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

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INFN Bologna and CERN

Working Experience Week at CERN for students of the European School Brussels III

What does *CERN* stand for ?

Conseil Européen pour la Recherche Nucléaire

European Council for Nuclear Research

1953

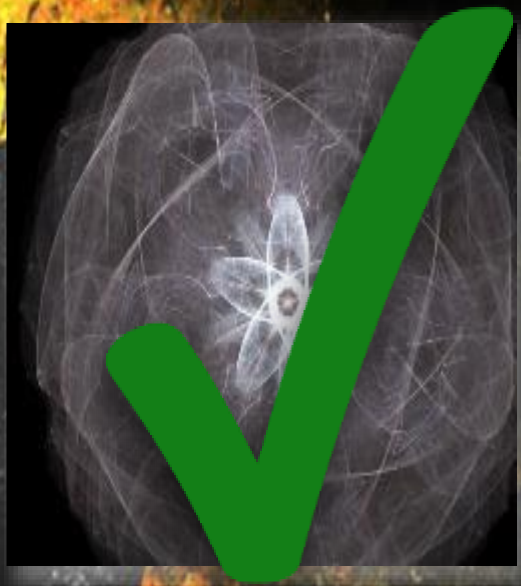
What is *CERN's* name ?

Organisation Européenne pour la Recherche Nucléaire

European Organization for Nuclear Research

1954

Nuclear?



European laboratory for particle physics

Member States

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)

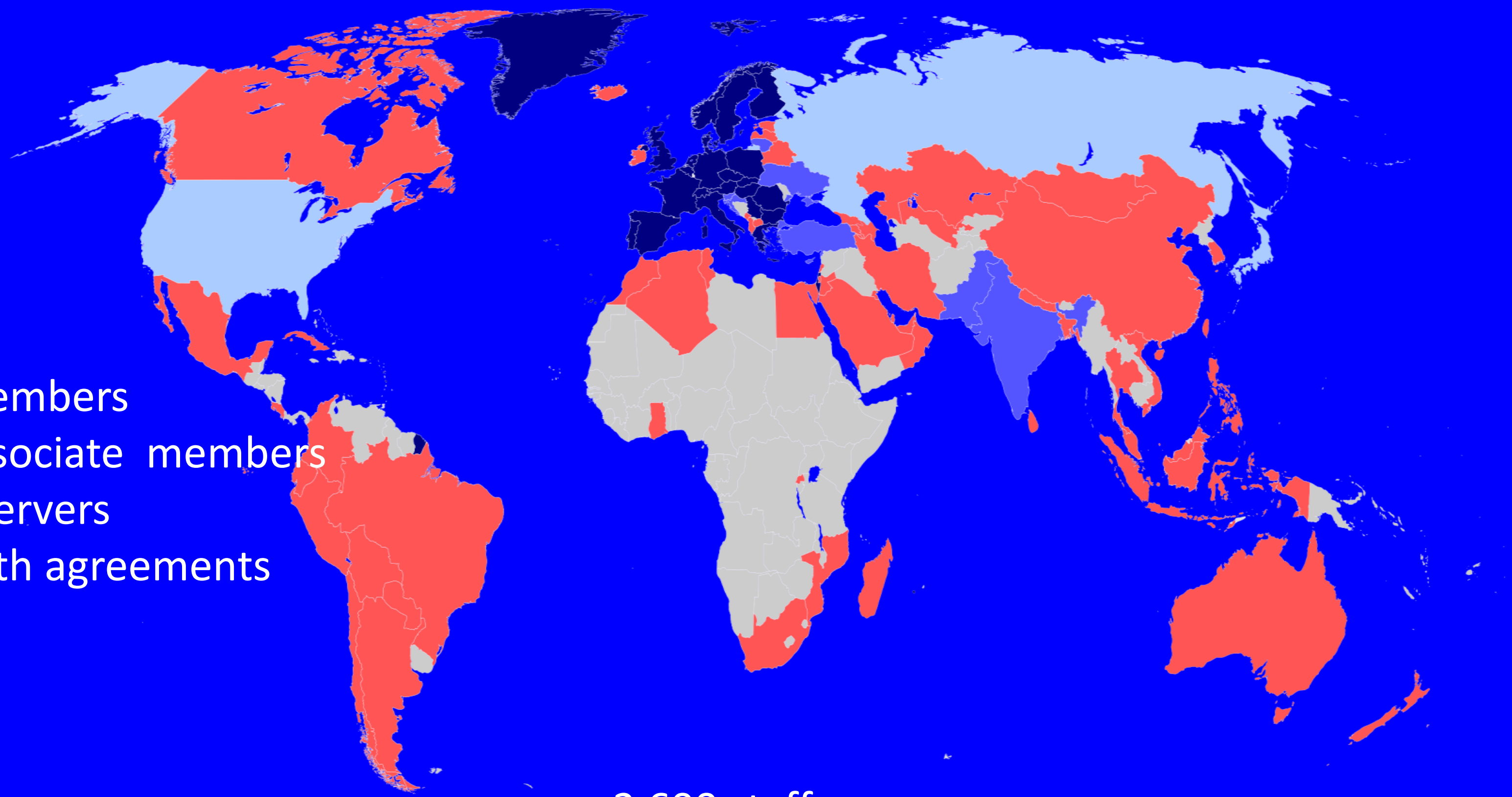
Associated

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

Estonia (2021)
Latvia (2022)

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

A world collaboration



23 members
10 associate members
2 observers
61 with agreements

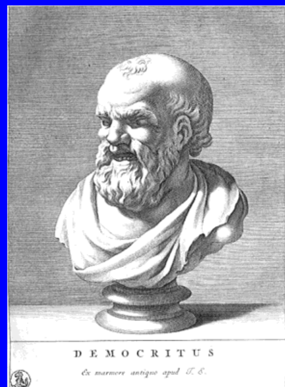
2 600 staff
800 fellows and apprentices
550 students
15 000 users
2 000 external companies

~ 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

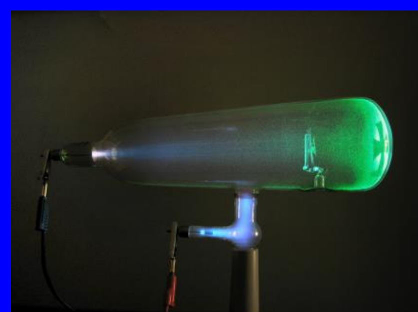
Democritus believed that all matter is made of indivisible elements, the atoms



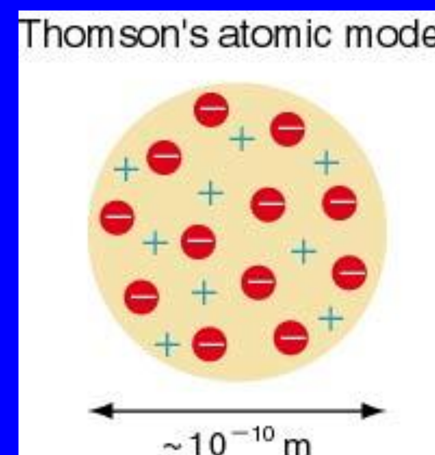
Mendeleev's periodic table of elements (1869) – 80 different indivisible atoms

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	Ti 204	Pb 207	Bi 209					
			Th 232		U 238				

JJ Thomson

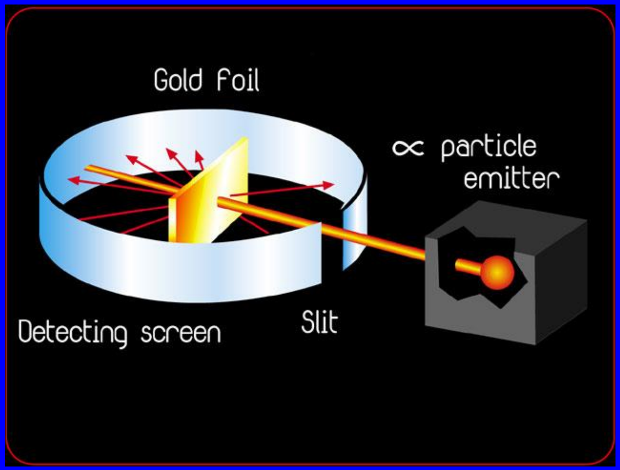


Discovery of the electron with cathode ray tube
first elementary particle
1896

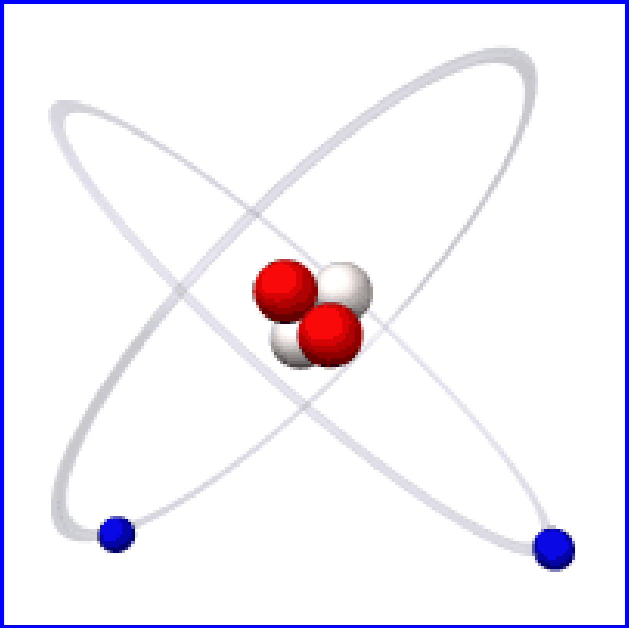


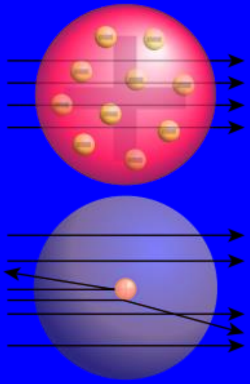
Thomson's plum pudding model (1904)

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



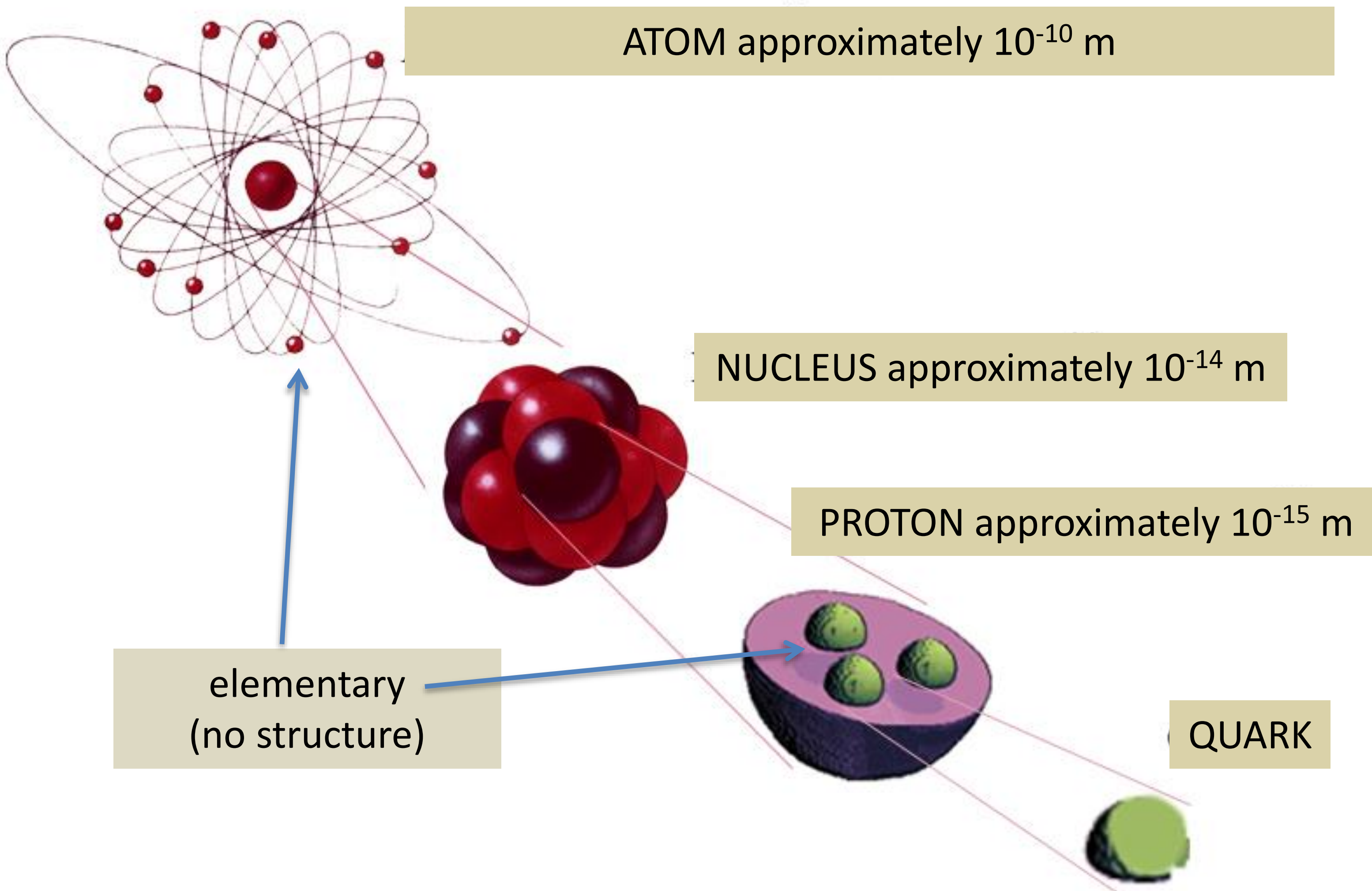
alpha scattering experiment
Geiger – Marsden





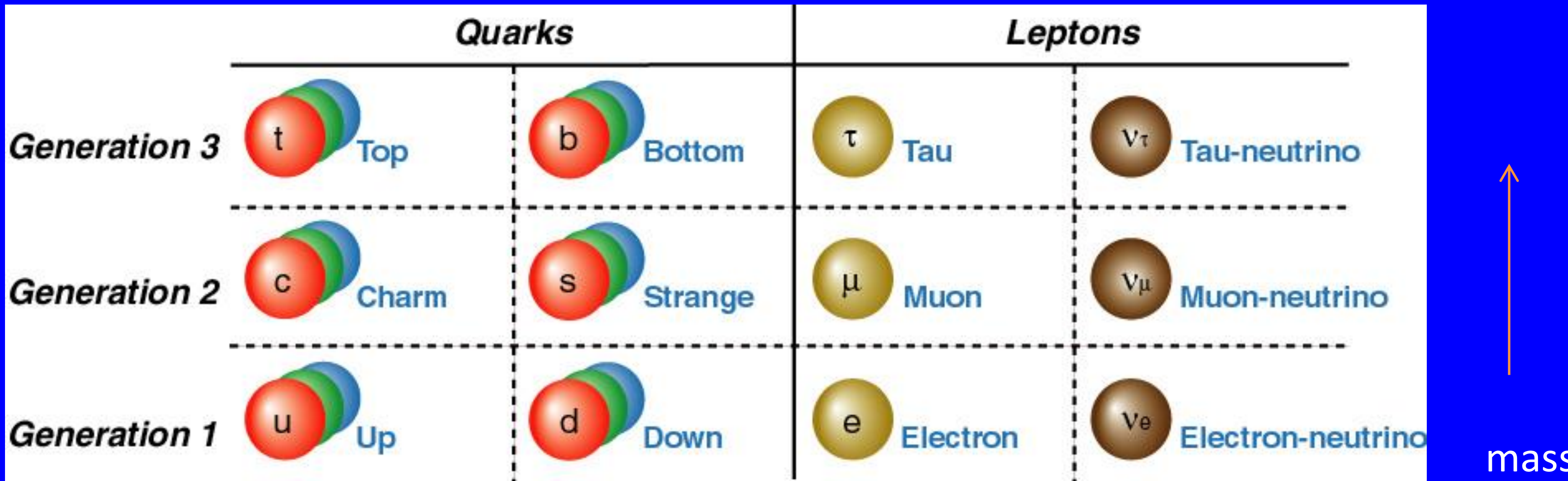
Nucleus: most of the mass, positive charge; atom is mainly empty
Later on found that the nucleus consists of protons and neutrons

