From the Origins to Antimatter

- What is matter made of?
  - A history of particles
  - Quarks
  - Anti-Particles
- History of the universe
- Matter and antimatter
  - Where has all the antimatter gone?
  - The LHCb experiment

30/03/09 HEP Master Class

Patrick Koppenburg
Imperial College
London

Fundamental Questions

What is the world made of?

i.e.

What are the fundamental constituents of matter?

Fundamental Questions

What is the world made of?

What holds them together?

i.e.

What are the fundamental constituents of matter?

i.e.

What are the fundamental forces of Nature?

Fundamental Questions

Wh ?

What are the fundamental constituents of matter?

Wh l

c

History of Matter

The ancient Greek knew four elements

4

B.C.

History of Matter

The Chinese tradition knows five elements

5

B.C.

History of Matter

Eventually one realised that some elements are fundamental.

The systematic classification lead to Mendeleev’s Table

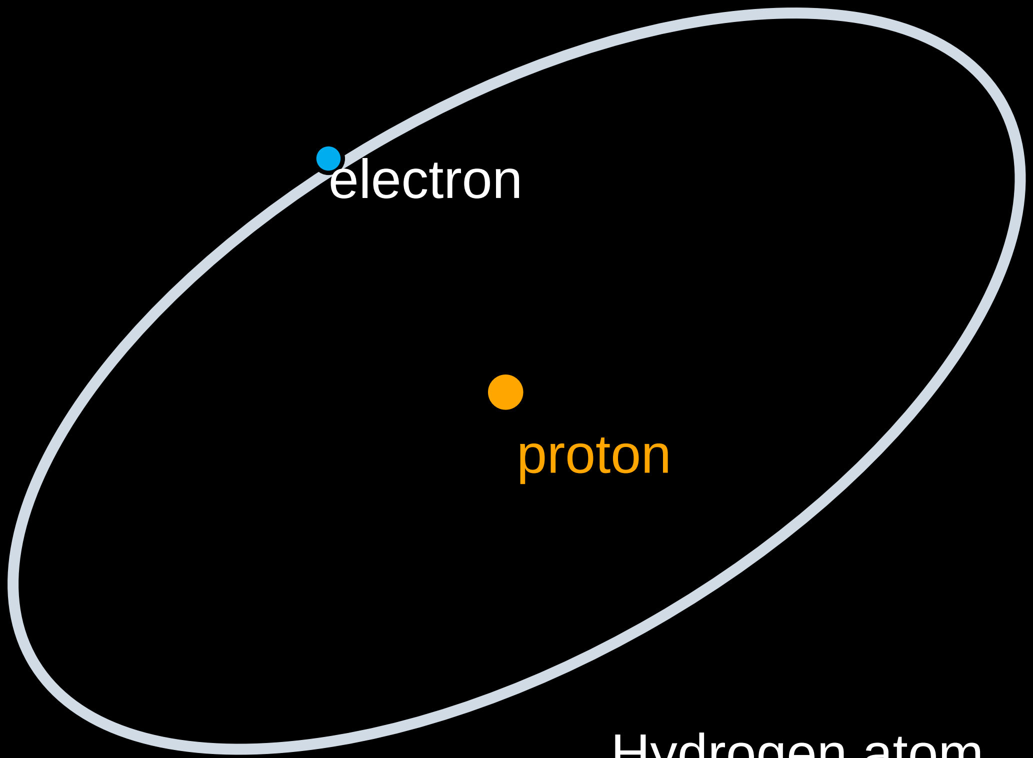
92

1869

History of Matter

- Electron e discovered in 1897 by J.J. Thomson
- Proton p discovered in 1918 by Ernest Rutherford

➜ The periodic table is still valid but the elements are not fundamental any-more



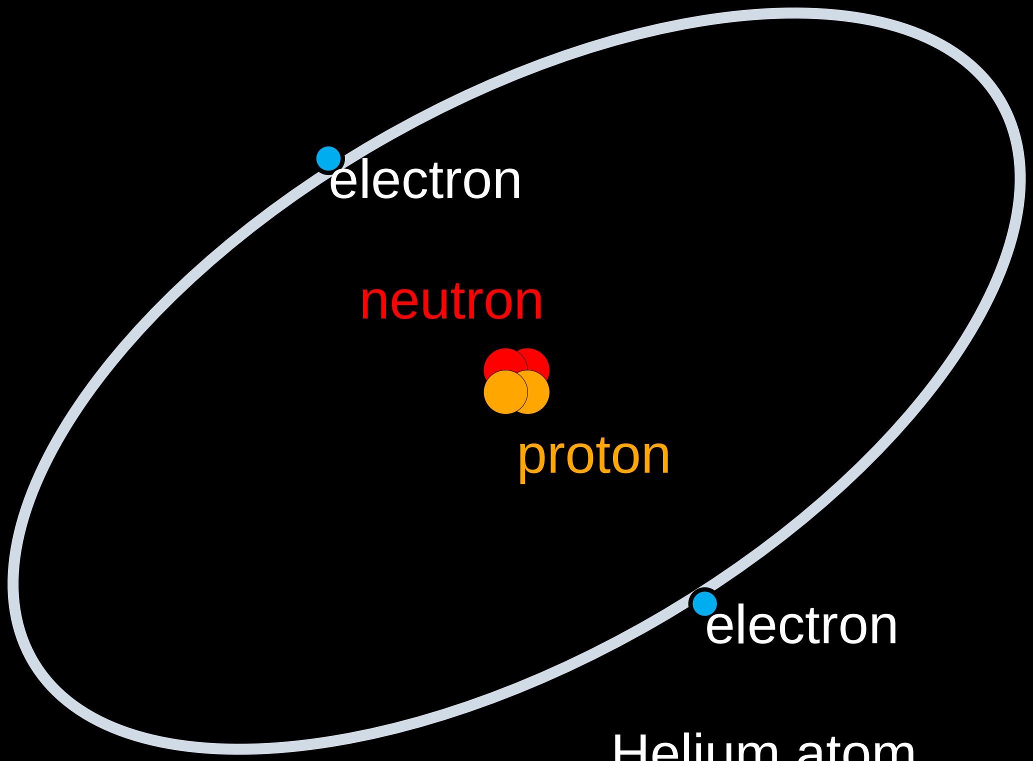
Hydrogen atom

2

1918

History of Matter

- Electron e discovered in 1897 by J.J. Thomson
- Proton p discovered in 1918 by Ernest Rutherford
- Neutron n discovered in 1932 by James Chadwick



Helium atom

3

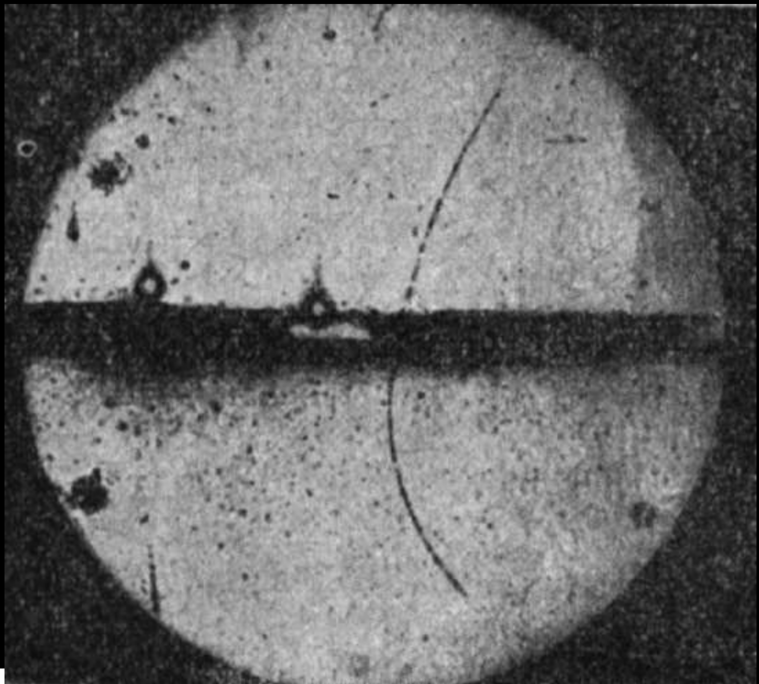
1932

History of Particles

- Positron e^+ discovered in 1932 by Carl D. Anderson.
  - Confirmed independently by Patrick Blackett, founder of this lab.

→ Discovery of antiparticles!

First evidence of a positron in a cloud chamber (1932).



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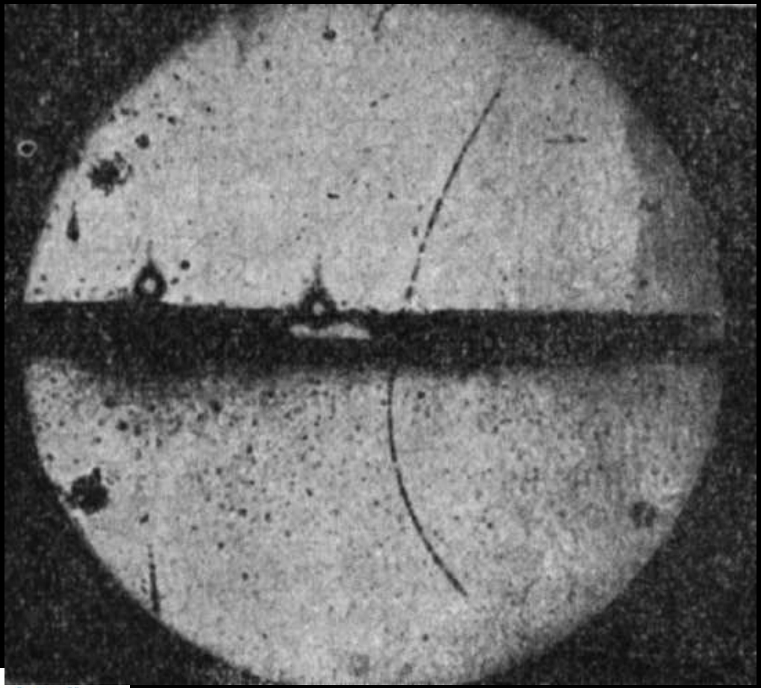
1932

History of Particles

First evidence of a positron in a cloud chamber (1932).



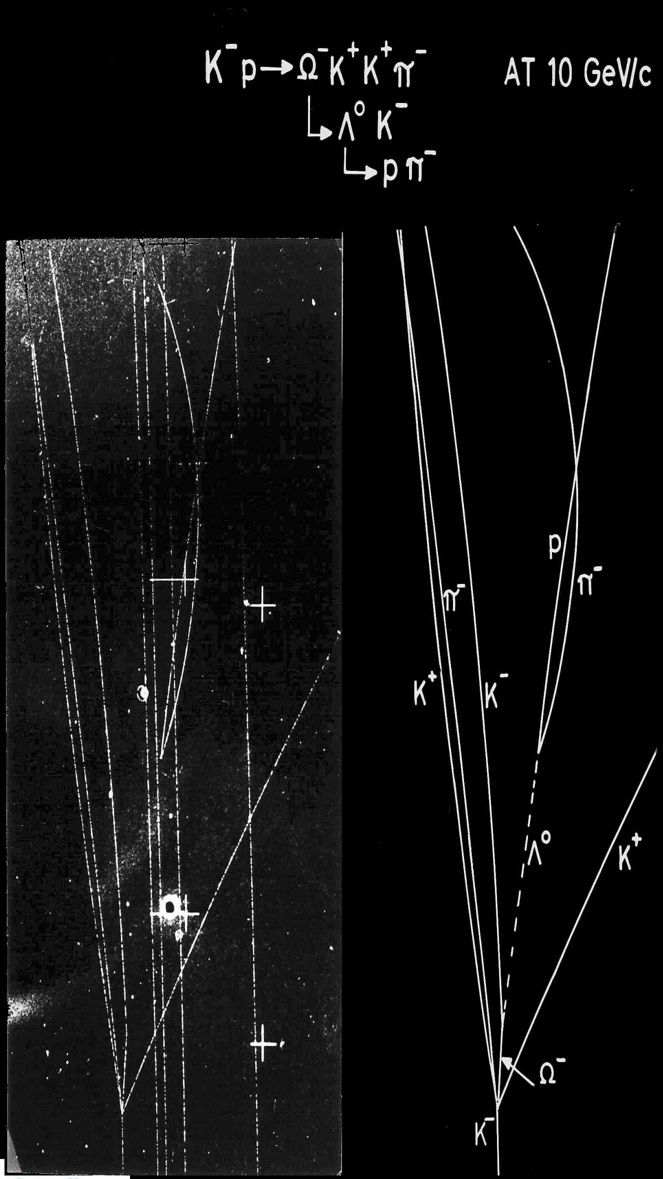
- Positron e^+ discovered in 1932 by Carl D. Anderson.
- Antiparticles:
  - For every particle there exists an antiparticle with identical mass but opposite charge.

➜ The electron and the positron are not really different particles.

3

1932

History of Particles



- Positron e^+ discovered in 1932 by Carl D. Anderson.
- 1936: Muon μ, by Anderson again
- 1947: Pion π
- 1947: Kaon K
- 1947: Lambda Λ, Omega Ω
- 1955: Antiproton $\overline{p}$
- 1956: Antineutron $\overline{n}$
- 1956: Neutrino ν
- Continue for years. . .

50

1956

History of Particles

- Positron e^+ discovered in 1932 by Carl D. Anderson.
- 1936: Muon μ, by Anderson again
- 1947: Pion π
- 1947: Kaon K
- 19
- n
- 1956: Neutrino ν
- Continue for years...

"Who ordered that?"

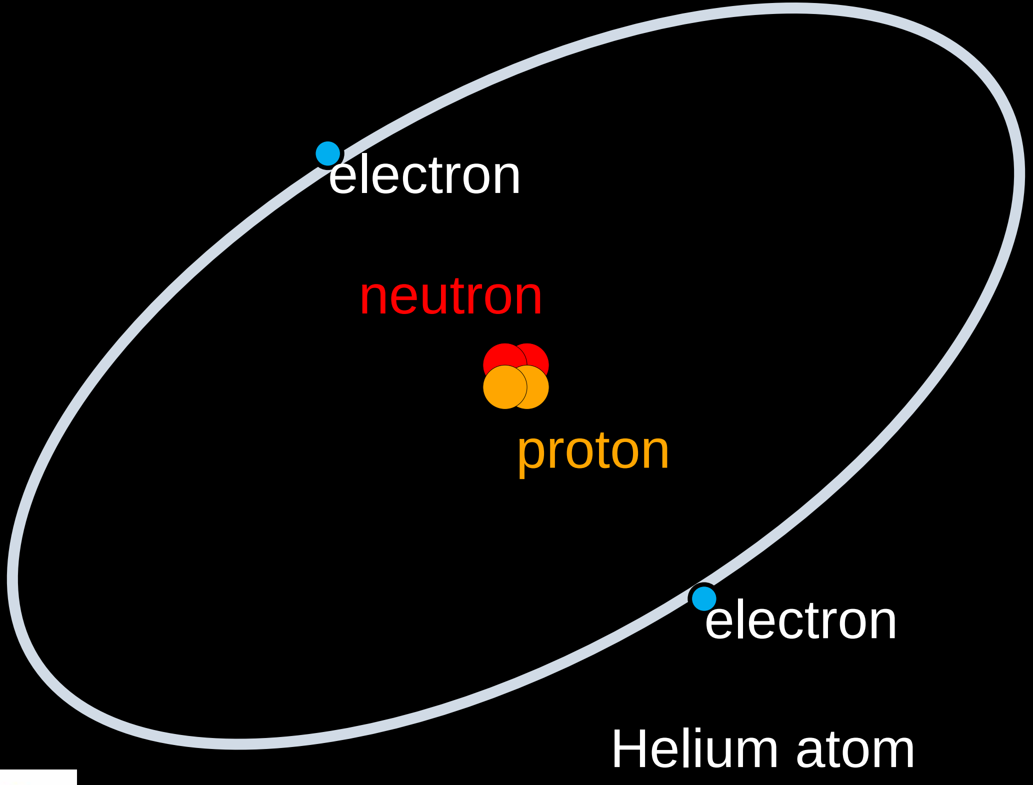
Clearly, particle physics needed its Mendeleev

