

Probing the Secrets of the Universe with the Large Hadron Collider at CERN

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What does *CERN* stand for ?

Conseil
Européen pour la
Recherche
Nucléaire

European
Council for
Nuclear
Research

1953

What is *CERN's* name ?

Organisation

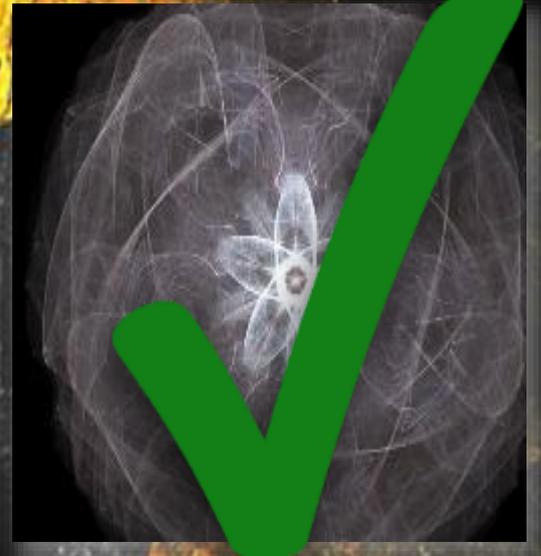
Européenne pour la
Recherche
Nucléaire

European

Organization for
Nuclear
Research

1954

Nuclear?



European laboratory for particle physics

Member States

Budget (2020)
 1,168 billion CHF
 0,970 billion GBP
 1,210 billion USD



-  Austria (1959)
-  Belgium (1953)
-  Bulgaria (1999)
-  Czech Republic (1993)
-  Denmark (1953)
-  Finland (1991)
-  France (1953)
-  Germany (1953)
-  Greece (1953)
-  Hungary (1992)
-  Israel (2014)
-  Italy (1953)
-  Netherlands (1953)
-  Norway (1953)
-  Poland (1991)
-  Portugal (1986)
-  Romania (2016)
-  Serbia (2019)
-  Slovakia (1993)
-  Spain (1961-1968, 1983-)

-  Sweden (1953)
-  Switzerland (1953)
-  United Kingdom (1953)

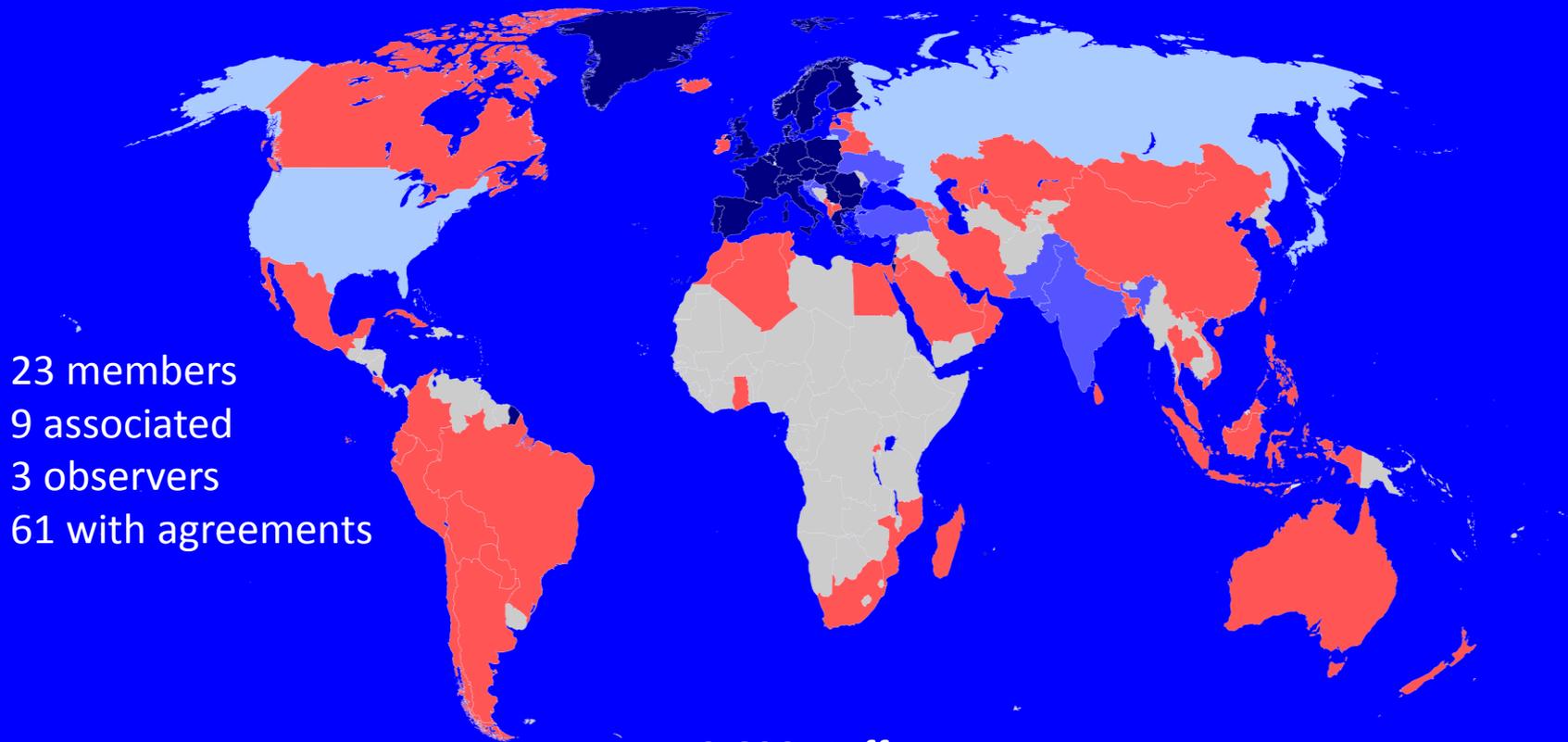
Associated

-  Croatia (2019)
-  Cyprus (2016)
-  India (2017)
-  Lithuania (2018)
-  Pakistan (2015)
-  Slovenia (2017)
-  Turkey (2015)
-  Ukraine (2016)

Estonia (2021)



A world collaboration



23 members
9 associated
3 observers
61 with agreements

2 600 staff
800 fellows and apprentices
550 students
15 000 users
2 000 external companies

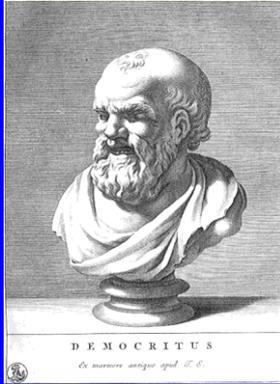
~ 20 000 persons in total

Fundamental research

- At CERN, using special tools (accelerators, detectors) we study :
- The building blocks of matter, the elementary particles that all matter in the Universe is made of
- The fundamental forces that hold matter together



Democritus believed that all matter is made of indivisible elements, the atoms

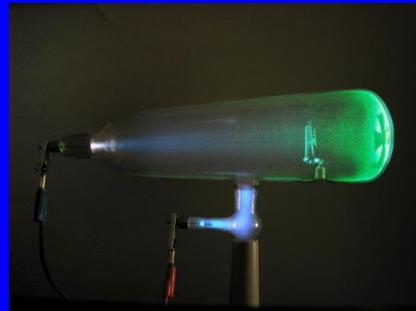


Mendeleev's periodic table of elements (1869) – 80 different indivisible atoms

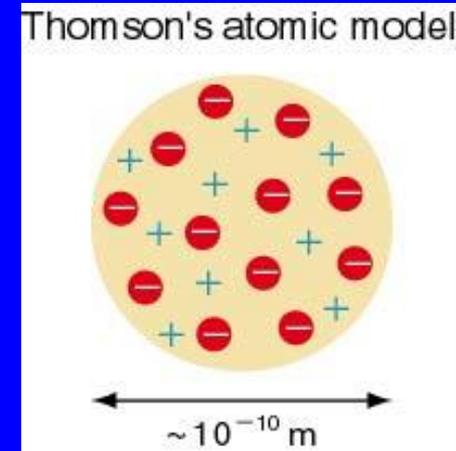
I	II	III	IV	V	VI	VII	VIII		
H 1.01									
Li 6.94	Be 9.01	B 10.8	C 12.0	N 14.0	O 16.0	F 19.0			
Na 23.0	Mg 24.3	Al 27.0	Si 28.1	P 31.0	S 32.1	Cl 35.5			
K 39.1	Ca 40.1		Ti 47.9	V 50.9	Cr 52.0	Mn 54.9	Fe 55.9	Co 58.9	Ni 58.7
Cu 63.5	Zn 65.4			As 74.9	Se 79.0	Br 79.9			
Rb 85.5	Sr 87.6	Y 88.9	Zr 91.2	Nb 92.9	Mo 95.9		Ru 101	Rh 103	Pd 106
Ag 108	Cd 112	In 115	Sn 119	Sb 122	Te 128	I 127			
Ce 133	Ba 137	La 139		Ta 181	W 184		Os 194	Ir 192	Pt 195
Au 197	Hg 201	Tl 204	Pb 207	Bi 209					
			Th 232		U 238				



JJ Thomson

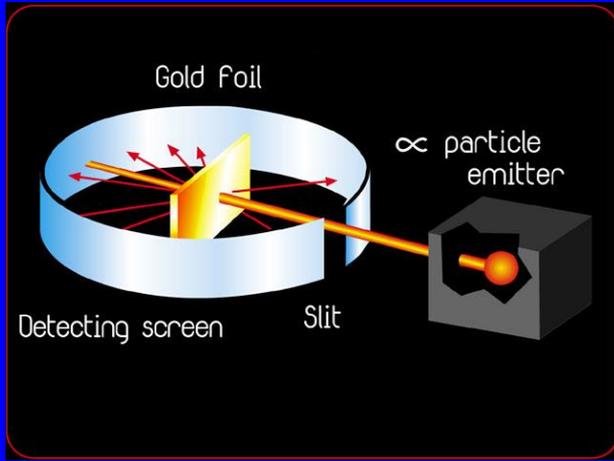


Discovery of the electron with cathode ray tube
first elementary particle
1896

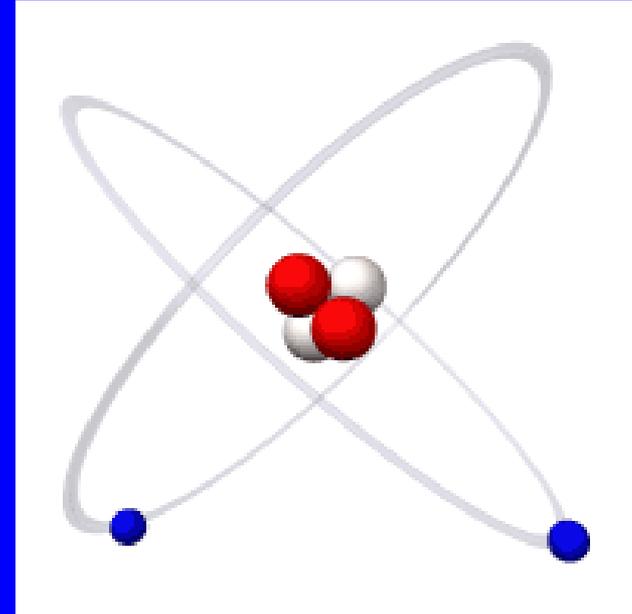


Thomson's plum pudding model (1904)

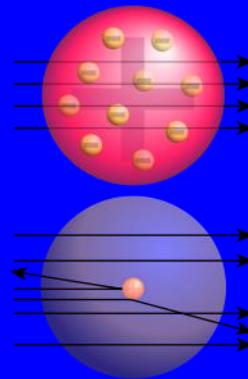
2011 : 100-year anniversary from the introduction of Rutherford's atomic model



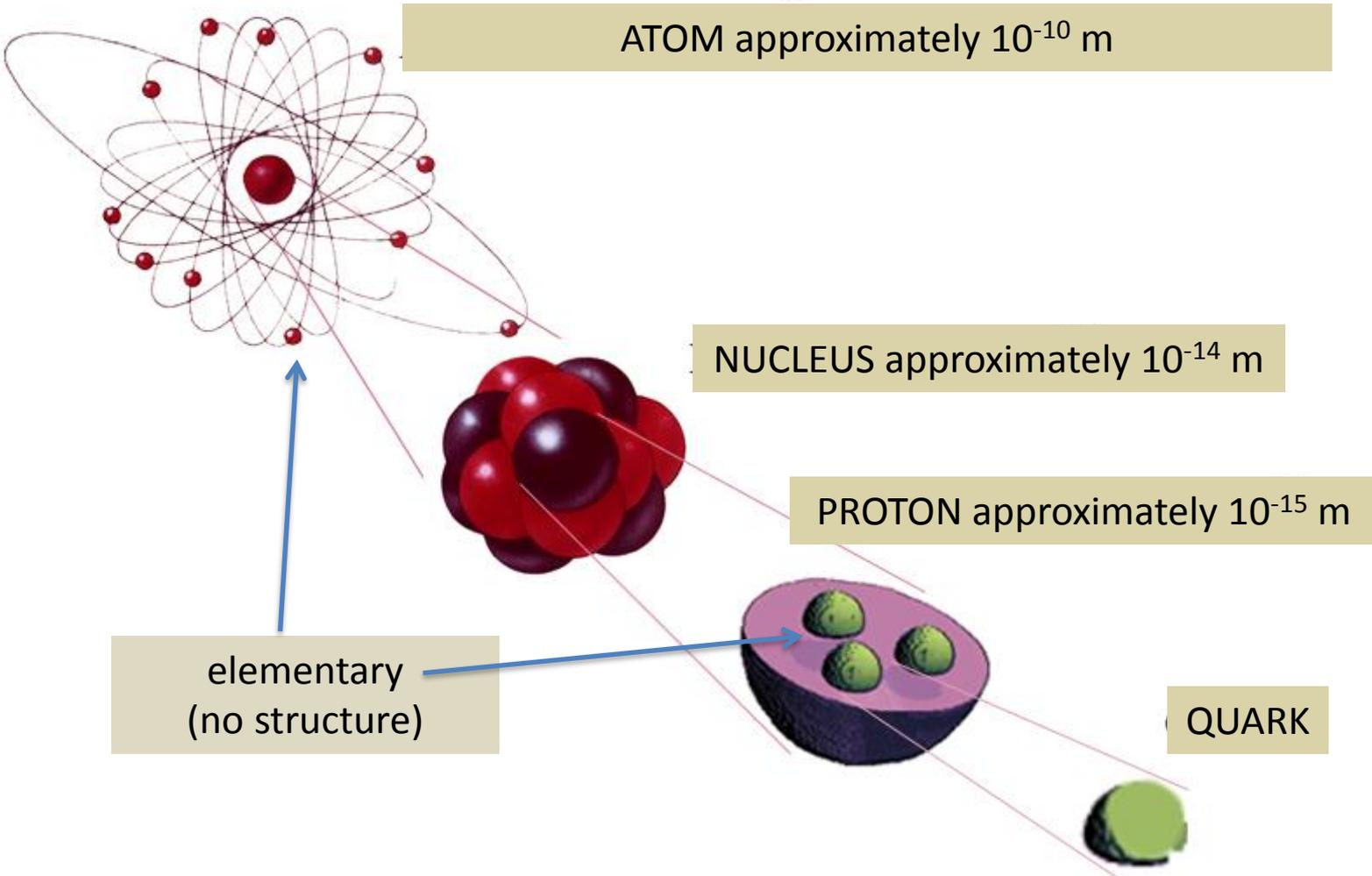
alpha scattering experiment
Geiger – Marsden



Ernest Rutherford

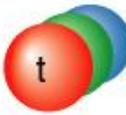
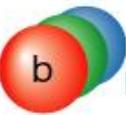
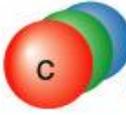


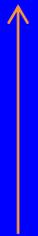
Nucleus: most of the mass, positive charge; atom is mainly empty
Later on found that the nucleus consists of protons and neutrons



Il y a environ onze milliards de milliards d'atomes de fer dans un milligramme de fer !