Ernest Rutherford



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

Periodic system of the elementary particles



charge 2/3 charge -1/3 charge -1 charge 0

In nature : elementary particles of the first generation ONLY

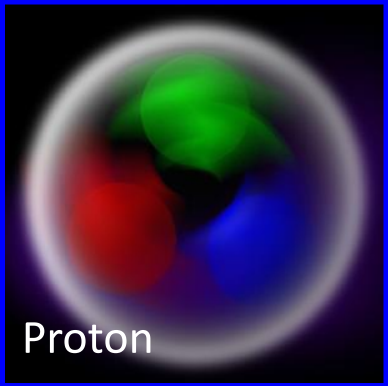
Those of the second and third generation decay to the lighter ones.
They have been seen in accelerator experiments

All particles have their antiparticles, with opposite electric charge

Quark Confinement

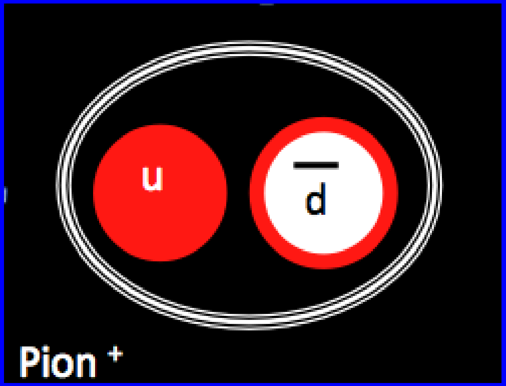
Quarks can not exist free in nature

They can only exist bound inside hadrons



baryons consisting of 3 quarks

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
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

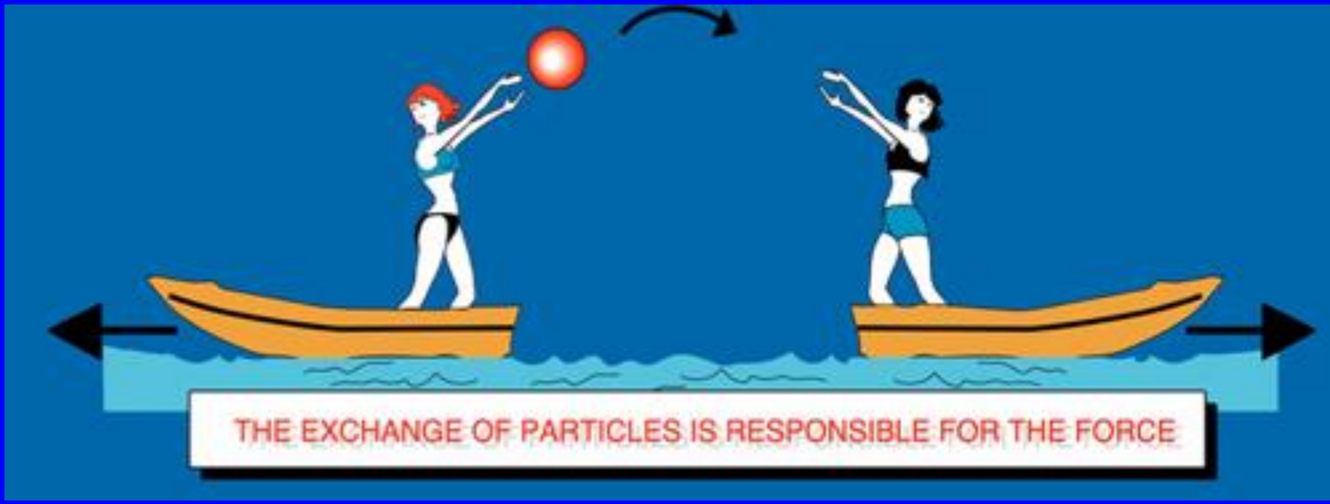
Mesons $q\bar{q}$

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	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Concept of interaction - force

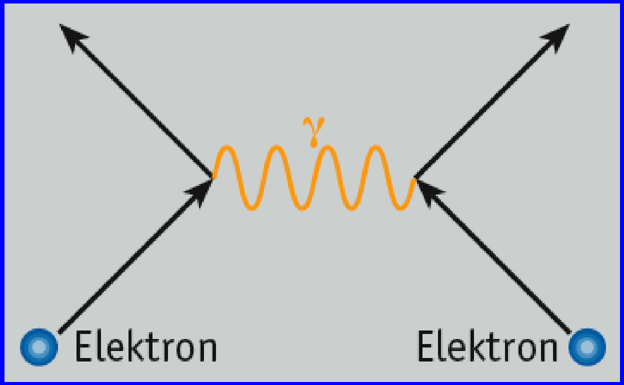
Particles interact with each other (feel each other) with various forces by exchanging special “particles”



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

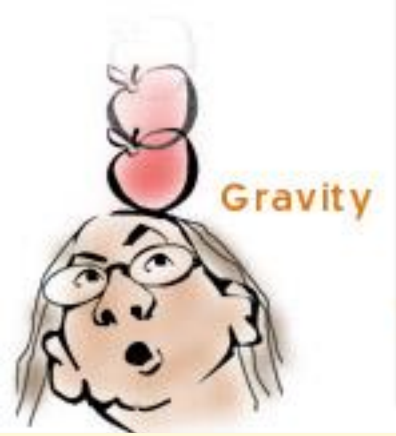


Feynman-Graph

4 Fundamental Interactions

4 Fundamental Interactions

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



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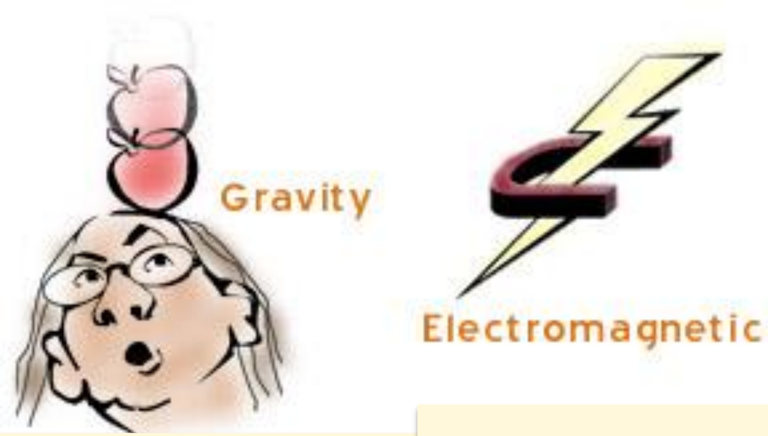

television, magnets,
chemical binding
strength: 1/137
range: infinite
mediator: photon

4 Fundamental Interactions

falling apples,
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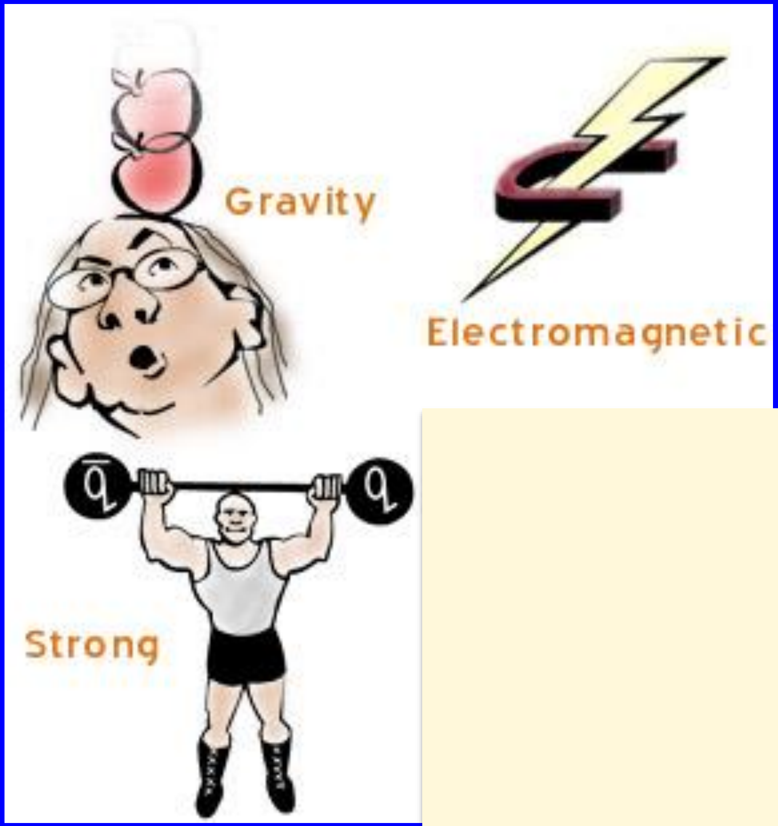

nuclear stability,
quark confinement
strength: 1
range: 10^{-15} m
mediator: gluons

4 Fundamental Interactions

falling apples,
planetary orbits
strength: 10^{-39}
range: infinite
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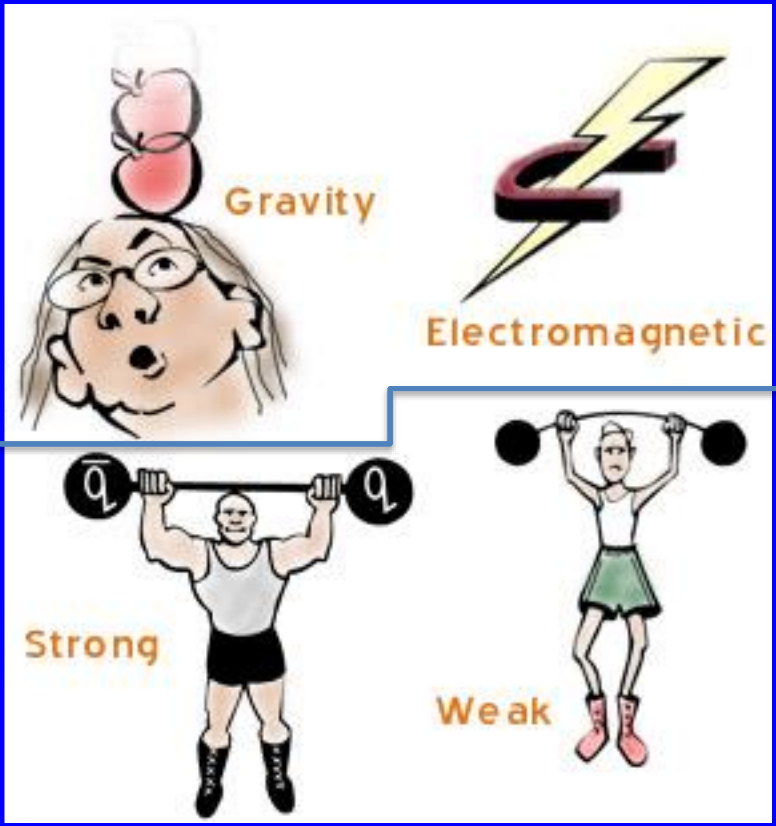
things we can relate to

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



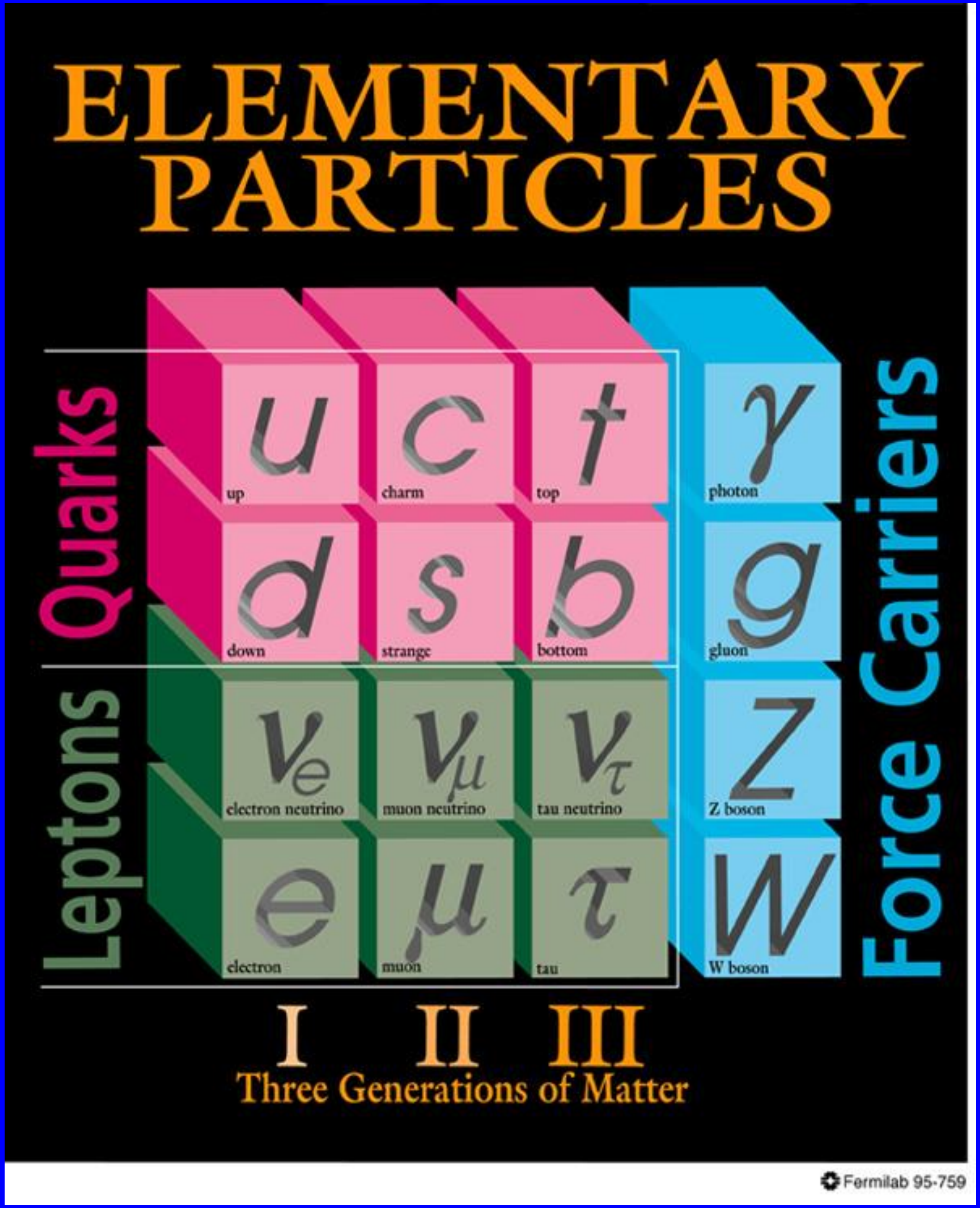
nuclear stability,
quark confinement
strength: 1
range: 10^{-15} m
mediator: gluons

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

things we cannot relate to

The Standard Model

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

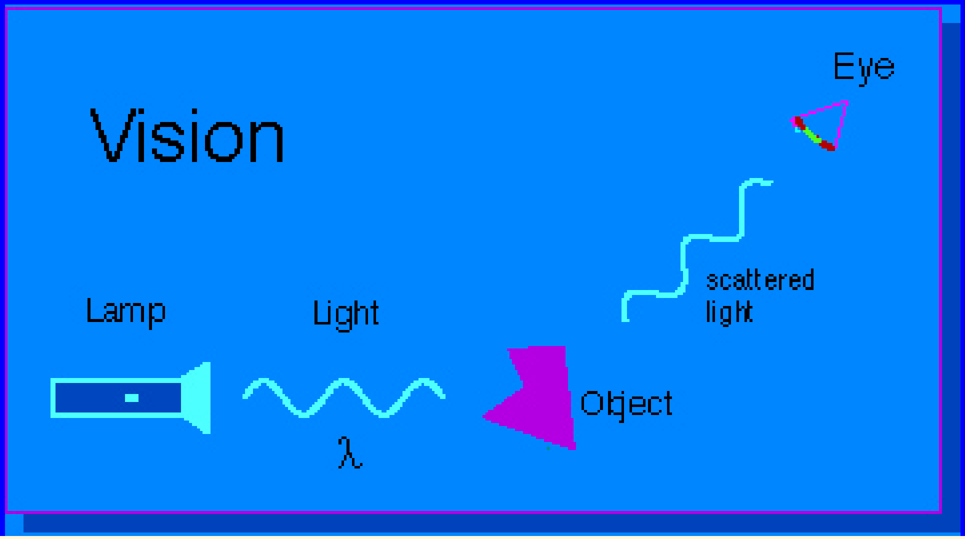


bosons
Bose-Einstein
statistics
Spin integer
(0, 1, 2,..)

