UNIVERSITY OF BIRMINGHAM

Frontier Science: The mystery of Antimatter

Cristina Lazzeroni
Professor in Particle Physics
STFC Public Engagement Fellow

ASE Frontier Science Lecture
University of Birmingham
Poynting Physics S02
7th January 2016, 14:30-15:30

Science & Technology Facilities Council

erc
European Research Council
Established by the European Commission

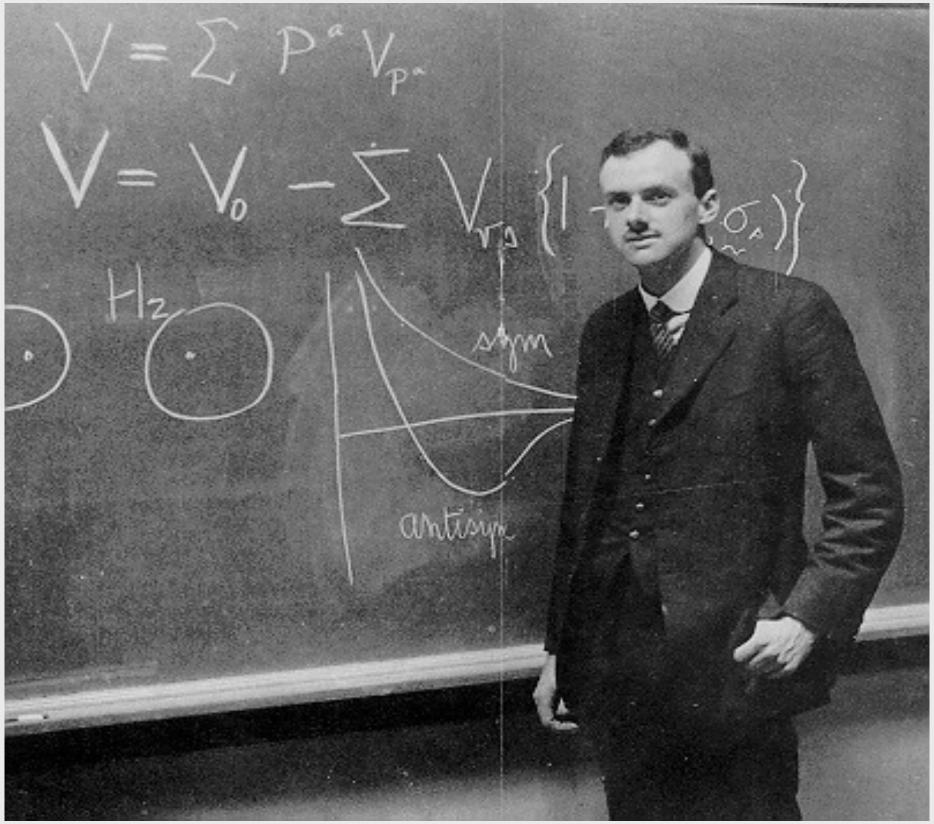
Cambridge, 1928 :

Dirac predicted the existence of the positron e+, same mass but opposite charge to e-

Quantum Mechanics

Special Relativity

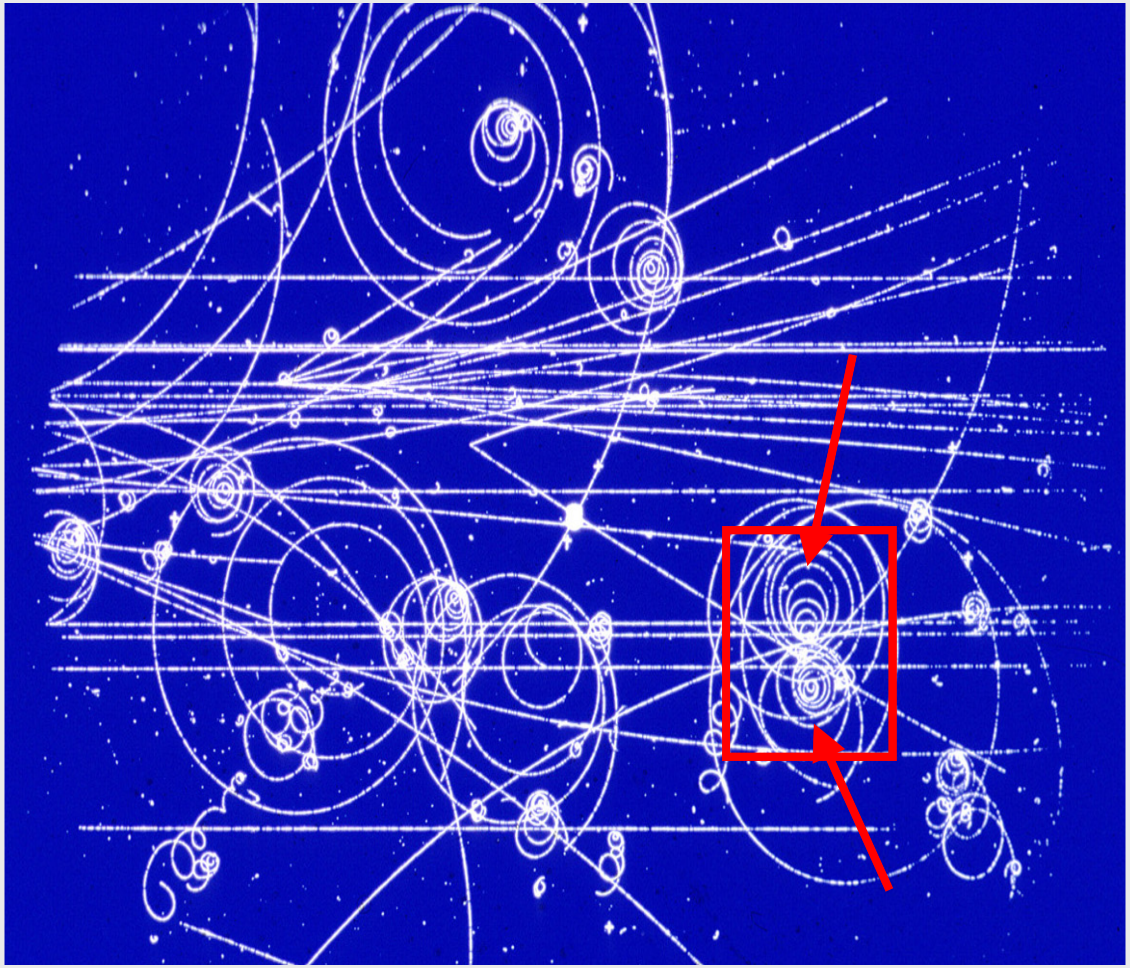
$$\left(i\hbar\gamma^{\mu}\partial_{\mu} - mc\right)\psi = 0$$



The Dirac Equation

Since then, many observations done but mechanism/origin not yet clear

Particle Beam interacting in Hydrogen - Positron discovered by Anderson in 1933



- Then studied in Bubble Chambers

- Charged particles leave a trail of bubbles after they pass through, similar to the trails left by jet airplanes

<u>Electrons and positrons tracks are common</u>

Antimatter

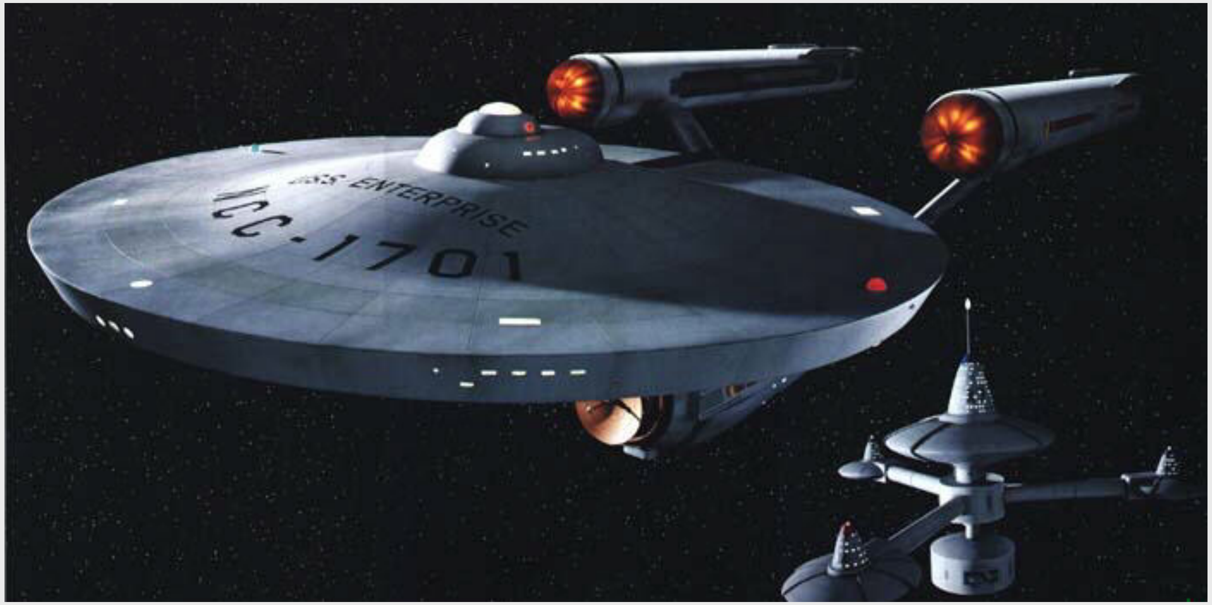
❖ Every fundamental particle has its antiparticle.

- These have the same mass but opposite charge.

electron	e^-	e^+	**positron**
up quark	$u^{+2/3}$	$\bar{u}^{-2/3}$	**up anti-quark**

and, if they are unstable : the same lifetime

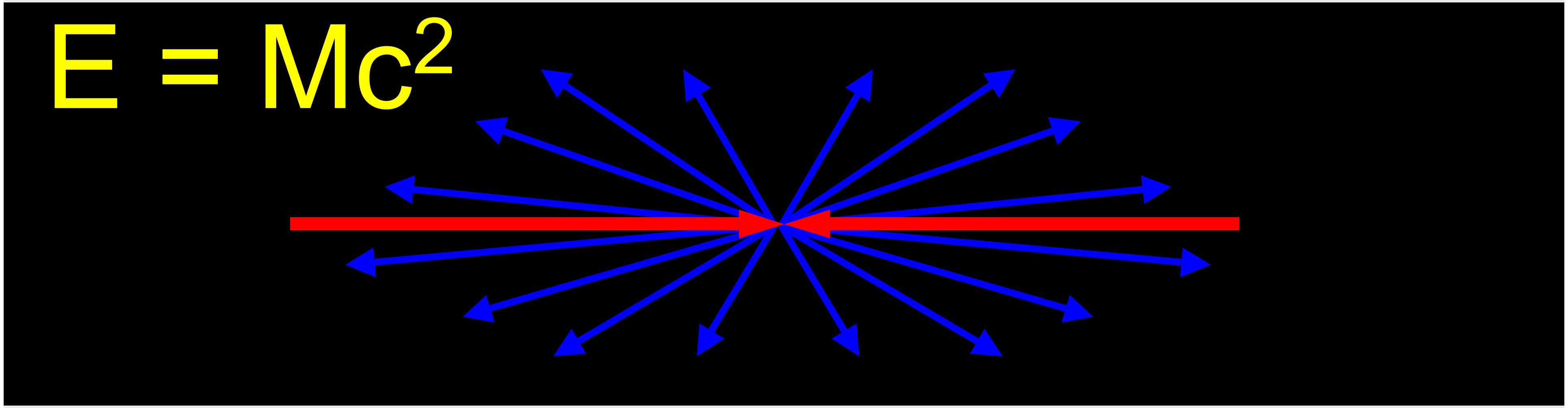
Antimatter exists…



Where is the largest concentration of antimatter in the known Universe?