Periodic system of the elementary particles

	Quarks		Leptons	
Generation 3	 t Top	 b Bottom	 τ Tau	 ν_τ Tau-neutrino
Generation 2	 c Charm	 s Strange	 μ Muon	 ν_μ Muon-neutrino
Generation 1	 u Up	 d Down	 e Electron	 ν_e Electron-neutrino



mass

charge 2/3

charge -1/3

charge -1

charge 0

In nature : elementary particles of the first generation ONLY

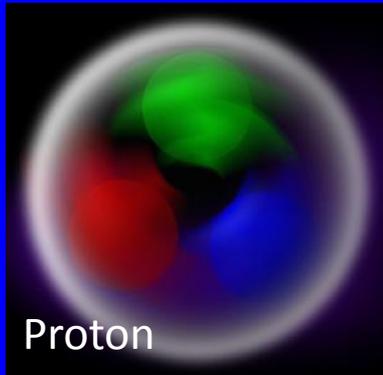
Those of the second and third generation decay to the lighter ones.
They have been seen in accelerator experiments

All particles have their antiparticles, with opposite electric charge

Quark Confinement

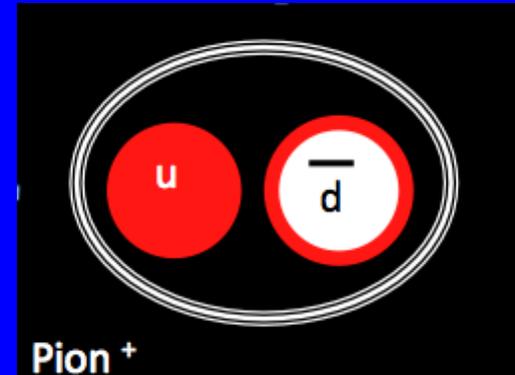
Quarks can not exist free in nature

They can only exist bound inside hadrons



Proton

baryons
consisting of
3 quarks



Pion +

mesons
consisting of
a quark and
an anti-quark

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
\mathbf{p}	proton	\mathbf{uud}	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	-1	0.938	1/2
\mathbf{n}	neutron	\mathbf{udd}	0	0.940	1/2
Λ	lambda	\mathbf{uds}	0	1.116	1/2
Ω^-	omega	\mathbf{sss}	-1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

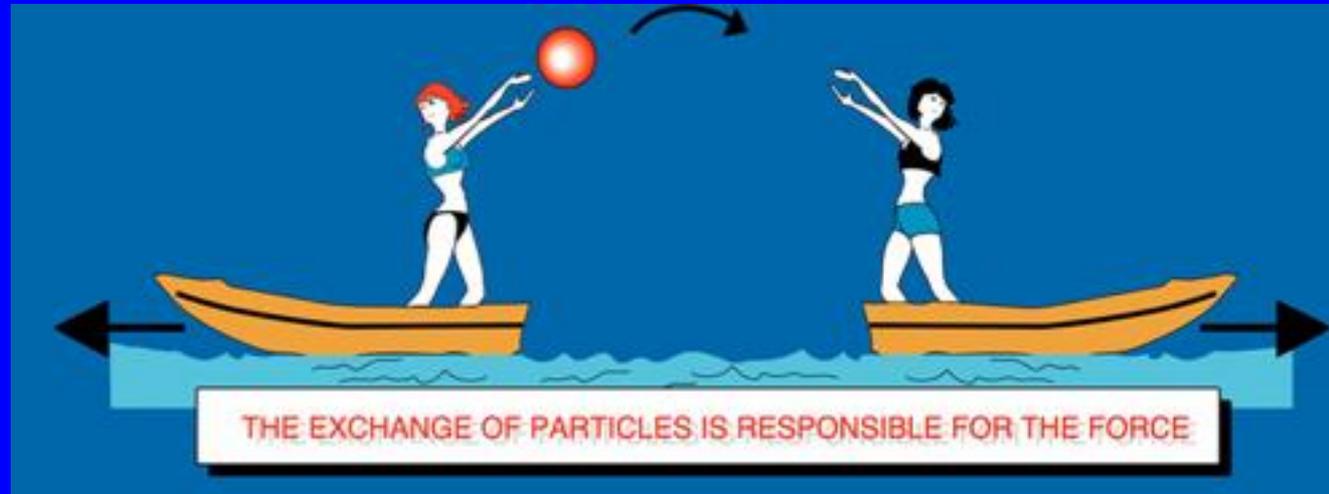
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.140	0
\mathbf{K}^-	kaon	$\mathbf{s}\bar{\mathbf{u}}$	-1	0.494	0
ρ^+	rho	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.776	1
\mathbf{B}^0	B-zero	$\mathbf{d}\bar{\mathbf{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c}\bar{\mathbf{c}}$	0	2.980	0

Concept of interaction - force

Particles interact with each other (feel each other) with various forces by exchanging special “particles”

and

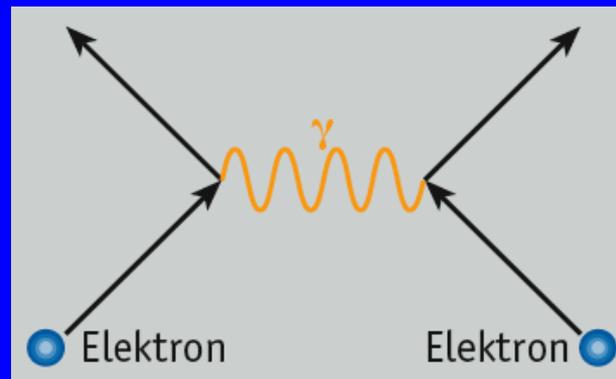
Forces are mediated by the exchange of “particles”, the force carriers



Example

The interaction of charged particles (attraction or repulsion) is done by the exchange of photons

The photon (γ) is the carrier of the electromagnetic force

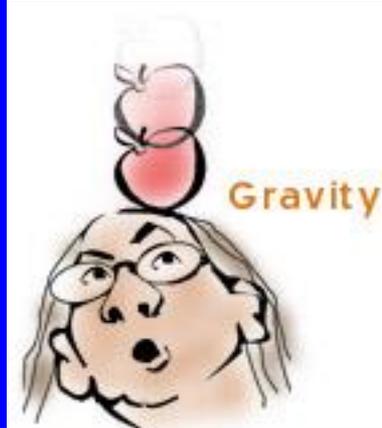


Feynman-Graph

4 Fundamental Interactions

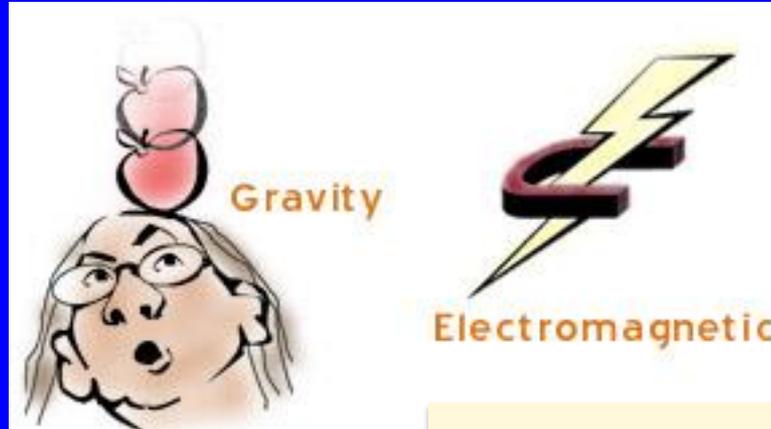
4 Fundamental Interactions

falling apples,
planetary orbits
strength: 10^{-39}
range: infinite
mediator: graviton?



4 Fundamental Interactions

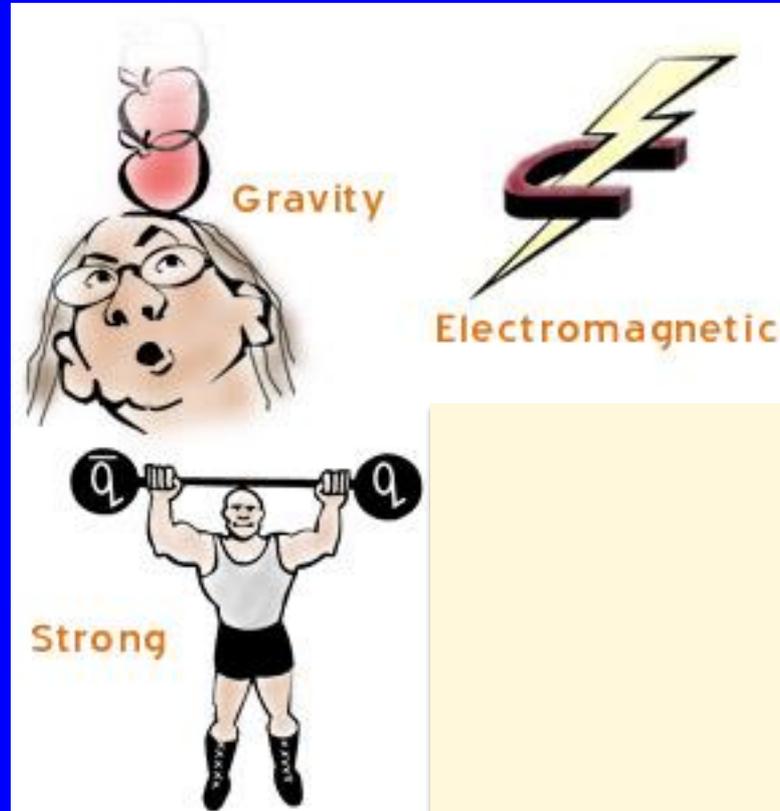
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mediator: graviton?



television, magnets,
chemical binding
strength: $1/137$
range: infinite
mediator: photon

4 Fundamental Interactions

falling apples,
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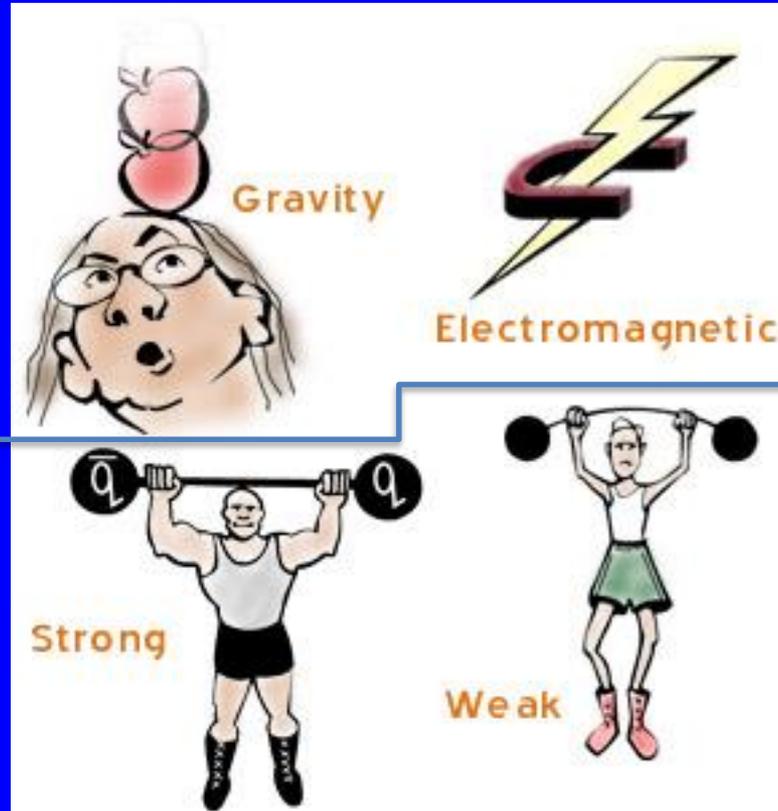
television, magnets,
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strength: $1/137$
range: infinite
mediator: photon

nuclear stability,
quark confinement
strength: 1
range: 10^{-15} m
mediator: gluons

4 Fundamental Interactions

falling apples,
planetary orbits
strength: 10^{-39}
range: infinite
mediator: graviton?

things we can relate to



television, magnets,
chemical binding
strength: $1/137$
range: infinite
mediator: photon

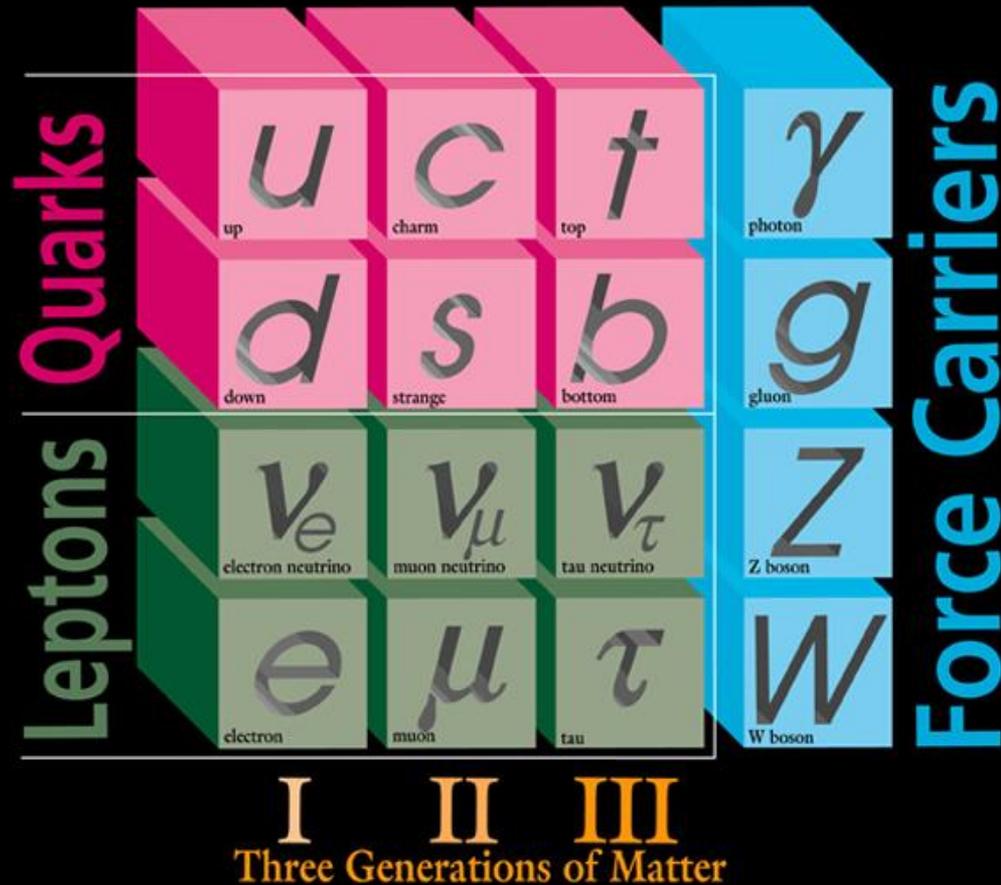
nuclear stability,
quark confinement
strength: 1
range: 10^{-15} m
mediator: gluons

radioactive β -decay
strength: 10^{-5}
range: 10^{-18} m
mediator: W,Z-Bosons

things we **cannot** relate to

The Standard Model

ELEMENTARY PARTICLES



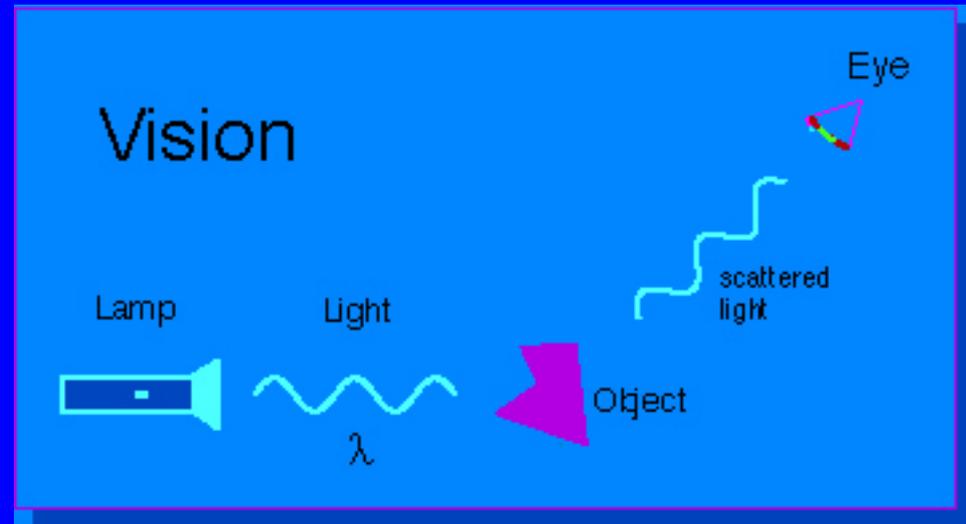
fermions
Fermi-Dirac
statistics
Spin half-integer
(1/2, 3/2,...)

bosons
Bose-Einstein
statistics
Spin integer
(0, 1, 2,..)