50

1956

Quarks

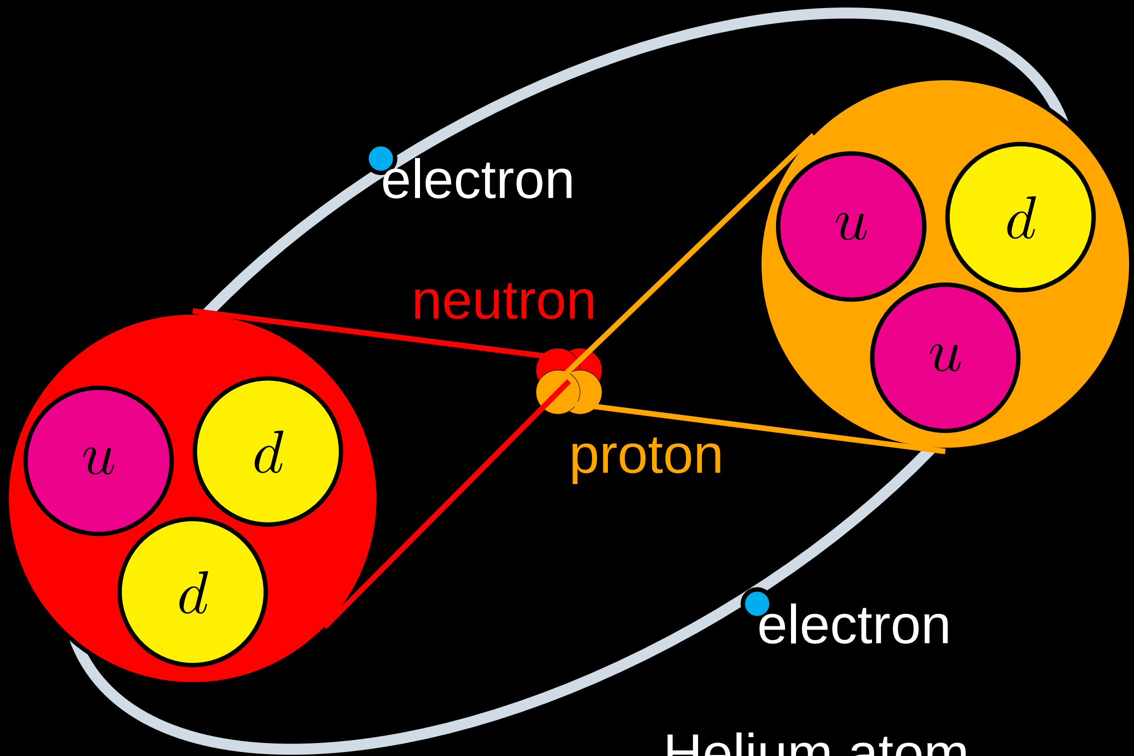
Protons and neutrons are not fundamental particles.



Quarks

Protons and neutrons are not fundamental particles. They are made of quarks.

- Proton: up & up & down
- Neutron: up & down & down



Helium atom

This allows to explain many other particles:

- pion π^+: up & anti-down

Adding the strange quark one gets:

- kaon K^-: strange & anti-up
- kaon K^0: strange & anti-down
- Lambda Λ: strange & up & down

Constituents of Matter

Quarks	$+\frac{2}{3}$	u	
	$-\frac{1}{3}$	d	s
Leptons	-1	e	μ
	0	ν_e	ν_μ

7

1969

Constituents of Matter

Quarks	$+\frac{2}{3}$	u	c	t
	$-\frac{1}{3}$	d	s	b
Leptons	-1	e	μ	τ
	0	ν_e	ν_μ	ν_τ

12

Now

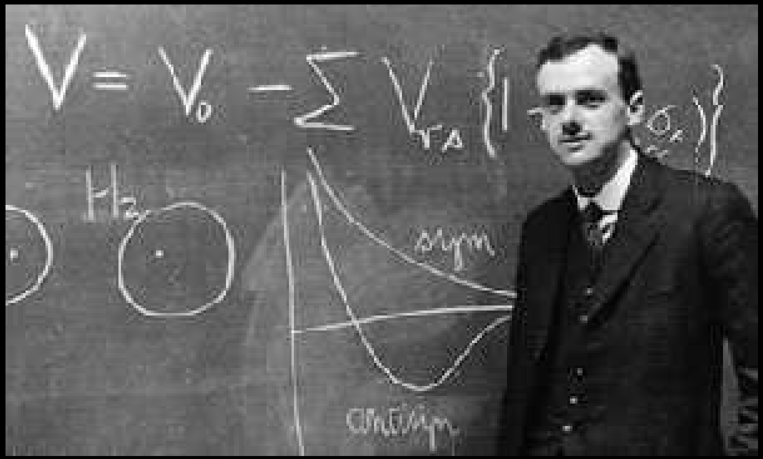
Constituents of Antimatter

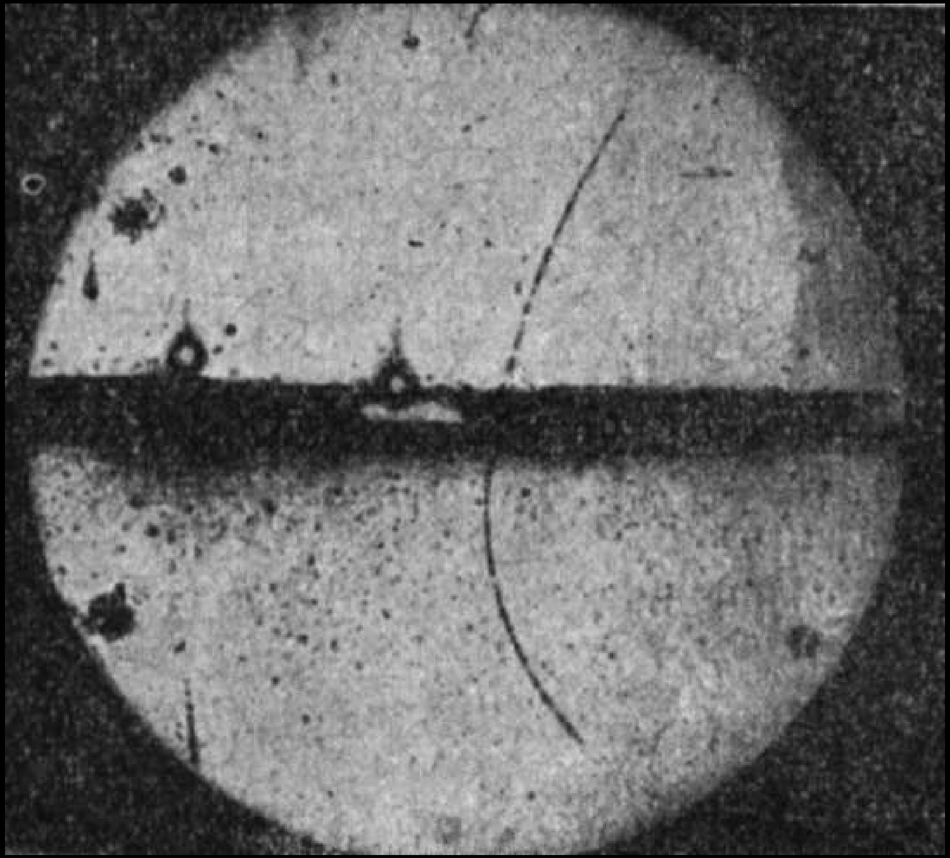
Quarks	$-\frac{2}{3}$	$\bar{u}$	$\bar{c}$	$\bar{t}$
	$+\frac{1}{3}$	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons	$+1$	e^+	μ^+	τ^+
	0	$\overline{\nu}_e$	$\overline{\nu}_\mu$	$\overline{\nu}_\tau$

Predicted Particles

Many particles have been predicted before they have been observed

- The positron is the negative-energy solution of Dirac's equation (1927)
  - Discovered in 1932

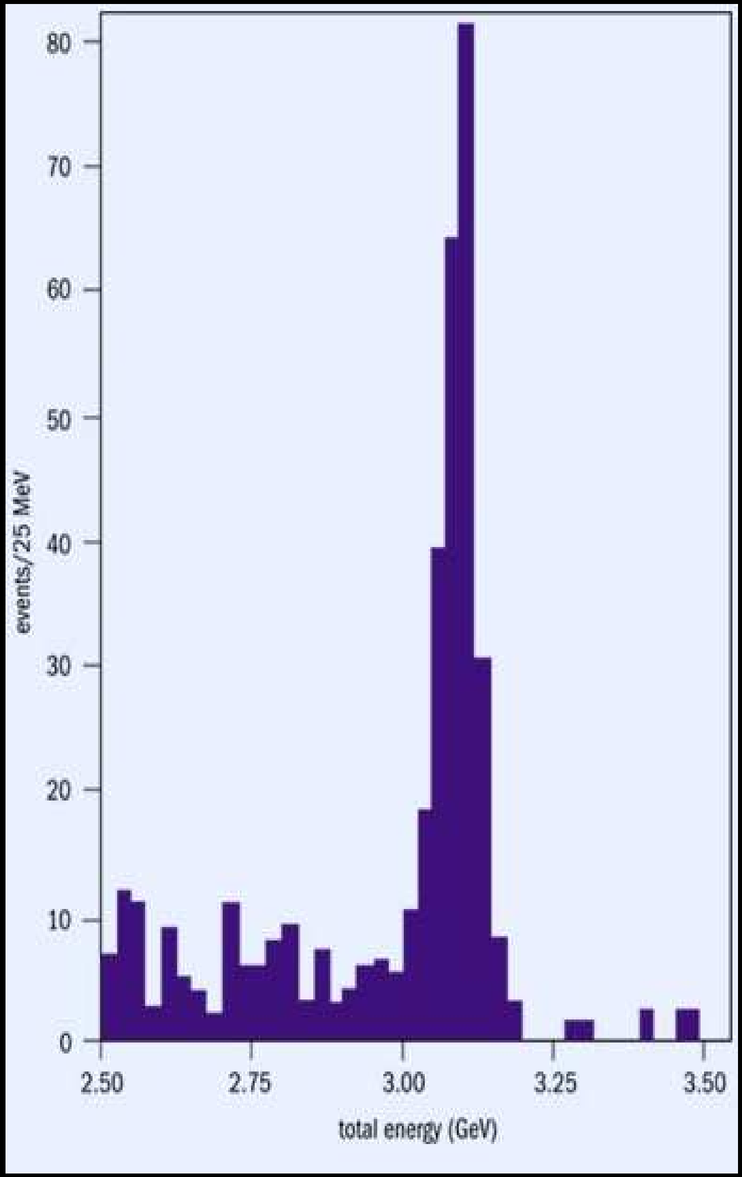




Predicted Particles

Many particles have been predicted before they have been observed

- The positron is the negative-energy solution of Dirac's equation (1927)
- The charm quark c was needed to explain why $K^0 \not\to \mu^+\mu^-$ (1970)
  - Discovered in 1974

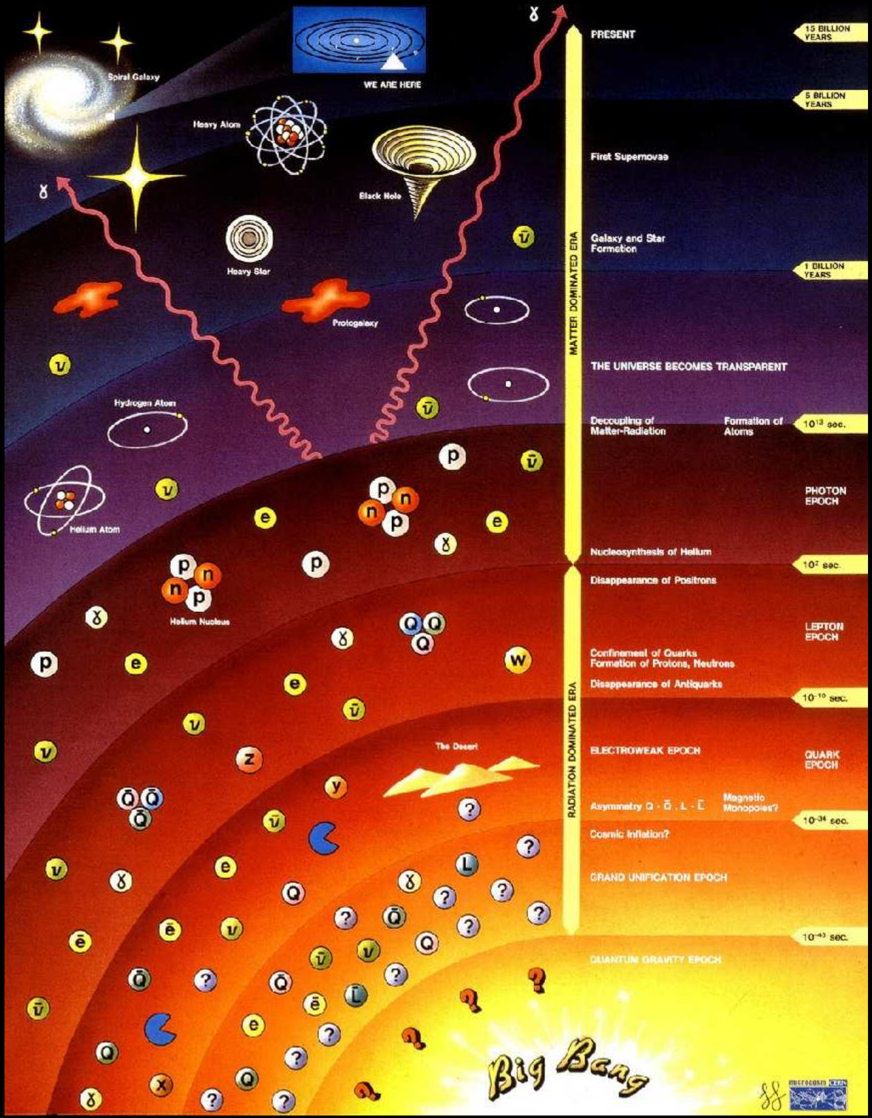


Predicted Particles

Many particles have been predicted before they have been observed

- The positron is the negative-energy solution of Dirac's equation (1927)
- The charm quark c was needed to explain why $K^0 \not\to \mu^+\mu^-$ (1970)
- The bottom and top quarks b & t were postulated to explain asymmetries in K^0 decays (1973)
  - b discovered in 1977
  - t Discovered in 1995
- Same story for the Higgs boson (?) ➜ See Jon's talk

History of the Universe



Now ($t = 13.7 \cdot 10^9$ years) $T = 3\,\mathrm{K}$

Stars form ($t = 10^9$ years) $T = 15\,\mathrm{K}$

Atoms form ($t = 300,000$ years)

Nuclei form ($t = 100$ s) $T = 10^9\,\mathrm{K}$

Protons and neutrons form,
Antiquarks disappear (10^{-10} s)

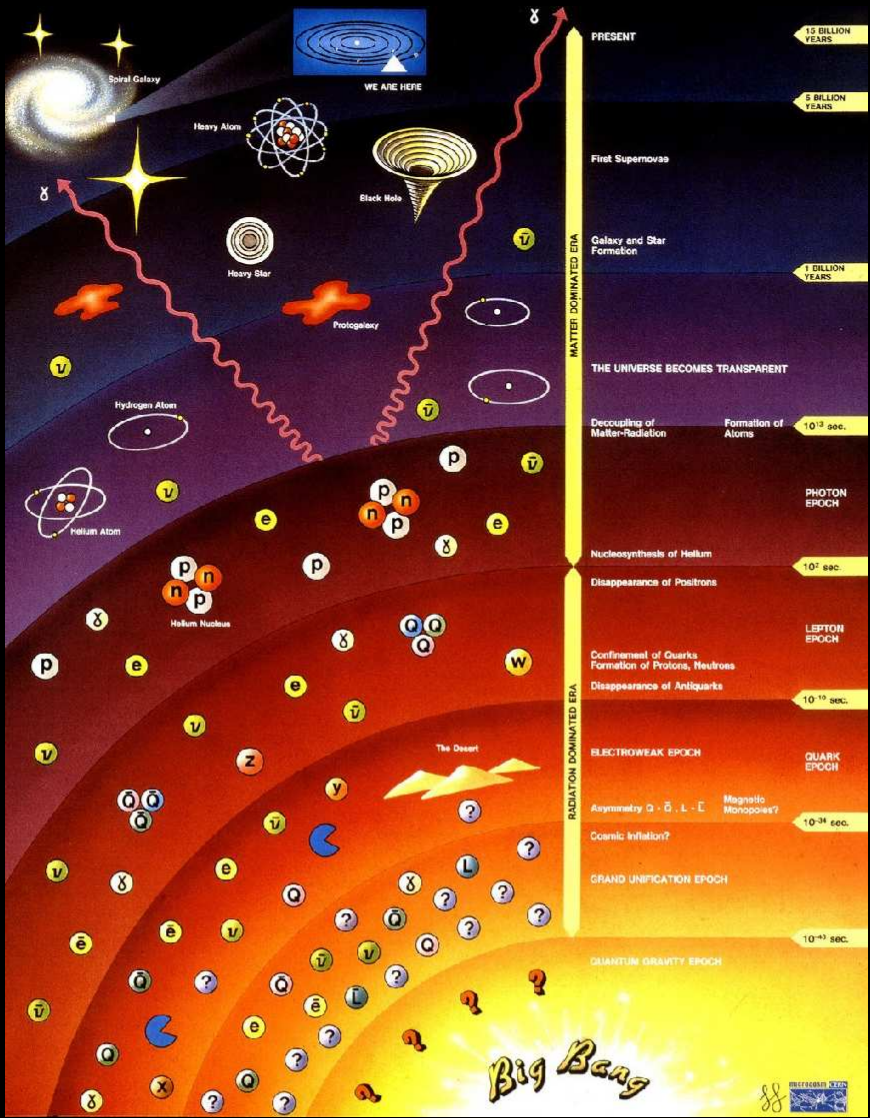
Quarks form ($t = 10^{-34}$ s?)