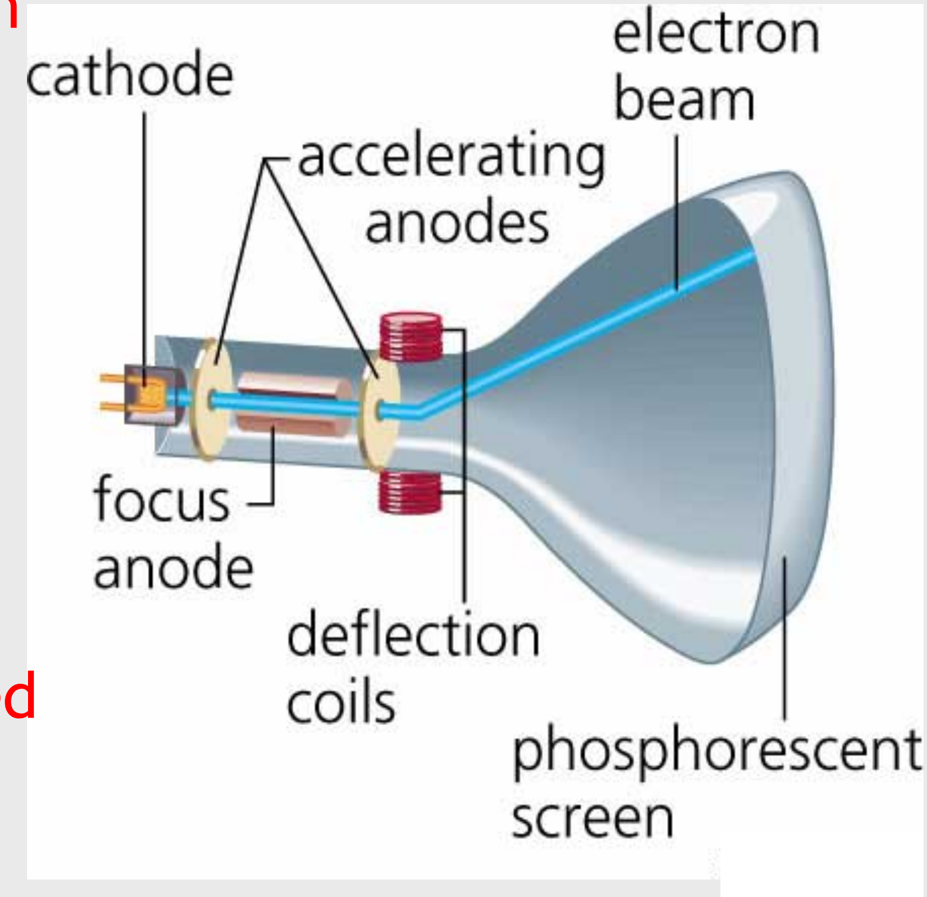
Particle accelerators !!!

Particles accelerated to speed of light :



Protons smashing together can produce all sorts of particles, seen in the earliest moments of the universe

- TV accelerate electrons through a potential difference (battery)
- Bend them using magnets
- Image on light-emitting screen



Particle physics accelerators are giant cathode ray tubes!

A USEFUL UNIT

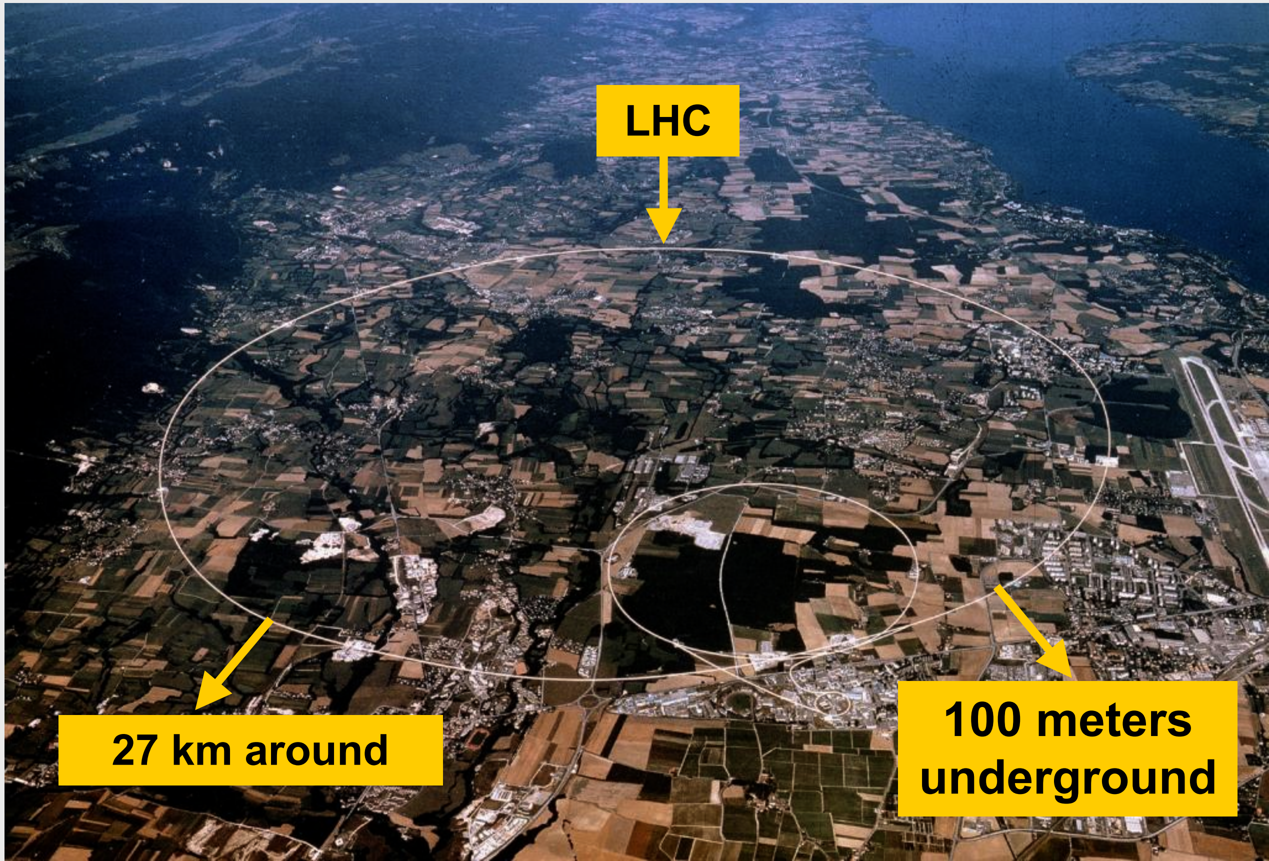
A particle of charge q accelerated through a voltage V acquires a kinetic energy KE=qV.

1 volt gives an electron an energy of 1 electron-volt (eV)

- A cathode ray tube TV accelerates electrons to ~ 20,000 eV
- A Large Hadron Collider accelerates protons to 7,000,000,000,000 eV

The Large Hadron Collider

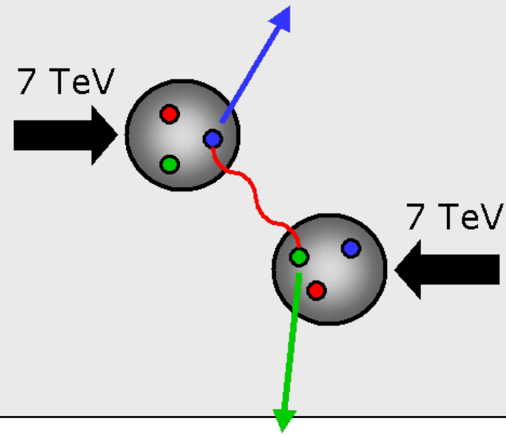
LHC is an accelerator located at CERN



Protons circulate in opposite directions and collide inside experimental areas

The Large Hadron Collider - facts

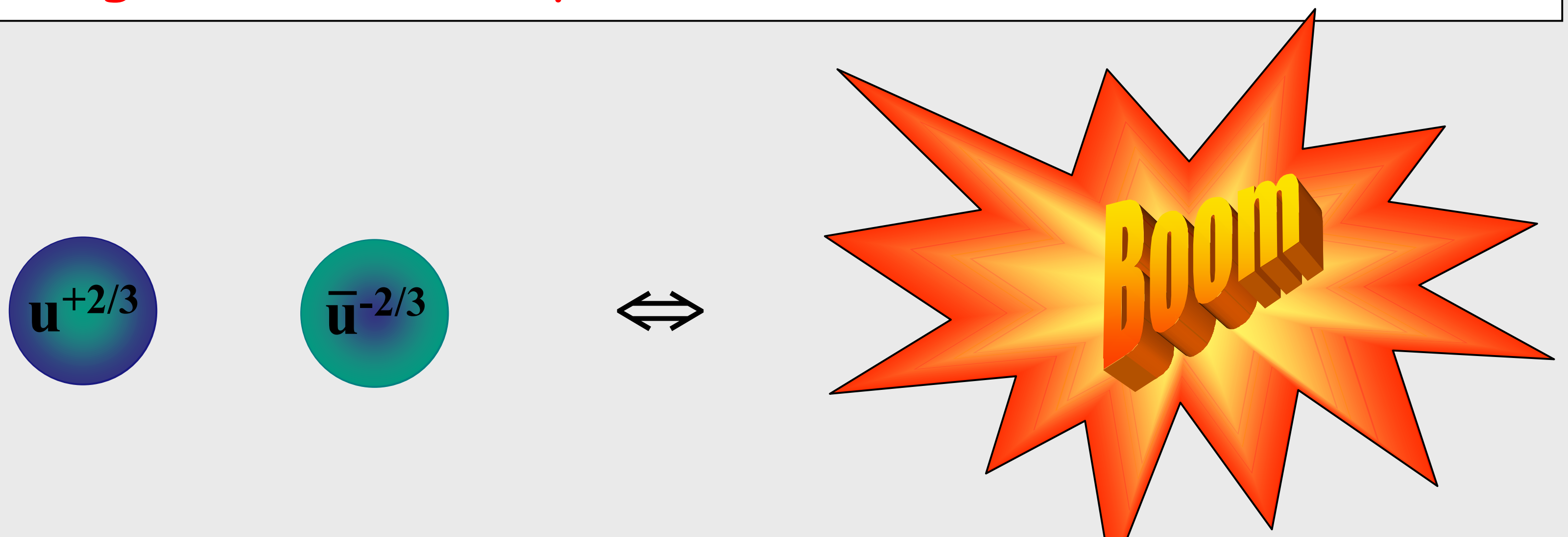
Colliding protons with 7 TeV each (7×10^{12} = 7 trillion electron-volts)



- 27 km circumference
- Each proton goes around the 27km ring over 11,000 times a second.
- Protons collide in 4 locations about 600 million times a second
- 300 trillion protons in the beam
- Energy of proton beam in LHC > 0.3 GJ **(family car travelling at 1000 mph)**
- Super-conducting magnets cooled to ~ 1.9 K (colder than Outer Space).
- Vacuum as low as interplanetary space (10^{-13} atm)

Antimatter - what we see at accelerators

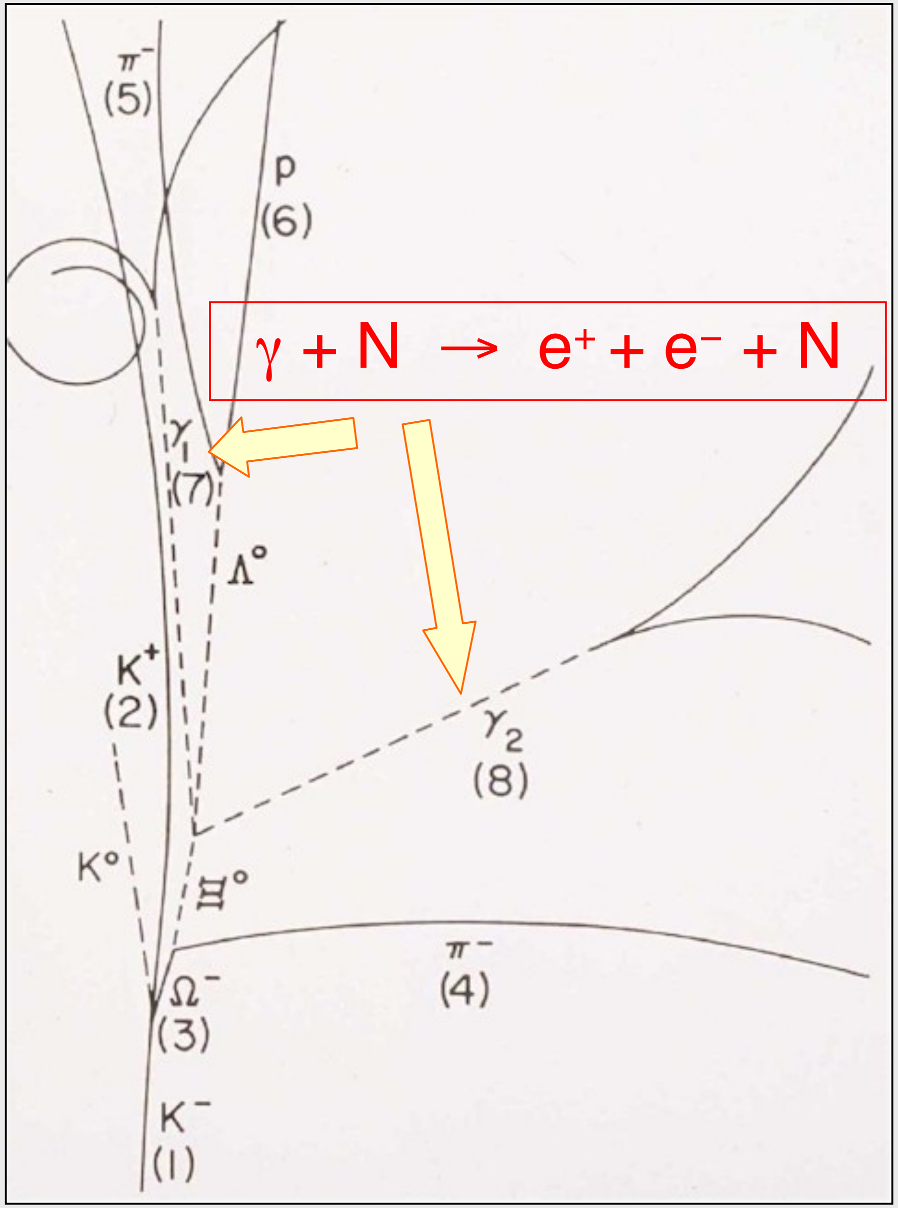
- If a particle and antiparticle each of mass (m) collide they annihilate with the production of energy (E) in the form of radiation – the total mass (2m) is converted into energy.
  - using the famous equation: $E = mc^2$



The opposite is also true; given enough energy, one can create matter with equal amounts of antimatter.