The “Right” Light to Look Inside of Things

Vision works by scattering of ‘visible’ light

$$\lambda = 400-700 \text{ nm}$$



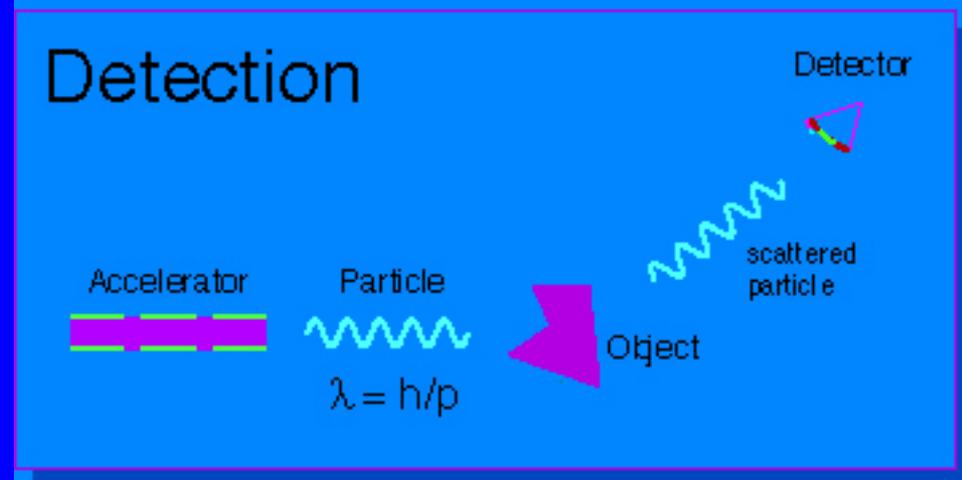
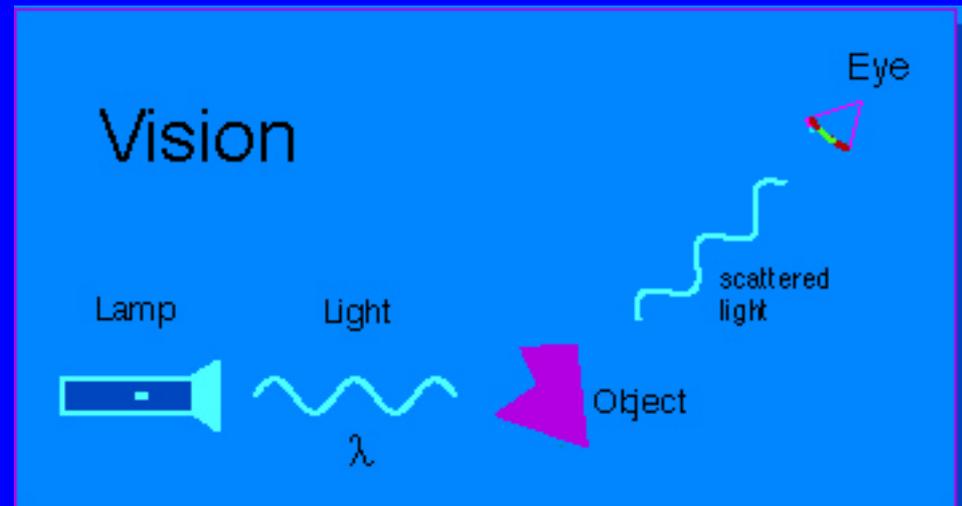
The “Right” Light to Look Inside of Things

Vision works by scattering of ‘visible’ light

$$\lambda = 400\text{-}700 \text{ nm}$$

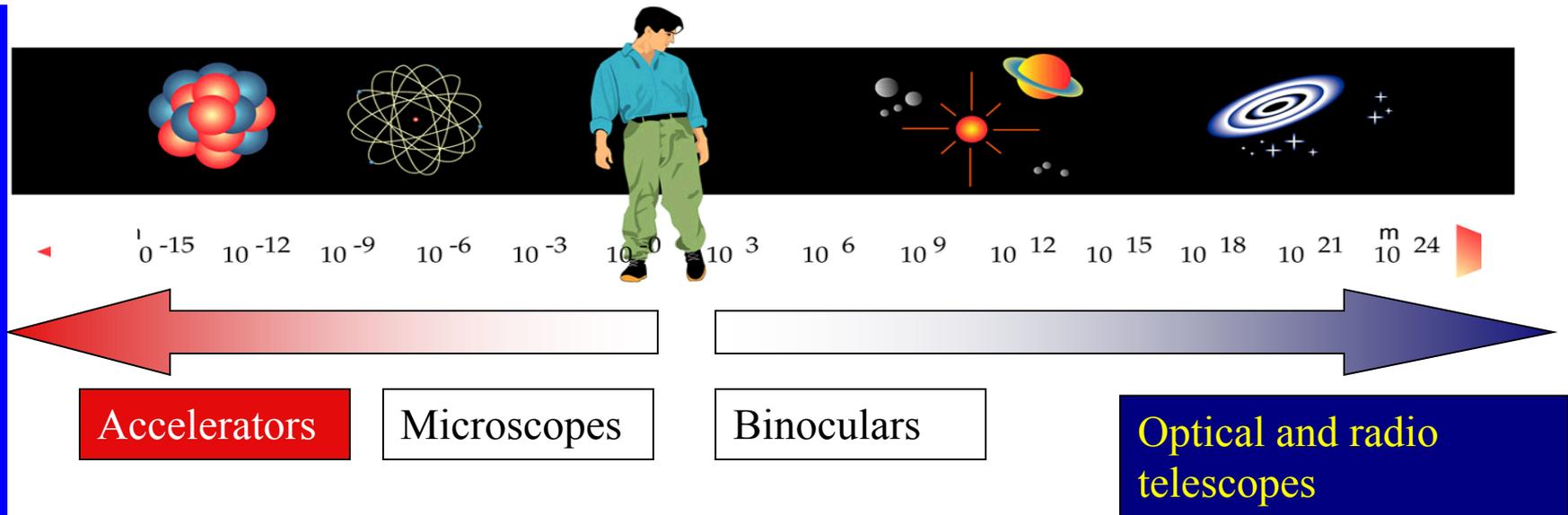
“Vision” of even smaller structures via scattering of particles

$$\lambda = h/p$$



CERN's mission : to build particle accelerators

Why accelerators? To investigate Particle Physics

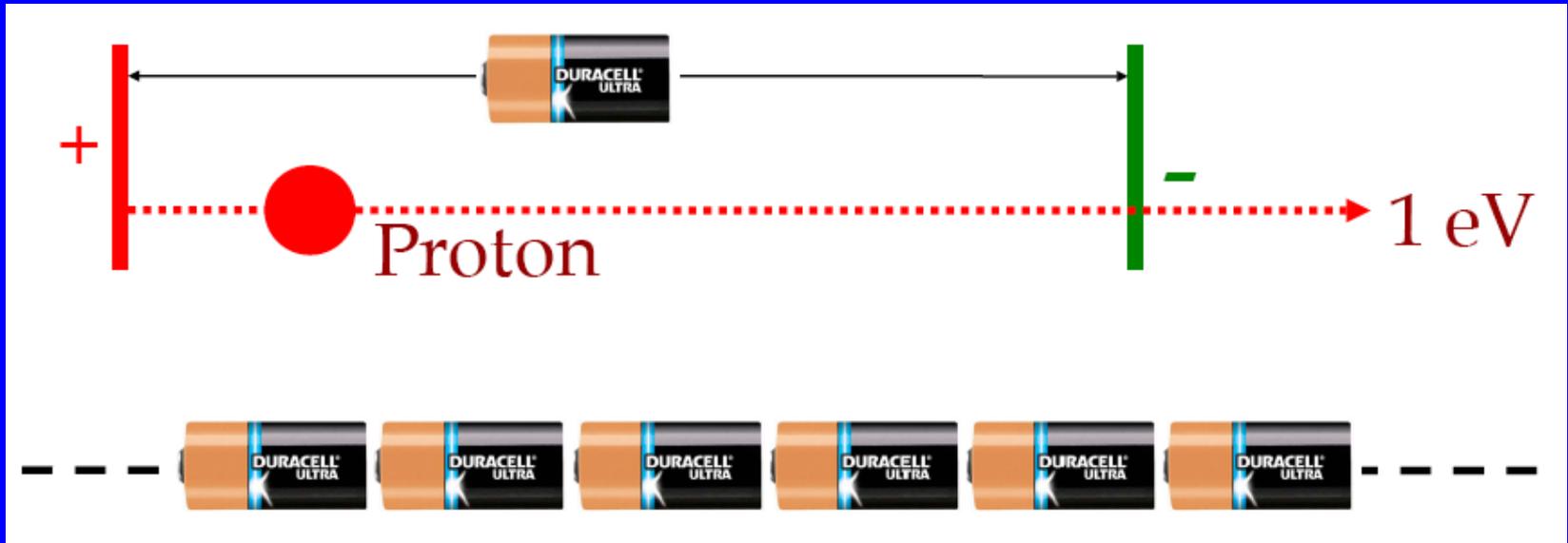


Particle physics looks at matter in its smallest dimensions

Accelerators are “microscopes” for the study of the microcosm
With accelerators will also create new particles $E=mc^2$

Accelerators

Energy given to a charge in an electric field: $E = q \cdot V$



Units of energy

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule}$$

The energy of the elementary charge (that of the electron) accelerated by a potential difference of 1 Volt

$$1 \text{ keV} = 10^3 \text{ eV} = 1000 \text{ eV}$$

$$1 \text{ MeV} = 10^6 \text{ eV} = 1\,000\,000 \text{ eV}$$

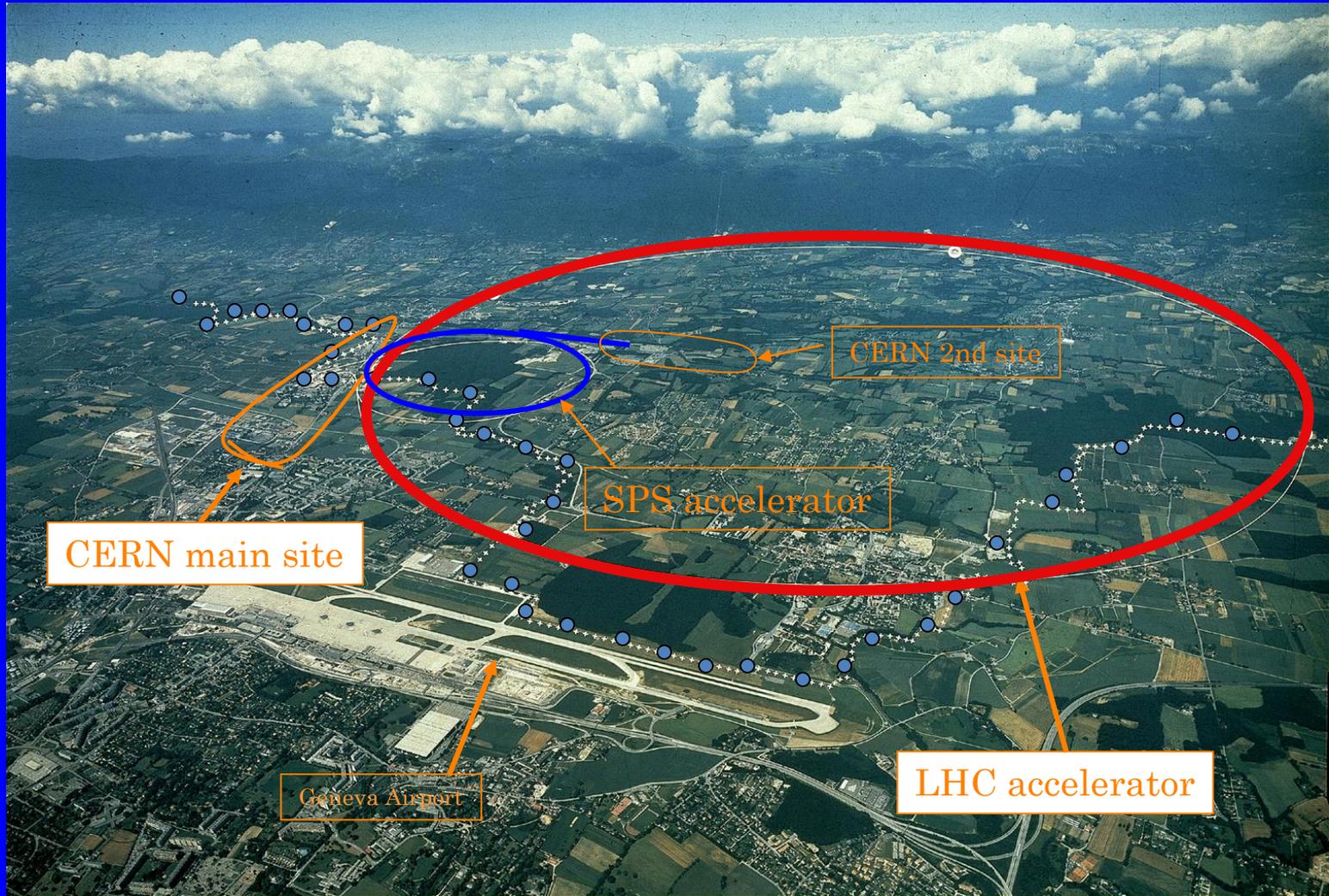
$$1 \text{ GeV} = 10^9 \text{ eV} = 1\,000\,000\,000 \text{ eV}$$

$$1 \text{ TeV} = 10^{12} \text{ eV} = 1\,000\,000\,000\,000 \text{ eV}$$

Mass – energy equivalence $E = mc^2$

$c=1$ natural units

mass expressed in units of energy



CERN main site

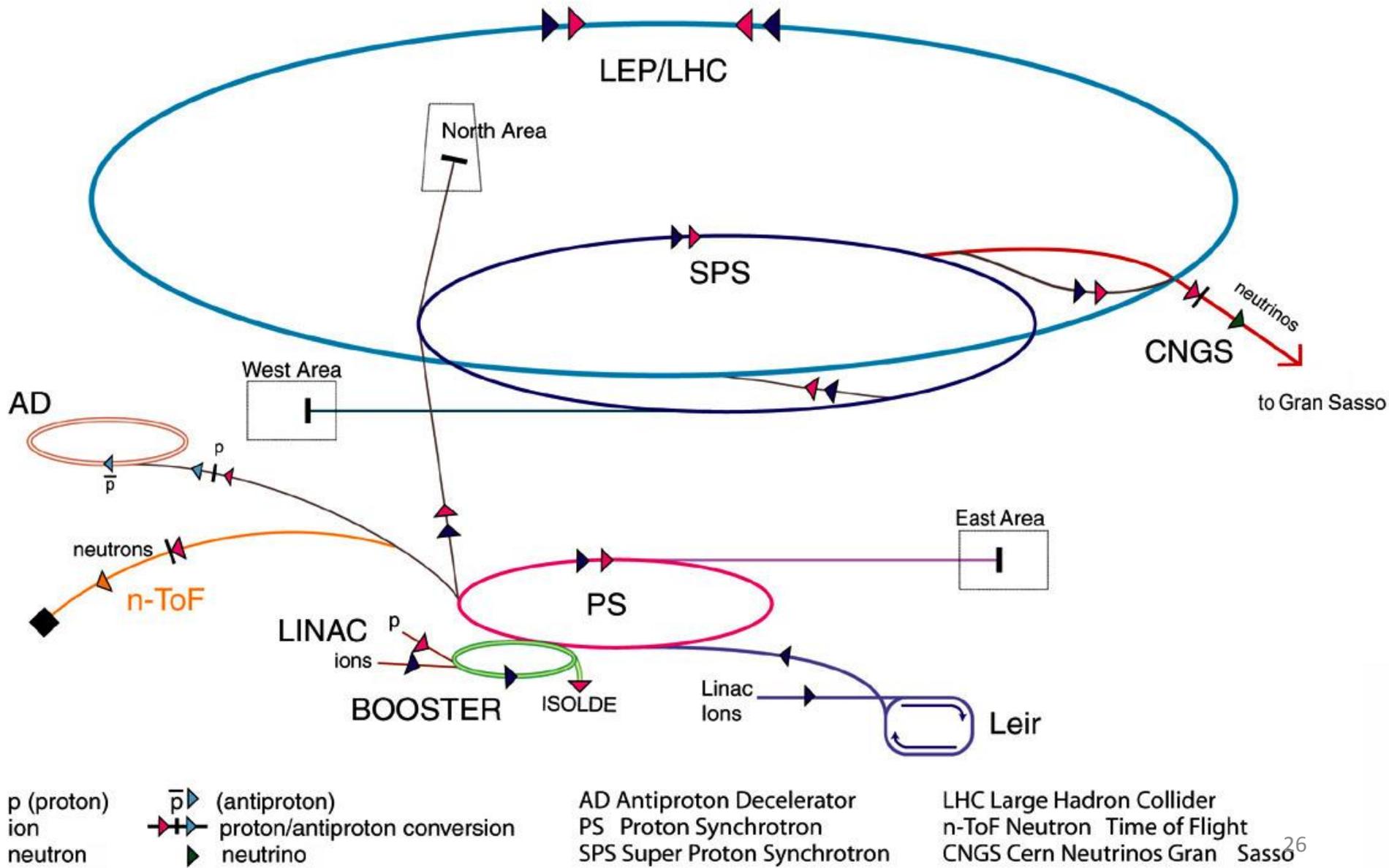
Geneva Airport

CERN 2nd site

SPS accelerator

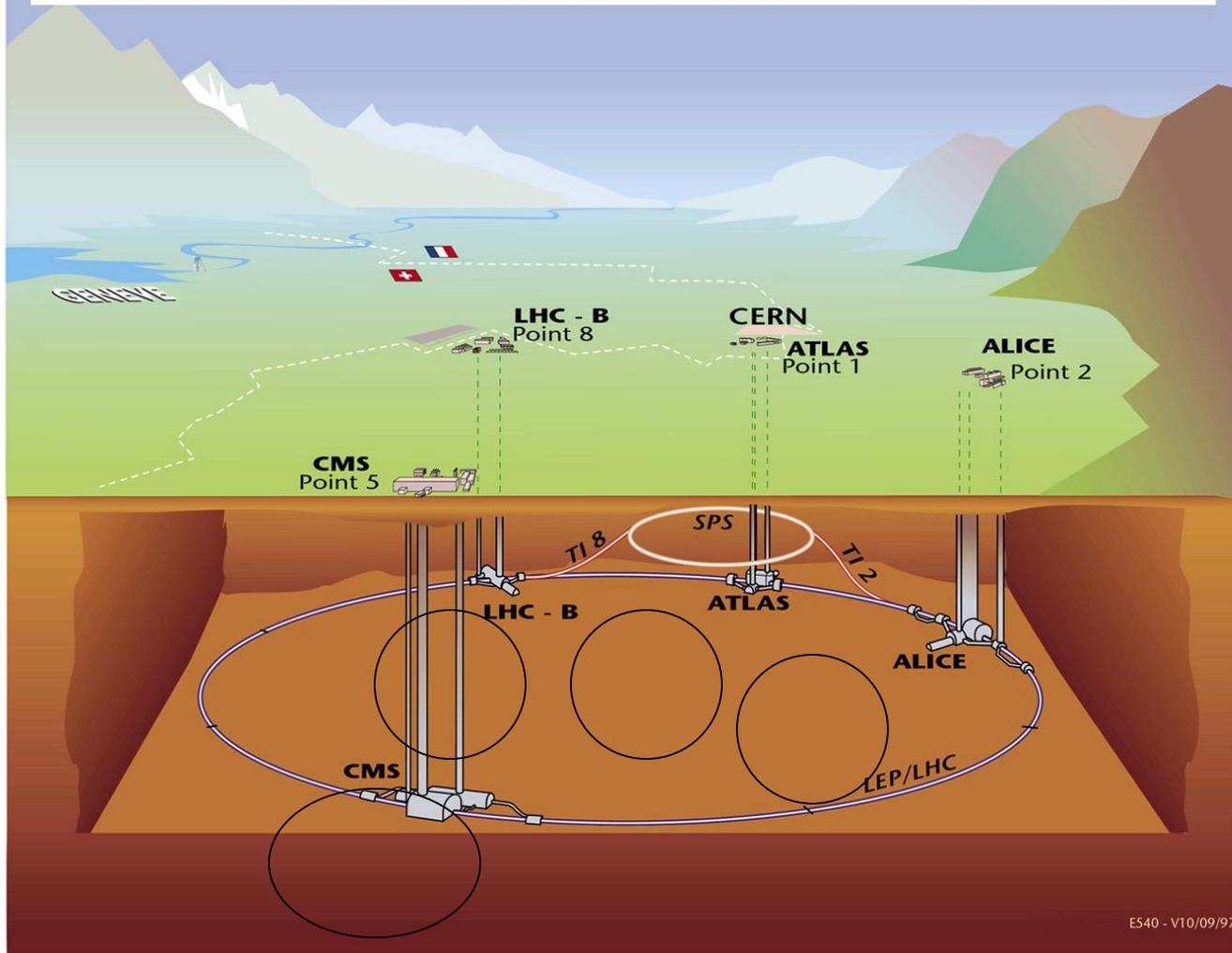
LHC accelerator

The CERN accelerators



The Large Hadron Collider (LHC)

Overall view of the LHC experiments.



