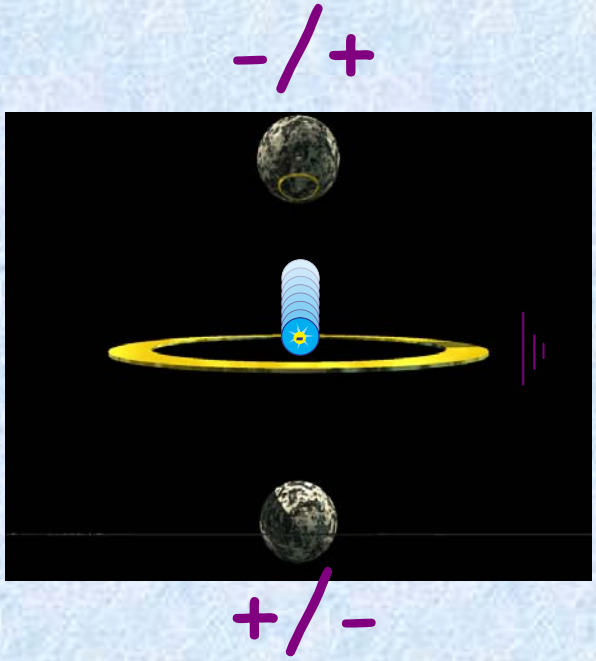
Isolate (few) particles and
observe for long times:

PARTICLE TRAPS

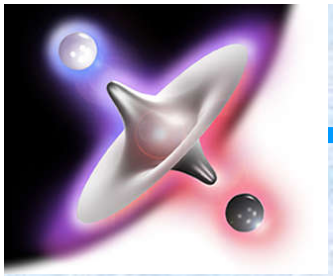


RF-trap (“Paul trap”)

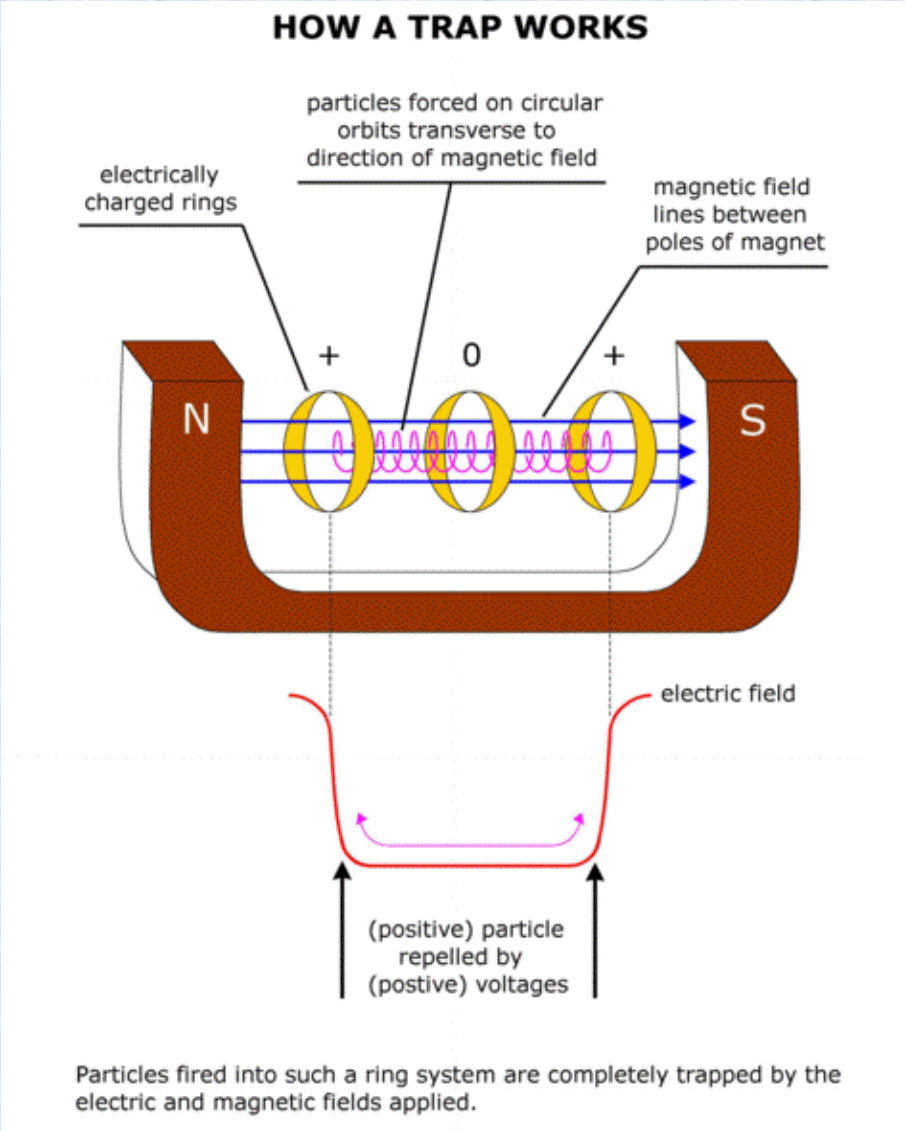
A radio-frequency current on the electrodes maintains an alternating electric field that confines charged particles in a small space.