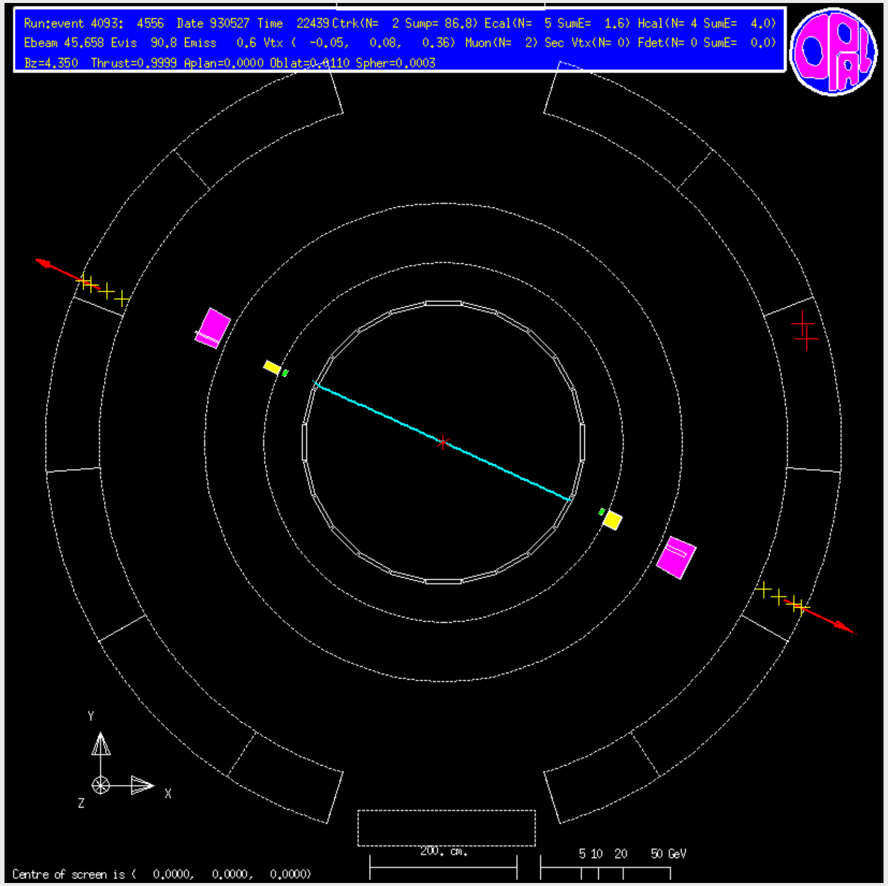
- So far, our experiments show that equal amounts of matter and anti-matter are produced when energy is converted into matter – for every up quark created, an up anti-quark is also created etc.

- So, equal amounts of matter and anti-matter should have been created during the Big Bang.

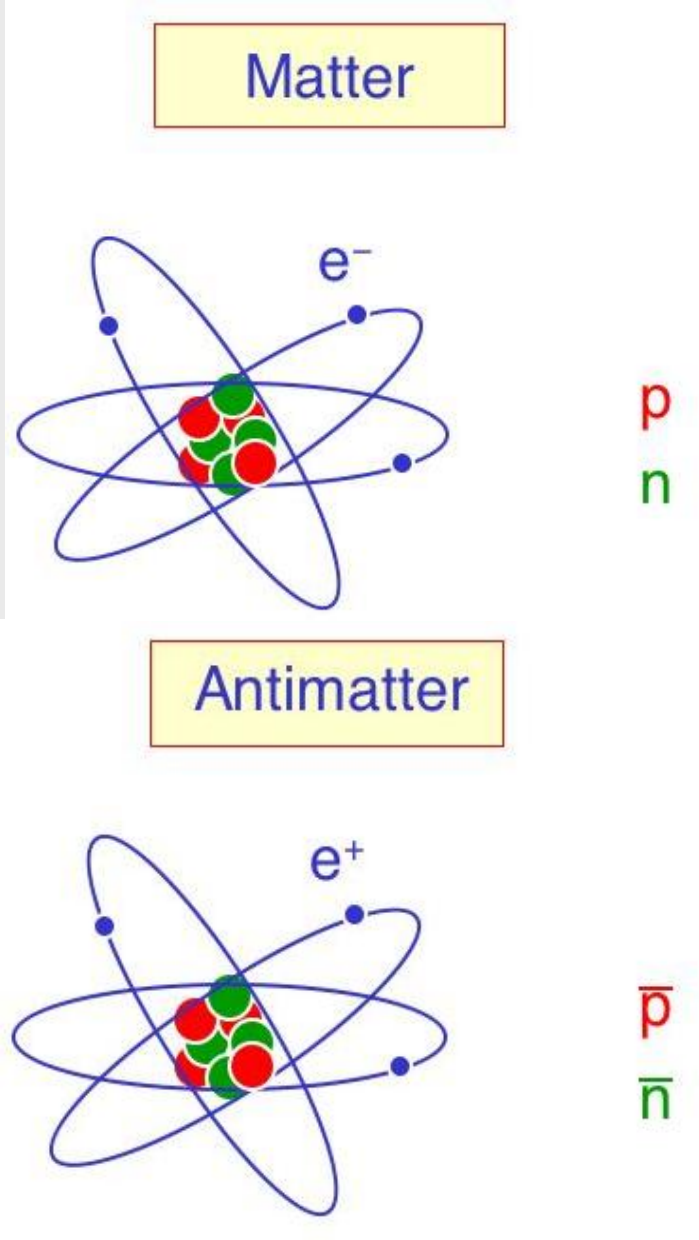


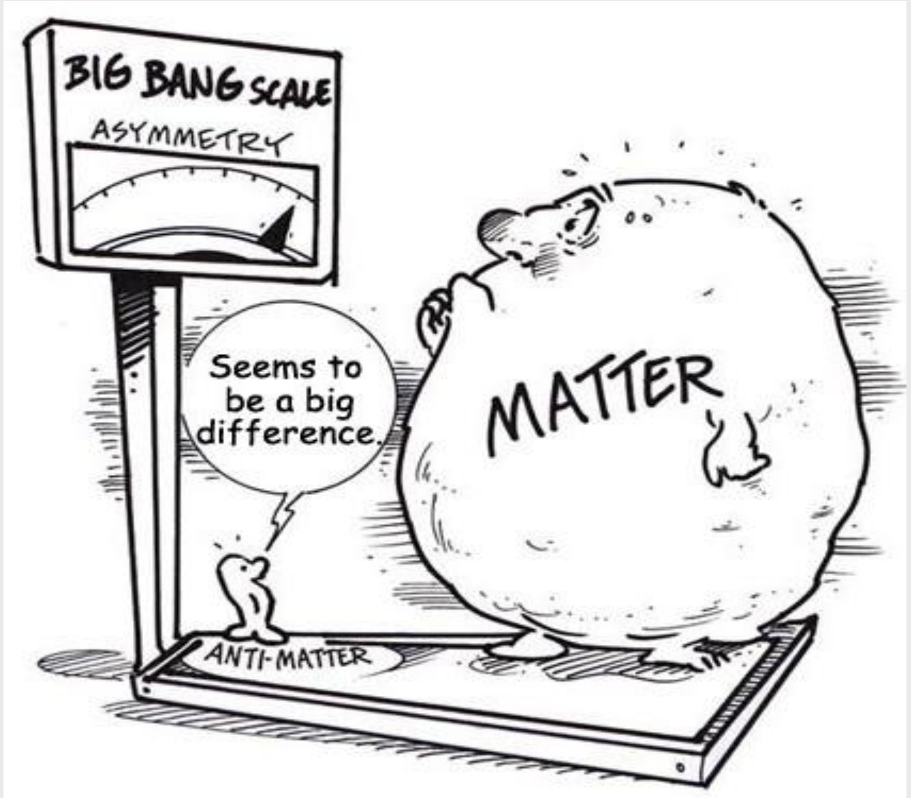
$\gamma + N \rightarrow e^+ + e^- + N$

$e^+ + e^- \rightarrow \mu^+ + \mu^-$



Matter and Anti-matter

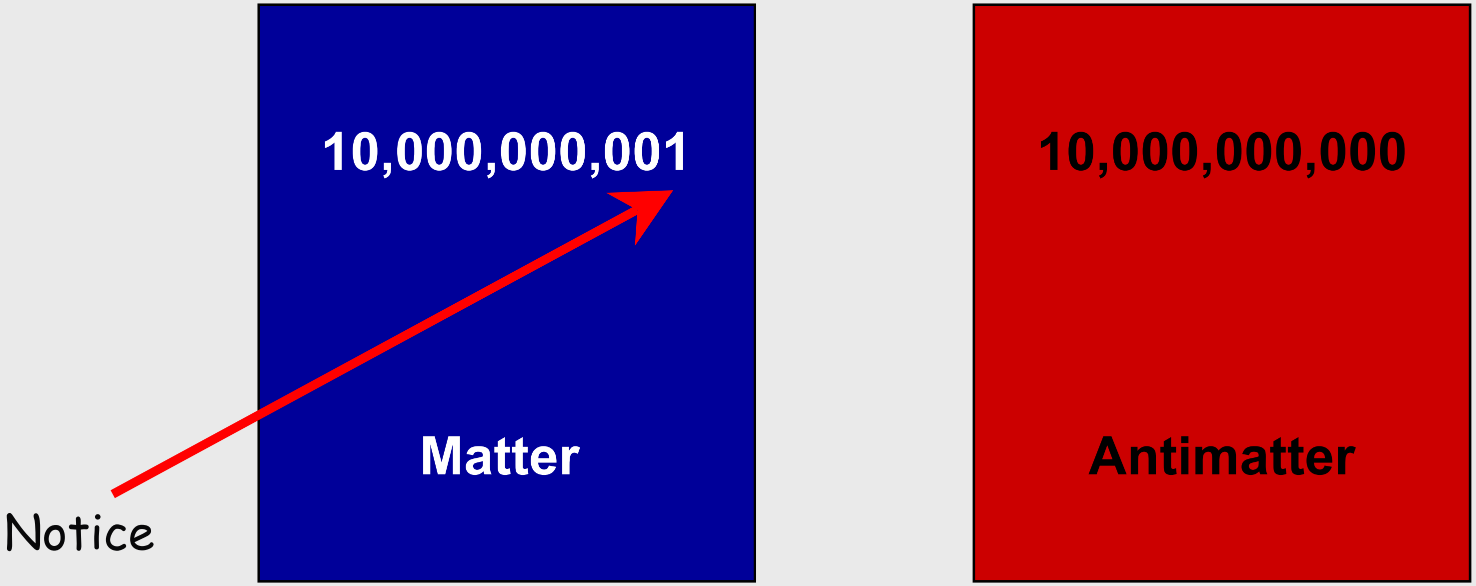




- But we live in a universe made from matter.
- Where did all the anti-matter go?