The largest accelerator in the world, in a ring of 27 km circumference

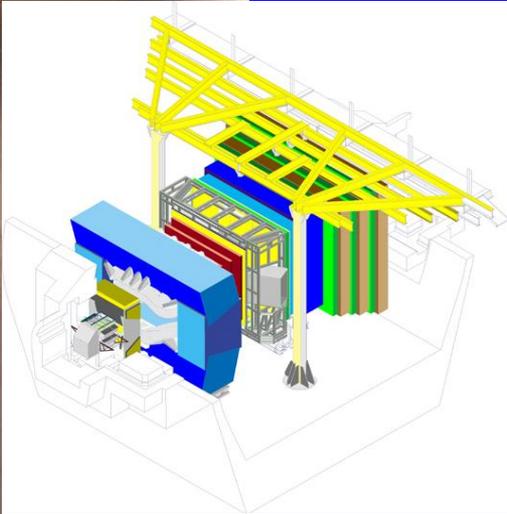
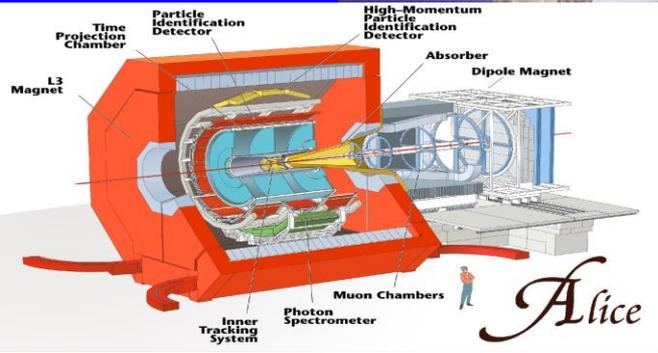
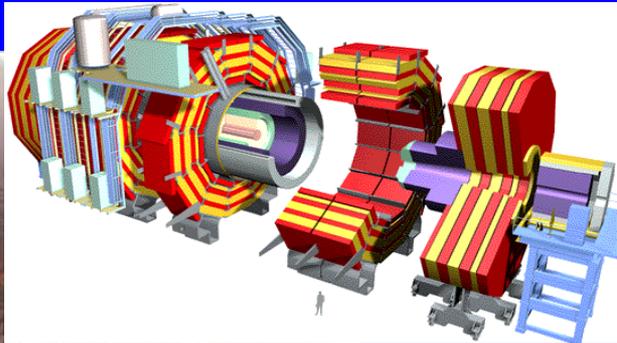
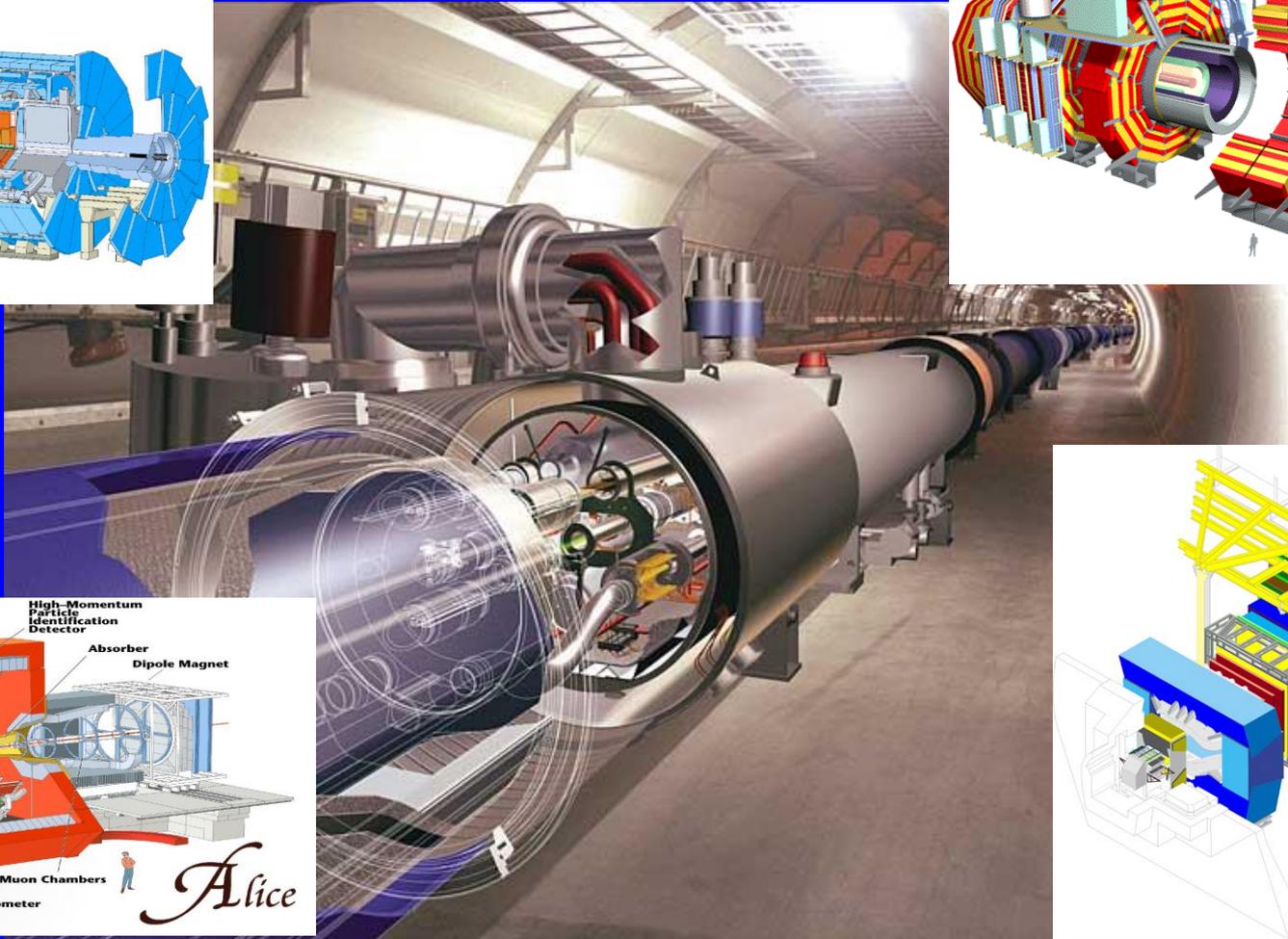
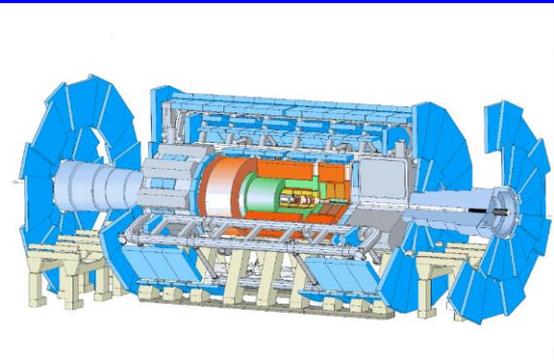
At LHC two beams of protons collide at the highest accelerator energy (13 TeV up to now and will reach 14 TeV)

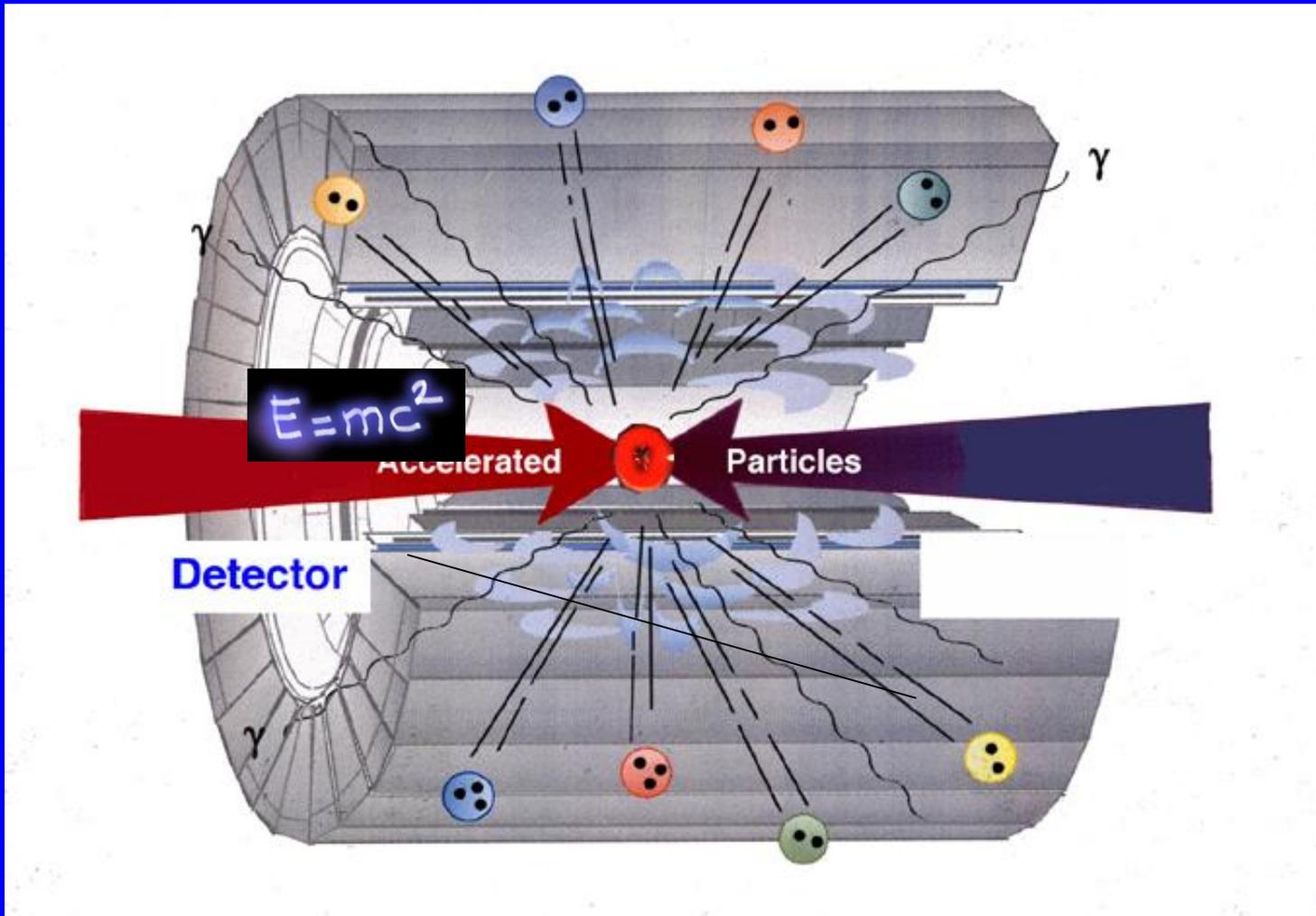
LHC is the coldest place in the universe: its superconducting magnets, cooled with liquid helium, operate at 1.9 K (-271° C) just above absolute zero

E540 - V10/09/97

The LHC is located in a tunnel 100 m underground

4 big experiments are installed at LHC





1) We concentrate energy on protons by accelerating them

2) We collide protons – their energy is liberated at the point of collision

3) New particles are produced - transformation of energy to mass

We “see” these new particles and measure their characteristics with detectors

Particle Detectors

- They “see” the particles produced from beam-beam or beam-target collisions
- The detection is based on interaction of the particles with the detector material and results –in most cases- in the production of an electrical signal

Various types of detectors

Solid state detectors (semiconductors, e.g. Si)

Gaseous detectors

Scintillators ...

They convey information about

The particle energy (calorimeters)

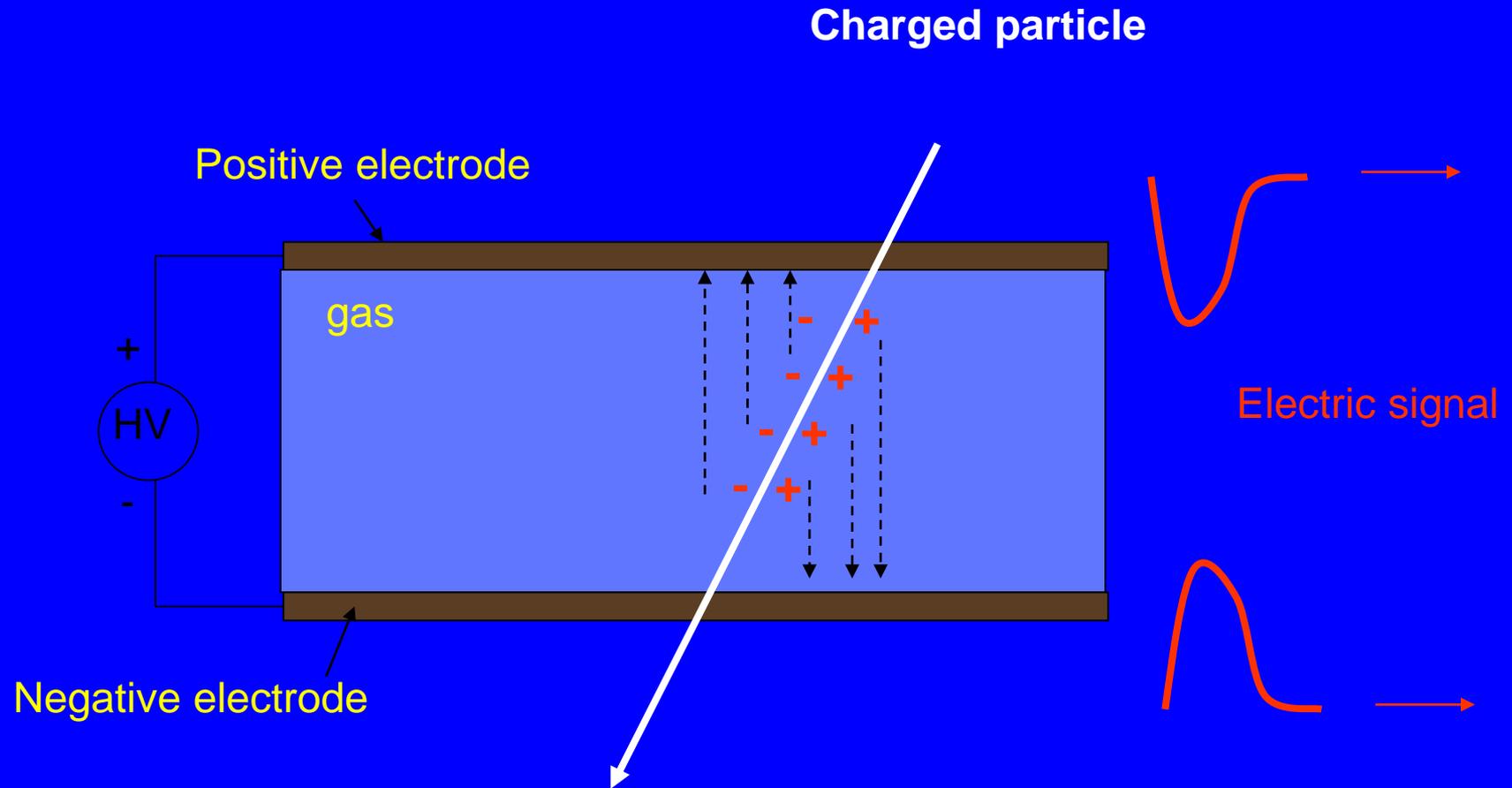
The particle type (particle identification)

The particle trajectory (tracking devices)

Most particles produced from the collisions have a very short life – they decay immediately and we see their “children”, their decay products.