The "Right" Light to Look Inside of Things

Vision works by scattering of 'visible' light

λ = 400-700 nm



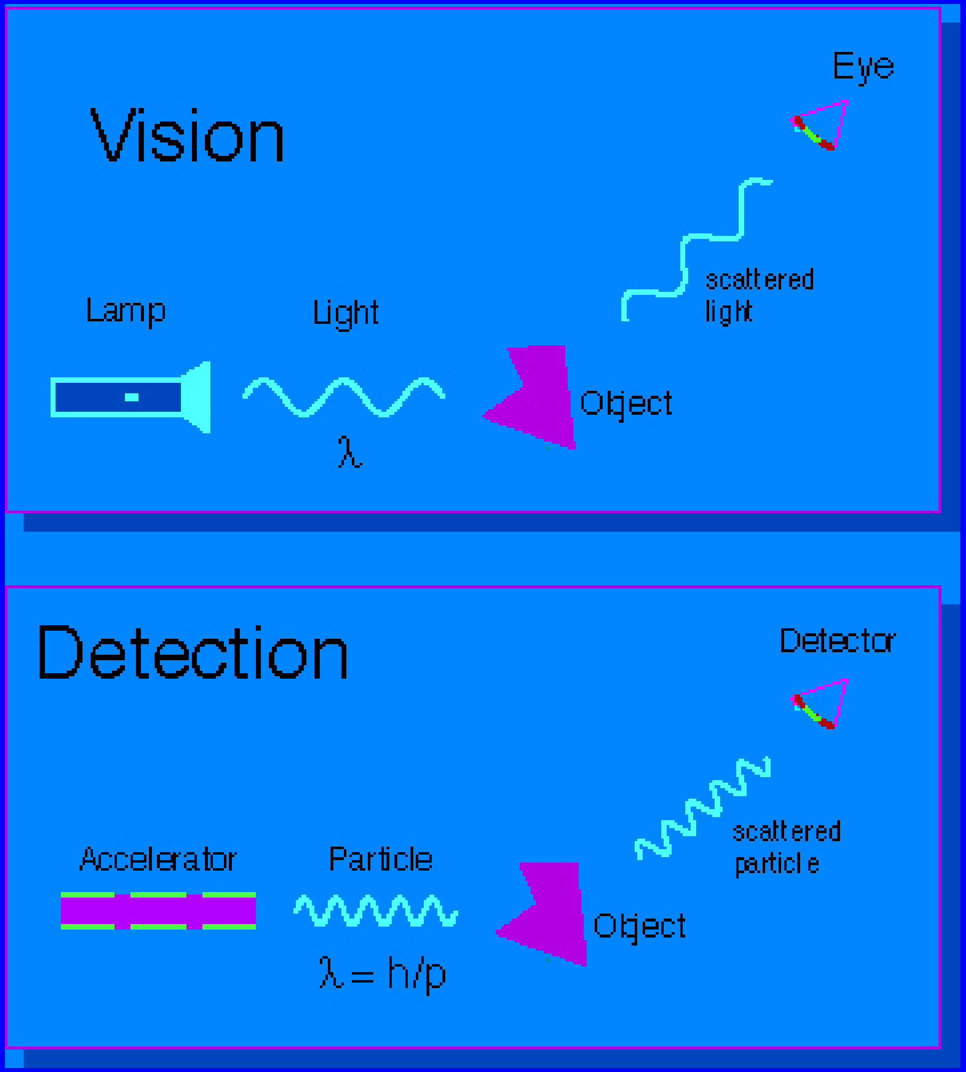
The “Right” Light to Look Inside of Things

Vision works by scattering of ‘visible’ light

λ = 400-700 nm

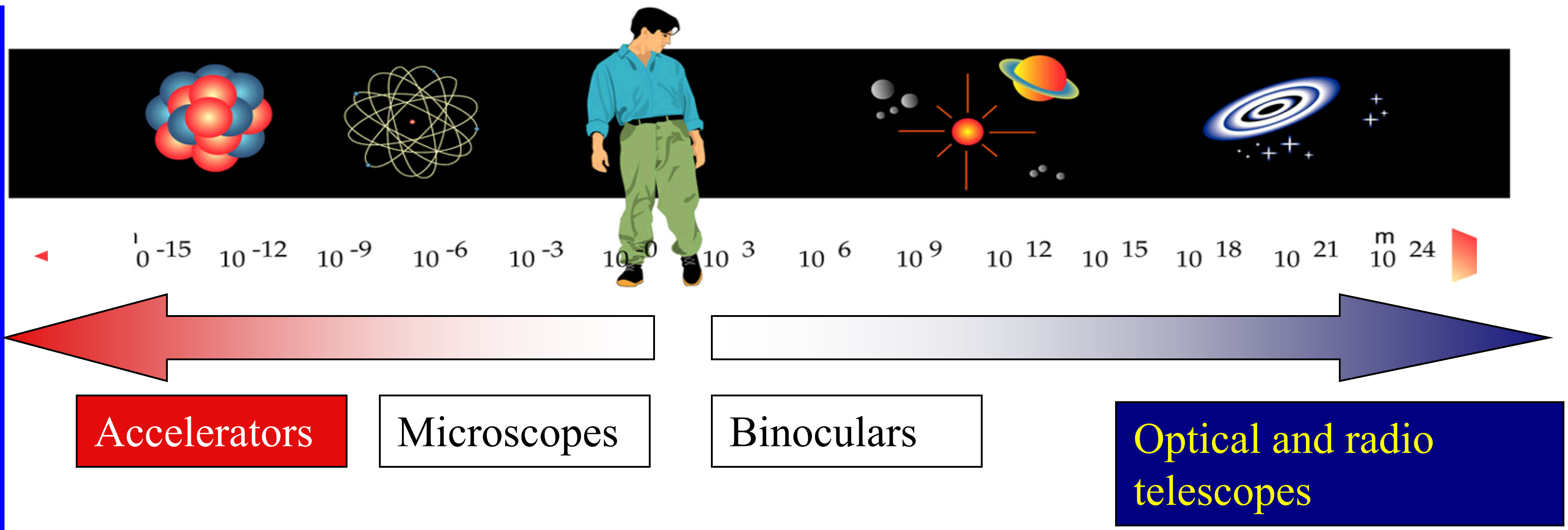
“Vision” of even smaller structures via scattering of particles

$\lambda = h/p$



CERN's mission : to build particle accelerators

Why accelerators? To investigate Particle Physics



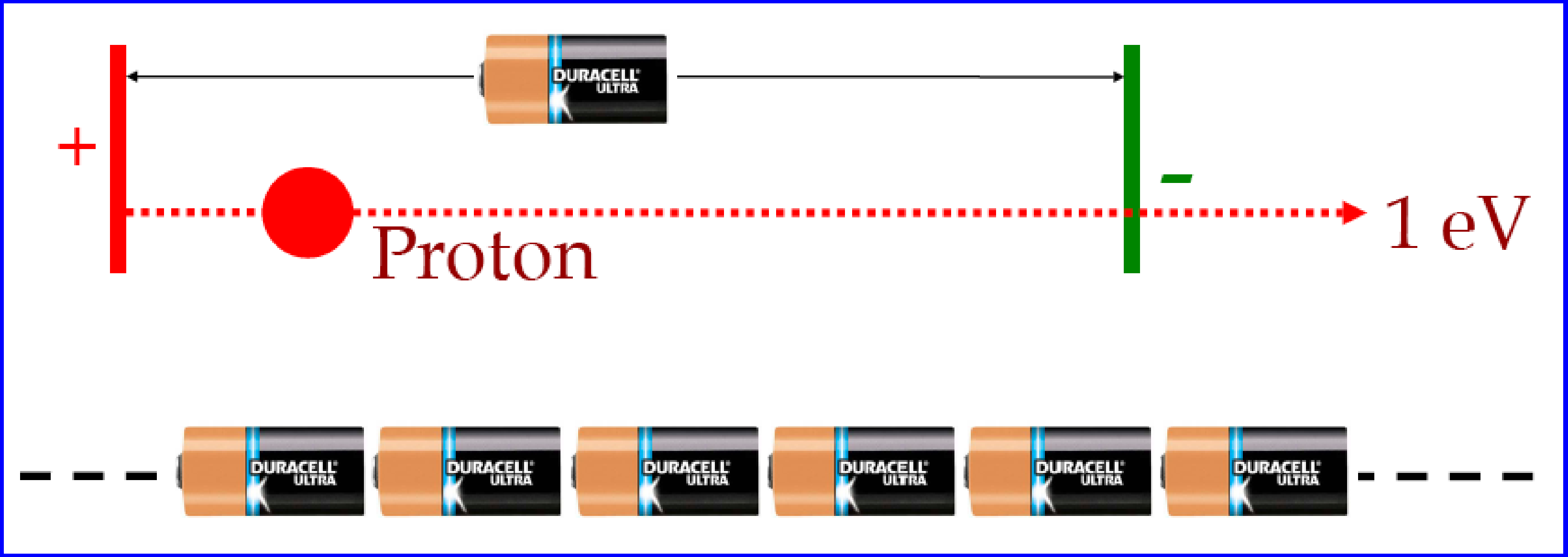
Particle physics looks at matter in its smallest dimensions

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•V



Units of energy

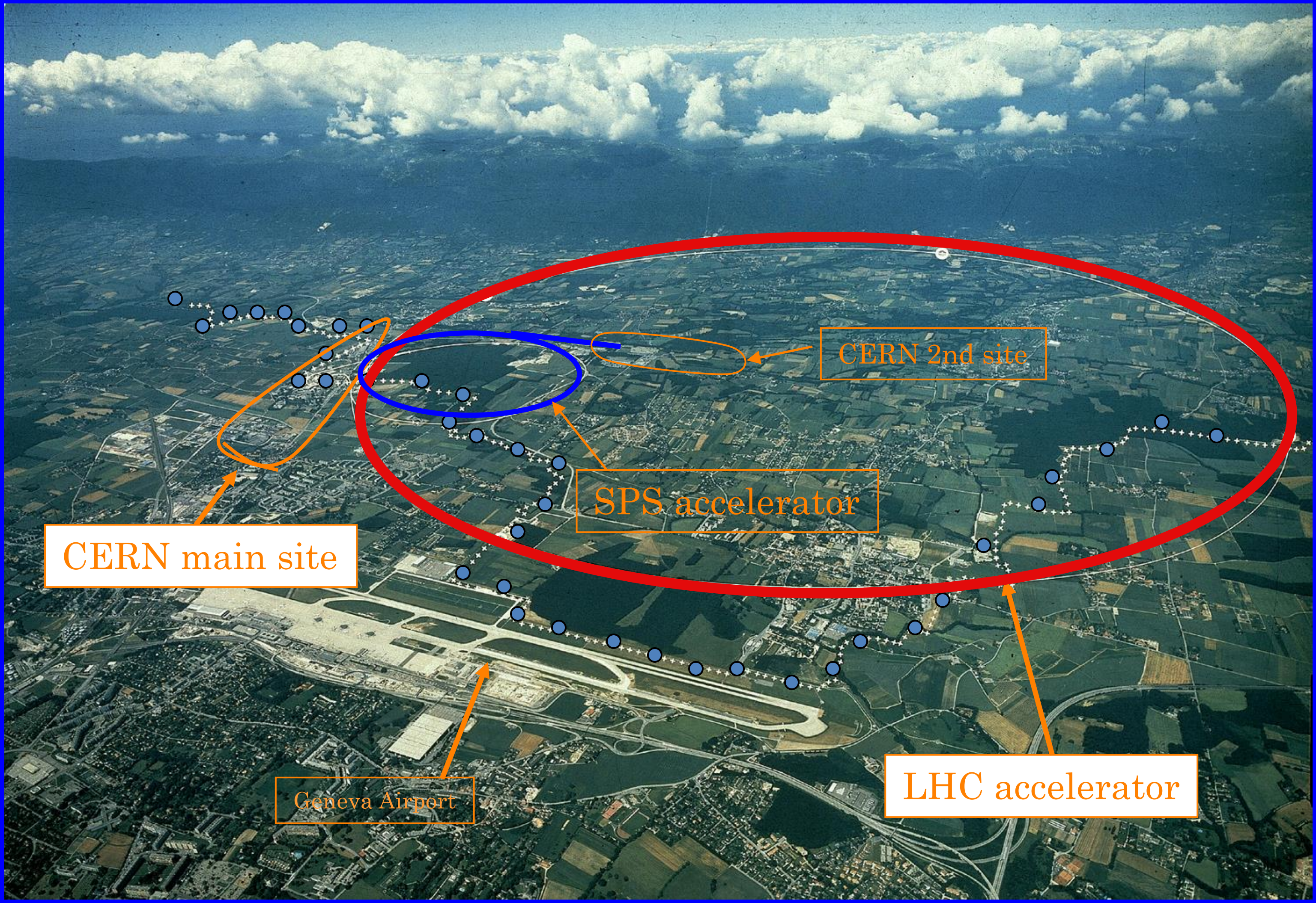
$1\ eV = 1.6 \times 10^{-19}$ Joule

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

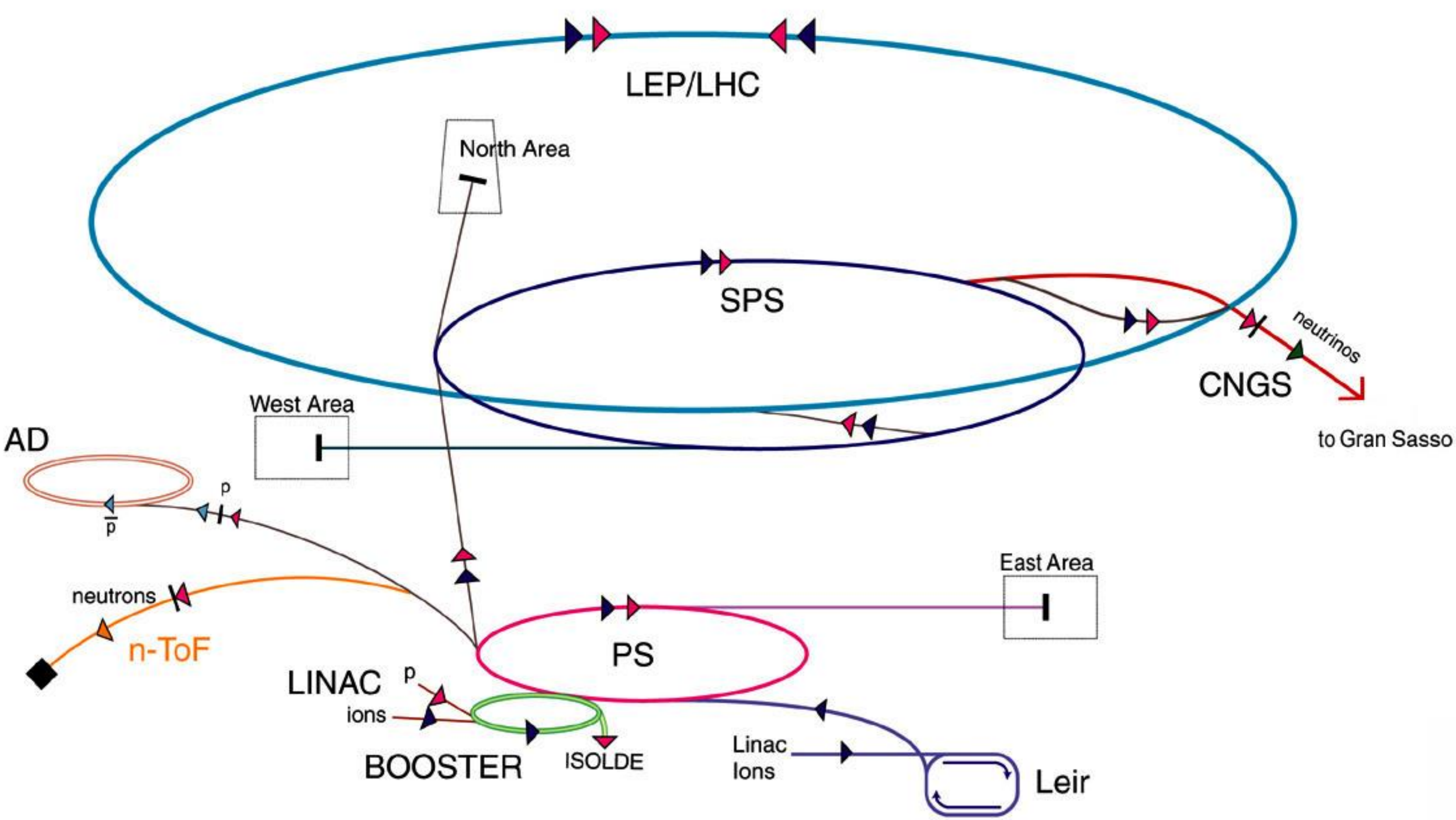
1 keV = 10^3 eV = 1000 eV
1 MeV = 10^6 eV = 1 000 000 eV
1 GeV = 10^9 eV = 1 000 000 000 eV
1 TeV = 10^{12} eV = 1 000 000 000 000 eV