$T = 10^{28}\,\mathrm{K}$

????

Big Bang ($t = 0$)

History of the Universe



At large temperatures the reaction below occurs:

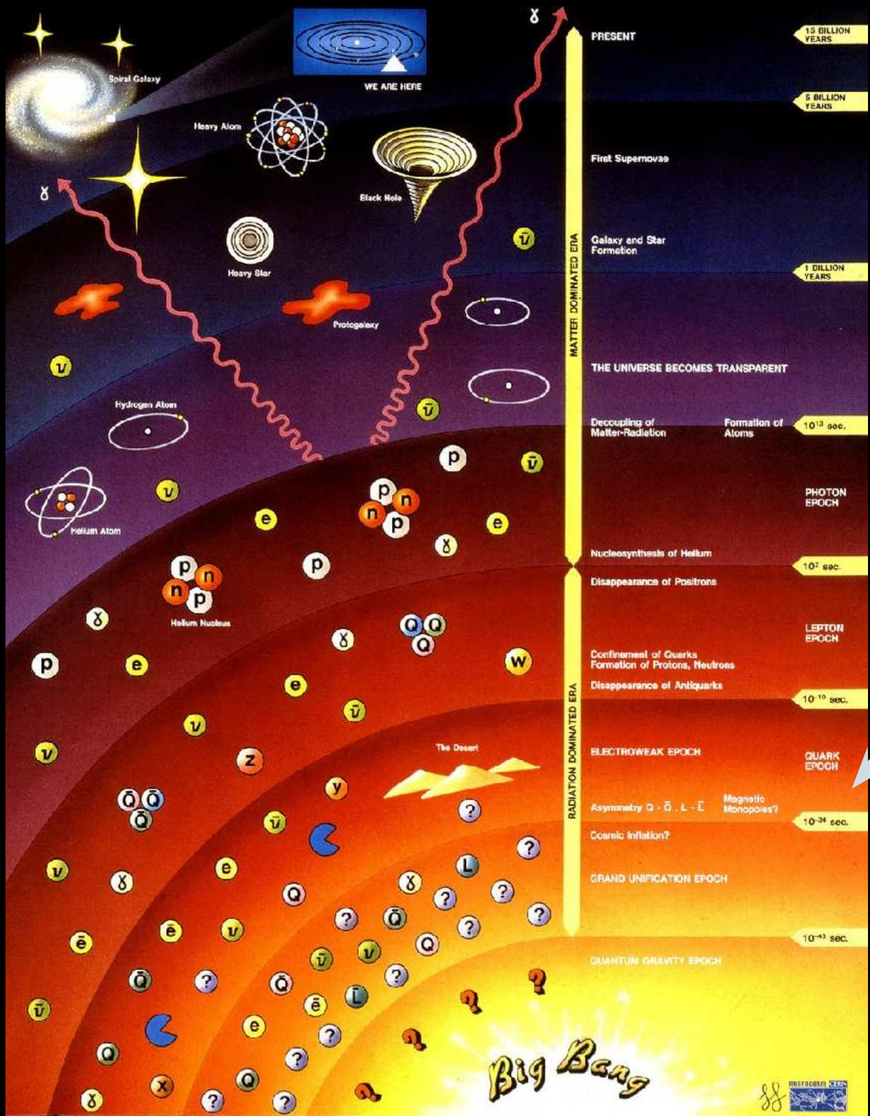
$$\gamma + \gamma \leftrightarrow \text{particle} + \text{antiparticle}$$

For a particle of mass m, the photons must have energy $E_\gamma > mc^2$.

As long as $E = kT > 2mc^2$ such pairs create and annihilate. Below this threshold the reaction stops.

Particle	Mass	T
W boson	80 GeV$/c^2$	10^{15} K
d quark	5 MeV$/c^2$	10^{11} K
electron	511 keV$/c^2$	10^{10} K

History of the Universe

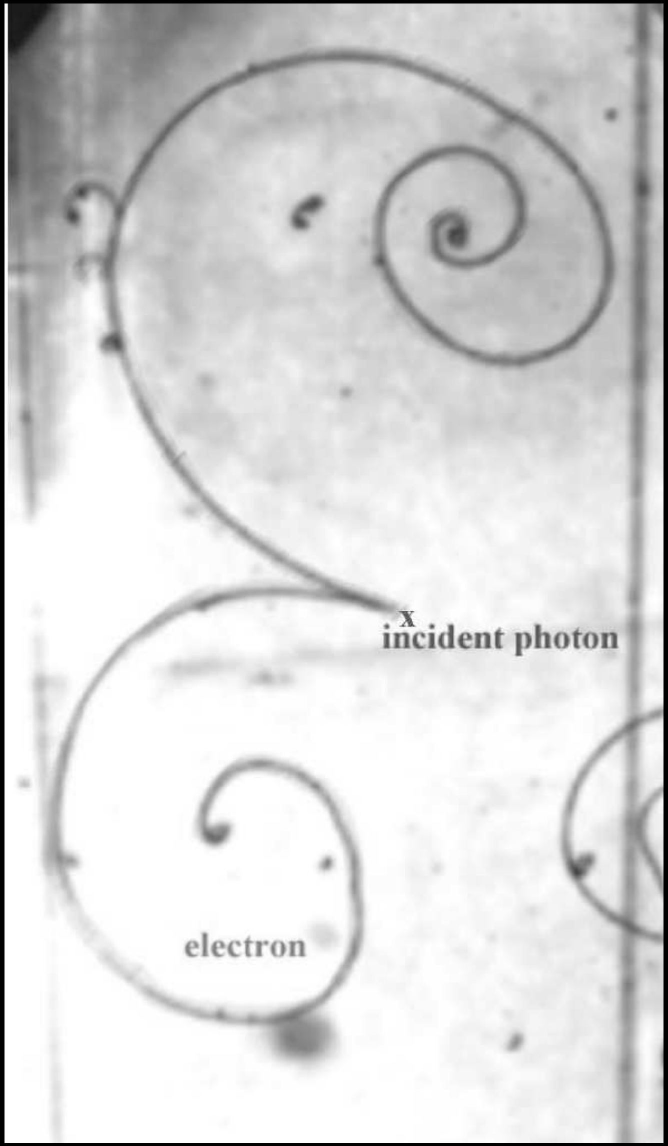


In collider experiments we recreate the conditions of the primordial Universe according to the available energy.

Accelerator	Energy	T
LEP	200 GeV	10^{15} K
Tevatron	2 TeV	10^{16} K
LHC	14 TeV	10^{17} K

Particle	Mass	T
W boson	80 GeV$/c^2$	10^{15} K
d quark	5 MeV$/c^2$	10^{11} K
electron	511 keV$/c^2$	10^{10} K

There's something wrong



- This bubble chamber picture shows a pair creation

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

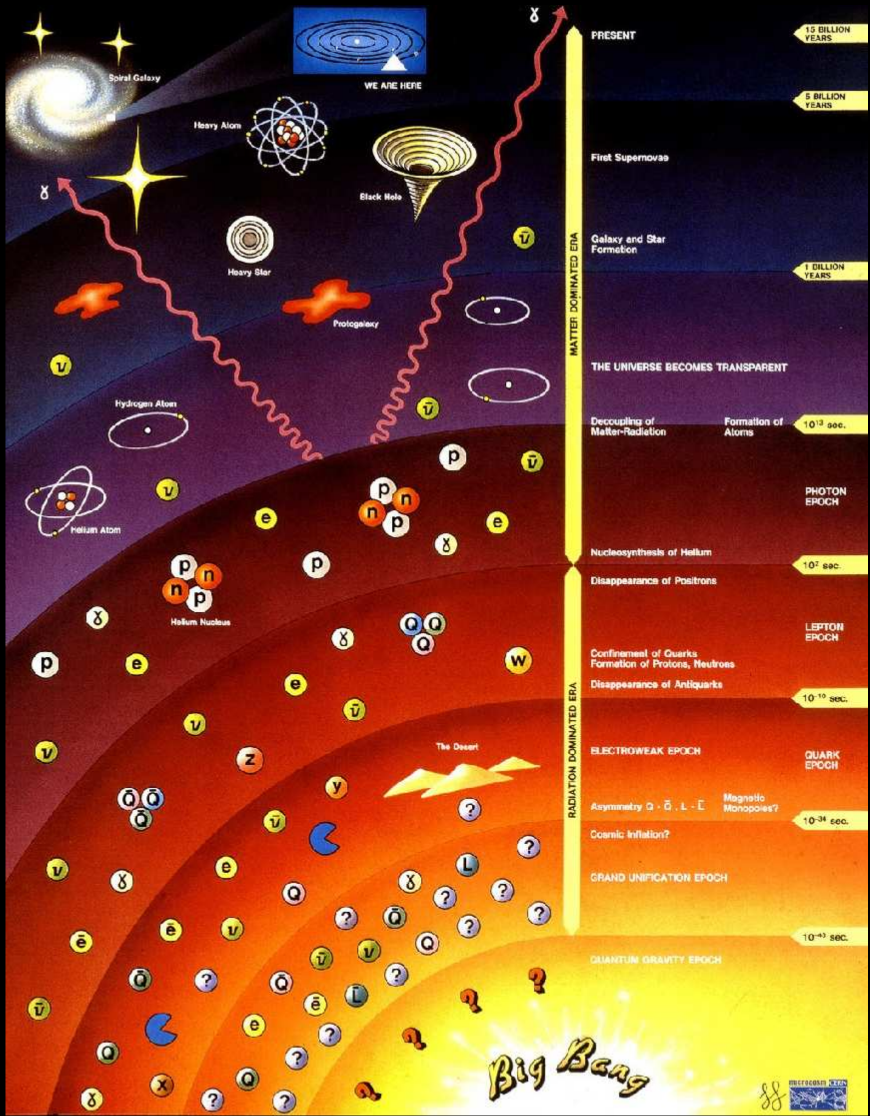
- Particle and antiparticles are always created in pairs
- And they annihilate by pairs

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

- Hence:

$$\text{Particles} - \text{Antiparticles} = 0$$

There's something wrong



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- Particle and antiparticles are always created in pairs
- And they annihilate by pairs

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

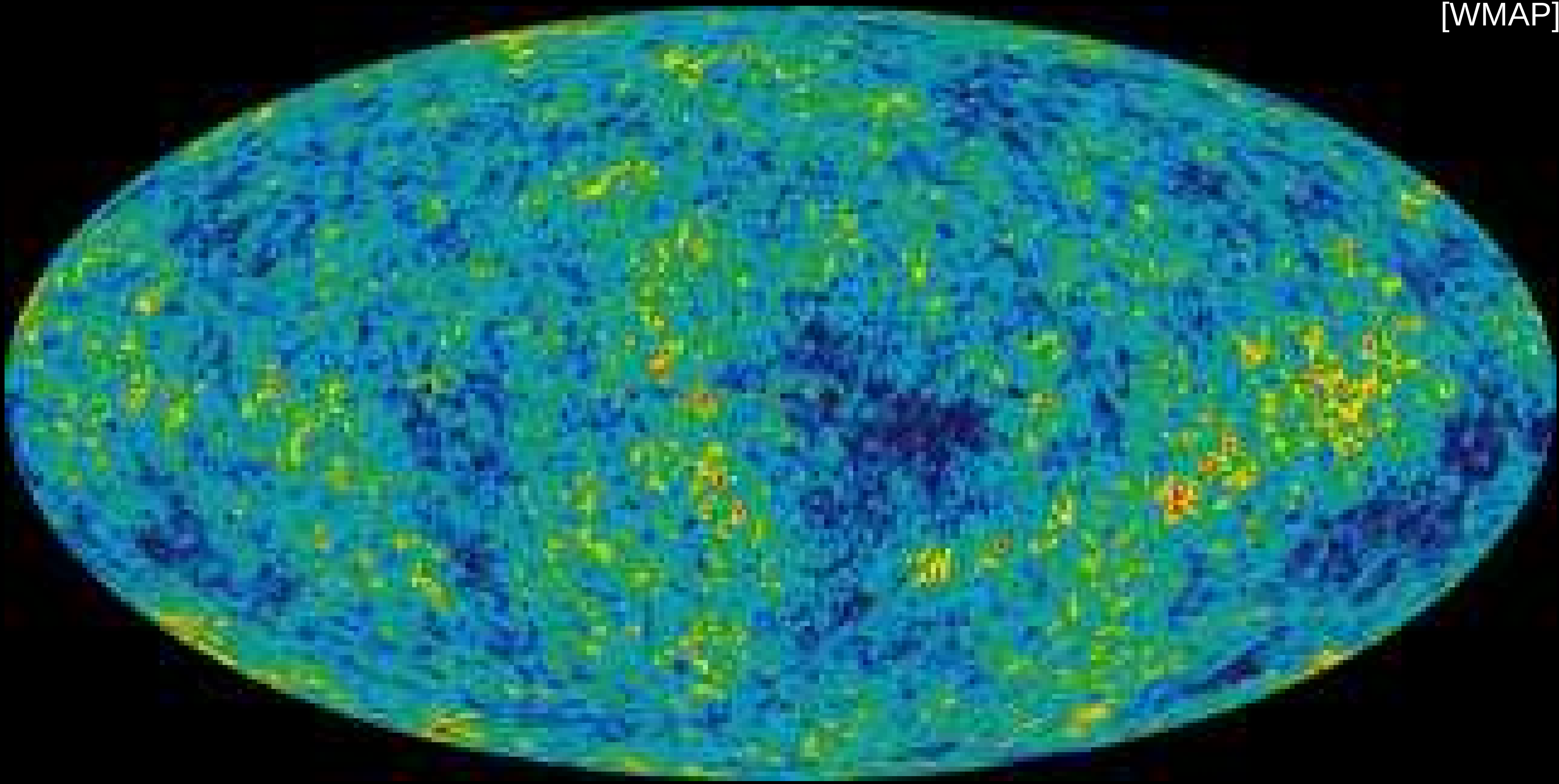
- Hence:

$$\text{Particles} - \text{Antiparticles} = 0$$

- So where have all antiparticles gone?