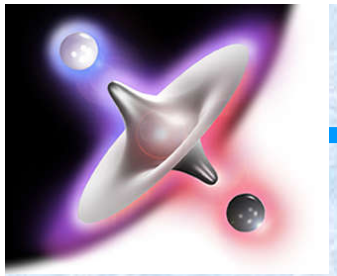
QuickTime™ and a
H.263 decompressor
are needed to see this picture.



Magnetic traps

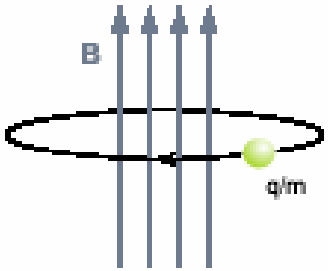


Particles fired into such a ring system are completely trapped by the electric and magnetic fields applied.



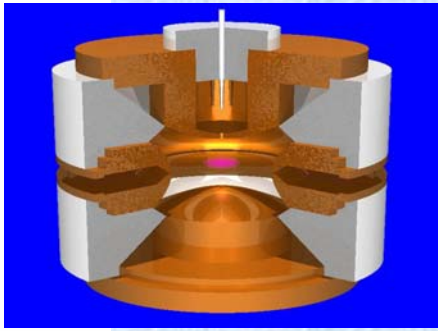
Special case: Penning trap

Motion of a charged particle in pure magnetic field:



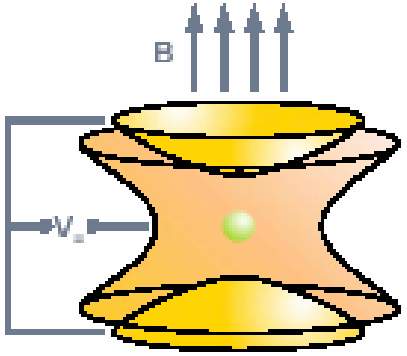
Cyclotron frequency:

$$f_c = \frac{1}{2\pi}\frac{q}{m}B$$

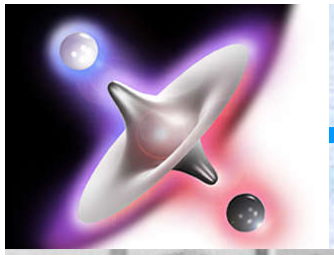


Penning trap:

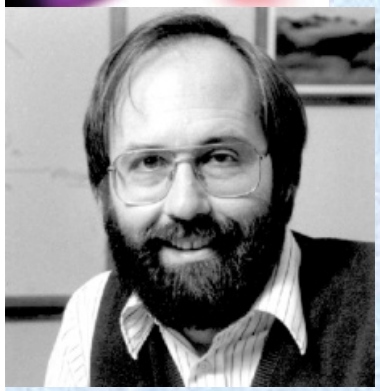
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field



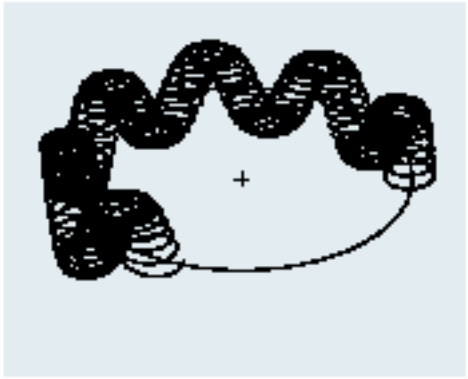
H. G. Dehmelt
1959



Antiproton Charge-to-Mass ratio (PS 196, LEAR)