Mass – energy equivalence $E = mc^2$

c=1 natural units
mass expressed in units of energy


CERN 2nd site
SPS accelerator
CERN main site
Geneva Airport
LHC accelerator

The CERN accelerators



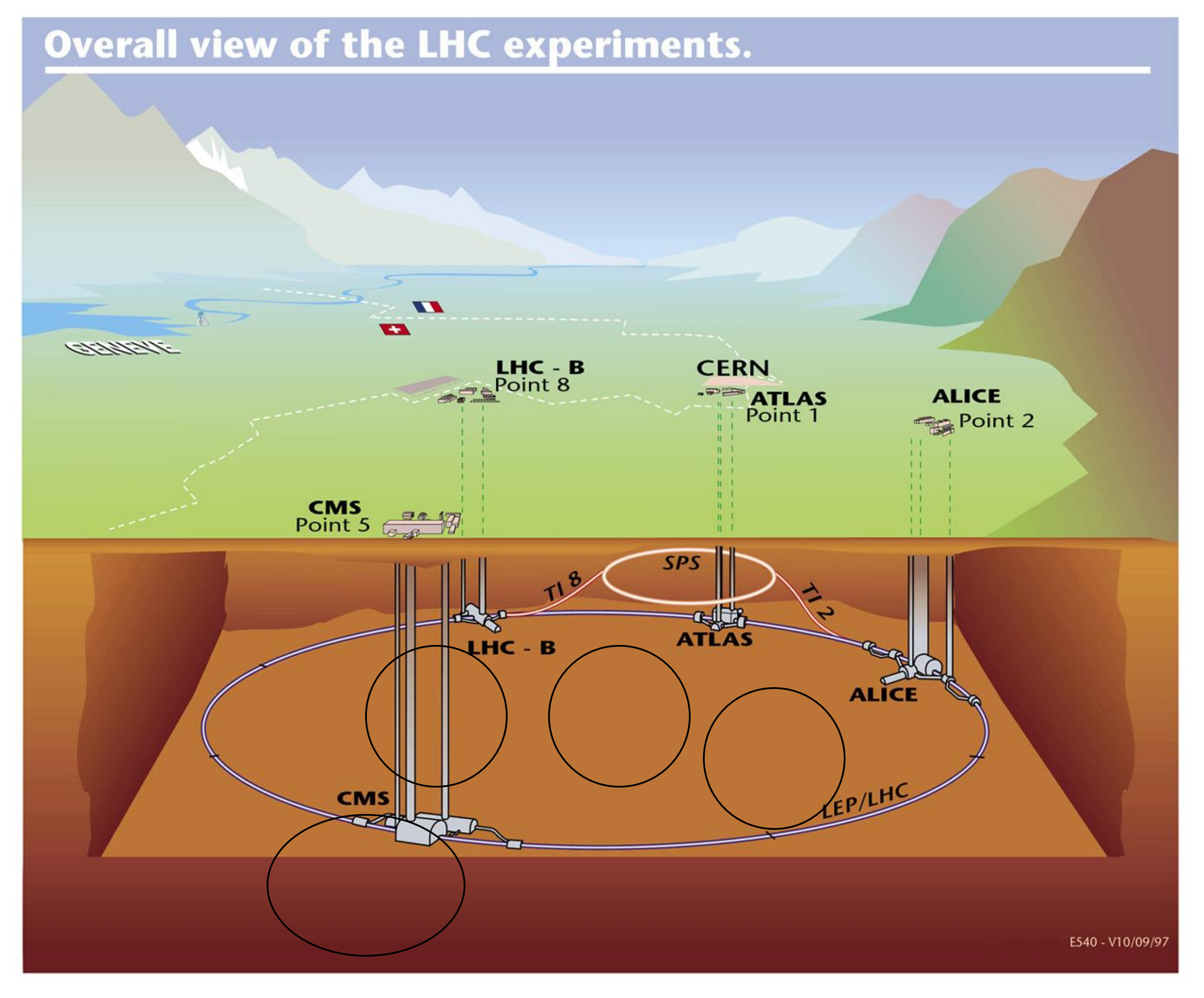
p (proton)
ion
neutron

p̄ (antiproton)
proton/antiproton conversion
neutrino

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS Cern Neutrinos Gran Sasso

The Large Hadron Collider (LHC)



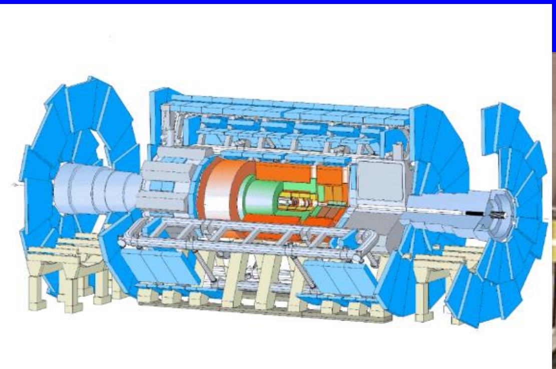
The largest accelerator in the world, in a ring of 27 km circumference

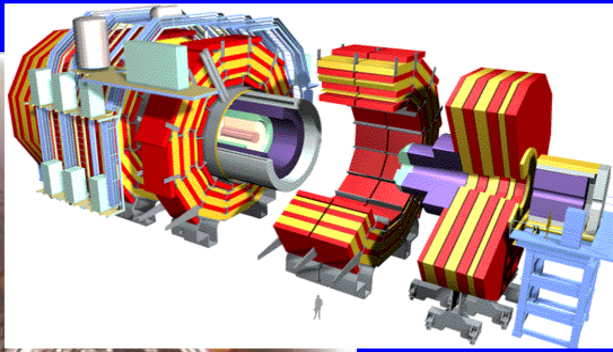
At LHC two beams of protons collide at the highest accelerator energy (13 TeV up to now and will reach 14 TeV)

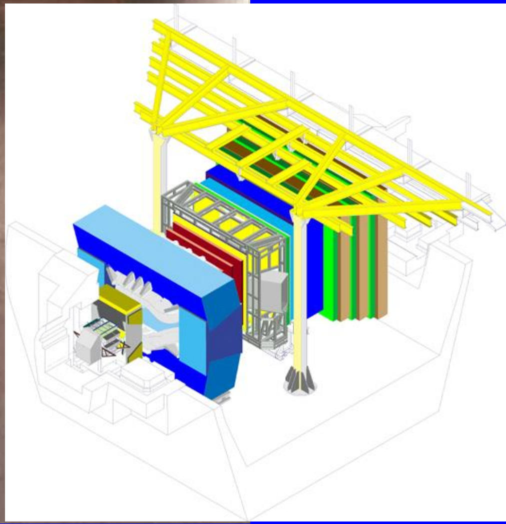
LHC is the coldest place in the universe: its superconducting magnets, cooled with liquid helium, operate at 1.9 K (-271^{o} C) just above absolute zero

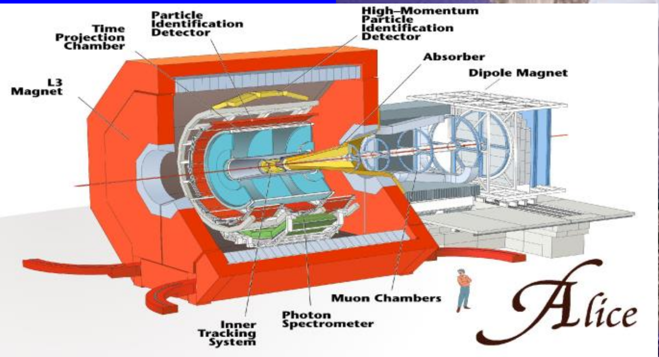
The LHC is located in a tunnel 100 m underground

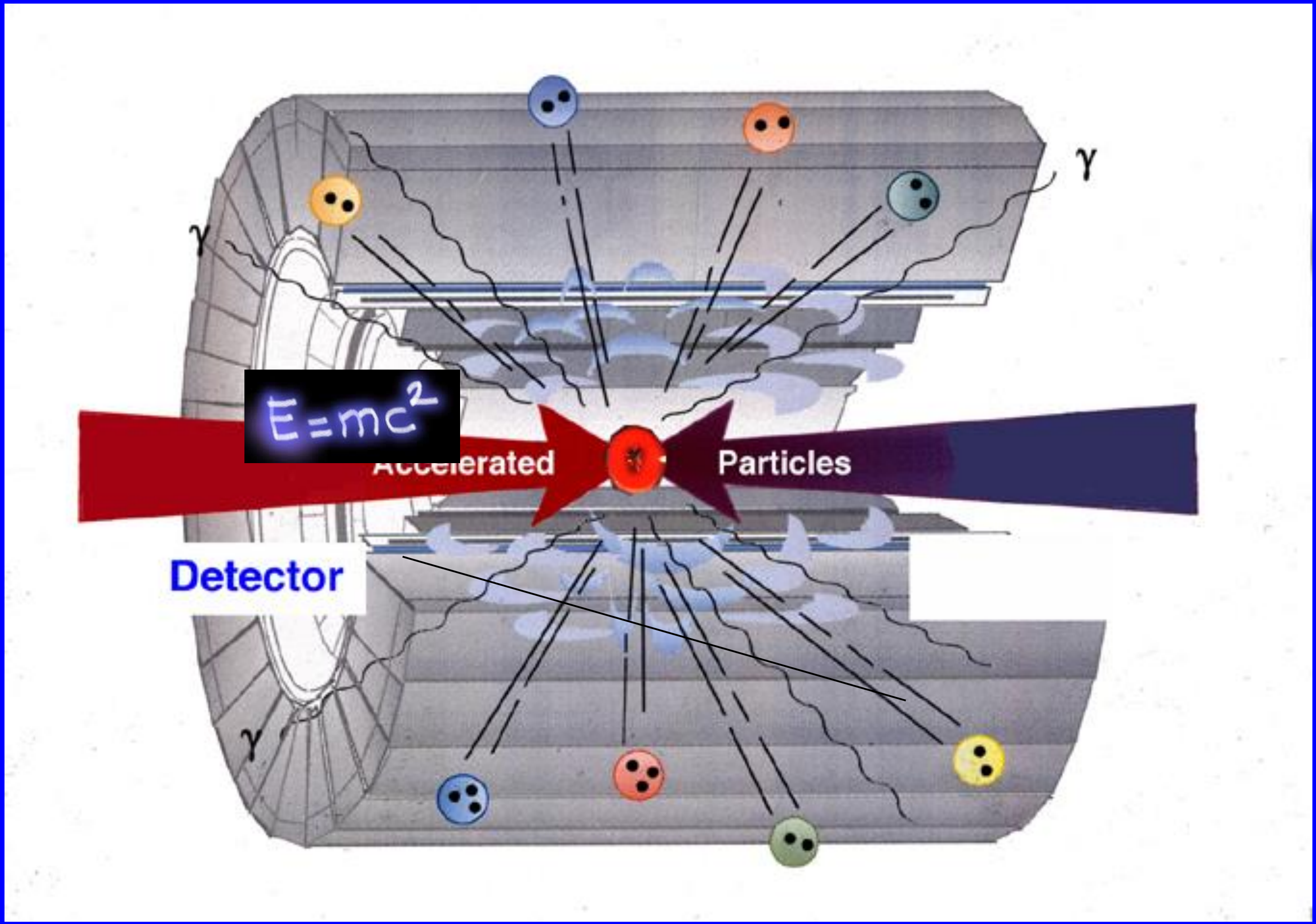
4 big experiments are installed at LHC











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

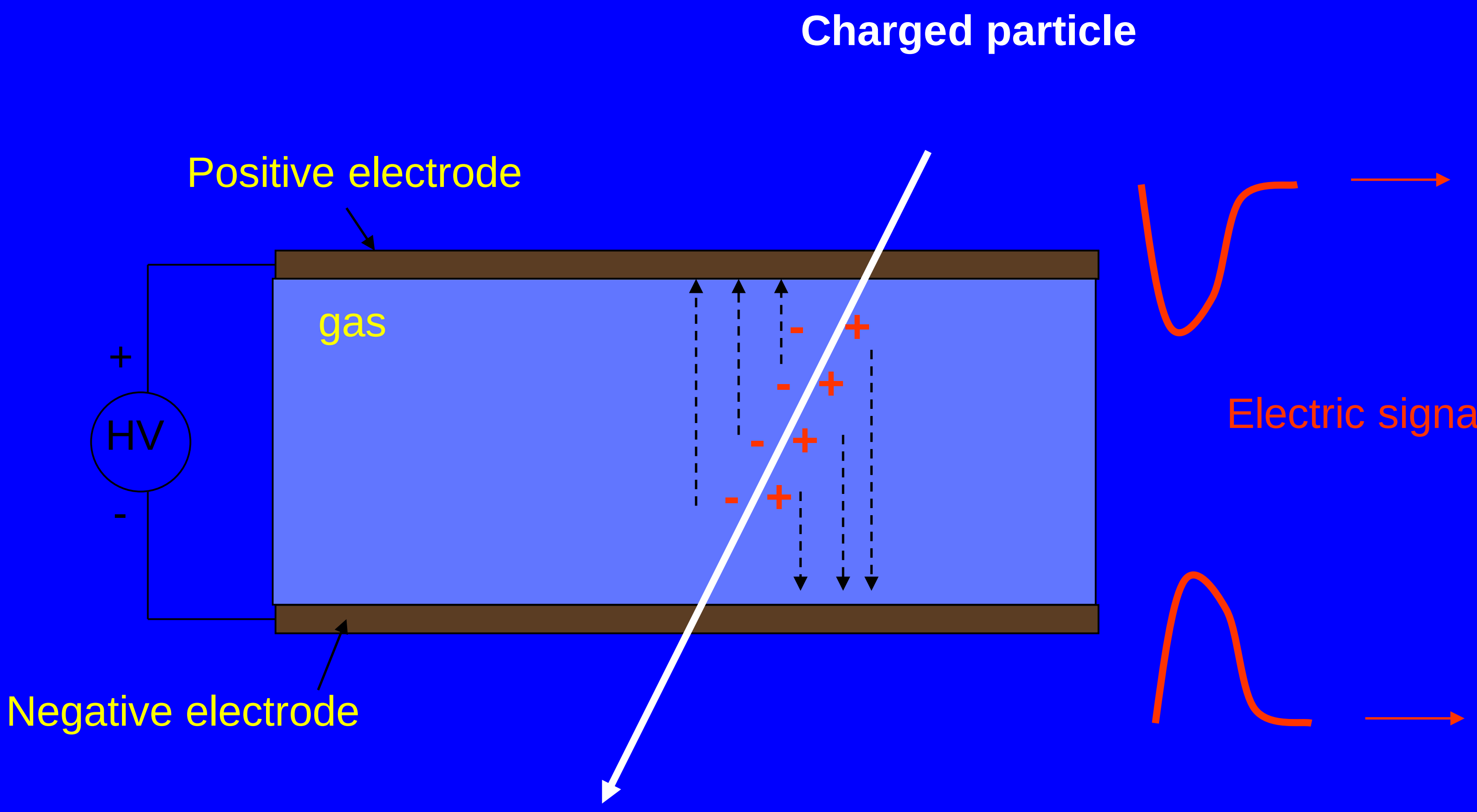
Solid state detectors (semiconductors, e.g. Si)
Gaseous detectors
Scintillators …