Antimatter in the Universe

[WMAP]

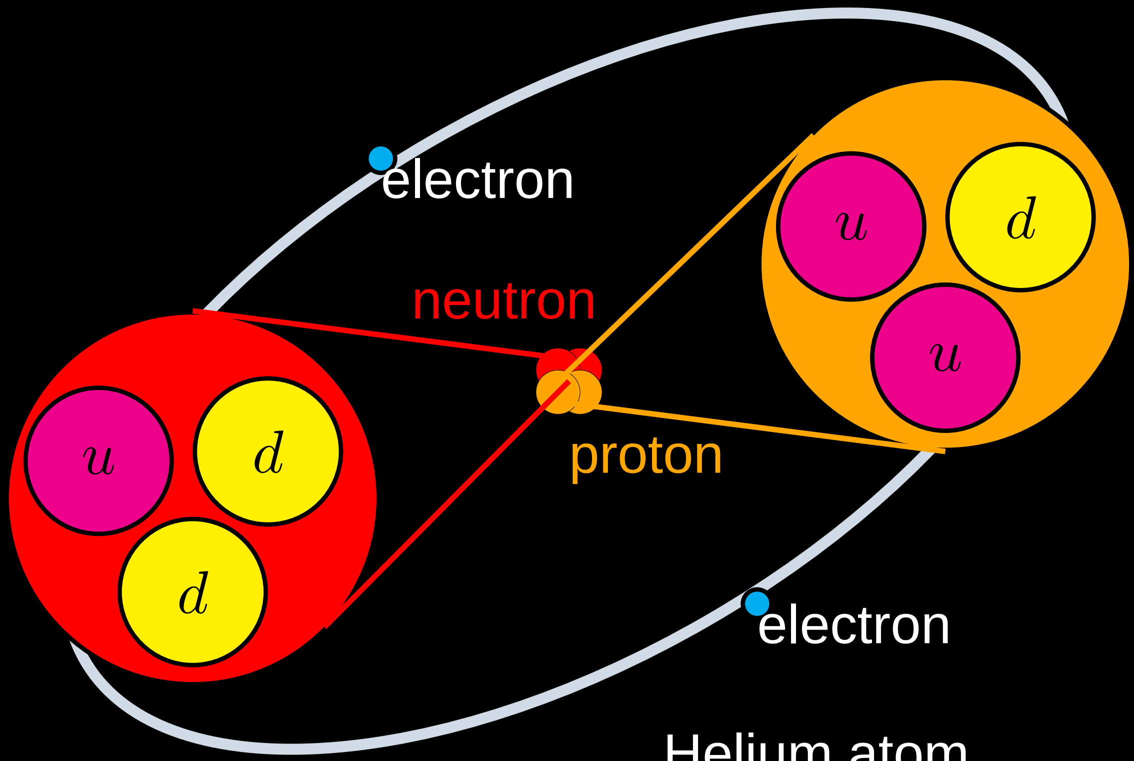


There should be annihilation photons — can't see any.
Is there any antimatter in the universe?

Antimatter exists!

Antimatter factory:

1. Replace electrons by positrons
2. Replace all quarks by antiquarks



Helium atom

Antimatter exists!

Antimatter factory:

1. Replace electrons by positrons
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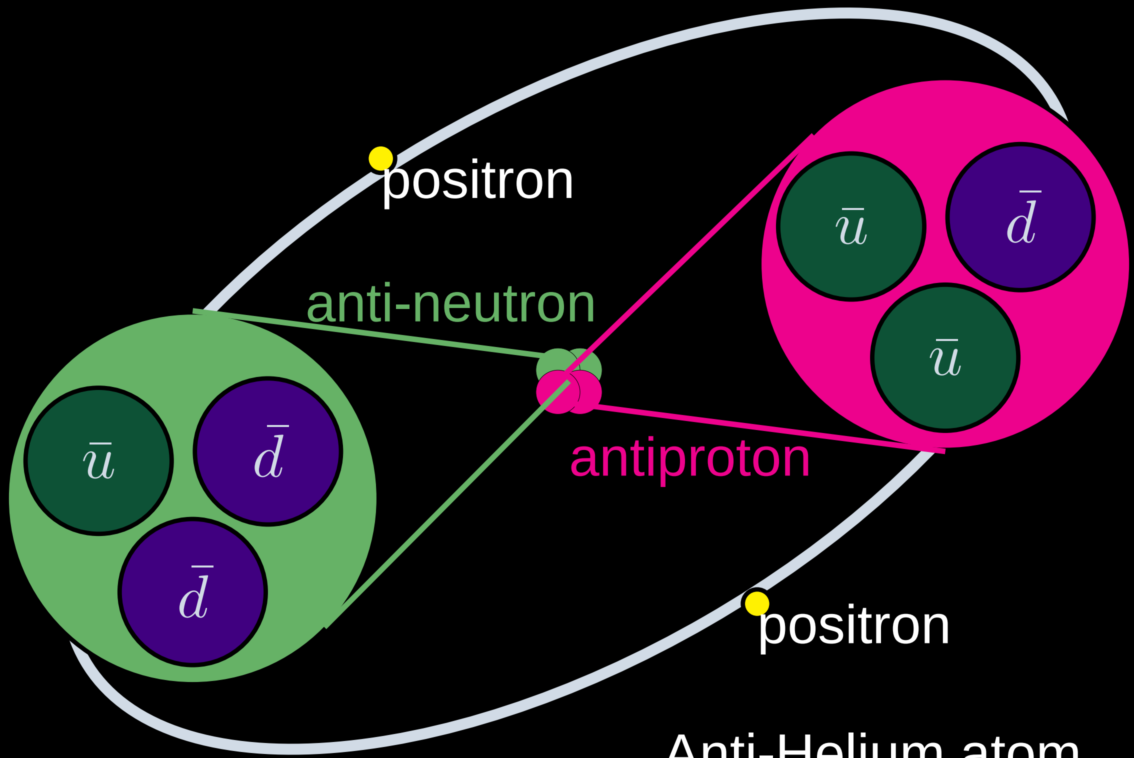


Anti-Helium atom

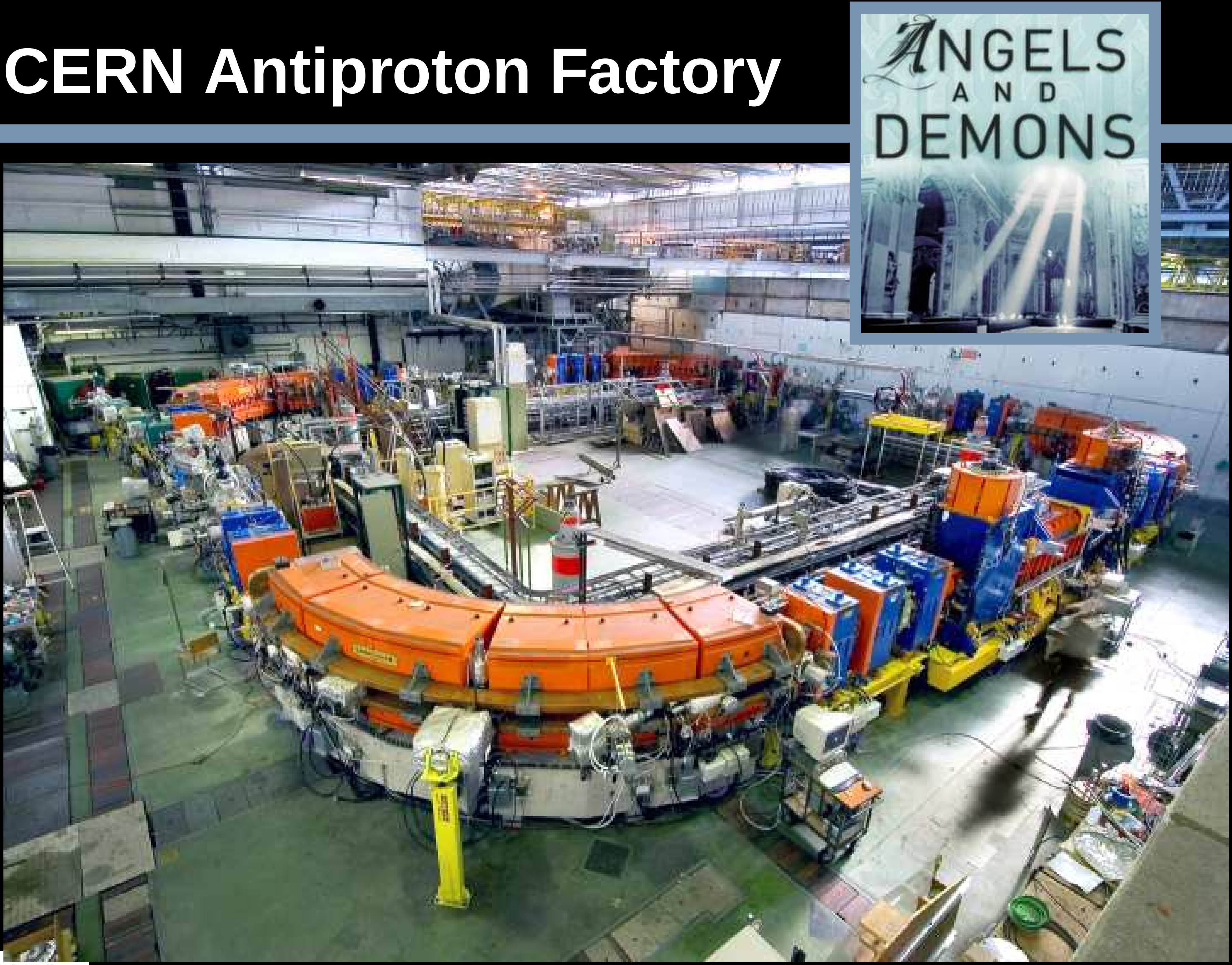
CERN has an anti-atom production facility.

- Produced thousands of anti-hydrogen atoms
- Survive for milliseconds

→ Still allows to study them

Does antimatter have the same properties as matter?

CERN Antiproton Factory



If there was a tiny difference

$10^{10} + 1$ quarks

10^{10} antiquarks

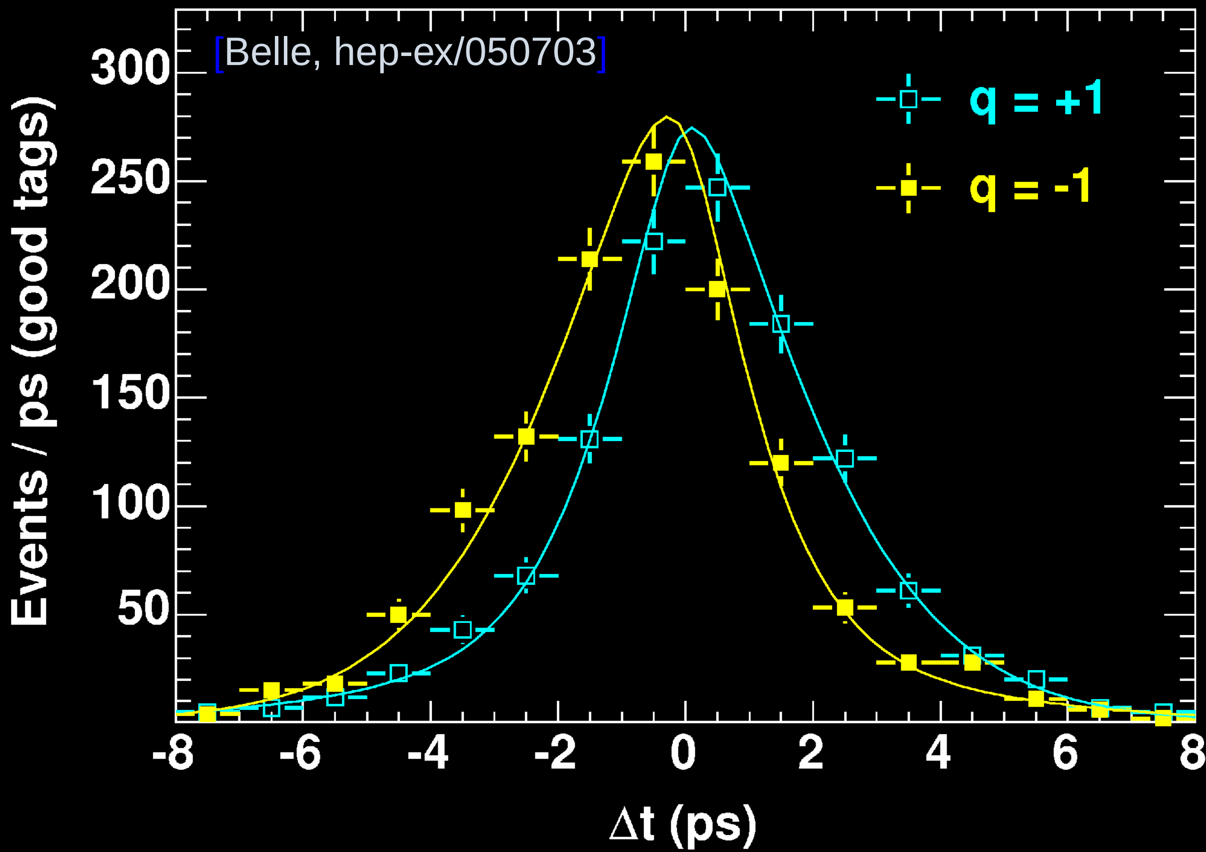
- If some mechanism slightly favoured matter of antimatter it could explain why there's any matter left and not just photons.
- Such a mechanism exists: CP violation

If there was a tiny difference

You are here

- If some mechanism slightly favoured matter of antimatter it could explain why there's any matter left and not just photons.
- Such a mechanism exists: CP violation

CP violation exists

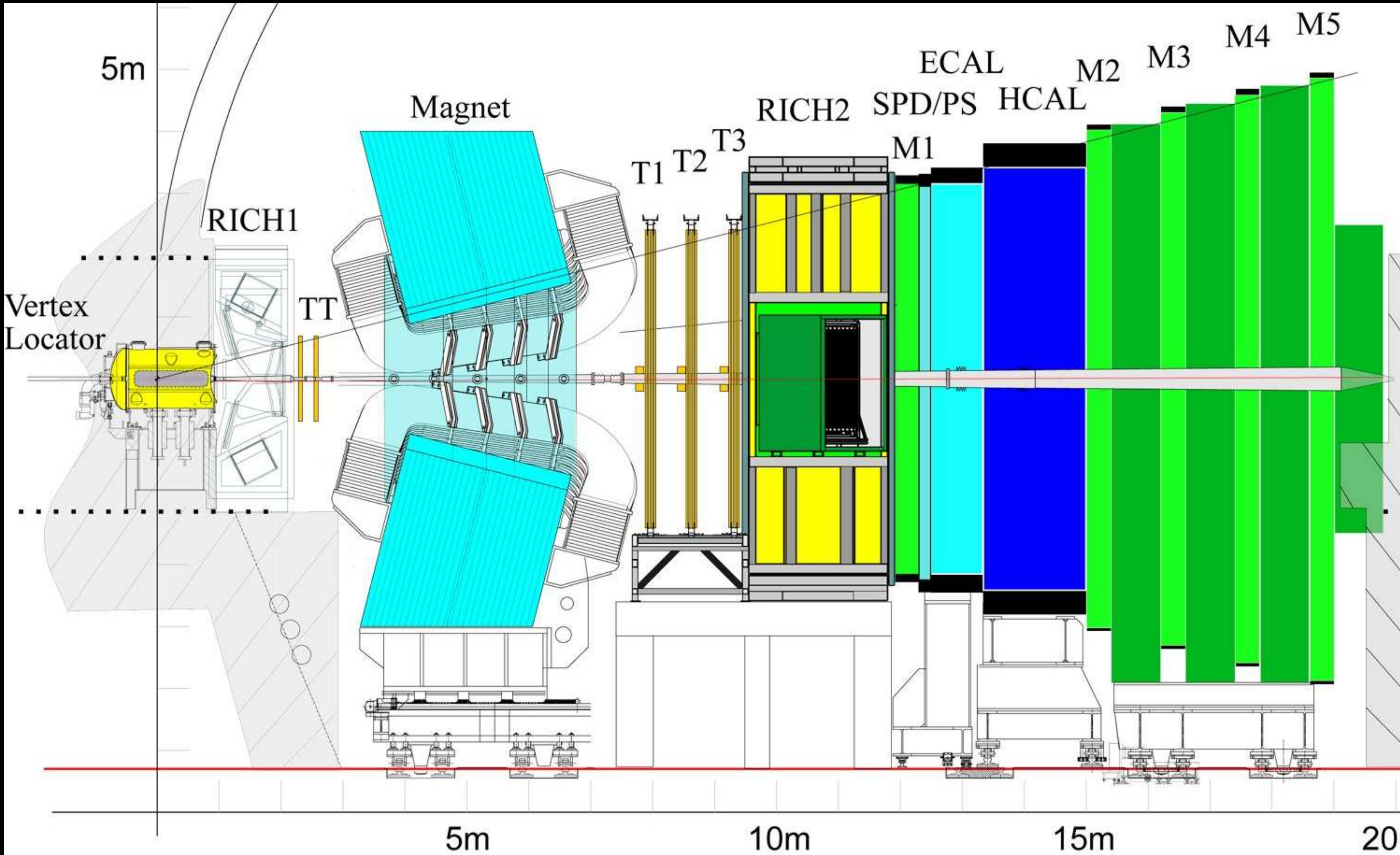


The strongest matter-antimatter asymmetry ever measured:
Number of $b \rightarrow c\bar{c}s$ and $\bar{b} \rightarrow \bar{c}c\bar{s}$ decays versus time.