Particles we “see” in our detectors can be : electrons, photons, muons, pions, kaons, protons and hadron jets (originating from quarks)

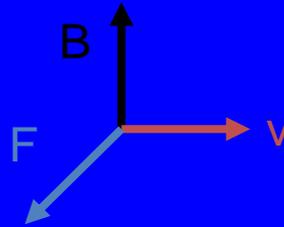
Gaseous detectors : principle of operation IONISATION



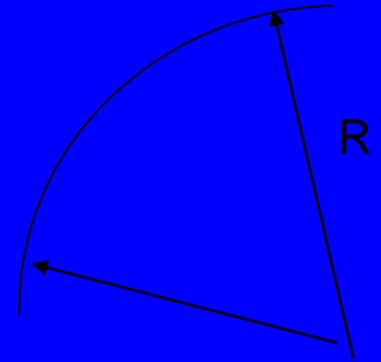
Momentum measurement

From the curvature of the trajectory of a charged particle inside a magnetic field
Lorentz force

$$|F| = q v B$$

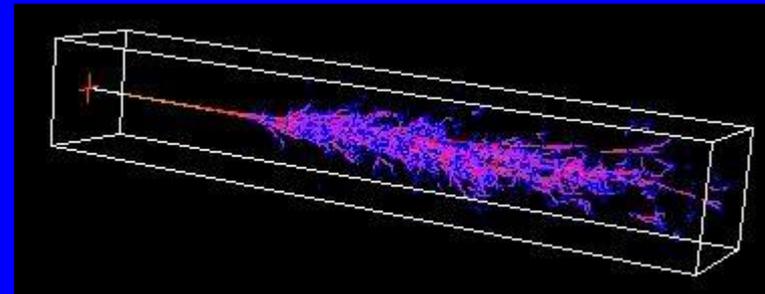


The curvature is inversely proportional to the momentum
From the radius of curvature we calculate the momentum



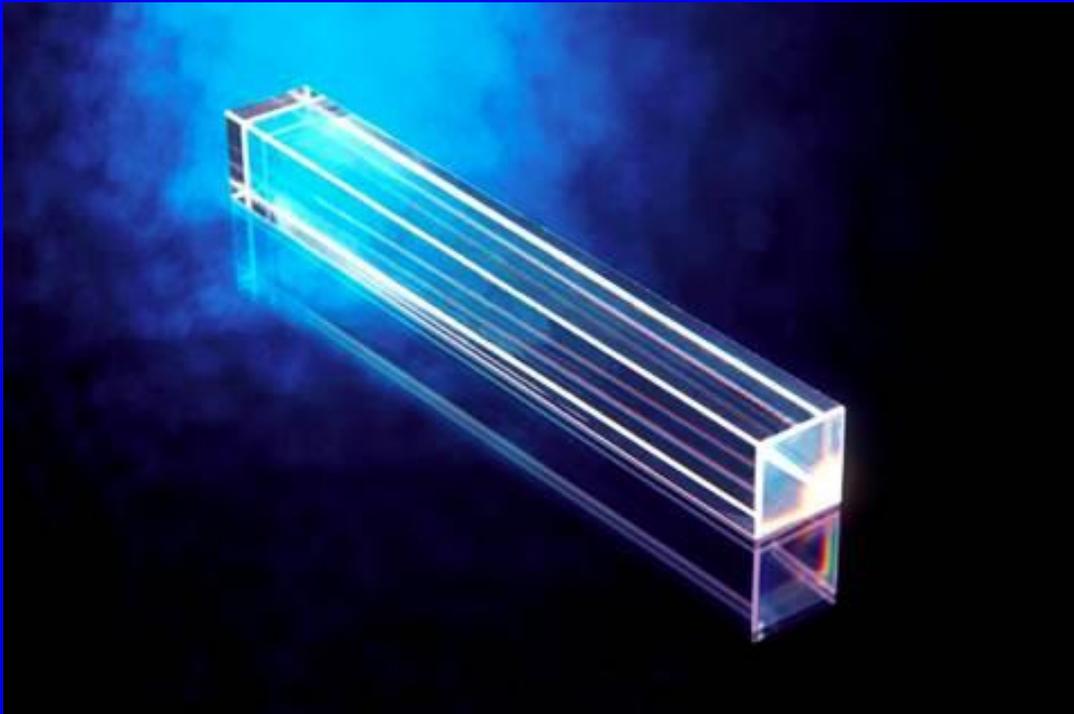
Energy measurement

Particles are stopped
All their energy is absorbed
inside calorimeters



Scintillators

PbWO_4 : heavy and transparent

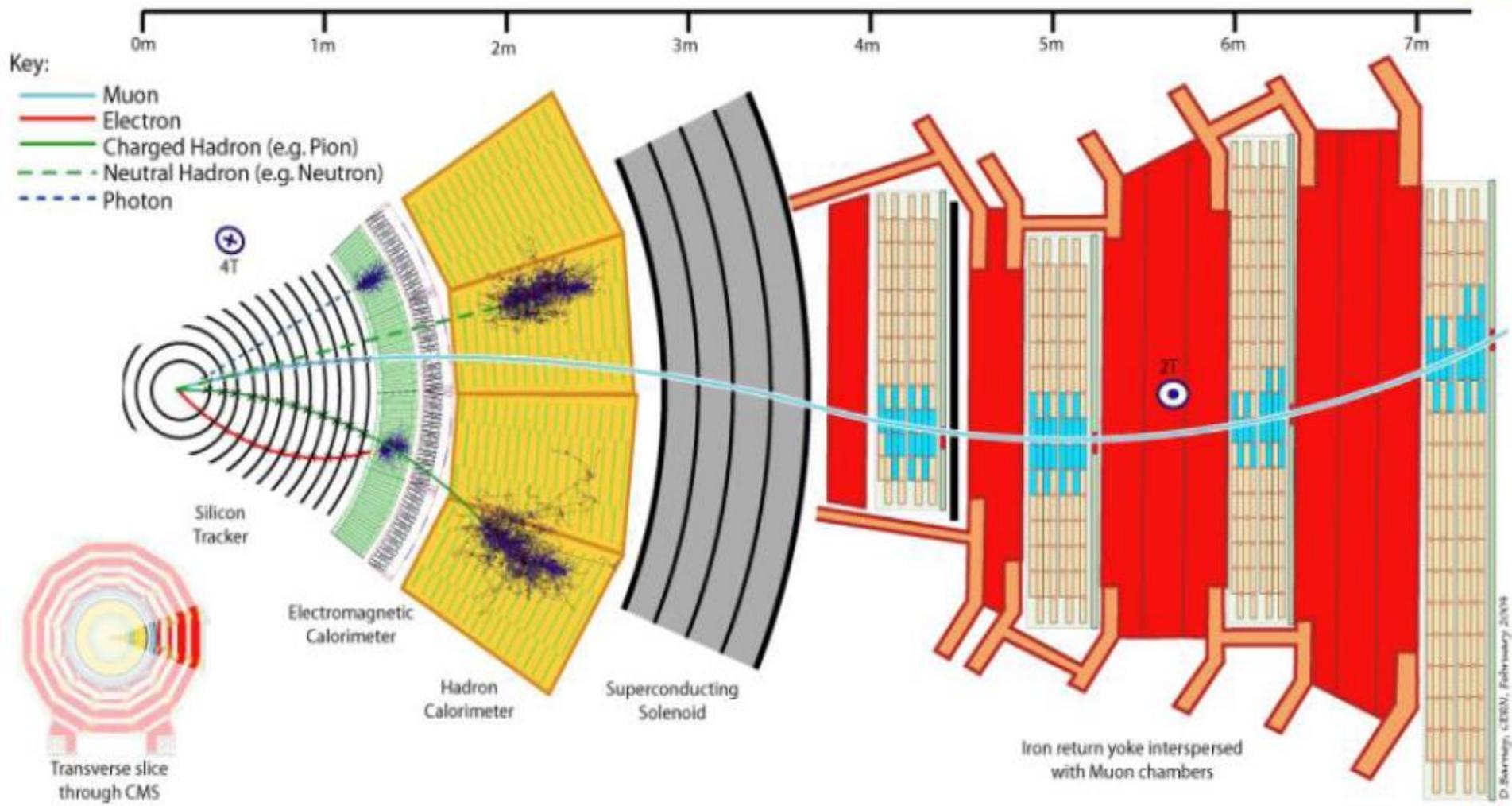


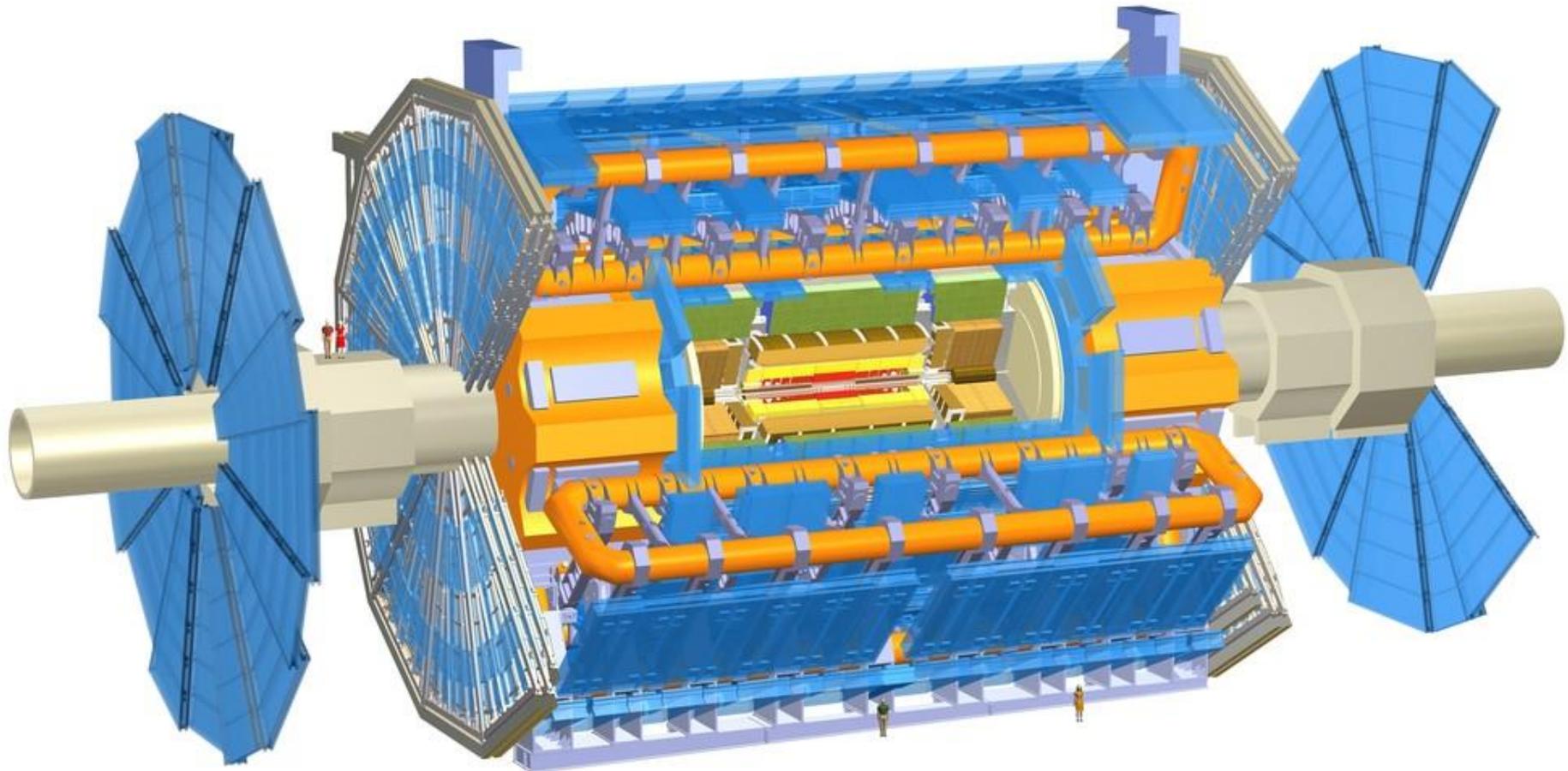
Electromagnetic calorimeter

- Photons are converted into electron-positron pairs
- Electrons excite the atoms of the crystal
- Excitation is followed by de-excitation -> emission of light (UV photons)
- UV photons are detected by a photodiode at the end of the crystal, which converts photons to electrons