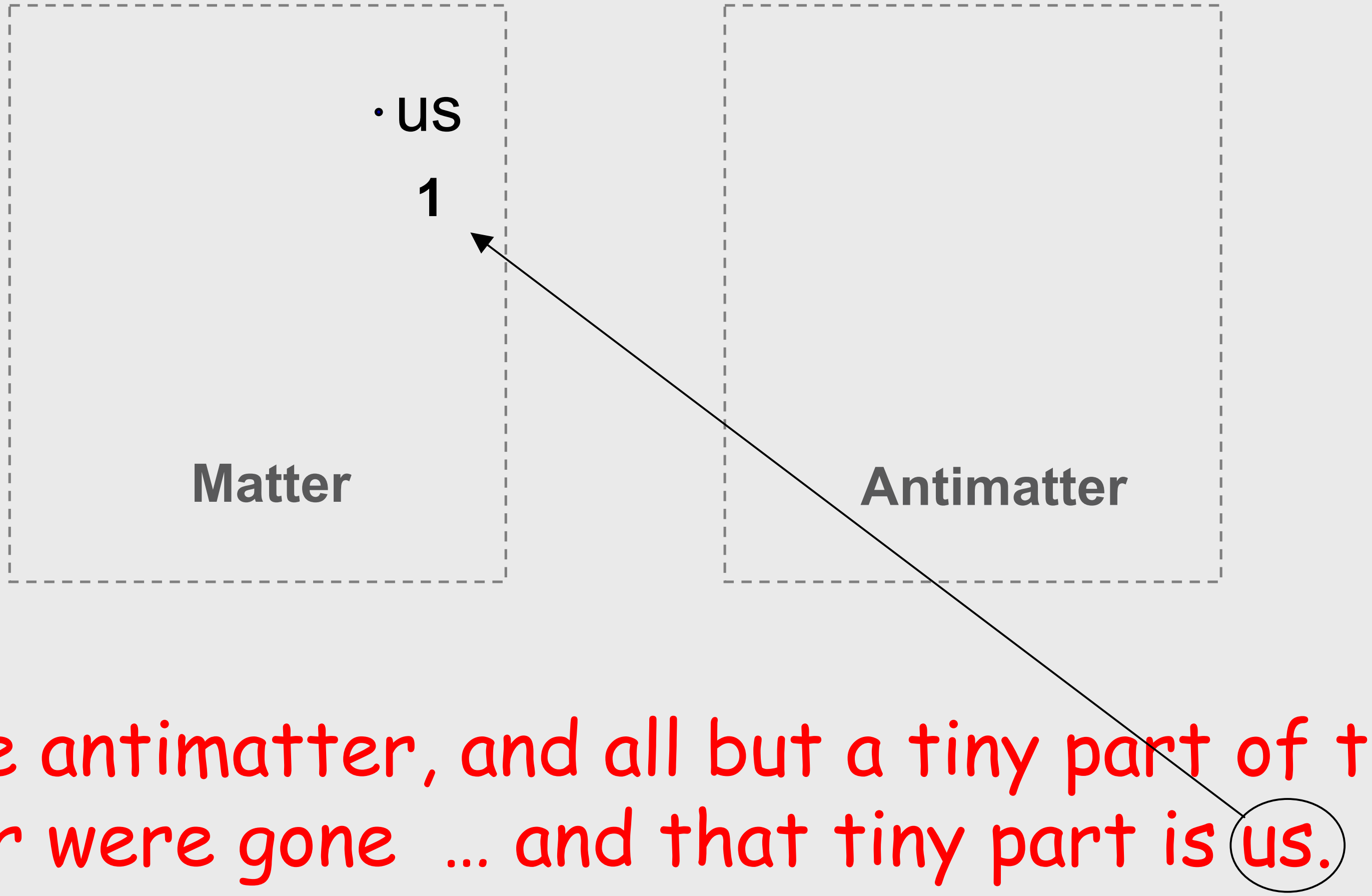
We are lucky because…

Immediately after the Big Bang,
the matter and antimatter… were NOT exactly equal



The Great Annihilation followed !!!

After the Great Annihilation…



All the antimatter, and all but a tiny part of the matter were gone … and that tiny part is us.

MYSTERIES OF THE EARLY UNIVERSE

the Universe was born with
equal amounts of matter and antimatter

$t = 0$

(T ~ 10^{13} K)

(and Baryon violation
and phase transitions)

CP violation :

↓

the Universe contains
slightly more matter than antimatter

$t \sim 1 \mu\,\mathrm{sec}$

Particles and anti-particles annihilate :

↓

the Universe contains only matter
(and lots of photons)

$t \sim 1\,\mathrm{sec}$

MYSTERIES OF THE EARLY UNIVERSE

the Universe was born with
equal amounts of matter and antimatter

$t = 0$

($T \sim 10^{13}$ K)

CP violation :

(and Baryon violation
and phase transitions)

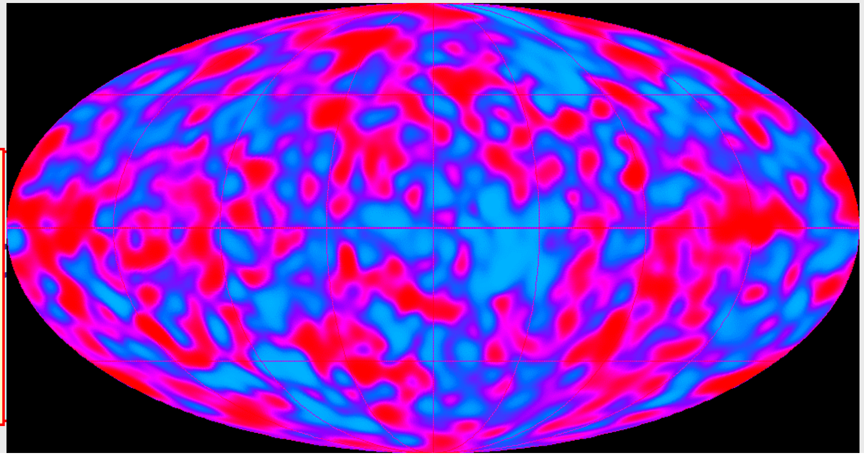
slig… …tter

$10^9 + 1$	protons
10^9	antiprotons

$t \sim 1 \mu\,\text{sec}$

Particles and anti-particles annihilate :

1	proton
0	antiprotons
2×10^9	photons



CP Violation

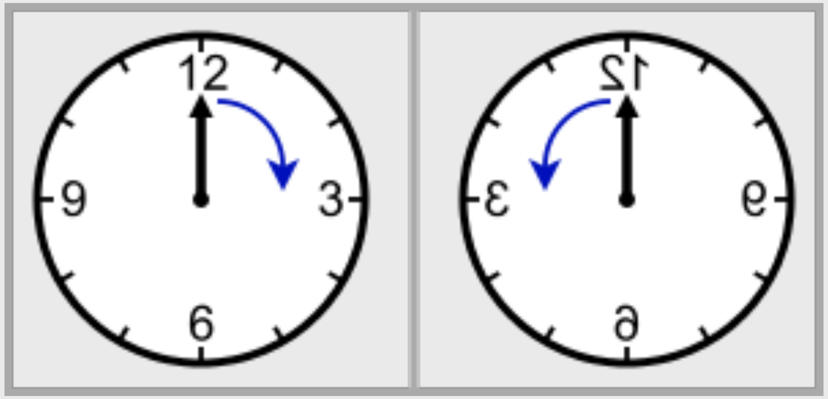
CP violation is one of the necessary conditions for the imbalance matter/antimatter to happen

⇒

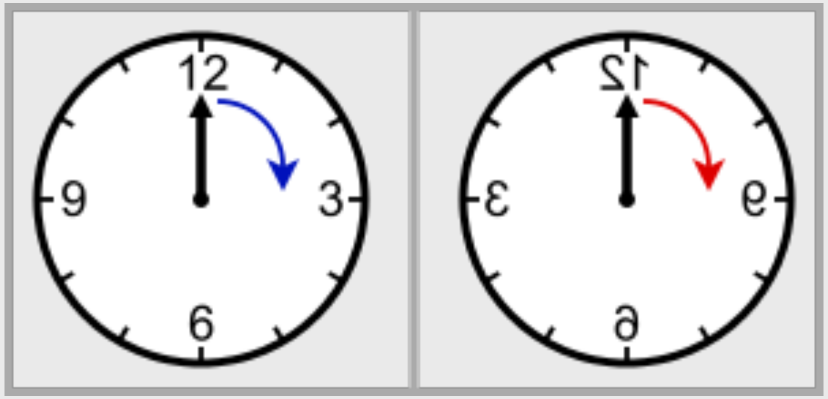
P = parity (reflection in mirror)

C = charge conjugation (swap particle with antiparticle)

Parity



conservation



violation

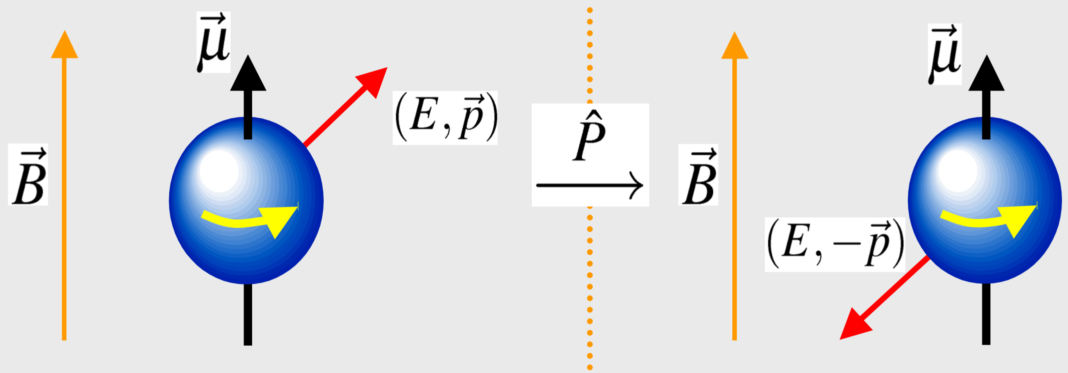
Parity Violation in β-Decay

1957: C.S.Wu et al.

beta decay of polarized cobalt-60 nuclei

$$^{60}\text{Co} \rightarrow {}^{60}Ni^* + e^- + \overline{\nu}_e$$

Electrons emitted preferentially in direction opposite to applied field



If parity were conserved:

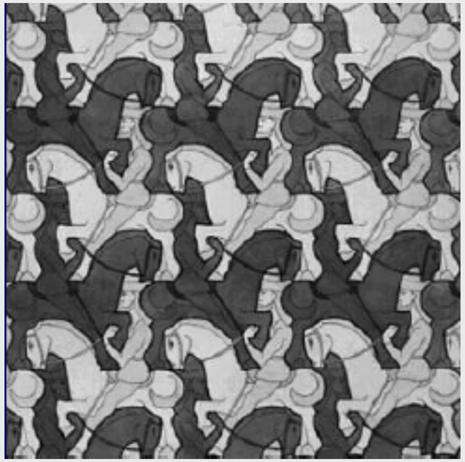
equal rate for producing e^- in directions along and opposite to the nuclear spin.