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

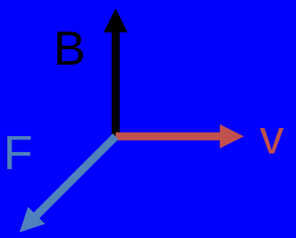


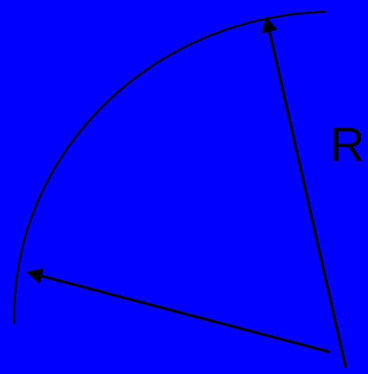
Momentum measurement

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

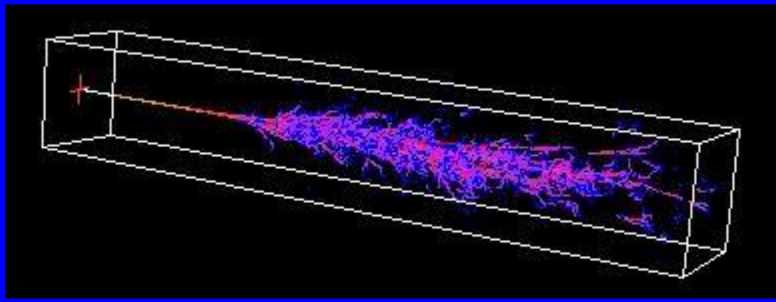
From the radius of curvature we calculate the momentum

Energy measurement

Particles are stopped

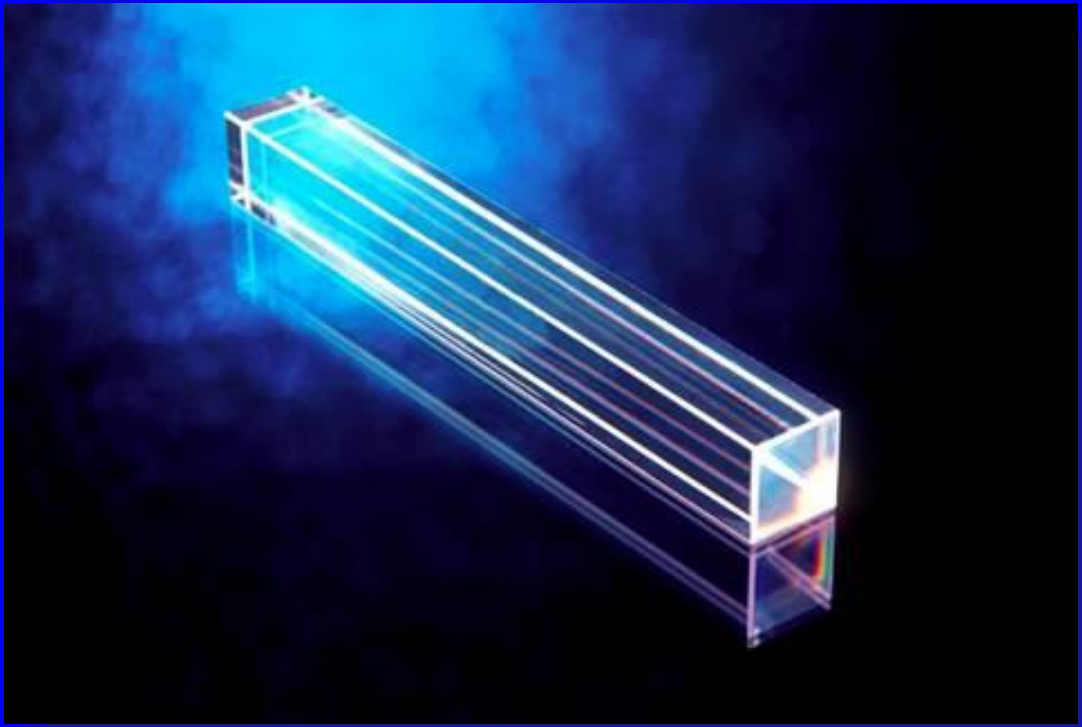
All their energy is absorbed

inside calorimeters



Scintillators

$PbWO_4$: heavy and transparent



Electromagnetic calorimeter

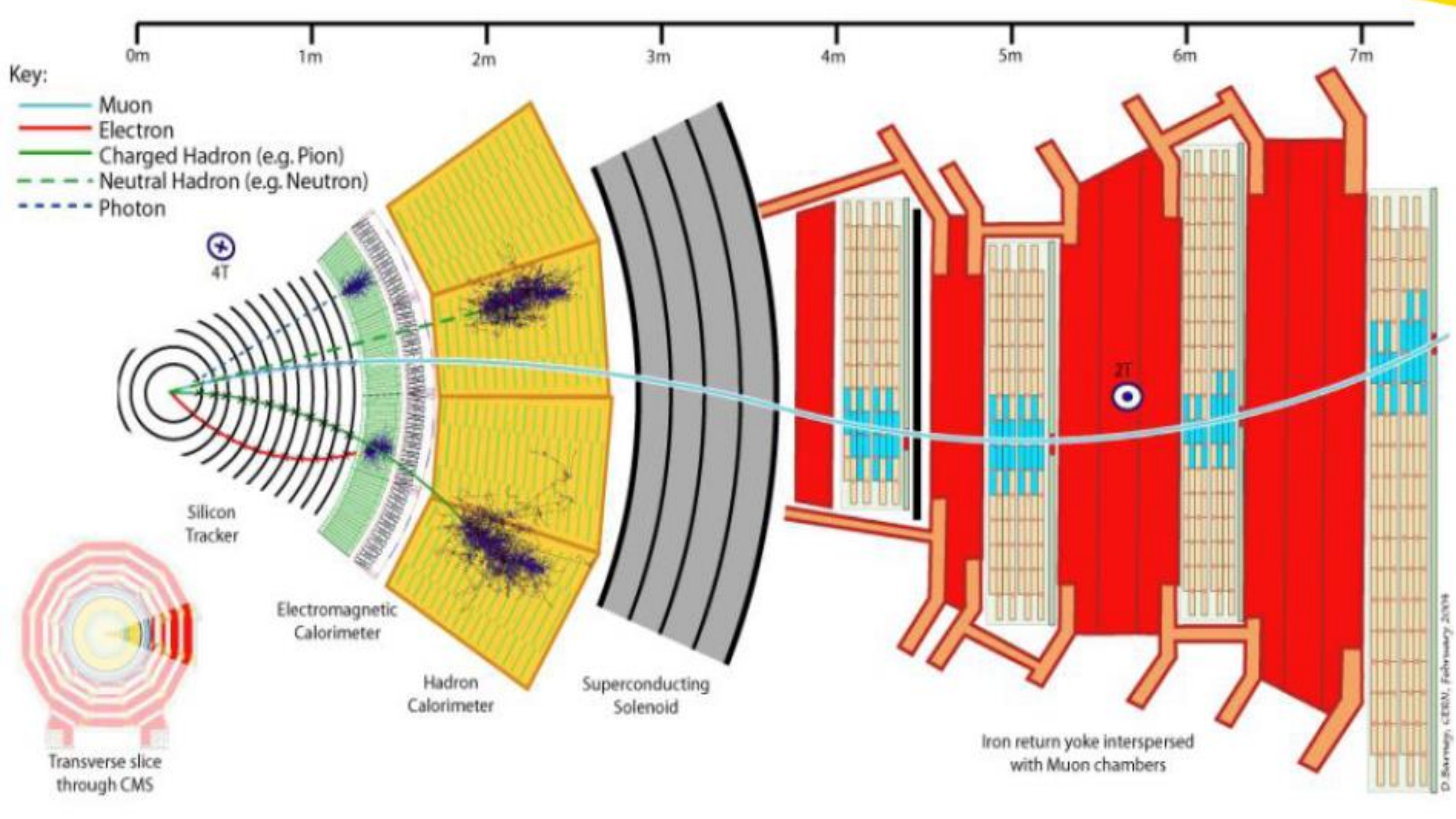
- Photons are converted into electron-positron pairs

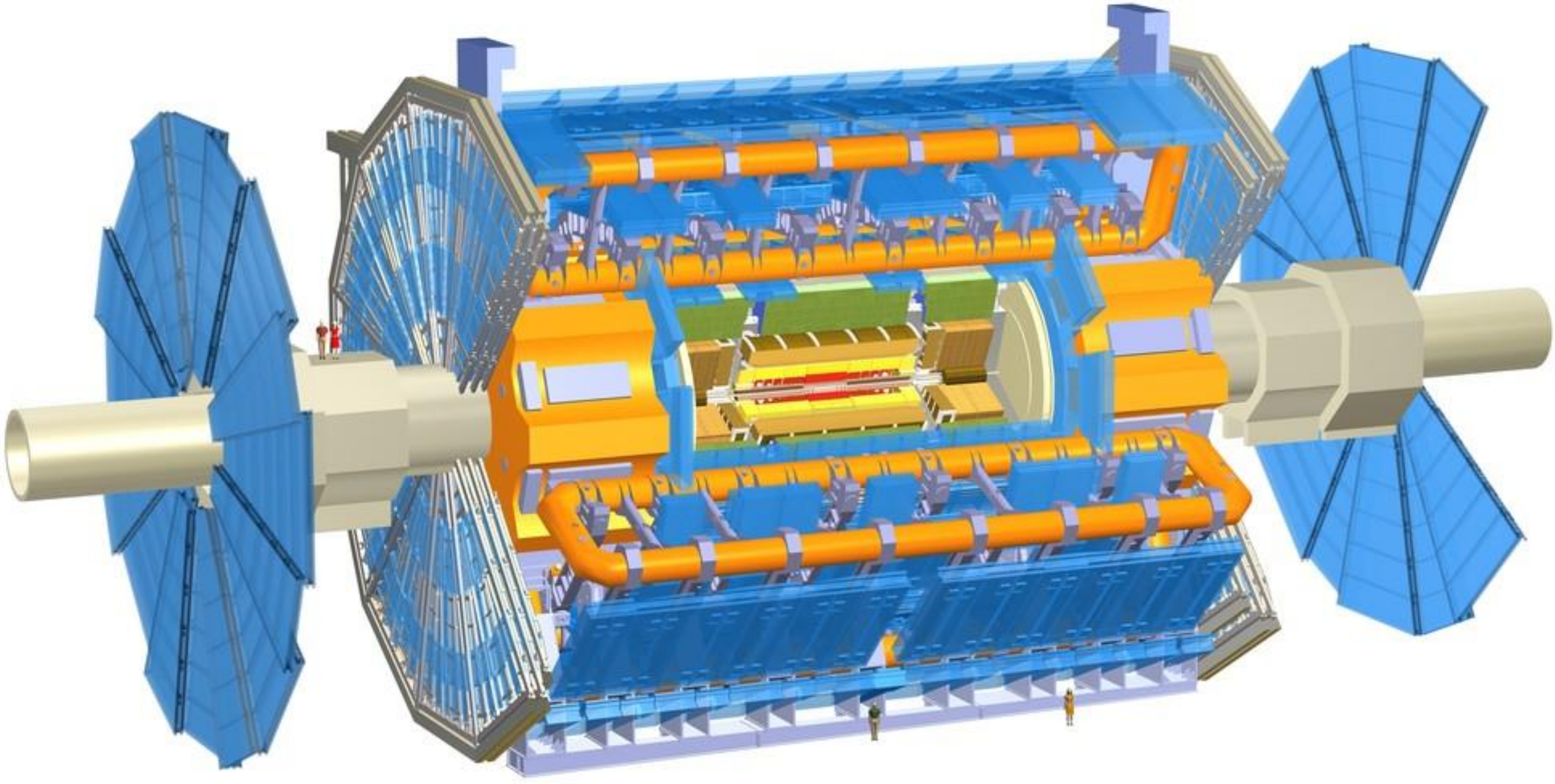
- Electrons excite the atoms of the crystal