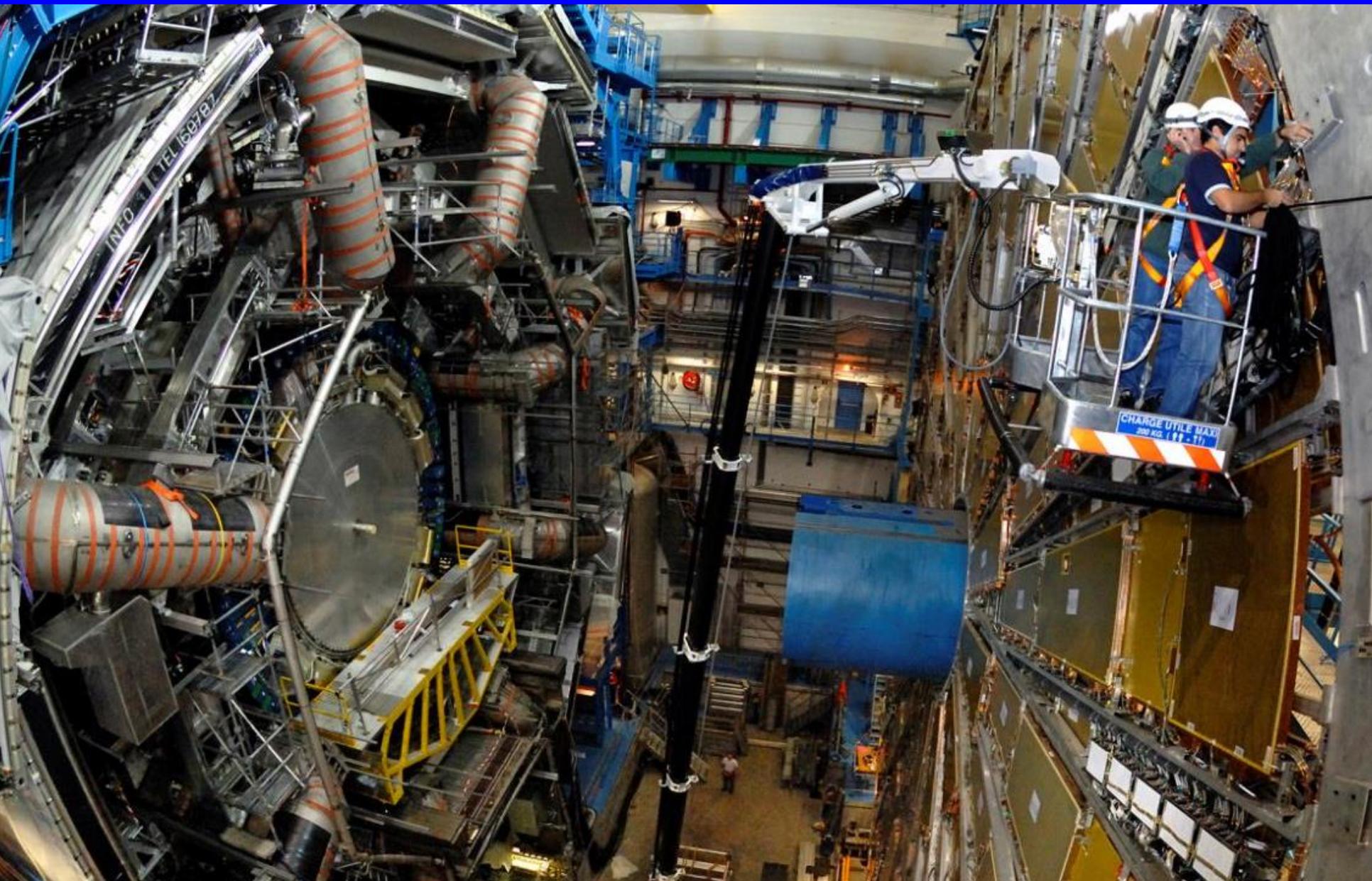
Electric signal



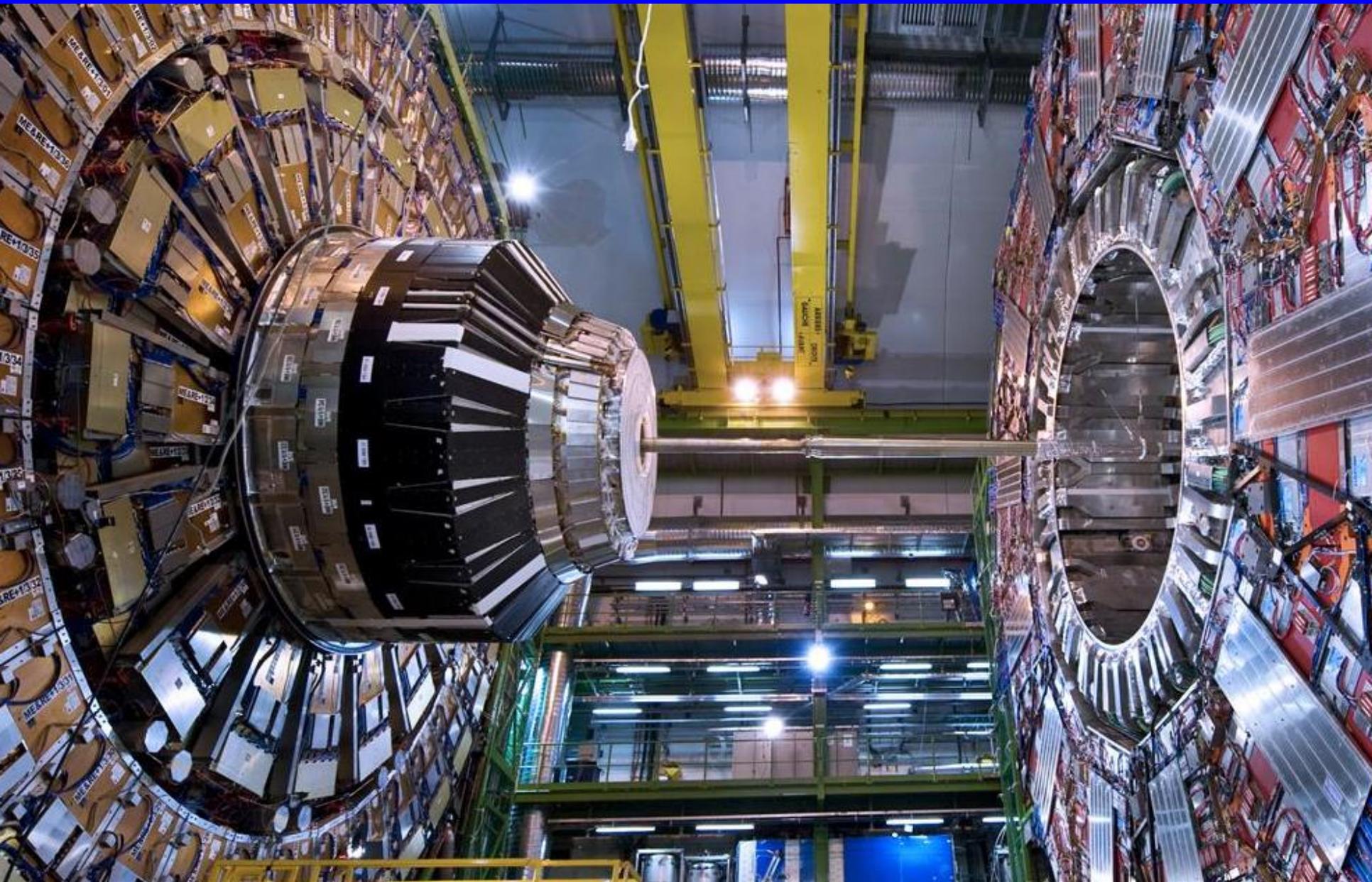


25 m x 25 m x 46 m 7000 tons

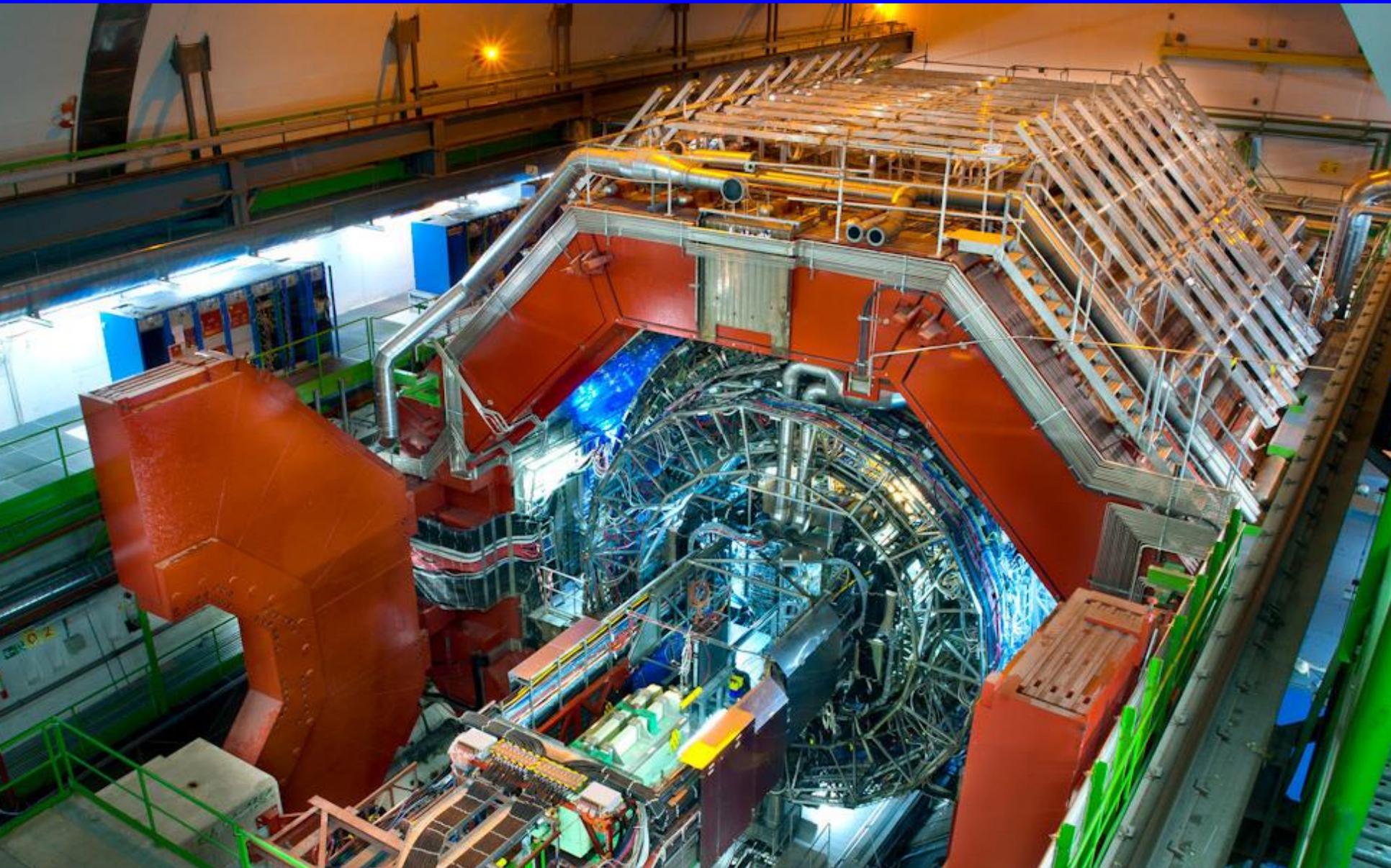
ATLAS : A Toroidal LHC Apparatus



CMS : Compact Muon Solenoid

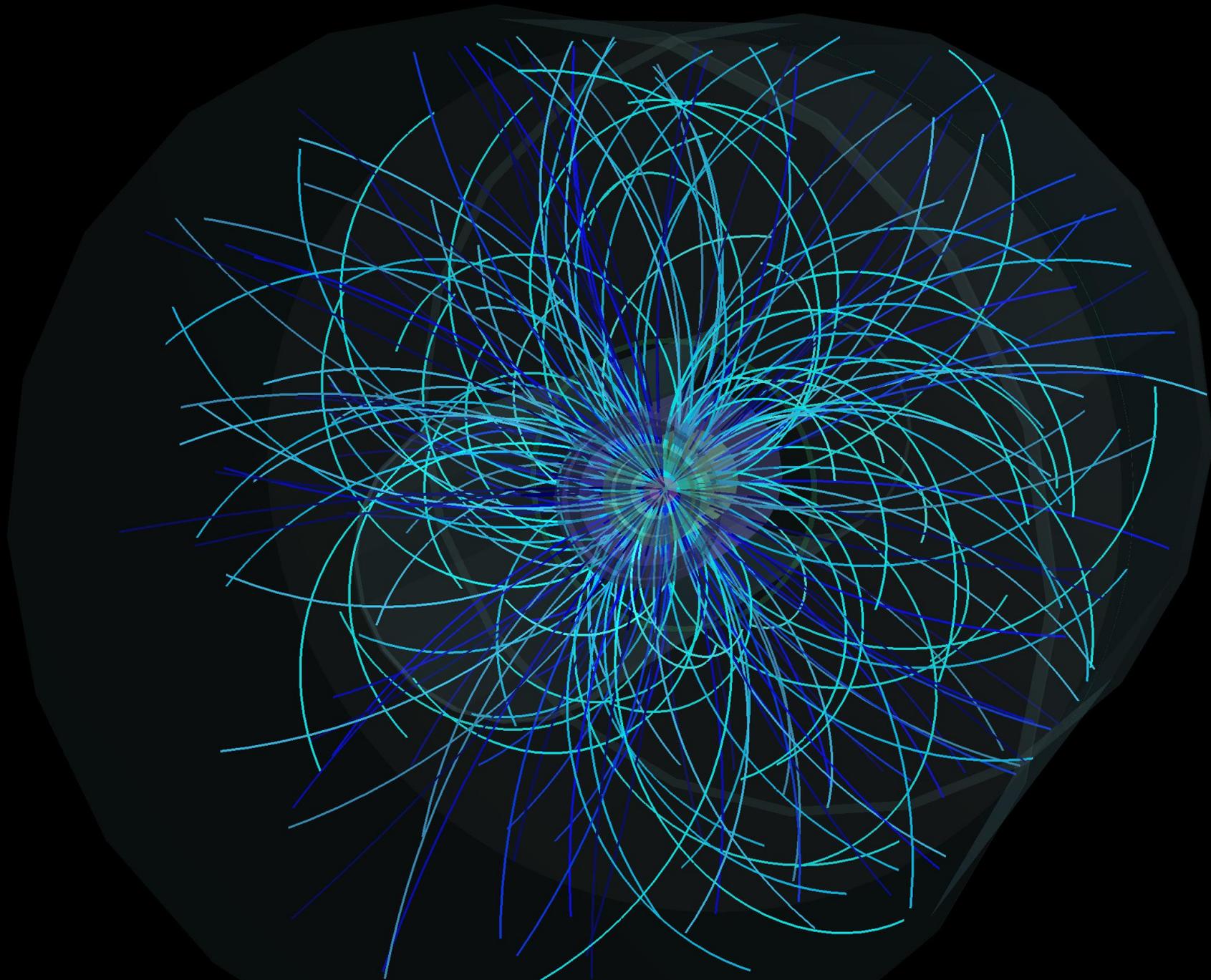


ALICE : A Large Ion Collider Experiment



LHCb : LHC bottom (or beauty) experiment

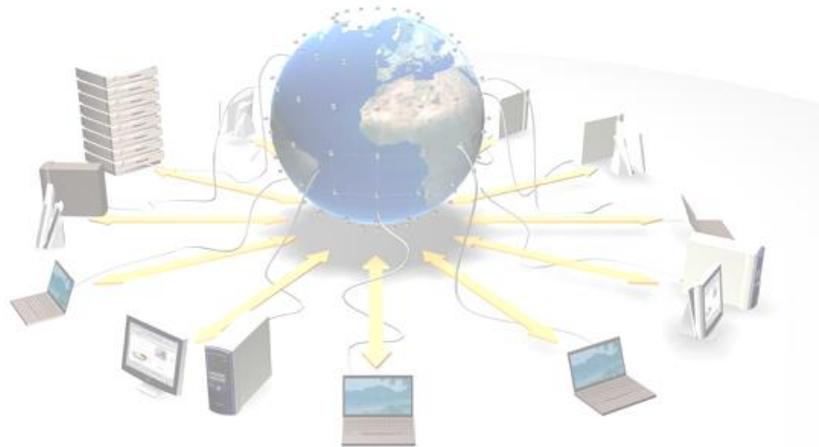




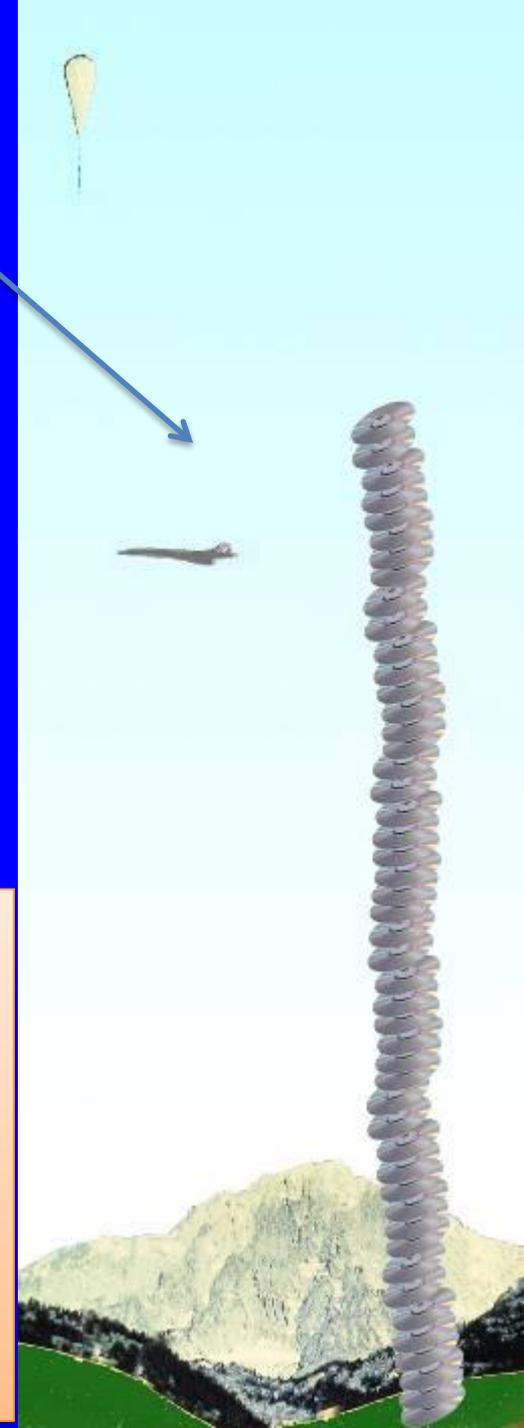
For every collision the detectors produce electrical signals which are then transformed into digital information. This is read out and recorded by computers.

20 km CD
per year
from the LHC
experiments

The GRID



Hundreds of thousands of computers in hundreds of computer centres all around the world are connected to the Grid: they share their processing power and their storage capacity to analyse the data from the LHC experiments.



Some facts about LHC

- protons in LHC in bunches (of 100 billion p) every 25 ns;
- accelerated from 450 GeV to 7 TeV
- reaching a speed of **99.9999991% the speed of light**
- 40 million times/s bunches pass each collision point
- **The protons go around the LHC ring 11245 times/s**
- 31.2 MHz crossing rate
- 20 collisions expected in average (from 100 on 100 billion p)
- **600 million proton collisions per second**
- After filtering, 1000 collisions of interest per second
- **>10 Petabytes/year of data**

1 Megabyte (1MB)

A digital photo

1 Gigabyte (1GB) = 1000MB

A DVD movie

1 Terabyte (1TB) = 1000GB

**World annual
book production**

1 Petabyte (1PB) = 1000TB

**Annual production of one
LHC experiment**

1 Exabyte (1EB) = 1000 PB

**World annual information
production**

LHC + detectors consume ~ 120 MW

During LHC operation CERN consumes ~ 200 MW

(comparable to Geneva consumption)

**With LHC we are looking for answers to the
unanswered questions**

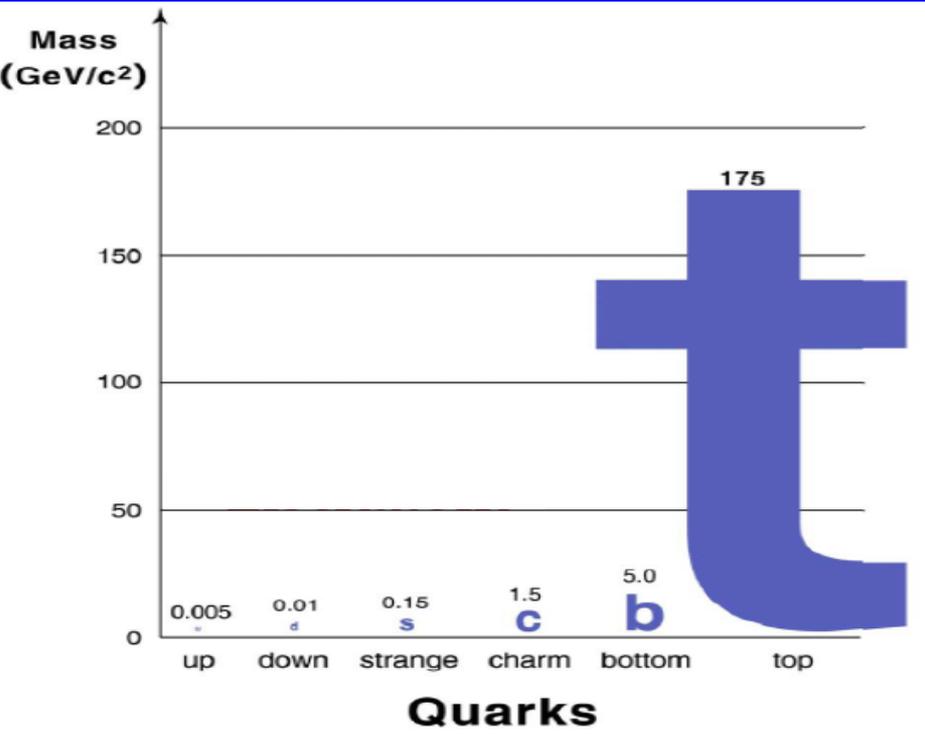
Why do particles have mass? Why do they have so different masses?