CP (Charge Parity) Violation

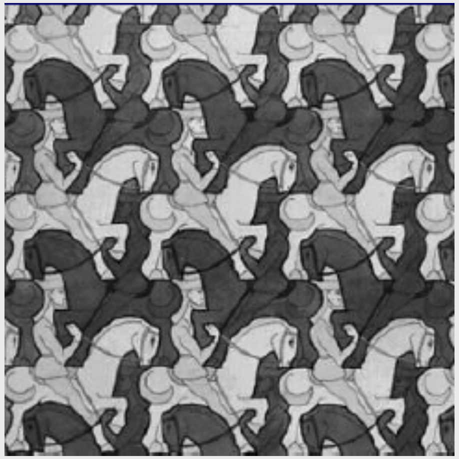
optical analogy

P (parity) =mirror

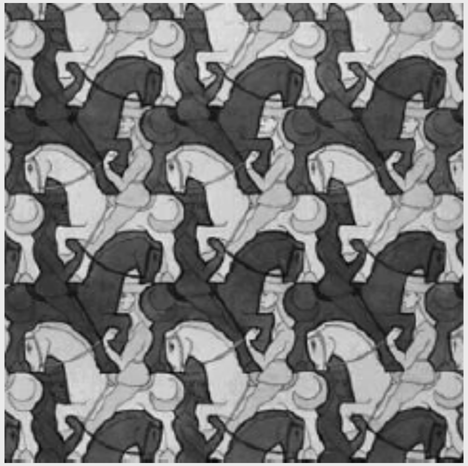
C (charge conjugation) =anti-image



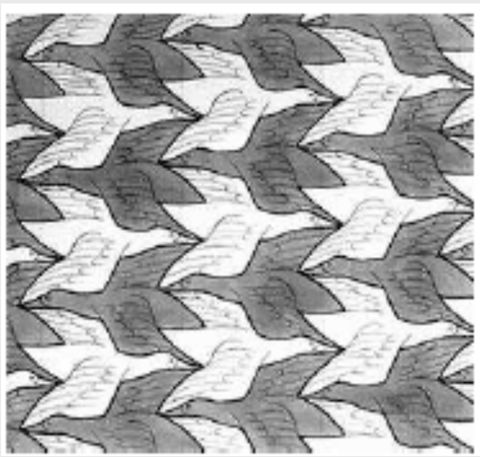
P

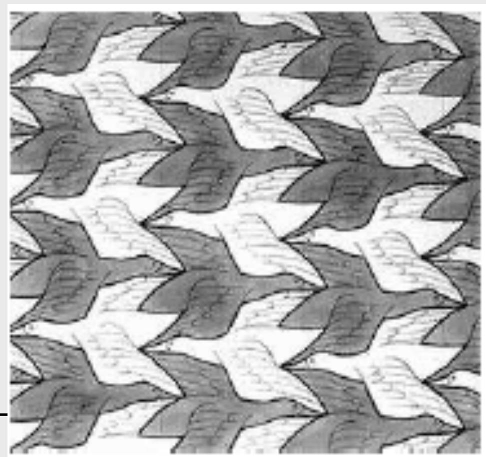


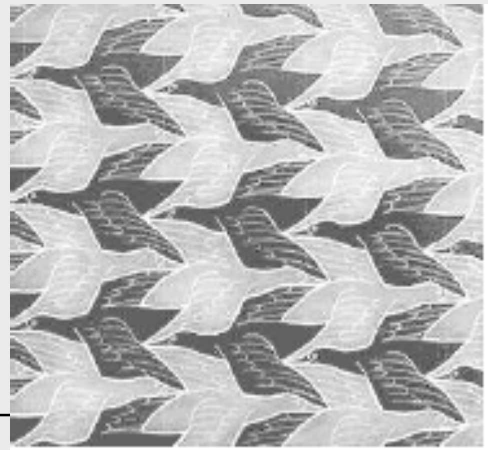
C



CPC



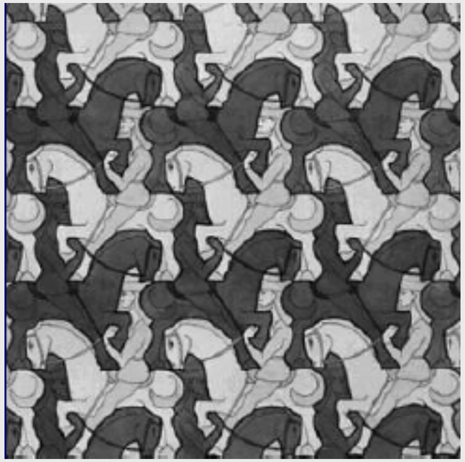




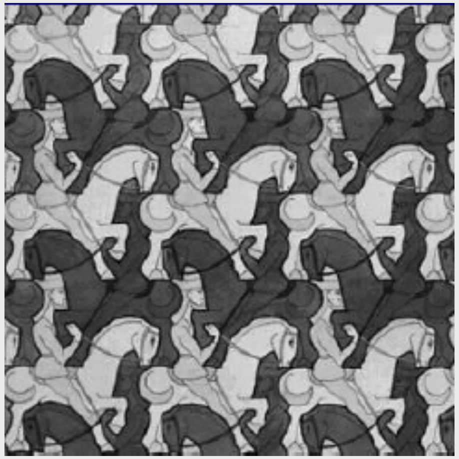
CPV

P (parity) =mirror

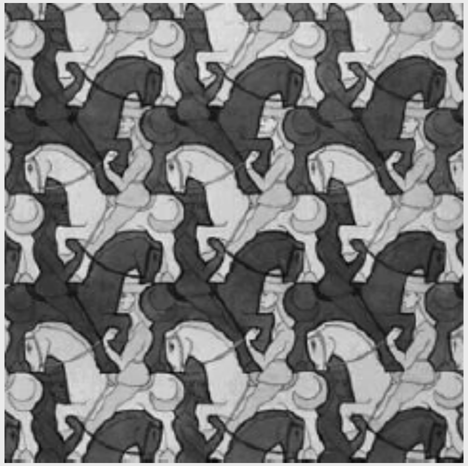
C (charge conjugation) =anti-image



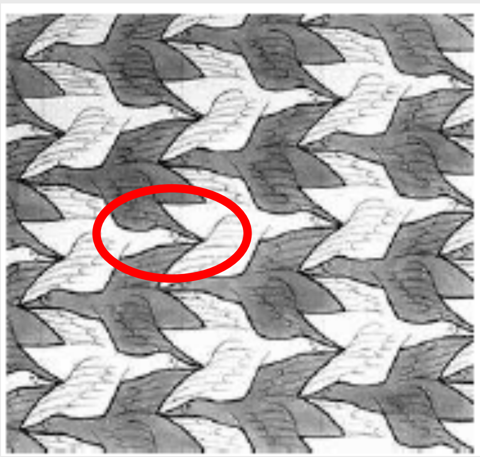
P

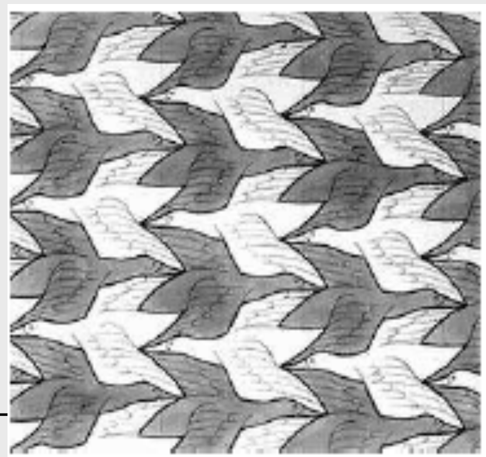


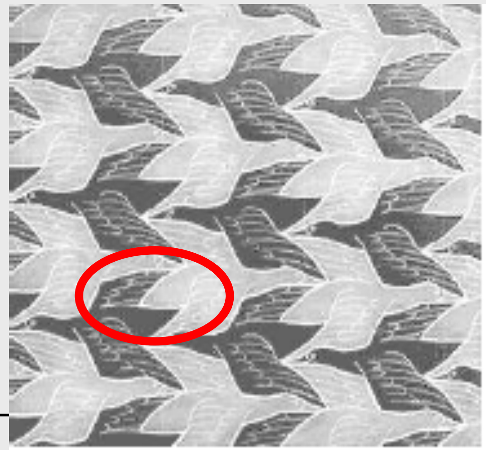
C



CPC

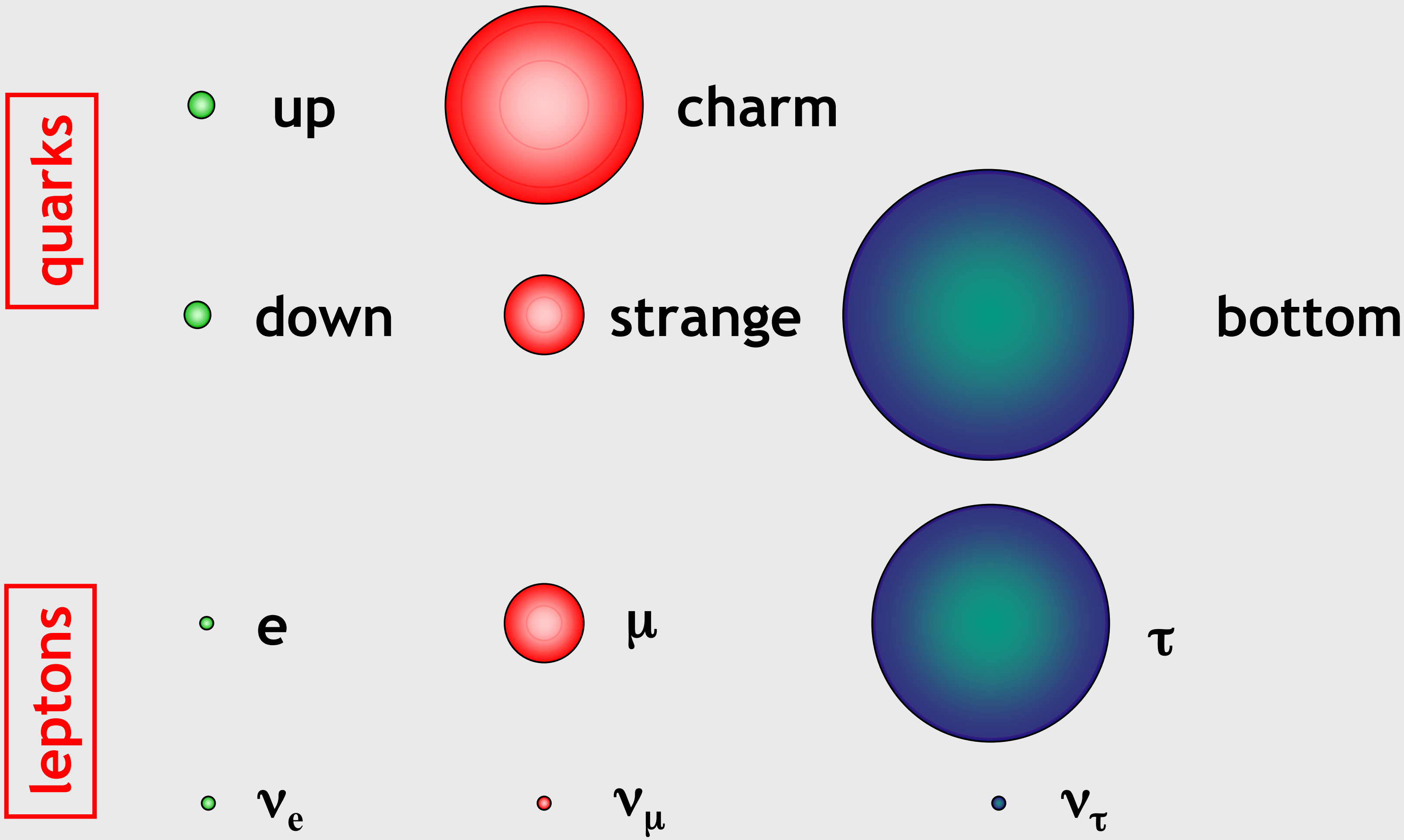






CPV

Quarks and Leptons

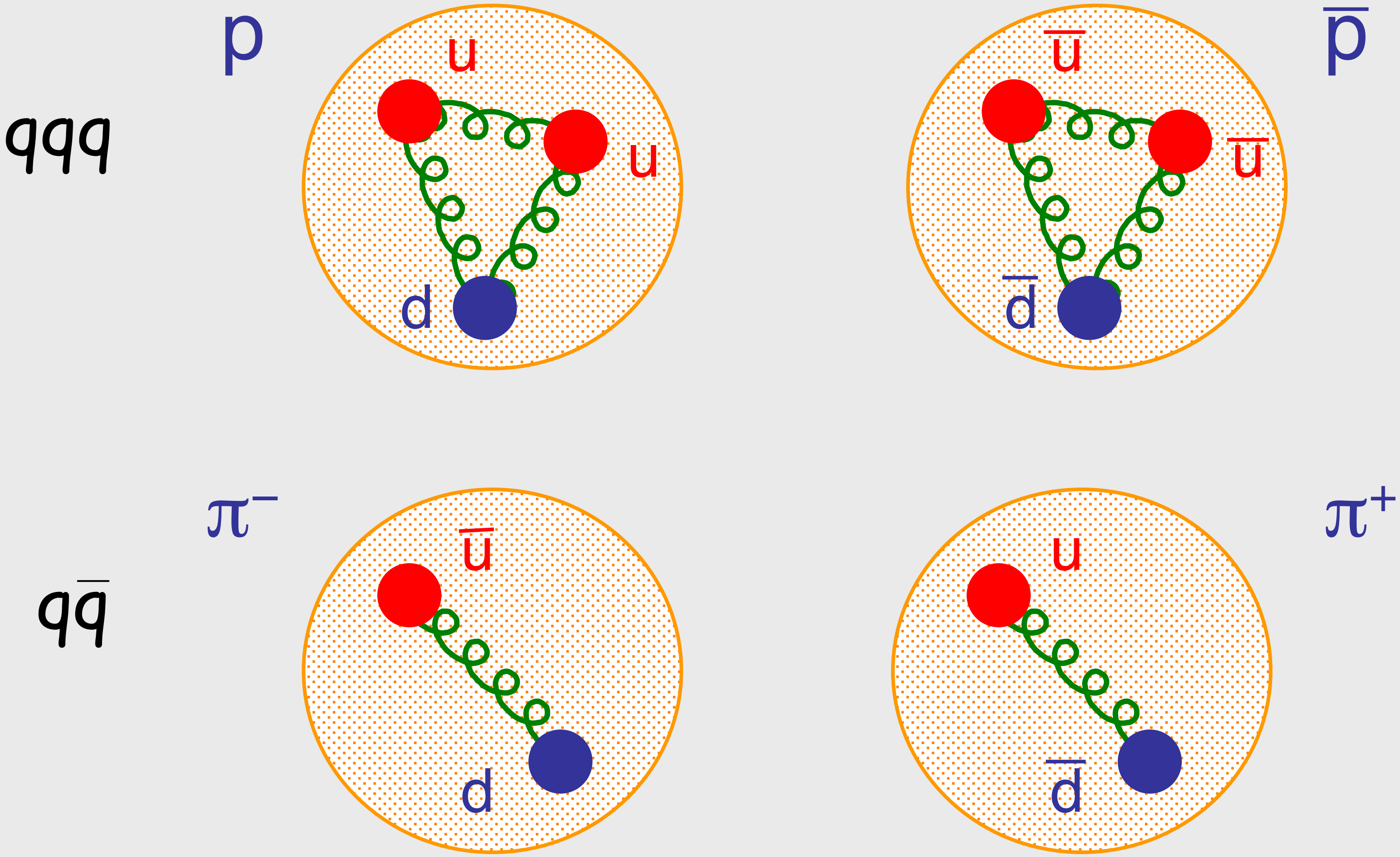


And the Top Quark

Discovered in 1995 …

Weighs about the same as a gold nucleus!