- 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 phtons to electrons

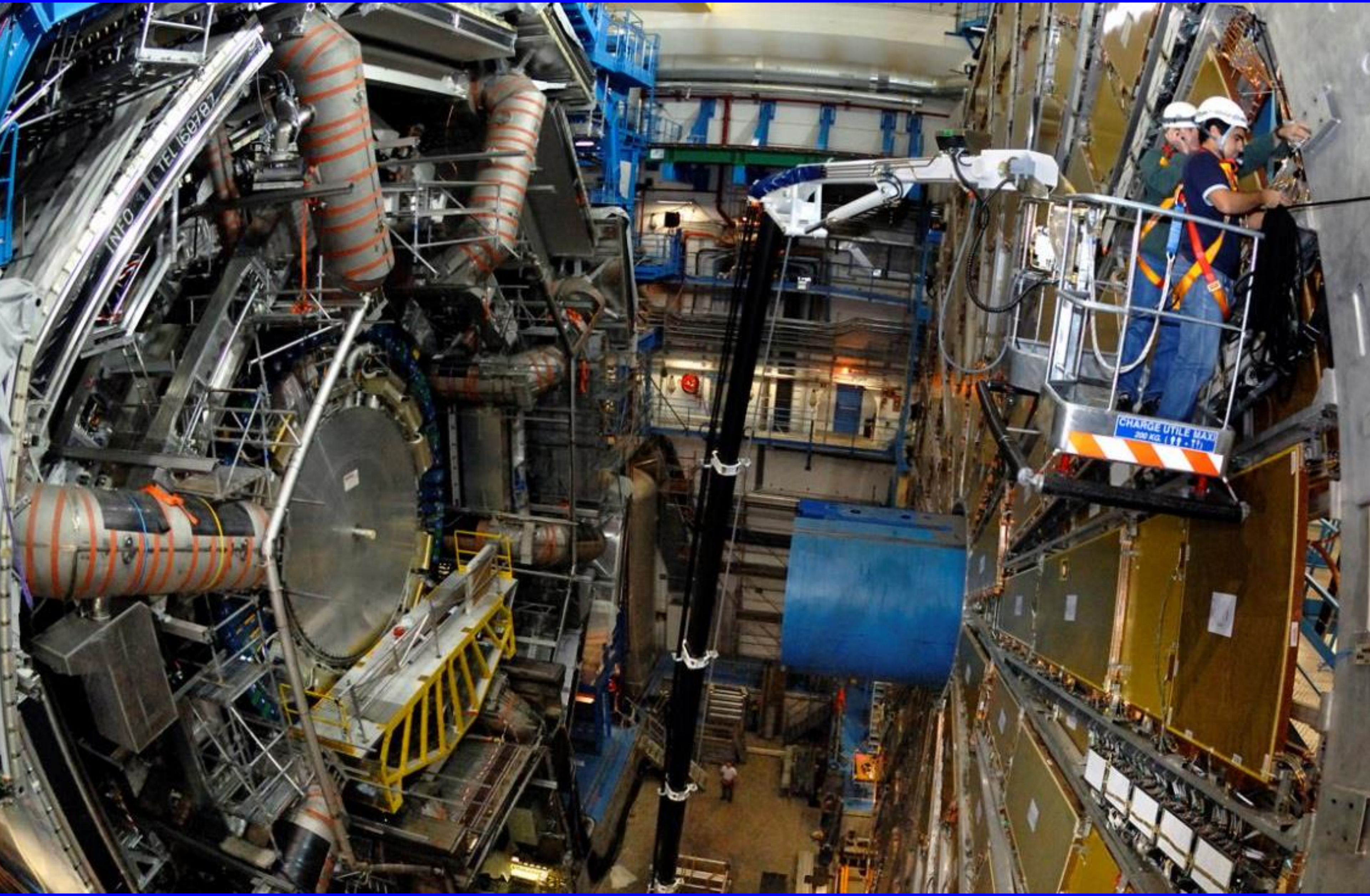
→ Electric signal


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS

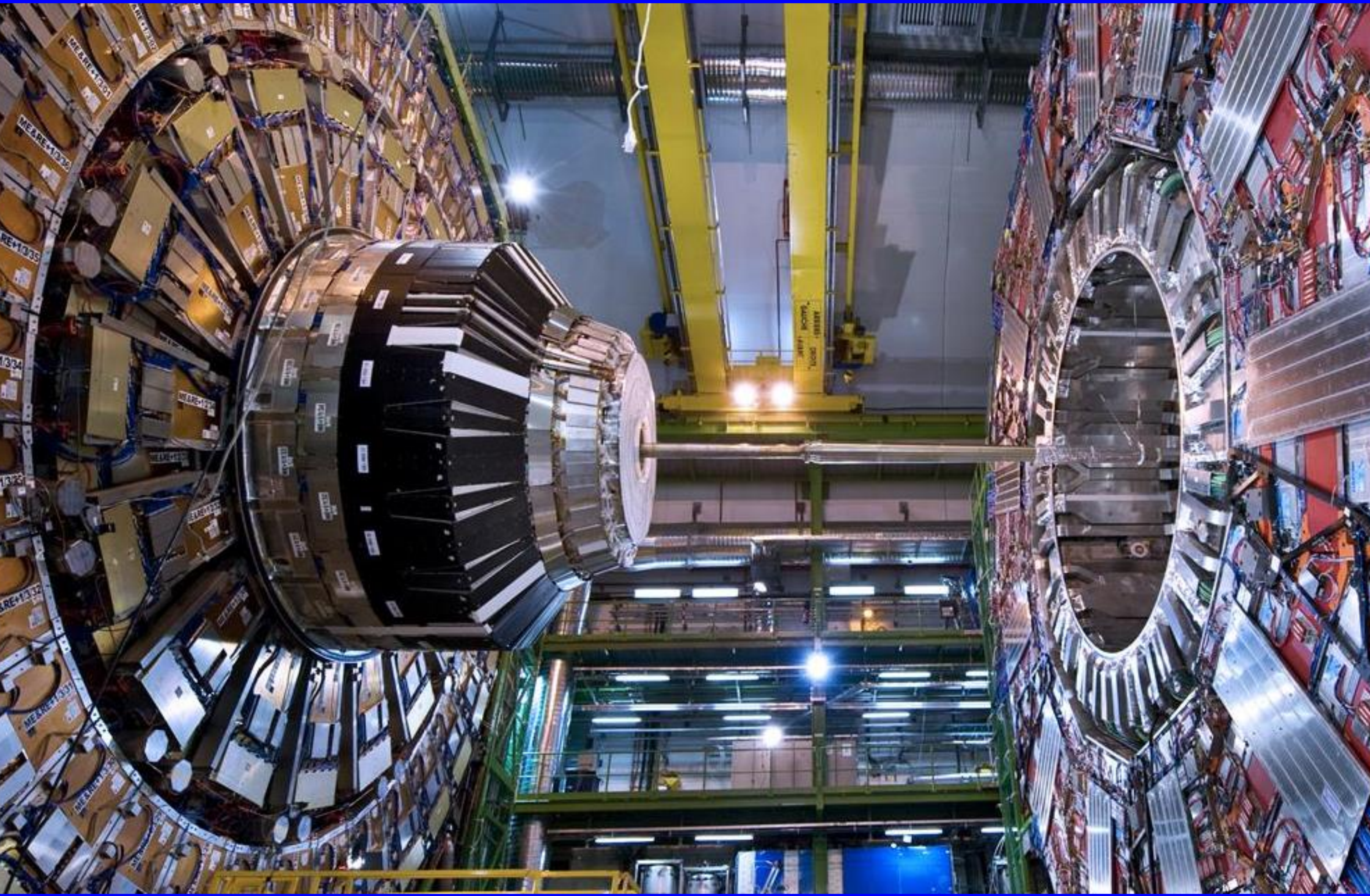


25 m x 25 m x 46 m 7000 tons

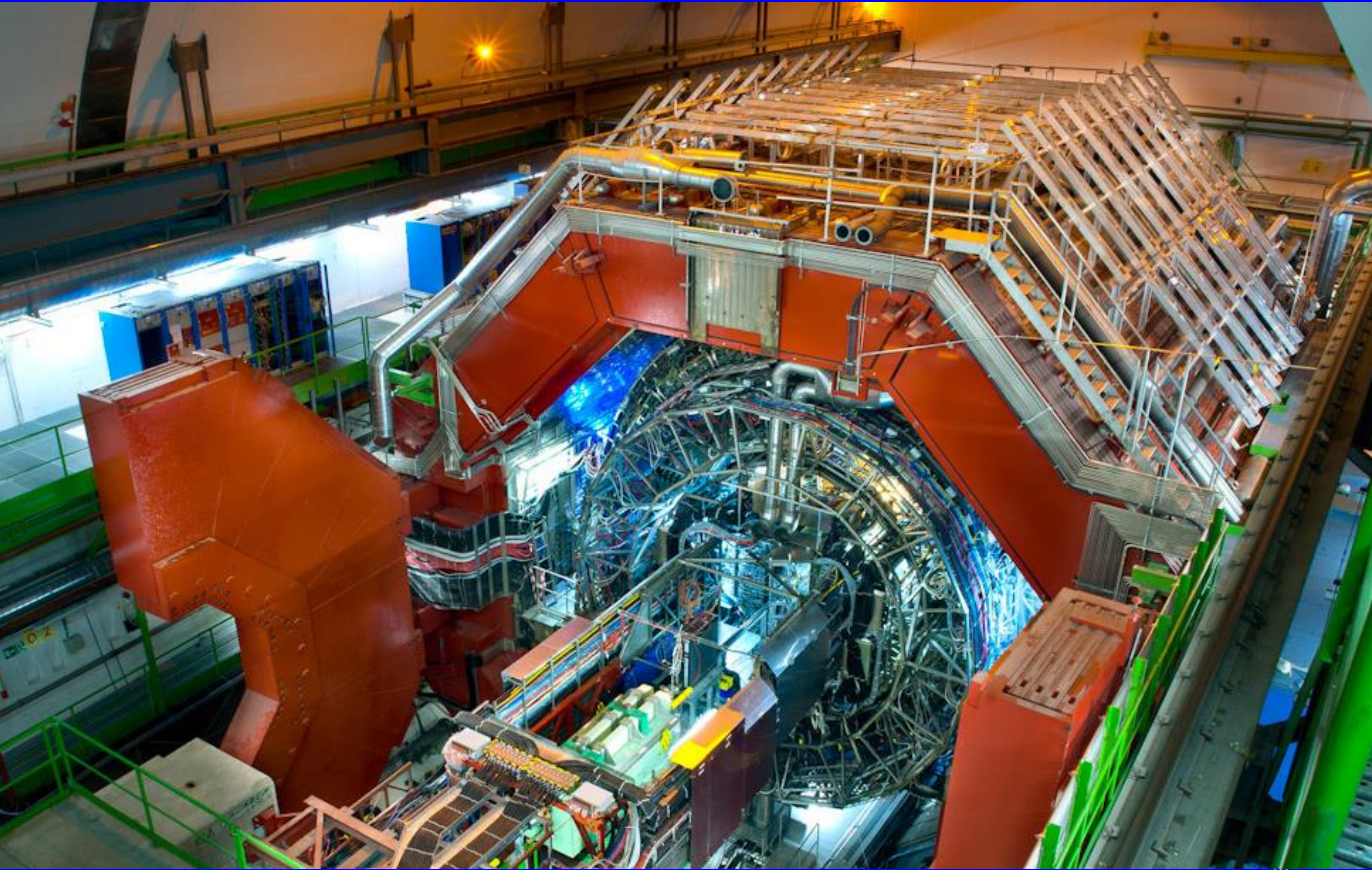
ATLAS : A Toroidal LHC Apparatus



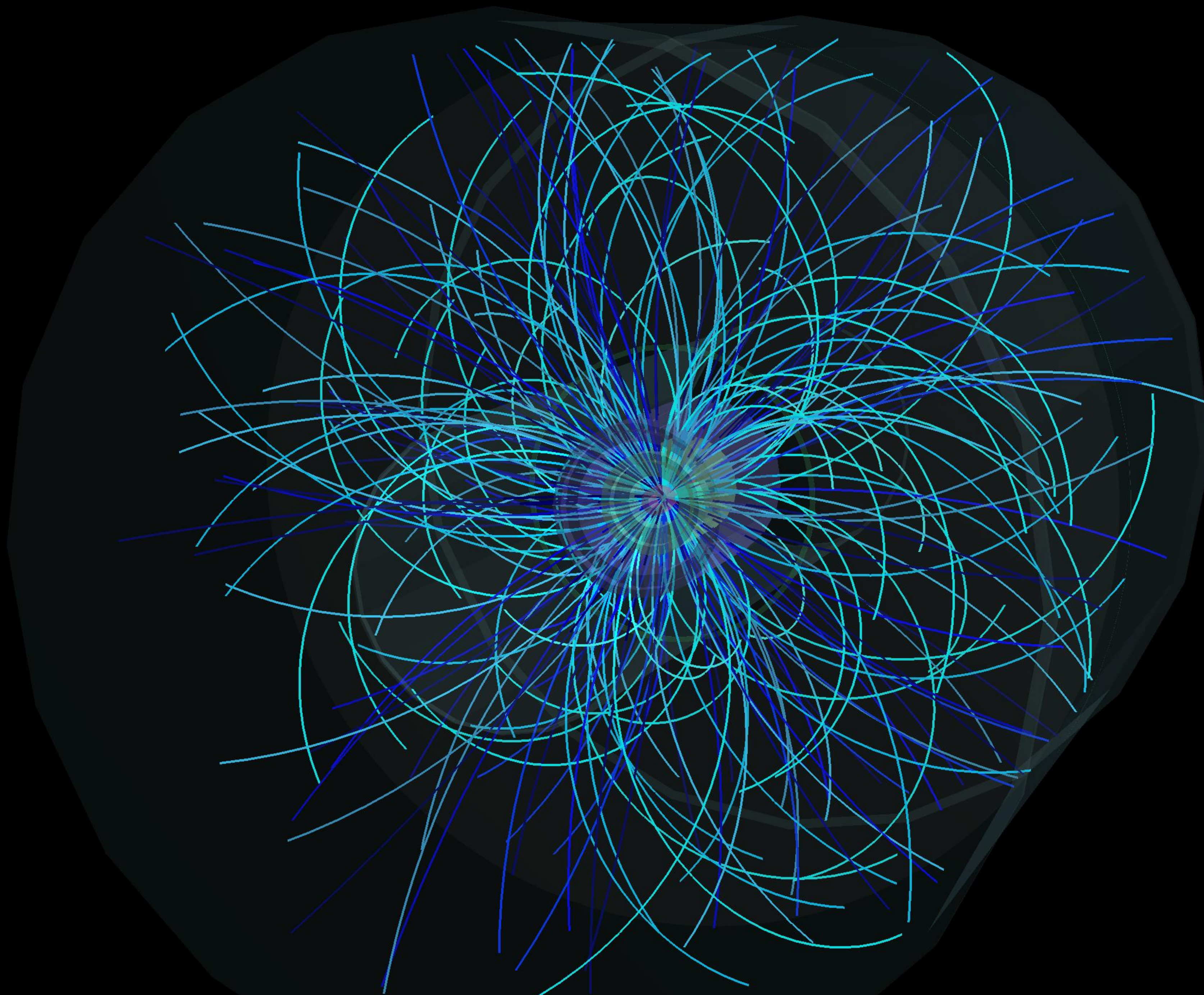
CMS : Compact Muon Solenoid



ALICE : A Large Ion Collider Experiment

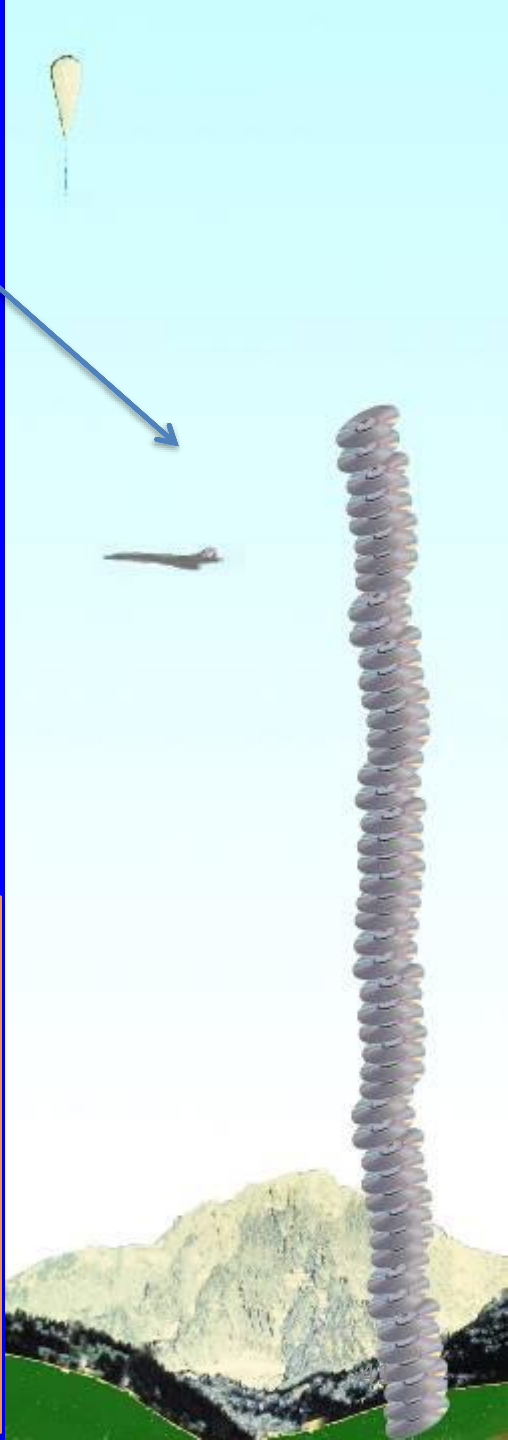


LHCb : LHC bottom (or beauty) experiment



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

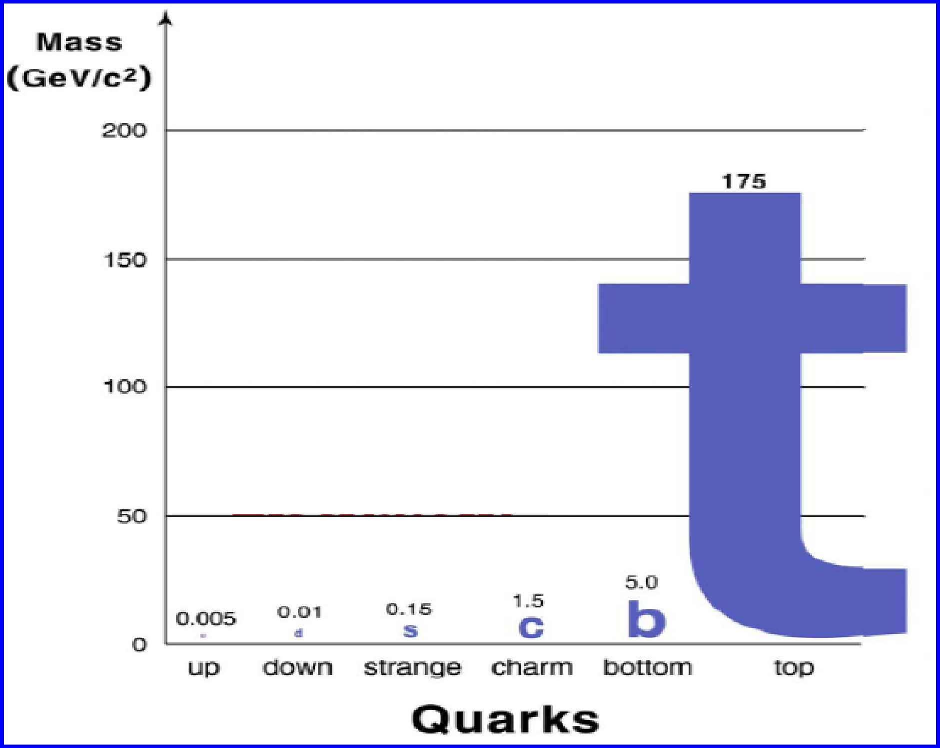
1 Petabyte (1PB) = 1000TB
Annual production of one LHC experiment

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 Models 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.