The Standard Model foresees that elementary particles have zero mass.

The Higgs field fills the Universe and the interaction of particles with it gives them their mass, big or small, depending on the strength of the interaction.
The Higgs field is connected with the Higgs boson.



Peter Higgs visiting the ALICE experiment
CERN Open Day - April 2008



Probable answer : the Higgs* mechanism, which also foresees the existence of the elusive Higgs particle.

*Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism



The Higgs boson is detected via its decays

$H \rightarrow \gamma\gamma$

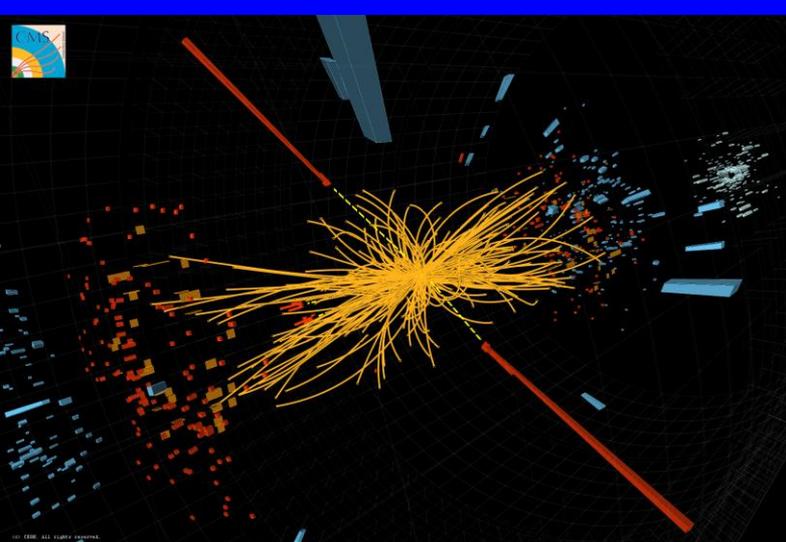
$H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$

$H \rightarrow ZZ \rightarrow eeee$

$H \rightarrow WW$

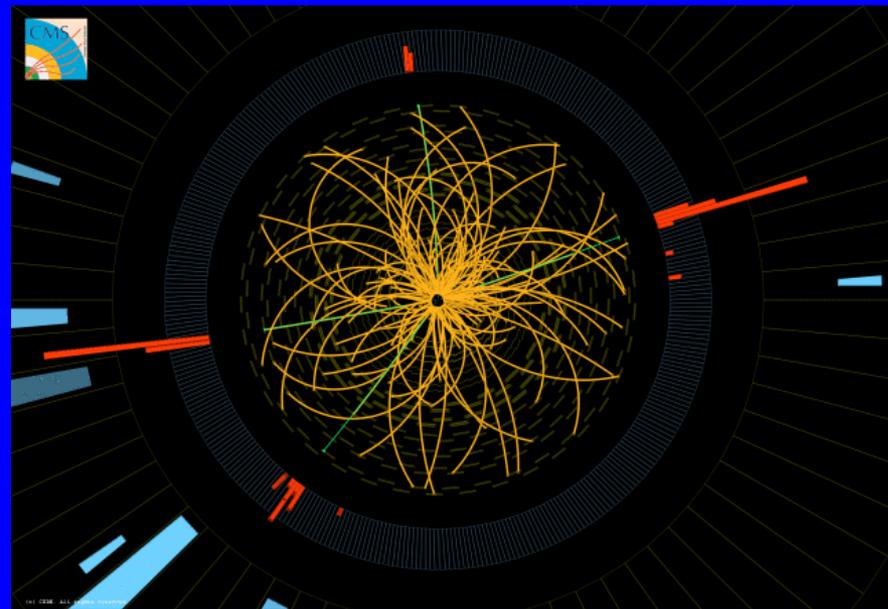
$H \rightarrow \tau\tau$

$H \rightarrow bb$

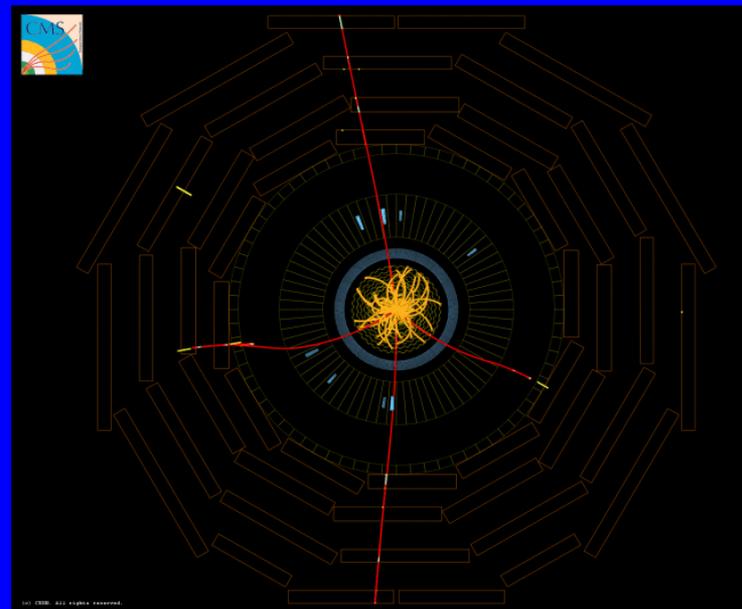


2 photon candidate Higgs event from proton-proton collisions at LHC

Higgs candidate events

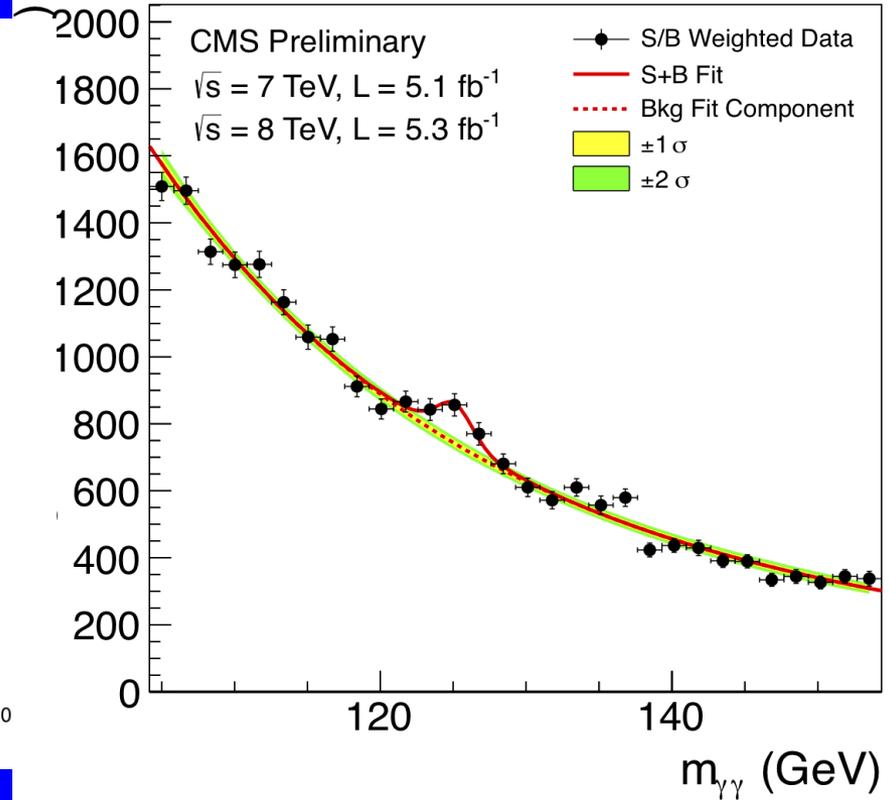
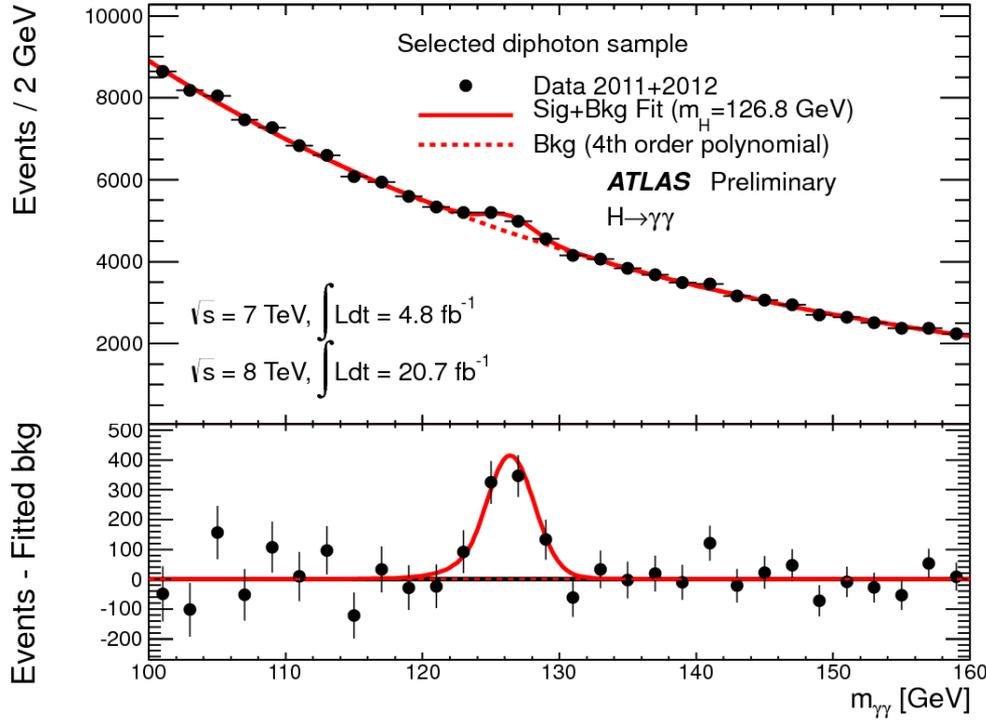


4 electron candidate Higgs event from proton-proton collisions at LHC



4 muon candidate Higgs event from proton-proton collisions at LHC

Invariant mass of the two photos : the peak at 126 GeV is the Higgs boson



The peak seen after subtraction of the irreducible two-photon background is the Higgs

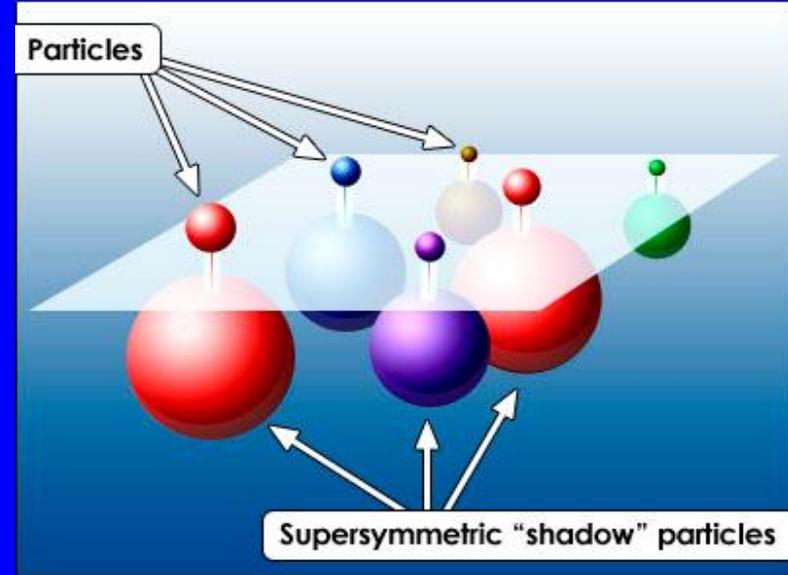
SUperSYmmetry (SUSY)

Symmetry between matter (elementary particles -> fermions) and forces (force carriers -> bosons)

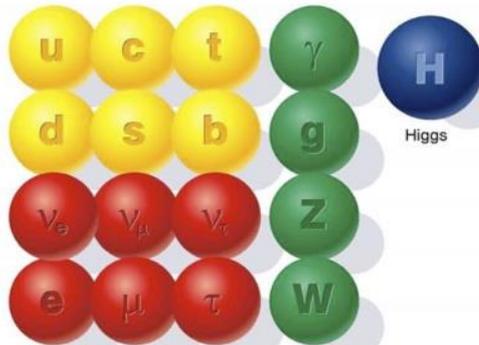
Why is SUSY needed?

To unify the forces

To solve problems in the Standard Model (deviations in the Higgs mass)

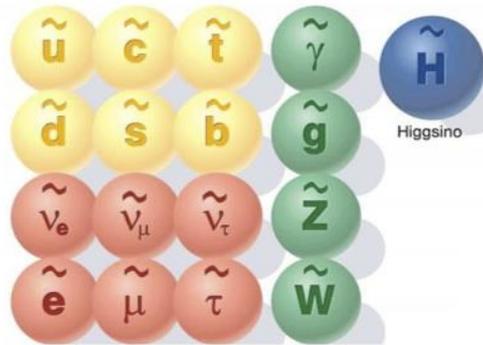


The known world of Standard Model particles



- quarks
- leptons
- force carriers

The hypothetical world of SUSY particles

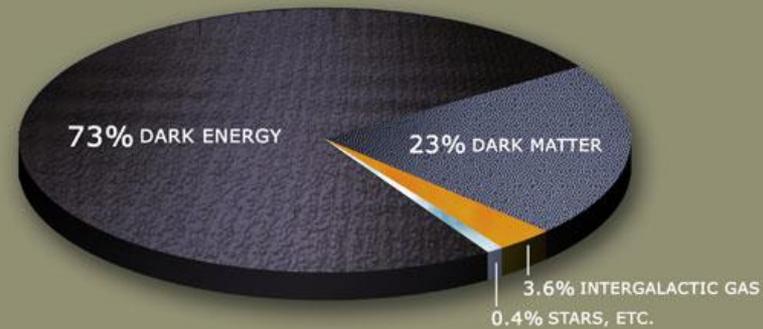


- squarks
- sleptons
- SUSY force carriers

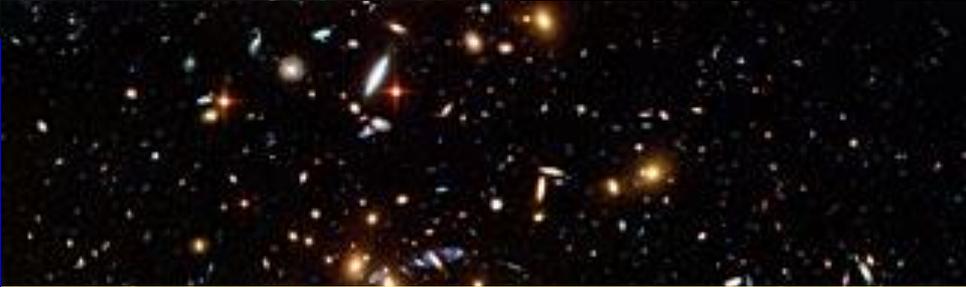
Every particle with spin s has its supersymmetric partner with spin $s-1/2$

Quark ($s=1/2$) -> squark ($s=0$)
 Gluon ($s=1$) -> gluino ($s=1/2$)

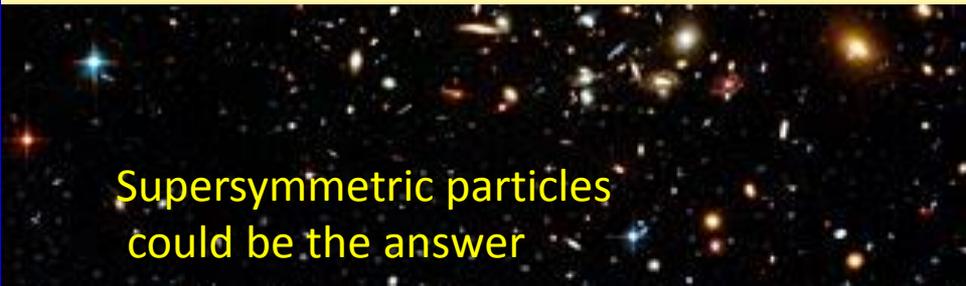
Dark Matter



4 % only is the visible matter

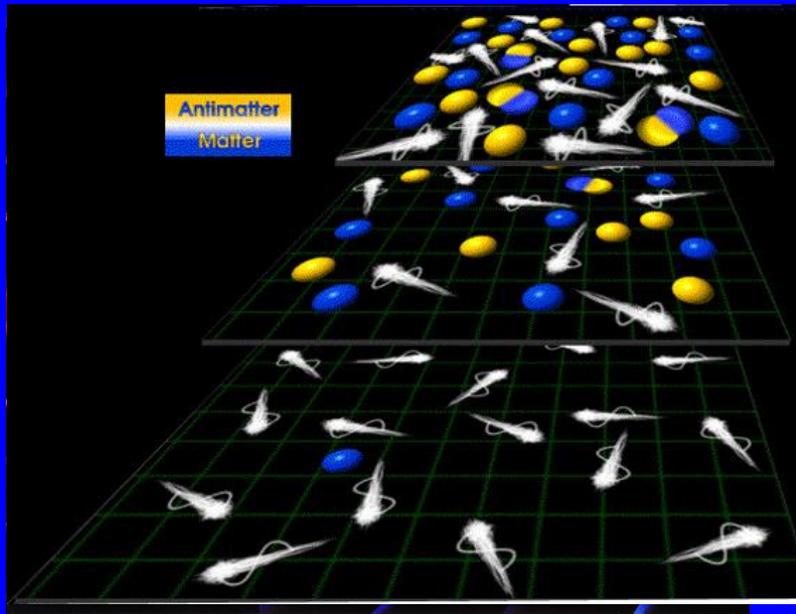


Galaxies in our universe are rotating with such speed that the gravity generated by their observable matter could not possibly hold them together; they should have torn themselves apart long ago. The same is true of galaxies in clusters, which leads scientists to believe that something they cannot see is at work. They think something we have yet to detect directly is giving these galaxies extra mass, generating the extra gravity they need to stay intact. They call this mysterious stuff dark matter.