Hadrons are made up by quarks



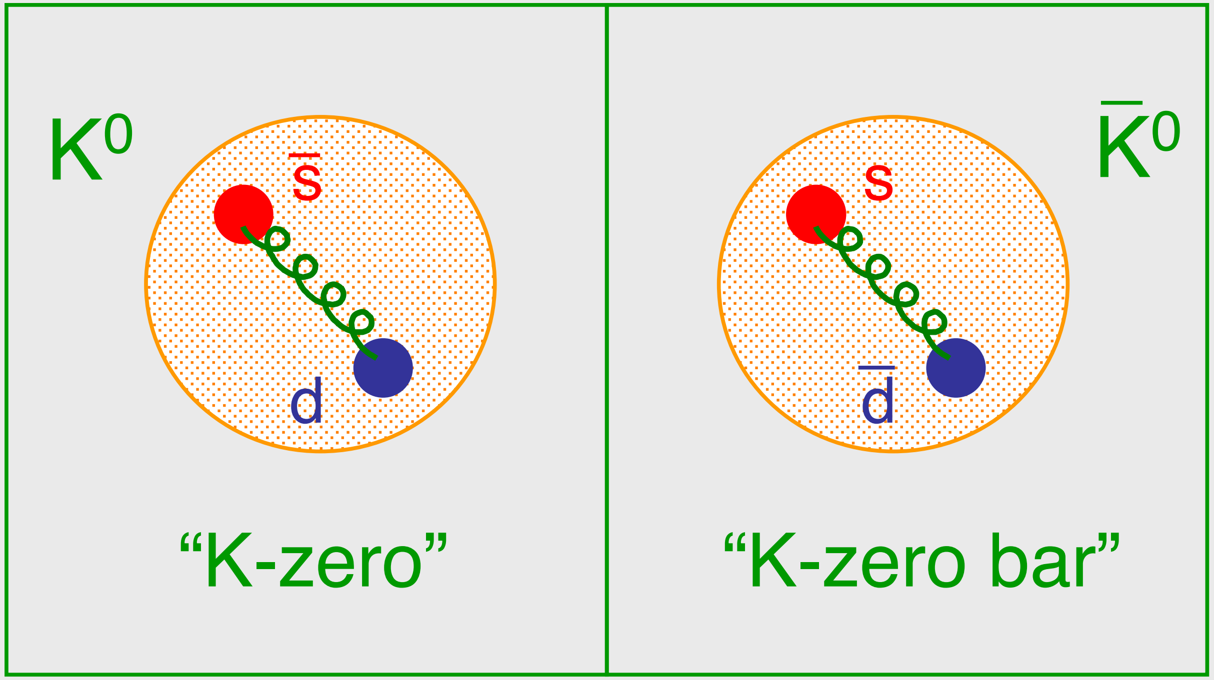
Quark transitions - the only known source of CP violation

How is CP violation studied ?

- Discovery of CP Violation in 1964
- Nobel Prize in Physics in 1980 – James Cronin, Val Fitch

Neutral Kaons:

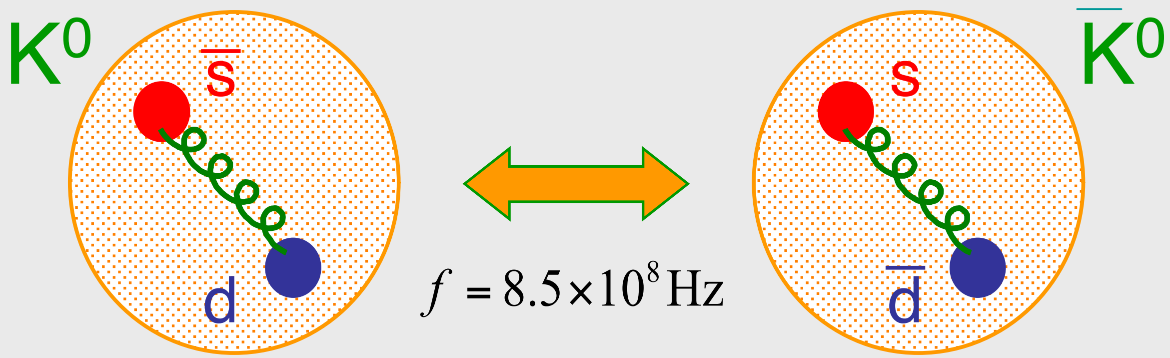
neutral particles containing a strange quark or antiquark



Kaon mass :

$$\frac{m_K}{m_e} = 974$$

The neutral kaons can "mix" :



$f = 8.5\times10^{8}\,\mathrm{Hz}$

The particles we see decaying are :

K_S "K-short"	K_L "K-long"
$K_S \approx \frac{1}{\sqrt{2}}\left(K^0 + \bar{K}^0\right)$	$K_L \approx \frac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right)$

A Quantum mechanical mixture of

K^0 and $\bar{K}^0$

K_S and K_L have very different lifetimes :

K_S : $\tau_S = 0.9 \times 10^{-10}$ sec

K_L : $\tau_L = 5.2 \times 10^{-8}$ sec

e.g. For a beam of energy 100 GeV :

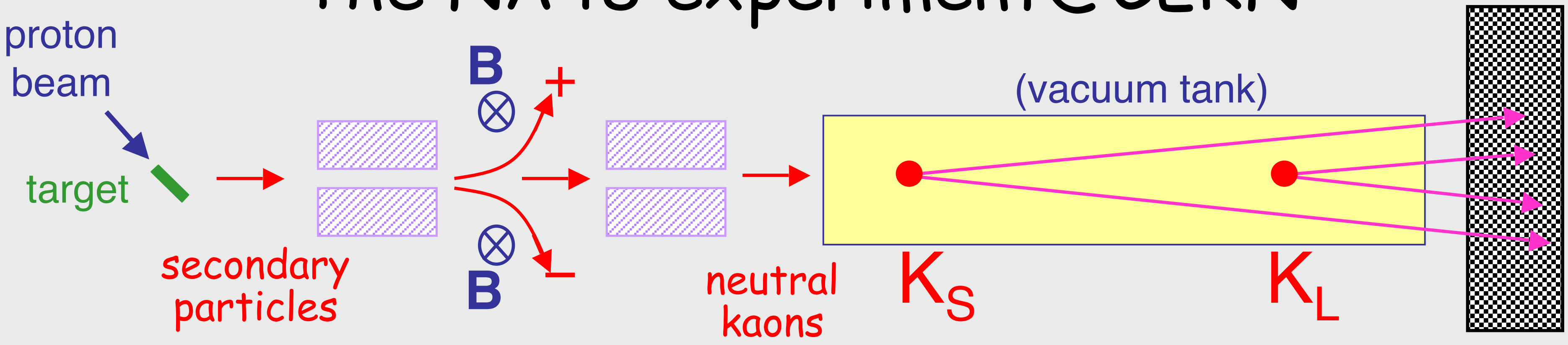
Average distance travelled before decay is

K_S : 5.4 m

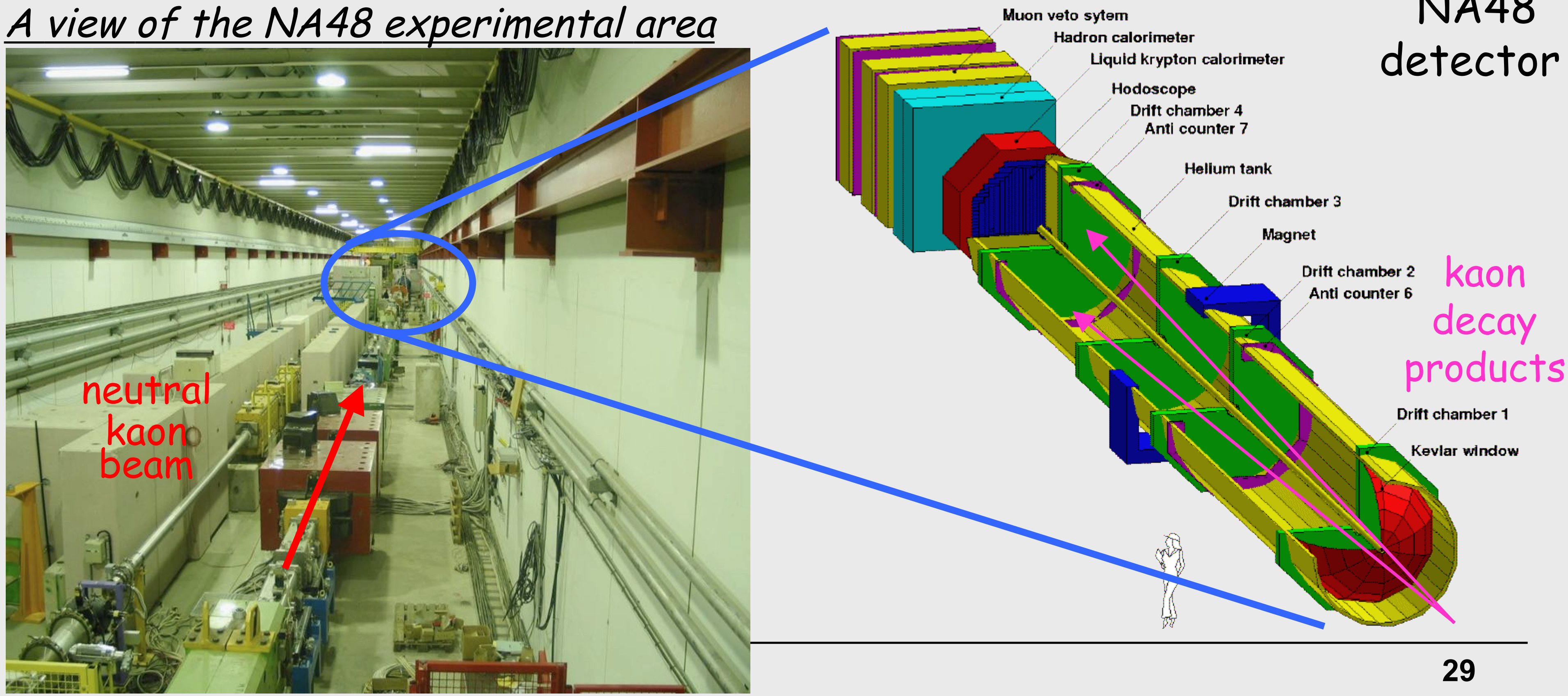
K_L : 3.1 km

The beam starts out as an equal mix of K_S and K_L but eventually only K_L are left

The NA48 experiment@CERN



A view of the NA48 experimental area



CP violation

The K has revealed subtle differences between matter and antimatter

For example, the decay $K_L \to \pi^- e^+ \nu_e$

occurs slightly (0.3%) more often than $K_L \to \pi^+ e^- \bar{\nu}_e$

More e^+ than e^- in K-long decays

⇕

allows unambiguous definition of matter and antimatter

In an Anti-world :

In the $\overline{\text{NA48}}$ experiment at $\overline{\text{CERN}}$ ….