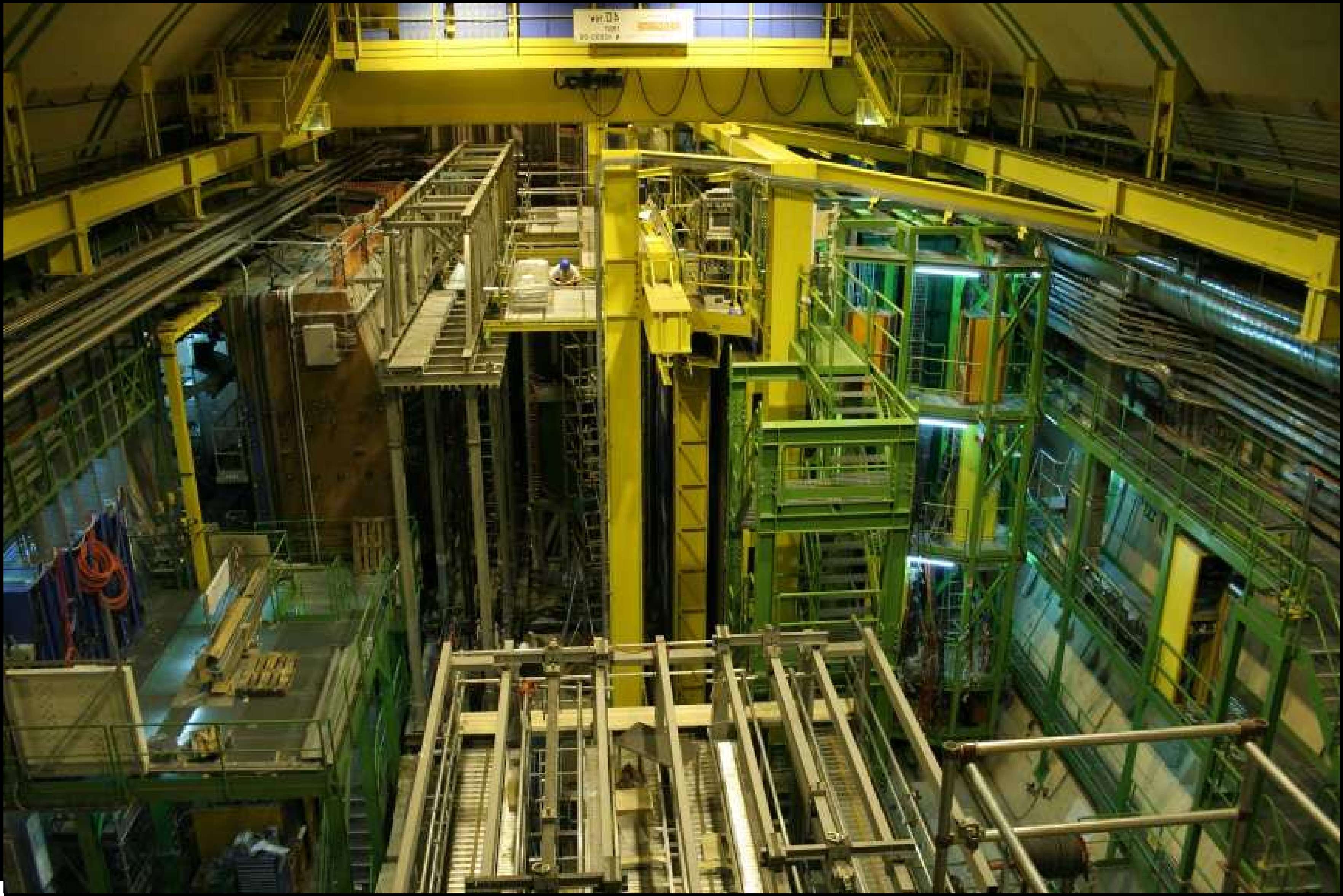
Yet it's not enough: The asymmetry is a factor 10^{10} too small!

The LHC beauty experiment

The LHC beauty experiment

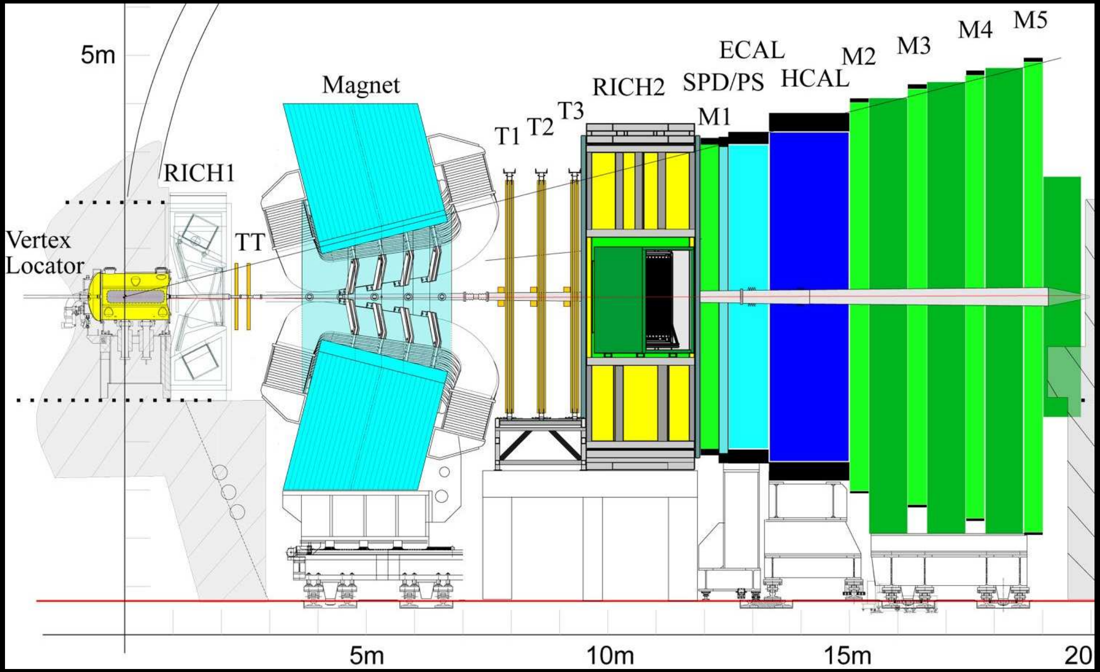


The LHC beauty experiment



The LHC beauty experiment

- Starting data taking end of this year
- We'll have 10^{12} $b\bar{b}$ quark pairs produced a year. That's 10^5 a second.
- But we need to fish them out of $> 10^7$ collisions per second



- And we can only write out 2000 collisions per second (that's still $600\,000$ GB a year)
- Which 2000 out of $> 10^7$ we keep must be decided in real time . . . there's a new collision coming every 25 ns.

Huge technical challenges ahead. . .

Cherenkov Radiation

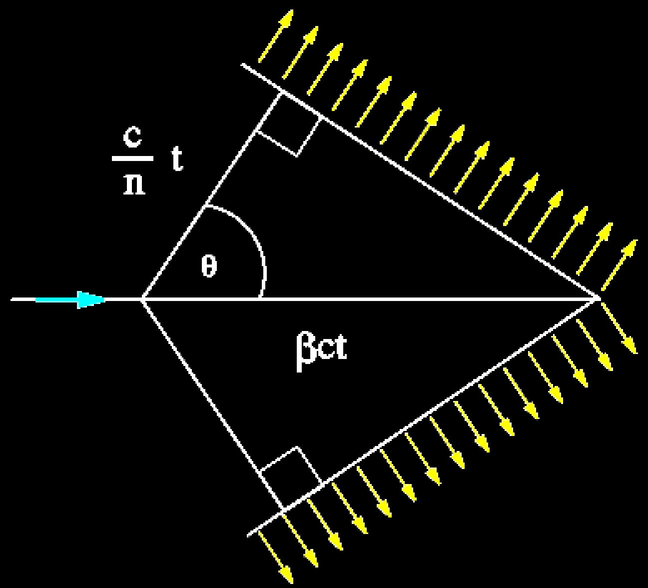
- Cherenkov radiation is emitted by charged particles crossing a transparent medium at a speed higher than the speed of light *in that medium*.

$$v = \frac{c}{n}$$

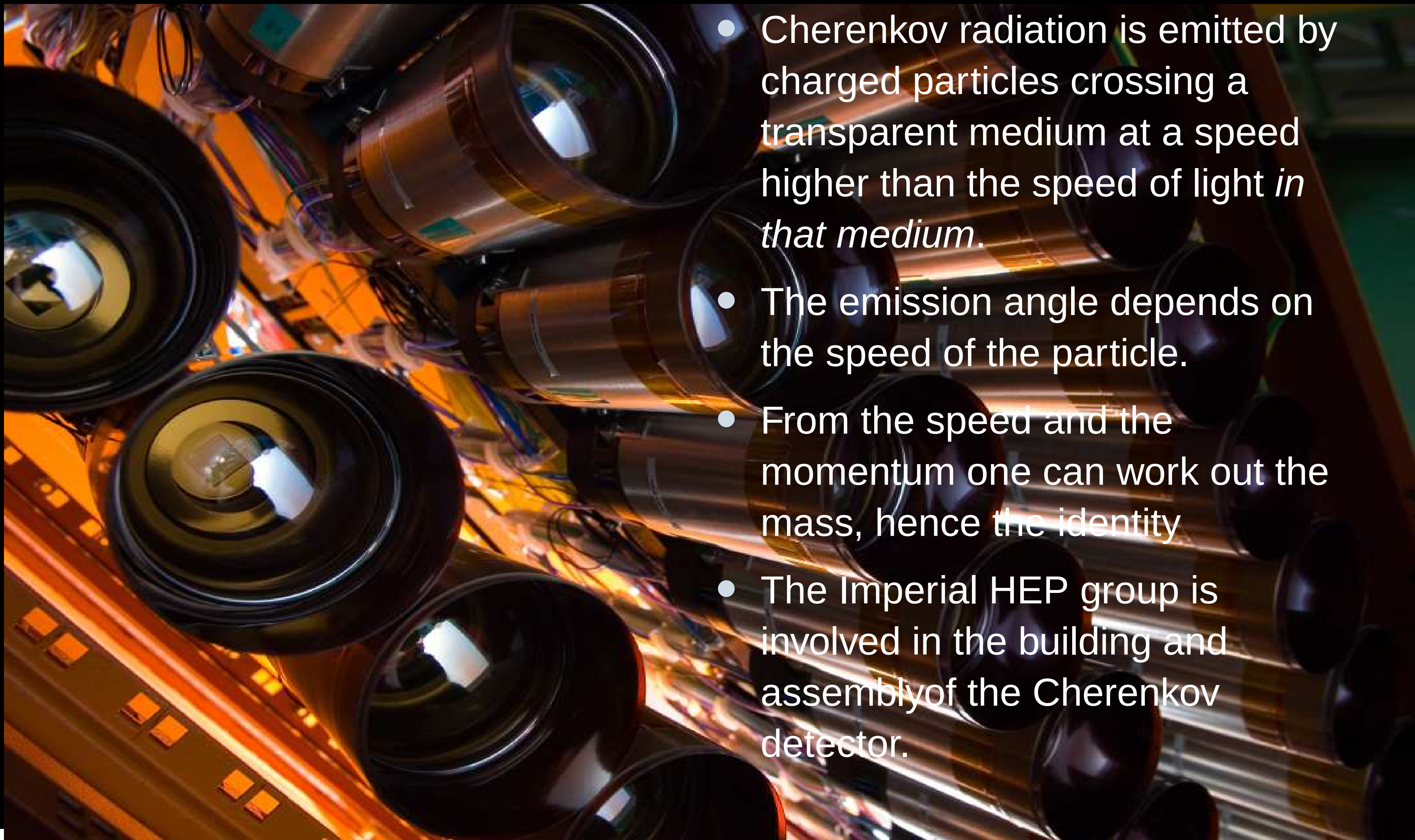
- Like boom of a supersonic aircraft.

Cherenkov Radiation

- Cherenkov radiation is emitted by charged particles crossing a transparent medium at a speed higher than the speed of light *in that medium*.
- The emission angle depends on the speed of the particle.

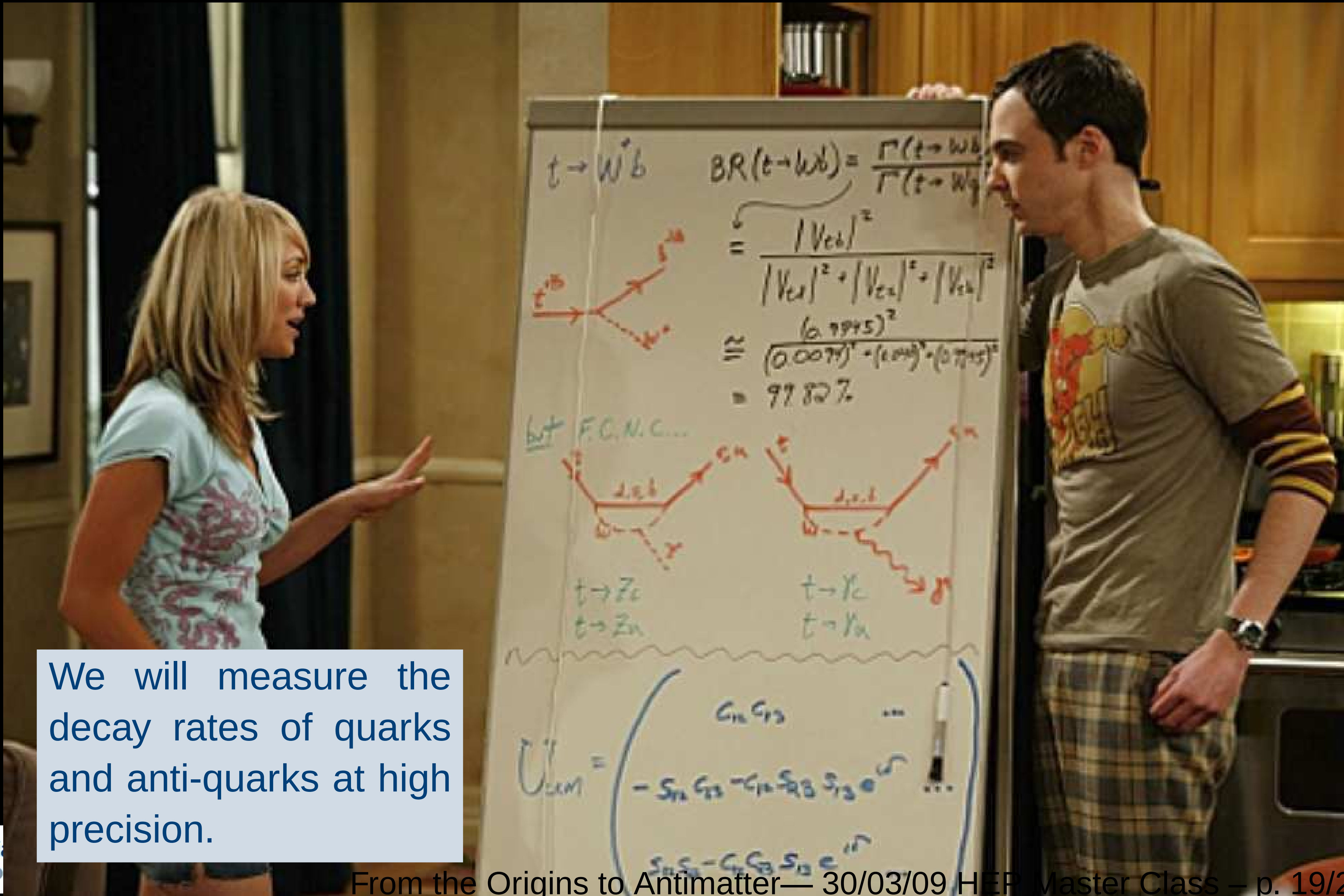


Cherenkov Radiation



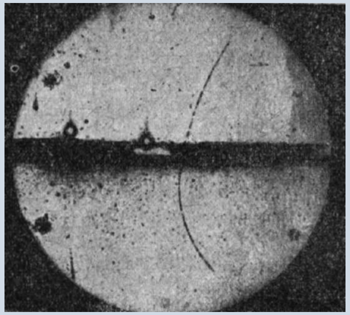
- Cherenkov radiation is emitted by charged particles crossing a transparent medium at a speed higher than the speed of light *in that medium*.
- The emission angle depends on the speed of the particle.
- From the speed and the momentum one can work out the mass, hence the identity
- The Imperial HEP group is involved in the building and assemblyof the Cherenkov detector.