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

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

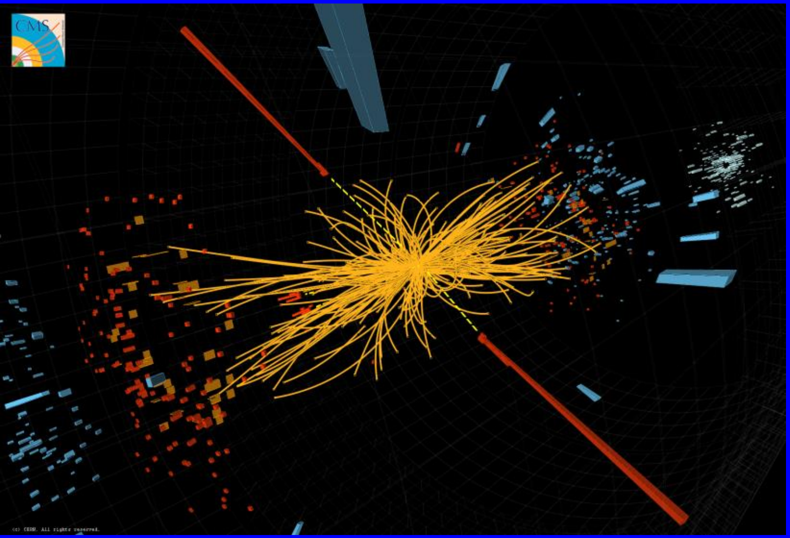
***Englert-Brout-Higgs-Guralnik-Hagen-Kibble** mechanism

Higgs update seminar – CERN - 4 July 2012

a historic day for CERN

Discovery of a new boson announced

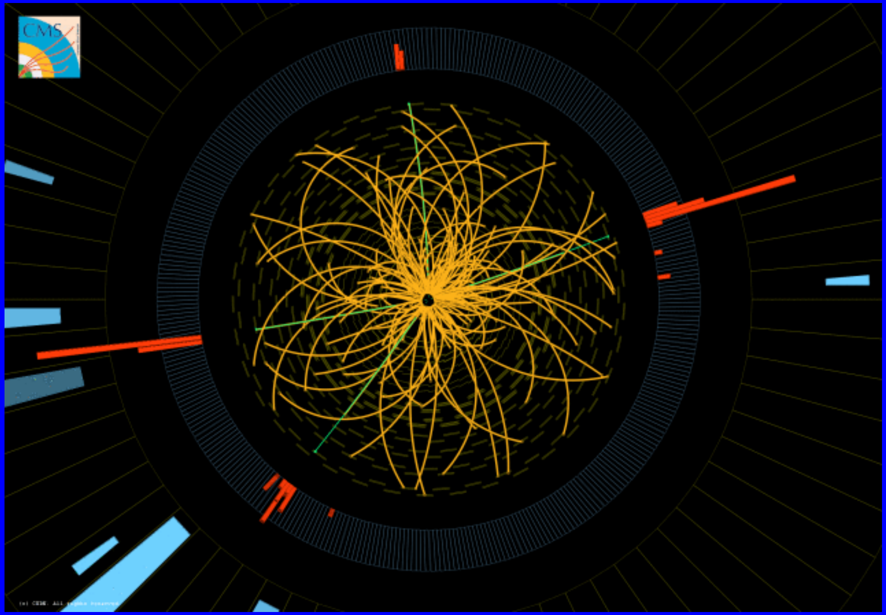
The Higgs boson is detected via its decays



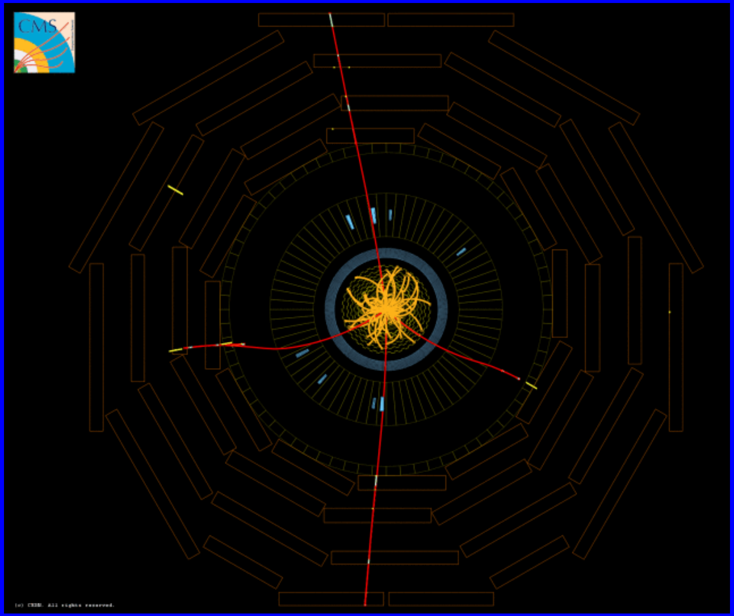
- H-> γγ
- H-> ZZ->μμμμ
- H-> ZZ->eeee
- H->WW
- H->ττ
- H->bb

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

Higgs candidate events

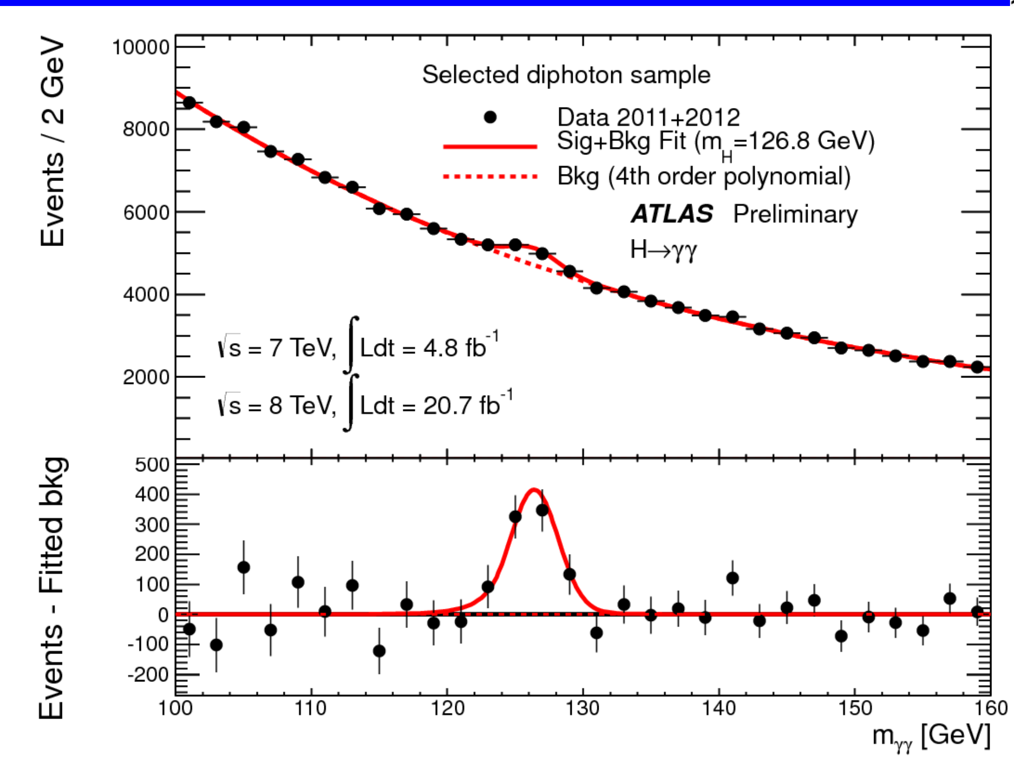


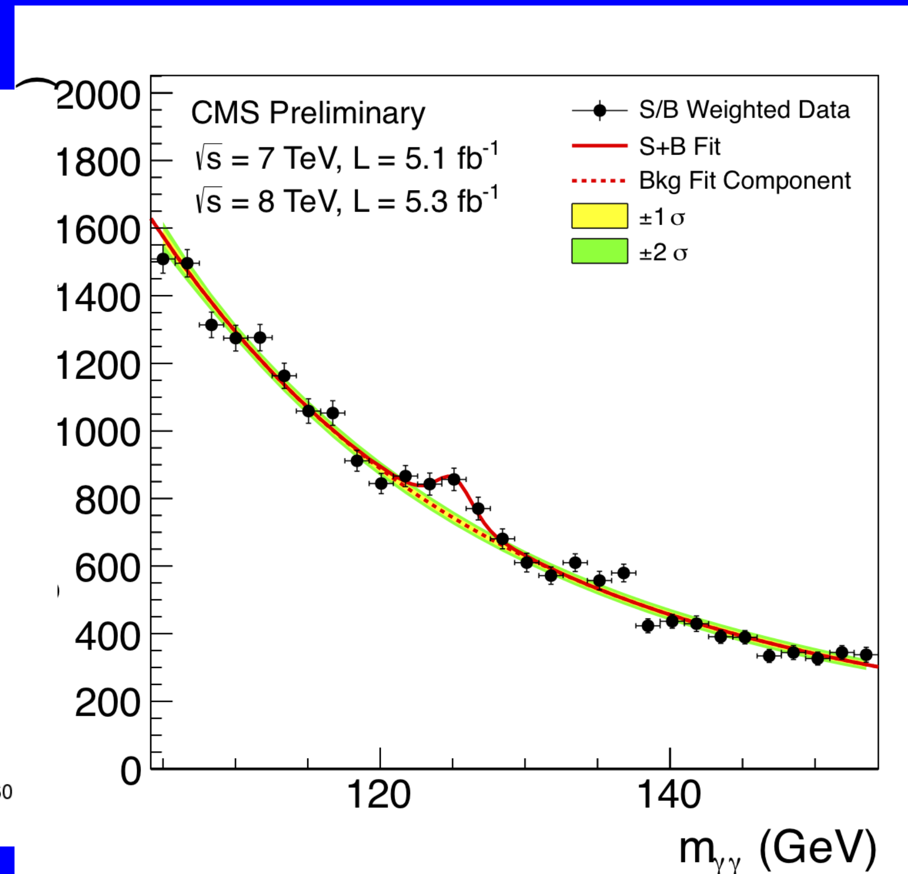
4 electron candidate Higgs event from proton-proton collisions at LHC



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





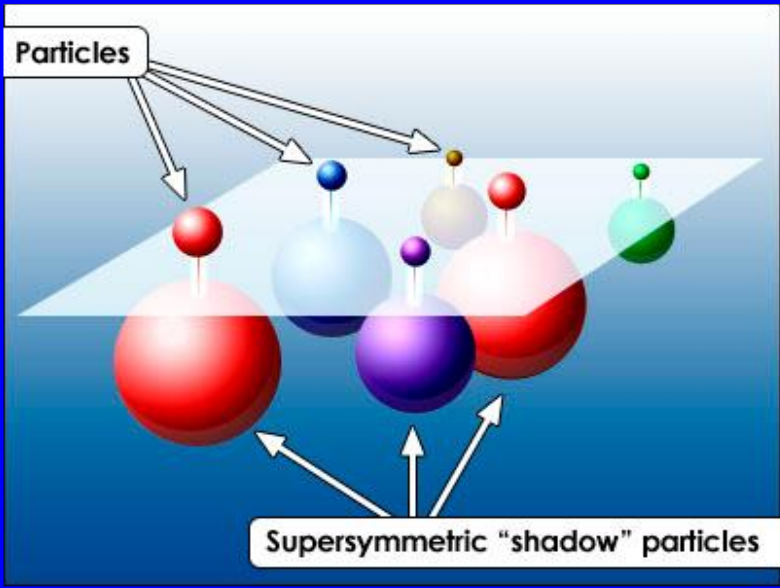
The peak seen after subtraction of the irredicible two-photon background is the Higgs

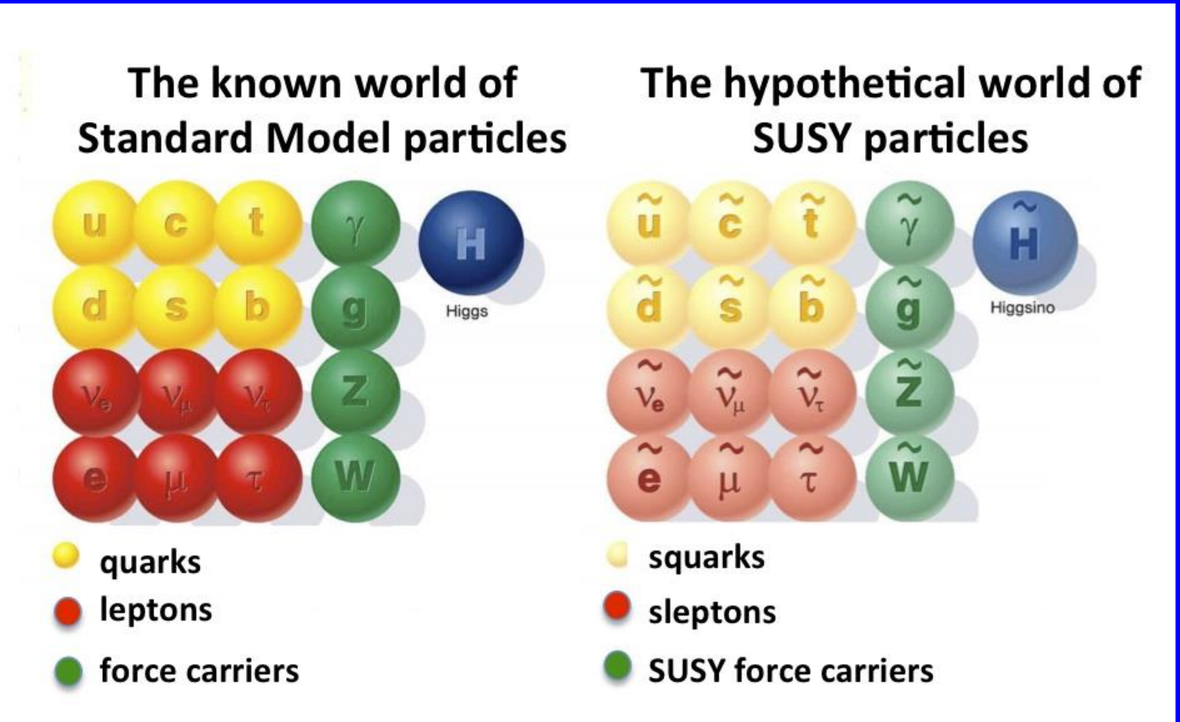
SUperSYmmetry (SUSY)