The neutral kaon beams starts out with **opposite** amounts of K^0 and $\overline{K^0}$

But, just as in our world :

the neutral kaon beam still starts out as an equal mix of K_S and K_L and eventually becomes pure K-long

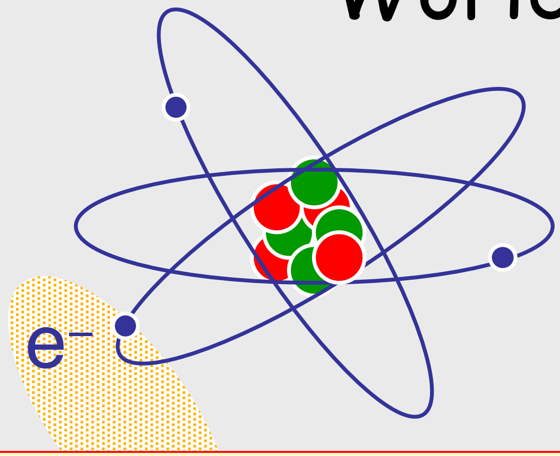
And, the decay:

$$K_L \to \pi^- e^+ \nu_e$$

still occurs slightly (0.3%) more often than:

$$K_L \to \pi^+ e^- \overline{\nu}_e$$

Our World

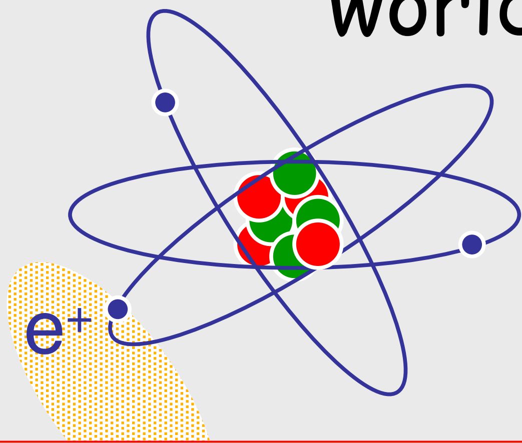


p

n

more e^+ than e^- in K-long decays

An Anti-world

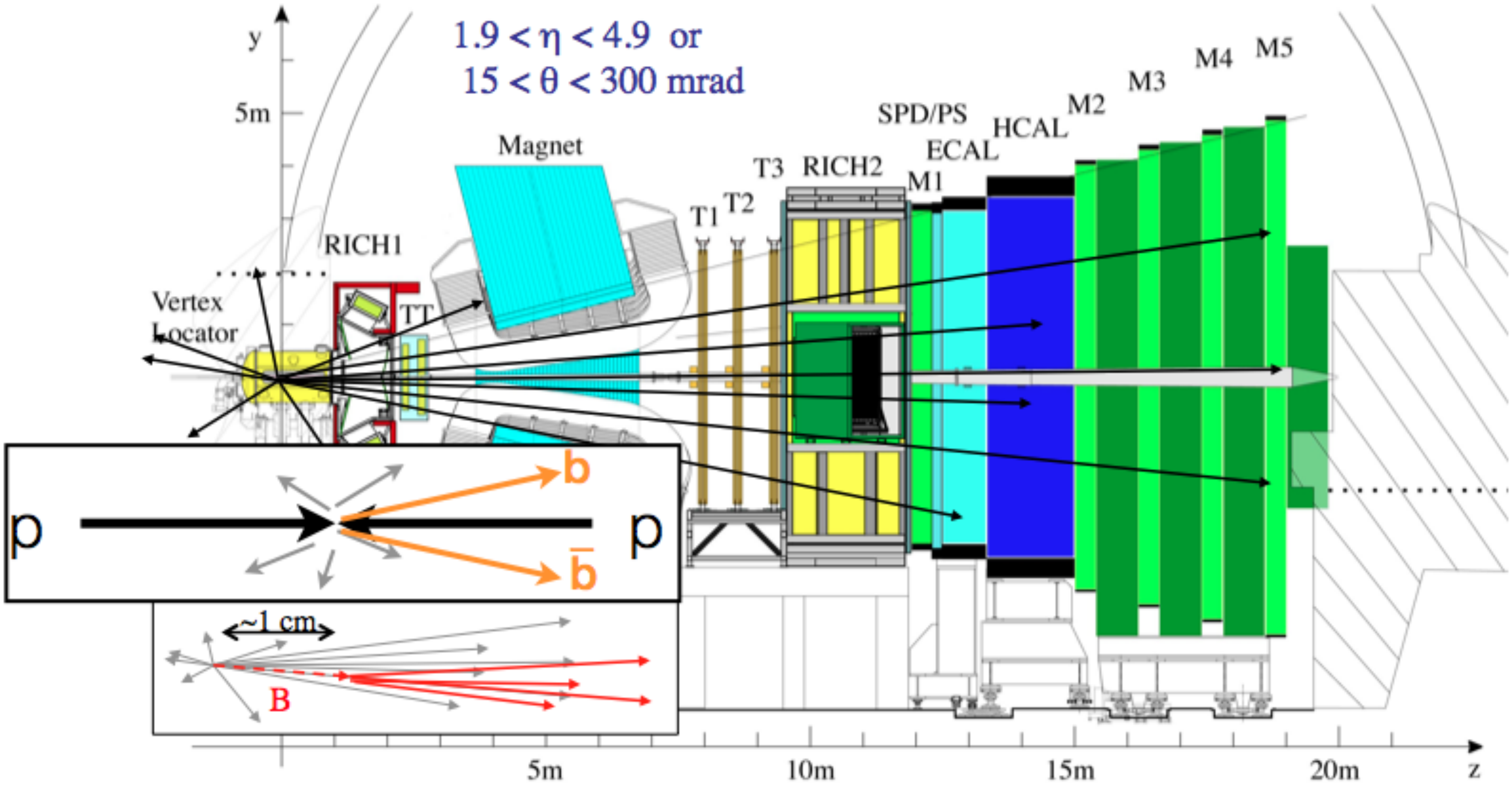


$\bar{p}$

$\bar{n}$

more e^+ than e^- in K-long decays

CP violation in B mesons at LHC

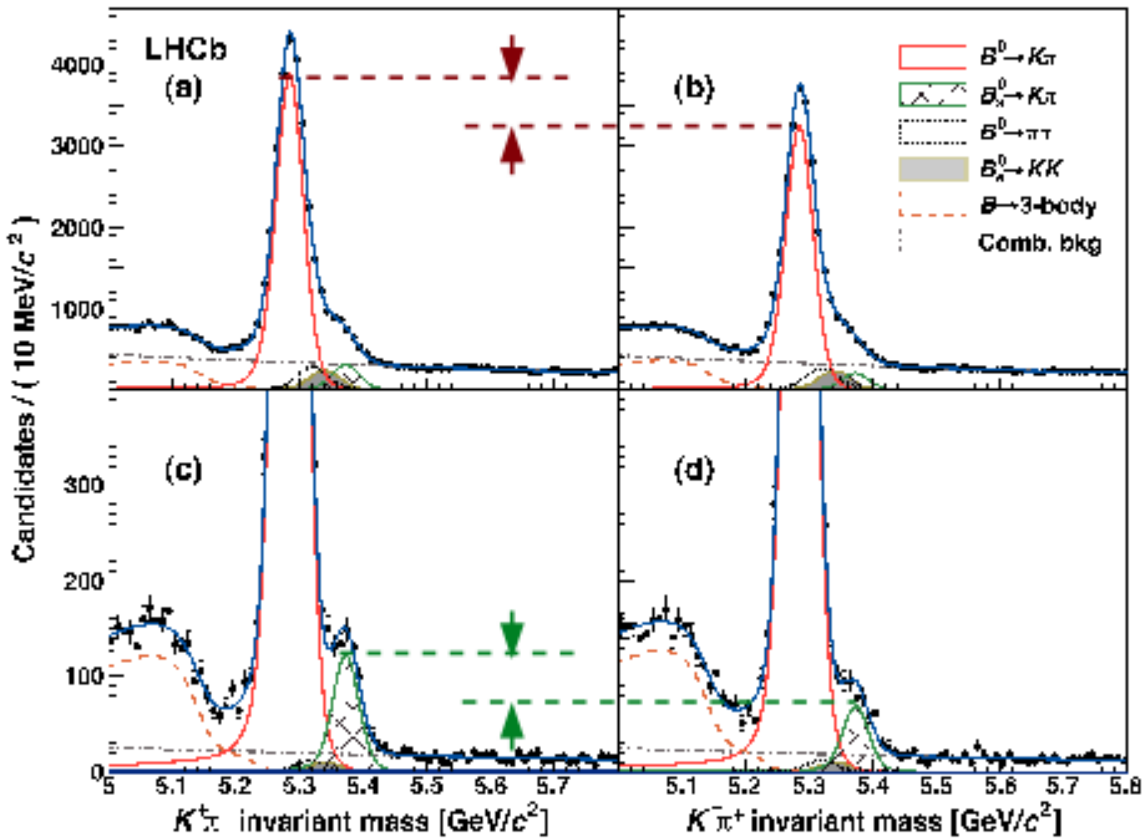


The LHCb experiment is studying tiny differences in behaviour between beauty quarks and beauty antiquarks

Example: CP violation in B_S mesons

- Define

$$A_{CP} \equiv \frac{N(B^0_{(s)}) - N(\overline{B}^0_{(s)})}{N(B^0_{(s)}) + N(\overline{B}^0_{(s)})}$$



- First observation of CPV in B_s decays!

Looking for new sources of CP violation, and as a window on New Physics

Open questions:

What is the origin of CP violation ?

Can we find enough CP violation processes to explain what is needed in the Big Bang ?

Thank you !

Any questions ?

Other Particle Physics Sessions:

Particle Zoo and Feynman Diagrams
Muirhead 118
7th January 2016, 10:00-12:00

ASE Frontier Science Lecture: The Mystery of Antimatter
Poynting Physics S02
7th January 2016, 14:30-15:30

Schools' STEM exhibitions: HiSPARC project
Aston Webb Great Hall
8th January 2016, 9:00-12:30

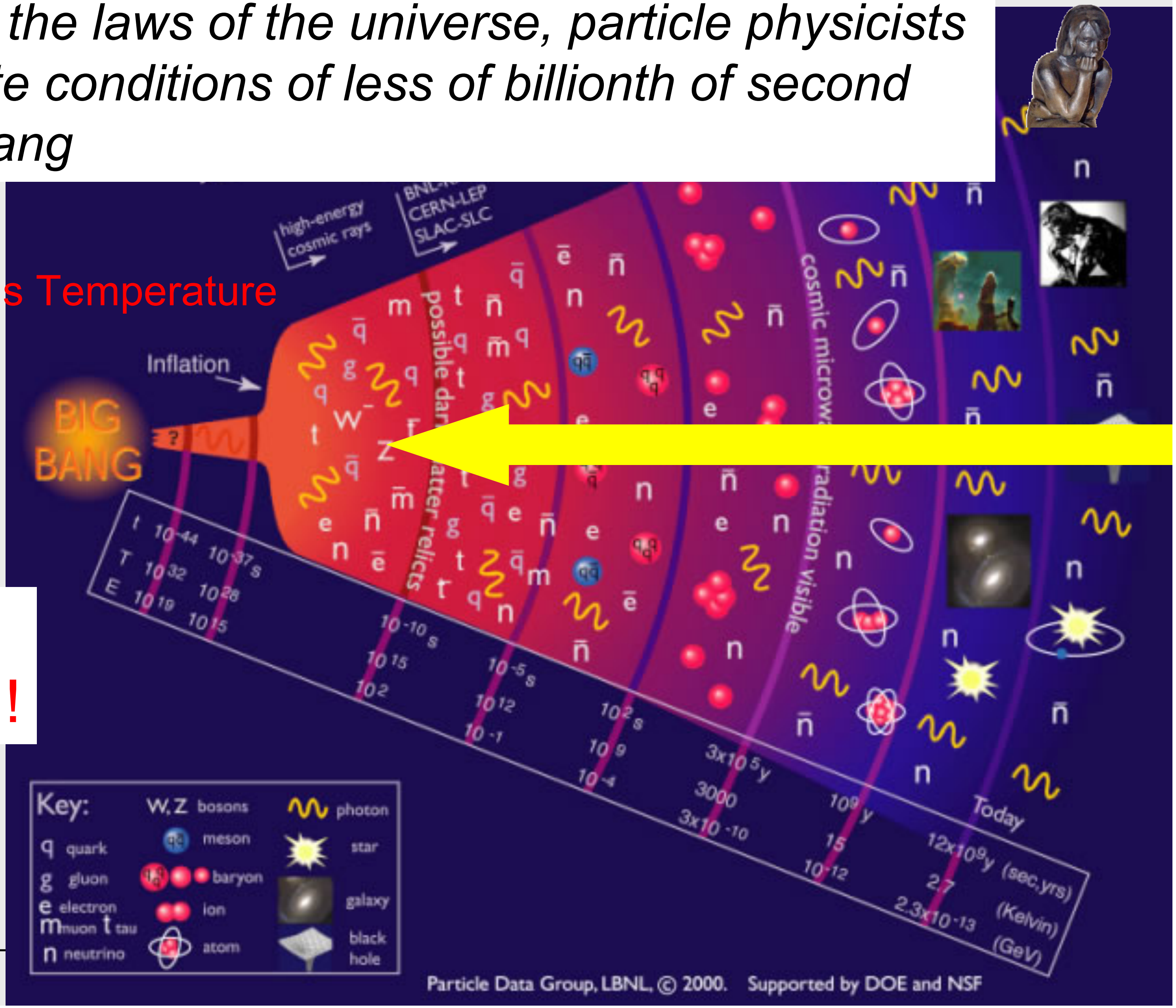
Particle Teaching Resources: LHC Minerva
Learning Centre LG13
8th January 2016, 9:30-11:30

Particle World for Primary
Arts LR8
8th January 2016, 13:45-15:45

Spares:

Over 12 billion years ago, the Big Bang gave birth to the Universe, creating space, time, energy and matter.
To understand the laws of the universe, particle physicists want to recreate conditions of less of billionth of second after the Big Bang

100 million x Sun's Temperature



Use accelerators !