Supersymmetric particles
could be the answer

The mystery of antimatter



13,7 billion years ago: Big Bang
Transformation of energy to mass in a gigantic scale

$t \sim 0$:

quantity of matter = quantity of antimatter

$t \sim 0.001$ s :

all antimatter has disappeared
but some matter is left
most energy is photons

Today :

>2,000,000,000 photons for every proton or neutron

Why is our Universe made of matter only?

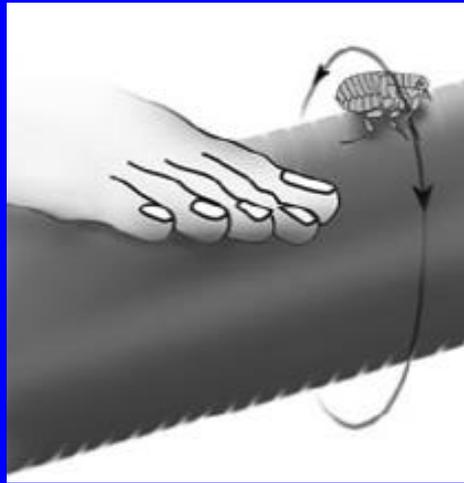
Is it because matter and antimatter have slightly different properties?
(such as mass, charge, ..)

➤ experiments at Antiproton Decelerator (AD) where antimatter is created

Or is it because they have different decay properties?

➤ LHCb experiment at LHC, studying decays of hadrons with b-quarks

Do we live in a world with extra dimensions?



The acrobat is moving in **one** dimension
The insect is moving in **two** dimensions, but one of them is very small

Extra dimensions might exist, but they would be **so small** that we **can not perceive** them

Evidence of extra dimensions could explain the mystery of gravity : why it is so much weaker than all other forces

Maybe it acts partially in another dimension

Extra dimensions are also needed by **string theory**

- Fundamental particles are not like points or dots, but rather small loops of vibrating strings.
- All the different particles and forces are different oscillation modes of a unique type of string.

String theory requires

- six additional spatial dimensions!
- these extra dimensions are apparently 'curled up' so small that we do not see them.

Up to now..

- Searches for SUSY : no experimental signal – limits
- Dark matter : No experimental signal
e.g. WIMPs : weakly interacting massive particles – dark matter candidates
- The Standard Model seems to be the theory describing our world

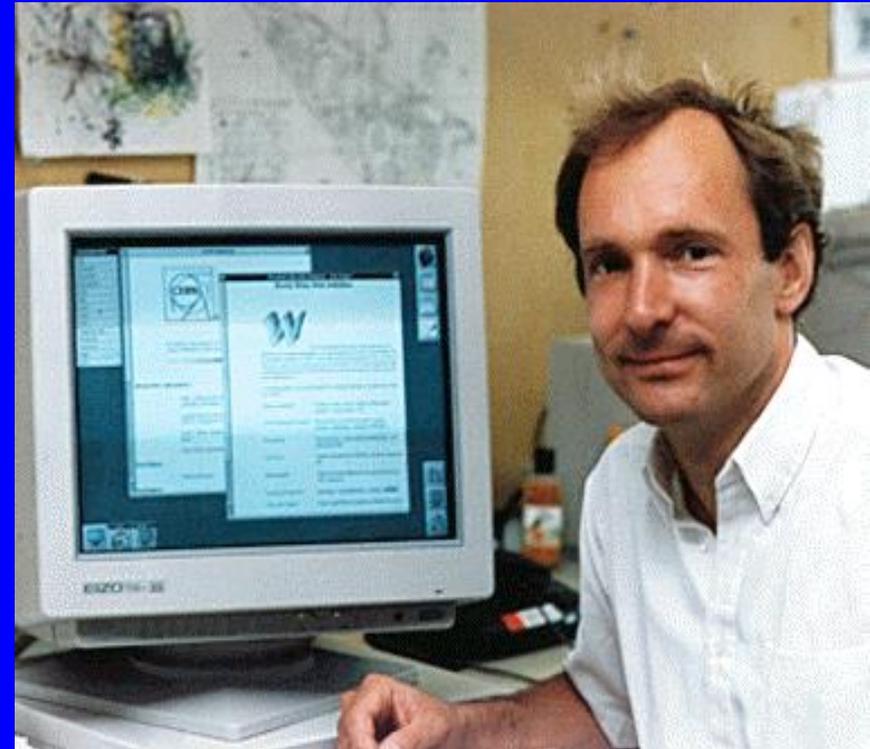
What next?

- The LHC is stopped since end of 2018 for a planned, 3-year long shutdown (LS2)
- To allow upgrade work leading to the High Luminosity LHC (~2025)
- In order to increase the number of collisions collected
- And thus increase the statistics
- Which will increase the discovery potential of this superb machine

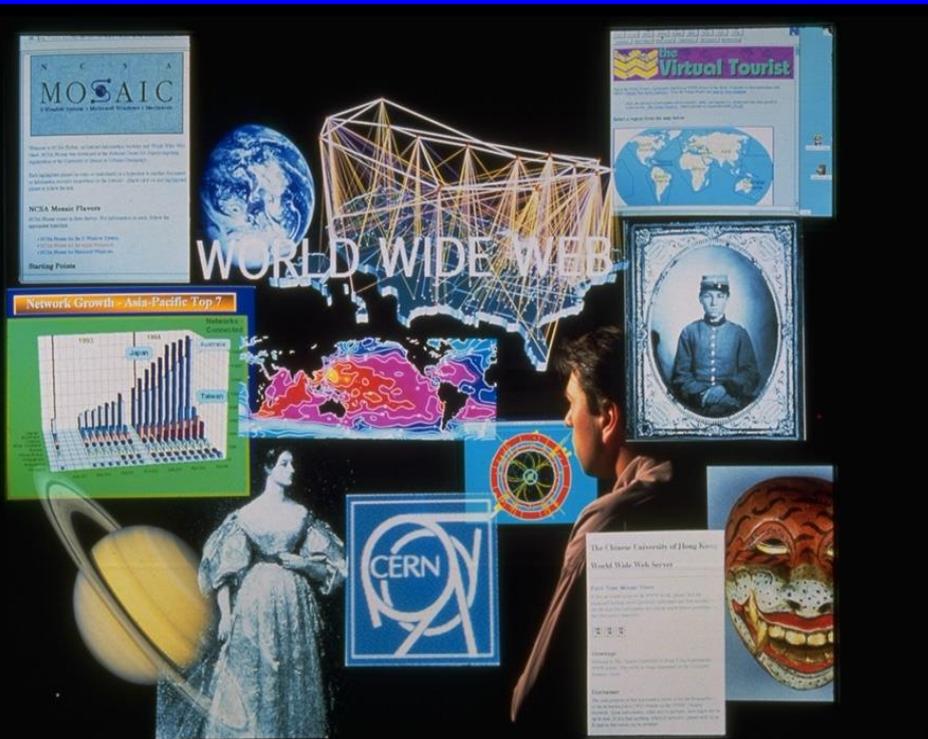
..and what are the benefits for society?

World Wide Web

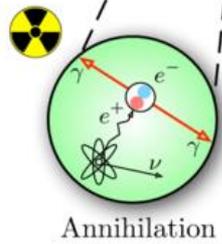
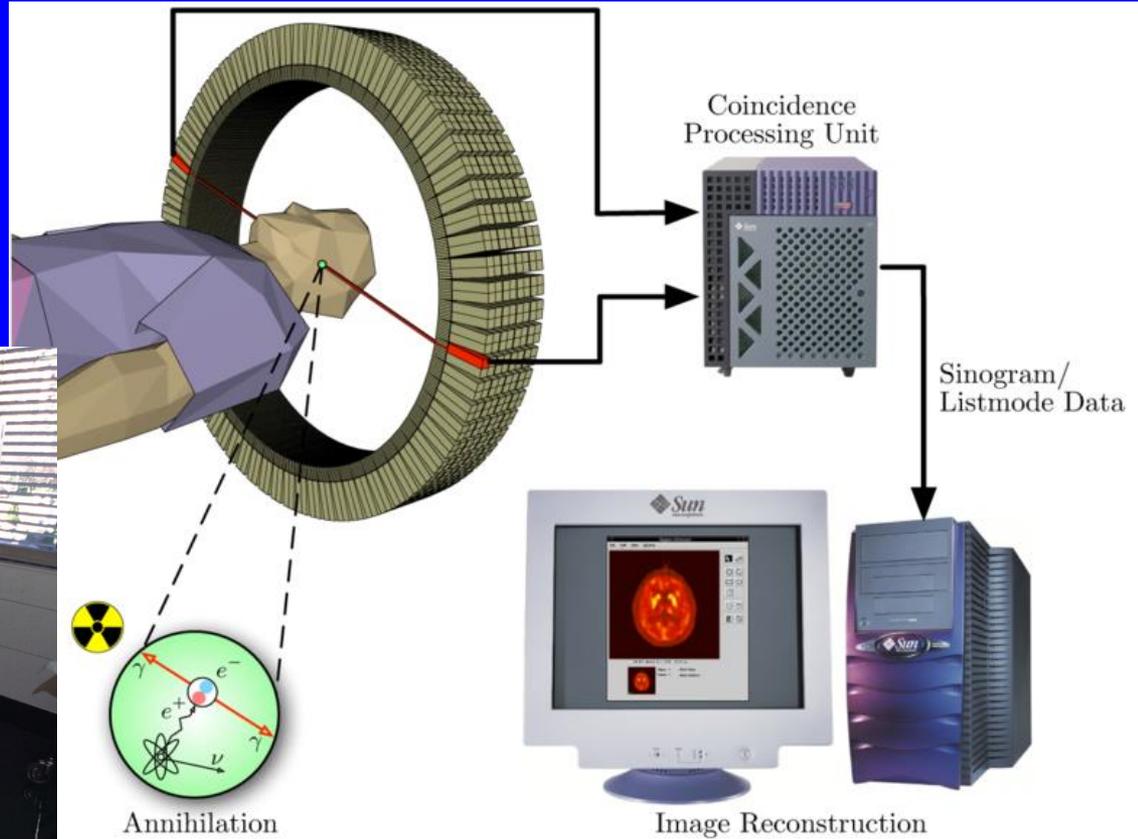
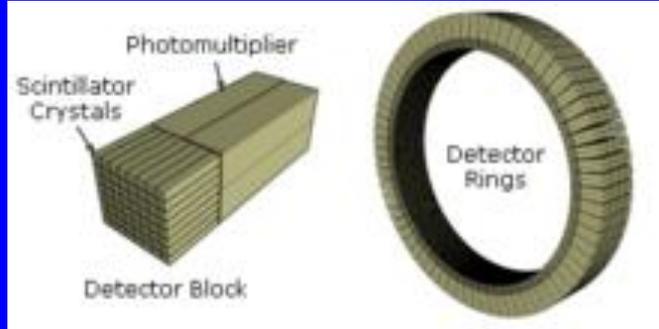
Invented by **Tim Berners-Lee**,
a **CERN** physicist, in **1989**,
to meet the need of physicists in
Institutes all over the world for
automatic information sharing



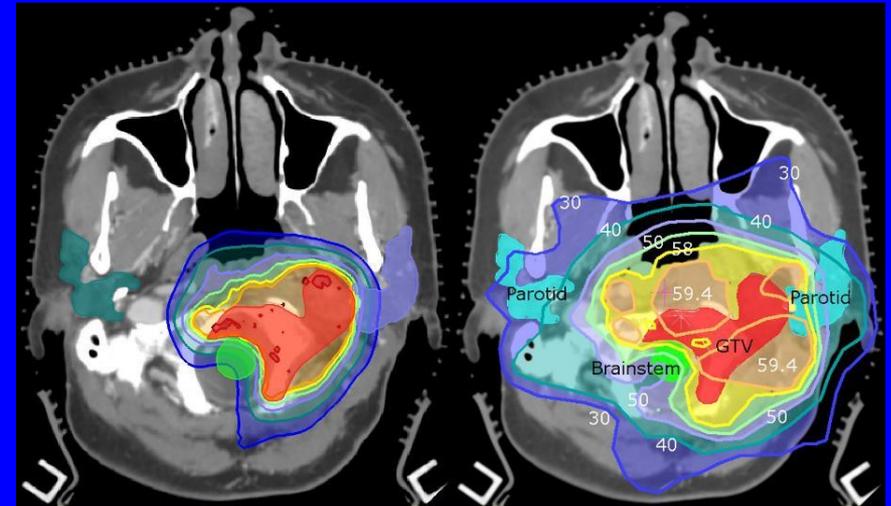
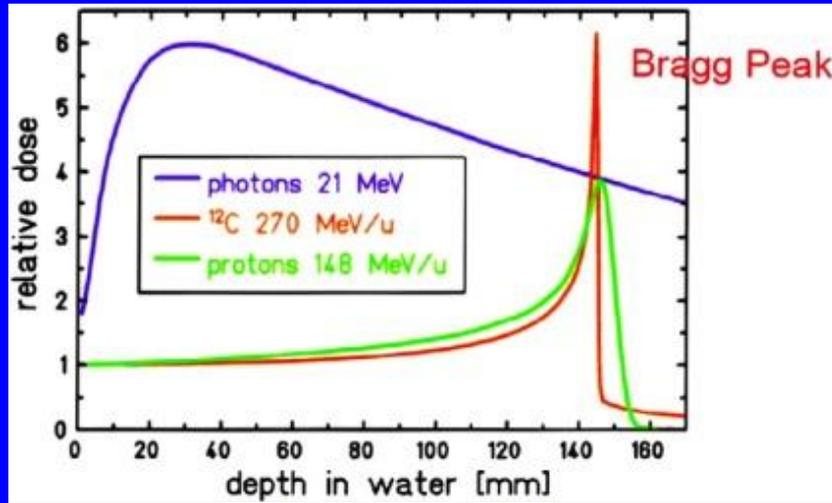
WWW combined with Internet
has changed our way of life



Medical application : Positron Emission Tomography (PET)



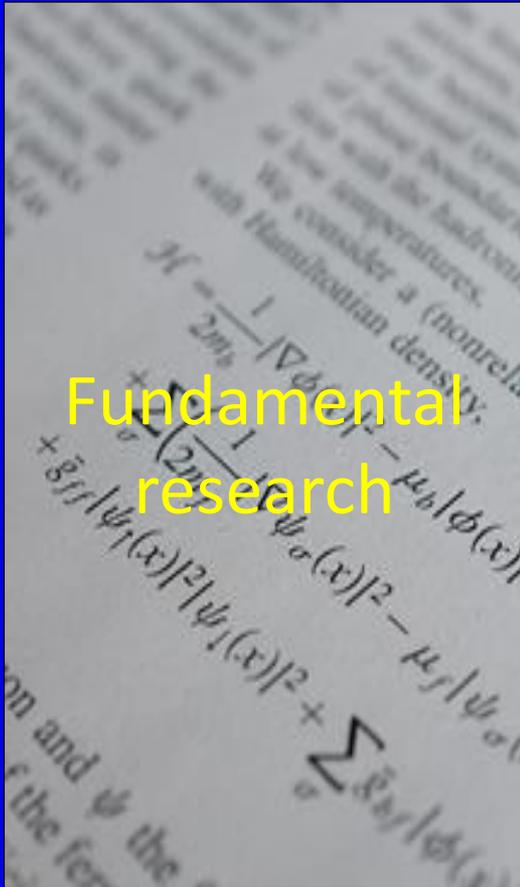
Medical application : Hadron Therapy



Hadron Therapy "ordinary" radiotherapy



In a nutshell...



Fundamental
research



Largest
international
Scientific
collaboration



Technology
Transfer in
Benefit of
society



Thanks for your attention!

backup

Example : neutron decay (radioactive beta decay)

a particle decays into a less massive particle + force-carrier(W) Boson, which then decays into other particles

The force-carrier particle mediating the decay seems to violate conservation of energy because of its high mass but "virtual" bosons exist so briefly, that no "rule" is broken

Heisenberg uncertainty principle $\Delta E \Delta t \approx h$.