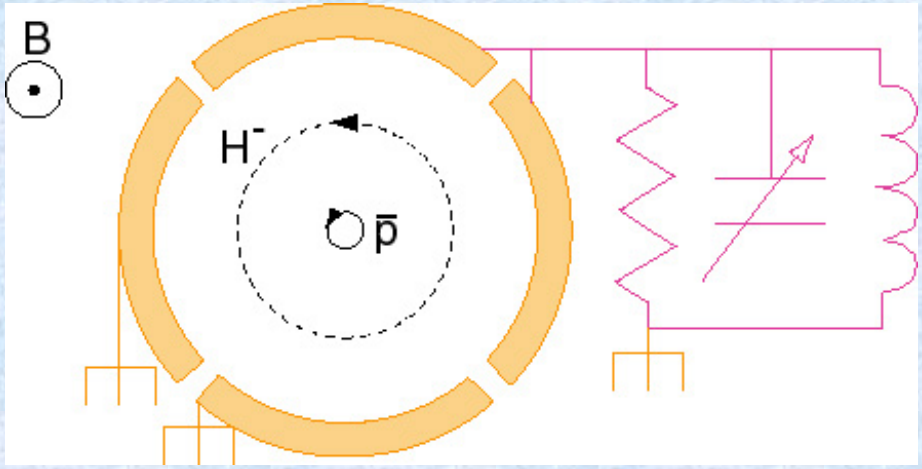


G. Gabrielse



Typical frequencies
$q = \pm e$, $B = 3$ T

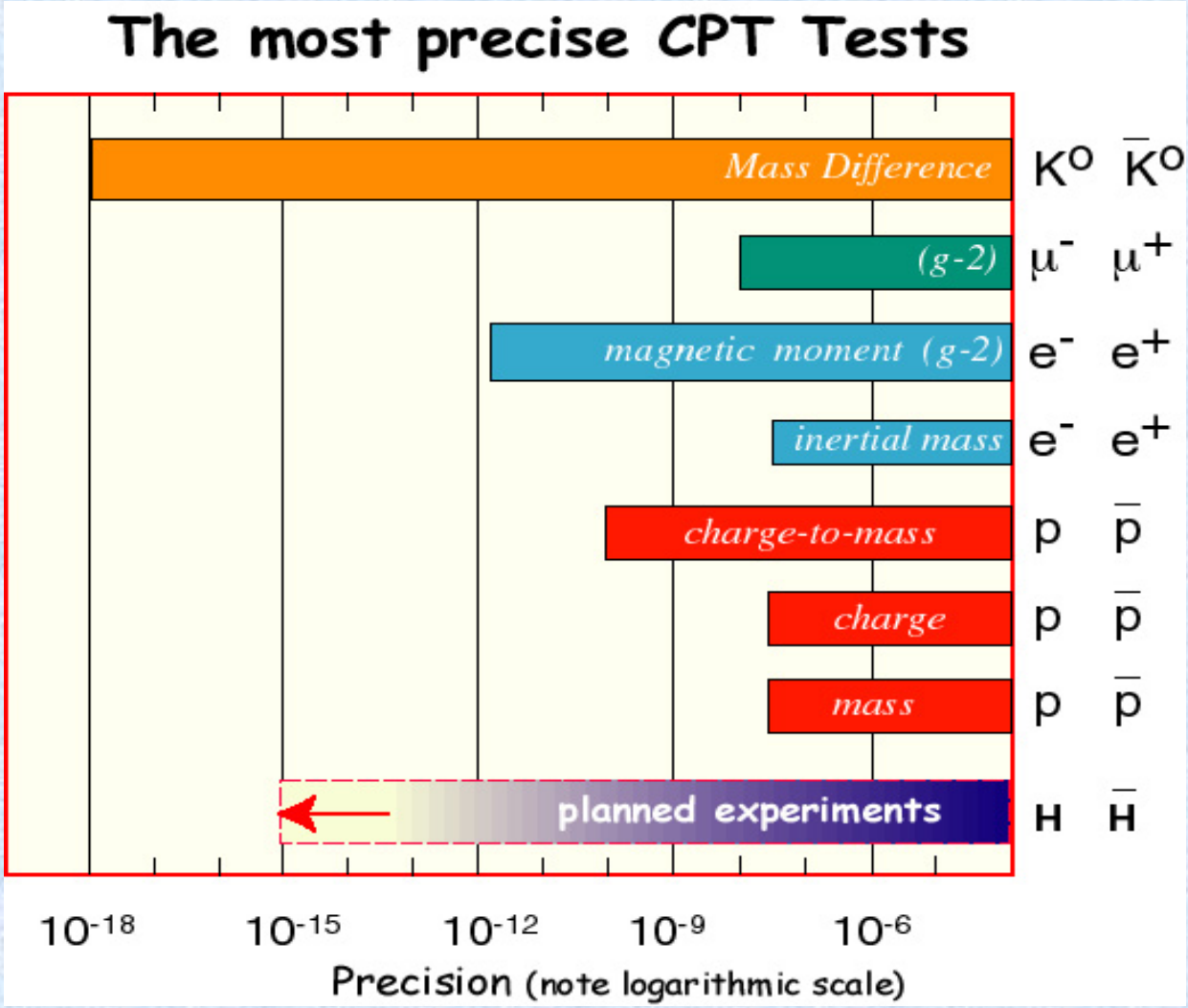
$\Rightarrow$ $f_- \approx$ kHz
$f_+ \approx 45$ MHz $(p/\bar{p})$
$f_+ \approx 100$ GHz $(e^{\pm})$

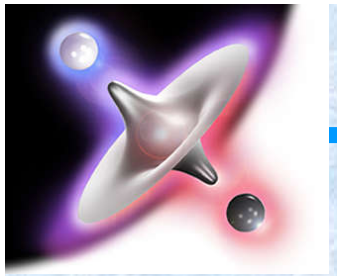


Compare cyclotron frequency of antiprotons and H- ions (B = 5.3 T)

Q/M difference (proton/antiproton) : $< 9 \times 10^{-11}$

Summary “Precision Measurements”





How do we 'make' antiprotons / antihydrogen ?

To do what?

Antimatter in our daily life?