Decay rates of heavy quarks



We will measure the decay rates of quarks and anti-quarks at high precision.

Conclusion



We study the fundamental constituents of matter

- . . . and the fundamental forces
  - ➜ See Jon's talk

We need huge accelerators to see tiny particles

- Allows to recreate the conditions of the primordial universe

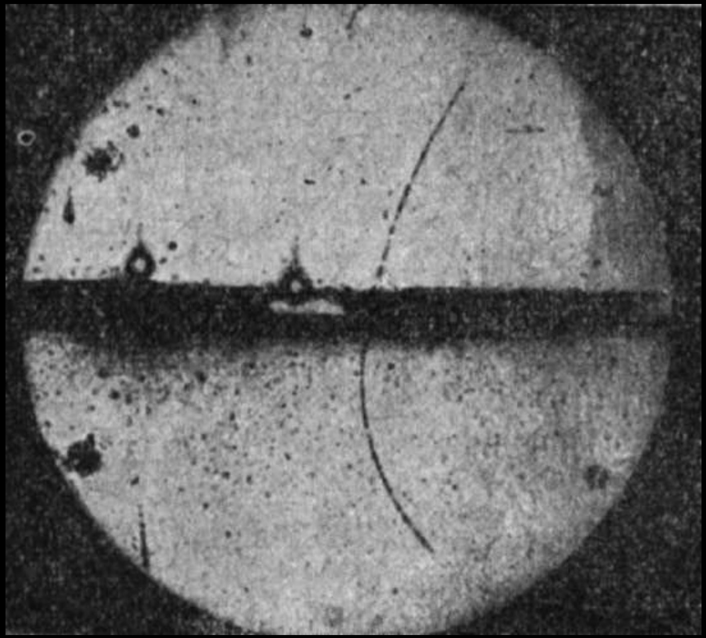
But there's something wrong

➜ where has all the antimatter has gone?

- The LHCb experiment will (hopefully) find out
- But maybe the solution is in the lepton sector
  - ➜ See Julia's talks

Backup Slides

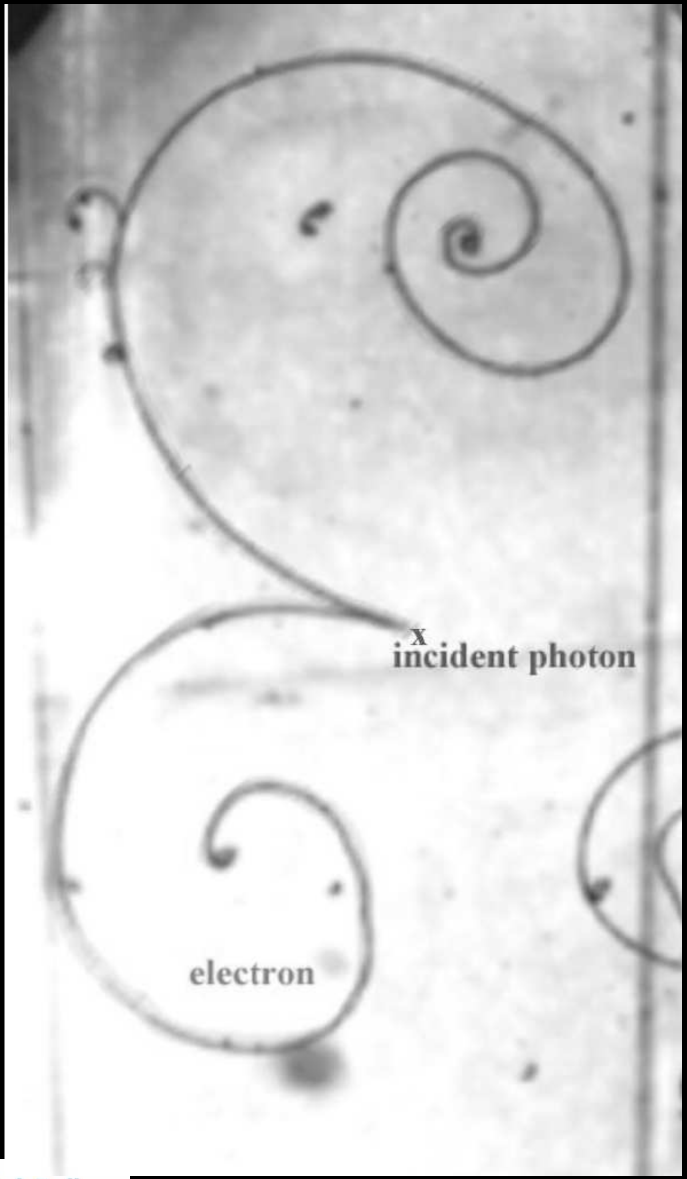
Cloud & Bubble Chambers



Cloud Chamber

- A cloud chamber contains a supercooled, supersaturated water vapour.
- When a charged particle crosses it, the vapour gets ionised.
- The ions act as condensation nuclei, around which mist will form.
- Invented by Charles Wilson in 1911.

Cloud & Bubble Chambers



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- When a charged particle crosses it, the vapour gets ionised.
- The ions act as condensation nuclei, around which mist will form.
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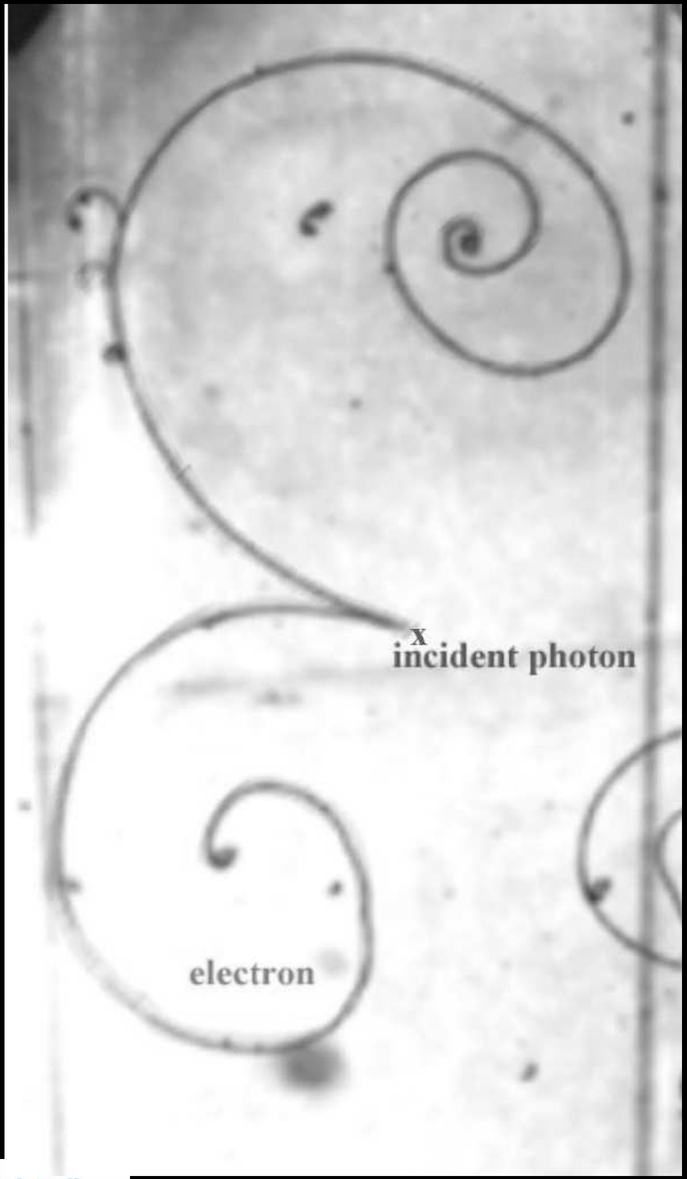
Bubble Chamber

The liquid is superheated and the ions cause the creation of bubbles (invented in 1952)

Magnetic Field



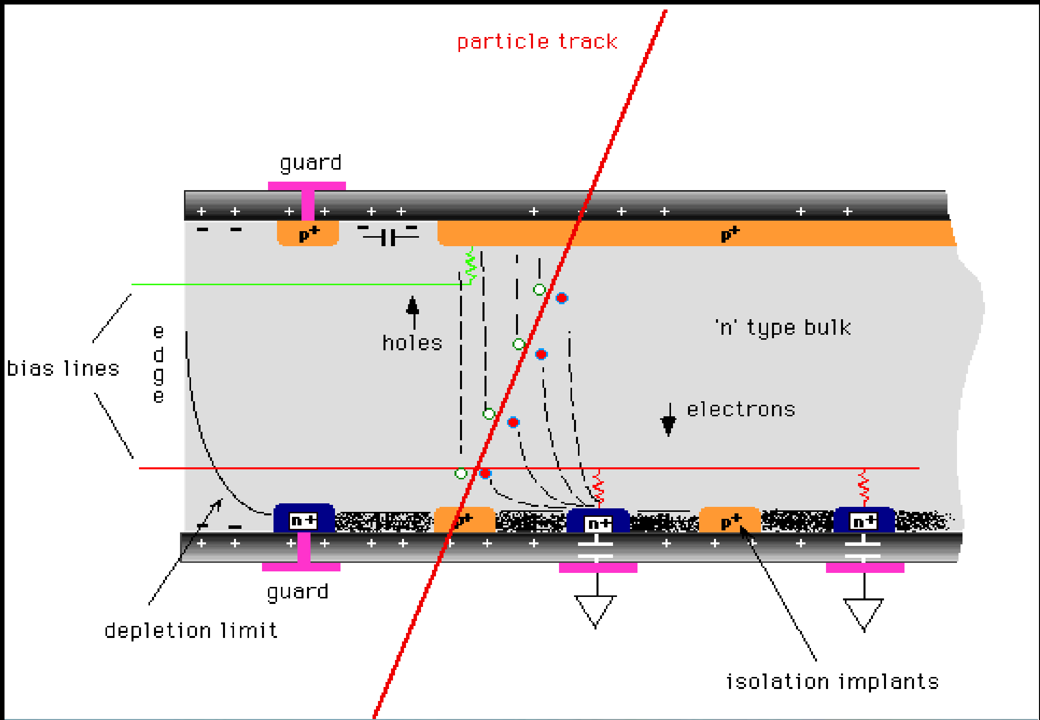
In almost all particle physics experiments a magnetic field is applied

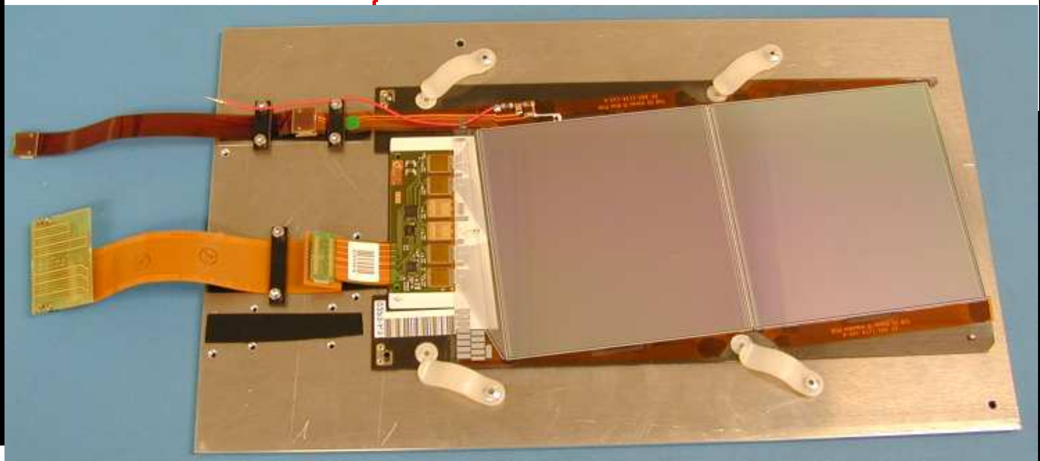
- Bends the trajectory of charged particles
- Allows to determine
  1. the charge, if you know the direction
  2. the momentum
  3. the mass, if you know the energy

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

➜ which identifies the particle

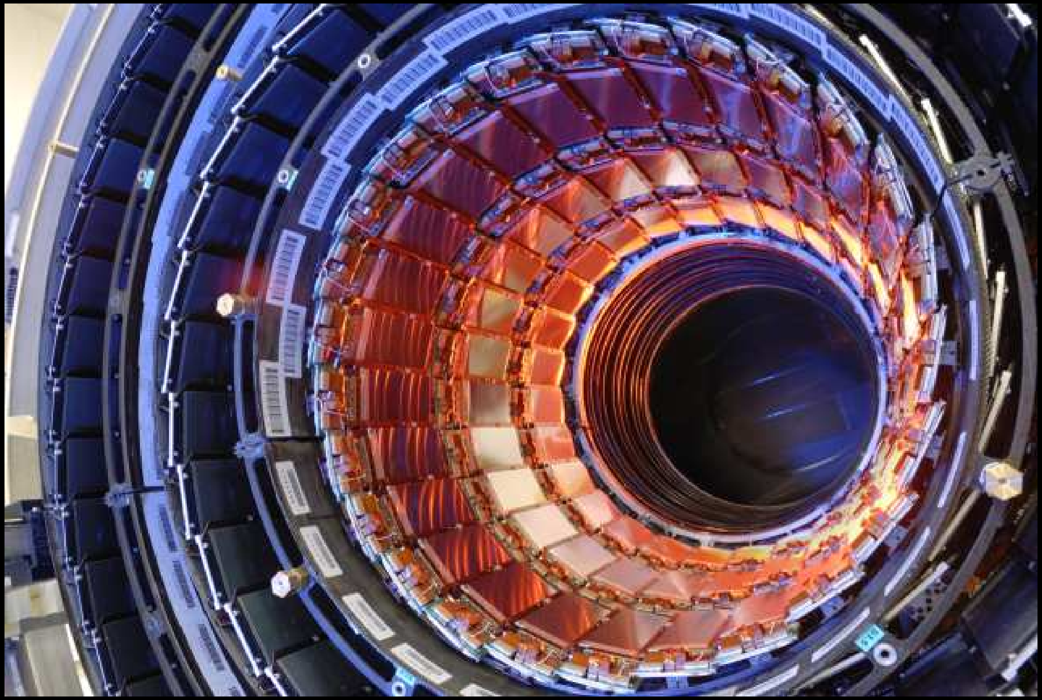
Silicon Detectors





- Modern replacement of bubble chambers
- The particle ionises the silicon
- The charges drift to the surface due to an electric field
- The charges are collected on read-out strips or pixels
- One gets a digital signal, like in a digital camera