The Future

- Will we see a deeper structure to the quarks?

- Will we understand why there are three families of quarks?

- Is the new particle really the Standard Model Higgs boson?
- Is it the only Higgs boson ?

- Will we find the origin of CP violation ?

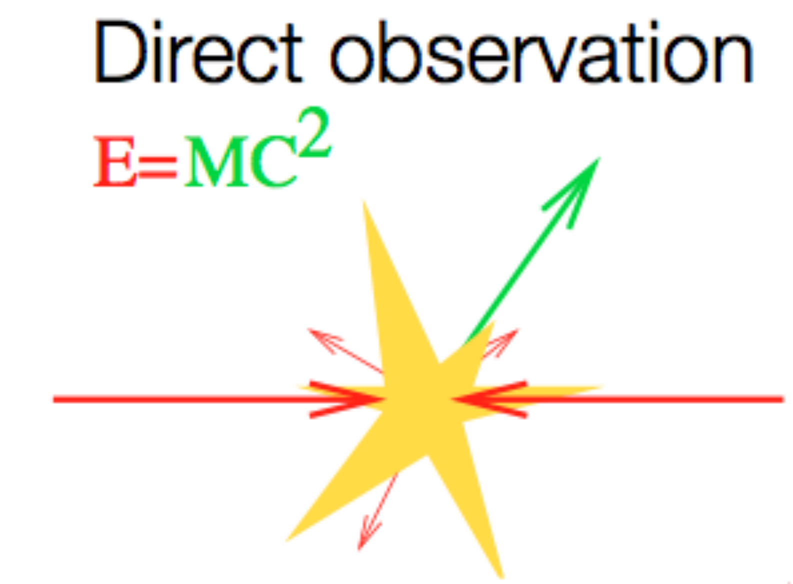
- Will we see Supersymmetry, Extra Dimensions, or something completely unexpected ?

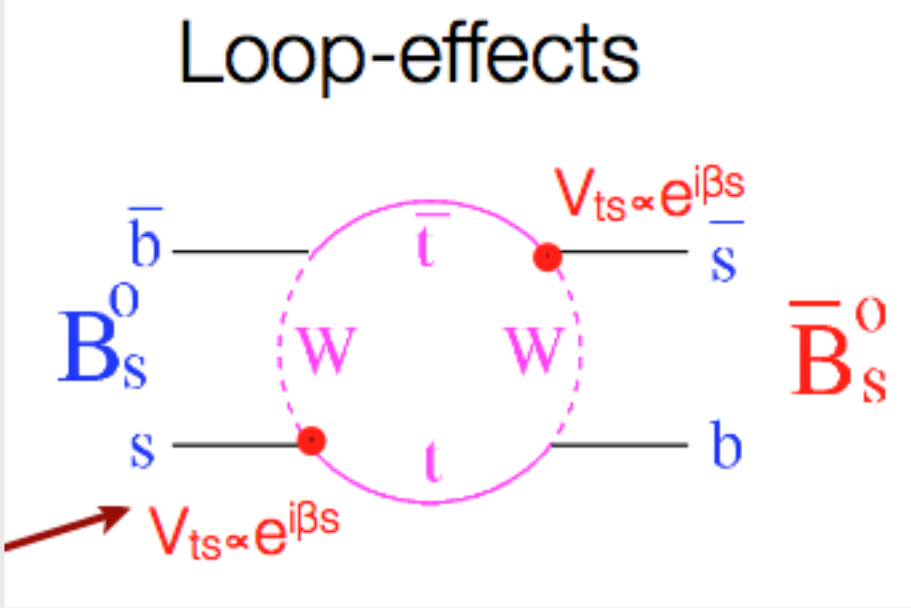
… it's early days, much more data to come at higher energy…

- The LHC will restart in 2015 and run for 15-20 years !

WATCH THIS SPACE!

CERN LHCb experiment studies CP
as a window on new physics





Sensitive to new particles that can be much heavier than those directly produced

Antimatter in the story of

ANGELS & DEMONS

In the Angels and Demons story, the bad guys go to a laboratory called "CERN".

They steal half a gram of antimatter in a canister, which they then take to Rome to use as a bomb.

A feather weigths about ½ gram.

If We Could Accumulate It

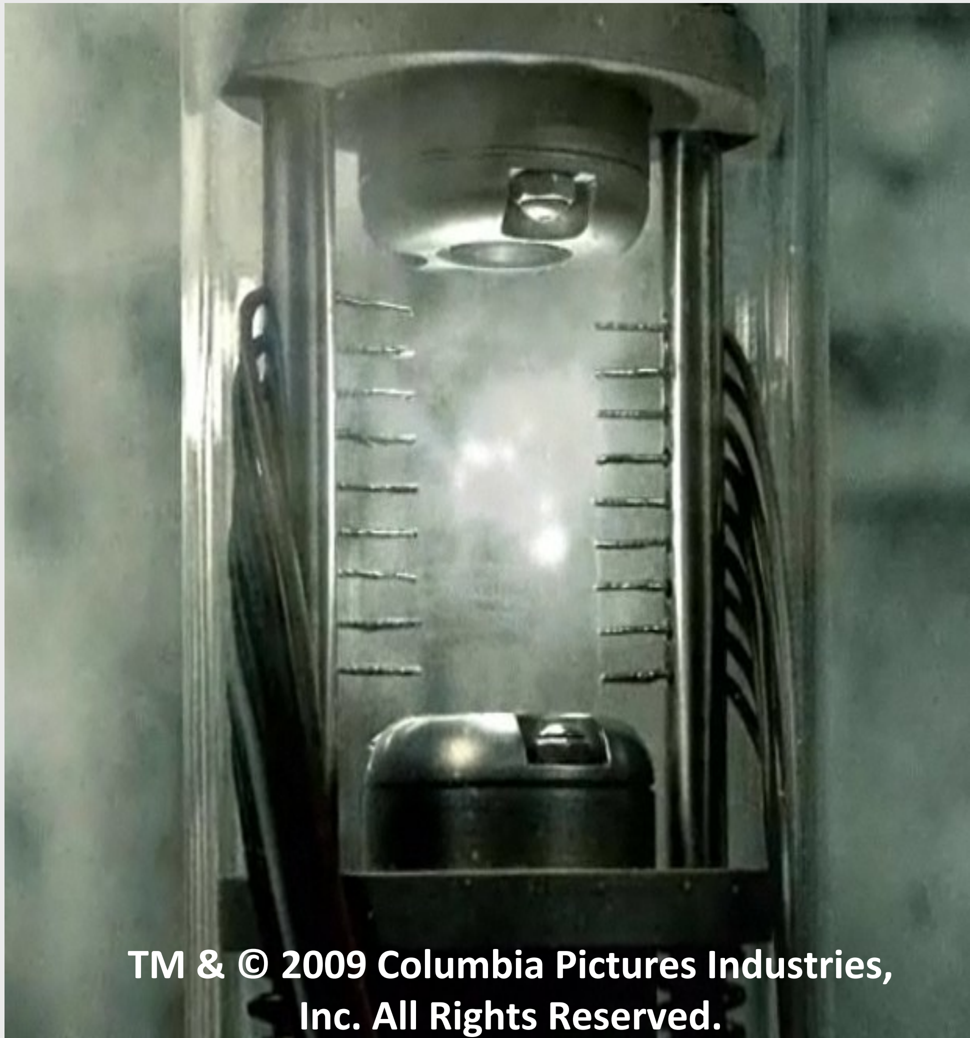
If we had some means to accumulate half a gram and

if we could put it in a container and

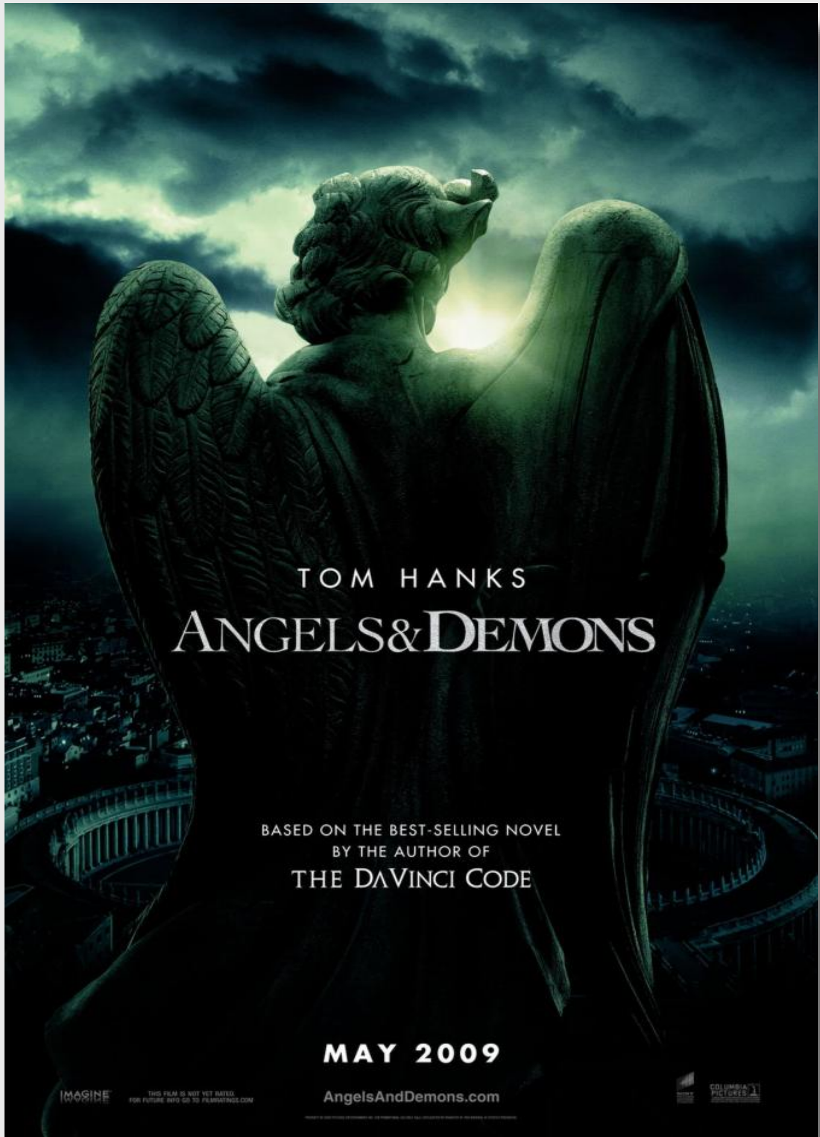
if we could transport it safely to another site,

it would indeed be a powerful bomb as in

ANGELS & DEMONS



How Long to Get Half a Gram?



All the antimatter produced in accelerators annihilates within a fraction of a second.

If LHC could somehow accumulate all the antimatter it produced,

it would take 100 million years to get ½ a gram of antimatter.