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)

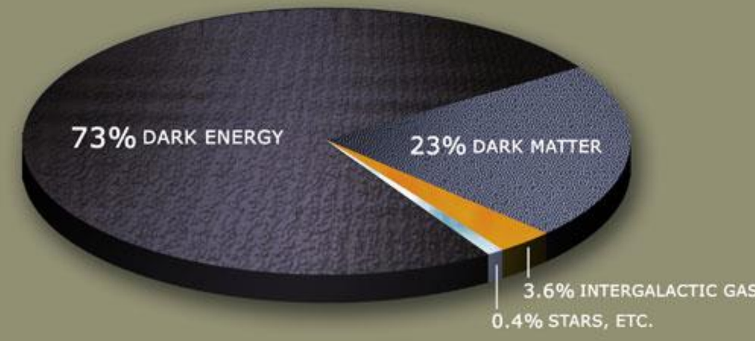




Every particle with spin s has its supersymmetric partner with spin s-1/2

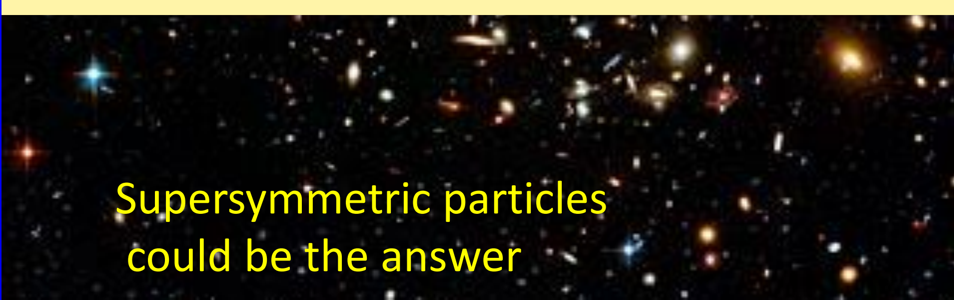
Quark (s=1/2) -> squark (s=0)
Gluon (s=1) -> gluino (s=1/2)

Dark Matter



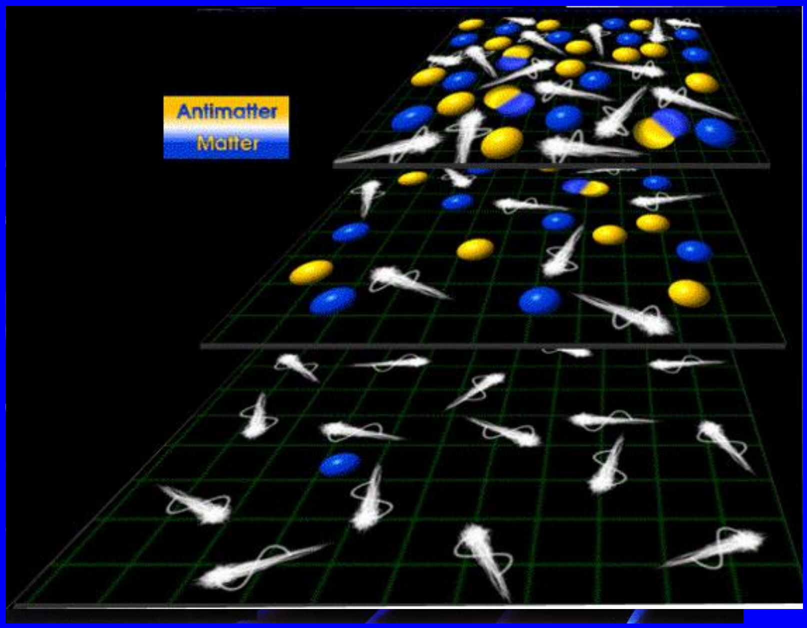
4 % only is the visible matter

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 ~ 0 :

quantity of matter= quantity of antimatter

t ~ 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

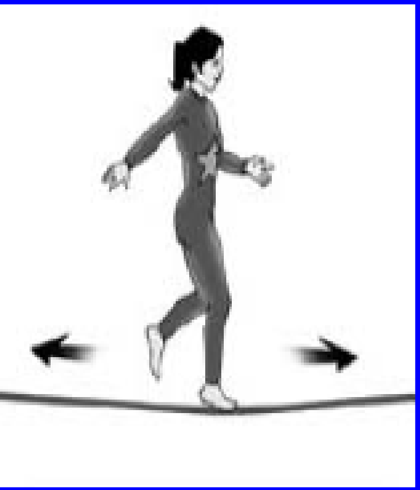
Why is our Universe made of matter only?
Is it because matter and antimatter have slightly different properties?
(such as mass, charge, ..)

- 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 it 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

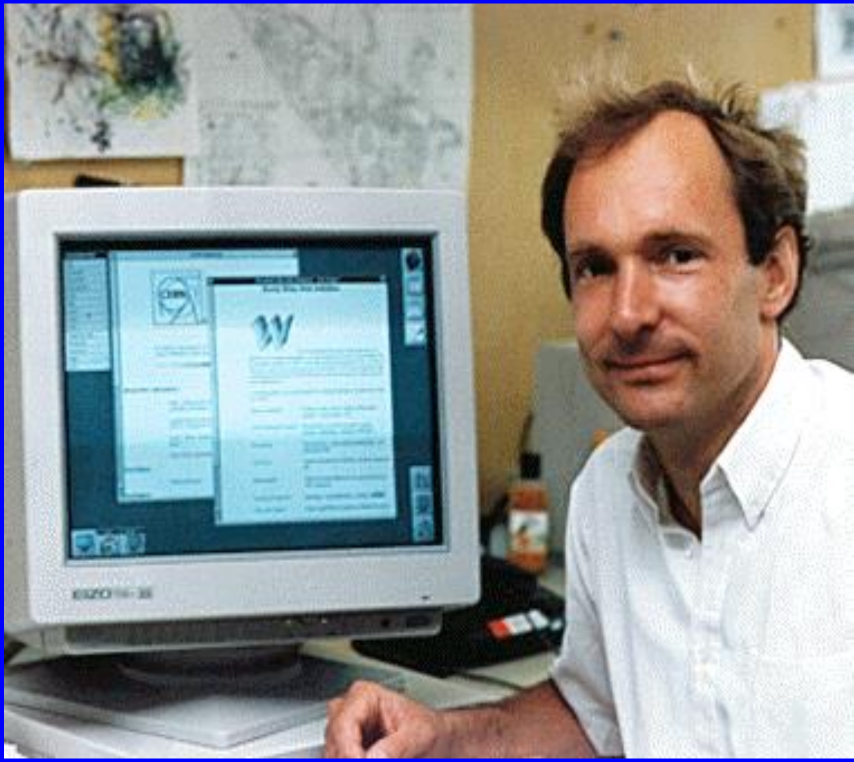
What next?

- The LHC had stopped between 2019 and beginning of 2022 for a planned, 3-year long shutdown (LS2)
- To allow upgrade work leading to the High Luminosity LHC (~2026)
- 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?

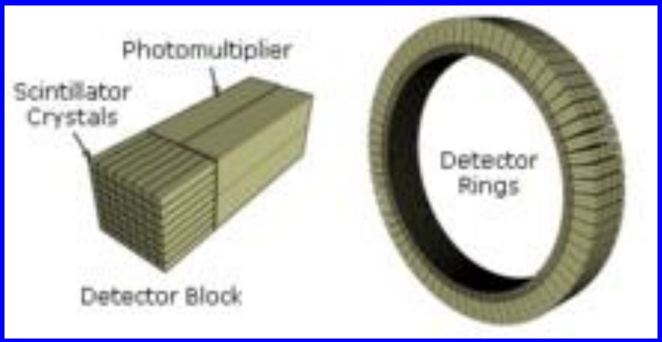
World Wide Web

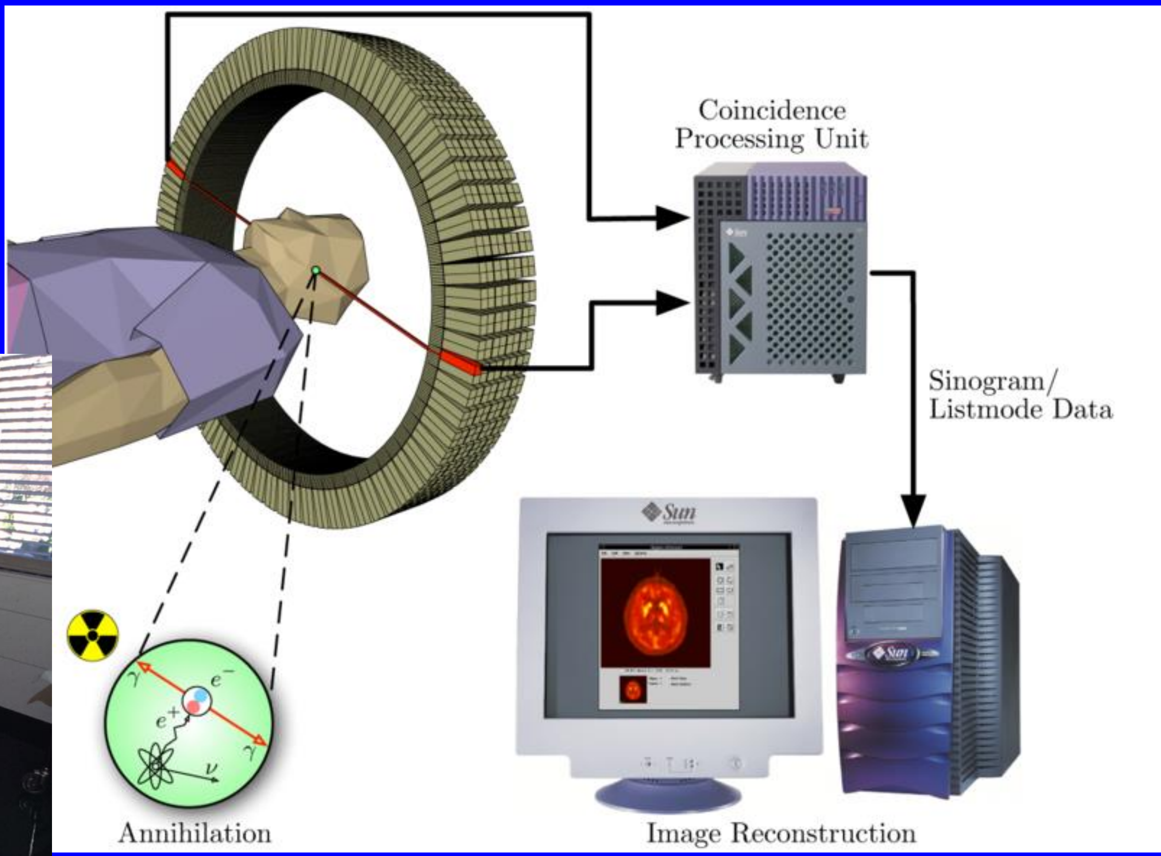
Invented by Tim Berners-Lee,
a CERN physicist, in 1989,
to meet the need of physicists in
Institutes all over the world for
automatic information sharing



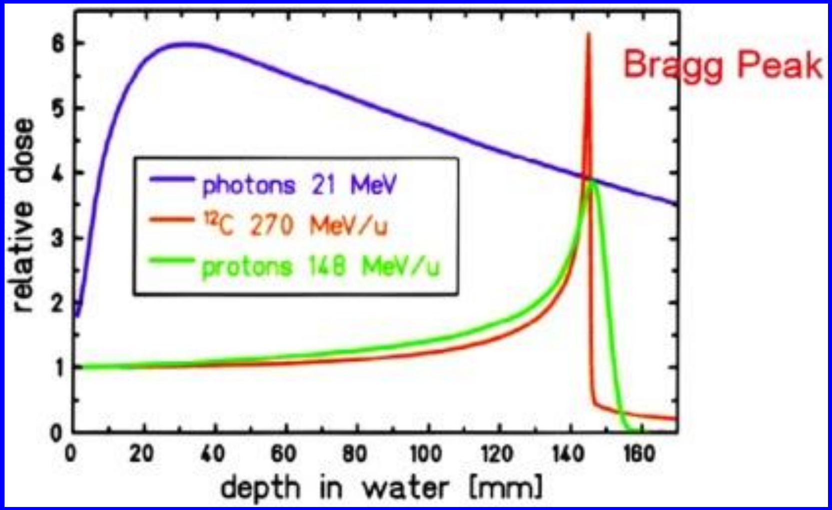
WWW combined with Internet
has changed our way of life

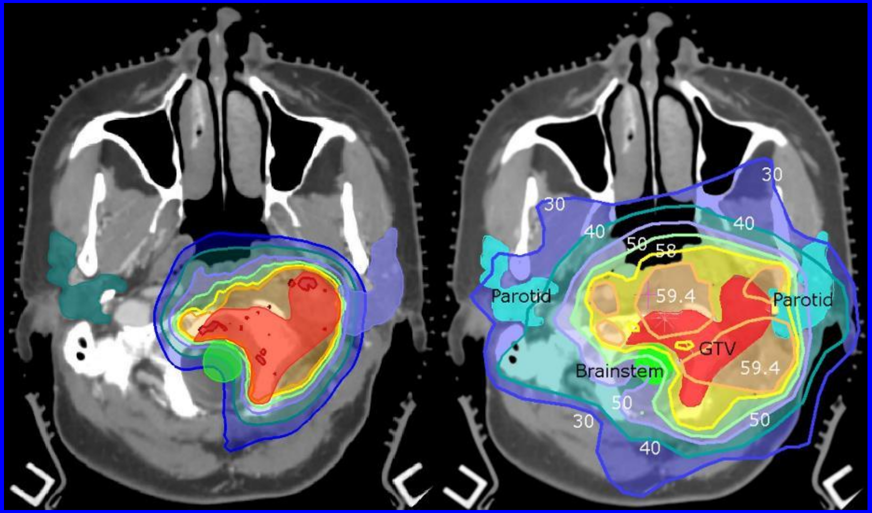
Medical application : Positron Emission Tomography (PET)





Medical application : Hadron Therapy





Hadron Therapy "ordinary" radiotherapy

The first touch screens were used at the CERN SPS controls

ANOTHER OF CERN'S MANY INVENTIONS!

CERN has often been the incubator for the development of innovative technologies but very few people know about the capacitive touch screens invented for the consoles of the SPS Control Room in 1973. The Bulletin interviewed their inventor, Bent Stumpe, who also developed the CERN tracker ball and the computer-programmable knob.

Bent Stumpe, inventor of the CERN touch screens, tracker ball and programmable knob. Here we see him with one the first touch screens developed in 1973.

A specific goal, a lot of motivation and the technical skills to do it: that's all you need to create something nobody else has ever done before. Back in the 1970s, the SPS was being built and its control room required the installation of thousands of buttons, knobs, switches and oscilloscopes to operate the machine. Frank Beck, newly recruited from the DD Division to be in charge of the central control hub in the SPS control room, asked Bent Stumpe for solutions to the following problem: how to build the hardware for an 'intelligent' system which, in just three console units, would replace all those conventional buttons, switches, etc.

In just a few days, the Danish engineer, also from the DD Division, came up with a (hand-written) proposal to build a touch screen with a fixed number of programmable buttons, a tracker ball to be used as computer-controlled pointing device and a programmable knob. Following this proposal, Bent Stumpe was recruited by the SPS Controls Group to develop

In a nutshell…


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 ΔEΔt≈h.