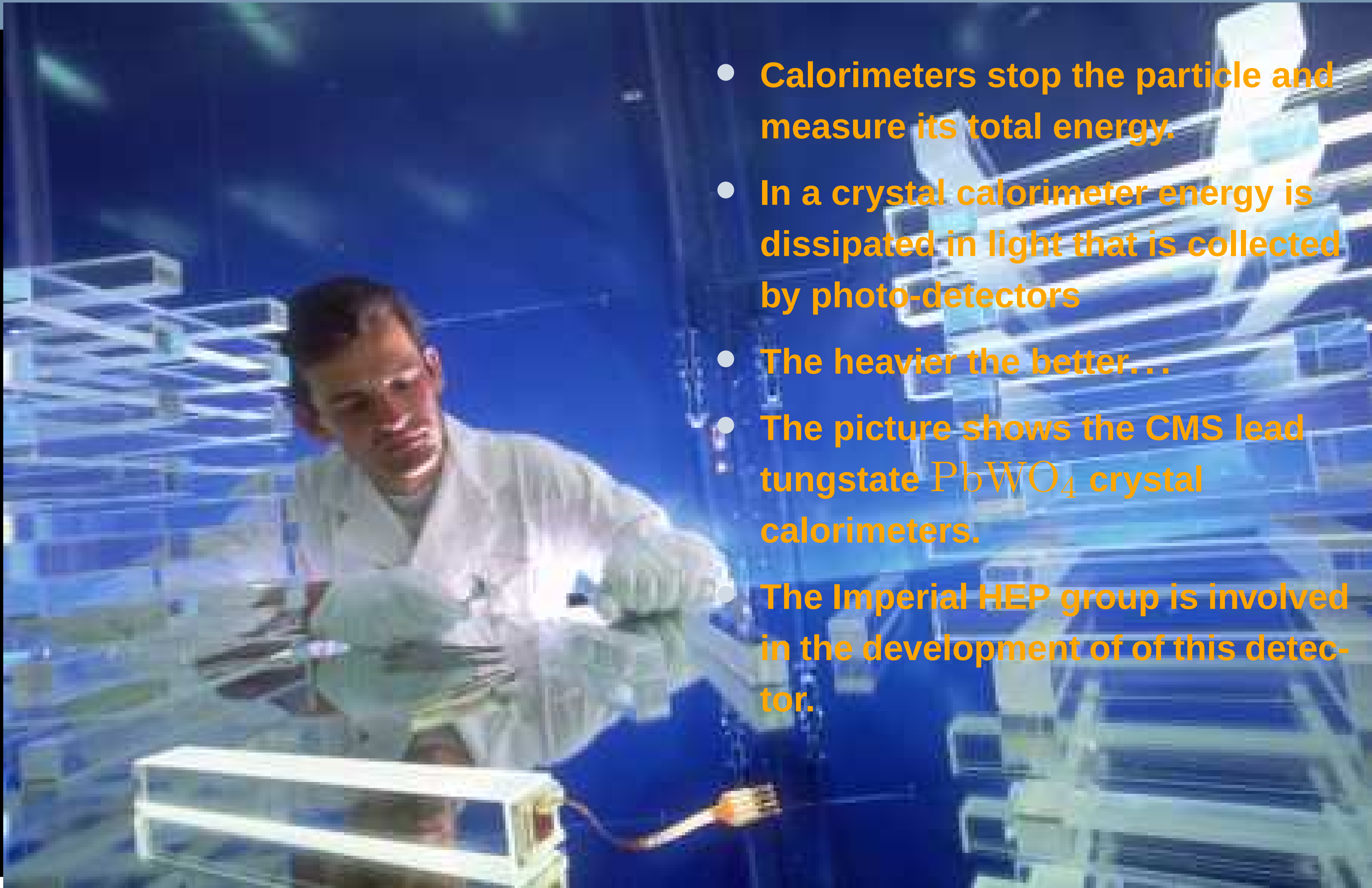
Silicon Detectors



The Imperial HEP group is involved in the development of the CMS experiment silicon tracker.

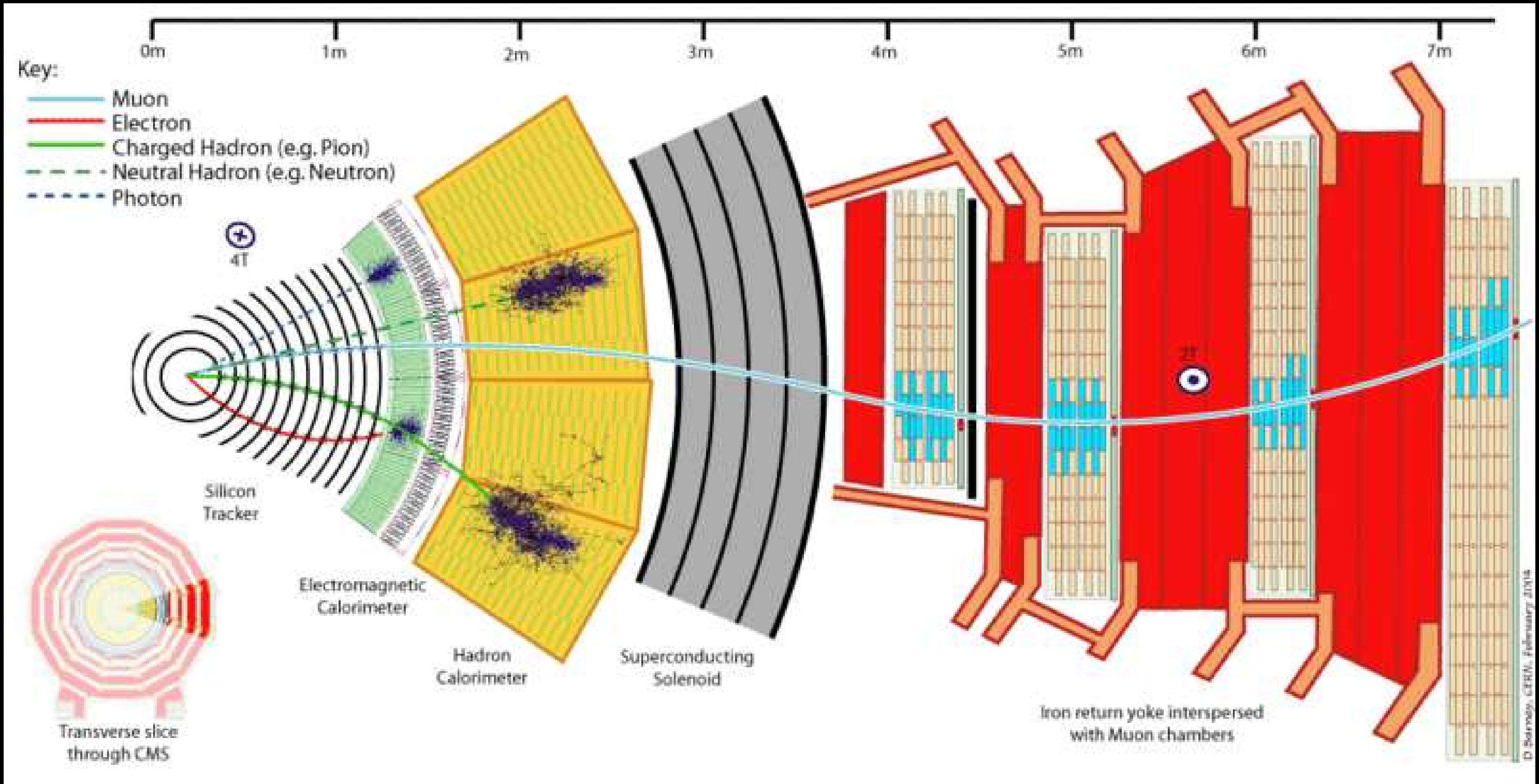
- Modern replacement of bubble chambers
- The particle ionises the silicon
- The charges drift to the surface due to an electric field
- The charges are collected on read-out strips or pixels
- One gets a digital signal, like in a digital camera
- The small sensors are assembled in big layers to form a huge detector

Calorimeters



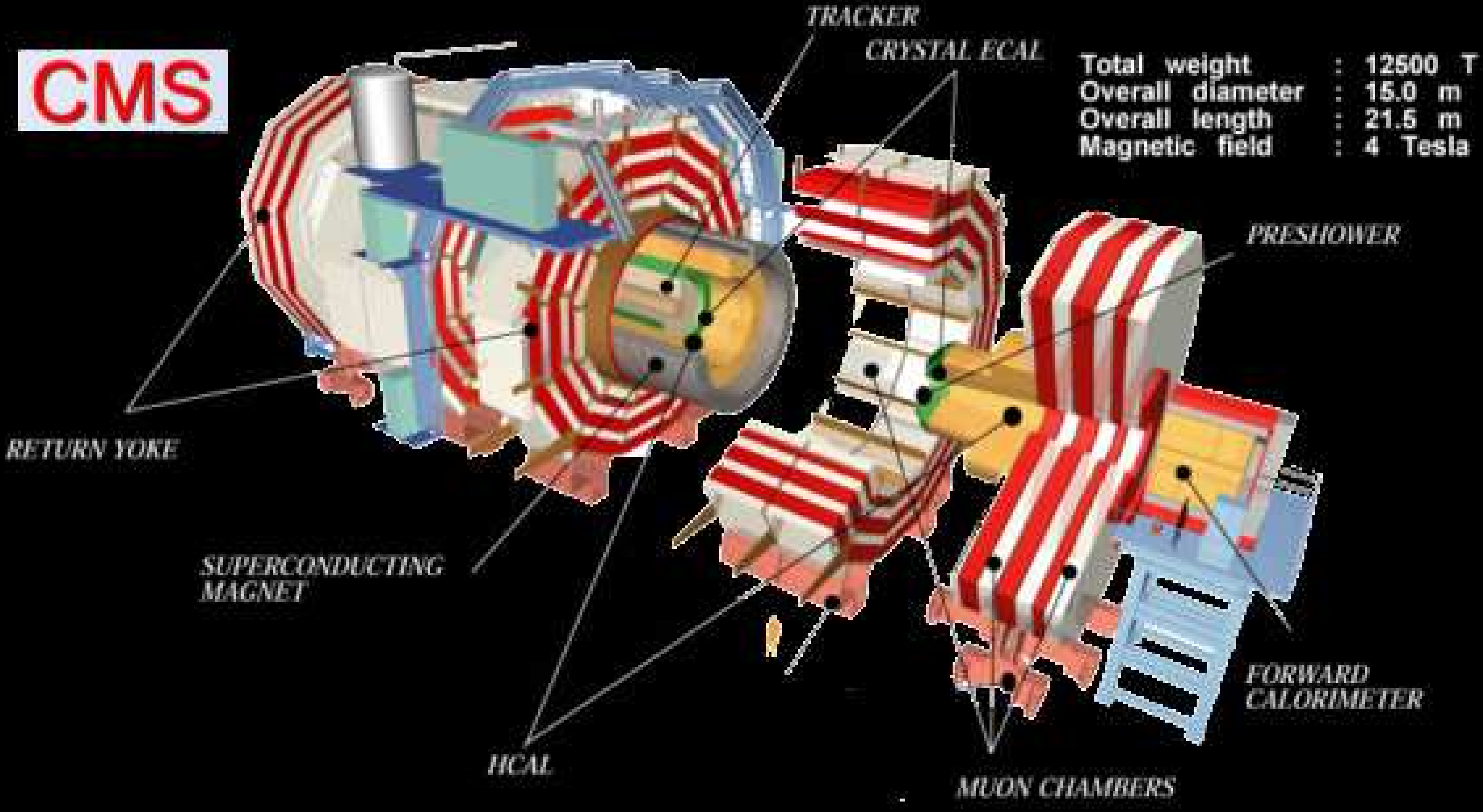
- Calorimeters stop the particle and measure its total energy.
- In a crystal calorimeter energy is dissipated in light that is collected by photo-detectors
- The heavier the better. . .
- The picture shows the CMS lead tungstate $\mathrm{PbWO_4}$ crystal calorimeters.
- The Imperial HEP group is involved in the development of of this detector.

LHC detectors



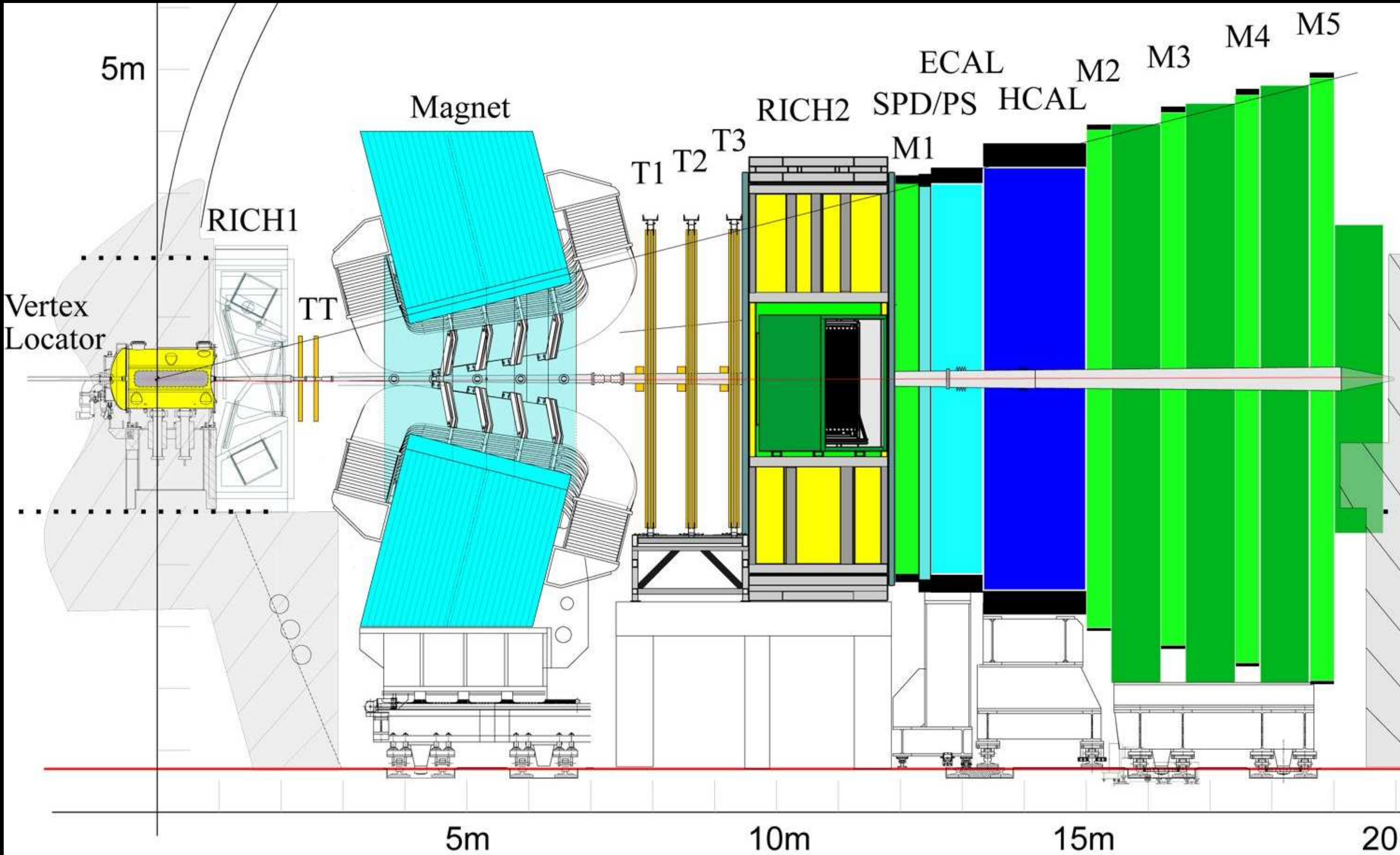
Modern detectors are a succession of sub-detectors, each specialised in the detection of given particles.

LHC detectors



They are assembled as a cylindrical onion around the collision point.

LHC detectors



Four Forces

Gravity: Holds you on your chair. Keeps the earth on its orbit.

Electromagnetic Force: Interaction of charges. Holds electron in atom. Ensures you don't fall through your chair.

Weak Force: Responsible of decays of quarks and leptons.

Nuclear Strong Force: Holds the quarks together.

Four Forces

- If you want to hit a bird you need to transfer force to it.
- This force is transmitted by a force carrier. In this case a stone.

- All four forces have their force carrier
- They are particles hat are exchanged during the interaction

Four Forces

Force	Carrier	Mass
Electromagnetic Force	Photon γ	0
Weak Force	W and Z bosons	80 GeV$/c^2$
Nuclear Strong Force	Gluon g	0
Gravity	Graviton ?	$?$

Gravity is *not* described by the Standard Model of Particle Physics

The Standard Model

Quarks	$+\frac{2}{3}$	u	c	t	γ
	$-\frac{1}{3}$	d	s	b	W
Leptons	-1	e	μ	τ	Z
	0	ν_e	ν_μ	ν_τ	g

Electron-volt

- Joules and kg are useless in particle physics

$$m_e = 9.1 \cdot 10^{-31}\ \mathrm{kg} \qquad \mathrm{E}_{\mathrm{LHC}} = 1.1 \cdot 10^{-9}\ \mathrm{J}$$

- We use electron-volt eV:
  - The potential energy of one electron at a potential of $-1\ \mathrm{V}$.
  - The kinetic energy of the protons at the LHC is 7 TeV. Each proton has been accelerated by a potential of $7 \cdot 10^{12}\ \mathrm{V}$.

Electron-volt

- Joules and kg are useless in particle physics

$$m_e = 9.1 \cdot 10^{-31}\ \mathrm{kg} \qquad \mathrm{E_{LHC}} = 1.1 \cdot 10^{-9}\ \mathrm{J}$$

- We use electron-volt eV:
- We also use eV/c^2 for masses, using $E = mc^2$
  - The mass of the electron is 511 keV$/c^2$
  - The mass of the proton is 938 MeV$/c^2 \sim 1$ GeV$/c^2$.
  - There are $N_A = 6 \cdot 10^{23}$ protons in a gramm.
  - ➜ 1 GeV$/c^2 \sim 1\mathrm{g}/N_A$.

Electron-volt

- Joules and kg are useless in particle physics

$$m_e = 9.1 \cdot 10^{-31}\ \mathrm{kg} \qquad \mathrm{E_{LHC}} = 1.1 \cdot 10^{-9}\ \mathrm{J}$$

- We use electron-volt eV:
- We also use eV/c^2 for masses, using $E = mc^2$
- In the literature all masses are given in eV. Often the $/c^2$ is omitted.

$\boxed{\pi^0}$ $\qquad I^G(J^{PC}) = 1^-(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

π^0 MASS

The value is calculated from $m_{\pi^\pm}$ and $(m_{\pi^\pm} - m_{\pi^0})$. See notes under the $\pi^\pm$ Mass Listings concerning recent revision of the charged pion mass.

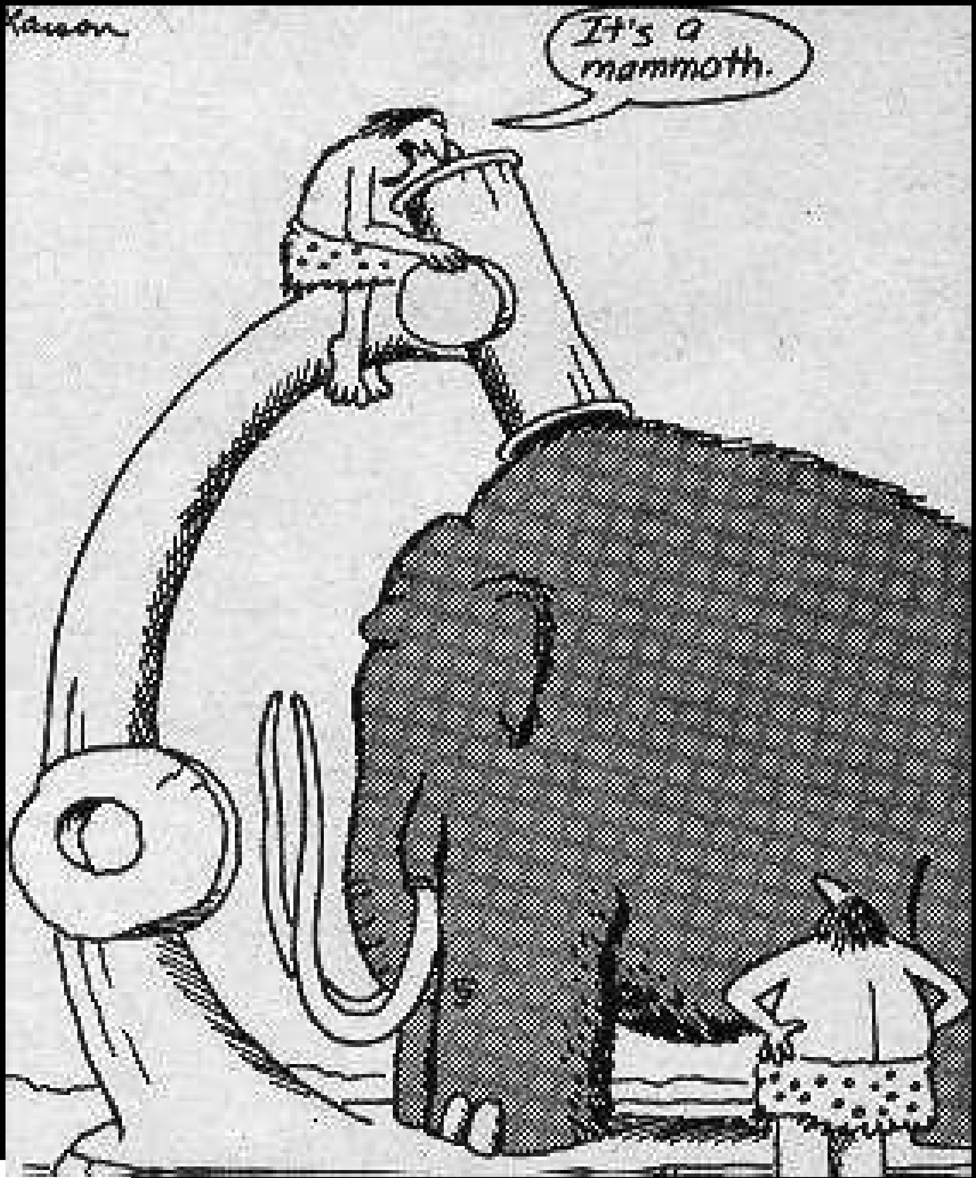
VALUE (MeV)	*DOCUMENT ID*
134.9766±0.0006 OUR FIT	Error includes scale factor of 1.1.

Some properties

Particle		q	Mass	Lifetime
Electron	e	-1	511 keV$/c^2$	∞
Muon	μ	-1	105 MeV$/c^2$	$2 \cdot 10^{-6}$ s
Tau	τ	-1	1.8 GeV$/c^2$	$3 \cdot 10^{-13}$ s
Down	d	$-\frac{1}{3}$	~ 5 MeV$/c^2$	∞
Up	u	$+\frac{2}{3}$	~ 2 MeV$/c^2$	∞
Strange	s	$-\frac{1}{3}$	~ 100 MeV$/c^2$	$9 \cdot 10^{-11}$ s
Charm	c	$+\frac{2}{3}$	~ 1.3 GeV$/c^2$	$4 \cdot 10^{-13}$ s
Bottom	b	$-\frac{1}{3}$	~ 4.2 GeV$/c^2$	$2 \cdot 10^{-12}$ s
Top	t	$+\frac{2}{3}$	175 GeV$/c^2$	~ 0

There is a factor $350\,000$ between the t and the e mass. . . Why?

How do we see small things?



Down to ~ 1 micron, things can be seen using visible light. Depending on the optics.

➜ Microscope

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Then one hits limitations due to the visible light wavelength. The wavelength has to be smaller than the object.

$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy	Tool
Atom	10^{-10} m	0.01 MeV	Electron Microscope
Nucleus	10^{-14} m	10 MeV	Alphas

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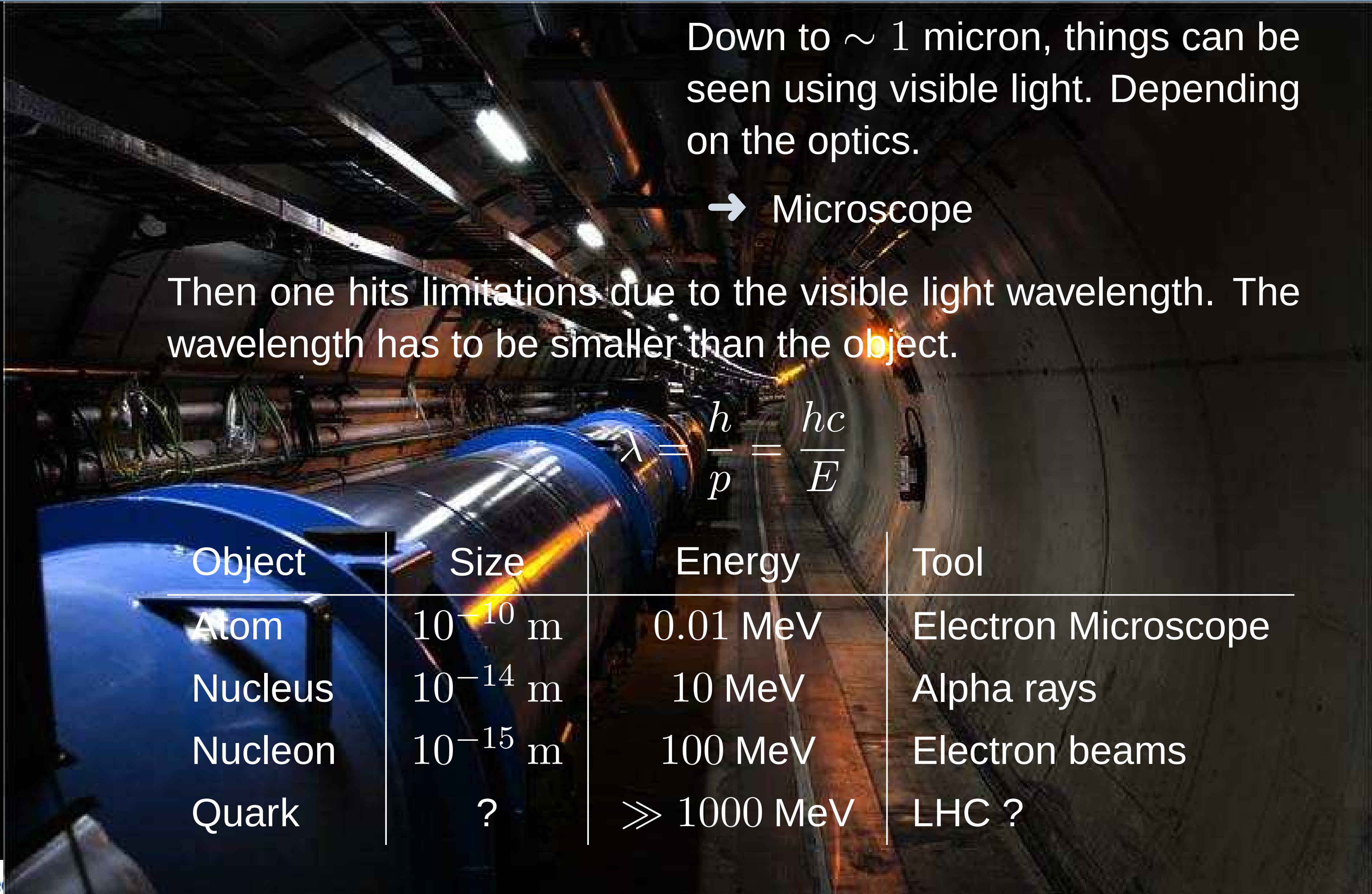

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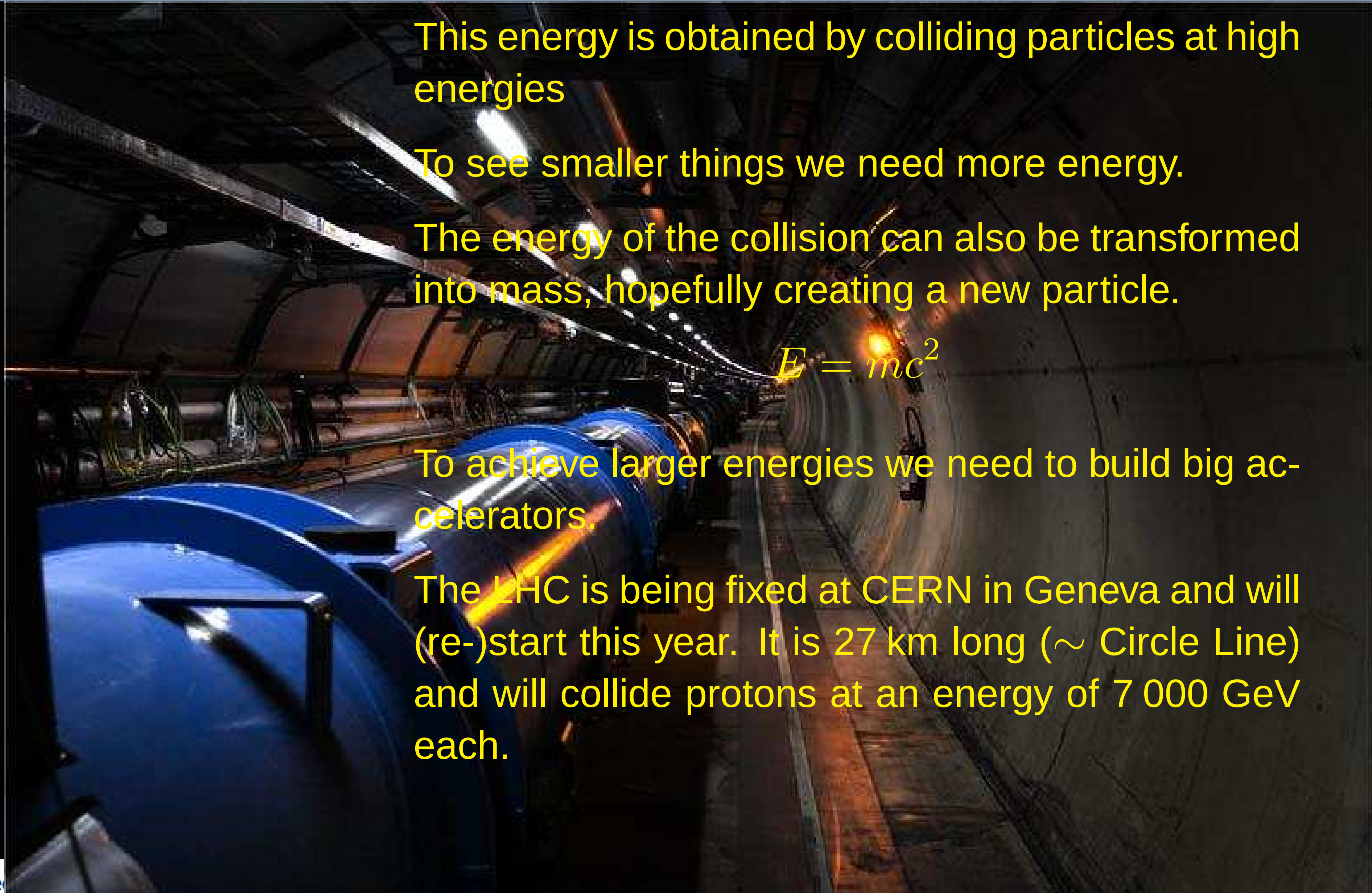
Object	Size	Energy	Tool
Atom	10^{-10} m	0.01 MeV	Electron Microscope
Nucleus	10^{-14} m	10 MeV	Alpha rays
Nucleon	10^{-15} m	100 MeV	Electron beams
Quark	?	$\gg 1000$ MeV	LHC ?

Accelerators



This energy is obtained by colliding particles at high energies

To see smaller things we need more energy.

The energy of the collision can also be transformed into mass, hopefully creating a new particle.

$$E = mc^2$$

To achieve larger energies we need to build big accelerators.

The LHC is being fixed at CERN in Geneva and will (re-)start this year. It is 27 km long ($\sim$ Circle Line) and will collide protons at an energy of 7 000 GeV each.